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The Decline of Striped Bass in the Sacramento-San Joaquin Estuary, California

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Abstract

The abundance of young striped bass *Morone saxatilis* in the Sacramento–San Joaquin Estuary has suffered an unsteady but persistent decline from population levels that were high in the middle 1960s. The decline was particularly severe in 1977 and abundance of young striped bass has been low every subsequent year. The adult striped bass population also has fallen during the past 20 years, but the exact period over which the decline occurred and the rate of decline are not clear. The adult population is now about one-quarter of its former size and there is little sign of recovery. We believe the Sacramento–San Joaquin striped bass population and the fishery that it supports are in serious danger. The cause is most likely one or more of four factors. (1) The adult population is now so low that egg production may be inadequate. (2) The plankton food supply of young striped bass in the western Sacramento–San Joaquin Delta and Suisun Bay has been greatly reduced each spring. Diversion of water from the delta for agricultural purposes is a prime suspect for the decrease in food production. (3) Large numbers of young fish are lost by entrainment in water diversions. (4) The population is stressed by toxic substances such as petrochemicals and pesticides. Additional studies are underway to help determine the principal cause(s) of the striped bass decline.

Striped bass *Morone saxatilis* were introduced into the Sacramento–San Joaquin Estuary in 1879. Their abundance increased dramatically, enabling sport and commercial fisheries to develop before 1900. The commercial fishery was closed in 1935 due to pressure from sport fishermen (Stevens 1980). The population has never been dominated by rare strong year classes and until recently has been relatively stable. Now, however, the adult population is one-quarter of what it was 20 years ago, and the production of young over the past 8 years has been one-third to one-half of the expected values. These meager year classes of young probably will further depress the adult stock as they are recruited into the fishery.

This paper summarizes current thinking regarding potential causes of the declines of both young and adult striped bass. The initial work was done by California Department of Fish and Game (CFG) staff in 1980–1981. The analysis was continued by the CFG staff and a "Striped Bass Working Group" of scientists organized by the State Water Resources Control Board in 1982 to review the potential causes and identify corrective action. Kelley chaired this group. Other members were Stevens; Kohlhorst; Miller; James F. Arthur, United States Bureau of Reclamation; Louis W. Botsford, University of California, Davis; Thomas C. Cannon, Envirosphere; Gerald C. Cox and Richard M. Sitts, California Department of Water Resources (Sitts now is with Envirosphere); Stephen R. Hansen and Charles H. Hanson, Ecological Analysts (Hanson now is with Tera); Martin A. Kjelson, United States Fish and Wildlife Service; Jerry L. Turner, D. W. Kelley and Associates; and Roger S. C. Wolcott, Jr., and Thomas G. Yocom, National Marine Fisheries Service.

The Estuary

The Sacramento–San Joaquin Estuary begins where the Sacramento and San Joaquin rivers join to form the Sacramento–San Joaquin Delta (Fig. 1). It embraces the salinity gradient, which extends about 80 km from the western delta to San Pablo Bay and sometimes to San Francisco Bay. Freshwater outflows often range from a winter or spring high of 1,500–4,500 m^3/second to summer lows around 100 m^3/second released

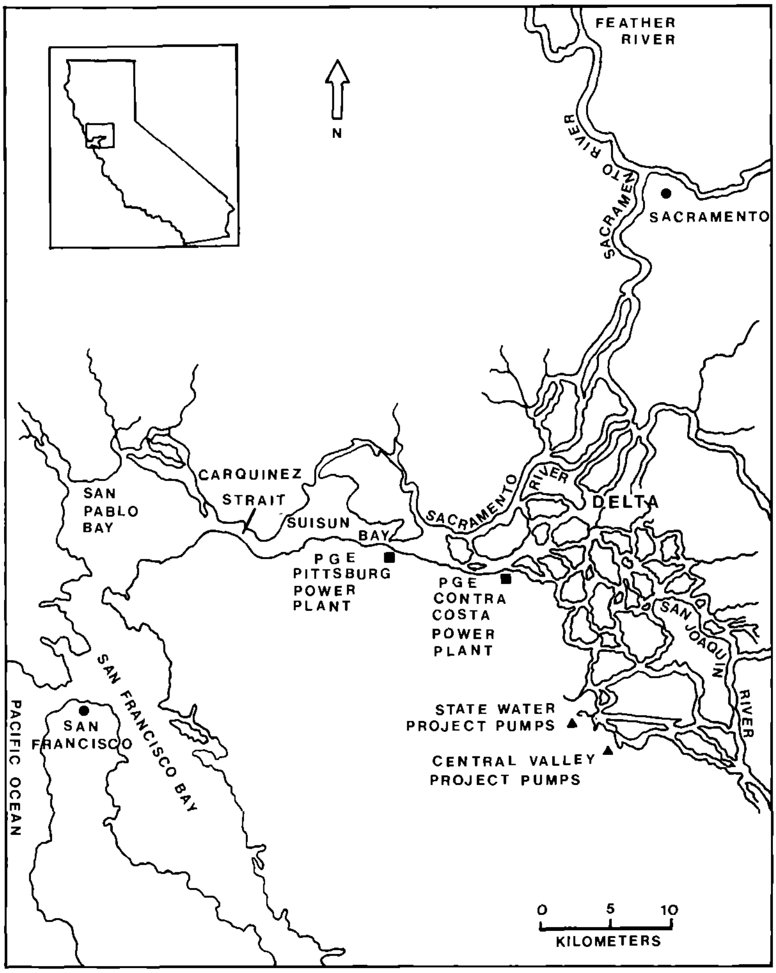

FIGURE 1.—*Sacramento–San Joaquin River system. The principal striped bass nursery areas are the broad channels of the western delta and Suisun Bay.*

from upstream reservoirs to keep salinity out of the delta and to protect fish. The historical average freshwater outflow to the ocean of about 1,100 m^3/second has been reduced by about one-half as a result of consumptive uses upstream and diversions from the delta (Chadwick 1977).

As in other estuaries, there is a zone at the upper end of the salinity gradient called the "critical zone" (Massmann 1963), "null zone" (Conomos and Peterson 1974), or "entrapment zone" (Arthur and Ball 1979), where the meeting of bottom saline water and surface fresh water produces vertical circulation cells and little net flow. Phytoplankton and zooplankton populations are often largest in this zone (Arthur and Ball 1979; Orsi and Knutson 1979) and its location is thought to be important to the young of many fishes, including striped bass (Massmann 1971; Turner and Chadwick 1972). The zone is farther downstream, usually in Suisun Bay, when freshwater outflows are high, and upstream in the western delta when the outflows are low. Plankton production is much greater when the zone is located in Suisun Bay, possibly because of the shallow tidal flats where the photic zone constitutes a greater percentage of the total depth than in the deep channels of the delta (Arthur and Ball 1979).

Sport Fishery

Striped bass is the major sport fish in the estuary. Striped bass anglers fish from the Pacific

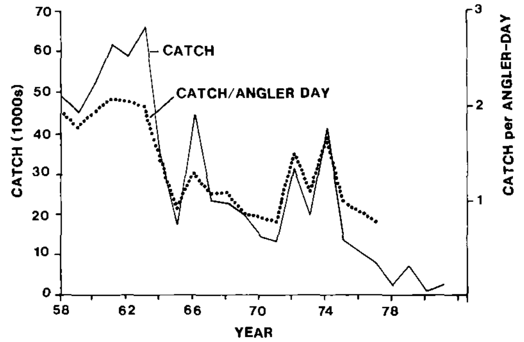

FIGURE 2.—*Trends in striped bass catch and catch per angler day reported by charter boats in the San Francisco Bay area.*

Ocean beaches near San Francisco upstream through the estuary into the Sacramento and San Joaquin rivers more than 200 km above the delta. Angling occurs the year around, but fishing localities vary seasonally in accordance with the striped bass migratory pattern. The fall migration of striped bass upstream from San Francisco Bay to the delta is marked by good fishing in San Pablo and Suisun bays. Fishing in the delta also improves gradually with the movement of striped bass into that area and then declines as the water temperature drops in winter.

