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A REVIEW OF INFORMATION USED AS THE BASIS FOR THE U.S. ENVIRONMENTAL PROTECTION AGENCY'S PROPOSED WATER QUALITY STANDARDS

prepared for

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NOTICE

This draft report was prepared as a technical document for reference use by California Urban Water Agencies and others in preparing their comments to the U.S. Environmental Protection Agency on "Water Quality Standards for Surface Waters of the Sacramento River, San Joaquin River, and San Francisco Bay and DElta of the State of California, January 6, 1994." This draft technical report is not part of the CUWA formal comments to EPA.

PREFACE

This report was prepared for the California Urban Water Agencies (CUWA) by The Metropolitan Water District of Southern California as a part of a CUWA review of the U.S. Environmental Protection Agency's proposed "Water Quality Standards for Surface Waters of the Sacramento River, San Joaquin River, and San Francisco Bay and Delta of the State of California (40 CFR Part 131)". The Metropolitan Water District of Southern California commissioned this report as a part of CUWA's overall review and evaluation of this standard. This report addresses the following scientific questions:

1) What is the scientific basis for the standards as represented by the background information prepared for the San Francisco Estuary Project's Workshops on managing freshwater inflow to the Bay?

2) What is the scientific basis for the standards as represented by the published results of the workshops (WRINT.SFEP 5)?

3) What is the scientific basis for the standards as represented by the San Francisco Estuary Project's publication entitled " Managing Freshwater Discharge To The San Francisco Bay/Sacramento-San Joaquin Delta Estuary: The Scientific Basis For an Estuarine Standard"?

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INTRODUCTION

The 1993 report from the San Francisco Estuary Project (Project) entitled " Managing Freshwater Discharge To The San Francisco Bay/Sacramento-San Joaquin Delta Estuary: The Scientific Basis For An Estuarine Standard" (Schubel Report) is the culmination of a series of workshops designed to develop an estuarine standard for the San Francisco Estuary. Prior to the first workshop held August 27-29, 1991, two papers were developed to function as background information for all participants and to theoretically provide an equal starting point for everyone. These two working papers are: 1) A synopsis of evidence presented to the State Water Resources Control Board in the Bay-Delta hearings on the functioning and benefits of the entrapment zone by David Fullerton, Resource Scientist, Natural Heritage Institute, dated June 13, 1991 (Appendix A) and 2) A discussion of the issues relevant to the entrapment zone in the San Francisco Bay Estuary by Wim Kimmerer of BioSystems Analysis, Inc.; Dave Peterson, Fred Nichols and Larry Smith of the U.S. Geological Survey (USGS); Alan Jassby of the University of California, Davis (UCD); and Lee Miller of the California Department of Fish and Game (CDFG), dated August 12, 1991(Appendix B). In addition, the third draft of the Status and Trends Report on Aquatic Resources in the San Francisco Estuary authored by Bruce Herbold, Alan Jassby and Peter Moyle of the University of California, Davis was available to all participants as a reference document. The correspondence (Appendix C) transmitting one of the working papers identifies the workshop as a "Workshop on the Entrapment Phenomena", thus it is important to remember that the focus of the workshop was on the entrapment zone.

SUMMARY OF FULLERTON'S PAPER

David Fullerton's paper was designed to summarize the testimony and evidence which was presented to the State Water Resources Control Board (SWRCB) during the first phase of the Delta Hearings in 1987. He states "... Evidence presented in the Hearings was remarkably congruent. Participants agreed on the basic functioning of the entrapment zone and the impacts on primary production of alternative locations within the Estuary. The primary disagreement centered on the appropriate standards to be used to place the entrapment zone so as to maximize phytoplankton concentrations in Suisun Bay. Also, as discussion moved away from primary production, to discussions of higher trophic levels, the level of uncertainty increased over the relationship between Delta outflow, the location of the entrapment zone and effects on the biota.

In general, the testimony and exhibits agreed that placement of the entrapment zone in Suisun Bay during the spring and summer months has major environmental benefits. The conjunction of the entrapment zone and the broad shoals of Suisun Bay leads to high concentrations of phytoplankton which provide food for young striped bass and other species and which provide support for a strong pelagic food chain generally."

Salient points from Fullerton's paper are as follows:

1. Phytoplankton species appear to be the dominant source of primary productivity in the Bay as a whole as a result of the filling and diking of most of its wetland areas.
2. Suisun Bay is considered an important area biologically because prior to 1977 major blooms of neritic diatoms were typical there each summer and fall. The reductions in

primary production levels since then have been of great concern.
3. Most scientists working on the problem believe that the conjunction of the entrapment zone with the shoals of Suisun Bay is the dominant factor leading to the high productivity of Suisun Bay and reduced outflow from the Delta moves the entrapment zone upstream in areas where conditions are not right for high phytoplankton production.
4. Prior to the 1976-77 drought, the prevailing theory was that lower flows would result in increased levels of phytoplankton production since reduced turbidity would increase the levels to which light could penetrate and thus increase production. Exactly the opposite happened. The 1976-77 levels of phytoplankton production was the lowest recorded to that time.
5. The current theory is that the establishment of an entrapment zone adjacent to Suisun Bay results in some type of optimum physical process that results in increasing the residence time of phytoplankton, minimizes the low turbidity area associated with decreased phytoplankton production, facilitates the transport of phytoplankton produced in the shoal areas to the channel areas, and flows higher than 25,000 cubic feet per second actually decrease the residence time and push the phytoplankton out of Suisun Bay.
6. The theory summarized in 5. above is supported by some important observations including: 1) phytoplankton production is positive in the shoals and negative in the channel, but phytoplankton in the channel can exist at high concentrations; concentrations are greater at the edge of the channels than in the center with tidal mixing apparently conveying phytoplankton produced in the shoals to the channel, 2) phytoplankton levels dropped during the extremely high flows of 1983, and 3) the summer phytoplankton bloom coincides with the increase in flows as the entrapment zone moves back into Suisun Bay with the first rains of the year.
7. Other theories on the fluctuations observed in phytoplankton productivity that have been explored and generally rejected as controlling factors include light penetration, nutrients and predation. However, it is important to note that Fred Nichols of USGS has postulated that an increase in the densities of marine benthic invertebrates in 1976-77 and most recently (1986) the Asian clam (*Potamocorbula amurensis*) may in fact be a major predatory factor since at the densities recorded this species has the capability to filter the entire water column of Suisun Bay each day.
8. Estimates of the range of flows which would place the entrapment zone adjacent to Suisun Bay differed during the Hearings. The question is difficult in that the entrapment zone cannot be exactly correlated with either outflow levels or salinity. But will vary with tides, wind and the recent flow patterns. A number of estimates of the flows necessary to place the entrapment zone adjacent to Suisun Bay were presented and range from 5,000-15,000 cubic feet per second depending on the presenter. P.B. Williams in his testimony proposed that a bottom salinity standard be set at 2 parts per thousand (ppt) to locate the null zone at approximately Chipps Island (74 kilometers from the Golden Gate Bridge). According to Williams, with the null zone at Chipps Island, the length of the entrapment zone would be about 10 miles (16.1 kilometers), putting it in Suisun Bay. **(Author's note: placement of the leading edge of the entrapment zone at Roe Island (64 kilometers from the Golden Gate Bridge) would place the majority of the zone downstream from the preferred shoal habitat areas in the Suisun Bay complex).**
9. Zooplankton populations have been statistically correlated with levels of chlorophyll a,

implying that zooplankton abundance is strongly correlated with primary productivity.
10. The most important zooplankton in the Pelagic food chain are the cladocerans, the copepods and the mysid shrimp *Neomysis mercedis*. Adult copepods, particularly *Eurytemora affinis*, and cladocerans are the first food taken by young striped bass. *Neomysis* consumes both *Eurytemora* and other zooplankton and phytoplankton. Striped bass switch to a diet dominated by *Neomysis* as they continue to grow. Numerous other fish species are heavily dependent on these species as food items.
11. All parties agreed that the distribution of zooplankton is closely related to salinity levels. Thus, the various species move upstream and downstream in accordance with the level of outflow and thus, salinity.
12. The dominate zooplankton in Suisun Bay were the copepods Acartia and *Eurytemora* and *Neomysis* in 1963. *Eurytemora* achieves its greatest abundance in the entrapment zone, but is also found upstream. *Neomysis* adults tend to live above the entrapment zone with young most abundant within it. *Neomysis* abundance increases in the spring, peaks in the late spring and early summer and declines sharply in the fall. The location and distribution of *Neomysis* is thought to be due to the interaction between vertical migration patterns of the shrimp, tidal flows, and the circular flows associated with the entrapment zone. **(Author's note: salinity is not mentioned as a controlling factor).**
13. In 1979, the copepod Sinocalanus was introduced to Suisun Bay. Since that time, the population of *Eurytemora* has been reduced. However, the total copepod abundance has shown no long term trend. Some estimates are that *Eurytemora* has been reduced by 90%.
14. Attempts have been made to correlate zooplankton abundance with changes in chlorophyll a, salinity at Chipps Island, temperature, or CVP-SWP export pumping rates. Results indicated that zooplankton abundance was most closely related to chlorphyll a. All important Suisun Bay zooplankton were found to be related to chlorophyll a, although the *Neomysis* relationship was not linear. *Neomysis* was also correlated with Delta outflow. The reason is thought to be the reduction in usable habitat as the entrapment zone moves upstream with reduced flows.
15. The point is made that primary production in Suisun Bay depends upon adequate flows to position the entrapment zone opposite the shoals in the Bay. Zooplankton production is dependent upon phytoplanton production. Thus, increases in *Neomysis* and other entrapment zone zooplankton will depend upon Delta outflow adequate to stimulate entrapment zone blooms. **(Author's note: the entire discussion on the lower levels of the food chain are based totally on the position of the entrapment zone and not specifically 2 ppt salinity.** The entrapment zone is characterized as a zone of turbidity maxima and lower salinities in the 1-6 ppt range.
16. When discussing higher trophic levels (fish), Fullerton indicates that the placement of the entrapment zone is the most critical factor which then allows the physical processes of the Estuary to develop the turbidity maxima, concentrate primary production, increase residence time of primary food organisms, and provide a transport and concentration mechanism for young fish. **(Author's note: the levels of salinity necessary to accomplish these physical processes is not mentioned).** The only variable mentioned is the flow necessary to provide transport for larval and juvenile fish and establish the location of the entrapment zone at a desirable location within Suisun Bay.

SUMMARY OF KIMMERER, et. al

Wim Kimmerer was asked to review the literature regarding the entrapment zone and provide a place to start discussions of the entrapment zone at the workshops. He developed a series of eight issues and then asked other knowledgeable scientists to comment on his initial review. This process resulted in the working paper that was developed for the workshop participants. The eight issues reviewed and commented upon by the co-authors are as follows:

1. What is the physical, chemical, and biological definition of the entrapment zone (EZ) in the San Francisco Bay estuary?

Physical: Kimmerer's assessment is that the conceptual model of the EZ is too simplistic based on what really happens. He questions a definite two-layer flow pattern but instead proposed an asymmetrical unidirectional flow velocity on each side of the tide. Also, the mixing processes and development of the turbidity maxima are much more complicated than originally thought and can be caused by a number of other factors. Dave Peterson of USGS concludes that the circulation patterns in the estuary are poorly understood and that a significant commitment of sampling gear and resources would be necessary to adequately describe it. Dave references Marlene Noble suggesting that approximately a dozen or so upward scanning acoustic doppler current meters would be needed to adequately extract the 3-D circulation structure from the background noise for tidal and subtidal frequencies given full exposure to tidal, river flow and wind events and regimes at Chipps Island. It is important to note that the idea of using a single salinity measurement to "define" the EZ is not realistic. Larry Smith of USGS prefers to use the terms null zone and high turbidity zone instead of EZ. The null zone is the landward extent of gravitational circulation as defined by low-pass filtered current measurements. It is a zone instead of a location because several factors make precise location impossible. These factors include local bathymetry, variations in the tides and wind, small variations in freshwater inflow, and measurements limitations of current meters.

Chemical: Kimmerer notes that the EZ is an area where there is a concentration of organic and inorganic materials as a result of particle settling velocities and organism swimming behavior. Dave Peterson indicates that in the summer/fall of most wet-intermediate-dry years (but not very dry years) the dissolved inorganic nutrient distributions in northern San Francisco bay show a minimum in concentrations when plotted with salinity in the region of the chlorophyll (phytoplankton) and turbidity maximum in Suisun Bay. This indicates the dynamics between photic and aphotic processes are shifted towards photic processes and, generally dissolved oxygen and pH distributions support this interpretation. Peterson concludes that the role of gravitational circulation in the creation of the turbidity maximum is very important and its role in maintaining the chlorophyll maximum is less certain.

Biological: Kimmerer concedes that a concentration of particles and organisms does occur in the EZ, growth rates of organisms may not be enhanced there. He also concludes that the EZ represents a rather small part of the total volume of the estuary, so elevated production there may represent a small part of total system production. Fred Nichols of USGS concludes that benthic invertebrate larvae can also be transported up estuary to the EZ in bottom currents driven by tidal flows and gravitational circulation. Larry Smith concludes that a zone of high phytoplankton concentration corresponds well to a high turbidity zone whenever particle sources, sinks, and densities are similar. He also suspects that zooplankton and larval fish maxima would roughly correspond to these same zones, because they have evolved mechanisms to make it so. Alan Jassby assumed that the purpose of this working paper was to summarize information on the organic carbon budget of the Bay pertinent to the role of the entrapment zone. Jassby concludes: 1) phytoplankton productivity in the channel is reduced by the presence of an entrapment zone, 2) shoal areas and the subembayment as a whole do have enhanced phytoplankton productivity when an entrapment zone is present. An entrapment zone has opposite effects on channel and shoal productivity. Since shoal productivity is dominant, the net effect is an increase in subembayment productivity as a whole, 3) the enhanced primary productivity due to the presence of an entrapment zone may have little effect on the overall supply of organic carbon. Primary productivity plays a minor role in Suisun Bay's organic carbon budget. The dominant source appears to be organic carbon from river discharge. Approximately 10% of the total organic carbon from riverine sources consisted of particulate organic carbon which is available for further consumption. Most of the particulate organic carbon is due to riverine phytoplankton or phytoplankton-derived detritus. Organic carbon introduced into the water from the practice of flushing waterfowl ponds may be a larger source than phytoplankton production. Stable isotope results indicate that at certain times, much of the particulate organic carbon in the EZ is of riverine origin. Also, bacterioplankton productivity can greatly exceed phytoplankton productivity. Variations in phytoplankton productivity due to positioning of the EZ may not be ecologically important and may have little effect on the overall magnitude of organic carbon sources, 4) the effects of entrapment on residence time of food particles is more important than the effect on primary productivity. The higher residence time of food particles increases the likelihood that the particles will become incorporated into the food web and not lost. The physical factors which increase the residence time does not increase the total amount of particulate organic carbon but acts to concentrate it in and near the EZ, and 5) Since the overall carbon supply is not significantly enhanced by the EZ, increased consumption of particles in the EZ may be at the expense of downstream food webs. Based on estimates of substrate oxygen consumption and benthic respiration in the Bay, then the carbon that comes into the northern bay is consumed in the northern bay. If material is not trapped in Suisun Bay, then, perhaps it enters the food web downstream. The location of the EZ in Suisun Bay may be reducing the food sources available to San Pablo Bay. The entrapment zone thus results in a spatial redistribution, but not an increase, of food sources within the Bay. **(Author's note: an increase in the volume and/or efficiency of substrate oxygen consumption by benthic invertebrates (i.e. increases in Asian clam populations) could have very detrimental effects on those species of plants or animals whose food web is sensitive to organic carbon fluctuations).**

2. What components of the estuarine ecosystem (i.e. species, food web, or habitat) are significantly affected by processes occurring in the EZ?

Kimmerer concludes that the data available do not support the hypothesis that the EZ provides for a greater growth rate or avoidance of predators since there have been no demonstrated differences in growth rate for organisms inside and outside the EZ. Also predators are found inside the EZ. He concludes that the primary advantage to an organism with the presence of the EZ is reduced transport out of the estuary. Fred Nichols of USGS feels that flow conditions affect the distribution and species composition of benthic invertebrates depending on the salinity (greater than 5 ppt for a sustained period of greater than 16 months).

3. To what extent are particles and populations concentrated by gravitational circulation, and to what extent by other physical processes such as exchange between shoals and channels coupled with wind-driven resuspension?

Kimmerer concludes that the dominant means of producing maxima in zooplankton, chlorophyll, some phytoplankton species, and turbidity is gravitational circulation, although other mechanisms (i.e. tidal exchange, recurring tidal eddies, sills) may be important at some times and places. Larry Smith of USGS cites two papers that suggest the the summer salt balance in the northern reach, or the mean mixing of fresh water seaward, can be maintained almost entirely by processes other than gravitational circulation. These processes are tidal pumping and trapping. Tidal pumping refers to the horizontal asymmetry of tidal and net currents that leads to later and longitudinal exchanges among water masses. Tidal trapping refers to the isolation of a water mass in an off-channel area during part of the tidal cycle and subsequent release of the mass later. Tidal pumping and trapping mechanisms can increase water residence times in the estuary and when coupled with wind-wave action increase the resuspension of sediments in the shallows which result in the accumulation of particles in channels adjacent of large off-channel areas. The accumulations of particles in the channels are subsequently carried landward to the null zone by gravitational circulation and result in a high turbidity zone. Smith cites Ray Krone's seasonal sediment zone concept in which the source of sediment for the high turbidity zone in the summer originates from sediment deposited in San Pablo Bay in the winter and is moved upstream by the processes described above.

4. To what extent is the concentration of biota in the EZ caused by physics, and to what extent by biology, e.g. altered growth rate within the EZ, trophic interactions, or behavior?

Kimmerer concludes that the concentration of biota in the EZ is a result of behavioral adaptations designed to prevent flushing out of the estuary and to some extent providing and increased opportunity for efficient foraging, although no increase in growth rates have been observed for fish feeding within versus outside the EZ. He also notes that freshwater zooplankton species transported to the estuary do not concentrate like those species native to the estuary. Fred Nichols of USGS notes that growth rates of one clam species appeared to be related to the seasonal maxima in pelagic and benthic diatoms in the vicinity. Lee Miller of CDFG describes the early life history of striped bass and concludes that they use the EZ as a mechanism to avoid transport out of the estuary although the percentage of larval and young striped bass associated with the EZ is small relative to the total population size. He cites no differences in growth rates. The presence of the EZ does concentrate a number of important prey items for striped bass. Miller also suggests that high outflows tend to distribute striped bass larvae over a greater area where higher average bottom salinities exist and primary prey items like *Eurytemora* concentrations are higher than in fresh water. Miller further postulates that the accidental introduction of the Asian clam, *Potamocorbula amurensis* has been the cause of a major decline in the concentrations of *Eurytemora* in the EZ. Finally he notes that an entrapment situation is not necessary for striped bass and cites populations in freshwater that are sustained without an EZ.

5. How do location and the timing and extent of movement of the EZ affect ecosystem components?

Kimmerer concludes that the longitudinal location of the EZ may play a role in the abundance of *Eurytemora* and *Neomysis* with lower abundances noted when the EZ is located in the Delta. He also notes that there is possible relationship between abundance and the volume of the EZ. Kimmerer speculates that the complex topography in eastern Suisun and Honker bays causes eddies or other persistent circulation features that increases residence time and abundance. Fred Nichols of USGS notes that the effects of the physical processes within the EZ on the structure of the benthic community has not been studied.

6. Do any effects of position of the EZ occur because of topography, or through correlates of EZ position, e.g. freshwater flow, entrainment, or inputs of nutrients or organic matter?

Kimmerer concludes that the effects of position of the EZ depends mainly on topography, i.e. on the presence of shallow water adjacent to the EZ. Position of the EZ depends mainly on freshwater outflow. The degree of stratification and presumably the strength of entrapment within the EZ presumably depends on freshwater flow, since the asymmetry of ebb and flood tides would increase as freshwater flow increases. He believes that an upstream location of the EZ would increase the vulnerability of some species to export pumping. Fred Nichols of USGS indicates that the benthic invertebrate communities of San Pablo and Susisun Bay are quite different, but under prolonged periods of low flows, the constriction at Carquinez Strait ceases to be a barrier to upstream transport of benthic invertebrate larvae. The introduction of *Potamocorbula amurensis* has created a biological barrier to interchange of benthic invertebrate communities between the bays presumably by preying on larvae transported upstream.

7. How can measurements of salinity or electrical specific conductance be used as an index of EZ position? Are better indices or measurements available?

Kimmerer concludes that the location of the EZ could be determined by taking a series of vertical profiles of longitudinal net velocity where the upstream edge of the EZ would be at the null zone where the net velocity at the bottom would be zero. Measuring net velocities is very difficult and not considered feasible. He suggests an operational definition of EZ position is needed. He suggests alternative operational definitions could be based on the turbidity maximum, the salinity difference between surface and bottom, and selected ranges of salinity or electrical specific conductance. The location of the turbidity maximum is the operational definition most closely related to the concept of entrapment, however there are two major drawbacks. These are: 1) other sources of elevated turbidity and 2) differences in turbidity among stations must be determined. This method requires a large number of measurements, however *in situ* transmissometry or nephelometry with an on-deck readout would avoid the problem but a longitudinal transect would be required. Salinity gradient from surface to bottom has been used to estimate EZ position by assuming that the EZ occurs where the gradient decreases to zero in an upstream direction. However, a vertical gradient is not necessary to produce entrapment, since the ebb-flood asymmetry in flow velocities is produced mainly by the longitudinal salinity gradient. The use of salinity needs to be calibrated against other indices of EZ position. **(Author's note: a range of salinity or electrical specific conductance is suggested as an operational definition for the location of the EZ).** Surface salinities are suggested but they have a number of problems relating to EZ position as stratification increases with flow and thus become less representative of the water column. Samples could be taken at the bottom or some fixed depth to solve this problem. Dave Peterson of USGS noted that the question assumes that the connection between salinity and circulation has been documented, which he says has not.

8. To what extent can the EZ be positioned by different freshwater flow scenarios?

Kimmerer presents his first outflow versus position of EZ equation, which has changed since this paper was written. Dave Peterson of USGS states:

"Before attempting this question a more general question might be: to what extent can the salt field be positioned by different freshwater flow scenarios?

On a monthly time scale, the surface salinities near the channel sites can be estimated roughly ± 1 salinity unit as a function of delta flow. Estimates from some near-bottom time series are also available. To the best of my knowledge time series observations from shoals are almost none to non-existent.

Given the above, then, the circulation remains to be coupled to the salt field over a wide range of time & space scales. Until this is more complete, utilizing EZ or related concepts for purposes of estuarine management seems premature."

SUMMARY OF THE WORKSHOP

The first of two workshops was held August 27-29, 1991 in Tiburon, California. The workshop was facilitated by Dr. J.R.Schubel of the Marine Sciences Research Center, State University of New York at Stony Brook. A report of the workshop proceedings entitled "An assessment of the entrapment zone and other estuarine surrogates for managing freshwater inflow to the San Francisco Bay Estuary" was entered as WRINT.SFEP.5 in the 1992 SWRCB hearings.

Exhibit 1 of the report outlines the pre-workshop goals as:

1. To critically review the current understanding of entrapment processes and phenomena in San Francisco Bay and to assess the importance of the entrapment zone (EZ) to the estuarine ecosystem. The workshop will examine how entrapment occurs, to what extent it occurs in a single, well-defined EZ, how various freshwater flow scenarios affect the position of the EZ and how EZ position affects biological components of the estuary. Participants will identify scientific areas of agreement and disagreement.

This assessment was designed to provide the basis for pursuing the remainder of the goals of the workshop.

2. To evaluate the scientific validity of using the position of the entrapment zone as a surrogate for managing freshwater inflow to protect the San Francisco Bay ecosystem and important societal values and uses.

3. To identify and evaluate the scientific validity of other estuarine properties and phenomena as potential surrogates for managing freshwater inflows to protect the ecosystem and important societal values and uses of San Francisco Bay.

4. To assess how the value of the position of the EZ and other surrogates for managing freshwater inflows to San Francisco Bay would be affected by other management and engineering actions.

Exhibit 2 of the report summarizes the conclusions concerning the use of the EZ as a tool for managing freshwater inflow to San Francisco Bay including:

1. The value of the position of the EZ as a tool for managing freshwater inflows may have been exaggerated because of the:
    1. Large uncertainty in understanding the importance of EZ position and EZ processes to sedimentation, to nutrient cycling, to contaminant cycling, to biology, etc. It's not only EZ position that counts, but also strength of the EZ.
    2. Poor correlation between EZ position and important "values," e.g. success of year classes of striped bass.
    3. Difficulty in measuring the position of the EZ precisely and accurately.
    4. Existence in San Francisco Bay of multiple EZs of different kinds and causes.
2. The terms entrapment zone, turbidity maximum and null zone are related, but not synonymous.
3. Measuring surface salinity is not the best way to establish the location of the EZ, the turbidity maximum or the null zone. Some measure of bottom salinity (combined with optical back scattering) would be better - more diagnostic.
4. There is significant scatter in the relationship of the position of the EZ to success of year classes of important species.
5. The use of surface salinity to define the location of the EZ adds bias and ambiguity to apparent EZ position.
6. A number of processes contribute to formation and maintenance of the EZ and, at certain times of the year there may be more than one EZ in San Francisco Bay.
7. Although use of the EZ as a management tool may not be justified scientifically, there are advantages to using one, or more, estuarine properties and phenomena which respond clearly and unambiguously to freshwater inflow to manage freshwater inflow rather than relying entirely upon flow itself.
8. The salinity distribution would be a better choice than the position of the EZ for this purpose.

Schubel notes:

> " It should be clear from Exhibit 2 that early in the workshop the participants rejected the EZ as the most appropriate response of the estuary to changes in freshwater inflow for use in managing inflow."

Since the participants rejected use of the EZ as a management tool for managing freshwater inflow, they then examined other factors as a surrogate for managing inflow. Schubel further states:

> " If a major purpose of setting discharge standards for the rivers that flow into San Francisco

Bay is to conserve and, if appropriate, to restore important ecosystem functions and values and societal uses of the estuary, then the best "measures," upon which standards should be set are a combination of freshwater inflow and some response of the estuary to that input.

It is extremely desirable to add a second standard; one that measures the response of the estuary to the input of freshwater from Delta outflow. The ideal index for that standard is an index that is simple to measure, inexpensive to measure, one that can be measured accurately, one that has ecological significance, one that integrates a number of important estuarine properties and processes and one that is meaningful to a large number of con[s]tituencies.

The workshop examined a number of surrogates for managing freshwater inflow. The one which received the greatest attention was near-bottom salinity. Salinity was judged to be a better --a more desirable and diagnostic measure --than the EZ and, indeed, was judged to be the best measure for an estuarine standard for flows identified by workshop participants."

These statements by Schubel reflect the single minded purpose of the entire workshop. That purpose was to find a practical surrogate that could be used to manage freshwater inflow to the estuary. Exhibit 3, entitled "Primary reasons for selecting salinity as the measure for creating a standard for managing freshwater inflows", documents three reasons:

1. The salinity distribution is of fundamental importance to the ecosystem.
2. The salinity distribution is a result of the interplay of freshwater inflow, geometry of the basin, diversion in the delta and tidal regime.
3. Accurate measurement of salinity is direct, easy and economical; measurements are robust.

