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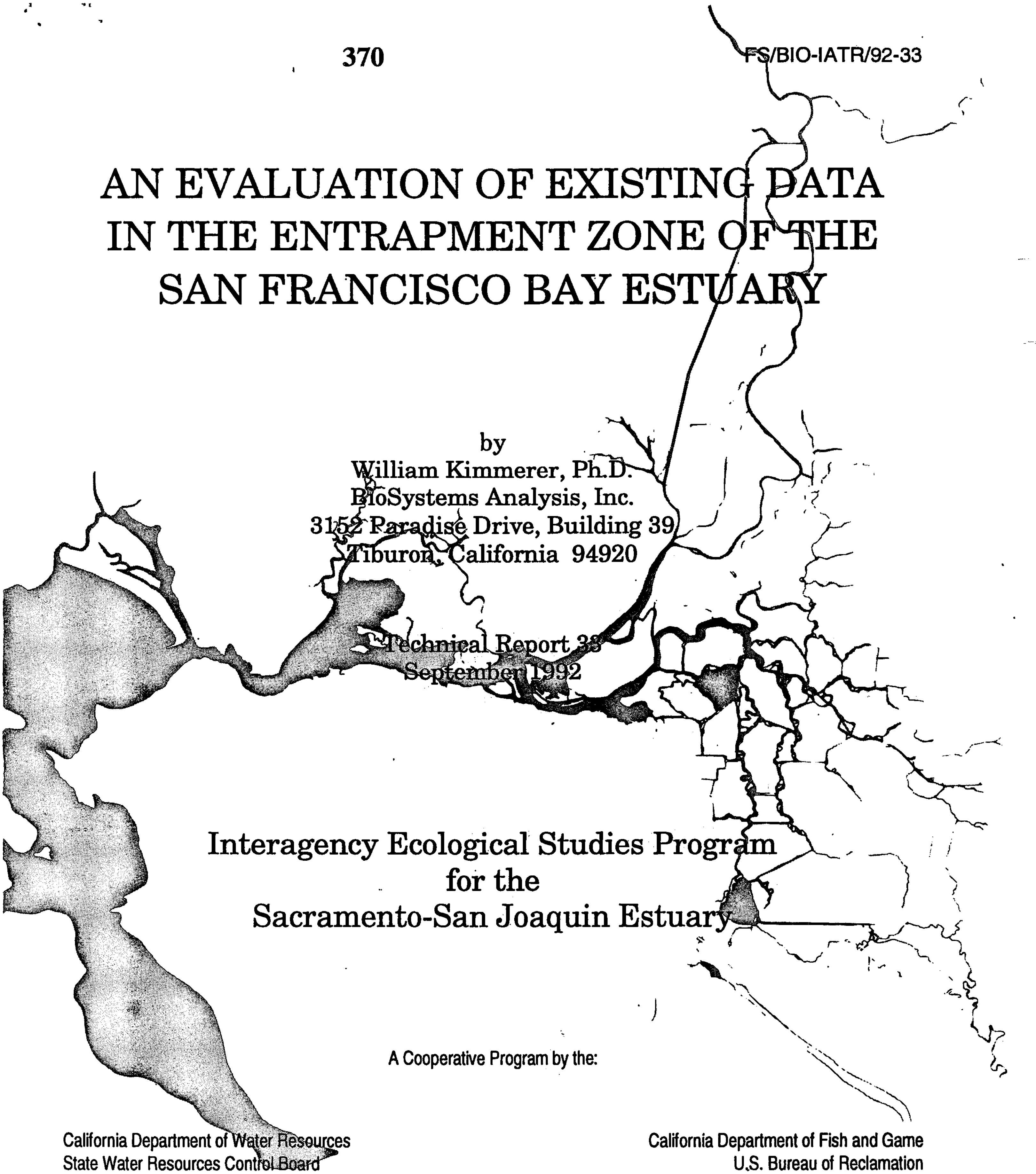
AN EVALUATION OF EXISTING DATA IN THE ENTRAPMENT ZONE OF THE SAN FRANCISCO BAY ESTUARY



by
William Kimmerer, Ph.D.
BioSystems Analysis, Inc.
3152 Paradise Drive, Building 39
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Technical Report 33
September 1992

Interagency Ecological Studies Program for the Sacramento-San Joaquin Estuary

A Cooperative Program by the:

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CONTENTS

EXECUTIVE SUMMARY

This report presents an analysis of available information on the entrapment zone of the San Francisco Bay/Delta estuary. The analysis synthesizes information from the literature on this estuary with the available data in an assessment of the importance of the entrapment zone to the estuarine food chain leading to the early stages of fish such as striped bass and delta smelt. This study has two components: a review of the literature on entrapment phenomena and related issues, and an analysis of data from the Interagency monitoring programs. The objectives of this study were to describe the entrapment zone and to assess its importance to biological production, the importance of its geographic position to production, and the possible effect of historical changes in the entrapment zone on the abundance of important organisms.

The basic physical phenomenon of entrapment is reasonably well understood. This understanding has increased greatly, and the current conceptual model of entrapment is very different from that of a few years ago. Concentrations of particles in an estuary can be enhanced through a variety of mechanisms. We focus here on the mechanism by which particles are trapped through the interaction of their sinking with current shear. The longitudinal density gradient in an estuary produces a landward-flowing, bottom current if tidal flows are subtracted out. Particles that sink out of the surface layer are transported back upstream by the net bottom current and become concentrated near the upstream limit of this net landward flow.

Effectiveness of the entrapment zone in trapping particles depends on the relative magnitudes of freshwater flow rate and tides. Tidal currents cause shear that vertically mixes the water column, opposing stratification and generally spreading out concentrations of particles. In addition, longitudinal tidal dispersion causes most of the upstream flux of salt and possibly of the flux of particles, particularly when freshwater flow is low. On the other hand, extremely high freshwater flow results in a very short residence time for particles. Thus, intermediate flows coupled with relatively weak tidal currents appear to result in the greatest amount of trapping. The entrapment zone moves downstream during high-flow conditions and upstream when flow is low.

The physics of entrapment are further complicated by the bathymetry of the estuary. Lateral circulation cells and exchange between shoals and channels by tidal or wind-driven circulation could be as important as vertical velocity shears in producing maxima in turbidity or other properties. A turbidity maximum can also occur without vertical or lateral shear at locations where the cross-sectional area increases and kinetic energy is at a minimum.

ton, and *N. mercedis* consumes *E. affinis*, there is no evidence that abundance of food limits abundance of either of these species. In fact, nearly all of the correlation can be explained as similar responses to salinity and season. Thus, elevated phytoplankton biomass occurring when the entrapment zone is downstream does not necessarily translate to elevated abundance of zooplankton or to higher survival of larval fish. In addition, correlations between zooplankton abundance or chlorophyll and flow at fixed stations are merely the result of movement of their salinity-related patterns in response to flows.

Both the seasonal timing and total quantity of freshwater flows have changed substantially with a historical increase in water exports from the Delta. These changes have presumably caused shifts in the seasonal pattern of entrapment zone position. Significant long-term declines have also occurred in a number of variables in the estuary, including total suspended matter, phytoplankton biomass, abundances of both *E. affinis* and *N. mercedis*, and populations of striped bass and delta smelt. Some of these declines have been attributed to changes in Delta outflows. However, there are two reasons why changes in flows and entrapment zone position are not likely to be the cause of the declines in the lower trophic levels. First, entrapment zone position in any one season or averaged over the year has not changed significantly between 1972 and 1987, the period over which most of the data were collected. Second, the magnitude of the declines is much larger than the magnitude of the effects of entrapment zone position. Thus the declines are not directly attributable to changes in flow or position of the entrapment zone.

Phytoplankton and zooplankton abundance declined more in 1988 than during any previous period, partly because of grazing by the recently introduced clam *Potamocorbula amurensis*. Concurrent declines in striped bass and delta smelt indices may be related to this introduction, although this effect cannot be distinguished from that of the drought in effect since 1986.

To summarize, the entrapment zone is important habitat for a number of species, although its importance to striped bass and other fish has not been fully demonstrated. For maximum production of zooplankton the entrapment zone should be at least as far downstream as the confluence of the Sacramento and San Joaquin rivers, which would require a Delta outflow of about 8,000 to 9,000 cfs. This position would also improve the chances of good year classes of striped bass and delta smelt.

There has recently been some discussion and analysis of the use of entrapment zone position as a substitute for outflow standards. This idea has been discarded in favor of a standard using a fixed bottom salinity value close to that of the entrapment zone. This shift in emphasis was done to simplify the standard, and does not imply that the entrapment zone is unimportant.

ACKNOWLEDGMENTS

Funding for this research was provided by the State Water Contractors and the Department of Water Resources. I thank Randy Brown for helping to obtain that funding and for helpful comments throughout the preparation of this report.

This report is the result of a large number of discussions with nearly everybody involved in research on this part of the estuary. Jim Orsi of the Department of Fish and Game and Jim Arthur and Doug Ball of the Bureau of Reclamation provided data and a lot of knowledge and historical perspective. Zach Hymanson of the Department of Water Resources provided me with the DWR data. I thank members of the Interagency Food Chain Group for helpful discussions and comments on various drafts of this report: Doug Ball, Heidi Bratovich, Tim Hollibaugh, Zach Hymanson, Don Kelley, Peggy Lehman, Dave Mayer, Lee Mecum, Lee Miller, Steve Obrebski, and Jim Orsi. Jim Arthur, Don Stevens, and Larry Smith also provided helpful comments on the report.

Chapter 1

INTRODUCTION

For the past two decades, the Interagency Ecological Studies Program has collected data on a variety of physical, chemical, and biological variables in the San Francisco Bay/Delta estuary. These investigations have provided one of the world's longest-term data records for an estuary, constituting an impressive body of information.

Much has been learned from these data and from studies designed to investigate and explain patterns observed in the data. However, much of the knowledge gained in this effort is anecdotal and not fully supported by rigorous analyses of the data. For example, many scientists working in this area believe the entrapment zone of the estuary is important to survival and subsequent recruitment of larval and juvenile fish and to the food chains on which they depend (*eg*, Arthur and Ball 1979). Although studies of this and other estuaries and some findings on striped bass provide reasons to believe this might be true, this general opinion has yet to be firmly supported using the data at hand. Analysis of much of the data has been insufficient either in amount or rigor to resolve basic questions about trends and patterns in the data.

This report synthesizes the literature on this estuary with the available data in an assessment of the importance of the entrapment zone to the food chain of the estuary and to early life stages of important fish. This study has two components:

- A review of the literature on the entrapment zone and related issues.
- An analysis of data from the Interagency monitoring programs.

The purpose of this report is to present an objective analysis of existing information. This is an important step in evaluating where we are in our understanding of the ecology of the bay and of the effect of freshwater inflows. It should also prove useful in suggesting how directed research projects might reveal further detail of the effects of flows and diversions.

The objectives of this study were to assess to what extent the following questions could be answered using the monitoring data:

- What are the characteristics of the entrapment zone in the San Francisco Bay/Delta estuary?
- What is the importance of the entrapment zone to biological production?
- How important are changes in position of the entrapment zone to the abundance or production of the species that use the entrapment zone?
- Is the long-term historical decline in many of the indicators of biological production related to changes in the entrapment zone?

Chapter 2 presents a review of the literature relevant to the entrapment zone of the San Francisco Bay/Delta estuary. Chapter 3 describes the results of several analyses of data on the entrapment zone. Chapter 4 summarizes our knowledge of the entrapment zone in this estuary and presents some recommendations for future activities.

LITERATURE REVIEW

This literature review is focused on the entrapment zone of the San Francisco Bay/Delta estuary and on an explanation of the entrapment phenomenon. The literature on the San Francisco Bay/Delta estuary is less extensive than those for other North American estuaries (*eg,* Chesapeake Bay, St. Lawrence). However, a number of key publications provide a firm basis for examining the role of the entrapment zone. These papers have resulted to a large extent from efforts of Interagency Program investigators, but relatively few of the data reported are from the ongoing Interagency monitoring programs. Rather, most of these studies have reported results of special investigations conducted for particular purposes.

In addition to published literature, I have included in this review several analyses that have not been published in widely available literature but that have received considerable peer review.

General Concepts

A number of terms have been used to describe the enhanced particle concentration commonly occurring in estuaries: *eg,* estuarine turbidity maximum, maximum turbidity zone, entrapment zone, or null zone. Although these terms do not all have identical meanings, they refer to related phenomena (see Glossary). Briefly, an estuarine turbidity maximum or maximum turbidity zone is a location of elevated turbidity due to concentration of particles. An estuarine turbidity maximum can arise through entrapment or through other mechanisms such as wind-driven disturbance on shoals. An entrapment zone is an area where variations in flow interact with particle settling to trap particles, and a null zone is the upstream limit of tidally-averaged 2-layer flow. These concepts are discussed in the next section, "The Physics of Entrapment".

