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THE SAN FRANCISCO BAY/DELTA STRIPED BASS FISHERY: ANATOMY OF A DECLINE

by

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I. Introduction

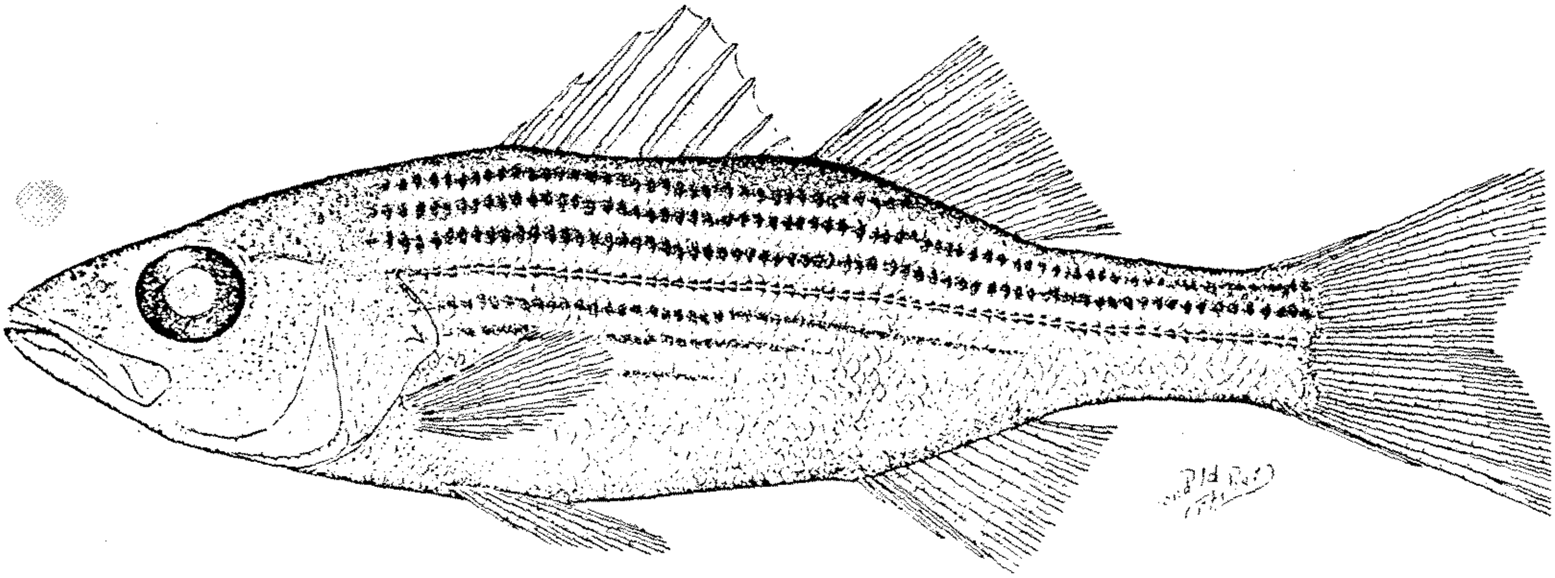
The striped bass population in the San Francisco Bay/Delta estuary has been declining over the past two decades. Though the decline has been studied intensively, the causes are not completely understood. In this report we provide a review of theories about the decline, empirical evidence, and relevant experimental results. We also suggest what sort of research might help us better understand the fishery population dynamics, especially as they are affected by changes in the Bay/Delta hydrological regime. Figure 1 is an illustration of a striped bass.

The next section begins with a description of the striped bass life cycle and its ties to the estuarine food chain. In section III we review the population data, describing sources, estimation techniques, and the recent trends. Section IV is about causes of the decline. We review the existing literature and offer some new hypotheses based on new statistical analyses. Section V provides a kind of summing up, as reflected in the statements of participants in the 1987-88 hearings before the State Water Resources Control Board (SWRCB) on the subject of Bay/Delta water flows and the status of fisheries. In this concluding section, we also indicate how we intend to proceed; the nature of further statistical and simulation modeling we believe can shed light on the impact on the fishery of policies affecting water flows and possibly also of pollution controls and hatchery operations.

II. Life History of the Striped Bass in the San Francisco Bay/Delta Estuary

A. The Bay/Delta environment

The San Francisco Bay/Delta Estuary can be subdivided into four or five regions as shown in Figure 2. The Central Bay is bounded by the Golden Gate Bridge on the west, the Oakland Bay Bridge on the south, and the Richmond-San Rafael Bridge on the north. Below the Bay Bridge is the South Bay. Above the Richmond-San Rafael Bridge is the Northern Reach, which includes



Striped bass, drawn from a specimen 4 inches in standard length.

From "Studies on the Striped Bass (*Roccus saxatilis*) of the Atlantic Coast," a dissertation presented to Yale University in candidacy for the degree of Doctor of Philosophy by Daniel Merriman, June 1938.

Figure 1. The striped bass, as shown in Raney (1952), p. 5. The striped bass is a large fish, ranging up to forty or more pounds, with the average catch around six to ten pounds (Albert, 1987).

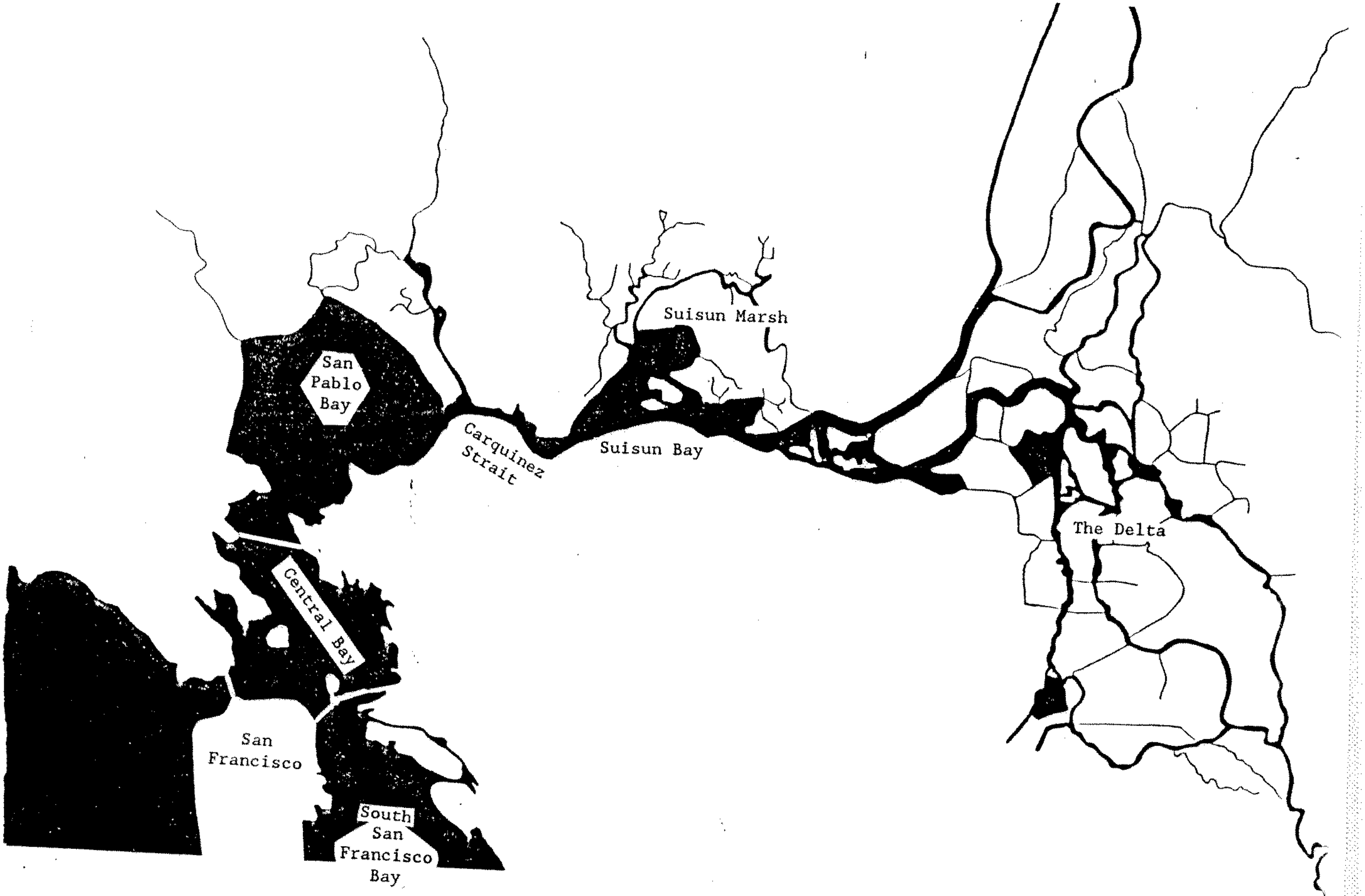


Figure 2. The San Francisco Bay/Delta Estuary.

San Pablo Bay and Suisun Bay. The network of interlaced channels to the east of Suisun Bay is the Sacramento/San Joaquin Delta.

Tidal flows form the dominant currents in the Bay, with freshwater inflow usually having a smaller but still important influence on currents and with wind-generated waves important in mixing. Aside from mixing that can occur between the South and the Central Bay, there is very little freshwater inflow into the South Bay, with most of the inflow coming from Coyote Creek and the sewage outfalls from the South Bay cities. The Northern Reach receives large fresh water inflows from the Sacramento/San Joaquin Delta. This inflow is very seasonal, with most of it coming from winter rainfall and spring snow melt in the mountains. By far the largest part of this inflow comes from the Sacramento River, with the remainder coming from the San Joaquin.

The inflowing fresh water mixes gradually with the salt water of the bay system; and, until it is well mixed, the fresher water forms a layer that floats above the saltier water. The location of the zone of mixing changes depending on the magnitude of inflows. With very high volume inflow, the mixing zone moves downstream into San Pablo Bay or even into the Central Bay. But with very low inflow levels, the mixing zone moves up into the western edges of the Delta. The upstream portion of the mixing zone tends to act to accumulate small particles and drifting organisms and, so, is called the entrapment zone. The position of this zone has an important impact on the ecology of the area and, in particular, the position of this zone in the spring can affect the reproductive success of the striped bass.

B. Striped bass life cycle

Striped bass are voracious predatory fish that, as Raney (1952) summarizes, will eat "practically every marine form found in the San Francisco Bay area." That includes crabs and clams and every kind of fish of a suitable size. The State Water Contractors (1987) report that the important prey species are northern anchovy in the summer and pacific herring in the winter, though most recent reports (Hedgepeth and Mortensen, 1987) mention that the most common prey of adult bass are shad and young striped bass.

Males are mature at two to three years and about 10 inches in length while females mature later at 4 or 5 years and around 16 to 18 inches (Raney, page 34). They can grow to be more than 4 feet long and over 40 pounds. The adult bass follow an annual cycle of migration (Chadwick, 1967). They spend the summer feeding in San Francisco Bay and the nearby areas of the Pacific Ocean. Apparently the cold California Current keeps these bass from undertaking the extensive ocean migrations that have been seen in Atlantic Coast striped bass. In the fall they begin to migrate into fresh water, with many of the adults passing through the San Pablo Bay-Carquinez Strait areas and then spending the winter in the Delta (but not all--adult bass does not necessarily spawn every year). In the winter they are relatively inactive, present in the Delta as shown by net surveys, but seldom caught by fishermen in that season. In spring, as water in the inflowing Sacramento and San Joaquin Rivers warms up, the bass swim upstream to spawn. In the Sacramento River the peak of spawning occurs around 100 miles up river. The spawning run up the San Joaquin is blocked by salinity in the river from agricultural return flows, so the spawning is limited to the lower reaches that receive fresh water due to cross-Delta flows of Sacramento River water drawn toward the export pumps at Tracy (Radtke and Turner, 1967). Most spawning in the San Joaquin occurs in the broad channels between Antioch and Venice Island (see Figures 3 and 4 for a depiction of the Delta and spawning migration). After spawning, the adults return to the salt waters of San Francisco Bay and the ocean.

The fecundity of female striped bass ranges from around 250,000 eggs per newly mature female to over 1 million eggs from an eight-year or older bass (Wang, 1986). Estimated annual production in the San Francisco Bay system is in the order of several hundred billion eggs. The eggs are nonadhesive and slightly more dense than water so the eggs and newly hatched larvae drift downstream with the bottom currents. Where they reach the entrapment zone they accumulate. The eggs generally hatch in two days, and the infant bass are about 3 millimeters long. After hatching, the larvae depend on yolk sac absorption until they reach about 6 millimeters in length. They then begin feeding on the smaller zooplankton. Their mobility is limited at this stage, so survival is dependent on the presence of adequate food nearby. Later on, as the larvae

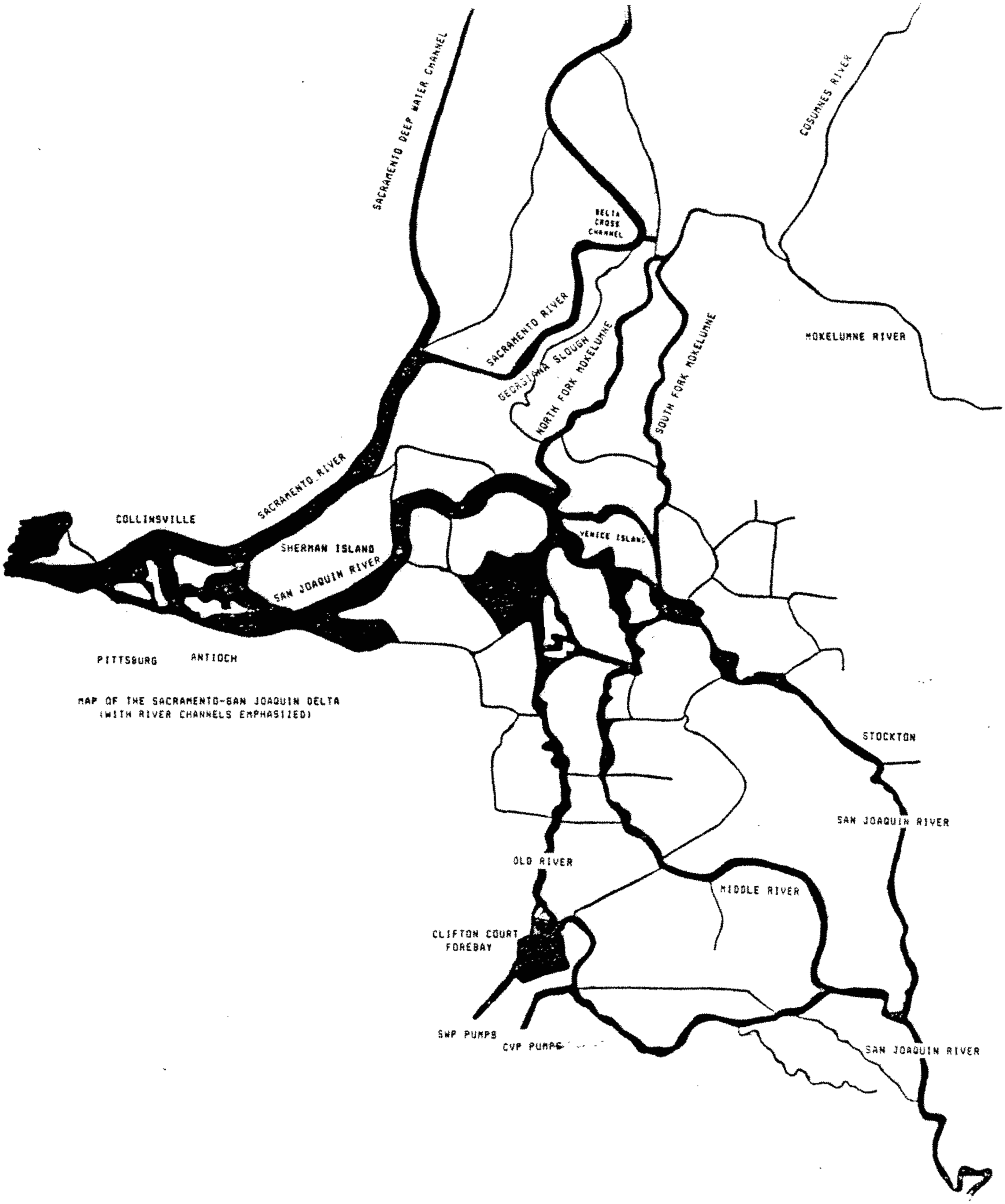


Figure 3. Delta spawning habitat. In the Sacramento River, spawning occurs far upstream, with the peak up past Sacramento. In the San Joaquin River, high salinity blocks the migration of the striped bass, so spawning is confined primarily to the broad channels between Antioch and Venice Island.

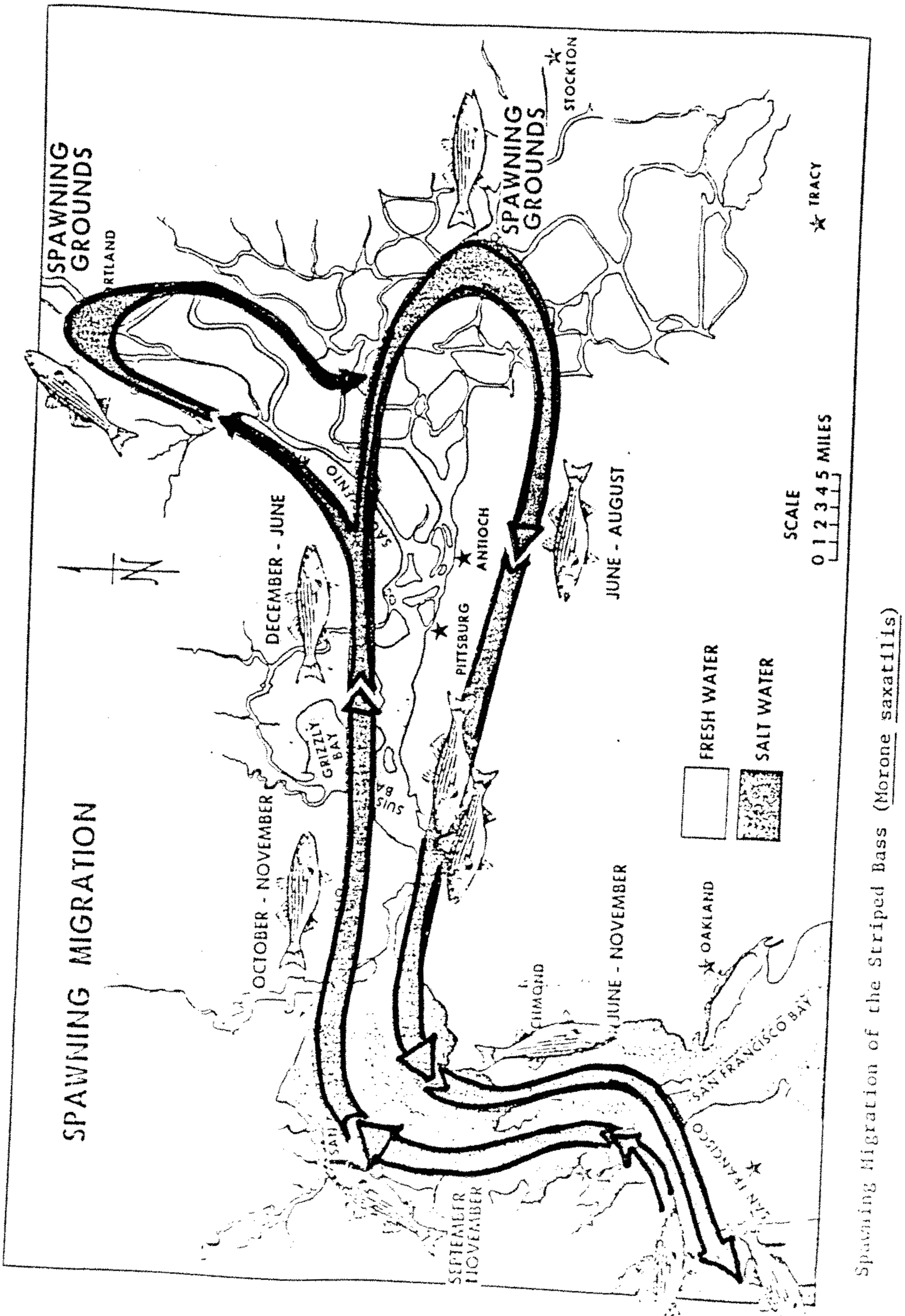


Figure 4. Striped bass spawning migration. National Marine Fisheries Service figure, taken from Hedgepeth and Mortensen (1987), p. 30.

grow they tend to prey on *Neomysis*. But at this early stage, *Neomysis* may prey on the larval bass (Wang, 1986). The combination of spawning habits and hydrology leads to two major striped bass nursery areas—the western Delta and Suisun Bay.

C. Larval food web

A simplified diagram of the young striped bass food chain is shown in Figure 5 Although the bass feed directly on zooplankton, they are ultimately dependent on the production of phytoplankton. The phytoplankton consists of a number of distinct and quite unrelated types of small floating organisms (blue-green algae, green algae, diatoms, dinoflagellates, etc.) that share the characteristic of photosynthesis. The amount of chlorophyll present is a reasonable measure of photosynthetic activity level and, thus, a good measure of primary productivity. The phytoplankton form the primary basis for food chains in the estuary. Populations of phytoplankton may fluctuate rapidly. Under the proper conditions, the numbers of a certain group or species may climb to high levels producing what is known as a bloom. Then, as the supply of nutrients is exhausted, or some other constraint is reached, the population may crash.

In general, the distinction between the types of phytoplankton is not important to the food chain, except to the extent that the size of the phytoplankton is important to the feeding behavior of the higher trophic levels. The term "net plankton" refers to those sizes large enough to be caught in a typical plankton net, and "nanoplankton" refers to smaller sizes that slip through the mesh. But here special mention should be made of the diatom *Melosira granulatum.* According to Ball and Arthur (1979), diatoms dominate the phytoplankton of the area from the Delta through San Pablo Bay. Diatoms are a type of algae that use silica to form a skeleton. They are single-celled organisms, but some types stay linked together as they reproduce and so form colonies in the form of plates or chains. *M. granulatum* tends to form chains. In spring, while at low population levels, it is eaten by copepods and by *Neomysis*; but during a bloom, when the colonies get larger, it is not eaten despite its increased availability. Apparently the chains are too big to be consumed. Since 1980, the increase in chlorophyll-a has been attributed to *M. granulatum* blooms in the

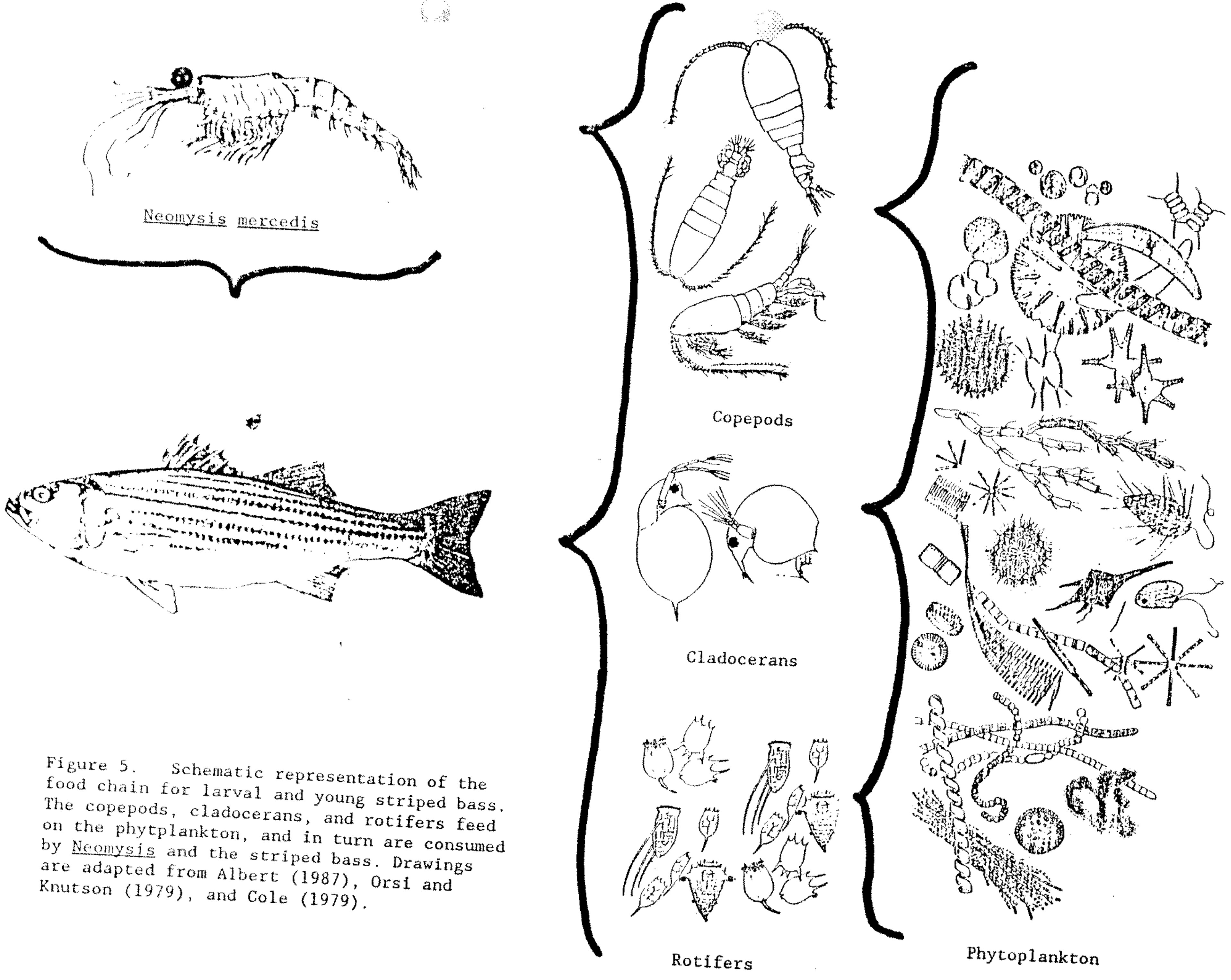


Figure 5. Schematic representation of the food chain for larval and young striped bass. The copepods, cladocerans, and rotifers feed on the phytplankton, and in turn are consumed by <u>Neomysis</u> and the striped bass. Drawings are adapted from Albert (1987), Orsi and Knutson (1979), and Cole (1979).

central and western Delta. So in these cases chlorophyll-a measurements do not give an accurate picture of food availability to grazing zooplankton (Hedgepeth and Mortensen, 1987).