Fishing success improves as the water warms in March. Those striped bass that have wintered in the bays start moving upstream to fresh water for spawning. During the spring, adults are spread through the delta and over 200 km north in the Sacramento and Feather rivers. Good fishing can be expected in the river spawning area at this time and occasional good catches are made in the bays.

By mid-June, most adult striped bass have left the delta and returned to brackish and salt water. During summer and early fall, fishing reaches its peak in Carquinez Strait, San Pablo Bay, and San Francisco Bay. Sometimes large numbers of striped bass migrate into the Pacific Ocean, where many are caught by surf-casters.

Most fishing is from shore and private boats, although charter boats are an important component of the fishery in the San Francisco–San Pablo Bay area. Charter boat operators are required to report catches to CFG. Although these boats generally have taken only 10–15% of the total catch and their fishing locations and methods have changed over the years, their reports are the best long-term striped bass catch records available (Stevens 1977a). From 1958 to 1980, the reported annual catch by charter boats declined from 48,900 to 1,400 striped bass (Fig. 2). Catches have been particularly low since 1976. The catch per angler-day on charter boats is available from 1958 to 1977. It decreased from 1.96 to 0.78 fish during this period, although the general downward trend in the fishery was interrupted by good fishing in 1966, 1972, and 1974.

Total catches on charter boats are affected by the number of anglers willing to pay for a day's fishing. Not surprisingly, fishing effort varies according to angler success (Miller 1974). Thus, low success has caused effort to drop off sharply in recent years, which probably has caused total catch on charter boats to decline more severely than the catch for the striped bass fishery as a whole. Nevertheless, our observations of the fishery have convinced us that the overall catch trend truly is downward.

Concern about the striped bass fishery resulted in a change in angling regulations in 1982. Now the minimum total length is 45.7 cm and the daily bag limit is two fish. From 1956 to 1981, the minimum length was 40.6 cm and the bag limit was three fish. Earlier regulations were more liberal: usually a 30.5-cm minimum length and a five-fish bag.

Decline of the Adult Striped Bass Population

The California Department of Fish and Game has measured adult striped bass abundance with Petersen population estimates and the catch per effort (CPE) of adult striped bass (total length $\geq$ 40.6 cm) captured during tagging studies. Modified Petersen mark–recapture population estimates (Bailey 1951) were calculated annually from 1969 through 1982. Striped bass were tagged with disc dangler tags (Chadwick 1963) during their spring spawning migration to the delta and Sacramento River. The ratio of tagged to untagged fish in the population was estimated during annual summer–fall creel censuses in the San Francisco Bay area and subsequent spring tagging operations.

The abundance estimation procedures are complicated by sex- and age-sampling biases (Chadwick 1967; Stevens 1977b). Hence, all of the abundance estimates are based on samples stratified by sex and age (Stevens 1977b). Variances for the stratified sex and age estimates were

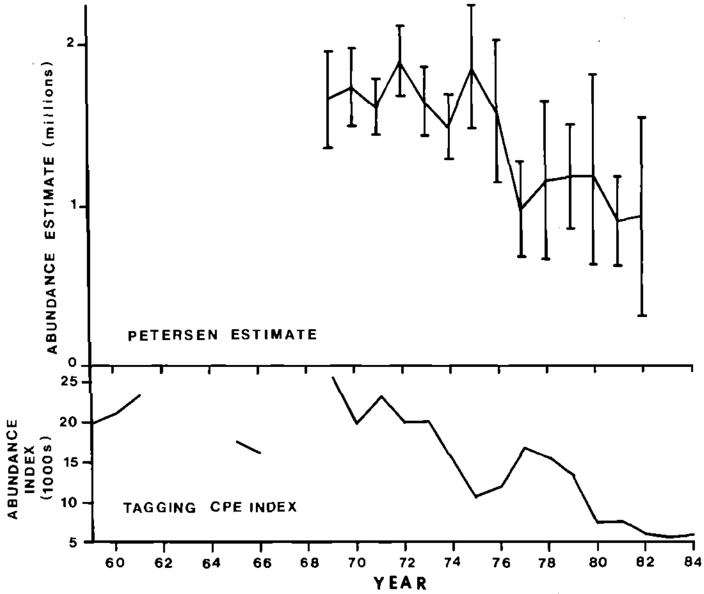

FIGURE 3.—*Trends in abundance of adult striped bass (≥40.6 cm total length) in the Sacramento–San Joaquin Estuary. Vertical bars for the Petersen estimates are 95% confidence intervals. CPE is catch per effort.*

calculated with Bailey's (1952) equation (4). These were summed to obtain the variance of the total population estimate for calculation of confidence intervals.

Sex was determined during spring tagging by applying external pressure to the abdomen of each fish. If milt was extruded, the fish was classified as male; otherwise it was classified as female. During the summer–fall creel census, sex was determined by dissection.

Age was determined from scales collected midway between the spinous dorsal fin and the lateral line. Scofield (1931) and Collins (1982) demonstrated that ages interpreted from California striped bass scales are valid.

According to the Petersen estimates, the striped bass population was remarkably stable between spring 1969, when the estimates began, and spring 1976 (Fig. 3). It then declined by about 40% and remained near this lower level through 1982.

Our second assessment of adult striped bass stocks is from catches of striped bass in CFG gill nets and fyke traps (Hallock et al. 1957) during tagging operations in the delta and Sacramento River. This CPE index is the sum of catches in the fishing gears after annual effort was standardized to four gill-netting boat-months and 36 fyke-trap-months. A boat-month is 20, 8-hour days of fishing a 183-m-long drift gill net (10.2–14.0 cm stretched mesh). A trap-month is 30, 24-hour days of fyke-trap fishing. In years when fishing occurred, effort ranged from 2 to 4.5 boat-months and from 11 to 42 trap-months.

Tagging began in 1958 (Chadwick 1968), but CPE records have been consistent only since 1959. Fyke traps were not fished in 1959–1961, 1965–1966, 1977–1978, or 1981. In those years, CPE indices were estimated by multiplying gill net catches by 1.61, the mean ratio of total catch to standardized gill net catch in 1969–1976 and 1979–1980. We did not include 1982–1984 in calculating the mean ratio because the ratio in those years was up to 2.3 times higher than in any previous year.

The CPE index indicates that the striped bass population declined steadily from the late 1960s to a low level in 1975. It then rose briefly, but declined to even lower levels by 1984 (Fig. 3).

There is no question that the population of adult striped bass in the estuary has fallen to a low level—much lower than when estimates were first available 20 years ago. However, the period over which the decline actually occurred and the rate of decline are not clear.

