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Abstract

The introduction of striped bass to the Sacramento-San Joaquin Estuary has established one of California's most important recreational fisheries. Striped bass requirements are being studied so they can be considered in planning for future water project and other development in the estuary. Study results have shown that striped bass spawning is affected by annual variations in salinity in the San Joaquin River, and survival of the young and subsequent recruitment to the fishery are related to the magnitudes of water diversions from the nursery area and river flows.

Mortality caused by entrainment in power plant cooling systems probably has been low relative to that caused by water development, but losses due to entrainment at power plants may be increasing because increased power production is causing lethal temperatures to occur more frequently.

Factors other than angling kill about 15 to 30% of the adult bass each year. Part of this mortality occurs during large die-offs in the Suisun-San Pablo Bay area when bass are migrating back to salt water after spawning. Attempts to determine the cause of these kills have been unsuccessful.

Reduced flows resulting from water development may change water circulation patterns in San Francisco and San Pablo bays. Such changes potentially affect the abundance and distribution of forage for adult bass. Water management actions that would benefit the striped bass resource include maintaining adequate freshwater flows through the estuary and moving the intakes for the federal and state water diversions to a location upstream from the nursery area.

ENVIRONMENTAL FACTORS AFFECTING STRIPED BASS (*MORONE SAXATILIS*) IN THE SACRAMENTO-SAN JOAQUIN ESTUARY

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The introduction of striped bass to the Sacramento-San Joaquin Estuary has established one of California's most important recreational fisheries. Striped bass requirements are being studied so they can be considered in planning for future water project and other development in the estuary. Study results have shown that striped bass spawning is affected by annual variations in salinity in the San Joaquin River, and survival of the young and subsequent recruitment to the fishery are related to the magnitudes of water diversions from the nursery area and river flows.

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Striped bass (*Morone saxatilis*) were introduced to the Sacramento-San Joaquin Estuary from the Atlantic Coast in 1879 (Skinner 1962; Smith and Kato 1979). They increased at a phenomenal rate: hundreds were caught 10 years after the introduction, and after 20 years over 540,000 kg were landed. From 1916 to 1935 when commercial fishing was outlawed, the commercial catch ranged between 225,000 and 450,000 kg annually.

As a result of the introduction, the striped bass fishery in the Sacramento-San Joaquin Estuary has long been one of California's top ranking sport fisheries. Presently about 200,000 anglers fish for striped bass each year and catch about 300,000 fish. In the only significant economic study, the Stanford Research Institute projected an annual net value of 7.5 million dollars for this fishery in 1970 (Altouney, Crampon, and Willeke 1966). Hence, striped bass are a major recreational and economic asset.

The viability of the striped bass resource depends on environmental conditions which have been and are being altered by water projects and other development. Due to potential impacts of future development, the California Department of Fish and Game (DFG) in cooperation with the U. S. Fish and Wildlife Service (USFWS), California Department of Water Resources (DWR), and U. S. Bureau of Reclamation (USBR) has been studying the environmental requirements of striped bass. This chapter reviews the major findings of those studies.

THE ESTUARY

The Sacramento-San Joaquin river system forms a tidal estuary (Fig. 1). Approximately 1,130 km of channels interlace the Delta at the junction of the rivers. These channels vary in width from around 50 m to about 1.5 km, and generally they are less than 15 m deep. Water flowing to the ocean passes through Suisun, San Pablo, and San Francisco bays. A vast area of these bays is less than 2 m deep at mean lower-low tide. However, the channels range up to 100 m deep in San Francisco Bay just inside the Golden Gate.

The salinity gradient generally is about 80 km long extending from San Pablo Bay to the western Delta (see also Conomos 1979). River flows into the Delta are quite variable and are partially controlled by upstream reservoirs. Inflows peak in winter and spring. Water development in the system now removes about half of the flow that would normally go to the ocean. Water is exported from the southern Delta via two large pumping plants. One is a 130 $m^3 \cdot s^{-1}$ plant built by the USBR in 1951; the other is a 170 $m^3 \cdot s^{-1}$ plant completed by the DWR in 1968. The flow