Since this report discusses how the entrapment zone affects biological production, it is useful to define this and related terms (see also Glossary). Abundance (sometimes density or concentration) is the number of organisms in a functional group (*eg,* phytoplankton) or population (*eg,* striped bass) per spatial unit (area or volume). Note that the term "abundance index" often refers to a measure of total size of a population; *ie,* summed over the area or volume of interest.

Biomass is the amount of biological material in a functional group or population per unit of area or volume. It can be expressed in units of weight (wet weight, dry weight, carbon, nitrogen) or caloric content. Productivity is the rate at which a functional group or population creates additional biomass per area or volume. It is the product of biomass times the mean specific growth rate of organisms in the group (Ricker 1958). Production usually refers to productivity accumulated over time (*eg,* 1 year), but many workers do not distinguish between production and productivity (see Glossary for further information). For animals, growth rates are poorly known but vary less than biomass, so production can be estimated from biomass or abundance (Kimmerer 1987). Production of phytoplankton in San Francisco Bay is also readily predictable from biomass, light, and water clarity, since nutrients are rarely limiting (Ball 1975; Cole and Cloern 1984).

Salinity is used in this and other reports as an index of relative position in the estuary. Salinity is commonly expressed in parts per thousand, but the correct expression of salinity using the Practical Salinity Scale (UNESCO 1981) is unitless, being based strictly on conductivity and temperature. The interagency monitoring programs routinely measure specific conductance corrected to 25°C, from which salinity can be calculated if all of the salt comes from sea water. The advantage of doing this instead of expressing salt content as specific conductance is that the salinity value is a direct measure of the degree of dilution of sea water with fresh water. This is useful in considering the loss of substances from the estuary by mixing and dilution (Officer and Lynch 1981). However, salinity is not as useful when the salt content comes from sources such as agricultural drainage, as in the eastern and southern Delta. This report focuses more on areas of the estuary influenced by ocean water. Therefore, I express salt content as salinity (without units). Where appropriate, I add specific conductance values corrected to 25°C for reference, since many of the existing reports show only specific conductance.

Seasons in this report are defined as: winter (January-March), spring (April-June), summer (July-September), and fall (October-December).

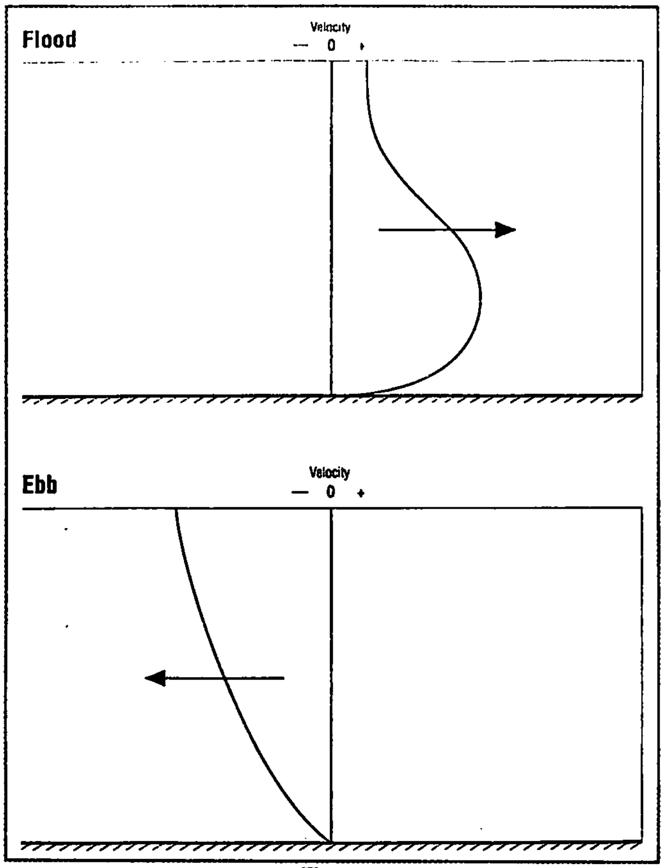


Figure 2
SCHEMATIC OF EBB AND FLOOD VELOCITY PROFILES
The differences between ebb and flood are vastly exaggerated.

produced by the horizontal density gradient; that is, gravitational circulation reinforces the flood near the bottom and the ebb at the surface (Smith 1987), with stratification enhanced on the ebb and disrupted on the flood (Uncles and Stevens 1990). Averaging over the tidal cycle yields a small net 2-layer flow similar in its effect to that seen in the high-flow condition. The principal differences are that with strong tidal flows, turbulence within the entrapment zone is greater, residence times of particles are shorter, stratification is reduced or eliminated, and the net 2-layer flows are small relative to instantaneous flows.

Entrapment occurs in this 2-layer flow as depicted schematically in Figure 3 (Arthur and Ball 1979, 1980). Particles sinking out of the surface water become entrained in the deeper current and are carried back upstream. Near the landward margin of this region of net 2-layer flow, turbulent mixing or a net upward movement prevents settlement of particles having a certain range of settling velocities, and these become trapped in the region. Between the two layers is a "plane of no net motion" at which no net landward or seaward velocity exists. Where the upstream edge of this plane intersects the bottom, 2-layer flow ceases and all of the flow is seaward; this region, referred to as the "null zone", is closely associated with the entrapment zone. Note, however, that these concepts apply only to tidally-averaged flows, and would be difficult to observe directly.

The interaction of tidal and freshwater flows largely determines the position of the null zone and the residence time of particles therein. Moderate freshwater flows move the null zone downstream, increase stratification, reduce water residence time, suppress turbulent mixing across the halocline, and thereby increase entrapment of negatively buoyant particles relative to low flows (Walters and Gartner 1985; Smith and Chang 1987; Smith 1987; Nunes Vaz *et al* 1989; Moon and Dunstan 1990; L. Smith, U.S. Geological Survey, pers. comm. 1991). Very high freshwater flows result in very short residence times and advection of particles out of the entrapment zone (Moon and Dunstan 1990). Strong tidal flows reduce stratification, increasing the residence time of water and neutrally buoyant particles (Nunes Vaz *et al* 1989) but reducing the trapping capability of the entrapment zone for negatively buoyant particles (Walters and Gartner 1985).

The conceptual model of entrapment in the previous paragraphs is greatly simplified relative to current understanding of the phenomenon. Even in an estuary of simple cross section without shoals, nonlinear interactions between tidal and mean flows can cause longitudinal transport of salt and particles (Jay 1991). Estuarine circulation and particle transport is usually examined with an Eulerian approach, *ie* relating to fixed stations, whereas a Lagrangian approach (relating to the tracks of individual

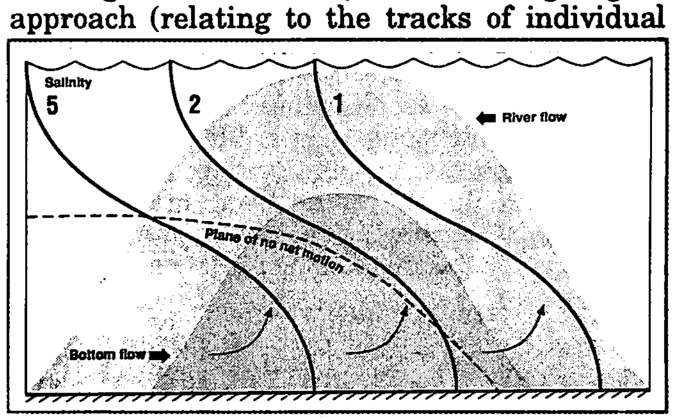


Figure 3
SCHEMATIC DIAGRAM ILLUSTRATING THE CONCEPTUAL MODEL OF AN ENTRAPMENT ZONE
Shaded areas indicate the location of the turbidity maximum.
Actual shapes of the lines will vary.

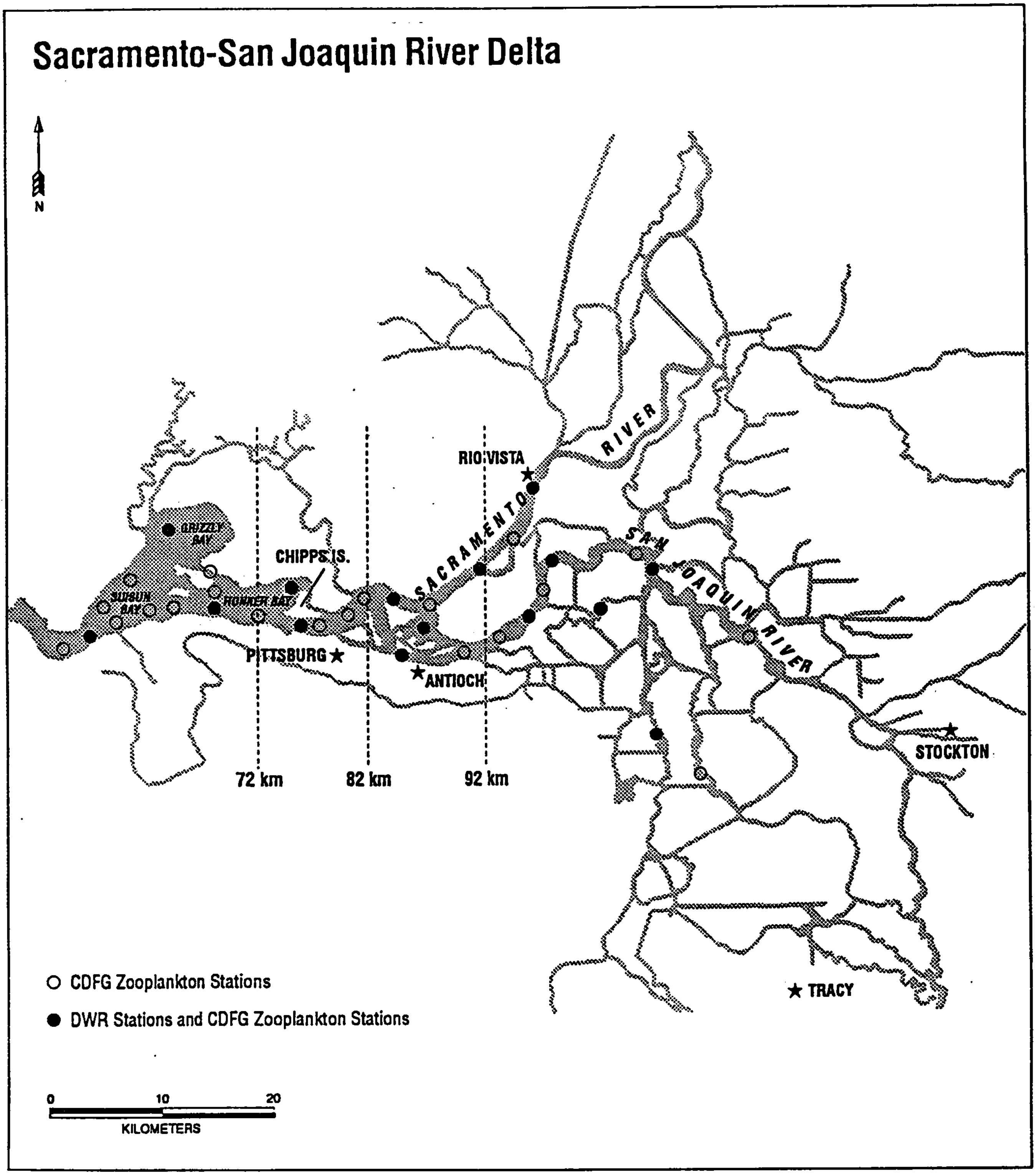


Figure 4

LOCATION MAP FOR DWR AND CDFG SAMPLING STATIONS

Vertical lines indicate distances from Golden Gate Bridge used to define four categories of entrapment zone position.

Francisco Bay/Delta estuary. This is related because the declines could be associated with historical changes in entrapment zone position. Declines have been noted in phytoplankton (Orsi and Mecum 1986; Arthur 1987), zooplankton (Orsi and Mecum 1986), striped bass (Stevens *et al* 1985), and delta smelt (Stevens *et al* 1990; Moyle *et al* 1992).

This section begins with a discussion of several other estuaries in which detailed studies of the entrapment zone have been undertaken. This is followed by discussions of the significance of the entrapment zone to various important components of the ecosystem, based on existing literature.