Adult Mortality Rate

Increased mortality helps account for the decline in adult striped bass abundance. Annual

TABLE 1.—*Number of tagged fish released, response rate, and mortality rates for striped bass age 5 and above in the Sacramento–San Joaquin Estuary.*

Year	Number released		Response rate[a]	Annual mortality rate	Exploitation rate	Expectation of natural death
	Males	Females				
1969	4,662	4,131	0.576	0.369	0.224	0.145
1970	1,585	1,889	0.551	0.395	0.148	0.247
1971	2,024	1,454	0.528	0.301	0.165	0.136
1972	4,002	4,407	0.504	0.407	0.185	0.222
1973	3,570	3,453	0.481	0.475	0.188	0.287
1974	2,710	3,035	0.460	0.399	0.241	0.158
1975	1,106	1,480	0.439	0.460	0.237	0.223
1976	2,008	1,741	0.419	0.456	0.269	0.187
1977	707	612	0.398	0.489	0.241	0.248

[a] 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 decreased over the years as catches of tagged fish became more common, 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 was estimated as the product of those three ratios taken from the regression lines.

mortality rate A was calculated as the complement of annual survival rate S (Ricker 1975) for striped bass age 5 and older. Younger fish were not fully vulnerable to CFG sampling and, because their mortality differs from that of older fish, they could not be included without inducing bias in the overall mortality estimates.

Survival rate was estimated from tag returns by the maximum-likelihood method of Brownie et al. (1978). This technique fits tag return data to specific models of survival and recovery rates and allows the investigator to choose the model that best fits the data. Their model H2 was the most appropriate model as determined by chi-square goodness-of-fit tests. Based on the distribution of tag returns, this model indicates that survival and recovery rates varied annually and that the reporting rate for newly released fish was different from that for survivors of releases in previous years.

Expectation of natural death was calculated by subtracting exploitation from total annual mortality. Exploitation rate u for ages 5 and greater was estimated from returns of nonreward tags corrected for incomplete reporting of tag recoveries by anglers:

$$u = \frac{R}{M};$$

R = number of tags recovered in the first year after tagging;
M = number of tags released at the beginning of the tag-return year.

We estimated response rate (fraction of recovered tags that anglers actually returned to us) annually by comparing return rates for nonreward tags with those for reward tags (Chadwick 1968). Reward tags with values of $5, $10, and $20 were used and we assumed all recovered $20 tags were returned. Corrections ranged from 0.398 to 0.576 (Table 1). Response corrections were applied only to voluntary returns by anglers through the mail. Tags observed during our summer–fall creel census in the San Francisco Bay area were assumed to be completely reported.

Estimated annual mortality of adult striped bass increased from less than 40% in 1969 to almost 50% in 1977. (Due to data processing delays, we do not have subsequent estimates.) Increased exploitation accounts for most of the increase in mortality after 1969; the greatest change occurred between 1970 and 1976 when the harvest increased from 15% to 27%. The positive trends in annual total mortality and exploitation from 1969 to 1977 were both statistically significant ($P < 0.05$). Most of the annual variability in total mortality apparently resulted from fluctuations in natural mortality which varied considerably from year to year but did not have a statistically significant trend.

Although the source of fishing mortality is obvious, the potential causes of natural mortality are more obscure and difficult to assess. The Striped Bass Working Group explored two potential sources of this natural mortality: toxic substances and an inadequate food supply.

Toxic substances and the health of striped bass from the Sacramento–San Joaquin system have

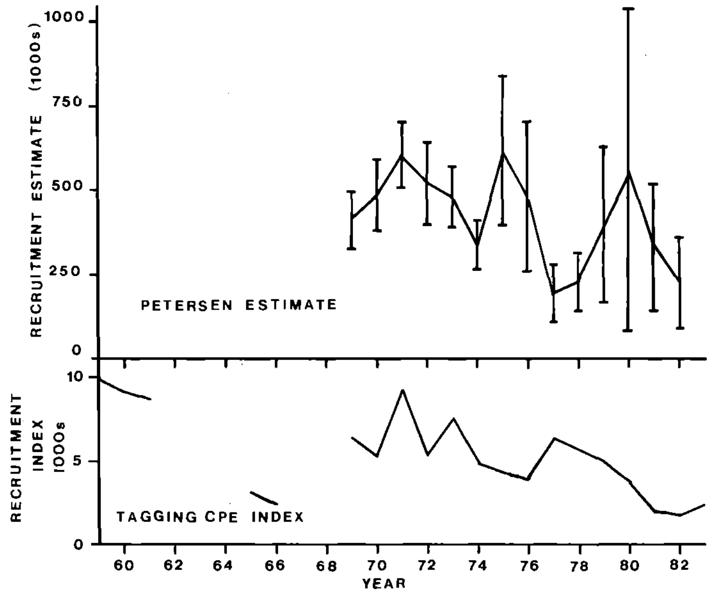

FIGURE 4.—*Trends in striped bass recruitment at age 4 in the Sacramento–San Joaquin Estuary. Vertical bars for the Petersen estimates are 95% confidence intervals. CPE is catch per effort.*

been studied since 1978 (Whipple et al. 1981). Whipple and her staff at the National Marine Fisheries Service's Tiburon laboratory found that gonads, liver, and muscles of adult striped bass accumulated toxic substances, primarily monocyclic aromatic hydrocarbons (MAH), chlorinated hydrocarbons, and heavy metals. They found significant inverse correlations between concentrations of MAH and zinc in striped bass and fish health as measured by liver, gonad, and egg condition. High tissue concentrations of MAH and zinc also were associated with greater parasite infestation. Although these results suggest that toxic substances could affect adult striped bass mortality, there is no direct evidence that they have. Indeed, general water quality conditions in the estuary have been much improved in recent years.

The food supply for adult striped bass in the estuary has not been well measured, but any food shortage long and severe enough to cause mortality should affect growth. Collins (1982) found that, although 1970 and later year classes averaged 2 cm smaller than the 1965 to 1969 year classes, the actual growth rates of adult fish had not changed. Instead, the size reduction was due to recent slower growth during the first year of life.

Reduction in Recruitment

Reduced recruitment of young to the adult population also helps explain the decrease in total striped bass abundance. Although age-4 striped bass are not fully vulnerable to CFG sampling, they represent the first age group that is fully recruited to the fishery; thus, we used measures of their abundance to index recruitment. Scales were not collected before 1969, so earlier age-4 indices were based on the abundance of 50–59-cm fork length fish (Collins 1982).

Petersen estimates indicate recruitment is highly variable with no strong trend, although 1980 was the only above-average year after 1976 (Fig. 4). The estimates were highest (over 550,000 fish) in 1971, 1975, and 1980, and lowest (below 250,000 fish) in 1977, 1978, and 1982. The CPE index of age-4 striped bass also suggests recruitment has been relatively low in recent years, the result of a long-term decline since at least the early 1970s and possibly since 1959 (Fig. 4).

Abundance of Young

If year-class strength is set early in life, the number of adult striped bass would be affected by the number of young surviving in prior years. To evaluate the importance of initial year class

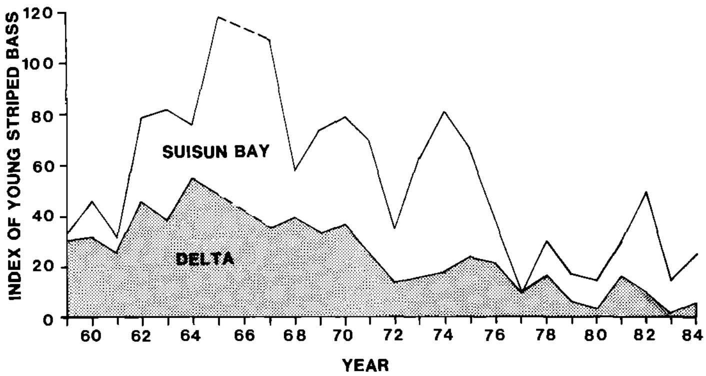

FIGURE 5.—*Annual index of young striped bass abundance by area in the Sacramento–San Joaquin Estuary. No sampling was conducted in 1966.*

strength, we calculated correlation coefficients between both of our measures of recruitment and the abundance of young 4 years earlier as measured by the CFG summer tow-net survey.