The freshwater zooplankton, in general, is dominated by three types of floating/drifting animals: copepods, cladocerans, and rotifers. Copepods and cladocerans are both types of small crustaceans with adults on the order of 1 to 5 millimeters long. Rotifers are much smaller. The cladocerans, sometimes called water fleas, are confined to freshwater species. Copepods are found in both fresh and salt water, though any particular species is likely to be limited to one or the other or to some range of salinity. Most of the zooplankton feed on the phytoplankton or on detritus, but some species are predatory and will eat smaller zooplankton.

In the Bay/Delta estuary, the opossum shrimp, *Neomysis mercedis,* is the largest in size but the least numerous of the zooplankton (California Department of Fish and Game, 1987b). Over its life cycle, it ranges from 2 to 17 millimeters in length. It eats both phytoplankton and smaller zooplankton while it is small, but, as it gets larger, it eats only zooplankton. *Neomysis* is the most important food item for young striped bass.

The copepod *Eurytemora affinis* is a favored food of larval striped bass, but its population may have been affected by the presence of the introduced Asian copepod *Sinocalanus doerri. Eurytemora* is an estuarine species with its greatest density in the entrapment zone but also ranging up into fresh water. *Acartia* is also an estuarine copepod, but it tends to be more abundant seaward of the entrapment zone. *Acartia* is the only native copepod showing no long-term decline in abundance (California Department of Fish and Game, 1987b).

One frequently mentioned benthic organism is the tube-building amphipod, *Corophium* sp. It is the most abundant benthic macroorganism in the Delta. According to Kelley *et al.* (1966, page 83), *Corophium* was found to be a common food item of young bass; but, because of the small numbers and the small size, their overall contribution to the bass food supply was considered negligible. The other benthic organism that comes up in the literature is the bivalve, *Mya arenaria,* an edible clam that Nichols (1985) suggests may have been responsible for increased benthic grazing in Suisun Bay during the 1976-1977 drought.

D. Ecology of Suisun Bay

Now that we have presented an overview of the striped bass life cycle and food web, we discuss the separate geographical habitats, starting with Suisun Bay. To understand the ecology of Suisun Bay, particularly in the spring, one must understand the impact of the entrapment zone. The entrapment zone is an area of increased turbidity that is caused by the pattern of mixing of fresh and salt water. At the upstream end of the estuary, the water is completely fresh, but at the ocean end it is salty. In between, there is a region of partial mixing where the lighter, partly fresh water overlies the more dense salty water. The salinity gradient creates a density driven current that moves salt water landward along the bottom while the partly mixed brackish water moves seaward in the surface layer (see Figure 6). Any material that tends to sink would be moved landward in the bottom current to its upper end. That upper end of the salinity gradient is thus known as the entrapment zone because certain materials tend to accumulate there.

The entrapment zone moves up and down the estuary depending on tidal flows and changes in inflow. High inflows push the zone downstream toward the ocean, and lower inflows allow it to move inland (see Figure 7). At low flow rates, the stratification of fresh water over salt water becomes less pronounced and the zone shrinks and becomes weaker. Increased turbulence from tides or winds also tends to weaken the zone. The zone does not trap all suspended material, only material with a certain rate of sinking. Light material does not sink and so is swept downstream. Heavy particles sink to the bottom. Only intermediate particles which are dense enough to sink out of the upper layer of water but light enough to remain suspended are trapped.

Although Horne (1987) seems to dispute this, most researchers seem to view phytoplankton as the basis for productivity in the estuary (see Williams and Hollibaugh, 1987). Arthur and Ball (1979) note that the production of phytoplankton appears to be enhanced when the entrapment zone is located in upper Suisun Bay. In more recent accounts, Cloern *et al.* (1983 and 1985) describe the phytoplankton dynamics of Suisun Bay. In general, the availability of light and of certain inorganic nutrients controls the growth rate of phytoplankton, and the amount of predation can

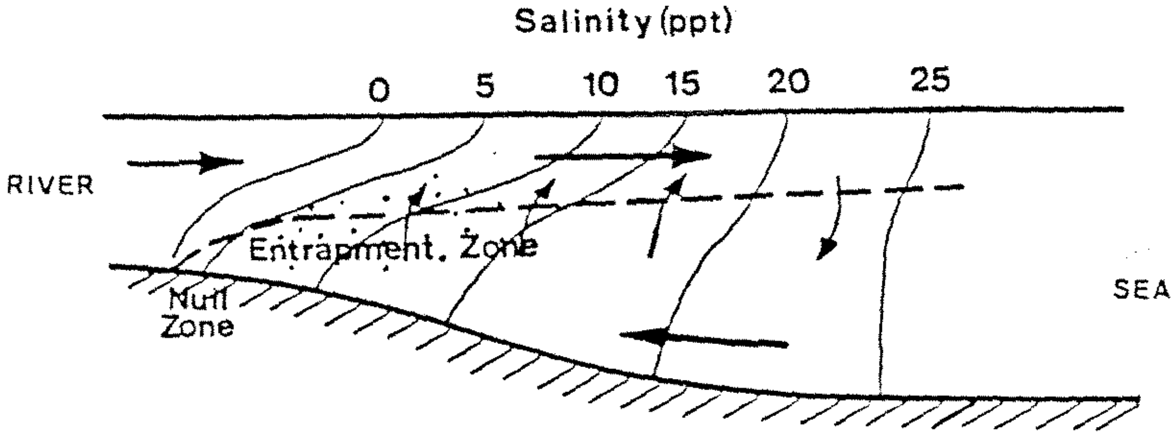


Figure 6. Entrapment zone schematic, from Williams and Hollibaugh (1987) (their figure 12). In the zone of mixing, the fresher water flowing into the estuary forms a layer above the more dense saline water. Tidal currents move both layers in and out twice a day. But in addition, there is a net seaward movement of the upper fresh water layer. As mixing occurs, this upper layer increase in volume due to the incorporation of more saline water into the partly fresh water, and thus has a volume greater than the total freshwater inflow. So to keep the flows in balance as the fresh layer moves seaward, there must be a compensating landward flow of the lower saline layer. This compensating flow runs from the seaward end of the mixing zone to the freshwater end. The upper end of the return flow, where the landward flowing saline bottom current meets the seaward flowing fresh water bottom current, is thus an area with zero net flow.This is the area known as the null zone, and it marks the upstream end of the entrapment zone.

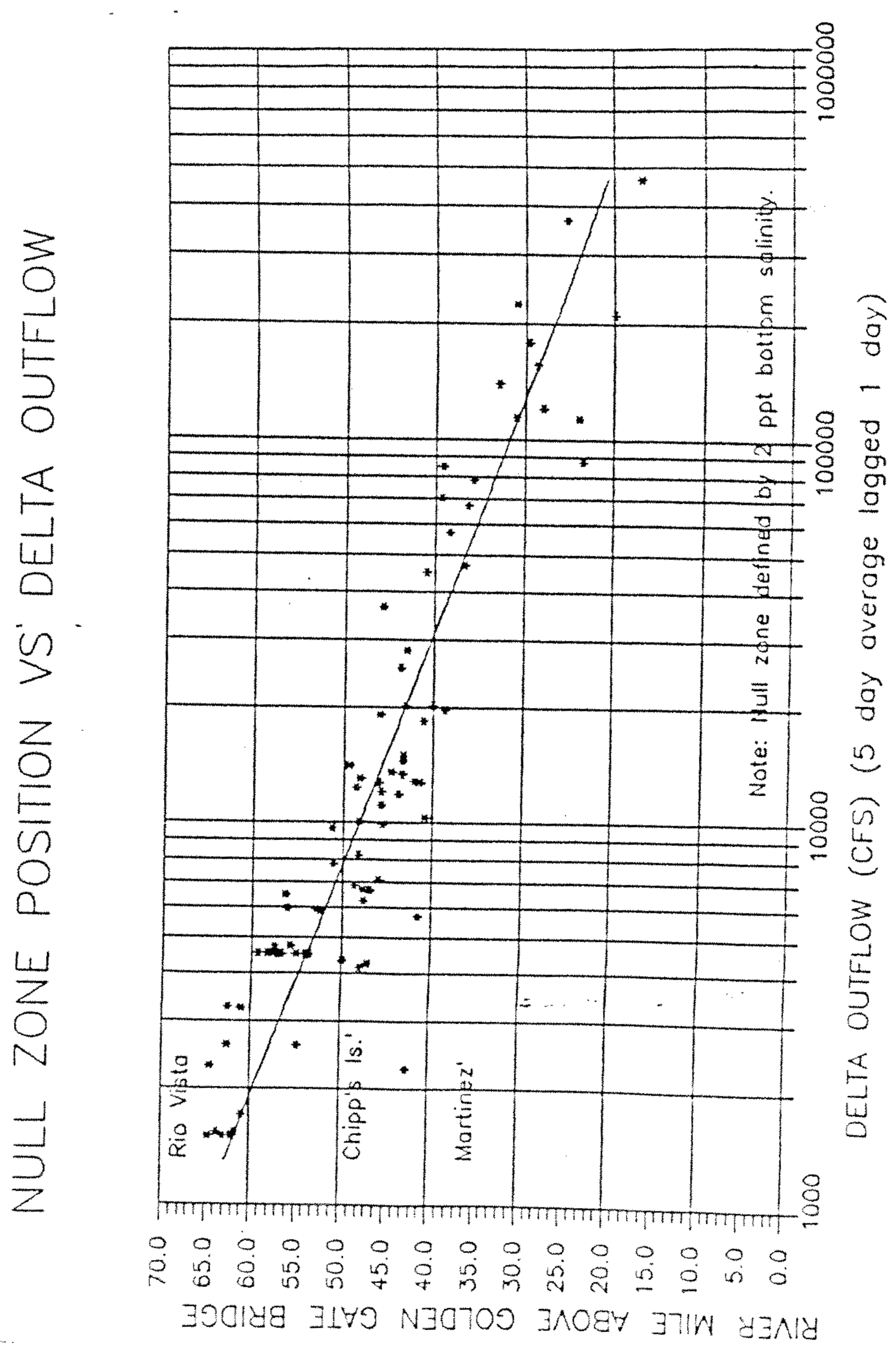


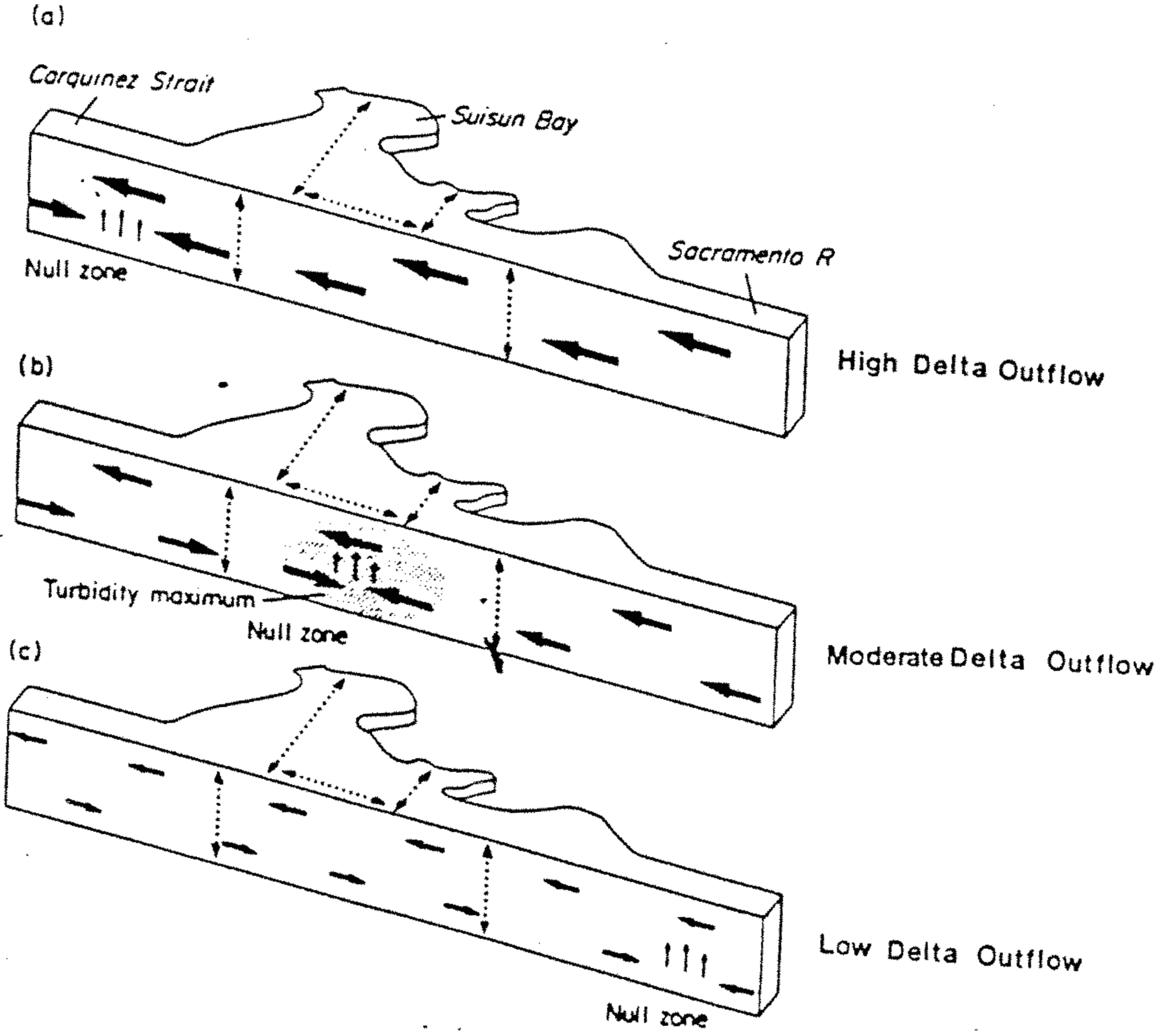
Figure 7. Taken from Williams and Hollibaugh (1987) (their figure 23).

affect the size of the standing crop. In addition, in moving water the residence time becomes important. In order for a large standing crop to develop, the growth rate of the phytoplankton must be greater than the rate at which the flow carries away the stock.

The concentration of nutrients in the estuary is generally high enough not to be limiting. The estuary is turbid and the turbidity is caused by river inflow, so light availability can be limiting. Residence time is also important. Cloern *et al.* (1985) describe the different regimes in three areas: South Bay, San Pablo Bay, and Suisun Bay. All three areas have deep channels flanked by broad shallow areas. South Bay is far removed from river inflow so that it has low turbidity and a long residence time and growth rates are high. But benthic grazing keeps the standing crop low. By contrast, Suisun Bay is close to the river inflow and, so, is turbid. This limits the growth rate of the phytoplankton, particularly in the channels. But the shallow areas have enough light penetration to sustain a modest rate of growth. The problem here is the residence time. The growth rate is not high enough to compensate for the loss of stock from the flats out to the channels. But when when the entrapment zone is located in that region, diatoms are caught and cycled back onto the flats so that a standing crop can develop (see Figure 8). It is possible that the dominant diatom species in this area is determined by the sinking rates, with production being dominated by those diatoms whose sinking rate is most appropriate for being caught in the entrapment zone.

The hypothesis of Cloern *et al.* (1983) is that the dynamics of river discharge exert a controlling influence on the phytoplankton population of Suisun Bay. When outflow is in a range that positions the entrapment zone adjacent to the shallows of Suisun Bay, then the standing crop of diatoms increases. If the entrapment zone is not in that area, then the standing crop is low.

Orsi and Knutson (1979) note that the opossum shrimp, *Neomysis mercedis,* is most abundant in the entrapment zone; but they are not sure whether this is because they are concentrated there by hydrological forces or because that area is somehow optimal for them. They found that *Neomysis* populations were positively correlated with chlorophyll-a and outflow. Knutson and Orsi (1983) found in a 14-year study (1968-1981) that the highest *Neomysis* densities occurred in



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

Figure 8. From Cloern et al. (1983), p. 422. According to some researchers, productivity in Suisun Bay is enhanced when moderate Delta outflow positions the null zone in the area of Suisun Bay.

the 1.2 to 4.6 percent salinity range, which corresponds to the entrapment zone, and that populations declined progressively outside of that range. Laboratory tests and field reports indicate that *Neomysis* can tolerate much grater salinity so that concentration in the entrapment zone is most likely due to circulation patterns and the shrimps' habit of vertical migration over the tidal cycle.

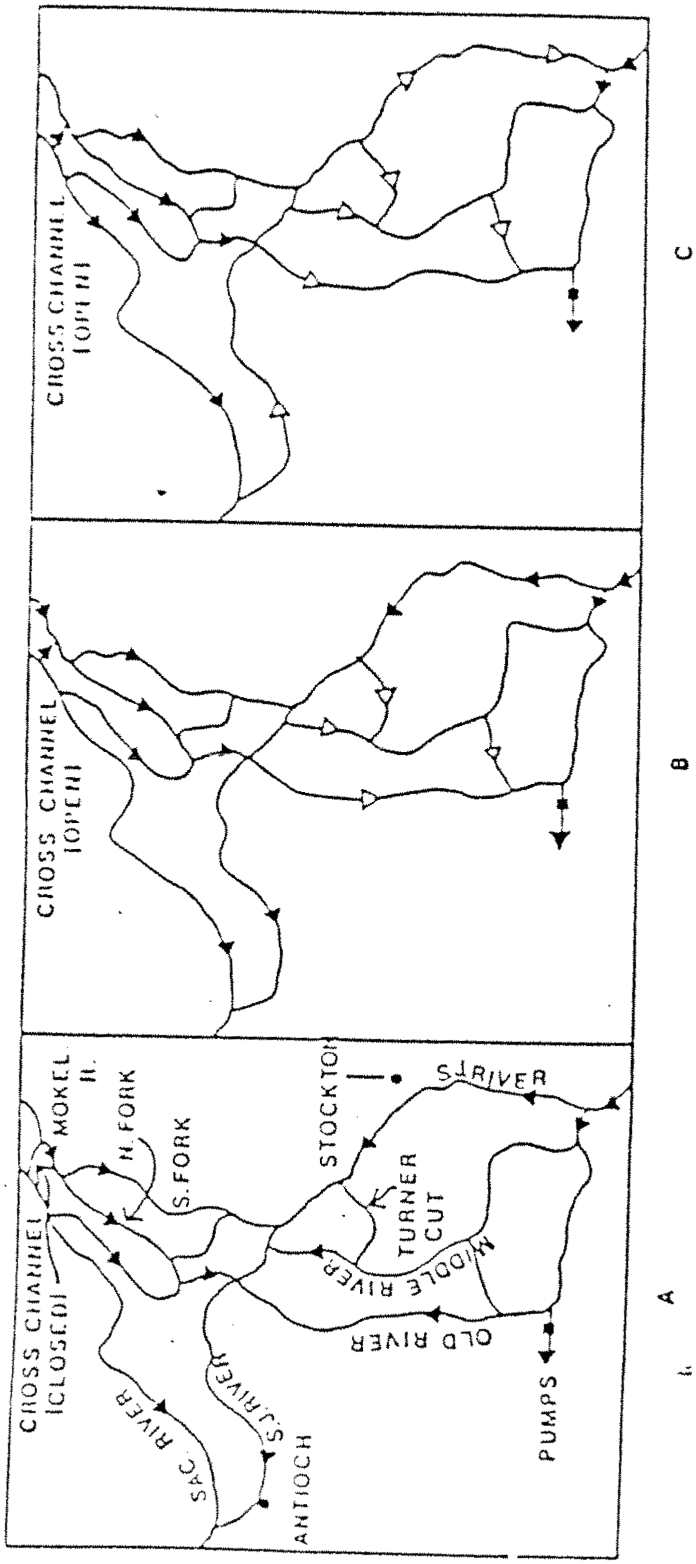
Knutson and Orsi note that the highest *Neomysis* populations "occurred in eastern Suisun Bay and the western Delta, from Chipps Island up to Collinsville in the Sacramento and to Antioch in the San Joaquin River. This is an area of deep, broad channels." High net water velocities form hydrologic barriers to the movement of the shrimp. Thus, "the effect of diversions is to render the east and south Delta and the San Joaquin River at the mouths of Old and Middle Rivers unsuitable for *N. mercedis*" (page 484). And high temperatures combined with low oxygen levels also block the shrimp. The effective habitat for the shrimp is confined to the area between the lower end of the entrapment zone and the high flows in the Sacramento above Rio Vista and Antioch in the San Joaquin, below the interior Delta channels that carry the cross-Delta flows (see Figure 9). Thus "The upstream shift in population associated with salinity intrusion reduced abundance" (page 483), by reducing available habitat.

Knutson and Orsi (1983, page 482) calculated the following linear regression equation for an index of *Neomysis* abundance, Y:

$$Y = 5.264 - 0.264 * X1 + 0.017 * X2 - 0.009 * X3 + 1.066 * X4$$

	X1	X2	X3	X4
t statistics:	-6.012	0.424	-2.176	3.497

with $R^2 = .96$; and where X2 is conductivity (as a measure of salinity), X2 is the chlorophyll-a concentration, X3 is water diversions in cubic meters per second, and X4 is an index of the copepod *E. affinis*–one food source for *Neomysis* One problem with using this equation to predict *Neomysis* abundance is that one needs to be able to predict the index for *E. affinis*. The



Net flow direction in important delta channels during A) normal downstream flow, B) cross-delta flow, and C) reverse flow.

Figure 9. From Orsi and Mecum (1986), p. 329. The arrows represent the net flw directions in the various Delta channels during three different flow regimes. The solid black arrows represent channels with normal downstream flow. The white arrows show channels where the flow has been reversed due to pumping to export water from the Delta.

authors explain that the surprising low coefficient on the chlorophylla term is probably due to the fact that chlorophyll-a is highly correlated with *E. affinis* populations. Phytoplankton is important not only as a food for *E. affinis* but also as food for *Neomysis* neonates. In conclusion, they point out that the low *Neomysis* populations since 1976 appear to be related to salinity intrusion and reduced food supply. They suggest that keeping the entrapment zone adjacent to the shallows of Suisun Bay during the summer would enhance *Neomysis* populations by providing a large habitat and an adequate food supply.

While it seems clear that positioning the entrapment zone in Suisun Bay increases the phytoplankton and *Neomysis*, it is less clear (or not at all clear) that it has a similar effect on copepods or cladocerans. According to the California Department of Fish and Game (1987b, page 81), "Only *Neomysis* appeared to have its abundance affected by the position of the salinity gradient but all species will have their distribution affected by it." It is unfortunate that we cannot locate any statement of the relationship between the entrapment zone and copepod and cladoceran populations since they are key parts of the striped bass food chain, but none of the reports have dealt with that topic directly. Almost by assumption, the cladoceran populations in Suisun Bay are controlled by the location of the salinity gradient since they are fresh-water organisms. The case of the copepods is less clear since, when the salinity gradient is further upstream, the salt-water copepods can move up into Suisun Bay to replace the brackish water and fresh-water species. One could assume that the increased standing crop of phytoplankton that is found when the entrapment zone is in Suisun Bay would be favorable to the zooplankton there and that the increased residence time fostered by the entrapment zone would also favor increased zooplankton populations, but with the exception of *Neomysis* we have not found that assumption confirmed (or discussed) in the literature.

