BEFORE THE STATE WATER RESOURCES CONTROL BOARD

WATER RIGHT PHASE OF THE BAY-DELTA ESTUARY PROCEEDINGS

Consideration of Interim Water Rights Actions pursuant to Water Code Sections 100 and 275 and the Public Trust Doctrine to Protect the San Francisco Bay/Sacramento-San Joaquin Delta Estuary

CAUSES OF DECLINE IN ESTUARINE FISH SPECIES

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TESTIMONY of

THE NATURAL HERITAGE INSTITUTE, representing

Friends of the River
Natural Heritage Institute
Planning and Conservation League
San Francisco Baykeeper
Save San Francisco Bay Association
Sierra Club
United Anglers of California

EXHIBIT WRINT-NHI-9

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I. INTRODUCTION: QUALIFICATIONS AND EXPERIENCE

My name is Peter B. Moyle and I am a Professor of Fisheries in the Department of Wildlife and Fisheries Biology at the University of California, Davis. I was Chair of the department for five years. I am author or coauthor of over 100 publications, mostly on the ecology and conservation of California's freshwater and estuarine fishes. My books and monographs include: *Inland Fishes of California* (1976); *Distribution and Ecology of Stream Fishes of the Sacramento- San Joaquin Drainage System, California* (1982, with five co-authors); *Fish: an Introduction to Ichthyology* (2nd edition, 1988, with J. Cech); *Techniques for Fish Biology* (1990, with C. Schreck); *The Ecology of the Sacramento-San Joaquin Delta: a Community Profile* (1989, with B. Herbold). I am also one of three co-authors of the San Francisco Estuary Project's *Status and Trends Report on Aquatic Resources in the San Francisco Estuary* (Herbold et al. 1992; Exhibit WRINT-SFEP-3), which is the most current and comprehensive study to date on the state of fish and invertebrate populations in the estuary.

In this testimony, I shall be referring frequently to the "upper estuary". By this term, I mean the Delta and the Suisun Bay and Marsh region of the Sacramento-San Joaquin estuary. I have been working in the upper estuary for 18 years and in that period of time I have seen fish abundances decline dramatically. In 1974, I began studies on delta smelt (*Hypomesus transpacificus*) and longfin smelt (*Spirinchus thaleichthys*). In January 1979, I established a monthly sampling program of the fishes of Suisun Marsh, using stations established in part by the California Department of Fish & Game (CDFG). I began this study because I was impressed by the abundance of fishes in the marsh channels, especially native fishes (such as delta smelt) and striped bass. The first publications from this effort were life history studies of two poorly known native species, Sacramento splittail (*Pogonichthys macrolepidotus*) and tule perch (*Hysterocarpus traski*) (Baltz and Moyle 1982; Daniels and Moyle 1983). In 1986, I published an analysis of the first five years of data, in which a decline of total fish abundance was noted (Moyle et al. 1986). I attributed the decline then largely to natural variation in estuarine conditions. However, subsequent studies have convinced me that natural factors are secondary to freshwater exports from the Delta as a cause of the decline in fish populations.

In the next few years, the decline in fish abundance continued and my colleagues and I became concerned not only about the decline but about the complete disappearance of delta smelt from our monthly samples. We therefore broadened the scope of our investigations beyond Suisun Marsh. Studies on the population trends and life history of delta smelt (Moyle et al. 1992) made us realize that it was in trouble throughout the estuary. This in turn led to the filing of state and federal petitions for endangered status. An ecological profile of the Delta, prepared for the US Fish and Wildlife Service, showed us that the decline was characteristic of much of the biota, not just the delta smelt (Herbold and Moyle 1989). An even more detailed study, commissioned by the San Francisco Estuary Project, confirmed our view that the ecosystem of the upper estuary is deteriorating rapidly (Herbold et al. 1992).

II. METHODOLOGY AND OUTLINE OF TESTIMONY

This testimony is based upon information generated for and reported in the *Status and Trends Report on Aquatic Resources in the San Francisco Estuary* (1992). This report is based on original analyses of data on aquatic organisms collected by many different agencies in many different sampling programs. This data were generously made available to us for the purposes of the report. Because of the extent and complexity of our analyses, I can only give you samples of it in this testimony. The samples will serve to illustrate the general downward trend in the biota of the upper estuary. Because there are many potential causes of the decline, I have developed a matrix to show their relative importance to 14 species, to help sort out species-specific causes from more general causes (Exhibit WRINT-NHI-10). The ratings used in the matrix are my best judgement of the relative importance of the potential causes, but the judgements are based largely on information presented in the *Status and Trends Report.*

I summarize the results of the *Status and Trends Report* to demonstrate the degraded condition of the estuarine ecosystem. I then review our findings on the biology and status of delta smelt and discuss other fishes in the estuary that are potential candidates for listing as endangered species. Next, I review the diverse explanations which have been suggested as possible causes of the decline of the biota and conclude that freshwater exports are the primary cause of the degradation. Finally, I introduce some possible solutions to this urgent problem.

III. POPULATION TRENDS IN DELTA ORGANISMS

The *Status and Trends Report* (exhibit WRINT-SFEP-3) presents data on population trends from a wide variety of species that use the estuary. The results of the independent surveys conducted by various agencies reinforce one another in demonstrating long-term declines in resident organisms, most of which have shown accelerated declines or lack of recovery in the past decade. The following examples illustrate the declines in major groups of organisms:

A. <u>Rotifers</u>

Rotifers are microscopic zooplankton species that feed on algae. They are one of the first links in estuarine food chains and are often important as food for larval fishes. Their numbers declined dramatically in the 1970's and have continued to decline, apparently at a slower rate, since then (Figure 1). The apparent slower rate of decline may reflect the difficulties of adequately sampling rotifers when they are at low population levels. The densities of rotifers today in the upper estuary are usually less than 10% of what they were in the early 1970's.

B. Cladocerans

Cladocerans (waterfleas) are crustacean grazers on phytoplankton that are typically most abundant in spring, in the freshwater portions of the Delta. When abundant, cladocerans are a major food of plankton-feeding fishes, such as threadfin shad and small striped bass. Cladocerans can respond quickly to locally abundant resources and "bloom" for short periods of time which sometimes confuses sampling efforts looking at long-term trends. Nevertheless, in general cladocerans are less abundant today than they were in the 1970's (Figure 2). Blooms are less frequent and average numbers in the Delta are typically three to four times less than they were in the 1970's.

C. Copepods

Copepods are small crustaceans that are extremely important in estuarine food webs, as they concentrate the energy found in the detritus and planktonic algae. They are consequently a major food of plankton-feeding shrimp and fishes.

In the Delta, there has been general decline in the abundance of native copepods, especially the dominant estuarine species, *Eurytemora affinis*. When averaged on an annual basis, it appears that the native copepods have been largely replaced by two recently introduced species, *Sinocalanus doerrii* and *Pseudodiaptomus forbesi* (Figure 3). However, the exotic copepods do not have the same habitat requirements as the native copepods and may consequently not be as available to fish, especially during the critical spring season. *Sinocalanus* is often most abundant in faster flowing water than *Eurytemora* normally occupies in significant numbers, while *Pseudodiaptomus* requires somewhat warmer temperatures than *Eurytemora* and thus becomes abundant later in the season.

D. Shrimp

Three shrimp species show a strong dependency on freshwater outflows through the Delta: *Neomysis mercedis, Palaemon macrodactylus*, and *Crangon franciscorum*. These species, but especially *Neomysis*, are important intermediate links in Delta food chains, making estuarine productivity available to fish such as juvenile striped bass, longfin smelt, and white sturgeon. All three species have show declines in abundance since 1980 (Kimmerer 1992; Herbold et al. 1992). The declines in the latter two species, to roughly one-third their numbers of a decade ago, are particularly striking because similar declines have not been exhibited by closely related species that are more marine (Figure 4).

E. Fishes

Most attention on the decline of fishes has been focussed on striped bass, American shad, and chinook salmon because their declines have taken place over a long period of time, are well documented, and have been closely tied to freshwater outflows (e.g., Stevens and Miller 1983; Stevens et al. 1985). However, almost all fish species in the upper estuary have declined in abundance, as demonstrated by the catches of the most abundant species in my own Suisun Marsh sampling program and in CDFG's fall midwater trawl survey (Figures 5 and 6). In Suisun Marsh in 1980, for example, we captured, on the average, about 50 fish per 5 or 10 minute tow of our trawl; at the present time, our catches average around 5 fish per trawl, a decline of about 90% in total fish abundance. Declines have been particularly severe in spring-spawning species, such as delta smelt and longfin smelt, that have pelagic (open-water) larvae.

IV. SPECIES IN JEOPARDY OF EXTINCTION

There is only one formally listed endangered species that uses the estuary: winter run chinook salmon. This unique run of fish will be treated in other testimony, so will not be covered here. Other fishes that are being considered for formal listing or that may qualify for it soon are: delta smelt, longfin smelt, spring-run chinook salmon, splittail, and green sturgeon.

A. Delta smelt

The delta smelt is currently being considered for listing as a threatened species by the USFWS, as the result of a petition submitted by the American Fisheries Society. A concise review of the biology and status of the smelt my colleagues and I recently published (Moyle et al. 1991, Exhibit WRINT-NHI-11) is only highlighted here.

1. The delta smelt is especially vulnerable to extinction because it has essentially a one year life cycle and a relatively low fecundity (reproductive potential).

2. The delta smelt is found <u>only</u> in the upper estuary.

3. It feeds principally on copepods and therefore concentrates where copepods are most abundant, in the vicinity of the entrapment zone.

4. The delta smelt, unlike striped bass, longfin smelt, and other species with planktonic larvae, does not show a strong correlation in abundance with Delta outflows. The substantial annual variation in abundance of the delta smelt results from its peculiar life history and probably masks any long-term trends linked to delta outflows.

5. Delta smelt populations crashed in the 1980's and have remained low, probably below the limits of past sampling programs to detect population fluctuations.

6. The biggest single change in the estuary during this period has been an increase in diversions by the SWP and CVP during the spring months, when delta smelt are spawning and their larvae are present in the water column.

7. During the past 5-6 years, delta smelt populations have been concentrated in the channels of the Sacramento River between Rio Vista and Collinsville, a severe restriction of their normally limited range. This is a region of reduced food availability and of high potential predation because of recent, large-scale introductions there of striped bass. Their concentration in this area also exposes them to increased likelihood of entrainment in the pumps of the CVP and SWP, as well as in local agricultural diversions in the Delta.

8. The delta smelt index calculated from CDFG's fall trawl survey has shown an increase in recent years. This rise is almost certainly an artifact of the sampling program and recent smelt distribution patterns rather than a reflection of increasing delta smelt numbers. The smelt have been highly concentrated in the deep channels of the Sacramento River and are mostly caught there by the trawls. This biases the delta smelt index (the measure of smelt abundance used) upwards because the index multiplies the catch times the volume of water at the sampling site. The upward bias is created by the fact the volume of water sampled by the trawls is smallest in the Sacramento River channels in comparison to the amount of water present. In contrast, the total number of trawl samples containing smelt in the fall survey has remained low, as have the numbers of smelt caught in six other surveys in the system.

B. Longfin smelt

Longfin smelt abundance has a strong correlation with delta outflows (Stevens and Miller 1983). They have a life history pattern similar to that of delta smelt, except they have a two year life cycle (rather than a one year life cycle) and prefer to live in the more brackish parts of the estuary. Longfin smelt populations have been in sharp decline since 1983 and are now the lowest ever recorded. Although their numbers are low, they remain widely distributed in the estuary. The factor most strongly associated with the decline has been the increase in water diverted by the SWP and CVP during the winter and spring months when the smelt are spawning (B. Herbold and P. Moyle, unpublished analyses). This can be shown using the regression equation relating outflow to longfin smelt numbers (Figure 9) to calculate what smelt numbers would have been in the absence of exports (Figure 10). This analysis shows that during the recent drought, current levels of water exports have pushed the longfin smelt to the brink of extinction. Continuation of this pattern will almost surely extirpate this species.

The longfin smelt is a strong candidate for listing as an endangered species in California because

(1) it is in such low abundance in the estuary,

(2) the only other population in California, in Humboldt Bay, has either been extirpated or is present in very low numbers, and

(3) the Sacramento-San Joaquin estuary population may represent a species or subspecies distinct from the other populations.

C. Spring-run chinook salmon

This distinctive run of salmon was once the most abundant salmon in California. They were nearly eliminated from the state by the construction of Shasta, Friant, and other dams which denied them access to upstream holding and spawning areas. Less than 1,000 wild spring-run chinook are remain--primarily in Deer and Mill Creeks, Tehama County. Conditions in the estuary--a relatively small cause of the total decline of this run compared to upstream effects--may be major factors contributing to their continuing decline. One of the most vulnerable stages of their life history is when the smolts are passing through the estuary in December through May. Adults move through the estuary mainly in March through July, although the wild fish are probably moving through mainly in April. Because of their continuing decline (present wild populations are less than 0.5% of the historic runs) spring-run chinook should be listed as an endangered species in California. A key factor in their recovery will be to have adequate delta outflows during the smolt outmigration period, to reduce their vulnerability to entrainment and to Delta predators.

D. Sacramento Splittail

The splittail is a large member of the minnow family that is now confined to the Sacramento-San Joaquin estuary. It is endemic to the Central Valley. Like longfin smelt, its abundance shows a strong correlation with delta outflows (Daniels and Moyle 1982) and its numbers have declined substantially in recent years (Figure 7). The splittail may qualify as a threatened species although its decline has been more gradual than the smelt species because it is relatively long lived (5-7 yrs).