Recruit abundance measure	Year classes in correlation	Correlation with young of the year
Petersen age-4 estimate	1965–1978	0.19 (NS)
Tagging CPE age-4 index	1965–1979	0.85 ($P < 0.01$)

Both correlations indicate a positive association between recruitment and young striped bass abundance, but only the CPE correlation was statistically significant. Thus, these results are not definitive, but they do suggest that recruitment of a year class to the adult stock is affected by its abundance early in life.

Decline in Young-of-the-Year Production

Since 1959, CFG has sampled young-of-the-year striped bass every second week from late

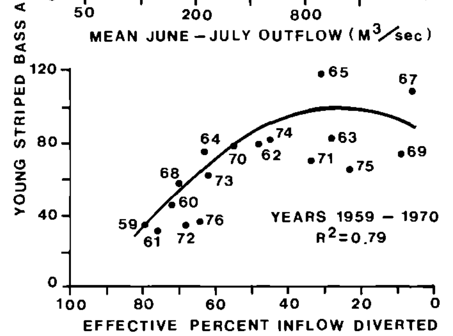

FIGURE 6.—*Relationship between total abundance of young striped bass in the Sacramento–San Joaquin Estuary and delta outflow and diversion. Curves are fits to 1959–1970 data.*

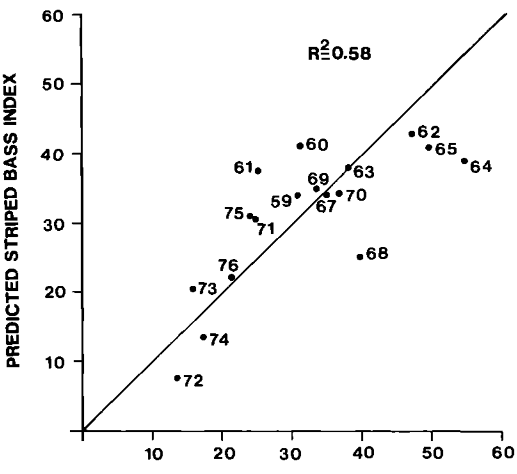

FIGURE 7.—*Relationship between actual and predicted striped bass abundance in the Sacramento–San Joaquin Delta. Predicted abundance = −170 − 0.196 (mean daily May–June water diversion rate by water projects and local agriculture) + 178(log_{10}mean daily May–June delta outflow) − 34.2(log_{10}mean daily May–June delta outflow)^2. All flows are in m^3/second.*

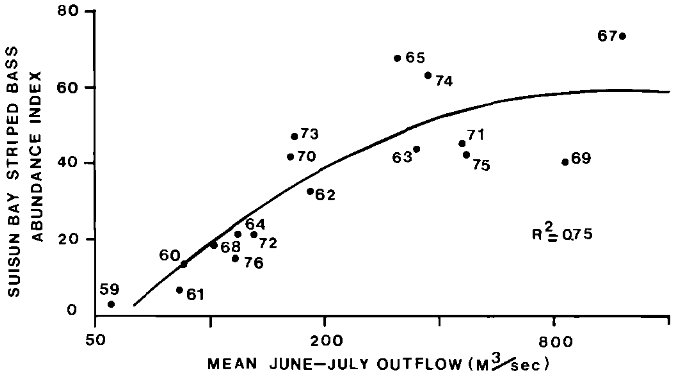

FIGURE 8.—*Relationship between young striped bass abundance in Suisun Bay and Sacramento–San Joaquin Delta outflow.*

June to late July or early August throughout the nursery habitat. The fish are measured and, when their mean fork length reaches 38 mm, a young-of-the-year index is calculated on the basis of catch per net tow and the volume of water in the areas where the fish are caught (Turner and Chadwick 1972).

The sampling for young striped bass occurs primarily in the delta and Suisun Bay. The young-of-the-year index has a well-recognized bias in high-flow years, when a larger proportion of the young is washed downstream into San Pablo Bay; the extremely large volume of water there is not sampled effectively. Hence, in very wet years, the index is an underestimate of the actual population (Stevens 1977a, 1977b).

This survey has revealed that abundance of young-of-the-year striped bass has been declining unevenly but persistently since high levels in the mid-1960s (Fig. 5). The decline has been most pronounced in the delta, but is clearly apparent in Suisun Bay despite greater year-to-year fluctuations there.

During the years 1959–1970, the abundance of young striped bass was highly correlated both positively with freshwater outflow from the delta and negatively with the percent of the river inflow diverted from the delta channels during spring and early summer by the federal Central Valley Project (CVP), the California State Water Project (SWP), and delta farmers (Fig. 6). Conditions during June and July provided the highest correlations. In years when outflow was high and the percent of river inflow diverted was low, the striped bass index was high; conversely, when outflows were low and the percent diverted was high, the young striped bass index was low (Turner and Chadwick 1972).

In the early 1970s, young striped bass abundance was lower than expected based on the 1959–1970 relationships with outflows and diversions. In the delta portion of the estuary, the decline was explained by increased diversion rates in May and June (Chadwick et al. 1977). Hence, for years 1959–1976, May and June outflows and the amount of water diverted in those months accounted for variations in young striped bass abundance in the delta (Fig. 7). Young striped bass abundance in Suisun Bay for those years was best explained by June–July outflow (Fig. 8). However, since 1977, the abundance of young striped bass has been considerably lower than predicted by the 1959–1976 regressions. Both juvenile striped bass abundance and our ability to predict it has been greatly reduced.

The Striped Bass Working Group reviewed several possible causes for the decline of young striped bass. They concluded that four remain as probable major contributors to the problem:

(1) the adult population, reduced by a combination of lower recruitment and higher mortality rates, produces fewer eggs;

(2) production of food for young striped bass has been reduced;

(3) large numbers of striped bass eggs and young are removed from the estuary by diversion with water needed for agriculture, power plant cooling, and other uses;

(4) point and nonpoint discharges of pesticides and other petroleum products may cause

TABLE 2.—*Fecundity of female striped bass in the Sacramento–San Joaquin Estuary.*

Age	Estimated eggs/ mature female (1,000s)	Maturity correction[a]	Estimated mean fecundity of females on spawning grounds (1,000s)	Migration correction[b]	Estimated mean fecundity of all females (1,000s)
4	243	0.35	85	0.16	14
5	447	0.87	389	0.90	350
6	652	1.00	652	1.00	652
7	856	1.00	856	1.00	856
≥8	1,427	1.00	1,427	1.00	1,427

[a] Fraction of female striped bass that are mature on the spawning grounds (Scofield 1931).
[b] Fraction of all female striped bass that migrate to the spawning grounds (from the female : male ratio in spring tagging from 1969 to 1978).

mortality of adults, reduce their ability to reproduce, or reduce the survival of their eggs and young.

Effect of Reduced Adult Stocks

We have hypothesized that the number of eggs being produced by the adult striped bass population has declined and that such a decline has contributed to the declining number of young.