Schubel's summary of the primary reasons for selecting salinity reveals several important points. First, the participants supported salinity distribution as the measure of managing inflows. It is important to note that the operative term is salinity distribution not, a particular salinity at a particular geographic location for a specified number of days depending on water year type. Second, the participants had identified salinity as the best surrogate for measuring inflow. Third, the participants used both scientific and economic factors to decide that salinity was the best surrogate measure of inflow by including direct, easy and economical as selection criteria.

In the section of this report entitled " The recommended approach," Schubel writes:

" ... there was further discussion of the use of salinity as the basis for a standard for managing delta outflow to protect important estuarine values and uses and living resources.

The workshop concluded that a combination of measures associated with freshwater inflow are needed to develop standards to ensure the required levels of protection for the estuary and its living resources. The minimum combination is river inflow and near-bottom salinity. Salinity should be thought of as a complement to measuring inflow. Reliable direct measurements of delta outflow would have great benefit to managers and scientists and the USGS program should move from the research and development phase to the monitoring phase as soon as practicable. Until then, the combination of river inflow, diversion and near-bottom salinity are the most appropriate set of measures. It represents the response of the estuary to different combinations of river inflow, diversions and withdrawals, tidal climatology and basin geometry.

A position of the 2 ppt near-bottom isohaline should be selected for each season which provides an appropriate level of ecosystem protection. These positions should become seasonal standards. They should be viewed as upstream limits of the excursions of the 2 ppt isohaline needed to provide the minimum level of environmental protection given the present level of scientific uncertainty. The proposed strategy for managing Delta outflow is to fix the upstream position of the near-bottom 2 ppt isohaline during different seasons using the best scientific evidence available to protect important ecosystem values and uses. The upstream position would vary from season to season and the downstream position of the 2 ppt isohaline would be unconstrained. There are different levels of scientific certainty/uncertainty associated with these positions for different species/values/uses for different seasons. Because of the uncertainty, the positions are somewhat elastic. From the environmental perspective, the uncertainty dictates taking a conservative approach, i.e. pushing the 2 ppt isohaline farther downstream than might be required with more information.

These seasonal standards should not be interpreted as static targets for location of the 2 ppt isohaline throughout any given season, year after year. Variability in flow, in circulation and mixing, in the salinity distribution and in the distribution of other important properties and processes is important in maintaining a healthy estuarine ecosystem.

The biological importance of seasonal and interannual variability and of extreme stochastic events should not be underestimated. ..."

Schubel also states:

" The positions prescribed for the near-bottom 2 ppt isohaline would be for operation of the existing State and Federal water diversion and distribution system. Any proposed change in that system should trigger a reevaluation of the positions. The movement of the 2 ppt isohaline to the prescribed position would be achieved through some combination of adjustments in river inflow and diversion.

Scientists at the workshop not only felt comfortable in advocating the position of 2 ppt near-bottom isohaline as the basis for the proposed management strategy, but were enthusiastic about it. They were not comfortable, however, in prescribing specific positions (i.e. specific salinity standards) during the workshop. All believed that this required the analysis and interpretation of data and information which were not available at the workshop and considerably more time for a critical and thoughtful assessment. ..."

The participants discussed the possible effects of implementing a standard on numerous estuarine resources and arrived at conclusions that are summarized in Table 1 of this[Schubel's] report. Each resource was rated as to what effect delta outflow, diversion and entrapment zone processes had on the importance of determining a strong year class of each species. The ratings were based on relationships of abundances to outflow and /or diversion and on the combined best professional judgment of the working group of fishery biologists at the workshop.

Exhibit 9 in the report is entitled " Salinity as a basis for a standard in managing freshwater inflow" includes the following points:

1. Salinity should be measured at 1 meter above the bottom.
2. The position of the 2 ppt isohaline at +1 meter is recommended for use as an interim standard. (Note: the leading edge of the turbidity maximum is located at about 2 ppt).
3. Salinity should be measured at six stations located along the channel between Emmaton and Carquinez Bridge.
4. Optical backscatter sensors should be combined with conductivity probes at these stations.
5. Surface salinity should also be monitored at these stations and correlated with bottom salinity.
6. The data should be telemetered to a convenient location for timely analysis and interpretation.
7. The monitoring data should be supplemented with detailed salinity surveys to map the distribution of salinity in three dimensions.
8. The salinity standard should take the form of the position of the 2 ppt isohaline in near-bottom channel waters as a function of season.

The conclusions and recommendations section of the report includes the following statement:

> " Members of the workshop recommend in the strongest terms possible that the strategy of assessing the effects associated with different flow scenarios and salinity responses outlined in this report be refined, enriched and extended using the best scientific and technical information possible. We recommend further that the results of this analysis should be used to set temporary seasonal standards for managing freshwater inflows to the San Francisco Bay estuary."

The major point that can be developed from the results of the first workshop is that water quality was never discussed as a problem. The entire discussion centered on developing some surrogate for management of flows into the estuary. Also, the recommendations from the workshop were very specific in their implementation requirements.

REVIEW OF THE REPORT ENTITLED: "Managing Freshwater Discharge To The San Francisco Bay/Sacramento-San Joaquin Delta Estuary: The Scientific Basis For An Estuarine Standard"

The review of the document was based on answering six key questions as this report related to the proposed EPA water quality standards. These questions were supplied by CUWA and are answered below:

1. What issues are related to the assumptions and methods behind the EPA standards?

1. The Environmental Protection Agency functionally assumes, although they state otherwise, that a cause and effect relationship exists between the position of X2 and the biological response as measured by the abundance indices. This assumption is false. Alan Jassby and J.R.Schubel very carefully assert that a cause and effect relationship may or may not exist, based on the theoretical, calculated location of X2, but they are unable to definitely demonstrate a cause effect relationship based on the existing data. It is extremely important to remember that X2 is being used as a surrogate for the 2 ppt isohaline which is a surrogate for the entrapment zone. It is the entrapment zone and not the location of X2 which is thought to increase the biological response. This supposed response has not been conclusively documented but only inferred from existing data. EPA mentions this situation in the introductory material for the standards but then ignores the lack of cause and effect relationship in the remainder of their rationale for the 2 ppt salinity standard. EPA also ignores the fact that X2 is a surrogate for an "imaginary" isohaline and is calculated from outflow data. Schubel reminds the reader that these relationships are statistical relationships and not based on field observations. Jassby also notes that the linear relationships he developed are based on the simplest of linear models and recommends that additional analysis may reveal different relationships than those demonstrated by his analysis. EPA mentions that the lack of a cause and effect relationship means that they cannot guarantee a positive biological response as indicated by an increase in the appropriate abundance index. However, this point is not emphasized to the reader of the proposed standards as it should be.

2. EPA assumes that the effects of outflow determines the location of X2. The California Department of Water Resources and others in the water community dispute the contention that inflow is a primary factor determining the daily location of X2. The participants at the series of workshops sponsored by the San Francisco Estuary Project selected the salinity distribution as best measure of managing freshwater inflow into the estuary. They decided that the calculated location of X2 was the most practical means of "measuring" salinity distribution. The Department of Water Resources and others believe that the antecedent location of X2 is the primary determinant of the location in the subsequent period. It is important to note that X2 is a theoretical, calculated location of an imaginary isohaline used to define a physical process that creates a high turbidity, mixing zone.

3. The recommendations from the workshops on the use of an entrapment zone to manage freshwater inflow resulted in the selection of salinity with a number of qualifiers as the best

surrogate to measure the effects of inflow. Those qualifiers included: 1) use of the salinity distribution as measured by 6-8 stations from Emmaton to the Carquinez Bridge, 2) allowing the natural variability in the location of the entrapment zone to fluctuate annually, seasonally, and more frequently as the physical conditions of the estuary dictated, 3) if the calculated X2 location was used as a standard, then the calculated location of X2 should be allowed to fluctuate naturally, 4) salinity was only a surrogate used to describe a physical process that occurred in the estuary, and 5) there should be a biological monitoring program implemented at the same time a standard was implemented to determine if there was a biological response to the flow standard. It was felt a monitoring program was necessary since cause and effect relationships could not be determined from the statistical relationships between calculated X2 location and the various abundance indices. EPA ignores the qualifiers in developing their standards. EPA proposes to use the calculated location of X2 at a particular location, for a fixed number of days, depending on water year type. This scenario is exactly opposite what the workshop participants intended. They emphasized that variability in the physical processes is what characterized the estuary and that static conditions were not desirable.

2. What issues are related to the adequacy of the data base used to develop the standards?

The selection of species and factors used as "indicators" are functionally represented as those indicative of estuarine health. The indicators are representative of the various trophic levels in the food web for the estuary. However, these same indicators are not representative of the estuarine biota as a whole. The indicators selected are those which seem to be most sensitive to variations in freshwater inflow. In fact, the purpose of the workshop was to look at the influence of flow on the biota. The workshops discussed a number of species other than those presented by Jassby but there is not a logical argument to disagree with the final selection of indicators given the charge of the workshop to address the influence of inflow on the biological community. However, it is extremely important to note that the species and factors selected for the final report are not representative of the estuarine biota as a whole, but only indicative of those which are apparently responsive to changes in freshwater inflow. This an extremely important distinction to keep in mind when using the final report results.

3. What issues are related to the analytical methods used to develop the standards?

The EPA adopted the results of the Schubel Report verbatim and did not conduct further analysis of the statistical relationships developed by Jassby. A further analysis of these data sets could have led EPA to a set of standards completely different than they have proposed. It appears that EPA had settled on a flow standard without regard to the multitude of other factors that were affecting the biology of the estuary. In fact, the emphasis behind the workshops and Schubel Report was to develop a management surrogate for outflow. Water quality parameters were never a consideration and salinity was never suggested as a water quality parameter that was of concern to the workshop participants. Salinity distribution was discussed as the best surrogate measure of the entrapment zone which produces mixing, turbidity maxima, and salinity gradients over a wide range of values. EPA's wholesale adoption of the Schubel Report without further analysis and reflection of the qualifiers behind the report has lead to the development of standards that do not accurately reflect the science that serves as the foundation of the report. The EPA has taken the results of this report and incorrectly and inappropriately applied them to the standard setting process.

4. **What issues are related to the biological validity of the conclusions of the report?**

1. All of the biological issues discussed in the report are valid except two which will be discussed in 2. and 3. below. Otherwise, the basic biological assumptions and conclusions in the report are valid. These include: 1) the need for a transport mechanism to move egg and larval forms downstream to what is believed to be better quality habitat, 2) the need for a transport mechanism to move egg and larval forms to a greater quantity of habitat than exists in upstream areas, 3) the need to transport organisms away from the influence of within Delta diversions and CVP-SWP pumping plants, 4) the need for a physical process that appears to increase estuarine residence time of organic carbon sources and organisms, 5) locating the physical process that produces conditions that apparently results in greater abundance indices adjacent to the shallow shoal areas of Suisun Bay, and 6) the lack of a demonstrated cause and effect relationship between location of X2 and a positive biological response as determined by an increase in abundance indices.

2. One biological conclusion of the report that is still contentious is the linear relationship of abundance to the location of X2. The level of analysis completed for the various indicator species was insufficient to completely define the relationship and response to varying locations of X2. In fact, the use of linear regression to describe the nature of the relationship between location of X2 and abundance, leads to a questionable conclusion that the abundance index would increase as the location of X2 moved downstream closer to the Golden Gate Bridge. No doubt, if you believe that the abundance index for a particular species truly reflects an increase in total population numbers, some species do appear to respond positively to a calculated position of X2 further downstream. However, some species, given the same assumption about the validity of the abundance index, do not respond positively to a position of X2 further downstream and actually demonstrate a decrease in abundance index as the calculated position of X2 moves downstream. Delta smelt are the best example of this decrease.

3. One other biological conclusion that is invalid is the use of molluscs as an indicator. The data Jassby used to develop the relationship is for two different species of clam. One is apparently better adapted to low salinity conditions and the other to higher salinity conditions. Thus the use of two different species would be like using fish versus X2 as one of the relationships. It adds little to the understanding of the processes controlling the biota in the estuary and should have been omitted as an indicator species since in reality the graphic presented represents two species.

5. What issues are related to the ability of the proposed standards to accomplish the desired goal?

1. Schubel and the participants all agree that a definite positive biological response to some specific position of X2 is impossible to predict given the current status of the data and analyses. EPA states in the background material for the proposed standards that they can not guarantee a biological response if the standards are implemented. The lack of a cause and effect relationship being demonstrated raises serious questions about the validity of the proposed standards and their ability to meet the stated objective of improving estuarine health.

2. The data do suggest that a standard based on locating X2 at Roe Island is not justified and in fact may actually be detrimental for some species. The data for some species suggest that placement of the leading edge of the entrapment zone as defined as the calculated location of X2 would actually result in reduced abundance (i.e. delta smelt) and not place the majority of the entrapment zone next to the shallow shoal areas of Suisun, Grizzly, and Honker bays as the workshop participants suggested. Some species may benefit with the location of X2 positioned near Chipps Island. The data suggest that allowing X2 up into the area around the confluence of the two rivers is usually detrimental.

6. What issues are related to further analysis and research?

1. Cause and Effect Relationships- Research is needed to define the necessary cause and effect relationships between the physical parameters and processes and the biological responses to these factors. Until these results are available, we will continue to guess at the mechanisms controlling the biology of the estuary.

2. Re-evaluation of the Abundance Index Concept- An analysis of the use of the abundance index data is absolutely essential. The data is probably being used for much more definitive and specific management purposes than was ever intended by its originators. Careful analysis of the entire data set and analysis procedures is needed to insure that the results obtained are sufficiently robust to justify and support any proposed management and regulatory proposals.

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SYNOPSIS OF EVIDENCE PRESENTED TO THE STATE WATER RESOURCES CONTROL BOARD IN THE BAY-DELTA HEARINGS ON THE FUNCTIONING AND BENEFITS OF THE ENTRAPMENT ZONE

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June 13, 1991

This paper has been prepared as part of a briefing packet for participants in a three day workshop, sponsored by the San Francisco Estuary Project, to be held from August 27 through 29, 1991.

The purpose of this paper is to summarize the testimony and evidence which was presented to the State Water Resources Control Board (SWRCB) during the first phase of the Bay-Delta Hearings in 1987 (Hearings) concerning the functioning and the importance of the entrapment zone. Other papers will present evidence which has been gathered since 1987.[1]

The first phase of the Hearings was designed by the SWRCB to allow interested parties to provide evidence to the SWRCB on the water needs of various so-called beneficial uses of water. Such beneficial uses include not only biological and environmental uses, but also agricultural and urban uses. Satisfying many beneficial uses simultaneously can cause difficulties, in that water used for one beneficial use -- for example, water used to position the entrapment zone in Suisun Bay to strengthen the pelagic food chain -- may reduce the water available for other users.

In later phases of the Hearings, the SWRCB is to set new standards for the San Francisco Bay-Delta Estuary which represent a balance between the needs of the aquatic environment and the needs of other users. The SWRCB may enforce these standards by altering existing water allocations from existing users on behalf of the environment.

Due to a number of delays, the Hearings have still over a year to run and no decision on reallocation of water will be made until 1992. Recommendations generated by the workshop could have considerable influence on the environmental standards set by the SWRCB and any ultimate reallocation of water.

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[1] In general, information in the following text is taken from the 1987 Bay-Delta Hearings Phase I record. References derived from the oral transcripts of the Hearings is in the following format: T,Session Number,Page. Oral and written testimony were in close agreement and written testimony has been the basis for most of the following.

Evidence presented in the Hearings was remarkably congruent. Participants agreed on the basic functioning of the entrapment zone and the impacts on primary production of alternative locations within the Estuary. The primary disagreement centered on the appropriate standards to be used to place the entrapment zone so as to maximize phytoplankton concentrations in Suisun Bay. Also, as discussion moved away from primary production, to discussions of higher trophic levels, the level of uncertainty increased over the relationship between Delta outflow, the location of the entrapment zone and effects on the biota.

In general, the testimony and exhibits agreed that placement of the entrapment zone in Suisun Bay during the spring and summer months has major environmental benefits. The conjunction of the entrapment zone and the broad shoals of Suisun Bay leads to high concentrations of phytoplankton and zooplankton which provide food for young striped bass and other species and which provide support for a strong pelagic food chain generally.

PHYSICAL PARAMETERS

The Bay-Delta Estuary in general and the North Bays and Delta in particular are well described by Hedgepeth[2] (see Figure 1)

> San Francisco Bay and Delta is one of the world's largest and most complex estuarine systems comprising numerous interconnected embayments, sloughs, marshes, channels, and rivers. From Central Bay, its connection with the Pacific Ocean at Golden Gate, the system extends to the southeast into South San Francisco Bay. To the north and northeast it extends to San Pablo Bay, through Carquinez Strait to Suisun Bay and the Delta region...
>
> Each embayment is dominated by wide expansive shoal areas surrounding deep and narrow channels. Narrow constrictions or straits form natural transitions from one embayment to another...
>
> Water heading toward the sea from the Delta passes through Suisun Bay, which is merely the wide combination of the Sacramento and San Joaquin Rivers below the Delta. Thirty-six percent of Suisun Bay is flooded by less than 3 feet of water at mean lower-low water...
>
> The runoff from 45,000 square miles of California's land surface drains from the Delta. A hundred years ago the Delta was an extensive tidal marsh, but it has been almost entirely reclaimed for agriculture...

As a result of reclamation, the Delta consists primarily of farmland surrounded levees, laced with a complex system of water channels. Downstream of the confluence of the Sacramento and San Joaquin Rivers is Suisun Bay.

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[2] Hedgepeth p. 1-3

Suisun Bay is made up of several subembayments -- Suisun, Grizzly, and Honker Bays, moving from west to east. On the northern edge of Suisun Bay is Suisun Marsh, an area of brackish managed and tidal marshes. Suisun Bay is the set of shoals farthest upstream and thus the easiest set of shoals in which an entrapment zone could be formed. A Chart showing photic depth as a percentage of average water column depth for Suisun Bay, San Pablo Bay, and the Delta is shown as Figure 2.

Flows through the Delta and through Suisun Bay are remarkably variable. In general however, typical unimpaired flows (flows which would occur given the current physical configuration without storage or diversion) peak during winter storms, then fall off slowly during the spring snowmelt in the Sierra Nevada and finally drop to very low levels during the late summer and fall.

In general, however, flows through the Delta are significantly altered by upstream diversions and storage and by diversion within and from the Delta. In particular, spring outflow and dry year outflow patterns have been significantly impacted, generally downward except in the late summer.

Figure 3 gives average unimpaired and existing Delta outflow in various types of years. Spring and summer outflows are significantly impacted by storage and diversion in median and dry years.

THE ENTRAPMENT ZONE PHENOMENON

All evidence presented to the SWRCB recognized the existence of an entrapment zone in the Estuary and agreed upon its physical description and functioning.[3]

The entrapment zone occurs at the freshwater -- saltwater interface. Freshwater has a lower density than salt water. When freshwater flows into saltier water it tends to flow over the surface of the saltwater. However, the flow is not frictionless. Thus, saltwater is entrained by the freshwater flow and pulled downstream along with the freshwater. This downstream flow of entrained salt water induces a compensating flow of saline water in the landward direction. The point at which the landward movement of the landward flowing stream is halted is called the null zone. Downstream of this point is an area called the mixing zone where entrainment, and thus mixing takes place. The upstream portion of the mixing zone is characterized by upwelling from the bottom which is of sufficient velocity to approximate the sinking rate of fine sediment and certain phytoplankton.

The seaward flowing upper current, the landward flowing bottom current and the upwelling at the upstream part of the mixing zone form a circular flow pattern which can concentrate

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[3] The primary evidence on the entrapment zone was presented by the California Department of Fish and Game (DFG), the United States Bureau of Reclamation (USBR), the Bay Institute of San Francisco, and Contra Costa County Water Agency (CCCWA) and the Environmental Defense Fund (EDF). The submissions with the submitting organizations are given in the bibliography.

particles, if their sinking rate approximates the upwelling velocity. Thus, particles may be carried upward into the upper current, then carried downstream until the upwelling is weakened, sink into the lower current and be carried upstream again. Figure 4 gives a schematic of the process.

The zone where this occurs is called the "turbidity maximum" or the "entrapment zone". Note that the entrapment zone does not encompass the entire mixing zone, but tends to be described more qualitatively as the region in which the circular flow pattern and entrapment leads to high turbidity in the water (Figure 5)[4]

The high degree of turbulence may also lead to flocculation and the creation of particles large enough to either sink to the bottom or to be entrapped. This include flocculation by diatoms.[5]

The length of the entrapment zone will be a function of both the bathymetry and the flow levels. Williams indicates that both the length of the entrapment zone and the upwelling velocity will increase with flow (Figure 6).[6] Arthur refers to theoretical maximum net vertical velocities of 3.4-3.7 m/day (approximately .004cm/s) at Delta outflow of 13,000 cfs.[7]

THE ENTRAPMENT ZONE AND PRIMARY PRODUCTIVITY

Phytoplankton species appear to be the dominant source of primary productivity in the Bay as a whole as a result of the filling and diking of most of its wetland areas.[8]

Suisun Bay has long been considered an important area biologically for this reason -- before 1977, major blooms of neritic diatoms were typical there each summer and fall (freshwater phytoplankton dominate in winter). For this reason, the depression in phytoplankton production in 1977 and the reduced production levels since then have been the cause of great concern.

The conclusion of most scientists working on the problem has been that the conjunction of the entrapment zone with the shoals of Suisun Bay is the dominant factor leading to the high productivity of Suisun Bay and that reduced outflow from the Delta moves the

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[4] Similar descriptions of entrapment zone dynamics are given in Hedgepeth p. 22, 35 etc.; Williams (1) p. 22-24; Arthur (2) p. 4-5; Ball (1) p. 41; Cloern (1) p. 422.

[5] Goldman p. 320. Cloern (1) p. 166 discusses flocculation of diatoms with inorganic particles and organic sediments. This may be required for diatoms to acquire the necessary sinking rates.

[6] Williams (1) p. 23. Figure taken from Festa and Hansen (1978).

[7] Arthur (2) p. 71.

[8] Williams (1) p. 8-9. Moyle (1989) p. 22. Hollibaugh T, 54, 220.

entrapment zone upstream into areas where conditions are not right for high phytoplankton production.

While the phenomenon of the entrapment zone has long been recognized, the relationship between the entrapment zone and phytoplankton concentration and production was not developed until the 1970's. Much of the data was gathered during the 1976-77 drought. Prior to this drought, the accepted notion was that extremely low Delta outflows would enhance concentrations of phytoplankton in Suisun Bay in that reduced turbidity would increase the depths at which phytoplankton could grow. In fact, just the opposite occurred. Phytoplankton concentrations were at extremely low levels, populations of Neomysis were also extremely low and striped bass reproductive success was the lowest to that date.[9]

The basic theory is as follows:

- The conjunction of the shoals of Suisun Bay with the circular two level-flow associated with the entrapment zone is responsible for the high productivity in Suisun Bay during springs and summers of normal flow, due to increased residence time of various neritic diatoms (which have sinking rates approximately equal to the upwelling velocities and can therefore be carried upstream in bottom currents and reinjected into the photic zone.)

Assumes phytoplankton is driving force !!

- Reduced flows move the entrapment zone back into the Delta where deep channels greatly reduce the percent of water volume in the photic zone. Entrapment may occur, but since the average growth rates are lower, blooms never develop in the entrapment zone. Meanwhile, phytoplankton in Suisun Bay either sink into the bottom landward current and are carried into the Delta or are consumed by benthos (which may greatly increase in numbers during prolonged dry periods: see below).[10]

- Increased flows push the entrapment zone out of Suisun Bay entirely so that residence time for phytoplankton is greatly reduced. Ball places these flow levels at above 25,000 cfs.[11]

The effect is very striking in that, ignoring the increased residence time due to circular movement of phytoplankton, the presence of the entrapment zone should actually depress the growth rate of the phytoplankton population compared to lower flows. Higher turbidity associated with the entrapment zone reduces the photic zone and increases the zone of negative growth. Moreover, the increased flows should lead to reduced residence times for

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[9] Arthur (2) p. 1-4, 25, 48; Ball (1) p. 39; Cloern (1) p. 426.

[10] Hedgepeth p.35; Williams (1) p. 17-18; Arthur (2) p. 1-5; Cloern (1) p. 422; Ball (1) p. 41.

[11] Ball (1) p. 51.

phytoplankton before they are carried downstream.[12]

The theory explains a number of observations:

- Phytoplankton production is positive in the shoals and negative in the channel. Yet, phytoplankton in the channel exist at high concentrations. Concentrations are greater at the edge of the channels than in the center. Tidal mixing apparently conveys shoal phytoplankton to the channel.[13]

- Neritic diatoms, which apparently flocculate until their sinking rate approximates the upwelling velocity, dominate the phytoplankton of Suisun Bay.[14]

- Peaks in phytoplankton at depth lag and occur upstream of peaks in surface phytoplankton in the channels.[15]

- The phytoplankton levels plummeted in the low flow years of 1977, 1978. A peak was observed at the position of the entrapment zone in the Delta, but at a much reduced level.[16]

- Phytoplankton levels dropped during the extremely high flows of 1983.[17]

- The early bloom generally begins on the western edge of the Suisun Bay as spring flows subside and the entrapment zone moves upstream into Suisun Bay. The summer bloom coincides with the increase in flows as the entrapment zone moves back into the Bay with the first rains of the year.[18]

increase in nutrients ?

One inconsistency noted by Cloern has been a September drop in chlorophyll a, even though flow conditions remained optimum. He notes that the drop coincided with decreased turbulence and wind and in increase in soil chlorophyll. The calmer conditions

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[12] Ball (1) p. 39.

[13] Cloern (1) p. 419.

[14] Cloern (1) p. 424; Ball (1) p. 41; Williams (1) p. 17. Arthur (2) p. 71 provides lab evidence that settling rates for the diatoms may be approximately 2.4-3.1 m/day. Whether or not the number is correct, it is of the same order of magnitude as the upwelling. In any case, if diatoms may increase their sinking rates by flocculation, small initial sinking rates are not critical.

[15] Arthur (2) p. ii.

[16] Arthur (2) p. 51.

[17] Cloern (1) p. 422.

[18] Arthur (2) p. 25, 26, 47.

may have caused phytoplankton to drop to the bottom.[19]

Another difficulty is mentioned by Ball (p. 48) who indicates that phytoplankton from upstream are frequently carried downstream and concentrated in the entrapment zone at flows from 10,000 to 30,000 cfs, and especially at flows from 15,000 to 30,000 cfs. According to Ball, high concentrations of Melosira were transported from the western Delta into Suisun Bay in June, 1982. This effect complicates the correlation of Suisun Bay blooms with flow. However, since the speciation is different, given species composition, the effects could be untangled. The effect also could have implications for flow standards to be set by the SWRCB. If the benefit of flows above 15,000 cfs is to bring upstream phytoplankton into the entrapment zone, then those flows would only provide these benefits when upstream phytoplankton concentrations were sufficiently high to raise concentrations in the entrapment zone.