E. <u>Green sturgeon</u>

The estuary contains the southernmost of the three known spawning populations of this poorly known species. Its population trends are not well documented but it is probably declining like the extensively studied (and much more abundant) white sturgeon. It is not certain if conditions in the estuary are affecting this species, but Moyle et al. (1992) have recommended treating it as a threatened species because it is apparently being overexploited throughout its range.

V. CAUSES OF THE DECLINE OF DELTA BIOTA

The *Status and Trends Report* (Exhibit WRINT-SFEP-3) shows, using the best available data, that most organisms that depend on the upper estuary for their existence, for which there is adequate data, have declined in abundance. Some recent Asiatic invaders provide the most notable exceptions. Many of the declining trends began at least in the early 1970's. During the last decade, the declining trends for some species have increased. Other organisms that had been regarded as having stable populations have recently shown rapid declines to low numbers. When searching for explanations of the declines the following factors must be considered:

1. While there are many factors having a negative effect on the biota of the upper estuary, the widespread, simultaneous declines in the abundance of a wide spectrum of organisms strongly suggests that one or two factors predominate as causes of the declines.

2. The cause(s) have to be persistent and long-term, with increased effects in recent years.

3. Many of the organisms showing declines have (or have had) a positive correlation in abundance with delta outflows.

4. Most of the declining organisms have a pelagic or free-swimming stage in their life history.

Many explanations have been put forth to explain the declines of species or groups of organisms in the upper estuary. For convenience, they can be lumped into 12 categories (Exhibit WRINT-NHI-10):

(A) Outside factors,
(B) Natural factors,
(C) Increased water clarity,
(D) Decreased nutrients from sewage,
(E) Pollution from toxic compounds,

(F) Decreased reproductive ability,
(G) Exploitation,
(H) Predation,
(I) Invasions by introduced species,
(J) Entrainment in power plants,
(K) Entrainment in diversions within the Delta, and
(L) Removal of fresh water by the State Water Project and Central Valley Project pumping plants.

A. Outside factors

A number of the organisms found in the upper estuary spend part (or most in the case of salmon) of their life history outside the region. Therefore their abundance can be strongly affected by what happens outside the upper estuary. The decline of the various runs of chinook salmon, for example, is largely the result of dams and irrigation diversions in upstream areas. Most of this decline took place prior to 1970. Likewise, the decline of organisms with close ties to the more marine lower estuary, such as starry flounder and grass shrimp, most likely are not related to factors outside of the estuary. Because most of the declining species depend on adequate environmental conditions in the upper estuary for their long-term survival, outside factors are probably important only for salmon and sturgeon. Even salmon and sturgeon survival is strongly affected by conditions in the upper estuary. For example, high outflows during the periods of outmigration of salmon smolts significantly increase smolt survival (Stevens and Miller 1983).

In the matrix rating causes of decline (Exhibit WRINT-NHI-10), outside factors are rated as having an effect on the populations of 9 of the 16 species used as examples. Outside factors are a major problem, however, only for salmon and sturgeon.

B. Natural factors

The amount of water flowing through the estuary is the natural factor that generally shows the strongest correlation with the distribution, abundance, and reproductive success of many estuarine organisms. The volume of fresh water flowing into the estuary depends heavily on annual precipitation and is consequently highly variable. The past 20 years have been exceptionally variable in precipitation. The wettest year on record (1983) and the wettest month on record (February 1986), and two of the longest and most severe droughts on record (1976-1977, 1985-present) have all occurred in the last 20 years. There is little doubt that the combination of floods and severe drought have contributed to the decline of the biota, particularly the accelerated declines noticed in recent years. There is little reason to think, however, that natural factors are the major cause of the declines, because species such as striped bass were in decline before this period began and the severity of the declines is more than would be reasonably attributed to natural factors alone. The amount of water diverted from the rivers and estuary has, until recently, been fairly independent of natural availability because of water storage in reservoirs and other factors. As a result, diversions have tended to take an increasing percentage of the water available during dry years. This loss of water exaggerates the natural declines in organisms that might occur during a drought, pushing several species increasingly close to extinction.

In the matrix (Exhibit WRINT-NHI-10), natural factors are shown to be a contributing factor to all the species but they are related to declines in a major way only for sturgeon and starry flounder.

C. Increased water clarity

One of the major past problems in the estuary was extensive siltation caused by hydraulic mining in upstream areas. Some silt from these operations was still entering the system as late as the 1980's and its gradual elimination from the water may have contributed to the increased water clarity observed in recent years in the lower Sacramento River. Greater clarity may have lead to aperiodic blooms of the diatom *Melosira granulata*, regarded as a nuisance in part because it is difficult for zooplankton to graze upon. This relatively minor change in the estuary is largely confined to areas affected directly by the Sacramento River. Therefore it is unlikely have contributed much to the decline of the biota of the entire upper estuary.

In the matrix (Exhibit WRINT-NHI-10), increased water clarity is shown as being unlikely to have had much effect on any of the example species.

D. Decreased nutrients from sewage

Until the late 1960's, the estuary was increasingly polluted with sewage, as measured by the rising biological oxygen demand (BOD) and suspended solids. Since then, both these measures have fallen dramatically and continue fall (Davis et al. 1991). Some have speculated that this decline in sewage may have resulted in a decline in the biota because fewer nutrients would be available to support estuarine food webs. Tsai et al. (1991) provide some correlational evidence that the decline of striped bass in Chesapeake Bay may be associated with decreased sewage discharges. Their results remain controversial and are not widely accepted by other scientists on this East Coast estuary (J. Cowen, pers. comm.).

This hypothesis is particularly unlikely to be valid in the upper estuary for two main reasons. First, much of the sewage discharge occurred in the lower estuary (San Francisco Bay) and there has not been a major decrease in <u>total</u> fish and shrimp populations there (although the abundance of individual species has shifted significantly). Second, the sewage contained toxic compounds and probably created toxic effects itself through oxygen depletion. Such effects would probably have effectively canceled any advantage to food webs gained by the addition of nutrients.

In the matrix (Exhibit WRINT-NHI-10), decreased sewage is shown to have had, perhaps, an effect on some zooplankton species but is otherwise insignificant.

E. Toxic pollutants

Because fish kills due to pollution are dramatic events, toxic compounds are frequently invoked as cause of biotic declines. However, Davis et al. (1991), in their review of the role of toxic compounds in the estuary caution that: "Unequivocal evidence does not exist for population level effects of anthropogenic chemicals upon any fish stock in this or any other estuary in the world (p. 134)." Nevertheless, C. Foe of the California Regional Water Quality Control Board, in an unpublished study, provides evidence suggesting that the unexpectedly low numbers of larval striped bass present since the mid-1970's was the result of exposure to herbicides applied to rice. Histological examination of larvae from the Sacramento River by W. Bennett and D. Hinton at UC Davis indicates that toxic compounds were indeed affecting the larvae. Despite this evidence, it can be argued that this toxic effect has been largely confined to striped bass:

1. Striped bass spawn later in the season than other fish in the estuary and move up the Sacramento River to spawn. There is some evidence they are attracted to the effluent of the Colusa Drain, a major source of the herbicides. These factors make the bass unusually vulnerable to the pesticides.

2. The striped bass population was already in decline before the new rice cultural practices that resulted in increased herbicide use were in place.

3. The herbicides were largely confined to the Sacramento River, not the entire upper estuary. While they have been shown to be toxic to crustaceans such as *Neomysis mercedis*, no estuary-wide declines of these organisms have been associated with the timing of herbicide presence in the river.

4. The pesticides are largely toxic to larval, not adult fish. Most other fishes with pelagic larvae spawn earlier than striped bass and/or lower in the estuary making them unlikely to encounter toxic concentrations of the pesticides.

In the matrix (Exhibit WRINT-NHI-10), toxic compounds are shown to have at best a minor effect on the populations of most the sample organisms, but they are considered to be a contributing cause to the decline of winter run chinook salmon, striped bass, and starry flounder.

F. Decreased reproductive ability

Don Stevens of CDFG has argued that one of the major causes of the striped bass decline has been a negative spiral of reproductive success. Fewer adult bass produce fewer eggs which results in fewer recruits into the next generation. This downward population spiral may be occurring but it does not explain why larval survival is low. In most fish populations, when adult populations are low, larval survival increases as long as conditions are favorable. A primary problem with this hypothesis is that it fails to explain the declines most of other species in the estuary.

In the matrix (Exhibit WRINT-NHI-10), decreased reproduction is shown to be a weak contributing factors only to salmon and striped bass.

G. Exploitation

Fisheries have undoubtedly contributed to the decline of some species. Decreased reproductive success of striped bass could result from removal of the largest fish from the populations. The biggest fish are mostly females and also produce the most eggs. Recognizing this problem in the decline of white sturgeon in the estuary, new angling regulations have been adopted to reduce the take of large females (Kohlhorst et al. 1990). The continuing decline of salmon can also be blamed in part on ocean fisheries, which capture the largest and oldest fish. Consequently, most runs to are populated mainly by three year old fish. However, exploitation is clearly a secondary factor that affects fish populations mainly after they have already suffered a severe decline. The importance of exploitation as a cause of systematic decline is diminished by the fact that most declining species are not exploited in any way. As a result, it is shown as having no affect on most species in the matrix (Exhibit WRINT-NHI-10).

H. Predation

The dominant piscivore in the estuary is striped bass; other species, such as channel catfish, Sacramento squawfish, and largemouth bass are also present in numbers. Piscivorous birds and mammal populations are probably too small to have much effect on fish populations. Predation is a natural phenomenon and usually is a problem only where humans create a situation unusually favorable to the predator. Usually this is a situation that concentrates prey, such as occurs in Clifton Court forebay in front of the SWP pumps or occurs in areas where fish "salvaged" from the pumping plants are returned to the estuary or salmon from hatcheries are planted on a regular basis. In these situations, predators may defeat attempts to mitigate for fish losses due to water projects by becoming habituated to feeding on planted fish. Such predation would at most help to keep populations depressed and would not necessarily be a cause of the declines, especially because striped bass are simultaneously both major predator and major prey.

In the matrix (Exhibit WRINT-NHI-10), predation is listed as a significant contributing cause to the decline only of salmon.

I. Invasions by introduced species

The Sacramento-San Joaquin estuary has suffered from invasions by exotic species ever since the first European ship arrived in San Francisco Bay with a load of fouling organisms on its bottom. Today most of the benthic invertebrates of the Bay are introduced species, as is the dominant predator in the upper estuary, striped bass. The typical pattern for a successful invader is to become extremely abundant for a few years after the invasion and then to gradually decline in abundance as it is integrated into the local ecosystem, with its populations regulated by local predators, competitors, and environmental conditions. In recent years, considerable concern has been expressed over the effects of two species of exotic zooplankton (copepods, *Sinocalanus doerii* and *Psuedodiaptomous forbesi*) and an exotic Asian clam, *Potamocorbula amurensis*. The copepod species have partially replaced a native copepod, *Eurytemora affinis*, which has been a key member of the food webs leading to fish, while the clam has become so abundant in Suisun Bay that its filter-feeding has removed much of the phytoplankton from the water column. All of these species became abundant after the biotic declines were well underway.

Of the two copepod species, *Sinocalanus* has been of particular concern because it appears to be much more difficult for larval fish to capture than the native species (Meng and Orsi 1991). However, it also inhabits faster moving water than other copepod species, so may be in part occupying space not previously used by copepods in the upper estuary. It also appears to be vulnerable to fish predation at night (W. Bennett, personal communication). *Pseudodiaptomus* is as vulnerable to larval fish predation as *Eurytemora* and is fed upon by delta smelt and other plankton-feeding fishes. Thus it does not appear to be a problem.

The Asian clam, *Potamocorbula*, became abundant in Suisun Bay after 1986, after the populations of much of the biota of the upper estuary had declined. The increased salinities of Suisun Bay caused in part by the prolonged drought would normally have allowed the marine softshell clam, *Mya arenaria*, to invade the bay, as happened in 1976-1977, with effects on zooplankton similar to those produced by the invasion of the Asian clam. The Asian clam appears to have replaced the "normal" invasion of the softshell clam. Laboratory studies indicate that adult Asian clams are tolerant of low salinities, so it may persist in Suisun Bay even if more "normal" conditions return. However, its inability to invade the delta may indicate that this may not be entirely the case (i.e. it may not be able to reproduce under low salinity conditions). In any case, if its populations follow the trajectories of other introduced species in the estuary, it will naturally become less abundant and more integrated into the ecosystem as the estuary recovers from its present stressed situation (assuming it is allowed to recover).

Overall, introduced species are shown in the matrix (Exhibit WRINT-NHI-10) as being a minor contributing cause to the declines of many (but not all) of the sample organisms.

J. Entrainment by power plants

PG&E has two large electricity generating plants on the estuary, at Pittsburg and Antioch, with 14 power units. Each unit is cooled by water, which is pumped through once, raising the temperatures of the water 15-20 F (8-11 C) before it is discharged. Each of the two plant's capacity for cooling water is 1500 cubic feet/sec (700,000 gallons per minute) although they are rarely running at full capacity. PG&E acknowledges that large numbers of fish larvae are entrained in (and killed by) the cooling water. Consequently, PG&E plants striped bass in the estuary as mitigation for these losses. How the operation of these plants affects the fish populations of the upper estuary overall is not well known (at least by me) but it is likely that they have been a fairly constant, rather than increasing, source of mortality over the past 20 years. However, the effects on the biota of power plant entrainment during years of low outflow and low fish populations needs to be evaluated.