Evidence from Other Estuaries

A large number of estuaries have been studied with regard to physical mechanisms, sediment transport, and specific aspects of biology or ecology. Turbidity maxima or entrapment zones have been described from many of them. Three characteristics that seem common to many estuaries are that chlorophyll concentrations are highest just upstream of the entrapment zone, that disruption of freshwater phytoplankton cells is a major source of detrital organic carbon to the entrapment zone, and that primary productivity is suppressed by high turbidity in the estuarine turbidity maximum (Morris *et al* 1978; Sharp *et al* 1982; Therriault *et al* 1990; Simenstad *et al* 1990a; Moon and Dunstan 1990). Two river-dominated estuaries provide particularly relevant information: the upper St. Lawrence estuary, which has received a great deal of study, and the Columbia estuary, in which intensive study has focused on the estuarine turbidity maximum.

The St. Lawrence estuary has probably received the most attention to physics and sediment dynamics of any river-dominated estuary. It is much deeper and larger than San Francisco Bay. A well-developed estuarine turbidity maximum occurs at surface salinities between about 1 and 6 (Lucotte and d'Angeljan 1986). Seasonal changes in turbidity appear to depend on tidal exchange between shoals and channels and seasonal patterns in vegetation on the tidal flats (Lucotte and d'Anglejan 1986; Lucotte 1989). Chlorophyll is greatly suppressed in the estuarine turbidity maximum, and primary production may be negligible there (Painchaud and Therriault 1989; Therriault *et al* 1990). The dominant source of organic carbon appears to be phytoplankton from the river, although the long residence time of particles in the estuarine turbidity maximum precludes identification of sources (Lucotte 1989). Attached bacteria, but not free-living bacteria, are enhanced in the estuarine turbidity maximum, while heterotrophic activity is maximum just upstream (Painchaud and Therriault 1989). Among the zooplankton, several species have maximum abundances in the estuarine turbidity maximum, although this region has been called a "graveyard" for freshwater and marine species because of osmotic stress (Bousfield *et al* 1975; Dodson *et al* 1989; Runge and Simard 1990). Maintenance of position within the estuarine circulation region has been inferred for some zooplankton (Runge and Simard 1990) and for certain larval fish (Fortier and Leggett 1983; Laprise and Dodson 1989; Dodson *et al* 1989), either through vertical migration or depth maintenance.

The Columbia River has been the site of two major recent interdisciplinary studies, of which the current one focuses explicitly on the estuarine turbidity maximum (Simenstad *et al* 1990a,b; Jay *et al* 1990). Circulation of the Columbia is perhaps understood as well as that of any estuary (Jay and Smith 1990a,b). A significant lateral circulation cell exists in which streamflow dominates in the southern, main channel and upstream flow dominates in the shallower northern channel. Note that this is the opposite pattern from that seen in Suisun Bay (see "The Entrapment Zone in the San Francisco Bay/Delta Estuary", page 6). Phytoplankton concentrations are high upstream of the estuarine turbidity maximum, then decline sharply as detrital carbon concentration increases in the estuarine turbidity maximum. Thus fluvial phytoplankton are the major source of organic carbon to the estuarine turbidity maximum, far greater than primary productivity there. The estuarine turbidity maximum appears to be a major processor of organic matter passing through, since most of the organic carbon there is processed by epibenthic consumers. Benthic infaunal abundances are suppressed, and epibenthic and zooplanktonic abundances are enhanced, within the estuarine turbidity maximum relative to upstream or downstream. Zooplankton occur in three distinct assemblages: a freshwater group, an estuarine turbidity maximum group, and an assortment of euryhaline marine species. The estuarine turbidity maximum group is dominated by the epibenthic copepod *Eurytemora affinis* and epibenthic harpacticoid copepods, with abundances on the order of 10,000 m^{-3} (Jones *et al* 1990).

the estuary shows the largest source is the rivers, presumably in the form of freshwater phytoplankton (Herbold *et al* 1992; A. Jassby, U.C. Davis, pers. comm. 1991). During low-flow periods in 1976 and 1977, isotope analysis of particulate organic carbon (POC) in the entrapment zone indicated most of the POC was from rivers, with the remainder from *in situ* production or resuspension (Spiker and Schemel 1979).

Zooplankton

Several papers have been prepared on the abundance of various zooplankton species in relation to the entrapment zone. The copepod *Eurytemora affinis* and the mysid *Neomysis mercedis* both appear to be entrapment zone species in that they tend to be most abundant in or near the entrapment zone (Heubach 1969; Siegfried *et al* 1979; Orsi and Knutson 1979; Knutson and Orsi 1983; Orsi and Mecum 1986). *E. affinis* is the most abundant species of zooplankton in the lower salinity (1-10) zones of estuaries on both the east and west coasts of the United States and Europe (*eg,* Heinle and Flemer 1975; Burkill and Kendall 1982; Miller 1983; Orsi and Mecum 1986). Both species are important food for larval striped bass: *E. affinis* during the first few millimeters of growth and *N. mercedis* after bass reach 10-14 mm in length (CDFG 1988b). Delta smelt also consume these zooplankton species (Moyle *et al* 1992). The copepod *Sinocalanus doerrii*, introduced around 1978, is most abundant upstream of the entrapment zone (Orsi *et al* 1983). A more recent introduction, *Pseudodiaptomus forbesi*, took up a position similar to that of *E. affinis* in 1988 (Orsi and Walter 1991).

In addition to the species listed above, several other species of zooplankton can be abundant in or near the entrapment zone (Ambler *et al* 1985). Most of these have abundance maxima well downstream of the entrapment zone. These species include two species of the ubiquitous copepod genus *Acartia*, several neritic species of copepod, and meroplanktonic forms such as barnacle nauplii (Ambler *et al* 1985). Microplankton such as rotifers can also be abundant in the entrapment zone but are not considered here.

Both of the common entrapment zone species, *E. affinis* and *N. mercedis,* have declined substantially over the duration of the sampling program (Knutson and Orsi 1983; CDFG 1988c). Causes of declines have not been determined, although declines in food or the introduction of *Sinocalanus* have been identified as possible causes of the decline in abundance of *E. affinis* (CDFG 1988c).

N. mercedis has a peak in abundance at a salinity around 2-3, close to the defined upstream end of the entrapment zone (Knutson and Orsi 1983). It is believed to maintain a higher population in the entrapment zone by the interaction of its vertical position with the estuarine circulation, rather than through mortality downstream due to physiological effects of salinity (Heubach 1969; Siegfried *et al* 1979; Orsi 1986). Abundance indices, which are estimates of the total population size, were higher when the entrapment zone was in Suisun Bay than when it was upstream (Siegfried *et al* 1979; Knutson and Orsi 1983). It was postulated that this was due to a reduction in habitat size in the restricted channels of the Delta (Siegfried *et al* 1979; Knutson and Orsi 1983). In addition, Knutson and Orsi (1983) stated that cross-Delta flows rendered the eastern and southern Delta unsuitable as habitat for *N. mercedis*, although it is not clear how this could happen. It is also not clear whether abundance indices were lower when the entrapment zone was in the Delta because of reduced habitat size alone, or whether there was also a reduction in abundance (*ie* number per cubic meter) within the entrapment zone.

There is no evidence in any of these studies that reproductive or growth rates of zooplankton are different in and out of the entrapment zone.

In one respect, the studies cited above made a significant error in analysis of the data. For the most part, the data were related to fixed stations rather than to salinity, and no account was taken of the salinity variation in calculating means or correlations between species. This resulted in some possibly spurious results. For example, significant correlations were noted between *N. mercedis* at certain stations and flow (Siegfried *et al* 1979), between *N. mercedis* and *E. affinis* (Knutson and Orsi 1983), and between zooplankton abundance and chlorophyll (Orsi and Mecum 1986). Since chlorophyll and many zooplankton species have similar spatial distributions, and since the entrapment zone and the abundance peak move upstream or downstream depending on freshwater flow, these correlations can arise through movement of the entrapment zone. This issue is discussed further in "Effect of Position of the Entrapment Zone", page 29.

It is commonly assumed that phytoplankton chlorophyll is a good measure of food availability for zooplankton. However, *E. affinis* can subsist on detrital matter and requires larger particles spawned in the San Joaquin and moved into Suisun Bay. Although Turner's model may be a good explanation of the relatively high YOY index of 1986, it does not explain why indices were consistently higher before 1977 than after. Recent sampling at fixed stations in the Delta offers some support to the idea that eggs and larvae originating in the San Joaquin River become trapped in the Delta in low flow years (Arthur 1990); data from the egg and larval survey also show that few of the larvae emerge from the Delta in low-flow years (CDFG 1988b).

Delta Smelt

Interest in delta smelt (*Hypomesus transpacificus*) has grown recently with petitions to state and federal agencies to list it as an endangered species. Two recent reports (Stevens *et al* 1990; Moyle *et al* 1992) provide a complete analysis of current data indicating the status of this species. Delta smelt spawn in early spring in shallow, fresh water, reach adulthood in 7 to 9 months, and generally live about one year. Apparently this species is concentrated in the entrapment zone at least during larval development, and in shallow water adjacent to the entrapment zone as adults (Moyle *et al* 1992). Of the seven independent programs that sample for abundance of delta smelt, all indicate a decline in abundance in the early to mid-1980s, but the timing is not the same in all studies. Moyle *et al* (1992) propose that the decline may be caused by upstream location of the entrapment zone, since the entrapment zone has been upstream of Suisun Bay during spring and summer in every year since 1983 except for 1986. However, only two of the seven studies show a high abundance in 1982 and 1983 and only one shows moderate abundance in 1986, the three years in the 1980s with the highest springtime freshwater inflows. CDFG analysis did not show a relationship between flow and delta smelt abundance (Stevens *et al* 1990).

Evaluation of the Current State of Knowledge

Little has been published on biological activity of the entrapment zone in the last 8 years, although several data summaries, including some information on the entrapment zone, were presented to the State Water Resources Control Board in 1987 and 1988 (Arthur 1987; CDFG 1988a,b). The subject has not been pursued vigorously, apparently because of changing agency priorities.

The early reports on entrapment zone position focused almost entirely on the phytoplankton. The analyses (Arthur and Ball 1980; Cloern *et al* 1983) offer the most parsimonious explanation of the observations (see "Evidence from Other Estuaries", page 9). However, these analyses do not rule out other explanations of high phytoplankton biomass when the entrapment zone is in Suisun Bay (Arthur and Ball 1980; Cloern *et al* 1983). No further analysis has apparently been conducted on alternative mechanisms for enhancement of phytoplankton.

A common assumption is that, since the food chain depends on phytoplankton, what enhances phytoplankton must also enhance zooplankton, larval fish, and adult fish. This link has not been established beyond a simple correlation among chlorophyll and abundance of *Eurytemora affinis* and *Neomysis mercedis* (CDFG 1988c). Since these trends could be due to other changes (*eg*, in estuarine hydrology), the correlations do not establish cause. Furthermore, it is likely that at least some entrapment zone species (especially *E. affinis*) may depend as much on organic detritus as on phytoplankton (Heinle *et al* 1977).

In fact, there is some evidence that the long-term declines in zooplankton and striped bass are not due to changes in phytoplankton. First, limited experimental data (Kimmerer 1990) showed no evidence of food limitation of *E. affinis*, which was the most abundant zooplankton species in the estuary. If food is not limiting the growth or reproduction of this species, then changes in phytoplankton will not be reflected in changes in abundance of *E. affinis*. Of course, the question of food limitation in zooplankton is far from being resolved. Second, the recent analysis of the decline in striped bass (Stevens *et al* 1989) discounts the importance of the food web in regulating the population size of bass (see "Striped Bass", page 12).

To summarize, the published and unpublished analyses to date show evidence that existence of the entrapment zone is important to phytoplankton, some zooplankton, striped bass, and possibly delta smelt. The position of the entrapment zone has been shown to be important to phytoplankton, and a reasonable mechanism has been proposed. However, analysis of its importance to higher trophic levels has depended on the link between phytoplankton, zooplankton, and fish, which has not been established quantitatively.

DATA ANALYSIS

This chapter describes analyses performed on data obtained primarily from the Interagency monitoring programs (Figure 4, page 7). Results are interpreted and compared with previous analyses in Chapter 4.

Zooplankton data, along with ancillary data such as surface specific conductance, chlorophyll *a* concentration, and Secchi disk depth, were obtained from the Department of Fish and Game. This data set includes samples taken at 81 stations between 1972 (1976 for chlorophyll) and 1988, mainly during March to November, all at or near high tide. Because of the consistency and the large number of stations, I have used these data wherever possible to describe the distribution of salt and particulate matter in the estuary.