Other possible explanations for the phenomenon have been explored and generally rejected as controlling factors:

Light	Monthly average insolation is generally constant. Thus, other factors must control population.
Nutrients	Inorganic nitrogen was depleted and considered limiting at times during studies by Arthur. However, depletion only occurred in the context of a large bloom. Silicon also declines to near-limiting levels during large blooms.[20]
Predation	In general, zooplankton predation of phytoplankton in Suisun Bay is relatively small, not enough to eliminate a bloom.[21] However, Nichols has postulated that the marked decline in phytoplankton concentrations during 1976-77 may have resulted from an invasion of marine benthic invertebrates which increased the population of — by an order of magnitude in Suisun Bay during this period. The combined filtering capacity of the clams was calculated to be enough to filter the Suisun Bay in a single day. For extended periods of low flow, then, a second mechanism may contribute to reduced phytoplankton populations.[22] However, Cloern argues that the invasion of marine benthic invertebrates could not explain short term flow fluctuations in phytoplankton population related to flow.

Figure 7, from Cloern (1) 418 shows a number of the effects mentioned. Cloern identifies a range of flows during which neritic diatoms increase (which presumably is due to the

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[19] Cloern (1) p. 165-166

[20] Arthur (2) p. 55

[21] Cloern (1) p. 166

[22] Nichols (1).

selective action of the entrapment zone) of 100-350 cubic meters/s (3,000 - 10,000 cfs). Note that:

- There was no phytoplankton bloom in 1977 when outflows were below the critical value.
- The bloom began early in 1977 when flows entered the critical range earlier than usual.
- Strong flows in the spring of 1978 were associated with high chlorophyll a levels, but low neritic diatom levels, implying that the chlorophyll a may have been carried down from upstream.
- Shoal chlorophyll a levels are consistently below levels in the shoals.
- An anomalous bloom of neritic diatoms occurred in May, 1975, despite flows which were above the critical range identified by Cloern. This may indicate that blooms based upon local productivity can occur at flow levels well above 10,000 cfs.

Figures 8-12 from Ball shows chlorophyll a, flow and salinity data from 1968 to 1985 in a different format.

Arthur, shows mean monthly Suisun chlorophyll a versus flow in Figure 13.

PLACEMENT OF THE ENTRAPMENT ZONE FOR MAXIMUM PRODUCTIVITY

Estimates of the range of flows which would place the entrapment zone adjacent to Suisun Bay differed somewhat during the Hearings. The question is difficult in that the entrapment zone cannot be exactly correlated with either outflow levels or salinity. But will vary with tides, wind and the recent flow patterns.

Entrapment zone position can be calibrated to outflow or salinity levels if the position of the entrapment zone can be found independently. Several methods have been utilized to find the approximate position of the entrapment zone.

Williams compared residual flow data from Peterson (Figure 14) and bottom current measurements from USBR to find the null zone and correlated this data with outflow estimates from DWR's DAYFLOW program. Methods indicated that the null zone could be located at Chipps Island (at the upstream edge of Suisun Bay) with flows of from 7,000 - 13,000 cfs. However, residual flows are difficult to obtain. Williams compared the flow data to the results from theoretical models of the flows necessary to maintain a bottom salinity of 2 ppt. The result correlated quite well (Figure 15). Thus, Williams proposed that a bottom salinity standard be set at 2 ppt to locate the null zone at approximately Chipps Island. According to Williams, with the null zone at Chipp's Island, the length of the entrapment zone would be about 10 miles, putting it in Suisun Bay.[23]

Another method is to ignore the null zone, but to note the position of high turbidity which characterizes the entrapment zone. Arthur and Ball interpreted this zone as occurring between surface salinities of 1 - 6 ppt. Williams notes that Arthur and Ball derived flows of 9,000 - 13,000 to maintain the zone of high turbidity in Suisun Bay.[24]

Finally, since maximum primary productivity is the professed goal of proper entrapment zone position, flow and chlorophyll a can be correlated to find the optimum flow. Presumably, this correlation gives the optimum location of the entrapment zone on the average. Arthur provides data showing this correlation and finds a broad peak in chlorophyll levels at flow from around 5,000 - 15,000 cfs Figure 13).[25]

Other estimates of minimum flows and salinities have been made.[26] The issue is an important one in that the SWRCB will probably be inclined to favor a standard, at least in dryer years, which provides significant phytoplankton productivity in Suisun Bay without providing a surplus of water for that purpose.

Placement of the entrapment zone may have an additional constraint put upon it by factors not directly related to primary productivity. For example, DFG testified that 6,500 cfs of outflow would be insufficient to allow striped bass larvae to be carried into the entrapment zone at all in great numbers.[27] Thus, for striped bass, both transportation and food supply may be determined by flow levels.

ZOOPLANKTON AND UPPER LEVELS OF THE FOOD CHAIN

Zooplankton populations have been statistically correlated with levels of chlorophyll a, implying that zooplankton abundance is strongly correlated with primary productivity. Typically populations are low in the spring, then increase greatly in the summer with peaks from August to October.[28]

The most important zooplankton in the Pelagic food chain are the cladocerans, the copepods and the mysid shrimp Neomysis mercedis. According to DFG, "adult copepods, especially adult Eurytemora affinis, and cladocerans are the first food items taken by young

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[23] Williams (1) p. 27-31.

[24] Arthur and Ball 1979. Referenced from Williams (1) p. 32.

[25] Arthur (2) p. 65.

[26] Arthur (2) p. 76 puts the minimum flow at 4,000 cfs. Ball (1) p. xvii puts the critical range at 5,000 - 10,000. Cloern (1) p. 419 puts the range at 4,500 cfs -- 12,000 cfs.

[27] T, 39, 95.

[28] Hedgepeth p.57-58.

striped bass. As young bass grow, the switch to a diet dominated by Neomysis mercedis. Numerous other species depend upon these zooplankton for a major part of their diets (see below). Neomysis consumes both Eurytemora, other zooplankton and phytoplankton.[29]

All parties agreed that the distribution of zooplankton is closely related to salinity levels. Thus, the various species move upstream and downstream in accordance with the level of outflow and thus, salinity. Of course, this lateral movement complicates efforts to track population levels when using stationary testing sites. In 1963, the dominant zooplankton in Suisun Bay were the copepods Acartia and Eurytemora, and Neomysis.[30]

Eurytemora achieves its greatest abundance in the entrapment zone, but is also found upstream.[31]

Neomysis is most abundant in the entrapment zone and immediately upstream. Adult Neomysis tend to live above the entrapment zone, while young Neomysis are most abundant within it. Neomysis abundance increases in the spring, peaks in the late spring and early summer and declines sharply in the fall. The location and distribution of Neomysis is thought to be due to the interaction between vertical migration patterns of the shrimp, tidal flows, and the circular flows associated with the entrapment zone.[32]

In 1979 the copepod Sinocalanus was introduced to Suisun Bay. Since that time, the population of Eurytemora has been reduced. See Figure 17.[33] However, the total copepod abundance has shown no long term trend.

Acartia abundance has shown no long term trend. [34]

Neomysis has also declined, though it reached high abundances during 1980 and 1982.[35]

Regressions have been run to test whether declines in zooplankton could be correlated with changes in chlorophyll a, salinity at Chipps Island, temperature, or CVP-SWP export pumping rates.[36] Results indicated that zooplankton abundance was most closely related

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[29] DFG Exhibit 28.

[30] Hedgepeth p.89, quoting from Painter (1966).

[31] Williams (1) p. 28; DFG 28 p. 13.

[32] Hedgepeth p.83-844; Orsi p.404; Knutson p. 482.

[33] DFG 28 p. 27-28.

[34] DFG Ex. 28 p. 38.

[35] DFG #28 p. 63.

[36] DFG #28 p.62.

to chlorophyll a. All important Suisun Bay zooplankton were found to be related to chlorophyll a, though the Neomysis relationship was not linear.[37] See Table 1 and Figures 18-21.

Neomysis was also correlated with Delta outflow. The reason for this is thought to be that the decreasing flows reduce usable Neomysis habitat. The downstream sector of Neomysis habitat is the entrapment zone. The upstream end is the central Delta where sustained cross Delta flows from the Sacramento River to the state and federal pumps make this region inhospitable. Thus, as the entrapment zone moves upstream with reduced flows, the available habitat contracts. In addition, movement of the entrapment zone out of Suisun Bay reduces the available food supply.

In the section on primary production, it was established that primary production in Suisun Bay depends, in large part, upon adequate flows to position the entrapment zone opposite the shoals in the Bay. When the entrapment zone moves upstream, production does not move upstream, but is reduced overall. The discussion above on zooplankton indicates that their populations are, in turn, dependant upon phytoplankton populations. Thus, increases in Neomysis and other entrapment zone related zooplankton will depend upon Delta outflow adequate to stimulate entrapment zone blooms.

HIGHER TROPHIC LEVELS

The relationship between the entrapment zone position, flows, phytoplankton, zooplankton, and the higher trophic levels is hampered by the fact that only a few species have been studied in great detail. Thus, many species have come to be represented by a few "indicator" species.

Studies in other water bodies, however, have linked productivity with higher trophic levels. Nixon (1982) looked at phytoplankton production versus fisheries yield data from numerous estuaries and coastal waters from around the world. A consistent relationship emerged between the two (Figure 22). Considering the high importance of phytoplankton primary production in the Estuary, it would be quite surprising if such a relationship did not also exist in the San Francisco Bay Delta Estuary.

The species most carefully studied with relation to the entrapment zone is the striped bass. Prior to 1977 a relationship between Delta outflow, Delta diversion and striped bass success had been established. However, since 1977, striped bass have had greatly reduced reproductive success. A number of hypotheses about the cause have been proposed. Among the possible causes are:

- Adult populations have declined to levels insufficient to produce enough eggs to permit population growth.

- Plankton abundance has been reduced, thus reducing food supply for young striped

[37] DFG #28 p. 64.

bass.

- Entrainment in state, federal and Delta island pumps.

- Toxics.

Given the complexity of the Estuary and the long life of the striped bass (given the ability to survive periods of suboptimal habitat), it is not surprising that strong correlations have been found between striped bass population and environmental conditions. However, several observations provide evidence that the location of the entrapment zone in Suisun Bay is important for striped bass abundance.

Suisun Marsh has been an important nursery area for the striped bass. Under normal circumstances, adult striped bass spawn in the Delta and upstream in the Sacramento Rivers. If flows are high enough, the eggs are carried down by the currents into the entrapment zone where they are trapped and concentrated by the same forces that concentrate phytoplankton (and thus, indirectly, zooplankton).

When the striped larvae are ready for their first feeding, it is important that a dense food supply be available, since young striped bass survival depends on rapid initial growth.[38] As noted above, copepods (especially Eurytemora) and the cladocerans are the first food taken by young striped bass. As they grow they switch to a diet dominated by Neomysis. As discussed above, both Eurytemora and Neomysis have declined in recent years. While the decline in Eurytemora has been balanced by the recently reduce Sinocalanus, striped bass apparently avoid this copepod.[39] Therefore, it is at least plausible to postulate that larvae and young striped bass have been impacted by reduced zooplankton populations (which have been correlated with chlorophyll a which is correlated with flow. And of course, transporting striped bass larvae into Suisun Bay requires flow.).

whoa?

This hypothesis is strengthened by the work of Stevens of DFG. Stevens examined crustacean zooplankton and concentrations both overall and at the time and place where striped bass larvae were located when they began feeding (Table 2) from 1972 to 1979 (years which span the period when the striped bass index dropped below predicted values). While total zooplankton concentrations have not shown a market decline, Table 2 shows a striking drop in zooplankton availability when striped bass need a strong food supply.

The benefits of utilizing Suisun Bay as a nursery area are twofold. First, this location of the entrapment generally increases the available food supply needed by the larvae. Secondly, the position increases the distance between the young bass and the state and federal pumps in the south Delta, thus reducing entrainment in the pumps.

The outflow requirements to flush striped bass into Suisun Bay may not be exactly the same

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[38] DFG #25 p. 95.

[39] DFG #25 p. 97.

as those needed to create the entrapment zone there, but there appears to be considerable overlap. DFG was not willing to quantify the flows necessary to flush striped bass into the entrapment zone before they hatched. However, they did testify that 6,500 cfs was too little. But others have indicated that the entrapment zone may be adjacent to Suisun Bay with flows as low as 4,000 cfs. If so, at least for part of the time, flows adequate to place the entrapment zone properly may not protect striped bass.

Delta Smelt have a similar reproductive pattern in which eggs are washed down and entrapped in the entrapment zone. However Delta Smelt survive only a single year. Several consecutive bad years could drive them to extinction. Delta Smelt may thus provide a better indicator species than the striped bass.

Clearly, not all species are dependant upon the salinities, circular current patterns, and food associated with having the entrapment zone placed at Suisun Bay. Fish which utilize productivity in the entrapment zone include: juvenile striped bass, young of the year striped bass, juvenile white and green sturgeon, adult American shad, black Crappie, white catfish, and young king salmon.[40]

Many other species rely on zooplankton and Neomysis as an essential part of their diet. Such species include the bay shrimp and oriental shrimp. These shrimp are, in turn eaten by fish.[41]

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[40] Orsi p. 403.

[41] T,39,53.

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ABBREVIATIONS

BISF	Bay Institute of San Francisco
CCCWA	Contra Costa County Water Association
DFG	California Department of Fish and Game
EDF	Environmental Defense Fund
SWRCB	California State Water Resources Control Board
USBR	United States Bureau of Reclamation

Figure 1 Nichols (2)

accompanied the state's growth (*16*). One result has been a greatly reduced freshwater flow into the estuary.

The Sacramento and San Joaquin rivers discharged about 34 km³ of fresh water into San Francisco Bay annually before 1850 (*20*). As California's population grew (Fig. 4A), the area under irrigation increased by about 30,000 ha per year (Fig. 4B), creating demands for both flood protection and reliable water supplies. In response, state and federal agencies built dams, reservoirs, and canals to increase storage capacity (Fig. 4C) and annual export rates (Fig. 4D). These facilities represent the world's largest man-made water system (Fig. 1), with a water-storage capacity of about 20 km³ (*16*). At present, nearly 40 percent of the historic (1850) flow of the Sacramento–San Joaquin river system is removed for local consumption upstream and within the Delta. Another 24 percent is pumped from the Delta and exported in aqueducts for agricultural and municipal consumption in central and southern California (Fig. 5). Now, the flow into San Francisco Bay is less than 40 percent of historic levels. To minimize up-estuary salt intrusion that results from lowered freshwater flows (and that is exacerbated by dredged channel deepening between San Pablo Bay and the Delta) (*11*), inflow during summer has been increasingly augmented (Fig. 6).

Nearly 86 percent of California's managed water supply is used in agriculture (*21*). If the state's reservoir capacity increases as projected (Fig. 4C) and conversion of arid land to new farmland through irrigation continues to be profitable, demands for water export will increase (Fig. 4D). As a result, average freshwater inflow to the bay in the year 2000 is projected to drop to 30 percent of the historic average (Fig. 5).

Ecological consequences of reduced river inflow. Both the physical process of diverting water and the changes in flow patterns resulting from water management have affected biological communities of the San Francisco Bay estuary. Disruption of the natural flow of water has most noticeably affected migratory fish—species dependent on the rivers for spawning. Construction of Shasta Dam (Fig. 1) in 1944 eliminated half of the salmonid spawning habitat in the Sacramento River system (*5*), requiring the augmentation of natural stocks with hatchery-reared fish. The operation of water diversion pumps at the southern end of the Delta during summer periods of low river flow causes water in Delta channels to flow upstream. Thus, hundreds of millions of juvenile salmon and striped bass (31 and 25 percent of typical year classes, respectively) are drawn into the water diversion pumps each year (*22*). Equal numbers are lost to numerous small siphons and pumps that collect irrigation water for local consumption in the Delta (*23*). These losses have contributed to a decline in the abundance of adult striped bass to less than 25 percent of that in the mid-1960's (*24*).

Effects of water diversions on the biology of the bay itself, although more difficult to identify or quantify because of simultaneous changes due to land reclamation, fishing, and waste disposal, can be deduced from observations made during two consecutive years of naturally low flows (1976 and 1977). Normally, fresh water is released during summer at a controlled rate between 100 and 400 m³/sec (Fig. 6). Under these conditions, the downstream-flowing river currents are balanced, in Suisun Bay, by the upstream-flowing bottom currents carrying salt water (Fig. 7). This convergence, or null zone, is a point where suspended particles, including sediment and planktonic diatoms, accumulate (*7, 25, 26*). Associated with this phytoplankton maximum are high abundances of pelagic herbivores (copepods and the mysid shrimp *Neomysis mercedis*) that are important food sources for larval or juvenile fish (*27*). During 1977, when Sacramento–San Joaquin river discharge in summer dropped below 100 m³/sec (Fig. 6), phytoplankton biomass in the upper estuary was reduced to 20 percent of normal levels (*26*), zooplankton abundance was significantly reduced, and both *Neomysis* abundance and striped bass recruitment fell to their lowest recorded levels (*27, 28*). Suppression of the pelagic food web during this unusual occurrence of extremely low flow suggests that (i) production of some pelagic fishes in the upper estuary may depend on a high biomass of primary producers and (ii) high phytoplankton biomass develops only when freshwater inflow exceeds 100 m³/sec (*26*).

Two theories have been proposed to explain the absence of a summer phytoplankton bloom in northern San Francisco Bay during extremely low inflows. The first theory (*26*) holds that the typical summer biomass maximum is dependent on a circulation pattern that positions the null zone adjacent to the productive shallows of Suisun Bay, where light availability is sufficient to sustain algal growth. When river discharge falls below 100 m³/sec, the null zone moves upstream into the deeper Sacramento River, where light availability is insufficient to sustain net photosynthesis and phytoplankton biomass remains low. The second theory (*29*) holds that reduced phytoplankton biomass during periods of persistent low river flow and high salinity results from increased grazing losses to immigrant benthic suspension feeders that are normally excluded from this region by winter freshets.

Both mechanisms, direct consequences of reduced freshwater inflow, probably contributed to the absence of a summer bloom during the 1977 drought. These findings illustrate the sensitivity of northern San Francisco Bay biological communities to persistent low river flow and suggest that further reductions in freshwater inflow (Fig. 5) could permanently alter the pelagic food web and fisheries yield there.

Other consequences of reduced inflow. Reduced freshwater inflow from the Sacramento–San Joaquin river system may also reduce the estuary's capacity to dilute, transform, or flush contaminants that are discharged into San Francisco Bay. Estimated residence time of water in northern San Francisco Bay ranges from a minimum of 1

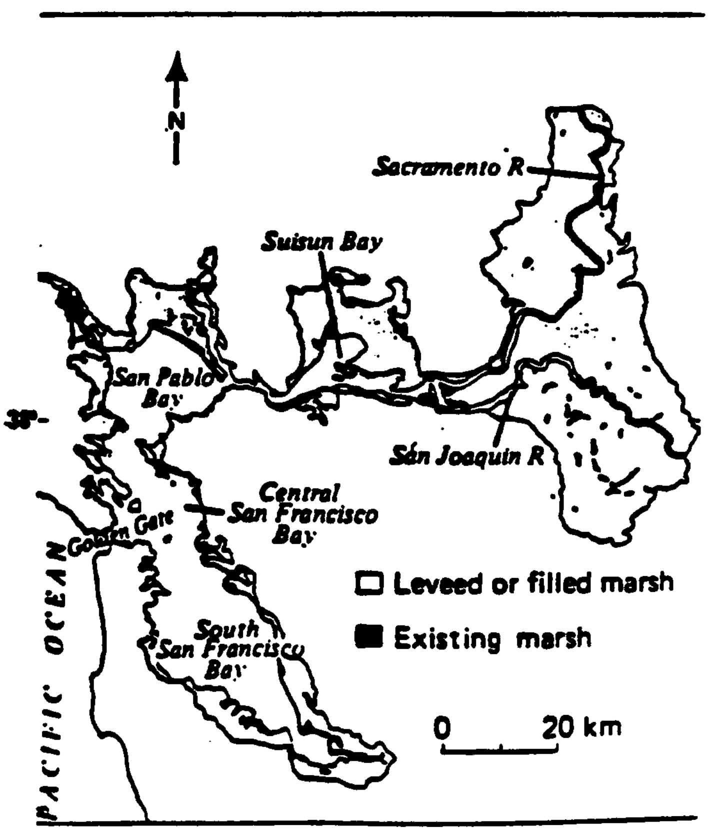


Fig. 2. Distribution of undiked tidal marshes around San Francisco Bay before 1850 and at present (*7*).

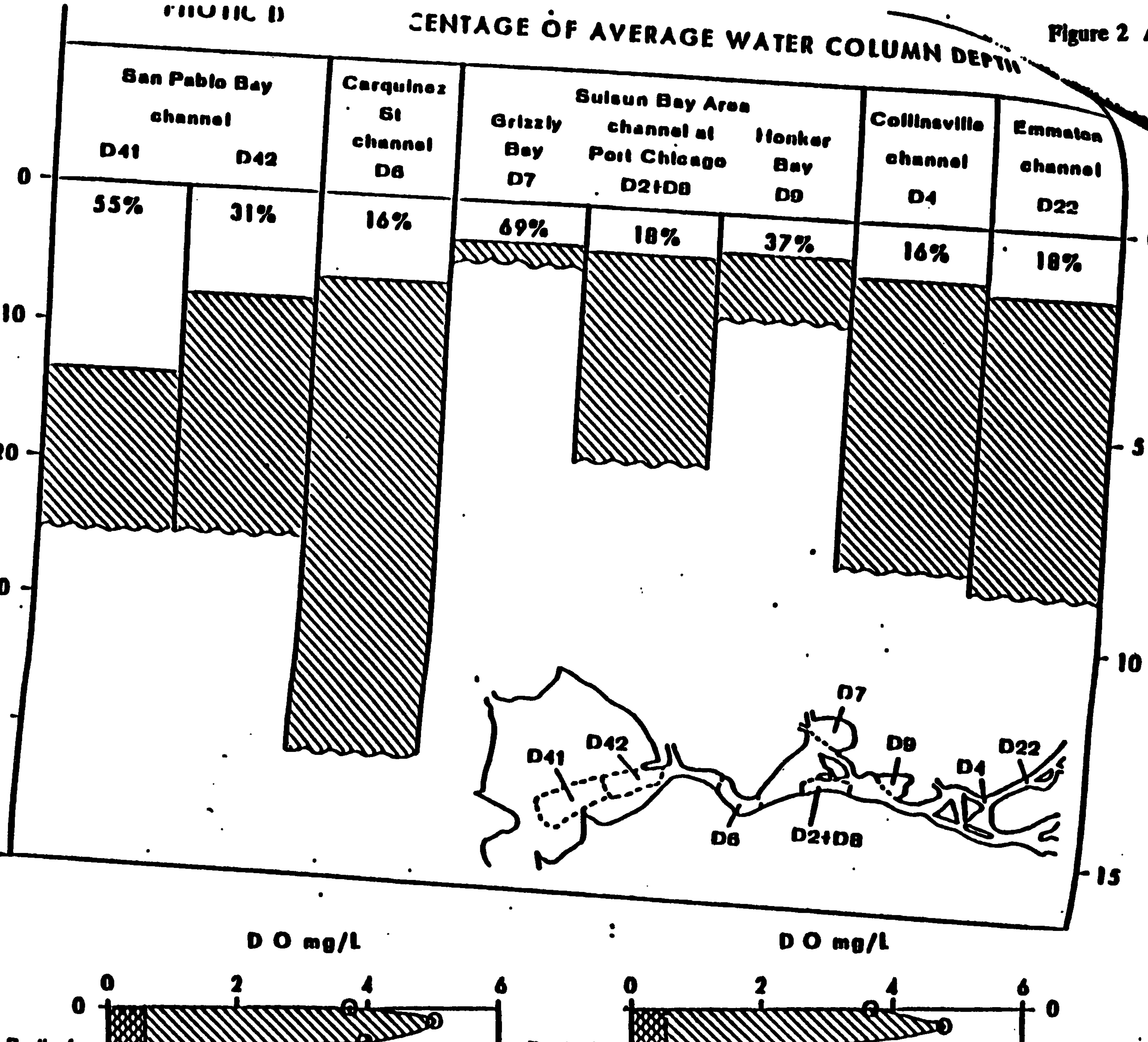


FIGURE D
CENTAGE OF AVERAGE WATER COLUMN DEPTH
San Pablo Bay channel
D41
D42
Carquinez St channel D6
Suisun Bay Area
Grizzly Bay D7
channel at Port Chicago D2+D8
Honker Bay D9
Collinsville channel D4
Emmaton channel D22
55%
31%
16%
69%
18%
37%
16%
18%
DEPTH feet
0
10
20
30
40
50
DEPTH meters
0
5
10
15
D41
D42
D6
D7
D2+D8
D9
D4
D22
D O mg/L
0
2
4
6
D O mg/L
0
2
4
6

Figure 3 Williams (2)

