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# American Shad and Striped Bass in California's Sacramento–San Joaquin River System

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*Abstract.*—American shad *Alosa sapidissima* and striped bass *Morone saxatilis* were introduced to the Sacramento–San Joaquin river system, which includes a large inland delta, during the 1870s. Both species supported commercial fisheries by the turn of the century. Legislative action terminated the commercial striped bass fishery in 1935 and the American shad fishery in 1957; thus, only sportfishing is legal now. American shad runs in 1976 and 1977 were about $3 \times 10^6$ fish. The present (1982) stock of adult (≥40.6 cm) striped bass is about $1 \times 10^6$ fish, down from about $1.7 \times 10^6$ in the early 1970s. Previous striped bass stock estimates are not available, but peak catches occurred in the early 1960s. Both species are spring spawners and their spawning grounds overlap, but American shad make greater use of the upper reaches of the Sacramento River system and striped bass make greater use of the delta. In summer, the main American shad nursery includes the lower Feather River, much of the Sacramento River, and the northern delta. Most young American shad leave the rivers and estuary by year's end, though some remain in the estuary for more than 1 year and may not go to sea. River flows transport essentially all young striped bass to the estuary within a few days after spawning occurs. By summer, peak concentrations of young striped bass are in the fresh–saltwater mixing zone. Year-class strengths of young American shad and striped bass vary widely, and high river flows during the spawning and early nursery periods have a positive effect on both species. However, since 1977, abundance of young striped bass has consistently been below expected levels. Populations of American shad and striped bass obviously have declined from their initial peaks in the early 1900s, probably largely in response to habitat degradation associated with human activities. Hatchery propagation and stocking are being tested as means of mitigating losses of striped bass to water projects and power plants. Despite some potential adverse impacts on native species, we believe that the introductions of American shad and striped bass have been beneficial to California.

The Sacramento River and San Joaquin River, the major streams in California's Central Valley, drain about 153,000 km$^2$ and form a tidal estuary from their junction in an inland delta to San Francisco Bay (Figure 1). The delta has large cultivated islands that were reclaimed from marsh in the latter part of the nineteenth and the early twentieth centuries. These islands are surrounded by approximately 1,130 km of interlaced channels varying in width from about 50 m to 1.5 km and generally less than 15 m deep. Suisun, San Pablo, and San Francisco bays to the west cover an area of about 1,125 km$^2$. More than 50% of Suisun and San Pablo bays is less than 2 m deep at low tide. In San Francisco Bay, shallows are somewhat less extensive partly because of landfill practices that have been associated with development of urban and industrial areas along the shore. Important marshes remain in the estuary, particularly around Suisun Bay, northern San Pablo Bay, and southern San Francisco Bay.

The historical annual flow from the rivers entering the estuary averaged about 1,100 m$^3$/s, but now only about one-half that amount passes through the estuary due to local use along the rivers and exports to the San Joaquin Valley and southern California (Chadwick 1977). Dams regulate flow in the major tributaries of the Sacramento–San Joaquin watershed. Seasonal flow patterns are modified by water storage behind these dams in winter and spring with subsequent release for diversion in summer and fall. Roughly 85% of the inflow to the delta originates in the Sacramento River, 10% is from the San Joaquin River, and 5% is from miscellaneous eastern valley streams. Water is diverted, primarily for agriculture, all along the rivers and in the delta. Largest diversions are by the U.S. Bureau of Reclamation's

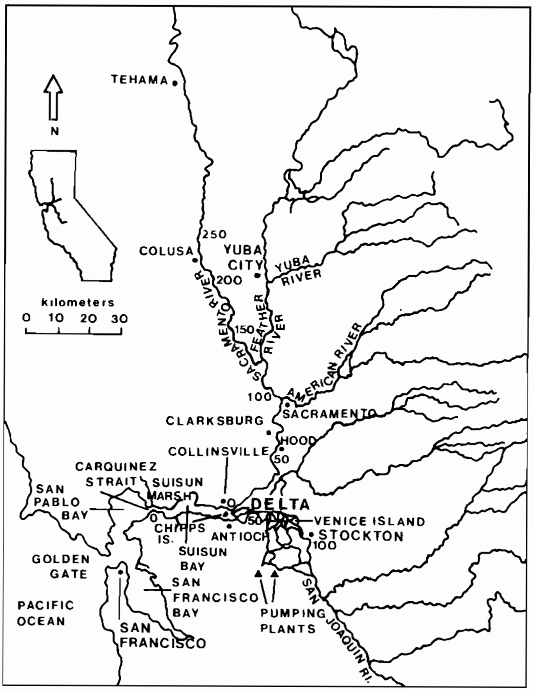


FIGURE 1.—Sacramento–San Joaquin River system. Numbers indicate locations in river kilometers as defined by Turner (1976).

Central Valley Project (CVP) and California's State Water Project (SWP) in the southern delta. Combined diversion rate by these projects averaged 190 $m^3/s$ in 1978 and could increase to about 270 $m^3/s$ in 25 years under present authorizations (Chadwick 1977).

## American Shad

### *Introduction and Fisheries*

American shad *Alosa sapidissima* were first introduced into the Sacramento–San Joaquin river system in 1871 when it was still largely unchanged by humans. Initially, about 10,000 young of the year were transported from New York and released into the Sacramento River near Tehama. An additional 819,000 young fish were stocked from 1873 to 1881 (Skinner 1962).