Data on chlorophyll, phytoplankton abundance, nutrient concentrations, and turbidity were obtained from the Department of Water Resources and the U.S. Bureau of Reclamation (DWR data set) from 1968 (1975 for phytoplankton species abundance) to 1989. DWR stations in the southeastern Delta were excluded, leaving a total of 16 stations.

Nearly all of the CDFG and DWR data were from samples taken near the surface, except for zooplankton samples, which were oblique tows. Data from the CDFG egg and larval survey were also used to examine the potential effect of the entrapment zone and its position on striped bass eggs and larvae.

Flow data were obtained from monthly output of the DWR DAYFLOW accounting program. Input data include measured flows into the Delta, estimates of minor flows to obtain total inflows, estimates of net consumption within the Delta, and measured export flows at the state and federal water projects. Net outflow is calculated by difference. Although these values have been criticized on the basis that they do not include tidal effects, the use of monthly means largely eliminates that problem, although it probably reduces the resolution of some of the analysis. The effect of the spring/neap tidal cycle on position of the entrapment zone is discussed later, in "Location of the Entrapment Zone" (page 18). Uncertainty in net Delta consumption introduces error to net outflow calculations, especially at low net outflow.

Methods

Principles used to guide the data analysis were:

- Use all of the relevant data rather than breaking them up into smaller segments.
- Account for known sources of variance, such as salinity, to permit more powerful analyses of other sources of variance.
- Use data that are consistent in time and space.

I believe many previous analyses of data from the estuary have been hampered by referring the data to fixed sampling stations. Tidal excursions and changes in streamflow cause the entrapment zone to move longitudinally within the estuary at time scales from hours to months. Since the salinity distribution moves up and down the estuary with the entrapment zone, data on the entrapment zone were analyzed in reference to salinity rather than to fixed stations. The section, "Location of the Entrapment Zone" (page 18) discusses potential problems in using surface salinity to represent entrapment zone position. In later sections, "Phytoplankton" (page 24) and "Effect of Position of the Entrapment Zone" (page 29), geographic position of the entrapment zone is also brought into the discussion as a separate variable to estimate its effect.

Another reason for referring all measurements to salinity is that this is the single most important variable affecting species composition at any point in the estuary (*eg,* Miller 1983). Each estuarine species has an optimum salinity range, and most species fail to survive at salinities well outside that range. Thus, much of the spatial variability in abundance of a given species can be explained simply on the basis of salinity. On the basis of salinity alone, one would expect to find each estuarine species to have high abundance in some salinity range and lower abundance elsewhere (*eg,* Miller 1983). By removing or accounting for the effect of salinity as a known factor, we can isolate other sources of variation. Furthermore, by removing the effects of salinity and perhaps season, we can determine whether correlations among species or trophic levels (Orsi and Mecum 1986) are due to common responses to salinity or to ecological interactions.

Details of data preparation and analysis peculiar to each data set are discussed below, along with the results of each analysis.

Physical Characteristics

The characteristics discussed here include flow conditions as described by the DAYFLOW variables, location of the entrapment zone, and its dependence on flow. Data used to define location of the entrapment zone included specific conductance and Secchi disk depth from the CDFG data set.

Flow Conditions

In this section I discuss historical patterns in freshwater flow to set the stage for a later analysis of possible causes of changes in the ecology of the entrapment zone and some of its species. Since Delta outflow affects entrapment zone position (Peterson *et al* 1975; Arthur and Ball 1978), understanding changes in flow is essential to understanding this segment of the estuary. Historical changes in flows since the inception of major flow diversions have been discussed by Arthur (1987). This section addresses changes during the period for which we have biological data.

An increasing trend exists in the data for export flows but not for Delta outflow. Figure 5 shows the historical trend in the anomaly (monthly pattern removed) of Delta outflow over the period for which we have zooplankton data (1972-1988). Although there are large interannual differences, no general trend in outflow is apparent over this period. Export flows, however, have increased by about 3,000 cfs over this period (Figure 6), but the percent of inflow exported reflects the cyclic pattern in outflow more than the trend in exports (Figure 7).

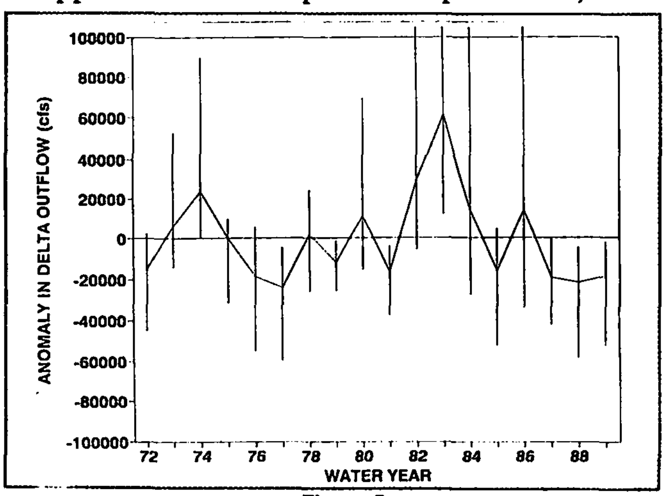


Figure 5
ANOMALY IN DELTA OUTFLOW
Annual means with 95% confidence limits indicated by vertical bars, calculated using monthly DAYFLOW values.

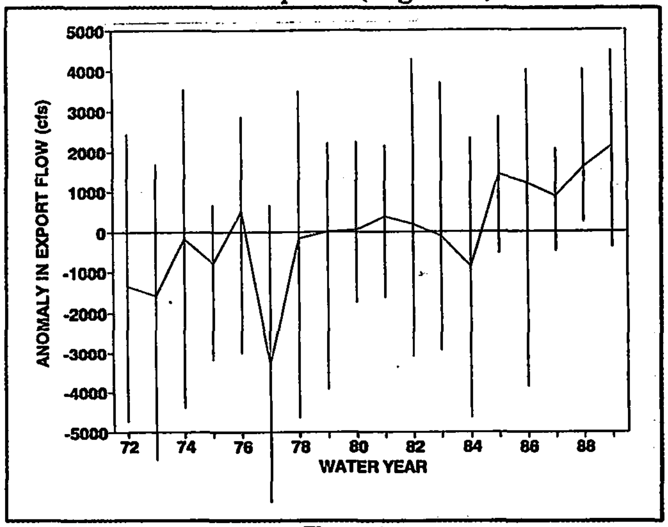


Figure 6
ANOMALY IN EXPORT FLOWS
Annual means with 95% confidence limits indicated by vertical bars, calculated using monthly DAYFLOW values.

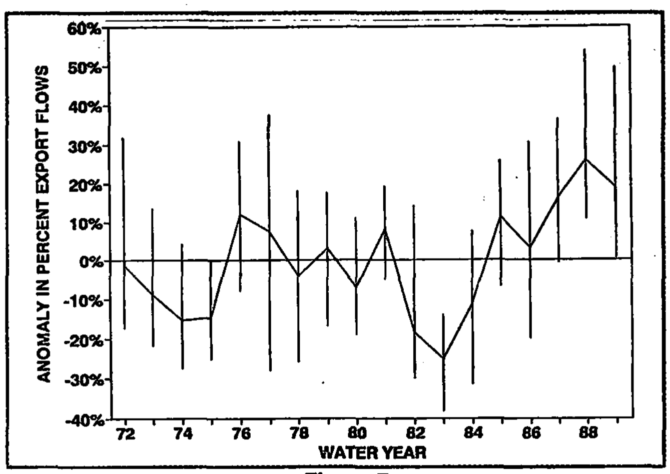


Figure 7
ANOMALY IN EXPORT FLOWS AS A PERCENT OF DELTA OUTFLOW
Annual means with 95% confidence limits indicated by vertical bars, calculated using monthly DAYFLOW values.

The upward trend in export flow is statistically significant (linear regression, $p<0.001$). The trend in percent exports is not quite significant ($0.05<p<0.1$), partly because of the large variations of outflow, and partly because inflows are varied to provide water for exports (Arthur 1987); however, a sharp upward trend has accompanied the current (1987-1991) drought. Note that starting the series at an earlier date would result in significant trends in percent export but that these would not be relevant for present purposes.

I determined the operationally-defined position of the entrapment zone from monthly mean data on specific conductance at each station in the CDFG zooplankton core data set plus the downstream stations. First I calculated an 11-km running mean value of specific conductance for every 2 km of distance from the Golden Gate Bridge between 60 and 120 km. The position of the entrapment zone was determined as the point where surface specific conductance was closest to 2 mS/cm. In months of high flows, the entrapment zone was out of the sampling area, so these months were dropped (including November through March every year).

I used the inverse of Secchi disk depth to indicate how the turbidity maximum deviates from the location of the 2 mS/cm point. Secchi disk depth is a measure of surface turbidity only, and therefore is only a rough indicator of the location of the turbidity maximum; however, as a crude measure of light penetration, it is biologically relevant. In addition, surface and bottom turbidity maxima in the entrapment zone approximately coincide (Arthur and Ball 1979). The long-term average position of the turbidity maximum occurs in salinity classes 13-17, corresponding to a salinity range of 1.2-6 (Figure 10).

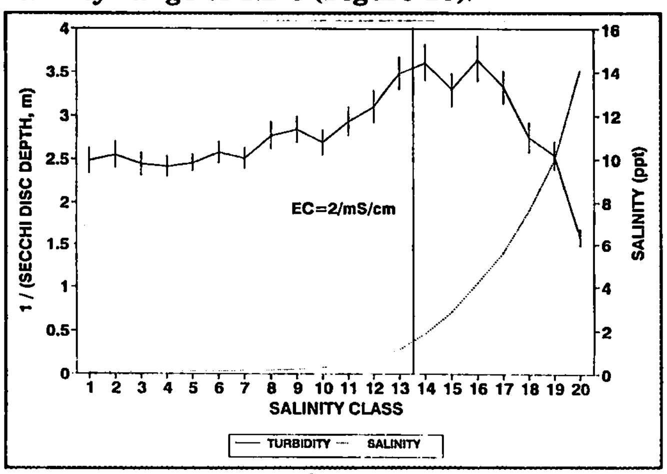


Figure 10
TURBIDITY MEASURED AS 1/SECCHI DISK DEPTH VS. SALINITY CLASS
Mean and 95% confidence limits (vertical bars) from CDFG core data set. The dashed line gives mean salinity in the class; the vertical line is the upstream end of the operationally defined entrapment zone.

To determine how the turbidity maximum varied with entrapment zone position, scatter plots of Secchi disk depth vs. salinity class (DWR data set) were examined for each month in the record, and a notation was made of the salinity class at which the minimum occurred. These data were converted to position using plots of salinity vs. position, and are plotted against location of the entrapment zone as defined above (Figure 11).

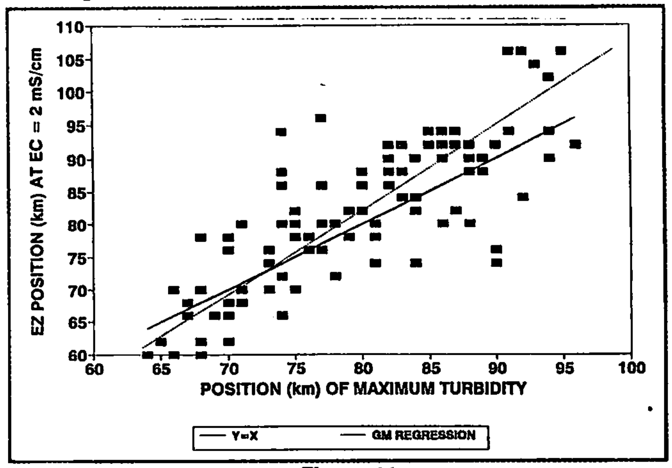


Figure 11
ENTRAPMENT ZONE POSITION BY THE OPERATIONAL DEFINITION VS. POSITION OF THE TURBIDITY MAXIMUM AS 1/SECCHI DISK DEPTH
Each point is a monthly mean from the CDFG data set. Solid line is for 1:1 correspondence; dashed line is the geometric mean regression.

The position of the turbidity maximum moves an average of 8 km relative to the operationally defined entrapment zone position as the latter varies between 65 and 95 km from the Golden Gate Bridge. That is, the mean difference between the turbidity maximum and the position of 2 mS/cm surface salinity is positive when both are upstream in the Delta and slightly negative when both are downstream in Suisun Bay. This may be due to the relationship of entrapment zone position with flow (Peterson *et al* 1975, see below).