In the matrix (Exhibit WRINT-NHI-10), power plants are shown to be a minor contributing cause to the declines of many (but not all) of the species.

K. Entrainment by in-delta diversions

One of the least studied factors affecting the biota of the estuary is the hundreds of unregulated, unscreened siphons that are used to carry water from delta channels to irrigate farmland on delta islands. These siphons are found throughout the delta and are operated according to the needs of individual agricultural operations (i.e. each siphon is operated for short periods of time according to crop demands). Jones and Stokes Associates (1990) estimate that the annual removal of water from these diversions is 2.3 million acre feet (2,352 thousand acre feet). Most of the siphons are small enough so that their effects are highly localized and are operated in such a fashion that their effects are not continuous. Nevertheless, it is highly likely that they are entraining large numbers of organisms, including larval fishes. This source of mortality, while probably significant, has also been a factor in the upper estuary for a long time and it seems unlikely as a consequence to have been a direct source of the recent decline of the biota of the upper estuary. However, it is quite possible that the siphons have <u>indirectly</u> become an increased source of mortality because of the increased flow of water across the delta caused by pumping of SWP and CVP. This change in flow patterns results in increased exposure of the estuary's biota to the siphons.

In the matrix (Exhibit WRINT-NHI-10), these diversions are shown to be a minor contributing factor to the decline of most of the example organisms.

L. Effects of CWP and CVP pumping plants

The effects of these two diversions are summarized well in the *Status and Trends Report* (1992):

> The greatest recent change in the hydrodynamics of the Delta is associated with diversion of water from the Delta [by the CVP and SWP]. The rate of these diversions has been increasing rapidly over the last 20 years and now takes as much as 60% of the inflowing water [Figure 8]. The State Water Project and federal Central Valley Project together comprise one of the largest water diversion projects in the world. In addition to simply altering the effective outflow downstream, diversion can alter the direction of net flow; opening of the cross-delta channel transports water of the Sacramento River through the lower reaches of the Mokolumne to supply the state and federal water projects. Low outflow, when combined with high rates of diversion, results in a net movement of Sacramento River water and water from Suisun Bay up the lower San Joaquin River channels. Diversions have intensified and broadened their impacts on flows within the Delta in the last few years. In water year 1987-1988 more water was exported than flowed into the Bay. **This export of water from the Delta has been the largest change in water use patterns over the last 20 years and has coincided with declines of fish abundance** (Pages 10-11, my emphasis)

The diversions affect fish and invertebrate populations in the following ways:

1. Direct entrainment of fish in the plants. The fish rescue facilities "salvage" thousands of fish each year but survival rates of the salvaged fish are probably low (but a systematic evaluation of survival rates has not been done). The salvage operations do not capture larval or small juvenile fish, which may pass through in the millions. Even larger fish leak through in substantial numbers, as fisheries in the California Aqueduct and associated reservoirs attest.

2. Increased predation on juvenile fishes. The action of the pumps draws small fish into Clifton Court Forebay where striped bass and other predators concentrate. By decreasing outflow and increasing flow through the Delta, the pumps increase the exposure time of outmigrating juvenile salmon to predators in the Delta.

3. Decreased residence time of water in Delta channels. This results in less time available for growth of phytoplankton populations and for the development of food webs in the channels. The overall result is a decline in Delta productivity.

4. Increased vulnerability to in-Delta diversions and poor water quality. The pumps increase flows across the Delta, which presumably increase the exposure of small fishes to Delta siphons. This also may result in increased exposure to irrigation

return water from the islands, which is laden with natural and artificial pollutants from the farmland and is likely to be higher in temperature. Fish and invertebrate populations may be reduced through a combination of increased entrainment and stress.

5. Placement of the mixing (entrapment) zone in river channels. There is strong evidence that high survival rates of juvenile and larval fish and large populations of zooplankton result when the mixing zone is located in Suisun Bay. During times of low Delta inflow, the action of the pumps moves the mixing zone up into the channels of the lower Sacramento River, between Rio Vista and Collinsville. While the exact mechanisms that account for the importance of having the mixing zone in Suisun Bay (increased food supplies, physical concentration of organisms, association with higher outflows etc.) are being debated, there seems little doubt that many fish species depend on this location for their long-term survival.

6. Increased vulnerability to invasion by exotic species. The increase in the proportion of water being diverted from the estuary, during a period of high climatic variability, seems to have made the upper estuary more vulnerable to invasion by exotic species including the chameleon goby, several species of copepods, the Asian clam, and other benthic organisms. It is likely that increasing the amount of fresh water in Suisun Bay would reduce the invasibility of the upper estuary by other species through a combination increased populations of native organisms and decreased favorability of the physical/chemical environment to brackish water invaders.

In the matrix (Exhibit WRINT-NHI-10), the SWP\CVP pumps are shown as being a major cause of decline of 10 of the 16 example species and as a major contributing cause of 5 of the 6 remaining. Only sturgeon are regarded as being affected in a minor way, although many are entrained in the pumping plants. Sturgeon have naturally a certain amount of immunity to the pumps because of their large size, long life spans, and ability to maintain populations even when successful spawning is infrequent, mainly in wet years.

VI. CONCLUSIONS

I draw two broad conclusions from this information I have presented:

1. Most of the biota in the upper estuary is in a state of decline, although some recent, largely undesirable, invaders are increasing in numbers. The decline is most evident in species with a planktonic stage to their life history and is severe enough to jeopardize the continued existence of these species in the estuary. The consequent loss of biotic diversity would impoverish the ecosystem as a whole.

2. The single biggest factor causing the declines is pumping by the SWP and CVP and the consequent flow reductions. The increase in percentage of water removed by the pumps and the increase in pumping in the spring months have been the biggest changes to the upper estuary in the past 20 years and coincide with the declines or increased declines of most estuary-dependent organisms. Many other factors may contribute to the demise of Delta organisms, but the effects of these factors are exacerbated by the effects of the pumps. The pumps help to create a near-perpetual state of drought conditions in the estuary. For most estuarine organisms periods of natural drought are a time of stress, resulting in reduced populations. When the effects of the pumps are added to the effects of a severe natural drought, the populations of many organisms become stressed to the point where their survival is in doubt. The action of the pumps also changes the hydraulic regime of the Delta, decreasing the suitability of Delta water for many organisms and increasing the exposure of these organisms to in-delta diversions, toxic wastes, and other factors.

VII. RECOMMENDATIONS

This testimony addresses measures that the Board can undertake immediately with the existing facilities in the upper estuary. There are additional near-term strategies for use of water in the Sacramento-San Joaquin drainage that the Board should actively explore that are likely to be efficacious in arresting the decline of the upper estuary, including water conservation, innovative use of Delta islands (e.g. for rearing fish), taking some farmland out of production, use of pulse flows for moving juvenile and larval fish through the Delta (with gradual ramping) and other measures.

The following are measures that could be implemented by the Board in the near future. They will reduce the number of days of reverse flows in the lower San Joaquin River, increase Delta outflows, and reduce entrainment of fish in diversions. The goal of these measures is to bring populations of Delta organisms back to levels at which they existed in the late 1960's and early 1970's.

Which?

1. Provide adequate outflows to move larvae of striped bass, Delta smelt, longfin smelt, and other species with pelagic larvae into Suisun Bay and to keep them there for 6-8 weeks, to keep them out of the influence of the SWP and CVP pumps (and provide other habitat related benefits). (These outflow requirements can be achieved either through pumping curtailments or by increasing by-pass flows.) Part of the increased flows should come from the San Joaquin River as they will be needed for striped bass from the initiation of spawning to July. Outflows will have to be sufficient (25,000 - 30,000 cfs) to keep bottom salinities at Roe Island at 2 ppt or less. Ideally, this should be a year around standard, but a February through mid-July standard may be sufficient to allow for estuarine recovery. A 0-2 ppt salinity standard for Suisun Bay is easy to measure, has a strong relationship with outflows, and correlates well with many biological variables.

Suisun Bay

2. Should the Board find it necessary to permit relaxation of these flow and salinity recommendations for aquatic organisms during critical and dry years, the formula must avoid relaxation of the fishery protection standards for more than two consecutive years. This would be necessary to protect chinook salmon (which have a three year life cycle), longfin smelt (two year life cycle), and Delta smelt (one year life cycle). The minimum flow requirement in dry and critical years should not be less than the flow needed in the Sacramento and San Joaquin Rivers to move pelagic eggs and larvae of striped bass, Delta smelt, and longfin smelt to suitable nursery areas in upper Suisun Bay. The Department of Water Resources estimates that Delta outflows required for this purpose are 12,000-14,000 cfs in March, April, May, June and the first two weeks of July. Additional flow pulses may also be necessary to move eggs and larvae downstream while minimizing the amount of water required. Relaxation of fish flows during critical and dry years will be much more acceptable once fish (and other aquatic organisms) have recovered from their present low levels. In effect, stabilizing the estuary will require more than mere maintenance of current population levels. A margin of safety needs to be built into the Board's interim standards.

3. Establish operational criteria for the CVP, SWP, and Contra Costa Canal to minimize direct and indirect entrainment losses when larval and postlarval fish are present in the San Joaquin River portion of the Delta. This most likely would require net downstream flows at Antioch of at least 1000 cfs during late February through June 15, and downstream flows greater than zero from June 15 to July 15.

4. To protect outmigrating salmon, barriers on delta sloughs need to be installed and/or closed to prevent cross-delta movement of fish, minimum outflow standards need to be set, and temperature standards need to be met.

> Barriers: Close Delta Cross Channel gates from November 1 through June 15, while salmon smolts are emigrating (starting November 1) through the spawning season of Delta smelt, longfin smelt, and striped bass (late February - June 15). The closure of the cross channel must coincide with adequate flows in the San Joaquin River so there will not be reverse flows when fish larvae are present in the Sacramento River. This standard would protect all species with pelagic larvae as well as outmigrating salmon of all runs. Georgiana Slough should also be closed with a gate during the same period. To protect juvenile San Joaquin salmon, a full barrier on upper Old River should be installed and closed in April and May, as well as September and November.
>
> Flow: Flow recommendations of the Delta salmon team which should be adopted include (1) export limitations of 6,000 cfs in wet years and 2,000 cfs in dry years, (2) minimum flows at Vernalis of 10,000 cfs in wet years and 2,000 cfs in dry years during mid April - mid May, (3) minimum flows at Jersey Point of 2,500 cfs from mid April to mid May, and (4) minimum flows at Rio Vista of 4,000 cfs during April - June.

Temperature: Set temperature standards for the lower Sacramento and San Joaquin Rivers so that outmigrating juvenile chinook salmon are not severely stressed. Ideally, water temperatures at Freeport on the Sacramento River and at Vernalis on the San Joaquin River should not exceed 65 degrees F at any time from April 1 through June 30 and from September 1 through November 30. If this temperature standard is not achievable, then outflows should be increased and/or exports decreased to reduce the exposure time of the salmon.

4. Develop and institute a "real-time" monitoring program for eggs and larvae of striped bass and other species that can be used to help manage outflows and diversions in the Delta. This will be valuable only if the agencies regulating flows and diversions have cooperative agreements that allow rapid response to short-term events, such as pulses of spawning.

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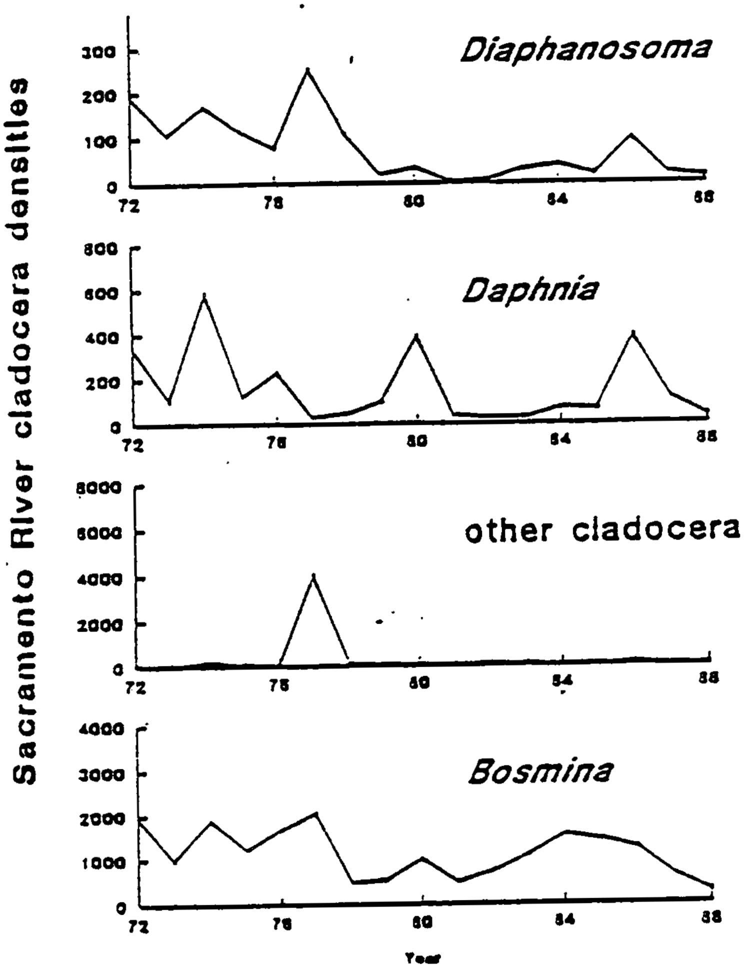

Figure 1. Mean densities (numbers per cubic meter) of abundant species of rotifers from Sacramento River 1972 through 1988, from Herbold et al. 1992. Similar graphs showing similar downward trends are available for the San Joaquin River and Suisun Bay as well.