The American shad population exploded and soon supported a major commercial gill-net fishery in the estuary during the spawning runs. American shad were sold in San Francisco markets by 1879. Catches regularly exceeded 450,000 kg from 1900 to 1945, and about 2.5 million kg were taken in 1917. After 1945, the fishery diminished and, in 1957, it was terminated by legislation due to public concerns about the impact of the gill nets on striped bass *Morone saxatilis* (Skinner 1962).

Although American shad were commercially important, enthusiasm for sportfishing did not begin until the 1950s when a major fishery developed on the spawning grounds in the upper Sacramento River system (Radovich 1970), particularly the mainstem Sacramento and the American, Feather and Yuba rivers. Once established, the popularity of fishing for American shad grew and, by the mid-1960s, an estimated 100,000 angler-days were expended (California Department of Fish and Game 1965). More recently, however, angler interest has declined. In 1977 and 1978, about 35,000 and 55,000 angler-days were expended to catch 79,000 and 140,000 American shad, respectively (Meinz 1981). The present bag limit is 25 fish/d, but most anglers typically release all or most of their catch.

An interesting, but secondary, means of catching American shad called "bumping" is practiced by sport fishermen at night in the delta (Radovich 1970). A long-handled chicken-wire dip net is fished in the prop wash of a slowly moving boat and when a shad bumps the net, the "bumper" quickly attempts to flip it into the boat. Essentially all fish caught are males, which apparently are attracted to the prop wash as they would be to a spawning female.

### *Spawning*

From 1975 to 1978, based on analysis of scales, 92% of the male American shad spawned for the first time in the Sacramento–San Joaquin river system as 3- or 4-year-olds and 79% of the females initially spawned as 4- or 5-year-olds (Wixom 1981). For both sexes, spawning appeared to occur for the first time as early as age 2 and as late as age 7. Once a fish spawned, it continued to do so annually.

American shad spawn from the tidal basin upstream into fresh water in both the Sacramento and San Joaquin rivers, although the primary spawning area is the Sacramento River system upstream from Hood (Hatton 1940; Stevens 1966a; Painter et al. 1977; Table 1).

Adults returning from the ocean begin passing through the delta in late March or April (Stevens 1966a). In fyke traps (Hallock et al. 1957) set in the Sacramento River at Clarksburg, American shad catches increase substantially through April and peak from the first to latter third of May

TABLE 1.—Life history strategies of American shad and striped bass in the Sacramento–San Joaquin river system.

| Feature | American shad | Striped bass |
|---|---|---|
| Migration to fresh water | Mar–May | Sep–May |
| Major spawning locations | Upper Sacramento River and major tributaries | Delta, mainstem Sacramento River |
| Major spawning period | May–early Jul | Apr–Jun |
| Temperatures during peak spawning | 17–24°C | 17–20°C |
| Major nursery areas of young fish | Lower Feather River, Sacramento River from Colusa downstream, delta | Delta, Suisun Bay |
| Usual environment after first year | Ocean, but a few fish remain in the estuary | Estuary, but many of the larger fish migrate to the ocean for several months each year |

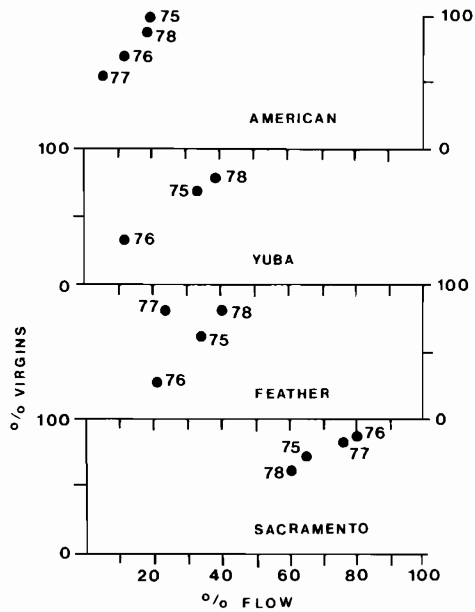


FIGURE 2.—Percentage of American shad spawning runs formed by virgins and percentage contribution of streams in the Sacramento River system to the flow downstream from their confluences with adjacent river branches.

(Table 2). River temperatures during May generally range from about 14°C to 21°C.

River flow may affect the distribution of American shad during their initial spawning runs in the Sacramento River system (Painter et al. 1980). Although this hypothesis is unproven, it is supported by some crude measures of the distribution of virgin spawners in the American, Yuba, and mainstem Sacramento rivers where percentages of the runs formed by virgins (Wixom 1981) tend to increase with the contribution of these streams to the flow immediately downstream from their confluences with adjacent river branches (Figure 2). Similar results were not obtained for the Feather River; however, this may reflect a longer residence period for young fish in that tributary allowing them to become imprinted for homing on their maiden runs. Sampling with beach seines reveals that many young American shad remain in the Feather River through summer, whereas few reside in the Sacramento River above Colusa, and the Yuba and American rivers (Table 3).