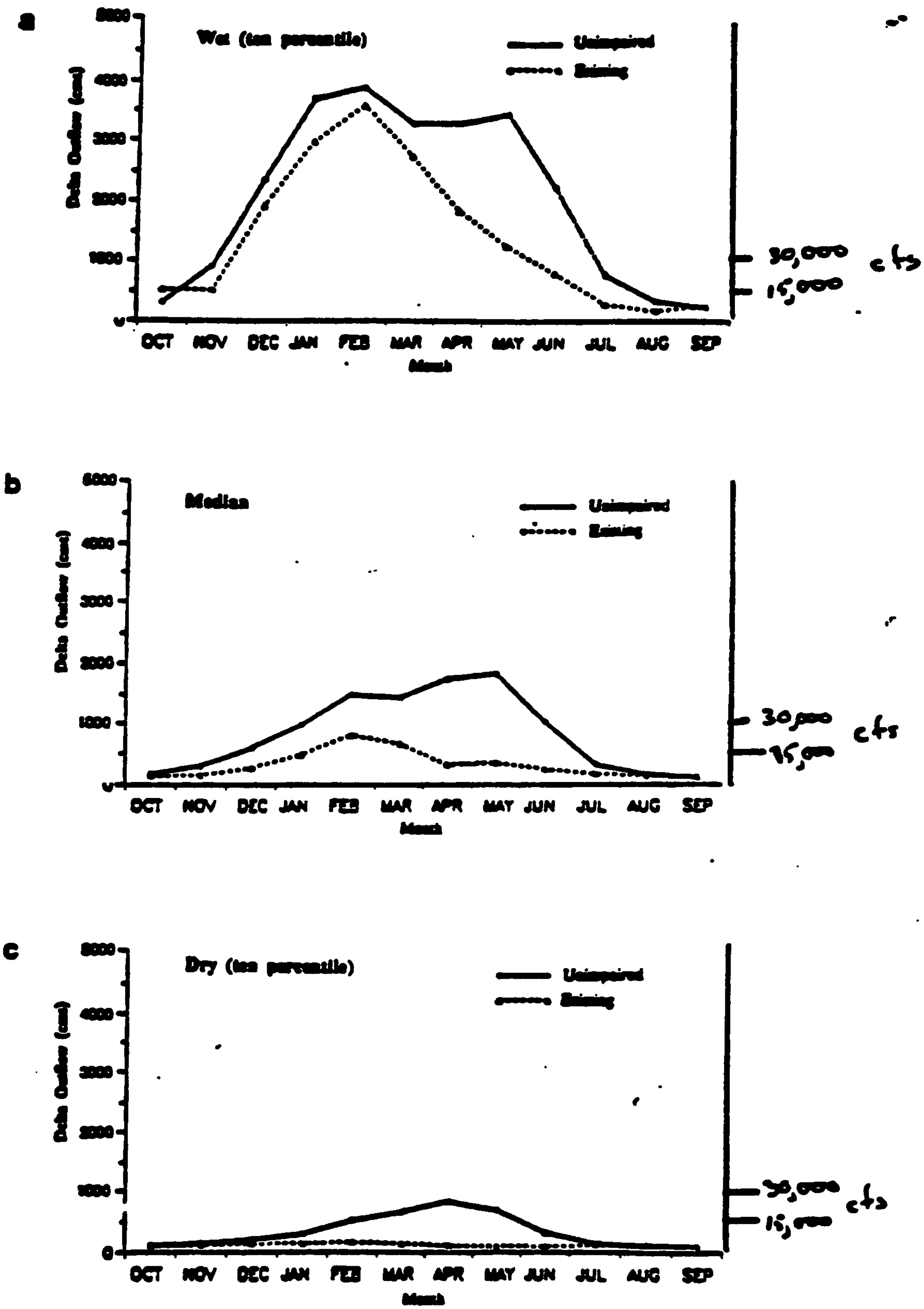
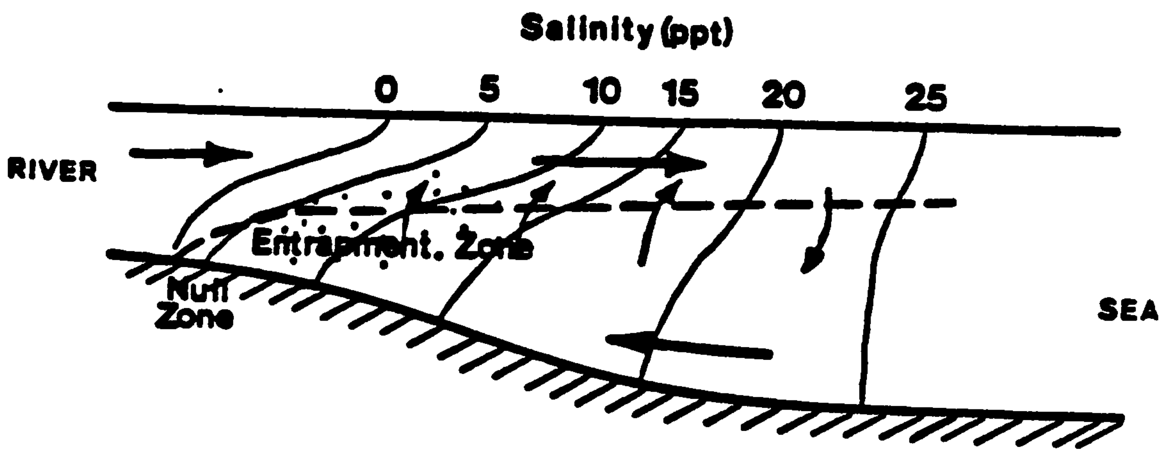


Figure 3. Changes in wet, median, and dry annual delta outflow hydrography



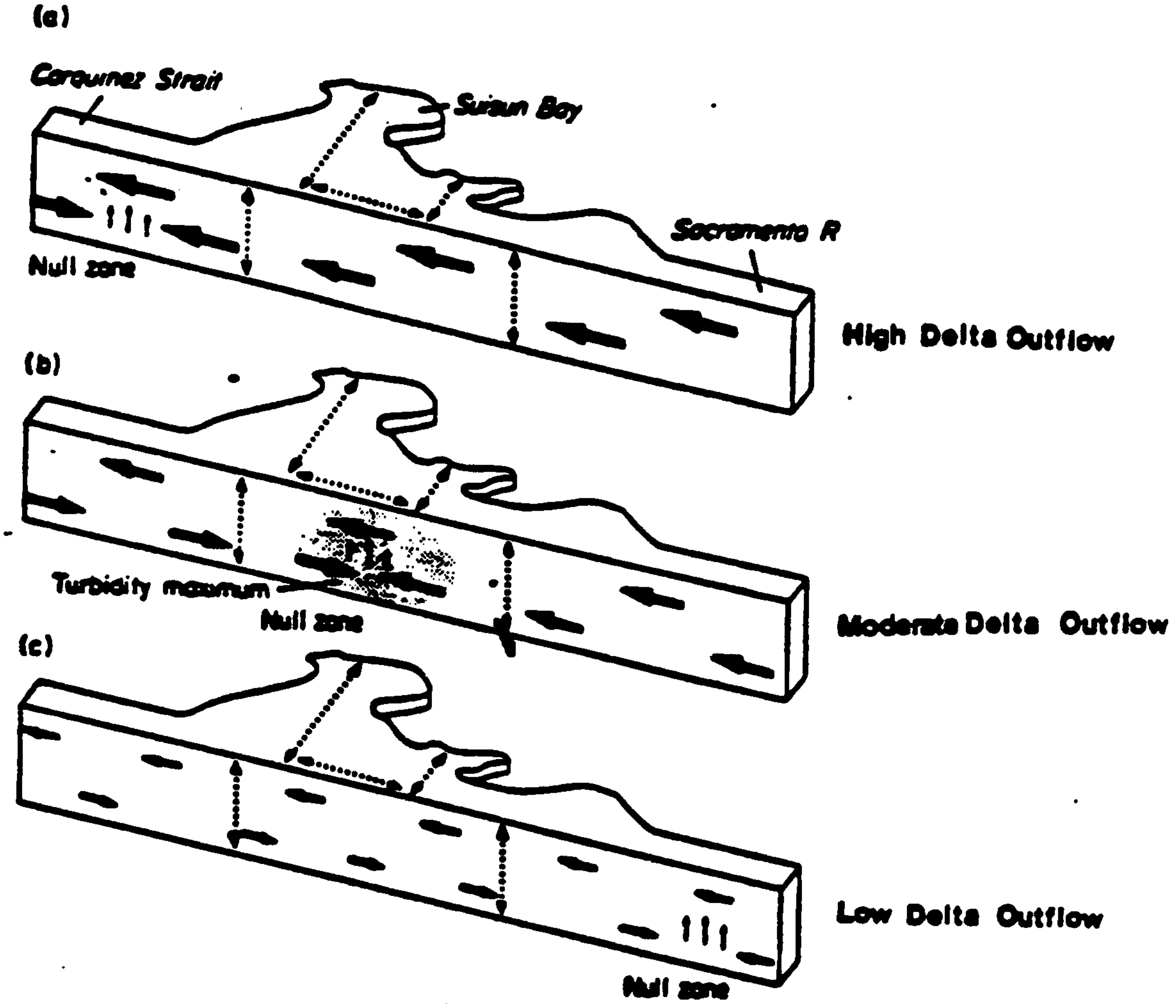
(K. R. Dyer, 1986)

Philip Williams & Associates
Consultants in Hydrology

Diagram of Estuarine Circulation for a Partially Mixed Estuary

FIGURE 12

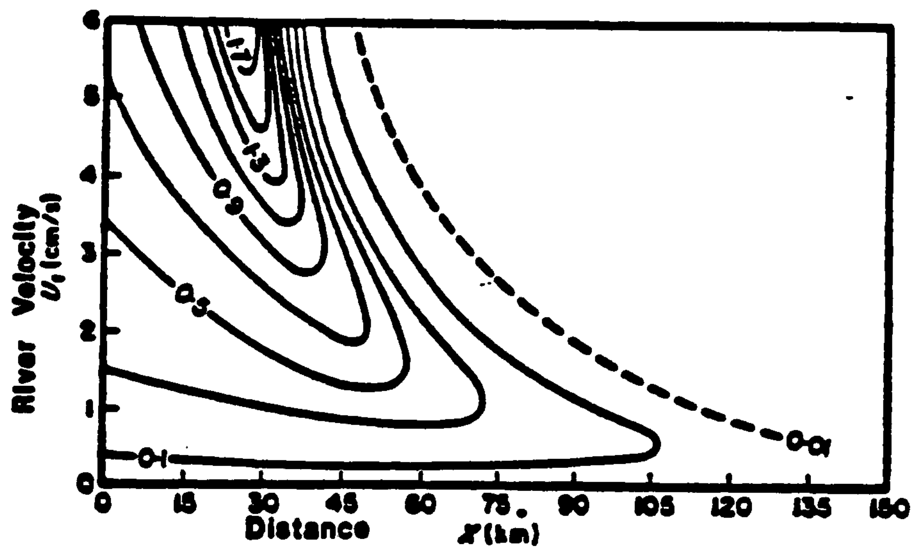
Figure 5 Williams (1)



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

(Cloern, et al, 1983)

Philip Williams & Associates Consultants in Hydrology	Influence of River Flow on Circulation in Suisun Bay	FIGURE 15



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)

Philip Williams & Associates Consultants in Hydrology	Influence of River Flow on Vertical Velocities in a Hypothetical Estuary	FIGURE 14

integral net production in the photic zone. Phytoplankton growth rate (k_2 = divisions day^{-1}) was calculated as $\log_2 (C_t + C_0)/C_0$, where C_t is mean net production in the water column (mg C m^{-2} day^{-1}) and C_0 is initial phytoplankton carbon (mg C m^{-2}). C_0 was estimated from chlorophyll *a* concentration, assuming a constant carbon : chlorophyll *a* ratio of 40 (R. L. J. Wong, unpublished data).

The FA study was comparable, but included biweekly sampling during spring and summer, only spectrophotometric determination of chlorophyll *a* from bottle samples, and more vertical profiles in Suisun Bay.

Results

During 1975, 1978 and 1979, discharge through the Sacramento–San Joaquin Rivers was representative of normal annual hydrographs (Figure 2). Mean monthly discharge peaked (to over 1000 m^3 s^{-1}) in February–March, then declined to relatively constant lower flows

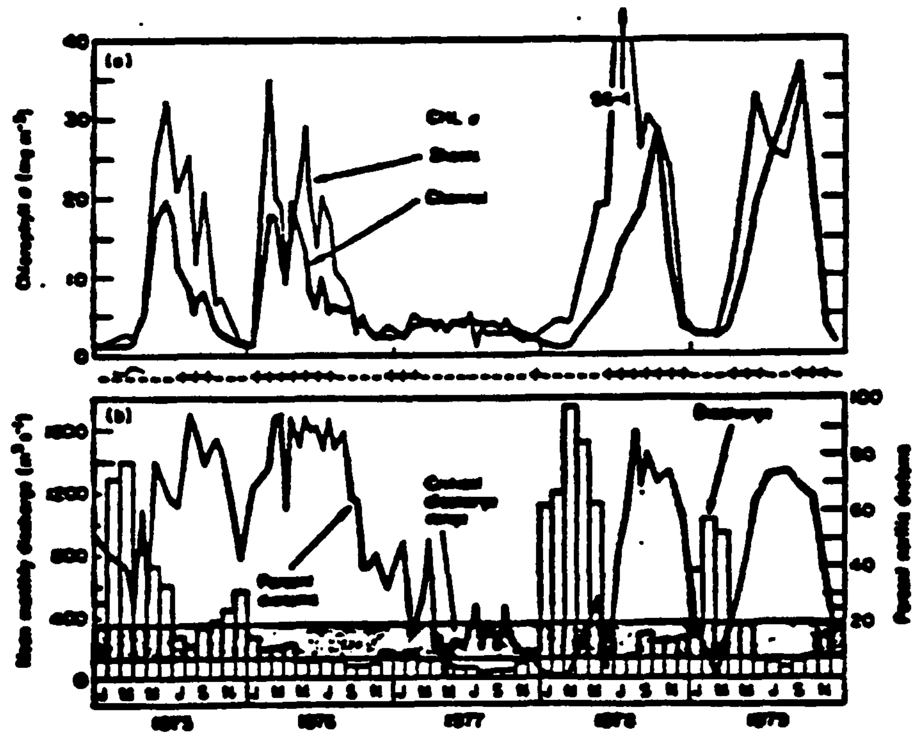


Figure 2. Seasonal changes in (a) chlorophyll *a* concentration, and (b) mean monthly river discharge (from U.S. Bureau of Reclamation, Sacramento) and percentage of neritic diatoms in Suisun Bay from 1975 to 1979. Chlorophyll *a* concentrations for 1975–77 are values in near-surface water at three sites (○, Figure 1) in the channel and one site (station 76) in the shoals (data from California Department of Water Resources, 1976, 1977, 1978). Chlorophyll *a* concentrations for 1978–79 are mean values at four sites (stations 3–6) in the channel and one site (station 76) in the shoals. Percentage of neritic diatoms is from samples taken at one channel station (6) and one shoal station (76). ▭, Critical range of river discharge when diatom biomass increases; symbols between frames represent times when mean monthly discharge fell within (+) or outside (−) this range.

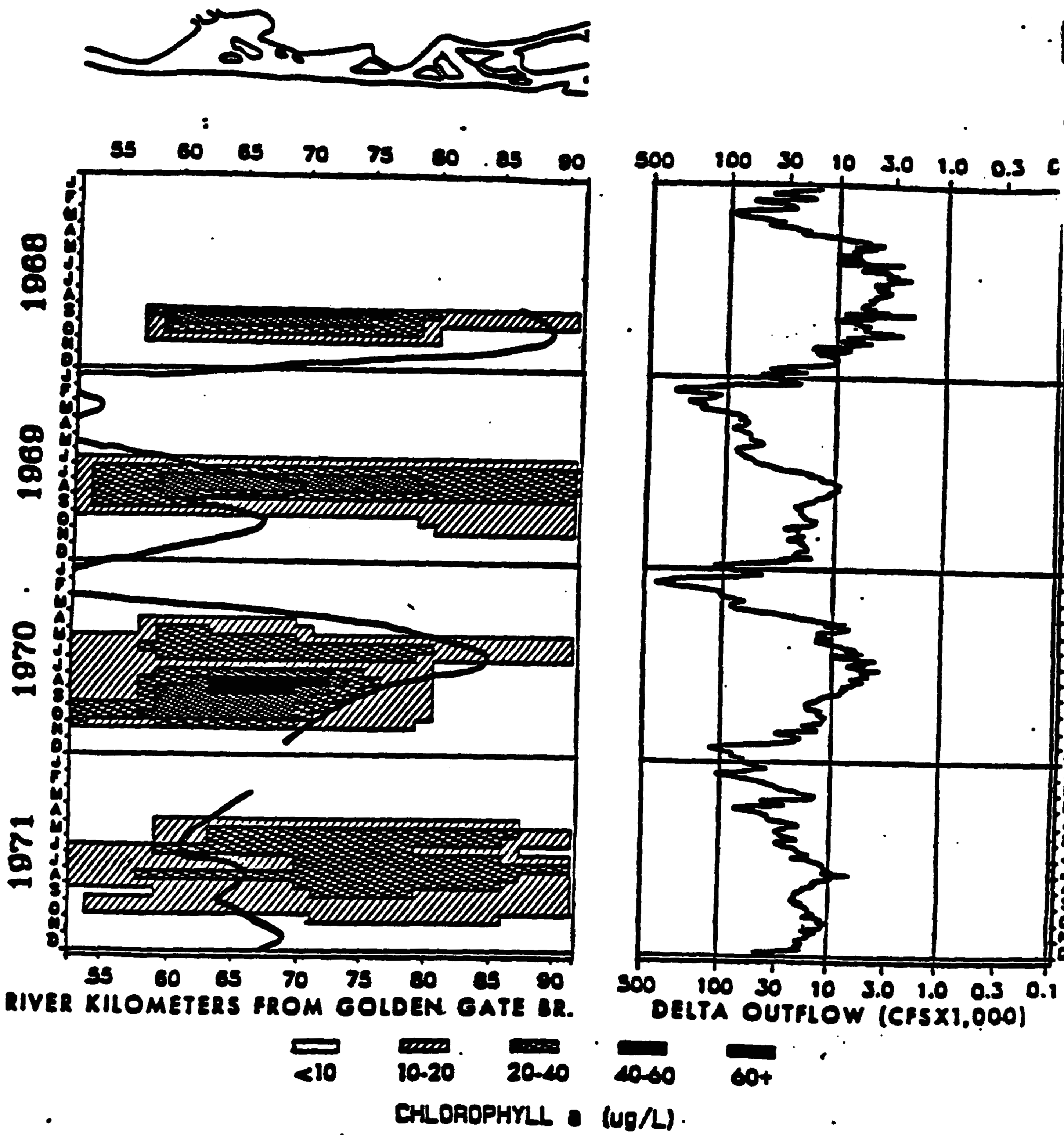


Figure 29a. The temporal and spatial relationship of high slack tide chlorophyll a along the Sacramento River channel from Martinez to Emmaton as related to salinity intrusion line and Delta outflow (the 2 ppt salinity line is approximately the location of the middle to upstream edge of the entrapment zone).

Figure 9 Ball (1)

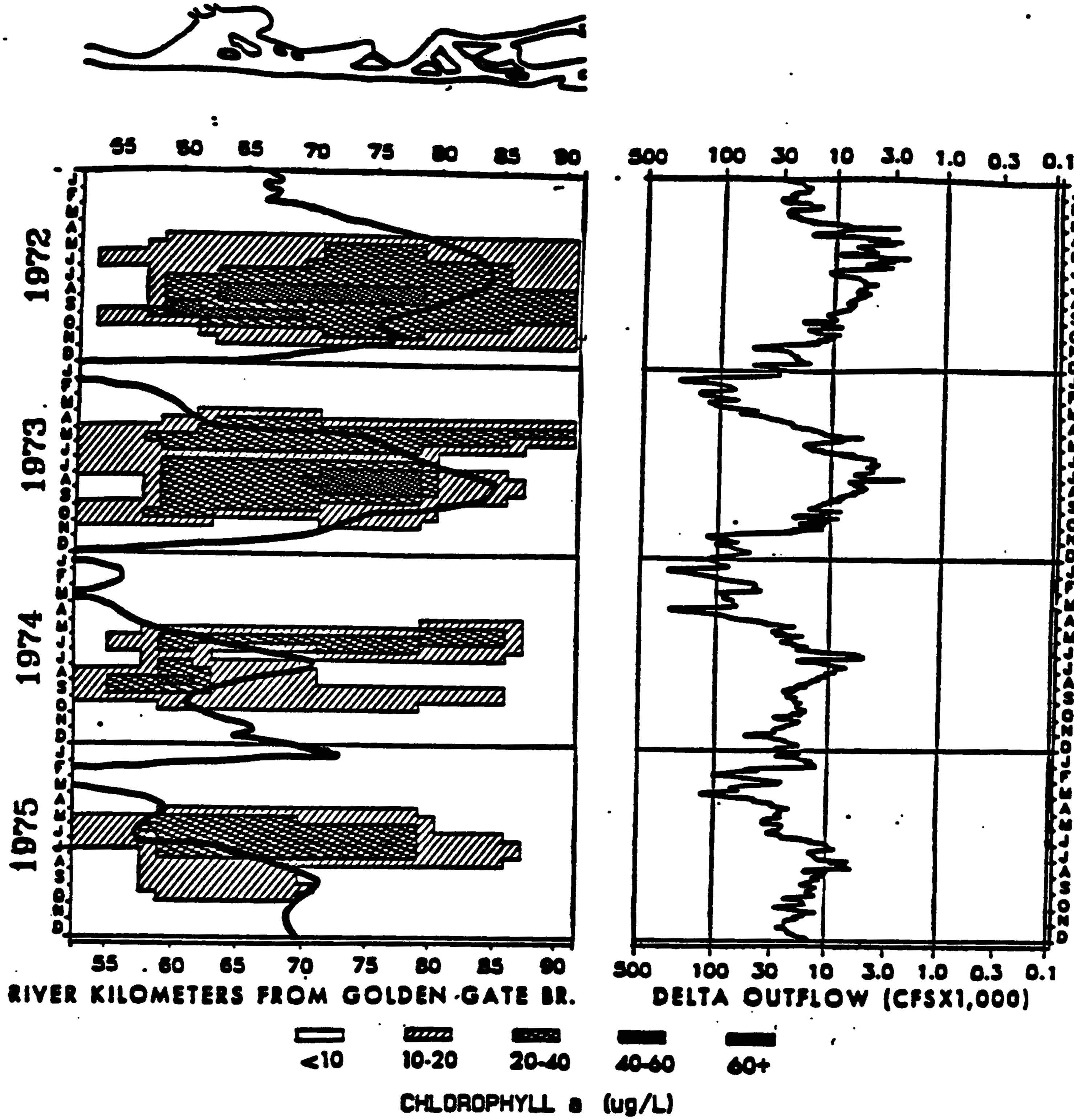


Figure 29b. The temporal and spatial relationship of high slack tide chlorophyll a along the Sacramento River channel from Martinez to Emmaton as related to salinity intrusion line and Delta outflow (the 2 ppt salinity line is approximately the location of the middle to upstream edge of the entrapment zone).

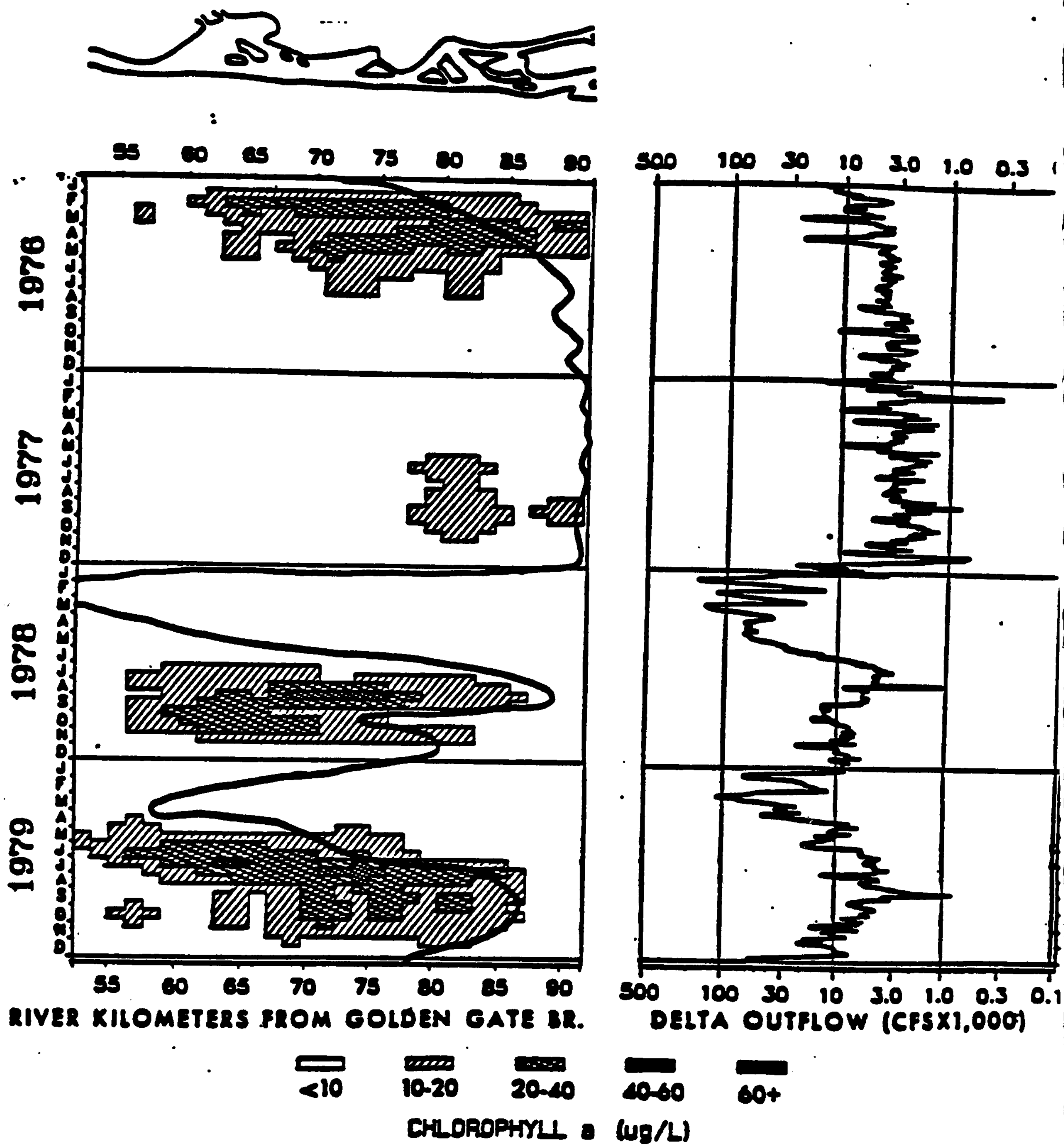


Figure 29c. The temporal and spatial relationship of high slack tide chlorophyll a along the Sacramento River channel from Martinez to Emmaton as related to salinity intrusion line and Delta outflow (the 2 ppt salinity line is approximately the location of the middle to upstream edge of the entrapment zone).

Figure 11 Ball (1)

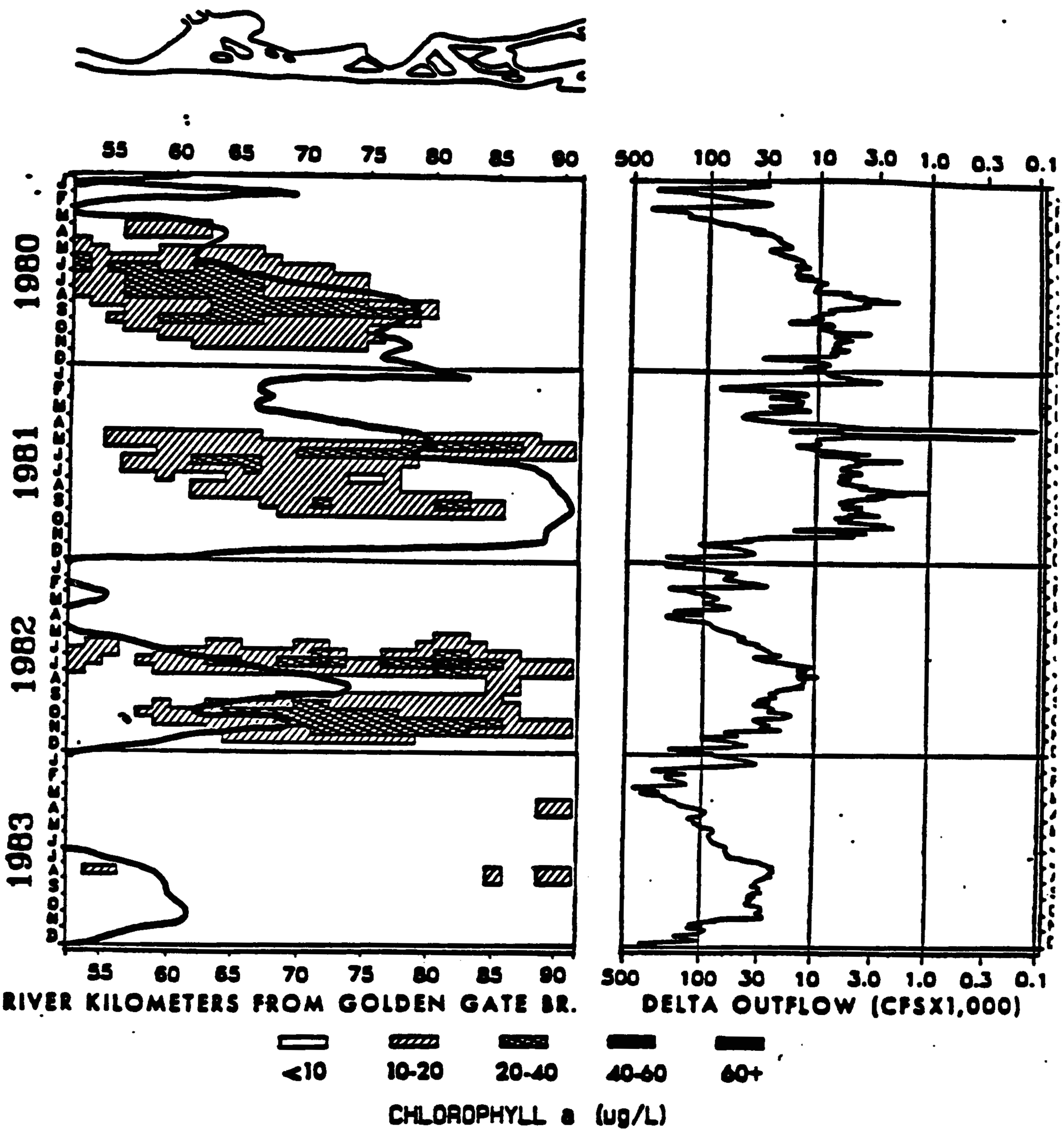


Figure 29d. The temporal and spatial relationship of high slack tide chlorophyll a along the Sacramento River channel from Martinez to Emmaton as related to salinity intrusion line and Delta outflow (the 2 ppt salinity line is approximately the location of the middle to upstream edge of the entrapment zone).