As flow increases, pushing the entrapment zone downstream, stratification also increases, so the difference between surface and bottom salinity increases (Arthur 1987). Since entrapment occurs over a range of salinities throughout the water column, the salinity of surface water of the entrapment zone is lower when stratification is strong (and flow is high). Figure 11 indirectly illustrates the discrepancy between surface salinity and the salinity defining the entrapment zone. However, the scatter in these data is large, mainly because of uncertainty in determining the point of minimum Secchi disk depth. The relationship is monotonic, meaning that as the actual entrapment zone moves downstream, the operationally defined position also moves downstream. Thus, the operational definition (*ie,* 2 mS/cm) is an unambiguous index of entrapment zone position, even though it is not identical to entrapment zone position.

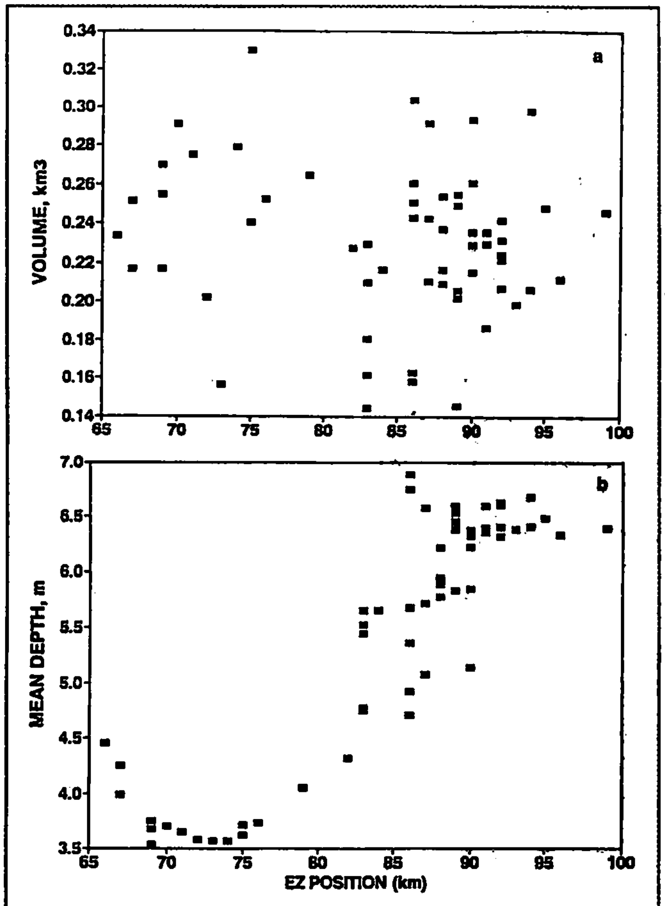


Figure 15

VOLUME AND MEAN DEPTH OF THE ENTRAPMENT ZONE

a. Volume of the entrapment zone, defined as the area with a salinity of 1-6 vs. operationally defined entrapment zone position (km from the Golden Gate). Each value is a monthly mean.

b. Mean depth in the entrapment zone (= mean volume/mean area).

Temperature and Transparency

Temperature anomalies show a slight but significant increase over the period 1968-1990 in the DWR data (Figure 16; $p<0.05$, linear regression) but not in the CDFG data ($p>0.1$). This may be partly because the CDFG data did not include 1968-1971, when the DWR temperatures were low, or 1989 and 1990 (because of the longer processing time for the CDFG data) when temperatures were high. However, the time of sampling in the DWR program shifted to later in the day in the mid-1970s, so this trend may be an artifact (D. Ball, U.S. Bureau of Reclamation, pers. comm. 1991).

Arthur (1987) stated that the historical increase in transparency in Suisun Bay could be accounted for by movement of the entrapment zone and streamflow. However, anomaly values for turbidity as 1/Secchi disk depth (DWR data set) have decreased significantly ($p<0.001$, linear regression of annual means, Figure 17). Thus, within the entrapment zone an increase in transparency has occurred over the period of record.

The effect of entrapment zone position on transparency within the entrapment zone was determined using inverse Secchi disk data from the DWR data set. I combined these data with data on position of the entrapment zone for each month and year. The position data were divided into four categories having roughly equal numbers of cases: less than 72 km, 72-82 km, 82-92 km, and 92 km or over from the Golden Gate Bridge. The first two categories place the entrapment zone in Suisun Bay or Honker Bay and the last two in the western Delta (Figure 4, page 7). The relationships of turbidity to salinity class were then determined separately for each position of the entrapment zone.

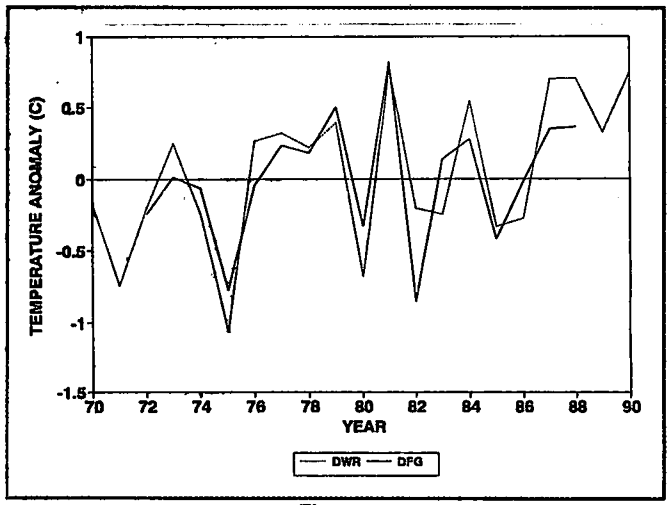


Figure 16

ANOMALIES IN TEMPERATURE

Annual means from DWR and CDFG data sets.

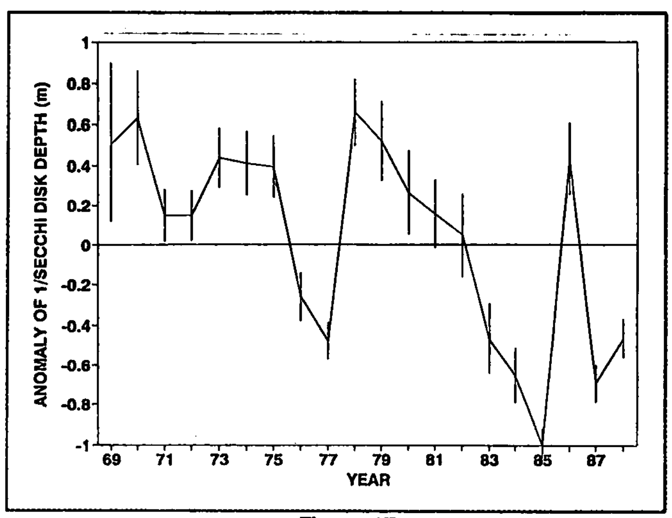


Figure 17

ANOMALIES IN TURBIDITY AS 1/SECCHI DISK DEPTH

From the DWR data set.

Annual mean and 95% confidence limits (vertical bars).

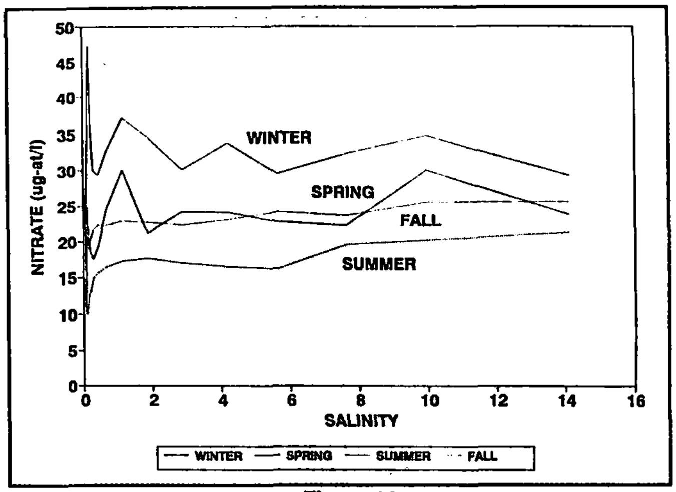


Figure 20
NITRATE VS. SALINITY, BY SEASON

Orthophosphate (Figure 21) was lowest at the freshwater end of the range of samples and relatively flat at other locations. However, total phosphorus had a broad maximum at intermediate salinities (in and downstream of the entrapment zone), indicating dissolved organic phosphorus was highest there, probably because of an overall increase in organic matter. Silica (Figure 21) declined almost linearly with salinity.

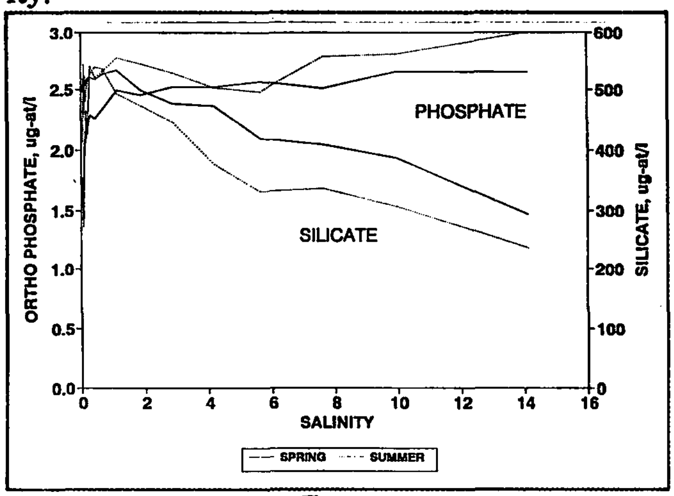


Figure 21
ORTHOPHOSPHATE AND SILICATE VS. SALINITY, FOR SPRING AND SUMMER

Nutrient concentration anomalies generally did not have a long-term trend, except that ammonium and orthophosphate increased significantly ($p<0.05$) in spring (Figures 22-25). These trends may reflect the decreasing phytoplankton concentrations (see "Phytoplankton", page 24), although they could reflect improvements in analytical practices, since variability among individual data declined as well. If the early years (1971-1973) are eliminated from the analyses, the trends become insignificant.

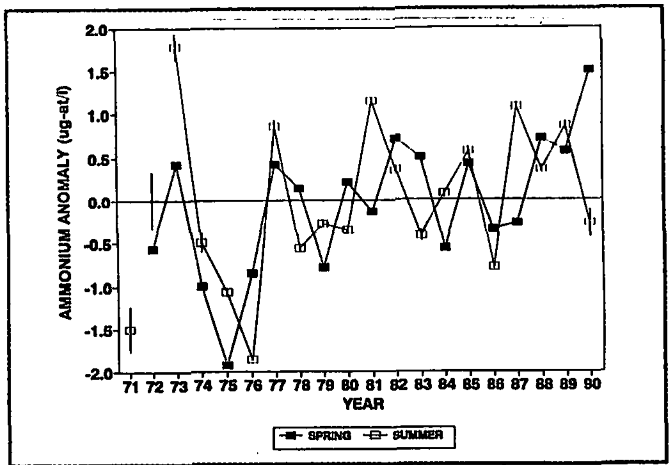


Figure 22
ANOMALIES IN AMMONIUM VS. TIME, FOR SPRING AND SUMMER
Seasonal means with 95% confidence limits (vertical bars) for summer only.

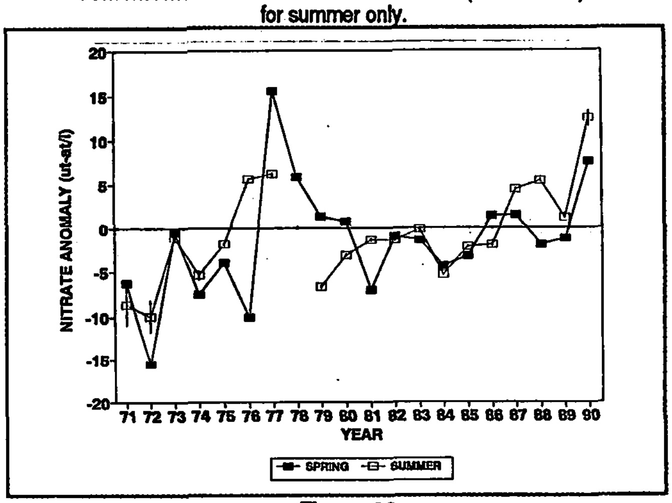


Figure 23
ANOMALIES IN NITRATE VS. TIME, FOR SPRING AND SUMMER
Seasonal means with 95% confidence limits (vertical bars) for summer only.