TABLE 2.—Catch of adult American shad in fyke traps set in the Sacramento River at Clarksburg. Open cells mean no sampling.

| Period | 1974 | 1975 | 1976 | 1979 | 1980 | 1982 | 1983 | 1984 | Mean |
|---|---|---|---|---|---|---|---|---|---|
| Mar 21–31 | 0 | 0 | 7 | 10 | 7 | 1 | | 2 | 3.9 |
| Apr 1–10 | 0 | 8 | 8 | 62 | 16 | 3 | | 7 | 14.9 |
| 11–20 | 50 | 38 | 65 | 56 | 19 | | | 29 | 42.8 |
| 21–30 | 380 | 174 | 59 | 213 | 30 | 153 | 120 | 68 | 149.6 |
| May 1–10 | 594 | 264 | 133 | 181 | 20 | 303 | | 178 | 239.0 |
| 11–20 | 389 | 427 | 168 | 220 | 122 | 356 | | 92 | 253.4 |
| 21–30 | 433 | 498 | 28 | 105 | 32 | 197 | 582 | 151 | 253.2 |
| May 31–Jun 9 | 137 | 109 | 30 | 14 | 3 | 149 | 538 | 23 | 125.4 |
| Jun 10–19 | 116 | 38 | 4 | 2 | 4 | 6 | 96 | 20 | 35.8 |
| 20–29 | 16 | 2 | | | | | 41 | | 19.7 |
| Annual index[a] | 2,115 | 1,558 | 502 | 863 | 242 | 1,216 | 2,811 | 570 | |

[a] Sum of catches from April 1 to June 9. In years when traps were not fished during some periods, catches were adjusted upward based on mean percentage of catch during those periods in years with complete data.

TABLE 3.—Mean catch per seine haul of young American shad in the Sacramento–San Joaquin river system. Sampling was almost weekly from July through September. Numbers of samples are in parentheses.[a]

| Area | Year 1976 | 1977 | 1978 |
|---|---|---|---|
| Sacramento River above Colusa | 0.0 (18) | 0.1 (38) | 0.1 (12) |
| Feather River above Yuba River | 0.0 (9) | 0.0 (8) | (0) |
| Feather River below Yuba River | 7.7 (18) | 7.2 (26) | 7.2 (8) |
| Yuba River | 1.1 (18) | 0.4 (15) | 0.0 (8) |
| Sacramento River from Colusa to Sacramento | 8.6 (15) | 3.6 (37) | 0.7 (13) |
| American River | (0) | 0.1 (11) | 3.9 (12) |
| North delta[b] | 3.0 (62) | 1.9 (43) | 8.5 (30) |
| South delta[c] | 0.2 (13) | 0.0 (10) | 0.0 (10) |

[a] Data from M. Meinz, California Department of Fish and Game.
[b] Rivers and sloughs north from San Joaquin River upstream to Sacramento.
[c] San Joaquin River and rivers and sloughs to the south.

Most repeat spawners in the Sacramento River system probably home to the tributary where they have spawned previously. During 1978, about 6,000 American shad were tagged on the spawning grounds. During subsequent years, 12 tags were returned from these fish. Nine of these returns were from the river of tag origin. Of the remainder, only one was an obvious stray from routes that led to the river where the fish were tagged (Table 4).

TABLE 4.—Distribution of tag recoveries during 1979 and subsequent years for American shad that were tagged while on their spawning grounds in the Sacramento River system in 1978.

| Recovery location | Spawning ground 1978: American River | Feather River | Yuba River | Upper Sacramento River |
|---|---|---|---|---|
| Delta and Sacramento River below American River | 0 | 1 | 0 | 1 |
| American River | 0 | 1[a] | 0 | 0 |
| Feather River above Yuba River | 0 | 2 | 0 | 0 |
| Sacramento River above Feather River | 0 | 0 | 0 | 7 |
| Total recoveries | 0 | 4 | 0 | 8 |
| Number tagged | 312 | 1,211 | 199 | 4,242 |

[a] Obvious stray from route back to 1978 spawning ground.

Sampling of American shad eggs with nets set in the Feather River indicates that spawning occurs predominantly from May to July at temperatures of 17–24°C (Painter et al. 1977).

*Nursery*

The location of the summer nursery of American shad may be discerned from a combination of seine surveys (M. Meinz, California Department of Fish and Game, personal communication), trawling in the delta (Stevens 1966a), and catches at the fish screens in front of the SWP diversion in the southern delta. The flow in most of the spawning areas is swift enough that the eggs are washed downstream before they hatch. During the seine surveys, few young American shad were ever captured in the Sacramento River above Colusa, in the Feather River above the Yuba River, in the Yuba River, in the American River except at its mouth in 1978, and in the south delta (Table 3). Young American shad were more numerous in the Feather River below the mouth of the Yuba River, in the Sacramento River from Colusa to Sacramento, and in the north delta. Despite the virtual absence of fish in seine hauls from the south delta, catches in trawls (Stevens 1966a) and at the SWP fish screens (Figure 3) reveal that young American shad are present in the south delta in summer. Increasing catches in trawls in the fall and at the fish screens in October and November are consistent with the seining data in demonstrating that many young American shad do not enter the delta until their out-migration. Thus, the main summer nursery of American shad appears to include the lower Feather River and to extend from Colusa on the Sacramento River to the north delta; modest numbers of fish also use the south delta.

In 1978, a wet year, the seine catches were notably lower in the Sacramento River and higher

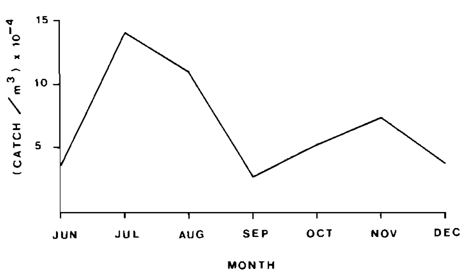


FIGURE 3.—Mean monthly catch of young American shad at the State Water Project fish screens in the Sacramento–San Joaquin Delta, 1968–1980 (Bay–Delta Fishery Project 1981).

in the northern delta than in 1976 and 1977, which were dry years. This difference probably reflects the transport of young fish by river flow, and suggests that annual flow differences cause the precise location of major concentrations of juvenile fish to vary.