There is one other way that outflow may affect the Suisun Bay food supply, at least in certain years. Nichols (1985) has described how the population of benthic invertebrates in northern San Francisco Bay underwent a dramatic increase in the drought year of 1977, presumably because the increased salinity made the area more suitable for the bivalve, *Mya arenaria*, and other species.

Nichols has shown that the increased benthic grazing could account for the unusually low phytoplankton biomass in Suisun Bay that year. The reduction in phytoplankton density could have had an impact on higher trophic levels such as *Neomysis mercedis* and, in turn, on striped bass populations. This effect is unlikely to occur except in prolonged low flow periods. And, as Nichols points out, it is not possible to distinguish the impact on phytoplankton from the effect of an upstream movement of the entrapment zone.

E. Ecology of the Delta

There is a different pattern of plankton dynamics in the Delta. As described by Ball and Arthur (1979), the standing crop of phytoplankton in the Delta is greatly influenced by residence time and by what flows into various parts of the Delta. The Sacramento River flows into the northern Delta, and it has low chlorophyll concentrations to begin with. That water flows through the northern and western Delta fairly quickly in relatively deep channels, so phytoplankton levels remain low. By contrast, the San Joaquin flows into the Delta more slowly carrying a rich load of nutrients along with a larger initial load of phytoplankton. The result is that the southern part of the Delta has generally higher phytoplankton levels. If no export pumping took place, the central and western Delta would probably also have high phytoplankton levels resulting from high residence time of the rich, slow-moving San Joaquin water. But export pumping in the spring and summer draws essentially all the San Joaquin flow directly to the pumps and also draws relatively unproductive Sacramento River water through the central Delta, in what is known as cross-Delta flow, and through the western Delta when reverse flows occur (See Figure 10).

The result is that the highest concentrations of phytoplankton in the Delta are found on the San Joaquin River near Stockton, and the concentration is inversely related to flow (Ball and Arthur, 1979). Data on the period 1969-1985 reveals that there has been a general decline in Delta phytoplankton concentrations since 1970 (California Department of Fish and Game, 1987b, page 16), with the largest declines occurring in the upper San Joaquin. Stevens *et al.* (1985) mention that there was a prominent spring bloom in the western Delta above the junction of the

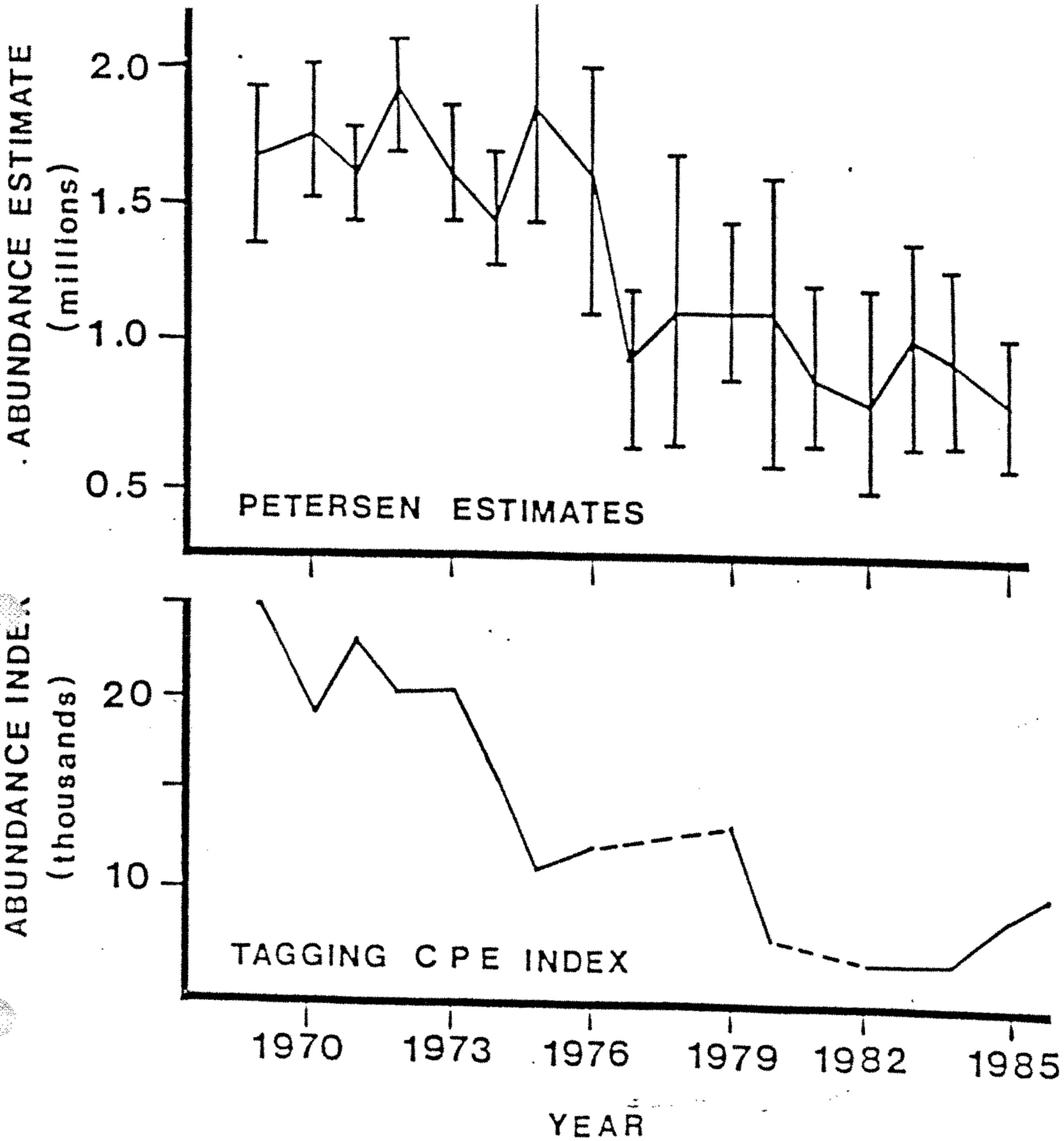


Figure 10. Population estimates of adult striped bass. The vertical bars in the Peterson estimates represent 95% confidence intervals. The dashed portions of the CPE index graph represent periods when the index was not calculated. Taken from DFG (1987a), p. 9.

Sacramento River and the San Joaquin River every year until 1977. They report that since then there have been only two notable spring blooms and both occurred just after the State Water Project (SWP) pumps were shut down for repairs. This suggests that the decline in phytoplankton in the Delta may be related to increased export pumping. Orsi and Mecum (1986) mention in passing an alternative hypothesis, that the decline may be related to reduced organic loading due to improved waste water treatment.

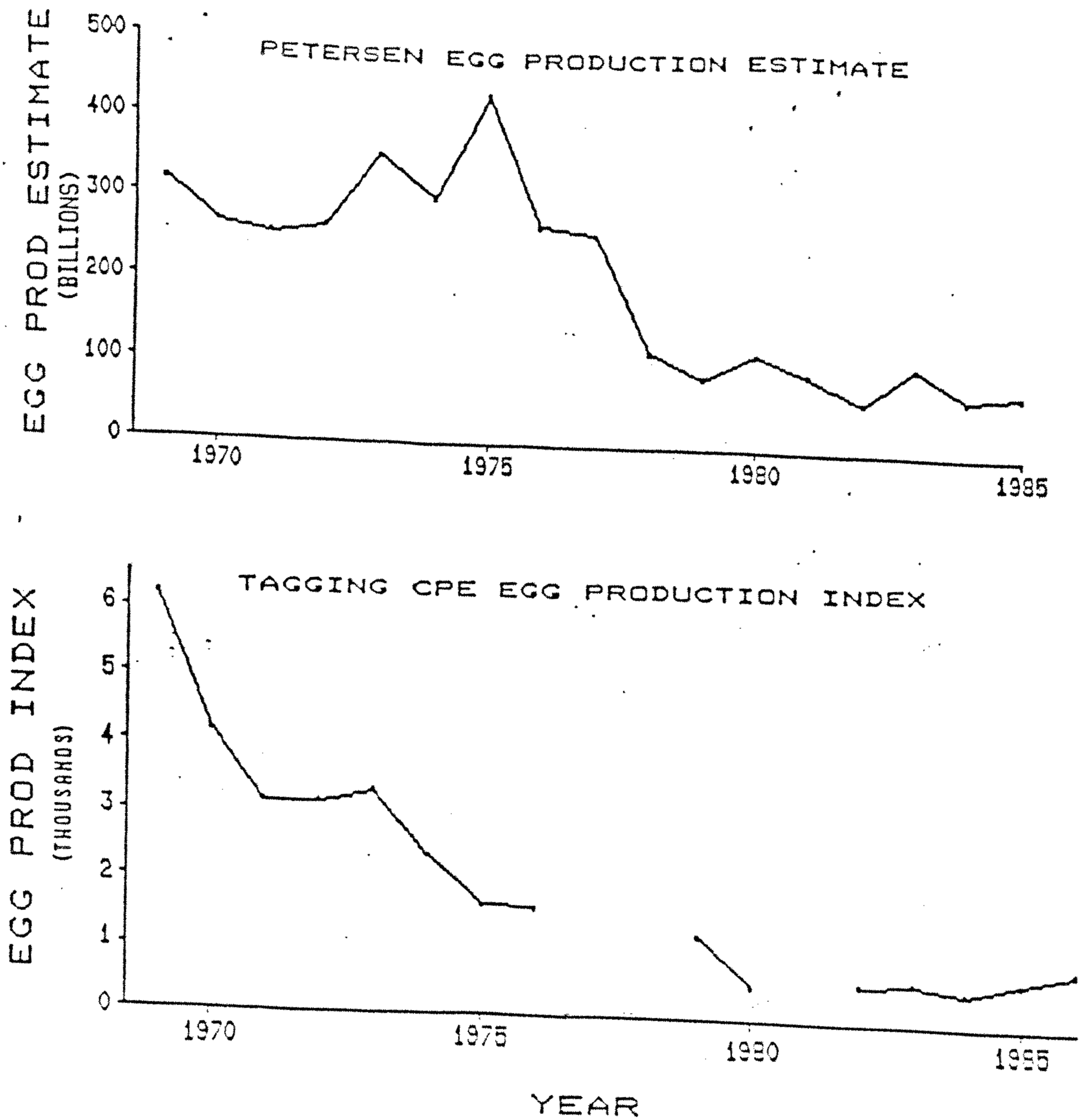
One would expect that the abundance of zooplankton would be related to the distribution of the phytoplankton. Orsi and Medum examined data from 1972 to 1978 and found a "statistically significant correlation between zooplankton densities and chlorophylla concentrations . . . " in the Delta. All species except one were also positively correlated with water temperature. This probably reflects the way temperature affects zooplankton egg development and growth. All freshwater zooplankton species were most abundant in the San Joaquin River near Stockton where the highest temperatures and chlorophyll concentrations are found.

Orsi and Mecum discuss the way the rate of water movement is an important determinant of zooplankton density in the same way that residence time is a determinant of the size of the phytoplankton standing crop. They explain that "if population size is to increase, the reproductive rate of zooplankton must exceed the advective rate of the water. Perhaps the most meaningful way of measuring advective rate is to consider the 'age' of the water, that is, how long it has been moving down a channel" (page 337). So, slower moving water may be expected to have more zooplankton and the "age" of the water may be related to population density. They point out that no species in the Delta was found to be significantly correlated with water velocity; but they explain that this is probably because, in the Delta, water velocity is not a good measure of water "age." Thus, they did not really answer the question of whether cross-Delta flows have reduced zooplankton levels in the central Delta; and, in fact, their report does not point to any data on months when there was not cross-Delta flow. They did note that "The influence of cross delta flow could be seen in the depressed concentrations in the San Joaquin River at the mouth of the Mokelumne River, where Sacramento River water first enters the San Joaquin" (pages 329 and

330). They tried to examine the effect of reverse flows on zooplankton in the lower San Joaquin River but could not separate that impact from the impact of high salinities which would exist even in the absence of reverse flows. They seem to feel that the low zooplankton densities found in the lower San Joaquin are, in theory, at least partly due to reverse flows but that the existing data cannot confirm or deny this. Cross and reverse flows are illustrated in Figure 11.

One interesting point revealed by this study was that the lowest recorded densities of freshwater zooplankton came during the drought year of 1977 at all stations except Hood on the Sacramento River. Hood was upstream of the influence of salinity intrusion, and the reduced flow that year meant that Hood experienced higher temperatures and higher chlorophylla levels than normal as well as lower net velocity. So the plankton population was higher that year at Hood instead of lower. On the San Joaquin, Stockton was also upstream of the salinity intrusion that year but chlorophylla was down during the drought as compared to the wet year, 1974, so zooplankton was also down. "Zooplankton abundance appeared to respond to the change in chlorophyll-a more than to any other variable" (page 335).

The California Department of Fish and Game (DFG) zooplankton report is not a complete analysis of the more recent data but it does note that "the patterns of zooplankton distribution and abundance in the Delta from 1972 to 1978 reported by Orsi and Mecum (1986) have not changed. . . . The long-term downtrends observed for most native zooplankton taxa are, for the most part, statistically related to chlorophylla which has also experienced a decline" (California Department of Fish and Game, 1987b, page 81). This report discusses the water movement question that Orsi and Mecum looked into in relation to cross-Delta flows and, in particular, compares 1979 to 1984. "Changes in pumping rates from 3,500 to 9,500 cfs as occurred during July and August of 1979 to 1984 should have caused large changes in net velocities in Old River, yet there was no perceptible effect on zooplankton densities. This may be because net velocities even at 3,500 cfs are so high that no significant reproduction can occur between the entrance of the water at the Delta cross-channel and the sampling station near Rock Slough. In that case zooplankton abundance in Old River may simple reflect its abundance wherever the water originates" (page 82).



Annual indices of striped bass egg production based on age-specific fecundity (Table 6) and Petersen and CPE measures adult bass abundance. Both indices indicate that egg production declined substantially from the late 1960s and early 1970s to the mid-1980s.

Figure 11. Taken from DFG (1987a), p. 41.

In addition to the general decline in zooplankton density, there has been a change in species composition. *Sinocalanus* is an introduced copepod that was first reported in this area in 1978, and it has increased substantially since then (California Department of Fish and Game, 1987b, page 34). At the same time, populations of the copepod *Eurytemora affinis* has undergone a relative decline. *Eurytemora* is a preferred food item for larval striped bass, but *Sinocalanus* is generally avoided. The result is that, even if zooplankton densities remained constant, this shift in species composition may have had an adverse impact on the striped bass larvae. It is not clear whether the food needs of the striped bass larvae are so specific that this could be important. "Nonetheless, the close association between *Eurytemora* abundance and larval bass survival from 1984 to 1986 indicates a need for a closer look at the importance of *Eurytemora*" (California Department of Fish and Game, 1987a, page 102).

III. Striped Bass Population Measurement and Trends

A. History of striped bass in the San Francisco Bay area

The striped bass was introduced to the Bay in 1879, and an important commercial fishery developed in a surprisingly short time. From 1890 to 1915, the annual catch was around one million pounds. The catch gradually fell off to about half that amount by 1935, when the commercial fishery was ended in order to protect the striped bass for sport fishing (Smith and Kato, 1979). The commercial fishing had been mainly with nets in the San Joaquin River. In the earlier years of the sport fishery, most angling took place in San Pablo Bay and upstream, but by the 1960s most striped bass fishing had shifted to north San Francisco Bay. Raney (1952) considered that the population had stabilized, at least through the late 1940s The annual sport catch now ranges from 100,000 to 400,000 bass. The early fishing limit was five bass at least 12 inches long. That was changed to three fish at least 16 inches long in 1956 and then in 1982 changed to a two-fish limit at 18 inches long in response to declining stocks.

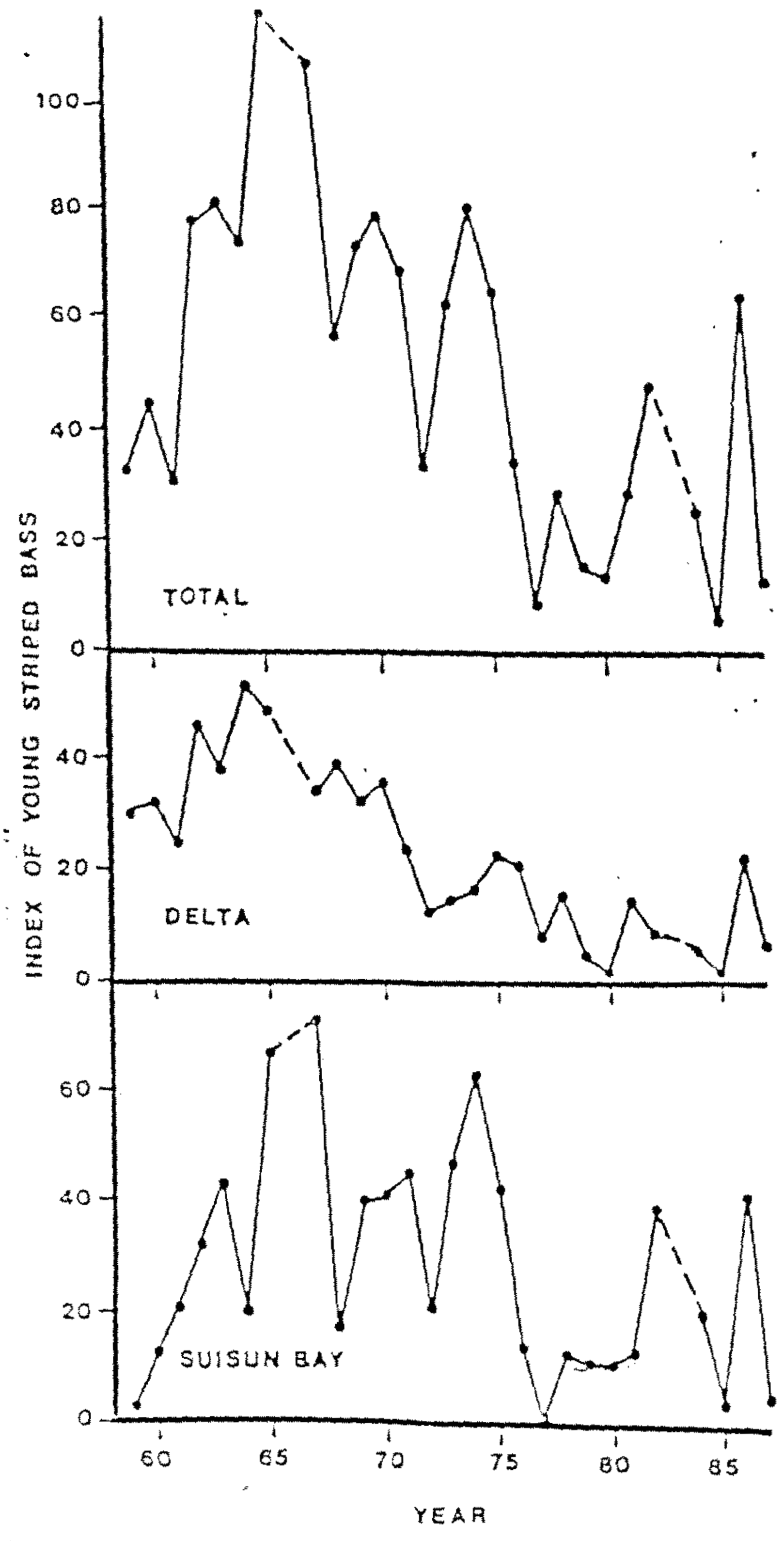
B. Adult population

Information on adult striped bass abundance is available from a number of different sources over various time periods. While none of these is perfect, in combination they draw a picture of a bass population that has clearly been declining from the levels of two or three decades ago. The earliest records are on the commercial catch during the period 1890 to 1935 (Smith and Kato, 1979). There seems to have been a general decline from a peak at 1900 of almost 1,000 tons of striped bass to a stable annual catch averaging around 300 tons from 1920 to 1935. This might imply a decline in the bass population; but, since the fish had only been introduced to this area in 1879, this change in catch may only reflect population shifts as the Bay system became accommodated to the bass.

When commercial fishing was halted in 1935, efforts were undertaken to monitor sport angling success. Stevens (1977a) gives a good description of these methods. A postcard survey of fishermen (sent to random buyers of fishing licenses) was begun in 1936 and continued intermittently for at least 40 years. Since 1938, party boat operators have been required to report on bass catch success. Neither method directly addresses the question of bass populations, and the changes in fishing methods and in fishing regulations over the years create additional problems when interpreting this data.. Most recent sources only cite the catch statistics from around 1958 or 1960 to the present since the change in catch limits in 1956 makes it difficult to compare the catch in the 1940s and 1950s to the catch in later decades. There is also the problem that poor angling success rates tend to decrease the amount of fishing. Nonetheless, these are the longest historical records relating to bass abundance, and they may be of some use in conjunction with data derived from other methods. Over the last 25 years, the charter boat catch has fallen from 50,000 or more to 10,000 or less and the catch per angler-day has fallen from around 1.0 to about 0.5 (California Department of Fish and Game, 1987a) Another catch-based estimate is an index drawn from DFG inspections of anglers' catches in the Bay area. This creel census index has been produced since 1969, and it shows a decline similar to that of the charter boat catch (California Water Resources Control Board, 1982).

There are also two more "scientific" methods that have been used since 1969 by the DFG: Petersen population estimates and the "catch per effort" index. In the latter, striped bass are caught by two different methods–fyke traps and gill nets–and the results are standardized to reflect the same amount of fishing effort by the DFG each year. This does not give a direct estimate of the numbers of striped bass, but it does give an index which should reveal changes in the population over time. In conjunction with this effort, a large number of the bass are tagged before release. Then the number of tagged fish in the following year's catch can be used to estimate the absolute size of the population by using Petersen's method. It is assumed that the proportion of tagged fish in the next year's catch is the same as in the population as a whole, so that the total population can be estimated by multiplying the number of tagged fish by a factor calculated from the proportion of tags in the following year's catch (Stevens, 1977a). Because of the small number of tagged fish that are re-caught, this method is considered statistically less reliable than the catch-per-effort index but it has the virtue of being an actual population estimate rather than just an index of relative change in the population. As shown on Figure 12, the catch-per-effort-index declined by two thirds from the early 1970s to the early 1980s, then recovered slightly in 1985-86. The Petersen estimates declined from around 1.7 million to less than 1.0 million over that same time period (California Department of Fish and Game, 1987a).