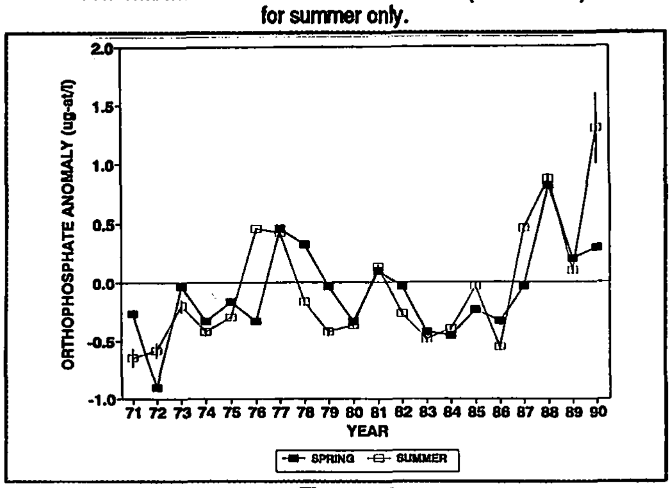


Figure 24
ANOMALIES IN ORTHOPHOSPHATE VS. TIME, FOR SPRING AND SUMMER
Seasonal means with 95% confidence limits (vertical bars) for summer only.

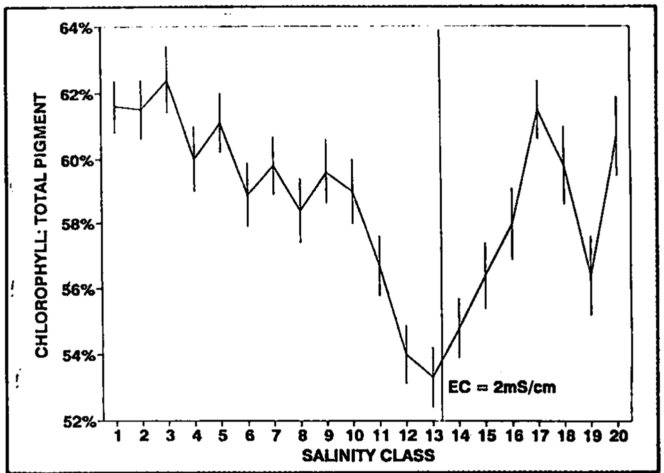


Figure 27

RATIO OF CHLOROPHYLL TO TOTAL PHOTOSYNTHETIC PIGMENT (CHLOROPHYLL PLUS PHAEOPIGMENTS) VS. SALINITY CLASS FROM THE DWR DWR SET

Means and 95% confidence intervals.

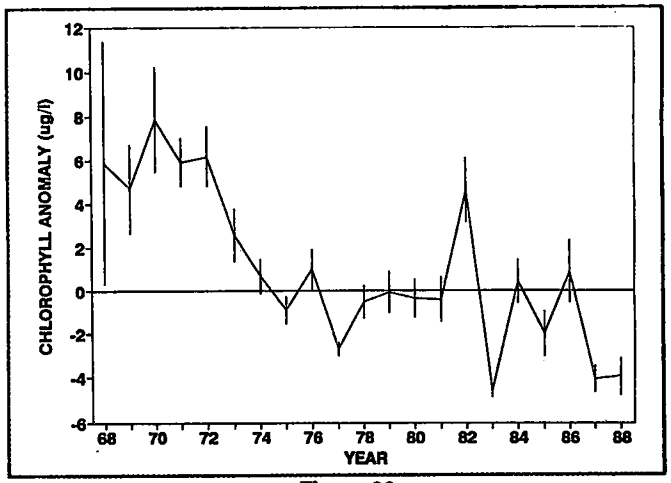


Figure 28

ANOMALIES IN CHLOROPHYLL VS. TIME

Annual mean and 95% confidence limits from DWR data set.

Chlorophyll values in both data sets have decreased over time since about 1972 (Figure 28). This decrease is statistically significant (regression, $p<0.001$) and comes to about 10 µg Chl/L over the entire period. Phaeopigments likewise decreased, but the ratio of chlorophyll to total pigments decreased; that is, phaeopigments decreased less than chlorophyll (Figure 29). This is unlikely to represent an increase in herbivory, since pelagic herbivores have, if anything, decreased (see "Zooplankton", page 11).

Chlorophyll data from the DWR data set were used in an analysis to confirm the importance of entrapment zone position reported by Arthur and Ball (1980) and Cloern *et al* (1983). The analysis was identical to that for turbidity (refer to "Temperature and Transparency", page 21).

Differences in chlorophyll among categories of entrapment zone position were not as clear as previously reported or as for turbidity, but were significant (Figure 30; $p<0.01$, analysis of variance of data in salinity classes 12-18). The means and confidence limits of chlorophyll across the broad peak (salinity classes 12-18) show that the two intermediate entrapment zone positions had higher mean chlorophyll concentrations than the uppermost or lowermost positions. However, in salinity classes 9-12, chlorophyll was highest when the entrapment zone was in the most downstream position. This offers some support, on the basis of the entire time series, to the ABC model.

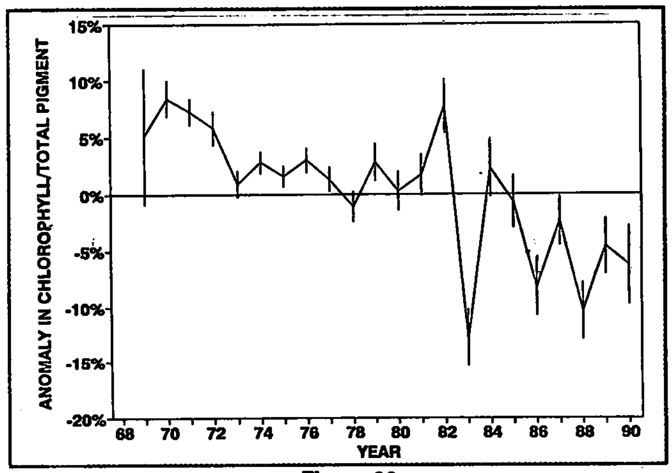


Figure 29

RATIO OF CHLOROPHYLL TO TOTAL PHOTOSYNTHETIC PIGMENT VS. TIME

Annual mean and 95% confidence limits from DWR data set.

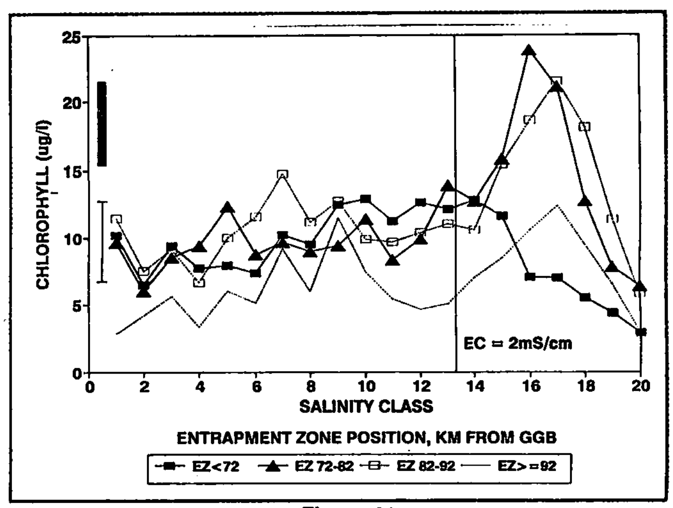


Figure 30

CHLOROPHYLL VS. SALINITY CLASS FOR FOUR RANGES OF OPERATIONALLY DEFINED ENTRAPMENT ZONE POSITION

Vertical bar at left is the mean of 95% confidence intervals for all points on the graph.

the distribution is skewed toward the low-salinity end of the distribution, which contains most of the samples.

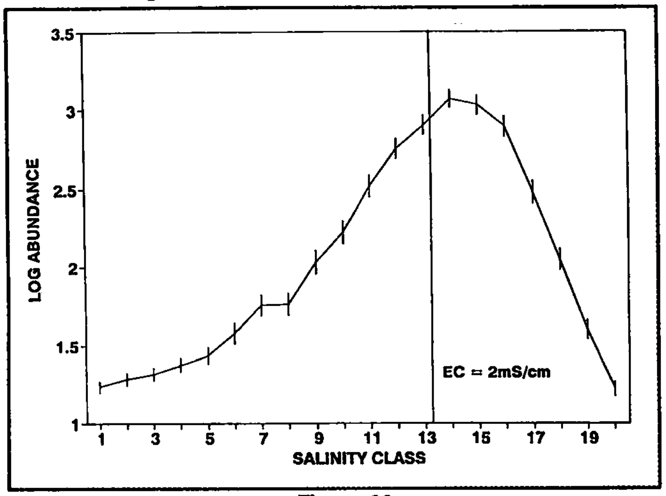


Figure 33
LOG OF ABUNDANCE OF *EURYTEMORA AFFINIS* VS. SALINITY CLASS
Log of abundance in number/m^{-3}+10.
Mean and 95% confidence intervals (vertical bars).

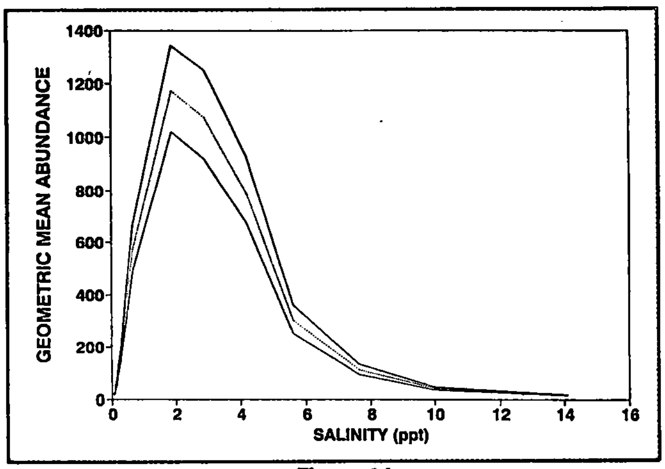


Figure 34
GEOMETRIC MEAN ABUNDANCE AND 95% CONFIDENCE INTERVALS FOR *EURYTEMORA AFFINIS*
Geometric mean in number/m^3.

Similar plots for *N. mercedis* (Figures 35 and 36) resemble those for *E. affinis*, except that the abundance of *N. mercedis* at low salinities is a greater proportion of the peak abundance than for *E. affinis*. Abundance peaks of both species were at a salinity of 2. Total adult calanoid copepods (mainly *E. affinis, Acartia* spp., and *Sinocalanus doerii*) did not have an abundance peak in the entrapment zone, having instead a gradual increase in abundance with increasing salinity (Figure 37).

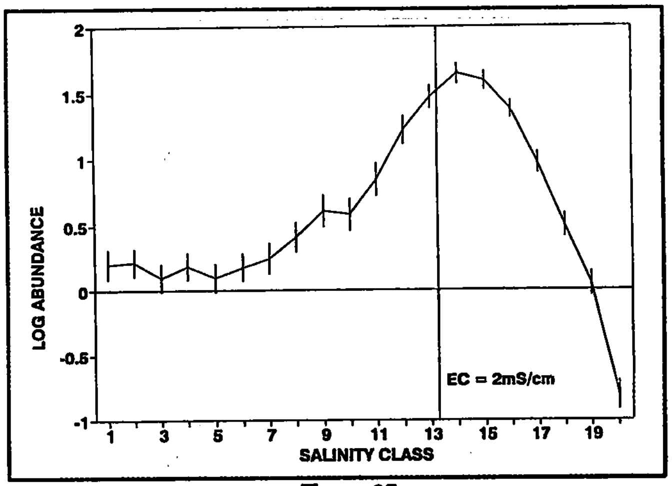


Figure 35
LOG OF ABUNDANCE OF *NEOMYSIS MERCEDIS* VS. SALINITY CLASS
Log of abundance in number/m^{-3}+0.01.
Mean and 95% confidence intervals (vertical bars).

