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1991 ANNUAL REPORT

Interagency Ecological Studies Program for the Sacramento-San Joaquin Estuary

Compiled by
Perry L. Herrgesell, Ph.D.,
Study Manager

June 1993

California Department of Water Resources
State Water Resources Control Board
U.S. Bureau of Reclamation
U.S. Army Corps of Engineers

California Department of Fish and Game
U.S. Fish and Wildlife Service
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HIGHLIGHTS

Environmental Factors

- Flows in the San Joaquin River were the lowest since the drought of 1976/1977 and contributed to the most significant dissolved oxygen depression measured in the Stockton Ship Channel since the current drought began in 1987. To increase fall flows, a temporary closure was completed on September 13 at the head of Old River to force more water down the San Joaquin River and through the Ship Channel. In spite of the closure, exceptionally low dissolved oxygen levels (3.0 mg/L or less) were measured near Rough and Ready Island in late September and early October. Levels in the Ship Channel recovered to greater than 5.0 mg/L in early November.
- Chlorophyll concentrations were low throughout most of the delta, Suisun Bay, and San Pablo Bay during 1991. Chlorophyll concentrations remained below 15 μg/L for the northern and central delta and below 6 μg/L for Suisun and San Pablo bays. In contrast, chlorophyll concentrations were high during the summer and fall in the southern delta, where chlorophyll concentrations reached 130 μg/L.
- An analysis of the 1972-1988 data showed long-term abundance trends for most native zooplankton taxa were down.
- The Department of Food and Agriculture has detected the introduced aquatic plant *Hydrilla verticillata* in several tributaries of the delta. Littoral zone vegetation surveys conducted by Department of Food and Agriculture and DWR, however, have not detected *H. verticillata* in the delta.
- Eight species of submerged and emergent plants have been seen or collected over six littoral zone surveys conducted by DWR in the delta.
- Littoral zone plant species assemblage and extent have remained stable between seasons and years.
- The Food Chain Group focused on three principal issues: zooplankton data analyses, introduced species, and the entrapment zone.

Striped Bass

- Interagency Program staff developed a new proposed water quality and biological monitoring program for the San Francisco Bay/Delta estuary. The proposed program may be submitted during the 1992 State Water Resources Control Board water right hearings. The proposal calls for a revised baseline monitoring program in Suisun Bay and the delta, 1-year pilot studies upstream of the delta and in San Francisco Bay (downstream of Suisun Bay), and special studies to evaluate high priority management issues. Recommendations on funding and implementation are included. The proposal was released for Interagency Program review in May 1992.
- In 1991, 8,375 adult striped bass were tagged. Based on tags applied in 1990 and recovered during the 1990 creel census, the adult striped bass population estimate for 1990 is 515,000. During the early 1970s, adult striped bass population estimates averaged 1.7 million.
- Tag recoveries indicate 12 percent of the adult striped bass population was harvested by anglers in 1990. Typically, harvest rates have ranged from 12 to 25 percent.
- The striped bass health monitoring program was terminated in October 1991.

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- DFG developed a regression model in which 79 percent of the annual variability in the estuary's adult striped bass abundance is accounted for by freshwater outflow and water exports from the delta during the initial year of life.
- Chameleon gobies, a small introduced fish established in the estuary in the 1980s, made up 80 percent of larvae sampled at Jersey Point and 32 percent of larvae sampled at Tracy Fish Collection Facility.

Chinook Salmon

- Abundance of fry in the northern and central delta was the lowest since sampling began in 1977.
- Most of the fry in the delta in 1991 remained and reared upstream until storm runoff increased streamflows in March.
- The mean annual smolt index (41.6 fish per 20-minute tow) showed relative smolt abundance at Sacramento was about half that observed in 1988 and 1989.
- The mean annual catch at Chipps Island was 12.5 salmon per 20-minute tow, similar to that in 1988 but less than in 1989 and 1990.
- Coded-wire-tagged smolts released at Princeton from Coleman National Fish Hatchery survived at a rate of 0.45 between Sacramento and Chipps Island. Assuming this survival rate is the same for the unmarked fish released from Coleman, we estimate that 14 percent of the fish passing Chipps Island were of Coleman origin.
- A total of 37 juvenile salmon in the winter-run size criterion were collected in the beach seine (1), Sacramento trawl (11), and Chipps Island trawl (25). These fish were released as soon as they were measured.
- Two CWT groups released at Sacramento on April 25 and 29 and recovered at Chipps Island had survival indices of 0.78 and 0.49 respectively. Flows were greater for the first release group and may have accounted for the higher survival.
- Survival of CWT smolts released in the San Joaquin River at Stockton, the mouth of the Mokelumne River, and Jersey Point indicated survival increased as the release point was moved downstream.
- Survival rate between Stockton and the lower Mokelumne junction under lower export conditions in May was significantly better than for the same reach in April, when exports were greater (4,283 versus 2,613).
- Survival of fish released at Jersey Point in both April and May was high and similar to each other. Flows at Jersey Point during the two release periods were also similar.
- The greatest number of fish recovered at the fish facilities were from the groups released farther upstream, both in April and May — generally the inverse relationship from that observed in survival at Chipps Island.

Other Estuarine Fishes

- The delta smelt study is on schedule, with full implementation scheduled for January 1992. The study plan is divided into 10 projects, which include:
  - » Monitoring programs to improve knowledge of delta smelt life history requirements and to determine the magnitude of losses to State, Federal, and agricultural diversions.
  - » Laboratory studies to evaluate other possible environmental threats to the population and to create a "refuge" population.
  - » A modeling study aimed at developing extinction probabilities based on delta smelt population dynamics.
- The 1991 fall midwater trawl abundance index increased to 689, from 360 in 1990. However, all other datasets used to document the population decline in the early 1980s have not shown an increase.

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- In recent years, the population has been concentrated in the lower Sacramento River.
- In fall 1991, 388 white sturgeon were tagged. Based on tags applied in fall 1990 and recovered during 1991, the 1990 abundance estimate of sturgeon longer than 40 inches is 26,800. This is the lowest estimate since 1974 (21,000) and is substantially below the estimated abundance in the 1980s, which ranged from about 84,000 to 128,000.
- Radio-tagging mature sturgeon and sampling for eggs with artificial substrates in the Sacramento River in late winter and spring 1991 suggests increases in flow stimulate spawning. Radio-tagged females moved rapidly downstream after spawning.
- In June and July 1991, 186 juvenile sturgeon were captured with setlines. No updated index of year-class strength was calculated, because fish captured this year have not been aged.

Entrainment of Eggs and Larvae

- Striped bass entrainment losses were estimated at 6.3 million eggs and 44.5 million larvae for the SWP and 5.6 million eggs and 22.6 million larvae for the CVP. Striped bass yearling equivalent losses were 15,117 for the SWP and 8,861 for the CVP.
- Known occurrence of delta smelt larvae in the southern delta (April through May) has been expanded to include mid-March through early June. Total catch is still less than 20 larvae per study season.
- Results of the egg and larva study indicate chameleon goby, threadfin shad, and prickly sculpin accounted for 99 percent of the total catch at all sites. Abundance of chameleon goby in the catch increased from 271 larvae in 1988 to 137,455 larvae in 1991 and comprised 87 percent of the total catch at all sites.

Delta Outflow/San Francisco Bay

- Trends for shrimp were similar to 1990, with abundance of *Crangon franciscorum* relatively low while the three species that prefer higher salinity waters had high annual abundance indices or increased in abundance from 1990.
- Abundance of juvenile Dungeness crabs was below average relative to previous years, but greater than the index for 8 of these 11 years.
- Abundance trends of fishes that use higher salinity waters as a nursery area has been mixed since the drought. The bay goby has had the most consistent increase in annual abundance each year since 1987, and this is partially attributed to the stable salinity regime associated with the drought. Other species, including staghorn sculpin, English sole, and speckled sanddab have had both low and high abundance indices since 1987. Several species, including Pacific herring, longfin smelt, jacksmelt, shiner perch, and starry flounder, had very low or record low indices in recent years and in 1991.
- Working papers directed at determining the biological basis and mechanisms for the strong positive relationship between freshwater outflow and abundance of *Crangon franciscorum*, longfin smelt, and starry flounder were prepared for Article VII negotiations and SWRCB hearings. These papers are presented in this report as "Freshwater Outflow Needs".
- For *Crangon franciscorum,* outflow is important in determining the number of recruits to the estuary and the size of the brackish water nursery habitat.
- Outflow is important in dispersal of longfin smelt larvae from their spawning areas in the rivers to their brackish water nursery habitat. Outflow also determines the volume of nursery habitat.
- Starry flounder juveniles migrate to the estuary from the ocean, and the number of recruits is related to outflow. As for

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C. franciscorum and longfin smelt, outflow is critical for establishment and maintenance of a brackish water nursery area.

- The open water monitoring survey was conducted monthly from February to October at 46 stations. The continued drought resulted in a distributional shift of several species upstream of the study area; in response, we added four stations in 1991. Three of the new stations are in the lower Sacramento River below Rio Vista and one is in the lower San Joaquin River below Big Break.
- The ring-net survey for Dungeness crabs was conducted monthly from July to December at 11 shore based stations.

Fish Facilities

- A successful predator removal program has been initiated at the Federal Tracy Fish Collection Facility. These efforts have dramatically reduced the size of predator striped bass found in the facility, and presumably increased salvage efficiencies for small prey species. Salvage records will be evaluated to determine the benefits provided by this program.
- USBR continuously sampled fish larvae at three locations in the delta as part of its Striped Bass Management Program in an effort to develop short-term actions to increase survival of striped bass larvae. Pulses of eggs and larvae occurred almost simultaneously at all sites in relation to increasing water temperatures.
- New samplers employed at Tracy Fish Collection Facility and at Jersey Point on the San Joaquin River decreased losses of eggs and larvae caused by amphipod predation and increased sampler retention of eggs and larvae.
- Chameleon gobies, a small introduced fish established in the estuary in the 1980s, made up 80 percent of the larvae collected at Jersey Point and 32 percent of the larvae collected at Tracy Fish Collection Facility.
- Continuous sampling for Sacramento River striped bass eggs and larvae at Bryte in 1991 indicated five spawning peaks of over 100 million eggs and larvae per day. The peaks lasted from 1 to 6 days and occurred from late April until early June. Most of the spawning occurred in May, with peaks of over 1 billion per day.
- A catch-per-unit-effort sampling program in Clifton Court Forebay was initiated during 1991 to monitor abundance of predatory fishes.
- Efforts have been renewed to develop fish protective facilities for a proposed diversion on the Sacramento River near Hood. This is essentially a continuation of research abandoned in 1982 when the Peripheral Canal was defeated.
- DFG has initiated the take-over of fish salvage, hauling, and salvage sampling at the SWP.

Hydrodynamics

- Simulations of 3-dimensional flow in San Pablo Bay illustrated the spring/neap pulsation of landward-flowing, net bottom currents and demonstrated the marked effect of Pinole Shoal on these currents. The simulations also demonstrated the pronounced sensitivity of net circulation to small differences of non-tidal sea level between Carquinez Strait and Central Bay.
- A hydrographic dataset appropriate for verifying 3-dimensional model codes has been collected in Carquinez Strait. The dataset includes time series of sea level, salinity, and temperature at each end of the strait; acoustic Doppler current profile time series in the interior of the strait; wind time series near the strait; and synoptic profiles of salinity, temperature, and velocity at interior cross sections.
- Analyses of sea level time series at San Francisco Bay monitoring stations show the dominant influence of the spring/neap cycle on mixing energy and the pro-

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nounced annual variations of the spring/neap cycle. Large variability of the spring/neap cycle (strong spring tides and weak neap tides) occurs in winter and summer. Similarly, periods of minimum variability (weak spring tides and strong neap tides) occur in spring and fall. Analyses of salinity time series show the interplay of freshwater inflow and the spring/neap cycle on salinity at bay monitoring sites. Inflow events result in lower salinities and stratification of the water column. Stratification diminishes or disappears during spring tides and reappears or strengthens during neap tides.

- Development was completed of a vessel-mounted flow-measurement system. This system can measure flow in a channel with depths greater than 4 meters during a bank-to-bank traverse. The system permits rapid, relatively inexpensive measurements of flow throughout much of the delta, makes feasible the calibration of continuous-flow monitoring equipment in delta channels, and permits measurement of tidal fluxes through narrow points in the bay. Measurements of flows at Chipps Island permitted calculation of net delta discharge on two occasions.

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Chapter 2

INTRODUCTION

Perry Herrgesell
Department of Fish and Game

This nineteenth annual report of the Interagency Ecological Studies Program for the Sacramento-San Joaquin Estuary describes results of study efforts during calendar year 1991. In some cases, the actual data discussed were collected during earlier years but were analyzed and interpreted during 1991. This annual report series is a mechanism to informally report recent findings and implications from ongoing Interagency work.

The Interagency Program

The Interagency Program was initiated in July 1970 by a Memorandum of Agreement between the California Department of Fish and Game, California Department of Water Resources, U.S. Bureau of Reclamation, and U.S. Bureau of Sports Fisheries and Wildlife (now Fish and Wildlife Service). The Memorandum of Agreement was an outgrowth of testimony at Water Rights hearing 1379, which indicated that construction and operation of the State Water Project and Federal Central Valley Project may have been contributing to fish and wildlife problems in the estuary. Testimony also indicated a need for more information regarding environmental needs of fish and wildlife and ways to design and operate the water projects to minimize detrimental effects on those resources.

The Memorandum of Agreement contained an appendix that described studies needed to define environmental requirements and agency responsibilities for conducting and funding the studies. Findings were to be documented in annual progress reports to be submitted to the State Water Resources Control Board and other agencies, organizations, and individuals.

Program Elements

The Memorandum of Agreement provided that the program be reviewed annually, with the goal of modifying the studies to reflect changes in engineering and biological needs. Under this provision, the Interagency Program has changed substantially from that envisioned by the originators. For example:

- The Fisheries element was expanded to include resident delta fish as well as striped bass, salmon, sturgeon, and most recently, delta smelt.
- The Water Quality element evolved from an emphasis on adverse effects of too much algae growing in the estuary (which could cause dissolved oxygen and esthetic problems) to a concern that in certain portions of the delta there may not be enough algae to support desired levels of fish resources.
- The Fish Facilities element was initially concerned with information related to designing fish protective features of the then-proposed Peripheral Canal. With voter defeat of the peripheral canal concept in 1982, emphasis of the program shifted to obtaining better understanding of effects of existing delta facilities on fish.
- The final element in the original program, Suisun Marsh, has gone from a planning program to one in which facilities have been constructed to maintain required water quality in marsh channels and soils. In that regard, the program has moved into a management mode and, in fact, is no longer a part of the Interagency Program. Primarily, this program now has responsibility for implementing the Suisun Marsh Plan of Protection and monitoring effects of the facilities on water quality and on plants and wildlife in the marsh. Activities of the program are not reported in this annual report.

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During the 1978 State Water Resources Control Board hearings to update Water Right Decision 1379, it became clear that it was necessary to expand studies into the lower portions of the estuary. Decision 1485, which resulted from this hearing, mandated that water permit holders for the major projects include a San Francisco Bay element in their studies. The Delta Outflow/San Francisco Bay Study was established in 1979 and began to develop information regarding the need for outflow standards to protect the bay portion of the system. That element of the Interagency Program began with a biological and hydrodynamic component and brought the U.S. Geological Survey and State Water Resources Control Board into the Program.

Another element in the present program, Data Management, was added in 1984. The vast amount of data collected in the various studies needed to be electronically stored to assure correctness and allow access by participating agencies. The Data Management Committee works to achieve standardized station locations, means of data entry, and data verification, among other tasks.

Since 1980, hydrodynamic studies have been carried out through a subcommittee of the Delta Outflow/San Francisco Bay Technical Committee. To be more responsive to overall program needs, a separate Hydrodynamic Study Committee was formed early in 1990.

Program Organization and Funding

The general Interagency Program organization chart is shown in Figure 1. Technical committees develop specific study proposals and budgets and exercise day-to-day technical supervision over individual studies. Agency coordinators resolve issues regarding funding and organization. Agency directors generally meet at least once a year to review progress and to resolve any major issues regarding differences in agency policy. An annual workshop is held to bring program participants and others up to date on the various program elements.

During the October 1991 Directors' briefing, the Directors recommended that the U.S. Environmental Protection Agency be invited to formally join the Interagency Program. The invitation was based on EPA's interest in the SWRCB's water quality process in the bay and delta and its involvement in the San Francisco Estuary Project. Both activities are closely aligned with Interagency Program studies. EPA accepted the invitation and signed the Memorandum of Agreement early in 1992, becoming the eighth member of the Interagency Program.

Table 1 lists funds contributed to individual program elements by the participating agencies in fiscal year 1990-91. The $7.2 million represents increased funding from last year. Note that no funds are identified for the data management activities. Funding for that element is derived from within the other program elements.

Program Goals

Goals of the Interagency Program are:

- To provide for the collection and analysis of data needed to understand factors controlling the distribution and abundance of selected fish and wildlife resources in the Sacramento-San Joaquin estuary and make the data readily available to other agencies and the public.
- To comply with permit terms requiring ecological monitoring in the estuary.
- To identify impacts of human activities on the fish and wildlife resources.
- To interpret information produced by the program and from other sources and, to the extent possible, recommend measures to avoid and/or offset adverse impacts of water project operation and other human activities on these resources. To seek consensus for such recommendations, but to report differing recommendations when consensus is not achieved.
- To provide an organizational structure and program resources to assist in planning, coordination, and integration of estuarine studies by other units of cooperating agencies or by other agencies.

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Figure 1
ORGANIZATION, INTERAGENCY ECOLOGICAL STUDIES PROGRAM

AGENCY DIRECTORS

David Kennedy ..... Department of Water Resources
Roger Patterson ..... U.S. Bureau of Reclamation
Don Maughn ..... State Water Resources Control Board
Stanley Phernambucq ..... U.S. Army Corps of Engineers
Boyd Gibbons ..... Department of Fish and Game
Marvin Plenert ..... U.S. Fish and Wildlife Service
John Klein ..... U.S. Geological Survey
Daniel McGovern ..... U.S. Environmental Protection Agency

AGENCY COORDINATORS

Harold Chadwick, Chair ..... Department of Fish and Game
Marty Kjelson ..... U.S. Fish and Wildlife Service
Steve Deverel ..... U.S. Geological Survey
Tom Wakeman ..... U.S. Army Corps of Engineers
Randy Brown ..... Department of Water Resources
Dave Beringer ..... State Water Resources Control Board
Ken Lentz ..... U.S. Bureau of Reclamation
Harry Seraydarian ..... U.S. Environmental Protection Agency

STUDY MANAGER

Perry Herrgesell, Department of Fish and Game

TECHNICAL COORDINATING COMMITTEES

Fisheries/Water Quality Program

Marty Kjelson, Chair ..... U.S. Fish and Wildlife Service
Jim Arthur ..... U.S. Bureau of Reclamation
Donald Stevens ..... Department of Fish and Game
Harlan Proctor ..... Department of Water Resources
Bellory Fong ..... Department of Water Resources
Jim Sutton ..... State Water Resources Control Board

Fish Facilities Study

Pat Coulston, Chair ..... Department of Fish and Game
Marty Kjelson ..... U.S. Fish and Wildlife Service
Marcia Whietman ..... National Marine Fisheries Service
Leo Winternitz ..... Department of Water Resources
Stein Buer ..... Department of Water Resources
Lloyd Hess ..... U.S. Bureau of Reclamation
Bruce Herbold ..... U.S. Environmental Protection Agency

Hydrodynamics Committee

Larry Smith, Chair ..... U.S. Geological Survey
Pete Smith ..... U.S. Geological Survey
Chuck Armor ..... Department of Fish and Game
Marty Kjelson ..... U.S. Fish and Wildlife Service
Tom Wakeman ..... U.S. Army Corps of Engineers
Tom Tamblyn ..... State Water Resources Control Board
Randy Brown ..... Department of Water Resources
Jim Arthur ..... U.S. Bureau of Reclamation

Delta Outflow/San Francisco Bay Study

Chuck Armor, Chair ..... Department of Fish and Game
Jim Arthur ..... U.S. Bureau of Reclamation
Marty Kjelson ..... U.S. Fish and Wildlife Service
Steve McAdams... Bay Conservation/Development Commission
Tom Wakeman ..... U.S. Army Corps of Engineers
Randy Brown ..... Department of Water Resources
Rick Oltman ..... U.S. Geological Survey
Ron Bachman ..... State Water Resources Control Board

Data Management Committee

Sheryl Baughman, Chair ..... U.S. Bureau of Reclamation
Joel Johnston ..... U.S. Geological Survey
Pat Brandes ..... U.S. Fish and Wildlife Service
Ann Baker ..... Department of Fish and Game
Sheila Greene ..... Department of Water Resources
Jim Sutton ..... State Water Resources Control Board

Table 1
PROGRAM FUNDING, FISCAL YEAR 1990-91
(Thousands of Dollars)

	DWR	USBR	DFG	SWRCB	USGS	USFWS	USCE	USEPA	Total
Fisheries/Water Quality	1982	1400	929	125		88			4524
Fish Facilities	567	126							693
Delta Outflow/San Francisco Bay	423	524							947
Hydrodynamic Investigations	313	15		200	298				826
Administration	60		177	15					252
Totals	3345	2065	1106	340	298	88	0	0	7242

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1991 Program Update

This section briefly updates selected administrative activities during 1991.

University Academic Research Involvement Program

Late in 1991, the University Academic Research Involvement Program was merged with the San Francisco Estuarine Project's Gaps in Knowledge program. The UARIP was started in 1990 to foster more scientific research by local universities on various aspects of the estuary. The UARIP established a grant program to support graduate students and post-doctoral fellows who work on the system. The Gaps in Knowledge program was started to fund research by agencies and universities that address management questions of significance in the estuary.

The merger allowed a larger program (funds available for 1992 total $500,000) and provided a stronger review process for related proposals of the Gaps in Knowledge program.

During 1991, six proposals were received for potential funding under UARIP. After review, the following projects were funded:

- Longitudinal Analysis of Attitudes of Policy Participants Regarding the San Francisco Bay-Delta, 1984-1991 (Paul Sabatier, University of California, Davis)
- Prehistoric Salinity Record in the San Francisco Estuary (James C. Ingle, Stanford University)
- Hydrodynamic Influence on the Survival of Wetlands in San Francisco Bay (Rodney J. Sobey, University of California, Berkeley)

Program Element Fact Sheets

The Coordinators determined that a better mechanism was needed to describe program elements to the Directors and asked the staff and Study Manager to develop fact sheets for each program element. Fact sheets, along with standardized and updated workplans, were finalized late in 1991 for the 1992 Directors' meeting.

Public Outreach Plan

With input from the Study Manager, the Coordinators developed a Public Outreach Plan for implementation during 1992. Development of such a plan was stimulated by comments at the 1991 Public Forum to the effect that the Interagency Program should do some things to heighten the positive image of the program. The plan contains the following activities to be carried out under the direction of the Study Manager:

- Increase and broaden notification of the Public Forum.
- Publish an article in DFG's *Outdoor California* and other popular magazines.
- Annually distribute an Interagency Program "State of the Estuary" news release.
- Increase interaction with water users, environmental groups, and academia.
- Develop and use Interagency Program stationery.
- Sponsor selected conferences or scientific meetings.

The Sacramento-San Joaquin Estuary

The Sacramento-San Joaquin estuary is briefly described here for those not familiar with the area. The estuary, shown in Figure 2, has been described in detail by several authors (for example, Conomos 1979). Geographic features identified in Figure 2 are often referred to in later discussions of the program elements.

By definition, an estuary is an area where tidal and river currents meet. As used in this report, the Sacramento-San Joaquin estuary consists of South and Central San Francisco Bay, San Pablo Bay, Suisun Bay, and the Sacramento-San Joaquin Delta. The actual extent to which tidal currents penetrate inland depends on freshwater flow and tidal phase.

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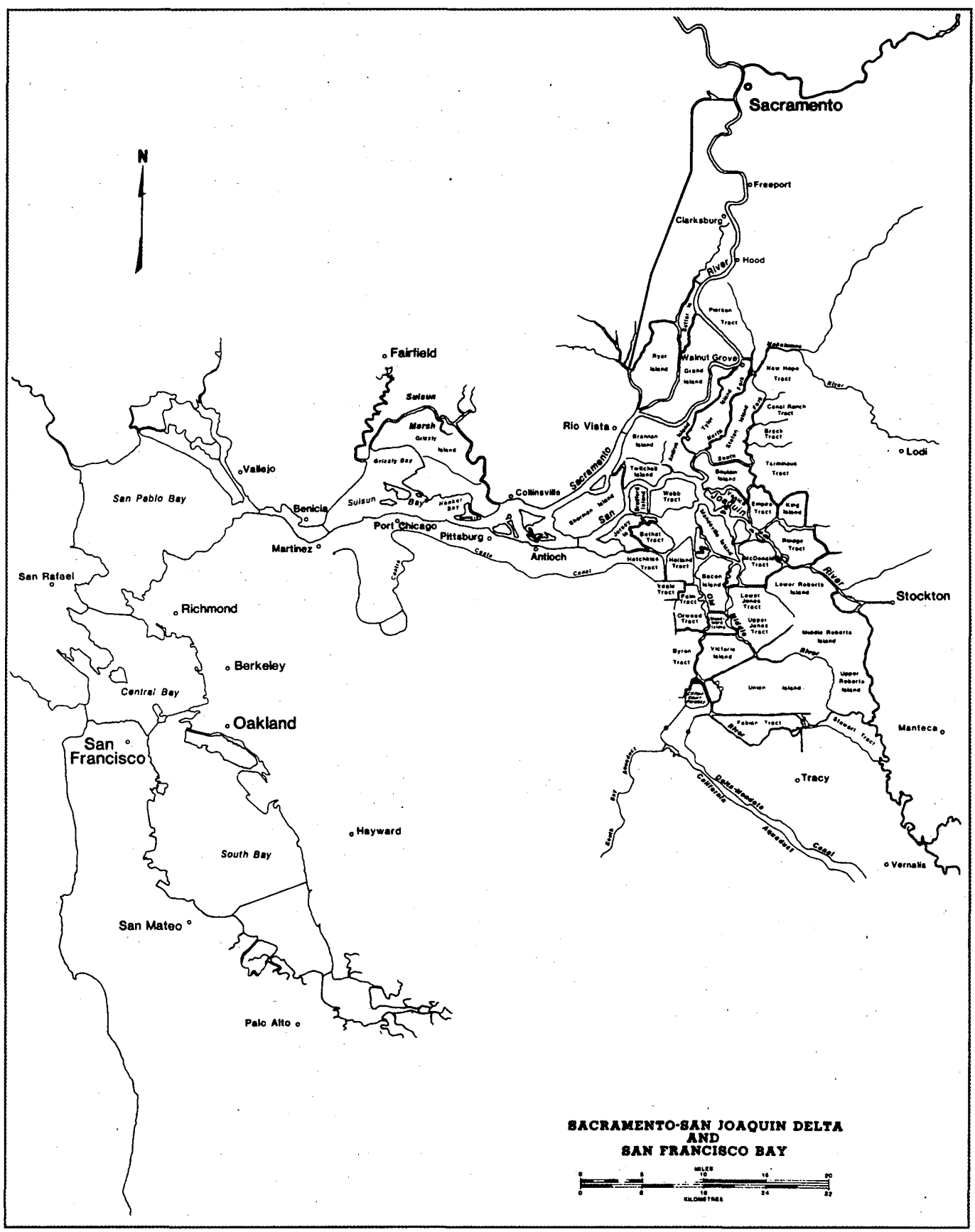
Figure 2
LOCATION MAP, SACRAMENTO-SAN JOAQUIN ESTUARY



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The Sacramento and San Joaquin rivers join to form a delta area that contains numerous islands protected by levees. The leveed islands are productive agricultural lands, and the surrounding levees and channels support populations of resident fish, provide nursery areas for both resident and migratory species, serve as passageways for migrating adult and juvenile fish, and are valuable habitat for a wide variety of wildlife.

The Sacramento and San Joaquin rivers are the major source of freshwater inflow to the estuary, with the Sacramento being the largest contributor. In an estuarine system such as this, total freshwater outflow can be an important factor regulating biological, physical, and chemical processes. The Sacramento-San Joaquin estuary is hydrologically complex, and freshwater inflow cannot be directly measured.

An index of inflow to San Francisco Bay, delta outflow, is calculated by summing the known inflows and subtracting in-channel and project diversions. DWR publishes the calculated flows as part of its DAYFLOW program. Figure 3 contains a plot of delta outflows for 1991, which was classified a critical year.

Average annual natural runoff to the estuary has been reduced significantly by hundreds of water diversions from upstream channels and in the delta and by the State Water Project and Central Valley Project pumps in the southern delta. At times, the combination of low streamflow and high delta depletions (by agriculture and the water projects) causes flows to move *upstream* in the San Joaquin River to the project pumps. This *reverse flow* occurs because most of the water pumped originates in the Sacramento system, and hydraulic conditions result in this water being drawn around the delta and up the San Joaquin River to the pumps.

During much of the year, streamflows and tidal flows interact most intensively in Suisun Bay. The fresh water, being less dense, flows downstream over the landward-flowing salt water, and the interaction of gravitational and tidal forces on material suspended in the water (algae, sediment, and small fish) can cause these materials to be concentrated. The area of maximum concentration has been termed the *entrapment zone* (or *null zone*). This zone is of ecological significance to many plants and animals residing in or migrating through the estuary. The location of the entrapment zone is primarily a function of freshwater flow from the delta; it can be in San Pablo Bay during high flows and in the eastern delta during low flows. More information on the entrapment zone can be found in Arthur and Ball (1980).

Downstream of Suisun Bay, the estuary is generally dominated by tidal forces, although moderate to high freshwater flows still dramatically affect circulation patterns. In San Pablo and Central bays, landward-flowing bottom currents distribute many bottom-dwelling organisms and free-floating larval and juvenile organisms throughout the estuary. In South Bay, however, often the bottom current is seaward and the surface current is landward (*reverse estuary*). Circulation patterns in the lower estuary are not well understood.

The Sacramento-San Joaquin estuary supports numerous species of fish, many of which are of economic importance. About 40 freshwater fish species (minnows, bass, sunfish, smelts, *etc*) are regularly caught in the delta. Four migratory fish — Chinook salmon, striped bass, American shad, and white sturgeon — are important economically and are particularly vulnerable to project operations.

In San Francisco Bay, more than 120 species of fish have been caught and identified in the sampling program. Many of the bay fish come from ocean populations that either actively migrate into the bay or are swept in by tidal and density-driven circulation patterns. The bay provides habitat during larval, juvenile, or adult stages of many of these finfish, as well as for shellfish.

In addition to such economically important species as Chinook salmon, striped bass, and waterfowl, the estuary provides habitat for

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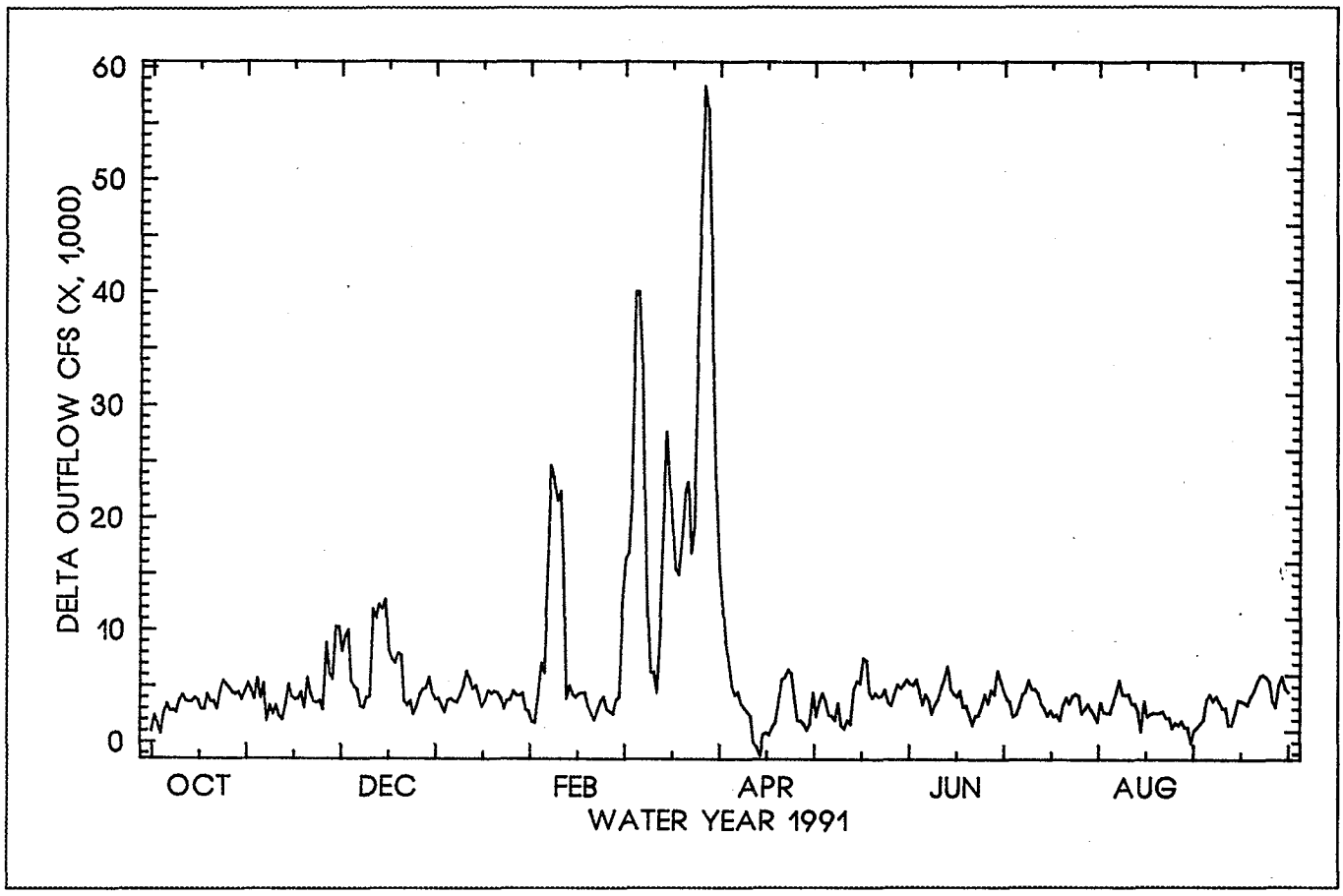
Figure 3
DAYFLOW NET DELTA OUTFLOW



numerous other animals and plants, which interact to form a complex and dynamic ecosystem.

The estuary is a focal point for water development in California because water transferred from Northern California moves through the delta. Diversion of water from the delta by the Department of Water Resources and the U.S. Bureau of Reclamation is by authority of water right permits granted by the State Water Resources Control Board. These permits are reviewed periodically to determine how the permits should be conditioned to protect fish, wildlife, and other beneficial uses. Data from the Interagency Program and others are used during these reviews to determine if changes are needed in operating criteria or water quality standards.

The Interagency Program is designed to evaluate impacts of the State and Federal water projects on the estuary. Other human activities and natural events also affect the system. Effects of changes in volume and quality of municipal and industrial wastes, irrigation return flows, dredging, bay filling, flooding of delta islands, introduction of exotic organisms, and major climatic events such as El Niño must be considered when trying to assess the impacts of diversions on the health of the estuary.

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ENVIRONMENTAL FACTORS

The DWR water right Decision 1485 compliance monitoring program was incorporated into the Interagency Program during 1990. This chapter reviews relevant findings of this program. More detailed reports on this program are available from Harlan Proctor at DWR.

Dissolved Oxygen Concentrations in the Stockton Ship Channel

Steven P. Hayes and John C. Baker
Department of Water Resources

Dissolved oxygen concentrations in the Stockton Ship Channel are monitored closely during the late summer and early fall because they can drop to levels of 5.0 mg/L or less due to low flows and warm water temperatures. Low dissolved oxygen concentrations can cause physiological stress to fish and can block migrating salmon. Dissolved oxygen monitoring sites are shown on Figure 4.

Because of the potentially adverse effects of low dissolved oxygen concentrations, a barrier was installed across the head of Old River by September 13, 1991, to divert more San Joaquin River water into the Stockton Ship Channel. Increased San Joaquin River flow through the Stockton Ship Channel can facilitate aeration, mixing, and flushing and can result in increased dissolved oxygen concentrations and improved conditions for migrating salmon.

Average daily flows recorded in the San Joaquin River during the late summer and early fall of 1991 were the lowest recorded since the 1976/1977 drought. From August through September, average daily flows in the San Joaquin River at Vernalis rarely exceeded 700 cubic feet per second, and they did not begin to exceed 1,000 cfs until late October. As a result, initial placement of the barrier could not significantly improve San Joaquin River flow downstream from the barrier and into the Ship Channel.

The lowest dissolved oxygen concentrations recorded during the current drought, which began in 1987, were measured in the Stockton Ship Channel during 1991. Surface and bottom dissolved oxygen samples collected on August 22 and September 6, prior to completion of the closure, showed little stratification (0.4 mg/L or less) throughout most of the Ship Channel and decreased eastward from the juncture of Disappointment Slough and Columbia Cut (Light 12) to the eastern end of Rough and Ready Island (Light 48), where the San Joaquin River joins the Ship Channel (Figure 5). Dissolved oxygen levels dropped to below 5.0 mg/L near Rough and Ready Island (Lights 41, 42, and 43), and surface and bottom values were below 4.0 mg/L at Light 48 in both surveys.

The strong vertical stratification detected in the turning basin on both preclosure studies appeared to be associated with a bloom of Cryptomonads. Surface chlorophyll *a* levels ranged from 30 to 50 μg/L in the turning basin throughout much of the pre- and post-closure study period. The high dissolved oxygen concentrations near the surface, a result of photosynthesis, decreased significantly at the bottom. The biochemical oxygen demand of bottom organic deposits, enriched by moribund and dead algae sinking to the bottom, and poor water circulation in the turning basin probably contributed to the exceptionally low dissolved oxygen concentrations measured at the bottom during both preclosure surveys (2.6 and 0.6 mg/L) and the September 20 and October 7 post-closure surveys (3.4 and 1.8 mg/L, respectively).

Because of the exceptionally low flows in the San Joaquin River during the fall, placement of the closure did not immediately improve circulation and raise dissolved oxygen concentrations in the Stockton Ship

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Figure 4
DISSOLVED OXYGEN MONITORING SITES

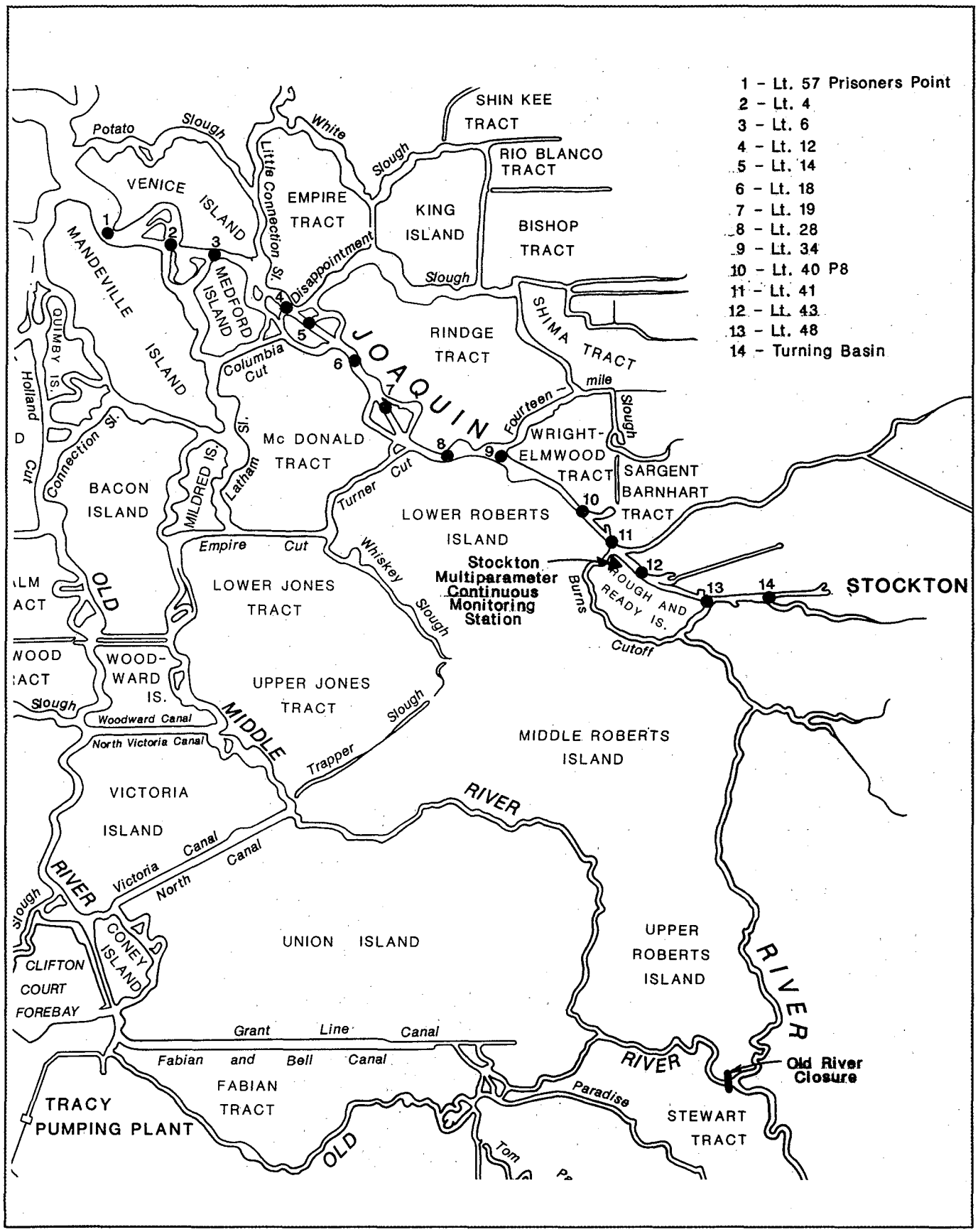

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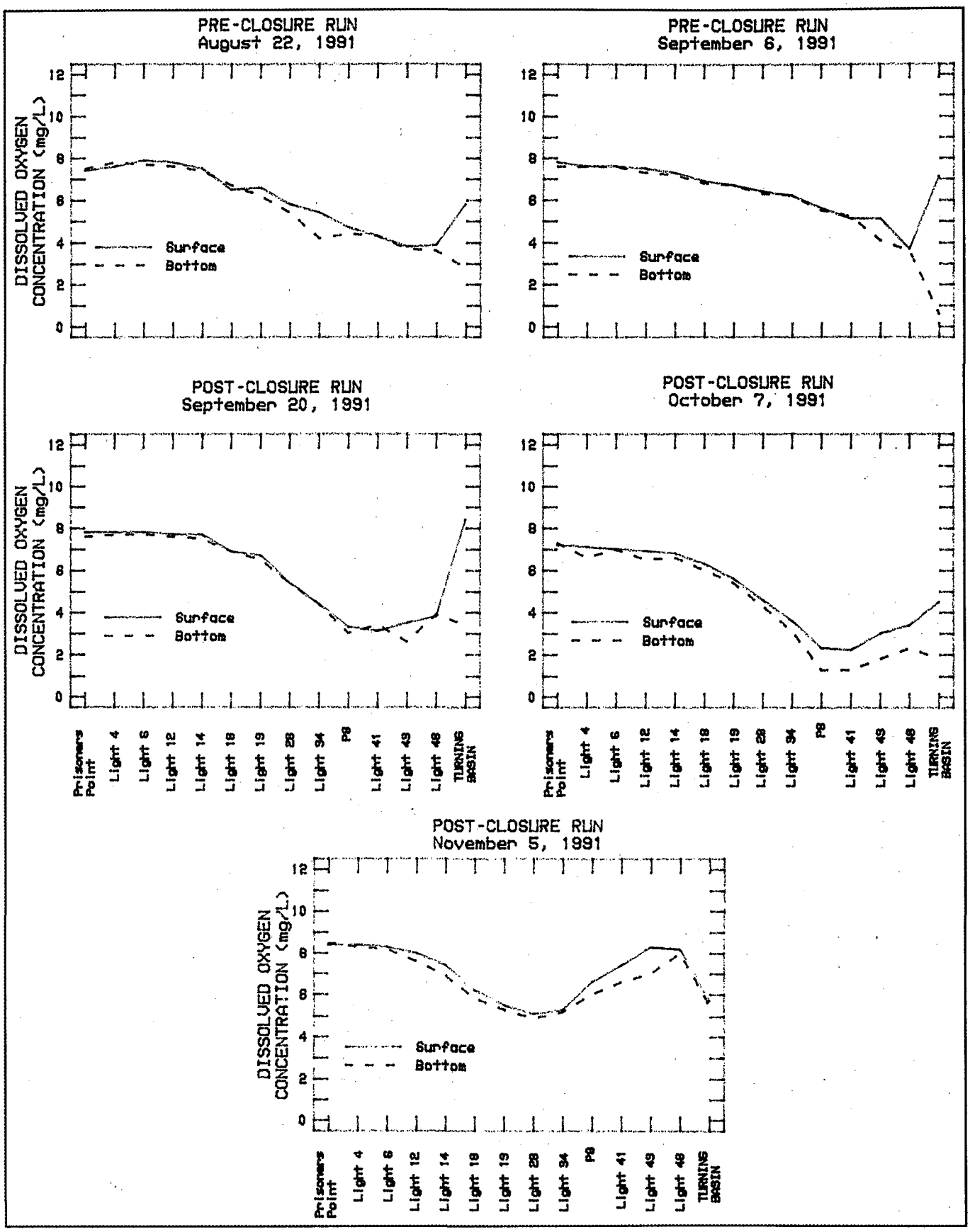
Figure 5
DISSOLVED OXYGEN IN THE STOCKTON SHIP CHANNEL



Channel. The dissolved oxygen "sag" below 5.0 mg/L identified in the Ship Channel during preclosure monitoring intensified and expanded after the closure was completed. Postclosure studies on September 20 and October 7 produced surface and bottom dissolved oxygen levels below 5.0 mg/L from Fourteenmile Slough (Light 34) and Turner Cut (Light 28) eastward to the Turning Basin (Figure 5). On September 20, a bottom sample near Rough and Ready Island (Light 43) measured 2.6 mg/L. On October 7, this "sag" area of 3.0 mg/L or less of dissolved oxygen had extended from Buckley Cove (P8) to Light 43 in both surface and bottom samples. Stratification of dissolved oxygen in the Ship Channel was also evident on October 7 from P8 eastward to Light 43, suggesting poor water circulation, warm water temperatures (23-24°C), and lack of significant tidal mixing in the area.

The final post-closure run, on November 5, showed a distinct recovery of dissolved oxygen levels throughout the Stockton Ship Channel (Figure 5). All values exceeded 5.0 mg/L except a bottom value of 4.9 mg/L east of Turner Cut (Light 28). Even with this recovery, dissolved oxygen values dropped beginning east of the Mokelumne River (Light 12) and decreasing steadily to Light 28. Recovery began again at Fourteenmile Slough (Light 34), and dissolved oxygen values increased steadily to full recovery at Light 48, where the surface value was 8.2 mg/L and the bottom value was 8.0 mg/L, perhaps due to the improved flow and mixing there. During the early part of November, average daily flows in the San Joaquin River at Vernalis showed a modest increase (maximum flow of 1,324 cfs on November 1). This increase, coupled with cooler water temperatures (16°C), could have contributed to the highly improved dissolved oxygen levels at Light 48. At the Turning Basin, there was no significant stratification, but dissolved oxygen levels dropped to 5.7 mg/L at the surface and 5.5 mg/L near the bottom. The lower dissolved oxygen levels were probably due to the residual effects of a subsiding algal bloom that had occurred previously in the area.

Phytoplankton

Peggy Lehman
Department of Water Resources

As required by Decision 1485, the DWR Compliance Monitoring Branch collects phytoplankton samples at 19 sites throughout the delta and Suisun Bay. Sample analyses include measurement of chlorophyll *a* concentration, an estimate of phytoplankton biomass, and enumeration and identification of phytoplankton species.

For this summary, selected sites were grouped into regions based on similarity of phytoplankton community assemblages (Lehman and Smith 1991). Phytoplankton production was summarized for the:

Northern Delta	C3, Greens Landing
Southern Delta	C7, Mossdale P8, Buckley Cove
Suisun Bay	D4, Point Sacramento D7, Grizzly Bay D9, Honker Bay
San Pablo Bay	D41, Pinole Point
Central Delta	D28a, Rancho Del Rio

Sampling locations and associated regions are presented in Figure 6.

Northern Delta

Chlorophyll concentrations in the northern delta were consistently below 3 µg/L in 1991. Concentrations peaked in January, declined during the spring, and remained stable (0.5 to 1 µg/L) throughout the summer and fall (Figure 7). Percent chlorophyll describes the ratio of chlorophyll concentration to chlorophyll plus phaeophytin concentration, and higher ratios occur in more rapidly growing phytoplankton populations. High percent chlorophyll values were calculated for February, April, and November, when the phytoplankton community was composed of diatoms, greens, and flagellates (Figure 8).

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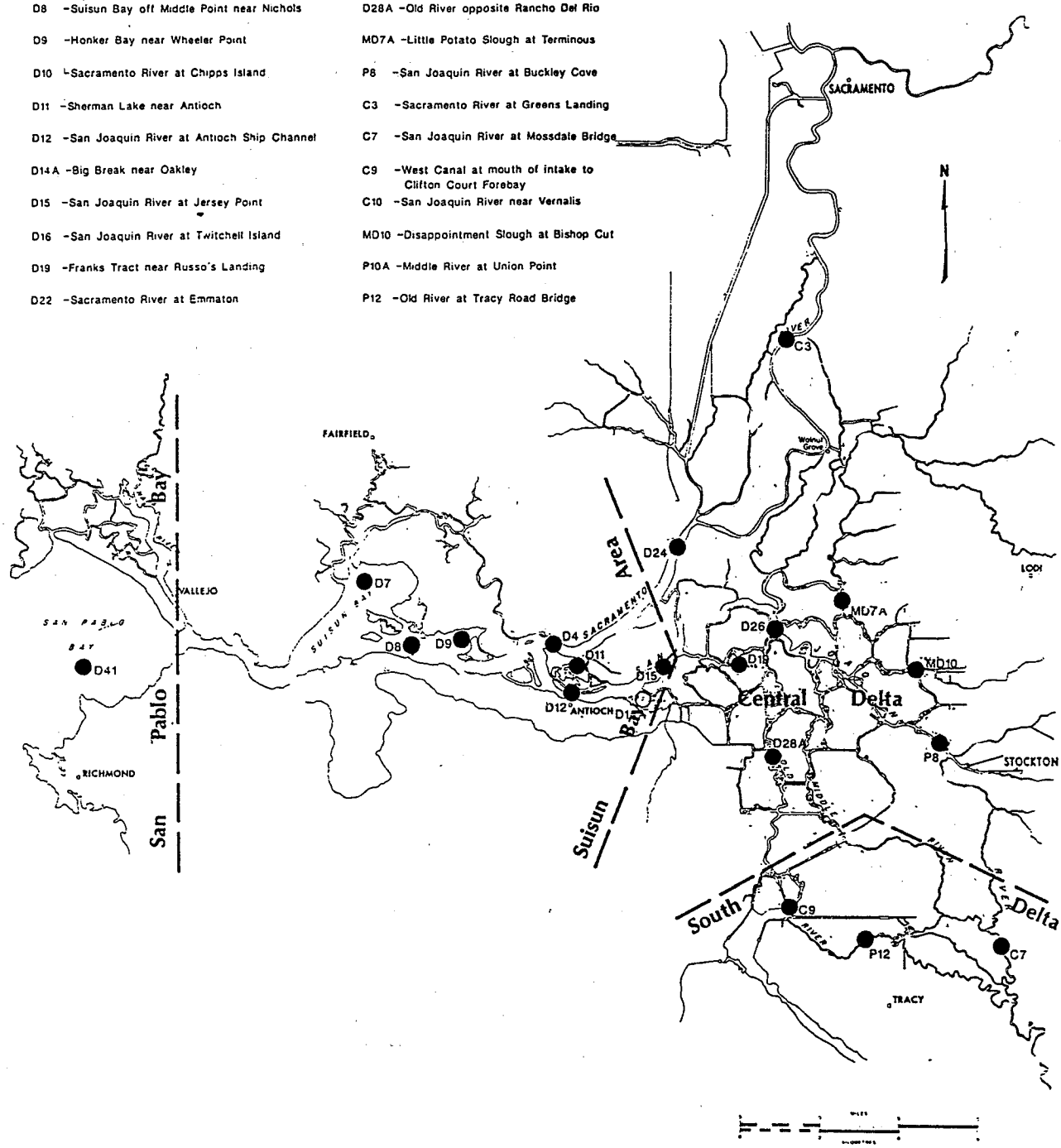
Figure 6
COMPLIANCE MONITORING SITES

Site Number	Site Name
D4	-Sacramento River above Point Sacramento
D6	-Suisun Bay off Bulls Head Point near Martinez
D7	-Grizzly Bay at Dolphin near Suisun Slough
D8	-Suisun Bay off Middle Point near Nichols
D9	-Honker Bay near Wheeler Point
D10	-Sacramento River at Chipps Island
D11	-Sherman Lake near Antioch
D12	-San Joaquin River at Antioch Ship Channel
D14A	-Big Break near Oakley
D15	-San Joaquin River at Jersey Point
D16	-San Joaquin River at Twitchell Island
D19	-Franks Tract near Russo's Landing
D22	-Sacramento River at Emmaton
D24	-Sacramento River below Rio Vista Bridge
D26	-San Joaquin River at Potato Point
D41	-San Pablo Bay near Pinole Point
D28A	-Old River opposite Rancho Del Rio
MD7A	-Little Potato Slough at Terminous
P8	-San Joaquin River at Buckley Cove
C3	-Sacramento River at Greens Landing
C7	-San Joaquin River at Mossdale Bridge
C9	-West Canal at mouth of intake to Clifton Court Forebay
C10	-San Joaquin River near Vernalis
MD10	-Disappointment Slough at Bishop Cut
P10A	-Middle River at Union Point
P12	-Old River at Tracy Road Bridge



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Chlorophyll maximum in the northern delta was somewhat higher during 1991 than for 1987 through 1989. However, among years, chlorophyll maxima during 1987 through 1991 were among the lowest on record (Figure 9). Relatively high percent chlorophyll values suggest the winter of 1991 had somewhat enhanced phytoplankton growth compared with the early years of the drought. Overall, however, percent chlorophyll concentrations were low compared with pre-1981 (Figure 10).

