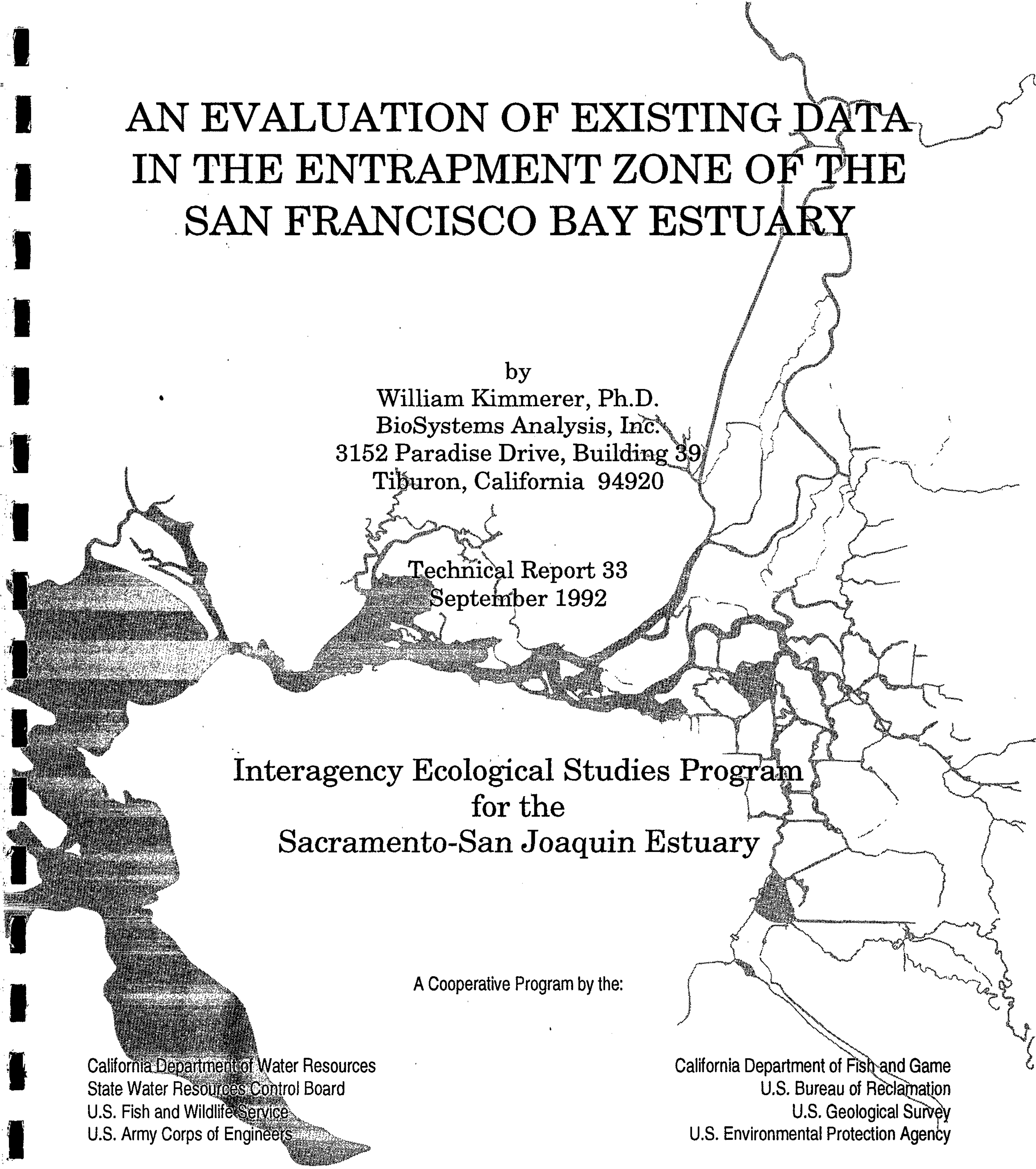
FS/BIO-IATR/92-33

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



by
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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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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.

For the greatest precision, the entrapment zone should be defined on the basis of either turbidity or tidally-averaged velocities. However, for several reasons an operational definition based on salinity or specific conductance is useful. An operational definition of 2-10 mS/cm specific conductance at the surface has been used in the past (Arthur and Ball 1979) and is used here because most of the available data include measurements of surface conductance. However, bottom salinity would be a better surrogate than surface salinity for turbidity or velocity measurements.

Numerous previous reports on the San Francisco Bay/Delta estuary discuss the entrapment zone and its biological importance. According to these reports, the entrapment zone is the site of the highest concentrations of certain species of phytoplankton and zooplankton in the estuary. Some phytoplankton species are trapped by the same mechanism as inert particles. Biomass of phytoplankton is apparently enhanced when the entrapment zone is downstream in Suisun Bay and reduced when it is upstream in the Delta. Some species of zooplankton and fish can maintain position in the entrapment zone by moving vertically into a depth of favorable currents. Existing reports do not demonstrate a convincing relationship between geographic position of the entrapment zone and zooplankton abundance per unit volume. Entrapment zone position could be important to the year-class strength of striped bass and delta smelt. Contrary to published reports, entrapment zone volume does not vary with entrapment zone position, although area is greater when the entrapment zone is in Suisun Bay (and mean depth is less) than when it is upstream.

Analysis of long-term monitoring data on nutrients, phytoplankton, and zooplankton reveals several pertinent facts about their relationship to the entrapment zone. Several species appear to be "entrapment zone species"; *ie,* maximum abundances are in the entrapment zone. Several of these species are more abundant when the entrapment zone is either downstream in Suisun Bay or at intermediate positions, compared to an extreme upstream location in the Delta. The mysid shrimp *Neomysis mercedis,* in particular, is much less abundant when the entrapment zone is upstream. The copepod *Eurytemora affinis* is significantly less abundant when the entrapment zone is upstream only in the fall, and total copepod abundance does not appear to be affected by entrapment zone position. Striped bass survival is generally higher when the entrapment zone is in Suisun Bay. Although a reasonable mechanism has been proposed for higher phytoplankton abundance when the entrapment zone is in Suisun Bay, mechanisms that produce elevated abundances of zooplankton and fish when the entrapment zone is in Suisun Bay cannot be determined from the existing data.

Correlations among phytoplankton biomass and abundances of the two zooplankton species have been used to infer a trophic dependence of each on the other. Although *E. affinis* and *N. mercedis* consume phytoplankton, 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.

The existing monitoring programs have provided a good database for detecting trends but have not included sufficient analytical effort to detect changes in the system in a timely manner. In addition, the programs have not incorporated the flexibility of design required to respond to changes once they have been detected. This points out an area in which the existing study program should be improved.

ACKNOWLEDGMENTS

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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.

Chapter 2

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).

The Physics of Entrapment

The entrapment phenomenon is well known from a number of estuaries, and the basic concepts have been understood since 1955 (Postma and Kalle 1955; Postma 1967). A number of publications have addressed the physics of entrapment (*eg,* Postma 1967; Festa and Hansen 1976, 1978; Officer 1976, 1980). The following description relies heavily on the detailed (if rather technical) discussions of estuarine circulation by Jay and colleagues (Giese and Jay 1989; Jay 1991; Jay and Smith 1990a,b; Jay *et al* 1990).

The concept of entrapment can be understood by considering a hypothetical, simplified estuary in which the relative magnitudes of streamflow, tidal flow, and shear are varied. If tidal flow is negligible, and ignoring shear between layers for the moment, streamflow enters the estuary and disperses as a surface layer of fresh water overlying denser sea water (Figure 1a). This surface layer decreases in thickness with distance from the river, but without shear and therefore turbulence at the interface, no mixing occurs. The halocline, the surface separating the layers of fresh water and salt water, is tilted down toward land. This compensates for the hydrostatic pressure exerted by the landward thickening of the freshwater layer so that the total pressure at a given depth below the halocline is the same at all locations. Fresh water flows seaward due to the slope in surface elevation; however, no motion occurs in the seawater layer since the longitudinal forces are in balance.

In a real estuary, the shear between the freshwater layer and the seawater layer produces turbulence near the halocline, which mixes fresh water and sea water across the halocline. The surface layer becomes progressively saltier toward the sea (Figure 1b). Since this layer is flowing seaward, it carries salt out of the estuary, so to conserve mass, an equal amount of salt (on average) must flow inward in the lower layer. This occurs because the horizontal density gradient causes dense sea water to flow toward less dense water nearer land. This circulation is referred to as "gravitational circulation", because the force of gravity acts on the surface slope to cause seaward flow of water at the surface and acts on the density gradient to cause landward flow of bottom water.

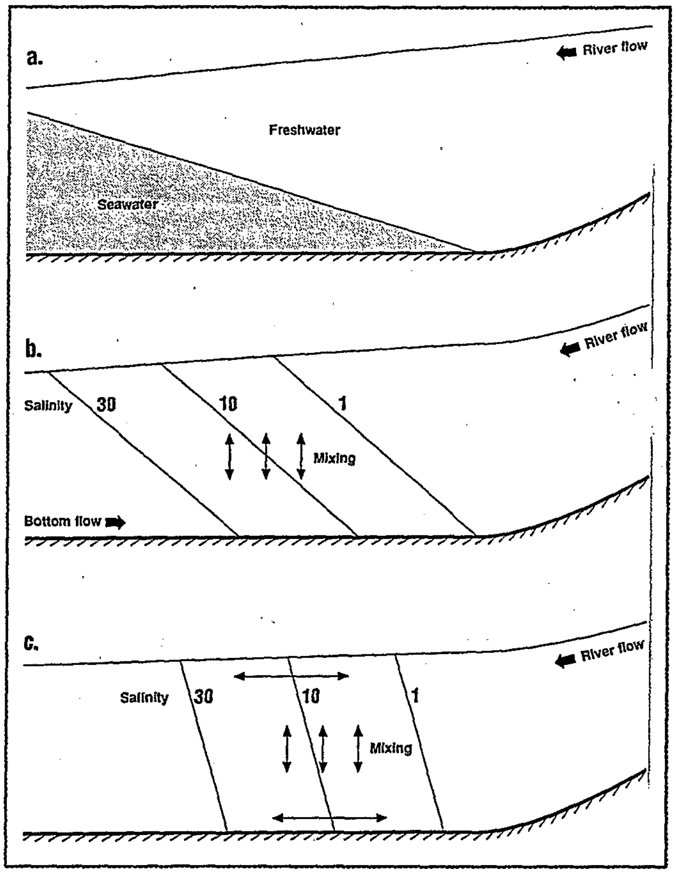

Figure 1
SCHEMATIC SHOWING EFFECTS OF RIVER FLOW, SHEAR, AND TIDES ON SALINITY PROFILES IN THE ESTUARY
a. No tides, no shear between layers.
b. Shear at the halocline but no tide.
c. Both shear and tide.

Tidal flow is important in most estuaries. In our hypothetical estuary, gradually increasing tidal flow and decreasing streamflow do several things (Figure 1c). First, tidal flow across the bottom introduces additional shear, which is the major source of turbulent energy for mixing and resuspension of particles. Second, tidal currents can override the weaker gravitational flows. Third, tidally generated turbulence can obliterate the vertical density gradient. And fourth, increasing tidal flow relative to streamflow moves the entrapment zone upstream (Peterson *et al* 1975).

Strong streamflow and weak (*ie,* neap) tidal flow result in a configuration like that described in Figure 1b, where 2-layer flow exists in at least part of the estuary. As tidal flows increase, stratification breaks down because of increasing turbulence due mainly to shear at the bottom (Figure 1c). Tidal velocities override first the bottom density current and then the surface current, so that at any time the flows are unidirectional at all depths. An ebb/flood asymmetry in vertical velocity profiles (Figure 2) is

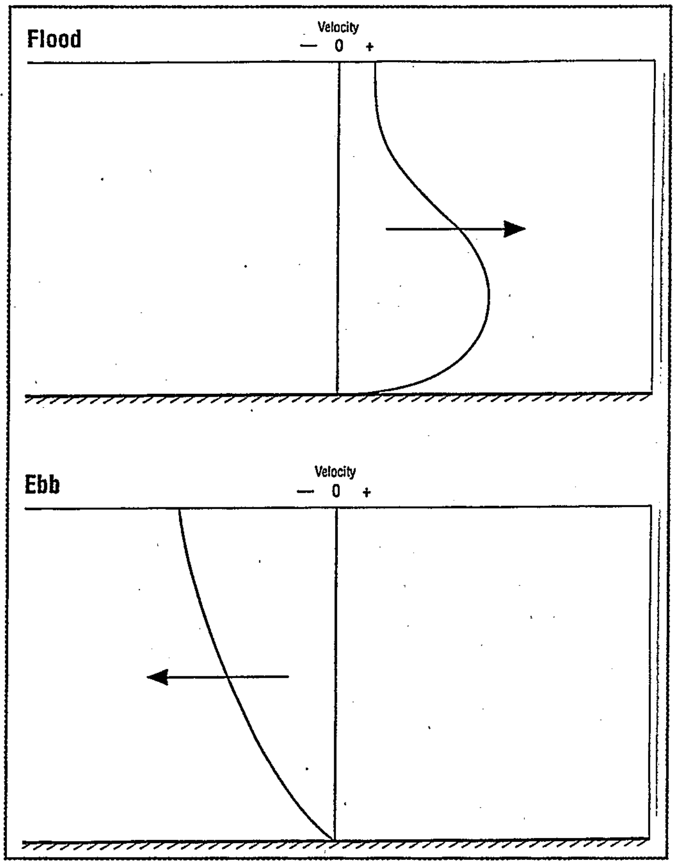

Figure 2
SCHEMATIC OF EBB AND FLOOD VELOCITY PROFILES
The differences between ebb and flood are vastly exaggerated.

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

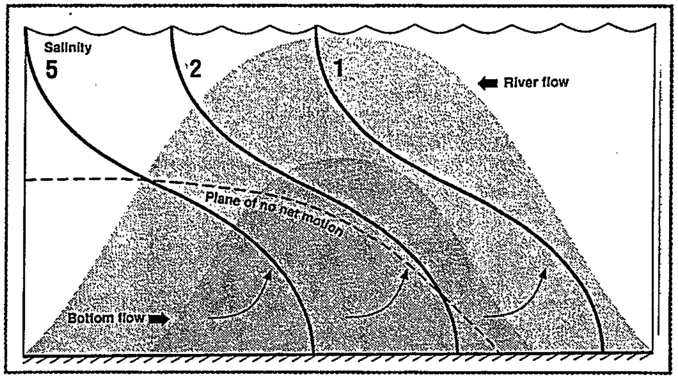

Figure 3
SCHEMATIC DIAGRAM ILLUSTRATING THE CONCEPTUAL MODEL OF AN ENTRAPMENT ZONE
Shaded areas indicate the location of the turbidity maximum. Actual shapes of the lines will vary.

particles) is more suited to understanding how particles accumulate (Jay 1991).

The above conceptual model implicitly assumes that the flow is uniform across the estuary. In most estuaries a pronounced lateral circulation exists that can be greatly complicated by the presence of shoals and multiple channels (*eg,* Lucotte and d'Anglejan 1986). This means net upstream and downstream flows need not balance at a given point; in general, some part of the cross section will be dominated by flood flows, and another part by ebb flows. The hypothetical upward (vertical) flow based on continuity (*ie,* conservation of mass) may not actually exist at any given point. Lateral circulation can also cause entrapment or concentration of both particles and organisms (*eg,* Alldredge and Hamner 1980; Lucotte and d'Anglejan 1986).

Longitudinal flows are also more complex than assumed above. Tidal pumping and trapping, which occur due to interactions of tidal flows with mean flow and bathymetry, cause about two-thirds of the longitudinal dispersion of salt in San Francisco Bay (Conomos 1979) and are, therefore, probably important in determining the distribution of particles. In addition, wherever tidal flows are correlated with concentrations of suspended particles, net particle transport will result; this can happen when strong bottom currents on the flood cause resuspension of material deposited during previous slack and ebb periods, as in the estuarine turbidity maximum of the Columbia River estuary (Jay *et al* 1990).

Another problem with the conceptual model of particle entrapment is that it is difficult to verify. The tidally-averaged longitudinal velocities can be calculated by continuous measurement of velocities over a tidal cycle, provided the cycle starts and ends with the same volume of water upstream of the sampling point. This will rarely be the case, although reasonable inferences of net velocities can be obtained from measurements made during strong flood and ebb. The hypothetical vertical circulation, however, is usually much too small to be measured.

Several alternative mechanisms exist for producing a turbidity maximum that may or may not be associated with the entrapment zone. One such mechanism is caused by a minimum in total kinetic energy at some point in the estuary (Giese and Jay 1989; Jay *et al* 1991). In most estuaries, including parts of the San Francisco Bay/Delta estuary, the cross-sectional area increases in a downstream direction (Peterson *et al* 1975). Streamflow averaged across the estuary has a lower velocity 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 owing to the slope of the river bed and interactions with the mean flow (Jay *et al* 1991). The combined energy of the tidal and stream flows, therefore, has 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 kinetic energy (Peterson *et al* 1975).