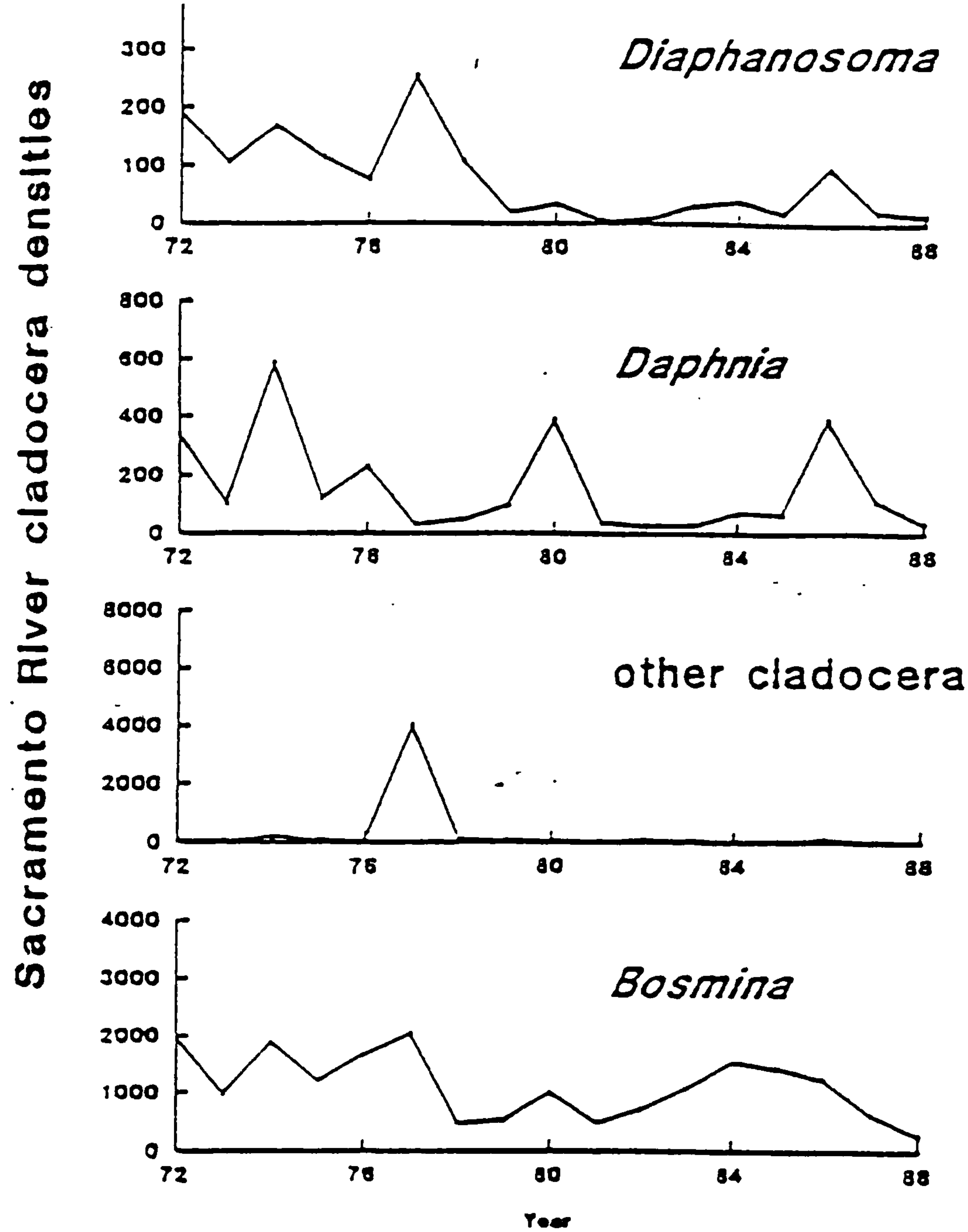

Figure 2. Mean densities (numbers per cubic meter) of the three most abundant species of cladocerans in the Sacramento River, 1972-1988. Similar graphs are available also for the San Joaquin River and Suisun Bay. From Herbold et al. 1992.

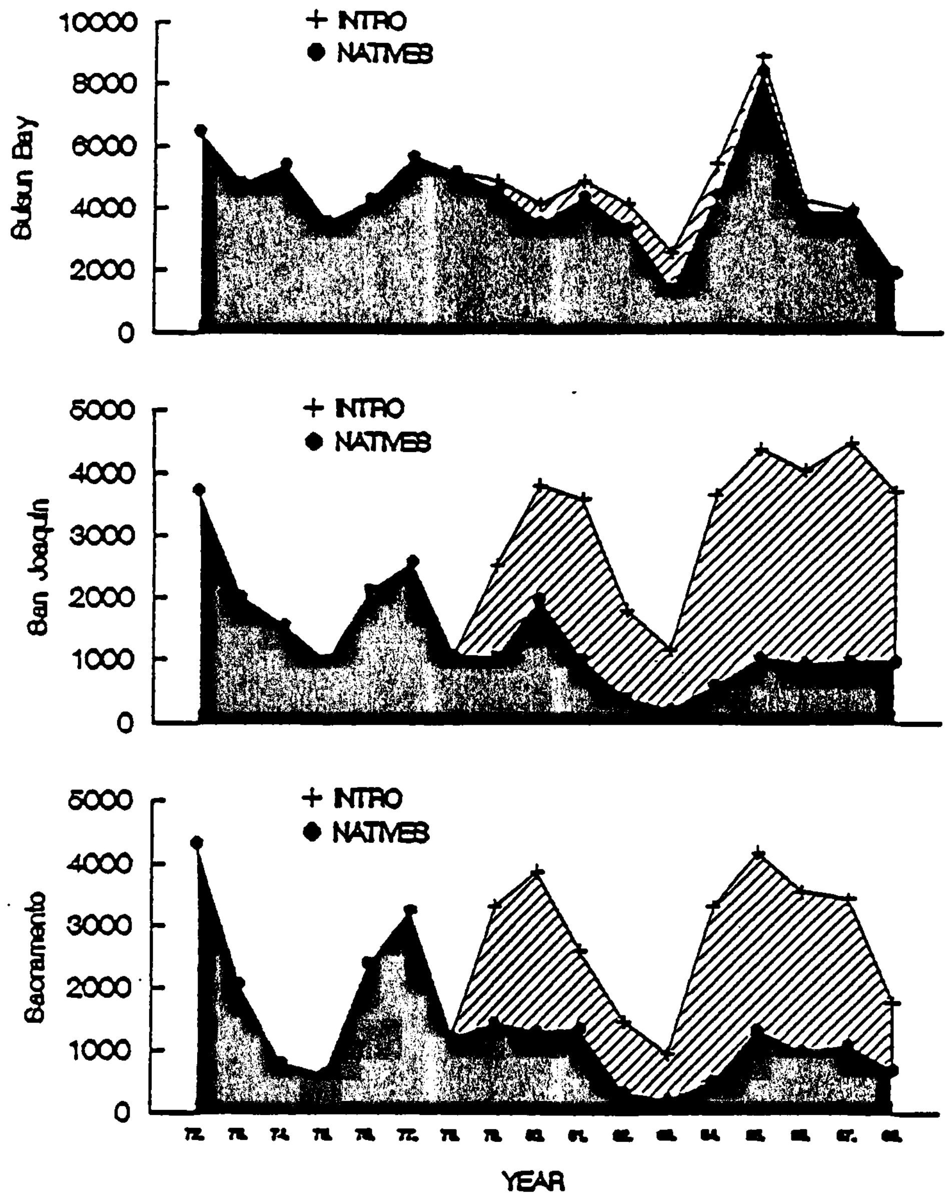

Figure 3. Comparison of densities (mean number per cubic meter) of native and introduced copepods in three areas: Sacramento River, San Joaquin River, and Suisun Bay. From Herbold et al. 1992.

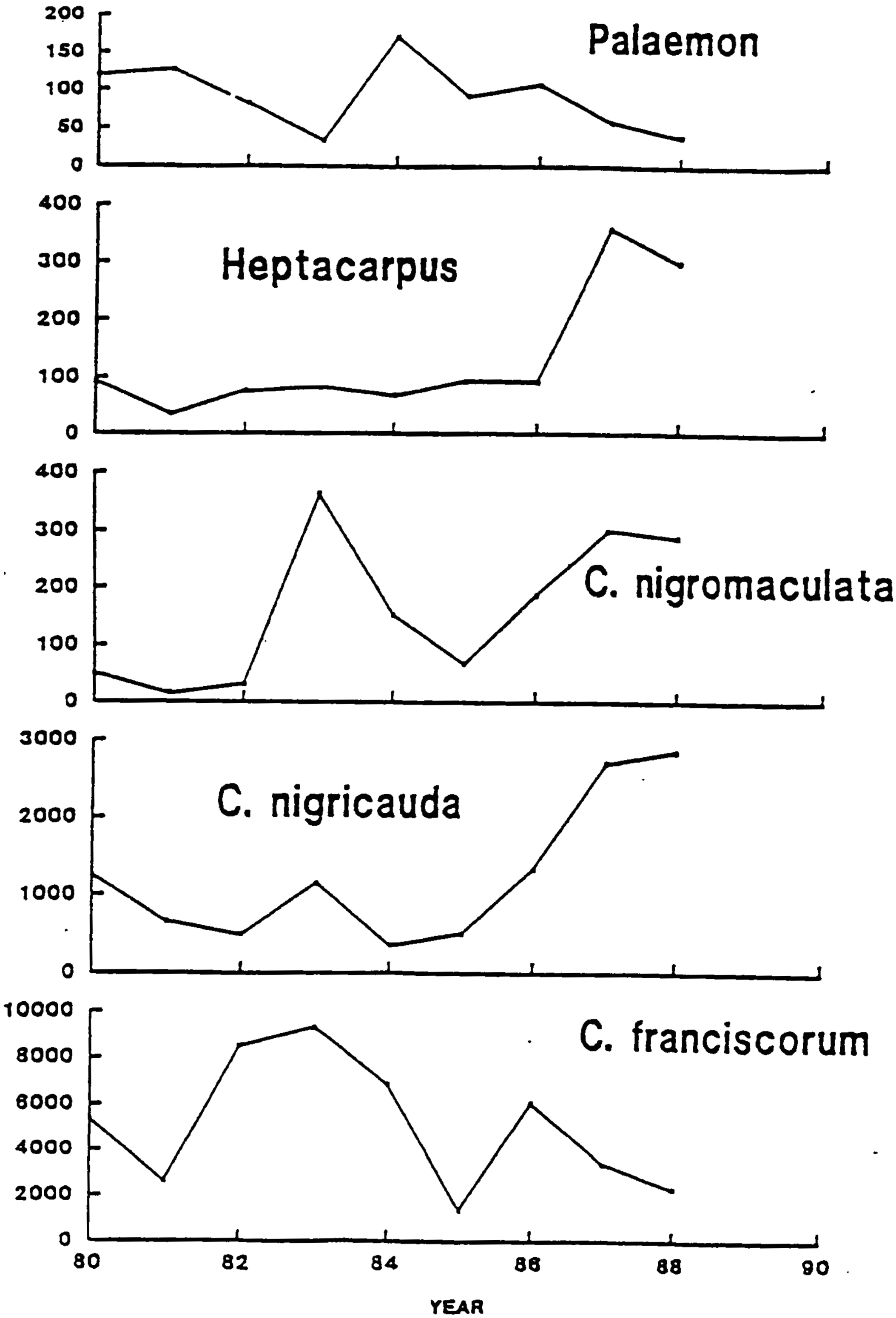

Figure 4. Abundance indices of 5 species of shrimp in otter trawls of the Bay Study 1980-1989. From Herbold et al. 1992.

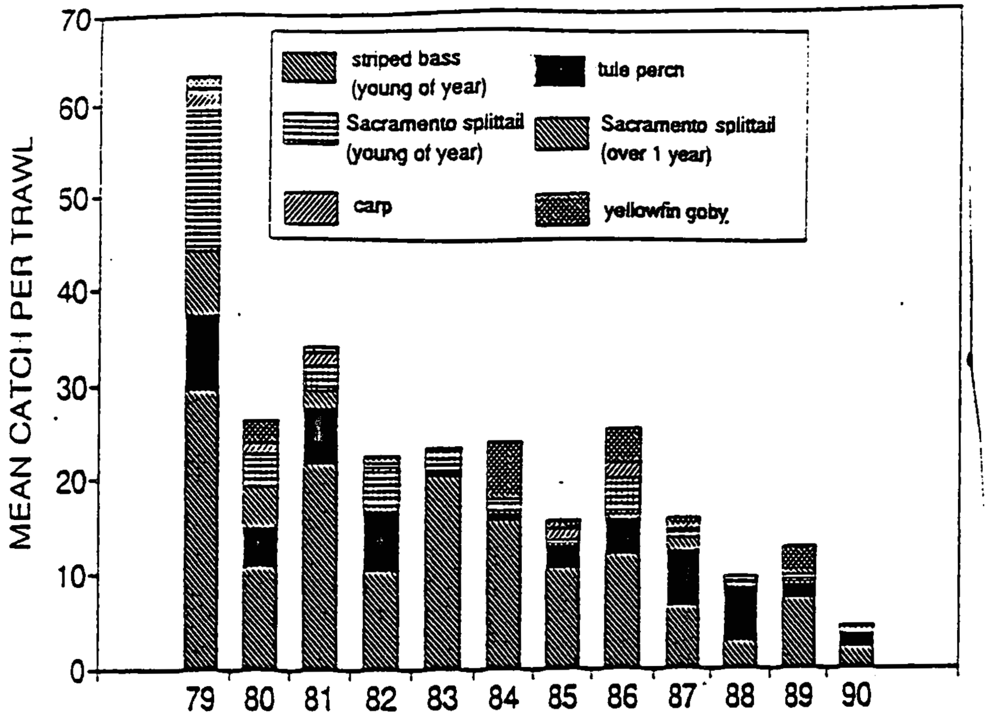

Figure 5. Abundance of six most frequently captured species collected by otter trawl sampling program by UCD in Suisun Marsh. From Herbold et al. 1992.