Figure 7
MEAN MONTHLY CHLOROPHYLL CONCENTRATION IN THE NORTHERN DELTA, 1991

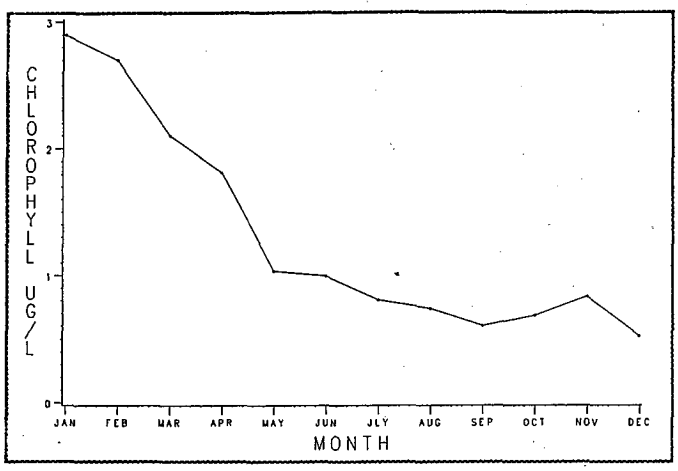


Figure 9
MEAN MONTHLY CHLOROPHYLL CONCENTRATION IN THE NORTHERN DELTA, 1971-1991

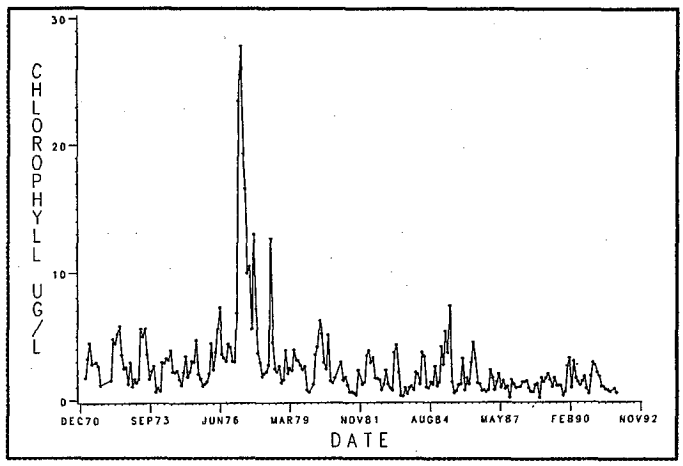


Figure 8
MEAN MONTHLY PERCENT CHLOROPHYLL CONCENTRATION IN THE NORTHERN DELTA, 1991

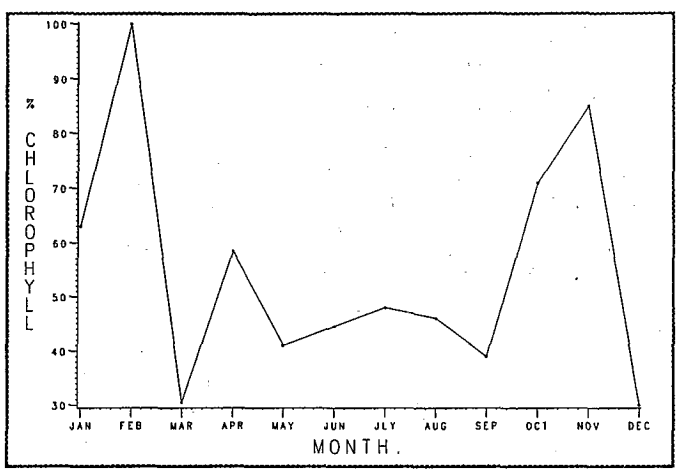
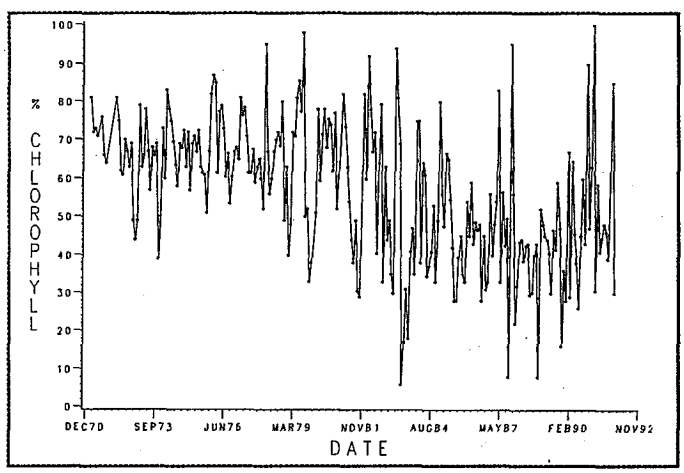


Figure 10
MEAN MONTHLY PERCENT CHLOROPHYLL CONCENTRATION IN THE NORTHERN DELTA, 1971-1991



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Central Delta

Chlorophyll concentrations remained below 4 µg/L in the central delta throughout most of 1991, except September (Figure 11). During September, chlorophyll concentration increased to 15 µg/L in association with a mixed phytoplankton community composed primarily of *Melosira granulata* and flagellates. Actively growing phytoplankton cells characterized the phytoplankton community throughout summer and fall, when the chlorophyll ratio was between 55 and 70 percent (Figure 12). Low chlorophyll ratios in November probably resulted from the decline of the September maximum.

Like the northern delta, the chlorophyll maximum was higher in 1991 than 1990, but reflected the characteristically lower chlorophyll concentrations measured during drought years (1977 and 1987 to 1991) or wet years (1982) (Figure 13). Percent chlorophyll values averaged about 60 percent over time, but interannual variation was concentration-dependent (Figure 14).

Figure 11
MEAN MONTHLY CHLOROPHYLL CONCENTRATION IN THE CENTRAL DELTA, 1991

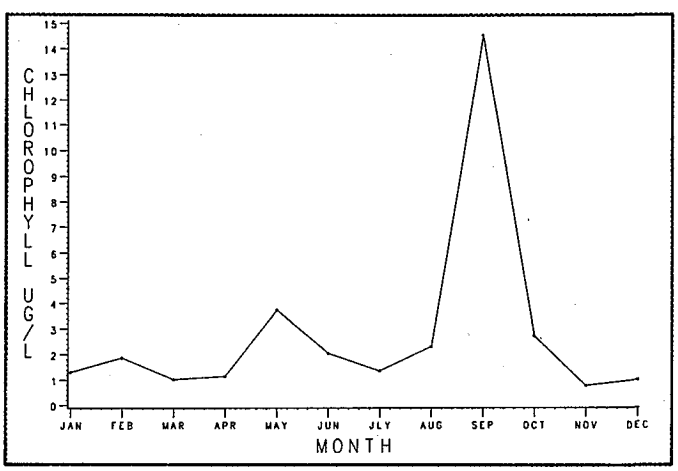


Figure 13
MEAN MONTHLY CHLOROPHYLL CONCENTRATION IN THE CENTRAL DELTA, 1971-1991

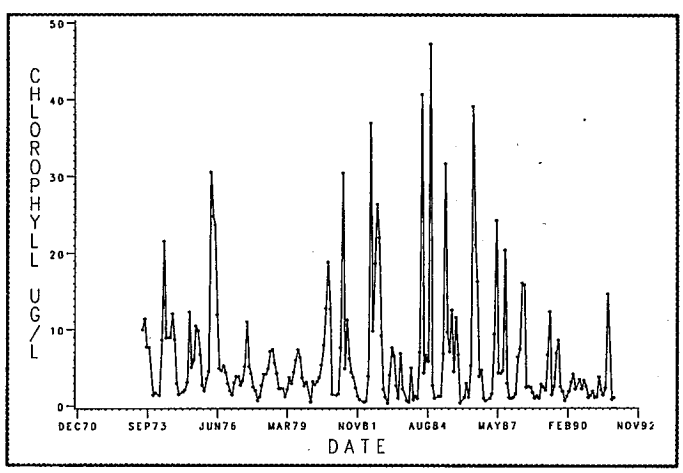


Figure 12
MEAN MONTHLY PERCENT CHLOROPHYLL CONCENTRATION IN THE CENTRAL DELTA, 1971-1991

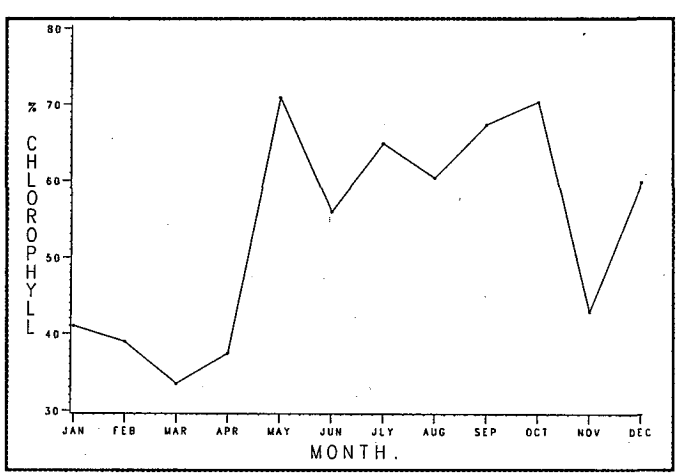
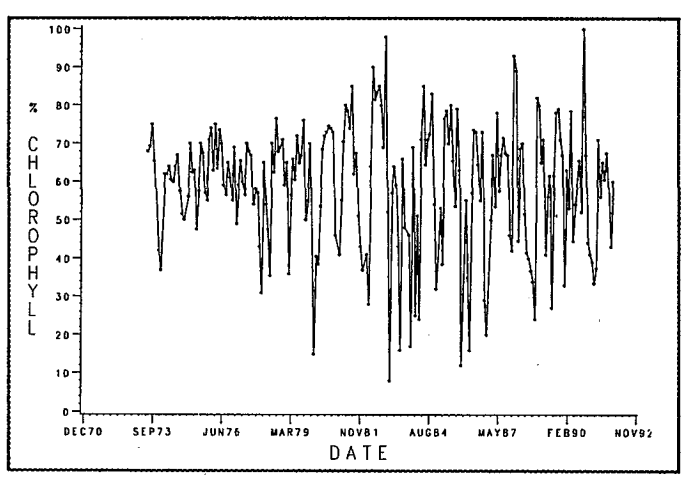


Figure 14
MEAN MONTHLY PERCENT CHLOROPHYLL CONCENTRATION IN THE CENTRAL DELTA, 1971-1991



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Southern Delta

Among regions, chlorophyll concentrations were highest in the southern delta. Chlorophyll concentrations remained above 10 µg/L throughout most of the year and reached maxima of 130 µg/L in June and September (Figure 15). Chlorophyll maxima were associated with the presence of a mixed phytoplankton community composed of diatoms, greens, and flagellates including *Thalassiosira* spp., *Cyclotella* spp., *Skeletonema potamos,* and flagellates. The high chlorophyll concentrations were accompanied by relatively low chlorophyll ratios of 60 to 67 percent (Figure 16).

Chlorophyll maxima were high in 1991 compared with 1978 through 1990 and were similar to those measured during the 1976-1977 drought (Figure 17). The chlorophyll ratio varied little but was within the low range of values measured after 1981 (Figure 18).

Figure 15
MEAN MONTHLY CHLOROPHYLL CONCENTRATION IN THE SOUTHERN DELTA, 1991

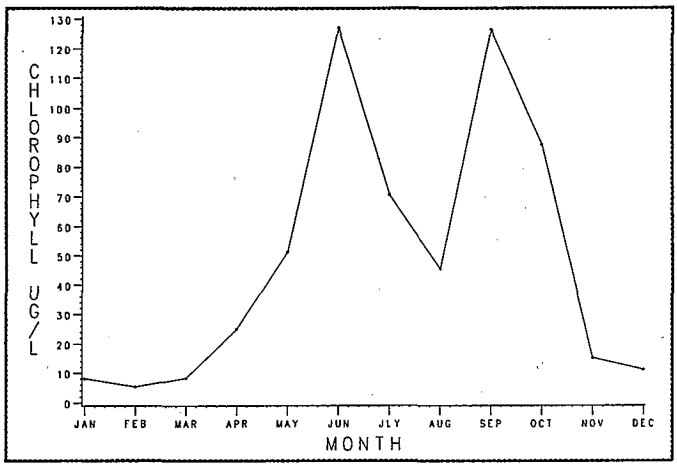


Figure 17
MEAN MONTHLY CHLOROPHYLL CONCENTRATION IN THE SOUTHERN DELTA, 1971-1991

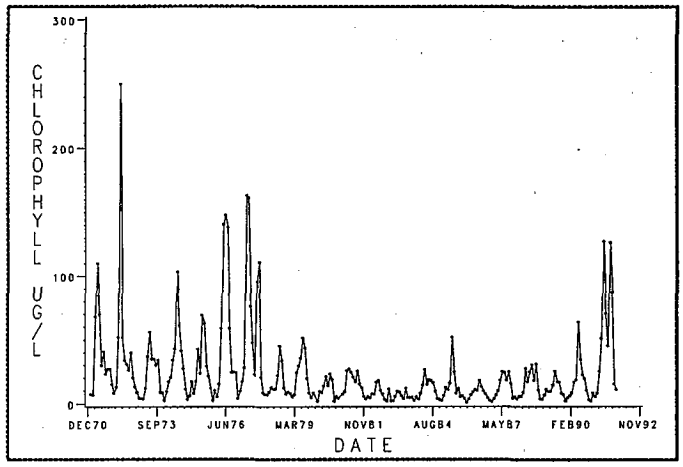


Figure 16
MEAN MONTHLY PERCENT CHLOROPHYLL CONCENTRATION IN THE SOUTHERN DELTA, 1991

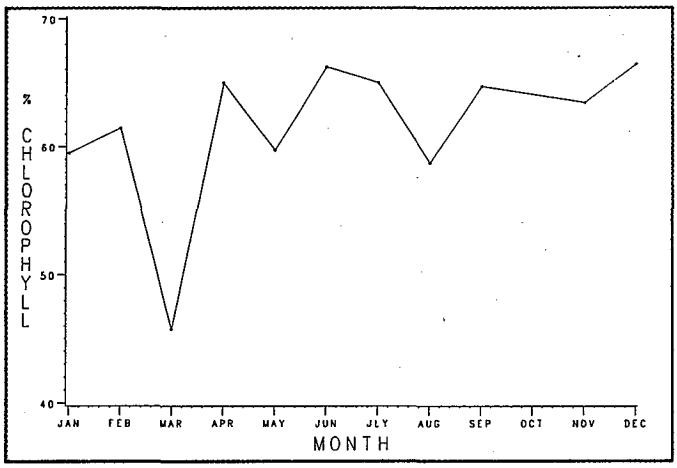
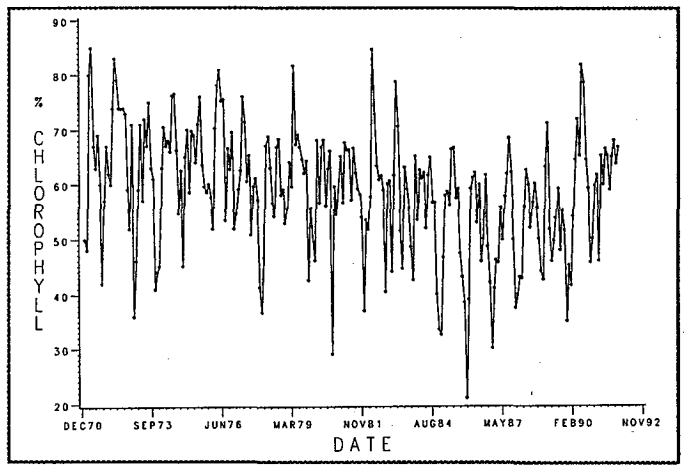


Figure 18
MEAN MONTHLY PERCENT CHLOROPHYLL CONCENTRATION IN THE SOUTHERN DELTA, 1971-1991



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San Pablo Bay

Chlorophyll concentrations in San Pablo Bay remained below 6 µg/L throughout the year (Figure 19). Chlorophyll maxima peaked in the spring and were associated with a phytoplankton community composed of greens, dinoflagellates, and flagellates. Even though chlorophyll concentrations were low, high chlorophyll ratios of 70 to 80 percent suggest these phytoplankton populations were growing rapidly (Figure 20). The comparatively lower percent chlorophyll ratios (54 percent) in May were probably associated with the decline of the April maximum.

Chlorophyll maxima in San Pablo Bay were somewhat higher in 1991 than in 1987 through 1989 but were far lower than those measured during the early 1980s (Figure 21). The low variation of chlorophyll concentration in 1991 was accompanied by relatively high and stable percent chlorophyll ratios compared with 1981 through 1990 (Figure 22).

Figure 19
MEAN MONTHLY CHLOROPHYLL CONCENTRATION IN SAN PABLO BAY, 1991

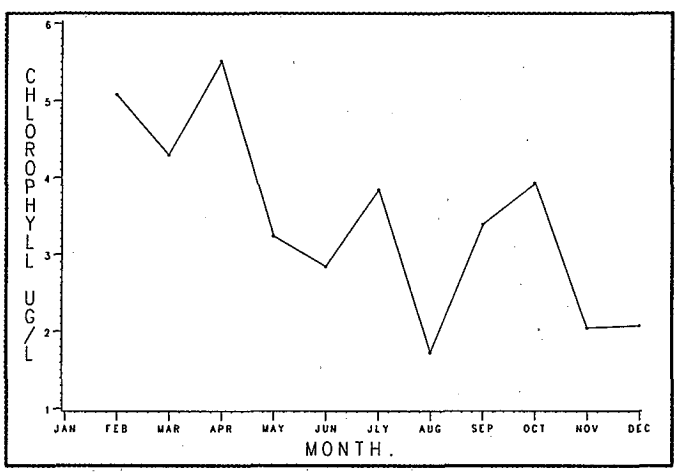


Figure 21
MEAN MONTHLY CHLOROPHYLL CONCENTRATION IN SAN PABLO BAY, 1971-1991

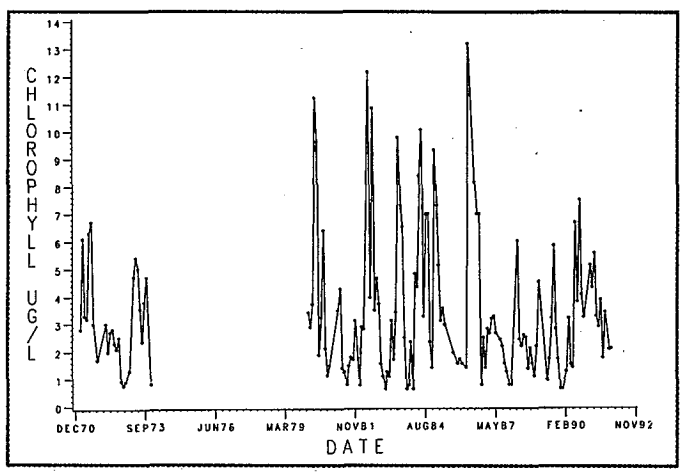


Figure 20
MEAN MONTHLY PERCENT CHLOROPHYLL CONCENTRATION IN SAN PABLO BAY, 1991

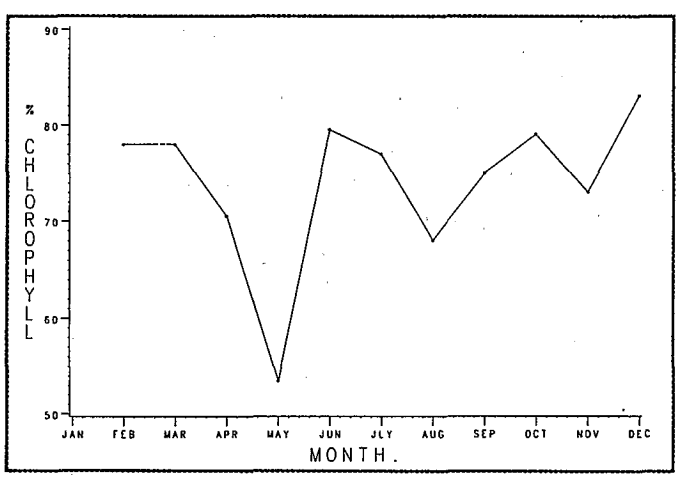
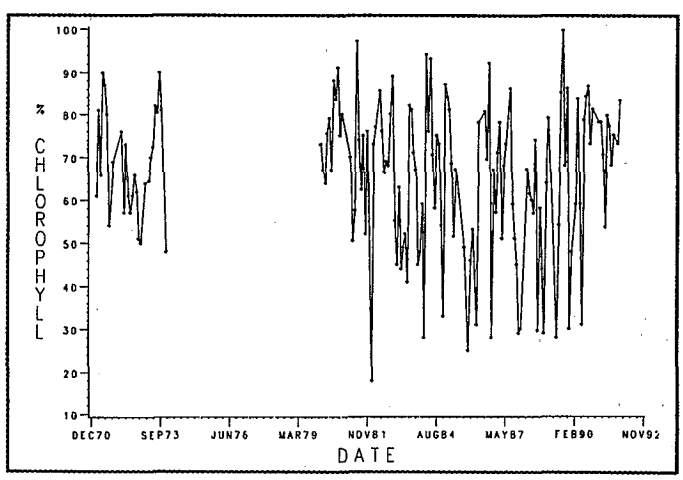


Figure 22
MEAN MONTHLY PERCENT CHLOROPHYLL CONCENTRATION IN SAN PABLO BAY, 1971-1991



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Suisun Bay

Chlorophyll concentrations did not exceed 2 µg/L in Suisun Bay throughout 1991 (Figure 23). The phytoplankton community was depauperate and composed of a few diatoms and flagellates. Low chlorophyll ratios indicate only 30 to 50 percent of the chlorophyll in the water column was associated with actively growing phytoplankton and may demonstrate the influence of benthic grazing on cell breakdown observed in this area since 1987 (Nichols 1985) (Figure 24).

Chlorophyll concentrations continued to be an order of magnitude lower in 1991 compared with other years (Figure 25). Low chlorophyll concentrations have been measured in Suisun Bay since 1987 as a result of increased benthic grazing associated with introduction of the Asian clam *Potamocorbula amurensis*. The potential impact of benthic grazing on the phytoplankton community was also suggested by the lower chlorophyll ratios measured since 1987 (Figure 26).

Figure 23
MEAN MONTHLY CHLOROPHYLL CONCENTRATION IN SUISUN BAY, 1991

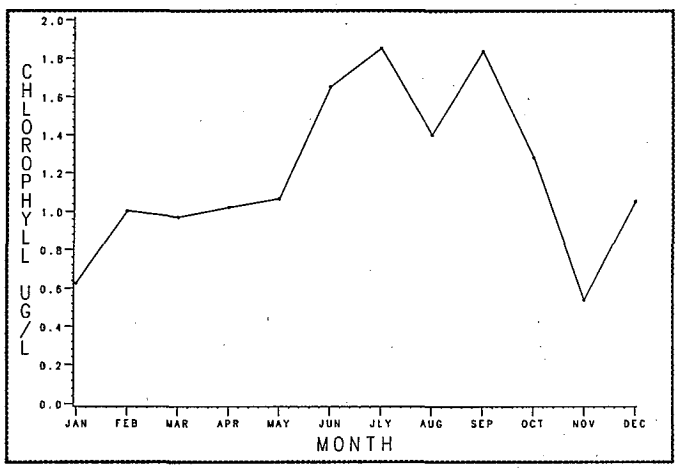


Figure 25
MEAN MONTHLY CHLOROPHYLL CONCENTRATION IN SUISUN BAY, 1971-1991

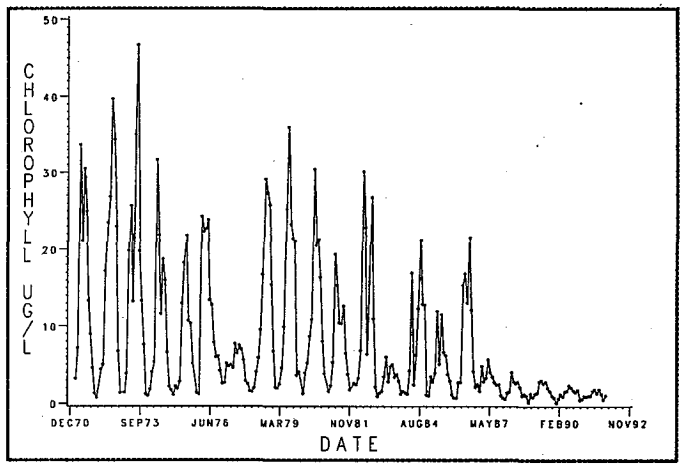


Figure 24
MEAN MONTHLY PERCENT CHLOROPHYLL CONCENTRATION IN SUISUN BAY, 1991

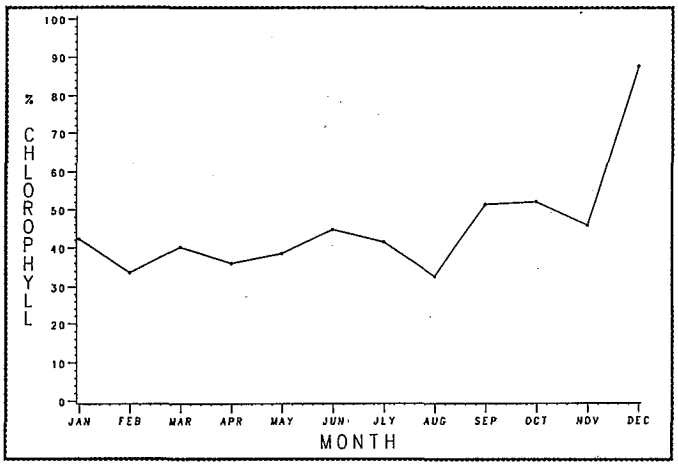
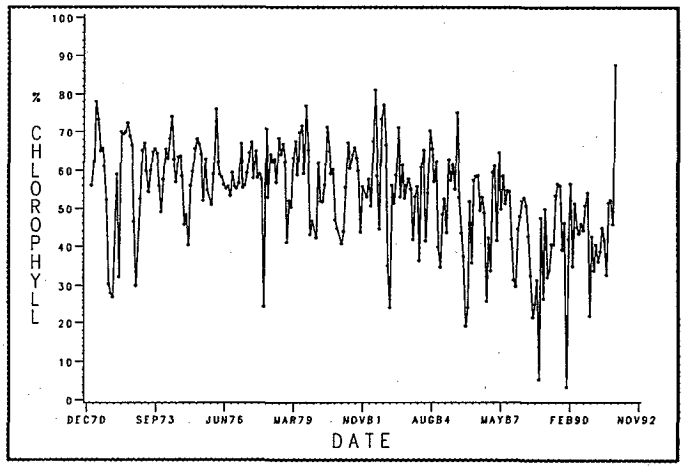


Figure 26
MEAN MONTHLY PERCENT CHLOROPHYLL CONCENTRATION IN SUISUN BAY, 1971-1991



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Zooplankton

James Orsi
Department of Fish and Game

Zooplankton are small aquatic organisms that constitute an important element in the food chain that leads from algae to fish. They range in length from less than 100 micrometers to several millimeters. Four major types of zooplankton are sampled in this study: rotifers, copepods, cladocerans, and mysid or opossum shrimp. Copepods are considered the most abundant life form on Earth.

During 1991, zooplankton study personnel published two papers in scientific journals. "Selective Predation by Larval Striped Bass on Native and Introduced Copepods" (Meng and Orsi 1991) presented work resulting from a cooperative laboratory study with the University of California, Davis, on the feeding of larval striped bass on several species of copepods. Larval bass fed most readily on *Cyclops,* followed by *Eurytemora,* then the introduced *Pseudodiaptomus forbesi.* Capture rates were lowest for the introduced *Sinocalanus*. The two introduced Asian copepods are, thus, the least available food items for larval bass. Differences in predation efficiency appeared to be related to swimming and escape behavior of the copepods rather than to size of copepod or presence of egg sacs. *Sinocalanus* leaped in unpredictable directions and then hung motionless, rendering itself undetectable by bass searching for disturbances in the water. The other copepods swam constantly and were incapable of making the extensive leaps of *Sinocalanus*.

"*Pseudodiaptomus forbesi* and *P.marinus*, the Latest Copepod Immigrants to California's Sacramento-San Joaquin Estuary" (Orsi and Walter 1991) was written in collaboration with the Smithsonian Institution. The paper described the introduction of *Pseudodiaptomus forbesi* and *P.marinus*, presumably from ballast water of trans-Pacific vessels. Since its introduction in 1988, *Pseudodiaptomus forbesi* has replaced *Eurytemora* in the entrapment zone during summer and fall. It extends well upstream from the entrapment zone as far as Stockton in the San Joaquin River, where it is very abundant. It does not develop high populations until June, rather late in the striped bass spawning season.

A report on long-term trends in *Neomysis* and zooplankton abundance from 1972 to 1988 was completed in 1991 and reviewed by the Interagency Coordinators. It will be published in 1992 as an Interagency Technical Report. (A version of the report will also be submitted for publication in the *Journal of Plankton Research.*) The report documents that long-term abundance trends for most native zooplankton taxa have been down (Figure 27). The exceptions are the freshwater cladoceran *Bosmina,* the marine copepod *Acartia,* barnacle nauplii, and crab zoea.

Neomysis had a downtrend from 1975 to 1978, followed by a period of stabilization at a lower level (Figure 28). In 1988, abundance of *Neomysis, Eurytemora, Acartia,* and *Sinocalanus* dropped sharply. The southern delta (Old and Middle rivers) was the area of the estuary with the greatest number of taxa showing declines. Fall was the season in which most taxa had declines. During the recent drought years, *Eurytemora* was most abundant in spring in the San Joaquin River above the mouth of the Mokelumne River. This was upstream from its usual location in the entrapment zone. Predation by the introduced Asian clam is a probable cause of its absence in the entrapment zone (Kimmerer, Gartside, and Orsi, unpublished).

Eurytemora has been essentially absent from our summer catches since 1988, but it reappears in fall at low densities. The upstream location and low abundance of *Eurytemora* during the striped bass spawning season means the most important component of the planktonic food supply of larval striped bass at the time of first feeding was low. Other significant planktonic elements of the larval bass diet, *Cyclops* and *Daphnia,* also had low population densities during the drought.

Neomysis abundance has been very low during the recent drought years, particularly during late summer and fall, and adult mysids have been shorter during summer. The small size of adults is probably a

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Figure 27
ABUNDANCE TRENDS OF SOME ZOOPLANKTON TAXA THAT DECLINED FROM 1972 TO 1988
Anomalies are annual means for all stations, corrected for salinity effects.

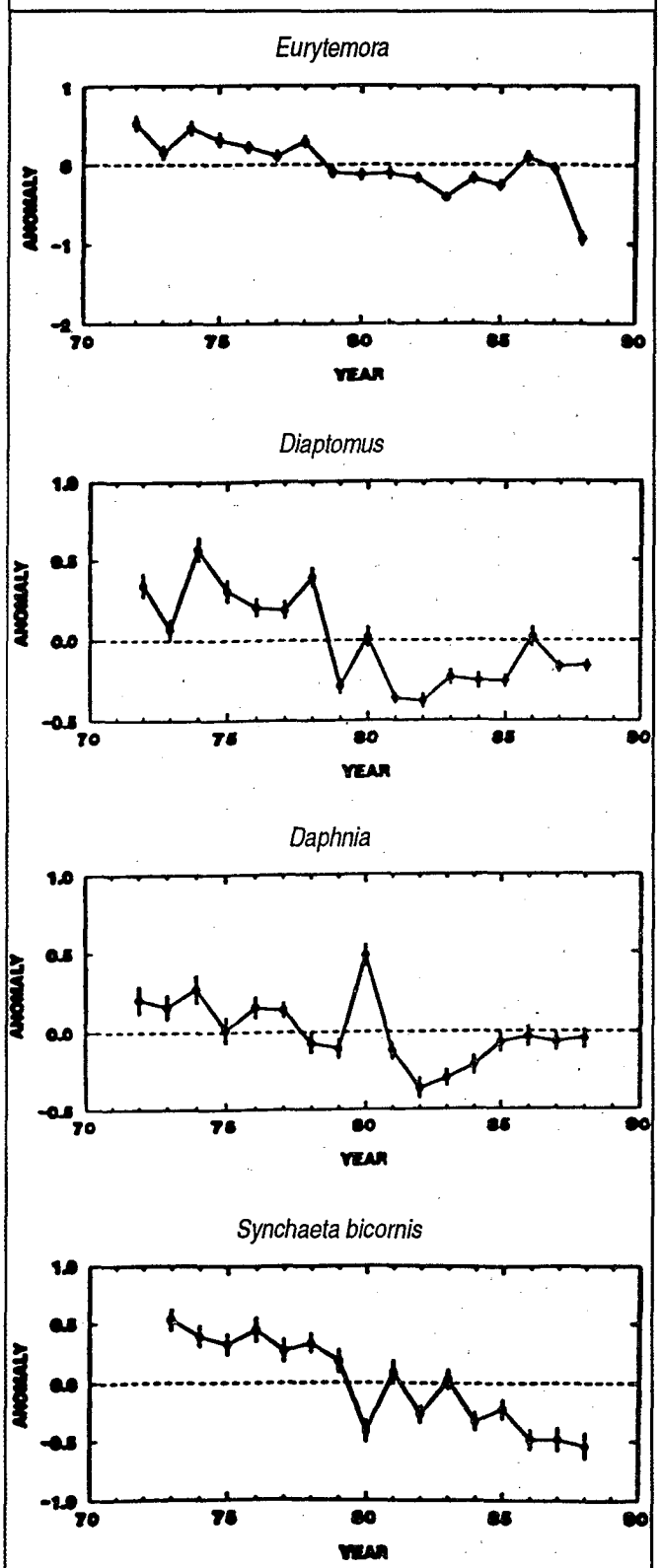
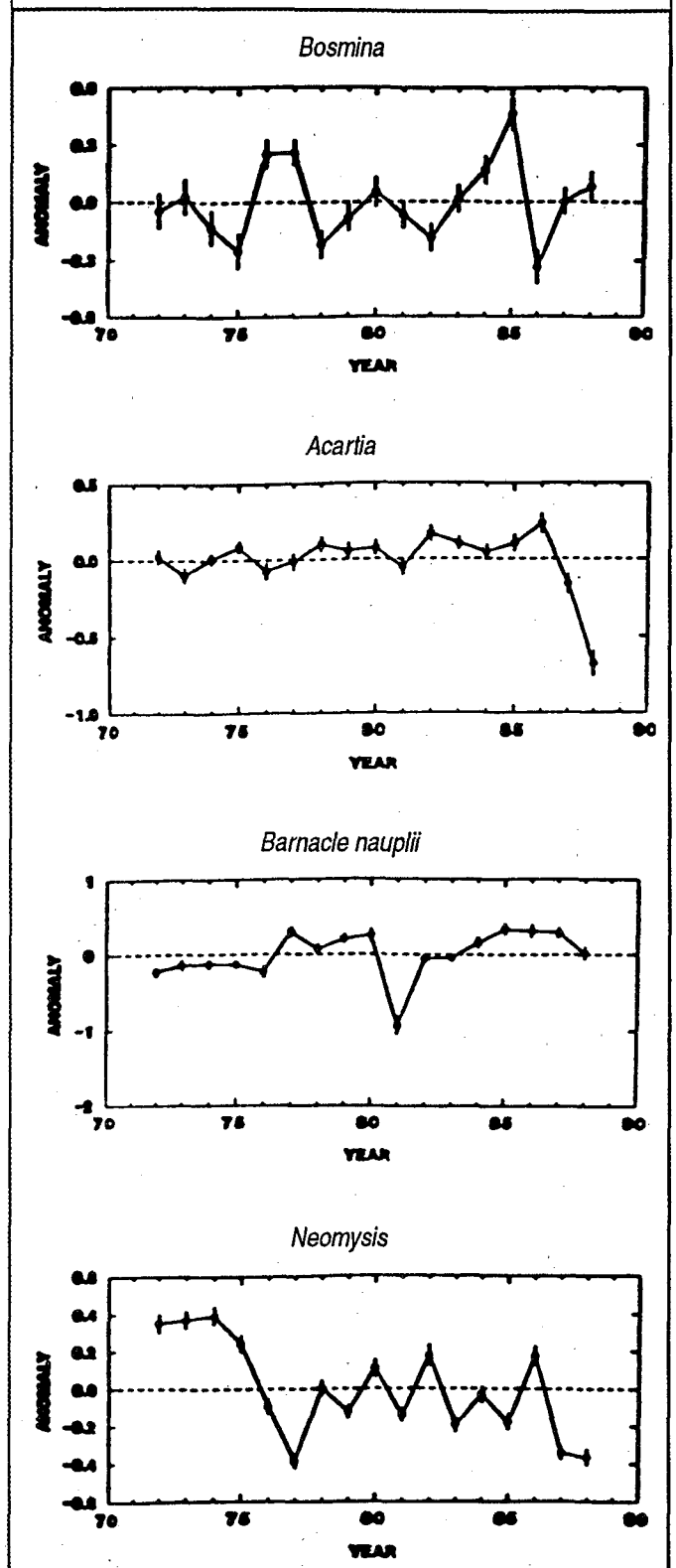


Figure 28
ABUNDANCE TRENDS OF SOME ZOOPLANKTON TAXA THAT DID NOT DECLINE FROM 1972 TO 1988
Anomalies are annual means for all stations, corrected for salinity effects.



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temperature effect, because mysids mature at shorter lengths and die younger when temperatures are high, as they have been in summer during the drought. Food supply for mysids (phytoplankton and zooplankton) has been low since 1988, but there is no evidence that food is at limiting levels. The low *Neomysis* abundance means striped bass greater than 38 millimeters long, the size at which they begin to feed heavily on *Neomysis,* do not have as much food as they did before the drought.

Future research on zooplankton should concentrate on two areas: vertical migration and food.

Vertical migration interacting with 2-layered estuarine flow enables zooplankton to remain in place in spite of the net seaward movement of the water. This has been shown for *Neomysis* in this estuary (Orsi 1986), but the vertical migration of each species is different and these differences determine the location of each species in the salinity gradient. For instance, *Eurytemora* has an abundance peak in the entrapment zone and *Sinocalanus* peaks in fresh water. We did vertical migration studies of *Eurytemora* and *Sinocalanus* several years ago, but these studies are incomplete.

The effects of food and the interactions of introduced and native species are also inadequately understood. Experiments in 1988 showed that *Eurytemora* was not food-limited at low ambient phytoplankton concentrations; however, this work needs confirmation and expansion. It would be useful to determine the actual limiting levels (those at which growth and reproduction are reduced) for important copepods and *Neomysis*. This problem is complicated because the zooplankton may feed on several food sources: algae, other zooplankton, and detritus. Species, size, and shape of the algae are also factors that affect the ability of zooplankton to utilize them.

Survey of Aquatic Vegetation

Zachary Hymanson
Department of Water Resources

Each fall DWR conducts a littoral zone vegetation survey of the delta. Primary objectives are:

- To augment the established annual survey conducted by the Department of Food and Agriculture to detect the presence of *Hydrilla verticillata* in the delta.
- To describe the type and extent of aquatic vegetation in the delta.
- To continue the compilation of a long-term database that could help in anticipating impacts to operation of the State Water Project.

Between 1989 and 1990, vegetative surveys were conducted twice annually, in spring and fall. Aerial photographs of each site were taken in conjunction with the spring surveys to facilitate documentation of long-term changes in aquatic vegetation. A summary analysis of survey results showed little seasonal variability in vegetative extent or occurrence (IESP 1991), so vegetative surveys are now done only once each year and aerial photography has been discontinued. This schedule will continue at least until the end of the current drought.

The Department of Food and Agriculture's annual delta survey for *H. verticillata* is part of a statewide program designed to detect the spread of this exotic aquatic weed. *H. verticillata* is native to Africa and was introduced into California in 1976 via Florida by the aquarium plant industry (Yeo and McHenry 1977). This fast-growing aquatic plant propagates by vegetative fragmentation, tuber sprouts, and turion formation. These fundamentally different, yet highly successful, forms of reproduction greatly broaden the potential habitat of this organism and render complete eradication of established populations extremely difficult.

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Once established, *H. verticillata* can quickly clog waterways and pumps, severely curtailing the utility of a water system. During its 1991 survey, the Department of Food and Agriculture did not find any *H. verticillata* in the delta (Aurelio Posadas, DFA, personal communication).

Methods

Each vegetative survey includes a sampling of ten representative sites within the central and southern delta (Figure 29). Site selection was based on a surface photograph reconnaissance survey conducted in October 1988. All sites were sampled from a DWR monitoring vessel. The following information was collected at each site:

- Water temperature and turbidity at one meter.
- Secchi disc depth.
- Water depth at the waterward edge of the submerged vegetation.
- Estimated distance any aquatic vegetation extended from shore.
- A general site description, including photographs.

After obtaining the descriptive information, a minimum of three random grab samples for aquatic vegetation were made using a "Hydrilla Hook". Initial collections of all plant species were sorted, washed, and pressed for preservation as herbarium specimens. The first collection of each species was identified by Dr. Doug Barbe of the Department of Food and Agriculture, Botany Laboratory. Subsequent collections were identified using voucher herbarium specimens.

Results and Discussion

Of the ten sites sampled during the survey, eight had aquatic vegetation (Table 2). Six species of submerged and emergent vascular plants and one species of algae were seen or collected. The plants collected were typical members of the delta flora and included the species *Egeria densa* (anachoris), *Myriophyllum spicatum* (milfoil), *Ceratophyllum demersum* (hornwort), *Potamogeton latifolius* (western pondweed), and *P. crispus* (crisp-leaved pondweed). *Scirpus acutis* (common tule) was seen at six sites. However, this plant could not be collected with the Hydrilla Hook, so its presence was documented with the site description photographs. The red alga *Compsopogon coeruleus* was growing epiphytically on submerged plants at Site 9. No *Hydrilla verticillata* was seen or collected. Overall, *S. acutis* was the dominant emergent species; *E. densa* and *M. spicatum* were the dominant submerged species.

The six surveys conducted to date show a stable assemblage of aquatic plants (Table 2). The same taxa have been seen or collected in each survey, with the exception of *Potamogeton nodosus,* which was only collected at Site 2 in the spring (May 1988) survey. Some species, such as *Egeria densa* and *Myriophyllum spicatum*, occur at several locations throughout the delta, although their distribution varies seasonally. Other species, such as *Potamogeton latifolius* and *P. crispus*, generally occur at one site and do not vary seasonally. Epiphytic algae are most often collected in the fall.

Analyses of previous data have revealed no obvious relationships between water quality variables and the occurrence of aquatic vegetation among seasons or years (DWR 1992). However, some patterns in surface water quality have emerged when results of all surveys were compared. Secchi disc depths were generally greater in fall than in spring (IESP 1991). Although water temperatures showed more variability, they tended to be lower in fall than in spring (IESP 1991).

Analysis of data from the fall surveys permits an examination of interannual variability. Secchi disc depth measurements showed limited variation among years, with the exception of measurements collected in November 1990 (Figure 30). The 1990 Secchi disk depths were somewhat greater than measurements from other years at six out of ten sites. Since light is probably the factor most limiting to littoral zone vegetation in the delta, this lack of variability suggests

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Figure 29
AQUATIC VEGETATION SURVEY SITES

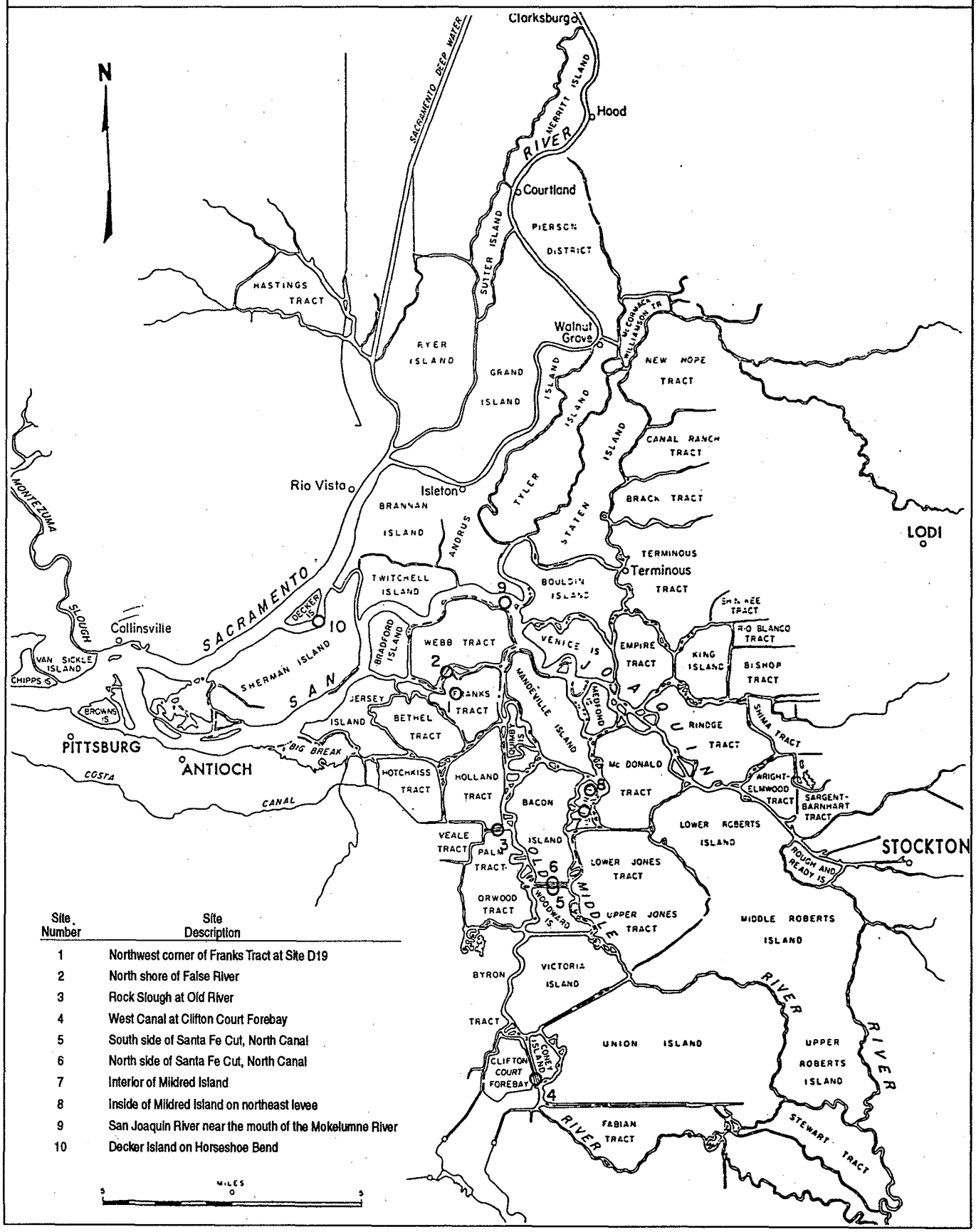

Table 2
DISTRIBUTION OF LITTORAL ZONE VEGETATION

Sampling Date/ Site Number	Plant Species: *Egeria densa*	*Myriophyllum spicatum*	*Ceratophyllum demersum*	*Potamogeton latifolius*	*Potamogeton crispus*	*Potamogeton nodosus*	*Eichhornia crassipes*	*Scirpus acrutis*
November 1991								
1*								
2	X	X	X					X
3	X	X						X
4	X	X						
5	X	X						X
6	X	X						X
7*								
8	X	X						X
9				X	X			
10	X							X
November 1990								
1*								
2	X	X	X					X
3							X	X
4	X							
5		X					X	X
6	X	X						
7*								
8	X	X	X					X
9				X	X			
10							X	X
May 1990								
1*								
2	X		X					X
3								X
4	X	X						
5	X							X
6		X						X
7*								
8		X						X
9				X	X			
10	X		X					X
November 1989								
1*								
2*								
3							X	X
4*								
5	X	X						X
6	X	X						X
7*								
8		X	X					X
9				X	X			X
10	X	X				X		
May 1989								
1*								
2		X	X			X		X
3								X
4	X	X						
5		X			X			X
6	X							X
7*								
8		X						X
9				X	X			
10	X							X

*No vegetation.

C—042741

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Table 2 (continued)
DISTRIBUTION OF LITTORAL ZONE VEGETATION

Sampling Date/ Site Number	Plant Species							
	Egeria densa	*Myriophyllum spicatum*	*Ceratophyllum demersum*	*Potamogeton latifolius*	*Potamogeton crispus*	*Potamogeton nodosus*	*Eichhornia crassipes*	*Scirpus acrutis*
November 1988								
1*								
2	X	X	X				X	X
3	X							X
4*								
5	X	X						X
6	X	X						X
7*								
8		X	X					X
9				X	X			
10	X							X

*No vegetation.

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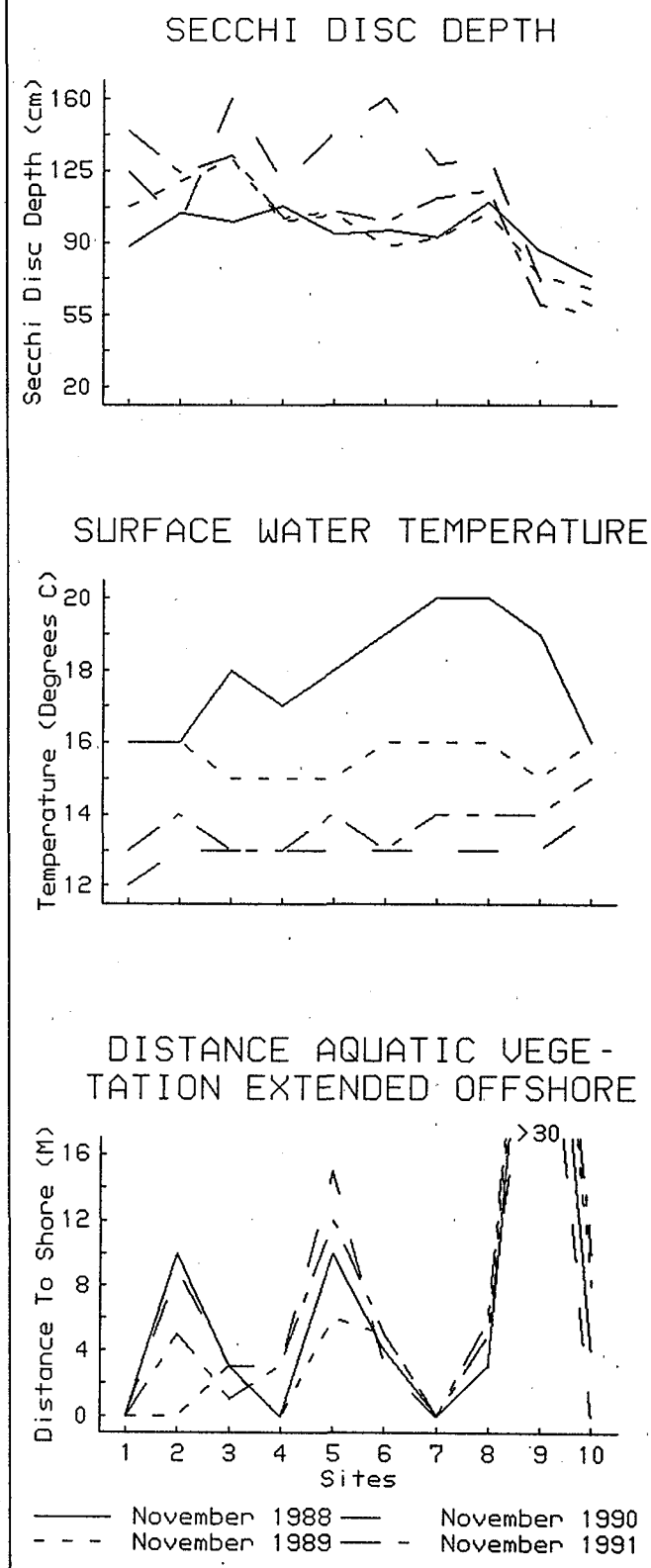
growth limitation due to light availability is fairly consistent among years.

Interannual variations in water temperature were more apparent (Figure 30). Temperatures were highest in 1988 and lowest in 1990. The largest temperature range was at site 8 (8°C), and the smallest range was at site 2 (3°C). However, these variations in water temperature probably had little effect on the littoral zone vegetation. All of the species collected have geographic ranges that place them in temperatures well above or below temperatures measured in the survey region (D. Barbe, DFA, personal communication). Conversely, low air temperature does affect the emergent species *Eichhorina crassipes* (water hyacinth), which generally suffers a substantial die-off each winter.

Measurements of vegetative extent (*ie,* the distance littoral zone vegetation extends out from the shoreline) were used to indicate changes in vegetative biomass, since these two variables are directly related. Increases in vegetative extent can have direct effects on water project operations by restricting channel water flow and accelerating the rate of sediment accumulation. With the exception of Sites 2 and 5, vegetative extent remained nearly constant over the four fall surveys (Figure 30). Variation at Sites 2 and 5 was caused by the inability to obtain accurate measurements at these sites. Both are in locations were it is difficult to see the shoreline. A similar result emerges when all surveys are compared (DWR 1992), showing there has been little variation in vegetative extent among seasons or years.

Data collected from the six surveys show species occurrence and vegetative extent are stable, even though some seasonal and annual variations in water quality patterns do occur. This stability probably results in part from the low streamflows and reduced seasonal variability in weather patterns associated with the current drought. The variability in vegetative extent or species composition is expected to increase when more seasonally variable streamflows occur.

Figure 30
VARIATIONS IN SELECTED PARAMETERS MEASURED DURING THE FALL VEGETATION SURVEYS



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Food Chain Group Activities

Zachary Hymanson
Department of Water Resources

The Food Chain Group was organized in January 1988 as a subcommittee of the Fisheries/Water Quality Committee. Throughout its existence, the Food Chain Group has undertaken a variety of tasks ranging from stimulating communication between agency staff regarding food chain issues to the design, execution, and reporting of applied research projects. During 1991, the group met one day each month to discuss data, hypotheses, analyses, and programs relating to estuarine food chain issues.

The Food Chain Group is composed of nine Interagency members from the Department of Water Resources, Department of Fish and Game, State Water Resources Control Board, U.S. Bureau of Reclamation, and Environmental Protection Agency; two members from San Francisco State University; one member from the University of California at Davis; and two members from consulting firms.

In February 1991, the Food Chain Group revised its goal and objectives to more accurately reflect the full potential of the group and because of new problems facing the Interagency Program.

Members of the Food Chain Group produced six working papers, two technical reports, and one journal publication during 1991. Two additional technical reports and one journal publication were sent out for review in 1991, but will not be distributed until 1992. Various members also made technical presentations of Food Chain Group studies at the 1991 Interagency Program workshop and the 11th Biennial Estuarine Research Federation Conference.

During 1991, the Food Chain Group focused on three principal issues: zooplankton data analyses, introduced species, and the entrapment zone. Following is a summary of the progress made on each issue, as well as a review of other pertinent items addressed by the group.

GOAL AND OBJECTIVES OF THE FOOD CHAIN GROUP

Goal

- To provide a source of integrated information and to promote an enhanced understanding of the food chains of important fishery resources in the Sacramento-San Joaquin estuary.

Objectives

- To detect significant and important changes that have occurred at the various levels of the food chain through a systematic examination of existing data.
- To investigate the underlying causes of the identified changes by developing and evaluating hypotheses relevant to the changes and to relationships among other elements of the food chain.
- To design and promote the implementation of applied research projects to test the above hypotheses, and to acquire information on aspects of the food chain not available through routine monitoring programs.
- Through the processes associated with the above activities, provide a forum for critical scientific discussion and peer review of food chain investigation results conducted by agency and outside scientists.
- To provide up-to-date information on changes within the food chain to Interagency Program management and others for use in establishing management objectives and recommendations.

Zooplankton Data Analyses

Zooplankton are a primary food source for several fish species that reside in the delta during some portion of their life cycle. Larval and young-of-the-year life stages, in particular, can be highly dependent upon zooplankton as a food source. Zooplankton species composition and abundance have changed in the upper estuary as a result of new species introductions and changes in native species stock abundances.

Late in 1990, three Food Chain Group members, Jim Orsi, Wim Kimmerer, and Steve Obrebski, formed a special working

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group to complete a summary analysis of the DFG zooplankton compliance monitoring data. Throughout 1991, the working group rigorously analyzed these data to determine the underlying changes in zooplankton species abundance and distribution. Analysis methods permitted a determination of changes in abundance and distribution after removing the known effects of season and salinity. Of the 20 zooplankton groups examined, 12 showed a significant decline in abundance, 7 showed no change, and 1 showed an increase. Additionally, the results show declines of species were scattered throughout the estuary and not distinctly confined to particular regions. Since these declines were detectable after removing the effects of season or salinity, other factors must be responsible. In October 1991, a report of this work was sent to the Interagency Program Coordinators for review as a technical report. This report will be available in 1992.