To examine this hypothesis, we first calculated an annual index of egg production from our Petersen estimates and age-specific fecundity data. The abundance of each age class from age 4 to ages 8 and older combined were multiplied by the estimated fecundity for the appropriate age (Table 2). The annual index of total eggs spawned is the sum of these products.

We have calculated that egg production in 1982 was only about 25% of what it was during the late 1960s and early 1970s (Fig. 9). At first glance, a 75% reduction in egg production would seem an obvious reason for the striped bass decline. 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. This is because we are accustomed to believing that if fewer are produced, a greater proportion will survive to maintain the population. There is evidence to suggest that this "density-dependent" survival principle does not presently apply to the Sacramento–San Joaquin striped bass population.

We calculated a survival index between the egg and 38-mm stage for years (1969–1982) when egg production estimates were available,

$$\text{survival index} = \frac{\text{index of abundance when mean length is 38 mm}}{\text{egg production index}},$$

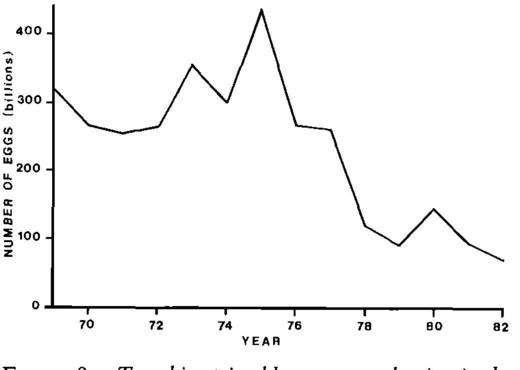

FIGURE 9.—*Trend in striped bass egg production in the Sacramento–San Joaquin Estuary.*

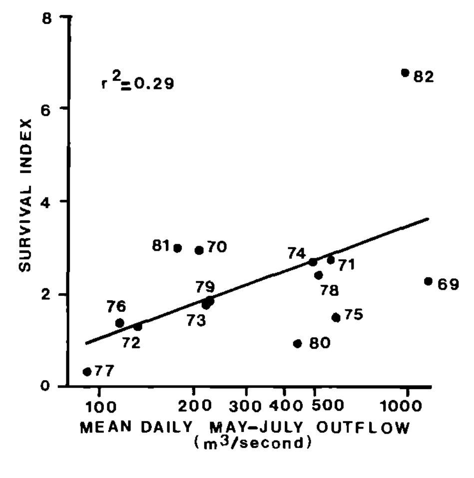

FIGURE 10.—*Striped bass survival index between the egg and 38-mm stages in relation to mean daily May–July freshwater outflow from the Sacramento–San Joaquin Delta. Survival = 2.39 $\log_{10}$ outflow − 3.70. Numbers next to points designate years.*

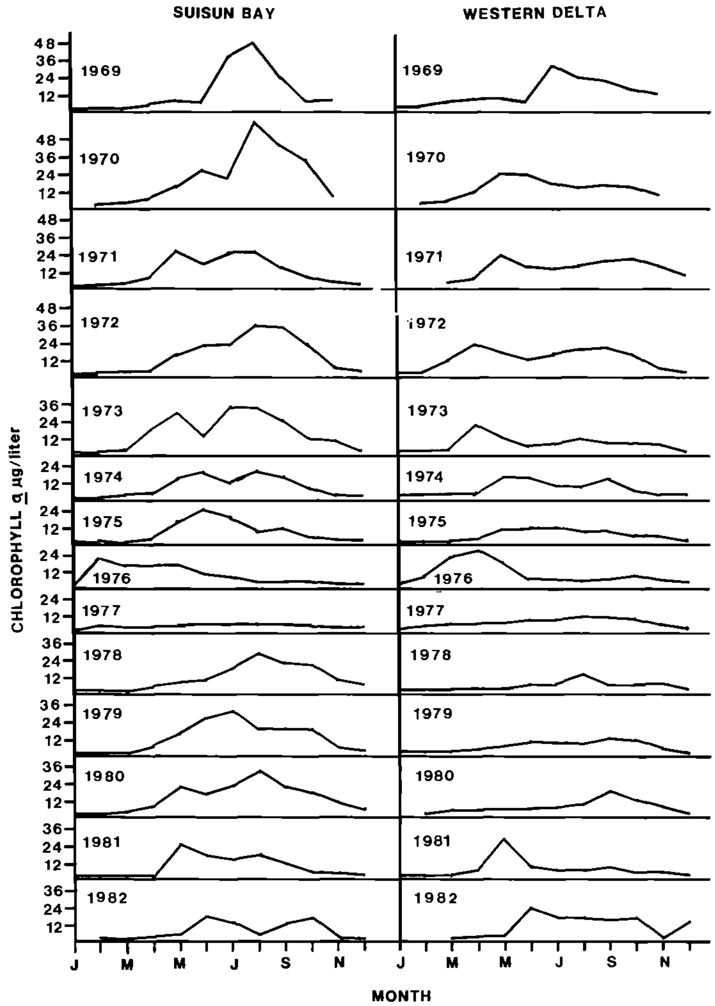

FIGURE 11.—*Mean chlorophyll-*a *concentrations in Suisun Bay and the western Sacramento–San Joaquin Delta.*

and regressed this survival index on $\log_{10}$(mean daily May–July outflow). This regression is statistically significant ($P < 0.05$), but it only accounts for 29% of the variation in survival (Fig. 10). These results, however, are affected by imprecision in the variables used to calculate the survival index. This imprecision is especially large in the Petersen estimates (Fig. 3).

Early work indicated that *abundance* of young striped bass in the summer was correlated with river flow suggesting that *survival* from eggs to the young-of-the-year stage could depend on flows and diversions (Turner and Chadwick 1972; Chadwick et al. 1977; Stevens 1977a). Our current analysis implies that the relationship between survival from egg to the 38-mm stage and flow has not changed substantially. Survival rates still appear to be controlled by delta outflow. The low egg production since 1976 has not resulted in higher survival rates. Hence, if the same relationship between survival and flow continued after 1976, a decline in egg production would have caused the young striped bass population to decline.

Reduced Food Production

In the Sacramento–San Joaquin Estuary, young striped bass begin feeding on small crustacean zooplankton a few days after they hatch (Eldridge

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

Year	Western delta: Crustacean zooplankton[a]	Western delta: *Neomysis mercedis* >4 mm[a]	Suisun Bay: Crustacean zooplankton[a]	Suisun Bay: *Neomysis mercedis* >4 mm[a]	Location of striped bass larvae: crustacean zooplankton[b]
1968		125.1		54.2	
1969		64.1		61.1	
1970		26.0		38.1	
1971		28.4		41.5	
1972	56,260	51.6	96,130	28.9	107,220
1973	32,210	44.9	81,550	86.6	83,350
1974	24,560	34.1	55,920	77.0	86,470
1975	13,130	17.7	38,450	54.9	86,220
1976	21,510	33.4	30,770	35.9	54,050
1977	73,620	16.0	55,700	0.8	38,850
1978	11,310	17.6	49,070	34.8	16,110
1979	10,230	15.3	45,010	25.5	29,370
1980		31.1		60.3	
1981		26.5		20.1	
1982		12.6		45.3	
1983		2.9		14.6	

[a] Mean concentration from April through June.

[b] Mean concentration where and when young striped bass are first feeding.