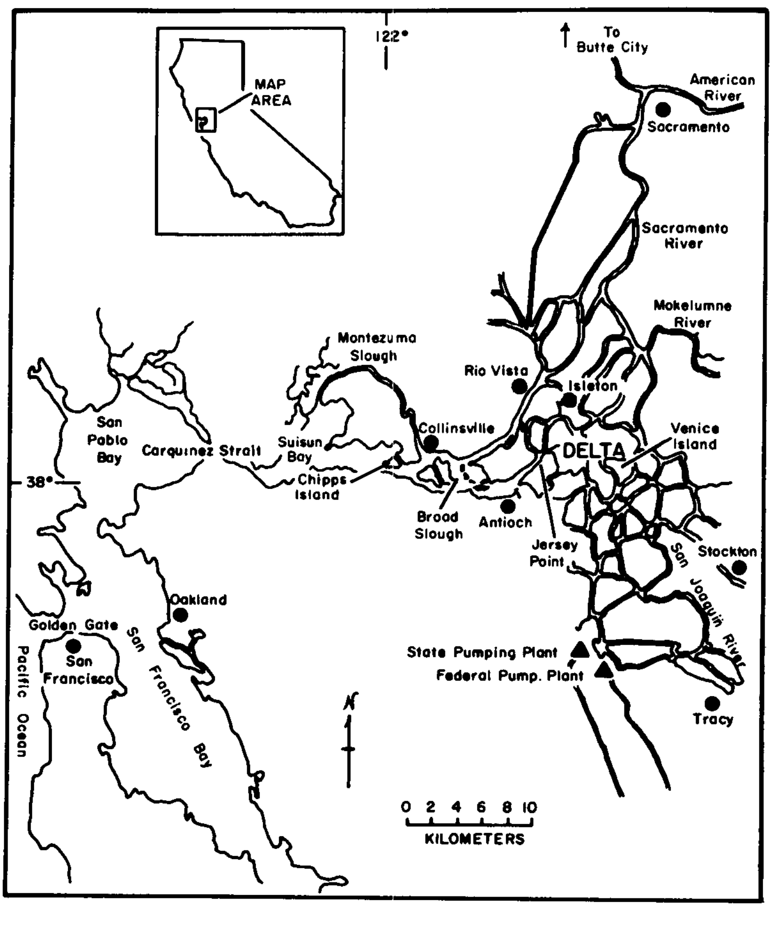

Fig. 1. The Sacramento-San Joaquin Estuary.

reductions and removal of water from the Delta affect the salinity gradient and cause changes in seasonal and geographical flow patterns in the various channels.

FISHERY

Tagging studies indicate abundance of bass larger than the 40.6-cm minimum legal size ranged from about 1.6 to 1.9 million fish from 1969 to 1975 (Stevens 1977a). Such abundance measurements are not available for prior years, but sport fishery records provide evidence that bass were two to three times more abundant in the early 1960's than at present (Stevens 1977b).

Since 1958 anglers have harvested from 11 to 37% of the legal population each year (Chadwick 1968; Miller 1974; Stevens 1977b; and unpublished data). From 1969 to 1975 an average of 60% of the catch was from San Francisco Bay, San Pablo Bay, and Carquinez Strait (unpublished data). About 2% of the catch was from the Pacific Ocean. The remainder of the catch came from Suisun Bay, the Delta, and the rivers upstream from the Delta.

Bass migrations cause the fishery to be seasonal throughout the estuary. From 1969 to 1975 more than 90% of the catch west of Suisun Bay was taken during summer and fall; whereas, almost 60% of the catch upstream was taken during spring.

LIFE HISTORY

Tagging studies demonstrate that most adults move to fresh water (the Delta or upstream in the Sacramento River) to spawn during spring. After spawning, adult bass return to salt water (San Pablo and San Francisco bays and the Pacific Ocean within about 32 km of the Golden Gate). Some adults begin moving back upstream toward fresh water again during fall. Others overwinter in the bays and move back upstream just before spawning during spring (Calhoun 1952; Chadwick 1967; Orsi 1971).

Striped bass are prolific. A 60-cm long female spawns about 700,000 eggs (Lewis and Bonner 1966). Spawning occurs from early April to mid-June and primarily in two areas, the San Joaquin River between Antioch point and Venice Island and the Sacramento River from Isleton to Butte City about 240 km upstream (Farley 1966; Turner 1976).