Local minima in kinetic energy also occur due to variations in depth. Currents in shoals adjacent to channels are generally slower in the absence of wind-driven mixing because of the greater importance of shear relative to gravitational forces (Postma 1988). This can cause particles to settle in shallow waters where they are available for wind-driven resuspension. In addition, tidal fronts can concentrate settling particles.

Flocculation, once believed to be the cause of the estuarine turbidity maximum (Postma and Kalle 1955), is still regarded as an important source of particles (Kranck 1984). Flocculation is most common at the upstream limit of salt penetration, where changes in surface charge of particles cause aggregation. Flocculation can cause increases in settling rates of particles, including some phytoplankton (Arthur and Ball 1980).

The Entrapment Zone in the San Francisco Bay/Delta Estuary

In the San Francisco Bay/Delta estuary, the existence of net 2-layer flow was demonstrated by the drifter experiments of Conomos and Peterson (1977). The position and strength of the entrapment zone is regulated by the interaction of tides and streamflow, with wind increasing mixing in shallow waters (Peterson *et al* 1975; Arthur and Ball 1979; Smith and Cheng 1987). The position of the tidally-averaged null zone varies from about 20 km from the Golden Gate Bridge at a Delta outflow of 2000 m^3/s (70,000 cfs) to 80 km (about the mouth of the San Joaquin River; see Figure 4) at 100 m^3/s (3,500 cfs) (Peterson *et al* 1975). This movement of the null zone occurs because variation in streamflow is much greater than variation in density-driven bottom currents. The downstream movement is more rapid than the upstream movement (Imberger *et al* 1977; Smith 1987) and may depend more on peak

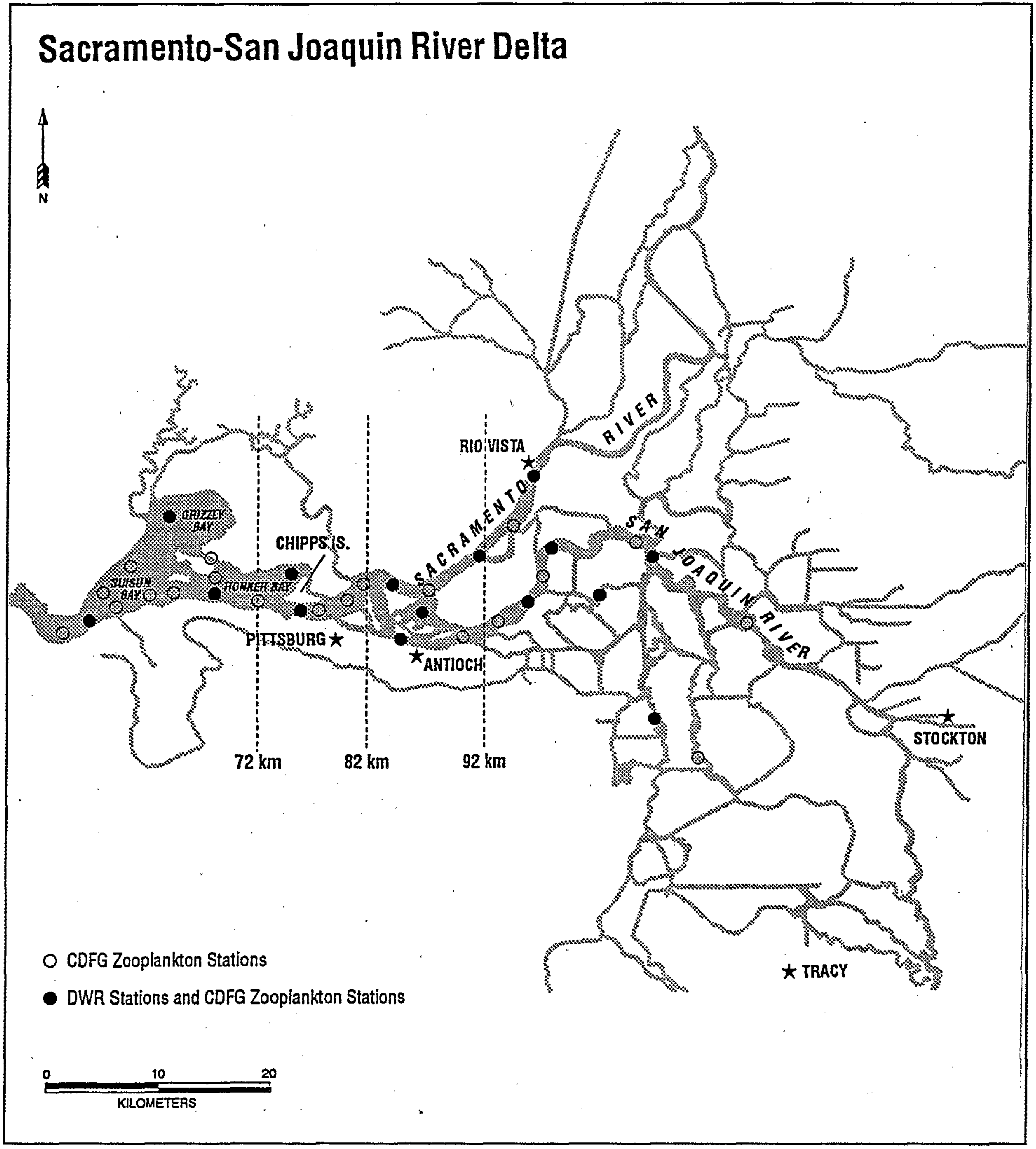

Figure 4
LOCATION MAP FOR DWR AND CDFG SAMPLING STATIONS
Vertical lines indicate distances from Golden Gate Bridge used to define four categories of entrapment zone position.

flows than on total volume summed over some time period (Imberger *et al* 1977). Residence time of water in San Pablo and Suisun bays decreases from about a month at low flows (100 m^3/s) to less than a week at high flows (1300 m^3/s) (Smith 1987), although residence time of particles is unknown.

The position of a given salinity, and therefore of the entrapment zone, also depends on the spring/neap tidal cycle in that the total volume of water in the Delta is higher during spring than neap tides (L. Smith, USGS, pers. comm. 1991). Actual Delta outflow is lower for a given calculated outflow (inflow less consumption and exports) during the transition between neap and spring tides than during the spring/neap transition because of the increase in total Delta volume on the neap/spring transition. Therefore, for a given calculated outflow, the entrapment zone would be farther upstream during spring tides than during neap tides. In addition to these sources of variation in entrapment zone position, periodic variations in sea surface elevation and winds, as well as nonlinear tidal effects, can alter longitudinal circulation (Walters and Gartner 1985) and therefore entrapment zone position.

A series of reports by Arthur and Ball (1978, 1979, 1980) discussed location of the entrapment zone and its biological significance. The entrapment zone contains elevated concentrations of suspended particulate matter, chlorophyll, and certain species including phytoplankton, zooplankton (including the mysid shrimp *Neomysis mercedis*), and juvenile striped bass. High tidal velocities and high freshwater outflows both result in greater resuspension of particles, enhancing turbidity within the entrapment zone. The lowest concentrations of suspended solids, phytoplankton, zooplankton, and juvenile bass in Suisun Bay occurred in the drought of 1976-1977, when the entrapment zone was farthest upstream (Arthur and Ball 1979).

Based on the distribution of suspended particulate matter over a wide range of flows and tides, Arthur and Ball (1978) stated that the entrapment zone occurred over a surface salinity range of 1-6 (measured as specific conductance of 2-10 mS/cm). This agrees with the location of the null zone reported by Peterson *et al* (1975). The use of surface salinity to identify entrapment zone position is discussed further in "Location of the Entrapment Zone" (page 18).

The Interagency Ecological Studies Program has measured vertical profiles of currents, salinity, temperature, and light transmission (as a measure of particle concentration) along transects up the bay starting in 1985. However, these data have not yet been fully analyzed. Preliminary analysis of two profiles shows entrapment of particles at a surface salinity around 1-6 (Rapp *et al* 1986; Hachmeister 1987). These profiles also illustrate the effects of flow and the spring/neap tidal cycle on stratification; high flows push the salinity intrusion downstream and enhance stratification, while spring tides tend to eliminate stratification. In addition, the current profiles illustrate ebb/flood asymmetry under moderate flow conditions, and 2-layer flow when freshwater outflow is high.

The source of sediments to the entrapment zone must ultimately be the rivers, but the discharge of sediments occurs mainly during high flows in winter (Krone 1979). Apparently much of this sediment is deposited downstream of Suisun Bay and resuspended in summer by strong winds (Krone 1979). The proximate source of sediment to the entrapment zone occurs through upstream transport of these resuspended sediments by net landward bottom currents (Conomos and Peterson 1977; Krone 1979).

The bathymetry of the San Francisco Bay/Delta estuary is complex, and therefore circulation is complex. In Suisun Bay the topography interacts with tidal flows to produce a net counterclockwise flow that is strongest during spring tides (Walters and Gartner 1985). This flow could be enhanced by estuarine circulation so that the null zone is farther west in the northern channel and Grizzly Bay than in the main channel of Suisun Bay (Mortensen 1987).

Biological Significance of the Entrapment Zone

The entrapment zone could be significant biologically in two ways. First, it provides habitat for "entrapment zone species"; *ie,* species that are most abundant in or near the entrapment zone. Second, as a location of elevated biomass and therefore (perhaps) productivity of lower trophic levels, it could serve as a source region of food for consumer species such as fish. Two issues are relevant to this discussion: the importance of the entrapment zone to various species in and near the entrapment zone; and the importance of the geographic position of the entrapment zone to productivity within the entrapment zone.

A related issue is the historical decline in many of the species and functional groups in the San

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).

While the above studies are instructive and provide information useful in understanding the entrapment zone of the San Francisco Bay/Delta estuary, analogies should be made with caution because of differences in bathymetry and controls on streamflow.

Phytoplankton, Bacteria, and Particulate Matter

Arthur and Ball (1978, 1979, 1980) showed that abundances of phytoplankton, zooplankton, and young striped bass are higher in the entrapment zone than in other locations. In addition, they showed that the biomass of phytoplankton is higher when the entrapment zone is in Suisun Bay rather than farther upstream. In 1978 manipulation of flows to keep the entrapment zone within Suisun Bay apparently resulted in high concentrations of phytoplankton, particularly relatively large diatoms. Settling rates of the most abundant diatom species were equal to the theoretical net upward water velocity in the entrapment zone determined by a numerical model; this suggested that these species were being retained within the entrapment zone (Arthur and Ball 1980). In addition, the ratio of chlorophyll to total pigments (*ie,* chlorophyll plus its breakdown products) was highest in the entrapment zone, indicating a greater proportion of healthy, growing cells (Ball and Arthur 1979).

Arthur and Ball (1980) presented a theory to explain the elevation of phytoplankton biomass when the entrapment zone was in Suisun Bay. This model was expanded by Cloern *et al* (1983) to include an analysis of the effects of mixing between shallow and deep locations. I refer to their explanation as the ABC model. According to this model, phytoplankton are generally light limited and therefore unable to maintain positive net production in the deep channels, where turbidity reduces the light below that needed for high rates of net photosynthesis. Production is high over the shoals, however, which are extensive in Suisun Bay. When the entrapment zone is in Suisun Bay, particles including phytoplankton are trapped by the estuarine circulation, but tidal exchange mixes phytoplankton between the shoals and the deep channels. Therefore, the average growth rate of phytoplankton in this area is high, resulting in high biomass and productivity. In the Delta, most of the channels are narrow and deep, with relatively little shoal area. Thus, according to the ABC model, average growth rate of the phytoplankton is lower when the entrapment zone is upstream, and less biomass builds up.

Cloern *et al* (1983) showed that the proportion of large phytoplankton (those larger than about 20 µm) in total chlorophyll and the abundance of large diatoms were highest when the entrapment zone was in Suisun Bay. They also showed that the growth rate of phytoplankton in the shoals was about tenfold that in the deep channels, owing mainly to a lack of light penetration into the deep waters. Nutrients do not limit the growth of phytoplankton, at least until biomass reaches extremely high levels during summer blooms (Ball 1975).

Several alternatives to the ABC model cannot be eliminated. The upstream or downstream movement of the entrapment zone is caused mainly by changes in freshwater inflow, which also influences the strength of bottom currents and, therefore, the ability of the entrapment zone to trap diatoms of a particular settling velocity. It is not clear whether the high phytoplankton biomass results from the postulated mechanism or simply from changes in the strength of entrapment. Furthermore, low biomass during extended droughts could be due to increased benthic grazing resulting from the gradual landward penetration of marine benthic grazers (Nichols 1985). However, the ABC model is the most consistent explanation of the low biomass when the entrapment zone was upstream for shorter periods.

Much less information is available on the detrital and bacterial components of particulate matter. The nutritive value of particles, defined as the ratio of protein to carbohydrate, was higher in the entrapment zone than elsewhere (Barclay 1981). The ratio of nutritionally useful materials to total particulate matter did not vary with sampling station, suggesting a similar mechanism for entrapment of nutritional and total particles (Barclay 1981).

Production of bacterioplankton in Suisun Bay during 1988 was five times higher than phytoplankton production, implying there are other important sources of organic matter not associated with phytoplankton (Hollibaugh 1990). Phytoplankton production was substantially depressed in 1988, probably because of grazing by the introduced clam *Potamocorbula amurensis* (Nichols *et al* 1990). Whether alternative organic matter comes from the rivers is unknown. However, this organic matter could provide alternative food for zooplankton and other herbivores. A recent analysis of supplies of organic carbon to 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 than those that make up total chlorophyll (Heinle *et al* 1977). In addition, microzooplankton could provide food for many of the larger zooplankton species. These major potential sources of food for zooplankton have received almost no attention in this estuary compared with the amount of analysis of phytoplankton.

Striped Bass

Striped bass (*Morone saxatilis*) range throughout the estuary and lower rivers but are concentrated in the low-salinity region of the estuary during early life (CDFG 1988b). This may not be considered an "entrapment zone species", since all life stages are found well upstream and downstream of the entrapment zone. However, it is most abundant just upstream of the entrapment zone during larval and early juvenile development, at least in recent years (Arthur and Ball 1980; CDFG 1988b). Furthermore, Fujimura (1991) has found that bass eggs are most abundant near the surface upstream of the entrapment zone, but larvae tend to be less abundant near the surface. Arthur (1990) found both eggs and larvae to be more abundant near the bottom than near the surface at a river station upstream of the entrapment zone. Either behavior would result in transport of eggs by streamflow to the entrapment zone, followed by retention of larvae in or just upstream of the entrapment zone. Hatching and development of larvae before they reach the entrapment zone could result in delayed transport because of reduced flow at depth, which may explain the tendency for the majority of the larvae to be found upstream of the entrapment zone (CDFG 1988b).

Recently, a good deal of attention has been paid to the long-term decline of striped bass in this estuary (Stevens *et al* 1985). The prevailing view of CDFG scientists (Stevens *et al* 1989) is that the decline was caused by removal of young bass by the project pumps, resulting in lower adult abundance and consequently reduced egg production. With the normally low survival of fish through egg and larval stages, reduced egg abundance causes a further reduction in abundance of young bass.

The argument of Stevens *et al* (1989) is as follows. Increased exports in the early 1970s resulted in poor survival of young bass, with an estimated population reduction of 31 to 84 percent by the late 1980s. This decline occurred primarily in the Delta (rather than in Suisun Bay). The resulting decline in recruitment produced a reduction in adult stocks, with concomitant lowering of egg production. The most plausible alternative explanation of the decline is that survival of early bass larvae is lower than it used to be because of the decline in zooplankton abundance. However, there is no evidence that survival of larvae has declined, and the ratios of young-of-the-year (YOY) to egg indices do not reveal a strong trend (Stevens *et al* 1989), although the data are highly variable. Variation in survival of early larvae may explain the dependence of YOY on flow in the estuary, but not the long-term decline. Growth rates of larvae measured since 1984 are variable between years, and this variation could be due to changes in food supply (L. Miller, CDFG, pers. comm. 1991), although starved larvae are either rare or absent from the estuary or are not captured (Bennett *et al* 1990). Growth rates do not vary between larvae captured in and upstream of the entrapment zone (L. Miller, pers. comm. 1991). Therefore, production, the product of biomass and growth rate integrated over time, is somewhat higher in the entrapment zone than outside.