During their out-migration, young American shad typically range in fork length from about 5 to 15 cm (Stevens 1966a). Most young American shad leave the estuary by year's end (Ganssle 1966; Stevens 1966a); however, some remain for more than 1 year and perhaps do not go to sea. Ganssle (1966) reported catching American shad in their second year of life in trawl tows in San Francisco, San Pablo, and Suisun bays. More recently, California Department of Fish and Game biologists have captured some yearling (about 20–30 cm fork length) American shad in these areas during trawl surveys in the spring and fall (1967 to 1985) and in gill nets fished in Suisun Bay (fall 1973) and the tidal sloughs of the Suisun Marsh (February, June, and October 1977 and 1978). In the Suisun Marsh, more than 30 of these fish (22–35 cm fork length) were taken during February when they were almost 2 years old.

Little is known about American shad at sea along the Pacific coast. The recapture of three of our tags by commercial bottom-fish trawlers from 1975 to 1977 has revealed that some Sacramento–San Joaquin fish inhabit the ocean off the northern California coast.

### *Abundance*

We estimated adult American shad abundance in 1976 and 1977 from mark–recapture data. Fish were captured in gill nets in the delta downstream from the sportfishing areas. Only those fish that appeared in good condition were tagged. Floy anchor tags (Dell 1968) were inserted into the musculature below the dorsal fin so the tag became anchored behind the neural spines of the vertebrae and pterygiophores that support the fin rays. About half of the tags offered a $5 reward. Each fish was categorized as a male or female by presence or absence of milt when finger pressure was applied in a squeezing motion near the urogenital area.

We did not observe many tags during sampling for recaptures. Thus, instead of the usual Petersen method, we divided annual estimates of catch by estimates of exploitation rates. Catches were estimated by multiplying estimates of angler effort, based on instantaneous-use counts, by catch per unit effort (Meinz 1981). These catch estimates were stratified according to sex ratios observed during Meinz's creel census. Mailed tag returns corrected for nonresponse were used to estimate exploitation rates (Table 5). The tags were conspicuous and the program was well publicized; therefore, we believe that tag recognition was high and tag returns accurately depicted the fraction of the population caught by anglers.

Due to the "catch-and-release" nature of the fishery, some fish in the catches were potentially recounted, which would lead to overestimates of abundance; since anglers only caught about 1 to 4% of the population, this bias was inconsequential.

The American shad run in 1976 was estimated to be $3.04 \times 10^6$ fish, consisting of $1.44 \times 10^6$ males and $1.60 \times 10^6$ females (Table 5). In 1977 the population estimate was $2.79 \times 10^6$ fish and consisted of $1.25 \times 10^6$ males and $1.54 \times 10^6$ females.

TABLE 5.—American shad mark–recapture, catch, and abundance estimates for the Sacramento–San Joaquin river system.

| | | Number of tags released | | Number of tags recovered | | | | |
|---|---|---|---|---|---|---|---|---|
| Year | Sex | Reward | No reward | Reward[a] | No reward[b] | Exploitation rate[c] | Catch[d] | Abundance estimate ($10^6$)[e] |
| 1976 | Male | 1,789 | 1,904 | 69 | 74 | 0.039 | 56,165 | 1.44 |
| | Female | 939 | 937 | 15 | 15 | 0.016 | 25,562 | 1.60 |
| 1977 | Male | 2,437 | 2,226 | 95 | 91 | 0.040 | 49,853 | 1.25 |
| | Female | 1,305 | 1,260 | 27 | 22 | 0.019 | 29,325 | 1.54 |

[a] Mailed tag returns were corrected for nonresponse. Response rate was 0.59 based on return of 10 of 17 $5 reward tags observed during 1976–1977 creel census.
[b] Mailed tag returns were corrected for nonresponse. Response rate was 0.40 based on overall 1976–1977 nonreward tag return rate (0.013) divided by reward tag return rate (0.019) times reward tag response rate (0.59).
[c] Total tags recaptured divided by total tags released.
[d] From Meinz (1981).
[e] Catch divided by exploitation rate.

Numbers of spawners may be less than our estimates of the total runs. Scale analyses suggest not all American shad in the delta migrate upstream to spawn or enter the fishery. A small sample of 15 shad was recovered in 1977 after being tagged in 1976. Six of those fish lacked spawning checks on their scales.

While our data indicate that American shad are abundant, past populations probably were larger. We speculate that in 1917, at an average weight of 1.4 kg/shad, almost $2 \times 10^6$ fish were caught in the $2.6 \times 10^6$-kg commercial fishery. While we do not know the efficiency of the early fishery, it is reasonable to speculate that the total shad population was several times the number landed, and perhaps two to three times greater than current runs.

Abundance of young American shad in the Sacramento–San Joaquin Estuary varies annually by more than an order of magnitude, and the strongest year classes occur in the years with the highest river flows during the spawning and nursery periods (Stevens and Miller 1983). There are two abundance indices. One is based on catches of out-migrants at the fish screens of the CVP and SWP diversions in the delta (1959–1984); the other is calculated from catches of out-migrants during a fall midwater trawl survey at 87 sampling stations scattered from San Pablo Bay through the delta (1967–1984, except 1974 and 1979). Logarithms (base 10) of the abundance indices are directly correlated with the volume of river inflow to the delta during various combinations of months in spring and summer. For example, $r = 0.77$ for $\log_{10}$(midwater trawl index) versus mean April-to-June flows ($P < 0.001$). Several factors may cause abundance to increase with river flow, including decreased predation and decreased losses to diversions. However, our preferred hypothesis is that high river flows increase availability of nursery habitat by dispersing spawners and young fish (Stevens and Miller 1983).