Bass eggs are semi-buoyant and drift with the water currents until they hatch in 2 to 3 days. As a result of the rapid downstream flow in the Sacramento River, most bass larvae reach the Delta before they have significant swimming ability or have started to feed. Mortality rates are high from the time eggs are spawned through the middle of the first winter (DFG et al. 1974). Probably only about one out of every 100,000 eggs survives to the end of the year (unpublished data).

Young bass abundance typically is greatest in the zone where fresh and salt water initially mix, presumably indicating better conditions for survival there (Turner and Chadwick 1972). Massmann (1963) referred to this region as the "critical zone" in estuaries, because it is the principal nursery area for many fishes. In the Sacramento-San Joaquin Estuary this zone is more productive than areas up or downstream; it has been variously termed the "null zone" (Conomos and Peterson 1974; Peterson et al. 1975) or the "entrapment zone" (Arthur and Ball 1979). At moderate flows this zone is located in the Suisun Bay area, and at low flows it is in the Delta (Turner and Chadwick 1972; Arthur and Ball 1979; Conomos 1979). Generally, the greatest densities of the principal food organisms of young bass (the opossum shrimp, *Neomysis mercedis* and copepod *Eurytemora* sp.) also occur in or near this zone (Heubach 1969; Orsi and Knutson 1979; DFG et al. 1975).

During their second year, many bass still live in the Delta and Suisun Bay, but others move into the rivers above the Delta and downstream into San Pablo Bay. They generally change from an invertebrate to a fish diet, although *Neomysis* is still important. In the Delta, threadfin shad (*Dorosoma petenense*) and young striped bass are the primary fish eaten (Stevens 1966).

Male bass mature when they are 2 or 3 years old, while females mature at 4 or 5 years. Once bass mature they take up the adult migratory pattern.

ENVIRONMENTAL FACTORS AFFECTING THE POPULATION

Water Quality and Spawning

Striped bass spawning and salinity of the rivers was monitored most years from 1963 to 1977. Salinity always was less than 200 $mg \cdot liter^{-1}$ total dissolved solids (TDS)[1] in the Sacramento River spawning area. Salinity generally was less than 200 $mg \cdot liter^{-1}$ TDS ($\leqslant 0.5$ ‰) in the San Joaquin River spawning area, although low river flows sometimes allowed higher salinity water to intrude from the west. Usually this area is less salty than the river either up or downstream because fresh water flowing from the Mokelumne and Sacramento rivers dilutes saltier agricultural return water coming from upstream and ocean water coming from downstream.

Several findings from the field monitoring and also laboratory experiments indicate salinity adversely affects bass spawning. Radtke and Turner (1967) reported that potential spawners are repelled by the salty, agricultural return water in the San Joaquin River upstream from Venice Island. More recently, L. W. Miller (pers. comm.) found that few bass spawned in the San Joaquin River during 1977 when the intrusion of ocean water caused salinities to exceed 5,000 $mg \cdot liter^{-1}$ TDS (≈ 5 ‰) in the usual spawning area. Bass were not deterred from spawning in this area by ocean salts causing TDS of 1,500 $mg \cdot liter^{-1}$ (≈ 2 ‰) in 1968 and 1972 (Turner 1976), but laboratory experiments indicate egg survival declines markedly when the salinity of the water in which they harden exceeds 1,000 $mg \cdot liter^{-1}$ TDS (≈ 1 ‰) (Turner and Farley 1971). Hence, water fresher than 1,000 $mg \cdot liter^{-1}$ TDS apparently is essential for optimum spawning success.

Effects of River Flow and Water Diversions on Young Bass Survival

Abundance of young bass has been monitored by a tow net survey conducted annually since 1959 (except 1966). Turner and Chadwick (1972) developed annual indices of young bass survival for 1959 to 1970 from this survey. These indices were directly correlated with outflow from the Delta[2] during all combinations of months from April to July. Survival was best correlated with flows for June and July combined. The variations in young bass survival appear to be important in determining subsequent recruitment to the fishery (Stevens 1977b; Chadwick et al. 1977).

From 1971 to 1976, young bass survival consistently was poorer than expected from Turner and Chadwick's analysis of survival and flow from 1959 to 1970 (Fig. 2) (Chadwick et al. 1977). The recent decrease in survival occurred solely in the Delta which is the farthest upstream portion of the nursery area. During this period, average May, June, and July water exports increased 83, 60, and 52% above 1959 to 1970 levels.