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

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

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

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

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

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

Variations in zooplankton density exhibited a different pattern from those in phytoplankton. Average concentrations of crustacean zooplankton were very high in the western delta in 1977 (Table 3), apparently due to low freshwater flows associated with a drought in 1976 and 1977 that allowed the entrapment zone to encroach upstream. In that region, average zooplankton densities were at their lowest levels in 1978 and 1979, the last years for which data are available. There was not a distinct decline in the average abundance of crustacean zooplankton in Suisun Bay after 1977, although their average concentration did decline each year from 1972 to 1976 and concentrations from 1977 to 1979 were lower than the average of the previous years.

Because the average spring zooplankton concentrations did not clearly decline, the Striped Bass Working Group also examined the trend in abundance of zooplankton restricted to the times when young striped bass began feeding and the geographical region where young striped bass were located when they began feeding. If food availability is critical to striped bass survival, conditions experienced by the initial feeding stages are likely to have the greatest impact on year-class strength. The region where young striped bass were centered when they began to feed varied annually depending on the amount of fresh water flowing through the estuary (Table 4). In the drier years, virtually all of the striped bass were in the delta. As flows increased, the young striped bass began entering Suisun Bay and, in the wettest years, most were in Suisun Bay. In 3 years (1974, 1978, 1979) information on young striped bass distribution was not available so it was estimated from the relationship between striped bass distribution and flow in years when data were available. The zooplankton abundance indices derived from this more restrictive analysis exhibited a much more striking decline than was evident from the average spring concentrations (Table 3).

In the western delta, opossum shrimp abundance was very low in the spring from 1977 to 1979, moderate in 1980 and 1981, and low again in 1982 and 1983. In Suisun Bay, the *Neomysis* population was near zero in 1977. After that spring, there were moderate populations of *Neomysis* in the normal- to high-flow years 1978, 1980, and 1982, but their abundance was low in the low-flow years 1979 and 1981 and the high-flow year 1983.

We believe that these plankton data reflect a widespread and major reduction in biological productivity of the western delta and Suisun Bay during and following the 1976–1977 drought. There is evidence of recovery in Suisun Bay, but generally not in the western delta. What has caused this change?

Biologists have long been aware that phytoplankton, zooplankton, *Neomysis*, and other striped bass food organisms in the delta are influenced by the quantity of flows of the Sacramento and San Joaquin rivers, the location of the entrapment zone, and also the growing use of the delta channels as conduits to carry water south to the export pumps of the CVP and the SWP (Turner 1966; Turner and Heubach 1966; Heubach 1969; Arthur and Ball 1979; Knutson and Orsi 1983). More than a decade ago, investigations in the delta provided good evidence that increasing net velocities through the channels of the interior delta would lower zooplankton and *Neomysis* populations. The broad, and often deep, channels of the western delta seemed not as vulnerable.

TABLE 4.—*Distribution of first-feeding striped bass larvae in relation to river flow passing through the Sacramento–San Joaquin Estuary in May. ND means not determined.*

Year	Location of larvae	May outflow (m^3/second)
1977	Delta	114
1976	Delta	115
1972	Delta	146
1968	Delta	191
1970	Delta	305
1973	Delta and Suisun Bay	331
1979	ND	379
1974	ND	723
1971	Delta and Suisun Bay	748
1975	Delta and Suisun Bay	816
1978	ND	1,156
1969	Suisun Bay	1,828
1967	West Suisun Bay	2,111

Because phytoplankton is at the base of food chains and should respond rapidly to environmental changes, we searched for reasons why it has been less abundant in recent years. Jerry Turner of the Striped Bass Working Group observed that only two notable spring blooms have occurred in the western delta since 1976, and both immediately followed shutdowns of the SWP diversion pumps for repairs (Fig. 12). The first incident was in May 1981 when the first samples following the pump shutdown indicated that a significant phytoplankton bloom had suddenly developed. The second incident of this kind occurred early in June 1982 when the SWP pumps again were shut down for repair work and a major phytoplankton bloom followed.

These results suggest that the water project diversions are, in some as yet unexplained way, having a major effect on the phytoplankton population and basic productivity of the western delta. The most apparent mechanism is that the residence time of water increases in the channels

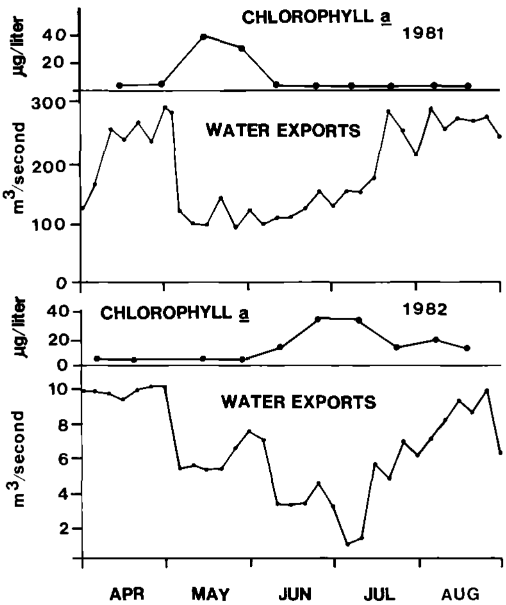

FIGURE 12.—*Trends in mean chlorophyll-*a *concentrations in the western Sacramento–San Joaquin Delta and water export rates at the federal Central Valley Project and State Water Project pumps from April to August 1981 and 1982. Note that phytoplankton blooms follow reductions in water export pumping.*

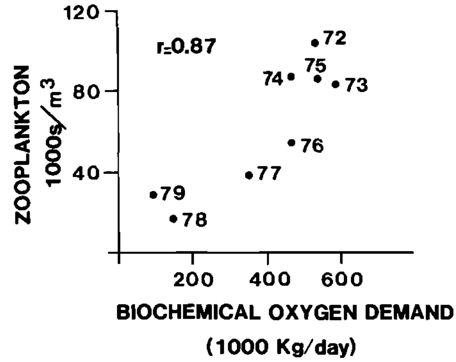

FIGURE 13.—*Relationship between zooplankton concentration at the time and place of initial striped bass feeding and an index of organic loading from point-source discharges in Suisun Bay and the western Sacramento–San Joaquin Delta.*

affected by the diversions when the pumps stop. However, attempts by ourselves and others to correlate the occurrence of spring phytoplankton blooms with more direct, although imperfect, measures of residence time have not provided conclusive results.

An alternative hypothesis to explain the reduced plankton populations was offered by Striped Bass Working Group member Charles Hanson. Inorganic nutrient concentrations have not fallen, but Hanson hypothesized that improved waste treatment at point-source discharges in the estuary during the first half of the 1970s has reduced the contribution of organic material to the system and may have contributed to a decline in the productivity of Suisun Bay and the delta, particularly in the production of microorganisms that are eaten by zooplankton. The abundance of zooplankton at the times and places where larval striped bass are concentrated is well correlated with Hanson's index of organic loading based on biochemical oxygen demand (BOD) data from six point-source discharges in Suisun Bay and the western delta (Fig. 13). In a multiple-regression analysis, the combination of May outflow and Hanson's index of organic loading in Suisun Bay and the western delta accounted for 80% of the variability in the striped bass index over the past decade.

These results suggest that changes in waste treatment may have contributed to reduced production of zooplankton and striped bass in the estuary and may be important in the striped bass decline. The Striped Bass Working Group concluded that this hypothesis is worthy of more detailed examination. That examination will require more careful assessment of organic input to the system from all sources, probably based on some measure other than BOD. Use of BOD as a measure of the value of organic detritus as an energy source to the ecosystem probably exaggerates the contribution of wastewater discharge.