The CDFG report (Stevens *et al* 1989) includes a quantitative analysis of the removal of striped bass by the export pumps and of the effect of declining adult stocks on young of the year. However, it fails to account for evident effects of toxicity or pollutants on both young (Foe and Connor 1989) and adult (Brown *et al* 1991) bass. Although these effects have not been correlated with declines in the bass, their occurrence warrants attention in explaining other long-term or short-term changes in bass abundance. In addition, the increase in adult mortality over the last decades (CDFG 1988a) could also lead to lower egg production. Although the CDFG report is quantitative in testing hypotheses using empirical relationships, no population model is presented to support the analysis outlined above. In the absence of such a model, it is difficult to separate the effects of reduced egg production and mortality at various life stages. Furthermore, the analysis fails to explain why long-term declines in survival of young bass would not be reflected in similar declines in survival of the larvae, which are found in fresher water and should be more vulnerable to pumping.

An alternative view presented by Turner (1990) is that years of high YOY index (*eg,* 1986) occur when eggs and larvae from the San Joaquin River spawning area are washed into the entrapment zone because of relatively high flows in the San Joaquin. The underlying assumption is that eggs spawned in the Sacramento River do not contribute as much to the population as eggs 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.

Chapter 3
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.

Most observations in the CDFG data set (around 14,000 records) were obtained in water of low rather than high salinities. To analyze effects of salinity in this large data set required a simplifying model. Instead of fitting an assumed salinity distribution to the data, I divided the salinity range into 20 classes containing roughly equal numbers of observations. Using equal observations gives approximately equal confidence intervals in all classes, avoiding the statistical problems that occur when the classes at one end of the distribution contain few observations. However, the salinity classes contain different salinity ranges (Table 1), and graphical displays are distorted. In several graphs discussed in following sections, the mean salinity in each class is used to eliminate this distortion.

Table 1
SALINITY CLASSES USED IN DATA ANALYSES

Salinity Class	Specific Conductance *(mS/cm)*		Mean Salinity
	Range	Mean	
1	0.08 - 0.14	0.10	0.059
2	0.14 - 0.16	0.14	0.079
3	0.16 - 0.18	0.16	0.088
4	0.18 - 0.20	0.17	0.098
5	0.20 - 0.22	0.19	0.109
6	0.23 - 0.26	0.22	0.123
7	0.26 - 0.32	0.25	0.141
8	0.32 - 0.40	0.30	0.166
9	0.40 - 0.56	0.38	0.212
10	0.56 - 0.80	0.53	0.297
11	0.80 - 1.21	0.78	0.441
12	1.21 - 1.93	1.21	0.681
13	1.93 - 3.16	2.00	1.134
14	3.16 - 4.78	3.30	1.872
15	4.78 - 6.84	5.04	2.880
16	6.84 - 9.24	7.28	4.191
17	9.24 - 12.0	9.71	5.627
18	12.1 - 15.31	13.0	7.627
19	15.3 - 20.21	16.8	9.965
20	20.2 - 41.82	23.3	14.115

The general objective of this analysis was to extract underlying patterns from the existing data. Often these patterns are obscured by effects such as salinity, as outlined above, or season. To eliminate these factors while retaining as much of the full data set as possible for analysis, I calculated anomaly values for many of the variables. An anomaly is the deviation of a particular datum from the mean of all data within some range. In the case of salinity, I took the mean of all data within each salinity class and subtracted it from each observation in that class. This resulted in an anomaly representing the deviation of that individual value from the mean. Most of the variance remaining in anomaly values is due to causes other than salinity. The variance due to differences in salinity within classes, presumably slight except at the high-salinity end of the distribution, is not removed and appears as error variance. This approach is useful in determining long-term trends or spatial patterns, which could be obscured by variation in salinity among stations. In addition to anomalies by salinity class, I also used anomalies by month to eliminate the average seasonal trend represented by monthly means to reveal trends in the annual means.

The zooplankton abundance data were log-transformed before analysis so that various statistical procedures could be performed. This is a common practice in analyzing abundance data, in which the variance is correlated with the mean, rendering commonly used statistical procedures invalid unless the data are transformed. Log transformation alters the structure of the variance so that changes by a given factor, say 2, are represented the same no matter what the base value. That is, a change in abundance from 1 to 2 has the same influence (and appearance on a graph) as a change from 1,000 to 2,000. This makes sense for biological data because populations grow exponentially in the absence of resource limitation; that is, they change by multiples.

A drawback to log transformation is that zeros cannot be transformed. I dealt with this problem by adding a constant to all values before transformation. The choice of the value to add can affect results of the analysis. I chose the added value to be a power of 10 close to the minimum non-zero values obtained. In other words, I assumed that a zero value was not zero but just below the detection limit. The value added was 10 for copepods and 0.1 for *Neomysis mercedis*.

The CDFG zooplankton data set contained a number of observations from stations or times of year not represented consistently throughout the period of record. For example, some stations were sampled only during a few years of the study; also, samples were taken in winter only in the first few years. To make the data set more consistent and thereby reduce bias, I extracted a core data set containing samples taken at 35 stations in March through November of each year. I also eliminated samples for which salinity data were not taken. The resulting data set contained 9,597 observations. For some purposes I added back downstream stations (San Pablo Bay) sampled only during high-flow periods, 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 inter-annual 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).

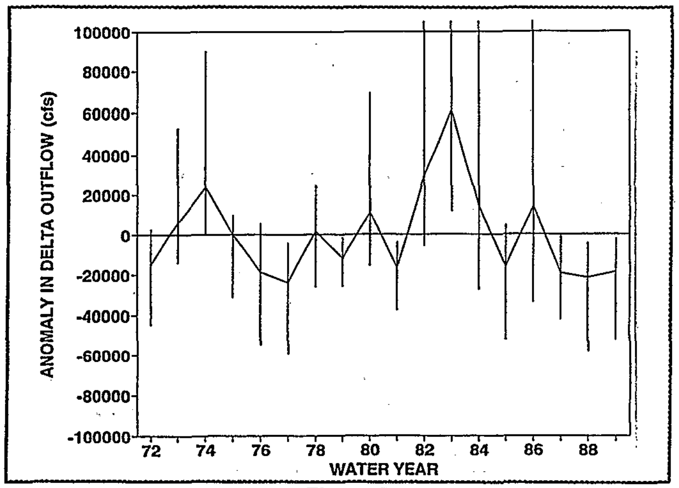

Figure 5
ANOMALY IN DELTA OUTFLOW
Annual means with 95% confidence limits indicated by vertical bars, calculated using monthly DAYFLOW values.

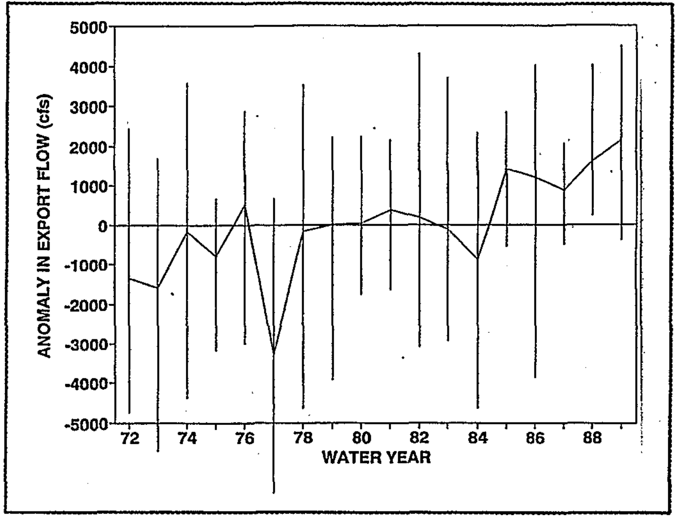

Figure 6
ANOMALY IN EXPORT FLOWS
Annual means with 95% confidence limits indicated by vertical bars, calculated using monthly DAYFLOW values.

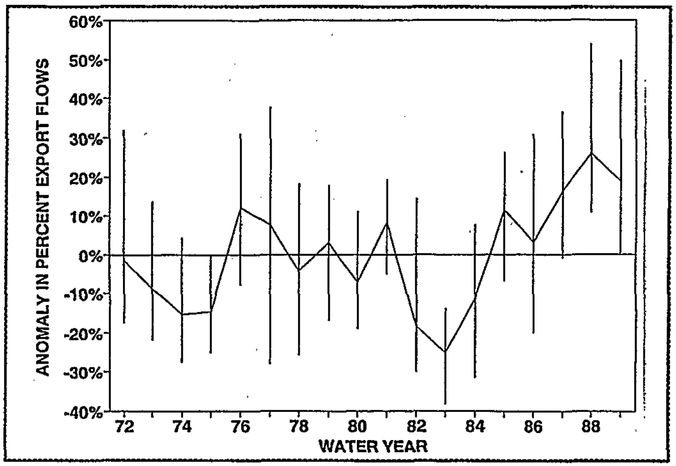

Figure 7
ANOMALY IN EXPORT FLOWS AS A PERCENT OF DELTA OUTFLOW
Annual means with 95% confidence limits indicated by vertical bars, calculated using monthly DAYFLOW values.

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.

The only season with a significantly increasing trend in percent exports during 1972-1989 is the fall ($p<0.05$, linear regression; Figures 8 and 9). Seasonally, export flows and percent exports are highest in summer and lowest in winter.

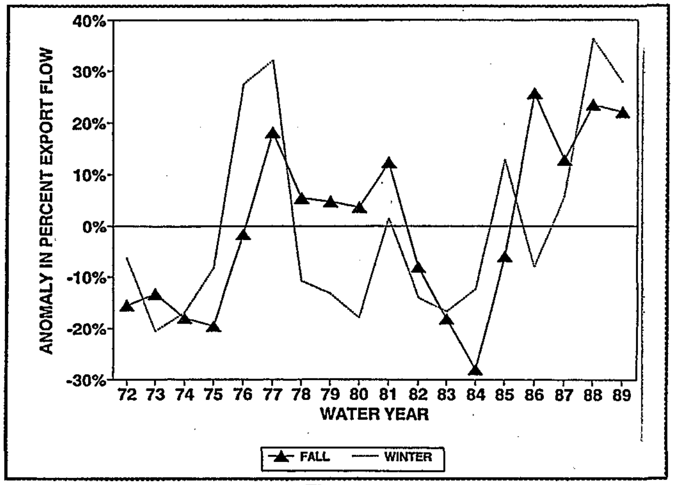

Figure 8
ANOMALY IN EXPORT FLOWS AS A PERCENT OF DELTA OUTFLOW, FOR FALL AND WINTER

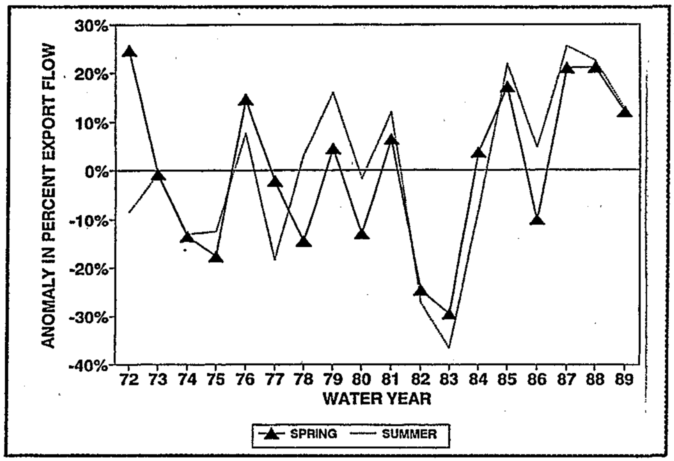

Figure 9
ANOMALY IN EXPORT FLOWS AS A PERCENT OF DELTA OUTFLOW, FOR SPRING AND SUMMER

Location of the Entrapment Zone

This section presents support for use of a fixed salinity or specific conductance value as an operational definition of the position of the entrapment zone. The entrapment zone is defined as the location where particles are concentrated by the action of circulation patterns. A clear indication of the location of the entrapment zone would require measurement or calculation of net flow velocities as a function of position in the estuary. These measurements have been made only a handful of times (Peterson *et al* 1975; Hachmeister 1987), so an operational definition of entrapment zone position is required. This could be based on location of the turbidity maximum or on a particular salinity value.

Arthur and Ball (1978) used 2-10 mS/cm surface specific conductance (at 25°C), corresponding to a salinity range of about 1.2-6, as an operational definition of the upstream and downstream ends of the entrapment zone. Since surface conductance is measured routinely in all the Interagency monitoring programs, this allows comparisons among different programs. The principal drawbacks of defining the entrapment zone by surface conductance are that this does not take stratification into account and that the entrapment zone may not always maintain the same spatial relationship to the salinity distribution.

Since turbidity is also routinely measured as Secchi disk depth, a turbidity maximum would seem to provide an operational definition more closely related to the actual phenomenon of entrapment than does salinity. However, several problems arise in using this definition. First, turbidity maxima can arise in the absence of entrapment (see "The Physics of Entrapment", page 4). Second, a Secchi disk permits the measurement of surface turbidity only; turbidity in the lower part of the water column may not be easily related to turbidity at the surface (*eg,* see Figures 9-11 in Arthur and Ball 1979). Third, the Secchi disk measurement is a rather crude and somewhat subjective measure of light penetration. Fourth, the position of the entrapment zone determined by turbidity depends on differences among stations, therefore requiring far more measurements than needed for a definition based on salinity.

Defining the entrapment zone using surface salinity has the advantage of simplicity in that a single measurement suffices to determine whether a station is in the (defined) entrapment zone or not. It also has a basis in physics: entrapment can occur only where density-driven circulation exists due to a horizontal salinity gradient. Since this can occur only where salinity is measurable, its upstream edge must be fairly close to the 2 mS/cm point. Furthermore, it is useful as a relative measure, since the entrapment zone position can vary widely within the estuary but only slightly relative to the salinity distribution (Peterson *et al* 1975).

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).

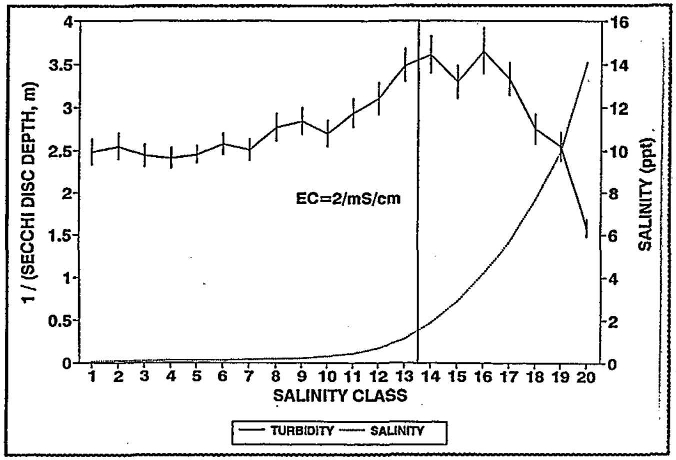

Figure 10
TURBIDITY MEASURED AS 1/SECCHI DISK DEPTH VS. SALINITY CLASS
Mean and 95% confidence limits (vertical bars) from CDFG core data set. The dashed line gives mean salinity in the class; the vertical line is the upstream end of the operationally defined entrapment zone.

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).

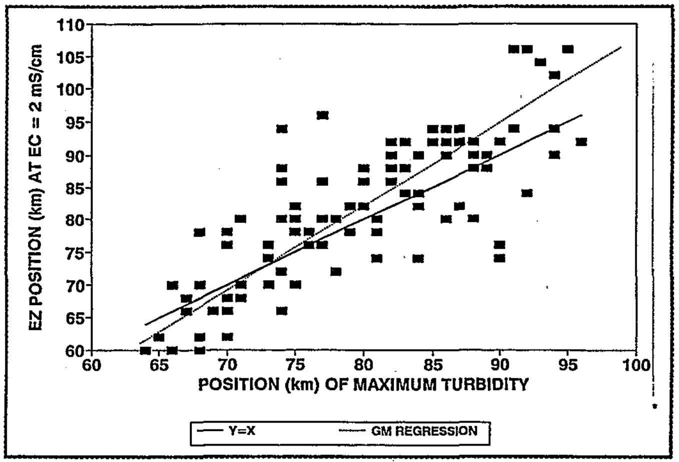

Figure 11
ENTRAPMENT ZONE POSITION BY THE OPERATIONAL DEFINITION VS. POSITION OF THE TURBIDITY MAXIMUM AS 1/SECCHI DISK DEPTH
Each point is a monthly mean from the CDFG data set. Solid line is for 1:1 correspondence; dashed line is the geometric mean regression.

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.

Entrapment zone position by the operational definition moves downstream with increasing flow (Figure 12, see also Peterson *et al* 1975; Arthur and Ball 1980; Arthur 1987). The rather wide range of entrapment zone positions for a given flow occur because I used monthly values from DAYFLOW, ignored tidal effects, and ignored the fact that entrapment zone position moves downstream on increasing flows faster than it moves upstream when flow decreases (Peterson *et al* 1975).