The findings led to a multiple regression of indices of young bass survival in the Delta against diversion rates and outflows from 1959 to 1976 (Fig. 3) (Chadwick et al. 1977). The analysis indicated that the survival-flow correlations are caused partly by local, state, and federal diversions removing more fish and perhaps their food organisms from the Delta when outflows are low than

[1] This value converts to a very approximate salinity value of $\leqslant 0.5$ ‰ (at water temperature of 20°C.) Other approximations are inserted parenthetically in text. (Ed.)

[2] The Delta outflow index is the mean calculated daily outflow past Chipps Island. The data are partly from DWR Water Supervision and Water Flow bulletins and partly supplied directly by DWR personnel. See also Conomos (1979).

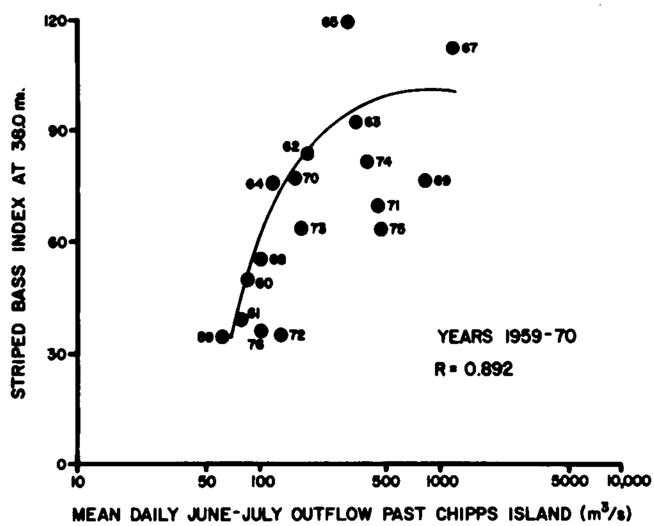

Fig. 2. Relation between abundance of young striped bass from Carquinez Strait upstream through the Delta, Y, and mean daily Delta outflow during June and July. Numbers indicate year from 1959 to 1976. The regression equation for 1959-1970 is Y = -488.3 + 429.2 (log mean daily June-July outflow) - 77.9 (log mean daily June-July outflow)^2 ; R = 0.892. (From Chadwick et al. 1977).

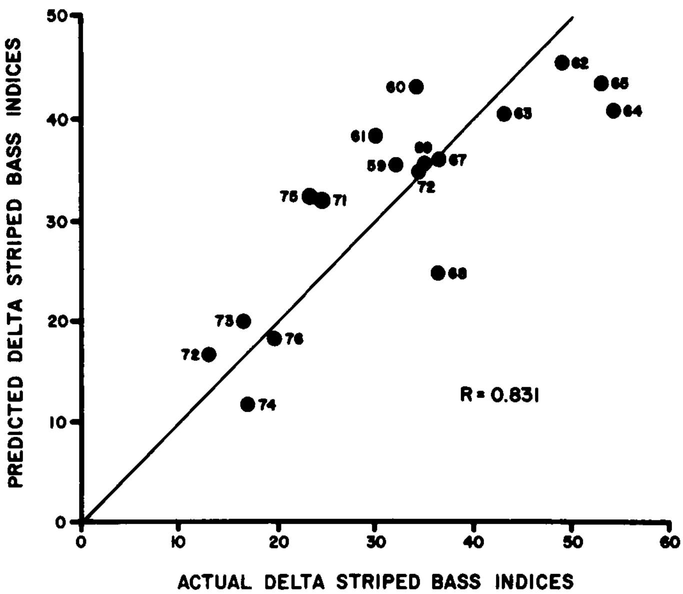

Fig. 3. Relation between actual abundance of young striped bass in the Delta and abundance predicted from May-June diversions and Delta outflow. Numbers indicate year from 1959 to 1976. The regression equation used to obtain the Y-axis coordinates is Y = -202.7 -0.25 (mean daily May-June diversions) + 225.9 (log mean daily May-June outflow) - 43.36 (log mean daily May-June outflow)^2 ; R = 0.831. Outflows in $m^3 \cdot s^{-1}$. (From Chadwick et al. 1977).