Effect of Reduced Food on Young Striped Bass

Whatever the reason, phytoplankton and *Neomysis* populations have been low in both Suisun Bay and the western delta during most years since 1976. Although trends in average zooplankton abundance are less striking, the abundance of zooplankton when and where larval striped bass begin feeding clearly has declined since 1971. How important is this decline in productivity to striped bass?

Larval striped bass begin feeding on small crustacean zooplankters when the fish are 4–7 mm long (Eldridge et al. 1982). As these larval fish grow, they eat more and larger organisms. Laboratory studies have shown that larval fish

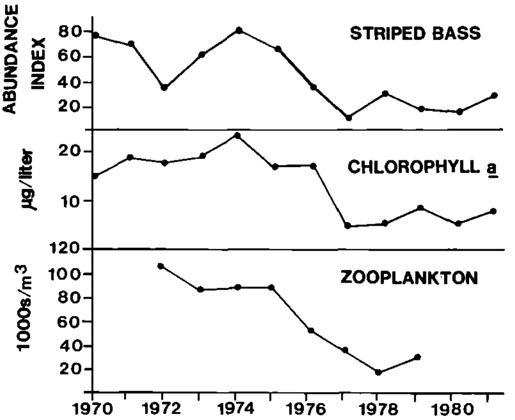

FIGURE 14.—*Concentration of chlorophyll* a *and zooplankton at the time and place of initial feeding by young striped bass (Table 4) compared with striped bass abundance in midsummer in the Sacramento–San Joaquin Estuary.*

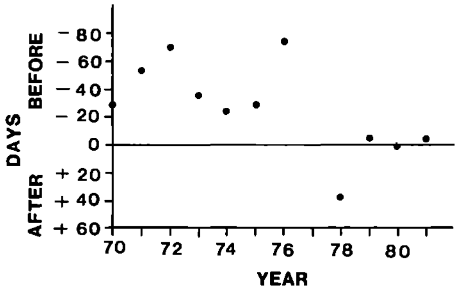

FIGURE 15.—*Number of days prior to or after initial feeding of larval striped bass that chlorophyll-*a *concentrations reached 10 µg/liter in the area of the Sacramento–San Joaquin Estuary where most striped bass larvae were located (Table 4).*

survival is directly related to the number of food organisms available to them (Daniel 1976; Miller 1978; Eldridge et al. 1981) and that high survival requires localized concentrations of food greater than are found in average field measures in the Sacramento–San Joaquin striped bass nursery area (Daniel 1976). The only fish that survive may be those that find themselves in dense patches of zooplankton. We compared the summer striped bass abundance index with phytoplankton and zooplankton densities 60 days earlier in the region where most striped bass began feeding. Since 1976, there has been very little phytoplankton or zooplankton where striped bass need it when they begin feeding (Fig. 14).

Striped Bass Working Group member Jerry Turner also found evidence that plankton population development has been delayed in recent years. Prior to 1977, chlorophyll-*a* concentrations where most of the striped bass began feeding reached 10 µg/liter from 3 to 10 weeks before the estimated date that young striped bass began feeding (Fig. 15). This should be a long enough period for high zooplankton populations to develop from feeding on the phytoplankton (Riley 1947). In 1977, chlorophyll-*a* concentrations in the delta never reached 10 µg/liter, and from 1978 to 1981, phytoplankton development where most young striped bass first began feeding, whether in the delta or in Suisun Bay, was delayed beyond the time that it was needed by the larval fish.

A comparison of mean chlorophyll-*a* concentrations in the western delta and Suisun Bay in April and May suggests that, in some years, the very early phytoplankton blooms in Suisun Bay may partially depend on phytoplankton being washed downstream from the western delta. As an example, note the May 1981 bloom in both the western delta and Suisun Bay (Fig. 11). The low concentrations of phytoplankton in the western delta since 1977 may be responsible for the lack of an early April–May peak in Suisun Bay, and would explain the delayed phytoplankton development where the young striped bass first begin feeding, whether in the western delta or Suisun Bay.

Entrainment Losses

Striped bass eggs, larvae, and juveniles are lost via entrainment in diversions of delta water by the CVP, the SWP, delta agriculture (DA), and the Pacific Gas and Electric Company (PGE). Fish losses depend on the density of organisms at the pump intakes, the pumping rate, and (in the case of PGE) mortality occurring during passage through the power plants before the cooling water is discharged back into the delta. Losses of striped bass have been estimated for power plants based on sampling within the cooling systems. Similar estimates of striped bass losses in CVP, SWP, or DA diversions are precluded by inadequate sampling. However, indirect estimates of these losses have been made by Richard Sitts of the Striped Bass Working Group (CVP, SWP), Alan Baracco of CFG (CVP, SWP), and Randall Brown of the California Department of Water Resources (DA). These estimates were de-

TABLE 5.—*Estimates of losses (in millions) of young striped bass to entrainment, Sacramento–San Joaquin Estuary. ND means not determined.*

Year	Central Valley Project and State Water Project pumps[a]	Delta agriculture[b]	Pacific Gas and Electric Company[c]
1968	1,878	ND	ND
1969	2	ND	ND
1970	1,784	ND	ND
1971	778	ND	ND
1972	4,527	ND	ND
1973	2,253	ND	ND
1974	ND	ND	ND
1975	234	ND	ND
1976	507	ND	ND
1977	249	ND	ND
1978	117	598	154
1979	286	562	62

[a] Estimates from 1968 to 1977 by A. Baracco, California Department of Fish and Game. Estimates for 1978 and 1979 by R. Sitts, Envirosphere Company and C. Hanson, Tera Corporation.

[b] Estimates by R. Brown, California Department of Water Resources.

[c] Estimates from 316b demonstrations for Contra Costa and Pittsburg power plants.

rived by multiplying estimates of striped bass egg and larva densities in the delta channels within the influence of the diversions by the amounts of water being diverted. The sampling of eggs and larvae is based on oblique tows with large plankton nets by CFG and PGE (Miller 1977; Stevens 1977b; PGE 1981a, 1981b). Baracco's estimates for the CVP and SWP are available from 1968 to 1977, CFG's striped bass egg and larva survey years. Sitts' estimates for the CVP and SWP, Brown's estimates for DA, and the estimates of losses at PGE power plants are available for 1978 and 1979.

Except for the PGE power plant estimates, these various entrainment-loss estimates are only gross approximations. They are subject to untested assumptions regarding sampling efficiencies, mortality occurring between the locations that were sampled and the diversion sites, and flow patterns in the delta channels. Yet the estimates, which range from millions to billions of fish, have convinced us that large numbers of small striped bass are lost from the estuarine population in many years (Table 5).

The evidence that survival from the egg to the 38-mm stage is independent of the striped bass population size suggests that the abundance of young striped bass surviving to midsummer is

TABLE 6.—*Irrigation return water as a percent of total Sacramento River flow.*

Month	1972	1973	1975	1976	1977	1980	1981
April	8.0	7.7		6.8	4.7	8.2	12.8
May	20.0	12.7	7.6	13.5	15.2	22.2	16.4
June	9.6	11.6	8.6	13.1	4.9	10.0	13.4
July	7.4	9.9	11.1	8.0	2.8	10.9	

reduced by the large losses from the combined entrainment at the PGE plants, CVP and SWP pumps, and DA diversions. In turn, this long-term reduction in young striped bass abundance probably has contributed to the decline in the adult striped bass population.