Introduced Species

Introduction and spread of exotic species have had pronounced effects on the ecology of this estuary and are, therefore, of interest to the Food Chain Group. The zooplankton working group examined trends in abundance and distribution of some exotic zooplankton species, and Lee Miller (DFG) investigated trends in abundance and distribution of *Gammarus daiberi* (formerly *Lagunogammarus* sp.). Analyses of data from the striped bass monitoring program show this introduced amphipod has become a substantial source of food for young striped bass.

Various members continued to work on determining the ecological impacts of *Potamocorbula amurensis*. During 1991, two technical reports were completed, one on clearance and assimilation rates of *P. amurensis* and another on the clam's distribution and abundance in the upper estuary. Additionally, the ability of *P. amurensis* to feed directly on zooplankton was investigated. Results of all these investigations show the clam is well established in many parts of the upper estuary and is able to consume bacteria, phytoplankton, and zooplankton. The relatively high concentrations of *P. amurensis* combined with its array of food sources suggest this clam is having a pronounced effect on the food chain of this estuary.

Entrapment Zone

The Food Chain Group continued to examine the ecological significance of the entrapment zone. In early 1991, the Food Chain Group completed a review of the first draft of Wim Kimmerer's report evaluating data and information on the entrapment zone in this estuary. Kimmerer reached the following conclusions:

- During the period of record, from about 1972 through 1988, no trend in entrapment zone position is evident, either for the data as a whole or for individual seasons.
- Although export pumping increased between 1972 and 1988, the larger interannual variation in delta inflow has masked any effect export pumping may have had on entrapment zone position during this period.
- The entrapment zone is the most productive area for some zooplankton species.
- For maximum production of zooplankton, the entrapment zone should be at least as far downstream as the confluence of the Sacramento and San Joaquin rivers.
- Recent changes in the estuary, particularly the introduction of *Potamocorbula amurensis,* appear to have substantially affected the abundance and distribution of *Eurytemora affinis* and may make conclusions regarding this zooplankton moot.
- The location of the entrapment zone is correlated with much of the biotic abundance in the estuary, but the mechanisms responsible for this relationship are unknown. In fact, the correlation may be due to underlying relationships with flow, strength of entrapment, or other variables rather than a direct effect of entrapment zone position.

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- The importance of the entrapment zone to striped bass has not been fully demonstrated. Variation in growth rate suggests growth of larvae is sometimes food limited and that variation in zooplankton could be important to bass. Thus, bass survival should be higher in the entrapment zone where zooplankton can be more abundant.
- Declines in the abundance of fish and zooplankton over the period 1972 to 1987 are significant but are not simply related to changes in flow or position of the entrapment zone.

Final revisions of Kimmerer's report were in progress at the end of 1991.

In December 1991, the Food Chain Group held an entrapment zone workshop. This day-long meeting focused on exchange of technical information about the entrapment zone in this estuary and the Columbia River estuary. David Jay and Charles Simenstad, the principal investigators of the Columbia River Estuary Project, presented an overview of their work to date. Much of the work in the Columbia River system has focused on physical processes, while the focus of work in this estuary has been on biological processes. This, combined with the fundamental differences between the two systems, makes comparisons difficult. Overall, there was a useful exchange of information, and the work in the Columbia River system could serve as a basis for design and execution of further studies in this estuary.

Other Activities

Throughout 1991, the Food Chain Group had regular discussions about changes in the striped bass fishery and the food supply of young bass. Changes in bass food stocks, along with other species of zooplankton, remain an important issue. The group's hypothesis is that the survivorship of bass eggs and larvae not lost as a consequence of human impacts would increase if food were more abundant, and these individuals could be enough to maintain higher population levels and occasionally provide good year classes.

The Food Chain Group also reviewed and commented on the individual based striped bass model being developed for this estuary. Development of this model is part of a larger effort by several East Coast investigators to produce individual based models for eight species of fish from three estuaries. Ideally, the entire life cycle of each species will be modeled, and compensatory mechanisms will be a part of each model. The goal is to predict the responses of the various species to anthropogenic disturbances.

The individual based striped bass model for this estuary will be complicated by the complex geography and hydrology of the system. Lee Miller will be working directly with the investigators throughout development of this model to provide verified data sets and input to model development. The Food Chain Group will be asked to critique this model as it is developed.

The Food Chain Group had a series of discussions regarding the various hydrodynamic models for this estuary. Invited speakers described the existing models, which were generally specific to one or more bays. The Food Chain Group continued to express the need for two hydrodynamic models:

- A transport model for nonconservative particles (*eg,* phytoplankton and eggs) for the upper estuary and especially the delta, where entrainment can be significant.
- A 3-dimensional hydrology model of Suisun Bay.

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Adult Striped Bass Tagging and Creel Census

David W. Kohlhorst
Department of Fish and Game

This element of the Striped Bass program consists of a mark/recapture (tagging) study to estimate size and age composition, abundance, and mortality rates of the adult striped bass population. Abundance indices also are developed directly from catches in nets and traps set to catch adults for tagging. Estimates of population strength when the fish are legal-size (recruits), at 3 to 4 years old, are compared to abundance indices during their first year to help isolate the life stage where population-limiting mortality may be occurring.

Total legal-sized striped bass abundance has been used to explore the relationship between adults and young production and losses to the export pumps over a series of years. Adult population estimates and tag returns are also used to estimate age-specific mortality rates (including fishing mortality) and, in combination with fecundity, potential total egg production.

Age and size composition of females captured for tagging on or near the spawning grounds are analyzed for temporal trends. Because larger fish produce larger and perhaps "higher quality" eggs, changes in the average size of spawning females over the spawning season may result in corresponding changes in survival. This hypothesis is being evaluated in conjunction with the Egg and Larval Survey. Funding for the creel census portion of this element was shifted in 1990 to the Hatchery Evaluation Program funded by the striped bass stamp. The creel census continues to provide information for the mark/recapture abundance estimates, as well as data on the contribution of hatchery-reared fish.

In 1991, we tagged 8,375 adult striped bass and observed 7,173 fish during the June to December creel census, 172 of which were tagged in 1991 or earlier years.

Based on tags applied in 1990 and recovered during the 1990 creel census, the adult striped bass population estimate for 1990 is 515,000, a substantial decline from the 1989 estimate of about 800,000. About 12 percent of the adult striped bass population was harvested by anglers in 1990, and total mortality was 59 percent in 1989, the most recent year for which an estimate can be made.

Impacts of Freshwater Outflow and Exports on Striped Bass

David W. Kohlhorst, Donald E. Stevens, and Lee W. Miller
Department of Fish and Game

As part of its participation in SWRCB's ongoing water rights hearings, DFG explored factors affecting adult striped bass abundance. A regression model indicates that outflow and water exports from the delta during the initial year of life are the primary factors controlling adult striped bass abundance. The resulting regression equations provide a quantitative approach for evaluating the impacts on striped bass of alternative outflow and water export standards for the estuary. This regression model will be revised based on comments at several workshops and will be incorporated into testimony presented to SWRCB in 1992.

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Mortality Rates for Striped Bass Eggs and Larvae

Lee Miller, Donald Stevens, and Kathleen Perry
Department of Fish and Game

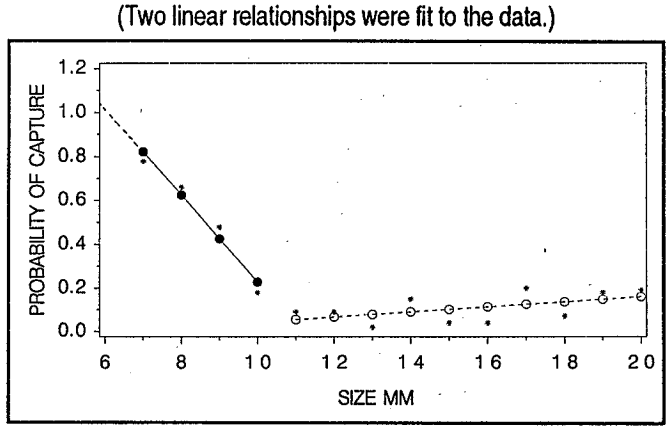
In 1991, we reestimated mortality over length and also estimated daily mortality rates for larval striped bass. Previous estimates of mortality based on rates of decline in abundance versus bass length have empirically appeared too high. Consequently we evaluated the efficiency of the egg and larval survey net to determine to what extent mortality estimates may have been affected by increased net avoidance as the larvae increased in length.

Net avoidance was determined by towing the egg and larvae net paired with a similar but larger net mounted on the frame used for DFG's annual summer tow-net survey. When mounted on the net frames, the egg and larvae net mouth size was 0.41 m^2 and the tow-net mouth size was 1.50 m^2. The larger net would be more efficient at capturing the large more mobile larvae because fewer of them would avoid its larger opening. Both nets were constructed of 500-micron net mesh, routinely used for the egg and larvae survey.

Capture probability for each size group of bass in the egg and larval survey net is based on the ratio of observed densities of larvae in the small net relative to estimated actual densities. Actual densities are estimated from an iterative process that considers changes in effective net mouth area of the large net as swimming ability increases with length of the larvae. We expected the densities of 5 and 6 mm larvae are equivalent in each net, because small larvae would not be able to avoid either net. However, densities of 5 and 6 mm larvae in the small net were 1.89 and 1.35 times their densities in the large net, suggesting greater hydraulic pressures caused extrusion of larvae 6 mm and smaller through the cod end of the larger net. These greater pressures would have been created because the mouth of the summer tow-net strained larger water volumes, but its cod end was identical to that of the egg and larvae net.

Measured capture probabilities for the egg and larvae net declined rapidly from 0.78 at 7 mm to only 0.18 at 10 mm and 0.09 at 11 mm (Figure 31). Extrapolation of a regression line fit to the probabilities for 7 to 11 mm larvae suggests the egg and larvae net is close to 100 percent efficient on 6 mm larvae. The escapement sampling was apparently not adequate to detect further decline in efficiency as larvae increased in length beyond 11 mm and became better swimmers. Capture probabilities remained low, with no distinct trend, fluctuating from about 0.02 to 0.20 for larvae between 12 and 20 mm. We conclude that at sizes greater than 10 mm, capture probability estimates exhibited too much random variation to accurately correct abundances for calculating mortality. Hence, we limited the mortality rate analysis to fish 6 to 10 mm long. Additional measurements of capture probabilities are planned for 1992 to improve estimates for larger striped bass.

Figure 31
PROBABILITY OF CAPTURE OF STRIPED BASS LARVAE BASED ON PAIRED TOWS OF THE STRIPED BASS EGG AND LARVAE NET WITH A LARGER NET
(Two linear relationships were fit to the data.)



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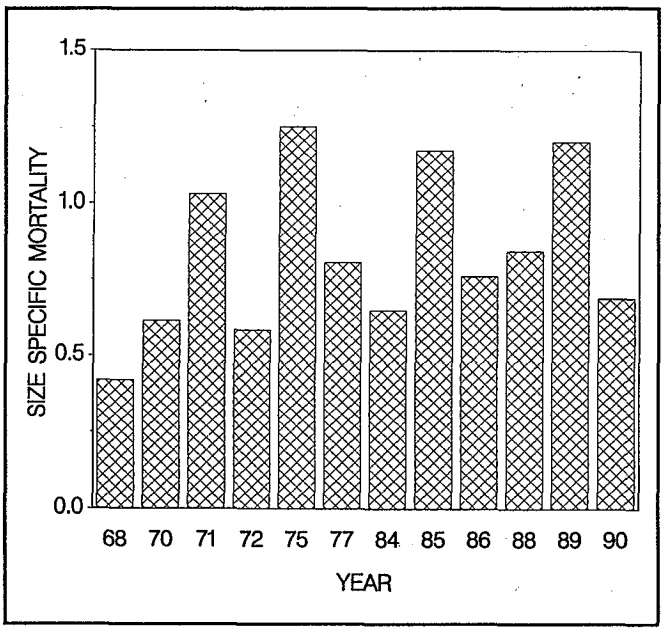
Mortality Over Length

Striped bass abundance for each length increment corrected for net efficiency was estimated by dividing measured abundances of larvae in the egg and larvae net by the appropriate capture probability. Logarithms of these corrected abundances were regressed on length from 6 to 10 mm to estimate average mortality rates for fish within this size range for each year (Figure 32). These rates are quite variable, ranging from about 0.4 in 1968 to 1.25 in 1975.

In the 1989 Annual Report, we described trends in larval striped bass survival between successive stages from egg to 9 mm based on uncorrected abundance estimates. These results covered the period 1968 to 1988 and also indicated that mortality varied annually but that there had been no persistent increase in mortality that would account for the decline in young bass abundance since 1977. These results support the hypothesis that the decline in egg production associated with reduced spawning stock is responsible for the persistent decline in young striped bass abundance.

Figure 32
SIZE-SPECIFIC MORTALITY RATES FOR 6-10 MM STRIPED BASS LARVAE FOR ALL YEARS OF RECORD
(In 1973, the survey started too late to adequately measure larvae less than 9 mm.)



We reevaluated the null hypothesis of no change in mortality rate using the "corrected" mortality estimates in Figure 32, which are now updated through 1990. The Wilcoxin rank-sum test, a non-parametric t-test (SAS 1988), was used to statistically test this hypothesis. This test again indicated there has not been a significant change in mortality rates since 1976 (p>:z:=0.42).

Daily Mortality Rates

Daily mortality rates were calculated for 1984 to 1990. These are the years we counted daily growth increments on larval bass otoliths (ear bones), which then allowed estimation of age in days and of daily mortality rates (Table 3). These mortality rates are within the range 0.1 d^{-1} to 0.4 d^{-1} reported for cohorts of striped bass larvae for the Potomac River (Houde 1988). Dey (1981) reported daily mortalities of 15 to 18 percent for post-yolk-sac larva in the Hudson River. Further analysis is needed through modeling efforts and life table construction to determine how well our estimates reflect reality.

Table 3
STRIPED BASS DAILY MORTALITY RATES BASED ON NET CORRECTED ABUNDANCES AND AVERAGE DAILY GROWTH RATES

Year	Post-Hatch to 10 mm
1984	0.116
1985	0.220
1986	0.159
1988	0.135
1989	0.169
1990	0.121
Mean	0.153

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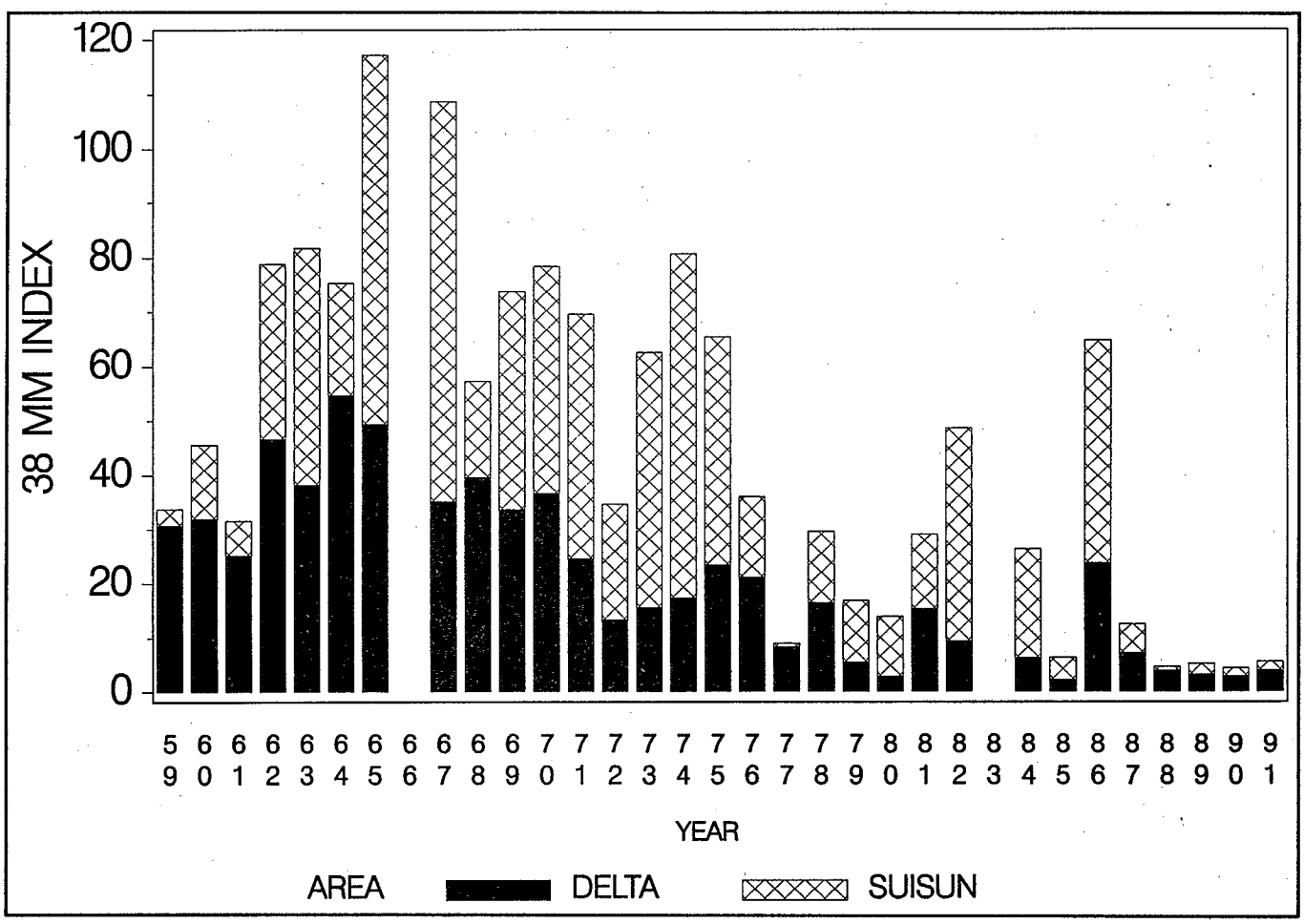
Summer Tow-Net Survey

Lee Miller, Donald Stevens, and Kathleen Perry
Department of Fish and Game

The striped bass summer tow-net survey is the basis for the annual index of young striped bass abundance. It has been conducted every summer since 1959 (except 1966) and has provided information on numbers of fish surviving in various parts of the estuary, as well as overall year class strength and population trends with regard to water management.

The abundance index is estimated when the mean length of striped bass in the survey is 38 mm. In 1991, three surveys were needed before the 38 mm size was bracketed and the index established. The 1991 index of 5.5, the fourth lowest on record, was set on July 25. Record and near-record low abundances have occurred in each of the recent drought years, 1987-1991 (Figure 33). The delta portion of the 1991 index was 3.9, and the Suisun Bay portion was 1.6.

Figure 33
STRIPED BASS 38-MM ABUNDANCE INDICES FOR THE DELTA AND SUISUN BAY



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Fall Midwater Trawl Survey

Lee Miller, Donald Stevens, and Kathleen Perry
Department of Fish and Game

The fall midwater trawl survey has been conducted annually, since 1967, except for 1974 and 1979, to index the monthly abundance of young striped bass from September to December. The monthly abundance index is sum of the products of the mean catch per tow in each of 17 subareas of the estuary and the water volume in each subarea. The sum of September-December indices is the annual index. Like the summer index, the fall 1991 index is one of the lowest on record (Table 4).

Table 4
YOUNG STRIPED BASS ABUNDANCE INDICES FOR THE TOW-NET SURVEY AND MIDWATER TRAWL SURVEYS, 1967-1991

Year	Tow-Net Index	Midwater Trawl Index	Year	Tow-Net Index	Midwater Trawl Index
1967	108.7	21,082	1980	14.0	1,463
1968	57.3	4,118	1981	29.1	4,533
1969	73.8	8,425	1982	48.7	4,468
1970	78.5	8,229	1983	No Index	12,496
1971	69.6	9,510	1984	26.3	6,602
1972	34.5	6,129	1985	6.3	1,760
1973	62.7	4,285	1986	64.9	3,944
1974	80.8	No Survey	1987	12.6	1,351
1975	65.5	4,548	1988	4.6	477
1976	35.9	746	1989	5.1	442
1977	9.0	885	1990	4.3	1,319
1978	29.6	2,601	1991	5.5	945
1979	16.9	No Survey			

The fall survey also provides data on abundance trends of other species. We recently updated correlations through 1990 between abundance indices and delta outflow, which were previously described (Stevens and Miller 1983) for American shad, *Alosa sapidissima*, and longfin smelt, *Spirinchus thaleichthys*. We also examined the relationship between flow and abundance for splittail, *Pogonichthys macrolepidotus*, a native species not previously evaluated.

Annual abundance indices were calculated as for striped bass and are presented for these three species in Table 5. Correlations between abundance indices and outflow were run for times that included spawning migration, spawning, and nursery periods for each species. Abundance of all three species is significantly correlated with delta outflow.

Table 5
MIDWATER TRAWL SURVEY ABUNDANCE INDICES FOR AMERICAN SHAD, LONGFIN SMELT, AND SPLITTAIL

Year	American Shad	Longfin Smelt	Split-tail
1967	3,502	81,737	66
1968	772	3,318	18
1969	4,056	59,497	26
1970	872	6,535	25
1971	1,544	15,988	18
1972	334	759	13
1973	1,085	5,897	4
1975	2,487	2,809	4
1976	338	654	1
1977	645	205	0
1978	2,444	6,675	37
1980	3,905	31,155	16
1981	1,434	2,202	18
1982	5,386	62,929	118
1983	2,929	11,876	152
1984	846	7,459	16
1985	1,596	992	15
1986	1,860	6,160	58
1987	899	1,508	29
1988	1,459	743	9
1989	1,878	456	4
1990	4,317	239	8
1991	3,016	134	18

American shad is an anadromous species. Its abundance is most highly correlated with May and May-June outflows (Table 6). This is the spawning period (Stevens, Chadwick, and Painter 1987).

Table 6
CORRELATION COEFFICIENTS BETWEEN LOGARITHM OF AMERICAN SHAD ABUNDANCE INDICES AND LOGARITHM OF OUTFLOW TO THE SACRAMENTO-SAN JOAQUIN ESTUARY, 1967-1991
(No data for 1974 and 1979.)
Coefficients are for the entire period between corresponding months on the two axes.

	April	May	June	July	August
April	0.571+				
May	0.618+	0.657+			
June	0.637+	0.666+	0.659+		
July	0.628+	0.639+	0.598+	0.486	
August	0.608+	0.603+	0.547+	0.432*	0.308

\+ $P < 0.01$
* $P < 0.05$

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Longfin smelt are estuarine; they migrate to the delta to spawn in late winter to early spring (Radtke 1966). Longfin smelt abundance is highly correlated with delta outflow for all combinations of months, January through August (Table 7).

Splittail are native minnows that are tolerant of brackish water. They spawn mainly in dead-end sloughs in the delta from early March to mid-May (Moyle 1976). Except for January alone, all combinations of monthly flows from January to August were well correlated with splittail abundance (Table 8). Flow combinations from April to August yielded the highest correlations. These months coincide with the spawning and early nursery period.

Table 7
CORRELATION COEFFICIENTS BETWEEN LOGARITHM OF LONGFIN SMELT ABUNDANCE INDICES AND LOGARITHM OF OUTFLOW TO THE SACRAMENTO-SAN JOAQUIN ESTUARY, 1967-1991
(No data for 1974 and 1979.)
Coefficients are for the entire period between corresponding months on the two axes.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Jan	0.854+							
Feb	0.844+	0.843+						
Mar	0.856+	0.792+	0.730+					
Apr	0.881+	0.845+	0.820+	0.865+				
May	0.891+	0.881+	0.844+	0.867+	0.847+			
Jun	0.896+	0.863+	0.852+	0.862+	0.838+	0.806+		
Jul	0.897+	0.870+	0.868+	0.859+	0.835+	0.798+	0.735+	
Aug	0.897+	0.870+	0.907+	0.854+	0.836+	0.804+	0.767+	0.709+

+ $P < 0.01$

Table 8
CORRELATION COEFFICIENTS BETWEEN SPLITTAIL ABUNDANCE INDICES AND OUTFLOW TO THE SACRAMENTO-SAN JOAQUIN ESTUARY, 1967-1991
(No data for 1974 and 1979.)
Coefficients are for the entire period between corresponding months on the two axes.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Jan	0.251							
Feb	0.515*	0.647+						
Mar	0.685+	0.752+	0.809+					
Apr	0.752+	0.822+	0.872+	0.792+				
May	0.781+	0.844+	0.880+	0.815+	0.798+			
Jun	0.793+	0.850+	0.877+	0.813+	0.777+	0.730+		
Jul	0.801+	0.855+	0.879+	0.822+	0.792+	0.769+	0.807+	
Aug	0.794+	0.839+	0.838+	0.866+	0.807+	0.789+	0.829+	0.768+

+ $P < 0.01$
* $P < 0.05$

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Striped Bass Egg and Larval Management Study

Jim Arthur, Steve Hiebert, and Melvin Ball
U.S. Bureau of Reclamation

In connection with the Bay/Delta hearings, USBR has proposed operational changes (such as curtailed water project export pumping, closing of the Delta Cross Channel gates, and pulse flows) in an effort to transport pulses of striped bass eggs and larvae to more favorable conditions in Suisun Bay. The first step in accomplishing this goal is to identify the timing and magnitude of spawning pulses in both the Sacramento and San Joaquin rivers. In addition, there needs to be an understanding of when losses of striped bass larvae occur at the pumps. For the past 3 years, USBR biologists have identified egg/larvae pulses in the Sacramento and San Joaquin rivers. Efforts in 1991 were designed to improve equipment and procedures for monitoring striped bass larval abundance. Sampling locations are identified in Figure 34.

Sacramento River at Bryte

USBR completed the third year of continuous monitoring for striped bass eggs and larvae in the Sacramento River at Bryte. Sampling gear was the same 500 micron mesh 6-inch-diameter net used in the 2 previous years. Sampling was conducted from mid-April to early July.

Objectives for the 1991 striped bass egg and larval study on the Sacramento River at Bryte included:

- Attempt to improve larval bass survival through modified water project operations based on sampling (if Sacramento River flows are adequate).
- Obtain more information on factors influencing bass spawning.
- Improve the design of sampling equipment to minimize mutilation of eggs and larvae.

Flows in 1991 were not adequate to conduct a modified water project operation study to enhance striped bass larval survival.

Water temperature has been the single factor consistently related to large peaks of bass spawning. From the 3 years of data, it appears that when water temperatures remain below a threshold in the low 60°sF (about 61°F), no or only minimal spawning occurs (Figure 35). What appears to be associated with substantial spawning is a 1°F or more mean daily temperature rise, for one to several days, when the water temperature is over the spawning threshold and when bass that are physiologically ready to spawn are in the spawning area. Once the water temperature levels off or starts declining, spawning tends to subside until the next temperature rise. Spawning cycles tend to repeat with temperature increases until the mean daily water temperature rises above the upper 60s later in the spawning season or until all the bass that are in spawning condition have done so.

The overriding factor influencing daily water temperature is air temperature, but streamflow plays a major role in determining when striped bass spawning begins. When Sacramento River flows are high, the water is cooler and may delay spawning several weeks over lower flows. In years with cool spring weather and very high spring flows, the water can be several degrees cooler, and the onset of spawning can be delayed several weeks.

There has been considerable variation in the length and duration of substantial spawning peaks (over 100 million eggs) in the last 3 years. In 1990, there were five substantial spawning peaks between late April and early June, but each peak lasted only a single day. During 1989 and 1991, there were also substantial peaks from late April to early June, but duration of peaks was 1 to 6 days. Peak levels of over 500 million eggs per day lasted only 1 or 2 days (Figure 35). What caused these differences is uncertain.

Effort continued in 1991 to improve the sampling gear to better quantify the results. In 1989, eggs and larvae were extremely mutilated at times, which probably resulted in underestimates. In 1990, a plastic bag

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Figure 34
MAJOR STRIPED BASS SPAWNING AREAS AND SAMPLING SITES

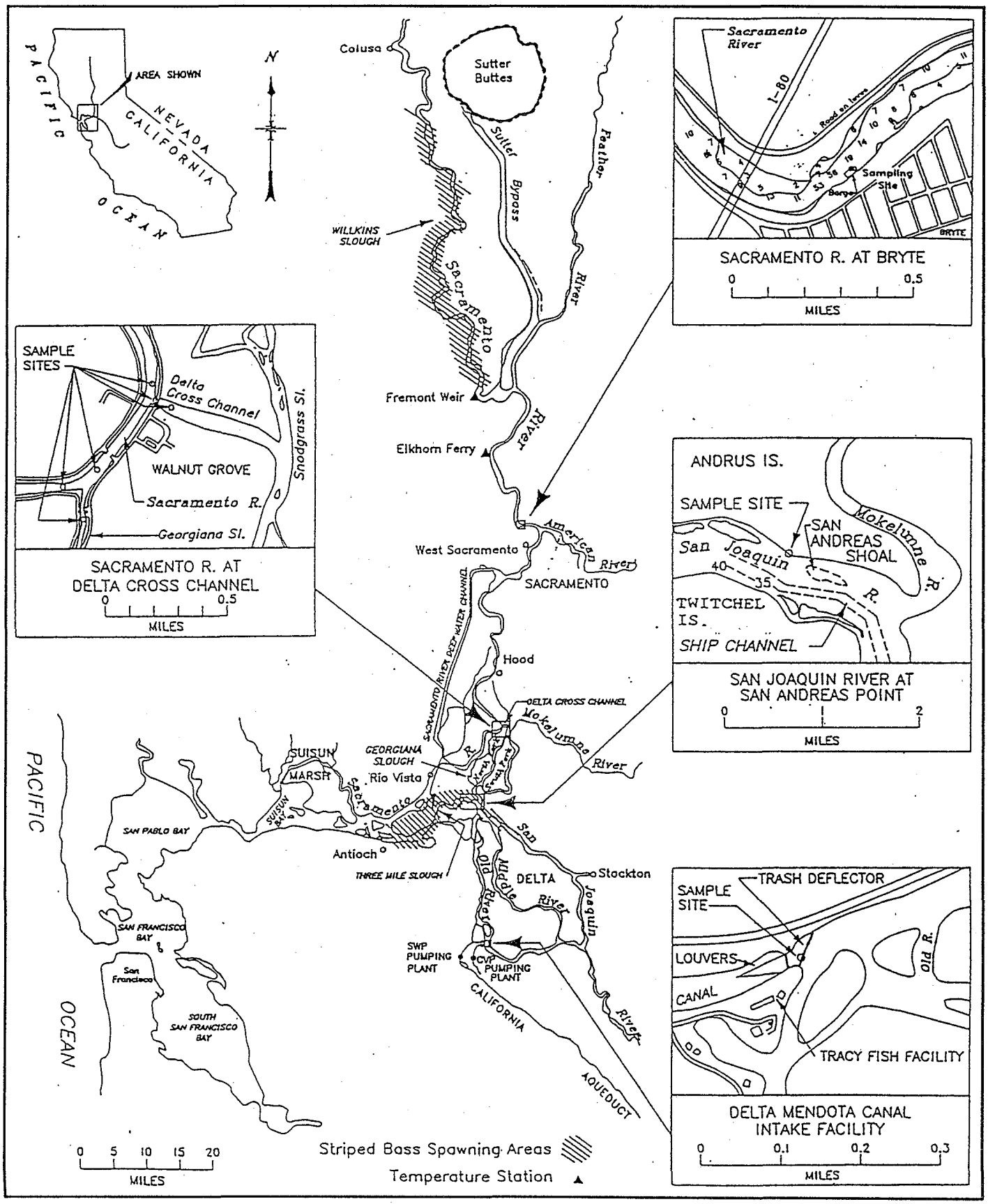

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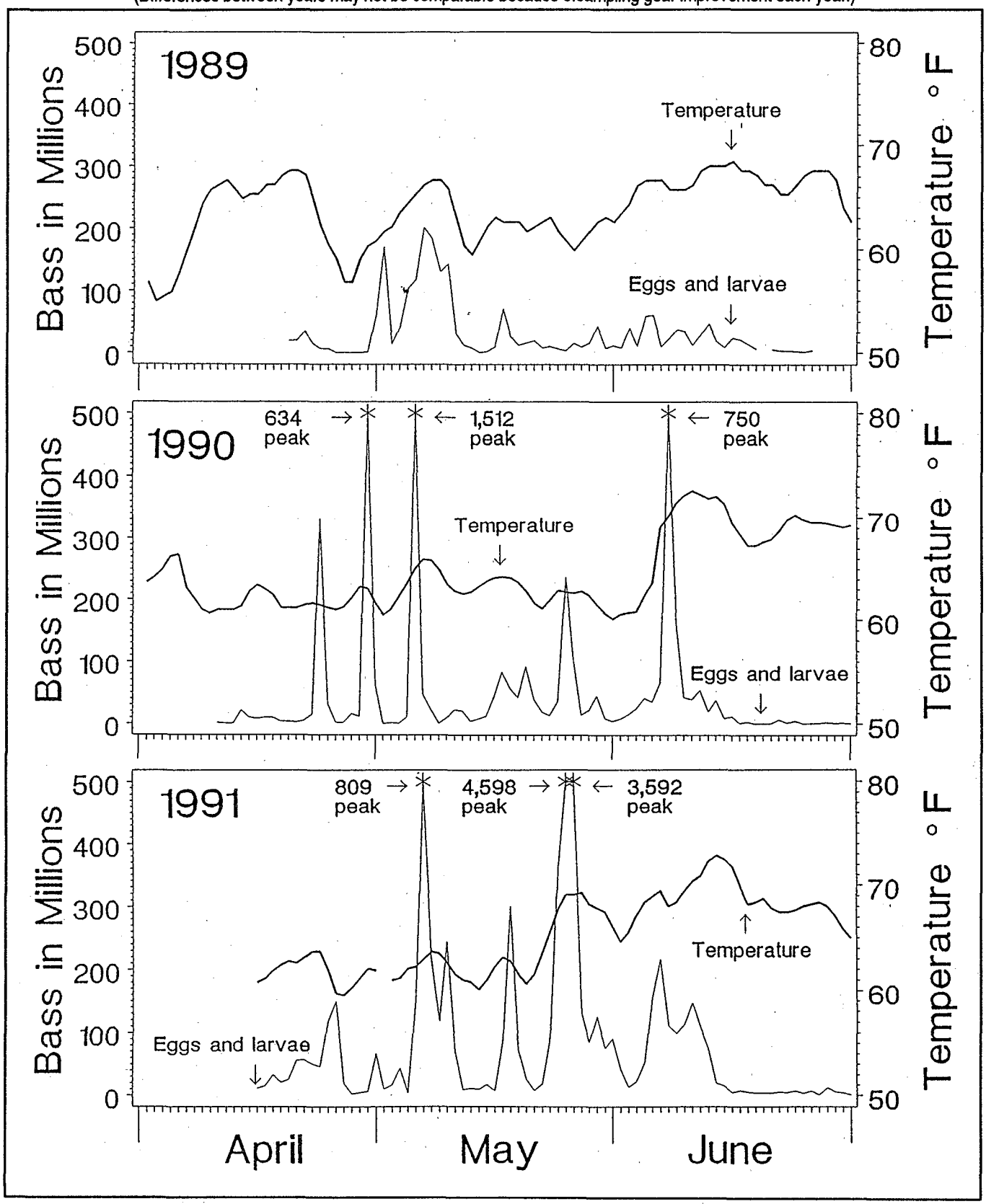
Figure 35
TOTAL DAILY NUMBERS OF STRIPED BASS EGGS AND LARVAE SAMPLED IN THE SACRAMENTO RIVER AT BRYTE, 1989-1991, VERSUS WATER TEMPERATURE AT WILKINS SLOUGH, NEAR THE PRESUMED CENTER OF BASS SPAWNING
(Differences between years may not be comparable because ofsampling gear improvement each year.)



with four small holes over was placed over the end of the sampling jar on the end of the net. This greatly reduced the flow rate through the screen on the jar and decreased specimen damage, resulting in greater efficiency.

In 1991, there were problems with the flowmeter used in the plankton net caused by a combination of unusually low flows due to the drought and dredging in the center of the channel, resulting in much lower flow velocity at the site. The flowmeters used in the nets were not turning at times when flooding tides occurred. Consequently, total counts in many of the samples may have been overestimated. New low-velocity flowmeters were not obtained until June. Nets were redesigned to fit over the 5-inch-diameter housing of the new meters, and they were tested against the existing nets. However, it was too late in the season and larval counts were too low to obtain comparable results. Consequently, the 1991 data appear to be overestimated relative to the other 2 years.

Jersey Point, San Joaquin River

A laboratory trailer was set up in conjunction with a submersible pump system suspended in the San Joaquin River off the end of an existing walkway at Jersey Point. This site was selected because of available power and good access to the river near the center of San Joaquin River striped bass spawning area, as established by the Department of Fish and Game. River water was pumped to the trailer and sieved through a 250-micron (0.01-inch) mesh net. The plankton net was plumbed so that samples could be collected by washing the net contents into buckets without net removal.

From April 17 through June 9, 257 samples were taken at hourly intervals, with an average of 6 per day during daylight hours. Pumped flow volumes were recorded to determine density of eggs and larvae. Striped bass larvae were sampled on 10 days during the sampling period and were the first life stage collected. Concentrations of striped bass eggs were three times larger than concentrations of larvae, with a peak on May 6. Together, striped bass eggs and larvae made up 7 percent of all eggs and larvae collected. Chameleon gobies made up the majority, at 80 percent of all eggs and larvae.

Tracy Fish Collection Facility

In addition to sampling striped bass larvae, a major effort was devoted to determining the timing and magnitude of delta smelt (proposed endangered species) larval losses at the Tracy Fish Facility.

A new type of continuous sampler was developed for eggs and larvae at the Tracy Fish Facility. The sampler operates by pumping, concentrating, separating, and preserving samples for a specific time or volume. Water containing eggs and larvae is pumped by centrifugal pump into a header box (energy dissipator), flows through an inclined 250-micron wedge-wire screen, and drops through a diverter into screened sample collection buckets. A small peristaltic pump, operating on a preset time, delivers a calculated concentration of formalin to the filled sample bucket to preserve samples and reduce predation by amphipods. A flowmeter installed in the inflow plumbing from the pump is connected to an electronic data logger that records the volume per sample. The continuous sampler collected 17 to 24 samples a day, representing an entire diel cycle. USBR recently applied for a patent for the system.

The automated sampling system was attached to the deck of a pontoon boat moored behind the trashracks. The system was located behind the trashracks for sampling in areas of increased turbulence of channel waters to reduce potential sampling errors caused by stratification of eggs and larvae by depth. A total of 622 samples were collected from April 27 through June 12. An additional 30 samples were taken with known numbers of eggs and larvae injected at various points in the sampler to determine the sampler's efficiency and a sampler-induced "loss" factor that could be applied to the data.

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Initial data indicate that continuous samplers can provide reliable indices of seasonal and diel densities of eggs and larvae with careful site selection, system verification, and determination of efficiency of organism retrieval from pumped samples. Continuous data taken upstream of water diversions may be able to serve as early warning signals and allow alteration of diversion patterns to minimize egg and larval entrainment.

In addition to continuous samples, 0.5-meter-diameter plankton nets were "fished" from the sampling deck at the depth of the intake to the continuous sampler. These samples were taken before the continuous sampler was installed and during operation for verification of pumped samples. A total of 193 net samples were taken from February 22 through July 18. All 1991 samples have been sorted and identified, and the data have been stored on computer. Taxonomic identifications were made by Johnson Wang, Technical Consultant and specialist on taxonomy of larval delta fish species. An annual report is being prepared at USBR's Denver Office.

Plankton net collections revealed the presence of 12 species of larvae. Species and percent composition data are given in Table 9. Research planned for 1992 includes incorporation of a screw-type pump designed to minimize abrasion of eggs and larvae, and modification of collection buckets to reduce predation on fish larvae.

Table 9
PERCENT COMPOSITION OF FISH EGGS AND LARVAE COLLECTED BY PLANKTON NETS AT TRACY FISH COLLECTION FACILITY
February 22 to July 18, 1991

Species (Eggs and Larvae Combined)	Percent Composition
Striped bass	17.2
Chameleon goby	31.6
Bigscale logperch	0.5
Prickly sculpin	48.5
Cyprinidae	1.4
Threadfin shad	0.5
Delta smelt	0.1
Sacramento sucker	0.1
White catfish	0.1
Rainbow trout	0.1
Centrarchidae	0.1
Longfin smelt	0.1

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Chapter 5

CHINOOK SALMON

Marty Kjelsen and Patricia Brandes
U.S. Fish and Wildlife Service

In 1991 we worked to update and refine our knowledge of factors influencing young salmon abundance, distribution, and survival in the Sacramento-San Joaquin estuary. This information is being used to develop recommendations to water users and the State Water Resources Control Board on how impacts of water operations in the delta can be lessened. Special emphasis was placed on understanding salmon smolt survival through the San Joaquin Delta, and specifically how a barrier in the southern delta at upper Old River might improve San Joaquin salmon smolt survival.

Overall objectives of the Interagency Salmon Study are to:

- Monitor the abundance of fry and smolt Chinook salmon rearing and migrating through the delta.
- Determine the impacts of water development in the delta on the abundance, distribution, and survival of juvenile fall-run salmon.
- Identify management measures that could lessen the impacts of water project operations on salmon using the delta and lower embayments of the estuary.

Elements of the study in 1991 were:

- Continue the beach seining survey to estimate the abundance of fall-run fry in January through March, as in past years.
- Continue the midwater trawl surveys in the northern delta and Chipps Island to estimate the abundance of fall-run smolts entering and leaving the Sacramento Delta and Central Valley.
- Use mark and recapture studies to determine the survival of fall-run smolts under varied environmental conditions.

Specific questions were:

- What is the survival rate of fish released in the Sacramento River under extremely low flow conditions and low temperatures?
- Where is the greatest mortality in the southern delta?
- Could a barrier at the head of Old River increase smolt survival through the San Joaquin Delta?
- What is the role of water exports on survival with and without a barrier in place?
- What is the impact on Sacramento and San Joaquin basin juvenile salmon migrating through the southern and central delta if more water is directed to the export pumps via lower Old and Middle rivers with such a barrier in place?

Abundance of Sacramento River Fry

Abundance of fall run fry in the northern and central delta was extremely low during January-March 1991 and the lowest since 1977 (Table 10). The 1991 northern delta data continue to support past findings that fry abundance in the northern delta in general decreases as inflow to the delta declines (Figure 36).

The 1991 abundance index in the lower Sacramento River was the highest measured since sampling began in 1981. This estimate was high, mainly due to an unusually high catch of 648 fry at Ward's Landing on March 20. Catches in all areas of the delta and at most stations increased during March after heavy storms and precipitation increased streamflow around March 5 and 6. Presumably these fry entered the northern delta after seining concluded on March 22 or moved through the northern delta later in the season as smolts.

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Table 10
AVERAGE CATCH PER SEINE HAUL OF FALL CHINOOK SALMON FRY IN THE NORTHERN AND CENTRAL DELTA AND LOWER SACRAMENTO RIVER
January through April, 1977 through 1991

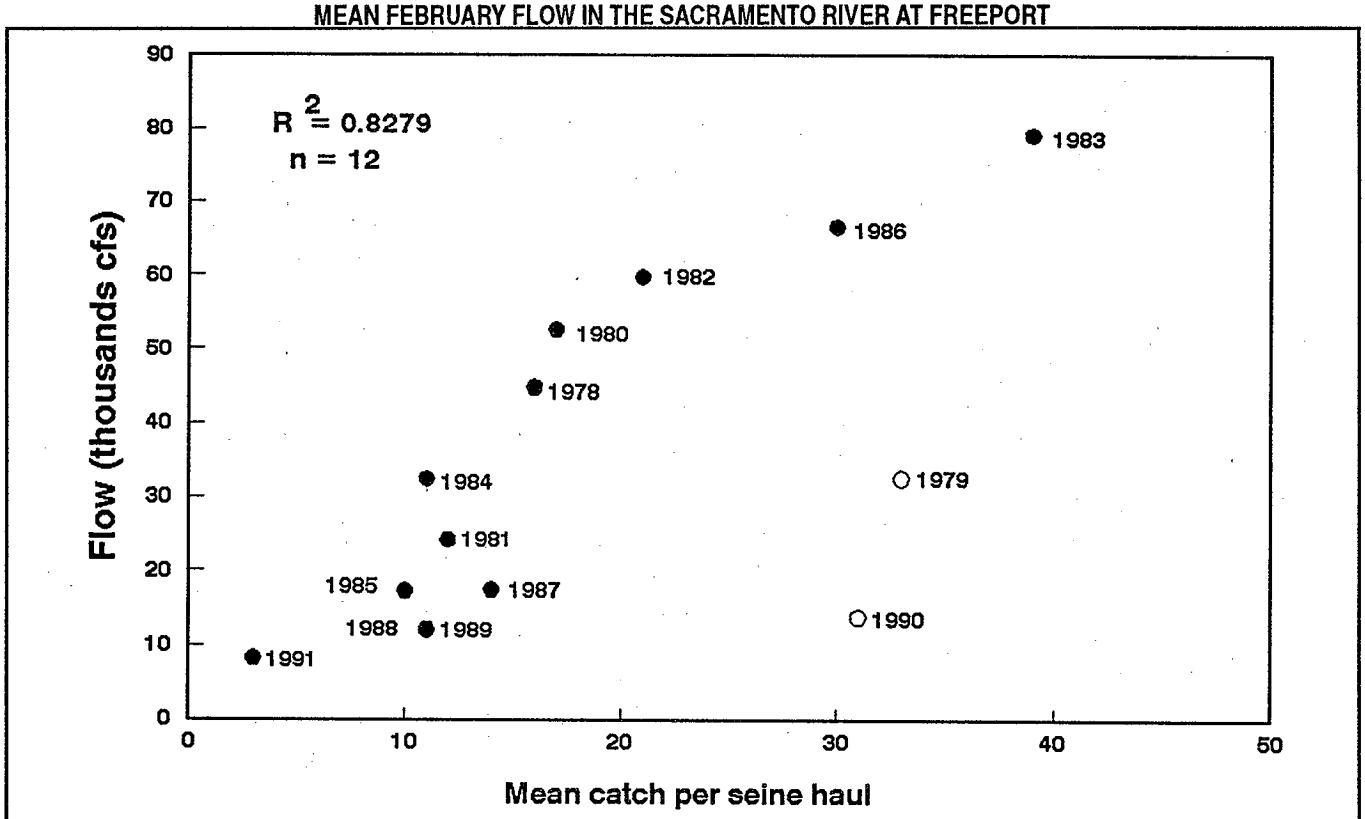
Year	Northern Delta	Central Delta	Lower Sacramento
1991*	3	3	32
1990*	31	4	11
1989*	11	4	25
1988*	11	5	9
1987*	14	4	18
1986	30	10	27
1985	10	3	2
1984	11	4	9
1983	39	9	30
1982	21	4	23
1981	12	2	23
1980	17	2	NS
1979	33	6	NS
1978	16	NS	NS
1977	0.4	NS	NS
n =	12	9	7

n Number of seining stations.
* January through March sampling period.
NS Not sampled.

The 1991 data appear to show that most fall-run salmon fry remained and reared upstream until flows increased in March (Figure 37). The change in mean size of salmon fry in beach seining catches over time supports this conclusion (Figure 38). Generally there were two fry populations present in 1991, with the first group entering the delta with increases in flow in early February, at an average size of about 38 millimeters. These fry grew to an average size of about 53 millimeters by the first of March. The second group of small fry (also around 38 millimeters) entered the delta after the large increase in flow in early March and increased to about 48 millimeters by the end of March.

During February and March, about 11 million fry from Coleman National Fish Hatchery were released at various locations in the upper Sacramento River. It would be helpful in understanding the behavior of both the "natural" and hatchery fish if it was possible to separate the two stocks in our sampling.

Figure 36
MEAN CHINOOK FRY CATCH PER SEINE HAUL IN THE NORTHERN DELTA VERSUS MEAN FEBRUARY FLOW IN THE SACRAMENTO RIVER AT FREEPORT



NOTE: 1979 and 1990 values were considered outliers and, thus, were not used in regression calculations.

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Figure 37
CHINOOK FRY CAPTURED PER HAUL DURING BEACH SEINING IN THE DELTA AND LOWER SACRAMENTO RIVER, 1991
Northern and central Delta catches were combined and averaged.
Mean daily streamflow was measured at Freeport from January 1 to March 24, 1991.

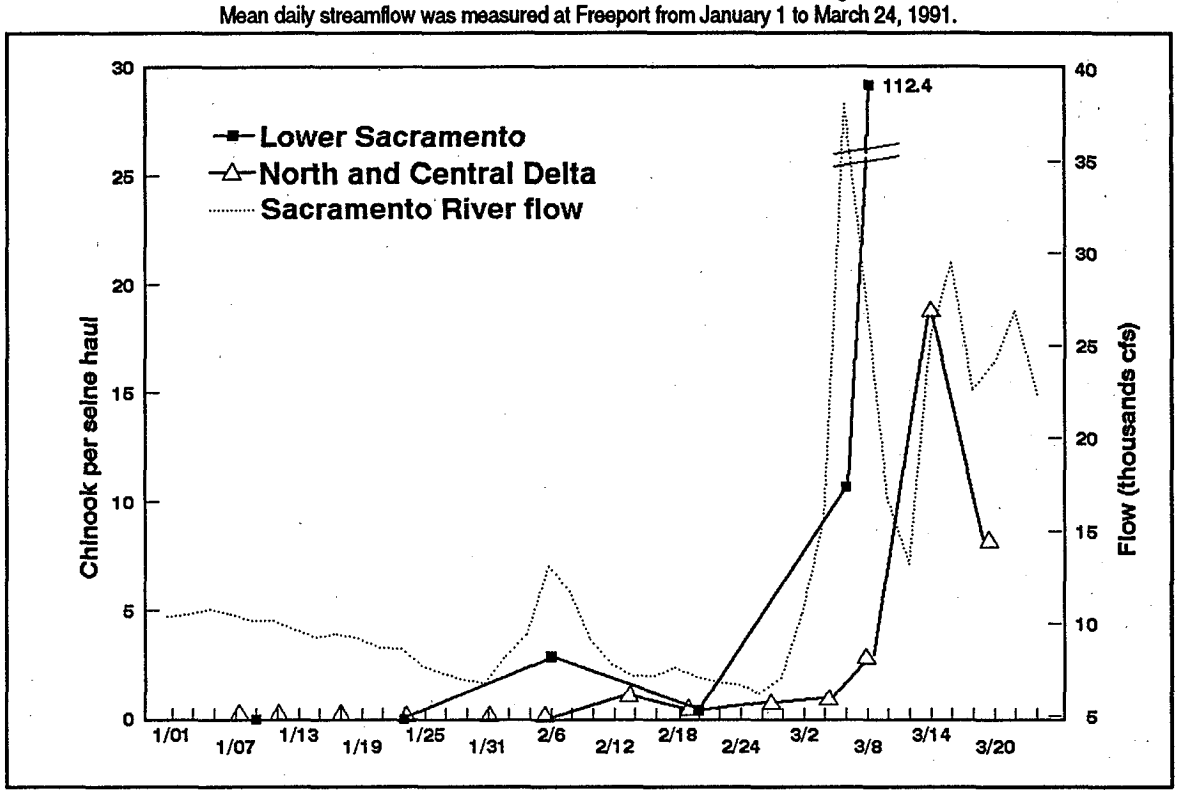
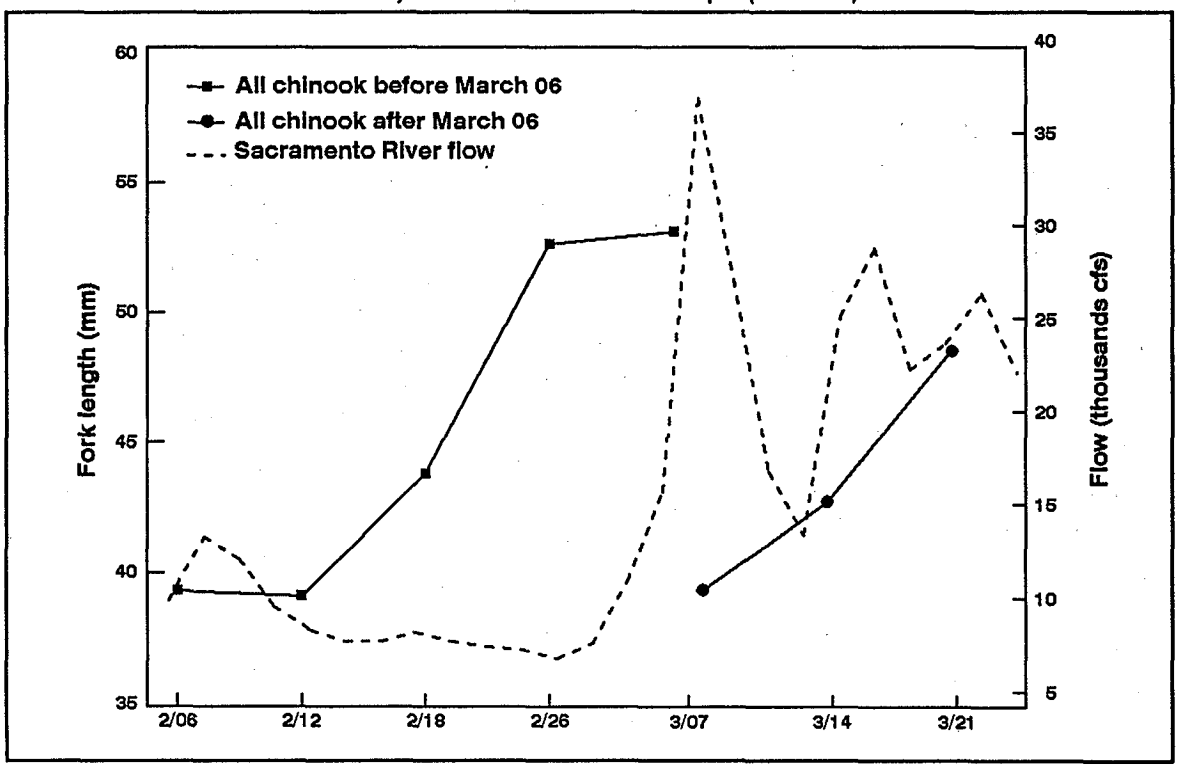


Figure 38
MEAN FORK LENGTH OF CHINOOK CAPTURED DURING THE 1991 BEACH SEINING SURVEY
Winter Chinook salmon (3) were excluded from length calculations.
Mean daily streamflow was measured at Freeport (DAYFLOW).



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Marking at least part of this production may help us to identify the "natural" and hatchery components.

It is difficult to assess the absolute abundance of fry in the delta and their relative significance to the total production of the Central Valley. From December 1991 until June 1992, a pilot program will be initiated to answer this question by indexing all the fall-run production (fry and smolts, concurrently) moving into the Sacramento Delta over the course of the season. By estimating the number of fry and smolts passing Sacramento over the entire season, and by estimating differential survival between smolts and fry, we hope to determine the significance of the delta on each life stage.

Survival of Sacramento River Fry

To increase the number of marked smolts available for release during April and May, no marked fry were released in the delta in 1991.

Abundance of Smolts at Sacramento

In the northern delta, a fourth year of trawling was done on the Sacramento River about 5 miles downstream of Miller Park, the same site used in 1988 and 1989. The sampling site in 1990 was near the town of Courtland, about 21 miles closer to Chipps Island than the Miller Park site.

Ten 20-minute tows were made about 3 times each week between April 15 and June 12 to index the number of smolts migrating into the Sacramento Delta.

The annual mean (fish per 20 minute tow) of salmon smolts passing Sacramento in 1991 was 41.6, about half that observed in 1988 and 1989 but greater than that observed in 1990 (Table 11). We would perhaps expect to see a greater number at Sacramento than at Courtland (the 1990 trawling site) because some fish die as they migrate downstream. We also believe the 1990 estimate was low because we inadequately sampled the Coleman fish as they passed Courtland that year. This would indicate that, in general, smolt abundance in 1991 was less than in the last few years. Considering both low Sacramento basin escapement in fall 1990 and continued drought conditions, this is not surprising.