These abundance measures are also discussed in Stevens *et al.* (1985). To summarize these reports, while the exact magnitude of the striped bass decline is not clear and the timing of the decline is also subject to different interpretations we do know that populations are much lower now than in 1974. The DFG has signed an agreement with Pacific Gas & Electric Company (PG&E) recently, and another with the Department of Water Resources (DWR) in December of 1986, for mitigation of striped bass losses to entrainment; and this mitigation will include stocking of bass from hatcheries as well as facilities to "grow out" the bass that are salvaged at the Skinner fish facility on Clifton Court. The DFG also began stocking yearling bass in the Delta in 1984 in a separate program funded by a special striped bass stamp fund (Brown, 1986). According to the DFG (1987a), more than two million bass have been stocked between 1981 and 1986 and



Annual index of young striped bass abundance by area in the Sacramento-San Joaquin Estuary. Young bass suffered an unsteady but persistent decline from the mid-1960s to 1985. The decline was most pronounced in the Delta, but also is clearly visible in Suisun Bay despite greater year-to-year fluctuations there. In 1986 young striped bass abundance rebounded to its highest level since 1975. No sampling was conducted in 1966 and the 1983 index was omitted because extremely high flows transported most young bass downstream from the area effectively sampled by the tow net survey

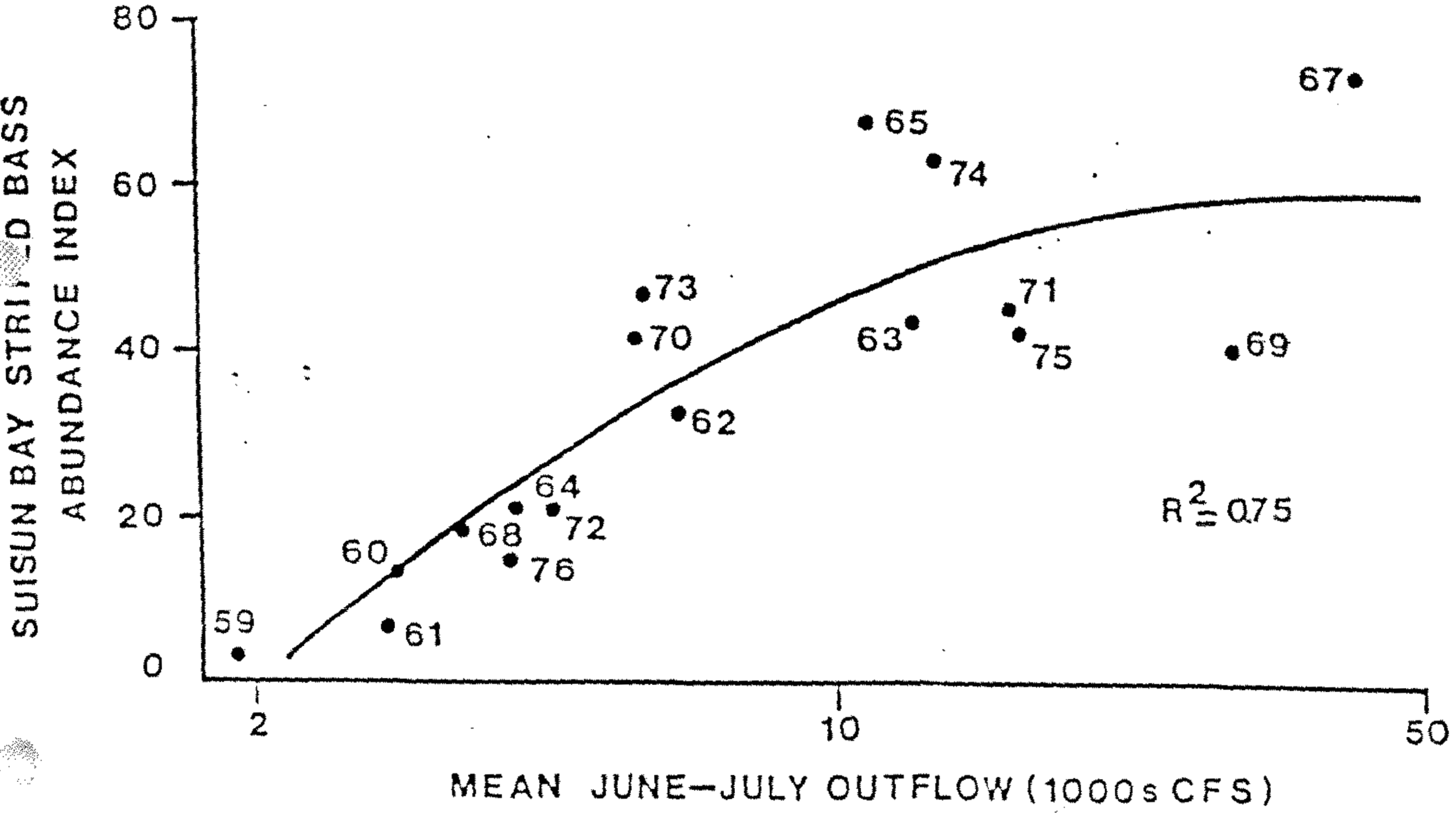
Figure 12. Taken from DFG (1987a), p. 29.

stocking continues at a rate over one million hatchery bass per year. Preliminary analysis indicates that around 15 to 20 percent of these bass survive to be recruited to the fishery at age three.

C. Measures of fecundity

There are two basic ways in which the annual production of striped bass eggs can be estimated. The first is the fecundity method which is based on measures of populations of adult bass. The second is direct measurement of egg numbers. The former method has been used by the DFG to produce annual egg production indices from 1969 to the present. It involves a three-stage process. First the number of mature females in each age class is estimated, either directly from the Petersen estimates or in the form of an index from the catch-per-effort index. Then the age-specific fecundity is estimated for each age class in terms of eggs per female and adjusted for the number of young female bass that either may not be mature or may not participate in the spawning migration. Finally, the estimated numbers of eggs are summed across all age classes. This produces either an egg production estimate (from the Petersen data) or an egg production index (from the CPE data) (California Department of Fish and Game, 1987a, page 39). In either case, these estimates show that there has been a large decline in egg production over the last 15 years (see Figure 13).

There are some problems with these estimates. For one thing, it is known that female bass in this estuary have a higher rate of egg resorption than in other areas, but no correction for this factor was included in these estimates. Of course, the indicated correction would not affect a trend in egg production. Another factor involves the reduction in the numbers of older females. The older females generally carry more eggs than younger ones do, but they have been less abundant in the population in recent years (Brown, 1986). Because so few of these older fish have been tagged, the confidence intervals for their population estimates are very broad. There has been some speculation that the reduction in numbers and the generally poor condition of older fish may be due to toxics and related stress (Whipple *et al.*, 1983).



Relationship between young striped bass abundance in Suisun Bay and Sacramento-San Joaquin Delta outflow from 1959-1976. Predicted index = -670 + 315($\log_{10}$ mean daily June-July Delta outflow) - 33.9($\log_{10}$ mean daily June-July Delta outflow)^2. All flows are in cubic feet per second. No change in this relationship is apparent after 1970.

Figure 13. Taken from DFG (1987a), p. 35.

The direct measurement of egg numbers (or of larval bass numbers) would involve sampling the number of eggs (or larvae) in a given volume of water and then extrapolating from a number of samples to the total volume of water to get to an estimate of the total number of bass eggs (or larvae). However, it is very difficult to effectively sample for the very small eggs, and it is especially difficult to sample larvae less than 6 millimeters long (Turner, 1987). Data on direct measurements of eggs and larvae are available only for certain selected years since 1967 and only in unpublished form (Fusfeld and Miller, mimeographed report cited by Turner, 1987). The limited data and the inherent inaccuracy in directly sampling the eggs does not permit a comparison between the field sampling estimates and the fecundity estimates (see Turner, Table 2). This is one area where data from a few more years would be quite helpful.

D. Larval bass data

Detailed information on striped bass larval populations have been collected by the DFG for 10 years out of the period 1968 to 1986. This is an incomplete record, missing the years 1969, 1974, 1976, and 1978 through 1983 completely, with only partial data from 1973, and with data on eggs from only five years. But for those years when data was obtained, the sampling was quite intensive. In total, the larval bass surveys have included almost 7,000 samples taken from 70 stations in Suisun Bay and the Delta. Sampling of phytoplankton and zooplankton was added to the larval bass surveys beginning in 1984 (California Department of Fish and Game, 1987a, page 49). As those data become available, they will undoubtedly help in explaining patterns of larval bass distribution.

One problem with the larval bass data is that they have not been fully analyzed until recently (Turner, 1987). Turner limits his analysis to larval populations 6 millimeters and larger on the grounds that the estimates of smaller larvae are not sufficiently accurate, due to difficulties in sampling. He assumes that the year-class size is determined by the time the larvae reach 8 to 10 millimeters in length since there is a significant correlation between the number of 8 millimeter larvae and the YOY index ($R^2 = .86$). Therefore, he focuses on the progression of larval bass populations from 6 millimeters to 9 millimeters. In linear regressions a number of factors seem to have a significant effect on the population of 6 millimeter larvae, but an inspection of the data reveals that these relationships are mainly due to two outliers (1971 and 1975). "When both data points were removed in the calculation, the only significant relationship was between the number of 6 millimeter larvae and the sum of the total flow into Georgiana Slough and the Delta Cross Channel" (page 15). It is hard to see why there would be a positive correlation between 6 millimeter larvae and these cross-Delta flows, since most researchers believe that cross-Delta flows are not good for the bass. Turner suggests that this relationship arises because the high cross-Delta flows are correlated with a flushing effect. "Larger flows diverted through these channels with constant pumping rates in the south Delta, results in more water going down the lower San Joaquin River, flushing the eggs and pre-6 millimeter larvae that are found there, further down into Suisun Bay" (page 17). We feel that these regressions should be viewed with caution since they include so few data points and do not take into account the differences in fecundity between years. It seems reasonable to believe that, if fecundity matters at all, the most obvious impact would be on the very small life stages such as 6 millimeters or less.

Regardless of these regression results, Turner seems to believe that 6 millimeter larvae populations are enhanced by high flows and relatively smaller diversions which "tend to move more striped bass eggs and pre-6 millimeter meter larvae further downstream out of the Delta" (page 41). Much of Turner's report does not rely on statistical analysis but is based on a visual comparison of plots of larval bass concentrations, comparing years with similar outflow.

Turner calculates the rate of population decline for larval bass from the 6 millimeter size up to 9 millimeter and concludes that the rate of decline has been increasing in recent years. The DFG report (1987a) agrees with this analysis; and their calculations suggest that the rate of decline has also increased in Suisun Bay, though not as much.

18-millimeter bass would not have as much impact as the entrainment of 1,000 38-millimeter bass since, in the absence of entrainment, not all those 18-millimeter fish would be expected to reach 38 millimeters in length. Most reports consider only the loss of bass 18 millimeters or longer since the smaller fish are difficult to measure. Sampling to measure losses to eggs and larval bass was not conducted until 1985 (Turner, 1987, page 44). Wendt (1987) asserts that losses of larvae of less than 18 millimeters do not add appreciably to total losses when measured in terms of yearling equivalents. This assertion is contradicted by the DFG, who now believe that the losses to entrainment are more serious than previously thought. DFG (1987a) reports estimates of losses of 47 percent for larvae between 6 and 14 millimeters and then extrapolates to losses of 73 percent for eggs on up to 20 millimeters. Their estimates are based on data gathered in 1985, a year in which very few bass larvae were transported down to Suisun Bay. A similar analysis for 1986 yielded an estimated effective loss to entrainment of 31 percent of 20 millimeter larvae. "Overall, our larval bass percent reduction analysis indicated that CVP-SWP entrainment severely reduces the striped bass larva population with the greatest impact occurring in the drier low flow years" (California Department of Fish and Game, 1987a, page 78). For estimates of 1985 and 1986 entrainment losses, see Table 1. There is some disagreement on the impact of entrainment on larval bass.

Wendt (1987) has developed a model of losses at the SWP's Skinner Fish Facility to bass 18 millimeters and larger in June, July, or August. The model is:

$$Yt = -.0001(Qw) + .027(St) + .00025(Qp) - .044(Ss) + 12.098$$

where Yt is 1n(losses) at SWP in June, July, or August; St is the total striped bass index; Qw is the western Delta flow in the lower San Joaquin River; Qp is total Delta exports (SWP + CVP); and Ss is the average size in millimeters of that month's catch at Skinner. The Skinner Fish Facility is a system of screens and nets that is designed to screen out fish from water pumped by the SWP so that they can be transported back to the Delta. Thus, salvage losses refer to striped bass that either pass through the screens and are entrained by the pumps and exported, or do not

E. Entrainment data

There is no doubt that there are losses of young striped bass to entrainment at the pumps of the Central Valley Project (CVP) and the SWP, at PG&E power plants, and at the numerous small Delta agricultural diversions. The questions that remain are how large are those losses and how can they be reduced. Chadwick *et al.* (1977) report that in some years as many as 40 to 80 million striped bass larvae pass through the fish screens and are exported down through the CFP and SWP. Stevens *et al.* (1985) report that export entrainment ranged from hundreds of millions up to several billion per year during the period 1968-1979. They also report an estimated loss to Delta agricultural diversions of over 500 million bass per year and on the order of 100 million bass per year to PG&E diversions. Records of losses to entrainment at the SWP have been kept since 1968, and estimated annual losses there average 5 million fish longer than 18 millimeters, or about 500,000 yearling equivalents (Wendt, 1987). Not only are these estimates highly variable but also all except Wendt's numbers are gross estimates and do not relate these losses of young bass to lowered production of adult bass.

There are a number of difficulties involved in the estimation procedures. At the SWP, estimates of losses do not include losses to predation that may occur while the bass are confined to Clifton Court. In the Delta agricultural diversions, there are far too many diversions to monitor and no one has any good idea of how much water is diverted, let alone how many larval bass. The general presumption, however, is that these diversions have not changed significantly over time and thus, while they contribute to larval bass mortality, they are not likely to be the cause of the recent decline in bass populations (California State Water Resources Control Board, 1982). Losses at the PG&E power plants depend not only on the number of bass entrained by the cooling systems but (since the water is discharged back to the Delta) also on the percent of entrained bass that survive. Recent operational modifications have reduced power plant entrainment losses by about 75 percent (California Department of Fish and Game, 1987a, page 70).

Measurements of the impact of entrainment losses on adult bass populations require an estimate of the survival of those fish if they had not been entrained. The loss of 1,000

Table 1. Taken from DFG (1987a), p. 73 and p. 77. Note that the estimated numbers of fish do not decline consistently as size increases. This indicates that there are obvious errors in the data for the smallest size classes.

Estimated impacts of larval striped bass entrainment in 1985.

Size Group (mm)	$\hat{N}_0$[1]	Entrainment SWP	Entrainment CVP	Entrainment Total	S_E[2]	u[3]	S_{WO}[4]
Eggs	10,266,780,000	85,879,841	84,858,059	170,737,901		.0166	
4	603,710,000	4,733,873	1,945,492	6,679,365		.0111	
5	4,118,750,000	98,263,547	78,225,038	176,488,586		.0428	
6	10,427,200,000	204,234,102	163,958,264	368,192,365	.112	.0353	.122
7	1,170,120,000	23,966,600	15,066,159	39,032,759	.353	.0334	.373
8	413,160,000	12,892,114	4,640,096	17,532,210	.373	.0424	.399
9	153,920,000	6,519,574	1,834,874	8,354,448	.440	.0543	.477
10	67,760,000	1,516,429	1,036,541	2,522,970	.364	.0372	.386
11	24,640,000	0	445,760	445,760	.685	.0181	.700
12	16,880,000	2,583,701	0	2,583,701	.690	.1531	.829
13	11,640,000	337,700	445,760	783,459	.600	.0673	.654
14	6,980,000	211,378	0	211,378		.0303	

[1] Index of number of fish entering each length interval.
[2] Estimated actual survival to next length interval
[3] Harvest of fish by entrainment (Total entrainment ÷ $\hat{N}_o$).
[4] Estimated survival if there were no entrainment.

Estimated impacts of larval striped bass entrainment in 1986.

Size Group (mm)	$\hat{N}_0$[1]	Entrainment SWP	Entrainment CVP	Entrainment Total	S_E[2]	u[3]	S_{WO}[4]
Eggs	5,492,730,000	3,773,199	9,273,122	13,046,321		.0024	
4	570,160,000	365,160	159,006	524,167		.0009	
5	2,830,290,000	15,877,707	6,948,947	22,826,654		.0081	
6	9,414,780,000	10,829,521	6,685,103	17,514,624	.288	.0019	.289
7	2,707,340,000	5,677,200	5,396,107	11,073,307	.456	.0041	.459
8	1,234,600,000	3,058,530	3,869,975	6,928,505	.433	.0056	.436
9	534,540,000	2,340,376	2,141,980	4,482,356	.649	.0084	.656
10	347,030,000	3,140,890	3,863,765	7,004,654	.458	.0202	.471
11	159,070,000	1,786,771	3,136,863	4,923,634	.844	.0310	.873
12	134,240,000	1,671,626	1,802,764	3,424,390	.657	.0255	.678
13	88,250,000	814,674	1,709,896	2,524,570	.667	.0286	.691
14	58,830,000	1,333,116	543,503	1,876,619			

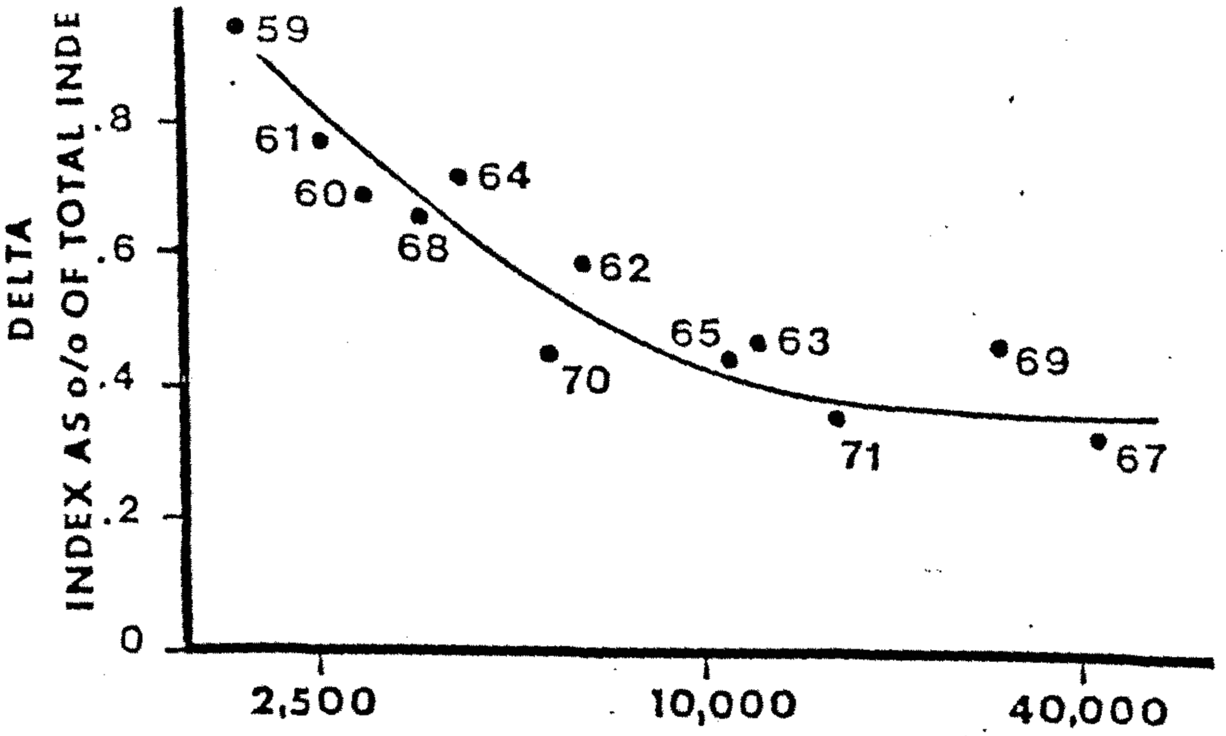
[1] Index of number of fish entering each length interval.
[2] Estimated actual survival to next length interval.
[3] Harvest of fish by entrainment (Total Entrainment ÷ $\hat{N}_o$).
[4] Estimated survival if there were no entrainment.

survive the screening and transport process. Wendt's report indicates that about half the striped bass 18 millimeters and larger that are drawn into the Skinner Fish Facility are successfully salvaged, with the other half either dying or being pumped into the California Aqueduct.

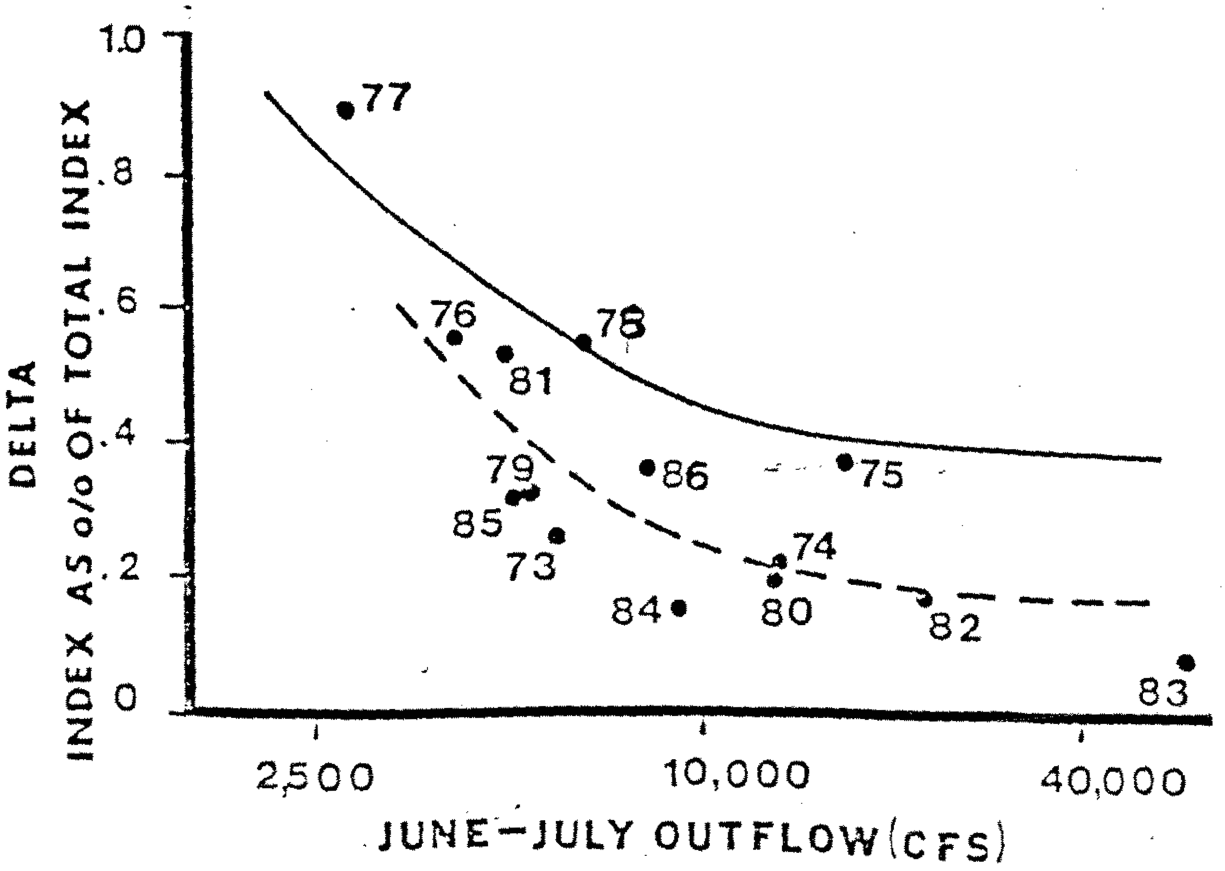
F. Young of the year population data

The number of young bass that survive to reach adulthood is an important determinant of adult population size. Much effort has recently gone into the study of the population of young bass. Since 1959, DFG has calculated an index of the abundance of young bass. Many more bass eggs are spawned than can ever develop, so mortality rates are very high for young bass. For the index to be consistent, it must be measuring the young at the same point in their development every year. But since the timing of spawning is not exactly the same every year, the index strategy is based on the mean size of the little fish. Every two weeks the young bass are netted and counted in a number of locations throughout the Delta and Suisun Bay, in what is known as the tow net survey. When the mean length of the young bass reaches 1.5 inches (38 millimeters) sometime in midsummer, the numbers collected in that period are used to construct the young of the year (YOY) index (also known as the 38 millimeter index). There is an index for Suisun Bay and a separate one for the Delta, and those two added together give the total YOY index (see Figure 14).

According to Stevens *et al.* (1985), the YOY index is significantly correlated with the catch-per-effort index four years later but is not significantly correlated with the Petersen estimates with a similar lag. So the relationship between the YOY index and the adult population is not well defined, but the results "do suggest that recruitment of a year class to the adult stock is affected by its abundance early in life." How directly the one affects the other is dependent upon the strength of compensation effects.



Relationship between outflow past Chipps Island and the Delta index of young striped bass as a percent of the total index from 1959 to 1971. Line drawn by eye.



Relationship between outflow past Chipps Island and the Delta index of young striped bass as a percent of the total index from 1973 to 1986. Solid line copied from (a). Dashed line drawn by eye from 1973 to 1986 data points.

Figure 14. Taken from DFG (1987a), p. 33.

Atlantic Coast striped bass populations are subject to what is known as a "dominant year class" phenomenon, where recruitment is dominated by very large year classes at intervals of six years or so (Boreman and Austin, 1985). This pattern does not seem to hold for San Francisco Bay striped bass, but the YOY index does show a lot of variability. From a low in the 30s during the period 1959-1961, the index rose to over 100 during the period 1965-1967. Since then it has declined unevenly. It reached an all-time low of 6.3 in 1985, rose to around 40 in 1986, and then dropped again to 12.6 in 1987 (California Department of Fish and Game, 1987).