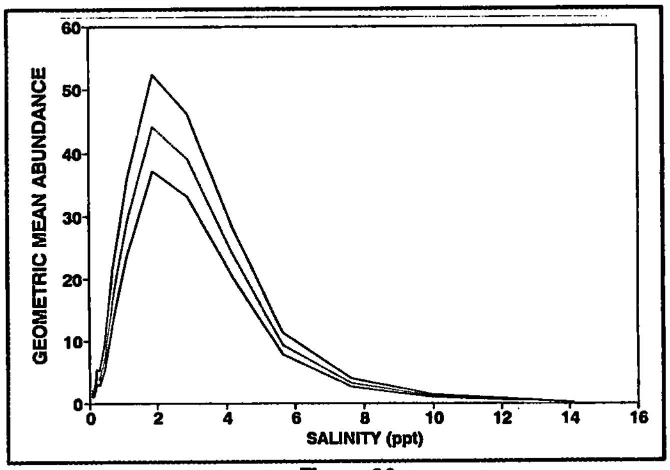


Figure 36
GEOMETRIC MEAN ABUNDANCE AND 95% CONFIDENCE INTERVALS FOR *NEOMYSIS MERCEDIS*
Geometric mean in number/m^3.

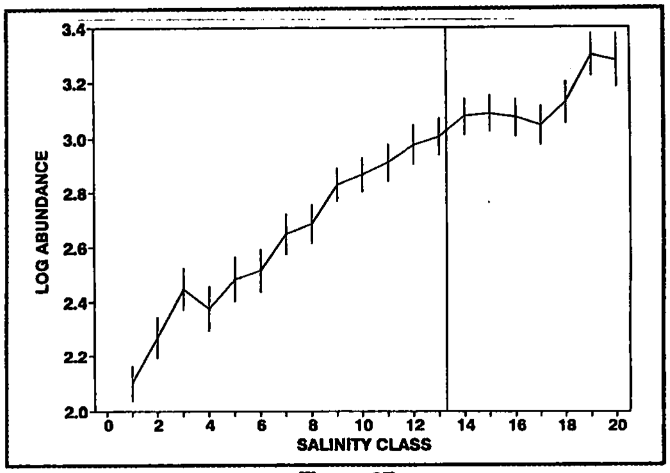


Figure 37
TOTAL LOG OF ABUNDANCE OF CALANOID COPEPODS VS. SALINITY CLASS
Log of abundance in number/m^{-3}+10.
Mean and 95% confidence intervals (vertical bars).

In addition, it has been suggested that the decline may have been greater in spring months when striped bass larvae enter the estuary. This is also incorrect; the slope of the decline was greater in the summer and fall than in the spring (Figure 40).

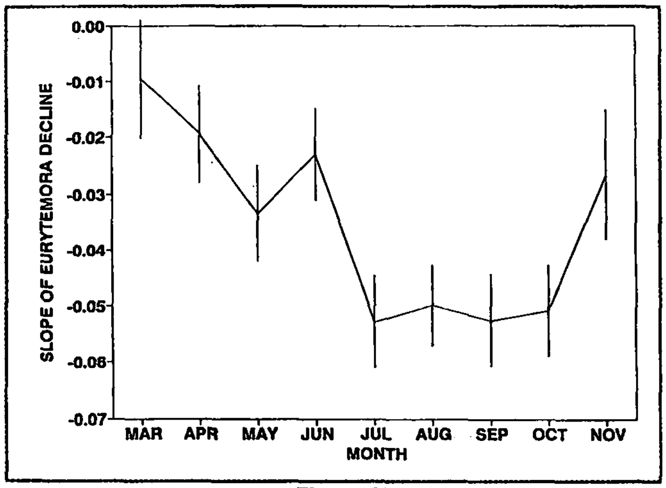


Figure 40
SLOPES OF LINEAR REGRESSION OF LOG ABUNDANCE OF *EURYTEMORA AFFINIS* VS. YEAR FOR 1972 TO 1987
Means and 9% confidence limits (vertical bars).
Calculated separately for each salinity class.

The abundance of *N. mercedis* was higher in the first four years of the study than in 1976-1987 (Figure 41; p<0.001, Mann-Whitney U-test using annual means). This is similar to patterns seen for several species of freshwater zooplankton (Obrebski *et al* 1992). In addition, abundance of *N. mercedis* apparently declined in 1988, as compared to previous years, but was not as low as in 1977 (Figure 41).

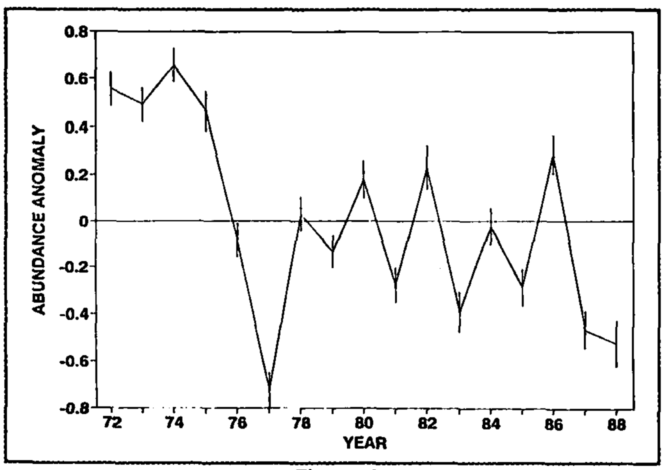


Figure 41
LOG ABUNDANCE ANOMALIES FOR *NEOMYSIS MERCEDIS*
Annual means and 95% confidence intervals (vertical bars).

Effect of Position of the Entrapment Zone

Position of the entrapment zone was determined by the operational definition (see "Location of the Entrapment Zone", page 18). Frequently in March and November, the sampling program did not cover a sufficient range of salinities to effectively sample the entrapment zone, so this analysis is confined to April through October. The core data set plus downstream stations were used to extend the salinity range as far as possible. Log-transformed abundance data for *E. affinis* and *N. mercedis* were combined with data on position of the entrapment zone for each month and year. Anomalies were not used because the salinity pattern was of interest, and because the entrapment zone is farther downstream in spring than in summer. Position data were divided into four categories and the analysis performed as reported for phytoplankton.

Results for *E. affinis* show that when the entrapment zone is upstream, peak abundance occurs at higher salinities and becomes narrower than when the entrapment zone is downstream (Figure 42). There is little difference in peak abundance. In Figure 43, the long-term linear trend with years has been removed, and means of the five highest contiguous abundance values (*ie*, the peak values) have been calculated by season. These peak values differ significantly among entrapment zone positions for the fall season, with highest values when the entrapment zone is 72 to 92 km from the Golden Gate Bridge. In spring, the differences are not quite significant (0.05<p<0.1), with the two highest means being those with the most downstream entrapment zone position.

Abundances of *N. mercedis* were lower when the entrapment zone was upstream (Figure 44), but this pattern also changed by season and was correlated with temperature in some cases. Since the temperature was higher when the entrapment zone was upstream, I calculated regressions of log *N. mercedis* abundance, combining data from the five contiguous salinity classes with the highest abundance as for *E. affinis*, vs. temperature separately for each season. I then used the residuals from the regression in an analysis of variance to test for differences among entrapment zone positions. This removed the confounding effect of temperature to the extent that this effect is linear. Differences among entrapment zone positions were significant in all seasons (Figure 45; p<0.01, ANOVA), with the lowest values always when the entrapment zone unlikely, and the shallows are an unlikely source region for export of zooplankton to the channels. Another mechanism for concentration must be sought.

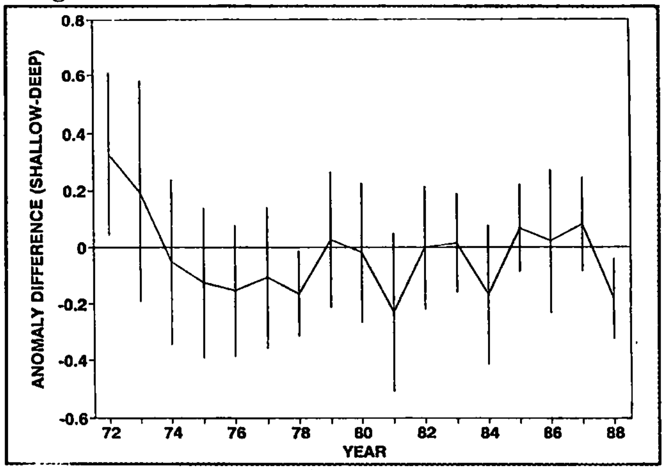


Figure 46

DIFFERENCE IN *EURYTEMORA AFFINIS* ABUNDANCE ANOMALIES BETWEEN TWO SHALLOW STATIONS IN GRIZZLY AND HONKER BAYS AND NEARBY DEEP STATIONS

Annual means and 95% confidence limits (vertical bars).

Effects of Export Pumping

The potential for effects of export pumping on zooplankton abundance is addressed in this section. Other possible causes of the relationship between entrapment zone position and zooplankton abundance are discussed in the next section and in Chapter 4.

A possible cause of reduced abundance when the entrapment zone is upstream is direct removal by the water projects. To determine the effect of export pumping on populations of entrapment zone zooplankton, I used three rather crude approaches. The first is based on the relationship between salinity and abundance of the two entrapment zone species and on the salinity of exported water. This does not generally exceed 0.25, at which abundances of both *E. affinis* and *N. mercedis* are less than 10 percent of their mean abundances within the entrapment zone (Figures 33 and 35, page 25). The export rate is about 0.01 km^3 per day in summer, based on DAYFLOW values. When the entrapment zone is upstream, its volume is about 0.25 km^3 (Figure 16, page 21). Assuming the population size is approximately equal to the volume of the entrapment zone multiplied by the long-term mean abundance from Figures 33 and 35, and that the abundance/salinity relationships upstream of the entrapment zone represent a mixing process, the proportion of the population exported will not exceed about 0.4 percent per day, since the volume exported is 4 percent of the entrapment zone volume and the maximum abundance exported is not over 10 percent of the entrapment zone abundance.

The second approach is based on the difference in abundance between the two rivers. Figure 47 shows the difference in abundance anomalies for *E. affinis* between stations in the two rivers matched for their distance upstream. Using anomalies eliminates differences between the rivers caused by differences in salinity. The equivalent pattern for *N. mercedis* is similar. Abundance anomalies were greater in the San Joaquin River, particularly at the upstream stations, when the entrapment zone was downstream and greater in the Sacramento at all stations when the entrapment zone was upstream. The underlying mechanism for this is unknown. When the entrapment zone is upstream of the confluence of the two rivers, the longitudinal density gradient should oppose net freshwater flow in the Sacramento but not in the San Joaquin, where net flow is often upstream. This implies a greater net upstream flow at depth in the Sacramento and upstream transport of zooplankton that avoid the surface. Upstream transport due to estuarine circulation in the San Joaquin may be reduced when the entrapment zone is upstream of the confluence, reducing transport of these organisms to the pumps. This question clearly needs more study.

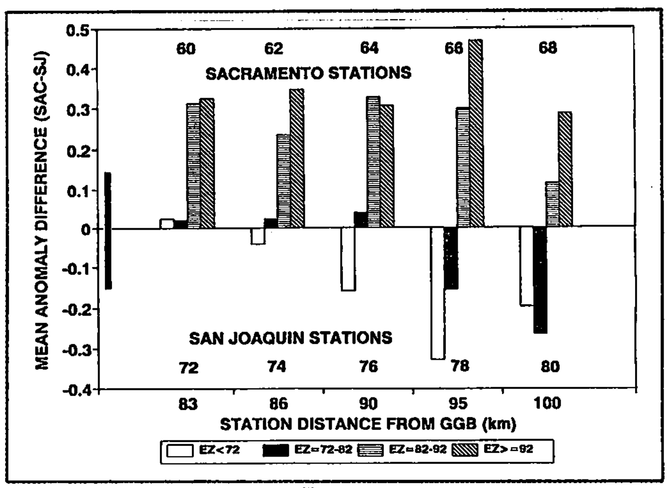


Figure 47

DIFFERENCES IN ABUNDANCE ANOMALIES FOR *EURYTEMORA AFFINIS* BETWEEN SACRAMENTO AND SAN JOAQUIN RIVER STATIONS MATCHED FOR DISTANCE UP THE ESTUARY FOR EACH OF FOUR POSITIONS OF THE ENTRAPMENT ZONE

Distances are given at the bottom; station numbers are within the box. Vertical bar at left is the mean 95% confidence interval for all bars in the graph.

effect disappears. Thus the relationship between *E. affinis* abundance and chlorophyll may be a result of similar relationships of these variables to other factors, such as salinity, season, and long-term trends.