The value of the correlations between young American shad abundance and river flow would be enhanced if a similar correlation existed between the year-class strength of adult American shad and flow in the natal year. We looked for such a correlation, using catches of adult American shad in striped bass fyke traps set in the Sacramento River during 8 years from 1974 to 1984. We standardized the annual catch of American shad to a trapping effort of 70 d (April 1–June 9). This standardized catch ranged from 242 fish in 1980 to 2,811 fish in 1983 (Table 2). Although the age composition of these American shad was not directly estimated, ages 3–5 generally form the bulk of the spawning run (Wixom 1981); thus, we correlated $\log_{10}$(catch) against 3-year means of April–June inflow to the delta 3 to 5 years earlier. The results were not conclusive. The correlation coefficient, 0.56, indicated a positive association between the catch and flow, but it was not statistically significant. Numerous factors, including variations in the age structure of the population (Wixom 1981), could have confounded this correlation. Alternatively, mortality may vary after the out-migration.

## Striped Bass

### *Introduction and Fisheries*

In 1879, 8 years after the American shad was introduced, 132 young striped bass from the Navesink River, New Jersey, were released into Carquinez Strait. A second plant of 300 fish from the Shrewsbury River, New Jersey, followed in 1882.

Like the American shad, striped bass experienced a population explosion soon after their introduction. Commercial harvesting started in the early 1880s and, by the turn of the century, exceeded 450,000 kg annually. The greatest recorded catch, over 900,000 kg, occurred in 1903. Subsequently, annual catches declined due to increased restrictions on the fishery (Craig 1928).

In 1935, the commercial fishery for striped bass was closed although the stock was not depleted (Craig 1930; Clark 1932, 1933). The closure stemmed largely from a social conflict between sport and commercial fishing interests which culminated with the closure of the commercial gill-net fisheries for chinook salmon *Oncorhynchus tshawytscha* and American shad in 1957. Thousands of striped bass were killed annually in the nets and could not be marketed legally. Closure of the chinook salmon and American shad fisheries reduced fishing mortality for striped bass, but the magnitude of the reduction cannot be estimated, because the precise magnitude of that incidental harvest is unknown and some illegal netting continues.

The striped bass sport fishery has become the most important fishery in the estuary and one of the most important fisheries on the Pacific coast. From 1969 to 1979, the annual catch varied from 107,000 fish (1978) to 403,000 fish (1975) (White 1986), and the annual recreational value is estimated to exceed 45 million dollars (Meyer Resources 1985).

Striped bass angling occurs the year around, but fishing localities vary seasonally in accordance with the striped bass migratory pattern (Stevens 1980). Tag recoveries (Chadwick 1967; Orsi 1971; White 1986) indicate that currently most adults inhabit salt water—San Pablo Bay, San Francisco Bay, and the Pacific Ocean—in the summer. The proportion entering the ocean varies from year to year, perhaps in response to water temperature (Radovich 1963). These fish begin returning to the delta in the fall although many overwinter in the bay area.

The distribution of fishing effort has shifted since the late 1950s as postspawning striped bass generally have migrated farther downstream and stayed there longer. Thus, fishing has improved in San Francisco Bay and the Pacific Ocean and declined in the delta. Also, the use of the Sacramento River as a spawning area appears to have increased, improving fishing there in the spring (Chadwick 1967). While significant environmental changes have occurred, data are insufficient to develop conclusions regarding causes of the changes in striped bass migrations.

Present fishing regulations include a 45.7 cm minimum length and a daily bag limit of two fish. From 1956 to 1981, the minimum length was 40.6 cm and the bag limit was three fish. Prior to 1956, regulations were more liberal: a 30.5 cm minimum length and five-fish bag limit generally was in effect.

Exploitation rates have been estimated almost annually since 1958. They have varied from 12 to 28% except for 37% in 1958 (Chadwick 1968; Miller 1974; White 1986) and are lower than those for Atlantic coast stocks (Kohlenstein 1981) that are fished commercially.

### *Spawning*

The majority of striped bass spawning, 62% on the average, occurs in the Sacramento River, the remainder in the delta (Farley 1966; Turner 1976; California Department of Fish and Game, unpublished data). Unlike the American shad, relatively few striped bass spawn in the Sacramento River tributaries. Striped bass migrate to the reach of the Sacramento River from Sacramento to Colusa in April and May just before spawning. The geographical center of spawning there has varied from river km 148 in 1966 to km 200 in 1963 (Turner 1976).

Tag returns provide evidence of strong homing by striped bass which spawn in the upper Sacramento River, but it is unknown if the pattern is inherited by progeny of fish that spawned there or if it evolves later in life (Chadwick 1967).

In the delta, Turner (1976) found that the bulk of spawning occurred in the San Joaquin River between Antioch (river km 34) and Venice Island (river km 61). A moderate amount of spawning apparently occurred below Antioch in 1967 and 1969, although high flows in those years may have transported eggs farther seaward.