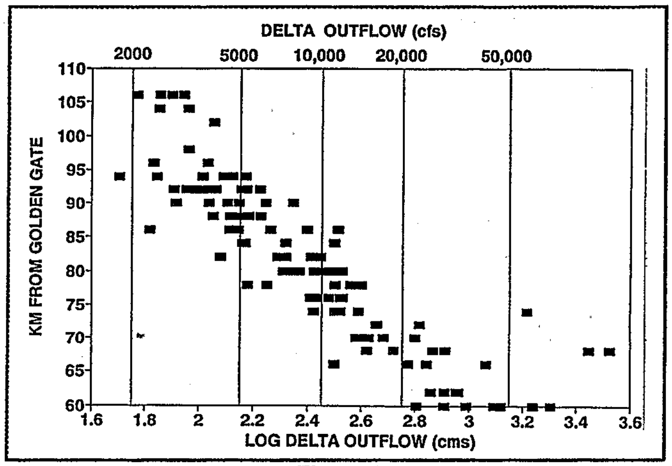

Figure 12
ENTRAPMENT ZONE POSITION BY THE OPERATIONAL DEFINITION VS. LOG DELTA OUTFLOW
(cubic meters per second)
Monthly means. Outflow values in cubic feet per second are given at the top for reference.

Plotting the time trend in entrapment zone position illustrates how the entrapment zone has moved between the Delta and Suisun Bay (Figure 13). As with outflow, no historical trend is apparent in entrapment zone position. This is confirmed by analysis of the anomalies in entrapment zone position with monthly variation removed, which also shows considerable interannual variability but no long-term trend (Figure 14). There is no significant long-term trend in the anomaly data, whether by year, month, or season (p>0.1, linear regression). Therefore, long-term trends in biomass or abundance over the period 1972-1988 cannot be attributed to changes in entrapment zone position, regardless of any linear or nonlinear correlations.

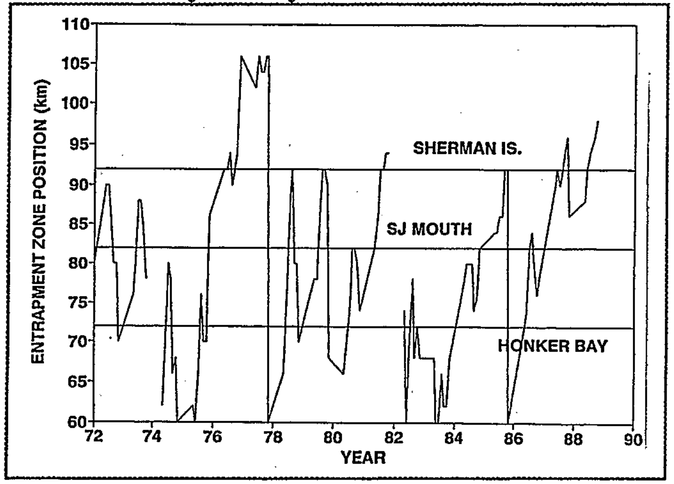

Figure 13
ENTRAPMENT ZONE POSITION VS. TIME
Position is kilometers from the Golden Gate.

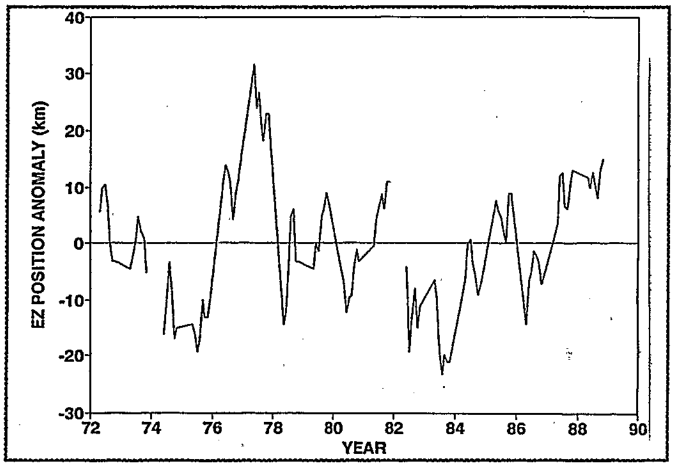

Figure 14
ANOMALIES IN ENTRAPMENT ZONE POSITION VS. TIME

A number of authors have referred to the decrease in habitat volume as the entrapment zone moves from Suisun Bay into the Delta (Siegfried *et al* 1979; Knutson and Orsi 1983). I calculated the approximate volume of water in the entrapment zone by summing the cross-sectional area between salinity values of 1-6 for each month in which entrapment zone position data were available. Cross-sectional area was obtained by trapezoidal integration of sounding data from nautical charts. In contrast to earlier reports, entrapment zone volume does not vary with position of the entrapment zone (Figure 15a). The reasons for the difference are that earlier reports of cross-sectional area (*eg*, Peterson *et al* 1975) did not include the San Joaquin River and that the slope of salinity with distance is greater up the San Joaquin than elsewhere in the estuary, so the length of the entrapment zone increases when it is upstream. The mean depth is much less when the entrapment zone is downstream (Figure 15b), which means the area of shallow-water habitat is much greater when the entrapment zone is in Suisun Bay than when it is in the Delta. This could have implications for the population size of epibenthic species such as bay shrimp.

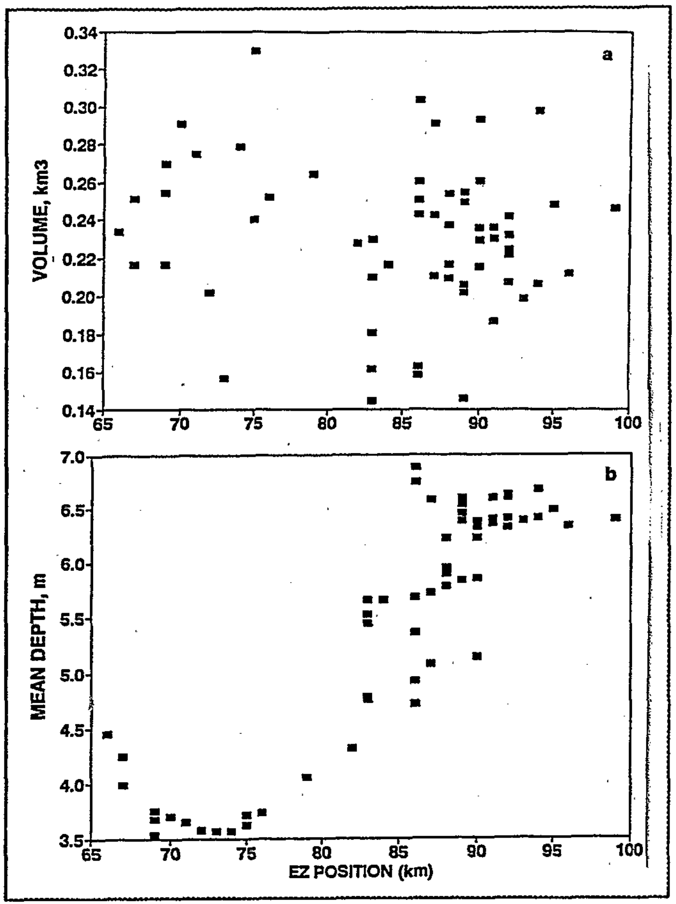

Figure 15

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.

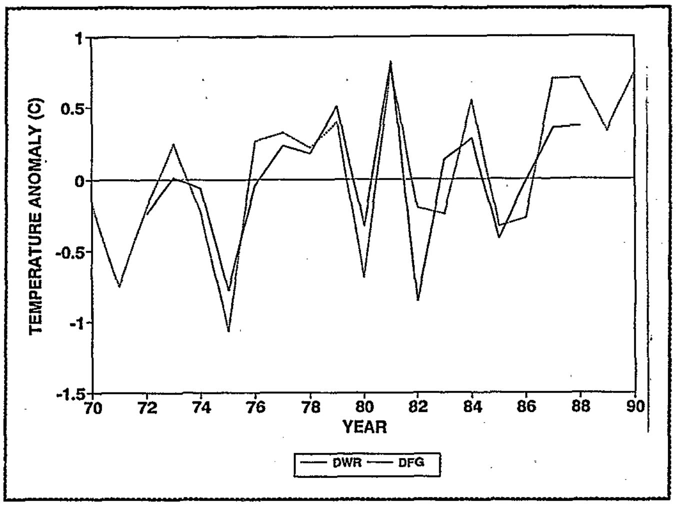

Figure 16

ANOMALIES IN TEMPERATURE

Annual means from DWR and CDFG data sets.

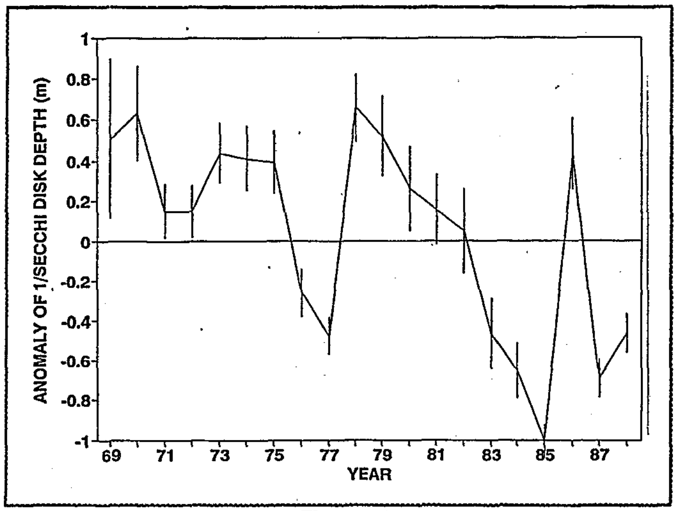

Figure 17

ANOMALIES IN TURBIDITY AS 1/SECCHI DISK DEPTH

From the DWR data set.

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

The height and position of the peak value of turbidity differed among the four entrapment zone positions (Figure 18). As the entrapment zone moves upstream, the peak occurs at a greater salinity; *ie,* farther downstream relative to the operationally defined point. Using all of the data from the four contiguous salinity classes with the highest values from each of the four curves, I tested for differences among the peaks, which were highly significant ($p<0.001$, ANOVA). Regression analysis revealed a linear trend in the peaks that explained virtually all of the variance explained by the analysis of variance (20%); thus the trend is strongly monotonic.

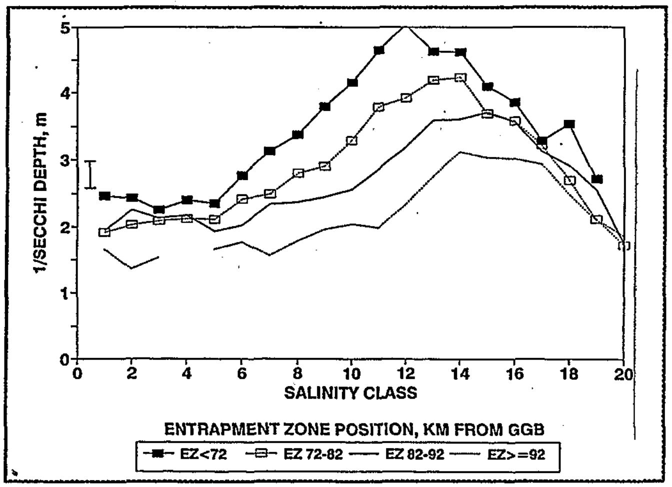

Figure 18
TURBIDITY AS 1/SECCHI DISK DEPTH VS. SALINITY CLASS FROM CDFG DATA SET FOR FOUR RANGES OF OPERATIONALLY DEFINED ENTRAPMENT ZONE POSITION
Vertical bar at left is the mean of 95% confidence intervals for all points on the graph.

Chemical Characteristics

This section discusses concentrations and inputs of nutrient elements and organic matter and briefly addresses toxic materials. Dissolved oxygen is not considered because it is always near saturation in and around the entrapment zone (Arthur 1987). These data were obtained from the DWR data set from 1968 to 1990. However, coverage was rather thin in the early years. Most of the nutrients vary substantially with salinity and season, so a small number of samples in a given year could seriously bias the annual mean. Therefore, I excluded years before 1971 from this analysis.

Nutrients considered here include nitrate plus nitrite, ammonium, orthophosphate, and silicate. Of the two forms of nitrogen, nitrate and nitrite (together) are more important components of stream water, while ammonium is representative of sewage input and recycling within the estuary. Phosphorus can come from either source, while silicate, derived almost entirely from weathering of rocks, enters in stream water.

Nutrients apparently limit phytoplankton growth only during the maximum summer phytoplankton bloom, if at all (Ball 1975; Cole and Cloern 1984). Therefore nutrient concentrations within the entrapment zone provide an index of the extent to which phytoplankton could develop. If all the major nutrients are present in excess (essentially this means above detection limits), then something else is limiting phytoplankton biomass, usually light. Also, the relationship of nutrient concentrations to salinity gives an indication of the non-conservative reactions of these nutrients; *ie,* incorporation into organic matter or other sources or sinks (Morris *et al* 1978; Officer 1979; Officer and Lynch 1981).

The relationship of nutrients to salinity was initially determined using salinity classes as discussed above, then converted to relationships with salinity using the mean salinity in each class.

Ammonium (Figure 19) was highest in winter and lowest in summer, with a minimum at salinities of 0.2-1, increasing at higher salinities, in all seasons. This reflects either a loss of ammonium in this region or, more likely, biological processes acting to reduce the concentration of ammonium.

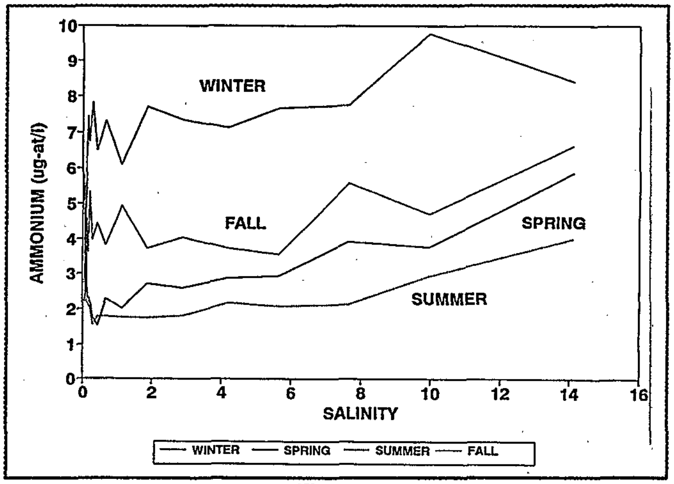

Figure 19
AMMONIUM VS. SALINITY, BY SEASON

Nitrate (Figure 20) has a sharp minimum at a salinity of 0.2 and a broad minimum during summer, but is relatively flat in other seasons.

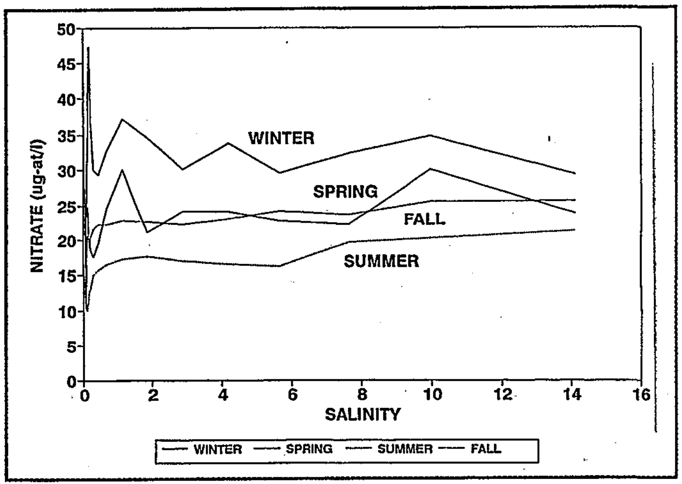

Figure 20
NITRATE VS. SALINITY, BY SEASON

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.

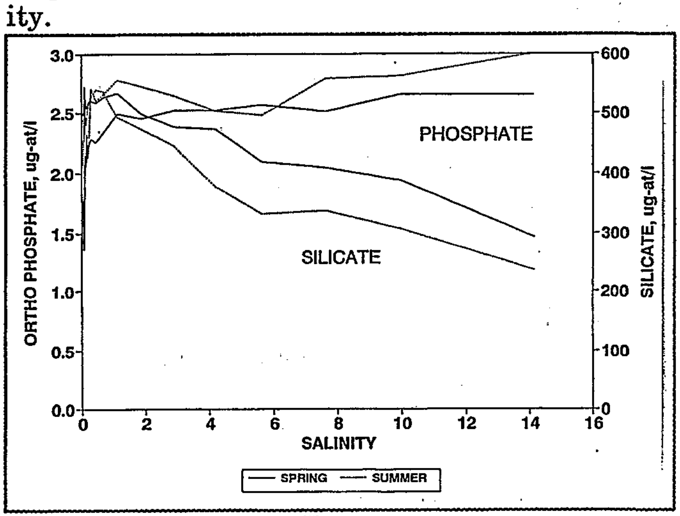

Figure 21
ORTHOPHOSPHATE AND SILICATE VS. SALINITY, FOR SPRING AND SUMMER

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.