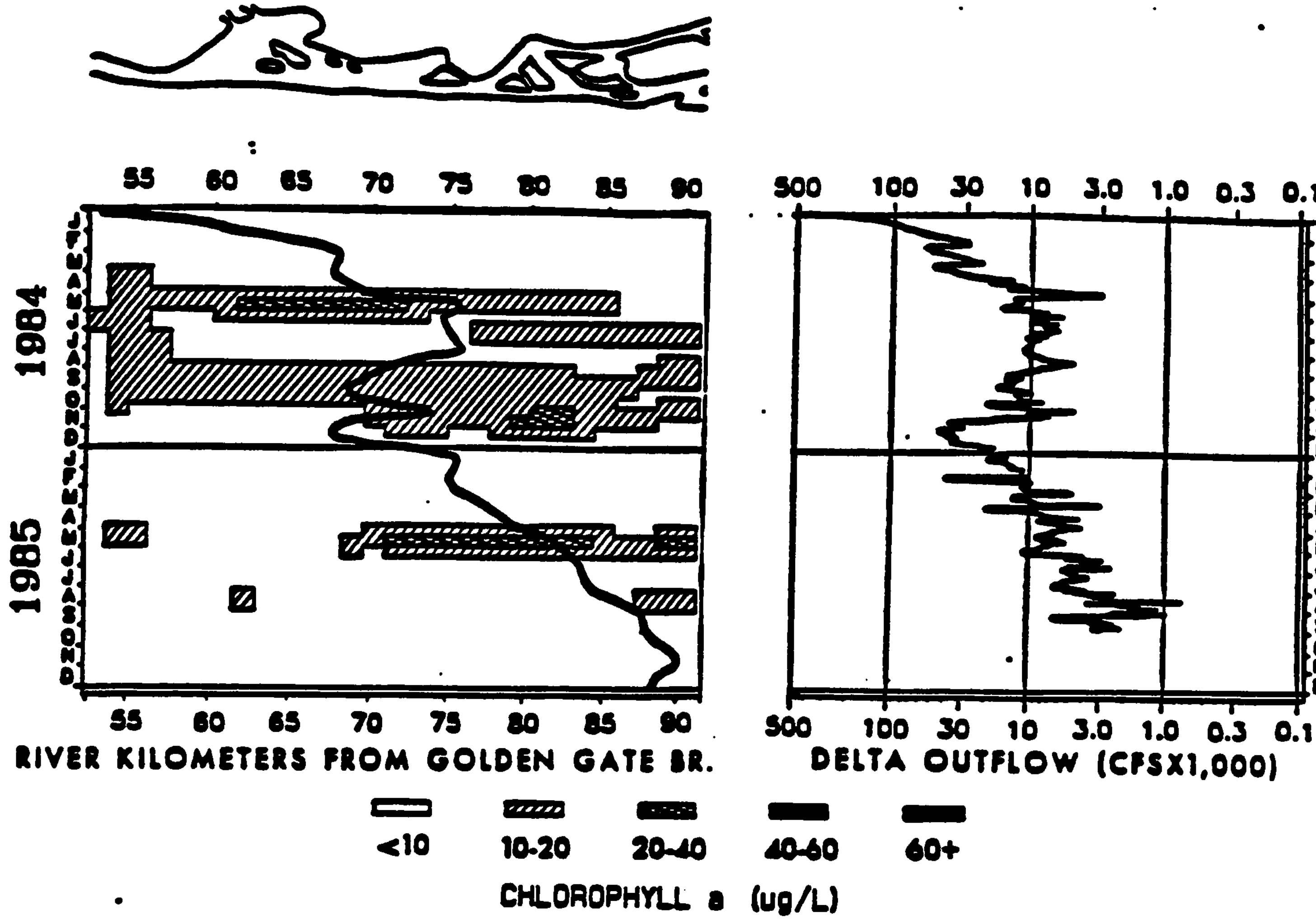


Figure 29e. The temporal and spatial relationship of high slack tide chlorophyll a along the Sacramento River channel from Martinez to Emmaton as related to salinity intrusion line and Delta outflow (the 2 ppt salinity line is approximately the location of the middle to upstream edge of the entrapment zone).

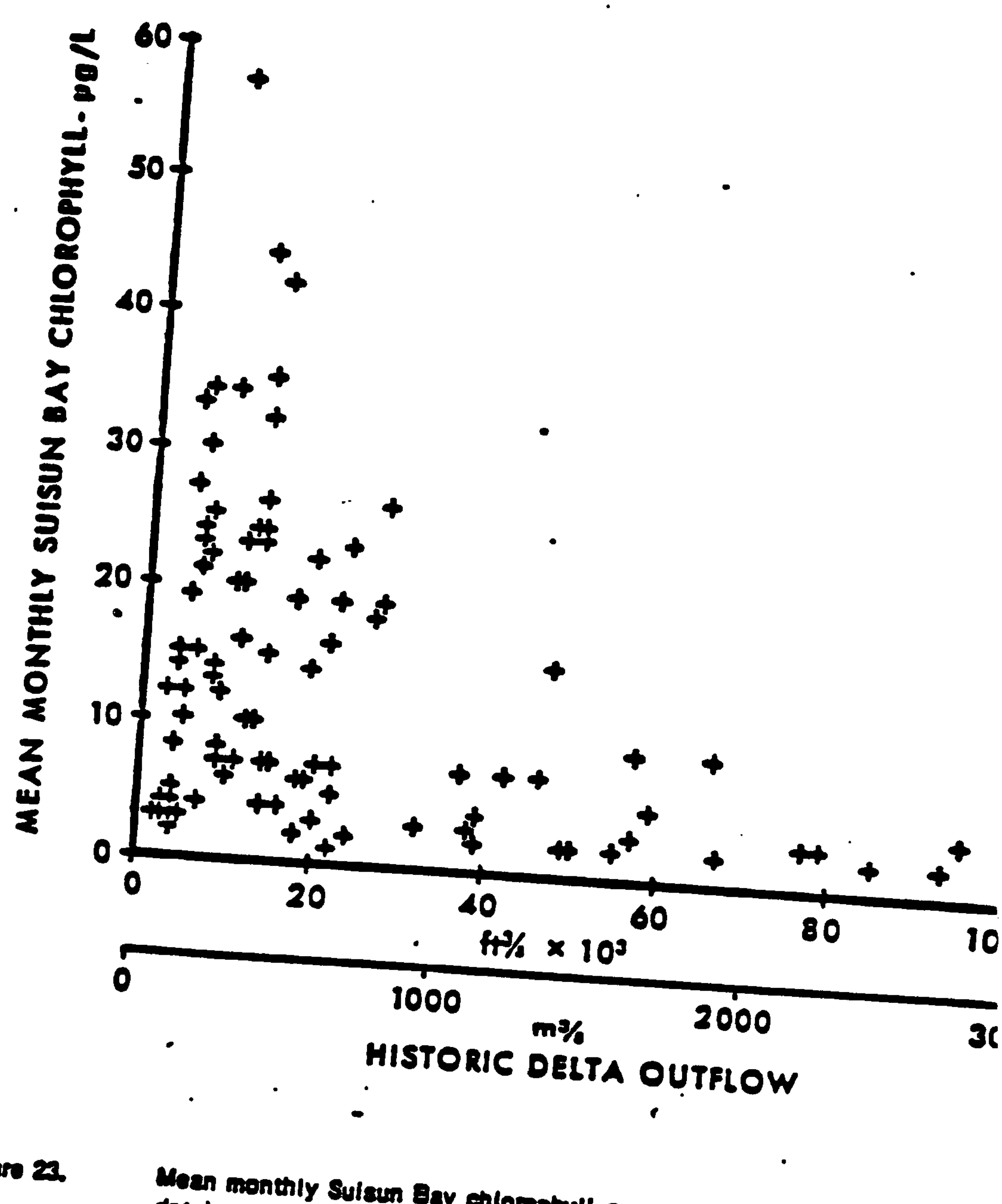
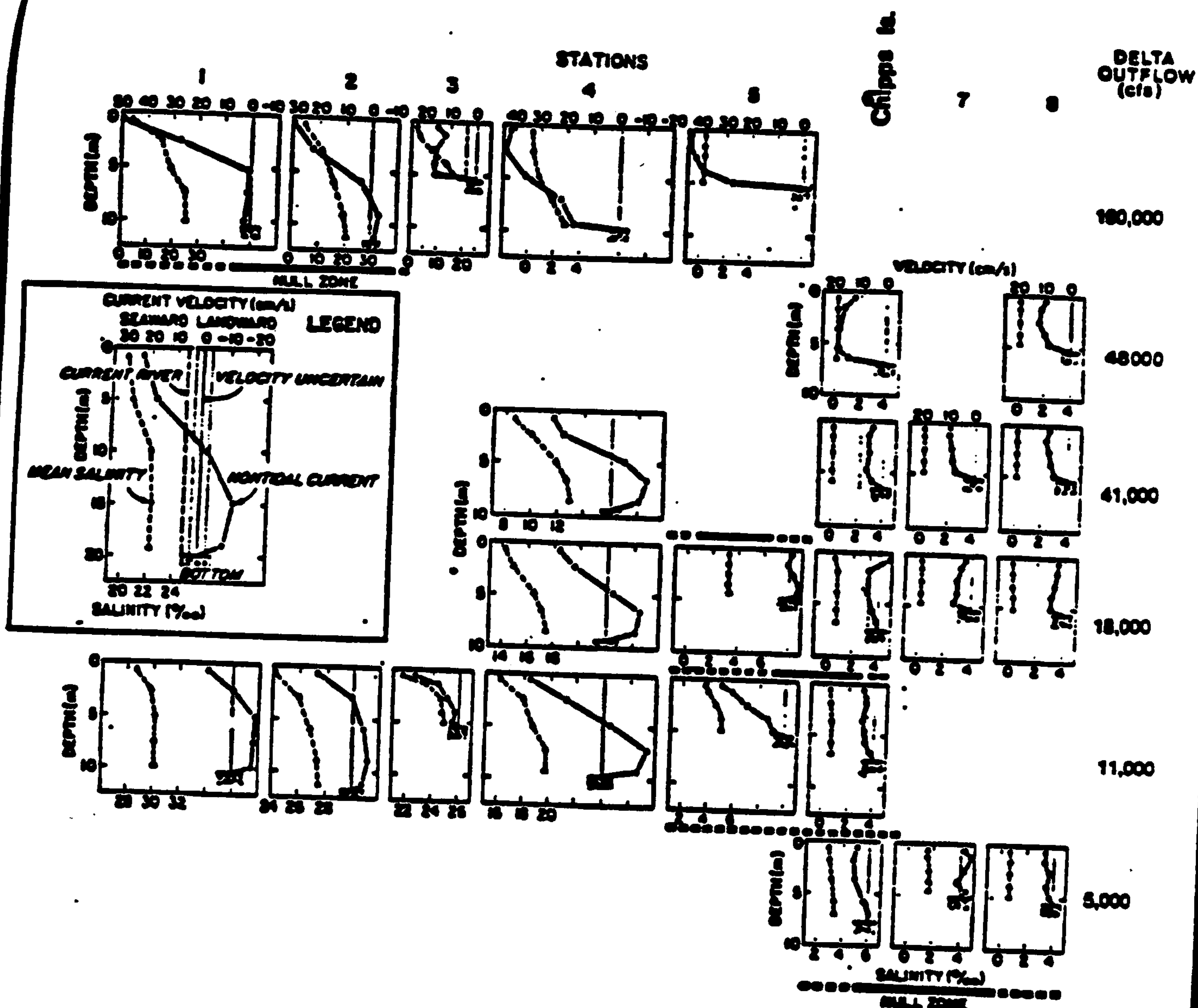


Figure 23. Mean monthly Suisun Bay chlorophyll *a* measurements (Service, DWR, a data) vs. historical Delta outflows, 1969–1979 (February through Nov

Figure 14 Williams (1)

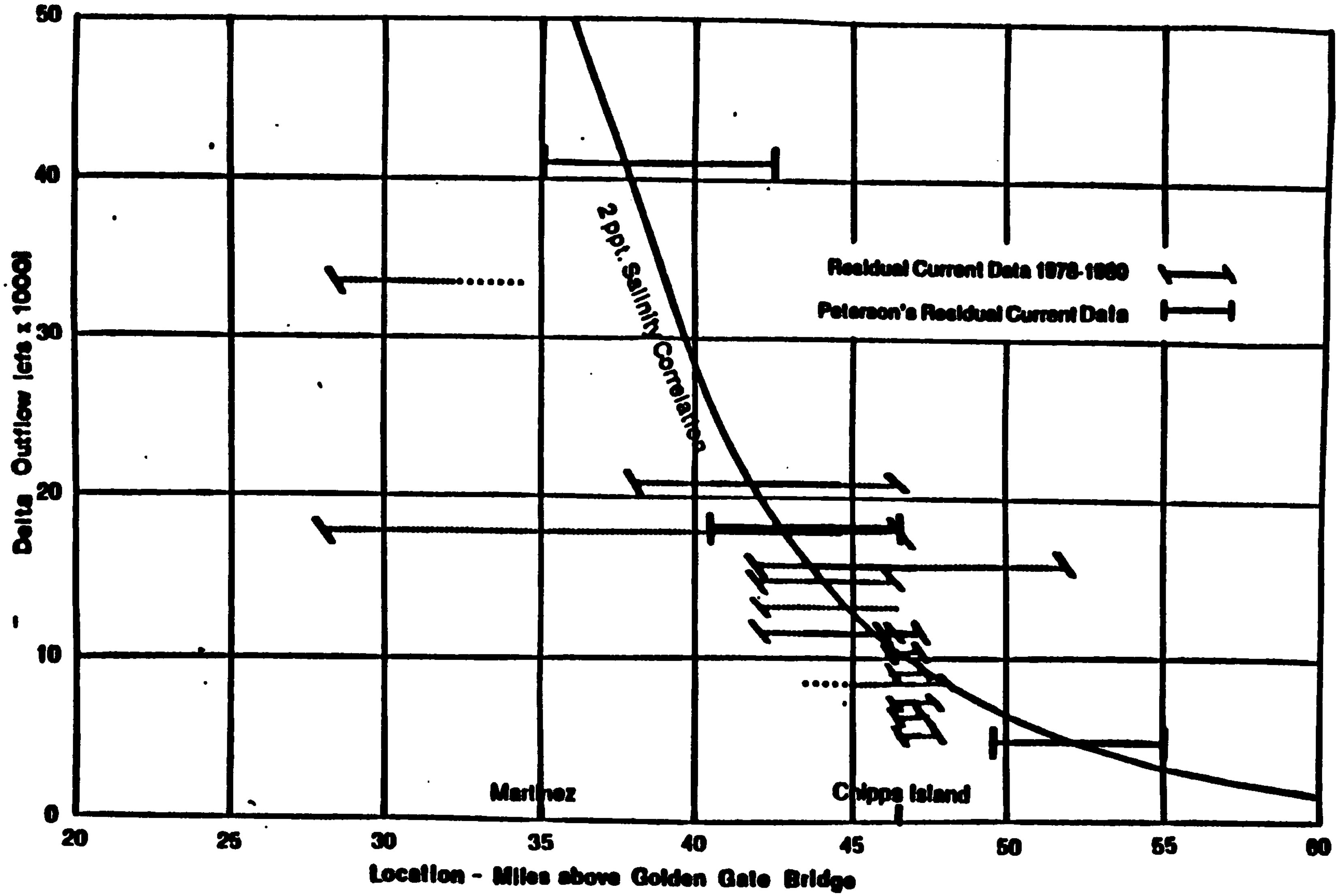


Non-tidal currents and mean salinity at Stations 1 through 8 in San Francisco Bay estuary during different river discharge conditions. Profiles are from half-hourly velocity and hourly salinity measurements over a 24·8-h tidal cycle. The location of null zone is indicated by a solid line beneath the 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)

Philip Williams & Associates Consultants in Hydrology	Location of Null Zone (Peterson)	FIGURE 17

Figure 15 Williams (1)



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Location of Null Zone Defined by Residual Velocity

FIGURE 21

Figure 17 DFG #25

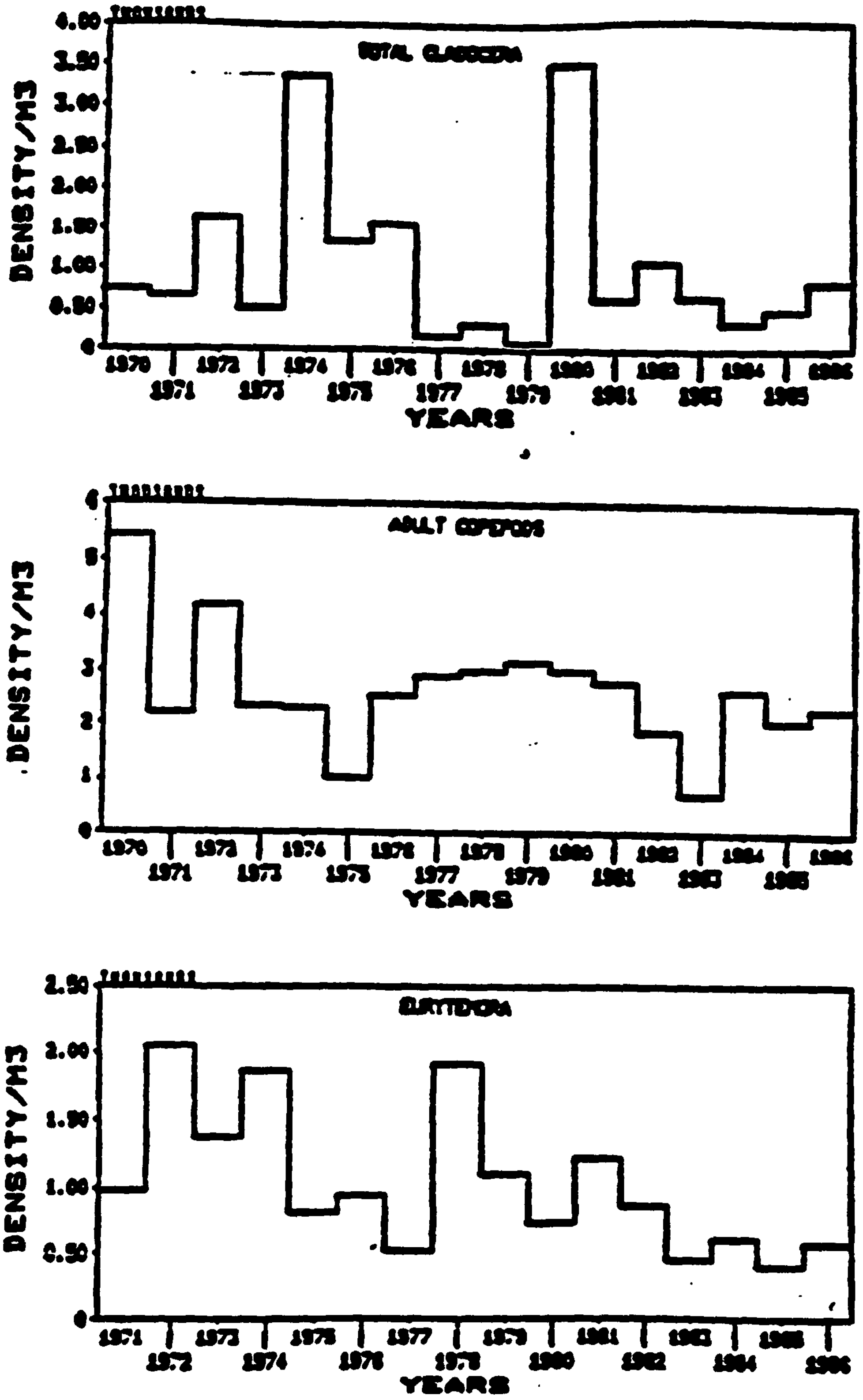


Figure 28. Trends in abundance of the zooplankton utilized by larval striped bass as food. The area-wide decline in the highly preferred copepod Eurytemora does not exactly match the decline of young bass, but its recent abundance generally has been low and may be contributing to the young bass decline.

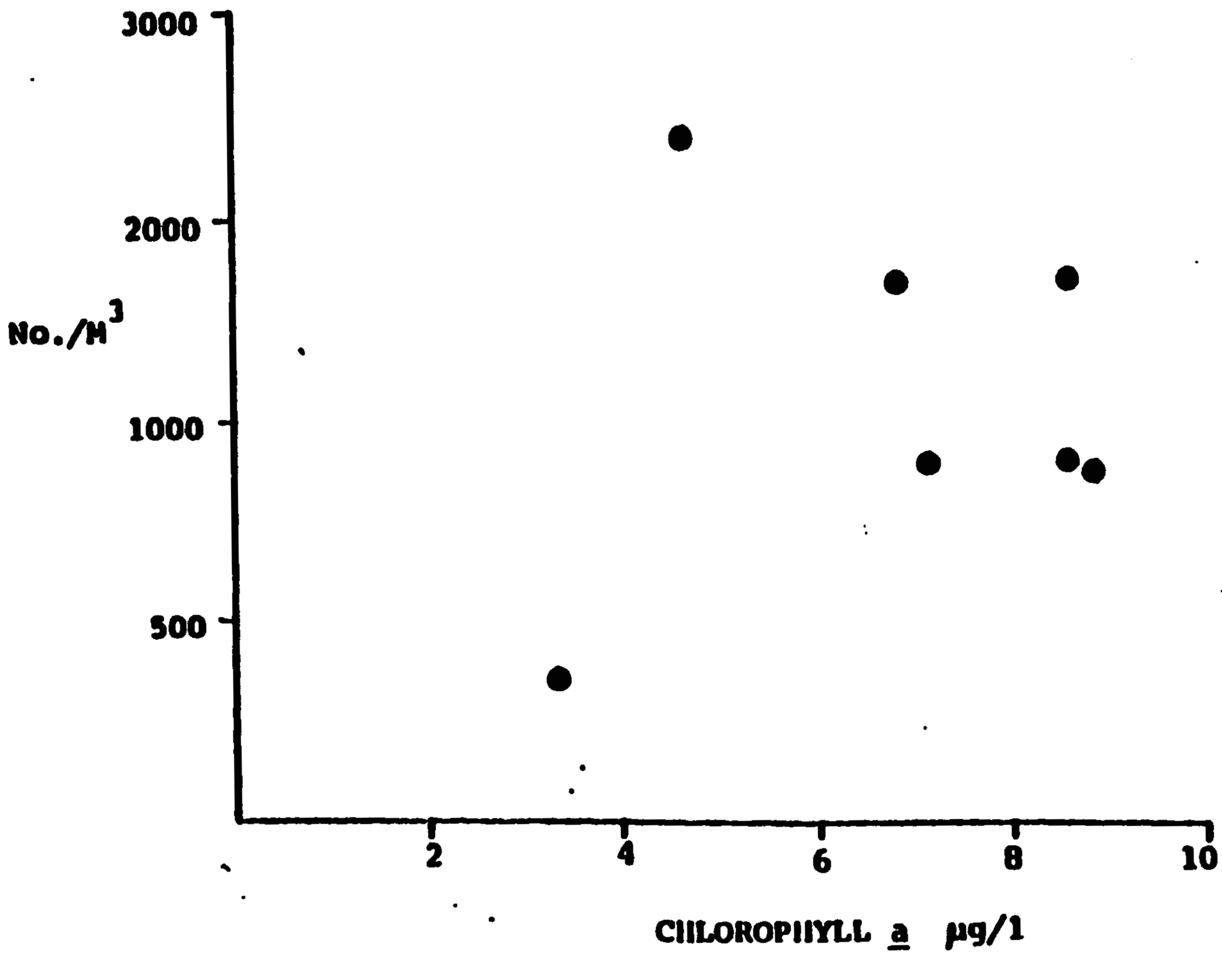


Fig. 40. Sinocalanus abundance vs. chlorophyll a concentrations in the delta, March-November means 1979-1985.

Figure 19 DFG #28

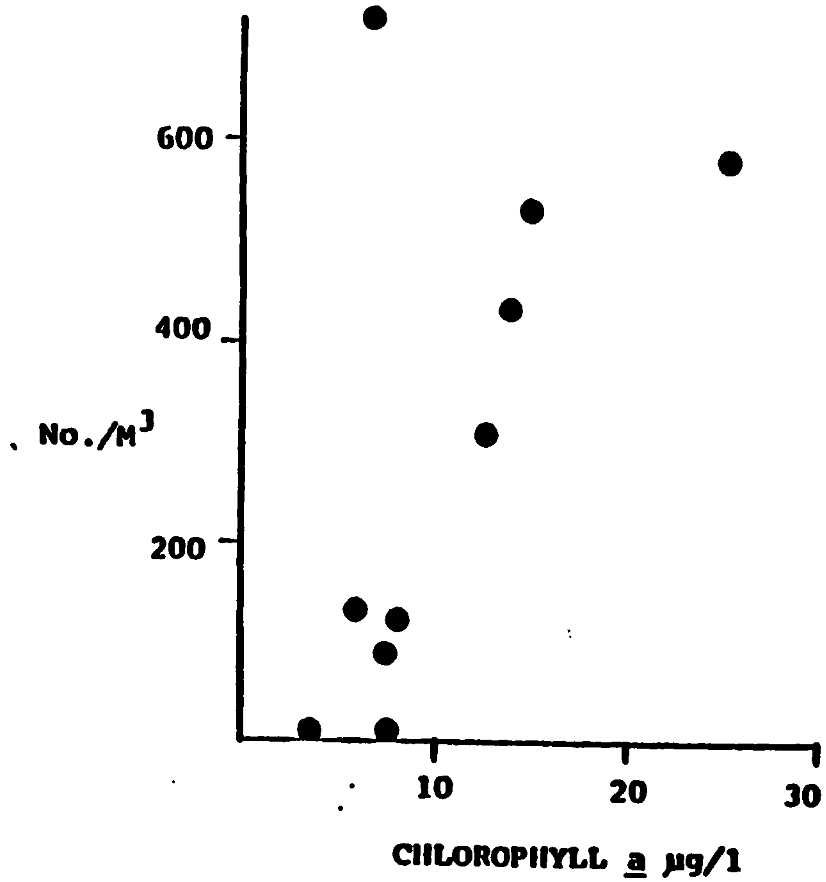


Fig. 41. *Diaptomus* abundance vs. chlorophyll *a* concentrations in the upper San Joaquin River, March-November means, 1972-1985.