The migration farther up the San Joaquin is blocked in many years by a reverse salinity gradient that results from the use of the interior delta channels to carry Sacramento River water, characteristically low in dissolved solids, to the CVP–SWP pumping plants, and relatively high concentrations of dissolved solids coming from the upper San Joaquin River due to agricultural drainage. Total dissolved solids (TDS) of about 350 mg/L appear to repel the upstream migrants (Radtke and Turner 1967).

The striped bass and American shad spawning seasons overlap (Table 1). As for American shad, the time of striped bass spawning varies annually depending on water temperature, which is a function of weather (Turner 1976). Both species begin spawning at about 17°C, but since many striped bass spawn in the delta, which warms earlier than the upper Sacramento River system, striped bass begin spawning earlier than the American shad. Striped bass spawning also ends earlier; few fish spawn at temperatures exceeding 20°C.

Based on 7 years of data, the middle of the striped bass spawning period in the delta averaged 15 d earlier than in the Sacramento River. Most striped bass spawning occurred in the delta between April 23 and May 25. In the Sacramento River, most spawning occurred between May 10 and June 12. The greatest deviations from this period in the Sacramento River were in 1966 and 1972 when 20–25% of the striped bass spawned before May 10, and in 1969 when about 25% spawned after June 12. The difference between the spawning periods was greatest when river flows, as estimated at Chipps Island in May, were high ($r$ = 0.85) reflecting an increased lag in the warming of the Sacramento River as flows increased (Turner 1976).

Total dissolved solids generally are low where the striped bass spawn. In 7 of the 9 years in which eggs were sampled in the delta, more than 80% of all newly spawned eggs were collected where TDS were less than 200 mg/L. However, in 1968 and 1972, salinity intruded into the spawning area and sizable numbers of eggs were spawned at higher TDS levels with no obvious effect on year-class strength. In the Sacramento River, TDS levels were always less than 200 mg/L (Turner 1976).

*Nursery*

The striped bass nursery overlaps that of the American shad, but it is predominantly farther downstream because the eggs and larvae from the Sacramento River drift to tidewater, where they coexist with larvae that were spawned in the delta.

By midsummer, flow patterns created by CVP–SWP operations have carried many of the young fish to the south delta, where they are lost through the water project export pumps. Other fish have drifted westward, as they did historically, to the fresh–saltwater mixing zone.

This mixing zone, or "entrapment zone" (Arthur and Ball 1979), is generally more productive than areas up or downstream, and its location varies annually. In high-flow summers, it is generally located in Suisun Bay; at low flows, it is in the delta (Turner and Chadwick 1972; Arthur and Ball 1979; Conomos 1979). Hence, the summer distribution of juvenile striped bass is correlated with river flow (Turner and Chadwick 1972; $r = -0.64$, $P < 0.01$, for percentage of the population in the delta versus $\log_{10}$[mean May–July delta outflow], 1959–1985).

Midwater trawl catches (Stevens 1977a) indicate that young striped bass remain concentrated in and around the entrapment zone until river flows increase due to fall or winter storms. At that time, they disperse throughout the estuary.

During their second and third years, striped bass are spread throughout the estuary and the rivers above the delta. Male striped bass mature when they are 2 or 3 years old, whereas females mature at 4 or 5 years. Once striped bass mature, they take up the adult migratory pattern.

*Abundance*

The striped bass population has been declining since the 1960s and is now at its lowest level since measures have been available. Adult striped bass (total length ≥ 40.6 cm) abundance is being measured with Petersen population estimates and the catch per effort (CPE) of fish captured during tagging studies (Stevens et al. 1985). Petersen estimates have been calculated annually from

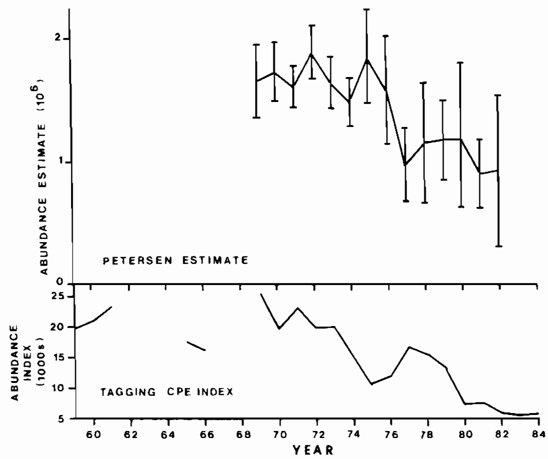


FIGURE 4.—Trends in abundance of adult striped bass (≥40.6 cm total length) in the Sacramento–San Joaquin estuary. Vertical bars for the Petersen estimates are 95% confidence intervals; CPE is catch per effort. (From Stevens et al. 1985.)

1969 through 1982, and the CPE measurements are available for 1959 to 1961, 1965 to 1966, and 1969 to 1984.

According to the Petersen estimates, the striped bass population was around $1.7 \times 10^6$ fish and stable between 1969, when the estimates began, and 1976 (Figure 4). It then declined to about $1 \times 10^6$ fish and remained near this lower level through 1982. 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 (Figure 4). Thus, the population of adult striped bass in the estuary has definitely fallen to a low level—much lower than when estimates were first available 20 years ago. However, the precise timing and magnitude of the decline are uncertain.