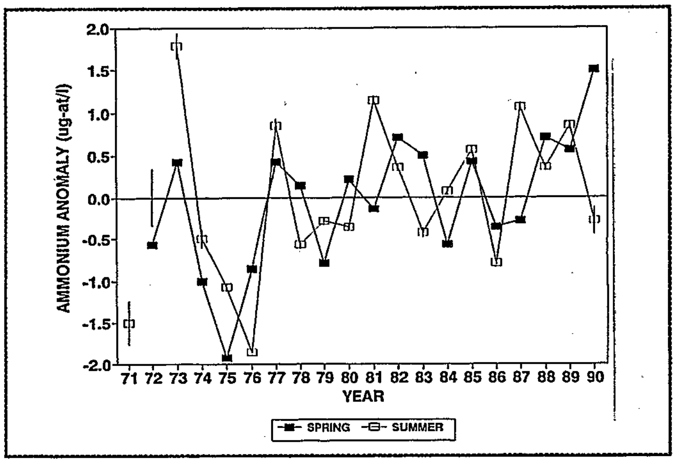

Figure 22
ANOMALIES IN AMMONIUM VS. TIME, FOR SPRING AND SUMMER
Seasonal means with 95% confidence limits (vertical bars) for summer only.

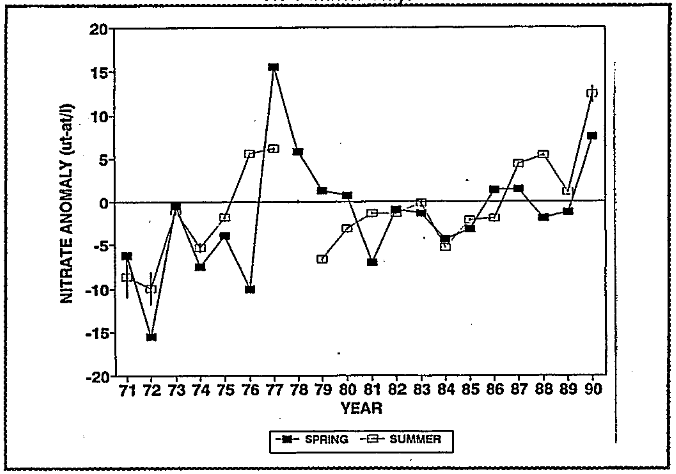

Figure 23
ANOMALIES IN NITRATE VS. TIME, FOR SPRING AND SUMMER
Seasonal means with 95% confidence limits (vertical bars) for summer only.

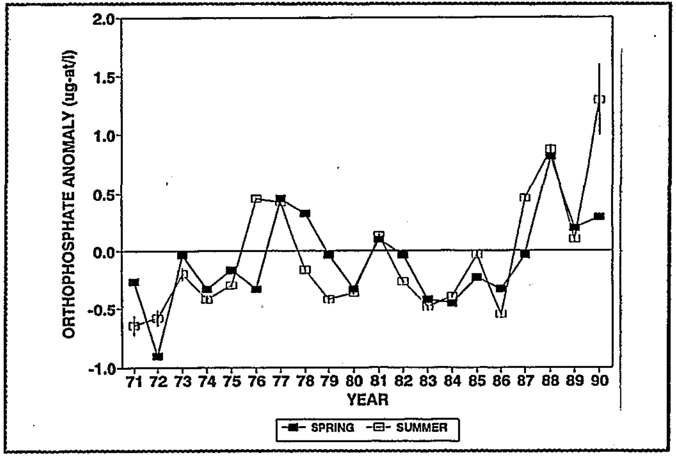

Figure 24
ANOMALIES IN ORTHOPHOSPHATE VS. TIME, FOR SPRING AND SUMMER
Seasonal means with 95% confidence limits (vertical bars) for summer only.

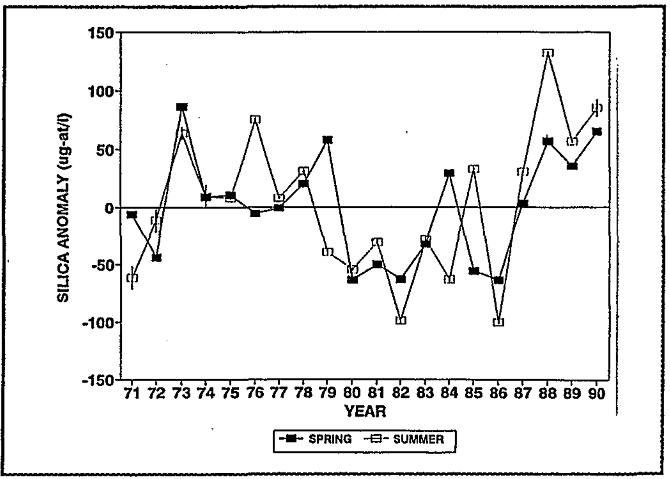

Figure 25
ANOMALIES IN SILICATE VS. TIME, FOR SPRING AND SUMMER
Seasonal means with 95% confidence limits (vertical bars) for summer only.

Toxic materials such as pesticides, hydrocarbons, and metals have been measured on occasion, but the detection limits are too high to measure environmental concentrations reliably (Arthur 1987). Nevertheless, there is concern over the influence of toxic materials, particularly agricultural pesticides, antifouling chemicals, and industrial wastes. In the upper estuary, the biggest problem would seem to be pesticide releases from the rice fields, which peak in mid-May (D. Wescott, Sacramento Regional Water Quality Control Board, pers. comm. 1990). A change in crops planted, with attendant changes in pesticide application, occurred around 1976 to 1982, coincident with some changes in estuarine biota (following sections). Crustaceans appear most sensitive to pesticides (Foe and Connor 1989). The declines in the crustacean zooplankton of the entrapment zone (see "Zooplankton", page 11) occurred in all months, but most steeply in July to October. Given the generation lengths of about a month, and assuming travel time is a few days, one would expect a large effect in June. Thus, the effect of these pesticides appears minimal.

Phytoplankton

Phytoplankton abundance has been measured in two ways: as chlorophyll in both the CDFG and DWR data sets and as abundances of phytoplankton species in the DWR data set. Chlorophyll *a* is the most commonly used measure of phytoplankton biomass, since all phytoplankton cells contain it. However, the chlorophyll per unit biomass (carbon or weight) varies widely, and there is no easy way to distinguish among the many phytoplankton species. Enough is known about phytoplankton biology to demonstrate that different species have vastly different requirements and responses to the environment. Thus chlorophyll is only a crude measure of phytoplankton abundance; but, on the other hand, it is easy to measure and uniquely indicative of phytoplankton. Also its degradation products, known collectively as phaeopigments, are produced in digestion and can be useful as indices of herbivory. Primary production is not routinely measured but can be calculated from chlorophyll, water transparency, and incident light (Cole and Cloern 1984, 1987).

The two data sets for chlorophyll have similar patterns with respect to salinity if similar time periods and stations are used; when data from winter, before 1976, and the stations in the eastern Delta are eliminated from the DWR data set, results are similar to those from CDFG (Figure 26), with a broad peak in salinity classes 15-18 and low values at higher salinity.

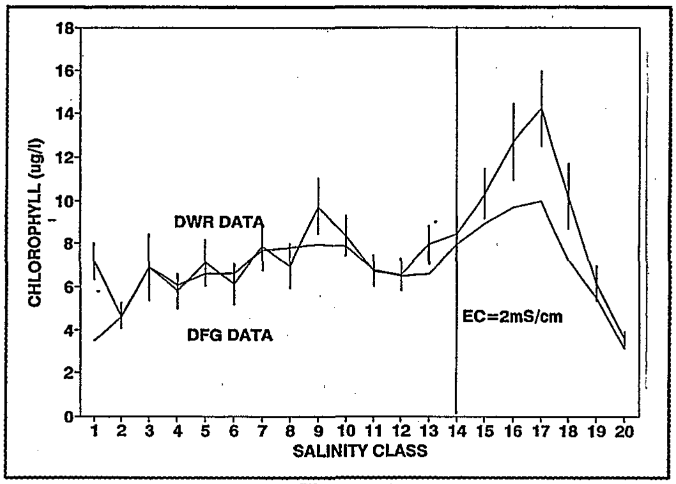

Figure 26
CHLORPHYLL VS. SALINITY CLASS FROM DWR DATA SET AND CDFG DATA
Means and 95% confidence limits for DWR data set; Means only for CDFG data.

The ratio of chlorophyll to total pigment (*ie,* chlorophyll plus phaeopigments) in the DWR data set was lowest at the upstream edge of the entrapment zone, higher in more saline water, and highest in the freshwater samples (Figure 27). The overall difference was small, and may have occurred through disruption of cells of freshwater algae on encountering significant salinity, since the abundance of herbivores is highest somewhat farther downstream in the entrapment zone (see "Zooplankton", page 11).

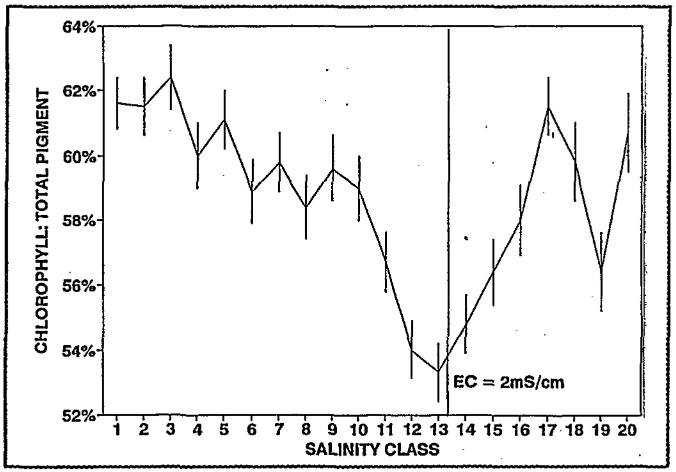

Figure 27

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

Means and 95% confidence intervals.

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.

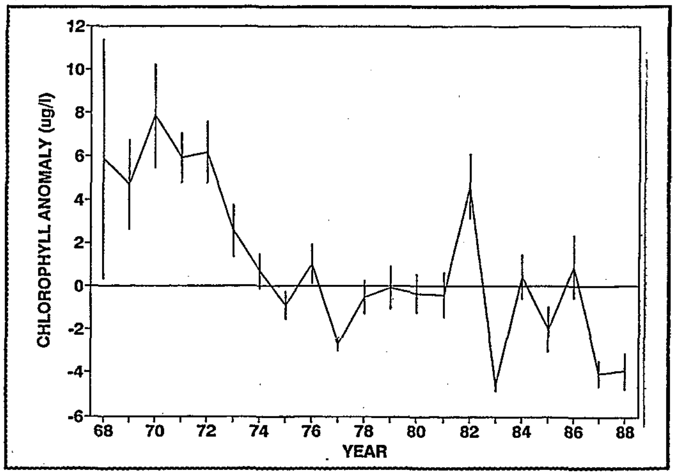

Figure 28

ANOMALIES IN CHLOROPHYLL VS. TIME

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

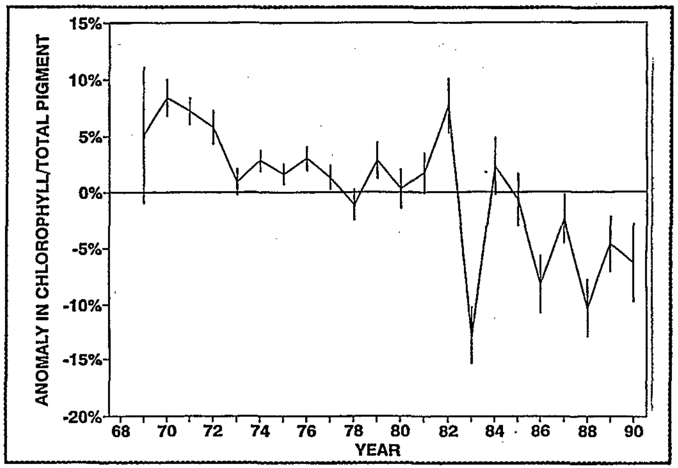

Figure 29

RATIO OF CHLOROPHYLL TO TOTAL PHOTOSYNTHETIC PIGMENT VS. TIME

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

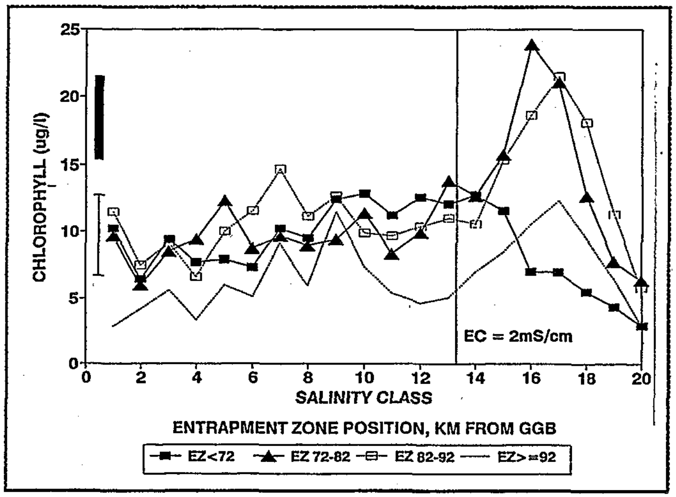

Figure 30

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.

Cell count data are available from 1975 on. I analyzed data for only a few common diatoms, since these are reported as important in the entrapment zone and some are known to provide good food for herbivores (*eg,* Cahoon 1981). The diatoms *Thalassiosira* sp. and *Skeletonema costatum* were most abundant when the entrapment zone was at intermediate positions, based on monthly means (Figures 31 and 32). This provides some support for earlier findings (Arthur and Ball 1980, Cloern *et al* 1983) showing these diatoms were most abundant when the entrapment zone was downstream, although high values occur when the entrapment zone is as far upstream as the confluence of the Sacramento and San Joaquin rivers. However, the operationally defined entrapment zone position is about 5 km upstream of the actual center of the turbidity maximum (Figure 11, page 19), so the proposed mechanism appears to hold in these data as well.

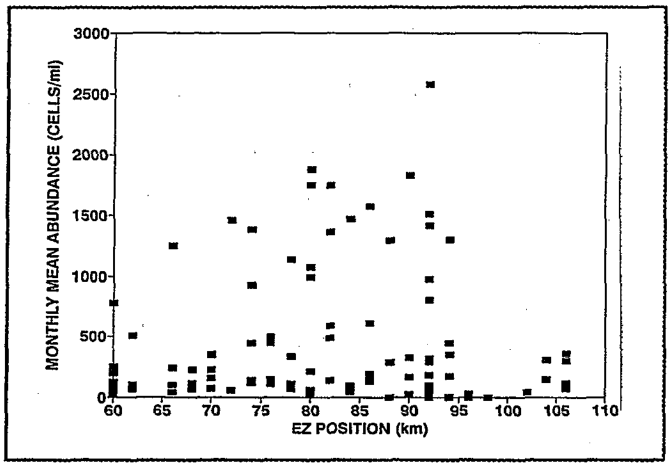

Figure 31
MONTHLY MEAN ABUNDANCE OF *THALASSIOSIRA* SPP. VS. OPERATIONALLY DEFINED ENTRAPMENT ZONE POSITION
Zero data values have been omitted.

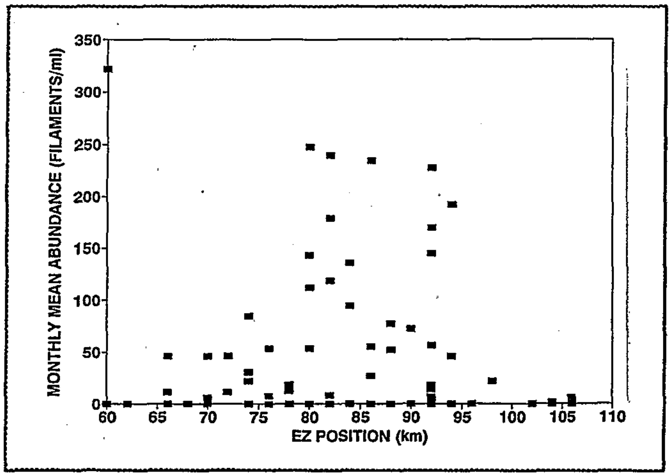

Figure 32
MONTHLY MEAN ABUNDANCE OF *SKELETONEMA COSTATUS* VS. OPERATIONALLY DEFINED ENTRAPMENT ZONE POSITION
Zero data values have been omitted.