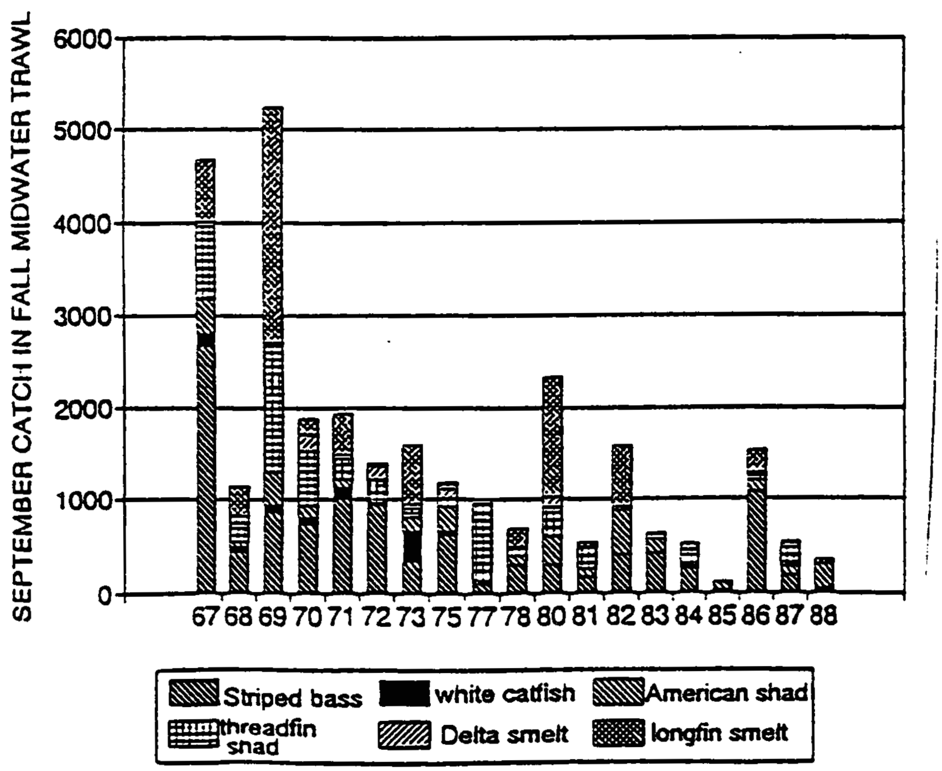

Figure 6. Catch of six most abundant species during September by the fall midwater trawl survey 1967-1988. From Herbold et al. 1992.

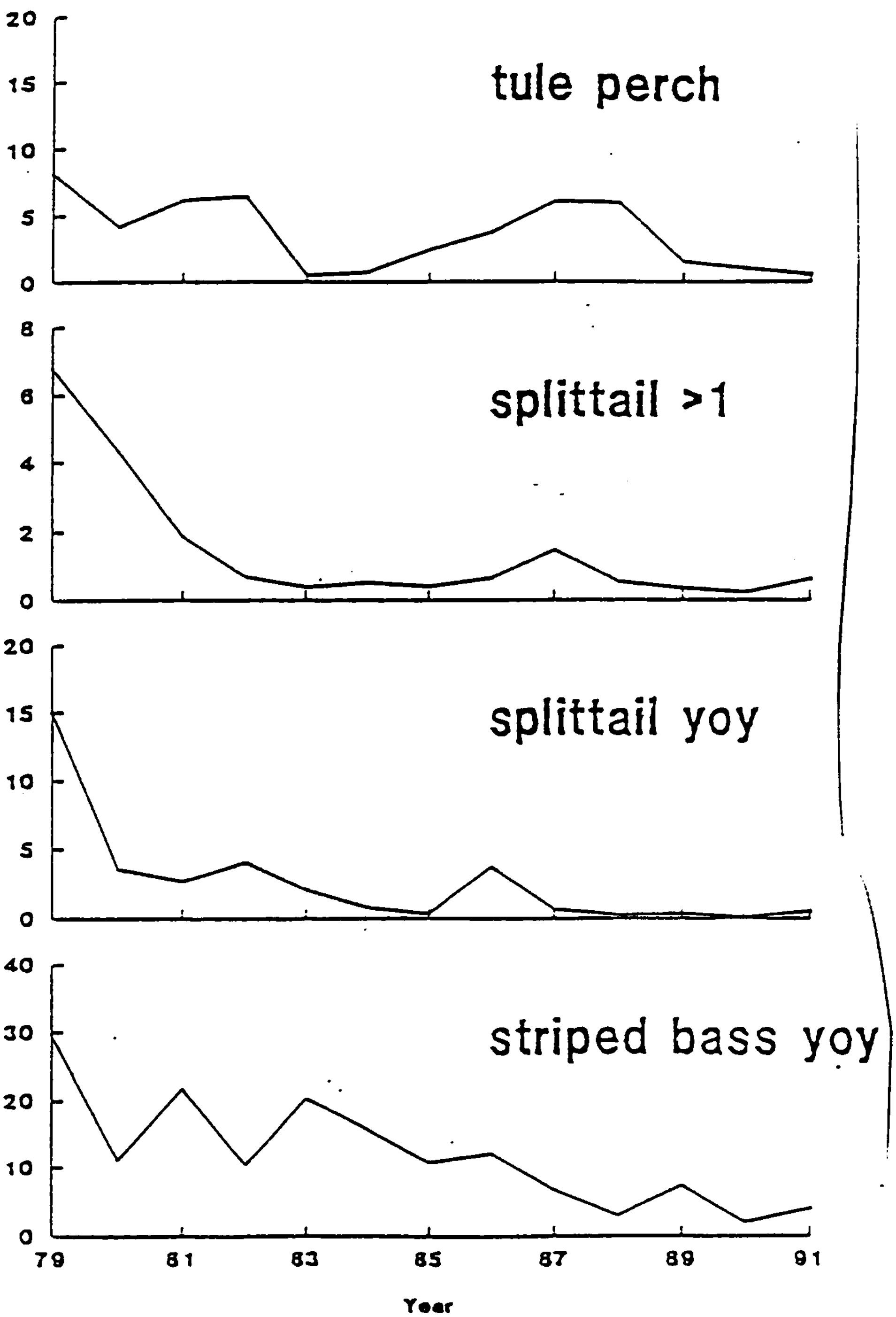

Figure 7. Mean number of fish caught per tow of a trawl, for the four most abundant species in Suisun Marsh, 1979-1981. P. Moyle, unpublished data.

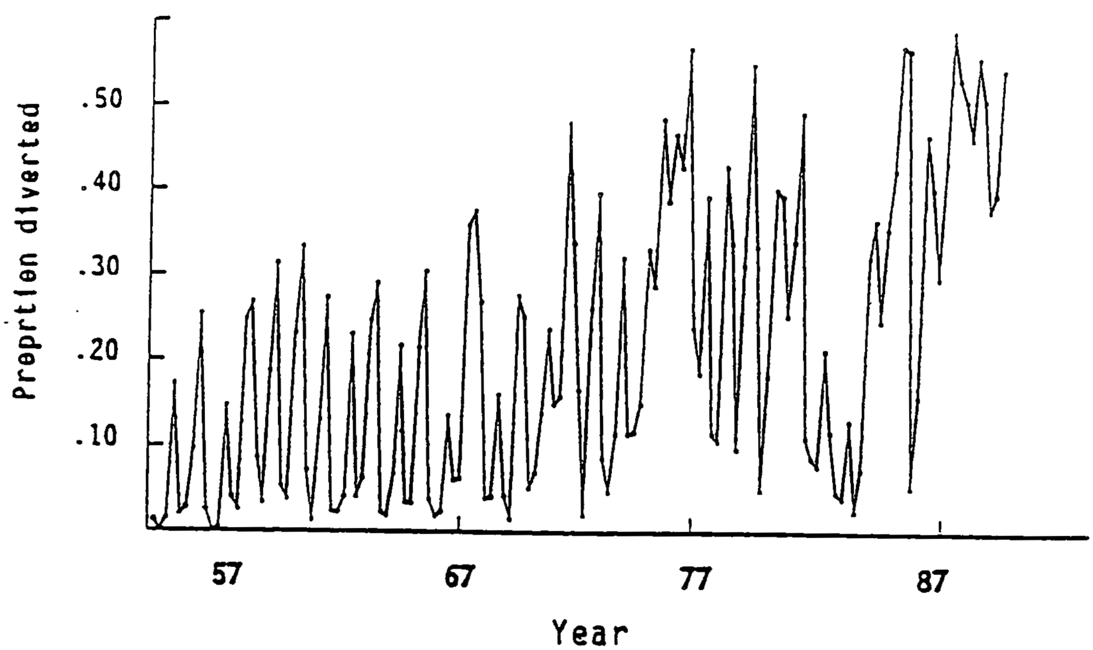

Figure 8. Quarterly proportion of delta inflow exported by State Water Project and Central Valley Project Pumps, from the DAYFLOW model. From Herbold et al. 1992.

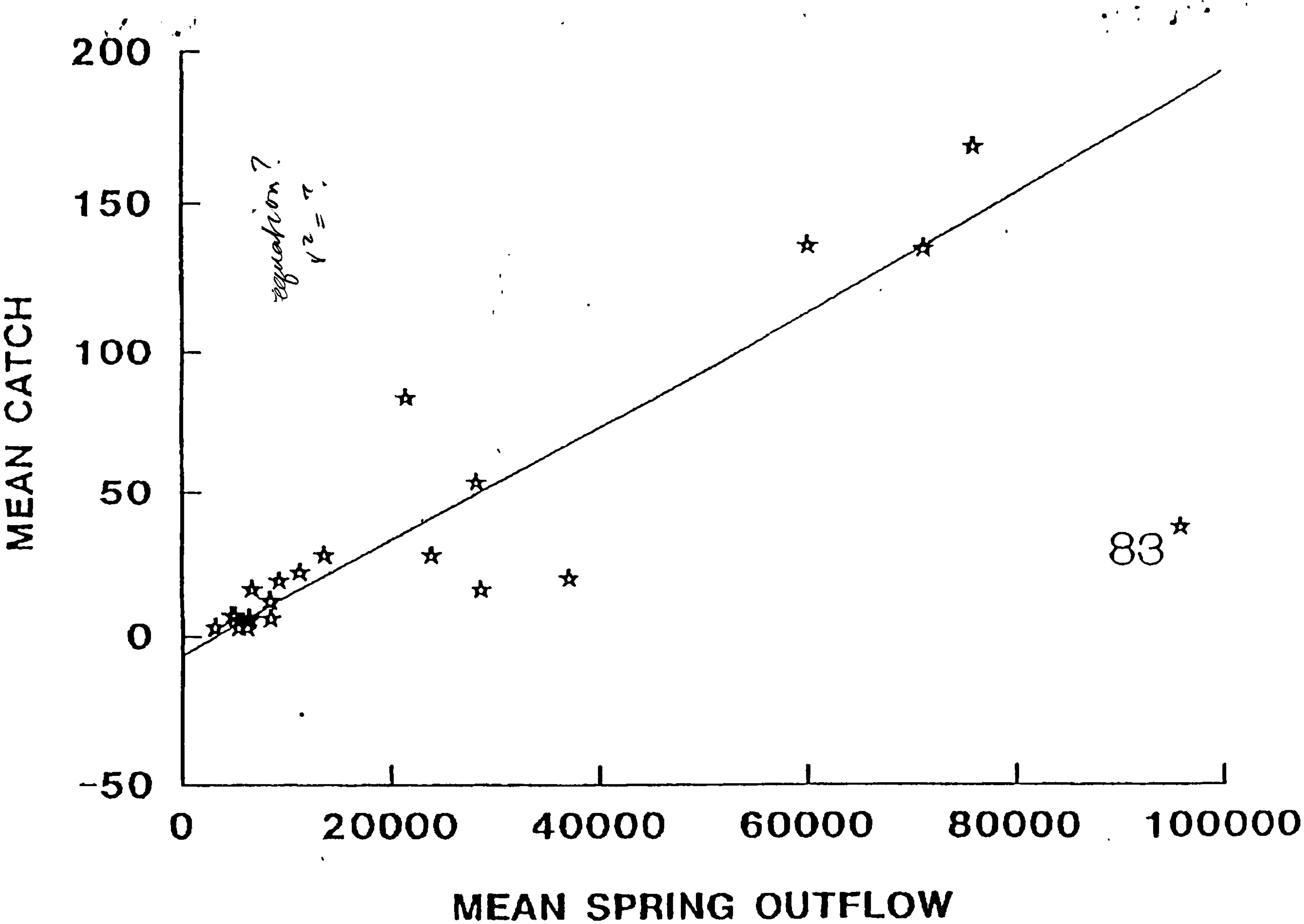

Figure 9. Relationship between mean spring Delta outflow (cfs) and mean catch of longfin smelt in the CDFG fall midwater trawl survey in trawls that contained smelt. Analysis by B. Herbold, U.S. E.P.A.