Catch records from the charter boat fishery suggest that peak striped bass abundance in recent years occurred in the early 1960s. Charter boat operators are required to report catches to the California Department of Fish and Game. Although these boats presently take only about 14% of the total catch (White 1986) and their fishing locations and methods have varied over the years, their reports are the best long-term striped bass catch records available (Stevens 1977b). In the late 1950s and early 1960s, success on charter boats exceeded two fish per angler-day. After 1963, success dropped and, while fluctuating irregularly, was frequently less than one fish per angler-day from 1969 to 1982 (Figure 5).

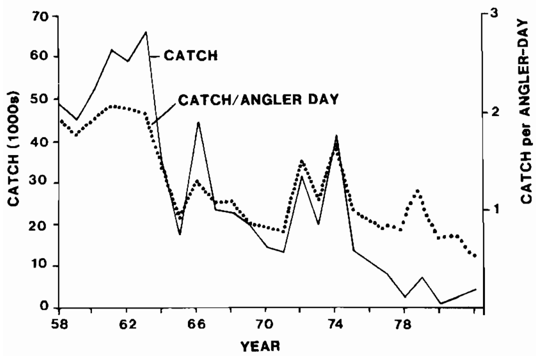


FIGURE 5.—Trend in striped bass catch on charter boats in the Sacramento–San Joaquin estuary.

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, decreased effort associated with the generally low success in the late 1970s and early 1980s caused total catch to decline even more severely than catch per angler-day. In 1980, the total catch on charter boats was only about 1,400 fish, substantially lower than the 47,000 to 67,000 striped bass landed each year from 1958 to 1963 (Figure 5).

The recent decline in adult striped bass abundance has been accompanied by below-average recruitment and an increase in annual angler harvest from about 15% of the population in 1970 to about 27% in 1976. Generally, these exploitation rates would be considered safe, but increased survival or recruitment obviously are needed to reverse the population trend (Stevens et al. 1985). Increased survival potentially could be attained by reducing exploitation or other mortality factors.

Abundance of young-of-the-year striped bass has been measured annually, except for one year, since 1959. The population is sampled every second week from late June to late July or early August throughout the nursery habitat. When their mean fork length reaches 38 mm, a young-of-the-year index is calculated on the basis of catch per net tow weighted by the volume of water in the areas where the fish are caught (Turner and Chadwick 1972; Stevens et al. 1985).

The index of young striped bass abundance has varied from 6.3 to 117.2 during the 26 survey years. From 1959 to 1976, variations in spring and early summer river flow and water diversion rates largely accounted for the annual variations in young striped bass abundance, high river flows being beneficial and high diversion rates being detrimental (Turner and Chadwick 1972; Chadwick et al. 1977; Stevens et al. 1985). Thus, in the Sacramento–San Joaquin river system, high river flows benefit both young striped bass and American shad.

Since 1977 the abundance of young striped bass has been considerably lower than predicted by regressions based on the 1959–1976 data. Several factors have been identified as probable major contributors to the decline of young striped bass (Stevens et al. 1985): (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 declined; (3) large numbers of striped bass eggs and young have been removed from the estuary by diversion of water needed for agriculture, power plant cooling, and other uses; (4) toxicants may cause mortality of adults, reduce their ability to reproduce, or reduce the survival of their eggs and young.

Correlations indicate a positive association between indices of young striped bass abundance and subsequent recruitment to the adult population. This suggests that past losses of young striped bass have contributed to the decline of the adult stock and that the recent decline in young striped bass abundance is leading to a further reduction of adults (Stevens et al. 1985).

## Discussion

The explosion and spread of the populations of American shad and striped bass shortly after their introductions reveals that environmental conditions formerly were nearly ideal for these species in the Sacramento–San Joaquin river system. At the time of the introductions, although the rivers and delta were largely leveed, the rest of the system was relatively undeveloped by humans. There were hundreds of kilometers of rivers suitable for spawning; no major dams blocked the runs and reduced the freshwater flows that disperse the young. California agriculture and industry were just beginning, so losses of young fish to water diversions and toxic wastes would have been minimal. Also, the native fish fauna contained few top predators in those areas used extensively by the young of both species.

The American shad and striped bass populations have declined since the early 1900s. Striped bass, in particular, have not coped well recently. Available evidence indicates that neither population has been overfished, but there is substantial evidence that the favorable environment initially experienced by both species has become less friendly due to human activities.

American shad and striped bass have similar spawning strategies and early life histories and also overlapping nurseries; thus, both species are vulnerable to many of the same environmental disturbances. The most obvious of these have been the construction of dams in the upper reaches of the rivers; water diversions by water projects, power plants, and farms along the rivers and in the delta; and discharges and accidental spills of toxic substances by municipalities, industries, and agriculture. Specifically, these perturbations have had the following adverse effects.

(1) River flows have been reduced in quantity and quality. Year-class strengths of both American shad (Stevens and Miller 1983) and striped bass (Turner and Chadwick 1972; Chadwick et al. 1977; Stevens 1977b; Stevens et al. 1985) correlate positively with river flow during the spawning and nursery periods. Flows must be ample to attract American shad spawners into Sacramento River tributaries, transport and disperse the young of both species to suitable nursery habitat, repel salinity intrusions in the striped bass spawning area in the western delta, dilute the salinity of the upper San Joaquin River that repels striped bass spawners, and reduce the probability of entrainment of young fish and their food organisms in water diversions. Water project dams and pumps have reduced flows during the spring and early-summer periods, which are most critical in this respect.