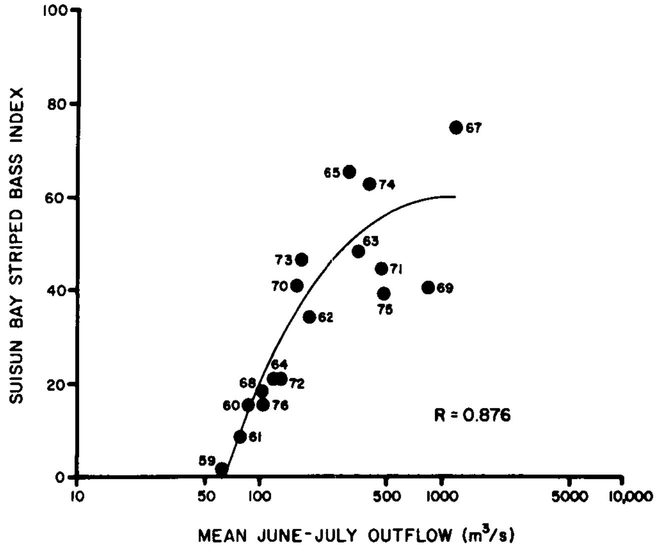

Fig. 4. Relation between abundance of young striped bass downstream from Collinsville (Suisun Bay index), Y, and mean daily Delta outflow during June and July. Numbers indicate year from 1959 to 1976. The regression equation for 1959-1970 is Y = -294.3 + 234.8 (log mean daily June-July outflow) - 39.0 (log mean daily June-July outflow)^2 ; R = 0.876. (From Chadwick et al. 1977).

when outflows are high. Fewer fish are diverted when flows are high because the diversions take a smaller fraction of the flow carrying eggs and young and high flows transport more fish to Suisun Bay where there are few diversions (Fig. 4) (Chadwick et al. 1977).

Bass are removed from the Delta by local diversions because most of those diversions are not screened (Allen 1975). The export diversions have louver screens, but as pumping increases these diversions remove more bass because the screens are ineffective on bass too small to swim well. The screens do not attain 50% efficiency until the bass grow to 19 mm long (about 1-mo old). Above 19 mm, screen efficiency increases gradually to about 85% for bass longer than 100 mm (about 5-mo old) (Skinner 1974).

Another effect of water export pumping is that it causes high flow velocities in the channels which convey water from the Sacramento River to the pumping plants in the southern Delta. High velocities reduce standing crops of important bass food organisms (copepods, cladocerans, and *Neomysis mercedis*) (Turner 1966; Heubach 1969).

The survival-flow relations apparently are not caused solely by diversions, however. There is evidence that high flows enhance survival in other ways. From 1938 to 1954, before significant water exports existed, recruitment of bass to the fishery was correlated with outflow when the recruits were young (Stevens 1977b), and it is unlikely that local diversions caused the correlation (Chadwick et al. 1977). Also, in 1977, there was abnormally low survival of young bass which was associated with extremely low outflows (Table 1). The 1977 results are not explained by diversion rates (L. Miller pers. comm.).

The way in which flow controls the spatial distribution of young bass in the estuary may be a major mechanism controlling the survival-flow relations. When high flows disperse young bass over more of the estuary, competition for food may be reduced (Stevens 1977b; Chadwick et al. 1977).

Recent studies (Orsi and Knutson 1979) also reveal that when flows are low, standing crops of foods are reduced in the critically important fresh-salt water mixing zone. Delta outflow was considerably lower than normal throughout 1976 and 1977, and the mean 1976-77 summer

TABLE 1. YOUNG BASS ABUNDANCE AND OUTFLOW[a] FROM THE SACRAMENTO-SAN JOAQUIN DELTA.

	1977	Mean (1959-1976)	Previous low
Bass abundance index (units)	6.7	67.7	33.9 (1959)
Mean April to July outflow ($m^3 \cdot s^{-1}$)	86	573	140.0 (1976)

[a] *Mean calculated daily outflow past Chipps Island.*

abundance index for *Neomysis mercedis* was only about 25% of the 1968-1975 mean (A. Knutson pers. comm.). Indices of smaller zooplankton abundance also were below normal in 1976 and 1977 (J. Orsi pers. comm.).