Table 11
MEAN CATCH OF CHINOOK SALMON SMOLTS PER 20-MINUTE TOW DURING APRIL-JUNE AT SACRAMENTO (1988-1991) AND COURTLAND (1990)

Year	April	May	June	Annual Mean*
1991	59.3	60.9	4.8	41.6
1990	26.3	43.3	10.9	30.7
1989	22.0	137.3	6.4	80.0
1988	27.4	208.4	4.8	80.1

* Index for April, May, and June divided by 3.

In 1991, we estimated the absolute abundance of smolts passing Sacramento, based on trawl efficiency and the number of unmarked fish caught in the trawl during the sampling season.

We estimated trawl efficiency by recovering fish released at Miller Park in the Sacramento trawl. Although we only released two groups at Miller Park, we used four unique tag codes (two codes per release group). Efficiency estimates are based on recovery of the two tag codes released at Miller Park on April 25. We restricted ourselves to these two codes because our sampling effort was not as great for the group released on the April 29. We only used the March 26 recoveries, and we assumed the majority of fish were vulnerable to our trawl on that day. We also took into account the April 26 sampling effort (180 minutes), which was 12.5 percent of the total number of minutes that day (1440). Dividing the number of fish recovered from each tag group by y, where y = the number released times the fraction of time sampled (0.125), produces an estimated efficiency of 0.0064 for the Sacramento trawl. Following the same methodology we used for expanding our Chipps Island catch (Appendix 12, p. 125, USFWS Exhibit 31) results in an absolute estimate at Sacramento of around 33 million smolts.

This is the first year we have made these estimates. However, if trawl efficiency is assumed to be the same between years, it would be possible to arrive at absolute estimates for past years. Additional efficiency work is warranted to confirm absolute abundance estimates.

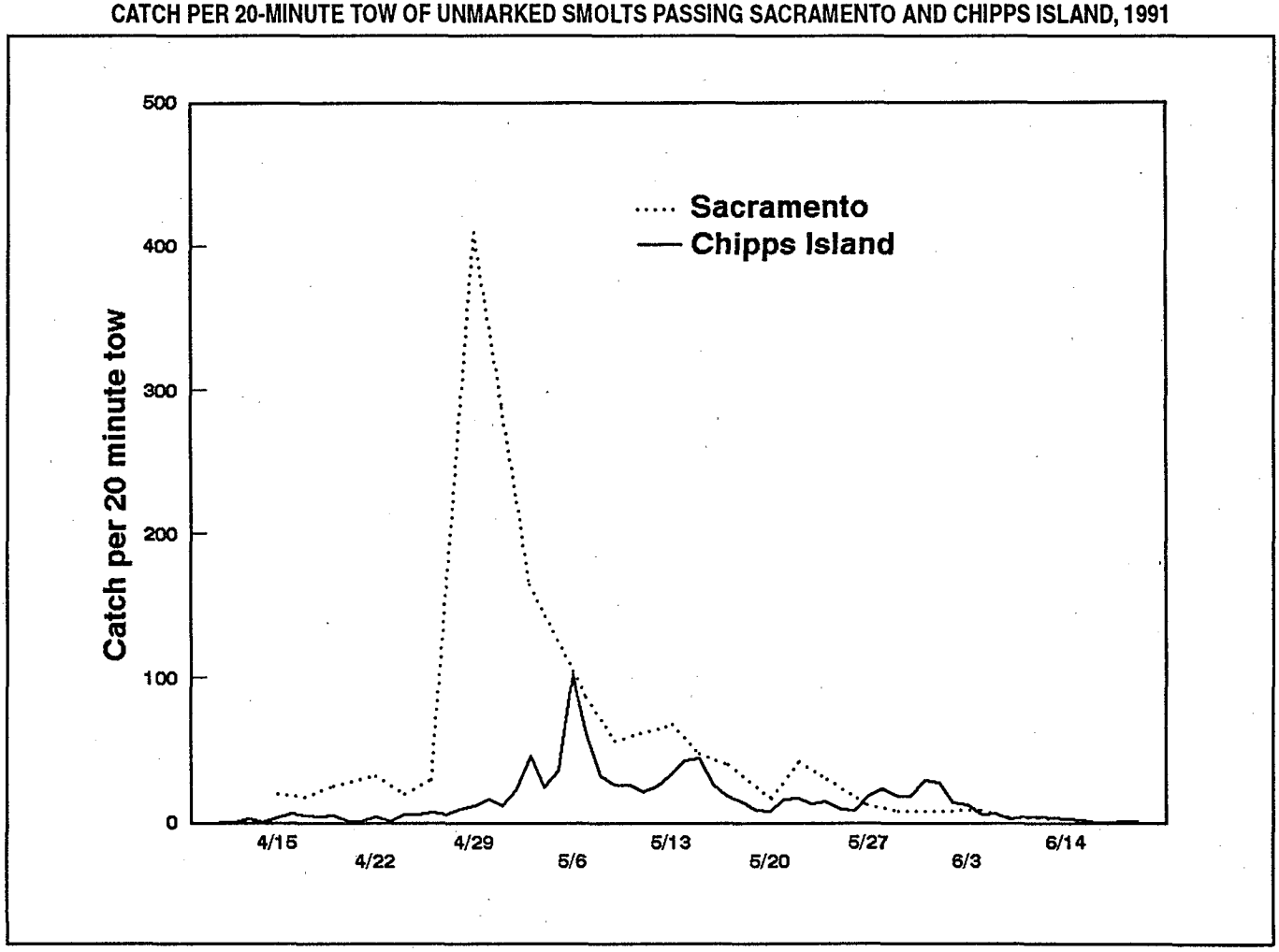
Because there is extreme variability in catches between days at Sacramento, sampling only 3 days a week may not be adequate to estimate absolute numbers. We have been limited by an inadequate number of boat operators and are exploring the possibility of obtaining a smaller trawling or push-net vessel to use at Sacramento, which either boat operators or biologists could operate.

The distribution of fish recovered at Sacramento in 1991 is shown in Figure 39. A greater percentage of the total production migrated in April in 1991 than in past years (Table 12), undoubtedly due to the 6 million smolts released at Princeton between April 22 and May 6. The peak of these hatchery fish, observed on April 29, was 409.8 fish per 20-minute tow. Knowing when the peak influx of smolts enters the delta is critical to scheduling and evaluating the benefit of various salmon protective measures.

Table 12
PERCENT DISTRIBUTION OF MIDWATER TRAWL CATCH OF CHINOOK SALMON SMOLTS AT SACRAMENTO (1988-1991) AND COURTLAND (1990)

Year	April	May	June
1991	47	49	4
1990	33	54	13
1989	6	91	3
1988	14	83	3
X (1988-1991)	26	68	6

Figure 39
CATCH PER 20-MINUTE TOW OF UNMARKED SMOLTS PASSING SACRAMENTO AND CHIPPS ISLAND, 1991



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It was noteworthy that a total of 8 CW1/2T smolts were recovered at Sacramento; these were released as fry on March 4 at Coleman National Fish Hatchery and on March 8 at Red Bluff Diversion Dam. We recovered them between April 15, our first day of trawling at that site for the season, and May 3, which would indicate some of these fry may have migrated past the trawling site before April 15. Additional sampling at Sacramento in 1992 may allow us to better track when marked fry released up-river are moving into the delta and perhaps estimate survival for them as a group. Inferences could also be made about survival of unmarked fry released from Coleman Hatchery and their relative contribution to the production.

Abundance of Sacramento River Smolts at Chipps Island

The mean catch per 20-minute tow in 1991 was 5.2 for April, 26.9 for May, and 5.5 for June. The annual index was 12.5. The lowest index since 1978 was 10, in 1984, and the highest was 48, in 1983. The annual index of 12.5 in 1991 was lower than in 1989 (19) and 1990 (20) and similar to 1988 (12). All four years have been dry or critical water years. Comparison of indices at Chipps Island and Sacramento in 1989 and 1991 supports the conclusion that abundance at both sites was lower, by about half, in 1991 than in 1989 (Table 13).

Table 13
SMOLT ABUNDANCE INDICES AT SACRAMENTO AND CHIPPS ISLAND, 1988-1991

Year	Sacramento*	Chipps Island
1988	80	12
1989	80	19
1990	31	20
1991	42	12

* Sampling site in 1990 was Courtland.

Catch distribution over time at Chipps Island is provided in Figure 39. The majority of fish passed Chipps Island in May (72 percent) and the least in June (12 percent) (Table 14). In June of 1990 and 1991, more outmigrants passed Chipps Island than in the recent past. Early June temperatures in 1990 (66°F on June 4) and 1991 (68°F on June 4) were somewhat more favorable and may have allowed the protracted migration.

Since 1985, the percentage of the annual number of outmigrants has been smaller in June and greater in April (Table 14), possibly because warmer, drier years (which account for 6 of the last 7 years) cause fish to grow faster and thus migrate out sooner. Another possible reason is that fish that historically migrated later may have had high mortality rates and thus may have been genetically removed from the population. The primary reason appears to be that the mass release of Coleman Hatchery fish beginning in 1985 shifted the hatchery release schedule to earlier in May and, in 1991, to late in April.

Table 14
PERCENT DISTRIBUTION OF MIDWATER TRAWL CATCH OF CHINOOK SALMON SMOLTS AT CHIPPS ISLAND, 1978-1991

Year	April	May	June
1991	14	72	12
1990	31	56	12
1989	29	62	9
1988	27	70	3
1987	44	54	2
1986	37	55	8
1985	26	63	11
1984	11	66	23
1983	19	49	32
1982	18	49	33
1981	34	50	16
1980	14	34	52
1979	19	52	29
1978	27	40	33
x (1978-1991)	26	54	20

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Absolute Abundance of Sacramento River Smolts

We estimated the number of fall-run smolts passing Chipps Island from April through June 1991 to be about 17 million (see App. 12, p. 125, USFWS Exhibit 31 for methods), which was somewhat less than estimated in 1989 and 1990 (21 million). Average efficiency of the Chipps Island trawl for 1980 to 1984 was 0.0055. This value, used in calculating absolute abundance, compares to a value of 0.0064 for the Sacramento trawl.

Since sampling at Chipps Island began in 1978, the lowest measure of absolute smolt abundance (12 million) was in 1984 and the highest measure (53 million) was in 1983. If the estimate of smolt survival to adult in the ocean fishery is about 2 percent, then the number of adults in the ocean fishery from the 1991 Central Valley juvenile outmigration would be around 340,000. Between 1980 and 1990, Central Valley stocks have averaged 365,000 fish in the ocean fishery. Fall-run accounts for about 80 percent of the total Central Valley escapement (Central Valley Salmon and Steelhead Restoration and Enhancement Plan, 1990); thus we would estimate about 300,000 of the ocean catch was from fall-run stocks.

Our estimate of 340,000 fish in the ocean fishery, based on juvenile sampling may be somewhat high, but it is within a realistic range.

Survival of Unmarked Sacramento River Smolts

Trawling at Sacramento began on April 15, and we estimated 33 million smolts at that site. We estimated 17 million smolts at Chipps Island, and if we assume very few of the smolts at Chipps Island are the result of fry rearing in the delta (substantiated by our low northern delta beach seine index) and few are the result of production in the San Joaquin basin, then average survival through the delta for the season is estimated to be 52 percent.

Few of the smolts recovered at Chipps Island were likely to be from the San Joaquin basin, because 1990 escapement in the San Joaquin basin accounted for less than 1 percent (941/114,125) of the total fall-run Central Valley escapement (Dick Painter, DFG, pers comm).

Migration Rate of Sacramento River Smolts

Migration rates were estimated for unmarked "natural" (or wild) smolts and for unmarked and marked hatchery smolts.

We estimated that unmarked natural smolts migrated between Sacramento and Chipps Island to be about 5.5 miles per day. This was calculated based on the early apparent peaks at Sacramento on April 22 and at Chipps Island on May 3 (Figure 39).

About 6,568,413 unmarked hatchery smolts were released at Princeton between April 22 and April 29 and on May 6. There was a large peak of unmarked fish at Sacramento on April 29 and a peak at Chipps Island on May 6. This translates to a migration rate of 8.5 miles per day, which is similar to the rate measured in 1990 and slower than in 1988 and 1989.

The peak of the marked group of fish released at Princeton on May 2 was recovered at Sacramento 5 days later and at Chipps Island 9 days after release. This would yield a migration rate of 15 miles per day from Sacramento to Chipps Island. Why unmarked hatchery fish migrate so much slower than marked fish is unclear. Most likely, the two groups migrated at similar rates and the peak we observed at Chipps Island for the unmarked hatchery migration estimate may have included some natural fish and thus biased the estimates low. Even at 15 miles per day, migration rates for unmarked hatchery fish were slower in 1991 than in 1988 and 1989. Estimates for the natural fish also are slower than in past years when the trawling site was at Sacramento (Table 15).

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Table 15
MIGRATION RATES FOR UNMARKED WILD AND HATCHERY CHINOOK SALMON MIGRATING THROUGH THE NORTHERN DELTA* TO CHIPPS ISLAND AND MEAN SACRAMENTO RIVER FLOW AT FREEPORT DURING MIGRATION

Year	Unmarked Wild Fish	Mean Flow	Unmarked Hatchery Fish	Mean Flow
1991	5.5	9,047	8.5 (15)	6,471
1990	4.3	11,901	18.5	8,618
1989	9.5	16,119	19.0	16,020
1988	5.7	12,813	16.0	11,800

* 1988, 1989, 1991 - Sacramento to Chipps Island
1990 - Courtland to Chipps Island

Sacramento River flows at Freeport were extremely low in 1991 during migration of both the natural fish and the hatchery fish. This may have caused the decrease in migration rates. Data from 1988 and 1989 also seem to confirm that lower flows decrease the migration rate through the Sacramento Delta. Further analysis is needed to see if flow is correlated to migration rate.

In the four years that we have measured the migration rate of Coleman Hatchery and natural fish in the northern delta, we have found that hatchery fish tend to migrate substantially faster than the natural fish. There may be several reasons for this. Fish migrating in the large hatchery group may tend to migrate as a group and thus arrive sooner to Chipps Island than the natural fish. Also, there may be a stimulating effect by releasing the fish into the warmer water of the delta in comparison to that of the hatchery or transport truck. Generally, more of the fish released from the hatchery are of smolt size and actively migrate, whereas the natural fish may be somewhat smaller and their migration slower.

It is difficult to accurately measure the migration of natural and unmarked hatchery fish migrating through the delta. The method we have used is simplistic and is based on the number of days between peak catches at Sacramento and Chipps Island. The results should be viewed with caution until hatchery and natural stocks can be separated with a high degree of confidence.

Coleman Hatchery Smolt Contribution

We estimated that Coleman Hatchery smolts released at Princeton survived at a rate of 0.45 between Sacramento and Chipps Island, based on comparisons of survival to Chipps Island and Sacramento of a coded wire tagged group of smolts released at Princeton (Table 16). (This compares with estimates of 0.64 for the Red Bluff tag group and 0.69 for the Battle Creek tag group.) We also estimated a 79 percent survival rate between Princeton and Sacramento for the Coleman production released at Princeton. Given that our survival estimates are reasonable, we estimate about 5.1 million of the 33 million fish (about 15 percent) recovered in the Sacramento trawls and 2.3 million of the 17 million (about 14 percent) estimated at Chipps Island were smolts of Coleman origin.

Table 16
SURVIVAL ESTIMATES FOR CHINOOK SALMON RELEASED AT BATTLE CREEK, RED BLUFF, AND PRINCETON

Code	Release Site	Release Date	Survival at Sacramento	Survival at Chipps Island	Estimated Survival Between Sacramento and Chipps Island
5-1-11-1-13	Battle Creek	April 30	0.3077	0.2058	0.69
5-1-11-1-12	Red Bluff	May 1	0.5516	0.3526	0.64
5-18-45 to 48	Princeton	May 2	0.7865	0.3556	0.45

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To further evaluate Coleman's total contribution to Chinook production in the Central Valley, we need to include the smolts derived from fry released from Coleman Hatchery. For fry and smolts released at Red Bluff Diversion Dam in 1987 and 1988, we estimated that smolts survived an average of three times the rate for fry (a 1 to 0.29 smolt to fry ratio), and if that is similar to the survival rate of fry in 1991, the 11 million fry Coleman planted in February and March of 1991 would equate to about 3.2 million smolts. This would increase Coleman's contribution to the overall production at Sacramento to be about 25 percent.

Winter-Run Recoveries

All winter-run fish collected in 1991 were measured and promptly returned to the river. One juvenile salmon within the winter size criteria (revised criteria by Frank Fisher, DFG-Red Bluff, 2/26/92) was caught in 1991 beach seine sampling. It was 95 millimeters and was recovered at Elkhorn (lower Sacramento River area) on March 6. Between April 15 and May 20, 11 winter-size juvenile salmon were recovered in the Sacramento midwater trawl; they ranged from 101 to 155 milli- meters. In the midwater trawl at Chipps Island, 25 winter-size salmon were collected between April 2 and May 24; they ranged between 100 and 178 millimeters.

Of 946 coded wire tagged smolts, 5 recovered at Chipps Island were also in the winter size criteria but were known to be fall-run hatchery fish. They ranged from 110 to 115 millimeters and were kept for tag recovery and decoding purposes. This illustrates the problem of using size alone to determine what is a winter-run fish. With the February 26 winter-run size criteria, there was substantially less overlap (5 versus 72) with our marked fall-run fish than we estimated with previous criteria (January 1992).

Survival of CWT Smolts in the Northern Delta

In 1991, two groups (100,000 per release group) of coded wire tagged fish were released into the Sacramento River. Both groups were released in late April at Miller Park (site 1 on Figure 40) to evaluate the effect of very low flows under low temperatures on smolt survival in the Sacramento Delta. Recoveries were made by daily midwater trawl sampling at Chipps Island and at the CVP and SWP fish facilities. Recoveries at Chipps Island were converted to survival indices, and fish facility recoveries were expanded to account for the fraction of time sampled to estimate the total number of marked fish passing through the salvage facilities. Additional recoveries will be made in the ocean fishery in future years.

Releases on April 25 and 29 at the same release temperature (62 degrees Fahrenheit) resulted in a survival index of 0.78 and 0.49 respectively (Table 17). Flow at Freeport was 7,220 cfs on April 25 and 5,760 cfs on April 29 and may account for the greater survival from the April 25 group. Increased flows may increase the migration rate, which in turn may increase overall survival. Additional analysis is warranted on the role of flow in survival of salmon migrating through the Sacramento Delta. Combined exports at the CVP and SWP were 4,810 cfs on April 25 and 4,686 cfs on April 29 and would not appear to account for the greater survival from the first release group. The Delta Cross Channel was open during both releases. Sampling variability alone may account for the differences in survival.

In 1991, a total of 9 marked fish, expanded for the fraction sampled (8 from the April 25 release and 1 from the April 29 release) were recovered at the fish facilities from CWT fish released at Miller Park into the Sacramento River. This translates to 0.004 percent of the total number of the Sacramento groups released. Although this percentage is low, many more fish may be lost before they reach the actual salvage facilities because of various indirect impacts of the pumps.

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Figure 40
CWT SALMON RELEASE SITES AND TRAWLING LOCATIONS, 1991

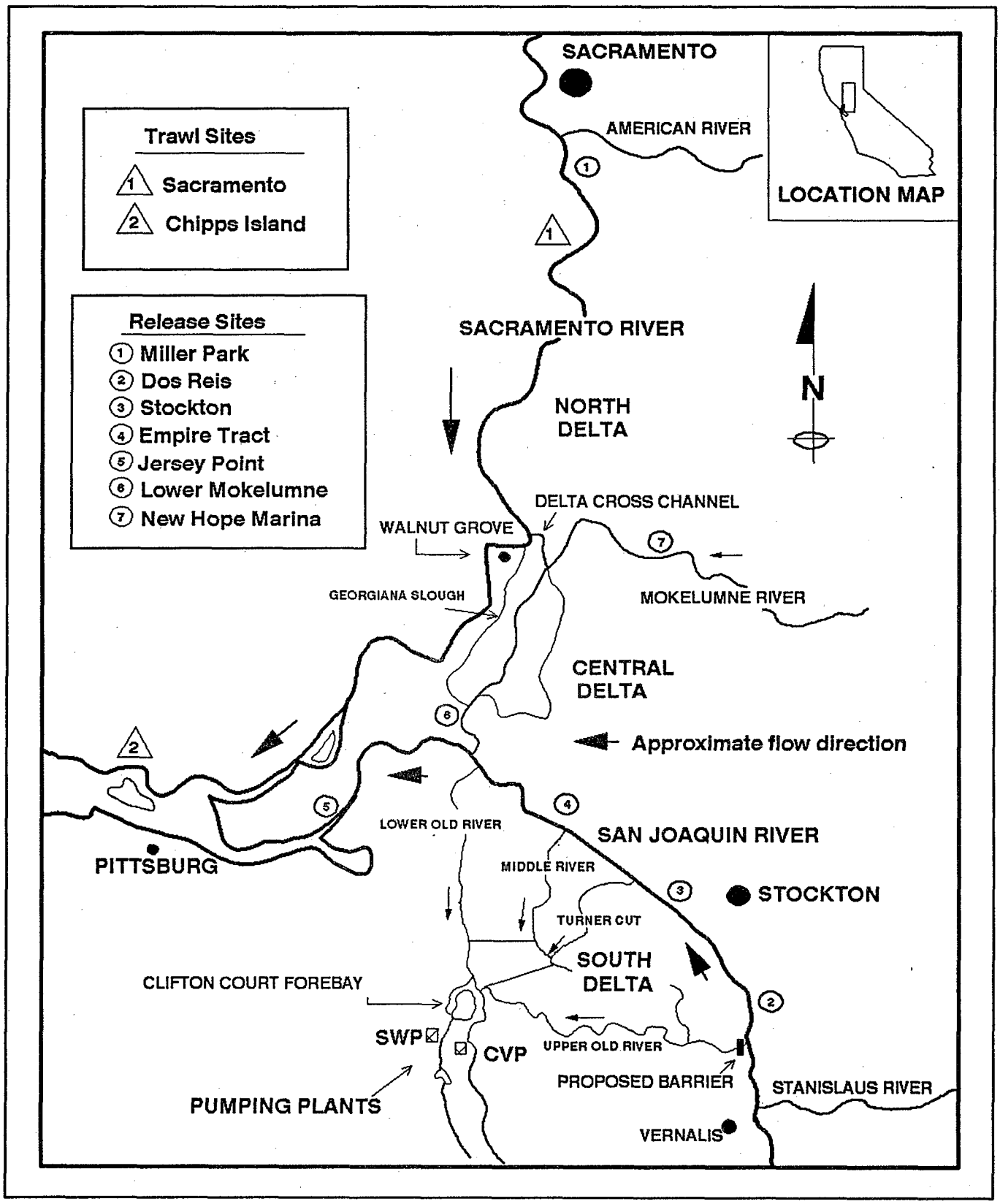

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Table 17
CHIPPS ISLAND TAG SUMMARY, SURVIVAL CALCULATIONS, AND EXPANDED FISH FACILITY RECOVERIES FOR CWT CHINOOK SALMON RELEASED IN 1991

Code	Release Site	Release Date	Temp (°F)	Size (mm)	Number Released	Number Recovered	Sampled	Estimated Survival	First Day Recovered	Last Day Recovered	Expanded Recoveries CVP	Expanded Recoveries SWP
Sacramento River Releases												
H6-01-14-02-07	Miller Park	04/25	62	80	51392	35	0.1389	0.637	05/01	05/06	0	8
H6-01-14-02-08	Miller Park	04/25	62	83	51272	50	0.1389	0.913	04/30	05/09	0	0
Total					102664	85	0.1389	0.775	04/30	05/09		
H6-01-14-02-09	Miller Park	04/29	62	81	53430	21	0.1371	0.373	04/27	05/16	0	0
H6-31-24	Miller Park	04/29	62	79	54158	34	0.1349	0.605	05/04	05/10	0	1
Total					107588	55	0.1371	0.485	04/27	05/16		
San Joaquin River Releases in April												
H6-01-14-01-14	Dos Reis	04/15	60	80	52097	8	0.1374	0.145	04/23	05/11	2302	1282
H6-01-14-01-15	Dos Reis	04/15	60	80	50902	9	0.1389	0.166	04/23	05/02	3170	1244
Total					102999	17	0.1374	0.156	04/23	05/11		
H6-01-14-02-01	Buckley Cove	04/16	59	80	51128	15	0.1389	0.275	04/24	05/06	272	1860
H6-01-14-02-02	Buckley Cove	04/16	59	78	48213	11	0.1389	0.214	04/25	05/02	66	774
Total					99341	26	0.1389	0.245	04/24	05/06		
H6-01-14-02-03	Empire Tract	04/17	61	79	48255	25	0.1389	0.485	04/24	05/09	74	792
H6-01-14-02-04	Empire Tract	04/17	61	77	47347	29	0.1370	0.581	04/24	05/12	57	609
Total					95602	54	0.1370	0.536	04/24	05/12		
H6-01-14-02-05	Lower Mokelumne	04/18	61	79	47289	79	0.1389	1.564	04/23	05/03	0	276
H6-01-14-02-06	Jersey Point	04/19	63	82	52139	94	0.1375	1.705	04/23	05/17	20	274
San Joaquin River Releases in May												
H6-31-25	Buckley Cove	05/06	65	78	49393	7	0.1368	0.135	05/11	05/30	12	31
H6-31-26	Buckley Cove	05/06	65	85	50427	13	0.1376	0.244	05/11	05/16	40	33
Total					99820	20	0.1368	0.190	05/11	05/30		
H6-31-27	Lower Mokelumne	05/09	64.5	84	45706	31	0.1378	0.640	05/12	05/18	22	13
H6-31-28	Jersey Point	05/13	61	86	49184	89	0.1389	1.694	05/14	05/23	6	0
BioSystems Releases												
H6-48-37 to 46	New Hope	04/23	60	95	80041	139	0.1389	1.630	04/27	05/06	8	112
H6-48-57 to 63 & H6-49-01 to 03	New Hope	05/06	65	96	101980	48	0.1359	0.45	05/10	05/21	0	0
Up-River Releases												
H5-1-1-1-10	Coleman	03/04		50	52567	6			04/23	05/22	0	0
H5-1-1-1-11	Red Bluff DD	03/08		50	53792	3			04/26	05/04	0	0
H5-1-1-1-12	Red Bluff DD	05/01		76	64700	24	0.1368	0.353	05/11	05/30	0	0
H5-1-1-1-13	Battle Creek	04/30		74	64698	14	0.1368	0.206	05/11	05/28	0	0
H5-18-45	Princeton	05/02				4			05/14	05/19		
H5-18-47	Princeton	05/02				10			05/11	05/21		
H5-18-48	Princeton	05/02				10			05/10	05/30		
Total				74	64737	24	0.1356	0.356	05/10	05/30	0	0

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Verification of Smolt Survival Model

When using our smolt survival model (Kjelson *et al* 1989) to predict survival through the delta given the environmental conditions in 1991, we found the model predicted survival for the April 29 group very closely but underestimated the actual survival index observed on April 25 (Table 18). We plan to reevaluate the model with recent data to determine if flow is a significant factor affecting survival of smolts through the Sacramento Delta. The model already includes temperature, exports, and percentage of water diverted at the Delta Cross Channel and Georgiana Slough as significant factors.

Observed estimates of survival were divided by 1.8 to approximate actual survival, as was done in developing the Kjelson *et al* model.

Model estimates of annual survival between April and June averaged 0.28. This compares to 0.52 based on the number of salmon caught throughout the season and an average estimate of net efficiency. However, in the model, we had to divide all estimates by 1.8 to obtain survival indices between 0 and 1; if we similarly divide the observed annual estimate by 1.8, we estimate smolt survival through the system to be 0.29. It may be necessary to divide all abundance indices and estimates at Chipps Island by 1.8 to make comparisons between the model and observed values compatible.

However, the difference between the original 0.52 annual estimate and the one generated through the model may be accounted for by smolts migrating past Chipps Island that were not sampled at the Sacramento trawl because they entered the delta as fry before Sacramento trawling began in April. In addition, some of the smolts may have originated in the San Joaquin basin and thus biased the survival estimate high.

Migration Rate of Sacramento River Smolts

Our estimate of smolt migration rates of CWT fish released at Sacramento in 1991 was 7.5 miles per day on April 25 and 8.6 miles per day on April 29 and was similar to groups released from Sacramento in the previous 3 years (Table 19). Migration rates in 1991 for CWT groups released at Sacramento may have decreased because the flows were low and possibly because temperatures were favorable.

Table 19
SUMMARY OF MIGRATION RATES ESTIMATED FROM CWT CHINOOK SALMON RELEASED AT SACRAMENTO AND RECOVERED BY TRAWL AT CHIPPS ISLAND, 1988-1991

Year	Migration Rate (miles per day)	Flow at Freeport (cfs)*
1991	7.5	7,220
	8.6	5,760
1990	9.5	5,958
1989	11.4	13,604
	11.4	12,748
1988	8.9	11,792
	12.0	12,259

* Mean daily flow during the migration period to Chipps Island.

Table 18
PREDICTED AND OBSERVED SURVIVAL ESTIMATES FOR CWT CHINOOK SALMON RELEASED AT SACRAMENTO IN 1991
(Plus Flow, Temperature, and Combined Exports on Release Date)

Release Date	Observed	Predicted	Flow at Freeport	Water Temperature	CVP/SWP Exports
04/25/91	0.78÷1.8=0.43	0.29	7,220 cfs	62°F	4,810 cfs
04/29/91	0.49÷1.8=0.27	0.28	5,760 cfs	62°F	4,686 cfs

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San Joaquin River Studies

Coded wire tag data generated since 1985 has shown, in general, that fish released in the San Joaquin River downstream of the Upper Old river junction, survive better than those released into upper Old River (Table 20). This infers that any natural smolts diverted into upper Old River would have greater mortality than those migrating down the mainstem San Joaquin. A full barrier has been proposed for installation at the head of Old River as a management alternative to improve fall-run smolt survival down the San Joaquin River. This would force all migrating salmon down the mainstem San Joaquin and prevent them from being diverted into upper Old River and directly toward the SWP and CVP pumping plants (Figure 40).

Modeling Efforts in 1991

During the scoping phase of the Bay/Delta water right hearings, we were asked to model potential benefits of a barrier at the head of Old River to salmon smolts migrating through the San Joaquin Delta under different flow and export conditions. For comparison purposes, we also needed a model to represent conditions and smolt survival without the barrier. Two models were

Table 20
SURVIVAL INDICES FOR CWT CHINOOK SALMON SMOLTS RELEASED AT DOS REIS AND IN UPPER OLD RIVER, 1985-1991

Release Date	Survival to Chipps Island	Ocean Recovery Rate	Flow at Stockton (cfs)	CVP/SWP Exports (cfs)	Temp on Release Day °F
Upper Old River Releases					
04/29/85	0.62				
05/30/86	0.20	0.011			
04/27/87	0.16	0.005			
04/21/89	0.09	0.00073		High	
05/03/89	0.05	0.00044		Low	
04/17/90	0.02			High	
05/13/90	0.01			Low	
Mean	0.16				
Dos Reis Releases*					
04/22,23/82	0.70**		7,861	5,598	65
04/30/85	0.59		513	6,311	70
05/29/86	0.34	0.021	2,514	5,386	70
04/27/87	0.38***	0.012	471	6,093	70
04/20/89	0.14	0.00062	112	10,297 (High)	69
05/02/89	0.14	0.00096	790	2,470 (Low)	71
04/16/90	0.04		0	9,549 (High)	68
05/02/90	0.04		490	2,461 (Low)	68
04/15/91	0.16		60	5,153 (High)	60
Mean (85-87, 89-91)	0.24				

* 5-day averages after release date.
** Original survival estimate modified (0.60) based on the ratio of recovery rates between the Dos Reis and Merced River releases.
*** Original survival estimate modified based on the ratio of recovery rates between the Dos Reis and upper Old River releases.

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derived to use with the DWR hydraulic operational models to estimate the benefits and costs of installing a full barrier at the head of Old River. This section summarizes how these models were constructed.

The model estimating smolt survival without the barrier was derived using past adult escapement data from the San Joaquin basin because we did not have adequate smolt survival data to develop meaningful relationships. Adult production is generally representative of smolt abundance 2-1/2 years earlier. In the analyses, we assumed smolt survival was an indicator of smolt abundance and was linearly related to adult production. This assumption is generally true, because less of the overall natural mortality occurs after the smolts enter the ocean.

The index of adult production used in the analyses was defined as adult escapement in year *i* divided by parental escapement in year *i*–3. The index also was adjusted to reduce high escapement contribution by grilse salmon (see Bill Loudermilk, unpublished draft report, 1988).

To relate adult production to smolt survival, we divided each adult production index value by 12 to get values into a typical smolt survival range of 0 to 1. The adult production index from 1969 to 1986 ranged from 0.2 to 11.09. Consequently, the smolt survival index was for 1967 to 1984 (year *i*–2) and ranged from 0.017 to 0.924.

The smolt survival model was used in conjunction with DWR operational studies to reflect present conditions and resulting salmon smolt survival in the San Joaquin Delta without installation of a barrier. Inflow and exports were the hydraulic conditions experienced by the juveniles during outmigration.

A multiple regression analysis was conducted between Vernalis flow (mean daily flow from March 15 to June 15), combined CVP and SWP exports (mean daily exports from March 15 to June 15), and the index of San Joaquin salmon smolt survival from 1967 to 1984. The multiple regression was significant ($p<0.01$), and the adjusted r-squared was 0.77 (Figure 41). The data in 1979 (year *i*–2) were an obvious outlier and were not included. This was the relationship used to evaluate effects of flow and exports on salmon smolt survival without a barrier (Figure 42).

To estimate the benefits on smolt survival of varied export and flow conditions with a barrier, another model was developed.

In several years since 1985, coded-wire-tagged experiments have been conducted to evaluate the difference in survival between smolts released into upper Old River and into the main San Joaquin River at Dos Reis. Since Dos Reis is downstream of the junction with upper Old River, it served as the best (and only) data to estimate survival of smolts migrating down the San Joaquin River with a barrier in place. In past years we have noted that fish do get pulled upstream and are diverted into upper Old River to the pumps; thus, our estimates of survival to Chipps Island from Dos Reis are probably biased low.

Data were limited to 8 data points, so standard multiple regression analyses were not possible. In a linear regression, smolt survival (from Dos Reis releases) was correlated to flow at Stockton and an r-squared value of 0.477 was obtained (Table 20). Although this is not significant at the 0.95 percent confidence level, it was significant at the 0.90 percent level.

We also believed export levels affect smolt survival but since our data set was so small we could not detect a relationship. Theoretically, we wanted to estimate the change in the survival/flow relationship for various export levels. Historical data were obtained when combined CVP/SWP exports averaged 6,000 cfs (range between 2,400 and 10,200). We hypothesized that a similar relationship with flow probably would exist at other export levels and only the intercept of the relationship would change.

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Figure 41
OBSERVED AND PREDICTED SURVIVAL, 1967-1984
o Indicates outlier; not used in regression.

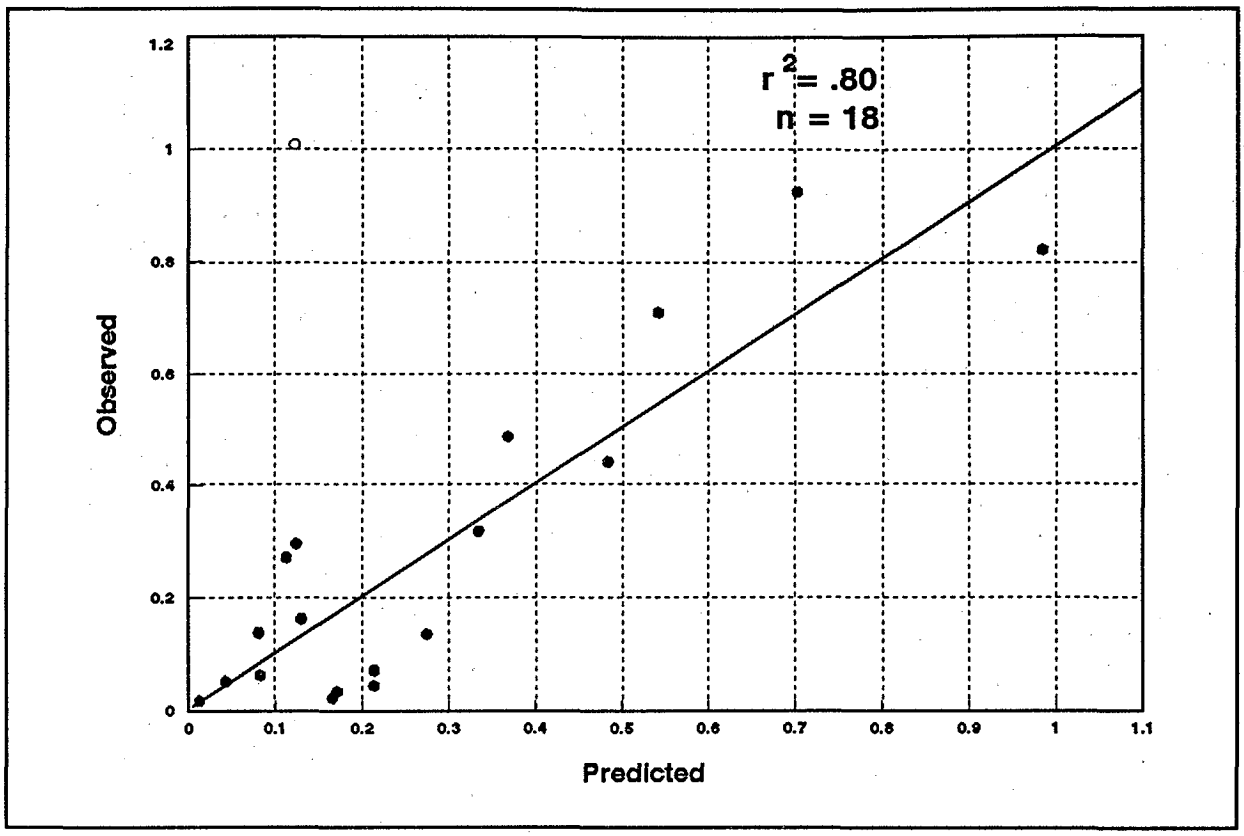
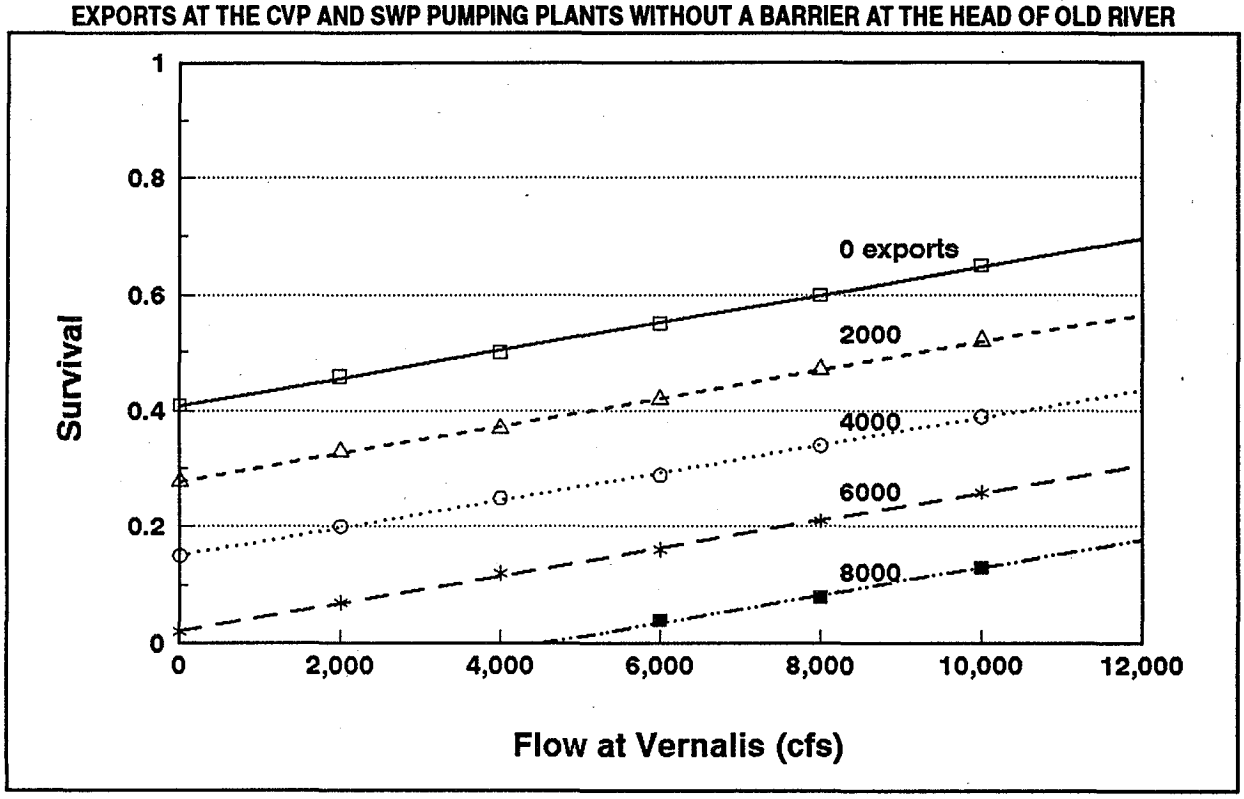


Figure 42
RELATIONSHIP BETWEEN SAN JOAQUIN RIVER SMOLT SURVIVAL, FLOW AT VERNALIS, AND EXPORTS AT THE CVP AND SWP PUMPING PLANTS WITHOUT A BARRIER AT THE HEAD OF OLD RIVER



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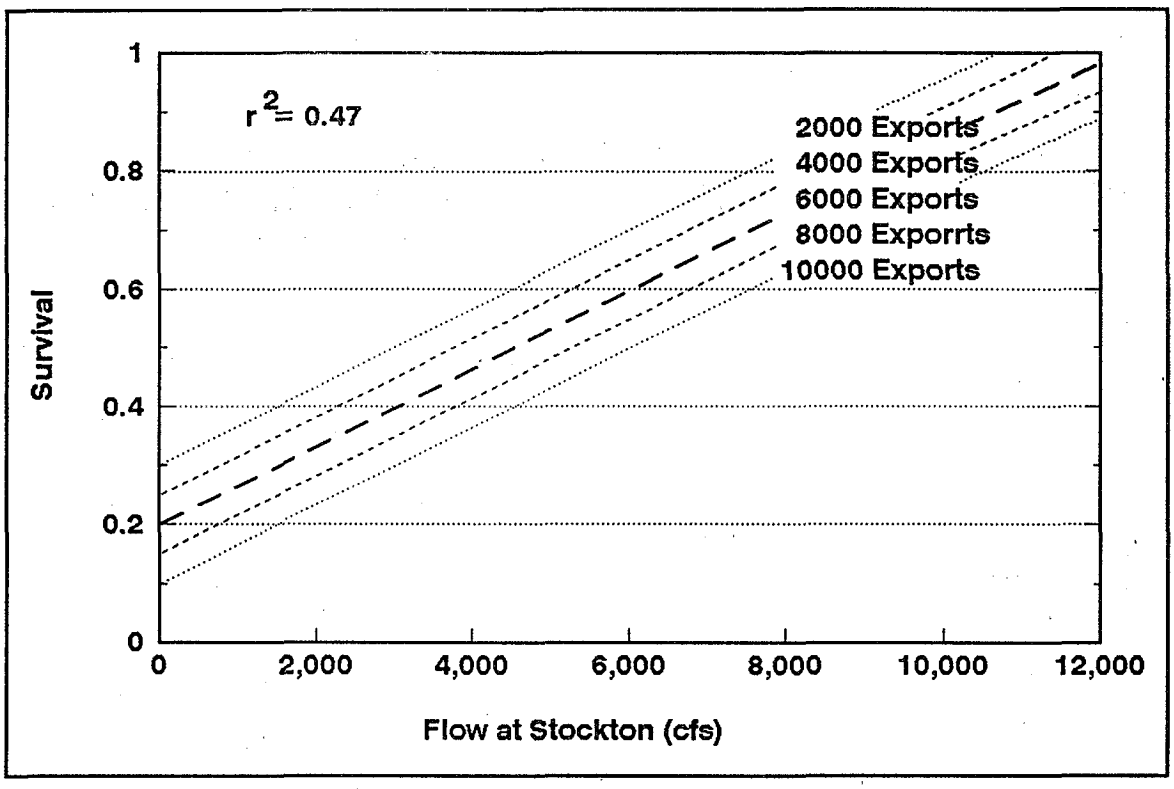
The range between bands in the relationship without a barrier varied by about 0.10 survival units per 2,000 cfs increase in exports (Figure 42). We have theorized that exports would not have as great an effect on survival with a barrier as they would without a barrier because the fish are farther downstream, where there is more tidal influence, before they encounter channels diverting water south toward the pumping plants. This hypothesis affected the relationship by narrowing the bands between export levels at any specific flow level.

Data in 1989 and 1990 also support a narrower band, as the difference in survival ratios of the Dos Reis group divided by the upper Old River group in those years, between high (~10,000 cfs) and low (~2,000 cfs) export at generally low-flow levels at Stockton (0 to 800 cfs), indicated roughly double smolt survival (0.05 units), not a quadruple change (0.1 units).

There is some risk in relying on the 1989 and 1990 data, as the results were so low that they may not represent the true relationship between smolt survival, exports, and flow. However, that was the best available data and we used it with our best professional judgment. We estimated that the constant of the linear regression would change by 0.05 units of survival for every 2,000 cfs increase in exports (Figure 43).

We supplied SWRCB our best estimates of potential benefits to San Joaquin smolt survival under different environmental conditions using a barrier at the head of Old River. However, we need to measure survival under different conditions with the actual barrier in place to fully understand the benefits and costs of such a measure.

Figure 43
RELATIONSHIP BETWEEN SAN JOAQUIN RIVER SMOLT SURVIVAL, FLOW AT STOCKTON, AND COMBINED EXPORTS AT THE CVP AND SWP PUMPING PLANTS WITH A BARRIER AT THE HEAD OF OLD RIVER



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Southern Delta CWT Experiments

An effort was unsuccessful in April 1991 to install the upper Old River barrier for testing purposes. An attempt will be made to install it in 1992 to evaluate its impact on smolt survival.

The 1991 CWT smolt survival experiments in the southern delta were designed to measure smolt survival during periods of high and low exports. Releases were made to assess changes in survival due to increased flow of water (and presumably fish) toward the pumping plants in Old River, Middle River, and Turner Cut that would occur if a barrier was present and exports were not curtailed. This increase in flow toward the pumps could increase downstream mortality; this needs to be weighed against benefits of the barrier to assess its net value.

Additional groups of fish were released at Jersey Point, on the lower San Joaquin River, to evaluate the effect of reverse flows on smolts migrating through the western delta.

Groups of coded-wire-tagged fish were released on the mainstem San Joaquin River at Dos Reis, Stockton-Buckley Cove, Empire Tract, and Jersey Point and in the lower Mokelumne River at Lighthouse Marina (sites 2 through 6, Figure 40). Fish were released from April 14 to April 19 during a period of higher pumping and low water temperatures. The second group of fish were released at sites 3, 5, and 6 between May 6 and May 13 during a period of lower pumping and slightly higher water temperatures than those observed in April (Table 17).

Figure 44 illustrates that during the first release, export and reverse flow conditions were changing dramatically in a matter of just a few days, whereas migration of all the fish of a particular group to Chipps Island takes a minimum of a week, making analysis of the data difficult.

Average total exports during the time the release groups were migrating past Chipps Island were 3,222 cfs from April 23 to May 17 and 2,329 cfs from May 11 to May 30. Average San Joaquin inflow at Vernalis was 978 and 1,102 cfs, respectively, for the two periods.

Throughout the analyses we have used average conditions during periods we feel most closely represent what the individual groups of fish were exposed to.

Except at Jersey Point, releases were made on an ebbing tide or high slack for consistency and to assure immediate downstream migration. Due to the short distance from Jersey Point to Chipps Island (12 miles) and potentially short travel time, we thought we might miss sampling the Jersey Point group. Therefore, we released both Jersey Point groups on a flooding tide to spread their distribution and to increase the chance of adequate sampling at Chipps Island.

Chipps Island Recoveries of April Release Groups

Survival of all five groups released in April in the San Joaquin Delta and recovered at Chipps Island showed consistently better survival as they were released closer to the western delta (Table 21). Survival of fish released at Dos Reis was the poorest, and survival of fish released at Jersey Point was best. This would lead us to believe smolts have mortality throughout their migration to the western delta.

Since Dos Reis is the farthest from Chipps Island and may reflect only the higher mortality because of the greater distance to Chipps Island, we attempted to correct the survival indices to reflect the survival rate per mile in each reach of the San Joaquin River between Dos Reis and Jersey Point. This was done by dividing the farthest upstream survival index by the next lower downstream site.

Also among the five release groups, variability between temperatures on the day of release ranged between 59 and 63 degrees Fahrenheit. Work on the Sacramento Delta has shown that temperature is an important variable affecting smolt survival in that area of the delta. To factor out the potential bias

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Figure 44
FLOWS INTO CLIFTON COURT FOREBAY AND CENTRAL VALLEY PROJECT AND AT JERSEY POINT, APRIL 1 TO JUNE 5, 1991
The two release periods are bounded by solid vertical lines.

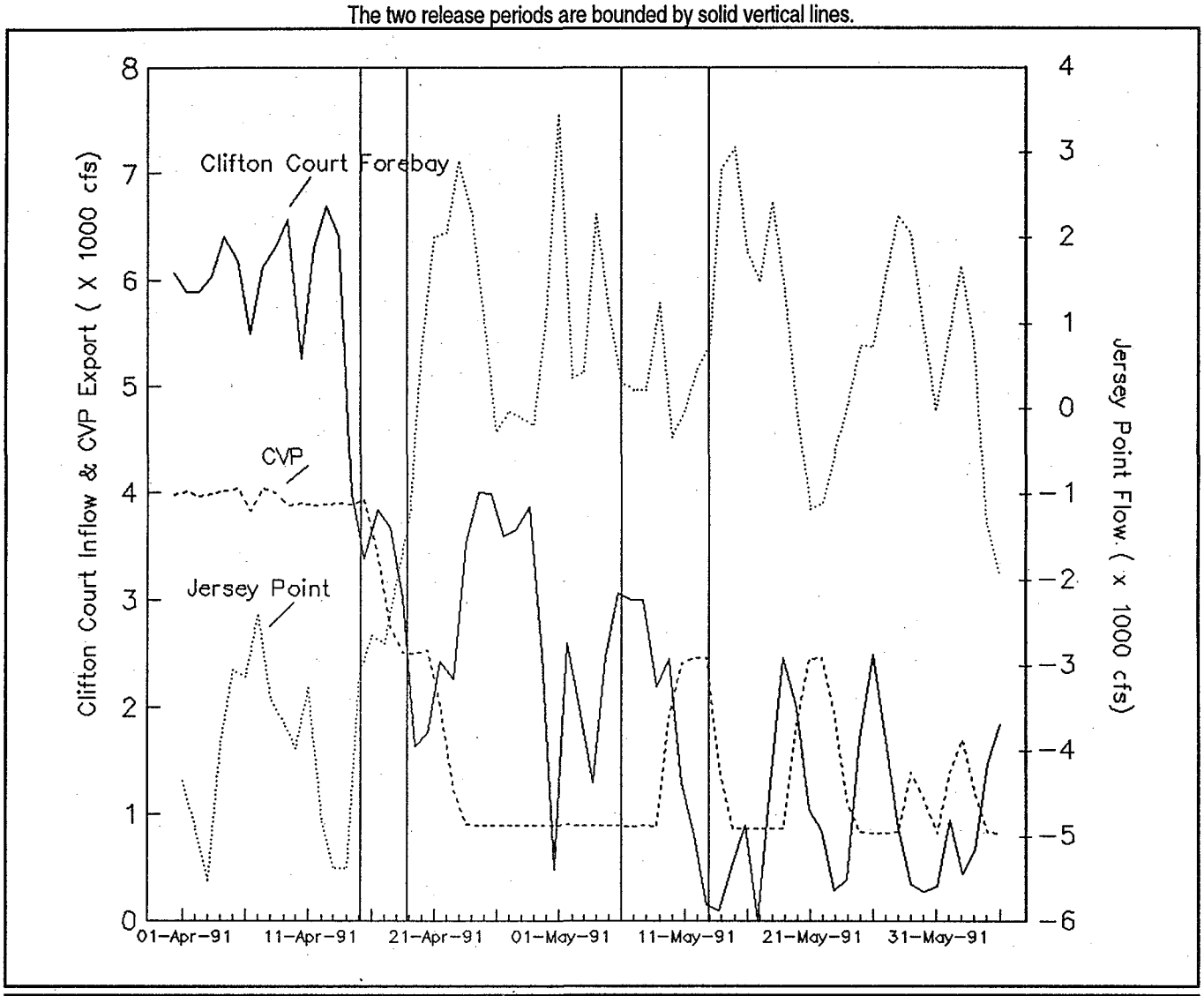

Table 21
TEMPERATURE CORRECTIONS TO 59 DEGREES FAHRENHEIT AND EFFECT ON SURVIVAL INDICES FOR MARKED CHINOOK SALMON RELEASED IN APRIL AND MAY 1991

Release Month	Release Site	River Mile	Temp (°F)	Uncorrected Survival Index	Corrected Survival Index*
April	Dos Reis	50	60	0.156	0.122
	Stockton	39	59	0.245	0.136
	Empire Tract	29	61	0.536	0.368
	Lower Mokelumne	19	61	1.564	0.939
	Jersey Point	12	63	1.705	1.087
	New Hope	26	60	1.630	0.940
May	Stockton		65	0.190	0.315
	Lower Mokelumne		64.5	0.640	0.547
	Jersey Point		61	1.694	1.011
	New Hope		65	0.460	0.465

* Uncorrected survival indices were divided by 1.8 before standardizing for temperature.

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of temperature in the southern delta experiments, we assumed the relationship between temperature and survival was similar between basins.

Southern delta survival indices were standardized to one temperature (59°F), using the temperature/mortality relationship for reach 3 of the Sacramento River between Ryde and Chipps Island in the Kjelson *et al* model (1989). To standardize for temperature, we needed to bring all the survival estimates to values between 0 and 1, as has been done in the model. Therefore we divided all the survival indices by 1.8 before standardizing for temperature.

Figure 45 shows temperature-standardized survival of smolts in each reach throughout migration to Chipps Island. The survival rate per mile, also shown, was calculated by dividing the survival for each reach by the number of miles in each reach.

The April survival rate per mile between Dos Reis and Stockton (0.08) was actually twice as good as the survival rate per mile between Stockton and Empire Tract and between Empire Tract and the lower Mokelumne junction (0.04).

The survival rate on a per-mile basis was the greatest between the lower Mokelumne site and Jersey Point and was 17 times greater than that between Stockton and the lower Mokelumne release site. This analysis shows the greatest mortality in the southern delta in 1991 was on the main San Joaquin River between Stockton and where the lower Mokelumne River enters the San Joaquin. This mortality is even greater than that between Dos Reis and Stockton. This is not surprising considering that the number of diversions off the main river in that reach is greater than in other areas. Once fish are diverted toward the pumping plants, migration is delayed and they are exposed to potentially greater temperatures, high in-channel and Clifton Court predation, and direct impacts of the pumping plants. This analysis suggests mortality is significantly reduced once salmon smolts reach the lower Mokelumne junction.

The trawls may bias survival estimates of fish released nearest Chipps Island (lower Mokelumne and Jersey Point) by catching clumps of these fish. It is likely that the closer fish are released to Chipps Island, the less they spread out thoroughly at the sampling site. Confirmation of these survival estimates will be made by ocean recoveries.