In regard to the quantity of flow, abundance of not only American shad and striped bass, but also the abundance of other anadromous fishes in the Sacramento–San Joaquin river system, specifically chinook salmon and longfin smelt *Spirinchus thaleichthys*, is known to benefit from high flows (Stevens and Miller 1983). In contrast, our American shad results are in discord with Crecco and Savoy's (1984) results for the Connecticut River, where American shad year-class strength and flow are inversely correlated.

(2) Food supplies for young fish have been reduced. An adequate supply of zooplankton must be available at the time and place that the young fish initially feed. A decline in zooplankton has coincided with the recent decline in young striped bass abundance and provides one of the most likely explanations for the recent low abundance of young striped bass (Stevens et al. 1985). Considerable evidence exists that populations of phytoplankton, zooplankton, opossum shrimp *Neomysis mercedis*, and other organisms in the estuarine food web have been reduced through effects of water project operations on the quantity of flows of the Sacramento and San Joaquin rivers, the location of the entrapment zone, and the growing use of the delta channels as conduits to carry water south to the CVP and SWP pumps (Turner 1966; Turner and Heubach 1966; Heubach 1969; Arthur and Ball 1979; Knutson and Orsi 1983; Stevens et al. 1985).

(3) Fish have been entrained in water diversions and lost. The magnitude of entrainment losses of both species to diversions by water projects, local agriculture, power plants, and other industry have been on the order of $10^6$ to $10^9$ fish annually since the 1950s. Screens help save the larger individuals, but only operational constraints can save larval fish. The recent decline of the adult striped bass population began in the 1960s, lagging the onset of major water project operations by only a few years. This pattern suggests that entrainment losses and other impacts of water diversions have contributed substantially to the decline and that striped bass losses, at least, are not materially compensated by subsequent reductions in density-dependent mortality.

(4) Pollution is a potentially important stressor. We cannot define the overall effect of pollution because the data base is inadequate, but we do know that large quantities of potentially toxic substances reach the river system. Major waste treatment facilities discharge into the delta and bays; although they have been much improved in the last decade, other important sources of pollution still exist. Much of the watersheds of the Sacramento and San Joaquin rivers are treated with pesticides, a variety of toxicants enter the rivers and bays with runoff from industrial and urban areas whenever it rains, and accidental spills of all sorts commonly occur (Stevens et al. 1985). Recent studies of the health of adult striped bass from the Sacramento–San Joaquin system have revealed that gonads, liver, and muscles have accumulated toxic substances, primarily monocyclic aromatic hydrocarbons (MAH), chlorinated hydrocarbons, and heavy metals (Whipple 1984). Health, as measured by liver, gonad, and egg condition, is inversely correlated with concentrations of MAH and Zn in the tissues. High tissue concentrations of MAH and Zn also are associated with greater parasite infestations. Quantities of Hg in striped bass flesh have been

sufficient to trigger health warnings regarding its consumption by humans.

While American shad and striped bass have similarities in their life history strategies, there are also differences that appear to benefit the American shad, which has not had a recent decline paralleling that of the striped bass. Two differences in their life history strategies may be relevant.

(1) The major striped bass nursery is in the estuary (Chadwick 1964; Turner and Chadwick 1972), whereas the American shad nursery is partly upstream. Perhaps American shad have not suffered the same fate because the upstream environment has not been degraded as much as that of the estuary.

(2) American shad spend most of their lives in the ocean. In contrast, striped bass live mostly in the estuary; only the larger fish go to sea and only for a few months each year. Thus, due to various sources of pollution in the region surrounding the estuary, striped bass probably are exposed to more toxicity. Toxic exposure of American shad has not received the same attention that Whipple (1984) has given to adult striped bass, however.

All identified adverse changes in habitat quality are associated with human activities. The California Department of Fish and Game has been attempting to counter these changes by working with water development agencies during project planning and with control agencies such as the State Water Resources Control Board and regional water quality control boards.

Mitigation for striped bass losses in the form of annual stocking of about 200,000 yearling hatchery fish is currently required of the Pacific Gas and Electric Company by the water quality control boards. Hatchery production is also being negotiated between the Departments of Fish and Game and Water Resources to mitigate effects of the State Water Project. Additionally, the Department of Fish and Game is experimentally stocking about 500,000 marked yearling striped bass annually. This stocking and the evaluation of its effectiveness are funded by a $3.50 stamp that must be purchased by every striped bass angler.

There has been no attempt to mitigate or restrict American shad losses other than by fish screens on diversions and indirectly through constraints placed by the control agencies on water project and power plant operations for protection of striped bass and chinook salmon.

Subsequent to the introductions of striped bass and American shad, two native fishes experienced disastrous declines. One, the thicktail chub *Gila crassicauda,* once common, apparently is now extinct (Shapovalov et al. 1981); another, the Sacramento perch *Archoplites interruptus,* formerly the major top predator, now is very rare in the delta. However, assessments of the impacts of American shad and striped bass on these and other natives are precluded by introductions of numerous other fishes, particularly centrarchids and ictalurids in the late 1800s, and by vast environmental changes such as the construction of levees that eliminated delta tidal marshes and flood plains of the rivers upstream, dams that blocked spawning runs, the various water diversions, and toxic discharges. American shad, being plankton feeders and spending most of their lives in the ocean, undoubtedly have had less impact than striped bass, which are more estuarine and prey on both introduced and native species (Stevens 1966b; Thomas 1967). Considering that even with the present depleted stock, the annual recreational value of the Sacramento–San Joaquin striped bass population is estimated to exceed $45 million (Meyer Resources 1985), and that American shad also support a popular fishery, we believe that the introductions of these species have been of substantial benefit to California.

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