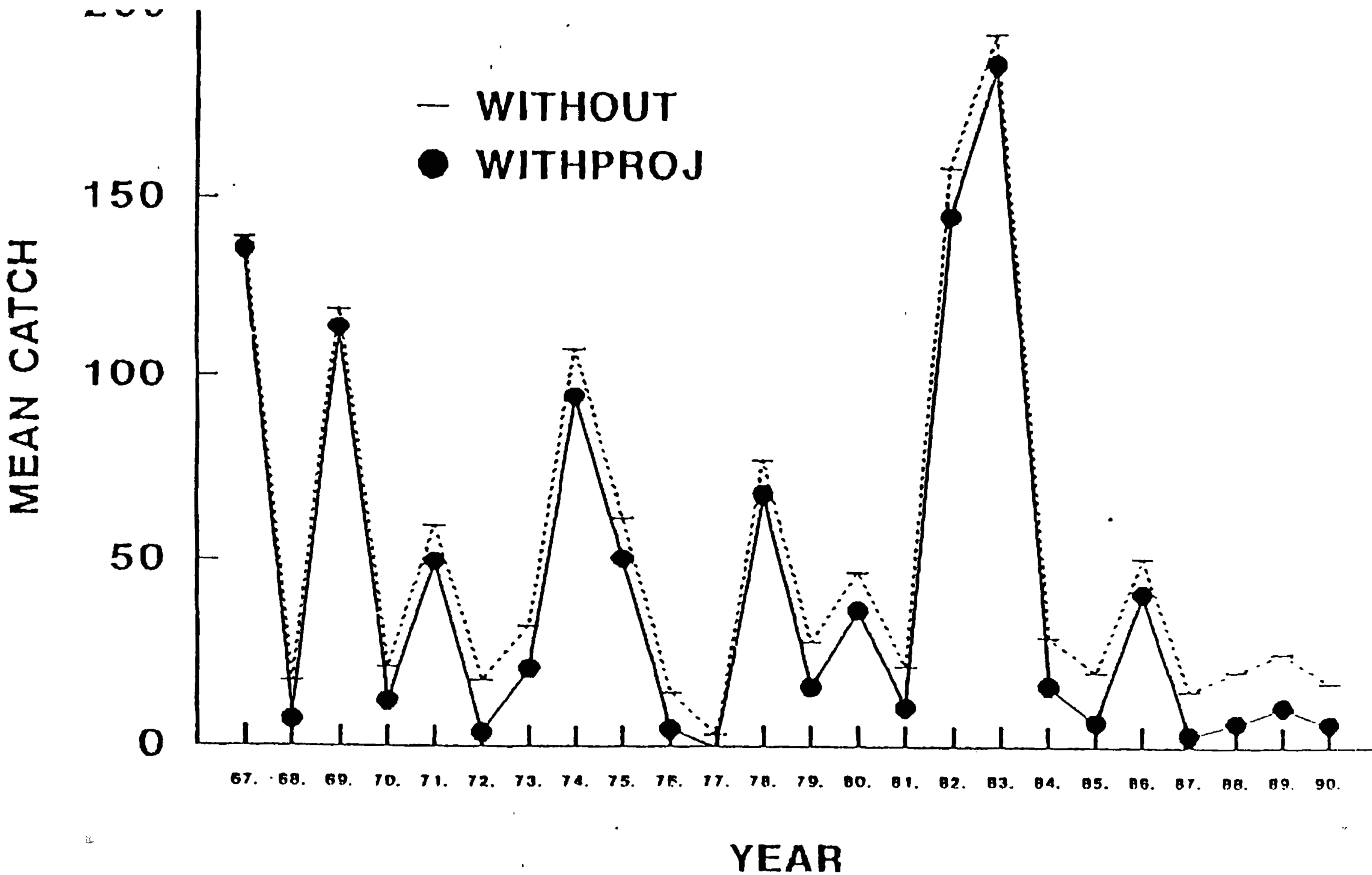

Figure 10. Mean Catch of longfin smelt by year in the fall midwater trawl surveys of CDFG. The upper (dotted) line shows the expected catch if water were not exported by the CVP and SWP pumps. Analysis by B. Herbold, U.S. E.P.A.

Exhibit WRINT-NHI-10

Table of Ratings of factors causing the declines of key species in the upper Sacramento-San Joaquin Estuary since 1970

	Delta Dependency	Out of Delta Factors	Natural Factors	Increased Water Clarity	Decreased Sewage	Toxic Compounds	Decreased Reproduction	Exploitation	Predation	Introduced Species	Power Plants	In-Delta Diversions	SWP/CVP Pumping
Keratella	LOW	-	3	4	2	4	-	-	-	4	-	3	2
Daphnia	LOW	-	2	3	3	4	-	-	-	4	-	3	1
Eurytemora	HI	-	2	3	-	4	-	-	-	1	-	3	2
Neomysis	HI	-	2	3	-	4	-	-	-	2	3	3	1
Crangon	MED	3	2	-	-	4	-	-	-	2	-	4	2
salmon													
winter run	MED	1	2	4	-	2	3	2	2	3	3	3	1
spring run	MED	1	2	4	-	4	3	2	2	3	3	3	1
fall run	MED	1	2	4	-	4	3	2	2	3	3	3	1
striped bass	HI	4	2	-	4	2	3	3	-	3	3	3	1
sturgeon (both)	LO	1	1	-	-	4	-	2	-	-	2	-	3
American shad	MED	2	2	4	-	4	-	3	4	3	-	3	1
delta smelt	HI	-	2	-	-	-	-	-	-	4	3	3	1
longfin smelt	HI	-	2	-	-	-	-	-	-	3	3	4	1
threadfin smelt	LOW	-	2	-	4	4	-	-	4	3	4	2	1
starry flounder	LOW	2	1	-	-	2	-	-	-	-	-	-	2
splittail	HI	2	2	-	-	4	-	-	4	3	4	2	2

1 = major cause of decline
2 = secondary contributing cause
3 = minor contributing cause
4 = possible minor cause (but unlikely)
\- = not a cause

EXHIBIT WRINT-NHI-11

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Life History and Status of Delta Smelt in the Sacramento-San Joaquin Estuary, California

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Abstract.—The delta smelt *Hypomesus transpacificus* is endemic to the upper Sacramento-San Joaquin estuary. It is closely associated with the freshwater-saltwater mixing zone except when it spawns in fresh water, primarily during March, April, and May. The delta smelt feeds on zooplankton, principally copepods. Its dominant prey was the native copepod *Eurytemora affinis* in 1972–1974 but the exotic copepod *Pseudodiaptomus forbesi* in 1988. Because the delta smelt has a 1-year life cycle and low fecundity (mean, 1,907 eggs/female), it is particularly sensitive to changes in estuarine conditions. Tow-net and midwater trawl samples taken from 1959 through 1981 throughout the delta smelt's range showed wide year-to-year fluctuations in population densities. Surveys encompassing different areas showed declines in different years between 1980 and 1983. After 1983, however, all studies have shown that the populations remained at very low densities throughout most of the range. The recent decline of delta smelt coincides with an increase in the diversion of inflowing water during a period of extended drought. These conditions have restricted the mixing zone to a relatively small area of deep river channels and, presumably, have increased the entrainment of delta smelt into water diversions. Restoration of the delta smelt to a sustainable population size is likely to require maintenance of the mixing zone in Suisun Bay and maintenance of net seaward flows in the lower San Joaquin River during the period when larvae are present.

The delta smelt *Hypomesus transpacificus* is a small fish endemic to the upper Sacramento–San Joaquin estuary, California (McAllister 1963; Moyle 1976; Wang 1986). It has declined in abundance in recent years, and its ability to persist in the estuary is in doubt because of major environmental changes that include increased diversion of freshwater inflow for irrigated agriculture and urban use (Nichols et al. 1986; Moyle et al. 1989; Williams et al. 1989). Reduced freshwater outflow is correlated with poor year-classes of striped bass *Morone saxatilis*, chinook salmon *Oncorhynchus tshawytscha*, American shad *Alosa sapidissima*, longfin smelt *Spirinchus thaleichthys*, and splittail *Pogonichthys macrolepidotus*, presumably because of decreased survival of larvae and juveniles (Turner and Chadwick 1972; Stevens 1977a; Kjelson et al. 1982; Daniels and Moyle 1983; Stevens and Miller 1983; Stevens et al. 1985). Since the late 1970s, most fishes with pelagic larvae have declined in the upper estuary, including delta smelt (Moyle et al. 1985; Herbold and Moyle, unpublished data). Stevens and Miller (1983), however, did not find any relationship between delta smelt abundance and outflow.

We here present information on delta smelt (1) life history, (2) diet, especially in relation to the recent invasion by several exotic species of zooplankton (Orsi et al. 1983; Ferrari and Orsi 1984), (3) fecundity, (4) population trends since 1959, (5) distribution patterns since 1980, and (6) factors affecting abundance. This information supports the proposed federal listing of delta smelt as a threatened or an endangered species.

Life History

Delta smelt are confined to the Sacramento–San Joaquin estuary, mainly in Suisun Bay and the Sacramento–San Joaquin Delta (Figure 1). Historically, the upstream limits of their range have been the upper limits of the delta (Sacramento on the Sacramento River and Mossdale on the San Joaquin River); the lower limit is western Suisun Bay (Radtke 1966; Moyle 1976). During times of exceptionally high outflow from the rivers, they may be washed into San Pablo Bay, but they do not establish permanent populations there (Ganssle 1966). Delta smelt inhabit surface and shoal waters of the main river channels and Suisun Bay, where they feed on zooplankton, as documented

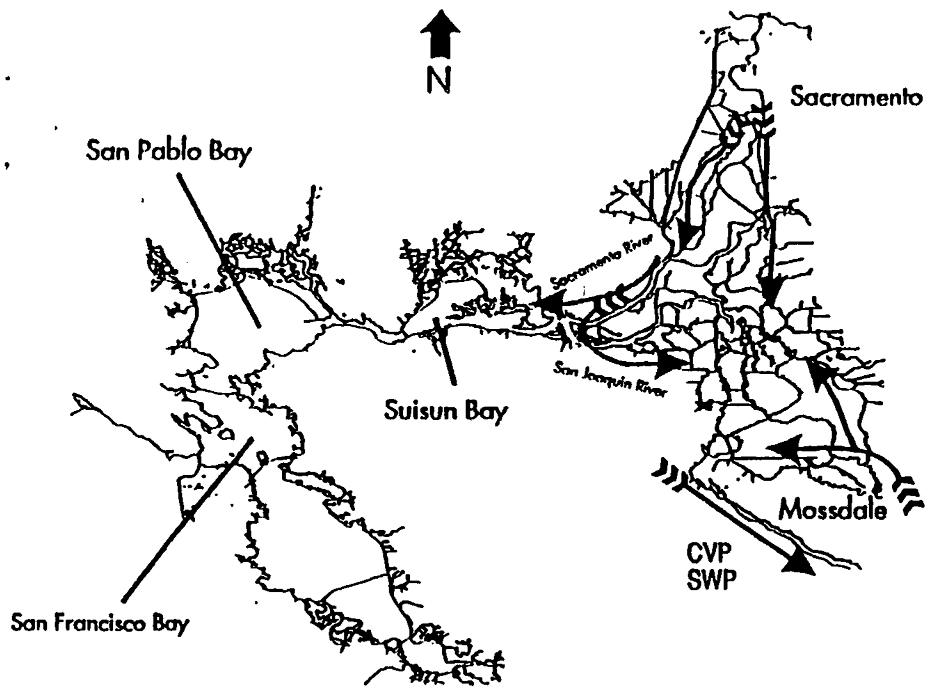

FIGURE 1.—Historical range of delta smelt in the Sacramento–San Joaquin estuary. Delta smelt have been found regularly in Suisun Bay. Years of high outflow have distributed them as far downstream as San Pablo Bay. Upstream limits, occurring usually during the spawning migration in spring, are at Mossdale on the San Joaquin River and Sacramento on the Sacramento River. The arrows show the directions of water flow during periods of high diversions and low outflow. Note the flow of Sacramento River water across the delta and the net reverse flow of the lower San Joaquin River. CVP = Central Valley Project, SWP = State Water Project.

in this paper. Their distribution within the estuary shifts from year to year depending on outflow.

Captures of larvae indicate that spawning takes place in fresh water at any time from late February through May, when water temperatures range from 7 to 15°C (Wang 1986). During this period, adults move from Suisun Bay or river channels in the lower delta to spawning areas upstream. Spawning apparently occurs along the edges of the rivers and adjoining sloughs in the western delta (Radtke 1966; Wang 1986), but spawning behavior has not been observed. Embryos are demersal and adhesive, sticking to substrates such as rocks, gravel, tree roots, and emergent vegetation (Moyle 1976; Wang 1986). Hatching occurs in 12–14 d if development rates of embryos are similar to those of the closely related wakasagi *Hypomesus nipponensis* (Wales 1962).