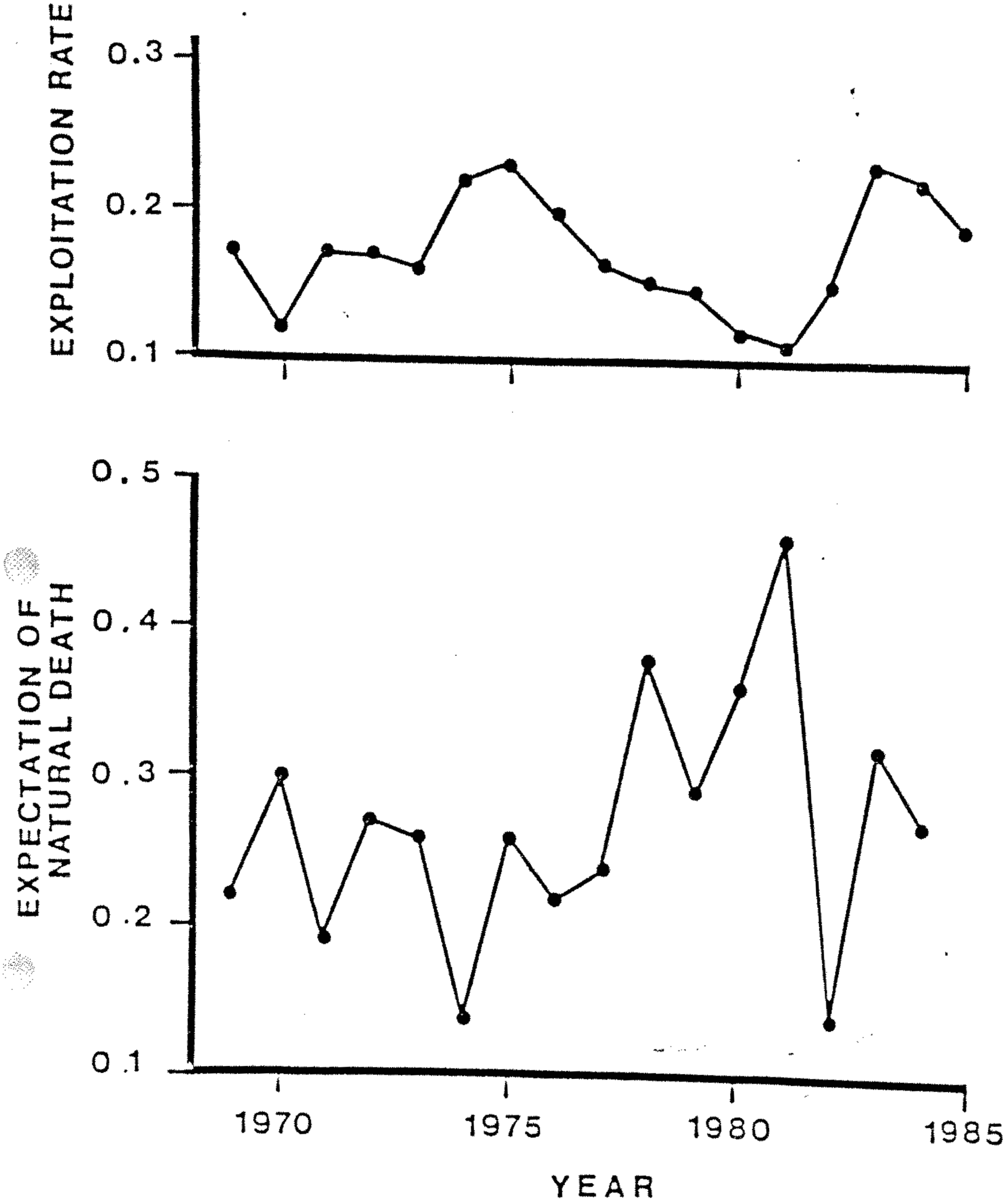
G. Outflow relationships

While the recent decline in the YOY index may be a cause for concern in itself, there are two aspects that have drawn the most attention. The first is that the Delta portion of the index has declined very consistently and significantly over this period. The second is that a relationship between Delta outflow and the YOY index that held throughout the 1960s and early 1970s no longer seems to hold. However, Chadwick *et al.* point out that the relationship between flow and the Suisun Bay portion of the YOY index continued to hold through the mid-1970s (see Figure 15).

The relationship between outflow and the YOY index was first reported by Turner and Chadwick (1972) using data from 1959 through 1970. They tested the correlation between the index and Delta outflow averaged over various months and combinations of months and found that the correlation was highest when using the average outflow in June and July. Their equation was

$$\text{YOY index} = -.865.3 + 441.7 * \log \text{outflow} - 50.5 * (\log \text{outflow})^2$$

The correlations are significant at the 1 percent level, with $R^2 = 0.889$. Turner and Chadwick interpret this equation as indicating that "survival increases rapidly as mean June-July outflows increase from 2,000 to 10,000 cfs, but survival survival changes little at flows above 10,000 cfs" (page 446). They note two general patterns of geographical distribution of the bass. In years of high outflow, there is a single population peak near the upstream end of the salinity gradient. In



Estimates of exploitation rate and expectation of natural death for striped bass in the Sacramento-San Joaquin Estuary from 1969 to 1985. The decrease in exploitation from 1975 to 1981 probably reflects reduced angler effort in response to the declining striped bass population and poor fishing. The pattern of subsequent increase in exploitation reflects an increase in availability of bass to the fishery despite continued low population levels. Most high values and the greatest variability in "natural mortality" occurred in the late 1970s and 1980s.

Figure 15. Taken from DFG (1987a), p. 15.

years of low outflow, the early season distribution is more evenly spread from the salinity gradient up into fresh water but, as the season progresses, the concentrations decline in the freshwater areas so that, by the end of the summer, the distribution is similar to that of high outflow years. Turner and Chadwick propose special explanations for the correlation between outflow and the YOY index. One is that it might be due to diversion since there is a close relationship between Delta outflow and the proportion of Delta inflow diverted. Other possibilities include predation effects, spawning time, detrital food supply, and the location of the entrapment zone.

Stevens (1977) uses data on striped bass catch to show that there is a relationship between the YOY index and recruitment of adult bass to the fishery three years later. However, his analysis seems to show that YOY index underestimates the year class size in years of high flows (10,000 to 30,000 cfs). He speculates that the YOY index does not count the bass that are flushed into San Pablo and San Francisco Bays in years of high flow.

Chadwick *et al.* (1977, page 23) report that "survival since 1970 has consistently been poorer than would be expected from the 1959-1970 relationship. Nonetheless, the relationship with outflow has not changed since 1970 for that portion of the young bass population in Suisun Bay. Thus, the decrease in survival has occurred in the Delta portion of the population, apparently as a result of greater water exports during May, June, and July." They review the relationship between the YOY index and measures of catch three years later and conclude that most of the variability in survival in the striped bass year classes occurs before the bass reach 38 millimeters in length. They discuss three factors that might affect larval bass survival: diversions, power plant entrainment, and the magnitude of outflows. They point out that cannabalism, as a source of mortality, was substantial but was compensatory. Data were insufficient to estimate the impact of entrainment losses through diversions, but they conclude that it is significant. "Considering the large reproductive potential of striped bass and the known and suspected compensatory processes, our judgement until recently was that compensatory processes were dominant in controlling population size. It is now clear that density independent processes, particularly mortality due to losses in water diversion from the Delta, play a major role in controlling population size" (page 33). They further conclude that current evidence shows that power plant entrainment has minimal impact on the bass populations but additional work is necessary to verify that finding. Finally, higher outflow appears to increase survival by transporting the bass downstream to favorable nursery areas. Chadwick *et al.* estimate the following equation (with $R^2 = 0.831$) for the Delta index

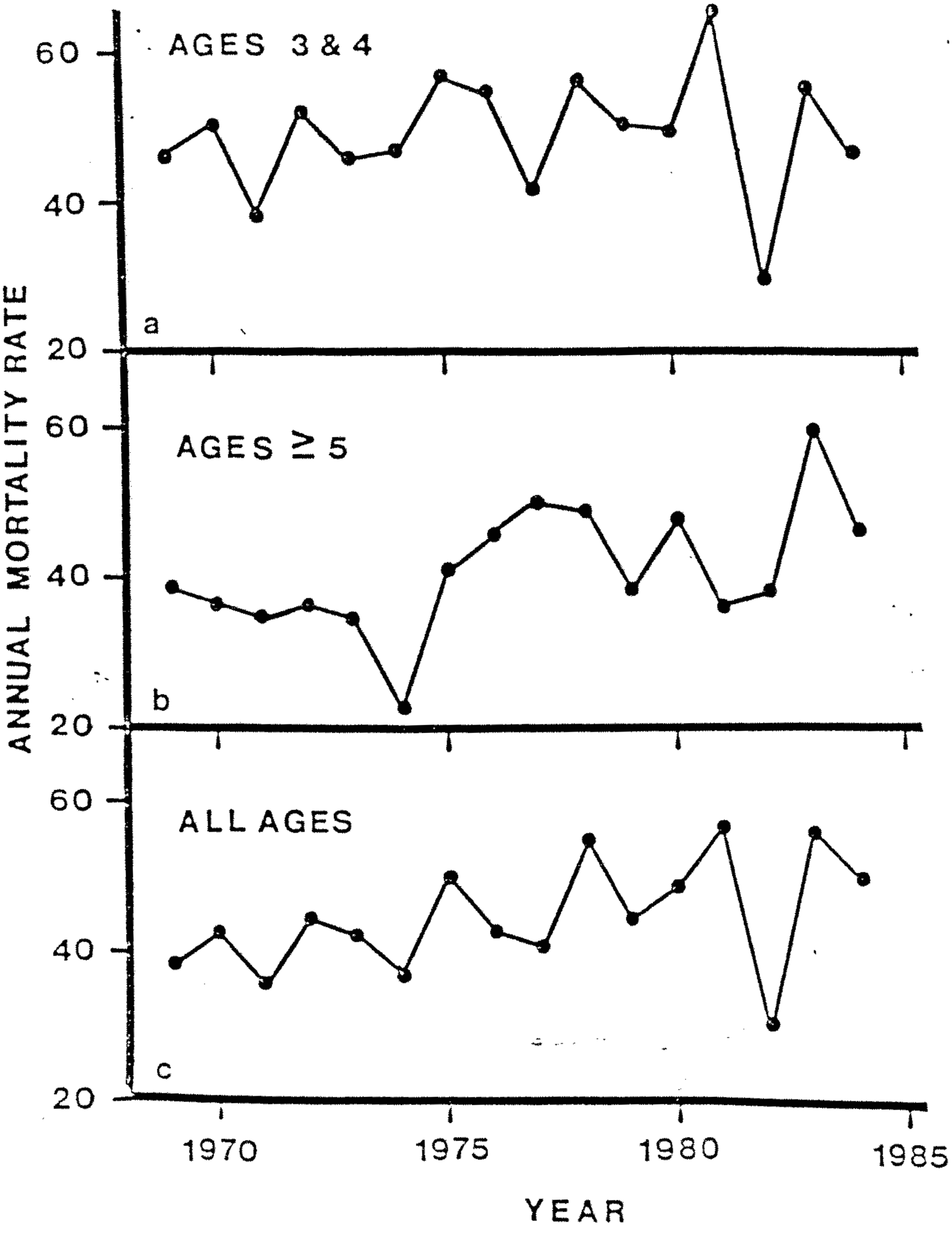
$$\text{Delta YOY index} = -202.7 - 0.25^*(\text{May-June diversions}) + 225.9^*(\log \text{May-June outflow}) - 43.36^* (\log \text{May-June outflow})^2.$$

The relationship is based on data from 1959 to 1976. However, since 1977 the YOY index has been consistently lower than that predicted on the basis of the regression (Stevens *et al.* , 1985) (see Figure 16). In fact, since 1977 both the Delta portion and the Suisun Bay portion of the YOY index have been lower than predicted on the basis of regressions.

IV. Possible Causes for the Striped Bass Decline

A. Adult mortality

The estimates of adult striped bass mortality rates are calculated from the same data used to estimate the populations. The number of tags returned by fishermen are used in standard fishery population calculations to estimate both the total mortality rate and the mortality due to angler harvest. Then the difference between those two numbers is taken to be the estimate of the natural mortality rate. "The total adult mortality rate has increased from around 0.40 in the early 1970s to 0.53 in the most recent years" (California Department of Fish and Game, 1987a, page 14) (see Table 2 and Figures 17 and 18). The estimated angler harvest rate has fluctuated between 10 percent and 25 percent per year with no obvious pattern, with years of low harvest rates often occurring during years of high estimated natural mortality and vice versa. This makes it difficult to ascribe the general increase in the mortality rate either to angling or to "natural" mortality since



Estimates of annual mortality rates for striped bass in the Sacramento-San Joaquin Estuary from 1969 to 1984. The upward trend from 1969 to 1984 is most apparent if the unusually low 1982 estimates in a) and c) are omitted. Those estimates may be affected by imprecision associated with the small number of bass tagged in 1982 and 1983.

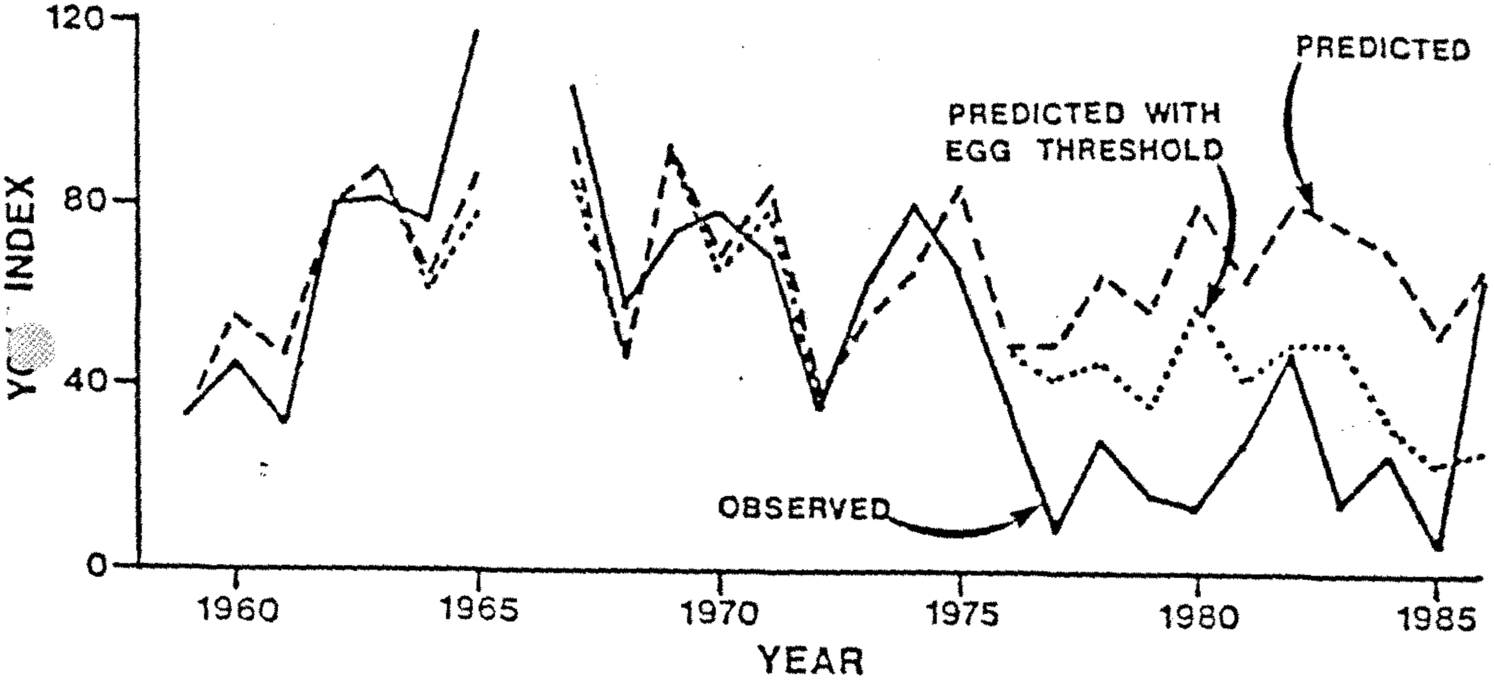
Figure 16. Taken from DFG (1987a), p. 13.

Table 2. Taken from DFG (1987a), p. 12.

Number of tagged fish released, response rate, and mortality rates for striped bass in the Sacramento-San Joaquin Estuary.

Year	Number Released	Response Rate[1]	Exploitation Rate	Expectation of Natural Death	Annual Mortality Rate Ages 3&4	Annual Mortality Rate Ages ≥5	Annual Mortality Rate All Ages	Source
1958	3,891		0.372	0.309			0.681	Chadwick 196
1959	2,965		0.247	0.219			0.466	"
1960	3,358		0.243	0.156			0.399	"
1961	1,609		0.190	--			--	"
1965	3,889		0.142	0.203			0.345	Miller 197
1966	2,996		0.179	--			--	"
1969	16,416	0.658	0.171	0.224	0.477	0.399	0.395	
1970	14,373	0.618	0.121	0.309	0.504	0.366	0.430	
1971	18,127	0.498	0.171	0.198	0.383	0.352	0.369	
1972	18,377	0.512	0.170	0.275	0.527	0.364	0.445	
1973	15,385	0.512	0.167	0.267	0.469	0.351	0.434	
1974	13,785	0.459	0.229	0.142	0.473	0.220	0.371	
1975	8,852	0.407	0.240	0.265	0.578	0.419	0.505	
1976	10,511	0.473	0.208	0.223	0.553	0.462	0.431	
[illegible]77	4,955	0.431	0.170	0.242	0.425	0.508	0.412	
[illegible]78	4,253	0.354	0.163	0.389	0.579	0.494	0.522	
1979	11,055	0.412	0.155	0.299	0.515	0.385	0.454	
1980	6,405	0.493	0.123	0.365	0.502	0.486	0.488	
1981	7,402	0.498	0.111	0.460	0.660	0.368	0.570	
1982	3,437	0.372	0.159	0.148	0.300	0.383	0.307	
1983	3,094	0.456	0.237	0.328	0.562	0.606	0.565	
1984	4,829	0.363	0.223	0.278	0.544	0.475	0.501	
1985	7,404	0.409	0.198	--				

[1] Estimated fraction of recovered nonreward tags that anglers actually return. The estimation assumes all recovered $20 reward tags were returned. Because $20 tags were not released every year and response generally decreased annually as catches of tagged fish became more common through the mid-1970s, we calculated linear regressions of return rate ratio on year for (1) nonreward:$5 tags, (2) $5 tags:$10 tags, and (3)$10 tags:$20 tags. Response for each year before $20 tags were first used (1978) was estimated as the product of observed and predicted ratios. Response from 1978 to 1985 is the observed return rate ratio for nonreward:$20 tags.



Botsford's mathematical model prediction of the 38 mm young striped bass index based on (1) the 1959-1976 relationship between this index and outflow and diversion rates (top line) and (2) the relationship in (1) and an egg production threshold. Including the egg production threshold substantially improves predictions, but does not fully explain the decline from 1977 to 1985.

Figure 17. Taken from DFG (1987a), p. 107.

Figure 18

"neither component of mortality alone showed an overall trend during this period" (California Department of Fish and Game, 1987a, page 16).

There are several possible causes of increased mortality rates that have been discussed in the literature. They include the effects of toxic substances, increased parasites, declining adult food supplies, and the impact of fishing and some unknown amount of poaching.In the summary report of the Cooperative Striped Bass Study (COSBS), Jung *et al.* (1984) hypothesize that there has been a reduction in the number of spawning adults due to poorer health (e.g., body and liver condition) and to increased adult mortality which, in turn, are at least partially due to the combined effects of parasitism and pollutants. Poorer health presumably decreases the likelihood that a female adult will spawn and increased adult mortality decreases the number of potential spawners.

To test the hypothesis that pollutants have reduced the number of spawning adults, the COSBS tried to find a "control population" to make comparisons with the striped bass population from the Bay/Delta. Based primarily on field data from 1978-1980, the COSBS found relationships between fish condition and fish location that include:

- Striped bass from the San Francisco Bay/Delta were in poorer health (body and liver condition) than fish from Coos River, Oregon. In addition, fish from the Coos River had lower concentrations of chlorinated hydrocarbons and heavy metals than those found in Bay/Delta striped bass.

- A 1982 sample of Hudson River striped bass indicated that they were also in better health than those from the Bay/Delta. Moreover, fish from the Bay/Delta had higher levels of DDT and metabolites than Hudson River fish. Yet, fish from the Hudson River had higher concentrations of PCBs in gonads and in muscle and higher concentrations of chlordane and dieldrin in gonads than did Bay/Delta fish.

- Lake Mead fish on the other hand, had poorer body condition than Bay/Delta striped bass, an indication of starvation and insufficient food supply.

- Fish from the Bay/Delta had higher tissue concentrations of petrochemicals than did those from Coos River or from Hudson River except for some xylenes, which were high in all populations of fish sample.

Although striped bass from the Bay/Delta appeared to have the worst health, Jung *et al.* (1984) were unable to find a "control population" since all populations examined had been impacted in some way by pollutants or had significant environmental differences or both.

Evidence in support of the hypothesis that pollutants adversely affect the number of spawning adults consists of the finding that poor body, liver, or blood condition has been significantly correlated with high concentrations of heavy metals and petroleum hydrocarbons (Jung *et al.*, 1984). With regard to petroleum hydrocarbons, the COSBS found significant levels of alicyclic hexanes (AHs) and monocyclic aromatic hydrocarbons (MAHs)including benzene, toluene, ethylbenzene, and three isomers of xylene in tissues of striped bass collected in the field. Levels of MAHs in the tissues of field-collected fish corresponded to levels reached in tissues of fish exposed in the laboratory experiments (Jung *et al.*, 1984). Higher levels of MAHs in prespawning Bay/Delta striped bass were correlated with

- significantly more monocytes in the peripheral blood–a condition that may reflect red blood cell destruction due to MAH toxicity;
- redder or hemorrhaged livers;
- a higher percentage of immature white blood cells, dark red blood cells, and young red blood cells–a condition that indicates blood cell destruction followed by a high production of immature cells.

In addition to the effects on the fish of these components in liver and blood, the muscle tissue appeared to differentially accumulate toluene, which had been shown previously to cause the tainting or bad flavor in other fish species.

Phillips (1987), however, argues that the significance of this correlation of MAH concentrations with liver and blood condition is hard to ascertain because MAHs have very short half-lives in fish. On the one hand, the correlation depends on the chance sampling of highly contaminated individuals. On the other hand,

> [i]t is highly possible that individual fish would be exposed to MAHs at some point in spawning migration suffer toxic effects from this, but not be sampled for analysis until after the MAHs have been excreted. As a result, even if MAHs . . . in *Morone saxatlis* were exerting toxic effects, it would be difficult to demonstrate a correlation between the effects and elevated levels of the contaminant in the fish.

COSBS measured heavy metals only in the ovaries from fish in 1978 but in the liver, gonads, and muscle fillets in 1980 and 1981 samples. There were relatively high levels of zinc, copper, and other metals in adult striped bass livers and gonads. The concentrations of zinc and other metals correlated with decreased body and liver condition in the 1980 and 1981 fish (Jung *et al.*, 1984).

Initial results of the COSBS showed that pollutant interactions were affecting the fish. The data showed that hydrocarbons and metals were interactively associated with deleterious liver condition (Jung *et al.*, 1984).

Jung *et al.* (1984) also found evidence of a link between pollutants and lesion scars from parasite infections. Based on field-collected fish, their specific findings include:

- The higher the petrochemical (MAH) concentrations, particularly toluene and ethylbenzene, the more severe is the host reaction to parasite infections.
- The higher the zinc levels in the liver the greater the number of lesions and granulomas in the liver tissue.

Since the lesions represent severe reactions that are the result of an immune system disorder in only Bay/Delta striped bass, this correlation between pollutants (heavy metals and MAH concentrations) and lesion scars is consistent with the hypothesis that pollutants exacerbate, but do not cause, lesions.

In a follow-up study to the COSBS, Knudsen and Kohlhorst (1987) used univariate techniques to analyze data for 1978-1985. In the *Final Report for 1985* for the the Striped Bass Health Monitoring program, they concluded that striped bass health had not improved over the period. Their specific findings include:

- Body condition had not improved..
- Neither the parasite load nor the pollutant burden–except for chromium and alicyclic hexanes–had decreased.
- Parasites were less abundant in fish with high levels of petroleum hydrocarbons and pesticides. (This finding appears to contradict that of the COSBS.)
- Skeletal abnormalities were associated with high burdens of trace elements in liver tissue. (This finding is consistent with the hypothesis that pollutants increase adult mortality since skeletal abnormalities are likely to reduce the chances of survival.)

As a follow-up to the research of the COSBS and to that of Knudsen and Kohlhorst, the DFG (1987c) used the principal components analysis of 17 variables for the eight-year period, 1978-1985. The DFG found that the component "older fish with more parasites" was not associated with any pollutant variable. This finding also appears to contradict the COSBS argument that the higher the concentration of petroleum hydrocarbons the higher the degree of parasitism.