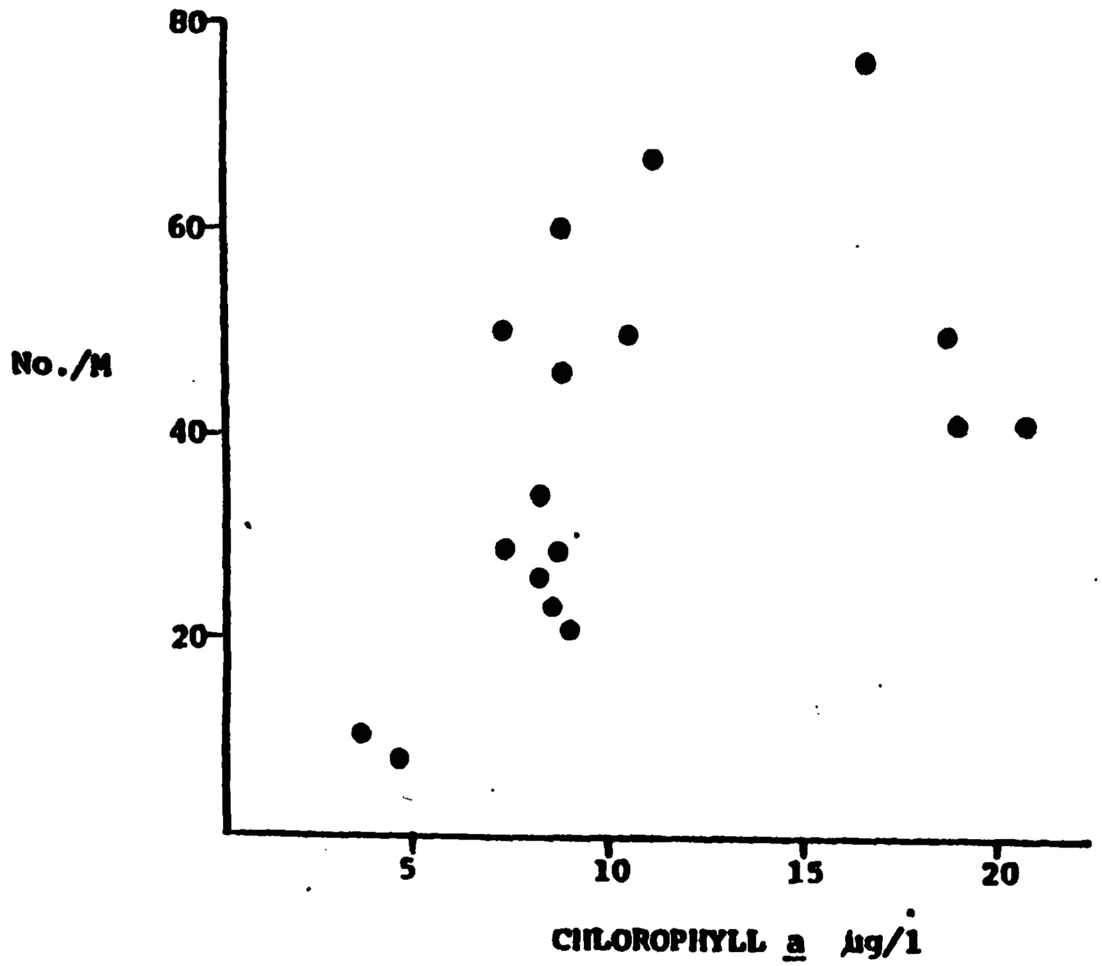


Fig. 42. *Neomysis* abundance vs. chlorophyll *a* concentrations in all areas combined, March-November means 1969-1985.

Figure 21 DFG #28

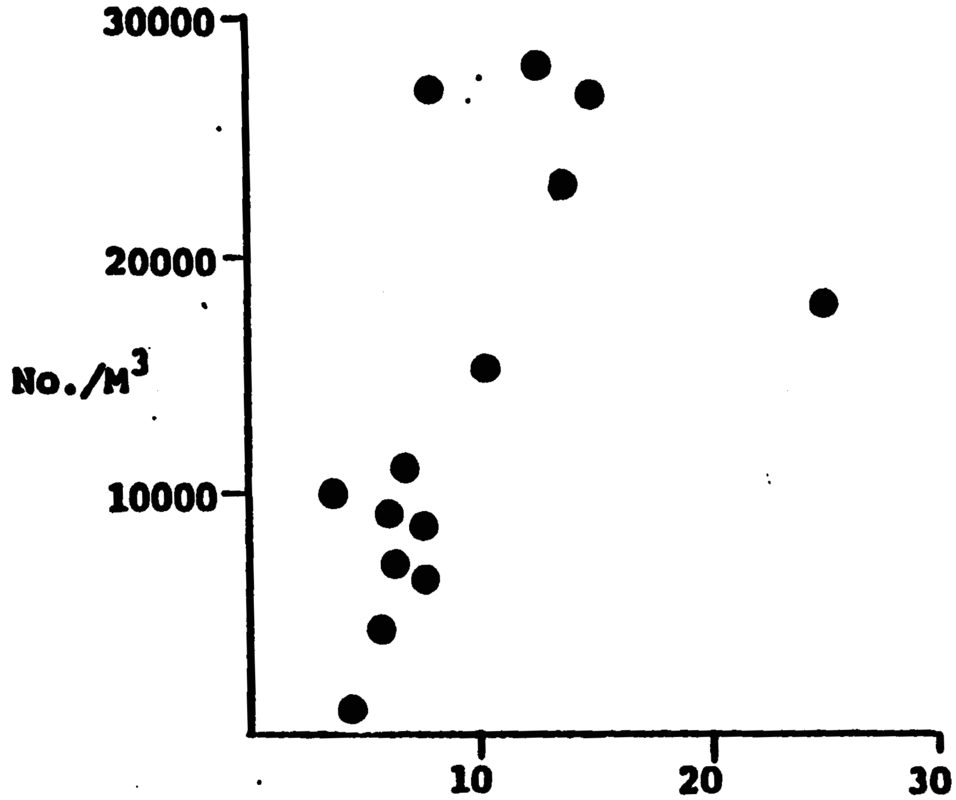
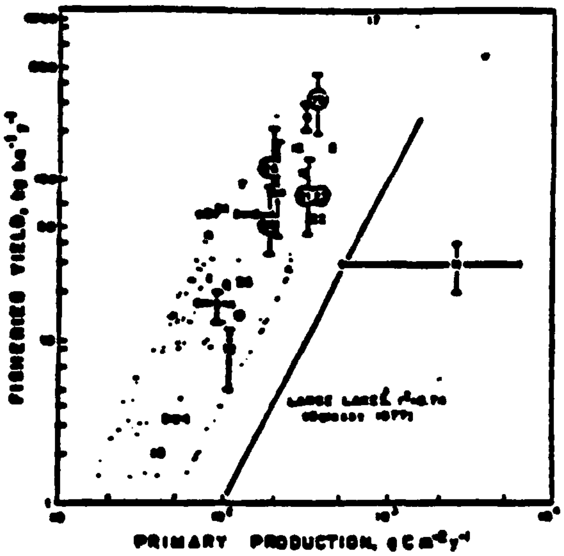


Fig.45 . Cladoceran abundance in the upper San Joaquin River vs. chlorophyll a concentrations, March-Novmeber means 1972-1985



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 Stille, 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 Estuarine Productivity	FIGURE 3

Table 2. Results of stepwise multiple regressions by taxon and time period. Only variables that achieved significance are listed.

Taxon	Time Period	Area	Independent Variables	t Ratio	P	R^2	df
Eurytemora	March-Nov.	Suisun Bay	Chlorophyll *a*	3.63	>.01	61.56	8
		All Areas	Chlorophyll *a*	4.93	>.01	65.96	8
Sinocalanus	March-Nov.	Delta	None				
		All Areas	Chlorophyll *a*	3.40	>.05	83.26	3
Diaptomus	March-Nov	Upper San Joaquin R.	Chlorophyll *a*	5.94	>.01	81.53	6
Neomysis	March-Nov.	Suisun Bay	Chlorophyll *a*	2.41	>.05	58.06	8
			Chipps EC	-2.29	>.05		
		All Areas	Chlorophyll	2.40	>.05	63.27	8
			Chipps EC	-2.84	>.05		
Native Cyclopoids	March-Nov.	Upper San Joaquin R.	Chlorophyll *a*	6.54	>.01	78.08	10
		Delta	Chlorophyll *a*	3.40	>.01	49.03	9
Limnoithona	March-Nov.	Delta	None				
		All Areas	None				
Cladocera	March-Nov.	Upper San Joaquin R.	Chlorophyll *a*	2.45	>.05	33.36	9
		Delta	Chlorophyll *a*	2.50	>.05	34.21	11

Table 1 Continued

Table 2 (cont.)

Taxon	Time Period	Area	Independent Variables	t Ratio	P	R^2	
Rotifers	March-Nov.	Upper San Joaquin R.	Chlorophyll a	5.47	>.01	79.30	
			Exports	-2.40	>.05		
			Chipps EC	-2.39	>.05		
		Delta	Chlorophyll a	3.65	>.01	56.28	
			Exports	-2.42	>.05		
Synchaeta bicornis	March-Nov.	Suisun Bay	Chlorophyll a	5.92	>.01	76.11	1:
		All Areas	Chlorophyll a	3.44	>.01	51.77	1:

Table 2 Stevens

TABLE 3.—*Mean concentrations (numbers/m³) of food organisms utilized by young striped bass for different areas of the Sacramento-San Joaquin Estuary.*

Year	Western delta: Crustacean zooplankton[a]	Western delta: *Neomysis mercedis* >4 mm[a]	Suisun Bay: Crustacean zooplankton[a]	Suisun Bay: *Neomysis mercedis* >4 mm[a]	Location of striped bass larvae: crustacean zooplankton[b]
1968		125.1		84.2	
1969		64.1		61.1	
1970		26.0		38.1	
1971		28.4		41.5	
1972	56,240	51.6	96,130	28.9	107,320
1973	32,210	44.9	81,550	86.6	83,350
1974	24,560	34.1	55,920	77.0	86,470
1975	13,130	17.7	38,450	54.9	86,220
1976	21,510	33.4	30,770	35.9	54,050
1977	73,620	16.0	55,700	0.8	38,850
1978	11,310	17.6	49,070	34.8	16,110
1979	10,230	15.3	45,010	25.5	29,370
1980		31.1		60.3	
1981		26.5		20.1	
1982		12.6		45.3	
1983		2.9		14.6	

[a] Mean concentration from April through June.
[b] Mean concentration where and when young striped bass are first feeding.

et al. 1982). As they grow, they feed on larger zooplankters such as the opossum shrimp *Neomysis mercedis* (Heubach et al. 1963).

Information collected by CFG, the California Department of Water Resources, and the United States Bureau of Reclamation enabled the Striped Bass Working Group to evaluate trends in productivity of the nursery area during recent years. Phytoplankton are monitored by chlorophyll-*a* measurements. The largest crustacean zooplankton are sampled by 10-minute oblique tows from bottom to surface with a 154-μm-mesh Clark-Bumpus net. Pumps are used to sample zooplankton that pass through a 154-μm-mesh screen. Opossum shrimp are captured in 10-minute tows with a conical plankton net (Knutson and Orsi 1983). Generally, all plankton categories have been sampled at more than 30 locations at least twice monthly during the striped bass spawning and nursery period.

Phytoplankton monitoring data were available for this analysis from 1969 to 1982, crustacean zooplankton data from 1972 to 1979, and opossum shrimp data from 1968 to 1983. Although more recent plankton data have been collected, they are not yet available for analysis.

The data provide evidence of a general overall decline in the productivity of the striped bass nursery area during recent years. The decline has been great enough to cause a major reduction in the amount of food available for young striped bass.

In the western delta, upstream from the junction of the two rivers, there was a prominent spring bloom of phytoplankton each year until 1977, except for 1969 and 1975 (Fig. 11). No spring bloom occurred from 1977 to 1980. Blooms did occur briefly in May 1981 and in June 1982.

In Suisun Bay, an area with generally high biological productivity due to the presence of the entrapment zone in the spring and summer, we have learned to expect a small phytoplankton bloom in spring followed by a larger bloom in late summer. However, for almost 2 years, from summer 1976 to summer 1978, there was no bloom in Suisun Bay. Since 1978, Suisun Bay phytoplankton populations have recovered substantially.

Variations in zooplankton density exhibited a different pattern from those in phytoplankton. Average concentrations of crustacean zooplankton were very high in the western delta in 1977 (Table 3), apparently due to low freshwater flows associated with a drought in 1976 and 1977 that allowed the entrapment zone to encroach upstream. In that region, average zooplankton densities were at their lowest levels in 1978 and 1979, the last years for which data are available. There was not a distinct decline in the average

Read
12/31/93

A DISCUSSION OF ISSUES RELEVANT TO THE ENTRAPMENT ZONE IN THE SAN FRANCISCO BAY ESTUARY

Working Paper
Submitted for
San Francisco Estuary Project
Technical Workshop on the Entrapment Zone

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BioSystems Analysis, Inc.

Dave Peterson, USGS
Fred Nichols, USGS
Larry Smith, USGS
Alan Jassby, U.C. Davis
Lee Miller, CDFG

August 12, 1991

This paper introduces eight issues for consideration at the workshop. Each of the issues is discussed here by one or more of the authors listed above. The initial discussion of each issue, by Kimmerer, is based on a general review of the literature pertaining to the entrapment zone of this estuary, as well as analyses of data gathered in the monitoring programs of the Interagency Ecological Studies Program. Further discussion of some of the issues was prepared by the other authors listed above. In writing these responses all authors have assumed that readers are familiar with the estuary and with basic terminology of estuarine physics and biology.

The eight issues to be discussed are:

1. **What is the physical, chemical, and biological definition of the EZ in the San Francisco Bay estuary?**

2. **What components of the estuarine ecosystem (i.e. species, food web, or habitat) are significantly affected by processes occurring in the EZ?**

3. **To what extent are particles and populations concentrated by gravitational circulation, and to what extent by other physical processes such as exchange between shoals and channels coupled with wind-driven resuspension?**

4. **To what extent is the concentration of biota in the EZ caused by physics, and to what extent by biology, e.g. altered growth rate within the EZ, trophic interactions, or behavior?**

5. **How do location and the timing and extent of movement of the EZ affect ecosystem components?**

6. **Do any effects of position of the EZ occur because of topography, or through correlates of EZ position, e.g. freshwater flow, entrainment, or inputs of nutrients or organic matter?**

7. **How can measurements of salinity or electrical specific conductance be used as an index of EZ position? Are better indices or measurements available?**

8. **To what extent can the EZ be positioned by different freshwater flow scenarios?**

1. What is the physical, chemical, and biological definition of the EZ in the San Francisco Bay estuary?

The entrapment zone is a region of the estuary in which particles and organisms are trapped by the interaction of their settling with current shear. The description of entrapment appearing in most of the literature on the topic[1] can be summarized as follows: a gradient in water surface elevation causes surface freshwater to flow downstream over a layer of saltier water. Turbulent mixing across the interface entrains salt water from the deep layer into the surface layer. The horizontal salinity gradient causes an inward flow at depth, which supplies the salt water to be entrained. An upward flow is assumed to occur between the two layers. Particles or organisms that sink or swim out of the surface layer are entrained in the upstream and upward flows, becoming trapped in this part of the estuary.

Although the description above is a useful conceptual model of entrapment, it ignores several effects that are probably important in San Francisco Bay. The upward flow is calculated from continuity, not generally measured. It is embedded in a shear layer in which typical vertical turbulent velocities may be much larger than this calculated flow.

Another problem with this description is that tidal velocities often far exceed the flow velocity of the surface freshwater layer or the deep saline layer. Instead of a two-layer flow, one more often sees unidirectional flow on each tide, with an asymmetry between ebb and flood current profiles: on the flood, flow velocity is relatively greater at depth, while on the ebb it is relatively greater near the surface. The ebb-flood asymmetry is produced by the horizontal gradients in surface elevation and density; that is, gravitational circulation reinforces the flood near the bottom and the ebb at the surface. Net transport, obtained by integrating velocity profiles over depth ranges and over a tidal cycle, is upstream at depth and out at the surface; however, measuring this net transport can be difficult because the net velocities are a small fraction of the instantaneous velocities. However, this net transport still results in entrapment of particles.

A third problem is that turbidity maxima can occur through other mechanisms (see Issue #3).

Particles of organic or inorganic material as well as phytoplankton and zooplankton can become locally concentrated by the above mechanism if their settling rates are sufficient to remove them from the surface layer. Organisms that swim may migrate vertically to maintain position through interaction with net two-layer flow, producing a local concentration as with settling particles[2]. Different particle settling velocities or organism swimming behavior would result in different locations of the maximum.

Although particles and organisms are concentrated in the EZ, growth rates of organisms may not be enhanced there (See Issue 4). Also, the EZ represents a rather small part of the total volume of the estuary, so elevated production there may represent a small part of total system production.

D. Peterson

A. What is the physical definition..?

The seaward limb of the EZ is the gravitational circulation cell (or cells). To this end the impressive drifter experiments of Conomos provide a gross overview of the mean current structure. As a first approximation in constructing this, note that bottom drifters are entrained and transported into the bay from 25 km offshore and beyond.

Question #1. What role, if any, do tidal currents play in this offshore regime of near-bottom landward flow into the Bay?

Marlene Noble, for example, feels most if not all of this flow is associated with gravitational circulation but a tidal contribution cannot be ruled out.

As an aside, it is interesting Garvine (1991) seems surprised (?) impressed (?) that the mean near-bottom landward flow off of the mouth of the Delaware estuary is relatively strong and extends at least 40 km offshore for an estuary/shelf system with weak vertical stratification.

Assuming the above mentioned drifter experiments offer some 3-dimensional insight, note a second feature, the San Pablo Bay (shoreline) convergence of bottom drifters (Figure from Conomos enclosed).

<u>Question</u> <u>#2.</u> What does this shoreline convergence mean?

Given the scanty (in time and space) field observations with instruments, who knows or can explain it in a convincing way? And, if field observations are lacking in detail, are there any helpful results from numerical simulation experiments? Festa and Hansen's paper from the past (1976) is at the very least helpful in indicating the complexity of the problem. Their paper is entitled "A two-dimensional numerical model of estuarine circulation: the effects of altering depth and river discharge." Perhaps not fully appreciated in estuarine literature is how sensitive their model results are to very small changes in channel depth (their Fig. 12). Given that I'm not knowledgeable about numerical simulation experiments of estuarine dynamics, I am not aware if researchers have sorted out what a 3-D channel/shoal response might look like (e.g., Festa & Hansen are 2-D, the drifters trajectories dropped into channels [at the surface and at depth] and subsequently washed up on the shoreline are roughly 3-D). The point I'm trying to make here is that the bay has a weird geometry and given that physical oceanographers know geometry is very important in developing, modifying and maintaining complex circulation patterns and structures that are not yet completely understood (or at least not yet completely documented) and given the sparse observations, it is difficult to develop hard information on the Bay's physics.

<u>Question</u> <u>#3.</u> Given the above can the circulation in the bay <u>ever</u> be adequately

documented or known given, as you discussed, the complexity of the problem?

Marlene Noble suggested a relatively tight spacing of upward scanning acoustic doppler current meters (for example, roughly a dozen or so across the Chipps Island section) probably has the temporal/spatial resolution to extract the 3-D circulation structure from background noise for tidal and subtidal frequencies given full exposure to tidal, river flow and wind events and regimes. In effect many dozens of instruments would be used if the entire northern reach were studied simultaneously. Of course more realistically such instruments will be used in smaller numbers (and are being used), which ultimately will advance our understanding of the Bay's physics.

<u>Question</u> <u>#4.</u> If the EZ concept does in fact have useful management implications what about its historical perspective, is this relevant and can it ever be known?

For example, to the extent the "position" of the EZ is related to the question of salt penetration, does the salt field change significantly in the bay with channelization? It is my understanding most of the channelization took place well before the 1920's whereas salinity observations were made after this period.

B. <u>What is the chemical definition</u>..?

In the summer/fall of most wet-intermediate-dry years (but not <u>very</u> <u>dry</u> years) the dissolved inorganic nutrient distributions in northern San Francisco bay show a minimum in concentrations when plotted with salinity in the region of the chlorophyll (phytoplankton) and turbidity maximum in Suisun Bay. This indicates the dynamics between photic and aphotic processes are shifted towards photic processes and, generally, dissolved oxygen and pH distributions support this interpretation. As you have discussed the chlorophyll and turbidity maximum may or may not be associated with the physics of the EZ but you suspect that the turbidity maximum is most simply explained by gravitational circulation and it is even less clear what role gravitational circulation may play in maintaining the chlorophyll maximum (see also attached from Peterson and others, 1989).

C. What is the biological definition?

Question #5. What controls phytoplankton dynamics in San Pablo Bay?

I don't know and until this is clearly known it seems hard to comment on this question. I'm not familiar with the zooplankton observations you referred to. As you know zooplankton studies from other estuaries have inferred some of the classic examples of the importance of estuarine-type circulation on larval and fish egg transport and development.

A. Jassby

Among the many issues regarding the entrapment zone is its effect on the supply of organic carbon/energy for fueling the San Francisco Bay food web. The purpose of this working paper is to summarize information on the organic carbon budget of the Bay pertinent to the role of the entrapment zone.

1. Phytoplankton productivity in the channel is reduced by the presence of an entrapment zone. Net water column productivity for channel and shoals in 1980 can be estimated using morphometric data[3], 14C uptake measurements[4], and typical assumptions about respiratory losses[5] (Table 1).

In Suisun Bay, net productivity in the channel is negative because of the small photic depth:channel depth ratio. As net photic zone productivity ($M\ L^{-2}\ T^{-1}$) and respiration ($M\ L^{-3}\ T^{-1}$) are roughly proportional to biomass in the Bay, the effect of increased biomass is simply to lower net productivity in the channel, i.e., to make it even more negative. The presence of an entrapment zone therefore should decrease channel productivity.

2. Shoal areas and the subembayment as a whole do have enhanced phytoplankton

productivity when an entrapment zone is present. If the presence of an entrapment zone increases the biomass in shoal areas, then their productivity, which is typically positive, will be enhanced. So an entrapment zone has opposite effects on channel and shoal productivity. As shoal productivity is dominant, the net effect is to increase subembayment productivity. The increases can be substantial, as they are essentially proportional to biomass.

3. The enhanced primary productivity due to the presence of an entrapment zone, however, may have little effect on the overall supply of organic carbon. An inventory of organic carbon sources for Suisun Bay in 1980 suggests that primary productivity typically plays a minor role[5] (Table 2). The dominant source appears to have been organic carbon from Delta discharge, even when only 10% is considered to have been available for further consumption. POC constituted at least 10% of riverine TOC, and most of the POC was due to riverine phytoplankton or phytoplankton-derived detritus. Tidal marsh export of organic carbon also may be a larger organic carbon source than phytoplankton productivity, especially considering the large numbers of waterfowl in Suisun Marsh and the practice of flushing waterfowl ponds.

Two additional pieces of evidence suggest phytoplankton productivity is secondary: Stable isotope results indicate that much of the POC in the entrapment zone may at times be of riverine origin[6], and bacterioplankton productivity can greatly exceed phytoplankton productivity[7]. So variations in phytoplankton productivity due to positioning of the entrapment zone may not be ecologically important. Stated another way, the entrapment zone position may have little effect on the overall magnitude of organic carbon sources.

4. As far as the supply of organic carbon to the food web is concerned, the effect of entrapment on residence time of food particles is more important than the effect on primary productivity. Particles with certain characteristics, including those capable of entering the food web, have a higher residence time in a given region when an entrapment zone is present. This applies to particles from upstream and from tidal marsh export, as much as

to locally-produced phytoplankton. There are two main consequences. First, the longer particles reside in a given region, the more chance they have of contributing to the food web in that region. Second, even though the production of POC may not be enhanced, its loss is retarded and biomass accumulates compared to non-EZ conditions. As a result of these factors, the flow from organic carbon sources into the food web must be relatively high in the entrapment zone.

5. Because the overall carbon supply is not significantly enhanced by the EZ, increased consumption of particles in the EZ may be at the expense of downstream food webs. Organic carbon sources for the northern reach (i.e., from Golden Gate to Chipps Island) totalled 1.1×10^{11} g C yr^{-1} in 1980[3]. If we assume a $C:O_2$ ratio of 1, which appears to be the mean ratio for benthic respiration in the Bay[8], then these sources should give rise to an oxygen consumption of 2.9×10^{11} g C yr^{-1}. In comparison, Peterson[9] estimated a substrate oxygen consumption of 2.3×10^{11} g C yr^{-1} for the northern reach based on a mass balance for oxygen. The correspondence is remarkably close, perhaps to close given that (O_2 consumption):(C source) ratios are much lower in most estuaries. If the results are too be believed, however, they imply that most of what comes *into* the northern reach is consumed *within* the northern reach. If material is not trapped within Suisun Bay, then, perhaps it enters the food web downstream before the Golden Gate. The entrapment zone may be robbing Paul (San Pablo) just to pay Peter. The entrapment zone thus results in a spatial redistribution, but not an increase, of food sources within the Bay.

F. Nichols

Benthic invertebrate larvae can also be transported up estuary to the EZ in bottom currents driven by tidal flows and gravitational circulation (Questions 2, 4-6).

L. Smith

Definitions. I prefer to use the terms null zone and high turbidity zone instead of the term entrapment zone, which your answer to question 1 suggests is ambiguous. The null zone is defined to be the most landward extent of gravitational circulation in the bay as defined by low-pass filtered current measurements. It is a zone instead of a location because several factors make precise location impossible. These factors include local bathymetry, variations in the tides and wind, small variations in freshwater inflow, and measurement limitations of current meters.

A high turbidity zone, however, can be defined by averaging measurements of suspended particulate matter (SPM) over the water column. Such a zone is likely to have multiple longitudinal maxima because of the variety of mechanisms that affect SPM concentrations. Secchi-disc measurements may not be adequate to define high-turbidity zones in northern SF Bay because surface SPM concentrations may correlate poorly with concentrations elsewhere in the water column.

A zone of high phytoplankton concentration corresponds well to a high turbidity zone whenever particle sources, sinks, and densities are similar. I don't know how significantly these whenevers are violated in northern SF Bay, but I suspect that that zones of high turbidity and high chlorophyll overlap. I would also suspect that zooplankton and larval fish maxima would roughly correspond to these same zones because they have evolved mechanisms to make it so.

2. What components of the estuarine ecosystem (i.e. species, food web, or habitat) are significantly affected by processes occurring in the EZ?