After hatching, the buoyant larvae are carried by currents downstream into the upper end of the mixing zone of the estuary, where incoming salt water mixes with outflowing fresh water (Peterson et al. 1975; other synonyms or related terms for this region include null zone, entrapment zone, and zone of maximum turbidity). The mixing currents keep the larvae circulating with the abundant zooplankton also found here (Orsi and Knutson 1979; Siegfried et al. 1979; Stevens et al. 1985). Growth is rapid, and the juvenile fish are 40–50 mm fork length (FL) by early August (Erkkila et al. 1950; Ganssle 1966; Radtke 1966). Delta smelt become mature at 55–70 mm FL and rarely grow larger than 80 mm FL. The largest delta smelt on record was 126 mm FL (Stevens et al. 1990). Delta smelt larger than 50 mm FL become increasingly rare in March–June samples, indicating that most adults die after spawning, having completed their life cycle in 1 year (Erkkila et al. 1950; Radtke

1966; California Department of Fish and Game, unpublished data).

Methods

Sampling.—Only two smelt species commonly occur in the Sacramento–San Joaquin estuary—delta smelt and longfin smelt; once past the larval stages, they are easily distinguished on the basis of color, smell, and gross anatomy (Moyle 1976; Wang 1986). Delta smelt were collected in four independent surveys: (1) a summer tow-net survey by CFG, (2) an autumn midwater trawl survey in the upper estuary by CFG, (3) a monthly midwater trawl survey in the lower estuary by CFG (bay survey), and (4) a monthly otter trawl survey of Suisun Marsh, a tidal marsh next to Suisun Bay, by the University of California, Davis (UCD). In all surveys, fish captured were identified, measured (FL in CFG studies, standard length [SL] in the UCD study), and either returned to the water or preserved for dietary analysis.

The summer tow-net survey samples the delta and Suisun Bay during June and July to determine the abundance of young striped bass (Turner and Chadwick 1972). The sampling gear and methods were described in detail by Turner and Chadwick (1972) and Stevens (1977b). This sampling program began in 1959 and has been conducted in all subsequent summers except 1966, although no records were kept of delta smelt numbers in 1967 and 1968. On each survey, three tows are made at each of 30 fixed sites; two to five surveys are made each year at 2-week intervals. To standardize effort among years, we used only the data from the first two surveys of each year. Annual abundance indices for delta smelt were calculated by summing, over all sample sites, the products of total catch in all tows at a site and the water volume at the site in acre-feet (Chadwick 1964). The index for each year is the mean of the indices for the two surveys. Except during wet years (when fish are washed into San Pablo Bay), the summer tow-net survey encompasses the nursery areas of delta smelt, so it should provide a good indication of abundance in early summer.

The autumn midwater trawl survey is conducted with a 17.6 m-long trawl with a mouth opening of 3.7 m² (described by Von Geldern 1972). The trawl is dragged at about 70 cm/s and is most effective in catching fish less than 10 cm long. Collecting sites were established at standardized locations scattered from San Pablo Bay through Suisun Bay and the delta upstream to Rio Vista on the Sacramento River and to Stockton on the San Joaquin River. Each month, unless severe weather or malfunctioning equipment interfered, 87 sites were each sampled with one 12-min, depth-integrated tow. Surveys were conducted in September, October, November, and December from 1967 through 1988 (except for 1974 and 1979), in November 1969, and in September and December 1976. Monthly abundance indices for delta smelt were calculated by summing, over 17 subareas of the estuary, the product of the mean catch per trawl and the water volume for each subarea. The annual abundance index equals the sum of the four monthly indices; abundance indices for months not surveyed in 1969 and 1976 were extrapolated from the months actually sampled.

The bay survey is a monthly trawling program that began in 1980 (Armor and Herrgesell 1985). Its 42 sites are distributed throughout the lower estuary from South San Francisco Bay upstream to the confluence of the Sacramento and San Joaquin rivers. To permit comparison of catches across years, we restricted our analysis of the bay survey data to the 19 sites sampled in all years within the range of delta smelt. The bay study uses midwater trawls and otter trawls; since 1981, it has recorded salinity and temperature profiles at each sampling site.

The Suisun Marsh fish survey has been conducted monthly by UCD since 1979 with an otter trawl that has a 2 × 5.3-m opening (Moyle et al. 1985). Two 5- or 10-min tows are made at 10 consistent locations. Because the sloughs of the marsh are relatively shallow (2–3 m), the otter trawl samples most of the water column and is most effective in catching fish smaller than 10 cm SL.

In summary, the summer tow-net survey and the autumn midwater trawl survey provide long-term abundance data and encompass most of the historical range of delta smelt, but their data are available for only part of each year. The bay survey encompasses all months of the year, but it began in 1980 and is limited to the western half of the delta smelt's historical range. The Suisun Marsh study, begun in 1979, samples year-round in habitat types not sampled by other studies but in a limited geographic area.

Feeding habits.—Diet was determined by examining the stomachs of (1) adults captured between September 1972 and July 1974 in the midwater trawl and tow-net surveys, (2) postlarvae collected in May 1977, and (3) adults captured in surveys during November and December 1988. Each fish was measured (SL), and its stomach con-

TABLE 1.—Diet (percent volume) of delta smelt in 1972–1974 and 1988.

Food category or statistic	1972				1973								1974	
	Sep	Oct	Nov	Dec	Jan	Mar	Jun	Jul	Sep	Oct	Nov	Dec	Jan	Feb
					Prey (% of volume)									
Copepoda[a]	39	5	98	84	37	23	100	88	81	81	87	28	17	85
Neomysis mercedis	58	95	1	16	43	12		3	14	14	1	8	6	14
Corophium spp.								6	5	5	10	13	4	1
Gammaridae					13	1								
Daphnia sp.	3		<1		1	34						12	4	
Bosmina longirostris											2	33	68	
Chironomidae					4	30					<1	4	<1	
Others					2			3				2	1	
					Delta smelt samples									
Mean standard length (mm)	61	67	63	60	64	62	58	41	51	56	58	60	61	65
Number of stomachs	23	20	23	30	50	64	5	15	129	84	60	60	44	72
Percent empty	43	10	50	27	40	16	0	20	16	23	0	23	20	0

[a] Copepods were mainly *Eurytemora affinis* in 1972–1974 and *Pseudodiaptomus forbesi* in 1988.

tents were examined. All food organisms were identified and counted, and their relative volume was determined with the points system of Hynes (1950). When the 1972–1974 stomachs were examined (in 1974), copepods were not identified to species. However, examination in 1989 of the stomachs of 45 additional delta smelt from the same samples indicated that the only copepod present was *Eurytemora affinis*.

Fecundity.—Fecundity was determined from ovaries removed from 24 females collected in mid-January and early March 1973. Ovaries from each female were air-dried until eggs were hard and could be easily separated from other tissue. Once the ovarian tissue was removed, eggs were weighed to 0.01 mg. Subsamples of eggs were then removed, weighed, and counted until at least 20% (by weight) of the eggs had been counted. Total number of eggs was calculated with the number-per-weight proportion determined from the subsamples. All eggs were counted from four ovaries, and the fecundity was compared with that determined from subsamples; the comparison indicated the subsample method overestimated fecundity by about 15%. Consequently, we calculated two means—the uncorrected mean based on the actual estimates and the corrected mean based on the estimates minus 15%.

Abundance trends.—Abundance data for the four surveys were summarized in several ways to permit comparison of various data sets. For the bay and UCD studies, which had year-round sampling at fixed sites, summaries comprised (1) number of delta smelt per trawl for each month, expressed as an abundance index, (2) presence or absence of delta smelt in trawls for each month, (3) mean number of delta smelt caught per trawl in those trawls containing delta smelt for each month, and (4) total delta smelt caught per trawl for each year. The results of the various analyses were similar, so those that showed trends most clearly were used.

Environmental factors.—Four major factors were examined in relation to distribution and abundance of delta smelt: salinity (measured as conductivity in CFG studies), temperature, depth, and freshwater outflow. At each sampling station in the bay and UCD studies, and at many of the sampling stations of the summer and autumn surveys, temperature and conductivity or salinity were measured at the surface by various means. Some conductivity measurements were also made with a conductivity bridge in the laboratory from water samples collected in the field. To determine the location of the mixing zone, we used conductivity data collected monthly since January 1981 by the bay study, which measured both surface and bottom conditions by mounting the probe on a weighted support, dropping it to the bottom, and retrieving it to the surface. Values of salinity were calculated from the measured conductivities and temperatures. Large differences in salinity between the surface and bottom indicated the presence of stratification. A small salinity difference indicated the water column was well mixed or consisted entirely of fresh water.

A single depth measurement (m) at mean low water was used to characterize each study site for the duration of the study, although factors such as tide and outflow resulted in depths at each site varying as much as 1 m among sampling times.

TABLE 1.—Extended.

Food category or statistic	1974		1988	
	Apr	Jul	Nov	Dec
	Prey (% of volume)			
Copepoda[a]	22	69	100	82
Neomysis mercedis		23		
Corophium spp.	2	1		1
Gammaridae				<1
Daphnia sp.	13			2
Bosmina longirostris	59			13
Chironomidae				2
Others				
	Delta smelt samples			
Mean standard length (mm)	65	44	58	61
Number of stomachs	25	161	23	16
Percent empty	0	42	19	0

Data used to examine monthly amounts and patterns of freshwater outflow were obtained from the DAYFLOW data base of the California Department of Water Resources (DWR). DAYFLOW contains estimates of a number of variables related to the amount of fresh water flowing through the estuary, including net delta outflow, the proportion of water diverted, and the amount and direction of flow in the lower San Joaquin River (DWR 1986).

Results

Feeding Habits

Postlarval delta smelt (mean SL, 15 mm; N = 24) collected in 1977 fed exclusively on copepods; their stomachs contained 68% *Eurytemora affinis*, 31% *Cyclops* sp., and 1% harpacticoid copepods. Adults fed primarily on copepods at all times of the year, although cladocerans were seasonally important; opossum shrimp *Neomysis mercedis* usually were of secondary importance (Table 1). In the 1972–1974 samples, the principal copepod eaten was *Eurytemora affinis*, but in the 1988 samples the dominant copepod was *Pseudodiaptomus forbesi*, an exotic species first noted in the estuary in 1987. A few *Sinocalanus doerrii*, an exotic species first collected in 1978 (Orsi et al. 1983), were also eaten in 1988.

Fecundity

Mean corrected fecundity for delta smelt (N = 24) was 1,907 eggs, with a range of 1,247–2,590 (uncorrected mean was 2,191, with a range of 1,433–2,975). Lengths of fish examined were from 59 to 70 mm SL. There was no relationship between length and fecundity. All eggs were about

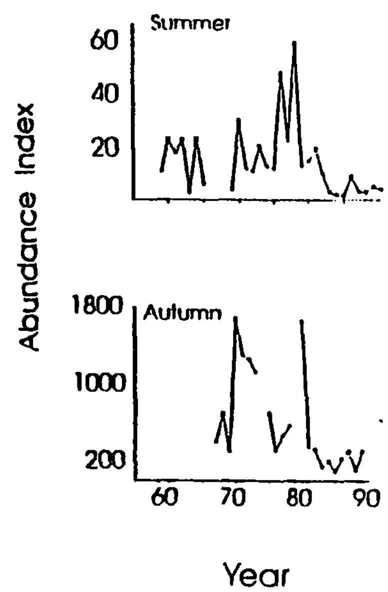

FIGURE 2.—Trends in total catches of delta smelt from two sampling programs encompassing more than 20 years each throughout the historical range of delta smelt but undertaken during a limited part of each year. The autumn midwater trawl samples have been taken in deepwater habitats from September to December of most years since 1967. Summer tow-net surveys, which sample midwater populations of smaller fishes during June and July, began in 1959 and have provided data on delta smelt abundance for all years except 1966–1967. Abundance indices are products of total catch and water volume, summed over standard suites of sampling areas.

the same size, so each fish probably spawned over a fairly short time.

Abundance Trends

In the two long-term studies, catches of delta smelt varied widely across years (Figure 2). In the summer tow-net survey, the peak index of 62.5 in 1978 was 78 times greater than the lowest index of 0.8 in 1985. Before 1981, the index fluctuated between 3 and 62.5. After 1981, the index declined, and it has remained below 10 since 1982. Although similar low indices occurred in 1963, 1965, and 1969, they did not occur in consecutive years as in the 1980s. In the autumn midwater trawl survey, the highest index was 1,675 (in 1970), which was 15 times greater than the lowest index of 109 (in 1985). Until 1980, the annual index fluctuated between 470 and 1,675 (mean catch of

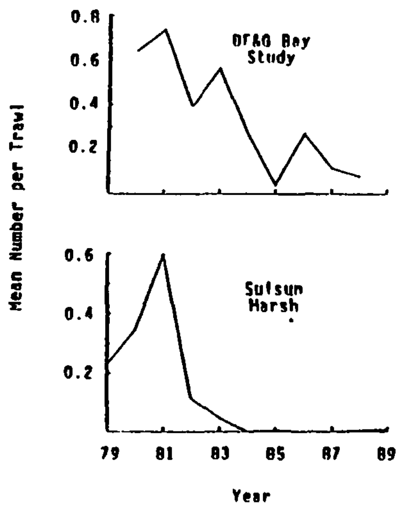

FIGURE 3.—Trends in delta smelt catches from two monthly sampling programs in the lower Sacramento–San Joaquin estuary. Sampling began in 1979 in Suisun Marsh, a shallow-water habitat in the middle of the delta smelt's historical range. The DFG Bay Study has sampled the western half of the delta smelt's historical range since 1980.