It is not surprising that the monitoring data show less effect of entrapment zone position than data previously reported. Those earlier data were taken in studies designed specifically to answer questions about the entrapment zone. The monitoring program has broader objectives and is not as well suited to answering specific questions about the entrapment zone. Many of the monitoring stations are upstream of the entrapment zone for much of the time, and only a small number of samples are taken each month from within the entrapment zone.

Previous analyses of chlorophyll have shown correlations with net Delta outflow (Ball 1987). This could be the result of the change in entrapment zone position, but could also be an artifact of the shape of the chlorophyll distribution with respect to salinity. Since chlorophyll is high at intermediate salinities, it would be positively correlated with outflow at stations where salinity is usually high; *ie,* those downstream of the entrapment zone. This points out the importance of referring data from water-column measurements to salinity rather than to geographic position.

Zooplankton

The CDFG zooplankton monitoring data set included abundance (number/m^3) of adult *Eurytemora affinis* and all sizes ≥4 mm of *Neomysis mercedis*. *N. mercedis* has been sampled since 1968 but, for consistency with other zooplankton data, we have considered only samples taken from 1972 on. Several other species are discussed briefly in the "Zooplankton" section in Chapter 2 (page 11).

Responses to Salinity

Distribution of any estuarine species will normally have an abundance peak at some salinity and a decline toward zero at higher and lower salinities. *E. affinis* has a broad abundance peak at a salinity of about 2 (Figure 33). The apparently steeper drop toward higher salinities is an artifact of the choice of salinity classes, since there were few classes above the peak. The corresponding distribution of geometric mean values vs. salinity (Figure 34) gives a better perspective of the response of this species to salinity but is less useful for analytical purposes, since the distribution is skewed toward the low-salinity end of the distribution, which contains most of the samples.

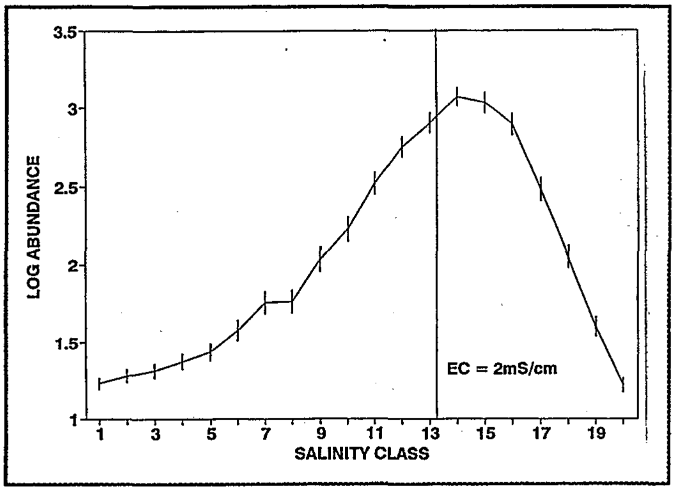

Figure 33
LOG OF ABUNDANCE OF *EURYTEMORA AFFINIS* VS. SALINITY CLASS
Log of abundance in number/m^{-3}+10.
Mean and 95% confidence intervals (vertical bars).

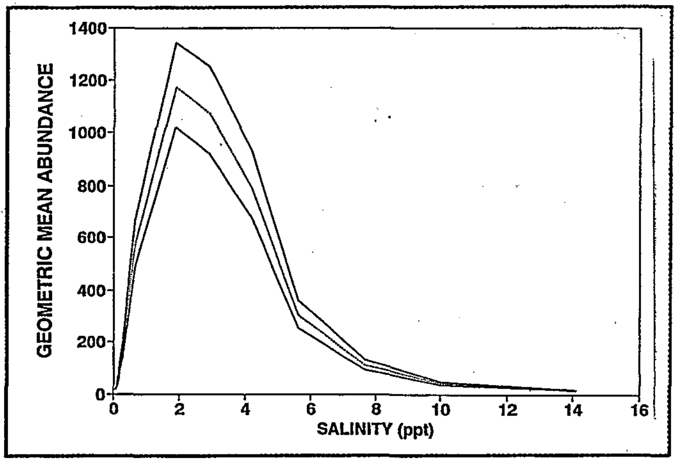

Figure 34
GEOMETRIC MEAN ABUNDANCE AND 95% CONFIDENCE INTERVALS FOR *EURYTEMORA AFFINIS*
Geometric mean in number/m^3.

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).

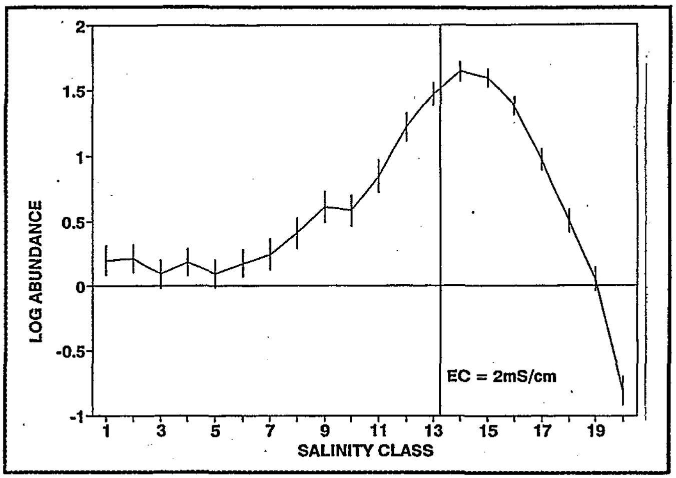

Figure 35
LOG OF ABUNDANCE OF *NEOMYSIS MERCEDIS* VS. SALINITY CLASS
Log of abundance in number/m^{-3}+0.01.
Mean and 95% confidence intervals (vertical bars).

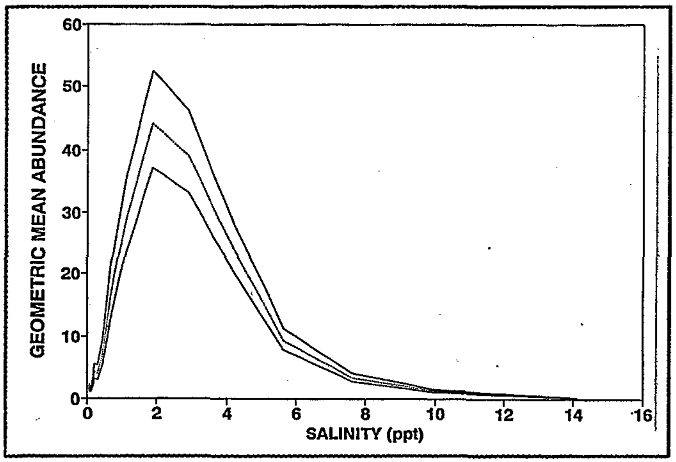

Figure 36
GEOMETRIC MEAN ABUNDANCE AND 95% CONFIDENCE INTERVALS FOR *NEOMYSIS MERCEDIS*
Geometric mean in number/m^3.

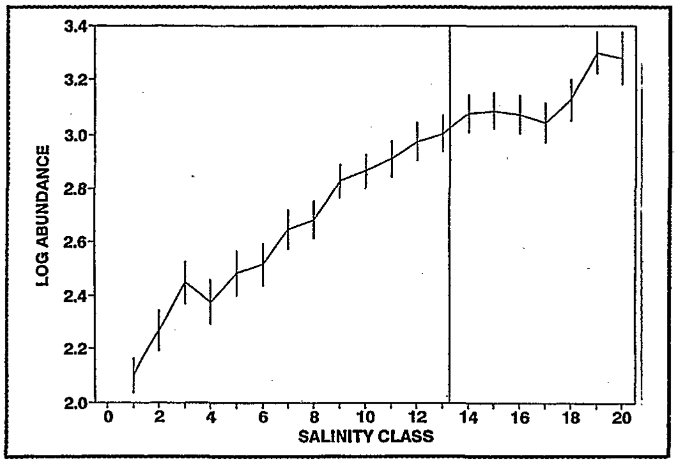

Figure 37
TOTAL LOG OF ABUNDANCE OF CALANOID COPEPODS VS. SALINITY CLASS
Log of abundance in number/m^{-3}+10.
Mean and 95% confidence intervals (vertical bars).

Laboratory studies show *E. affinis* to have a broad tolerance to salinity from nearly 0 to about 20, with an optimum at 12 (Katona 1970; Roddie *et al* 1984) and maximum feeding at 15 (Powell and Berry 1990). It occurs in fresh water at Stockton (J. Orsi, CDFG, pers. comm. 1990) and elsewhere (Ban and Minoda 1991). *N. mercedis* is found in fresh water, and Heubach (1969) found that rates of reproduction were highest from fresh water to a salinity of 3.6. Distributions of these species are not, therefore, regulated by salinity alone. Other potential regulatory factors include interactions between behavior of these species and the complex circulation of the estuary, and spatial differences in birth and mortality rates.

As with chlorophyll, correlations of zooplankton species abundance with flow can be expected because of their distributions with respect to salinity. These correlations should be regarded as artifacts except when the effect of salinity is accounted for, as in the following section.

Historical Trends

To obtain a clear record of the historical trends in abundance of the entrapment zone species, anomaly values were calculated by subtracting the means for each combination of salinity class and month from the data. These anomaly values were then combined by year to get means and confidence intervals for each annual value. Plots of these values by year (Figure 38) show that *E. affinis* declined in the 1970s and again in 1987 and 1988. A linear regression of annual mean abundance vs. year (through 1987) is significant ($p<0.001$), as is a quadratic regression fit to the same data ($p<0.001$). The quadratic function gives a better fit to the data because the rate of decline decreased in the late 1970s.

The decline in 1988 cannot be tested using annual means, since there is only one point in the data set so far. Using the monthly mean anomalies gives a significant difference between 1988 and earlier years but involves some statistical constraints (the assumption of independence may be violated). Nevertheless, the difference between 1988 and previous years is exceptionally large, representing a threefold difference between 1988 and 1983, the next lowest previous year. Furthermore, data for 1989-1991 (not shown), show the abundance of *E. affinis* has remained exceptionally low.

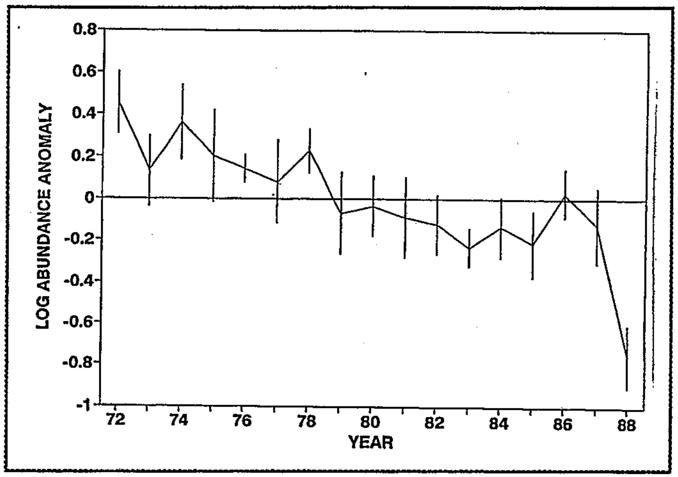

Figure 38
LOG ABUNDANCE ANOMALIES FOR *EURYTEMORA AFFINIS*
Annual means and 95% confidence intervals (vertical bars).

There has been some concern that the interior Delta has become less suitable habitat for young striped bass than it once was, and there is speculation that the early decline in *E. affinis* was more severe in the Delta than in Suisun Bay. Keeping with the practice of referring the data to salinity rather than location, it is clear the decline occurred equally throughout the system. The decline in *E. affinis* abundance in the 1970s occurred in all salinity classes but was, if anything, steeper in the classes near the center of the abundance peak (Figure 39) and least in class 20.

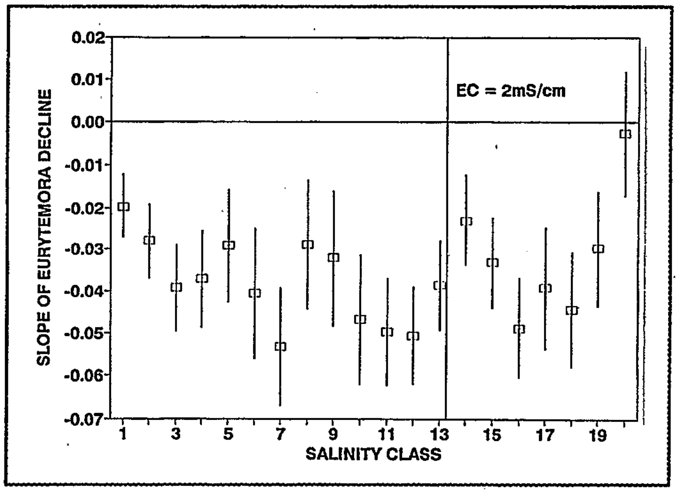

Figure 39
SLOPES OF LINEAR REGRESSION OF LOG ABUNDANCE OF *EURYTEMORA AFFINIS* VS. YEAR FOR 1972 TO 1987
Means and 9% confidence limits (vertical bars).
Calculated separately for each salinity class.

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).

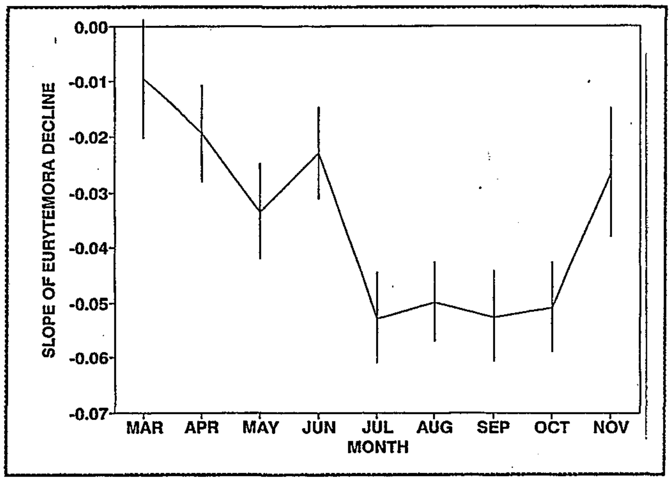

Figure 40
SLOPES OF LINEAR REGRESSION OF LOG ABUNDANCE OF *EURYTEMORA AFFINIS* VS. YEAR FOR 1972 TO 1987
Means and 9% confidence limits (vertical bars).
Calculated separately for each salinity class.

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).

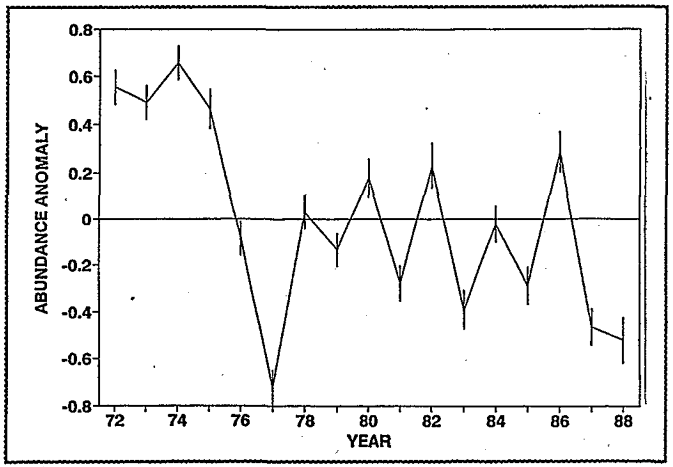

Figure 41
LOG ABUNDANCE ANOMALIES FOR *NEOMYSIS MERCEDIS*
Annual means and 95% confidence intervals (vertical bars).

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

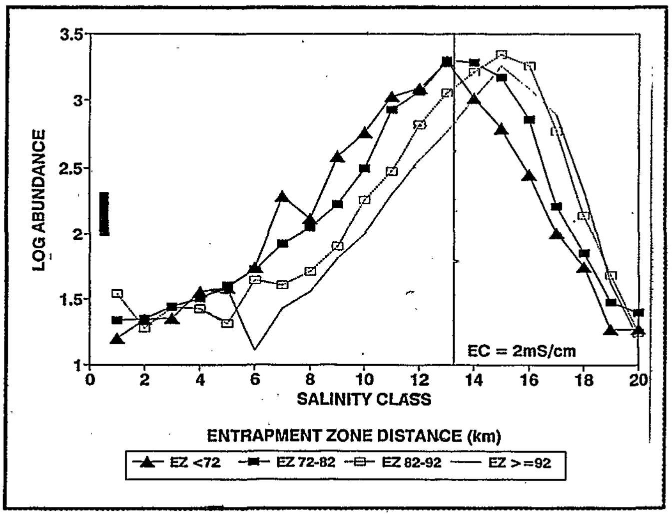

Figure 42
LOG ABUNDANCE OF *EURYTEMORA AFFINIS* VS. SALINITY CLASS FOR FOUR RANGES OF OPERATIONALLY DEFINED ENTRAPMENT ZONE POSITION
Log abundance in number/m3+10.
Vertical bar at left is the mean 95% confidence limit for all points.