There are two parts to this question: first, what components are affected by the presence of an EZ, and second, what components are affected by its position. The second question is discussed in Issue 5. All species found commonly within the EZ are probably affected by its presence. For example, some phytoplankton are concentrated there but growth rates may be reduced by the high turbidity[10]. Phytoplankton species concentrated include several common estuarine diatoms such as *Skeletonema* spp. and *Thalassiosira* spp[1]. Zooplankton of certain species are concentrated there, including the copepod *Eurytemora affinis*, the mysid shrimp *Neomysis mercedis*, and several other taxa[11]. Early life stages of fish including delta smelt[12] and striped bass[13] appear to be most abundant in the vicinity of the EZ.

The principal species mentioned above form a subset of the food web of the entrapment zone: *E. affinis* feeds on diatoms, *N. mercedis* on diatoms and on *E. affinis*, and striped bass larvae and delta smelt on zooplankton. It is therefore tempting to consider the concentration maximum in these species as a trophic effect. However, limited evidence suggests that the enhanced food supply in the EZ may not result in enhanced feeding for some species (See Issue 4); i.e. there may be little or no trophic advantage for organisms to be in the EZ. Thus the effect of the EZ on the food web appears to be limited to the enhanced concentration of organisms.

Any selective advantage conferred by accumulation in the EZ is apparently not related to feeding. Alternative advantages include predator avoidance and avoidance of transport out of the system. Predator avoidance appears to be an unlikely advantage of EZ residence since the predators reside there too. However, it would be very advantageous for organisms to avoid being washed out of the estuary. Since the EZ organisms listed above have at most limited swimming ability, they must either have population turnover times that are short relative to residence time of the water[14], or they must use circulation to increase their residence time relative to that of the water. Using vertical positioning within the EZ is one way to do this. Thus, the EZ can be seen as habitat for species that are capable of exploiting this feature of the estuary.

For at least some EZ species, the EZ represents qualitatively different habitat from other areas. *E. affinis* is most abundant in a salinity range of 1-6, and its abundance declines sharply at higher salinities (Figure 1). However, this species is known to have a broad tolerance to salinity from nearly 0 to about 20, with an optimum at 12[15]. Its low abundance outside the EZ is therefore a result either of predation or of transport back into the EZ. There is no evidence that the abundance or activity of predators is higher outside than inside the EZ, and several species of planktivorous fish are more abundant in the EZ.

Bacteria appear not to be particularly affected by EZ processes[16]. The importance of the EZ to microzooplankton other than copepods and rotifers is also unknown, since none of the sampling programs includes these organisms.

<u>D. Peterson</u>

As you probably know a very rough estimate of the importance of gravitational circulation in maintaining the salt balance in the Bay is one third gravitational circulation and two thirds eddy diffusion. To my knowledge no such estimates have ever been made for particles, but one might assume gravitational circulation plays a stronger role in particle transport than for dissolved salts. Of course tidal climate clearly plays a very important role in the ultimate disposition of sediments. I'm not convinced, however, that the unusually high efficiency of trapping sediments in the Mare Island or the Napa River tributary estuary is adequately explained by tidal phenomena (as the Scripps Institution of Oceanography coastal engineers seem to believe). In brief, in my opinion essentially zero is known about this topic in the Bay. For purposes of discussion two useful views of this topic include the 1970's paper by Festa and Hansen (a gravitational circulation control) and 1980's paper by Uncles (a tidal/river-flow control). But before attempting to hypothesize about this question a comprehensive overview of sediment dynamics and budgets in the Bay from a long term perspective would be useful.

F. Nichols

In late summer, immediately following the summer phytoplankton maximum in water column of the EZ and coincident with a period of reduced ebb tidal velocities, a large proportion of the phytoplankton cells (same species as previously dominant in the water column) settle to the bottom (Nichols and Thompson 1985 -Hydrobiologia). There is insufficient data to determine the ecological importance of this reservoir of organic matter at the bottom, how the amount accumulated during any year is determined by hydrodynamic processes (river flow), or the eventual fate of these deposited cells (e.g., resuspension and transport versus burial).

The benthos of the EZ, particularly in Suisun Bay, is strongly determined by hydrodynamic processes occurring in the EZ. Benthic invertebrate species composition and abundance, for example, are determined by seasonal and interannual patterns in river flow which, in turn, determine (through gravitational circulation) the transport of larvae and juveniles in bottom currents. During periods of high river inflow, the benthos consists of a few fresh- and brackish-water species because most estuarine species are intolerant of alternating periods of inundation by fresh and salt water. During prolonged dry periods (>16 months) when river flows remain below 1000 m /s and salt content remains high (>5 o/oo), large numbers of estuarine (salt dependent) species are able to penetrate the barrier of Carquinez Strait (see Issue 6) and become established in the Suisun Bay region (Nichols et al., 1990). Presumably, larvae (and perhaps juveniles) are involuntarily transported upstream from established adult populations in San Pablo Bay.

3. To what extent are particles and populations concentrated by gravitational circulation, and to what extent by other physical processes such as exchange between shoals and channels coupled with wind-driven resuspension?

A number of physical processes other than gravitational circulation can be important in concentrating particles and organisms. All seem to depend on interactions between variations in velocity and settling of particles or swimming behavior of organisms.

In most estuaries including the San Francisco Bay estuary, the cross-sectional area generally increases in a downstream direction[17]. River flow velocity averaged across the estuary is lower where the cross-sectional area is larger. In addition, tidal currents generally decrease from the mouth of the estuary to some upstream point where they vanish. The combined tidal and river velocities (mean absolute or root-mean-square) therefore have a minimum at some intermediate point. This minimum results in settlement of particles during slack water and subsequent resuspension during tidal flows, causing a turbidity maximum near the area of minimum current velocities.

Lateral variation can also concentrate particles or organisms. Tidal exchange between channels and shoals, particularly under windy conditions, can produce local maxima in turbidity and perhaps phytoplankton. Local maxima in abundance of zooplankton and presumably other organisms can occur associated with recurring tidal eddies or with sills[18].

I believe that in the San Francisco Bay estuary the dominant means of producing maxima in zooplankton, chlorophyll, some phytoplankton species, and turbidity is in fact gravitational circulation, although these other mechanisms may be important at some times and places. The position of the turbidity maximum maintains a fairly monotonic relationship (with some variation) with the position of a given surface salinity value (Figure 2). The peak value of *E. affinis* also occurs at around the same salinity in each month. If different mechanisms were concentrating these components at different flows, one would expect to see the peaks occur at different salinity values.

L. Smith

Mechanisms for creating a high turbidity zone. The often-repeated explanation for an observed high turbidity zone in northern SF Bay is the interaction of delta-derived particles with the null zone, as you have described. This explanation suggests that the high turbidity zone should overlap the null zone. It ignores, however, other published concepts of northern SF Bay.

A first approximation of the seaward mixing of land-derived particles is the seaward mixing of fresh water. Fischer and Dudley (1975) and Conomos (1979) suggest that the summer salt balance in the northern reach, or the mean mixing of fresh water seaward, can be maintained almost entirely by processes other than gravitational circulation. If they are correct, then the physical mixing of particles in the northern reach might be dominated by these other processes.

Fischer and Dudley call these other processes tidal pumping and trapping. Tidal pumping refers to the horizontal asymmetry of tidal and net currents that leads to lateral and longitudinal exchanges among water masses. Tidal trapping refers to the isolation of a water mass in an off-channel area during part of the tidal cycle and subsequent release of the mass later. Although pumping and trapping mechanisms are not entirely distinct, together they can effectively increase the net (tidally averaged) longitudinal diffusion of a water mass, lengthening the time that some water takes to move through the bay.

If an off-channel area is shallow, its currents are significantly smaller than those of the channels, and negatively buoyant particles tend to settle to the bottom, further lengthening their residence times in the bay. This increased residence time, coupled with wind-wave generated resuspension of sediments in the shallows can lead to the accumulation of particles in channels adjacent to large, off-channel areas. The large amount of maintenance dredging done in Mare Island Strait might be explained as settling of trapped sediment without wind-generated resuspension.

Another concept that departs from the usual explanation is Ray Krone's seasonal sediment movement concept. His idea is that the source of SPM for the summer high turbidity zone is San Pablo Bay rather than the delta. He hypothesizes settling of delta-derived particles in the shallows of San Pablo Bay during winter runoff events, followed by wind resuspension during the summer. Those sediments that exchange into the channels sink toward the bottom and are subsequently carried landward to the null zone by gravitational circulation. I am unaware of a dataset, other than collected for his thesis, that confirms or denies his concept. However, this concept would make separate the summer sources of SPM and chlorophyll in the area of the null zone.

4. To what extent is the concentration of biota in the EZ caused by physics, and to what extent by biology, e.g. altered growth rate within the EZ, trophic interactions, or behavior?

Particles concentrated in the EZ have settling rates sufficient on average to remove them from the surface layer but not enough to remove them from the water column. Concentration of biota in the EZ is complicated by growth and mortality as well as behavior.

Phytoplankton are apparently concentrated in the EZ by settling as for inert particles, although settling rates may be enhanced through flocculation[1]. Growth is generally light limited in this part of the estuary, so net growth in the channels may be lower than that in shallow areas[3]. However, tidal exchange between the shoals and channels may enhance production for the system as a whole, since growth rates are higher in shoals.

There is little evidence that growth of the zooplankton is food-limited, although considerably more work needs to be done[19]. If they are not limited by food, there is no reason to expect zooplankton growth or development rates to be higher in the EZ than out.

The question of food limitation in striped bass larvae is also still open, although they are never classified as starved, according to histological and morphological characters[20]. Growth rates are variable between years[21], and the variation is consistent with a hypothesis that reduced growth is caused by low food concentrations, but alternative explanations cannot be ruled out. Furthermore, there is no evidence that growth rates or feeding rates are enhanced in the EZ relative to other locations in a given year.

If growth rates (and therefore trophic interactions) of zooplankton and striped bass larvae are not higher within the EZ, then their behavior may be the principal mechanism for concentration. Specifically, organisms that swim downward, or that migrate vertically on a tidal cycle, can avoid being washed out of the estuary, thereby becoming concentrated. This is a common behavioral pattern in estuarine organisms. In the San Francisco Bay estuary, some zooplankton including *N. mercedis*[2] and possibly *E. affinis*[22] avoid the surface waters or migrate on a tidal cycle. Striped bass eggs and larvae occupy progressively deeper strata during early development, which should concentrate them in the EZ[23].

Freshwater zooplankton species presumably arrive in the estuary by transport from reservoirs. They are unlikely to have the behavioral mechanism to remain in the estuary, since there is no selective pressure to do so. Their abundances generally decline monotonically with salinity, implying that they are not being concentrated within the EZ[24]. The lack of abundance peak may imply a lack of behavioral mechanism for position maintenance, or it salinity stress may prevent such a response.

To summarize, there is no evidence that the growth or mortality rates of any species are altered in the EZ relative to other locations. Since motile organisms do not generally sink passively, behavior may be the only means for them to become concentrated.

F. Nichols

The issue of different growth rates inside the EZ is not necessarily covered in the term "concentration of biota". There is some evidence, from a two-year study of growth of the clam *Macoma balthica* at four locations around the bay, that proximity to the EZ may be a factor in increased clam growth rates. The clams at an intertidal site in Southhampton Bay (off Carquinez Strait) grew much faster and achieved a maximum size that was much greater than at intertidal sites elsewhere in the bay (Thompson and Nichols 1988). The timing and magnitude of growth rates appeared related to the seasonal maxima in pelagic and benthic diatoms in the vicinity.

L. Miller

My response to question 4 is mainly a discussion of striped bass and what we know about their relationship to the EZ. Striped bass eggs are spawned and hatch in freshwater. Spawning occurs mostly above Sacramento on the Sacramento River. The eggs hatch en route to the estuary, a distance of about 160 km. Eggs and larvae spawned on the San Joaquin River are located on the order of 15-25 km above the EZ. The larvae from both areas move seaward with freshwater flows, tending to accumulate upstream of the EZ. In most years San Joaquin River inflow is low relative to the inflow from the Sacramento River but the San Joaquin River eggs and larva are kept in suspension by tidal currents.

The EZ was initially defined in terms of specific electrical conductance (EC) as the segment of the estuary between 2 mS/cm and 10 mS/cm[1]. However we recognize this to be an approximate definition and we are still in the process of defining it as per Wim's comments. I have used a surface measurement of 1 mS/cm EC as an upstream limit and 10 mS/cm as the downstream limit. Based on this definition we find the highest concentrations of the early stages of bass, 6 mm to 14 mm long, located upstream of the EZ in the EC range of 0.500-0.999 mS/cm, a transition area from fresh water to salt water (Figure 2a). This raises the question of whether entrapment is occurring upstream of where we think it occurs, or at least upstream of where I conveniently defined the EZ, or whether something else is happening? We will need to explore this with analyses of data from additional years.

The proportion of the larval striped bass population in the EZ, as defined here, is small but tends to increase with size. Bass are free swimming and at a length of 8 mm to 9 mm they can evade sampling gear and probably can control their location. They could remain in fresh water or presumably move even downstream of the EZ since salinity should not be a barrier. Striped bass larvae survive best in the laboratory at 10.5 ppt. (Bayless 1972, cited in Setzler et al. 1980) which is approximately an EC of 17 mS/cm. Even 9 day old striped bass larva, which are about 6 mm, have optimal survival at salinities of 6.75 ppt (Lal et al, 1977 cited in Setzler, et al. 1980) which is comparable to an EC of roughly 11 mS/cm.

Wim's suggestion that accumulation in or near the EZ is due to their behavior coupled with the physical process of entrapment appears to be what is occurring. The early development of a swim bladder and a mid-depth to bottom orientation in the EZ (Fujimura,1991) suggests a behavioral capability to control their vertical distribution. Settling out to the mid-depth to bottom would result in their accumulation in or near the EZ rather than moving further seaward in the surface flow. Such behavior has likely evolved as a survival strategy for retention in the estuarine environment where higher turbidity as well as higher food concentration favor survival compared with the marine environment. Two important food sources, Neomysis and Eurytemora, were historically more concentrated in the brackish environment in this estuary as well as in estuaries to which striped bass are native.

The accumulation of bass near in the EZ during spring and early summer could be independent of entrapment or their settling out behavior but reflect better feeding conditions which enhances survival in the EZ relative to survival at other locations. We cannot readily compare the survival of young bass in the EZ with survival in other areas because immigration into the EZ and emigration out of other areas is occurring.

We did compare growth rates of young bass less than 14 mm caught in the EZ with growth rates of young bass from upstream of the EZ using otolith data for 1984 and 1988. The results did not demonstrate greater growth for larvae captured in the EZ. Thus bass appear to have no growth or survival advantage related to more food in the EZ when compared to the upstream areas. However they are much less subject to entrainment in Delta water exports by being further downstream.

The advantages of being in the EZ may be greater for young bass after the larval stages when they switch to Neomysis and larger shrimp. I hope to present results from analyses currently underway which may help shed light on the use of the EZ by post larval stages.

In this estuary young bass abundance at the 38 mm size is strongly correlated with Delta outflow and Delta diversions, a response not clearly demonstrated for other striped bass populations. Mechanisms hypothesized by Turner and Chadwick (1972) to explain this abundance-flow relationship are: (1) dilution of toxics by higher flows. (2) Distributing bass away from the Delta where water export entrainment losses have been identified as having major impacts on the abundance of young bass. (3) Distributing the bass to Suisun Bay where food supply conditions are enhanced by higher production in the shoals.

An ancillary hypothesis for this third mechanism is that when outflow is high two layered flow conditions are stronger. Striped bass larvae entering the estuary under high flow conditions would settle out over areas with higher average bottom salinities than would be the case when the two layered flow system is weaker under low flow conditions. This would tend to place larvae into a prey field where Eurytemora concentrations are much higher than they are in fresh water. We have seen some evidence of this in 1986 when flows were high, bass survival was high and the population was exposed to higher concentrations of Eurytemora (CDFG,1988). We have not tested growth rates in and above the EZ for 1986 but overall growth rates were higher in 1986 than in other recent years. However, freshwater food resources were also more abundant and other factors may also have contributed to the high survival in 1986.

We need to test whether or not the EZ provides a better environment with greater outflow conditions and if so why. In many estuaries there are positive correlations between fish or shrimp abundance and outflow. Such relationships in this estuary have been found for splittail, American shad, longfin smelt, starry flounder, and Crangon franciscorum, as well as striped bass. In some cases e.g., American shad, the flow effects are unlikely to be related EZ phenomenon but factors upstream. However for other cases the EZ may be important.

Since 1988, the accidental introduction of Potamocorbula amurensis has apparently been the cause of a major decline in the concentrations of Eurytemora in the EZ. However the trophic picture for striped bass is also complicated by new exotic food resources common to both freshwater and the EZ and have to some extent filled the void left by the decline of Eurytemora. We are still sorting this out.

A final observation. It is also apparent that an entrapment situation is not necessary for striped bass. Striped bass are an estuarine species but there are freshwater populations that are sustained in the Santee-Cooper system and the Colorado River without an EZ. However a similar environmental situation exists in that a lake or reservoir provides an environment were the net flow is reduced.

5. How do location and the timing and extent of movement of the EZ affect ecosystem components?

Depending on freshwater flow and tides, the position of the EZ can vary from the western delta nearly to the ocean[13], although it is usually found east of Carquinez Strait. There has been considerable speculation and some evidence that the position of the EZ affects biomass and productivity in the EZ. There are two aspects to this question, each of which should be considered separately. First, the volume of the EZ can vary with its longitudinal position, since the cross-sectional area changes with position[13]. At a given abundance or biomass (i.e. per unit volume), the total population size varies with the volume of habitat. Second, the abundance or biomass can vary within the EZ. These two effects could be related, in that a smaller habitat could increase losses to mixing out of the population center, resulting in a lower abundance in the population center.

When the EZ is upstream of the confluence of the two rivers, its volume is considerably less than when it is in Suisun Bay (Figure 3). This effect has been implicated in the reduced population size of *N. mercedis*[25].

A convincing argument has been made that dependence of phytoplankton biomass on EZ position is a result of exchange between shallows and channel waters[1,4]. According to this model the combination of enhanced growth in the shallows with entrapment in the channel results in higher biomass when the EZ is in Suisun Bay compared to when it is in the delta. A similar mechanism has been suggested for delta smelt, although the only evidence to support this is higher abundance in shallow waters than deep[8].

The size of the *N. mercedis* population depends on EZ position through habitat volume[18], but also through changes in abundance[26]. In the fall and perhaps in the spring, the abundance of *E. affinis* is higher when the EZ is in an intermediate position, and lowest when it is in the delta[27]. The mechanism for this is unclear, since zooplankton generally are less abundant in shallow water and, since they are less abundant in the surface layer they are less likely to be transported into the shallows. One possibility is that the complex topography in eastern Suisun and Honker bays causes eddies or other persistent circulation features that increases residence time and abundance[14].

F. Nichols

To the extent that the physical processes determining the position of the EZ (e.g., river flow) also determine the transport and final settlement of benthic invertebrate larvae (Question 2), the benthic community of Suisun Bay in any given year is related to the timing and position of the EZ during the previous year or so. However, it is not clear that the entrapment of invertebrate larvae by physical processes within the EZ determines the structure of the benthic community there. This has not been studied.

6. **Do any effects of position of the EZ occur because of topography, or through correlates of EZ position, e.g. freshwater flow, entrainment, or inputs of nutrients or organic matter?**

The effects of position of the EZ discussed in the Issue 5 depend mainly on topography, i.e. on the presence of shallow water adjacent to the EZ. Position of the EZ is confounded by several other variables. EZ position depends mainly on freshwater outflow, and is therefore related to several other effects that may be important.

The degree of stratification and presumably the strength of entrapment within the EZ presumably depends on freshwater flow, since the asymmetry of ebb and flood tides would increase as freshwater flow increases. This could result in greater trapping of some species relative to advective losses.

An upstream position of the EZ would increase vulnerability of some species to export pumping. This mechanism has been blamed for low abundances of striped bass and delta smelt in years of low freshwater outflow[8,9], although the evidence for population effects of export pumping is not complete. Export losses of *E. affinis* do not appear to be major sources of mortality[28], although abundances used in that analysis were not necessarily the same as those in the exported water.

D. Peterson

Beyond the obvious, its hard to say much toward a 3-D type question without some solid 3-D knowledge.

F. Nichols

The constriction of the estuary at Carquinez Strait represents a major barrier to benthic invertebrates, preventing upstream dispersal of species from San Pablo Bay into Suisun Bay except during prolonged dry periods. During normal or high river inflow years, the enhanced down-estuary flows through the Strait and coincident low salinities prevent benthic species resident in San Pablo from transiting the Strait and becoming established in Suisun Bay. As a result, the benthic communities of San Pablo and Suisun Bays are quite different. During prolonged periods of low flows, however, the constriction ceases to be a barrier to the upstream transport. Thus, during such dry periods (prior to the arrival of the Asian clam, *Potamocorbula amurensis*), the San Pablo and Suisun Bay benthic communities had many species in common.

The effects of the biotic barrier at Carquinez Strait confound the effort to uncover simple relationships between the position of the EZ and benthic community dynamics. To further complicate the situation, since 1987 the large population of the new clam in Suisun Bay has itself become a barrier, presumably by preying on arriving larvae.

7. How can measurements of salinity or electrical specific conductance be used as an index of EZ position? Are better indices or measurements available?

By definition the position of the EZ is the location of entrapment as defined under Issue 1. This could be determined by taking a series of vertical profiles of longitudinal net velocity; the upstream edge of the EZ would be at the null zone where net velocity at the bottom was 0. The problem with this method is that net velocities are very difficult to measure, especially when tidal flows are large. Therefore an operational definition of EZ position is needed.

Alternative operational definitions can be based on the turbidity maximum, the salinity difference between surface and bottom, and selected ranges of salinity or electrical specific conductance (EC).

The location of the turbidity maximum is the operational definition most closely related to the concept of entrapment, but there are two drawbacks to using it to define EZ position. First, other sources of elevated turbidity (See Issue 3) can confound the use of turbidity in this way. Second, this method requires that differences in turbidity among stations be determined. Since this can be a rather noisy variable, a large number of measurements must be averaged to find the maximum. This problem could be avoided by using *in situ* transmissometry or nephelometry with an on-deck readout; however, determining the location of the EZ would still require a longitudinal transect.

The salinity gradient from surface to bottom has been used to estimate EZ position by assuming that the EZ occurs where the gradient decreases to 0 in an upstream direction[5]. However, a vertical salinity gradient is not necessary to produce entrapment, since the ebb-flood asymmetry in flow velocities is produced mainly by the longitudinal salinity gradient (See Issue 1). Thus, while this measure may be useful it needs to be calibrated against other indices of EZ position.

Arthur and Ball[1] suggested using fixed values of surface EC to define the EZ. This has the advantages that it is extremely easy to measure, can be used to determine EZ position while in the field, has a historical precedent, and can be used to determine EZ position on historical data for much of which only surface EC readings were taken. However, surface EC is not simply related to EZ position (Figure 2). Stratification increases with flow, so surface EC becomes less representative of water column conditions as the EZ moves downstream. This problem could be solved through the use of EC or salinity values from the bottom or some fixed depth, although this could not be applied to the historical data.

Since many of the field teams are now equipped with CTDs, it should be possible routinely to determine salinity profiles at each station. However, relationships among all of the measures of EZ position need to be developed so that both the historical and future data can be interpreted similarly.

D. Peterson

Festa and Hansen (1976) showed it in their 2-D steady-state numerical simulation experiments (note they refer to null point not EZ). However, when asked are better measurements or indices available(?), this seems to assume the connection between salinity and circulation has been documented which it has not.

8. To what extent can the EZ be positioned by different freshwater flow scenarios?

The effect of flow on EZ position is fairly clear[13]. Further analysis using CDFG data on monthly EC values taken near high tides during April to October and DWR DAYFLOW estimates of monthly mean delta outflow give a relationship:

$$EZ = 147 - 27.5 \, LOG_{10} \, Q, \quad r^2 = 0.80,$$

where Q is flow (m^3/s) and EZ represents EZ position by the operational definition of 2mS/cm specific conductance (about 1.2 salinity), in kilometers from the Golden Gate. The standard error of the estimate is ± 1.30. Presumably much of the residual variance is due to the spring-neap tidal cycle, the use of aggregated (monthly) values, the use of DAYFLOW estimates (which incorporate several untested assumptions about water consumption and distribution in the delta), and the implicit assumption of steady state.

From this relationship it can be seen that, within the range of data used, flow has a logarithmic relationship with EZ position. A change in flow by a factor of 2 would move EZ position by 8 km, with 95% confidence limits of ± 0.74 km or 9%. The differences in EZ position that have been observed (or assumed) to influence productivity or biomass in the EZ are on the order of 10-20 km. To effect movements of that magnitude, delta outflow flow would need to change from its baseline level by a factor of 2.3-5.3. It should be possible to refine these estimates further using available data, most notably the CTD profiles taken by USGS and USBR, once these data are available.

The above discussion relates operationally defined EZ position to net delta outflow, but does not consider flows within the delta or reverse net flows in the lower San Joaquin River, both of which could affect either EZ position or the apparent effects of EZ position on some of the biota. Hydrodynamic modeling or more detailed field studies are needed to provide better information on this question.

D. Peterson

Before attempting this question a more general question might be: to what extent can the salt field be positioned by different freshwater flow scenarios?

On a monthly time scale, the surface salinities near the channel sites can be estimated to roughly ± 1 salinity unit as a function of delta flow. Estimates from some near-bottom time series are also available. To the best of my knowledge time series observations from shoals are almost none to non-existent.

Given the above, then, the circulation remains to be coupled to the salt field over a wide range of time & space scales. Until this is more complete, utilizing EZ or related concepts for purposes of estuarine management seems premature.

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17. Peterson, D. H., T. J. Conomos, W. W. Broenkow, and P. C. Doherty. 1975. Estuarine and Coastal Marine Science. 3:1-11.

18. Alldredge, A.L. and W.M. Hamner. 1980. Est. Coastal Mar. Sci. 10:31-37.

19. For *E. affinis*, ratios of eggs to females do not appear to be closely related to chlorophyll, nor have they declined much over the period 1980-1988, despite a large decrease in chlorophyll in 1988 (W. Kimmerer, unpubl.). A limited number of experiments in late summer 1988 (when chlorophyll was very low) showed no food limitation of reproductive rates in *E. affinis* (Kimmerer, W.J. 1991. In prep.)

20. Striped bass larvae are never classified as starved, either in or out of the EZ, according to histological and morphological characters (Bennett, W.A., D.J. Ostrach and D.E. Hinton. 1990. The Nutritional Condition of Striped Bass Larvae from the Sacramento - San Joaquin Estuary in 1988: An Evaluation of the Starvation Hypothesis Using Morphometry and Histology. Submitted to: CA Dept. of Water Resources).

21. CDFG. 1988a. Factors Affecting Striped Bass Abundance in the Sacramento - San Joaquin River System. Exhibit 25, entered by the CDFG for the State Water Resources Control Board 1987 Water Quality/Water Rights Proceeding on the San Francisco Bay/Sacramento -San Joaquin Delta. 149 pp.