A correlation between inverse Secchi depth and *E. affinis* abundance is more robust, with r^2=0.035; that is, turbidity explains about 3.5 percent of the variance in *E. affinis* anomaly ($p<0.001$). This may suggest that some of the variation in *E. affinis* abundance is an artifact of the influence of light levels on vertical distribution, or it could simply mean that both variables respond similarly to changes in physical conditions. This correlation is unlikely to have arisen from a sampling artifact. The zooplankton samples are taken by oblique tows from the bottom to the surface, and the vertical distribution of *E. affinis* is broad (Orsi, pers. comm.). Furthermore, at current values of turbidity in the entrapment zone, the 1 percent isolume would be at about 1 meter depth, so light would probably not penetrate the water column in the channels sufficiently to cause movement of *E. affinis* toward the bottom.

Striped Bass

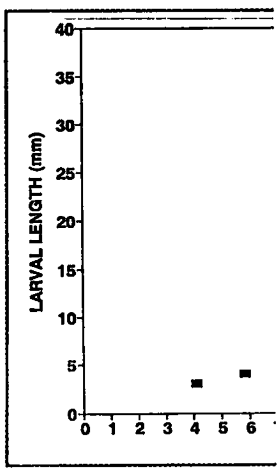
Considerable analysis has gone into the data on striped bass, and relatively little new analysis has been done for this report. A great deal more could be done, particularly with the data on spatial and temporal distribution of bass larvae. These data consist of abundances of eggs and of larvae in 1-mm size intervals from samples taken every 4 days at a large number of stations. A thorough analysis of these data to determine spatial and temporal patterns of growth and mortality would require considerable effort, including a calibrated hydrodynamic model, which is not yet available.

Most of the analysis presented here uses the annually aggregated abundance indices, which consist of time- and volume-weighted total numbers of striped bass eggs and of larvae in each size class. Several assumptions are implicit in this use of the data:

- Growth and mortality of a given size class are nearly constant within any one year,
- Exchange among various parts of the habitat is sufficient to ensure that a single population exists; *ie,* that there are not isolated subpopulations.
- Sampling is frequ nt able average of ab

This is clearly not t in large peaks of nl (Arthur 1990). How may be short enoug quately, since they t ke millimeter (CDFG 1 98

As pointed out in Cl confined to the ent ap most abundant the e median salinity cla size class, for 1986 r cause bass larvae w re sis robust; howeve high-flow year may liest larvae, 3-5 mm n fresh water, but as th occupied a generall so that the largest la va the upstream edge o Given that the actu what upstream of th o tion when flow is h h indicates these fish, the entrapment zon behavior of larvae t at movement toward t



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LENGTH VS. SA IN
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CDFG contends th resulting in lower y an any of the three in ce larval survey), egg a the period 1969 to leveled off or incr ıs

superimposed on fluctuatio partly to changes in entrap

- For *E. affinis* and *N. merce* abundance with entrapme probably not due to chang population to export pum exposure to in-Delta withd
- During the entire period 19 striking and apparently pe the entrapment zone have vertent introductions of ne unrelated to characteristic zone other than its suitabil species, which would be diff out knowing the identity tions.

Mechanisms for Zooplankton and La Entrapment Zor

The relationship between dance and entrapment zone a number of possible caus attempt to list them and to or against each one. Only directly to the position of t the remainder ascribe the r relate of entrapment zone entrapment zone is downs phytoplankton abundance stratification and presuma are strong. The postulated

1. A similar model to that and Ball (1980) and Cloe for zooplankton: that is, shallow than deep water lation is larger when the adjacent to shallow wate

   For: None

   Against: Abundances of *E. affi* less at shallow stat pared to nearby cha

2. Higher phytoplankton bi ity when the entrapmen support more rapid zoo therefore higher abunda

   For: Abundances of entr highest near the pea tion, abundances o remarkably stable o 1988), suggesting such as food supply.

   Against: Correlations betwee phyll appear to be

DISCUSSION

To the extent possible, the following section attempts to answer each question posed in the Introduction and evaluates the ability of the available literature and this analysis to answer them. The next section discusses a number of hypotheses for the enhancement of zooplankton abundance at intermediate or downstream positions of the entrapment zone. Next, recommendations are provided for future data gathering and analysis, and a series of conclusions is presented.

Questions on the Entrapment Zone

This section presents points relevant to answering each of the questions posed in the Introduction. It also discusses utility of the monitoring data in providing answers not available in existing reports.

Characteristics of the Entrapment Zone in the San Francisco Bay/Delta Estuary

In general, the physical, chemical, and biological characteristics of the entrapment zone have been well known for over a decade. Analysis of the monitoring data has provided only a few additional insights. This does not reflect a deficiency in the data (or, I hope, the analysis), but rather reflects the fact that considerable effort has gone into special studies designed to address specific questions regarding the entrapment zone.

The following key points have emerged regarding the entrapment zone of the San Francisco Bay/Delta estuary.

- The entrapment zone is a persistent feature of the estuary.
- The operational definition of the entrapment zone used by Arthur and Ball (1979), *ie,* a salinity range of 1-6, should be regarded as a useful surrogate for actual data on velocity profiles for determining the approximate location of the entrapment zone in the historical data; a better surrogate would be bottom salinity.
- The operationally-defined entrapment zone moves upstream and downstream in response to flow, but with considerable variation due to effects of tide and variation in flows.
- As the operationally-defined position of the entrapment zone varies from 65 to 95 kilometers from the Golden Gate Bridge, the difference between the operationally-defined position and the position of the turbidity maximum varies by about 8 kilometers. This is because the operational definition uses surface conductivity, ignoring the increase in stratification occurring with a more downstream position of the entrapment zone.
- Concentration of particles, chlorophyll, some phytoplankton and zooplankton species, and larval stages of delta smelt and striped bass are enhanced in the entrapment zone.
- Nutrient concentrations are not remarkably different in the entrapment zone than elsewhere except possibly during phytoplankton blooms.

Importance of the Entrapment Zone to Biological Production

Biological production has two components, biomass and growth, either or both of which could vary within the estuary. Although growth is rarely measured, primary production and phytoplankton biomass have been measured fairly often. Again, the importance of the entrapment zone to biomass or abundance of most species has been fairly clear for some time. Following are key points arising from this analysis.

- Phytoplankton specific growth rates are probably depressed in the entrapment zone relative to other areas of similar depth because of reduced light penetration.
- Phytoplankton biomass is enhanced, probably by entrapment of species with net sinking rates in a range at which they are entrained by mixing or net upward flow in the entrapment zone.
- There is no evidence that growth rates of zooplankton or larval striped bass are higher in the entrapment zone than outside the entrapment zone.
- Based on the (limited) evidence to date, the elevated abundance of zooplankton and fish is likely a result of entrapment rather than a response to higher food levels.
- Production of zooplankton and fish is probably more closely related to biomass than to growth

- How well does the position of entrapment as determined by tidally-averaged velocity profiles agree with the location of the entrapment zone defined by surface turbidity or bottom salinity?
- What is the relationship between surface salinity and salinity profiles at various entrapment zone positions, outflows, and spring/neap tides?
- What is the relationship between the strength of entrapment, as determined by peaks in concentration of various substances, and the position of the entrapment zone?
- How do zooplankton and striped bass larvae move longitudinally in the estuary as a result of their vertical positions?
- What is the actual magnitude of export losses from entrapment zone populations?
- What is the magnitude of loss due to in-Delta withdrawals?

None of these questions is trivial. If the study is planned for several years from now, it might benefit from close ties to a major study funded by the National Science Foundation to examine similar questions in the Columbia River estuary. To the extent that the two estuaries are similar, it would be beneficial to establish and maintain close ties with that project. Several members of the Food Chain Group, myself included, are doing that now.

Conclusions

During the period of record, from about 1972 to the present, no trend in entrapment zone position is evident, either for the data as a whole or for individual seasons. This is because the entrapment zone is most affected by outflow, which has been highly variable during this period. In addition, variation within and between years is large enough to swamp the variation due to increasing exports. This is not to say exports have had no effect, merely that during this period the increase in export flows formed a minor part of the variation in outflow. In fact, exports have averaged about 34 percent of exports plus outflow for the entire period, a substantial fraction. An increase of outflow of 34 percent would move the entrapment zone downstream on average by about 5 kilometers. In the summer, exports are about equal to outflow on average, and elimination of exports (and maintenance of inflows) would move the entrapment zone downstream by about 8 kilometers.

The key conclusions of this effort are as follows.

- The entrapment zone is the most productive area for some zooplankton and larval fish.
- Location of the entrapment zone is correlated with abundance of many of the biota of the estuary, but the mechanism for this is not known; in fact, the correlation may be due to underlying relationships with flow, strength of entrapment, or other variables rather than a direct effect of entrapment zone position.
- Importance of the entrapment zone to striped bass is not fully demonstrated, although variation in growth rate suggests growth of larvae is sometimes food limited and that variation in zooplankton could be important to bass, and therefore bass survival should be higher in the entrapment zone.
- Although export pumping has increased during 1972 to 1988, the larger interannual variation in Delta inflow has masked any effect on entrapment zone position during this period. However, net flows in Delta channels may have changed during this time.
- For maximum production of zooplankton of the upper estuary, the entrapment zone should be at least as far downstream as the confluence of the two rivers.
- Declines in biological variables over the period 1972 to 1987 are significant but apparently not simply related to changes in flow or position of the entrapment zone.
- Recent changes in the estuary, particularly the introduction of *Potamocorbula amurensis*, may make conclusions regarding *Eurytemora affinis* moot.
- Existing monitoring programs have provided a good database for detecting trends but have not included sufficient analytical effort to detect the changes in a timely manner, nor have they incorporated the flexibility needed to respond to changes detected.

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GLOSSARY

Abundance. The number of organisms per unit volume or area, usually expressed as numbers per cubic meter or square meter or multiples of those units. Equivalent to Concentration or sometimes Density.

Abundance index. A number assumed proportional to the total number of organisms in a population (*eg,* juvenile striped bass). This use is misleading, since it refers to Population size (total numbers) instead of Abundance (defined above).

Analysis of Variance (ANOVA). A form of statistical analysis in which the total variance in the data is partitioned into the variance from different sources, which is then compared with the remaining (error) variance.

Anomaly. The difference between a data value and the mean for some grouping or class (*eg,* year, month, salinity class).

Bathymetry. Topography of the bottom of the estuary, measured from mean lower low tide elevation.

Benthos. Organisms living on or in the bottom (Benthic organisms). Epibenthic organisms are found on or immediately above the sediment surface.

Biomass. The amount of weight or mass of living material in a given category per unit volume or area, usually expressed as dry weight, carbon, energy, or for phytoplankton, chlorophyll.

Chlorophyll. A photosynthetic pigment found in all green plants. Chlorophyll *a* is used as a measure of phytoplankton biomass.

Confidence limit. A measure of the degree of certainty with which we can state a given statistic. If we have a sample mean with 95% confidence limits, there is a 5% chance that the actual population mean falls outside those limits.

Copepod. A class of small crustaceans that make up the bulk of the zooplankton in the ocean and most estuaries; these may be the first or second most abundant animals on Earth.

Correlation. A measure of the degree of linear association between two variables: a value of 1 means they have an exact, linear relationship, –1 means they are exactly but inversely related, and 0 means they are completely unrelated. The squared correlation (r^2) gives the proportion of variance in one variable that can be attributed to its relationship to the other variable.

Detritus. Non-living particulate organic matter, usually derived from living organic matter.

Entrapment zone. The area of the estuary where flow convergence results in the concentration of particulate matter; this usually operates through the interaction of particle (or organism) sinking and net up-estuary flow at depth (See Operational definition below).

Estuarine turbidity maximum. An area of the estuary where turbidity is enhanced, either by entrapment or other mechanisms.

Euryhaline. Capable of surviving and living in a wide range of salinity.

Flocculation. Aggregation of fine particles by electrostatic attraction.

Gravitational circulation. Two-layer flow in an estuary, in which the slope of the surface of the water from the river to the ocean drives a seaward flow, while denser, saline water is driven inward by the effect of the longitudinal density gradient. These flows are often detectable only as net (*ie,* tidally-averaged) flows, if the tidal flows are much larger than the freshwater flow.

Spring/neap tides. An oscillation in amplitude (high tide minus low tide height) of the tides on a 2-week cycle; the tidal amplitude can vary by more than a factor of 2.

Tidal fronts. Boundaries between waters of different salinity in a horizontal direction, commonly observed at the surface.

Tidal pumping and trapping. Longitudinal dispersion caused by differences in travel time of the progressive tidal wave moving along different pathways (*eg,* parallel channels of different depth) and resulting differences in phase.

Tidally averaged. Averaged over one complete tidal cycle so that tidal effects are removed.

Turbulence. Irregular motion of water caused mainly by shear between layers of water moving at different relative velocities. Responsible for most small-scale mixing.

Zooplankton. Animal plankton.