On April 23, BioSystems Inc., a consulting firm working in the area, released a group of coded-wire-tagged Chinook smolts into the Mokelumne River near New Hope Marina (site 7, Figure 40). Although these fish were somewhat larger that our Mokelumne River release, (Table 17) the raw survival index was similar (1.63) to that of our lower Mokelumne release group (1.56), which would lessen the concern that the survival index for the lower Mokelumne River and Jersey Point releases are biased high. In Figure 45, the temperature-corrected survival estimates showed no apparent mortality between the New Hope and lower Mokelumne release sites, but this may be because larger fish were released at New Hope and larger fish typically survive better.

Chipps Island Recoveries of May Release Groups

The uncorrected survival indices of fish released at Stockton, lower Mokelumne, and Jersey Point in early May also showed greater survival the closer the release group to the western delta, with the Jersey Point group surviving the best and Stockton group the worst (Table 21). When we evaluated survival between each reach of the San Joaquin River at a constant temperature, we found survival was lowest between Stockton and the lower Mokelumne release sites and about 2.5 times greater between the lower Mokelumne and Jersey Point (Figure 45).

On May 6, BioSystems, Inc. released an additional group of fish at the New Hope Marina, on the Mokelumne River. This group showed high survival (temperature corrected) on a per-mile basis down the Mokelumne River in May, even greater than for the reach between the lower Mokelumne

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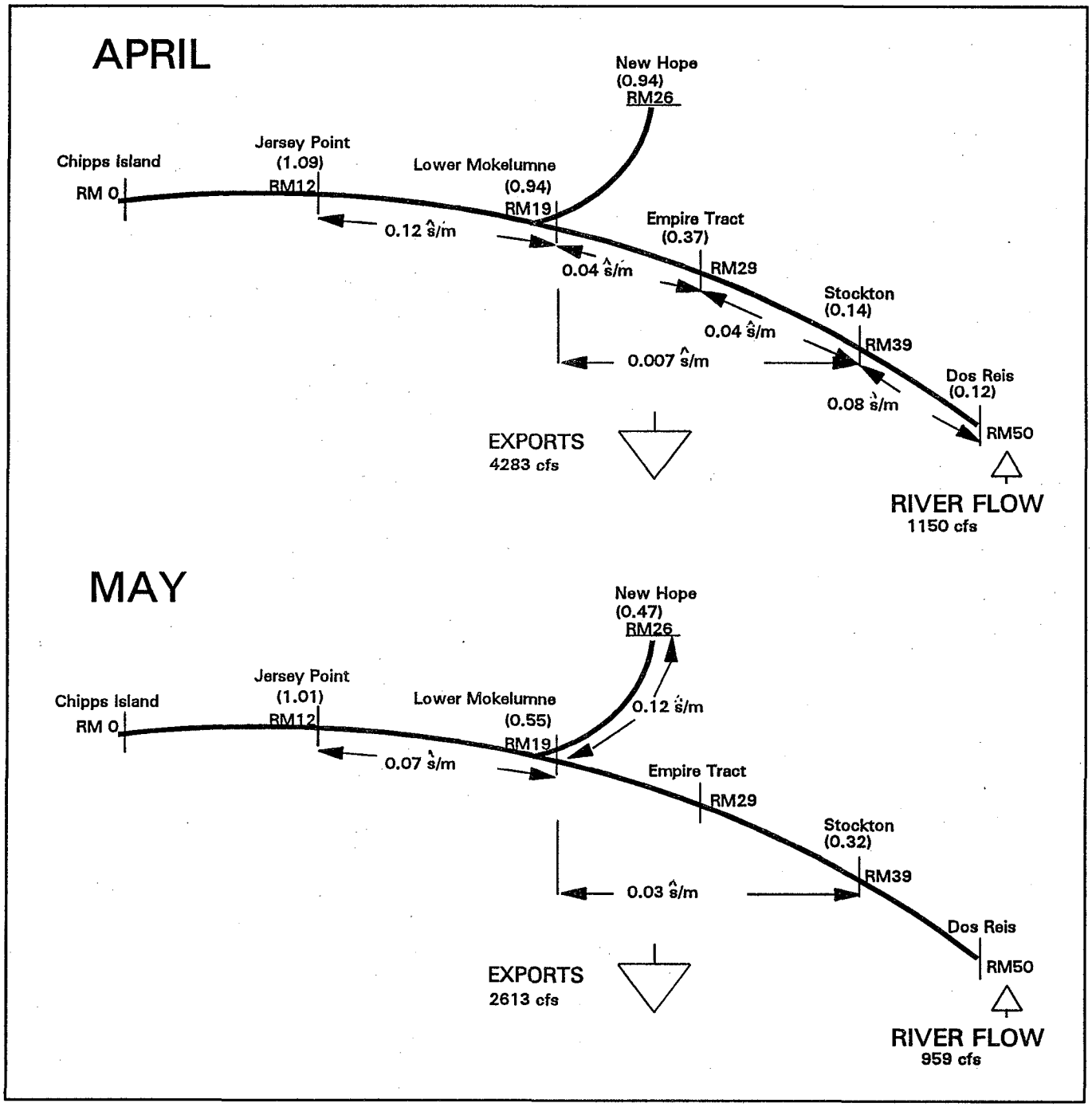
and Jersey Point. Again, these New Hope fish were somewhat larger, which would perhaps increase their survival relative to the other CWT groups. The New Hope raw survival indices appeared reasonable, supporting the results obtained from the lower Mokelumne and Jersey Point release groups. Unadjusted mortality for the Jersey Point group was very low in May, as it was in April.

Figure 45
TEMPERATURE-CORRECTED SURVIVAL PER RELEASE GROUP TO CHIPPS ISLAND AND SURVIVAL (s/m) BETWEEN RELEASE LOCATIONS
April exports and streamflow encompass April 16 (release date at Stockton) to May 6 (last capture at Chipps Island).
May exports encompass May 6 to May 30.
CVP/SWP and streamflow were measured at Vernalis.



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Comparison of April and May Releases

Figure 45 shows the difference in survival rates, corrected for temperature, between reaches in April and May. The survival rate between Stockton and the lower Mokelumne junction in May (0.03), under lower export conditions was significantly (4.2 times) better than the survival rate for similar distance in April (0.007) when exports were greater (4,283 versus 2,613) (Table 22). During the same period, inflows into the San Joaquin River at Vernalis were greater in April (1,150 cfs) than they were in May (959 cfs) and thus would not account for the higher survival we saw in May after correcting for temperature.

Positive flow past Stockton for the Stockton groups during both April and May was about 100 to 150 cfs and is a function of flow at Vernalis and exports (DWR Bulletin 76). We attribute the additional mortality in April to the higher exports.

Survival between the lower Mokelumne site and Jersey Point was also greater (about 2 times) in April than in May. It appears all conditions were more favorable in May than in April for the lower Mokelumne groups, except flows through the central delta, which were greater in April.

Survival for the Mokelumne River between New Hope Marina and the lower Mokelumne release site was greater in April than in May. Conditions such as exports, Jersey Point flow, and flow into Georgiana Slough and the Delta Cross Channel appeared to be more favorable in May and would not explain the survival differences observed (Table 22).

Temperatures were lower in April by 3.5°F at the time of release. Although we tried to correct for the influence of temperature,

Table 22
AVERAGE DAILY FLOW AND EXPORTS,
DATE OF RELEASE UNTIL DATE THE LAST FISH WAS RECOVERED AT CHIPPS ISLAND
(In Cubic Feet per Second)

	Sacramento River Flow		San Joaquin River Flow		Exports		
Release Group	Freeport	Cross Channel/ Georgiana Slough	Vernalis	Jersey Point	CVP	SWP	Total
Miller Park, 04/25	6,396	3,726	1,334	1,049	896	2,167	3,063
Miller Park, 04/29	6,345	3,784	1,127	925	1,203	1,916	3,119
April Releases							
Dos Reis	7,051	4,068	1,079	314	1,611	2,697	4,308
Stockton	7,034	4,038	1,150	496	1,552	2,731	4,283
Empire Tract	6,867	4,010	1,090	564	1,466	2,548	4,014
Lower Mokelumne	6,798	3,933	1,210	760	1,410	2,731	4,141
Jersey Point	6,730	3,858	1,057	1,010	1,325	2,079	3,404
May Releases							
Stockton	7,490	3,589	959	831	1,371	1,242	2,613
Lower Mokelumne	6,942	3,695	763	1,347	1,504	902	2,406
Jersey Point	7,662	3,159	1,063	969	1,540	803	2,343
BioSystems Releases							
New Hope, April	7,864	3,451	893	695	1,353	1,041	2,395
New Hope, May	7,303	3,568	927	1,027	1,609	1,013	2,622

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we may be underestimating the influence of temperature in the San Joaquin Delta.

Fish released at Jersey Point in both April and May survived at high levels and were similar to each other (Table 21). Although initially we suspected reverse flows would be greater during the higher pumping period, comparison of conditions while the fish were observed at Chipps Island indicated flow at Jersey Point was similar for both groups (Table 22). This may be why the groups of fish also survived similarly.

In both months the vast majority of mortality was associated with the area between Stockton and the lower Mokelumne junction and, during times of higher pumping, survival through that area is much less.

Generally, survival for the Dos Reis group released in April 1991 was better than for similar release groups in 1989 and 1990, most likely attributable to the generally lower temperatures in 1991 (Table 20). Survival in 1991 was still lower than in 1982, 1985, 1986, and 1987.

Fish Facility Recoveries

The greatest number of fish recovered at the SWP and CVP fish facilities were from the farther upstream groups, both in April and in May — generally the inverse relationship from that observed in survival at Chipps Island (Figure 46). The New Hope releases by BioSystems, Inc. had fewer recoveries at the fish facilities than for our similar lower Mokelumne releases, possibly because they released larger fish and released them farther from the facilities than the other release groups (Figure 40).

We saw between 6 and 56 times more marked fish at the fish facilities from the April groups than for corresponding groups released in May. This may reflect the greater effect of the pumps on migrating salmon during periods of higher exports (see Table 23).

Both our recoveries at the fish facilities and estimates of survival in 1991 would support a conclusion that diversion toward the pumps and fish facilities, especially upstream of the lower Mokelumne junction, increases mortality of San Joaquin smolts migrating to Chipps Island.

A greater number of marked fish for all groups except the Dos Reis group were recovered at the SWP (Table 17). This is not unexpected because Clifton Court Forebay is the first diversion facility to which salmon smolts are exposed when drafted south in southern delta channels other than upper Old River.

Figure 46
COMBINED CVP/SWP FISH FACILITY RECOVERIES AND TEMPERATURE-CORRECTED SURVIVAL TO CHIPPS ISLAND FOR GROUPS OF CWT FISH RELEASED IN THE SOUTHERN DELTA, 1991

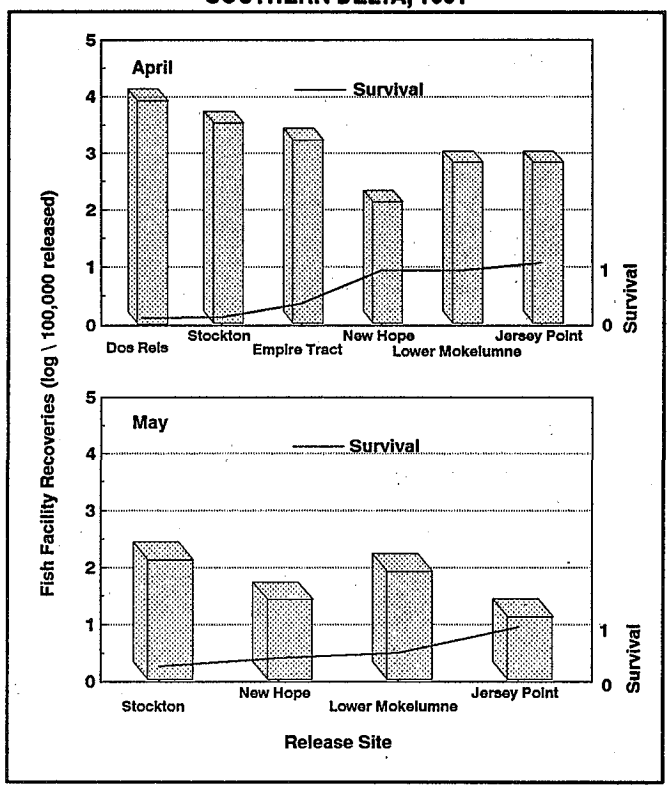

Table 23
PROPORTION OF TAGS RECOVERED AT THE CVP AND SWP FISH FACILITIES
Calculated by expansion of tag recoveries for groups released in the southern Delta divided by the number released.

Release Site	April	May	Ratio
Jersey Point	0.0056	0.0001	56
Lower Mokelumne	0.0058	0.0008	7
New Hope	0.0012	0.0002	6
Empire Tract	0.0160		
Stockton	0.0299	0.0012	25
Dos Reis	0.0776		

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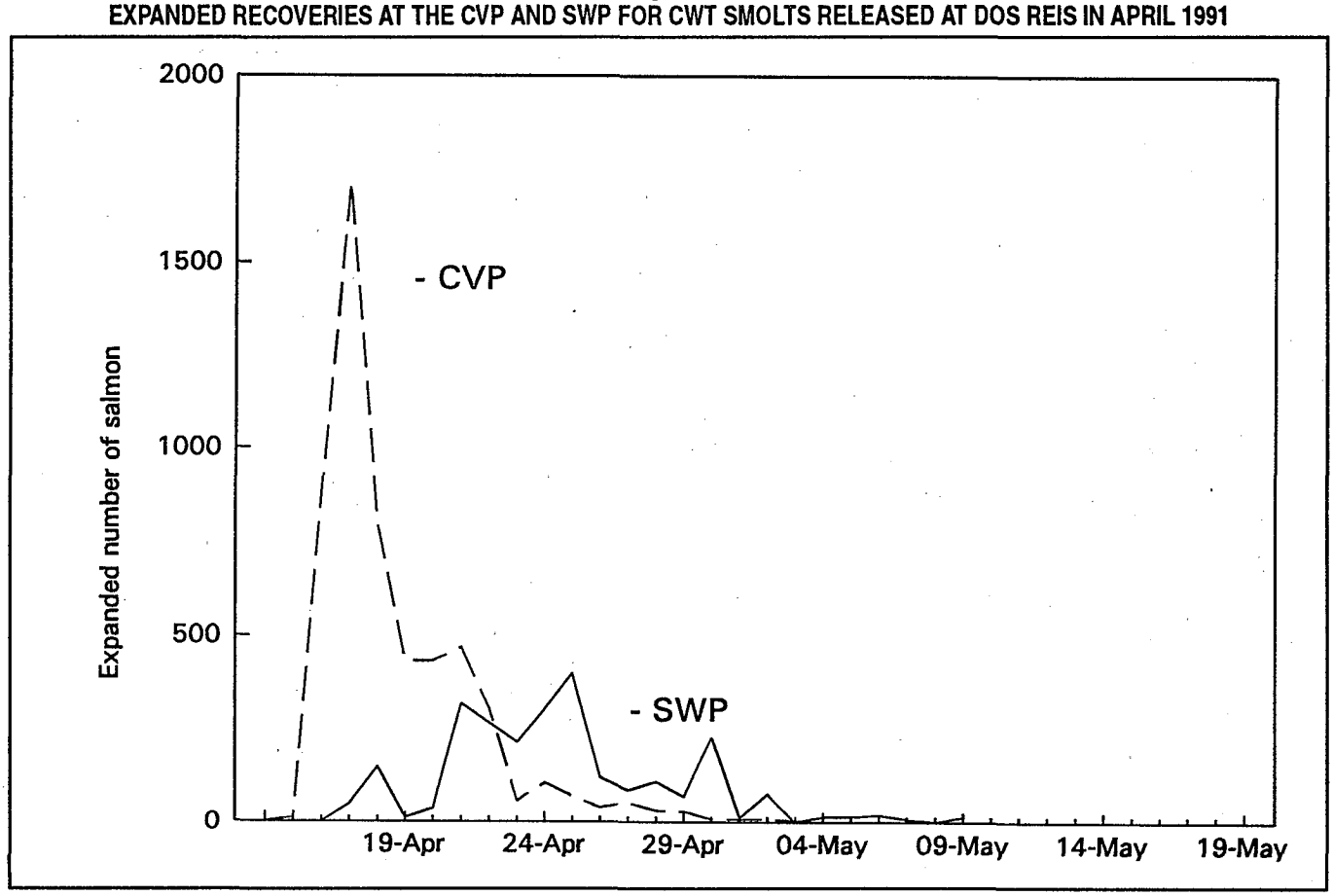
We have some indication from trawling at Mossdale that a large group of the Dos Reis fish (the number recovered in the trawl was 296) were actually carried upstream past the junction of upper Old River and most likely were diverted to the CVP fish facility via upper Old River. That may be why we saw a larger proportion of this group at the CVP facility than at the SWP facility (Figure 47). This also would tend to underestimate survival for this group because some of this group was diverted via upper Old River, where survival has historically been less. All of our past data from Dos Reis releases during low inflow conditions likely suffer this survival bias and would indicate survival differences between the Dos Reis and upper Old River groups are greater than raw survival indices would reflect.

Past research by the Fish Facility Program on predation rates in Clifton Court Forebay has indicated that losses through the forebay for Chinook smolts can be as high as 85 percent. If this is true, the expanded number of fish diverted to the SWP fish facility would be much higher. For instance, for the Stockton group released in April, 2,635 marked fish (expanded for effort) were recovered at the SWP fish facility and 338 at the federal facility. The total number of fish released from this group was 99,341. About 3 percent of the group was recovered at the fish facilities, and survival indices to Chipps Island were about 25 percent. To standardize the Chipps Island estimates to absolute estimates, we divide by 1.8. This results in a survival estimate of 14 percent. So far we have been able to account for less than 20 percent of the total release group. Given that predation in Clifton Court is 85 percent, we can then account for 17,566 more fish, another 18 percent of the release group, for a total accounting of 35 percent. This would indicate indirect pumping mortality (that occurring in delta channels) before fish get to the facilities and Clifton Court Forebay is significant — in this example, 65 percent.

Figure 47
EXPANDED RECOVERIES AT THE CVP AND SWP FOR CWT SMOLTS RELEASED AT DOS REIS IN APRIL 1991



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Model Verification

If we assume the Stockton release group most represents the survival of fish migrating down the San Joaquin River if a barrier were in place, we can then verify the model to represent survival with a barrier present. Flow at Stockton averaged about 100 cfs, and exports averaged about 4,283 cfs in April and 2,613 cfs in May. Under these conditions, the model predicts survival to be 0.24 in April and 0.28 in May. If we divide these estimates by 1.8, as we have to obtain absolute survival in the Sacramento Delta, we obtain 0.13 for April and 0.16 for May. Observed survival estimates (corrected for temperature) were 0.14 in April and 0.31 in May. This comparison appears to show the theoretical model may have underestimated the impact of exports on salmon smolt survival through the San Joaquin Delta. Additional data gathering and refinement of this model is warranted to estimate the benefits of installing a barrier for San Joaquin smolts under various flow and export conditions.

Conclusions

When evaluating results of the 1991 study as a way to predict the benefits of a barrier at the head of Old River, we reached the following conclusions.

- The group of fish most representative of fish migrating down the San Joaquin River with a barrier in place would be the Stockton release group. Releases were made in April and May when exports were 4,283 and 2,613 cfs, respectively. Survival, corrected for temperature differences, was about twice as good for the low export period. This would indicate additional benefits can be obtained with a barrier by decreasing exports simultaneously.
- The impact of increasing the amount of water drafted from the Sacramento River into the central delta toward the pumping plants did not appear to decrease survival of fish diverted into the Mokelumne from the Sacramento River in 1991. In fact, the increase in flow in the Mokelumne system itself may account for the increase in survival for the group released in April in the central delta during the higher drafting period.
- Although the data infer that installation of a barrier will likely improve smolt survival through the San Joaquin Delta, it is imperative to recognize that a barrier alone most likely will not solve mortality problems for smolts migrating down the San Joaquin. Additional measures, such as increased flows and decreased exports, are also needed to ensure adequate survival through the San Joaquin Delta system.
- It is critical that the barrier be placed in upper Old River and survival of smolts migrating down the river be measured over a wide range of environmental conditions.

Future Needs

Results of these and previous studies are being used to evaluate benefits and costs of both operational and structural salmon protective measures for the scoping and water right phases of the Bay/Delta water quality hearings and in planning for future Interagency salmon studies. The information also is being used in the Article 7 negotiations called for in the Four Pumps Agreement between DWR, DFG, and USBR and in the proposed SWP Delta Water Management programs.

Additional work is in progress in the southern and central delta, where understanding of smolt survival is less certain. Also, additional evaluation is needed on impacts of the pumping plants on fry entering the delta and the apparent relationship between adult runs and the amount of water being exported.

Additional studies on the San Joaquin Delta should include:

- Evaluate San Joaquin smolt survival under a wide range of inflow/export ratios, with particular emphasis on ratios between 2.0 and 5.0 when inflow is greater than about 5,000 cfs.

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- Test the benefit of a full barrier in upper Old River to smolt survival under high and low export conditions between April 15 and May 15; this is scheduled for 1992.
- Use hydraulic modeling to define the likely pattern of migration through the southern delta under varied flows, export rates, and tidal conditions.
- Continue to evaluate the effect of high cross-delta flow on survival of smolts migrating out of the San Joaquin basin, as would occur if the SWP used its full pumping capacity of 10,300 cfs. A full barrier in upper Old River with high exports would cause more reverse flows in Turner Cut, lower Old River, and Middle River and would more closely represent conditions proposed in the SWP delta alternative projects.
- Evaluate smolt survival in the San Joaquin Delta at varied temperatures (60 to 70°F).

Information we have implies indirect mortality associated with the pumps is significant. Perhaps fish that live to be salvaged are a large proportion of those that survive to Chipps Island. During 1992, the Fish Facilities study will be releasing marked fish into Clifton Court Forebay, which may provide a way to measure the number of survivors at Chipps Island that are a product of the salvage process.

The Sacramento River Delta smolt model and recent field studies have helped us better understand factors that may influence smolt survival in the Sacramento side of the delta. This work has identified areas where further research is needed, such as:

- Expand knowledge to include other races of salmon and the impacts of the pumping plants on their survival and distribution.
- Evaluate smolt survival in the central delta under various temperature and flow conditions.
- Further evaluate reasons for the unexplained high mortality in the central delta.

In early 1992, the Delta Cross Channel gates were closed to protect winter salmon from being diverted into the central delta and being impacted by the pumps. Additional work is being proposed to release marked late-fall fish in February and March to evaluate the differential mortality of being diverted into the central delta for the endangered winter run.

The Fisheries Committee has shown interest in an expanded salmon monitoring program for all races throughout the Central Valley to run year round. The specific proposal is to be developed in early 1992 and implemented by September of that year. Part of that proposal will evaluate other methods for monitoring the movement and distribution of juvenile salmon in the delta.

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Chapter 6

OTHER ESTUARINE FISHES

Delta Smelt

Dale Sweetnam,
Department of Fish and Game

The delta smelt *(Hypomesus transpacificus)* is a small euryhaline fish that lives only in the Sacramento-San Joaquin estuary. Information from seven independent studies has demonstrated a dramatic decline of the delta smelt population and low population levels since 1983. A rough estimate placed the delta smelt population at several hundred thousand fish in 1985 (Stevens *et al* 1990). Based on September-December midwater trawl survey data, this represents an 80 percent drop in the population since 1983 compared to the average from 1967 to 1982 and a 90 percent decline from the peak level observed in 1980 (Stevens *et al* 1990).

As a result of these findings, Dr. Peter Moyle at the University of California, Davis, petitioned the California Fish and Game Commission in 1989 to list delta smelt as an endangered species. The Commission later denied the petition but directed the Department of Fish and Game to initiate studies to monitor the delta smelt population and to address several management and recovery objectives. In 1990, Dr. Donald Erman, president of the California-Nevada chapter of the American Fisheries Society, petitioned the U.S. Fish and Wildlife Service to list delta smelt as a Federal endangered species. In September 1991, the U.S. Fish and Wildlife Service proposed listing the delta smelt as a threatened species.

The purpose of the delta smelt study is to monitor and investigate factors that may affect delta smelt population levels to ensure their long-term survival and to address the management and recovery objectives set forth by the Fish and Game Commission. The study is also intended to provide the U.S. Fish and Wildlife Service with information relevant to the proposed Federal listing of the delta smelt as a threatened species.

The study plan has been divided into ten projects designed to increase understanding of specific aspects of delta smelt life history and to help evaluate potential threats to the population. Study design included input from a committee of representatives of the Department of Fish and Game, Department of Water Resources, U.S. Bureau of Reclamation, U.S. Fish and Wildlife Service, State Water Resources Control Board, private contractors, and researchers from the University of California at Davis.

The delta smelt study is on schedule, with full implementation scheduled for January 1992 (Figure 48).

Surveys of Adult Distribution

During late winter and spring, trawl and seine surveys of adult delta smelt distribution are conducted to define spawning areas and requirements. Artificial substrate surveys to collect delta smelt eggs are used to detect spawning.

Midwater Trawl Surveys During Spawning Season

Delta smelt spawn from late February through May (Moyle *et al* 1992) or from mid-February to June or July with peaks in late April and early May (Wang 1991). By extending DFG's fall midwater trawl survey throughout the early part of the spawning season, migration to specific areas of the estuary will be documented. Delta smelt are presumed to spawn in the rivers and adjoining sloughs in the western delta and Suisun Marsh (Moyle *et al* 1992), areas under tidal influence with moderate to fast flows (Wang 1991), and dead-end sloughs (Radtke 1966). These spawning locations and associated environmental conditions are critical to delta smelt spawning and must be verified.

Single 12-minute stepped-oblique midwater trawl tows (17.6-meter-long net with an

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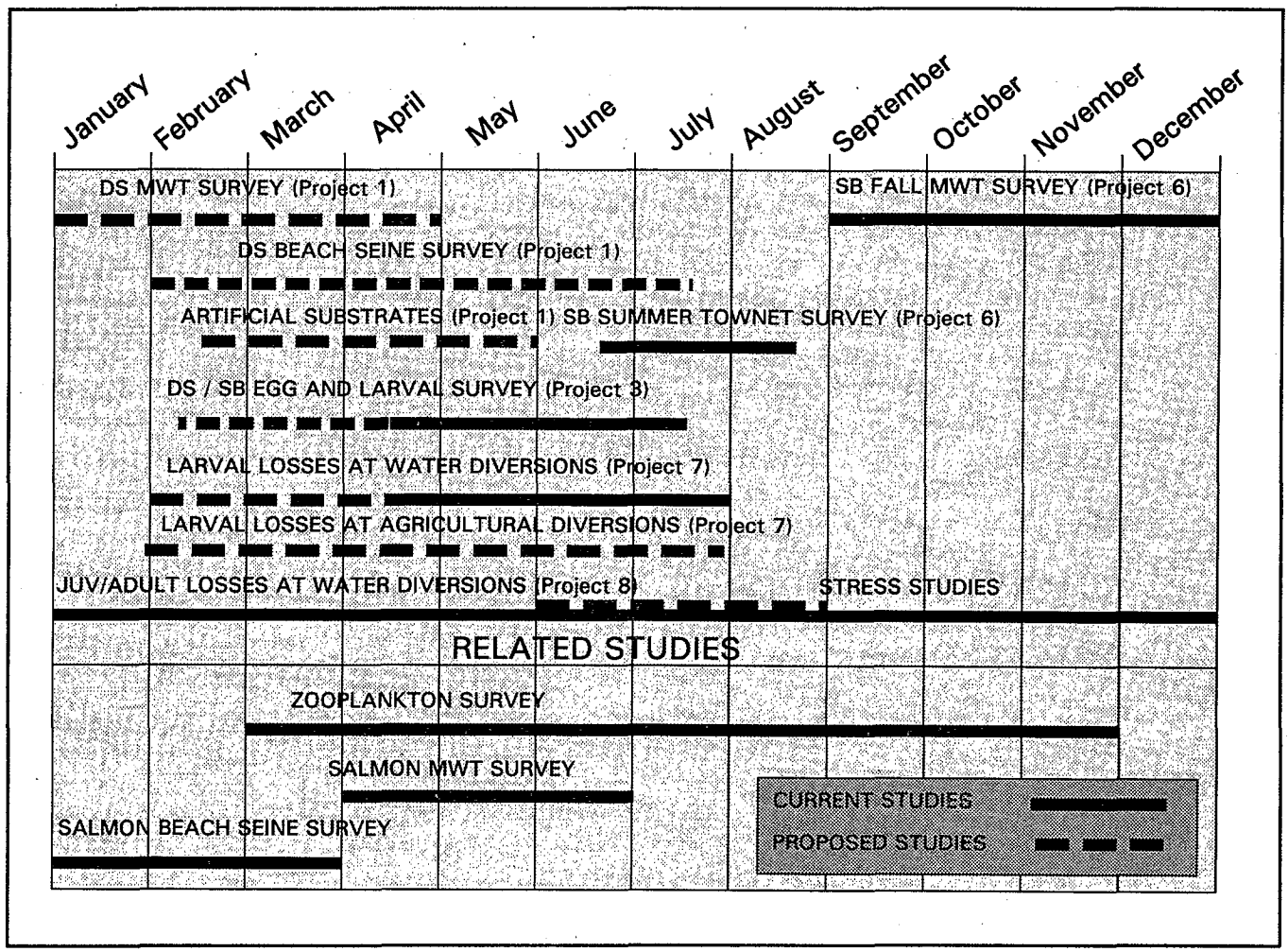
Figure 48
TIME TABLE OF FIELD SAMPLING FOR DELTA SMELT STUDY
(Current studies are presented as solid lines, proposed studies as dashed lines.)



opening of 3.7 m^2 [12 feet by 12 feet], after Von Geldern 1972) will be made monthly at about 95 sites throughout the estuary (Figure 49). All fish species will be identified and measured. Physical parameters that will be measured include: water temperature, tide, water depth, electrical conductivity (micro-Siemens/cm), transparency (Secchi depth), and duration of tow. Volume of water that passed through the net will be estimated (flowmeter).

Modifications have been proposed for the standard midwater trawl net to reduce delta smelt escapement and ensure consistency in striped bass sampling. An 1/8-inch bobbin-net cover over the rear end of net and cod-end may be used to measure losses of delta smelt and to produce a correction factor for the larger mesh net. Net evaluation studies began in August 1991.

The proposed sampling would run from January through April (Figure 48). The spatial scale will include existing fall striped bass midwater trawl stations plus additional stations near possible spawning areas. These additional stations include one in the Napa River (341), three in the central delta (913-915), one in Cache Slough (716), four on the north and south forks of the Mokelumne River, and six on the Sacramento River as far upstream as Hood. If high delta outflows warrant sampling farther downstream, 22 stations will be added in San Pablo Bay.

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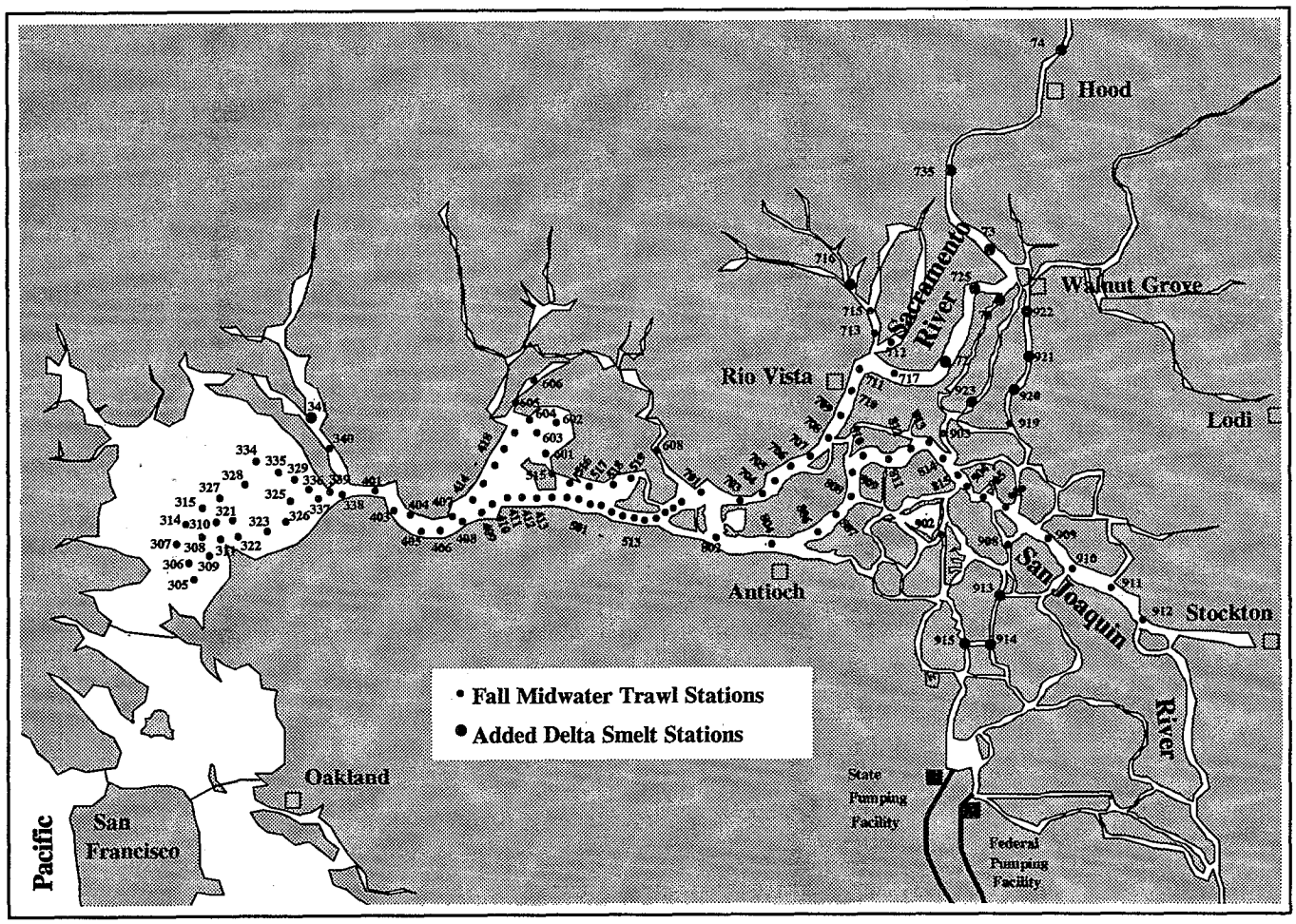
Figure 49
DFG DELTA SMELT MIDWATER TRAWL STATIONS, 1992
Solid dots are current fall midwater trawl stations; circles are added delta smelt stations.



Beach Seine Surveys During Spawning Season

Beach seine surveys will identify adult delta smelt abundance and distribution during spawning season in low velocity areas such as side channels, backwater locations, and dead-end sloughs. The literature is vague as to habitat where delta smelt actually spawn. For example, Wang (1986) reports that delta smelt may deposit eggs over submerged branches and stems or in open water above sandy or rocky substrates. Beach seining should demonstrate whether delta smelt use these low velocity areas to spawn and thus aid in identifying spawning habitat.

A 50-foot by 4-foot, 1/4-inch mesh beach seine with a 4-foot by 4-foot bag will be used to sample near-shore locations throughout the estuary. One seine haul will be done per sampling site. This survey will be run in conjunction with the Interagency (USFWS) salmon fry survey, possibly with several added sites.

The proposed beach seine survey will be done weekly from December through March at about 35 sites in Suisun Marsh, Cache Slough, the delta, and the Sacramento River (Figure 50). Sites are limited by accessibility and suitable habitat to allow proper fishing of the seine. Seining by boat may be tried in several otherwise inaccessible areas such as dead-end sloughs if proper habitat can be located.

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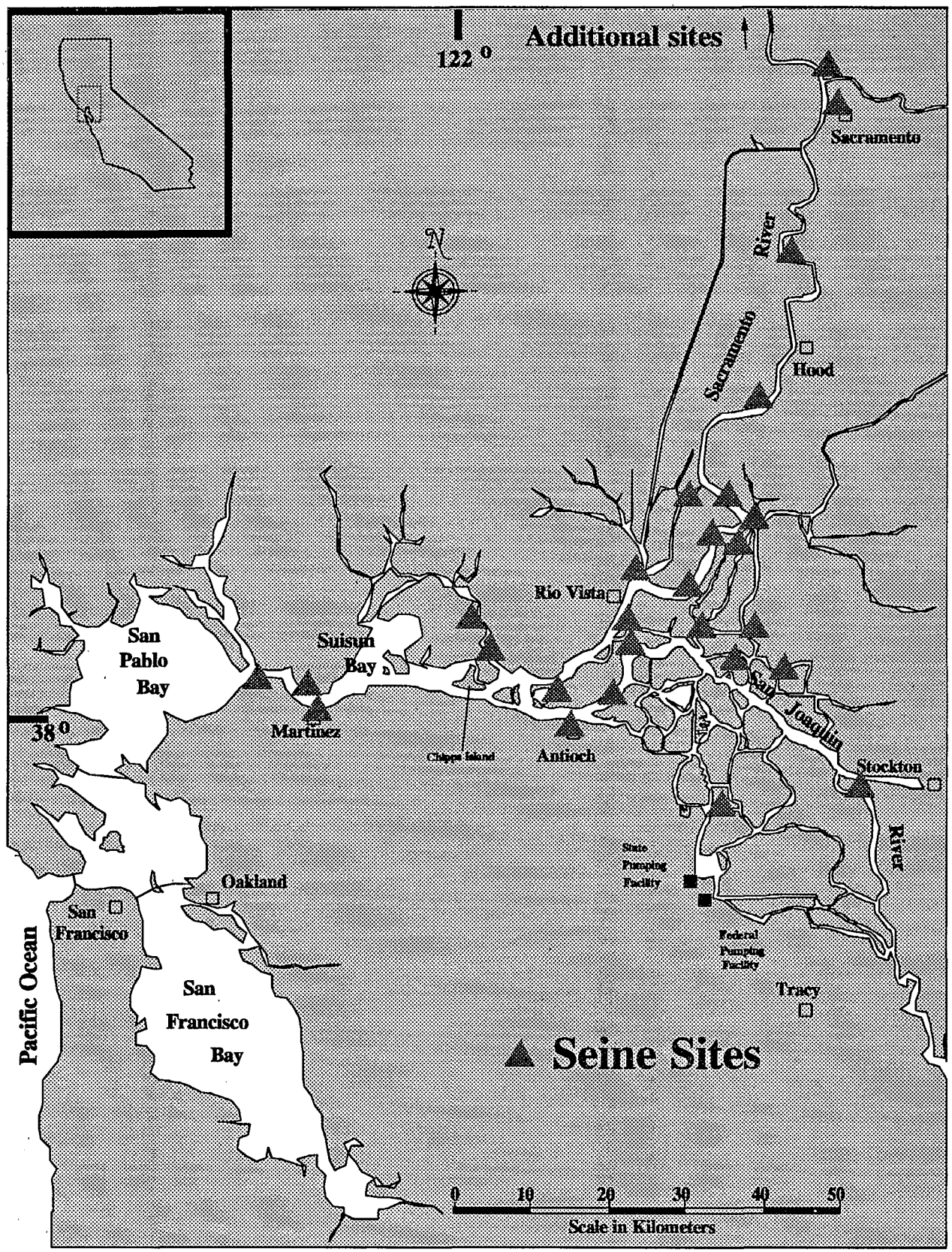
Figure 50
RECOVERY SITES FOR DELTA SMELT BEACH SEINE SURVEY
Additional sites on the upper Sacramento River do not appear on this map.



Artificial Substrate Sampling

Delta smelt eggs are demersal and attach to aquatic vegetation (Moyle *et al* 1992; Wang 1986). Hence, artificial egg-collecting substrates could be used to specifically identify spawning locations. Eggs of other smelt species have been similarly collected (Misitano 1977; Moring 1985).

Sampling requires placing frames fitted with burlap sheets (Moring 1985), to which eggs adhere, in areas of adult fish concentrations (for methods, see McCabe 1990). The 1-square-meter frames will be raised and inspected every 2 or 3 days. Sampling will begin in late March and continue through May. Artificial substrates will be placed in accessible areas with suitable habitat where the trawl or seine surveys have indicated adult delta smelt abundance is high.

Differentiation of Delta Smelt from Longfin Smelt During Early Larval Stages

The purpose of this project was to produce a reliable key to differentiate larval delta smelt from longfin smelt starting at hatching size (5.5-6 mm, Wang 1986) and larger. Larval delta smelt are easily confused with longfin smelt, and these species coexist over a large portion of their range. Proper identification of delta smelt is necessary if the overall program is to be successful.

Dr. Johnson Wang has developed a key based on taxonomic characteristics such as morphological differences of gas bladder formation and relationship of the gut to the gas bladder. An Interagency technical report released in October 1991 (Wang 1991), is now being used in the laboratory for smelt identification.

Timing, Distribution, and Abundance of Larvae and Their Food Supply

This project will monitor larval delta smelt occurrence, distribution, and abundance along with associated environmental conditions. Surveys of larvae are necessary if we are to identify factors controlling survival and abundance of young smelt and their food supply. Surveys developed for striped bass egg and larval monitoring will be extended to obtain information about delta smelt.

A 505-meter nitex egg and larval net attached to a sled will be towed in a stepped-oblique fashion. A Clark-Bumpus net of 154-meter mesh attached to the upper frame of the net will be used to collect zooplankton samples. Single 10-minute tows will be made at about 80 stations throughout the estuary (Figure 51). Physical parameters measured will include: water temperature, tide, water depth, electrical conductivity (micro-Siemens/cm) measured at the surface and at the bottom, transparency (Secchi depth), and duration of tow. The volume of water that passed through the net will be estimated (flowmeters mounted across the mouths of the nets).

Since delta smelt spawn earlier than striped bass, the 1992 survey will start February 12, two months earlier than the striped bass egg and larval survey, which normally starts in mid-April. Sampling will generally occur every fourth day, but during late March and April it will be every second day.

All historical systematic egg and larval stations will be sampled except for upper Sacramento River stations (81-85). To identify optimal delta smelt spawning areas, additional areas sampled will include Cache Slough, North and South Fork Mokelumne River, and several dead-end sloughs.

All samples will be sorted in the laboratory. Gut analysis will identify prey items and allow comparison with abundance of prey species in the Clark-Bumpus net and in the DFG zooplankton survey.

Cohort Identification from Otoliths

Using delta smelt collected in the sampling programs, specific cohorts of delta smelt will be identified by examining daily growth increments (circuli) of otoliths (ear bones). Cohort information will be used with larval and juvenile fish abundance data to determine when and where the majority of the population was spawned. These data, combined with environmental information such as food supply, water temperature, salinity,

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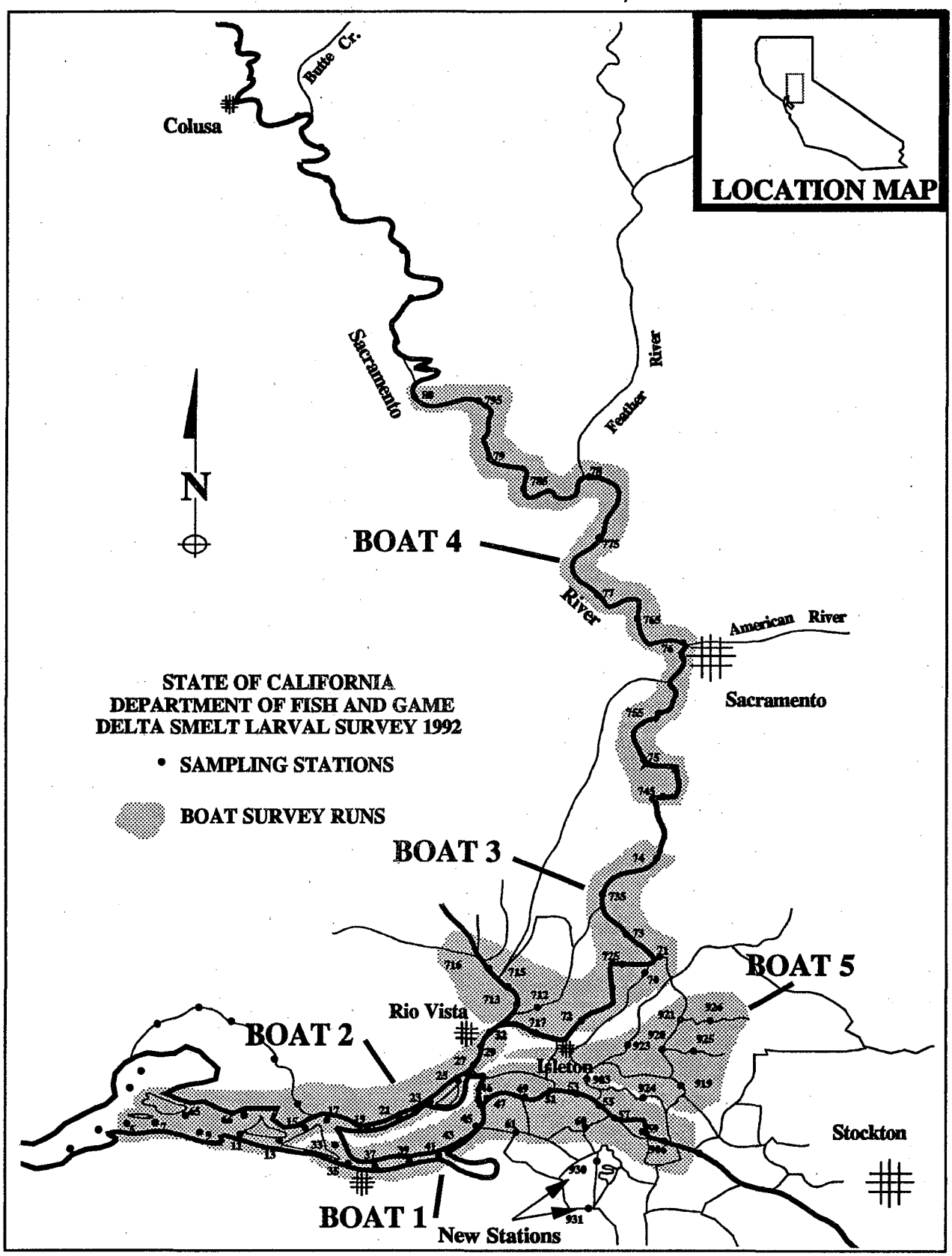
Figure 51
DELTA SMELT LARVAL SURVEY STATIONS, 1992



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diversions, and other water quality and quantity factors, will improve understanding of how environmental conditions impact delta smelt growth and survival.

Counts of circuli and measurements of their spacing allow evaluation of growth history, identification of cohorts, and estimation of the time surviving cohorts were spawned. An optical pattern recognition system *(OPRS)* will be used to scan otolith sections, measure distances between circuli, and create a manageable database.

Toxicity and Starvation Effects on Larvae

Histological and morphometric methods will be used to compare condition of larval delta smelt collected in the field with that of larvae held under various conditions in the laboratory. These analyses will allow evaluation of the extent to which delta smelt condition is affected by variations in food supply, toxicity, and parasites. This knowledge is important to evaluation of factors responsible for the population decline and to development of a recovery plan.

Histological analyses involve microscopic examination of retina attachment and digestive tract tissue development to indicate whether or not starvation is occurring. Liver histology provides good measures of the extent to which larval fish have been exposed to toxicity. Morphometric analyses consist of measuring various ratios involving fish length and body depth at various locations along the length of the fish. Body shape is then used as a measure of condition. Comparison of the condition of delta smelt larvae collected at different times and locations during the spawning season will allow evaluation of how often larvae are subjected to starvation or toxicity and whether starvation is associated with the lack of any specific food item or with particular times or areas.

DWR is contracting with Dr. Serge Doroshov (UC-Davis) and Biosystems Analysis, Inc., to develop culture and production techniques for delta smelt. Success will yield fish for the condition investigations and perhaps for release into the wild. DFG will try to supply these contractors with live spawning stock, but initial attempts at collecting live delta smelt have been unsuccessful. Of 257 collected in seines and trawls in 1991, only two survived for more than 48 hours. Apparently the smelt die due to stress incurred during capture. Other capture methods are being evaluated.

Abundance, Distribution, and Preferred Habitat of Older Juveniles

Surveys of older juvenile delta smelt are needed to identify critical nursery habitat and other requirements. Proposed sampling would supplement summer and fall surveys for young-of-the-year striped bass, with additional stations added for delta smelt. Net modifications are also being considered.

Entrainment Losses of Larvae

The significance of larval smelt losses to water project diversions will be assessed through a combination of the estuary-wide larval fish survey and sampling by DWR in the southern delta, using the same sampling methods. Sampling in 1992 will begin in mid-February.

USBR has been trying to continuously sample eggs and larvae at the CVP diversion and other sites. Several types of sampling devices have been used (for methods, see Arthur 1990).

At this time, there is no sampling of larval fish losses to agricultural diversions. DWR will develop a protocol for this sampling.

Salvage Losses of Older Juveniles and Adults

Fish screens at the SWP and CVP diversions prevent many older juvenile and adult delta smelt from entering the aqueducts and canals south of the delta. However, some of the smelt that approach the screens do pass through. Others that enter the water project facilities probably die due to handling during the screening and trucking process.

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Use of salt to reduce stress during handling and trucking appears to reduce mortality in striped bass, American shad, threadfin shad, and white catfish (Raquel 1989; Cech *et al* 1988; Odenweller 1990). However, of 2,590 delta smelt retained at the Byron growout facility in 1989, survival was reported to be 0 percent (Odenweller 1990). Studies aimed at reducing mortality could be done on delta smelt salvaged at the facility or maintained in the laboratory. Improved sampling procedures planned for 1992 should increase accuracy of estimates of delta smelt lost to these diversions.

Studies of the effects of handling and trucking on salvaged delta smelt, using methods similar to Raquel (1989) or Cech *et al* (1988), are being considered. Also, Dr. Cech (UC-Davis) has proposed studies on the environmental tolerances of delta smelt to changes in temperature, salinity, and water velocity.

Electrophoretic Analysis

The purpose of this study is to document genetic differences between delta smelt *(Hypomesus transpacificus),* wakasagi *(H. nipponensis),* and longfin smelt *(Spirinchus thaleichthys).* Studies of these related species are needed because hybridization is possible, and wakasagi adults and larvae have been collected from the American River (Stevens *et al* 1990; Moyle personal communication). Loss of genetic integrity is a threat to the delta smelt population.

Delta smelt, longfin smelt, and wakasagi will be collected from throughout the estuary and possibly other locations. Electrophoretic analysis of proteins will be used to document any detectable genetic differences between species and populations.

Modeling

Under this project, population dynamics techniques will be used to compute extinction probabilities and to evaluate how changes in the environment and water management might alter the probabilities. Data from the DFG summer tow-net and fall midwater trawl surveys will be used with environmental data (flow, diversions, reverse flow, *etc*) to look for spatial relationships that will help predict extinction probabilities. A population dynamics model will also be produced. Dr. Louis Botsford (UC-Davis) will lead this study.

Current Status

Of the seven datasets initially used to document the delta smelt decline, only the fall midwater trawl has shown any increase in abundance. The 1989 index has been reevaluated and corrected from 364 to 366 (Figure 52). The 1990 index has also been reevaluated and corrected from 427 to 360. The 1991 index was 689. An additional summer tow-net abundance index (2.0) obtained for 1991 indicates the population is still low (Figure 53). The other five datasets also failed to show increased abundance in 1991.

Figure 52
DELTA SMELT FALL MIDWATER TRAWL ABUNDANCE INDEX, 1967-1973, 1975-1978, 1980-1991

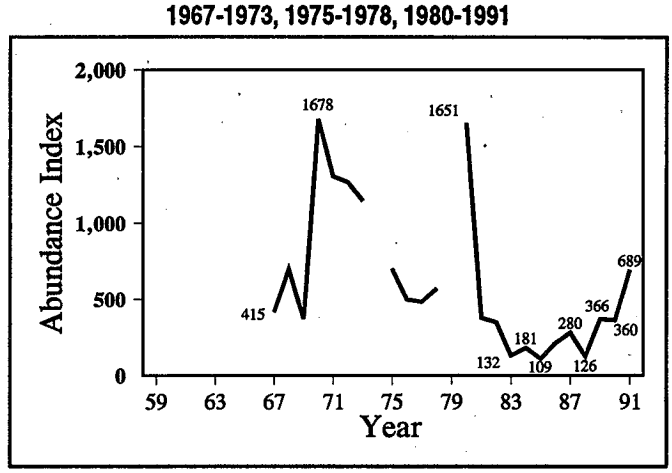
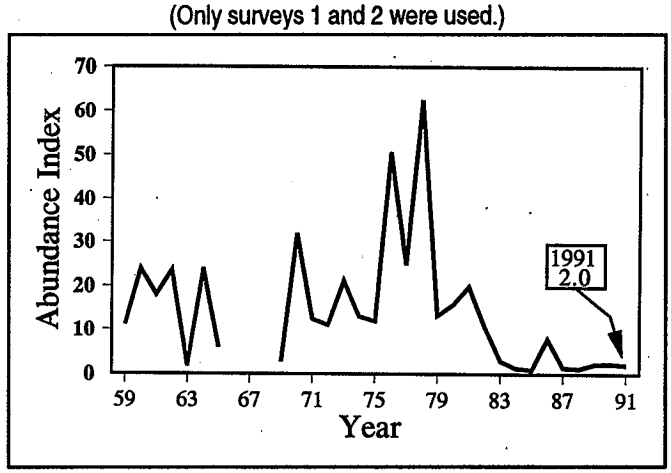


Figure 53
DELTA SMELT SUMMER TOW-NET ABUNDANCE INDEX, 1959-1965, 1969-1991
(Only surveys 1 and 2 were used.)



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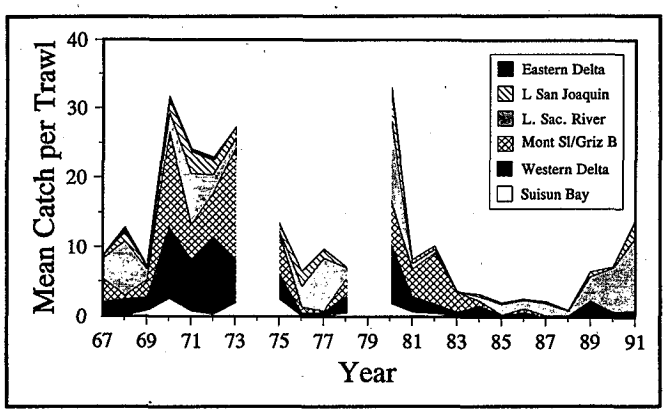
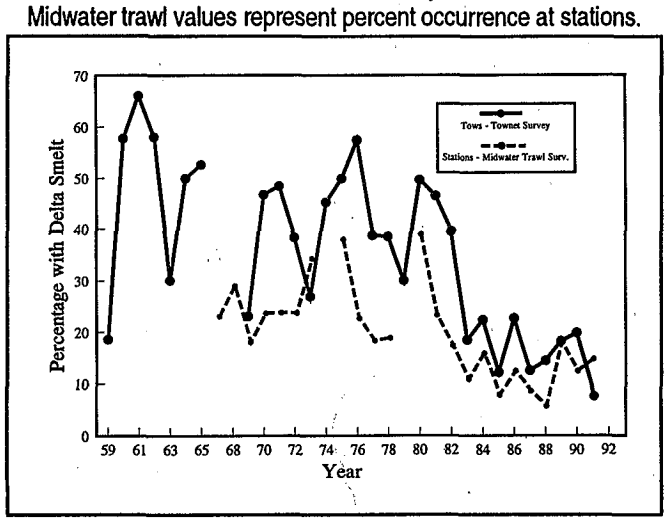
Although the recent increase in the fall abundance index suggests an increase in smelt abundance, it also continues to show reason for concern in that the smelt population has been concentrated in a single stretch of the lower Sacramento River (Figure 54). When the population was at higher levels, the population was more widely distributed throughout the estuary.