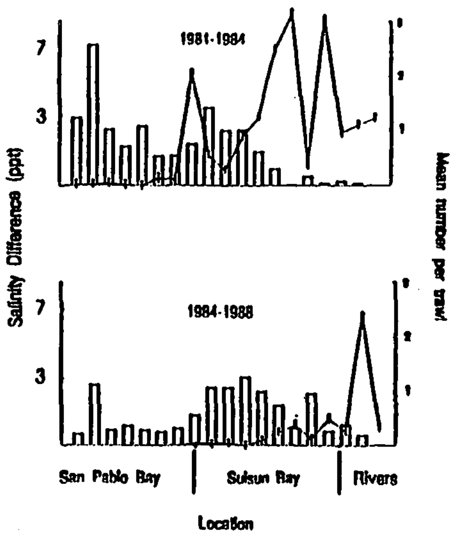

FIGURE 4.—Mean delta smelt catches per trawl (lines) in three regions in the Sacramento–San Joaquin estuary during the periods before (January 1981–September 1984) and after (October 1984–December 1988) the collapse of delta smelt populations. The location of the mixing zone is indicated by large differences (bars, parts per thousand) between salinities of surface and bottom waters in upstream areas. Upstream stations are to the right.

1–5 delta smelt per trawl) except in 1976, when it was 310. After 1980, the index was consistently less than 350 (mean catch of less than one delta smelt per trawl). The frequency of occurrence of delta smelt in the autumn trawls also declined. Until 1981, delta smelt were in 30–75% of the trawl catches. After 1981, they were never caught in more than 25% of the trawls.

The trend of decreasing numbers of delta smelt is reflected as well in annual catch data from the CFG bay survey and the UCD Suisun Marsh survey, for which effort was more or less constant (Figure 3). In both surveys delta smelt catch declined dramatically after 1981 and numbers have remained low. In the bay survey, delta smelt were caught in all months from 1981 through 1984 but only in 9 months in 1985, 10 in 1986, 6 in 1987, and 5 in 1988. During the 11-year Suisun Marsh survey, 468 delta smelt were collected, all but four before 1984; the peak catch was 229 fish in 1981.

Because of the delta smelt's 1-year life cycle, its abundance is potentially limited by egg production of the previous year-class. However, the wide year-to-year variability in abundance of this species prior to its decline in 1981 offers little evidence to support the effect of parent population size on subsequent recruitment. A spawner–recruit relationship based on the autumn midwater trawl data from successive years explained only about one-quarter of the year-to-year variability ($r^2 = 0.24$, $N = 19$). The weak stock–recruitment relationship suggests that environmental factors severely limit delta smelt abundance even in years of large population size.

Environmental Factors

Delta smelt are most abundant in low-salinity water associated with the mixing zone in the estuary, except when they are spawning. When the mixing zone is in Suisun Bay, where both shallow and deep water exist, the fish are caught most frequently in shallow water. In the bay survey, 62% of the delta smelt catch in Suisun Bay occurred at three stations less than 4 m deep. The remaining 38% were captured at six deeper stations. The salinity profiles from the bay study show that most of the delta smelt catches occurred either in Suisun Bay upstream of areas where there was a large difference between surface and bottom salinities or in the channels of the lower Sacramento and

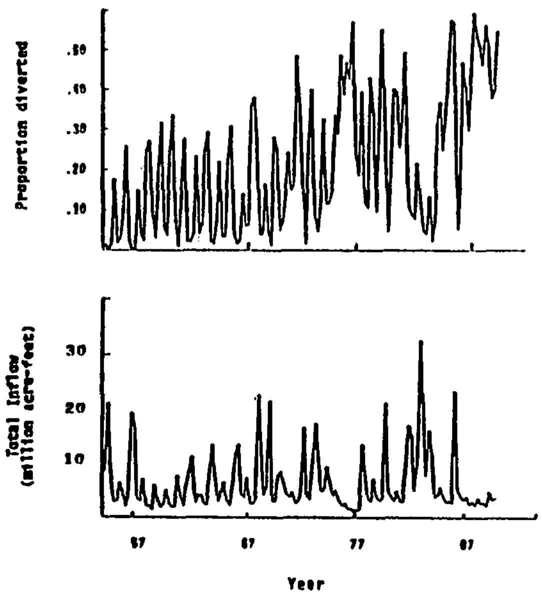

FIGURE 5.—Proportions of water flowing into the Sacramento–San Joaquin Delta that were exported from state and federal pumping plants in southern delta (top), and total freshwater inflows into the delta (bottom), 1957–1987. Points represent quarterly values.

San Joaquin rivers (Figure 4). A small peak in abundance regularly occurred downstream of the mixing zone at a shallow station adjacent to a tidal marsh. Delta smelt were captured in salinities of 0–14‰ (mean, 2‰; $N = 281$) and at temperatures of 6–23°C (mean, 15°C; $N = 281$). No relationship was found between surface temperature and delta smelt distribution at each station, because temperature varied more among months than among stations.

Between 1981 and 1984, the mixing zone was in Suisun Bay during October through March, except during months with exceptionally high outflows. During April through September, the mixing zone was usually upstream in the channels of the rivers. Since 1984, the mixing zone has been mainly in the channels of the rivers during all months of the year except during one period of record outflow in 1986. This shift in the zone's location during winter has coincided with an upstream shift and confinement of the delta smelt population to the deeper water of the main river channels (Figure 4).

Relationship of Abundance to Outflow

Movement of the mixing zone into river channels in the delta is related to the sporadic decrease in inflowing water during years of low precipitation and to the steady increase in the proportion of fresh water diverted each year and month by the pumps and canals of the State Water Project and federal Central Valley Project. Since 1983, the proportion of water diverted during October through March (the first half of the official water year) has remained at high levels (Figure 5). Because high levels of diversion pull Sacramento River water across the delta and into the channel of the San Joaquin River downstream of the pumps, the net movement of water in the lower San Joaquin River is frequently upstream during these periods (Figure 1). The number of days of net reverse flow of the lower San Joaquin River has increased during periods of low outflow in response to steadily increasing rates of diversion. Until 1984, years with more than 100 d of reverse flow were sporadic, and reverse flows rarely occurred during the delta smelt spawning season. From 1985 on, reverse flows have characterized the lower San Joaquin for more than 150 d of the year, and in every year except 1986 reverse flows have occurred for 15–85 d of the spawning season (Figure 6). Consequently, the restriction of the mixing zone to an area around the mouths of the rivers has greatly increased the likelihood of dis-

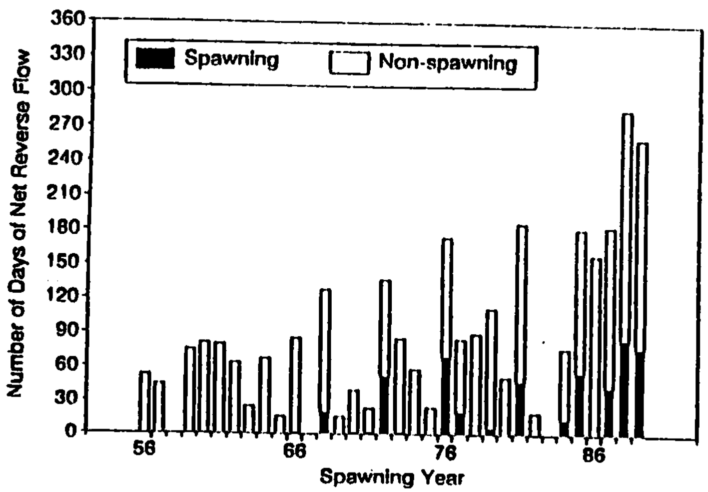

FIGURE 6.—Number of days of net reverse flow in the San Joaquin River during water years (October–September) 1956–1989. The black portion of each bar shows the number of the days of reverse flow that occurred during the spawning season of delta smelt (February–May).

placement of delta smelt. Reverse net flows in the lower San Joaquin have been a constant feature of the delta in recent years during the months when delta smelt are spawning except for 1986, when a record tropical storm in February produced enough water to maintain adequate flows through the spring of what was otherwise a dry year.

The recent decline in delta smelt has coincided with the increase in proportion of water diverted and the confinement of the mixing zone to a small area in the river channels. Low catches during the 1976–1977 drought also coincided with record high proportions of water diverted. Increasing rates of diversion since the earlier drought resulted in greater proportionate diversion during the more recent drought, so for 1988 the amount of water diverted exceeded the amount flowing out to sea.

Despite the correspondence of increased diversion and delta smelt decline, the relationship between outflows and delta smelt abundance is not a simple one, as it seems to be for other species (Stevens and Miller 1983). To see if delta smelt might be favored by moderate outflows, which would keep them in Suisun Bay, we regressed the autumn midwater trawl abundance index on delta outflow and delta outflow squared. Outflow squared would allow the regression values to decline if delta smelt abundance peaked at moderate flows and declined at high or low flows. No relationship was found; all values of r^2 were less than 0.23, after all possible subsets of data for two consecutive months from February to June were examined. These results may have been confounded by extreme conditions since 1982: most years have been unusually wet (1983) or unusually dry (1987–1991). Under such extremes, the responses of delta smelt to outflow may not have been consistent with patterns shown within the normal range of outflows.

Discussion

The delta smelt is adapted to living in association with the mixing zone of the Sacramento–San Joaquin estuary, where it feeds on copepods and other zooplankton concentrated there. Because it has a limited range, essentially a 1-year life cycle, low fecundity, and planktonic larvae, the species is unusually sensitive to changes in estuarine conditions. This sensitivity has caused its population to remain extremely low since 1980. As Pimm et al. (1988) showed, small species with variable populations, such as delta smelt, become increasingly vulnerable to extinction as their populations decrease. Thus, the delta smelt fits the definition of an endangered species under the U.S. Endangered Species Act, because it is in danger of extinction throughout its limited range. Given its persistence through 7 years of severe conditions, however, "threatened" status may be more appropriate.

A species may be threatened or endangered according to the Endangered Species Act because of: "(A) the present, or threatened, destruction, modification, or curtailment of its habitat or range, (B) over-utilization for commercial, recreational, or educational purposes, (C) disease or predation, (D) inadequacy of existing regulatory mechanisms, or (E) other natural or manmade factors affecting its continued existence." There is no evidence that reasons B or C have reduced delta smelt numbers, but A and D have both played a role. Other factors (E) possibly affecting the existence of delta smelt include toxic compounds in the water, reduction in abundance of key food organisms, and competition from recently introduced species of fish and invertebrates. However, evidence that other factors have reduced delta smelt abundance is weak or lacking, so only habitat destruction and inadequacy of regulatory mechanisms will be discussed.

Destruction of Habitat

The principal habitat of the delta smelt is the mixing zone and the freshwater area immediately upstream of it. Habitat for delta smelt increases when the mixing zone is in Suisun Bay, because the zone extends over a much wider area than when it is confined to the deep narrow channels of the delta. When the mixing zone is in Suisun Bay, the system is also more productive (Arthur and Ball 1979), so presumably more zooplankton is available as food, especially for larvae. Because the delta smelt is essentially an annual fish with relatively low fecundity, a food-rich area immediately downstream from its spawning areas must have been a consistent feature that promoted high survival of larvae during most of its evolutionary history.

Increased diversion of fresh water from the estuary has altered both the location of the mixing zone and the flow patterns through the delta during much of the year. The shift of the mixing zone to river channels not only decreases the amount of suitable habitat for delta smelt but results in decreased phytoplankton and zooplankton abundance (Arthur and Ball 1979; Herbold and Moyle 1989). During the months when delta smelt are spawning, the changed flow patterns presumably lead to greater entrainment of spawning adults and newly hatched larvae into water diversions. The combined effects of habitat constriction and fish entrainment provide the most likely explanation of the declines in abundance.

This problem has no doubt been exacerbated by drought conditions that have existed in the drainage since 1987, coupled with the record-high outflows in February 1986 (which flushed fish out of the estuary). However, since 1984 the percentage of inflow diverted has been higher, and has stayed higher longer, than in any previous period including the severe 1976–1977 drought.

Inadequacy of Existing Regulatory Mechanisms

The regulation of delta outflows, delta water quality, and flow patterns through the delta is complex and under the jurisdiction of several agencies (Herbold and Moyle 1989). The present regulatory system primarily benefits water exporters at the expense of fish and other estuarine-dependent organisms; even valuable sport and commercial fishes such as striped bass and chinook salmon have suffered major declines in recent years despite efforts to sustain them (Nichols et al. 1986). Large numbers of pelagic fishes, especially larvae, are entrained in water diversions of the federal Central Valley Project, the State Water Project, agriculture on delta islands, power plants of Pacific Gas and Electric Company, and other industries. Present rescue and mitigation efforts do not seem to compensate for the losses. This is particularly true of delta smelt, which (1) are frequently exposed to entrainment (Stevens et al. 1990), (2) are unlikely to survive any rescue attempts that involve handling of fish because of the high resultant mortality (personal observation), and (3) have received little attention from management agencies until recently. In short, the present mechanisms that regulate freshwater flows through the estuary have not adequately protected delta smelt.

Regardless of cause, the consistently low numbers of delta smelt in recent years indicate that immediate action is needed to reduce the probability of the species becoming extinct. In the past the delta smelt population has shown extreme fluctuations from year to year, as might be expected of an annual species with narrow habitat requirements in a highly disturbed system. Presumably, the population is continuing to fluctuate but at such low numbers that the fluctuations cannot be reliably detected with present methods. With such low numbers, the delta smelt population could fluctuate into extinction in a single year (Pimm et al. 1988).

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