The National Marine Fisheries Service (NMFS) conducted certain laboratory experiments on the effects of pollutants on striped bass survival and reproduction; but their research program was terminated before field studies were conducted, and there are no good time series data on the level of pollutants in bass tissues on which to base a statistical analysis. The result is that there is no way to make any explicit statistical connection between these pollutants and the size of the striped bass population, based on existing knowledge and research. A number of sources have suggested that water quality has been improving in recent years so, while it may be clear that pollution has affected striped bass adversely, it is unlikely that increased adult mortality due to toxic pollution has been the major cause of the recent decline in the striped bass population.

One study (Collins, 1982) looked at the growth rate of bass over the period from 1969 to 1978. One expectation is that any food shortage that was significant enough to affect the mortality rate of adult bass would also affect the growth rates of the bass. The results of that study do not support the hypothesis that there is a food supply problem for the adult base (California Department of Fish and Game, 1987a, page 23). The Striped Bass Working Group (1982) found no reason to believe that a decrease in food abundance has affected adult bass populations. There is a possibility that striped bass poaching may cause a portion of the estimated "natural" mortality rate, but there is no data available to evaluate that particular problem.

One point we should mention in passing is that there has been an annual die-off of adult striped bass in the San Pablo Bay/Suisun Bay area. Dead fish are found in this area during the spring or early summer. No one has yet been able to find any explanation for this phenomenon, though one source has suggested it may be due to liver disfunction. Since it has been occurring regularly for over 30 years (see Kohlhorst, 1975, and California Department of Fish and Game, 1987a, page 119) but does not seem to be increasing, most analyses do not pay much attention to it.

According to the DFG (1987a), the rate of angler harvest has fluctuated over the last 30 years but has not shown an overall trend (see Figure 19). The estimated rate rose from 1970 to 1975, fell gradually until 1982, and then rose sharply back to the levels of 1975. These changes may reflect changes in fishing effort in response to poorer results, combined with changes in the success rate for some undefined reason. It is difficult to sort out the nature of these fluctuations and determine whether they are an effect of changes in the bass population or a cause of those changes. As we noted earlier, the rate of angler exploitation is higher in periods when the natural mortality rate is lowest and is lowest when the natural rate is highest. This suggests that some of these apparent changes in mortality rates may be a statistical artifact since the natural mortality rate

Figure 19

is taken to be simply the difference between the angler exploitation rate and the total mortality rate. The result, again, is that, while the total mortality has increased over the period 1969-1985, neither natural mortality nor angler exploitation rate shows an overall trend in that period.

To summarize, over the last 15 years there has been an increase in the mortality rate for adult bass from 40 percent up to 53 percent but there is no strong evidence for ascribing that increase to any particular cause. Perhaps the more relevant question is whether this increase in mortality rate, whatever its cause might be, could be contributing to the long-term decline in striped bass populations that has been observed. We can conceptually divide the impact of increased mortality into two parts--the current generation effect and the impact on the subsequent generations. It is clear that the immediate impact of a modest increase in the mortality rate could not account for the very large decrease in the bass stocks that has occurred over the past 25 years. Only if that adult mortality is translated into reduced reproduction would it make a significant long-term difference. It seems unlikely that even a 33 percent increase in adult mortality would have a significant impact on reproductive success. If the concept of compensation has any validity and if the huge reproductive potential of the striped bass has any real meaning, then the implication must be that such an increase in adult mortality would be compensated for by increased survival of the young--unless there are other intervening factors. One such factor may relate to the number of older female bass. Since older females produce far more eggs than younger ones, their loss can have a disproportionate effect on reproduction. So if the increase in adult mortality has strongly affected the population level of older females, then the impact on egg production would be magnified. This remains an unanswered empirical question.

A case can be made that the reduced size of the adult population is connected with poor reproductive success due to reduced effective fecundity.. That point will be discussed below. Reduced fecundity may be due largely to the reduced size of the adult population. But the reduction in adult population can be attributed more to problems with young bass (which have undergone a very steep decline) than to the observed increase in adult mortality rates. We believe that the current evidence can support only a weak connection between the rate of adult mortality and the reproductive success of striped bass.

B. Reduced effective fecundity

The basic idea here is that a reduction in the number of bass eggs could lead to a reduction in the number of young bass produced. In most population models it is assumed that the size of an offspring generation is a function of the size of the parental generation and their reproductive rate. But that notion is not automatically accepted in the case of the striped bass. The reproductive capacity of the striped bass is phenomenal. There has been a large decline in the number of eggs produced each year. "But with the average female striped bass producing nearly a half million eggs, it is hard for some biologists to envision there not being a surplus of eggs" (Stevens *et al.*, 1985). It may be that the number of eggs produced is so high that even a very large reduction in fecundity may have no significant impact on the size of the next generation. If there were to be fewer eggs, then compensatory effects would tend to increase the survival rate of those eggs that were produced. So while reduced egg production is often mentioned as a possible cause of reduced population, there is no consensus or conclusive evidence on its importance. This section, then, will look at two aspects of the fecundity question: What has happened to the number of viable eggs produced and how might changes in that number affect the production of adult striped bass?

The estimates of egg production discussed earlier show a reduction of 50 percent or more between 1970 and 1980. These estimates are derived from adult population estimates, so that this reduction in fecundity largely reflects a similar reduction in the number of spawning adults. But there is another factor–pollution–which lowers fecundity. The impact of pollution on effective fecundity–the number of viable eggs per spawning female–may only be partly captured by these estimates.

In the summary report of the COSBS, Jung *et al.* (1984) hypothesize that there has been a reduction in effective fecundity. They argue that the impact of pollutants on effective fecundity represents the greatest impact on striped bass abundance. Pollutants and parasitism may reduce effective fecundity through any combination of the following mechanisms: (1) delayed rate of egg maturation (vitellogenesis), (2) partial egg resorption, (3) complete egg resorption in maturing ovaries, (4) no ovarian maturation in sexually mature fish, (5) egg death, and (6) actual reduction in the number of eggs produced. We might also note here another reason for a reduction in the number of eggs produced: higher mortality among older fish, which have higher fecundity than younger ones. (Although pollutants accumulated in adults may lower the production of viable gametes, both eggs and sperm, the research to date has not addressed the possibility of reduced production of sperm.)

To test the hypothesis that pollutants have reduced effective fecundity, the COSBS tried to find a "control population" to make comparisons with the striped bass population from the Bay/Delta. That is, a finding that striped bass from the Bay/Delta had less reproductive success and greater concentrations of pollutants in their bodies than did striped bass from other locations would have been consistent with this hypothesis. Based primarily on field data for 1978-1980, the COSBS did find that egg condition in striped bass from the Bay/Delta was significantly poorer than in striped bass from any other area sampled. Moreover, striped bass from the Bay/Delta had higher levels of DDT and metabolites than Hudson River fish. Striped bass from the Bay/Delta also had higher concentrations of petrochemicals in their tissues than did those from Coos River or from Hudson River. But fish from the Hudson River had higher concentrations of PCBs in gonads and muscle and had higher concentrations of chlordane and dieldrin in gonads than Bay/Delta fish. For this reason and for the reason that striped bass from other locations were contaminated to some degree with pollutants, the COSBS could not find a control population.

Although the COSBS and subsequent research teams have not used a control population, they have found evidence consistent with the hypothesis that pollutant concentrations in striped bass adversely affect reproductive success. The first piece of evidence consistent with this hypothesis is the COSBS finding that higher concentrations of petroleum hydrocarbons in tissues of prespawning striped bass from the Bay/Delta were associated with poorer ovary condition. That is, higher MAH levels in the tissues of prespawning adults were associated with yellower eggs, a greater fraction of eggs resorbed, and delayed or accelerated egg maturation. Poorer egg condition–lower fecundity, fewer calories in eggs, and yellower eggs–was particularly associated with high concentrations of ethylbenzene and 1,2-dimethylcyclohexane, which are among the more toxic and persistent of the low-boiling-point petrochemicals (Jung *et al.*, 1984). The concentrations of petroleum-derived hydrocarbons in striped bass tissues equalled or surpassed those observed in the laboratory to adversely affect blood and, particularly, egg maturation and egg survival (hatching success) (Whipple *et al.*, 1981).

The second piece of evidence consistent with the hypothesis of a detrimental impact of pollutants on reproductive success is the COSBS finding that concentrations of chlorinated hydrocarbons, particularly DDT, were correlated with abnormal egg development and coagulation of the yolk (Knudsen and Kohlhorst, 1987). The more specific findings of the COSBS include:

- There were relatively high levels of PCBs, DDT and its metabolites, and other chlorinated hydrocarbons (including toxaphene) in liver and gonads of fish from the San Francisco estuary.
- The presence of DDT (not metabolites DDD and DDE) in liver and gonads was associated with abnormal egg development and necrosis of eggs.
- Delayed maturation rates (vitellogenesis) were associated with PCBs in ovaries.
- Toxaphene and PCB residues in the eggs were above those levels reportedly harmful to the survival and development of fertilized eggs of other fish species (Jung *et al.*, 1984).

COSBS measured heavy metals only in the ovaries from fish in 1978 but in the liver, gonads, and muscle fillets in 1980 and 1981 samples. There were relatively high levels of zinc, copper, and other metals in adult striped bass livers and gonads. Cadmium, nickel, zinc, and copper correlated with reductions in egg viability in the 1981 San Joaquin River sample.(Jung *et al.*, 1984).

Initial results showed that pollutant interactions were affecting the fish. The data showed that hydrocarbons and metals were interactively associated with deleterious egg condition (Jung *et al.*, 1984).

Jung *et al.* (1984) also conducted laboratory experiments to determine the effects of representative pollutants (benzene and zinc) on striped bass. The results tended to corroborate the effects observed in field-collected fish. One of the major results of these laboratory experiments was that benzene-induced egg resorption in prespawning adult females was similar to the resorption observed in adult field fish. Also, adult fish with higher pollutant burdens were more seriously affected than juveniles when exposed to benzene.

Jung *et al.* (1984) estimated in a worst-case situation that the reduction in fecundity per spawner in 1978, due to the combined effects of pollutants, parasitism, and natural causes, was as high as 50 percent. This reduction represents a stress on striped bass abundance. Moreover, in a worst-case projection, they estimated the reduction in the number of viable eggs per spawner prior to spawning could be at least 45 percent due to pollution alone.

In a follow-up study to the COSBS, Knudsen and Kohlhorst (1987) used univariate techniques to analyze data for 1978-1985. In the *Final Report for 1985* for the Striped Bass Health Monitoring Program, they concluded that striped bass health had not improved over the period.

As a follow-up to the research of the COSBS and to that of Knudsen and Kohlhorst, the DFG (1987) used principal components analysis of 177 variables for the eight-year period, 1978-1985. Although the DFG found no "strong" component of pollution variables, the component "less alicyclic hexanes through time" and the component "monocyclic aromatic hydrocarbons" "explained 9.41 percent and 7.88 percent of the variance in the original data, respectively. Each of these two components was associated with increased egg resorption. The DFG argues that because the correlations among the individual variables for 1978-1985 were so small and because the components "explained" a relatively small proportion of the total variance in the raw data for 1978-1985,.this result does not constitute strong evidence in support of the hypothesis that accumulation of these compounds in fish adversely affects egg resorption.

This evidence suggests that the number of viable eggs has been reduced not only because the number of spawning adults has been reduced but also because of the pollution impact on the number of eggs per spawner and on the viability of those eggs. However, in order to show that the reduction in fecundity is important in the striped bass problem, a connection must be demonstrated between low fecundity and reduced populations in later life stages. Many reports have mentioned this as a "possible" cause of reduced striped bass populations but none seem confident enough to assert that it is a definite factor in reducing the population. This may be due to the fact that, despite these reductions, the number of eggs spawned is always huge. The survival percentage is highly variable, by at least a factor of ten, so it is difficult to isolate the impact of fecundity.

The Striped Bass Working Group ran a model simulation to test the hypothesis that low egg production since the 1960s has contributed to the decline of the YOY index (California Department of Fish and Game, 1987a, page 105). This test seemed to model the decline over the 1970s reasonably well, so the group concluded that egg abundance could be a factor in that decline although they did not demonstrate the connection (see Figure 20).

The circumstantial evidence for a relationship between egg production and striped bass production is very simple to present. The estimated egg production since the 1976-77 drought has averaged about one third of the levels prior to the drought (as measured by the Petersen egg production estimates) (see Table 3); so, if the number of eggs has any impact on the production of young bass, then clearly at least part of the decline in bass production since the drought must be due to the drop in egg numbers. This may not be the primary cause of the reduced numbers of bass since the drop in egg numbers is, itself, due, at least in part, to the drop in the bass population; but it is probably one reason why bass populations have not been able to recover.

In order to show whether fecundity is a factor in the striped bass decline, it is not enough just to show that a drop in the YOY index occurred around the same time as a drop in the number of eggs produced. One would want to show some statistical relationship. But, as mentioned earlier, other factors are involved that induce a lot of variability in the survival from egg to

Figure 20

Table 3. This table shows the 38 mm YOY indexes for the Delta, Suisun Bay, and the total. It also shows the Peterson fecundity estimates (in billions of eggs) for the years 1969 through 1986. There was no YOY survey taken in 1966. This data was supplied by DFG.

YEAR	INDEX DATE	DELTA YOY INDEX	SUISUN BAY YOY INDEX	TOTAL YOY INDEX	PETERSON FECUNDITY ESTIMATE
1959	July 12	30.7	3.0	33.7	
1960	July 17	32.0	13.6	45.6	
1961	July 21	25.2	6.4	31.6	
1962	July 26	46.8	32.1	78.9	
1963	Aug. 3	38.2	43.5	81.7	
1964	Aug. 2	54.7	20.7	75.4	
1965	July 31	49.4	67.8	117.2	
1967	Aug. 12	35.1	73.6	108.7	
1968	July 19	39.6	17.7	57.3	
1969	Aug. 9	33.6	40.2	73.8	319.1
1970	July 18	36.6	41.9	78.5	267.2
1971	Aug. 11	24.6	45.0	69.6	255.6
1972	July 25	13.4	21.1	34.5	265.4
1973	July 15	15.6	47.1	62.7	354.3
1974	July 22	17.4	63.4	80.8	300.6
1975	July 30	23.4	42.1	65.5	434.2
1976	July 16	21.1	14.8	35.9	269.0
1977	July 24	8.3	0.7	9.0	231.5
1978	July 23	16.5	13.1	29.6	129.6
1979	July 19	5.4	11.5	16.9	90.3
1980	July 15	2.8	11.2	14.0	125.7
1981	July 2	15.4	13.7	29.1	100.0
1982	July 30	9.5	39.2	48.7	68.4
1983	Aug. 5	1.2	14.2	15.4	121.7
1984	July 13	6.3	20.0	26.3	77.3
1985	July 16	2.2	4.1	6.3	92.0
1986	July 9	23.8	41.1	64.9	142.7
1987	July 22	7.3	5.3	12.6	*

38 millimeter size This makes the estimation of the impact of reduced fecundity difficult. We have combined a fecundity factor model with the model developed by Chadwick *et al.* (1977) for the Suisun Bay portion of the YOY index. In their model, the YOY index was a quadratic function of the volumeof outflow of fresh water from the Delta. The fecundity factor was designed so that at high levels of egg production the model is identical to Chadwick *et al* .; but, at lower levels, fecundity becomes important. The results from statistical tests run on this model suggest that reduced fecundity has had an impact on the reproductive success of striped bass, at least in Suisun Bay. These results will be discussed more fully later on. We just note here that they do support the idea that reduced fecundity has been a factor in retarding the recovery of the striped bass population.

One possible influence on striped bass spawning discussed in the earlier literature, but not in most of the more recent analyses, is salinity in the San Joaquin River. Although striped bass spend most of their lives in salt water, they spawn in fresh water. This is no problem in regard to the Sacramento River; but, because of agricultural diversions and return flows, the level of TDS (total dissolved solids) in the San Joaquin River is high enough to block the spawning migrations of the striped bass. Only the lower reaches of the river that are influenced by flows from the Mokelumne River and cross-Delta flows from the Sacramento River are fresh enough to support spawning. So spawning in the San Joaquin River is restricted to the western regions of the Delta, from Antioch to Venice Island (Radtke and Turner, 1967, and Turner, 1976). Most of the recent literature takes this limitation for granted and does not discuss it much. But, if flows were increased in the San Joaquin in order to dilute selenium concentrations or for other reasons, it might increase the spawning region for striped bass. Whether this would have any impact on the reproductive success of the bass is another question. The likely answer is that it would have little impact since the number of eggs actually spawned would not change.

D. Problems with young

1. Suisun Bay (entrapment zone)

The YOY index is the most used indicator of the production of young striped bass. This index is just the sum of two subindices, one relating to Suisun Bay and the other to the Delta. The two indices seem to be uncorrelated, perhaps because the ecological systems are rather different. Under these circumstances, it makes sense to consider the two areas separately. This section will look at what influences the Suisun Bay YOY index..

A number of reports have suggested that a lack of food for larval bass may be a cause of the decline in the production of young bass (California State Water Resources Control Board, 1982, and California Department of Fish and Game, 1987a). Behind that simple statement lies a complex ecological story, and that story is easier to tell if it is split into two parts. The first part involves the entrapment zone and relates primarily to the Suisun Bay portion of the YOY index. The question of food for larval bass in the Delta will be discussed in a later section.

Turner and Chadwick (1972) associated increased survival of young striped bass with years when the entrapment zone was located in Suisun Bay. They suspected that the shallows in that area enhanced productivity. Since that time, a number of authors have repeated and elaborated on the idea. Several observations seem relevant. The first is that the salinity gradient creates a density-driven current that moves salt water landward along the bottom while fresh water moves seaward near the surface. Any material that tends to sink would be moved landward in the bottom current toward its upper end.. That upper end of the salinity gradient is thus known as the entrapment zone because certain materials tend to accumulate there. The second observation is that striped bass eggs and striped bass larvae are just slightly more dense than water so they tend to be moved easily by the currents. The result is that after spawning they move downstream with the flow and are concentrated in the entrapment zone. The third observation is that when striped bass larvae begin to feed they have a very limited swimming ability so that they are dependent for their survival on food in their immediate vicinity. If a sufficient density of food is not available in the location where they begin feeding, then they simply will not survive. The last observation is that these larval striped bass will be in the vicinity of a favorable food supply most often when the entrapment zone is in Suisun Bay.

In an earlier section, the work of Cloern *et al.* (1983 and 1985) was cited to explain how the location of the entrapment zone can enhance the productivity of Suisun Bay in terms of phytoplankton; and Knutson and Orsi (1983) were cited in regard to the way the population of *Neomysis mercedis* tends to peak in the entrapment zone. But larval striped bass do not eat phytoplankton. Also, though many reports indicate that *Neomysis* is an important food for young striped bass, the smaller zooplankton species (copepods and cladoceras) are likely to be more important to the larval bass when the bass are small and just beginning to feed (California Department of Fish and Game, 1987a). However, though "*Neomysis* appeared to have its abundance affected by the position of the salinity gradient . . . all species will have their distribution affected by it" (California Department of Fish and Game, 1987b, page 81). Perhaps implicit in this statement is the idea that the number of smaller zooplankton located in Suisun Bay is affected by the salinity gradient. Cloern *et al.* (1983) suggest that their results (i.e., the relationship between the entrapment zone and phytoplankton productivity) have potential implications for the entire food web and that they consider this a crucial topic for further research. But Cloern *et al.* (1985) also note that the ratio between zooplankton and phytoplankton in Suisun Bay is small. We are forced to conclude that the relationship between the entrapment zone and zooplankton (other than *Neomysis*) remains an unanswered question.

The issue of adequate food supplies for larval striped bass can be viewed as having two components: quantity and location. Not only do the bass need enough food, but the food needs to be where the bass are. The above discussion suggests that, when the entrapment zone is located in Suisun Bay, the productivity of that area is enhanced. Perhaps more to the point is the observation that more striped bass larvae are located in Suisun Bay when the entrapment zone is there. Turner (1987) has analyzed the available data on larval bass populations and found that more of the larval bass are located in Suisun Bay in higher flow years. That observation is consistent with the view that the bass eggs and larvae are transported downstream and concentrated in the entrapment zone. Turner has also noted that larval bass survival is better when more of the larval bass are in Suisun Bay. This is consistent with the statistical models discussed earlier which show that the striped bass index for Suisun Bay is correlated with outflow. We may view this an a indication that, when the entrapment zone is positioned in Suisun Bay, conditions favor both movement of bass eggs and larvae into the Bay and development of an adequate food supply for those larvae.

A number of reports have pointed to the drought year of 1977 as a turning point for striped bass populations and have tried to explain that year's extraordinarily poor striped bass production. The very low outflow that year may well have severely depressed the productivity of Suisun Bay for phytoplankton, due to the upstream movement of the entrapment zone. Then again, Nichols (1985) may be correct in that benthic grazing may have had an impact on the standing crop of phytoplankton in Suisun Bay that year. There may have been a corresponding decrease in the Suisun Bay population of *Neomysis* and of other zooplankton types. But then, all this probably had little impact on the striped bass since few of the bass eggs and larvae would have been in Suisun Bay that year anyway due to the low flow conditions. The entrapment zone is important for the striped bass in Suisun Bay, not only because of its impact on phytoplankton and zooplankton but also because the number of bass eggs and larvae that get to Suisun Bay in the first place is strongly influenced by the level of Delta outflow and the position of the entrapment zone.

All of this gives us a better understanding of the way outflow may affect the striped bass in Suisun Bay, but it does not necessarily tie into the issue of their long-term decline. The record seems to show that there is a relationship between outflow and the striped bass index in Suisun Bay but that this relationship may have changed over time. The DFG (1987a, page 54) reports a large increase in the mortality rate for larvae less than 14 millimeters long in Suisun Bay when comparing years before and after the 1977 drought, but for the very small number of years involved (four pairs) this may not be statistically significant.

Without looking in detail at the hydrological patterns, it seems reasonable to hypothesize that, since the relationship between outflow and the Suisun Bay index still exists, the decline in the index over the past 25 years may be explained, at least in part, by a decrease in outflow over that period. Such a decrease might be due partly to normal variation in weather patterns, but it could also be due to increased diversion from the Delta and/or increased consumptive use either within or upstream of the Delta. Some simple statistical tests could help resolve this question. Another possibility is that the productivity of Suisun Bay may be affected by the reduction in egg production that has occurred, mainly since 1976.

Chadwick *et al.* (1977) develop a model for the Suisun Bay YOY index as a function of spring outflow. It is a quadratic relationship where increasing outflow tends to increase the SYOY up to a point, but beyond that point further increases decrease the SYOY. This is usually given the interpretation that, at very high outflows, some of the young bass are flushed out of Suisun Bay and down into San Pablo Bay. This model fit the data fairly well over the period, 1959-1970; but, in the latter 1970s and the 1980s, the SYOY ran consistently lower than would have been predicted based on that model and the earlier data.

We wish to investigate whether the discrepancy between the Chadwick *et al.* model and the later data could be explained by the reduction in egg production that occurred over the same time period. For this purpose, we develop a model that introduces a fecundity factor into the outflow relationship. The results of this investigation suggest that the reduction in fecundity may have caused the reduction in SYOY below the levels predicted by the earlier model.

An important question is what functional form to use for modeling this fecundity affect. From a biological perspective, it does not make sense to just add egg production as another linear term. The two factors are in a sequence. First the number of eggs is determined, and then the eggs are subjected to an environment that is at least partly determined by the level of outflow. Thus, fecundity might enter as some kind of multiplicative factor. But what we know about growth models puts some restrictions on the form that this factor could take. There must be an upper limit at which increased egg production does not lead to any increase in survival. At the other extreme, for low levels of egg production, survival should be directly proportional to the number of eggs. So we want a function that maps from an index of egg production to a multiplier in the range (0, 1) where the multiplier approaches 1 in the limit as egg production approaches infinity and where, as the production becomes small, the multiplier changes in direct proportion to the egg index. A functional form that fits these requirements is M = 1/(1 + 1/G), where M is the multiplier and G is egg production, with the restriction that G be positive.

This expression looks complicated enough, but then it has to be parameterized somehow so that the data can be allowed to show how large a G maps to an M near 1 and how small a G will map to M = aG, where *a* is a factor of proportionality. The parameterization must be done inside G in order to maintain the good properties that have been established for M. We have not been able to come up with a completely satisfactory parameterization. We wanted one that for large values in the data set M would be close to 1.0 but for small values would be determined by the data. Then, given that the range of M would be fixed at its upper and lower ends, the ideal form would have enough flexibility so that, for some arbitrary intermediate point in the data, M should shift up or down according to the best fit. In order to give all this flexibility, the function would probably need three parameters. If we had found such a flexible form, it would be difficult to estimate with this many parameters. The functional form we ultimately settled on has only two parameters, which causes certain problems with the estimation.