Figure 54
MEAN CATCH PER TRAWL FOR VARIOUS AREAS, FALL MIDWATER TRAWL SURVEY



The frequency of occurrence of delta smelt in trawl tows has remained low since 1983. The percentage of stations at which delta smelt were captured in the midwater trawl survey and the percentage of tows that captured delta smelt in the summer both show a striking decline from 1980 to 1983 (Figure 55).

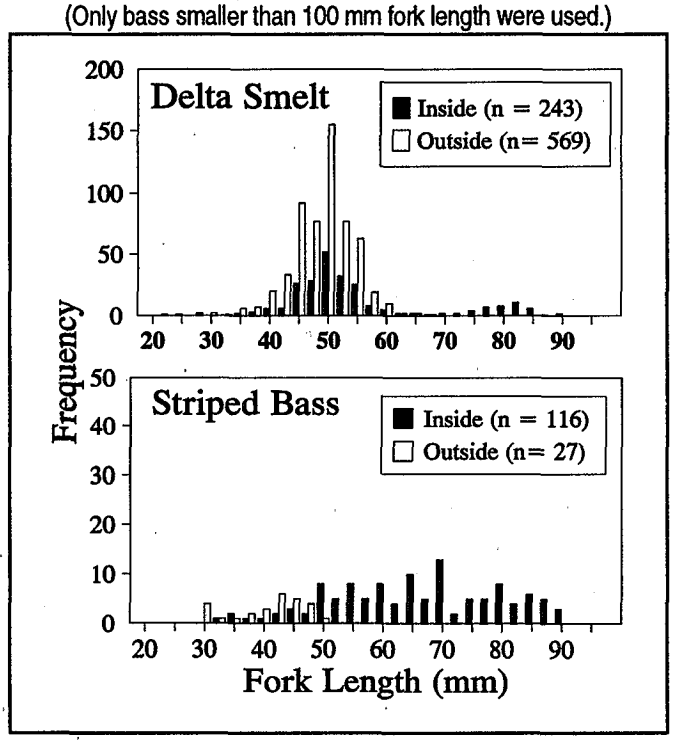
Figure 55
PERCENT CATCH OF DELTA SMELT IN TOW-NET AND MIDWATER TRAWL SURVEYS
Tow-net values represent percent occurrence in all tows in the first and second surveys.
Midwater trawl values represent percent occurrence at stations.



From 1959 to 1982, delta smelt were caught in 43 percent of the summer tow-net runs, but from 1983 to 1991 only 16 percent caught delta smelt. In 1991 alone, only 8.2 percent of the tows caught delta smelt. For the midwater trawl survey, 25 percent of the tows caught delta smelt from 1967 to 1982, and only 11 percent after 1982.

In August 1991, an evaluation was initiated of the net used in the DFG fall midwater trawl survey. A 1/8-inch mesh bobbinnet cover was placed over the standard 1/2-inch stretch-mesh cod end of the net to capture fish that escaped through the standard cod-end net. Because of high variances between catches, additional sampling is planned to fully evaluate net efficiency. Preliminary results suggest the standard midwater trawl was only 30 percent as effective at capturing delta smelt and about 80 percent as effective at capturing striped bass as the bobbinnet cover (Figure 56). There was a difference in the maximum size of escapement between the two species, presumably due to differences in body shape or behavior.

Figure 56
LENGTH/FREQUENCY DISTRIBUTIONS FOR DELTA SMELT AND STRIPED BASS IN A MIDWATER TRAWL NET EVALUATION STUDY, AUGUST 28 AND 29, 1991
Inside = Fish captured in the standard 1/2-inch cod-end.
Outside = Fish captured in the 1/8-inch bobbinnet cover.
(Only bass smaller than 100 mm fork length were used.)



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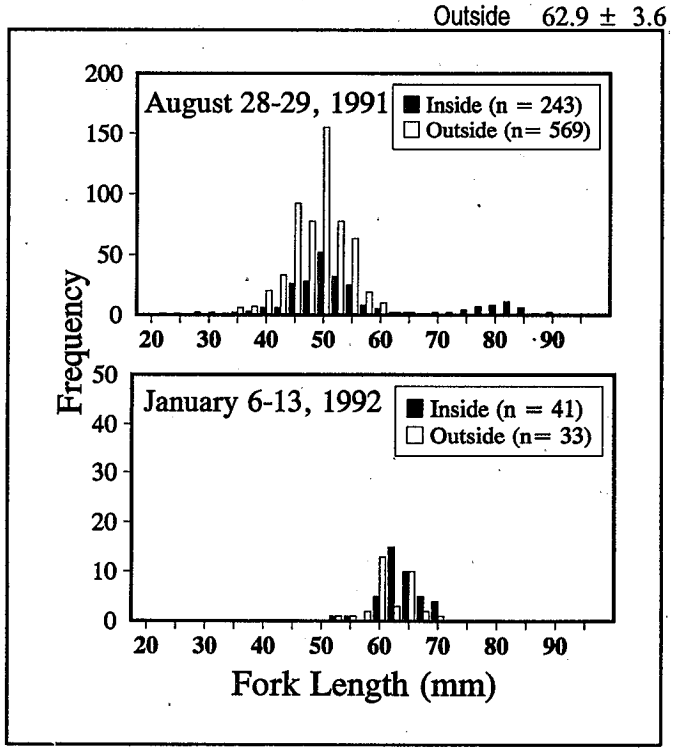
Additional sampling in January 1992 suggests that as the mean size of the delta smelt captured increases, the efficiency of the standard midwater trawl net also increases (Figure 57). The standard net was about 55 percent effective at capturing delta smelt and 100 percent effective at capturing striped bass (not shown on Figure 57). These results do not affect the interpretation of temporal trends observed in the fall midwater trawl abundance index. They do indicate that the proportion of the delta smelt population sampled by the midwater trawl is less than the proportion of the striped bass population sampled and that the magnitude of both past and recent abundance is somewhat greater than suggested by the initial estimates.

Figure 57
COMPARISON OF LENGTH/FREQUENCY DISTRIBUTIONS OF DELTA SMELT CAPTURED IN AUGUST 1991 AND JANUARY 1992
Inside = Fish captured in the standard 1/2-inch cod-end.
Outside = Fish captured in the 1/8-inch bobbinnet cover.
(Only bass smaller than 100 mm fork length were used:)

Mean Fork Lengths (mm sd):			
	August	Inside	56.2 ± 12.9
		Outside	50.1 ± 5.2
	January	Inside	64.9 ± 3.7
		Outside	62.9 ± 3.6



Seasonal movements can be observed from monthly geographical plots of delta smelt distribution. In September 1990 the population congregated in the lower reaches of the Sacramento River from Decker Island to Honker Bay (Figure 58). The population apparently dispersed in winter. In January 1991, some fish were observed in Montezuma Slough, Suisun Bay, Cache Slough, the Sacramento River at least as far upstream as Isleton, and the San Joaquin River almost to Stockton (Figure 59). Radtke (1966) described a similar seasonal movement in 1963 and 1964 as a spawning migration. This information on distribution and abundance of delta smelt will help focus future surveys to further assess population status.

Sorting and identifying samples from four "pilot" larval fish surveys from mid-February through March 1991 was completed, and data are awaiting keypunching. Initial review indicates that in 1991 delta smelt larvae were first observed on February 28 in the Sacramento River near Sacramento just south of the entrance to the deep water channel. Longfin smelt larvae were captured the same day from the Sacramento River above Locke. Delta smelt larvae were first observed in the delta on March 11, when larvae were caught in Cache Slough, the South Fork Mokelumne River, and the San Joaquin River near Antioch.

Otoliths from 20 delta smelt were removed, sectioned, and polished to determine if aging was possible. The daily growth increments were visible and because the otolith is flat, minimal polishing had to be done. Therefore, aging should be easier than for striped bass otoliths.

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Figure 58
DISTRIBUTION AND ABUNDANCE OF DELTA SMELT IN FALL MIDWATER TRAWLS, 1990

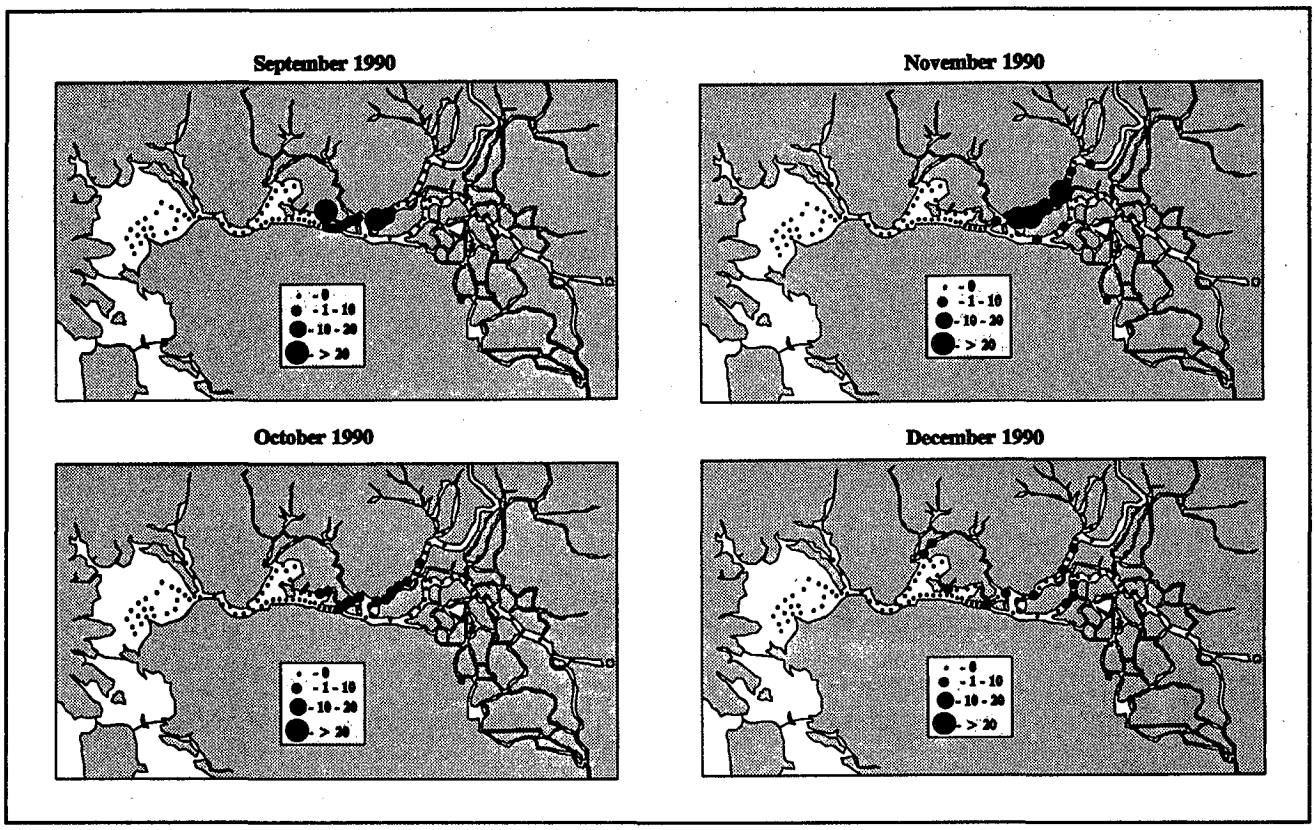
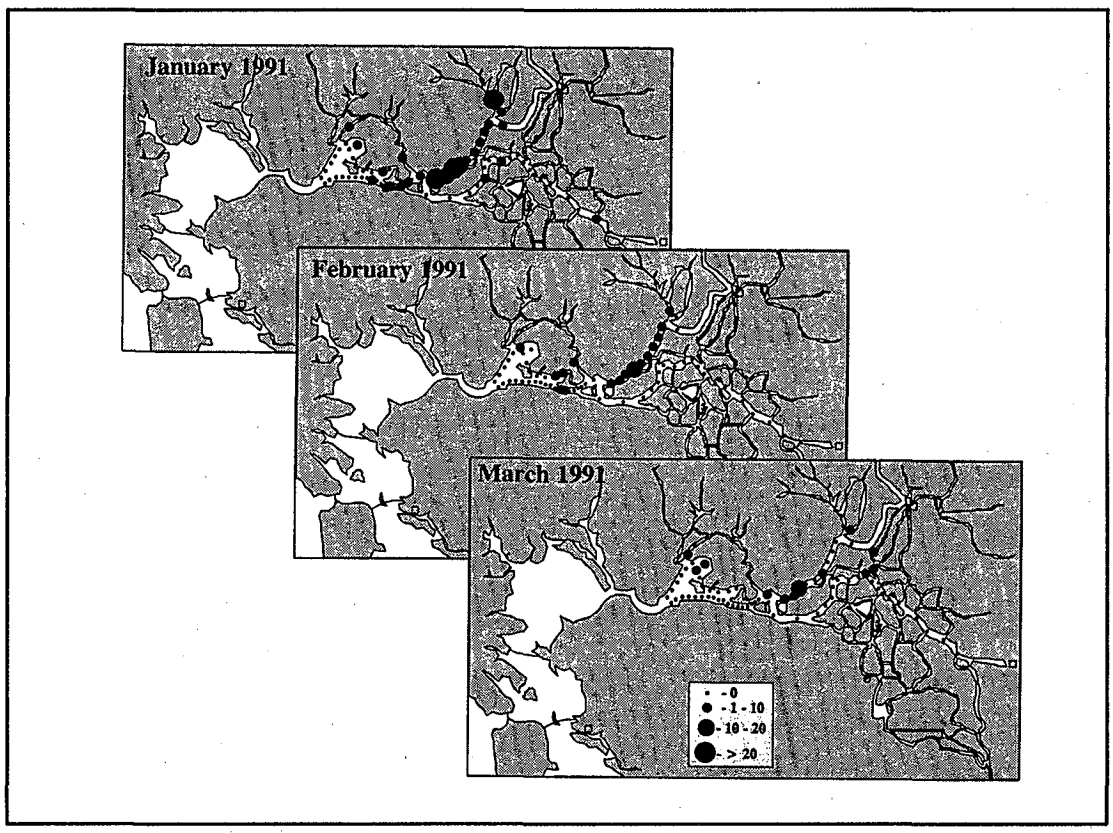


Figure 59
DISTRIBUTION AND ABUNDANCE OF DELTA SMELT IN PILOT MIDWATER TRAWL SURVEYS, 1991



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Sturgeon

David W. Kohlhorst
Department of Fish and Game

Sturgeon are an increasingly important sport fish in the Sacramento-San Joaquin estuary and its tributaries because of the burgeoning human population of Northern California and the decline in abundance of other major sport fishes. Of the two species of sturgeon (white and green) that inhabit the estuary, the white sturgeon is the most abundant and most important to the sport fishery; it will be discussed exclusively here.

Experience from the commercial sturgeon fishery in this estuary in the late 1800s and from exploited sturgeon populations elsewhere make it clear that harvest has the potential to depress the population. Therefore, our sturgeon studies have emphasized measurement of population parameters likely to be influenced by over-exploitation, such as harvest rate, survival rate, abundance, angler success rate, size of fish in the catch, and growth rate.

In the mid- to late 1980s, these studies indicated harvest rate was exceeding the level that could be sustained by the population; harvest reached a peak of 11.5 percent in 1986. Modeling based on the best available information suggested this level of exploitation would lead to a substantial population decline. To prevent this, in 1989 DFG recommended to the California Fish and Game Commission that angling regulations be changed to increase the 40-inch minimum size limit to 42 inches in 1990 and 44 inches in 1991 and that a maximum size limit of 72 inches be instituted. The Commission adopted these changes. At that time DFG indicated it would later ask for increases in the minimum size limit to 46 inches in 1992 and 48 inches in 1993. These changes were recommended to the Commission in fall 1991 and were adopted, to become effective March 1, 1992. We will monitor the effect of these changes by continuing to measure those population parameters likely to be influenced by exploitation.

Although we have some knowledge of adult sturgeon population dynamics, food habits, and migrations, we need to know more about juveniles and about factors affecting recruitment to the legal-sized population. Information about all life stages before sturgeon reach legal size is inadequate for managing a population subject to increased fishing pressure and additional anthropogenic alteration of its habitat by water diversions from the presumed nursery area and by channelization on the spawning grounds.

Present knowledge about early life stages includes information on spawning time and general location, larval distribution, and juvenile distribution and food habits. Attempts to develop an index of year-class strength from the age composition of older fish have not been successful.

To fill some of these gaps in our knowledge, we have undertaken new studies to better define spawning areas in the Sacramento River, which supports the major spawning run, and to develop an index of year-class strength and estimates of juvenile survival rates. This may allow important spawning areas to be protected from further deleterious habitat alterations and identification of environmental factors that might be controlled to increase survival and abundance of young sturgeon.

The 1991 sturgeon program consisted of four elements:

- A mark/recapture (tagging) study to estimate harvest and survival rates, abundance, and movements of the legal-sized population. Fish are captured in trammel nets in San Pablo Bay and tagged with $20-reward tags. Some tags are returned by anglers and others are recovered during the tagging operation.
- A radio-tagging study of movement of mature fish upstream to the spawning grounds in the Sacramento River. Fish are captured near Clarksburg using set-lines. Radio transmitters (a different frequency for each fish) are attached externally to the bony plates (scutes) on the back of the fish. Signals are detected by a scanning receiver operated from boats, vehicles, and aircraft.

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- Sampling with artificial substrates to collect sturgeon eggs and determine exact locations of spawning. Substrates are constructed of latex-coated animal hair (filter material) in a steel frame and are fished below known or suspected areas of sturgeon spawning. Twice each week, they are examined for attached eggs, cleaned of debris and sediment, and reset.
- A study to capture juvenile sturgeon to develop an index of year-class strength. Catches have been low, so we continue to experiment with different types of gear. In 1991, we sampled juvenile sturgeon using variable-mesh drift gill-nets and set-lines.

In fall 1991, we tagged 386 white sturgeon. We could not estimate abundance at the time of tagging (based on a multiple census technique using recaptures of fish tagged in 1991 during that same year's tagging) because no fish tagged in 1991 were recaptured. However, we were able to calculate a Petersen mark/recapture estimate of sturgeon abundance in fall 1990 based on the recapture during 1991 tagging of nine fish tagged in 1990. This estimate of 26,800 white sturgeon over 40 inches long is the lowest estimate since 1974 (21,000) and is substantially below estimated abundance in the 1980s, which ranged from about 84,000 to 128,000.

We applied radio transmitters to 30 sturgeon captured in the lower Sacramento River during the late winter spawning migration. We were able to follow six females and three males to the spawning area. It appeared that increases in flow in late March stimulated at least three of these fish (two females, one male) to spawn, after which they moved rapidly downstream. The other fish that moved upstream of Knights Landing wandered up- and downstream but never exhibited obvious spawning behavior. Two of these were caught by anglers, both unspawned. Stress of capture and handling apparently caused most of the sturgeon we tagged to abandon their spawning migration.

We sampled with artificial substrates continuously from April 16 to June 3 but collected only 10 sturgeon eggs, probably because we did not start the sampling until after the major spawning period (see radio-tagging results, above). All eggs were taken at just two locations, near Colusa, between May 7 and May 14. Based on the degree of embryological development, we estimated these eggs were spawned on four days between May 6 and 13. These spawnings followed an increase of 1,800-2,500 cfs in Sacramento River flow due to augmented releases from Lake Shasta. During this spawning period, water temperatures ranged from 57 to 63°F. Eight of the eggs were taken just downstream of a 25-foot-deep pool formed at a right-angle river bend. The eggs were collected in water 5 to 8 feet deep over a substrate of medium sand mixed with gravel up to 3 inches diameter.

We captured only three juvenile sturgeon in the single gill-netting survey in January 1991. Set-lining was much more successful; we caught 143 white sturgeon in June and 43 in July. Size of sturgeon caught by set-lines ranged from 22 to 154 inches (about 3 to 15 years old). Catch per effort in June setlining was 23.8 sturgeon per day, more than twice the catch rate of any other capture method tried since we started sampling for juvenile sturgeon in April 1989. Although setlining appears to be a promising technique for capturing large numbers of juvenile sturgeon, it is only effective if an adequate bait supply is available. So far, we have not secured a dependable source of bait, limiting continued use of this sampling method.

No updated index of year-class strength was calculated, because the fish captured this year have not been aged. The collected fin rays will be sectioned and read as soon as time permits.

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Chapter 7

ENTRAINMENT OF EGGS AND LARVAE

Stephani Spaar, Department of Water Resources

Water is exported from the Sacramento-San Joaquin Delta by the State Water Project and federal Central Valley Project pumping plants in the southern delta. Louver screens at the project intakes are efficient for fish more than 21 millimeters long; therefore, striped bass (*Morone saxatilis*) eggs and larvae are entrained with the export water. Eggs and larvae of other fish species present in the adjacent channels are also entrained.

The *Delta Pumping Plant Fish Protective Agreement* provides for annual determination of direct losses of striped bass caused by the SWP pumping plant diversions and the replacement of yearling equivalent size fish (size at age 1) to offset these losses. Yearling equivalents are the estimated numbers of fish that would have survived to age 1 and potentially contributed to the delta fishery.

The objective of this survey is to determine yearling equivalent losses of striped bass less than 21 mm SL *(standard length)* at the SWP and CVP facilities. These losses are calculated from the estimates of eggs and larvae entrained, which are based on estimated density of eggs and larvae near the project intakes and the amount of water diverted.

In 1991, another objective was added as part of the 1991 pilot study for delta smelt (*Hypomesus transpacificus*). This second objective is to determine the timing, abundance, and distribution of delta smelt larvae in the southern delta and impacts of SWP operations on the early life history of this species. The delta smelt portion of this study is conducted in accordance with an informal agreement with the California Fish and Game Commission to better determine the status of delta smelt and impacts of SWP operations.

DWR and DFG conducted the 1991 survey from February 4 to July 12 at seven locations in the southern delta (Figure 60). To estimate entrainment, Station 92 was used for the SWP and Station 96 was used for the CVP. Other channels near the diversion sites were also sampled to determine the source of eggs and larvae transported toward the pumps. The 1991 survey was conducted as in previous years (Raquel 1987 and 1988; Spaar 1990). Initial sampling began in early February at occasional intervals as part of the pilot study for delta smelt. Routine sampling resumed on April 1 for striped bass.

No sampling was conducted from April 16 to May 26 due to breakdown of the sampling boat. Striped bass densities for this period were estimated as the mean of daily densities for 1987-1990 over this same period. Entrainment of eggs and larvae was estimated as usual, based on these daily densities and project diversions.

State Water Project Entrainment

No striped bass eggs were collected near the SWP intake (Station 92) before April 16 or after May 26 (Figure 61). Eggs were probably present near the SWP between April 16 and May 26, based on patterns from past years and the presence of eggs at adjacent sites (Stations 94 and 96) when sampling resumed in late May. Based on mean 1987-1990 daily egg densities, striped bass eggs were probably most abundant during May 1-15 (Table 24).

No striped bass larvae were collected at this site before April 16 (Figure 61, Table 24). Larvae were probably present during the April 16-May 26 downtime, based on past studies, and were collected near the SWP when sampling resumed in late May. Based on mean 1987-1990 daily larval densities, striped bass larvae were probably most abundant during May 16-31. The actual late-May catches were dominated by the 7-10 mm size group, but some 6 mm larvae were present.

C—042796

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Figure 60
SOUTH DELTA EGG AND LARVA STUDY SAMPLING STATIONS AND STATE WATER PROJECT AND CENTRAL VALLEY PROJECT DIVERSION SITES IN THE SOUTHERN DELTA

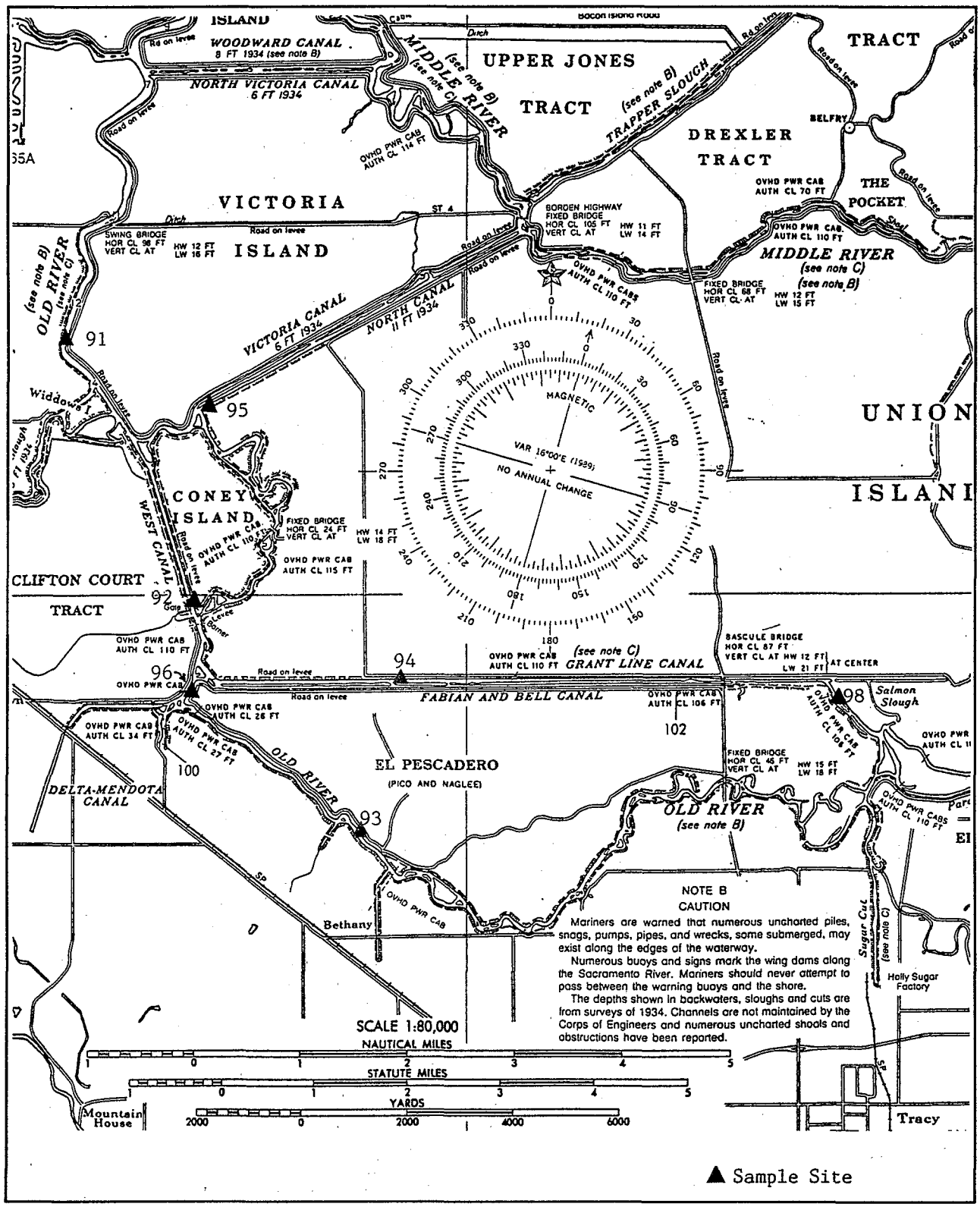

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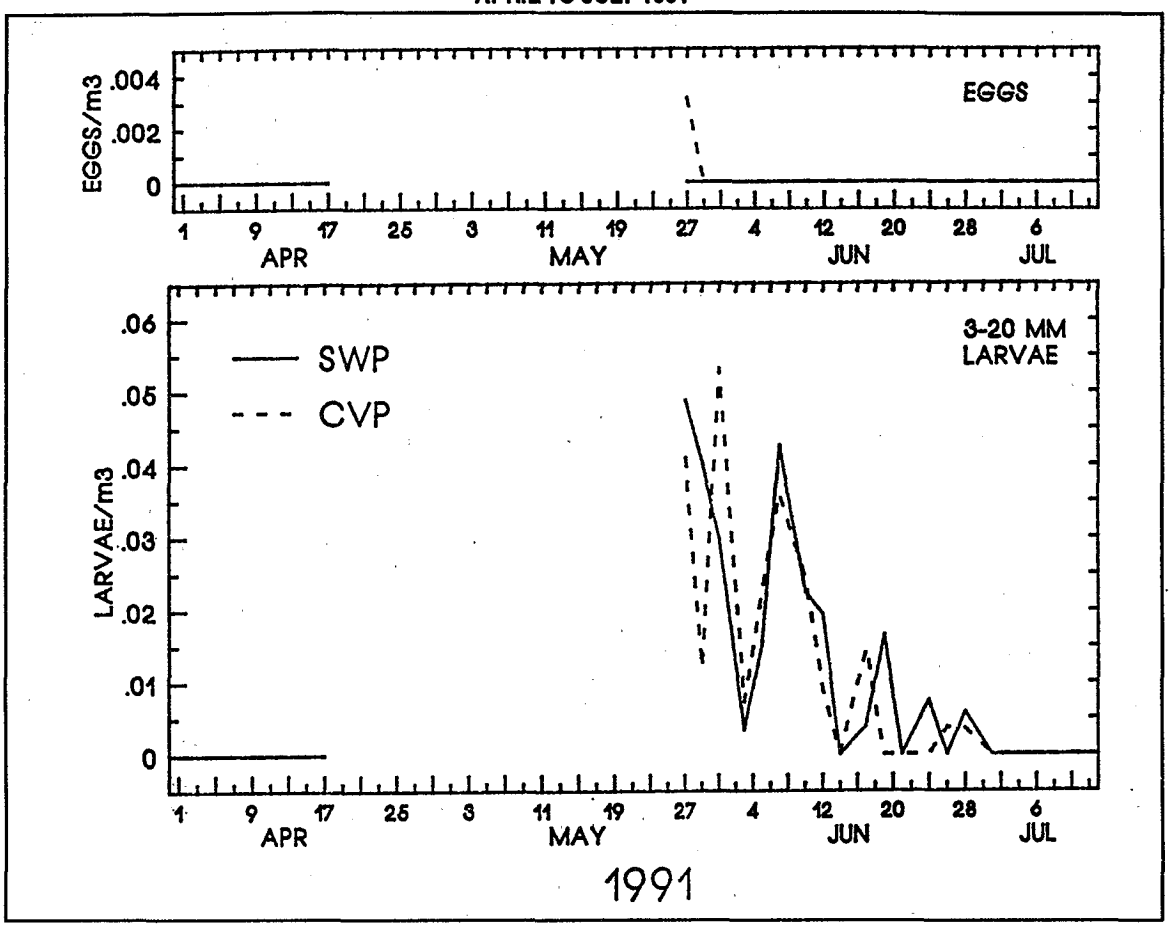
Figure 61
ESTIMATED DENSITY OF STRIPED BASS EGGS AND LARVAE AT THE STATE WATER PROJECT AND CENTRAL VALLEY PROJECT, APRIL TO JULY 1991



SWP export rates, volume of water sampled per tow, and several environmental parameters were averaged bimonthly (Table 25). Intake rates at the SWP were greatest during late March and early April, with a daily diversion of about 11,000-13,000 acre-feet. Diversions were reduced for an extended period from April 15 through July (Figure 62). During this period, daily diversion into Clifton Court Forebay was about 2,000-5,000 acre-feet or less, and at times no water was diverted. Water temperature and specific conductance were low in early April, probably due to the abundance of rain in March and resulting increased outflow.

Total estimated SWP entrainment was 50.8 million: 6.3 million eggs and 44.5 million larvae (Table 24). Due to the break in sampling from mid-April to late May, entrainment of eggs and larvae may be over or underestimated more so than in prior years. Estimated larval entrainment was probably highest during late April, when larvae were present and water diversion rates were moderate (Tables 24 and 25). Total estimated entrainment declined with each successive size group of larvae. Entrainment was estimated to be greatest for 6-mm larvae (Table 26).

Estimates of entrainment losses for striped bass eggs and larvae were converted to an equivalent number of age-1 fish by multiplying the entrainment estimates by the survival rates to age 1 for each size group (Ecological Analysts 1981). Striped bass yearling equivalent loss for the SWP was 15,117 fish (Table 27). Highest losses in terms of yearling equivalents were in the 7-10 mm size group.

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Table 24
MEAN DENSITY AND ESTIMATED ENTRAINMENT OF STRIPED BASS EGGS AND LARVAE AT THE STATE WATER PROJECT INTAKE, 1991

MEAN DENSITY *(Fish per 10,000 Cubic Meters)*

	Size Groups						
	EGGS	3-6 mm	7-10 mm	11-14 mm	15-18 mm	19-20 mm	3-20 mm
FEB 1-15	NS	NS	NS	NS	NS	NS	NS
FEB 16-28	0	0	0	0	0	0	0
MAR 1-15	0	0	0	0	0	0	0
MAR 16-31	0	0	0	0	0	0	0
APR 1-15	0	0	0	0	0	0	0
APR 16-30*	146	1159	286	2	0	0	1448
MAY 1-15*	534	1013	1373	124	8	0	2518
MAY 16-31*	86	1707	1743	195	27	0	3672
JUN 1-15	0	6	86	86	6	6	190
JUN 16-30	0	0	27	24	0	0	51
JUL 1-11	0	0	0	0	0	0	0

ENTRAINMENT *(Thousands of Fish)*

	Size Groups						
	EGGS	3-6 mm	7-10 mm	11-14 mm	15-18 mm	19-20 mm	3-20 mm
FEB 1-15	NS	NS	NS	NS	NS	NS	NS
FEB 16-28	0	0	0	0	0	0	0
MAR 1-15	0	0	0	0	0	0	0
MAR 16-31	0	0	0	0	0	0	0
APR 1-15	0	0	0	0	0	0	0
APR 16-30 *	1,812	13,578	3,511	30	0	0	17,120
MAY 1-15 *	4,263	6,398	9,251	800	56	0	16,505
MAY 16-31 *	204	5,121	4,421	554	83	0	10,180
JUN 1-15	0	19	258	178	26	26	507
JUN 16-30	0	0	123	105	0	0	228
JUL 1-11	0	0	0	0	0	0	0
TOTAL	6,279	25,117	17,564	1,666	166	26	44,540
GRAND TOTAL							50,818

NS = No sampling February 1-15, 1991.
*April 16 through May 26 estimated based on mean 1987-1990 densities over the same period.

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Table 25
BIMONTHLY MEAN OF ENVIRONMENTAL PARAMETERS AND DIVERSION RATES AT THE STATE WATER PROJECT AND CENTRAL VALLEY PROJECT INTAKES, 1991

STATE WATER PROJECT	Specific Conductance (µmhos)	Water Secchi (cm)	Water Volume Temperature (degrees C)	Diversion (acre-feet)	Sampled (cubic meters)
FEB 1-15	NS	NS	NS	4497	NS
FEB 16-28	868	68	13.3	2475	172
MAR 1-15	726	73	12.8	10923	198
MAR 16-31	582	68	11.7	12559	209
APR 1-15	390	51	15.0	11850	202
APR 16-30	NS	NS	NS	6236	NS
MAY 1-15	NS	NS	NS	3367	NS
MAY 16-31	517	37	19.4	2102	185
JUN 1-15	577	48	22.2	1679	266
JUN 16-30	656	42	20.6	2226	276
JUL 1-11	615	43	24.4	2461	276

CENTRAL VALLEY PROJECT	Specific Conductance (µmhos)	Water Secchi (cm)	Water Volume Temperature (degrees C)	Diversion (acre-feet)	Sampled (cubic meters)
FEB 1-15	675	79	8.9	6178	225
FEB 16-28	784	77	13.3	4005	194
MAR 1-15	937	52	12.8	6743	208
MAR 16-31	624	47	11.7	7983	177
APR 1-15	550	40	15.0	7836	182
APR 16-30	NS	NS	NS	3598	NS
MAY 1-15	NS	NS	NS	2592	NS
MAY 16-31	538	38	19.4	2477	293
JUN 1-15	669	39	22.2	1926	283
JUN 16-30	655	41	20.0	1620	280
JUL 1-11	555	45	24.4	2874	279

NS = No sampling February 1-15 (SWP) and April 16-May 26, 1991.

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C-042800

Figure 62
DAILY STATE WATER PROJECT INFLOW AND CENTRAL VALLEY PROJECT EXPORT, FEBRUARY THROUGH JULY 1991
SOURCE: California Department of Water Resources

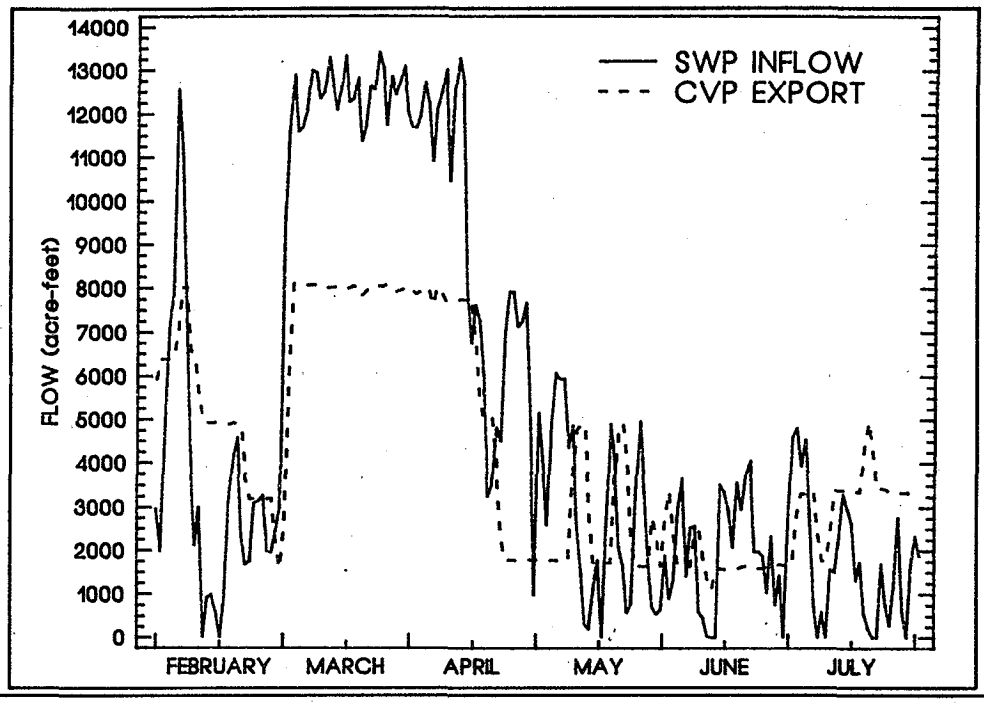

Table 26
TOTAL ESTIMATED DENSITY AND ENTRAINMENT OF STRIPED BASS EGGS AND LARVAE AT THE STATE WATER PROJECT AND CENTRAL VALLEY PROJECT INTAKES, FEBRUARY-JULY 1991*

	DENSITY (Fish per Cubic Meter)		ENTRAINMENT (Number of Fish)	
SIZE	SWP	CVP	SWP	CVP
Eggs	1.1068	1.3745	6,278,843	5,548,784
3 mm	0	0	0	0
4 mm	0.0018	0.0034	9,381	14,043
5 mm	1.0319	1.1385	5,493,290	3,296,832
6 mm	3.9360	3.0713	19,614,648	10,075,188
7 mm	2.0111	1.2773	9,451,446	3,895,499
8 mm	0.9751	0.6436	3,933,060	1,943,998
9 mm	0.7166	0.3205	2,362,375	946,999
10 mm	0.5482	0.3840	1,816,851	1,177,303
11 mm	0.2291	0.1681	725,963	511,072
12 mm	0.1405	0.0763	534,283	226,561
13 mm	0.0945	0.0709	213,550	202,833
14 mm	0.0685	0.0558	192,615	176,063
15 mm	0.0287	0.0277	78,194	80,162
16 mm	0.0176	0.0098	83,397	37,251
17 mm	0.0023	0.0080	3,992	28,890
18 mm	0	0.0028	0	12,220
19 mm	0.0097	0.0020	25,809	9,406
20 mm	0	0.0042	0	11,666

*April 16 through May 26 estimated based on mean 1987-1990 densities over that period.

C—042801

C-042801

Table 27
STRIPED BASS YEARLING EQUIVALENT LOSSES AT THE STATE WATER PROJECT AND CENTRAL VALLEY PROJECT EXPORT FACILITIES BASED ON DENSITIES AND WATER EXPORTS AT THE INTAKES, FEBRUARY-JULY 1991*

SIZE GROUP	SURVIVAL RATE TO AGE 1**	NUMBER OF YEARLING EQUIVALENTS SWP	CVP
EGGS	0.000047	295	261
3-6 mm	0.000124	3115	1660
7-10 mm	0.000338	5937	2692
11-14 mm	0.002509	4181	2801
15-18 mm	0.006415	1062	1017
19-20 mm	0.020414	527	430
TOTAL		15,117	8,861

* April 16 to May 26 losses are based on mean 1987-1990 densities for the same period.
** Survival rates to age 1 for different size groups were calculated by Ecological Analysts (1981). Egg survival rate was estimated by calculating the potential number of eggs spawned compared to the estimated number of age-1 fish in the estuary.

Central Valley Project Entrainment

No striped bass eggs were collected before April 16 near the CVP intake (Station 96) (Figure 61, Table 28) nor in the study area. Based on patterns from past years and the presence of eggs at this and adjacent sites (Stations 96 and 94) when sampling resumed in late May, eggs were probably present near the SWP between April 16 and May 26. Striped bass eggs were collected near the CVP only on May 28. However, eggs were collected at adjacent sites on Grant Line Canal (Stations 94 and 98) in late May and early June. The last eggs were collected in the study area on June 7 at Station 98. Based on mean 1987-1990 daily egg densities, striped bass eggs were probably most abundant during May (Table 28).

No striped bass larvae were collected at this site before April 16 (Figure 61, Table 28). Larvae were probably present during the April 16-May 26 downtime, based on past studies, and were collected near the CVP when sampling resumed in late May. Based on mean 1987-1990 daily larval densities, striped bass larvae were probably most abundant during May 16-31 (Table 24). The actual catches in late May were dominated by the 7-10 mm size group (Table 28).

CVP intake rates, volume of water sampled per tow, and several environmental parameters were averaged bimonthly (Table 25). Intake rates at the CVP were greatest during late March and early April, with a daily average of about 8,000 acre-feet diverted. CVP diversions were reduced for an extended period from April 15 through July (Figure 62). Diversions were lowest in late June, with a daily mean export of 1,600 acre-feet. Water temperature and specific conductance were low in early April, probably due to the abundance of rain in March and resulting increased outflow.

Total estimated CVP entrainment was 28.2 million: 5.6 million eggs and 22.6 million larvae (Table 28). Due to the break in sampling from mid-April to late May, entrainment of eggs and larvae may be over or underestimated more so than in previous years. Total estimated entrainment was highest during late May, when exports were moderately low and larvae most abundant. Entrainment was estimated to be the greatest for 6-mm larvae (Table 26).

Estimates of entrainment losses for striped bass eggs and larvae were converted to an equivalent number of age-1 fish by multiplying the entrainment estimates by the survival rates to age 1 for each size group (Ecological Analysts 1981). Striped bass yearling equivalent loss for the CVP was 8,861 fish (Table 27). The CVP losses in terms of yearling equivalents were highest for the 11-14 mm size group.

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Table 28
MEAN DENSITY AND ESTIMATED ENTRAINMENT OF STRIPED BASS EGGS AND LARVAE AT THE CENTRAL VALLEY PROJECT INTAKE, 1991

MEAN DENSITY *(Fish per 10,000 Cubic Meters)*

	Size Groups						
	EGGS	3-6 mm	7-10 mm	11-14 mm	15-18 mm	19-20 mm	3-20 mm
FEB 1-15	0	0	0	0	0	0	0
FEB 16-28	0	0	0	0	0	0	0
MAR 1-15	0	0	0	0	0	0	0
MAR 16-31	0	0	0	0	0	0	0
APR 1-15	0	0	0	0	0	0	0
APR 16-30*	121	1002	122	0	0	0	1124
MAY 1-15*	473	822	841	112	10	1	1786
MAY 16-31*	488	1477	1039	114	24	4	2659
JUN 1-15	0	0	150	51	6	0	207
JUN 16-30	0	0	17	18	0	0	35
JUL 1-11	0	0	0	0	0	0	0

ENTRAINMENT *(Thousands of Fish)*

	Size Groups						
	EGGS	3-6 mm	7-10 mm	11-14 mm	15-18 mm	19-20 mm	3-20 mm
FEB 1-15	0	0	0	0	0	0	0
FEB 16-28	0	0	0	0	0	0	0
MAR 1-15	0	0	0	0	0	0	0
MAR 16-31	0	0	0	0	0	0	0
APR 1-15	0	0	0	0	0	0	0
APR 16-30*	813	4,691	523	0	0	0	5,214
MAY 1-15*	2,784	3,512	3,722	586	63	9	7,892
MAY 16-31*	1,951	5,184	3,052	294	72	12	8,614
JUN 1-15	0	0	616	183	23	0	822
JUN 16-30	0	0	51	53	0	0	104
JUL 1-11	0	0	0	0	0	0	0
TOTAL	5,549	13,386	7,964	1,117	159	21	22,647
GRAND TOTAL							28,196

* April 16 through May 26 estimated based on mean 1987-1990 densities over the same period.

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Species Composition of Catch

The 1991 survey collected 15 varieties of larval fish over the survey area (Table 29). The most abundant fishes over all sites and at the SWP and CVP sites were:

Chameleon goby, *Tridentiger trigonocephalus*	137,455
Threadfin shad, *Dorosoma petenense*	14,775
Prickly sculpin, *Cottus asper*	4,804

These species accounted for 99 percent of the total catch at all sites; however, the chameleon goby alone comprised 87 percent of the total catch.

Moderately low in abundance and comprising less than 1 percent of the total catch were:

Striped bass (3-38 mm)	327
Lepomis spp.	285

Captured in very low numbers were:

Sacramento splittail, *Pogonichthys macrolepidotus*	18
Longfin smelt, *Spirinchus thaleichthys*	9
Delta smelt, *Hypomesus transpacificus*	7

Delta smelt larvae were collected on March 14; May 28 and 31; and June 5, 7, and 17 in North Canal (Station 95), Old River (Stations 92, 93, 96), and Grant Line Canal (Station 94).

Sixty-four American shad (*Alosa sapidissima*) and one mosquitofish (*Gambusia affinis*) were collected, the first of these species identified for this survey.

Table 29
LARVAL FISH SPECIES COLLECTED IN THE SOUTHERN DELTA, FEBRUARY THROUGH JULY 1991*

Species	Type***	Total Catch** All Sites	Total Catch** SWP	Total Catch** CVP	% Total Catch All Sites	% Total Catch of Species Caught at Site SWP	% Total Catch of Species Caught at Site CVP
Chameleon goby *Tridentiger trigonocephalus*	E	137,455	11,401	7,848	87	8	6
Threadfin shad *Dorosoma petenense*	E	14,775	466	545	9	3	4
Prickly sculpin *Cottus asper*	F-E	4,804	788	1,123	3	16	23
Striped bass *Morone saxatilis*	E	327	71	63	<0.5	22	19
Lepomis spp.	F	285	40	56	<0.5	14	20
Bigscale logperch *Percina macrolepida*	F	103	4	30	<0.1	4	29
Inland silverside *Menidia beryllina*	F-E	103	2	11	<0.1	2	11
Cyprinidae	F	84	12	26	<0.1	14	31
Ictalurus spp.	F	80	1	2	<0.1	1	3
American shad *Alosa sapidissima*	A	64	0	0	<0.1	0	0
Sacramento splittail *Pogonichthys macrolepidotus*	E	18	4	4	<0.1	22	22
Longfin smelt *Spirinchus thaleichthys*	E	9	4	2	<0.1	44	22
Delta smelt *Hypomesus transpacificus*	E	7	4	2	<0.1	57	29
Sacramento sucker *Catostomus occidentalis*	F	4	0	0	<0.1	0	0
Mosquitofish *Gambusia affinis*	F	1	0	0	<0.1	0	0
TOTAL		158,119	12,797	9,712			

* No sampling April 16 through May 26.
** Actual number of fish caught.
*** E = Estuarine, F = Freshwater, M = Marine, A = Anadromous

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Discussion

Due to boat problems, the 1991 survey missed the start of spawning activity and arrival of the first larvae in the southern delta. Striped bass spawning appears to have been later than in recent years, since no eggs or larvae were observed before April 16.

Results from previous years indicate eggs and larvae are generally first observed during April 1-15 and are more abundant by April 16-30 (Raquel 1987, 1988; IESP 1990, 1991; Spaar 1990). The peak period of egg density near the SWP and CVP intakes was probably in mid- to late May, as indicated by timing of observed egg occurrence and water temperatures. No eggs were observed April 1-15, but they were present in late May. Since 1985, eggs have generally been most abundant during the May 1-15 period.

Timing of spawning activity has been correlated with water temperature, flow, and salinity (Turner and Chadwick 1972). Spawning and egg abundance may occur earlier in the season (such as in 1987, when water temperatures were higher than normal due to drought) or later (as in 1986, due to wet year conditions and lower spring water temperatures). The concentration of rainfall in March 1991 increased flow and kept water temperatures low in late March and early April. Water temperatures in early to mid-April averaged 15 degrees Celsius, which is at the low end of the spawning range for striped bass (Wang 1986). A rise in water temperature within the spawning range appears to trigger spawning activity. Temperatures probably rose shortly after April 16, initiating spawning in late April or early May.

The peak period of larval density generally directly follows the peak period of egg density (Raquel 1987, 1988; IESP 1991; Spaar 1990). The 1991 survey was probably similar, with peak larval density at the SWP and CVP estimated to have been in late May.

As shown in Table 30, entrainment estimates for striped bass eggs and larvae have varied considerably over the history of the study (Raquel 1987, 1988; IESP 1990, 1991; Spaar 1990). Estimated entrainment of eggs at the CVP is usually higher than at the SWP because the CVP intake is near a spawning area upstream in Old River (Station 93). In 1991, spawning also occurred in Grant Line Canal (Station 94) and near Salmon Slough (Station 98). The higher density of eggs in this area in comparison to Old River probably resulted in a comparable loss of eggs at the SWP. In contrast, estimated entrainment of larvae is generally greater at the SWP, which could be attributed to a more abundant source of larvae in areas north of the site.

Table 30
ESTIMATED ENTRAINMENT OF STRIPED BASS EGGS AND LARVAE, 1985-1991
(Thousands of Fish)

	STATE WATER PROJECT		CENTRAL VALLEY PROJECT	
	Eggs	Larvae	Eggs	Larvae
1985	90,241	373,312	89,174	281,191
1986	3,964	50,583	9,743	40,499
1987	2,191	96,915	7,183	138,340
1988	9,156	125,580	25,761	108,965
1989	390	141,177	9,398	62,954
1990	6,374	28,671	3,003	46,728
1991*	6,279	44,540	5,549	22,647

* 1991 includes estimates for April 16-May 26 based on mean 1987-1990 densities for that period.

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Yearling equivalent entrainment losses of striped bass also vary between years and by site (Table 31) (Raquel 1987, 1988; IESP 1990, 1991; Spaar 1990). The magnitude of variation between years and by site is much smaller than that observed in the entrainment losses of eggs and larvae, due to the effect of survival rates to yearling equivalent size (age 1) applied to the egg and larval stages.

Table 31
STRIPED BASS
YEARLING EQUIVALENT ENTRAINMENT LOSSES, 1985-1991
(Number of Fish)

	State Water Project	Central Valley Project	Total
1985	68,488	46,360	114,848
1986	37,109	52,976	90,985
1987	43,846	71,958	115,804
1988	59,625	51,085	110,710
1989	56,306	30,997	87,303
1990	7,717	16,936	24,653
1991*	15,117	8,861	23,978

* 1991 includes estimated April 16-May 26 period based on mean 1987-1990 densities for that period.

In addition to striped bass, this study also provides information on delta smelt and other species in the southern delta. Reliable identifications of delta smelt are available for samples from 1989 to present for this area. Since 1989, this study has caught less than 20 delta smelt larvae each year, usually in April and May. The 1991 catch was similar in abundance, but delta smelt were caught as early as mid-March and through early June, extending its previously known time of occurrence in this area. The delta smelt catch comprises less than 0.5 percent of the study's total catch of all species each year. They have been collected at all sites except near Salmon Slough (Station 98). There do not appear to be many delta smelt spawning in this area, as indicated by the few larvae caught in this extensive sampling effort (Wang 1991). Delta smelt eggs are adhesive and demersal and not likely to be collected with an egg and larval sled towed in mid-channel. Delta smelt are known to occur in the San Joaquin River up to Mossdale, and spawning is likely to occur there also. In comparison to DFG's deltawide egg and larval study, catches of delta smelt in the southern delta are relatively small (Tim Heyne, pers comm).

The impact of the continuing drought on the southern delta can be seen in the major change in species composition of larval fishes within this area since 1988. Due to low freshwater outflow and intrusion of more saline water upstream into the estuary, the chameleon goby has been able to expand its range upstream and increase its numbers quickly, possibly by utilizing an empty niche (Johnson Wang, pers comm). From 1988 to 1991, the catch of chameleon goby larvae increased from 291 to 137,455, and it continues to dominate the species composition of larval fishes in the southern delta (Spaar 1990). Moyle and Herbold (1989) noted a similar increase in chameleon goby abundance in Suisun Marsh from 1987 to 1988. Prickly sculpin and threadfin shad were still abundant in the 1991 survey. The present abundance of prickly sculpin appears to be fairly stable and is similar to 1988 and 1989 abundances (IESP 1990, Spaar 1990). Threadfin shad have increased tenfold in abundance from 1990, with an abundance similar to the 1987 catch (12,182 fish) (IESP 1991, DFG unpublished data). Striped bass abundance appears to have declined since 1987.

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Chapter 8

DELTA OUTFLOW/ SAN FRANCISCO BAY

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Objectives of the Delta Outflow/San Francisco Bay studies are to:

- Determine how the abundance and distribution of fishes, shrimp, and crabs are affected by changes in the amount and timing of freshwater outflow to the bay.
- Identify the outflow-related mechanisms underlying any significant abundance/outflow relationships developed.
- Quantify the impacts water development projects would have on the identified mechanisms.

Species Update

Following is an update of abundance trends for various species of shrimp, crabs, and fish common to San Francisco Bay.

Caridean Shrimp

In 1991, abundance trends of the six major species of shrimp were similar to recent years. Abundance of *Crangon franciscorum* was again relatively low, and abundance of *C. nigricauda, C. nigromaculata,* and *Heptacarpus stimpsoni* continued to increase or remained relatively high (Table 32). It is difficult to compare the annual abundance indices from 1990 and 1991 to previous years because in these latest years we sampled only from February to October. The annual abundance index using January to December is usually less than an index based on February to October; however, this does vary by species and outflow. For example, in 1988 the January to December index of *C. franciscorum* was 84 percent of the February to October index, compared to 94 percent for *C. nigricauda* and 123 percent for *C. nigromaculata*.

The 1991 annual abundance index for *C. franciscorum* was the lowest since the study began and was comparable to the 1985 index. We believe some portion of the population was upriver of our sampling area during the recent drought. Therefore, to better sample *C. franciscorum* and several other

Table 32
ANNUAL ABUNDANCE INDICES FOR THE SIX MOST COMMON SPECIES OF CARIDEAN SHRIMP COLLECTED IN SAN FRANCISCO BAY, 1980-1991

Year	*C. franciscorum*	*C. nigricauda*	*C. nigromaculata*	*Palaemon*	*Heptacarpus*	*Lissocrangon*	Total
1980	5343	1255	49	121	94	0	6862
1981	2587	651	15	127	36	0	3415
1982	8498	495	31	83	75	0	9182
1983	9304	1152	363	33	80	0	10932
1984	6820	355	152	171	67	80	7645
1985	1329	505	68	91	92	22	2108
1986	6061	1344	188	106	92	140	7930
1987	3345	2716	300	58	328	56	6804
1988	2300	2856	288	39	299	7	5789
1989*	2859	3350	347	137	671	3	7367
1990**	1820	5118	980	103	561	19	8602
1991**	1294	5349	1332	150	1448	8	9580
All	4438	1937	311	99	283	30	7099

* January to August
**February to October

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species, several stations in the lower Sacramento and San Joaquin rivers were added in February 1991. Of all *C. franciscorum* collected in 1991, 9.7 percent were from these new stations. We have yet to determine how much greater the annual abundance index, which is weighted by sample area, would be with inclusion of these stations.