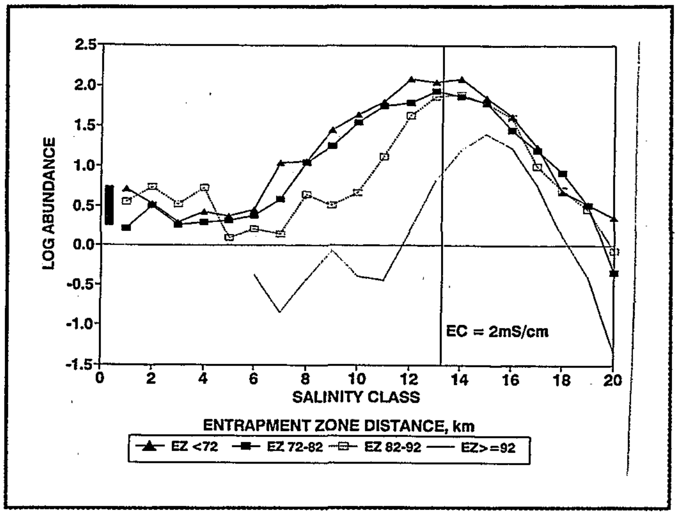

Figure 44
LOG ABUNDANCE OF *NEOMYSIS MERCEDIS* VS. SALINITY CLASS FOR FOUR RANGES OF OPERATIONALLY DEFINED ENTRAPMENT ZONE POSITION
Log abundance in number/m3+0.01.
Vertical bar at left is the mean 95% confidence limit for all points.

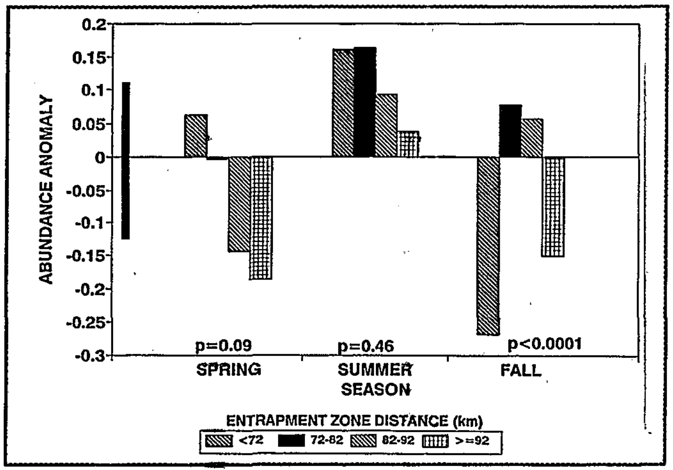

Figure 43
ABUNDANCE ANOMALIES OF *EURYTEMORA AFFINIS* FOR FOUR RANGES OF ENTRAPMENT ZONE POSITION, BY SEASON
Anomalies with salinity class, month, and annual trend removed.
Each value is the grand mean of values from the five contiguous salinity classes having the highest values of abundance.
Vertical bar at left is the 95% confidence limit for all bars on the graph.
ANOVA probability values are given at bottom.

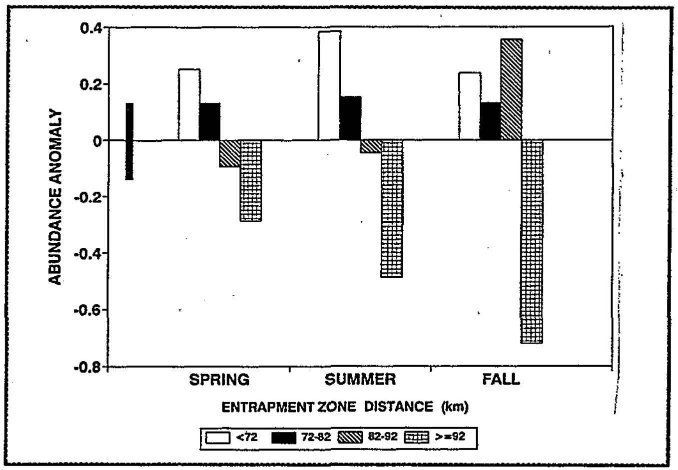

Figure 45
ABUNDANCE ANOMALIES OF *NEOMYSIS MERCEDIS* FOR FOUR RANGES OF ENTRAPMENT ZONE POSITION, BY SEASON
Anomalies with salinity class, month, and annual trend removed.
Each value is the grand mean of values from the five contiguous salinity classes having the highest values of abundance.
Vertical bar at left is the 95% confidence limit for all bars on the graph.

was more than 92 km from the Golden Gate Bridge. In spring, as for *E. affinis*, the highest abundance was with the entrapment zone at its farthest downstream position, while in fall *N. mercedis* was about equally abundant for all entrapment zone positions below 92 km.

These results agree with those obtained by Arthur and Ball (1980) and Cloern *et al* (1983) and reiterated in the section, "Phytoplankton" (page 24), for chlorophyll. The cause is not clear. Although there is reason to believe phytoplankton grow better in shallow water than in deep water owing to differences in light for photosynthesis, estuarine zooplankton in general avoid the surface and therefore are usually less abundant in shallow water than in deep water (Jacobs 1968). A comparison of abundance anomalies of *E. affinis* and *N. mercedis* at the two shallow stations in Suisun and Honker bays with values from nearby deep stations shows abundance of both species averaged significantly less in shallow water (Figure 46, p<0.01, t-test). Therefore, a higher growth rate in the shallows seems unlikely, and the shallows are an unlikely source region for export of zooplankton to the channels. Another mechanism for concentration must be sought.

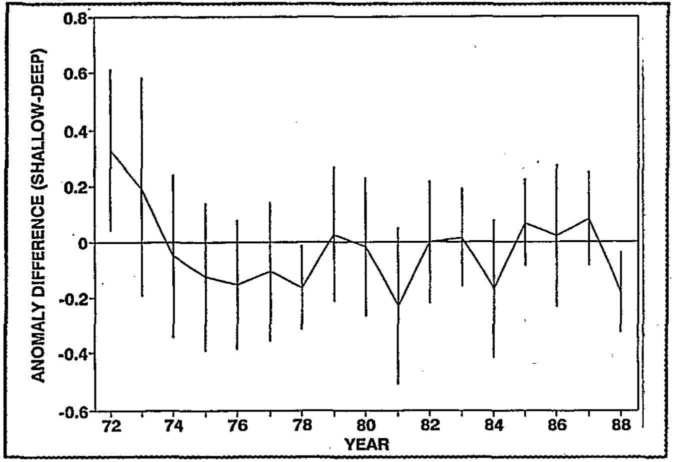

Figure 46
DIFFERENCE IN *EURYTEMORA AFFINIS* ABUNDANCE ANOMALIES BETWEEN TWO SHALLOW STATIONS IN GRIZZLY AND HONKER BAYS AND NEARBY DEEP STATIONS
Annual means and 95% confidence limits (vertical bars).

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.

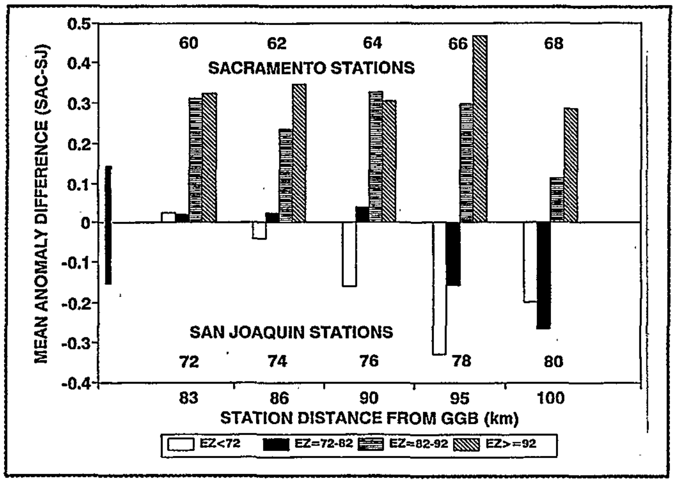

Figure 47
DIFFERENCES IN ABUNDANCE ANOMALIES FOR *EURYTEMORA AFFINIS* BETWEEN SACRAMENTO AND SAN JOAQUIN RIVER STATIONS MATCHED FOR DISTANCE UP THE ESTUARY FOR EACH OF FOUR POSITIONS OF THE ENTRAPMENT ZONE
Distances are given at the bottom; station numbers are within the box. Vertical bar at left is the mean 95% confidence interval for all bars in the graph.

For the third analysis, I used data from two stations in the southern Delta, one in Old River and one in Middle River. For each month, I calculated abundance of *E. affinis* in each of these locations. I used the DAYFLOW values for mean monthly exports to obtain the pumping rate. I assumed as a worst case that all the water going to the pumps came upstream through Old and Middle rivers, and that none of it came from the San Joaquin. This allowed me to avoid any questionable assumptions about flow splits within the Delta, resulting in a conservative figure for the rate of removal of *E. affinis* from the population. Next I calculated the mean abundance for each kilometer of distance along the estuary and converted this to absolute abundance (total numbers per kilometer) by multiplying by the estimated cross-sectional area. I then summed these values to obtain the size of the population for each month. Finally, I divided the population size into the estimated rate of removal by the pumps, calculated as described above, to arrive at the proportion of the adult population removed per day. I assumed juveniles of the same population would be removed at the same rate.

The median percent exported was 0.06 percent per day (Figure 48). Three values over 10 percent appear to have been spurious in that one of the two samples from Old and Middle rivers had much higher abundance than the other. About 13 percent of the values were more than 1 percent per day, and many of these values were in late 1987 and 1988, when abundances were greatly reduced in the entrapment zone (see "Historical Trends", page 28). Typical reproductive and growth rates of copepods of this size at spring to summer temperatures are 10 to 20 percent per day (Burkill and Kendall 1982; Kimmerer and McKinnon 1987). These results support the conclusion that export pumping has rarely (if ever) had a direct effect on the copepod population. The export of *Neomysis* should be similar, since the abundance patterns are similar. Differences in abundance due to differences in entrapment zone position are around fourfold (Figure 45, page 30). At a 0.06 percent d^{-1} rate of removal, in one year the population would decline by about 24 percent compared to its abundance without export losses. Since shifts in entrapment zone position occur over time scales of a year or less, export losses appear not to be the principal mechanism for the differences in Figure 45. However, calculations based on abundances actually exposed to the pumps would be more useful; these data are not yet available.

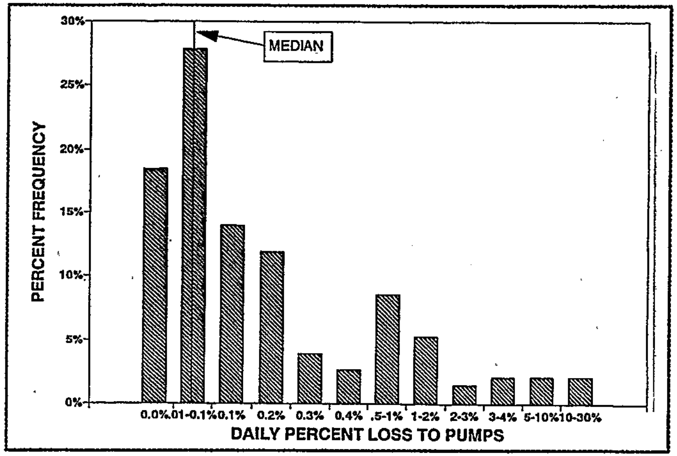

Figure 48
FREQUENCY DISTRIBUTION OF
ESTIMATED PERCENTAGE OF THE *EURYTEMORA AFFINIS*
POPULATION LOST TO EXPORT PUMPS

The effect of water withdrawals within the Delta could be a different matter. Gross consumption within the Delta is not measured, but estimated net consumption is on the same order as export flows (DAYFLOW). Since this occurs throughout the Delta, it may indicate a higher rate of loss to resident zooplankton populations than to export pumping.

Correlations of Zooplankton with Measures of Food Concentration

An additional possible explanation for the higher abundance of zooplankton when the entrapment zone is downstream is that food concentration is higher (CDFG 1988c). Although it is true that individual values of *E. affinis* abundance and chlorophyll are correlated, the relationship appears to be a result of similar responses to the physical environment. For example, examination of Figures 26 (page 24), 33, and 35 (page 27) reveals that chlorophyll and abundances of *E. affinis* and *N. mercedis* all peak in or near the entrapment zone and decline at high salinities. That fact alone would result in significant correlations, but these correlations are probably due to similarity in response of these variables to salinity (or position), not trophic level effects.

To analyze these correlations further, I used anomaly values with salinity and seasonal patterns and annual trends removed for both chlorophyll and *E. affinis* abundance. The regression is still significant ($p<0.001$), but explains only 0.3 percent of the variance in the *E. affinis* anomaly and 0.1 percent of the variance in the original data. If monthly means are used, even this minor 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 frequent enough to obtain a reliable average of abundance at all stages.

This is clearly not the case for eggs, which occur in large peaks of only a few days' duration (Arthur 1990). However, the sampling interval may be short enough to sample the larvae adequately, since they take several days to grow one millimeter (CDFG 1988b).

As pointed out in Chapter 2, striped bass are not confined to the entrapment zone, but they are most abundant there. Figure 49 presents the median salinity class of striped bass larvae, by size class, for 1986. This year was selected because bass larvae were abundant and the analysis robust; however, bass distribution in this high-flow year may have been atypical. The earliest larvae, 3-5 mm in length, were in relatively fresh water, but as the larvae developed they occupied a generally increasing salinity regime so that the largest larvae were most abundant at the upstream edge of the entrapment zone. Given that the actual entrapment zone is somewhat upstream of the operationally defined location when flow is high (as it was in 1986), this indicates these fish are strongly concentrated in the entrapment zone. This is consistent with the behavior of larvae that results in an ontogenetic movement toward the bottom (see Chapter 2).

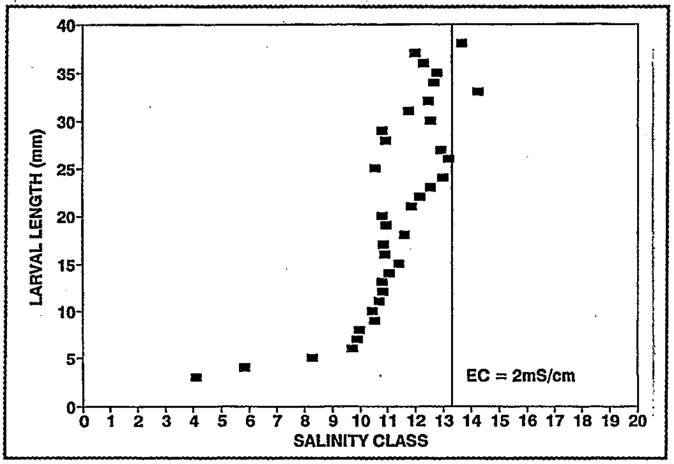

Figure 49
LENGTH VS. SALINITY CLASS AT WHICH MEDIAN STRIPED BASS ABUNDANCE OCCURRED, FOR 1986 EGG AND LARVAL SURVEY

CDFG contends the egg supply has declined, resulting in lower young-of-the-year indices. By any of the three indices (Peterson, CPUE, and larval survey), egg abundance has declined over the period 1969 to about 1980 and has then leveled off or increased slightly (Figure 50).

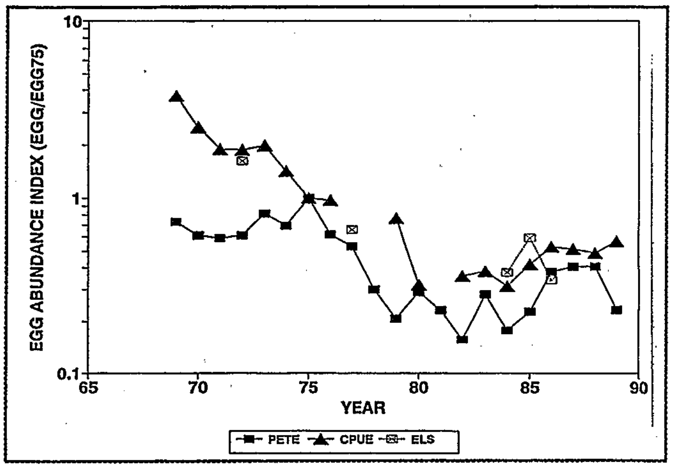

Figure 50
TIME TREND OF THREE EGG ABUNDANCE INDICES
Peterson abundance (PETE)
Catch per unit effort index (CPUE)
Egg and larval survey index (ELS)
All values have been scaled to make the 1975 values the same, then log transformed.