We specify G = (b4)*(E**b5), where E is an index of striped bass egg production measured by the DFG. The exponent, b5, controls the spread of G, with a larger b5 spreading out the higher values more as compared to the lower values. The factor, b4, then normalizes this result. The model that we estimate is then

$$SYOY = \left[b\,1 + b\,2 * \ln(OF) + b\,3 * (\ln OF)^2\right] * \left[\frac{1}{1 + 1/G}\right] \qquad (1)$$

The outflow (OF) terms in this expression (the left-hand factor on the right-hand side) are the same as in the Chadwick *et al.* model, and the right-hand factor represents the fecundity factor.

As an alternative, we also try a simpler form as an approximation to this rather complicated expression. Specifically, we specify the quadratic multiplier form

$$SYOY = [b1 + b2*\ln(OF) + b3*(\ln OF)^2]*[1 + b4*E + b5*E^2] \tag{2}$$

In this model, the left-hand factor is the same and the right-hand factor is a quadratic function of the fecundity index, E. Interestingly, this model, when estimated, generates parameter values that give a multiplier function that fulfills very precisely the criteria set out ex ante for such a function. For high values of egg production, the multiplier is very close to 1.0; but for lower values, the multiplier approaches direct proportionality to those values.

The results of the statistical tests are detailed in Tables 4 through 8, but they can be summarized here in terms of the fit of the data to the models. Fecundity estimates are not available prior to 1969, which affects the periods over which the models can be compared. Chadwick's model fit the data well for the period 1959-1970 ($R^2 = .79$) but not so well over the longer period, 1959-1986 ($R^2 = .45$) or over the more recent period, 1969-1986, ($R^2 = .42$). Both fecundity factor models give an improved fit over the later period ($R^2 = .66$ and $.69$).

Other models might be used with these data to explain why SYOY has been lower than expected in recent years. One approach is to use dummy variables. This is based on the idea that something has changed in the relationship between outflow and SYOY, i.e., although there is still a relationship, the parameters have changed. There is some discussion in the striped bass literature to the effect that a change occurred in the mid-1970s, but the nature and timing of the change is not certain. We estimated two dummy variable models , dividing the data set at different points (1969-1975 and 1976-1986), and 1969-1977 and 1978-1986). The earlier division occurs just before the two-year drought that many feel has had a long-term impact on the fisheries, and the latter division occurs just after the drought. In all four trials, (two models at two different division points), the value of R^2 was around .73, with adjusted R^2 around .63. Detailed results are given in Tables 9 through 13.

Table 4. Summary of results of OLS on data from 1959 to 1970
This run was an attempt to replicate Chadwick et al.'s results.

Model: $SYOY = b1 + b2*ln(OF) + b3*(ln(OF))^2 + e$

variable		estimated coefficient	standard error	T-ratio 8 D.F.
b1	constant	-646.60	355.19	-1.8204
b2	ln (OF)	131.28	78.55	1.6712
b3	ln $(OF)^2$	-6.083	4.301	-1.4144

analysis of variance from mean

SSE = 1125.9 R^2 = .794
SST = 5470.2 adjusted R^2 = .7427

Chadwick's results were quite different:

b1	-294.3	R = .876
b2	234.8	
b3	-39.0	

If Chadwick had used log to the base 10 instead of the natural log, then his results modified to be consistent with our use of the natural log (ln) would be:

b1	-294.3
b2	101.97
b3	-7.355

We have no explanation for the remaining discrepancy. One possibility is that the data on outflow could be different, since there are a number of ways to measure outflow. We intend to follow up on this in future research.

Table 5. Summary of results of OLS on data from 1959 to 1986
This run was on the most complete data set.

Model: $SYOY = b1 + b2*\ln(OF) + b3*(\ln(OF))^2 + e$

variable		estimated coefficient	standard error	T-ratio 24 D.F.
b1	constant	-772.19	313.06	-2.4666
b2	ln (OF)	161.57	68.21	2.3689
b3	ln $(OF)^2$	-7.99	3.69	-2.1663

analysis of variance from mean

SSE = 5954.4 R^2 = .4535
SST = 10896 adjusted R^2 = .4080

Table 6. Summary of results of OLS on data from 1969 to 1986
This run was over the period for which fecundity data (ie. eggs) was available, but there is no fecundity factor in this model.

Model: $SYOY = b1 + b2*\ln(OF) + b3*(\ln(OF))^2 + e$

variable		estimated coefficient	standard error	T-ratio 15 D.F.
b1	constant	-1272.5	459.86	-2.7672
b2	ln (OF)	270.28	98.29	2.7498
b3	ln $(OF)^2$	-13.916	5.223	-2.6643

analysis of variance from mean

SSE = 3192.5 R^2 = .4193
SST = 5497.3 adjusted R^2 = .3418

Note that the R^2 for this period is a lot lower than for the periods shown in table 2, and that for table 2 was less than in table 1. This reflects what many researchers have noted - that Chadwick's model does not seem to explain SYOY as well in recent years as it did over the earlier period.

Table 7. Summary of results of OLS on data from 1969 to 1986 in which a fecundity factor has been included. The fecundity factor parameters were determined through a grid search method, entering various parameters exogeneously and determining which set of parameters leads to the best fit.

Fecundity Factor: $F = \left(\frac{1}{1 + 1/G} \right)$ where $G = b4\, E^{b5}$; $E =$ egg ind

Model: $SYOY = \left[b1 + b2 \ln OF + b3 (\ln OF)^2 \right] \left[\frac{1}{1 + 1/b4 E^{b5}} \right] + e$

variable		estimated coefficient	standard error	T-ratio 13 D.F.
b1	constant	-2560.8	752.98	-3.4010
b2	ln (OF)	548.96	162.61	3.3759
b3	$\ln (OF)^2$	-28.515	8.73	-3.2647
b4	(exogeneous)	.0041	n/a	
b5	(exogeneous)	1.04	n/a	

analysis of variance from mean

SSE = 1856.7 R^2 = .6622
SST = 5497.3 adjusted R^2 = .5323

Table 8. Summary of results of OLS on data from 1969 to 1986 in which a quadratic form fecundity factor has been included. The parameters were determined in a non-linear regression which converged in one instance to these values. We could not confirm this convergence for other starting values for the non-linear procedure, but used a grid search method to confirm that these values do describe what is likely to be at least a local minimum. On its face this model with these parameters gives a smaller sum of squared errors than the previous models. In this run the fecundity factor parameters are entered exogeneously.

Fecundity Factor: $F = (1 + b4E + b5E^2)$ E = eggs index

Model: $SYOY = [b1 + b2 \ln OF + b3(\ln OF)^2][1 + b4E + b5E^2]$

variable		estimated coefficient	standard error	T-ratio 13 D.F.
b1	constant	-24.986	6.563	-3.8073
b2	ln (OF)	5.348	1.418	3.7707
b3	ln $(OF)^2$	-0.2776	0.07624	-3.6418
b4	(exogeneous)	0.3947	n/a	
b5	(exogeneous)	-.000577	n/a	

analysis of variance from mean

SSE = 1679.3 R^2 = .6945
SST = 5497.3 adjusted R^2 = .5770

Table 9. Summary of results of OLS run on data from 1969 to 1986, with dummy variable model 1. The years of the sample were divided into two sets - (1969-1975) and (1976-1986).

Model: $SYOY = b1 + b2*\ln(OF) + b3*(\ln(OF))^2 + b4*Di + b5*Di*\ln(OF) + e$

where Di = 0 for 1969-1975
and Di = 1 for 1976-1986

variable		estimated coefficient	standard error	T-ratio 13 D.F.
b1	constant	-864.71	353.33	-2.4473
b2	ln (OF)	189.71	75.54	2.5111
b3	$\ln(OF)^2$	-9.855	4.046	-2.4356
b4	Di	-47.568	68.961	-.6898
b5	Di*ln(OF)	2.8944	7.4954	.3862

analysis of variance from mean

SSE = 1481.4 R^2 = .7305
SST = 5497.3 adjusted R^2 = .6476

Table 10. Summary of results of OLS run on data from 1969 to 1986, with dummy variable model 1. The years of the sample were divided into two sets - (1969-1977) and (1978-1986).

Model: SYOY = b1 + b2*ln(OF) + b3*(ln(OF))^2 + b4*Di + b5*Di*ln(OF) + e

where Di = 0 for 1969-1977
and Di = 1 for 1978-1986

variable		estimated coefficient	standard error	T-ratio 13 D.F.
b1	constant	-1496.6	409.44	-3.6551
b2	ln (OF)	321.67	90.035	3.5727
b3	ln (OF)^2	-16.723	4.9298	-3.3923
b4	Di	-72.238	78.273	.92291
b5	Di*ln(OF)	5.7805	8.5413	.67677

analysis of variance from mean

SSE = 1481.6 R^2 = .7305
SST = 5497.3 adjusted R^2 = .6476

Table 11. Summary of results of OLS run on data from 1969 to 1986, with dummy variable model 2. The years of the sample were divided into two sets - (1969-1975) and (1976-1986).

Model: $SYOY = b1 + b2*\ln(OF) + b3*(\ln(OF))^2 + b4*Di*\ln(OF) + b5*Di*(\ln(OF))^2 + e$

where Di = 0 for 1969-1975
and Di = 1 for 1976-1986

variable		estimated coefficient	standard error	T-ratio 13 D.F.
b1	constant	-911.90	357.94	-2.5476
b2	ln (OF)	200.27	77.468	2.5852
b3	ln $(OF)^2$	-10.442	4.1976	-2.4877
b4	Di*ln(OF)	-7.8891	7.3859	-1.0681
b5	$Di*(\ln(OF))^2$	0.6067	.7935	.76463

analysis of variance from mean

SSE = 1469.5 R^2 = .7327

SST = 5497.3 adjusted R^2 = .6504

Table 12. Summary of results of OLS run on data from 1969 to 1986, with dummy variable model 2. The years of the sample were divided into two sets - (1969-1977) and (1978-1986).

Model: $SYOY = b1 + b2*\ln(OF) + b3*(\ln(OF))^2 + b4*Di*\ln(OF) + b5*Di*(\ln(OF))^2 + e$

where Di = 0 for 1969-1977
and Di = 1 for 1978-1986

variable		estimated coefficient	standard error	T-ratio 13 D.F.
b1	constant	-1569.3	432.72	-3.6265
b2	ln (OF)	338.00	95.464	3.5407
b3	ln $(OF)^2$	-17.635	5.2422	-3.3640
b4	Di*ln(OF)	-10.720	8.2812	-1.2945
b5	Di*$(\ln(OF))^2$	.93401	.89384	1.0449

analysis of variance from mean

SSE = 1456.3 R^2 = .7351
SST = 5497.3 adjusted R^2 = .6536

Table 13. Summary of the estimated linear coefficients in the various models. The coefficients b4 and b5 are not reported here because they do not have the same meaning in the various models.

Model	b1	b2	b3	adjusted R^2
linear 1959-70	-646.6	131.3	-6.083	.74
linear 1959-86	-772.2	161.6	-7.995	.41
GLS 1959-86	-554.1	113.1	-5.322	.49
linear 1969-86	-1272	270.3	-13.92	.34
Fecundity factor F = 1/1+1/G	-2561	549.0	-28.51	.53
Fecundity factor quadratic	-24.99	5.349	-.2776	.58
Dummy variable				
model 1				
75/76 split	-864.7	189.7	-9.85	.65
77/78 split	-1496.6	321.7	-16.72	.65
model 2				
75/76 split	-911.9	200.3	-10.44	.65
77/78 split	-1569	338.0	-17.63	.65

Note how these coefficients differ only by a factor of proportionality. For all the regressions here noted, b1/b2 is always in the range between 4.5 and 5.0, and b2/b3 is always in the range between 19 and 22. This suggests that Chadwick's basic model is robust with respect to time and the introduction of additional explanatory variables.

Given this relative consistency in the relationship between pairs of parameters, it becomes more difficult to understand the discrepancy between Chadwick's published coefficients and ours.

Since the number of parameters is the same in the dummy variable model as in the nonlinear model, it appears that the complicated nonlinear population model has no more explanatory power than the naive speculation that there may have been a change in the parameters of a linear model since 1976 or 1977.

At this point in our research, there is no clear basis for a choice among the competing models. The small sample properties of nonlinear models are not well defined, and the large number of parameters in relation to sample size suggests caution in interpreting the results. For purposes of comparison, partial results of the several models are summarized in Table 10.

What we can conclude from the results in Tables 4 through 13 is that the hypothesis that reduced egg production has led to a lower SYOY index cannot be rejected on the basis of the data. The data show that SYOY has been consistently lower than predicted based on the DFG outflow mode since the mid-1970s. Egg production has been consistently lower over the same period. A reasonable model based on biological principles can be constructed which can explain the lower SYOY on the basis of a relationship between eggs and SYOY. The data do not rule out the possibility that some other factor has caused the reduction in SYOY levels and that the contemporaneous reduction in eggs is unrelated to SYOY levels. But until such an alternative explanatory factor is identified, there must be a strong presumption that there is a relationship between egg production and SYOY.

2. Delta (cross-Delta flows; entrainment)

The decline in the YOY index for the Delta is much more consistent and unambiguous than the decline in the Suisun Bay. Two factors have been identified as particularly important in the Delta: reduction in larval bass food supply and entrainment. In discussing the problems with the Delta above Collinsville, the DFG suggests that "adequate food for larval bass survival must be considered as a possible factor in their survival in this area although we have little solid evidence to substantiate this (1987a, page 41). One possible hypothesis is that water exports have led to a diminished food supply. The most likely mechanism seems to be the increased water velocity through the Delta which reduces the residence time and thus affects zooplankton both directly and indirectly through its impact on the phytoplankton. But at this point there is no direct quantitative evidence that this has been the cause of the reduction in Delta zooplankton or that the decline in zooplankton has had any impact on the striped bass. "Does food availability account for the lower abundance and survival of young striped bass since 1977? Does it account for the good year class produced in 1986? Currently, the answers to these questions are not clear. The pertinent zooplankton data became available only a few weeks before this report was due and so far only a cursory analysis has been possible" (California Department of Fish and Game, 1987a, page 97).

The other factor that clearly affects the striped bass in the Delta is entrainment. There are three general categories of entrainment: at irrigation pumps for Delta agriculture, for coolant water at PG&E power plants, and at the export pumps of the SWP and of the Central Valley Project (CVP). Delta agriculture is not much discussed because the amount of pumping is unknown and the number of bass entrained in the pumps is difficult to quantify (in any event, pumping is presumed to have remained fairly constant over the period of interest). The PG&E plants have reportedly reduced the number of bass entrained, so that they cannot be suspected as a cause for the recent decline of the bass. That leaves the focus of most attention on the CVP and the SWP.

There are differences between CVP and SWP operations that are worth noting. The CVP pumps more or less continuously and takes out a fairly constant amount. Pumping is limited by the capacity of the Delta-Mendota Canal (DMC), which is about 4,600 cfs. Since the construction of the downstream San Luis Reservoir in the late 1960s, "CVP exports have tended to be near peak DMC capacity year-round, regardless of the water year type" (Arthur, 1987, page 20). The inlet is closer to the San Joaquin River than is the SWP, so the CVP takes in a larger portion of the lower quality San Joaquin water. The SWP has an ultimate capacity (pumps and canals out of Clifton Court Forebay) of 10,300 cfs, but actual exports usually run less than half that amount. Pumping began in late 1967. Clifton Court Forebay is used as a huge holding tank between the Delta and the SWP pumps. The gates into Clifton Court are opened only at certain times, calculated to take advantage of favorable tidal conditions to let in the best quality water that is available–meaning Sacramento River water, usually. The pumps then move the water out of Clifton Court whenever it seems appropriate–often at night to take advantage of lower electrical rates. Thus, while the average flow rates (on a 24-hour basis) at the SWP are around 2,000 to 3,000 cfs, the instantaneous flow rates into Clifton Court average around 7,000 cfs when the water is flowing and can run as high as 30,000 (Arthur, 1987).

Estimates of the number of striped bass lost to entrainment are speculative at best. The most detailed analysis has been done at the Skinner Fish Facility (Wendt, 1987), but that work was restricted to the impact on bass measuring 18 millimeters or longer. The DFG (1987a) believes that the entrainment of smaller bass larvae and eggs may well constitute a significant part of the losses to entrainment.

One purpose for Wendt's work was to determine the impact that alternative Delta transfer facilities or strategies might have on entrainment losses. An important finding is that the direction of flow in the lower San Joaquin is a significant determinant of entrainment losses–as might have been expected. When reverse flows pull Sacramento River water around Sherman Island and up toward the pumps, losses to striped bass increase. This is because ". . . in the Delta, most striped bass spawning occurs in the lower San Joaquin River from Antioch to Venice Island (Turner, 1976). This may represent almost half of the total striped bass spawned each year" (Wendt, 1987, page 5). Another important finding is that the size of cross-Delta flows does not (in Wendt's model) contribute significantly to salvage loss rates for bass over 18 millimeters. Ths might be because "most bass going from the Sacramento River directly to the export pumps arrive there at a size too small to be salvaged" (Wendt, 1987, page 5).

These findings bear significantly on possible solutions to the entrainment problem. Recall that there are two locations where striped bass tend to spawn. One location is upstream on the Sacramento River and the other is on the lower San Joaquin River. The reverse flows act directly on the lower San Joaquin population, drawing the larval and juvenile bass toward the pumps and also, to some degree, pulling the Sacramento River population around Sherman Island as they drift downstream. Short of building the peripheral canal, the most commonly mentioned solution to the reverse flow problem is to widen existing Delta channels or otherwise build a Delta transfer facility so that the Sacramento water needed for export can be transferred across the Delta and to the pumps of the SWP and CVP without the need for reverse flows around Sherman Island. By definition, this means increased cross-Delta flows.

The effect of cross-Delta diversion of Sacramento River water on the larval bass spawned in the Sacramento has long been a cause for concern. Decision 1485–promulgated by the SWRCB in 1978–included a requirement for temporary closures of the Delta cross channel intended to minimize the number of bass eggs and larvae transported out of the Sacramento and across the Delta toward the pumps. However, this requirement is only in effect during years with high flows, so that it has not provided any help in the low flow years when help is really needed (California Department of Fish and Game, 1987a). Wendt's model seems to show that increasing cross-Delta flows via a Delta transfer facility would not increase salvage losses since those losses are not correlated with cross-Delta flows. One possible flaw in his argument (which he points out) is that it assumes that losses to bass larvae smaller than 18 millimeters have a negligible impact on the numbers that survive to maturity. This is a point of some importance since fish screens have no ability to screen out those smaller sized larvae. The DFG also points out that while ". . . eliminating reverse flows is advantageous, it is obvious that this action is not the entire solution. With present export rates, substantial entrainment losses would continue to occur . . . (California Department of Fish and Game, 1987a, page 87). So, the beneficial impact of a Delta transfer facility on striped bass entrainment losses is not entirely clear. Screening the entrance to the Delta cross channel might reduce the number of fish transported across the Delta, but screens cannot effectively filter out the eggs and larvae.

One side note we might mention here is that every discussion of a Delta transfer facility that has come to our attention mentions as one benefit the reduction in "carriage water" needed to maintain the salinity balance in the western Delta. In other words, exports could be increased and Delta outflow could be reduced without violating the salinity standards in the Delta. What is never mentioned in this context is the negative impact that this increase in exports could have on the bass in the Delta or that the reduction in Delta outflow could have on the bass in Suisun Bay. A suspicious person might wonder if such a Delta transfer facility is really intended to help the striped bass or it it might just be a way to increase water exports while still meeting the technical requirements of Decision 1485.

The DFG has used the striped bass simulation model, STRIPER, developed by Professor L. W. Botsford of the University of California at Davis to estimate the impact of entrainment losses on striped bass populations (California Department of Fish and Game, 1987a, pages 108-116). They had good estimates of larval entrainment for only two years (1985 and 1986), and so they used rough estimates by assuming that entrainment varied linearly with percent of inflow diverted. This work confirmed that entrainment could have a substantial impact on striped bass populations and that earlier analyses had underestimated this impact. "We believe that this evidence indicates that entrainment is substantially more important in limiting bass production than was inferred from the correlation for the years, 1959-1976" (California Department of Fish and Game, 1987a, page 126).

3. *Pollutants and young striped bass*

Beyond the impact of pollutants on adult populations and on effective fecundity, pollutants may affect young bass both directly through increased mortality and indirectly through an impact on food supply. Both of those possibilities will be discussed in this section. The possible impact of temperature on young bass will also be covered.

It is possible that pollutants have reduced the number of larvae and that pollutants and parasitic cestode-induced lesions have increased the mortality of YOY juveniles and subadults. Jung *et al.* (1984) argue that concentrations of many synthetic chlorinated organic compounds (e.g., PCB and DDT) in the ovaries of field-collected prespawning females were high enough to adversely affect the subsequent development of their larvae. Extremely poor survival of larvae in the laboratory experiments at NMFS from 1976 to 1980 and in hatchery efforts at Elk Grove in recent years were attributed to the poor condition of adult females and their eggs (Jung *et al.*, 1984).

As part of the COSBS, Jung *et al.* (1984).conducted laboratory experiments to determine the effects of representative pollutants (benzene and zinc) on striped bass. The results of these experiments tended to corroborate the effects observed in field-collected fish. Many of their major results pertain to the effects of pollutant concentrations on juvenile striped bass and include:

a. The uptake of benzene and zinc appeared to be antagonistic; high concentrations of benzene in the liver were related to low zinc concentrations.

b. Benzene appeared to accelerate and increase the inflammatory response to parasitic roundworm larvae.

c. Benzene was associated with blood cell destruction followed by increased production of immature red and white blood cells.

d. Zinc was associated with impaired liver condition.

e. Zinc was associated with decreased levels of serum proteins hypothesized to be immunoglobins.

f. Juveniles exposed to benzene or zinc had higher levels of protozoan gill parasites than controls.

g. The effects of benzene and zinc together resulted in greater effects on the juveniles than either pollutant alone: (1) the inflammatory response to parasitic worms was accelerated, (2) blood cells and serum proteins were more deleteriously affected, and (3) liver tissue was more deleteriously affected.

Additional evidence consistent with the hypothesis that pollutants adversely affect larvae and juvenile striped bass comes from research conducted by Anatec Laboratories; juvenile striped bass and rainbow trout captured by trawling close to Chevron USA's refinery outfall in Castro Cove (near Richmond) exhibited a high incidence of fin erosion (Phillips, 1987). From the bioassay conducted on these fish, Anatec also found that striped bass and rainbow trout exhibited "statistically significant preferences for the effluent (i.e., nonavoidance) . . . particularly at low concentrations of the effluent" (Phillips, 1987). Moreover, in other bioassays conducted on a range of organisms, Anatec researchers induced fin erosion in striped bass exposed to effluent concentrations as low as 10 percent. Striped bass also exhibited lethal responses to effluent concentrations greater than 32 percent. The dose-response relationships suggested the possible presence of cumulative forms of toxicity (Phillips, 1987).

Pesticide runoff from farms in the Delta and Central Valley to the rivers and streams where striped bass spawn may harm the viability of larval and juvenile striped bass. In general, striped bass reflect the pattern of pesticide use in the Central Valley exhibiting elevated concentrations of aldrin, dieldrin, chlordane, hexachlorobenzene, dacthal, and toxaphene as compared to the same species from Coos River, Oregon (Phillips, 1987). In particular, Jung *et al.* (1984) argue that rice herbicides threaten spawning striped bass and their offspring. The use of herbicides in the Sacramento Valley increased considerably during the same period that striped bass abundance was declining, according to Brown (1987). In addition to the COSBS results, studies by the Central Valley Regional Water Quality Control Board (CVRWQCB) have shown significant toxicity in ambient waters in the catchment rivers, although the contaminants causing such toxic effects are rarely identified (Phillips, 1987).

Further evidence in support of the hypothesis that pollutants in spawning areas of the striped bass are harmful is the frequent occurrence during May and June for the period 1965-1981 of resident fish kills linked to pesticide-contaminated water in irrigation discharge drains and sloughs of the Sacramento Valley (Cornacchia *et al.*, 1984, and Stevens *et al.*, 1985). Each spring, coincident to the striped bass spawning period, rice growers drain their fields. The pond water has been found to be laden with herbicides. The discharges are located above and near Knight's Landing on the Sacramento River. Numerous dead fish have been found along these areas; the greatest number of dead fish are almost always carp. There have also been complaints about the taste of the drinking water by Sacramento residents coincident to these activities.