22. J.J. Orsi, CDFG, unpublished data.

23. Fujimura, R.W. 1991. Draft Technical Report: Observations on Temporal and Spatial Variability of Striped Bass Eggs and Larvae and Their Food in the Sacramento - San Joaquin River System. Interagency Ecological Study Program for the Sacramento - San Joaquin Estuary.

24. Based on plots of log abundance vs. salinity: Obrebski, S., J. Orsi, and W. Kimmerer. In prep.

25. Knutson, A. C., and J. J. Orsi. 1983. Trans. Am. Fish. Soc. 112:476-485.

26. Analysis of CDFG data shows that the abundance of *N. mercedis* is highest when the EZ is out of the Delta (Kimmerer in prep.).

27. Based on CDFG data (Kimmerer in prep.).

28. Based on analysis of CDFG zooplankton data (Kimmerer in prep.). The number of copepods exported, estimated from the rate of export pumping times the abundance at sampling stations in Old and Middle Rivers, averaged 0.06%/d (median) of the total population estimated by summing abundances in selected salinity classes times water volume in each class. Even in periods of upstream EZ position this fraction was less than 0.02%/d.

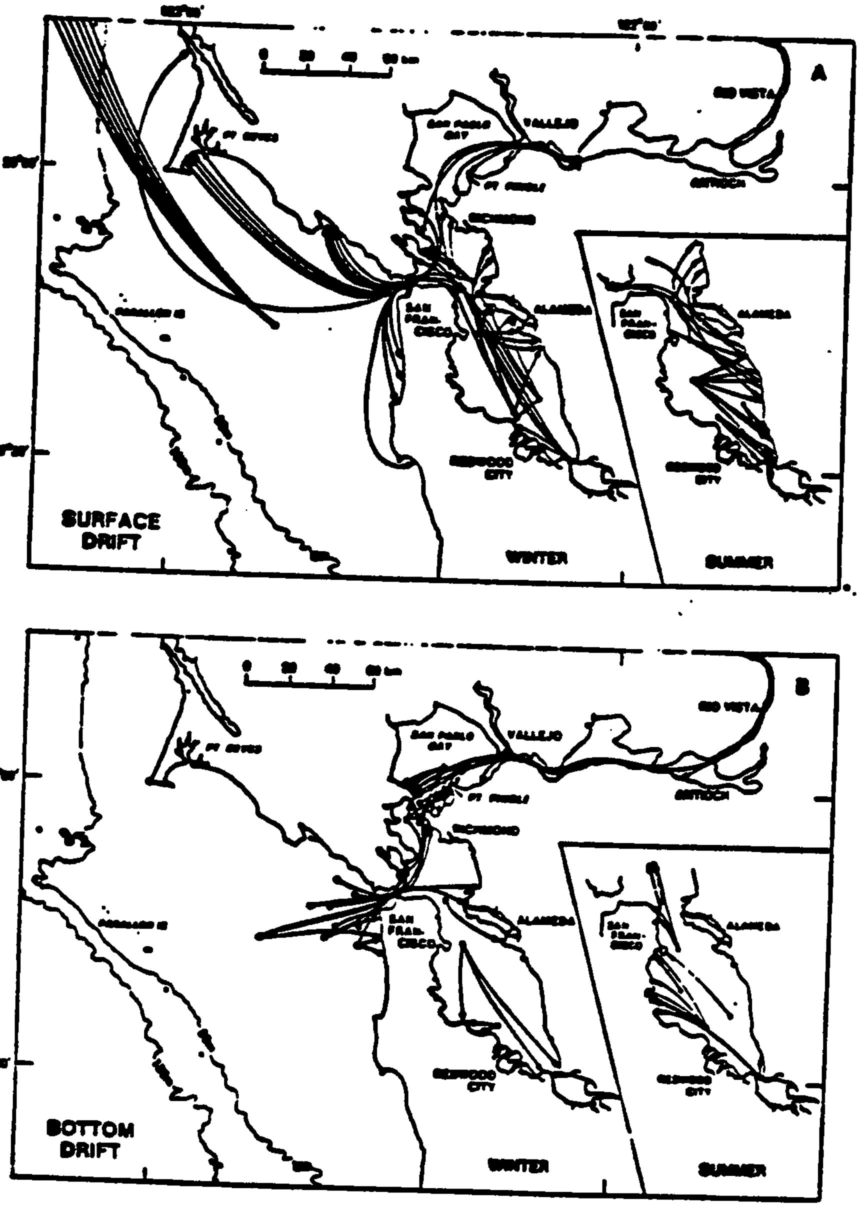


Figure 5. Release and recovery points for surface (A) and seabed (B) drifters in the bay and adjacent ocean. Drifter movements are shown as arrows drawn from release points to recovery locations and portray simplified paths of movement occurring within 2 months of release. Winter release: December 1970 (modified from 3). Summer release (southern reach only shown as inset): September 1971. Data are typical of 18 releases over a 3-year period (1970-1973).

Figure from Conomos & Peterson 1977.

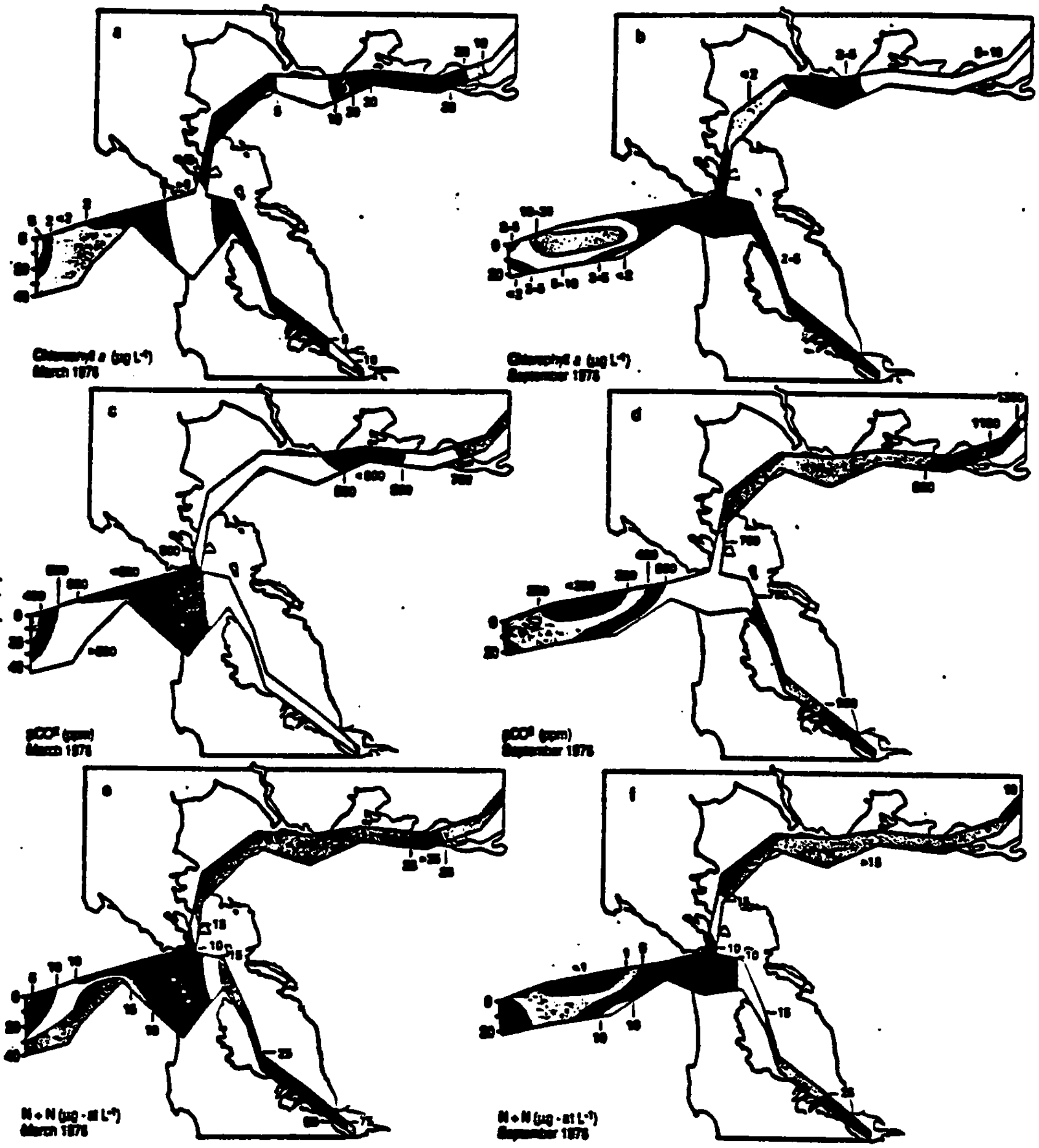


Fig. 19. Distribution of chlorophyll (panels a, b), partial pressure of carbon dioxide (panels c, d) and dissolved nitrate, plus nitrite (panels e, f) in the San Francisco Bay estuary during March and September 1976.

are typically aphotic because mean water column light is too low to sustain net photosynthesis.

The second hypothesis attributes low phytoplankton biomass to benthic filter-filtering invertebrates [Nichols, 1985]. In dry years such as 1961, 1976 and 1977, 1981, and 1985 benthic invertebrate populations increased in Suisun Bay in response to persistently elevated salinity (Nichols, 1985 and unpublished). If the increased filter-feeding invertebrate populations were responsible for the reduction in phytoplankton biomass, it follows that DSA would be anomalous in these years. The DSA pattern in midsummer 1961 was an exception. During that summer DSA behaved as expected for a normal summer, whereas during the other very dry years it did not. During 1961 the pattern of dissolved silica and other plant nutrients and the partial pressure of dissolved carbon dioxide (reflected in high pH measurements) all showed a very strong effect of phytoplankton photosynthesis into July, but not in the later surveys of September and November (see field and numerical simulation results in Figure 8 and compare with Figure 19).

We interpret the sequence of field observations from summer 1961 to winter 1962 as follows. Following the decline in summer delta flows, salinity near Pittsburg increased to over 10 parts per thousand in July. Numerical abundance of benthic invertebrates (e.g., the filter-feeding clam *Mya arenaria*) did not increase markedly, however, until September [Storrs et al., 1963]. After this increase in benthic invertebrate abundance the photic phytoplankton-dominated estuarine biochemistry apparently shifted to an aphotic (benthic invertebrate) dominated estuarine biochemistry, as reflected in decreased dissolved oxygen saturation, pH, and phytoplankton abundance, and in increased plant nutrient concentrations (cf., Figure 8 for pH changes). Inevitably, winter peak flows returned (February 1962) and salinity decreased sharply. Because the benthic invertebrates could not survive in low salinity water, their abundance declined sharply as well. Thus by the summer of 1962, the system apparently had returned to a more phytoplankton-dominated biochemistry.

Figure 1. Geometric mean and 95% confidence limits for *Eurytemora affinis*. Means determined by salinity class, then referred to mean salinity in the class.

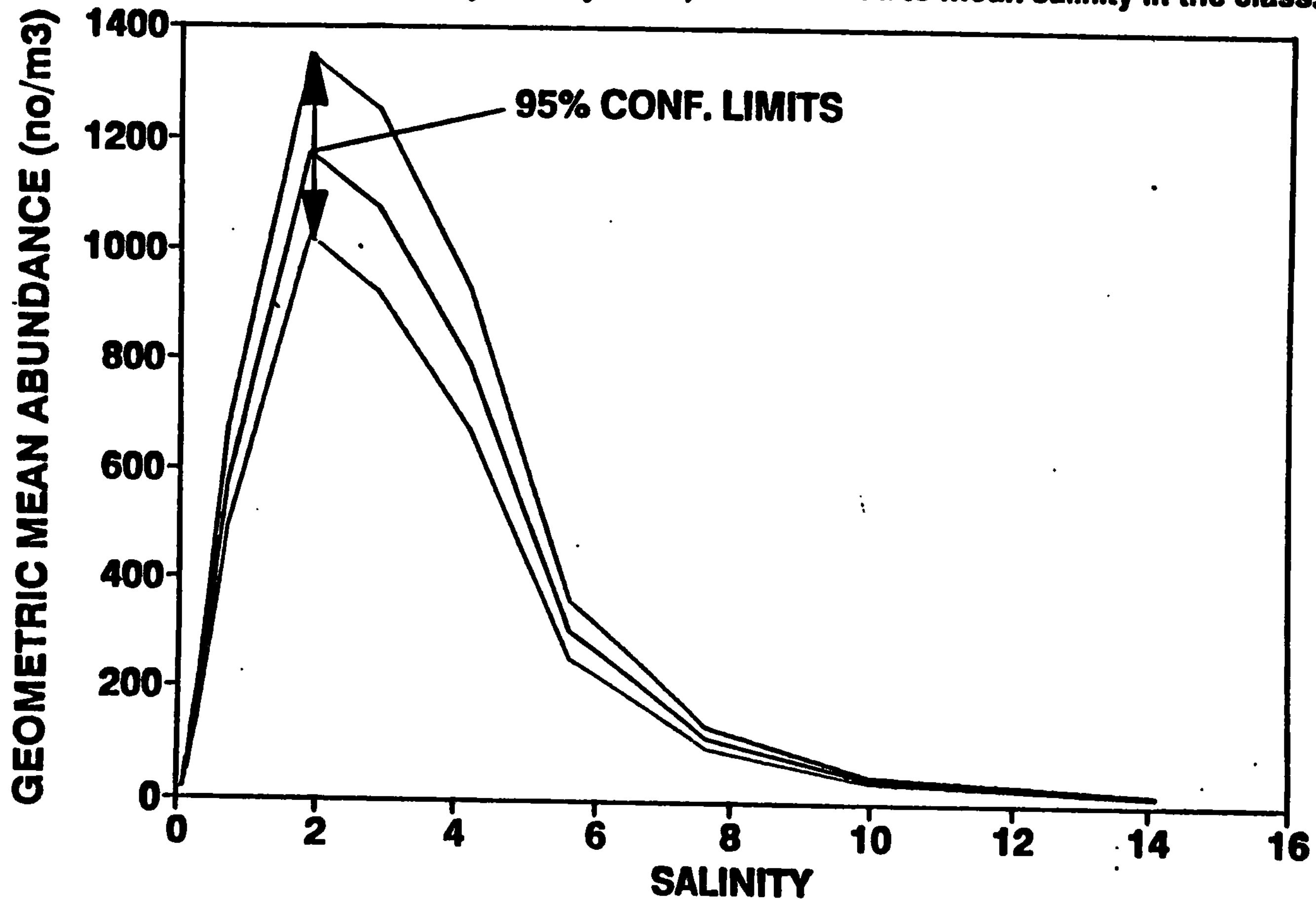
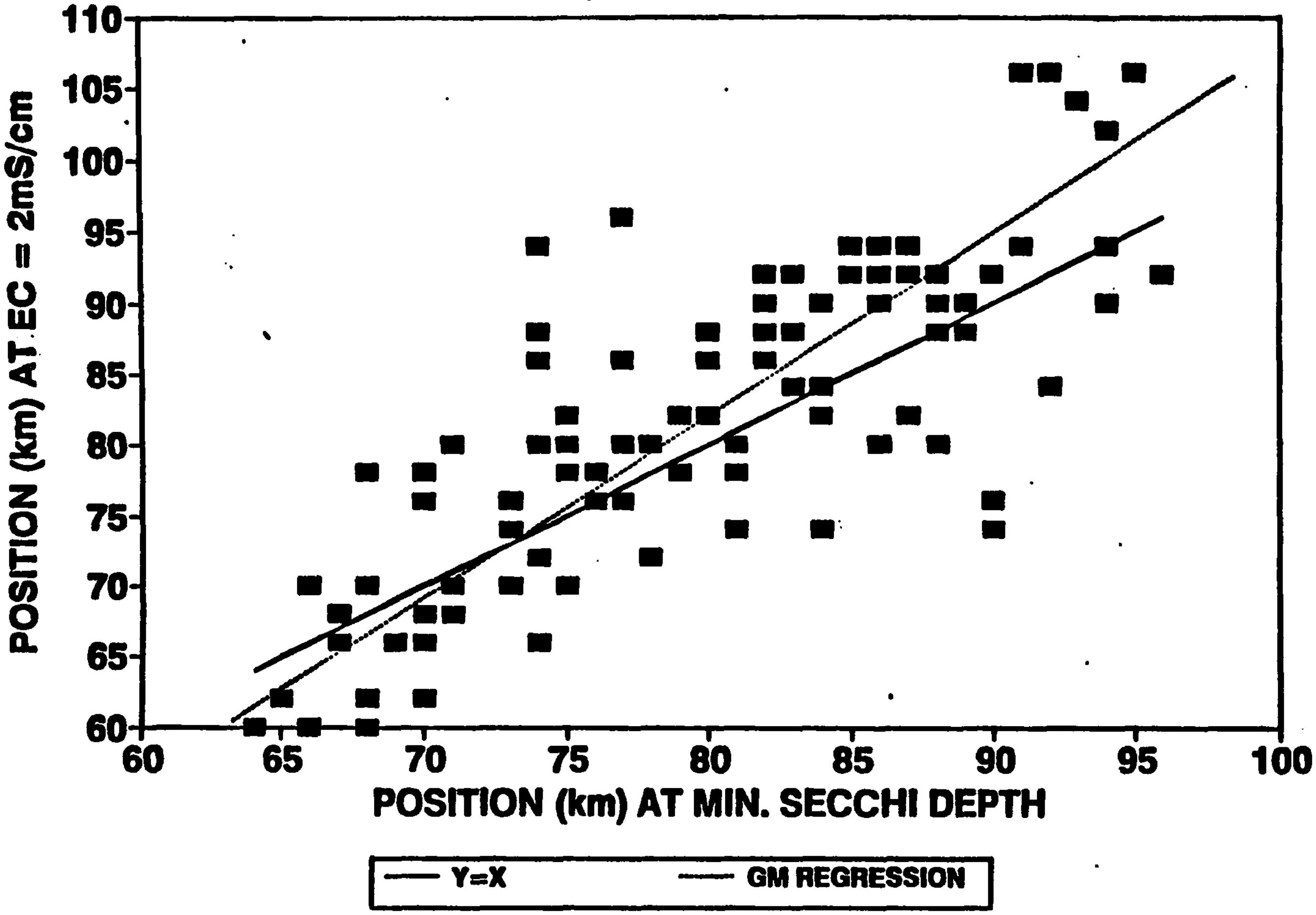


Figure 2. Distance from the Golden Gate at which EC=2 mS/cm vs. distance of minimum in monthly Secchi depth, from CDFG data.



ELS BASS VS EC GROUPS

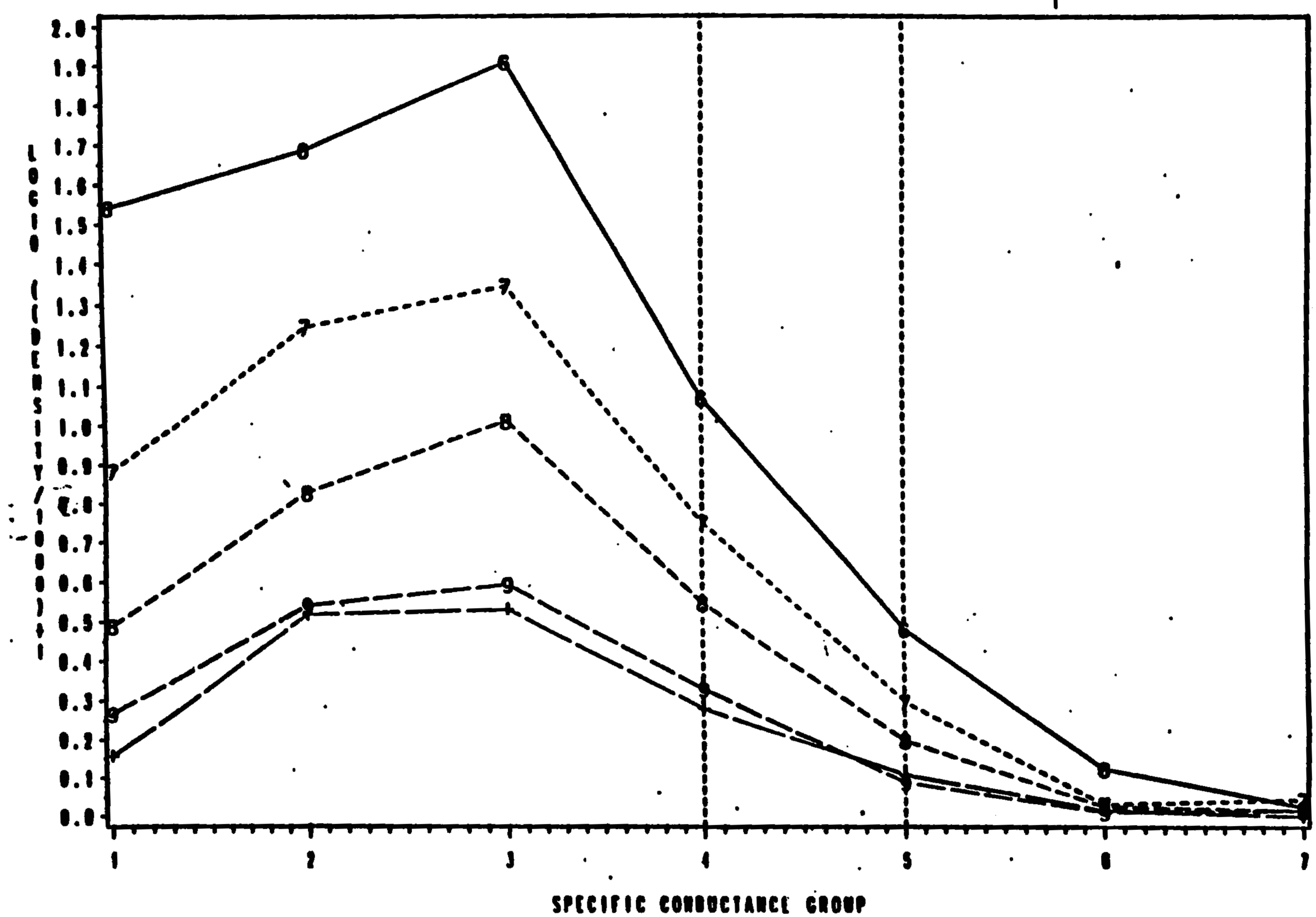
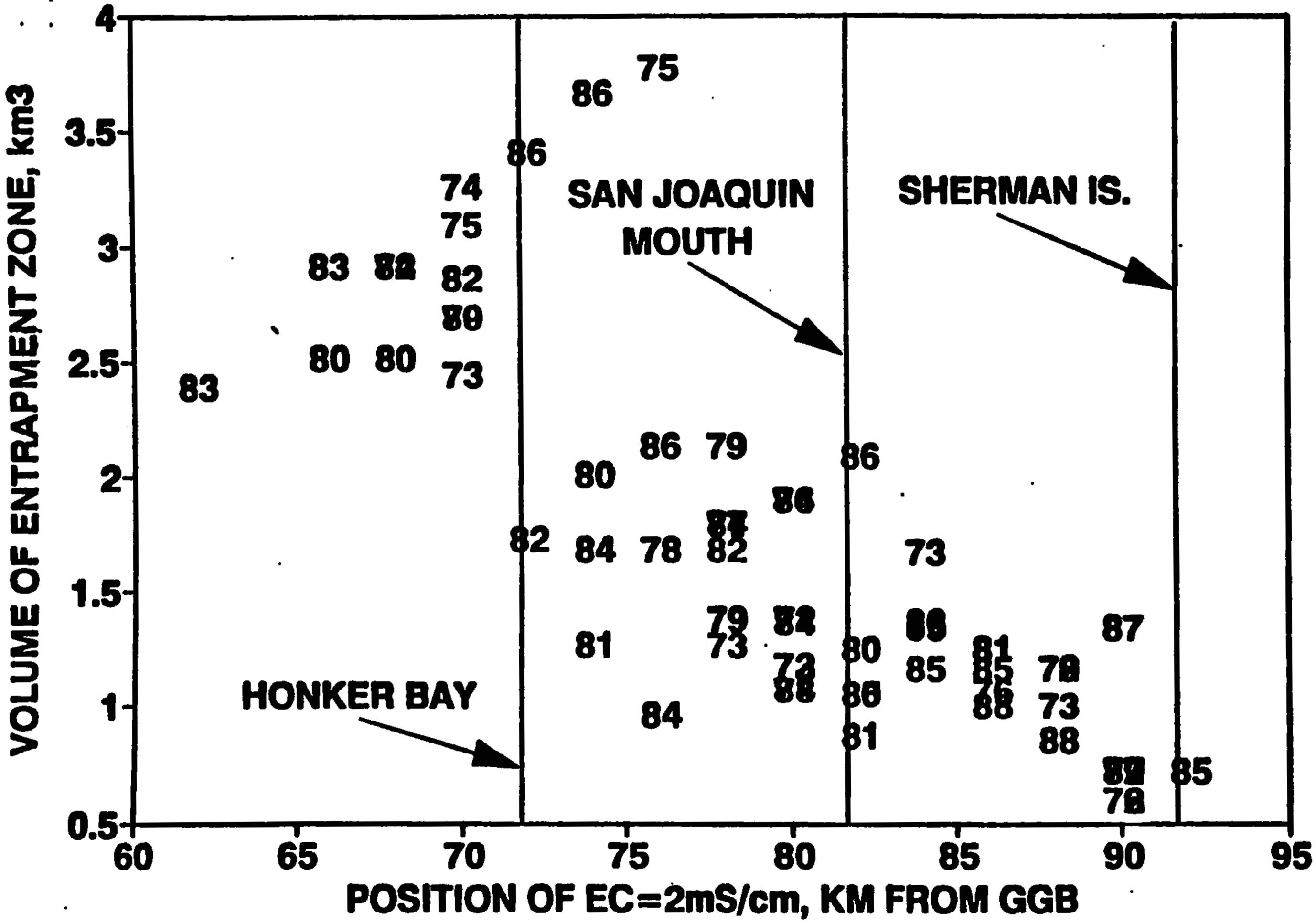


Figure 2a. The relationship between density of 6 mm to 14 mm striped bass and groupings of specific conductance (EC) for all samples made from April 12 through July 13 during the 1988 CDFG striped bass egg and larva survey in the Sacramento-San Joaquin Estuary. The vertical dotted lines encompass the EC range 1000 to 10000. The numbers indicate bass size. The plus indicates the combined 10mm-14mm densities.

Figure 3. Volume of entrapment zone estimatted as volume between 2 and 10 mS/cm, vs. distance of 2 mS/cm from Golden Gate. Numbers are years.



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21 August 1991

MEMORANDUM

SUBJECT: Transmittal of Synopsis of Evidence Presented to the State Water Resources Control Board Regarding the Entrapment Zone, and the Third Draft of the Status and Trends Report on Aquatic Resources

FROM: Tim Vendlinski, Estuary Project Staff TV

TO: Prospective Participants

Enclosed is a synopsis of evidence presented to the State Water Resources Control Board (SWRCB) regarding the entrapment zone (prepared by the Natural Heritage Institute), and the most recent draft of the Status and Trends Report (STR) on Aquatic Resources (prepared by investigators at U.C. Davis).

Please review the synopsis prior to the Workshop on Entrapment Phenomena scheduled for next week, August 27th-29th. The draft Aquatic Resources STR is offered to you as a reference document. If you have any questions or concerns, please contact me at 415.744.1989.