Effects of Power Plants and Other Industry on Young Bass Survival

Chadwick and Stevens (1971) and Chadwick et al. (1977) reviewed available striped bass temperature tolerance data and operation of the two Pacific Gas and Electric Company (PG&E) power plants which use up to 90 $m^3 \cdot s^{-1}$ of water from the striped bass nursery area for "once through" cooling. We concluded that mortality caused by these plants was minimal compared to that caused by the water project and agricultural diversions and other environmental factors associated with outflow. We based this conclusion on: (1) entrained bass usually were not exposed to lethal temperatures, (2) field tests suggested few fish were mechanically damaged, and (3) power plant effects were not evident in the statistical relations between young bass survival and flow and diversion rates even though there were two significant increases in cooling water demand (totaling 48% of the present demand) during the survival study.

Although power plants apparently have not been a major factor, evidence that losses of young bass are not nullified by compensatory mechanisms later in life (Chadwick et al. 1977) suggests that losses due to entrainment have had some, albeit perhaps small, impact on the fishery. The impact probably is increasing, as increased power production is causing lethal temperatures to occur more frequently (Finlayson and Stevens 1977; PG&E 1977).

Several other industries use water from the western Delta and/or have discharged wastes into the nursery area while bass survival has been monitored. However, their total water use is small (about 2 $m^3 \cdot s^{-1}$ during summer), compared to the amount used for export (up to 300 $m^3 \cdot s^{-1}$) by local agriculture (about 110 $m^3 \cdot s^{-1}$ during the summer), and by PG&E. Effluent standards also have become more stringent in recent years. Hence, presently, local industry probably does not significantly affect young bass survival.

Factors Affecting Adult Bass

Factors other than angling kill about 15 to 30% of the adult bass each year (Chadwick 1968; Miller 1974; Stevens 1977b). Part of this mortality is due to natural phenomena such as disease and old age and part probably is caused by the activities of man.

For at least 25 years, an unknown fraction of adult bass mortality has occurred during large die-offs in the Suisun-San Pablo Bay area. In recent years, the timing and location of these kills have been monitored by DFG employees walking along selected beaches. Monitoring is incomplete as the area surveyed is only a small portion of the shoreline and many fish must decompose without reaching shore. From 1,565 to 1,763 bass carcasses were counted each year from 1971 to

1973 (Kohlhorst 1973, 1975).

Attempts to determine the cause of the Suisun-San Pablo Bay kills have been unsuccessful. Factors examined but not definitely eliminated as causes include heavy metal and hydrogen sulfide poisoning, bacteriological pathogens, red tides, and various climatological factors. The die-offs occur only in late spring and summer when bass migrate from fresh to salt water which suggests osmoregulatory stress is a factor. However, similar die-offs do not occur in other estuaries so some other condition in the Suisun-San Pablo Bay environment must also contribute.

Adult bass spend roughly 6 to 9 months of the year in San Francisco and San Pablo bays so they are affected by factors degrading bay habitat. Over the years such factors have included toxic waste discharges, dredging, and land fill projects along the shoreline. More recently, however, planning and regulatory agencies have become fairly effective in managing these problems. This should reduce future adverse impacts.

Potential effects of upstream water development are of concern. Flow reductions could affect the carrying capacity of the bays in several ways. (1) Fresh water flows help dilute potentially toxic wastes that are not controlled by regulation or treatment. (2) The bays' capacity to produce food for bass may be influenced by flows transporting nutrients to these areas. Relations have been established between biological productivity and river flows in Mediterranean and eastern Canadian fisheries (George 1972; Sutcliffe 1972, 1973). (3) Landward bottom currents such as those defined by drifter studies (Conomos 1975) may be reduced. Effects of these currents on the distribution of fishes, crabs, and shrimps that are forage for bass in the bays never have been studied, but the strength of such currents affects the distribution and abundance of similar species in other estuaries (Kutkuhn 1966; Nelson et al. 1977). Changes in the distribution of forage obviously could affect the suitability of the bays as habitat for bass.

POTENTIAL MANAGEMENT ACTIONS

Management actions that would alleviate water project effects include maintaining sufficient freshwater flow to the ocean and moving the intakes for federal and state water exports to a location upstream from the striped bass nursery area. The latter could be accomplished by building the proposed "Peripheral Canal" which would transport water from the upstream margin of the Delta to the existing export pumps. Although this concept is simple, conflicting interests have prevented its implementation for more than 10 years. Chadwick (1977) discusses some of the actions being taken to help deal with these conflicting interests.

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