Toxic Wastes

The hypothesis that survival of young striped bass has been reduced due to increased toxicity of the environment is virtually impossible to test because the toxicity data base is inadequate. Although most of the major waste treatment facilities discharging into the bay and delta have been much improved in the last decade, large quantities of potentially toxic substances still reach the system, and many are not routinely monitored. Much of the watersheds of the Sacramento and San Joaquin rivers are treated with pesticides each year, and although records of pesticide use are available, most are not monitored in streams. A variety of unmonitored toxicants also potentially enter the rivers and bays with runoff from industrial and urban areas whenever it rains, and, of course, accidental spills of all sorts commonly occur.

Thus, our analysis of this hypothesis is rather qualitative. The Striped Bass Working Group searched for indirect evidence of potential toxicity problems in streamflow records during the spawning season. These records allowed us to examine the fraction of the Sacramento River flow formed by irrigation return water potentially laden with pesticides. We believed that this approach could provide some insight because in the spring most irrigation water in the Sacramento River basin goes to rice farming. In general, water is diverted from the river or from reservoirs through irrigation canals, fields are flooded, pesticides are applied, and eventually the water is drained into sloughs and subsequently flows back into the river. Major irrigation drains discharge into the river in regions where striped bass eggs and larvae are found in high densities.

We also searched water quality monitoring data and other sources for records of fish kills and concentrations of toxicants known to be harmful to fish.

From streamflow records, Striped Bass Working Group member Stephen Hansen estimated that the five major sources of return irrigation water contribute between 5% and 20% of the total Sacramento River flow at or near Sacramento during April–July (Table 6). Pesticides and herbicides used in rice culture (molinate, chlorophenoxy acetic acid, ethyl parathion, methyl parathion, thiobencarb) are applied extensively during these months. Also of concern are toxaphene and xylene (a common pesticide solvent), which are not used specifically on rice but are extensively applied elsewhere. Detectable concentrations of several of these pesticides have been found in the Sacramento River and its tributaries during this period (Finlayson et al. 1982).

Measured concentrations of molinate found have been as high as 300 μg/liter, a level toxic to fish (Finlayson and Lew 1983), but those of the other pesticides have generally been at sublethal levels. Yet spring kills of resident fishes (cyprinids, centrarchids, ictalurids) in irrigation discharge drains of the Sacramento Basin and in the Sacramento River itself are frequent and usually associated with pesticides. Recent, as yet unpublished, toxicity tests by CFG (B. Finlayson) reveal that young striped bass are more sensitive to molinate and thiobencarb than are the resident fishes. Striped bass eggs and larvae also may suffer chronic effects from concentrations below lethal levels. Thus, the evidence that we have seen suggests that toxic substances may be damaging the health of striped bass, but it is not possible to determine the degree to which they are responsible for the striped bass decline.

Summary and Discussion

The adult striped bass population of the Sacramento–San Joaquin Estuary has fallen to the lowest levels since stock assessments were first available; it probably has dropped to the lowest levels since its early development after the 1879 introduction from the east coast. Angler catches and catch per unit of effort have unsteadily but persistently declined, and angler harvest increased from about 15% of the population in 1970 to about 27% in 1976. Despite this increase, exploitation is still lower than for Atlantic coast stocks (Kohlenstein 1981) that are fished commercially. However, population studies reveal that mortality is exceeding recruitment and until the cause of the decline is found and corrected, there may be a need for more fishing restrictions.

The principal reason for low recruitment to the adult population appears to be poor production of young of the year. Extensive summer townet surveys have provided good evidence that less than one-half as many young of the year are produced now as were produced a decade ago. The Striped Bass Working Group of scientists, appointed by the State Water Resources Control Board to analyze the problem, concluded that the decline was probably the result of a combination of (1) reduced adult stock producing fewer eggs, (2) reduced food production in the nursery area, (3) entrainment losses into water diversions, and (4) toxicity.

The decline in adult striped bass abundance has resulted in a 75% decline in egg production since the early 1970s. Our analysis suggests that egg production now may be inadequate to maintain the population at former levels under present environmental conditions, even though billions of eggs are still produced each year.

Food production in the striped bass nursery area has been reduced substantially in recent years. Phytoplankton populations in the salinity gradient have been very low. In spring, blooms thought necessary to provide zooplankton production for young striped bass have been either eliminated or delayed beyond the time when most of these fish begin feeding. There is evidence suggesting that phytoplankton development has been suppressed by the use of the major delta channels as conduits to carry increasing amounts of water to diversions in the south delta. Experiments to learn more about this are underway.

Entrainment losses of striped bass eggs, larvae, and young in water diversions are very high and may be important. In recent years, survival rates have depended upon freshwater outflow in the spring and early summer, just as they did before the decline. High outflows in recent years have not, however, resulted in high striped bass populations as they previously did. Hence, reduced egg production due to lower adult populations has not resulted in a density-dependent increase in survival rates between egg and young of the year, and any losses of early life stages, including losses due to entrainment, could be contributing to the problem.

The effect of toxicity has been one of the most difficult to assess. Obvious water pollution has been greatly reduced in recent years by major campaigns and expenditures to improve waste treatment. Nevertheless, there is evidence that toxic petrochemicals and trace metals may be present in concentrations sufficient to affect the health of both adult and juvenile striped bass.

The striped bass situation in the Sacramento–San Joaquin Estuary parallels the loss of many so-called "renewable" natural resources. Several factors are identified as probable causes; some may combine in their effects. One such combination that we find very plausible for the striped bass decline is the reduced number of eggs and larvae that now drift downstream to enter the nursery habitat and the recent lower production of planktonic food organisms. Striped bass eggs and larvae wash down the river in groups, their final location depending upon spawning location and river flow. A lower initial abundance of such groups and a scarcity of dense patches of zooplankton greatly reduces the chance that enough larvae will find sufficient food to survive and maintain the striped bass population.

If our hypothesis is correct, stocking of hatchery fish large enough to avoid the limiting food conditions might be helpful. A hatchery program currently is underway due to pressure on the state legislature from anglers. In 1981, legislation was passed requiring striped bass anglers to purchase a $3.50 striped bass stamp. Sales of this stamp are raising about $2 million per year to be spent on research and management that has potential to enhance the striped bass fishery. Hatchery propagation is also planned to replace fish lost from the estuary by diversions.

All agencies charged with managing the estuarine resources are concerned about the plight of the striped bass and are searching for better answers and practical solutions. Maintenance of adequate outflow is recognized as being essential to protect striped bass. However, the events of recent years and our assessment have led to the conclusion that control of outflow alone is not enough.

We believe that current use of delta channels to convey water for export has contributed to the long-term decline of striped bass. There is good reason to believe that planned increases in export pumping and reduced delta outflows will exacerbate the problems of reduced food production and entrainment unless a properly designed and operated delta water transfer facility is built. An improperly designed project is likely to further reduce numbers of young striped bass, which, in turn, will reduce adult stocks. Further decline in adult stocks will reduce the number of eggs produced and thus, the striped bass population will continue to spiral downward.

Additional prudent action is needed by regulatory agencies to reduce losses to all sources of entrainment, to reduce the deposition of toxic substances, and to maintain adult populations and the needed egg production by experimental stocking. The effect of the additional restrictions that were placed on the fishery in 1982 to reduce fishing mortality should be evaluated as appropriate data become available.

An extensive effort to measure larval striped bass abundance and survival in relation to the zooplankton food supply began in 1984. This study, along with measures of egg production and of the success of the stocking program, may help solve the mystery of California's striped bass decline.

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