The 1991 abundance index of *C. nigricauda* was again high, but increased only slightly from 1990. Although the index for January to December could be slightly lower, it is reasonable to assume that the highest abundance index of *C. nigricauda* was in 1990 or 1991. Abundance of *C. nigromaculata* in 1991 was also a study period high. Abundance of *Palaemon macrodactylus* was high in 1991 relative to recent years but remained low when compared to the three species of *Crangon* and *H. stimpsoni*. *H. stimpsoni* had the most dramatic change in abundance in 1991; its abundance index increased almost 300 percent from 1990. The total shrimp abundance index in 1991 is comparable in magnitude to 1982 and 1983, but species composition was very different.

	% of Total Shrimp Abundance Index
1982 (High Outflow)	
C. franciscorum	93
C. nigricauda	5
C. nigromaculata	>1
H. stimpsoni	1
1991	
C. franciscorum	14
C. nigricauda	56
C. nigromaculata	14
H. stimpsoni	15

Total biomass of shrimp was undoubtedly less in 1991 than 1982 or 1983, as *C. franciscorum* is larger than any of the other species of shrimp commonly collected in the bay.

Dungeness Crab

In 1991, abundance of juvenile Dungeness crab *(Cancer magister)* was below average, although it was higher than in all previous years except 1984, 1985, and 1988 (Figure 63). In-bay abundance of juvenile Dungeness crabs is strongly related to ocean conditions in the winter, when the planktonic larvae are present in near-shore waters. Years with frequent storms, such as 1980, 1982, 1983, and 1986, or years with warm-water ocean events, such as 1982, 1983, and 1987 (Figure 64), predictably did not result in strong year classes of Dungeness crabs. The preferred nursery area in the bay is shallow, protected waters with salinities between 15 and 30 ppt. In 1991 juvenile Dungeness crabs were concentrated in the lower Napa River and the Carquinez Strait/lower Suisun Bay area through the summer and fall months.

Figure 63
ANNUAL ABUNDANCE INDICES OF 0+ DUNGENESS CRAB, *CANCER MAGISTER*
(May-July, Otter Trawl)

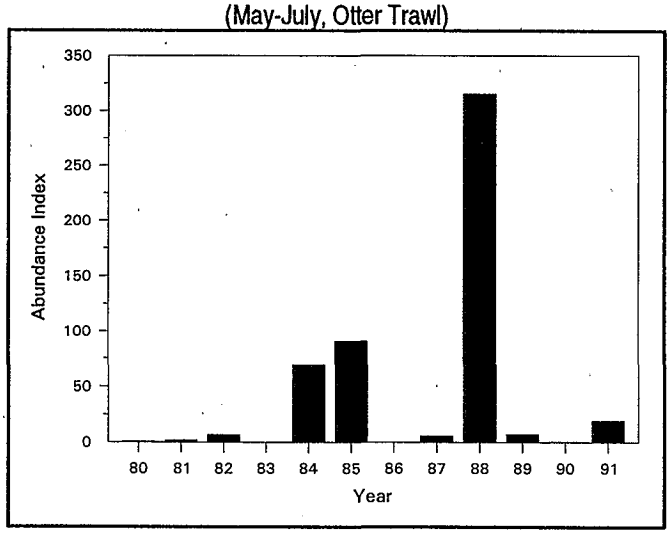
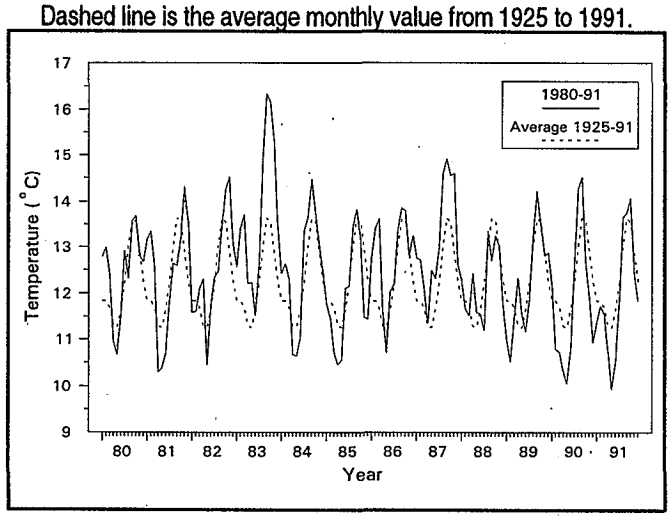


Figure 64
MONTHLY SEA SURFACE TEMPERATURES AT THE FARALLON ISLANDS, 1980 TO 1991
Dashed line is the average monthly value from 1925 to 1991.



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Fishes

This section summarizes abundance trends for 13 commonly collected species of fish. Each of these species uses the bay as a nursery area, although juveniles of many also rear in near-shore coastal areas. Some species, such as English sole and Pacific herring, utilize higher salinity waters (generally greater than 15 to 20 ppt) as a nursery area; others, such as longfin smelt and starry flounder, utilize lower salinity waters (Table 33). Life history strategies vary considerably, with larvae spawned in the ocean, the bay, or the freshwater portions of the delta (Table 34). For this discussion, species are grouped by the salinity range of their nursery area.

Table 33
NURSERY AREA OF SOME FISHES COMMONLY COLLECTED IN SAN FRANCISCO BAY
(Table limited to species discussed in this report.)

	Higher Salinity (>15-20 ppt)	Lower Salinity (<15-20 ppt)
Bay goby	✓	
California halibut	✓	
English sole	✓	
Jacksmelt	✓	
Longfin smelt		✓
Northern anchovy	✓	
Pacific herring	✓	
Plainfin midshipman	✓	
Shiner perch	✓	
Speckled sanddab	✓	
Staghorn sculpin	✓	
Starry flounder		✓
White croaker	✓	

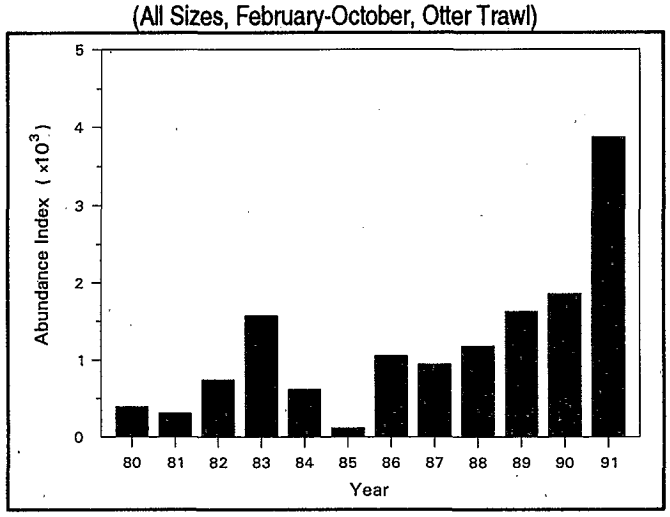
Table 34
SPAWNING/HATCHING AREA OF SOME FISHES COMMONLY COLLECTED IN SAN FRANCISCO BAY
(Table limited to species discussed in this report.)

	Ocean	Ocean/ Bay	Bay	Fresh Water
Bay goby			✓	
California halibut	✓			
English sole	✓			
Jacksmelt			✓	
Longfin smelt				✓
Northern anchovy		✓		
Pacific herring		✓		
Plainfin midshipman			✓	
Shiner perch			✓	
Staghorn sculpin			✓	
Starry flounder	✓			
Speckled sanddab	✓			
White croaker		✓		

Abundance trends for those species that use the higher salinity waters of the bay as a nursery area have been mixed in recent years. The hypothesis proposed by some researchers that abundance of "marine" species will increase during years with low freshwater outflow is not supported by our data.

Abundance of only one species, bay goby *(Lepidogobius lepidus),* consistently increased during the drought (Figure 65). This species is somewhat unique among bay fishes in that peak spawning is during late summer and fall (CDFG 1987). We hypothesize that the relatively stable salinities present from 1987 to 1991 resulted in higher survival of larvae and allowed juveniles to successfully colonize a larger area of the bay than during previous years. The presence of a large number of juveniles (<40 mm) relative to the number of adults in 1989 and 1990 in part supports this hypothesis.

Figure 65
ANNUAL ABUNDANCE INDICES OF BAY GOBY, *LEPIDOGOBIUS LEPIDUS*
(All Sizes, February-October, Otter Trawl)



Several other species had a trend of increasing abundance in recent years in comparison to the early 1980s. Annual abundance of plainfin midshipman *(Porichthys notatus)* and white croaker *(Genyonemus lineatus)* has been high since 1986 (Figures 66 and 67). Relatively stable bay salinities in recent years have probably contributed to their increased abundance. Plainfin midshipman migrate to shallow, protected waters to

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Figure 66
ANNUAL ABUNDANCE INDICES OF
0+ PLAINFIN MIDSHIPMAN, *PORICHTHYS NOTATUS*
(July-October, Otter Trawl)

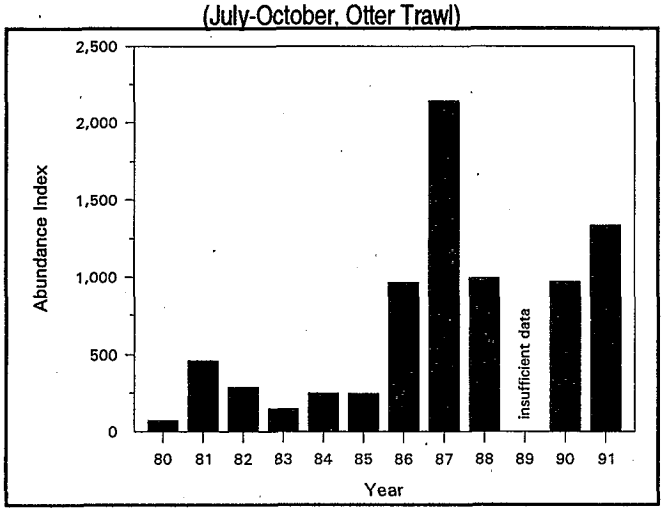


Figure 67
ANNUAL ABUNDANCE INDICES OF
WHITE CROAKER, *GENYONEMUS LINEATUS*
(All Sizes, February-October, Otter Trawl)

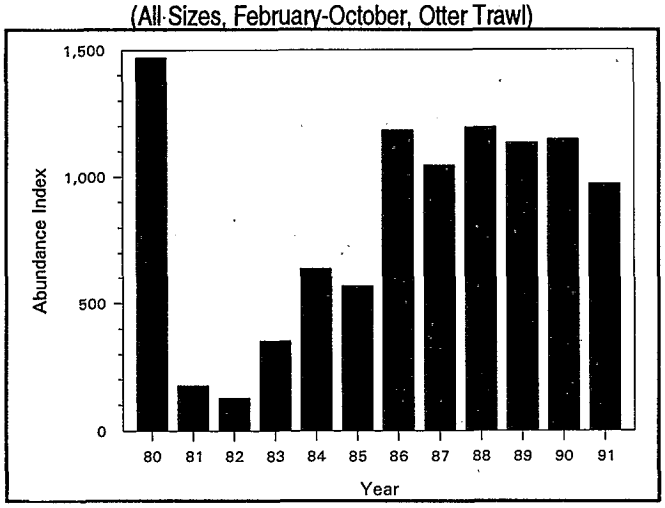
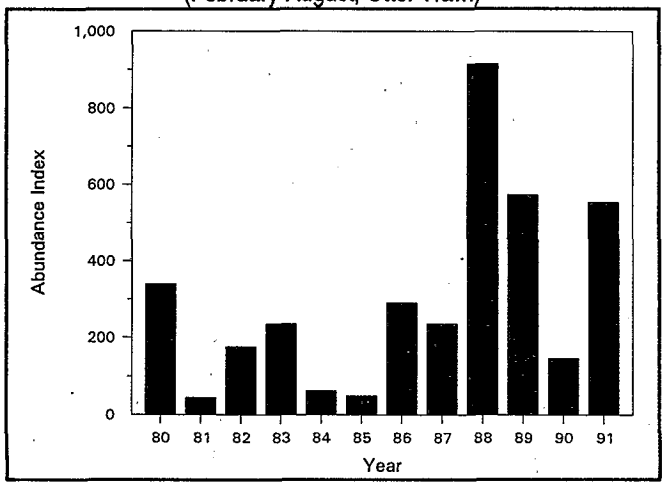


Figure 68
ANNUAL ABUNDANCE INDICES OF
0+ SPECKLED SANDDAB, *CITHARICHTHYS STIGMAEUS*
(February-August, Otter Trawl)

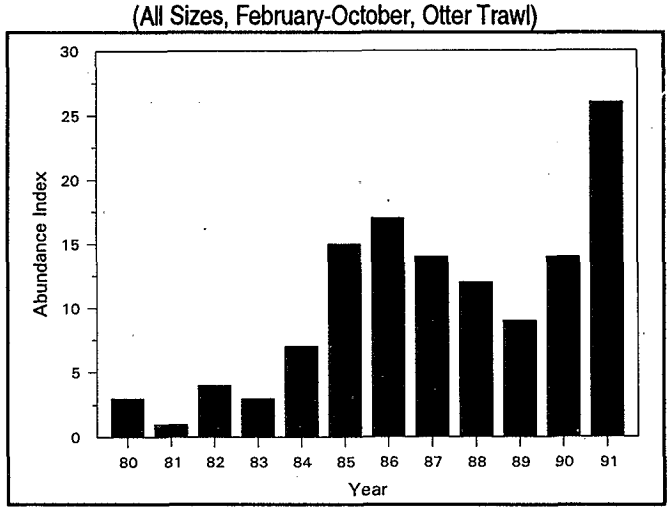


spawn in summer. White croaker spawn in the bay and ocean during winter and spring. Larger juveniles and adults of both species migrate to ocean waters, and ocean conditions may also affect their abundance. An additional factor that may affect the abundance of white croaker is intensification of the gill-net fishery for this species in the nearshore ocean area beginning in 1982. Depth and area restrictions on this fishery were implemented in 1986.

Annual abundance of speckled sanddab *(Citharichthys stigmaeus)* has been high during three of the last four years (Figure 68). This species spawns exclusively in the ocean, and juveniles have a long pelagic period, up to 180 days. Ocean and in-bay factors undoubtedly affect abundance of speckled sanddab in the bay, but we have not determined what the controlling factors are.

California halibut *(Paralichthys californicus)* are not as common in the bay as several other species of flatfish, but we have seen an increased number of juveniles and adults that are the result of strong year classes in 1983, 1987, and 1990 (Figure 69). These were years with warm-water ocean events (Figure 64), and we hypothesize that California halibut abundance in the San Francisco Bay area increased because of increased local spawning, higher survival of larvae, or migration of juveniles from more southern coastal areas with the warmer ocean waters.

Figure 69
ANNUAL ABUNDANCE INDICES OF
CALIFORNIA HALIBUT, *PARALICHTHYS CALIFORNICUS*
(All Sizes, February-October, Otter Trawl)



English sole *(Pleuronectes vetulus)* had no trend of increasing or decreasing abundance in recent years (Figure 70). Although larvae are spawned in the ocean during winter, we have yet to identify how ocean conditions affect English sole abundance. Juvenile English sole abundance declined in the bay earlier during the summers of 1988, 1989, 1990, and 1991 than in previous years, suggesting that mortality increased or they emigrated from the bay earlier in these years.

Northern anchovy *(Engraulis mordax)* abundance was relatively stable from 1988 to 1991 (Figure 71). Northern anchovy are numerically the most abundant fish in the bay and are part of a large central California coastal population. Adults migrate from the ocean to the bay in late spring and spawn through the summer. When bay temperatures and salinities decline in the fall, most adults emigrate to the ocean. Bay catches are composed of many cohorts spawned both in the ocean and the bay.

Abundance of several species that use the higher salinity areas of the bay as a nursery area have been consistently low in recent years. Jacksmelt *(Atherinopsis californiensis)* abundance has been low in the bay since 1985 (Figure 72). Adults migrate from nearshore coastal waters to the bay to spawn in

Figure 71
ANNUAL ABUNDANCE INDICES OF NORTHERN ANCHOVY, *ENGRAULIS MORDAX*
(All Sizes, April-October, Midwater Trawl)

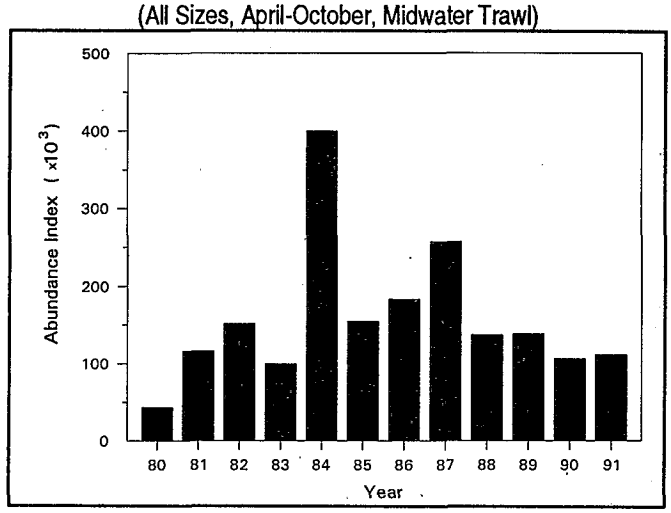


Figure 72
ANNUAL ABUNDANCE INDICES OF 0+ JACKSMELT, *ATHERINOPSIS CALIFORNIENSIS*
(July-November, Midwater Trawl)

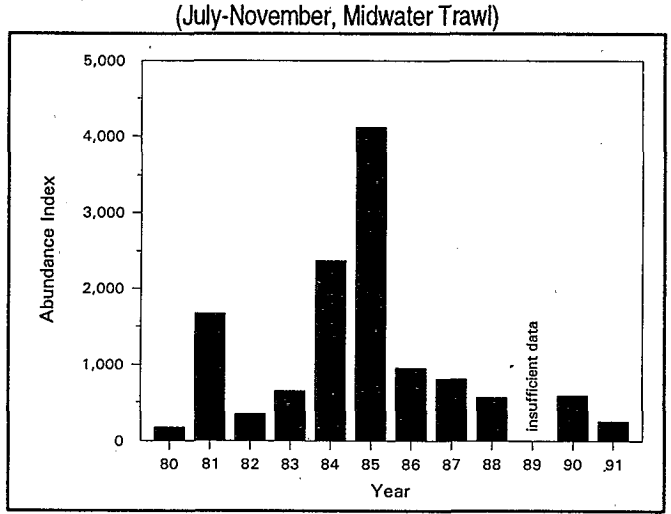


Figure 70
ANNUAL ABUNDANCE INDICES OF 0+ ENGLISH SOLE, *PLEURONECTES VETULUS*
(February-October, Otter Trawl)

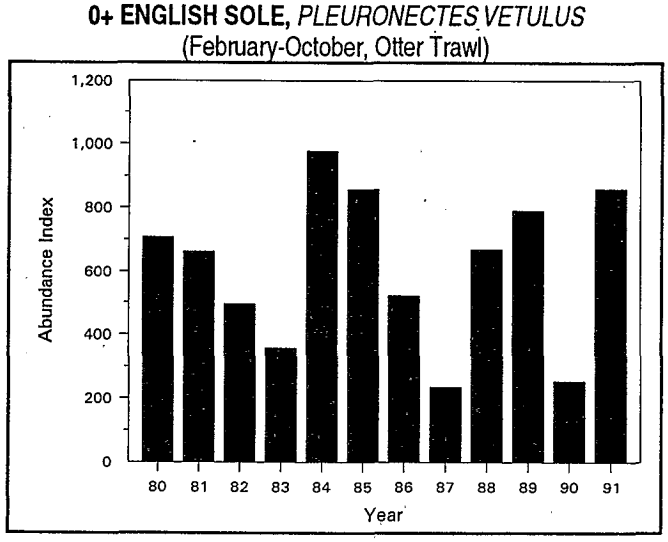
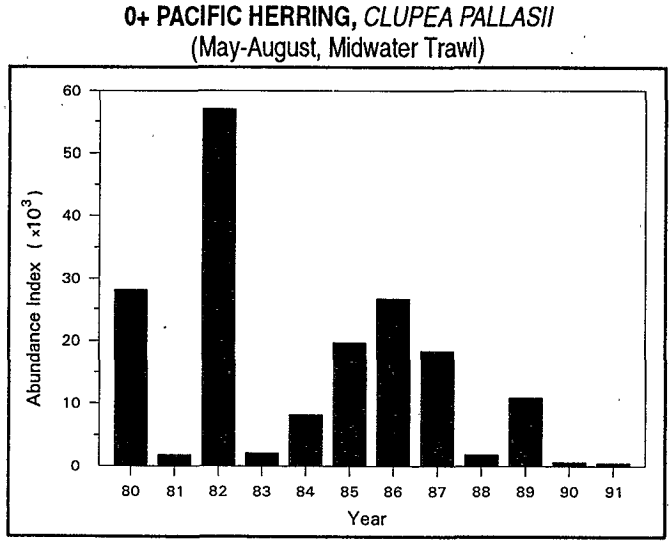


Figure 73
ANNUAL ABUNDANCE INDICES OF 0+ PACIFIC HERRING, *CLUPEA PALLASII*
(May-August, Midwater Trawl)



C—042811

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spring and early summer. Juveniles rear in shallow waters, including the littoral zone, and South Bay is an important nursery area. Abundance of juvenile Pacific herring *(Clupea pallasii)* was very low in the bay in 1990 and 1991 (Figure 73). Pacific herring adults migrate to the bay to spawn in winter, and juveniles rear in the bay for 6 to 8 months before emigrating to the ocean. Shiner perch *(Cymatogaster aggregata)* abundance has been low since 1986 (Figure 74). Shiner perch are resident in the bay and bear live young in the late spring and summer months. As with jacksmelt, South Bay is an important nursery area. We have not developed any hypotheses as to why juvenile abundance of these three species with very different life history strategies was low in recent years.

Staghorn sculpin *(Leptocottus armatus)* juveniles rear in shallow waters with a wide range of salinities (generally from 5 to 30 ppt). They spawn in the higher salinity portions of the bay during late fall and winter. Staghorn sculpin abundance was low and high in recent years (Figure 75). We have no hypotheses as to why abundance would fluctuate during the drought.

As a generalization, species that use the lower salinity waters of the bay as a nursery area had low abundance during years with low freshwater outflow. Abundance of starry flounder *(Platichthys stellatus)* and longfin

Figure 75
ANNUAL ABUNDANCE INDICES OF
0+ STAGHORN SCULPIN, *LEPTOCOTTUS ARMATUS*
(February-October, Otter Trawl)

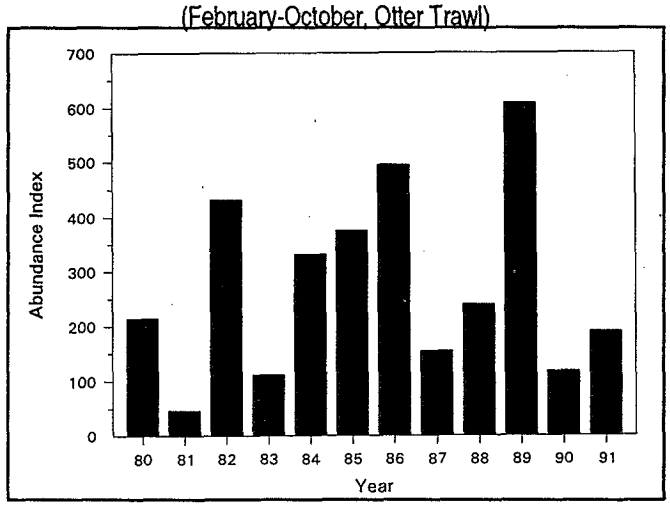


Figure 76
ANNUAL ABUNDANCE INDICES OF
0+ STARRY FLOUNDER, *PLATICHTHYS STELLATUS*
(May-October, Otter Trawl)

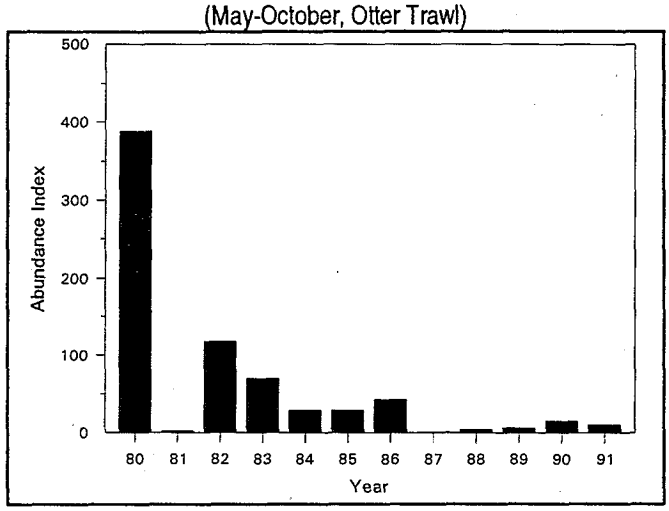


Figure 74
ANNUAL ABUNDANCE INDICES OF
0+ SHINER PERCH, *CYMATOGASTER AGGREGATA*
(May-October, Otter Trawl)

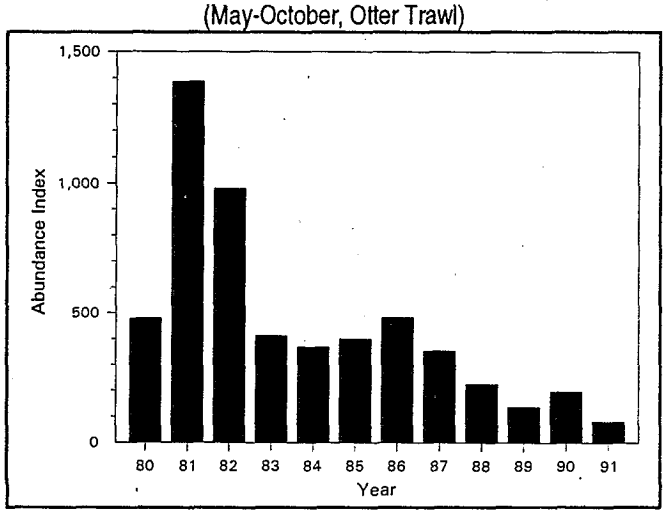
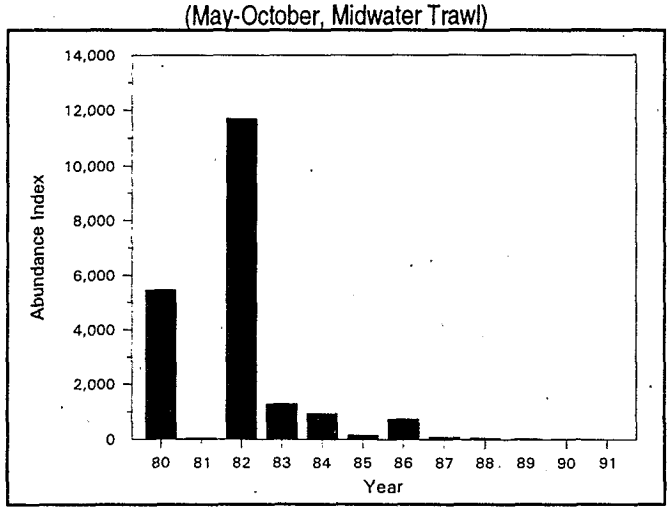


Figure 77
ANNUAL ABUNDANCE INDICES OF
0+ LONGFIN SMELT, *SPIRINCHUS THALEICHTHYS*
(May-October, Midwater Trawl)



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smelt *(Spirinchus thaleichthys)* juveniles was again low in 1991 (Figures 76 and 77). We are developing mechanistic-based models to explain the positive relationship between the abundance of these two species and outflow. Several mechanisms related to outflow are discussed in detail in the following section and in previous annual reports.

Freshwater Outflow Needs

Previous analyses indicated significant positive relationships between freshwater outflow and the abundance of *Crangon franciscorum*, longfin smelt, and starry flounder (CDFG 1987; IESP 1990, 1991). In 1991 we focused on continued data analysis and literature review to clarify our understanding of the life histories of these species and determine the mechanisms responsible for their outflow/abundance relationships. With this knowledge we were better able to determine the outflow requirements of each species.

Caridean Shrimp

Five species of Caridean shrimp are relatively abundant in the bay: *Crangon franciscorum, C. nigricauda, C. nigromaculata, Heptacarpus stimpsoni,* and *Palaemon macrodactylus*. *Crangon* spp. and *Heptacarpus* are native, and *Palaemon* was introduced from the Orient in the 1950s. The general life history of *Crangon* and *Palaemon* is as follows (Figure 78):

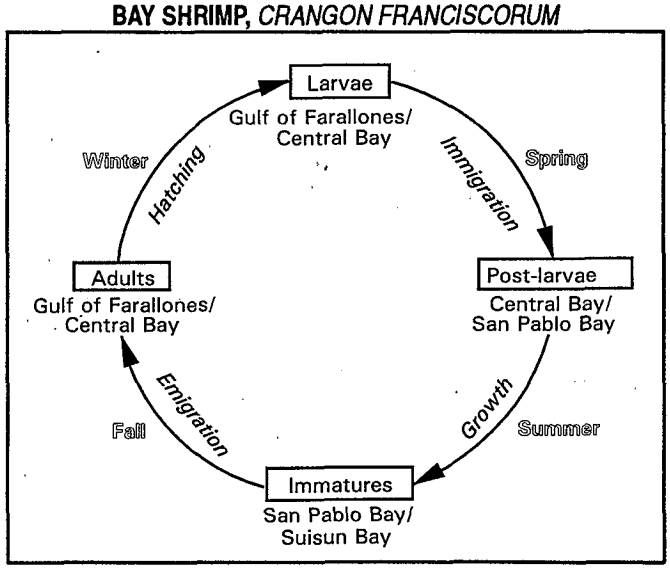
- Hatching of larvae in relatively high salinity waters.
- Migration of post-larvae and juveniles upstream to a lower salinity nursery area.
- Rearing of juveniles in the nursery area for 4 to 6 months.
- Migration of mature shrimp downstream to higher salinity waters to complete the life cycle.

These species mature when they are one year old and have a short life span, with males living 1 to 1.5 years and females 1.5 to 2 years. Some females hatch more than one brood of eggs during a breeding season. Little is known about the life cycle of *Heptacarpus, but it is assumed that* juveniles prefer lower salinity water than the adults, as we have collected smaller shrimp farther upstream than larger shrimp.

These species use the bay as a nursery area to varying degrees. Timing for hatching of larvae and recruitment of juveniles to the bay is slightly different for each species. *C. franciscorum* is estuarine-dependent, and its juveniles are found in brackish (2 to 22 ppt), relatively warm (16 to 22°C) waters. Peak abundance of small juvenile *C. franciscorum* consistently is during April to June. This peak is usually followed by one or two smaller abundance peaks in the summer, and occasionally another in the fall. Juvenile *C. franciscorum* are most common in San Pablo and Suisun bays in years with high outflow. Their center of distribution moves upstream to Honker Bay and the lower portions of the Sacramento and San Joaquin rivers during low outflow years.

C. nigricauda are found in higher salinity, cooler waters than *C. franciscorum,* but they are still an important component of the bay shrimp population. Juveniles are most common from 18 to 32 ppt and 12 to 20°C. Abundance of small juvenile *C. nigricauda* peaks in late spring or early summer, similar to *C. franciscorum*. Unlike *C. franciscorum*, fall and winter cohorts have been relatively

Figure 78
LIFE CYCLE OF THE BAY SHRIMP, *CRANGON FRANCISCORUM*



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large, especially during 1986/1987 and 1987/1988. In high outflow years, *C. nigricauda* are common only as far upstream as lower San Pablo Bay. In low outflow years, and most notably the recent drought years, their distribution expanded to lower Suisun Bay.

C. nigromaculata is mainly a shallow water, coastal species and is the most common crangonid in the near-shore ocean adjacent to San Francisco Bay. Juvenile *C. nigromaculata* occur at higher salinities (26 to 32 ppt) and a narrower temperature range (14 to 18°C) than either *C. franciscorum* or *C. nigricauda*. Recruitment of *C. nigromaculata* to the bay also appears to occur later than for *C. franciscorum* or *C. nigricauda*. From 1980 to 1988, abundance peaks of small juvenile *C. nigromaculata* occurred from May to November, but six of the eight peaks were after July. During years with high outflow, *C. nigromaculata* were limited to South and Central bays. Their distribution expanded to upper San Pablo Bay and occasionally Carquinez Strait during years with low outflow.

Heptacarpus stimpsoni is found in high salinity, cooler waters, similar to *C. nigricauda* and *C. nigromaculata*. There appear to be spring and fall peaks in abundance of small *Heptacarpus* in the bay. Its distribution is similar to that of *C. nigromaculata*, with shrimp concentrated in South and Central bays most years. Their distribution expanded upstream to upper San Pablo Bay and Carquinez Strait during the recent drought.

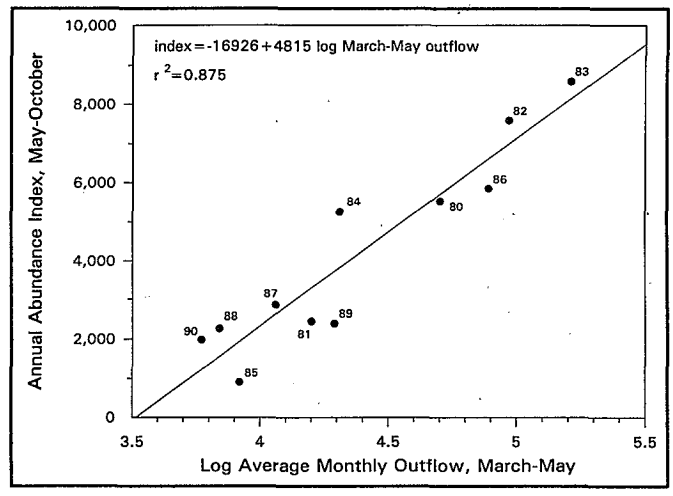
Palaemon is a resident estuarine species, and no life stages occur in the ocean. This species is highly adapted to estuarine conditions, and larvae are believed to use tidal vertical migrations to minimize downstream transport. *Palaemon* larvae hatch from April to August, and juveniles are most abundant from June to September. Juveniles prefer brackish, almost fresh water and are common in the rivers and tidal sloughs upstream of our study area. Adults are most common in Suisun Bay, the western delta, and areas adjacent to freshwater sources, such as the mouths of creeks in South and San Pablo bays.

Outflow to the bay affects shrimp at every life stage. It affects the distribution of mature shrimp and transports early-stage larvae hatched in the bay downstream and to the near-shore coastal area. Freshwater outflow creates salinity gradients believed to be used by late-stage larvae and post-larvae to identify the mouth of the bay and the upstream direction in their migration from the near-shore coastal area to the in-bay nursery area. Migration to the nursery area is aided by landward bottom currents, including gravitational currents, which increase in magnitude as outflow increases. Outflow also affects size and location of the nursery area, abundance of predators and food organisms, and timing of the downstream movement of mature shrimp.

We have previously reported a strong positive relationship between abundance of *C. franciscorum* and spring outflow (CDFG 1987, IESP 1990). The relationship between the annual abundance of immature *C. franciscorum* and outflow from March to May remained strongly positive with the addition of recent data (Figure 79).

The period from March to May, when most small juveniles are present, was selected as the most critical period in the life cycle of *C. franciscorum*. Outflow probably affects the number of juvenile *C. franciscorum* that

Figure 79
RELATIONSHIP BETWEEN THE ANNUAL ABUNDANCE INDEX OF IMMATURE *CRANGON FRANCISCORUM* AND THE LOG$_{10}$ OF THE AVERAGE MONTHLY OUTFLOW, MARCH-MAY



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recruit to the bay and, based on size and location of the nursery area, their subsequent survival and growth. *C. franciscorum* have evolved to use the bay as a nursery area in spring and early summer, when there is a salinity gradient that helps the small juveniles identify the mouth of the bay and the upstream direction, strong landward bottom currents to aid their upstream migration, and a large area of shallow, brackish water suitable for nursery habitat.

Importance of the size of the nursery area to recruitment success of *C. franciscorum* is in part confirmed by the strong positive relationship between the annual abundance index and an annual habitat index (Figure 80).

Figure 80
RELATIONSHIP BETWEEN THE ANNUAL ABUNDANCE INDEX OF IMMATURE *CRANGON FRANCISCORUM* AND THE ANNUAL HABITAT INDEX
(April-June, 1.6-21.6 ppt)

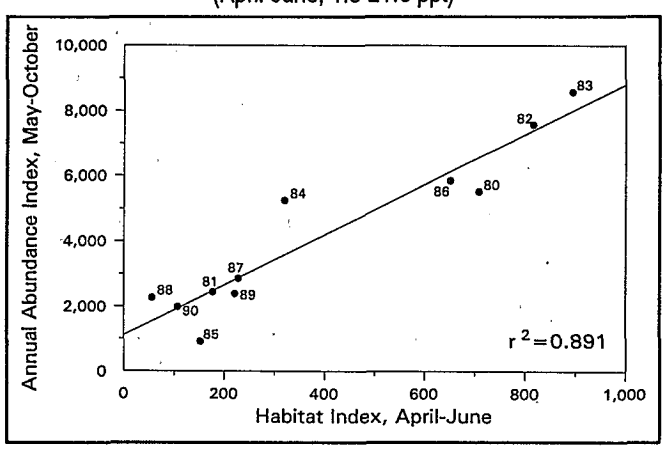
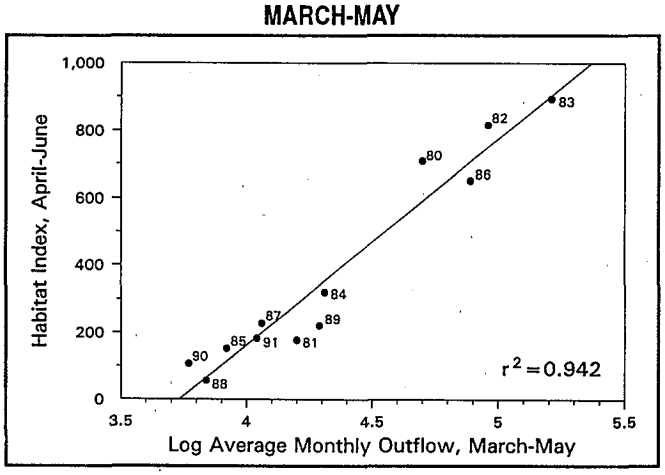


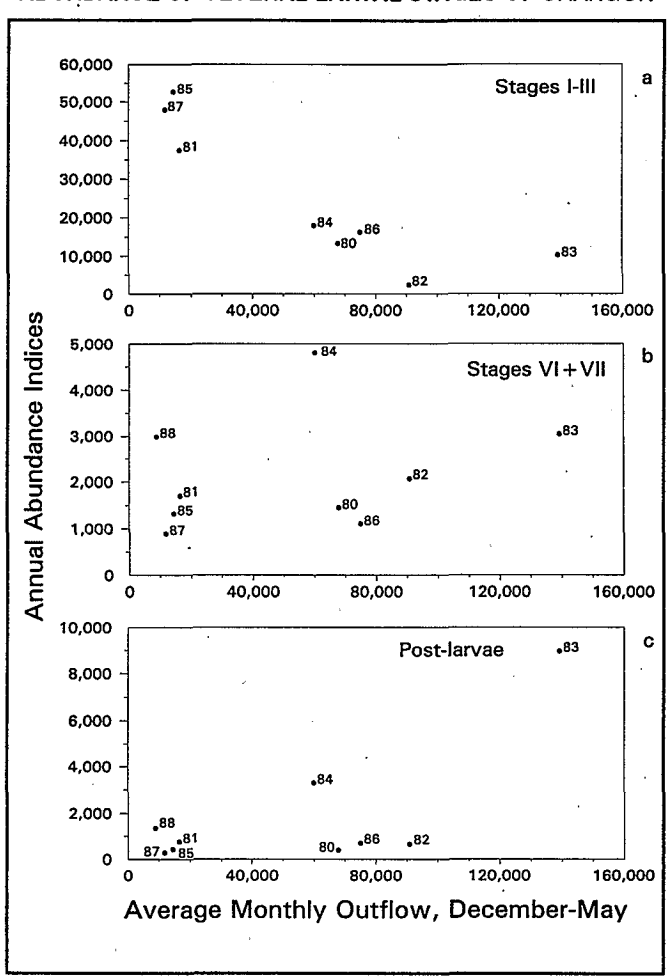
Figure 81
RELATIONSHIP BETWEEN THE ANNUAL HABITAT INDEX AND THE LOG 10 OF AVERAGE MONTHLY OUTFLOW, MARCH-MAY



The habitat index is the total area of shallow (less than 10 feet), brackish (1.6 to 21.6 ppt) water from April to June based on Bay Study data. As expected, there is also a strong positive relationship between the annual habitat index and outflow from March to May (Figure 81).

Outflow prior to March may also be important. In winters with low outflow, most ovigerous *C. franciscorum* remain in the bay because salinities are relatively high. As a result, early-stage larvae, which are in the upper portions of the water column and subject to downstream transport by surface currents (IESP 1991), are more abundant in the bay during low outflow years (Figure 82a). However, these are not the years with the highest abundance of late-stage *Crangon* larvae (Figure 82b), *Crangon* post-larvae (Figure 82c), or juvenile *C. franciscorum*.

Figure 82
RELATIONSHIP BETWEEN OUTFLOW AND ANNUAL ABUNDANCE OF SEVERAL LARVAL STAGES OF *CRANGON*



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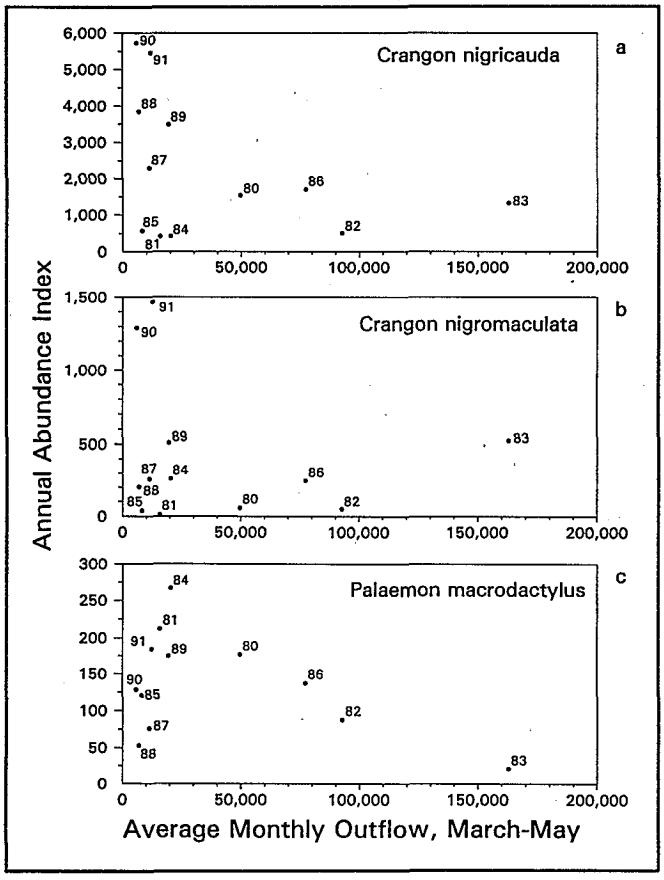
Other researchers have speculated that estuarine-reared larvae of some decapod crustaceans have a higher mortality rate than ocean-reared larvae (Strathmann 1982; McConaugha 1988). If this were true for *C. franciscorum*, high outflow during the winter would result in higher survival of larvae. Winter outflow is also important in determining the size and location of the nursery area the following spring.

The other species of shrimp do not have a significant relationship, positive or negative, between abundance and freshwater outflow. *C. nigricauda* annual abundance does not have a linear relationship with outflow (Figure 83a). Before 1987, high abundance occurred only during years with high spring outflow (1980, 1983, 1986). Since 1986, years with low outflow have had high abundance. This can be partly attributed to the recent drought, which has resulted in a large portion of the bay having salinities within the preferred range of *C. nigricauda* year round. There is no consistent relationship between outflow and abundance of *C. nigromaculata* (Figure 83b). There is a trend of increasing abundance since 1987, but before 1989 the highest annual abundance index was in 1983, a year with very high outflow. *Palaemon* abundance was low in years with high and low outflow; generally, years with moderate outflow had the highest abundance in our study area (Figure 83c).

Figure 83
RELATIONSHIP BETWEEN OUTFLOW AND ANNUAL ABUNDANCE OF THREE SPECIES OF SHRIMP

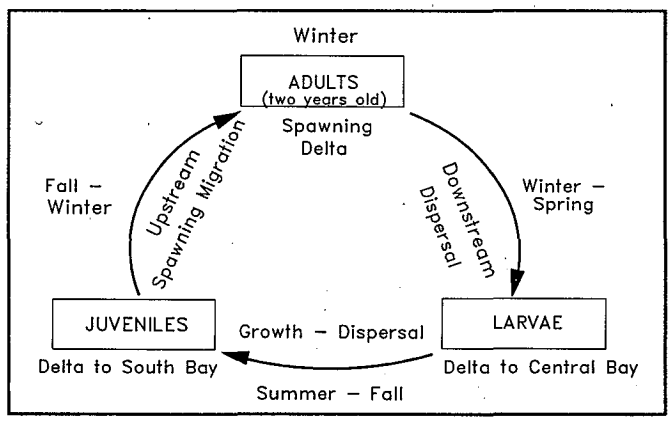


Longfin Smelt

The longfin smelt *(Spirinchus thaleichthys)* life cycle (Figure 84) begins with the spawning of adhesive eggs in the delta and freshwater portions of Suisun Bay from December through April (Moyle 1976; Simonsen 1977). In Lake Washington, Washington state, longfin smelt eggs hatched in 37 to 47 days at 7°C (Dryfoos 1965). Longfin smelt larvae were present in plankton samples collected in the western delta, Suisun Bay, and San Pablo Bay from December through May, with peak abundance in February and March (Figure 85). This suggests November-through-April spawning.

We hypothesize that the longfin smelt abundance/outflow relationship (Figure 86) results from increased larval dispersal and an increased volume of nursery habitat produced by high outflow. Timing of larval longfin smelt abundance corresponds well with

Figure 84
LIFE CYCLE OF LONGFIN SMELT, *SPIRINCHUS THALEICHTHYS*



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the historical peak outflow period (*ie* December-March) and should result in downstream dispersal of larvae.

A limited number of depth-stratified plankton samples collected with the Tucker trawl in 1990 showed the smallest larvae (6.0 to 11.9 mm TL) were present only in the surface layer of water, whereas larger larvae and small juveniles were at mid-depths and toward the bottom (Figure 87). This pattern of depth distribution would make small longfin smelt larvae susceptible to downstream transport by freshwater outflow. Larger larvae and juveniles, distributed deeper in the water column, would more likely maintain their position or be transported upstream by freshwater-induced gravitational currents.

Larvae appear to have been transported downstream by freshwater outflow (Figures 88 and 89). High outflows in the winters of 1980, 1982, 1983, 1984, and 1986 resulted in a major portion of the larval smelt population being transported to San Pablo Bay (Figure 89). During the low outflow years of 1981, 1985, 1987, and 1988, most of the larvae remained upstream of San Pablo Bay.

Figure 85
AVERAGE MONTHLY ABUNDANCE INDEX OF YOLK-SAC AND POST-YOLK-SAC LONGFIN SMELT LARVAE, 1980-1988

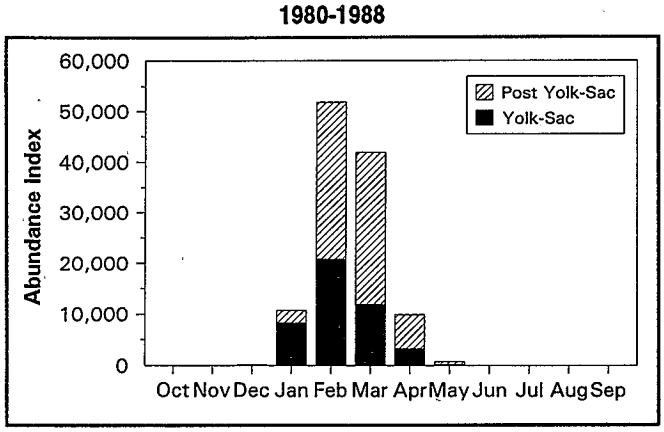


Figure 86
RELATIONSHIP BETWEEN LOG_{10} OF THE STRIPED BASS FALL MIDWATER TRAWL LONGFIN SMELT ABUNDANCE INDEX AND LOG_{10} OF THE AVERAGE FEBRUARY-MAY OUTFLOW AT CHIPPS ISLAND

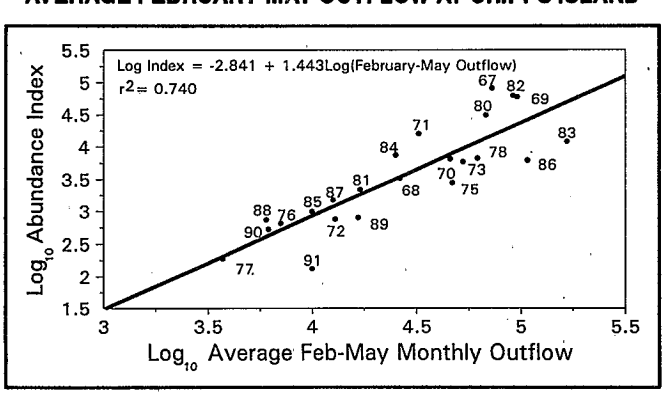


Figure 87
DEPTH DISTRIBUTION, BY LENGTH INTERVAL, OF LARVAL AND SMALL JUVENILE LONGFIN SMELT COLLECTED IN THE TUCKER TRAWL FROM THE LOWER SACRAMENTO RIVER, APRIL 1990
Surface samples were collected about 2 meters below the surface, mid-depth at 10 meters below the surface, and bottom at 16 meters (2 meters above the bottom).

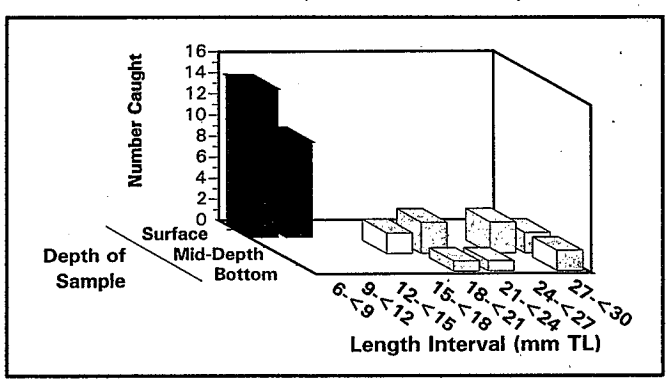


Figure 88
AVERAGE MONTHLY OUTFLOW AT CHIPPS ISLAND, 1980-1988

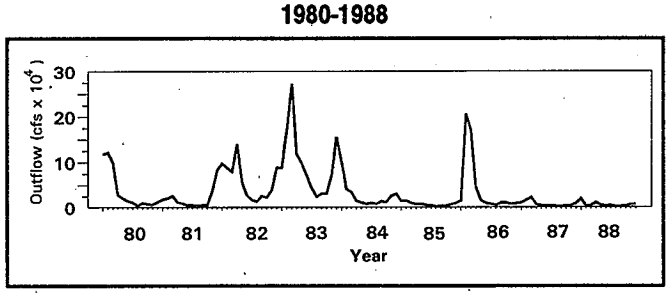
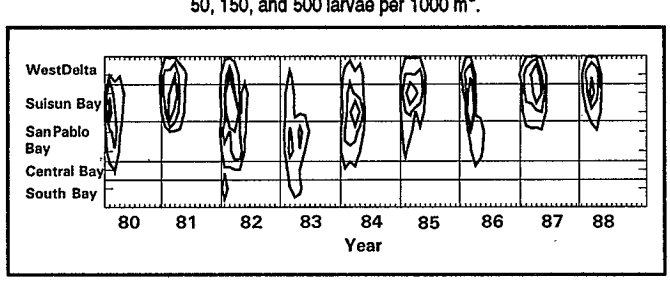


Figure 89
LARVAL LONGFIN SMELT DISTRIBUTION PLOTTED AS AVERAGE DENSITY BY MONTH AND EMBAYMENT, 1980-1988
Contour lines represent average densities of 50, 150, and 500 larvae per 1000 m^3.



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Distribution of young-of-the-year longfin smelt was similar to that of larvae in most years (Figure 90), suggesting larval transport was the major mechanism of dispersal. Young-of-the-year were present in and downstream of San Pablo Bay during high outflow years but were not distributed downstream of Suisun Bay during low outflow years except in 1985 (Figure 90). An upstream shift in young-of-the-year distribution was apparent as the year progressed in 1980, 1982, 1984, 1985, and 1986. In low outflow years, some young-of-the-year probably reared upstream of the sampling area.

During the winter following their first year, longfin smelt expanded their distribution downstream, generally into South Bay (Figure 91). This expansion did not seem related to outflow, as it occurred in both high and low outflow years. Even though longfin smelt were more abundant in South Bay as 1+ individuals than as young-of-the-year, densities remained highest in the brackish water of San Pablo and Suisun bays (Figure 91). These areas of intermediate salinity (2 to 20 ppt) were important to longfin smelt throughout their lives (Figure 92).

Longfin smelt probably mature during fall and winter as they approach 2 years of age (Dryfoos 1965; Moulton 1974; Moyle 1976). However, our data provided no evidence of a late-fall spawning migration. Instead, 1+ longfin smelt disappeared from our collections in August and September. They were collected again in small numbers throughout the bay between October and December. This suggests they began migration to freshwater spawning grounds well before spawning began in November, and some fish returned to the bay after spawning.

Data on age at maturity of longfin smelt are lacking for the San Francisco Bay population, but it is suspected that most spawn for the first time at age 2, similar to the Lake Washington population (Dryfoos 1965; Moulton 1974). Longfin smelt are now being collected monthly to determine age at maturity, spawning time, and fecundity.

Another way outflow may have affected abundance of longfin smelt was by creating brackish water nursery habitat. More than 90 percent of the larval and small (< 50 mm) juvenile longfin smelt were collected in areas with bottom salinities less than 18 ppt. We hypothesized that the salinity range of 0.1 to

Figure 90
YOUNG-OF-THE-YEAR LONGFIN SMELT DISTRIBUTION PLOTTED AS AVERAGE DENSITY BY MONTH AND EMBAYMENT, 1980-1988
Contour lines represent average densities of 3.5, 30, and 150 smelt per 10,000 m^3.

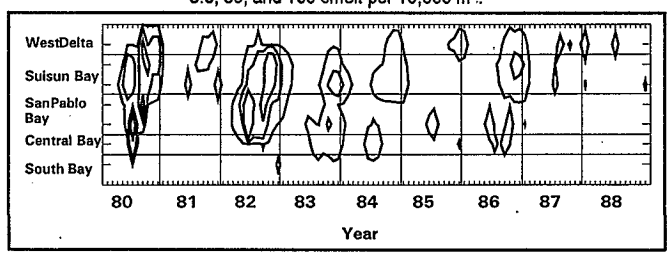


Figure 91
AGE 1+ LONGFIN SMELT DISTRIBUTION PLOTTED AS AVERAGE DENSITY BY MONTH AND EMBAYMENT, 1980-1988
Contour lines represent average densities of 1, 10, and 100 smelt per 10,000 m^3.