Recent toxicity tests by Finlayson (Stevens *et al.*, 1985) reveal that young striped bass are more sensitive to molinate and thiobencarb than are the resident fish (cyprinids, centrarchids, ictalurids). However, the percentage of spring-run or fall-run juvenile striped bass exposed to rice return flows during May and June is unknown. Moreover, Faggella and Finlayson (1987) have concluded that rice herbicides–molinate and thionbencarb–are unlikely to significantly affect larval or juvenile striped bass in the Delta. Neither molinate nor thiobencarb, though, is as toxic to striped bass as many other pesticides in use in the Delta and Central Valley regions (Phillips, 1987), so the general hypothesis of harmful effects of pollutants in the spawning areas on larval and juvenile striped bass has not been contradicted.

Pollutant loadings and concentrations may also adversely affect the food supply of striped bass and, thereby, affect the abundance of these fish. The effects of pollutants on the food supply appear to depend on location. For example, the evidence to date indicates that pollutants have not adversely affected the supply of phytoplankton for striped bass in the Delta. Specifically, Taberski (1987) evaluated algal growth in samples spiked with high and low levels of both molinate and thiobencarb. The tests indicated that the two herbicides had no effects on the growth rates of natural Delta alga and two common Delta alga, *Coscinodiscus* and *Melosira*, at concentrations much higher than have been reported for the Delta.

Upstream of the Delta, however, the agricultural drains and storm drains may be acutely toxic to phytoplankton and zooplankton, particularly in the summer months and for those drains entering the Sacramento River watershed. For example, molinate and thiobencarb used in the Sacramento Valley may adversely affect mysid shrimp and, perhaps, other zooplankton populations in the Delta. Faggella and Finlayson (1987) found that a hazard exists to *Neomysis* in the Delta during years with minimal dilution flows in the Sacramento River when agricultural drainage waters are poorly diluted by receiving waters in the rivers. In addition, Foe and Knight (1985) found that selenium levels above 70 µg/l caused adverse effects on growth of the green algae *Selenastrum capricornutum*. Typical composite drainage from the San Joaquin Valley contains roughly 100 µg/l of selenium. Thus, composite drainage from the San Joaquin and Sacramento Valleys may adversely affect one of the food sources of striped bass when they are upstream of the Delta.

Not all of the evidence however, indicates that upstream drainage is acutely toxic to the food supply. Marine Bioassay Laboratories (MBL) conducted 96-hour bioassays of San Joaquin Valley drainage on algae (phytoplankton), two common zooplankton (*Arcatia clausii* and *Eurytemora hirunoides*), *Neomysis*, and the oriental shrimp (*Palaemon macrodactylus*.) MBL (1984) found no acutely toxic effect of San Joaquin Valley drainage on these organisms. In addition, Taberski (1987) found no effects of molinate and thiobencarb on algal growth in samples of water draining from rice fields.

Moreover, selenium in the Delta-Suisun Bay area that originates from the San Joaquin Valley and from local sources near the Delta does not appear to adversely affect the survival of young striped bass through impacts on their food supply, according to results from a series of bioassays of San Joaquin Valley drainage (Brown, 1987). That is, although selenium may exert toxic effects on the upstream food supply of striped bass, when agricultural drainage reaches Vernalis, the San Joaquin River rim inflow station to the Delta, it has been diluted considerably and selenium concentrations are generally below 1 µg/l .

In contrast to the drainage to the San Joaquin River, the water in agricultural drains entering the Sacramento River during the summer is often acutely toxic to both the green algae, *Selenastrum capricornaturm,* and an invertebrate, *Ceriodaphnia*; and the addition of this drain water increases the toxicity of water in the mainstream Sacramento River–based on standard Environmental Protection Agency (EPA) acute toxicity tests conducted by the University of California at Davis (UCD) under contract with the CVRWQCB. Similar tests conducted during the winter did not demonstrate the presence of acute toxicity to the same organisms. Brown (1987a, page 12) summarizes additional results from the UCD tests

> Water from the American River (December, 1986, samples) suppressed *Selenastrum capricornatum* and *Ceriodaphnia* reproduction and caused an approximate 50 percent decrease in the reproduction of the invertebrate 3 to 15 miles downstream of the confluence of the American River with the Sacramento River. Algal production was decreased by about 50 percent, as compared to Sacramento River water above the American River, in water samples collected as far downstream as Freeport. Finally, American River water was acutely toxic to newly hatched fathead minnow larva during a 1986 storm event with urban runoff the suspected

source of the toxicity. A test conducted in 12987 indicated that such toxicity did not persist to the Delta (Chris Foe, CVRWQCB, personal communication).

Considering both the San Joaquin and Sacramento Rivers as sources, Brown seems to take the view that subsurface drainage should not present a problem to the Delta phytoplankton since concentrations of subsurface drainage water in the Delta have never exceeded a small fraction of one percent (Brown, 1987).

Mitchell (1987) has examined the possibility that adverse temperatures could have an effect on bass eggs and larvae. He concludes that low temperatures are not a problem since the bass do not spawn in cold water (usually waiting until they are cued by a major rise in water temperature). The bass could suffer some increased mortality if exposed to temperatures above 23° C while they are still small. Mitchell studied the pattern of bass spawning and of water temperature and concluded that "even in years when the potential for direct temperature effects was greatest, the majority of eggs indexed in the Sacramento River occurred as one or two sharp peaks sufficiently early in the season to allow eggs and larvae to reach cooler Delta waters and/or to grow beyond the most vulnerable sizes before temperatures reached harmful levels" (page 15). So, although some direct temperature mortality may occur in certain years, even in those years the impact is likely to be minor.

V. A Summing-up: Remaining Questions, Future Direction

Most analyses of the striped bass problem point to four or five possible causes, depending on how one counts. The usual list includes:

1. the impact of toxic chemicals and compounds on adults and young;
2. reduced food production available for young bass;
3. entrainment losses of young bass at water diversions for export, power plant cooling, and Delta agriculture;

4. changes in Delta hydrology that transport young bass into areas that are less favorable to their survival;

5. reduced egg production as a result of the declining adult population.

There seems to be little disagreement, with a prominent exception noted below, that the decline in the striped bass population of the San Francisco Bay/Delta Estuary has been the direct result of one or more of the items on the list. In fact, there seems to be little disagreement that *all* of the items have affected the bass adversely, with the possible exception of the last one. But there is no consensus on the relative importance of these factors.

Let us review the statements of the various parties in an attempt to see where they agree and where they disagree, both in their analysis of the current situation and in their recommendations for corrective action. We focus on testimony presented to the 1987 SWRCB hearings by four major players: the DFG, the U.S. Bureau of Reclamation (USBR), the State Water Contractors (SWC), and the Bay Institute.

Chadwick (1987) has summarized the conclusions and recommendations of the DFG. He states that the production of young bass continues to be enhanced by higher outflows and decreased by high diversions and by reverse flow in the lower San Joaquin River; but he also notes that production in recent years has been less than predicted, indicating either that some other factor is involved or that the outflow relationships are not completely taken into account in the statistical models. He concludes that the cause for the declining survival rate of young bass is uncertain. Although changes in food supply may be involved, this has not been positively demonstrated. Chadwick suggests that egg production may now be limiting but does not indicate any belief one way or the other on that point. He notes that toxics are harming the population but asserts that there is no evidence that they have been involved in the decline. He says that angler harvest has not contributed to the decline nor is there any evidence that increased competition or predation by other species has done so. With respect to policy, Chadwick makes no specific recommendations but suggests that increased outflow sufficient to transport larval bass to Suisun Bay would be beneficial as would reduction or elimination of reverse flows on the lower San Joaquin. In addition, the recommendations listed in California Department of Fish and Game, 1987a include increased efforts to reduce entrainment and further study on the question of toxicity.

Turner's 1987 report reflects his testimony on behalf of the USBR. He suggests stopping pumping at crucial times, flushing larval bass to below Collinsville, and modifying diversions through the central Delta so that larval bass and zooplankton are not carried off in canals. Breitzman (1987) makes the additional remark that flushing of larval bass to Suisun Bay should be maximized in wet years when operational flexibility is greatest. We might note that this hardly seems like a useful suggestion since larvae are transported in any event in wet years. He also states that "we believe we could analyze, identify, and implement structural and operational modifications which would reduce the negative effects of cross-Delta flows and reverse flows in the San Joaquin River."

The State Water Contractors (1987) emphasize the uncertainty and the "lack of consensus" on the importance of factors affecting striped bass. On the larval bass food supply, they state: "Factors contributing to the apparent reduction in phytoplankton and zooplankton, the extent of the reduction, and subtle changes in species composition are not understood. Furthermore, the linkage between changes in the phytoplankton and zooplankton communities and the survival and growth of larval and juvenile striped bass has not been established" (page 25). They only discuss bass food supply in the Delta. In addition to citing water exports and reduced residence time as one possible cause, they mention the improvement in sewage treatment leading to decreased nutrient loadings as an alternative hypotheses as well as a suggestion that phytoplankton and zooplankton populations may be depressed due to foraging pressure from certain introduced fish whose populations have been increasing. With regard to entrainment losses, they point out that, in contrast to Delta agricultural diversion, the export diversion facilities are screened to reduce entrainment and that design and operational changes can be made to further reduce losses. Beyond that, they cite the agreement by which the SWP will pay for mitigation of the losses at the Skinner

Fish Facility (mitigation will involve hatchery production and facilities to "grow out" young striped bass salvaged at Skinner).

With regard to the changing hydrology of the Delta, they plead ignorance, saying that "We do not understand the process through which outflow affects striped bass production or survival and have no clear explanation for the change in the outflow/striped bass relationship" (page 30). They then go on to address several aspects of the hydrology question. They look at the lack of correlation between the total YOY index and cross-Delta flows and conclude that "it is difficult to evaluate the actual benefit the striped bass population might derive from reduced cross-channel operations" (page 32). With regard to the entrapment zone, they say that "The unexplained changes in the relationship between striped bass year-class strength and striping outflows, which determine the location of the entrapment zone, during the last decade have led to uncertainty regarding the significance of the entrapment zone locations as a factor influencing striped bass survival and year-class strength" (page 36). And, again, they look at the lack of a simple correlation between the total YOY index and reverse flows and note that "if reversed flows were a significant factor influencing the survival of larval striped bass, then low survival rates should be detected in years when reversed flows were greatest and higher survival rates should be apparent when flows in the lower San Joaquin River were positive. . . . Based on available information, it is difficult to evaluate the actual benefit the striped bass population might derive from a reduction in the occurrence of reversed flows in the lower San Joaquin River" (page 38). The SWC policy recommendation is, essentially, that current standards be maintained until more is known about what has caused the striped bass decline. They suggest that the existing mitigation agreement does "provide reasonable protection for the striped bass fishery as affected by direct losses . . ." at the pumping plants (page 48) and the only sure way to increase the base population is with hatchery production. In the long run, the only way to solve Delta flow problems, if any, without severely impacting project water users is construction of a Delta transfer facility.

The view of the Bay Institute is represented by the report of Hedgepeth and Mortensen (1987) as well as by the Bay Institute closing brief (1988). The former does not include explicit recommendations, but its conclusions include the following: that cross-Delta flows reduce the Delta phytoplankton and thus the zooplankton, thereby reducing the food supply for larval bass; that reverse flows in the lower San Joaquin draw bass eggs and larvae toward Clifton Court Forebay, where they are subject both to increased predation and to entrainment by the pumps; and that productivity in Suisun Bay depends on the location of the entrapment zone adjacent to the shallows of the Bay. The conclusions in the Bay Institute brief emphasize the importance of flows and the position of the entrapment zone to the production of young striped bass as well as the importance of losses to entrainment. Recommendations include minimum outflow standards that are, allegedly, similar to those of the DFG: closure of the Delta cross-channel at certain times to minimize diversion of larval bass out of the Sacramento River, and limits on exports during May and June. We tend to agree with the conclusions and recommendations of the Bay Institute, which are, in turn, similar to those of the DFG and the USBR. We would, however, state them rather tentatively and recognize the need for further research--both to resolve remaining questions, such as those raised in the SWC report, and to provide a quantitative dimension to some of the conclusions and policy recommendations.

What sort of research is needed? In our view, a combination of statistical and simulation modeling will be helpful and constitutes the next phase of our study. As discussed earlier, primarily in section IV, statistical models have been developed to related young-of-year (YOY) striped bass populations to hydrological conditions in the Bay/Delta system. These models have also been differentiated to consider population/hydrology relationships separately for Suisun Bay and the Delta. We have experimented, again as discussed in section IV, with an extension of these models to include--for Suisun Bay--a fecundity, or egg production, factor. Unfortunately, none of the models, including our own, adequately consider population dynamics. The multigeneration life cycle simulation model, STRIPER, does this but is also not fully adequate to our purposes; population data are entered exogenously; and the model does not distinguish between the Suisun Bay and Delta populations.

We intend to explore the possibility of combining a model like STRIPER with improved models for YOY populations for both Suisun Bay and the Delta. Our hypothesis is that different explanatory factors are at work in the two regions. For Suisun Bay, the evidence suggests that outflow determines the position of the entrapment zone which, in turn, affects striped bass productivity. Since perhaps about 1977, some other factor seems to be involved as well. Our own preliminary statistical analysis suggests that reduced egg production could be the other factor.

Population dynamics in the Delta appear more complicated. Early models indicated that the Delta YOY index was related to outflow and the percentage of water diverted to export. But model-based predictions have not held up well in recent years. One possibility is that fecundity will have some explanatory power here, too; and we intend to specify and carry out appropriate statistical tests. But measures of outflow and diversion may be missing important information on Delta hydrology. Specifically, we intend to look at both cross-Delta and reverse flows, not just a catch-all measure of diversions. Our hypothesis is that cross-Delta flows reduce food supplies for larval bass, whereas the heavy pumping in the southwestern Delta that generates reverse flows leads to entrainment losses of the young fish.

Our ultimate objective in this phase of the study is to realistically simulate long-run impacts on the adult striped bass population of policies that affect the Bay/Delta hydrological regime, pollution, or fishing effort and thereby evaluate the policies on a comparative basis. For example, we hope to be able to compare the benefits, in terms of striped bass production and the value of that production, of alternatives such as increased outflow, decreased pumping for export, and perhaps also pollution controls and hatchery or stocking operations.

References

Albert, Ken. 1987. *Fishing in Northern California.* (Aptos, CA: Marketscope Books).

Arthur, Jim. 1987. "River flows, water project exports, and water quality trends in the San Francisco Bay-Delta Estuary." U. S. Bureau of Reclamation, Mid-Pacific Region,

Arthur, James F., and Melvin D. Ball. 1979. "Factors influencing the entrapment of suspended material in the San Francisco Bay-Delta Estuary." In T. John Conomos (ed), *San Francisco Bay: the Urbanized Estuary.*

Ball, Melvin D., and James F. Arthur. 1979. "Planktonic chlorophyll dynamics in the Northern San Francisco Bay and Delta." In T. John Conomos (ed), *San Francisco Bay: the Urbanized Estuary.*

Bay Institute, 1987.

Bay Institute. 1988. Closing Brief, Phase I Bay-Delta Hearing.

Boreman, J., and H. M. Austin. 1985. "Production and harvest of anadromous striped bass stocks along the Atlantic coast." *Transactions of the American Fisheries Society* 114:3-7.

Breitzman, Dennis E. 1987. Summary of direct testimony to the water right/water quality hearing, October 1987.

Brown, R. 1987. "Toxics and young striped bass," (Sacramento, CA: Department of Water Resources).

Brown, Randall L. 1986. *1984 Annual Report* of the Interagency Ecological Studies Program for the Sacramento-San Joaquin Estuary.

California Department of Fish and Game. 1987a. "Factors affecting striped bass abundance in the Sacramento-San Joaquin River System" (Sacramento, California).

California Department of Fish and Game. 1987b "Long-term trends in zooplankton distribution and abundance in the Sacramento-San Joaquin Estuary" (Sacramento, California).

California Department.of Fish and Game. 1987c. "The relationship between pollutants and striped bass health as indicated by variables measured from 1978 to 1985" (Sacramento, California).

California State Water Resources Control Board, Striped Bass Working Group. 1982. "The Striped Bass Decline in the San Francisco Bay-Delta Estuary" (Sacramento, California).

Chadwick, H. K. 1967. "Recent migrations of the Sacramento-San Joaquin river striped bass population." *Transactions of the American Fisheries Society* 96:327-342.

Chadwick, H. K., D. E. Stevens, and L. W. Miller. 1977. "Some factors regulating the striped bass population in the Sacramento-San Joaquin estuary, California." In W. Van Winkle (ed), *Assessing the Effects of Power-Plant-Induced Mortality on Fish Populations.*

Chadwick, H. K. 1987. "Conclusions and recommendations," California Department of Fish and Game, Summary of testimony to the State Water Resources Control Board, .

Cloern, James E., Brian E. Cole, Raymond L. J.Wong, and Andrea E. Alpine. 1985. "Temporal dynamics of estuarine phytoplankton: a case study of San Francisco Bay." *Hydrobiologia* 129:153-176.

Cloern, James E., Andrea E. Alpine, Brian E. Cole, Raymond L. J. Wong, James F. Arthur, and Melvin D. Ball. 1983. "River discharge controls phytoplankton dynamics in the Northern San Francisco Bay Estuary." *Estuarine, Coastal and Shelf Science* 16:415-429.

Cole, Gerald A. 1979. *Textbook of Limnology*, 2d ed (St. Louis, MO: C.V. Mosby Company).

Collins, Barry W. 1982. "Growth of adult striped bass in the Sacramento-San Joaquin Estuary," *California Fish and Game* 68:146-159.

Cornacchia, John W., David B. Cohen, Gerald W. Bowes, Rudy J. Schnagl, and Barry L. Montoya. 1984. "Rice herbicides: Molinate (Ordram) and Thiobencarb (Bolero): a water quality assessment." California State Water Resources Control Board, Toxics Substances Control Program, Special Projects Report No. 84-4sp, April 1984.

Fagggella, G. A., and B. J. Finlayson. 1987. "Hazard assessment of rice herbicides Molinate and Thiobencarb to larval and juvenile striped bass." California Department of Fish and Game, Administrative Report 87-2 (Sacramento) .

Foe, C., and A. W. Knight. 1985. "Selenium bioaccumulation, regulation, and toxicity in the green alga *Selenastrum capricornutum*, and dietary toxicity of contaminated algae to *Daphnia magna*.." In *Proceedings, Selenium in the Environment*, CATI, California State University, Fresno.

Hedgepeth, J. W., and W. E. Mortensen. 1987. "San Francisco Bay estuarine circulation and productivity of the estuary for striped bass and other species." The Bay Institute of San Francisco.

Horne, Alex. 1987. "Stability of San Francisco Bay-Delta." Appendix 4 to *Report on the San Francisco Bay, Phase 1,* (Sacramento: State Water Contractors).

Jung, M., J. A. Whipple, and M. Moser. 1984. "Summary report of the Cooperative Striped Bass Study (COSBS): a study of the effects of pollutants on the San Francisco Bay-Delta striped bass fishery." (Santa Cruz, California: Institute for Aquatic Resources).

Kelley, D. W.,

1966. "Ecological studies of the Sacramento-San Joaquin estuary, Part I: zooplankton, zoobenthos, and fishes of San Pablo and Suisun Bays; zooplankton and zoobenthos of the Delta." California Department of Fish and Game, Fish Bulletin 133.

Kelley, D. W.,

1982. "The striped bass decline in the San Francisco Bay-Delta Estuary," an analysis by the Striped Bass Working Group for the California State Water Resources Control Board. Nov. 1982.

Knudsen, Diane L., and David W. Kohlhorst. 1987. "Striped bass health index monitoring:" 1985 Final Report, California Department of Fish and Game.

Knutson, A C., Jr., and J. J. Orsi. 1983. "Factors regulating abundance and distribution of the shrimp, *Neomysis mercedis*, in the Sacramento-San Joaquin estuary." *Transactions of the American Fisheries Society* 112:476-485.

Kohlhorst, D. W. 1975. "The striped bass (*Morone saxatilis*) die-off in the Sacramento-San Joaquin Estuary in 1973 and a comparison of its characteristics with those of the 1971 and 1972 die-offs." California Department of Fish and Game, Anadromous Fisheries Branch Administrative Report No. 74-13.

Marine Bioassay Laboratories. 1984. "Toxicity bioassays: Vol. I." Main report submitted to U.S. Bureau of Reclamation.

Mitchell, W. T. 1987. "The potential for direct effects of high temperature on striped bass eggs and larvae in the Sacramento-San Joaquin River System." D. W. Kelley & Associates report to the California Department of Water Resources.

Nichols, Frederic H. 1985. "Increased benthic grazing: an alternative explanation for low phytoplankton biomass in North San Francisco Bay during the 1976-1977 drought," *Estuarine, Coastal and Shelf Science* 21:379-388.

Orsi, J. J., and Arthur C. Knutson, Jr. 1979. "The role of mysid shrimp in the Sacramento-San Joaquin Estuary and factors affecting their abundance and distribution." In T. John Conomos (ed) *San Francisco Bay: The Urbanized Estuary.*

Orsi, J. J. and W. L. Mecum. 1986. "Zooplankton distribution and abundance in the Sacramento-San Joaquin Delta in relation to certain environmental factors," *Estuaries* 9:326-339.

Phillips, David J. H. 1987. "Toxic contaminants in the San Francisco Bay-Delta and their possible biological effects." Aquatic Habitat Institute, August, 1987.

Radtke, L. D. and J. L. Turner. 1967. "High concentrations of total dissolved solids block spawning migration of striped bass, *Roccus saxatilis*, in the San Joaquin River, California." *Transactions of the American Fisheries Society* 96:405-407.

Raney, E. C. 1952. "The life history of the striped bass, *Roccus saxatilis* (Walbaum)." Bulletin of the Bingham Oceanographic Collection, Peabody Museum of Natural History, Yale University 14:5-97.

Smith, Susan E., and Susumu Kato. 1979. The fisheries of San Francisco Bay: past, present, and future." In T. John Conomos (ed) *San Francisco Bay: The Urbanized Estuary.*

State Water Contractors. 1987. "Recommendations of the State Water Contractors regarding the Sacramento-San Joaquin striped bass resource."

Stevens, D. E. 1977a. "Striped bass (*Morone saxatilis*) monitoring techniques in the Sacramento-San Joaquin Estuary." In W. Van Winkle (ed) *Assessing the Effects of Power-Plant Induced Mortality on Fish Populations.*

Stevens, D. E. 1977b. "Striped bass (*Morone saxatilis*) year class strength in relation to river flow in the Sacramento-San Joaquin Estuary, California." *Transactions of the American Fisheries Society* 106:34-42.

Stevens, D. E., D. W. Kohlhorst, L. W. Miller, and D. W.Kelley. 1985. "The decline of striped bass in the Sacramento-San Joaquin Estuary, California." *Transactions of the American Fisheries Society* 114:12-30.

Taberski, K M. 1987. "Phytoplankton growth dynamics in the Sacramento-San Joaquin Delta." Draft Report, California Department.of Water Resources.

Turner, J. L.. and H. K. Chadwick. 1972. "Distribution and abundance of young-of-the-year striped bass, *Morone saxatilis*, in relation to river flow in the Sacramento-San Joaquin Estuary." *Transactions of the American Fisheries Society* 101:442-452.

Turner, J. L. 1976. "Striped bass spawning in the Sacramento and San Joaquin rivers in Central California from 1963 to 1972." *California Fish and Game* 62:106-118.

Turner, J. L. 1987. "Effects of geographic distribution of larval striped bass in determining year class size of striped bass in the Sacramento-San Joaquin Estuary." ECOS, for U.S. Bureau of Reclamation.

Wang, J. C. S. 1986. "Fishes of the Sacramento-San Joaquin Estuary and adjacent waters, California: a guide to the early life histories." Interagency Ecological Study Program for the Sacramento-San Joaquin Estuary, Technical Report 9.

Wendt, P. G. 1987. "Preliminary evaluation of factors controlling striped bass salvage loss at Skinner Fish Facility: quantity and direction of flow in the lower San Joaquin River, striped bass abundance and size, and total Delta exports." California Department. of Water Resources.

Whipple, Jeannette A., Donald G. Crosby, and Marvin Jung. 1983. "Third Progress Report, Cooperative Striped Bass Study. State Water Resources Control Board Special Projects Report No. 83-3SP.

Whipple, J. A., M. B. Eldridge, and P. E. Benville, Jr. 1981. "An ecological perspective of the effects of monocyclic aromatic hydrocarbons on fishes." In F. J. Vernberg, A. Calabrese, F. P. Thurberg, and W. B. Vernberg (eds), *Biological Monitoring of Marine Pollutants*, Academic Press,.pp. 483-551.

Williams, Philip B., and James T. Hollibaugh. 1987. "A salinity standard to maximize phytoplankton abundance by positioning the entrapment zone in suisun bay." Philip Williams & Associated for the Contra Costa County Water Agency and the Tiburon Center for Environmental Studies.