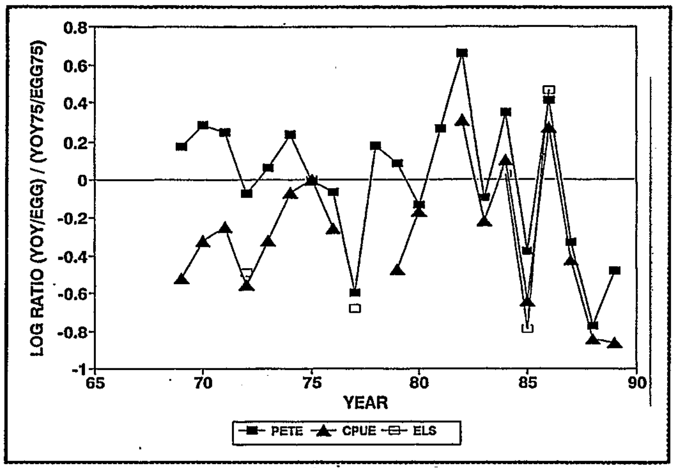

Figure 51
RELATIVE SURVIVAL OF EGGS TO YOUNG-OF-THE-YEAR FOR THREE EGG ABUNDANCE INDICES
Peterson abundance (PETE)
Catch per unit effort index (CPUE)
Egg and larval survey index (ELS)
Each value is calculated as the ratio of YOY index to egg index, scaled by the 1975 value, and log transformed.

Although the discrepancy among the egg abundance indices is as much as a factor of 5, all indices show a decline in egg abundance. Relative survival from egg to young-of-the-year, calculated as the log of the ratio of YOY to any of the egg indices, has apparently not declined over this time period (Figure 51); in fact, the highest values of relative survival occurred in the 1980s. Interannual variability in this survival index is large, however, with up to a tenfold variation in YOY for a given number of eggs. This interannual variability is significantly related to position of the entrapment zone (Figure 52; $p<0.001$, $R^2=0.33$, linear regression), although flow, which covaries with entrapment zone position, explains somewhat more variance ($R^2=0.43$).

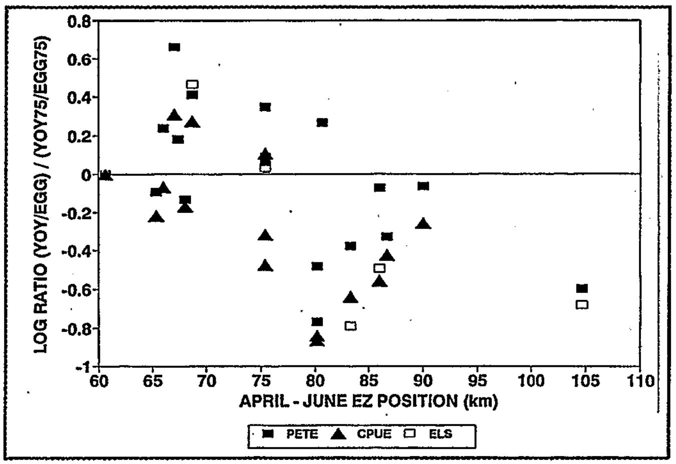

Figure 52
RELATIVE SURVIVAL BY THREE INDICES VS. ENTRAPMENT ZONE POSITION
(in kilometers from the Golden Gate)
Peterson abundance (PETE)
Catch per unit effort index (CPUE)
Egg and larval survey index (ELS)

Chapter 4

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

rate, which may be less variable spatially and temporally than biomass. If this is true, production of entrapment zone species of zooplankton and fish is higher in the entrapment zone than outside.

Importance of Entrapment Zone Position to Abundance or Production

The relationship of phytoplankton to entrapment zone position was well described, and its probable cause explored, by Arthur and Ball (1980) and Cloern *et al* (1983). These results were based on sampling and experimental studies designed specifically to elucidate the cause of the observed variation in phytoplankton biomass with entrapment zone position. Examining the monitoring data has added little to that area. The analyses of striped bass and delta smelt have also received a great deal of attention, and little has been gained by further analyses of the striped bass data. Because the zooplankton have received less scrutiny and have not been the subject of many special studies, there was a somewhat greater opportunity to learn more of the effect of entrapment zone position on these species than on others. To summarize, the following statements can be made regarding the effect of entrapment zone position.

- The volume of habitat, defined as a range of salinity values, does not vary with entrapment zone position. Mean depth is lowest when the entrapment zone is downstream and greatest when it is upstream, implying that shallow-water habitat area is greatest when the entrapment zone is in Suisun Bay.
- Phytoplankton biomass and production is enhanced when the entrapment zone is downstream, most likely by the mechanism proposed by Cloern *et al* (1983).
- Abundance of *Eurytemora affinis* is marginally higher when the entrapment zone is below 72 kilometers in spring and significantly higher when the entrapment zone is at 72 to 92 kilometers in fall, compared to other positions.
- Abundance of *Neomysis mercedis* is significantly higher when the entrapment zone is below 82 kilometers than when it is upstream, for all seasons.
- These differences in abundance of *E. affinis* and *N. mercedis* imply a difference in production.
- In years of moderate freshwater flow, striped bass move down into the entrapment zone during larval development. Survival from egg to young-of-the-year is positively correlated with position of the entrapment zone, but since correlations of survival with flow are higher, the relationship with entrapment zone may actually indicate a relationship with flow.
- Delta smelt year class strength may also depend on entrapment zone position, but the relationship is not straightforward.

Relationship of Historical Declines to Changes in the Entrapment Zone

The position of the entrapment zone is related to flows, which have changed substantially over the last decades both in quantity and timing (Nichols *et al* 1986). However, more recent changes in the estuary do not appear to be related to entrapment zone position, as discussed below.

- During 1972 to 1988, when the data analyzed here were collected, mean annual export flows increased by about 3,000 cfs.
- During the same period, no consistent trend in entrapment zone position is apparent, mainly because wide interannual variations in Delta inflow masked the trend due to the increase in exports.
- Most of the measures of biological abundance declined significantly over the period 1972 to 1988. These included chlorophyll, abundances of *E. affinis* and *N. mercedis*, striped bass YOY index, and delta smelt abundance.
- Survival of striped bass from egg to young-of-the-year varied considerably but did not change significantly over this period.
- Most of the measures of biological abundance and, by implication, production were related to entrapment zone position, with highest values when the entrapment zone was below the confluence of the Sacramento and San Joaquin rivers.
- The declines in abundance of these measures cannot be attributed to long-term changes in entrapment zone position because there was no trend in position; in addition, the magnitude of the differences in abundance among different entrapment zone positions was much less than the magnitudes of the declines for many of these measures.
- Entrapment zone position appears important in its relationship with relatively short-term, interannual variation in biological indicators; that is, the long-term trends in abundance are

superimposed on fluctuations in abundance due partly to changes in entrapment zone position.

- For *E. affinis* and *N. mercedis*, the variation of abundance with entrapment zone position is probably not due to changes in exposure of the population to export pumping. The effect of exposure to in-Delta withdrawals is unknown.
- During the entire period 1972 to 1990, the most striking and apparently permanent changes in the entrapment zone have resulted from inadvertent introductions of new species. These are unrelated to characteristics of the entrapment zone other than its suitability as habitat to new species, which would be difficult to predict without knowing the identity of future introductions.

Mechanisms for Variation of Zooplankton and Larval Fish with Entrapment Zone Position

The relationship between zooplankton abundance and entrapment zone position could have a number of possible causes. In this section I attempt to list them and to describe evidence for or against each one. Only one of these relates directly to the position of the entrapment zone; the remainder ascribe the relationship to a correlate of entrapment zone position. When the entrapment zone is downstream, flow is high, phytoplankton abundance is often high, and stratification and presumably net 2-layer flow are strong. The postulated mechanisms include:

1. A similar model to that proposed by Arthur and Ball (1980) and Cloern *et al* (1983) holds for zooplankton: that is, growth is faster in shallow than deep water; therefore the population is larger when the entrapment zone is adjacent to shallow water.

   For: None

   Against: Abundances of *E. affinis* and *N. mercedis* were less at shallow stations in Suisun Bay compared to nearby channel stations.

2. Higher phytoplankton biomass and productivity when the entrapment zone is downstream support more rapid zooplankton growth and therefore higher abundance.

   For: Abundances of entrapment zone species are highest near the peak in chlorophyll. In addition, abundances of zooplankton have been remarkably stable over the last decade (until 1988), suggesting a regulatory mechanism such as food supply.

   Against: Correlations between zooplankton and chlorophyll appear to be artifacts of covariation of each to other variables. Also, there is some experimental evidence that *E. affinis* reproduction is not food limited.

3. Higher input of organic matter to the entrapment zone with high flows results in higher biomass of bacteria and microzooplankton that provides alternative food sources to the zooplankton.

   For: Concentrations of nutritive material and bacteria are higher in the entrapment zone than outside. Whether these change with entrapment zone position and whether they have changed over time are unknown.

   Against: See 2.

4. The observed relationship is an artifact caused by failure of the methods to sample these organisms quantitatively.

   For: None

   Against: Pump samples taken at mid-depth and near the bottom show relatively small differences, suggesting zooplankton should be vulnerable to the net.

5. Zooplankton removal by export pumping or in-Delta withdrawals is enhanced when the entrapment zone is upstream and the zooplankton are more vulnerable to pumping.

   For: Clear relationships exist between outflow and entrapment zone position and between outflow and percent exported. In addition, the centers of populations of entrapment zone species are closer to the pumps and therefore more vulnerable when the entrapment zone is upstream.

   Against: Even with the entrapment zone upstream the amount of zooplankton exported was calculated to be small. However, the actual export rate has not been determined, nor have effects of Delta withdrawals.

6. Behavioral mechanisms for remaining in the entrapment zone are enhanced by the greater strength of 2-layer flow at intermediate (*ie*, less than flood) freshwater inflow rates.

   For: There is ample evidence that tidally mediated position maintenance is common in estuarine zooplankton, and some evidence that it happens in this estuary. There is no information with which to evaluate the effect of variation in the strength of entrapment.

   Against: None

7. Complex circulation in Suisun and Honker bays, caused by interactions of flow and bathymetry, provide a horizontally oriented entrapment mechanism that enhances the more usual vertically oriented mechanism, causing greater trapping of zooplankton.

   For: None

   Against: None

At this point it would be virtually impossible to rule any of these out, but the first three are unlikely to be correct. The lower abundances of zooplankton in shallow water are evidence that shallow water is not an unusually productive location for zooplankton. Furthermore, there is no *a priori* reason to expect higher growth in the shallows, since zooplankton are not generally dependent on light levels for feeding. The lack of food limitation of *E. affinis* in the 1988 experiments is a hint that zooplankton growth and abundance do not respond strongly to increased abundance of phytoplankton or detritus.

There is a possibility that an artifact of sampling produced the results shown. *E. affinis* and *N. mercedis* both remain out of the surface layer at least by day. The sampling method used, oblique tows from near the bottom to the surface, may miss some organisms very close to the bottom. If the vertical distribution changes with light level, then a strongly developed, turbid entrapment zone would result in a higher catch, since the animals would be farther off the bottom. However, light levels appear too low near the bottom to cause a migratory response.

The remaining mechanisms bear further investigation, since they appear to be the most consistent with the available information. The analysis reported above on abundance of *E. affinis* in Old and Middle rivers suggests export pumping is not a major source of losses from the population (Mechanism 5). This also appears to be the case for *Neomysis*. However, the effect of in-Delta withdrawals could be substantial, depending on the timing and location as well as the quantity of withdrawals.

Mechanism 6 implies that either the zooplankton detect and respond to changes in flow, or that their behavioral pattern is designed to maximize entrapment under intermediate to high flows. This seems likely on the basis of the extensive behavioral repertoire of zooplankton, but cannot be resolved with the monitoring data.

Mechanism 7 is also likely to operate. Zooplankton populations are often enhanced near topographic irregularities that result in eddies and other flow complexities (Trinast 1975; Alldredge and Hamner 1980). The circulation of Suisun and Honker bays is complex, and there is reason to believe eddies and tidal pumping and trapping can occur there. As with Mechanism 6, there is no way to resolve this with the data at hand.

Larval striped bass also appear to survive better when the entrapment zone is downstream of the Delta, and delta smelt may have higher year classes when the entrapment zone is downstream. The mechanisms for these relationships probably include those listed above, although some of the specific arguments are different for larval fish. For example, shallow regions of the estuary provide habitat for some planktivorous fish, including delta smelt (Moyle *et al* 1992), so maintenance of the entrapment zone in Suisun Bay, where mean depth is less, would provide more habitat for this species. In addition, the interannual variability in growth rates of larval striped bass may indicate food limitation, so bass growth (and probably survival) would be enhanced when the entrapment zone is downstream. Of the above mechanisms, 1, 2, 5, 6, and 7 all appear reasonable and somewhat supported by the evidence (substituting zooplankton for phytoplankton and fish for zooplankton).

Recommendations

The following recommendations are aimed primarily at improving the utility of the raw data gathered by the Interagency sampling programs. That is, the raw data need to be converted into knowledge.

- Effort should be allocated in equal proportions between gathering data and analysis, with procedures established to ensure timely analysis, reevaluation of usefulness of the data, and incorporation of the new knowledge into an accumulating conceptual model.
- Some effort should be reallocated from monitoring to special studies, either sampling and analysis for particular purposes or experimental work.
- The data storage system should be replaced with a modern relational database or another system more accessible to users.
- Some effort should be expended to determine the importance and role of microbial and microzooplankton activity in processing nutrients and organic matter in the entrapment zone and in providing food to higher trophic levels.

An additional series of recommendations relates to the need for a large-scale field study of the entrapment zone. Such a study was discussed by several Interagency groups in 1989, but may not be warranted until one or two wet years have passed and we can see what happens with the introduced clam. If such a study were to be undertaken, it should be designed carefully to answer at least the following questions.

- 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.

Halocline. In a vertical profile view of the estuary, the line marking the sharpest vertical rate of change of salinity. This can be thought of as a surface separating the upper low-salinity layer from a lower high-salinity layer.

Heterotrophic activity. The rate at which organic carbon is consumed and respired by microorganisms.

Horizontal density gradient. The change with distance along the estuary of mean water column density, which is positively related to salinity and, to a lesser extent, negatively to temperature.

Isolume. Depth of constant light level.

Log transformation. The process of taking logarithms of data so that the data are suitable for parametric statistical testing (*eg,* ANOVA, regression).

Null zone. The location in the estuary at which net landward flow near the bottom ceases and all tidally-averaged flow throughout the water column is seaward. This generally marks the upstream limit of the entrapment zone.

Operational definition of the entrapment zone. Since net flow velocities are difficult to measure except under high-flow conditions, an operational definition of entrapment zone position is required to permit analysis of the effects of entrapment zone position on characteristics of the estuary. The operational definition used here (after Arthur and Ball 1980) is the salinity range of 1.2-6 (specific conductance of 2-10 mS/cm).

Osmotic stress. The physiological stress placed on an organism by changes in salinity of the surrounding water.

Phytoplankton. Planktonic algae, consisting of single cells or chains of cells.

Plankton. Pelagic (*ie,* living in the water rather than on the bottom) plants or animals that are either small or have limited capabilities for motion.

Primary productivity. The rate at which phytoplankton or other plants convert inorganic carbon to organic carbon, usually expressed as carbon per unit volume or area per hour.

Production. The biomass of phytoplankton, zooplankton, or other group that is produced in a given time, usually expressed in terms of carbon per unit area or volume per day or year. It is equal to the product of biomass and growth rate averaged over the population and the chosen time period. Note that the term Productivity (above) is also often used in its more common meaning of capacity or ability to produce.

Regression. A statistical technique for fitting a straight or curved line to a set of data.

Residual. The difference between a data value and the value predicted by a regression line or other statistical model.

Salinity. The concentration of salt in water expressed as unitless numbers approximately equal to parts per thousand salt by weight. In ocean water, salinity is determined from a fairly simple relationship with conductivity at 25°C. In the upper reaches of an estuary, some of the conductivity is not due to sea salt, so the relationship with conductivity changes.

Secchi depth. The depth to which a Secchi disk, a white or black and white disk, can be lowered and just remain visible; a measure of water transparency.

Shear. Variation in the vertical direction of horizontal velocity, as at the bottom or across a density gradient. Shear is the source of energy for turbulence in the water.

Siemen. A unit of conductivity, also known as a mho.

Specific growth rate. The rate of growth of an organism divided by its weight, expressed as a proportion (or percent) per day.

Specific conductance. The electrical conductivity (inverse of resistance) measured in a standard cell, corrected to 25°C, and expressed in millisiemens (mS) or microsiemens (µS) per centimeter of distance.

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.

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