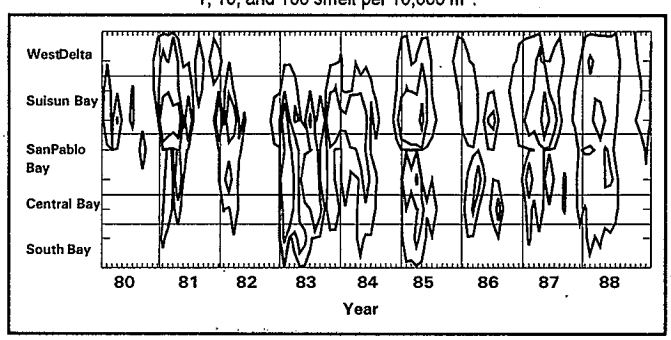
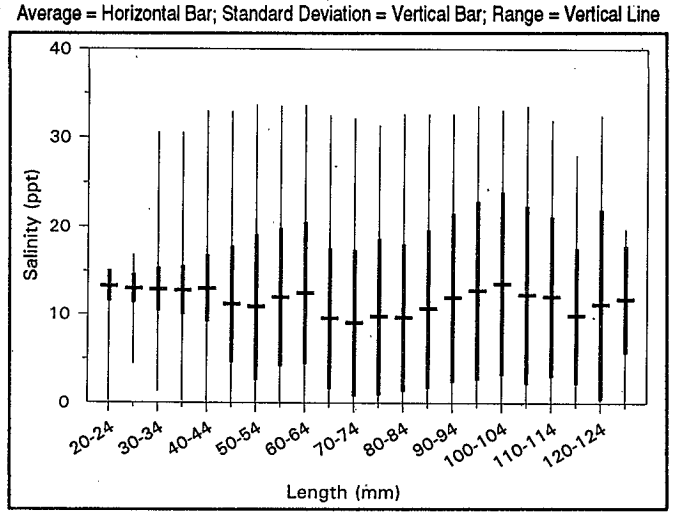


Figure 92
AVERAGE, STANDARD DEVIATION, AND RANGE OF AVERAGE PROFILE SALINITIES AT THE POINT OF CAPTURE FOR LONGFIN SMELT, BY LENGTH INTERVAL
Average = Horizontal Bar; Standard Deviation = Vertical Bar; Range = Vertical Line



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18.0 ppt represented critical nursery habitat and that the volume of this habitat in the bay during March through June (produced by outflow in February through May) influenced how many longfin smelt survived until fall. Nursery habitat volumes were estimated by summing the volume of water associated with all sampling stations having bottom salinities within the 0.1-18.0 ppt range during March through June. These volumes were log-transformed and compared to the resulting striped bass Fall Midwater Trawl Survey annual longfin smelt abundance index (Figure 93).

A significant positive relationship resulted ($r^2 = 0.750$, $p < 0.05$), suggesting that increased habitat volume had a positive effect on longfin smelt abundance. Furthermore, habitat volume was strongly and positively related to outflow ($r^2 = 0.917$, $p < 0.05$, Figure 94).

Figure 93
LONGFIN SMELT ABUNDANCE/HABITAT RELATIONSHIP
Relationship between $\log_{10}$ striped bass fall midwater trawl longfin smelt abundance index and $\log_{10}$ March-June 0.01-18 ppt bottom salinity habitat volume.

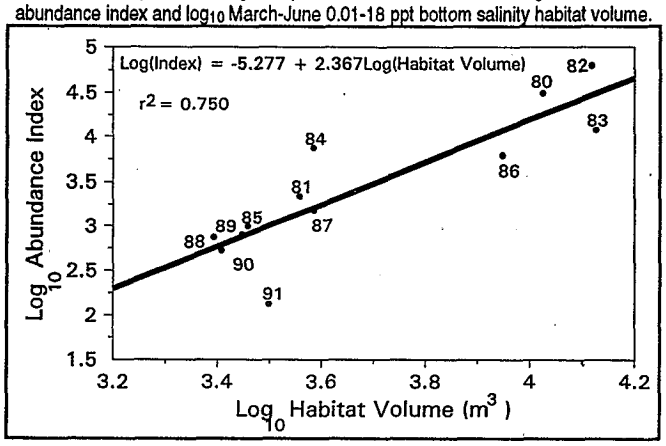
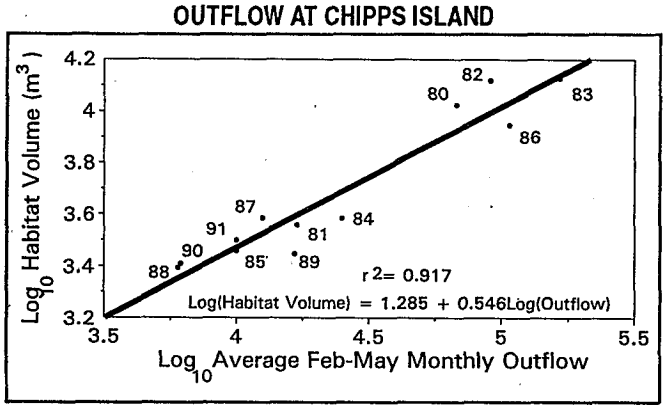


Figure 94
RELATIONSHIP BETWEEN LOG_{10} MARCH-JUNE HABITAT VOLUME AND LOG_{10} FEBRUARY-MAY AVERAGE MONTHLY OUTFLOW AT CHIPPS ISLAND



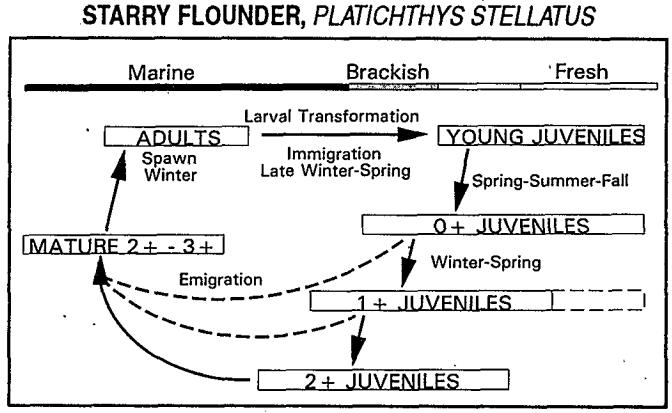
These data support the hypothesis that outflow dispersed longfin smelt larvae and created brackish water nursery habitat. In turn, increased larval dispersal and nursery habitat could have reduced intra-specific competition and allowed the larvae and juveniles access to an increased food source. Through these mechanisms, longfin smelt abundance would be increased with increasing outflow.

No significant relationship has been found between exports at the state and federal pumping facilities and abundance of longfin smelt. Yet, five years of drought have concentrated larvae and juveniles in and near the delta, where they were more susceptible to entrainment or other, as yet undetected, negative effects. Operation of water systems also can negatively affect longfin smelt abundance through diversion to storage upstream during winter and spring. This reduces winter/spring outflow and, hence, can also reduce longfin smelt abundance.

Starry Flounder

The starry flounder life cycle (Figure 95) begins with spawning between November and February in near-shore coastal waters (Orcutt 1950). No ripe female starry flounders were collected in San Francisco Bay during winter surveys in the mid-1980s (B. Spies, pers comm). From 1980 to 1988, relatively few (139) starry flounder larvae were collected relative to the number of young-of-the-year (1,680), suggesting little, if any, spawning in the bay during that period. Eggs and larvae are pelagic and

Figure 95
LIFE CYCLE OF STARRY FLOUNDER, *PLATICHTHYS STELLATUS*



found mostly in the upper water column. Starry flounder larvae are about 2 mm long at hatching and settle to the bottom in about 2 months, at about 7 mm (Policansky and Sieswerda 1979; Policansky 1982).

We hypothesize that the relationship between starry flounder abundance and freshwater outflow (Figure 96) results from an increased area of low-salinity (<22 ppt), shallow-water nursery habitat created before or during the March-through-June immigration period. Larval and transforming juvenile starry flounder (3 to <10 mm TL) were collected in San Francisco Bay primarily from February through May (Figure 97). This period overlaps and follows the historical peak outflow period (*ie* December-March). Starry flounder larvae migrating from coastal marine water may be able to use salinity gradients to locate the bay, as has been suggested for invertebrates (Hughes 1969). Tidal and gravitational currents during this period also are probably important in assisting immigration (Weinstein *et al* 1980; Boehlert and Mundy 1987, 1988).

Small young-of-the-year starry flounder (<70 mm) were collected primarily from water with bottom salinities less than 22 ppt and at depths less than 7 meters (Figure 98). Salinity and depth distributions may actually be lower than presented because the Bay Study does not sample as far into fresh water as young-of-the-year starry flounder have been collected (Radtke 1966), and the data used to generate this distribution were collected from stations deeper than 1.5 meters. These data and the fact that starry flounder become bottom dwelling at a small size (<10 mm) suggest that recently transformed starry flounder migrate to very shallow, fresh or slightly brackish water.

Young-of-the-year starry flounder also seem to select areas of relatively warm water as nursery habitat (Figure 99). Since surface water warms sooner than deeper water, temperature may be one reason starry flounder move into shallow water upon entering the bay.

Outflow affected the geographic distribution of young-of-the-year starry flounder in the bay. Young-of-the-year were distributed from the western delta downstream to at least western San Pablo Bay during high outflow years (1980, 1982, 1983, 1984, 1986;

Figure 97
NUMBER OF 3-10mm LARVAL STARRY FLOUNDER COLLECTED IN THE PLANKTON NET, BY MONTH, 1980-1988

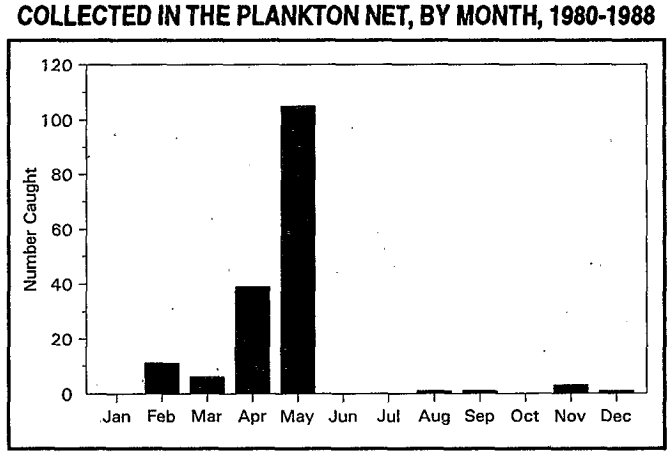


Figure 96
RELATIONSHIP BETWEEN LOG_{10} FEBRUARY-MAY 1+ STARRY FLOUNDER ABUNDANCE AND LOG_{10} MARCH-JUNE AVERAGE MONTHLY OUTFLOW AT CHIPPS ISLAND DURING IMMIGRATION

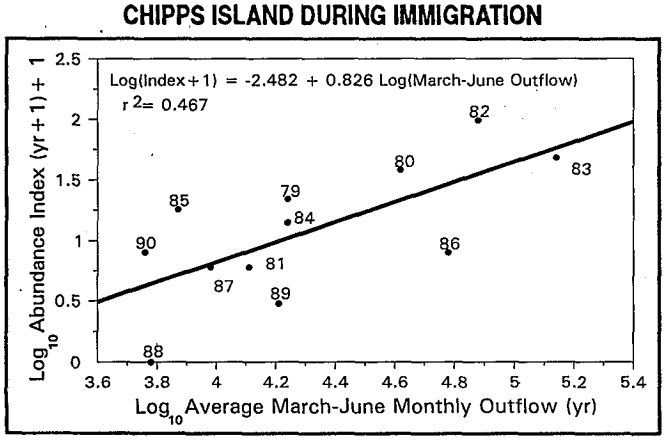


Figure 98
AVERAGE, STANDARD DEVIATION, AND RANGE OF BOTTOM SALINITIES AND DEPTHS AT THE POINT OF CAPTURE FOR STARRY FLOUNDER, BY LENGTH INTERVAL
Average = Horizontal Bar; Standard Deviation = Vertical Bar; Range = Vertical Line

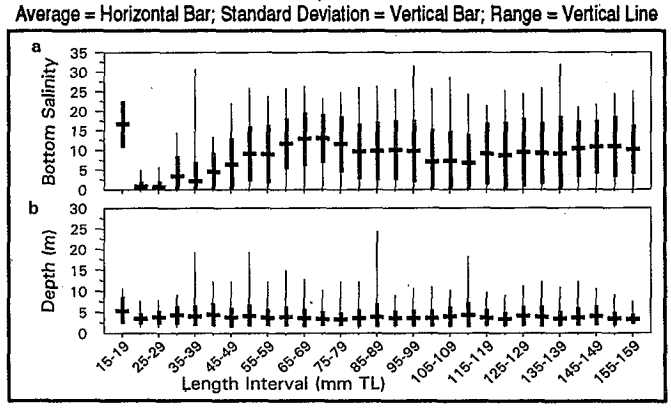


Figure 100a). During low outflow years, except 1985, few young-of-the-year were collected downstream of Suisun Bay. By their second year of life (average total length of 110 mm) most starry flounder moved out of fresh water in the western delta to brackish water in Suisun and San Pablo bays (Figure 100b). They remained in shallow, warm water (Figures 98b and 99). As with young-of-the-year, 1+ starry flounder were collected in higher numbers during high outflow years than during low outflow years. By their third year of life, starry flounder expanded their distribution to include the entire bay (Figure 101). By this age, starry flounder were rare in low salinity areas and many had migrated to the open coast.

Figure 99
AVERAGE, STANDARD DEVIATION, AND RANGE OF BOTTOM TEMPERATURES AT THE POINT OF CAPTURE FOR STARRY FLOUNDER, BY LENGTH INTERVAL
Average = Horizontal Bar; Standard Deviation = Vertical Bar; Range = Vertical Line

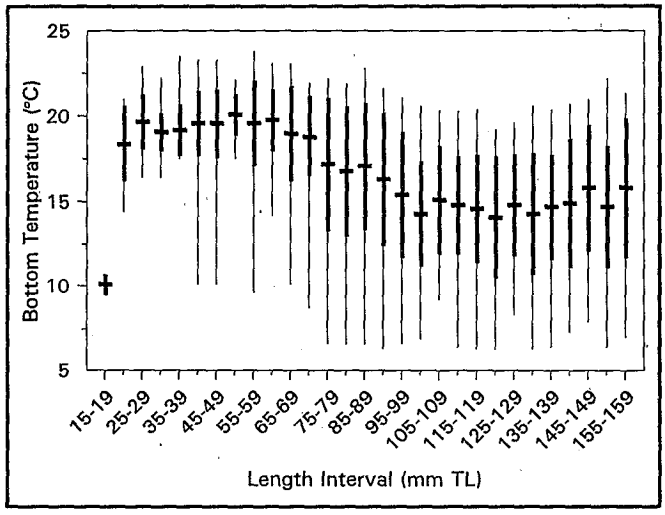
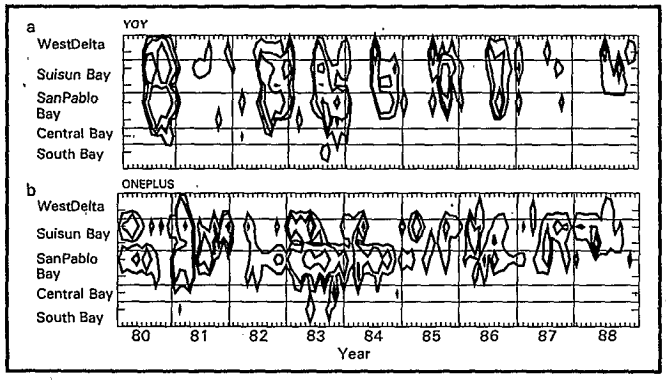


Figure 100
YOUNG-OF-THE-YEAR AND 1+ STARRY FLOUNDER DISTRIBUTION AS AVERAGE DENSITY BY MONTH AND EMBAYMENT, 1980-1988
Contours are at 1, 5, and 25 fish per 10,000 m^2.



Abundance of young-of-the-year starry flounder in the bay appeared to increase with an increased area of shallow, brackish, nursery habitat resulting from increased outflow. Starry flounder were considered recruited to the young-of-the-year population (*ie* most mortality had already occurred) by the time they reached 70 mm. Habitat selected by starry flounder less than 70 mm was used to represent critical nursery habitat. More than 90 percent of the starry flounder <70 mm were collected from water with bottom salinities ≤22 ppt and depths <7 meters.

Annual nursery habitat indices were calculated by summing the area represented by each sampling station with bottom salinities between 0 and 22 ppt and depths less than 7 meters from April through July. Since most starry flounder immigrated to the bay from March through June, outflow during this period was considered critical to creating the proper nursery habitat. Nursery habitat created by March-through-June outflow was determined from bottom salinities measured from April through July. The resulting habitat areas were log transformed and compared to log-transformed February-through-May 1+ starry flounder abundance indices from the subsequent year; a significant positive relationship resulted ($r^2 = 0.646$, $p < 0.01$, Figure 102). Abundance of 1+ starry flounder was used as a surrogate for young-of-the-year abundance because many young-of-the-year were believed to be distributed above the sampling area. This habitat area was positively related to March-through-June average monthly outflow at Chipps Island ($r^2 = 0.917$, $p < 0.001$, Figure 103).

Figure 101
AGE 2+ STARRY FLOUNDER DISTRIBUTION AS AVERAGE DENSITY BY MONTH AND EMBAYMENT, 1980-1988
Contours are at 1, 5, and 25 fish per 10,000 m^2.

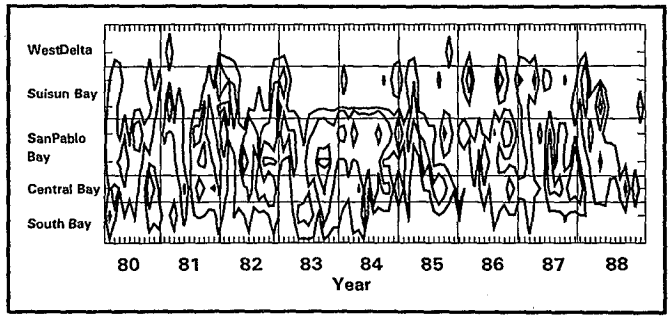


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Figure 102
RELATIONSHIP BETWEEN LOG_{10} FEBRUARY-MAY 1+ STARRY FLOUNDER ABUNDANCE INDEX AND LOG_{10} HABITAT AREA FOR YOUNG-OF-THE-YEAR STARRY FLOUNDER
Habitat area in square meters, depth <7 meters, bottom salinity <22 ppt, April-July.

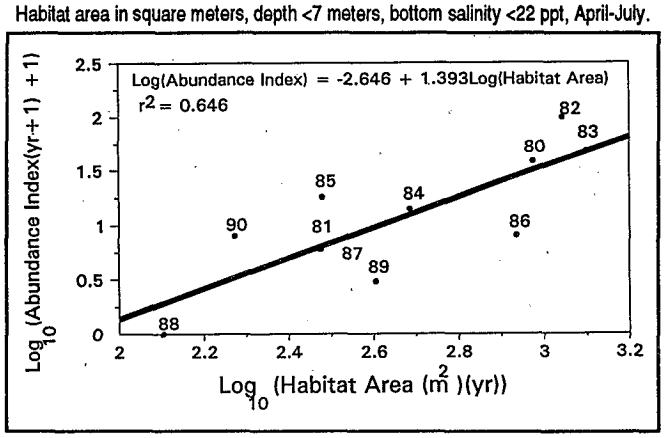
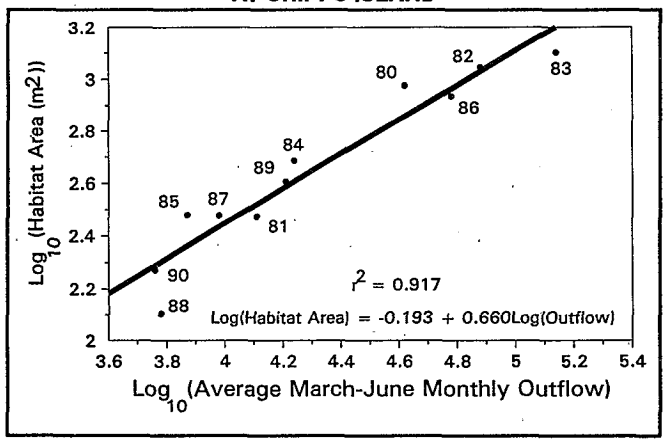


Figure 103
RELATIONSHIP BETWEEN LOG_{10} HABITAT AREA FOR YOUNG-OF-THE-YEAR STARRY FLOUNDER AND LOG_{10} AVERAGE MARCH-JUNE MONTHLY OUTFLOW AT CHIPPS ISLAND



Starry flounder abundance in the bay seems to be strongly associated with outflow. The strong positive relationship between critical habitat and outflow may be partly responsible for the outflow/abundance relationship. As suitable habitat area increases with increasing outflow, young-of-the-year starry flounder could have access to a greater food supply, and intra-specific competition within that habitat should decrease. These factors would improve survival of starry flounder reaching the bay. If outflow facilitated location of and immigration into the bay, as hypothesized, then outflow would also affect the number of small juveniles immigrating into the bay.

Abundance of both longfin smelt and starry flounder in the bay has declined in recent years. Five successive years of drought, plus high storage and exports, have resulted in a decline in longfin smelt abundance through 1991 to an index of 4, the lowest on record (Figure 77). A similar decline was observed for young-of-the-year starry flounder, but slight increases in abundance occurred in 1990 and 1991 (Figure 76). Since most starry flounder $\geq$2 years old live on the open coast, Bay Study data were insufficient to detect trends in adult abundance. However, it is reasonable to believe that after five consecutive years of poor recruitment of young-of-the-year starry flounder to the bay and continued natural and fishing mortality the adult population is in severe decline as well.

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Chapter 9

FISH FACILITIES

Tracy Fish Collection Facility

Charles Liston, Lloyd Hess, and Ron Brockman
U.S. Bureau of Reclamation

The U.S. Bureau of Reclamation is undertaking a major study to improve salvage at its Tracy Fish Collection Facility. As part of this study, USBR is making surveys to determine fish species composition in its canals south of the delta. Emphasis will be on concerns related to native fish, such as splittail, and endangered species, particularly winter Chinook salmon and delta smelt.

Fish predation on young salmon and juveniles of other species is a potential limiting factor for efficient fish salvage. New approaches aimed at removing predators were carried out quarterly in 1991. Studies are being planned, funded, and coordinated by the USBR Denver Office, Environmental Sciences Section, and the Mid-Pacific Region.

New developments include a fish trap that has greatly enhanced predator removal. Predators and other fish are trapped in the secondary louver sump area by using a hinged screen barrier. The secondary louver chamber is then drained, and fish are easily removed by dip net, measured and weighed, and transported to the delta in trucks. A total of 35 predator operations in February, May, September, and December removed 1,925 striped bass weighing a total of 1,459 pounds. Large bass (mean length 14.9 inches; range of 3.3 to 28.4 inches) dominated February samples, and sizes consistently decreased as the year progressed. Few large striped bass were taken in December, when mean length was 5.7 inches and range was 1.5 to 13.9 inches (Table 35). Efforts were adjusted to seven draw-down samples from each collection period for direct seasonal comparisons.

Salvage records are being analyzed to determine effects of predator removal. Early data indicate few large striped bass remain in Tracy Fish Collection Facility, but small bass continue to colonize and attempt to reside in the facility. A regular predator removal program needs to be incorporated into routine operation and maintenance. Experiments are planned to help determine the frequency of the removal process.

Fourteen additional species were taken with the predator removal samples, with striped bass, American shad, white catfish, and threadfin shad making up 98 percent of the total (Table 36). Adult white catfish, which may also be significant predators, were present mainly in May samples.

Table 35
SEASONAL COMPARISON OF STRIPED BASS COLLECTED AT TRACY FISH COLLECTION FACILITY
Total Number, Total Weights, and Total Lengths of Fish Removed from the Secondary Louver Chamber Following Drawdowns During 1991

Collection Periods	Number Collected	Total Weight *(pounds)*	Mean Length *(inches)*	Length Range *(inches)*
February 25-28	508	834.5	14.9	3.5 - 28.4
May 20-23	658	436.8	11.7	4.1 - 25.5
September 17-19	474	110.8	6.2	2.3 - 24.3
December 3 -5	240	25.1	5.7	1.5 - 13.9
Total	1880	1407.2		1.5 - 28.4

Adjusted to 7 drawdown samples from each collection period for direct seasonal comparisons.

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Table 36
TOTAL NUMBERS AND WEIGHTS OF ALL FISH SPECIES REMOVED FROM THE SECONDARY LOUVER CHAMBER FOLLOWING DRAWDOWNS AT TRACY FISH COLLECTION FACILITY, 1991

Species	Number Collected	Percent of Number Collected	Total Weight *(pounds)*	Percent of Total Weight
Striped bass	1,925	26.2	1,459.01	81.0
American shad	3,436	46.8	143.31	8.0
White catfish	531	7.2	105.56	5.9
Threadfin shad	1,313	17.9	50.61	2.9
Carp	2	0.03	25.02	1.4
Chinook salmon	84	1.1	8.84	0.5
Spittail	8	0.1	4.12	0.2
Channel catfish	27	0.4	1.30	0.07
Steelhead	5	0.07	1.26	0.07
Sacramento blackfish	1	0.01	1.25	0.07
Tule perch	5	0.07	0.77	0.04
Gobies	8	0.1	0.24	0.01
Bluegill	1	0.01	0.08	0.005
Golden shiner	1	0.01	0.03	0.002
Sculpin	1	0.01	0.01	0.0006
Totals	7,348	100	1,801.42	100

Sampling dates and numbers are:
February 25-28, 13 samples;
May 20-23, 8 samples;
September 17-19, 7 samples;
December 3-5, 7 samples.
Total number of samples = 35

Predator removal efforts were increased in 1992 and are being carried out monthly. Gill netting, fyke netting, and electrofishing also continue, to document the fish in channels surrounding Tracy Fish Collection Facility. Some 20 species have been identified using these methods. New experiments with a sieve net placed just downstream of the secondary louver chambers have indicated the potential species and numbers of fish that may not be louvered successfully. This tool is being refined in 1992.

A study plan for expanded evaluation of all steps in the fish salvage process, developed by the Denver Office, is under review and is being considered for funding by the Mid-Pacific Region.

Fishery studies at Tracy Fish Collection Facility have been successful due to cooperative efforts of USBR's Regional and Denver offices, staff at the collection facility and at Tracy Pumping Plant, Department of Fish and Game, and U.S. Fish and Wildlife Service. Continuation of this coalition is important for future efforts.

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North Delta Fish Protective Facility Planning

Pat Coulston
Department of Fish and Game

During fall 1991, DWR's Division of Planning began a renewed effort to develop fish protective facilities for a proposed diversion on the Sacramento River. In essence, this is a continuation of the fish protective facility development work associated with the Peripheral Canal, which was terminated in 1982 when the canal was rejected by referendum. The current planning effort is not yet directed at a specific size or type of diversion. Results of this investigation will also apply to development of fish protective facilities for other unscreened diversions in the delta and elsewhere.

A draft work plan for the phased development of a demonstration fish protective facility near the town of Hood was jointly developed by members of the Fish Facilities Technical Committee and Division of Planning in October 1991 (IESP 1991). Phase I of the draft work plan included an expanded fish "treadmill" to continue the stamina testing terminated in 1982 and facilities for evaluating sand bed filters as a possible method for screening fish. Phase II included a 200 cfs demonstration, gravity diversion, and screening facilities to test concepts advanced from Phase I. Phase III would modify the demonstration facility to be a 500 cfs diversion into Snodgrass Slough and include fish passage test facilities. At the end of 1991, planning was underway to hold a workshop in the spring of 1992 with national bioengineering experts to evaluate the approach proposed in the draft work plan and generally advise the Interagency Program on how to approach fish protective facility development in the 1990s.

Fish Losses at the California Aqueduct Intake

Pat Coulston
Department of Fish and Game

The 1986 pumping plant agreement between DWR and DFG calls for annual loss estimates of Chinook salmon, striped bass, and steelhead trout at the California Aqueduct intake near Byron. These estimates are used to determine the annual fishery mitigation obligation of the State Water Project. In addition to estimating these losses, DFG's Bay/Delta Division Fish Facility Unit processes and reports fish salvage data collected at the SWP and CVP delta export facilities.

Annual losses are calculated using a DFG model that uses results of egg and larval sampling in the southern delta, salvage sampling, and assumed efficiency and loss factors. Table 37 contains annual loss estimates for the three species since 1982 and the 5-year running average since 1986.

Clifton Court Forebay Entrainment and Loss Studies

Pat Coulston
Department of Fish and Game

Since the late 1970s there has been an expanding effort to understand the nature and extent of pre-screen fish losses at the SWP export facilities. Initial work indicated a large number of predatory fish (striped bass, channel catfish, largemouth bass, *etc.*) in Clifton Court Forebay and high pre-screen losses. Intensified studies of pre-screen losses in recent years have included the use of hydroacoustic and push-net techniques (IESP 1991) to examine the flux of entrained fish across Clifton Court Forebay. A substantial program of experiments planned for spring 1991 was canceled because of drought-related reductions in SWP export pumping. At the end of 1991, an intense interest had developed in gaining specific knowledge about pre-screen loss rates of winter-run Chinook salmon smolts, and studies were being planned for 1992.

Clifton Court Forebay Predator Population and Control Studies

Pat Coulston
Department of Fish and Game

During 1991 initial steps were taken toward development and evaluation of a predator control program for Clifton Court Forebay. Two predator-related programs were

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initiated. In the spring, a program of routine catch-per-unit-effort (CPUE) sampling began, with the purpose of monitoring predatory fish abundance in the forebay. In the fall, experiments were made with various sampling gear to evaluate potential effectiveness in a predator removal program.

The purpose of the CPUE program is to establish continuous, long-term population indices for predatory fish species in Clifton Court Forebay that can be used to evaluate the effectiveness of a predator control program. CPUE sampling of predatory fish began in March 1991. For sampling purposes, the forebay was divided into six

Table 37
ESTIMATED ANNUAL AND 5-YEAR RUNNING AVERAGE LOSSES OF STRIPED BASS, CHINOOK SALMON, AND STEELHEAD TROUT AT THE CALIFORNIA AQUEDUCT INTAKE

ANNUAL LOSSES

	Striped Bass (Yearling Equivalent)		Chinook Salmon (Smolt Equivalent)		Steelhead (Yearling Equivalent)	
Year	<20 mm	>20 mm	YOY	Yearling	YOY	Yearling
1982		244,347	230,043	3,193,747	0	73,478
1983		37,680	68,411	725,078	0	2,945
1984		873,853	290,696	947,503	0	1,713
1985	65,177	370,976	472,512	489,713	0	15,621
1986	35,315	944,061	1,147,249	2,300,866	0	15,663
1987	41,726	954,958	528,544	713,791	747	21,266
1988	59,625	874,055	409,103	747,953	0	25,080
1989	56,306	579,003	373,717	246,641	253	32,571
1990	7,717	401,353	90,098	188,228	0	19,187
1991	15,117	192,765	122,127	128,466	0	38,430

5-YEAR RUNNING AVERAGE

	Striped Bass (Yearling Equivalent)		Chinook Salmon (Smolt Equivalent)		Steelhead (Yearling Equivalent)	
5- Year Period	<20 mm	>20 mm	YOY	Yearling	YOY	Yearling
1982-1986						
Mean	50,246	494,183	441,782	1,531,381	0	21,884
Total Loss		544,429		1,973,164		21,884
1983-1987						
Mean	47,406	636,306	501,482	1,035,390	149	11,442
Total Loss		683,712		1,536,872		11,591
1984-1988						
Mean	50,461	803,581	569,621	1,039,965	149	15,869
Total Loss		854,041		1,609,586		16,018
1985-1989						
Mean	51,630	744,611	586,225	899,793	200	22,040
Total Loss		796,240		1,486,018		22,240
1986-1990						
Mean	40,138	750,686	509,742	839,496	200	22,753
Total Loss		790,824		1,349,238		22,953
1987-1991						
Mean	36,098	600,427	304,718	405,016	200	27,307
Total Loss		636,525		709,733		27,507

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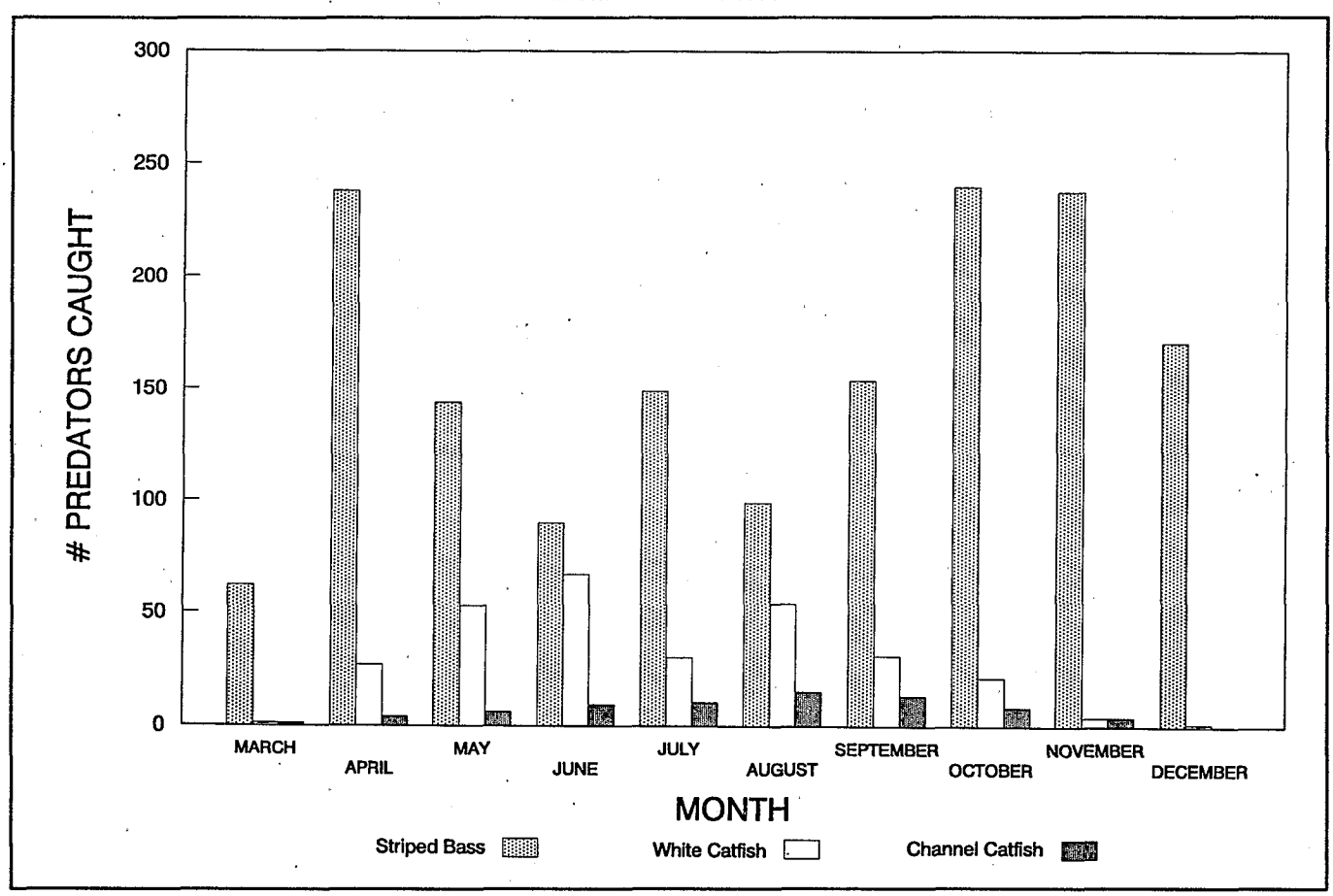
sections. Sampling was generally conducted one day per week during daylight, with all six sections sampled in random order each day. Two techniques were used to capture fish: variable-mesh gill-netting and standardized hook-and-line sampling.

During the first nine months, 1,952 predatory fish were captured. Striped bass, white catfish, and channel catfish were caught most frequently and comprised 81.2, 14.8, and 3.6 percent of the catch, respectively. Striped bass were caught with both sampling techniques; catfish were primarily caught by the gill-nets. Figure 104 shows temporal distribution of catches of these three species in 1991.

With only 9 months of data, it is not yet possible to assess to what degree fluctuations in CPUE are related to seasonal fluctuations in gear efficiency or changes in predator abundance. Calibration and standardization of the CPUE data will be accomplished over time as the data are related to estimates of actual population size and Clifton Court Forebay conditions during each season.

During fall 1991, several types of gear were used experimentally to assess their potential effectiveness for removing predators. A 2,000-foot-long seine, a 600-foot-long Kodiak-type seine, hook-and-line, and gill-nets were all generally effective. Gill-netting appeared least effective because of the mortality it causes. Hook-and-line is relatively efficient for striped bass, but tends to stress larger fish and capture few catfish. The seines appear to be most efficient for all species, and pilot removal efforts planned for spring 1992 will probably emphasize the use of the seines.

Figure 104
RESULTS OF PREDATOR MONITORING AT CLIFTON COURT FOREBAY, 1991
Monthly catch of striped bass, white catfish, and channel catfish during hook-and-line and gill-net predatory fish sampling, March - December 1991.



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Of interest to many in fall 1991 was the capture in Clifton Court Forebay of a 49-pound alligator gar *(Lepisosteus spatula)*, the first recorded from California waters. The gar was taken with the 2,000-foot seine.

Skinner Fish Facility Salvage and Hauling Operations

Pat Coulston
Department of Fish and Game

In 1991, the Department of Fish and Game began to assume fish salvage, hauling, and salvage sampling at John E. Skinner Fish Protective Facility. The first of six Fish and Wildlife Assistants who will work at the facility was hired in July. Hiring and training efforts are continuing. DFG is scheduled to completely assume operations by July 1, 1992.

Monitoring at Suisun Marsh Salinity Control Structure

Pat Coulston
Department of Fish and Game

The Suisun Marsh Salinity Control Structure was constructed to improve water quality in Montezuma Slough and Suisun Marsh during periods of low to moderate delta outflow. There is concern that the structure may create predation problems for juvenile fish (*eg,* Chinook salmon and striped bass) and may delay migration of adult anadromous fish. Pre-project sampling was conducted in 1987 and 1988. The sampling in 1991 is the third year of post-project sampling.

Presence of predators near the structure is determined by fishing variable-mesh gill-nets (set and drift nets) upstream and downstream of the structure during daylight. Before 1991, sampling was conducted on five days during May and June. In 1991, effort was increased to weekly sampling during April, May, and June.

In sampling before 1991, catch-per-unit-effort of predatory fish (striped bass and Sacramento squawfish) increased following placement of Montezuma Slough control structure, primarily due to an increase in striped bass CPUE (Coulston 1992). Squawfish density near the structure has apparently declined from pre-project levels. In 1991, overall predatory fish CPUE continued to be greater than pre-project levels (Table 38).

Examination of the stomach contents of 156 striped bass and 30 squawfish in 1991 indicates three-spine stickleback was the principal food for striped bass and chameleon goby was the principal food for Sacramento squawfish (Coulston 1992). Juvenile salmon were found infrequently in the stomachs of striped bass and not at all in the stomachs of squawfish. Delta smelt and juvenile striped bass were not identified in the stomachs of either species.

Observations of adult Chinook salmon captured in and striking gill-nets deployed during predatory fish sampling suggest the Montezuma Slough control structure may delay upstream migration of salmon while it is operating. During the 1988 through 1991, adult salmon have been seen near the control structure only when the radial gates have been lifted and the stop-logs removed, allowing natural flow (Coulston 1992). Although 1992 is the last planned year of predatory fish sampling at Montezuma Slough control structure, more detailed and specific studies of adult salmon migration may be proposed by the Fish Facilities Technical Committee.

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Table 38
COMPARISON OF COMBINED GILL-NET CATCHES OF STRIPED BASS AND SQUAWFISH NEAR THE MONTEZUMA SLOUGH SALINITY CONTROL STRUCTURE, 1987-1991

SPECIES COMBINED

Year	Catch	Mean Fork Length (mm)	Standard Deviation	Range (mm)	Effort (hours)	Catch per Unit Effort
1987	25	385	83.07	248-556	18	1.39
1988	134	365	85.38	238-630	94	1.41
1989	42	340	64.97	243-492	26.85	1.56
1990	85	354	87.90	224-793	36.7	2.32
1991	184	358	109.80	227-985	97.08	1.90

STRIPED BASS

Year	Catch	Mean Fork Length (mm)	Standard Deviation	Range (mm)	Effort (hours)	Catch per Unit Effort
1987	8	325	68.51	248-433	18	0.44
1988	57	345	103.20	238-630	94	0.61
1989	27	323	62.70	243-492	26.85	1.01
1990	72	340	86.40	224-793	36.7	1.96
1991	153	350	114.70	227-985	97.8	1.58

SQUAWFISH

Year	Catch	Mean Fork Length (mm)	Standard Deviation	Range (mm)	Effort (hours)	Catch per Unit Effort
1987	17	416	68.12	332-556	18	0.94
1988	77	380	66.19	273-525	94	0.82
1989	15	372	58.76	298-480	26.85	0.56
1990	13	412	74.10	296-519	36.7	0.35
1991	31	401	67.50	305-541	97.08	0.32

North Bay Aqueduct Fish Monitoring

Pat Coulston
Department of Fish and Game

The North Bay Aqueduct pumping plant in Barker Slough was completed in early 1988, and diversions began in June of that year. A fishery resource monitoring program was established to:

- Assess project impacts on the fish community in Barker Slough.
- Determine whether juvenile fishes are being drawn into the slough, where they would be subject to entrainment.

Fish community data collected in 1991 is consistent with that reported in past years. The most significant changes have been a reduction in relative abundance of brown bullhead and an increase in relative abundance of white catfish and tule perch, suggesting slough habitat may be changing to a more riverine condition.

The most important new information regarding effects of the North Bay Aqueduct is a report by Bennett (1992) on changes in larval fish occurrence in Barker and Lindsey sloughs. Results of spring ichthyoplankton sampling suggest abundance of larval striped bass in the sloughs has increased significantly since the project began operating. This suggests the aqueduct is drawing water into the sloughs from the Sacramento River, where the larval bass originate. Sampling indicates delta smelt and longfin smelt are present in the sloughs but are less abundant than striped bass. Future ichthyoplankton monitoring will begin early in the year to cover the likely period of longfin smelt peak abundance.

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Chapter 10

HYDRODYNAMICS

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Hydrodynamics became a separate element and technical committee of the Interagency Program during 1990, and the scope of the program was expanded to include the delta. The new committee was charged with reorganizing the hydrodynamics program and developing a 3-year workplan for 1991 through 1993.

To guide development of the workplan, the hydrodynamics committee asked each of the other Interagency Program technical committees to submit lists of unanswered technical questions about the bay, the null zone, and the delta that were important to studies by their committees. The hydrodynamics committee combined and ranked these questions in order of priority, with consideration given to whether the questions could be answered within a reasonable time and with available resources. Tables 39, 40, and 41 present these questions in order of rank, with tied rankings indicating an equal priority. The horizontal line on each table is a somewhat arbitrary divide between those questions (above the line) the committee felt could be answered in the foreseeable future (less than 5 years) and those (below the line) that probably could not.

Tasks under the new 3-year hydrodynamics workplan include continued data collection and multidimensional modeling in the bay and also involves new collection of flow data in the delta for use by the DWR Delta Modeling Section in developing a new public domain delta model by 1993. This new model will be available for the study team to do applications for the Interagency Program.

This report summarizes four tasks started during 1991. First, several 3-dimensional models for use on the bay are evaluated, and the application of one code to San Pablo Bay is reviewed. Second, a hydrographic dataset of Carquinez Strait appropriate for evaluating 3-dimensional models is described. Third, some analyses of sea level and salinity time series are reported. Finally, the development of a vessel-mounted, flow-measurement system that uses an acoustic Doppler current profiler is summarized.

Table 39
HYDRODYNAMIC QUESTIONS FOR SAN FRANCISCO BAY RANKED BY THE INTERAGENCY PROGRAM HYDRODYNAMICS COMMITTEE

Rank	San Francisco Bay Questions
1	What is the magnitude of the ocean-bay exchange for various freshwater inflows I and offshore current regimes?
2	What are the exchange rates between the channels and shallows in the embayments, and how are these rates affected by changes in freshwater inflow?
2	What is the relationship between delta outflow and salinity in various parts of the bay?
4	What is the relationship between gravitational circulation and delta outflow?
5	What effect does deepening the channel in North Bay by 10 feet have on gravitational circulation and salinity intrusion?
6	Identify the regions, surface areas, and volumes in specified salinity and temperature ranges for various delta discharges. In particular, what are the salinity differences between the shallows in San Pablo Bay north and south of the channel?
6	Runoff events of what magnitude/duration are necessary to produce how much stratification/exchange in South Bay?
6	How long do uncontrolled outflows take to arrive at various sites in the bay and how long does the bay salinity take to recover from these events? How large and lengthy must an outflow event be to alter normal current patterns significantly?
9	What would the spatial distributions of the non-motile organisms become for runoff events of various magnitudes/durations? What would be the horizontal salinity variations surrounding the areas of greatest accumulation? How does wind affect these results?
10	How long will it take a non-motile organism and an organism that moves only during flood tides to move along the bottom from the Golden Gate to the null zone for runoff events of various magnitudes and durations?
10	How far would the non-motile organisms move in a tidal cycle, week, or month for runoff events of various magnitudes and durations?
10	For selection of dredge disposal sites, what are the major areas of deposition and erosion in the bay?
13	What magnitude/duration of delta discharge is necessary to reduce the salinity of Suisun Bay to 5 ppt (San Pablo Bay to 10 ppt) and how fast does this occur?

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Table 40
HYDRODYNAMIC QUESTIONS FOR THE NULL ZONE RANKED BY THE INTERAGENCY PROGRAM HYDRODYNAMICS COMMITTEE

Rank	Null Zone Questions
1	What is the location of the null zone for a range of delta discharges? Assuming that placement of a high-turbidity zone in a given area is desirable, what delta outflows are needed to create this zone for a given range of physical forcings?
2	How fast does the null zone move seaward in response to a runoff event and how fast does it return landward after an event?
3	What are the residence times of dissolved and particle-bound contaminants in the null zone, and how do these times change with freshwater inflow?
3	Is there a way to estimate bottom salinities at sites where only surface salinities have been collected?

Evaluation of 3-Dimensional Models for San Francisco Bay

Accurate, 3-dimensional simulation of circulation in San Francisco Bay is the culmination of several major efforts. In addition to development and use of databases of bay bathymetry for model grids, and hydrographic data for model validation, an appropriate model algorithm must be selected and tested, and appropriate boundary conditions must be selected for model applications. Described below are results of an evaluation of three 3-dimensional models.

Criteria for selecting a 3-dimensional model for San Francisco Bay are accuracy in reproducing the physics of the bay and efficiency of the computational method. Efficiency is necessary because long simulations (months) are required to answer biological questions and because hundreds of thousands of computation points are needed to represent adequately the bay's complex geometry. Accuracy is particularly important because predictions of long-term mixing and transport depend primarily on net (tidally averaged) circulation, a small fraction of tidal circulation.

With these criteria in mind, the features of three 3-dimensional models available to the hydrodynamics program are reviewed along with results of applying one of the models to San Pablo Bay.

Table 41
HYDRODYNAMIC QUESTIONS FOR THE SACRAMENTO-SAN JOAQUIN DELTA RANKED BY THE INTERAGENCY PROGRAM HYDRODYNAMICS COMMITTEE

Rank	Delta Questions
1	For salmon studies, the greatest need is for knowledge of flow magnitudes and directions and residence times in delta channels.
2	For striped bass studies, the most important question is how much delta outflow is required to move larval fish from the delta to Suisun Bay and keep them there.
3	Where are striped bass eggs and larvae transported within the delta? How can project operations be changed to transport them to areas of high food abundance, recognizing that such areas may no longer be in the zone of high turbidity?
4	If zooplankton stocks remain low in Suisun Bay because of *Potamocorbula* and other benthic bivalves, how can entrainment losses of larvae that remain in the delta be minimized?
4	If striped bass eggs are transported through the delta in pulses, how might the flow be manipulated for short periods to move pulses into Suisun Bay?
6	Does export pumping affect the flow at the cross-channel gates?
6	Have operational variations of Clifton Court Forebay affected larval entrainment?
8	What is the degree of exposure of striped bass eggs and larvae to rice pesticides that enter the Sacramento River from the Colusa Drain?
9	What is the real variation of delta outflow over a spring/neap cycle, and how is it affected by atmospheric pressure?
9	During export pumping what is the salinity difference in the western delta between open and closed cross-channel gates?
9	What are the relative contributions of flood control, channelization, and water project storage and diversions on delta outflow?
12	A way of predicting the routes and travel times through the delta of water from different sources is needed for development of sampling schemes of dissolved and particle-bound pesticides and for analyses of pesticides data.
13	Is there a way to estimate bottom salinities at sites where only surface salinities have been collected?
14	Given that dredge materials are used to reinforce delta levees, which levees have the potential for releasing toxic materials to parcels of water that reach municipal or industrial water intakes?

EHSM3D Model

The 3-dimensional model that has been applied so far by the hydrodynamics program is referred to as EHSM3D *(Estuarine Hydrodynamic Software Model 3-D)*. The model was obtained in 1986 under contract between USGS and Aeronautical Research Associates of Princeton *(ARAP)* and is described in a final contract report by Sheng and others (1986). A report describing an

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earlier version of the model was prepared by Sheng and others (1983) with funding from USACE. Under the terms of the USGS contract, ARAP added a salt transport equation to the model, prepared documentation for the computer program, offered a workshop on the model, and demonstrated validity of the model with an application to Suisun Bay. During the contract with ARAP, and afterwards, the modeling team performed testing and some recoding of the 3-dimensional model for eventual application to San Pablo Bay. The model was delivered without graphics routines, so a major initial task was to write graphics programs to examine model output.

The EHSM3D model is a fully nonlinear 3-dimensional model that solves the equations of continuity, momentum, temperature, and concentration of salt using the finite-difference method and an external/internal mode-splitting technique. Mode-splitting simply refers to a technique whereby, in the model formulation, the governing equations are split into a system of 2-dimensional vertically averaged equations (external mode) and a system of 3-dimensional equations (internal mode) that are solved independently.

Because the EHSM3D model has been under continuing development during recent years, several subsequent versions of the model are now in use among federal agencies. The version of the model available for this study allows only rectilinear horizontal grids and retains the original boundary-fitted (sigma-coordinate) vertical grid. A two-time-level finite-difference scheme is used with a choice of differencing methods for the nonlinear advection terms. The turbulence closure is a relatively simple approach that is based on the eddy viscosity/diffusivity concept.

The model has been applied to San Pablo Bay using a 0.5-kilometer-square grid with 10 vertical layers and a 2-minute time step. The model has been calibrated for a low inflow period during October 1986 using measured velocity and salinity profiles and time-series data from eight current meters and three salinity stations. The agreement between measured and simulated data is generally very good. Most encouraging is that the model has been able to reproduce closely the vertical stratifications in the salinity field that range between 2 and 8 parts per thousand during a typical tidal cycle. The success in modeling the salinity has to do with the choice of turbulence model, but it also depends heavily on the proper specification of an initial salinity distribution. Rather than attempt simulations of several months to achieve a near-dynamic steady state independent of the initial salinity distribution, the initial salinities were specified from data.

A procedure was developed that uses any number of measured salinity profiles taken around the bay and performs interpolations along horizontal planes between profiles to fill in node points. Points along the centerline of the channel are interpolated first, and off-channel points in a second step. As long as the number and spacing of measured profiles are adequate, the initial condition can be estimated adequately, and simulations can be made without needing considerable "spin-up" time.

To study gravitational circulation, the model has been used to simulate a spring/neap cycle for conditions when longitudinal salinity gradients across the 20 kilometers of San Pablo Bay were about 10 ppt. Tidally-varying velocity profiles at 10-minute intervals were saved at locations along six cross sections of the bay (Figure 105) and arranged into time series corresponding to individual sigma planes. The time series were then low-pass filtered to reveal the nontidal velocities and interpolated onto horizontal planes. The 3-dimensional velocities were also depth-integrated to obtain vertically averaged velocities. The velocities were then rotated into the plane of each cross section, and the normal components were plotted.

Results show a pronounced gravitational circulation that modulates with the spring/neap variation in tidal current speed. Figure 106 shows the nontidal velocity distributions for the neap tides at each of the

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six cross sections. Strong up-estuary density currents are observed at cross sections 1, 2, and 3 because of the deep water and large cross-sectional areas at those locations. The strongest density currents (>35 cm/s) are found at cross section 1 near center channel. At cross sections 4, 5, and 6, the bottom currents are close to zero, or down-estuary. These cross sections are considerably more shallow than cross sections 1 and 2 and have smaller cross-sectional areas than cross sections 1, 2, and 3.

The consequence of the smaller areas is that river currents themselves, defined by dividing inflow by cross-sectional area, are significant enough to counteract the driving force of the density gradient and direct the bottom currents downstream. It is this interplay between river and density currents that causes a null zone to form. For the conditions shown in Figure 106 of about 900 m^3/s, a null zone has formed just downstream of cross section 4 (Pinole Shoals). Field measurements have verified this location as a place of frequent turbidity maxima.

A comparison of spring and neap tide distributions of nontidal currents is shown in Figure 107 for cross section 1. It is evident that the stronger upstream density currents occur on the neap tide when vertical mixing is a minimum. This phenomenon has previously been observed and discussed by Walters and others (1985) and has more recently been verified from the high resolution velocity profiles collected in Carquinez Strait with an acoustic Doppler current profiler (Burau and others, 1992). These data lend credibility to results from the model, although they do not constitute a proper validation because the data were not collected at the same time as the model simulations.

ECOM-si Model

ECOM-si is the product of a 3-year contract with Alan F. Blumberg of HydroQual Inc. that ended in 1991. Support for the contract came from USGS and DWR, and it was initiated to obtain a new 3-dimensional model to replace EHSM3D. ECOM is a 3-dimensional estuarine, coastal, and ocean model developed by Alan F. Blumberg and George L. Mellor beginning about 1975. The model has been used for a variety of hydrodynamic problems and is generally well-respected in the modeling community.

During the 3-year contract, the original ECOM model (Blumberg and Mellor 1987) was updated, with many significant advances for use in shallow estuaries and bays. So many changes were introduced that the new code became known as ECOM-si. The change in the model name reflected the most significant change in the code, which was to incorporate a new semi-implicit solution method. In addition to delivering the model code, documentation for the model was prepared and three workshops were conducted.

Features of ECOM-si that are particularly attractive are:

- It uses a semi-implicit solution method that permits time steps that are many times greater than the Courant limitation.
- It has a sophisticated turbulence closure sub-model, which may provide improved simulations of the vertical distributions of velocity and salinity in San Francisco Bay.
- It is efficiently programmed and is vectorized for fast execution on super computers.
- The model grid does not have to be rectangular (a curvilinear orthogonal grid is possible).
- A capability for flooding and drying of tidal flat regions is incorporated.
- The original ECOM model has been extensively tested and much of the coding from ECOM-si came from ECOM. (However, the new coding in ECOM-si has not been as thoroughly tested as ECOM.)

All the features listed above are capabilities in ECOM-si not found in EHSM3D. An important point, however, is that both models use a depth-following vertical coordinate (called the sigma-coordinate) used for coping with vertical movement of free surface.

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Figure 105
LOCATIONS OF SIX CROSS SECTIONS IN SAN PABLO BAY AND BATHYMETRIC PROFILES OF THESE SECTIONS

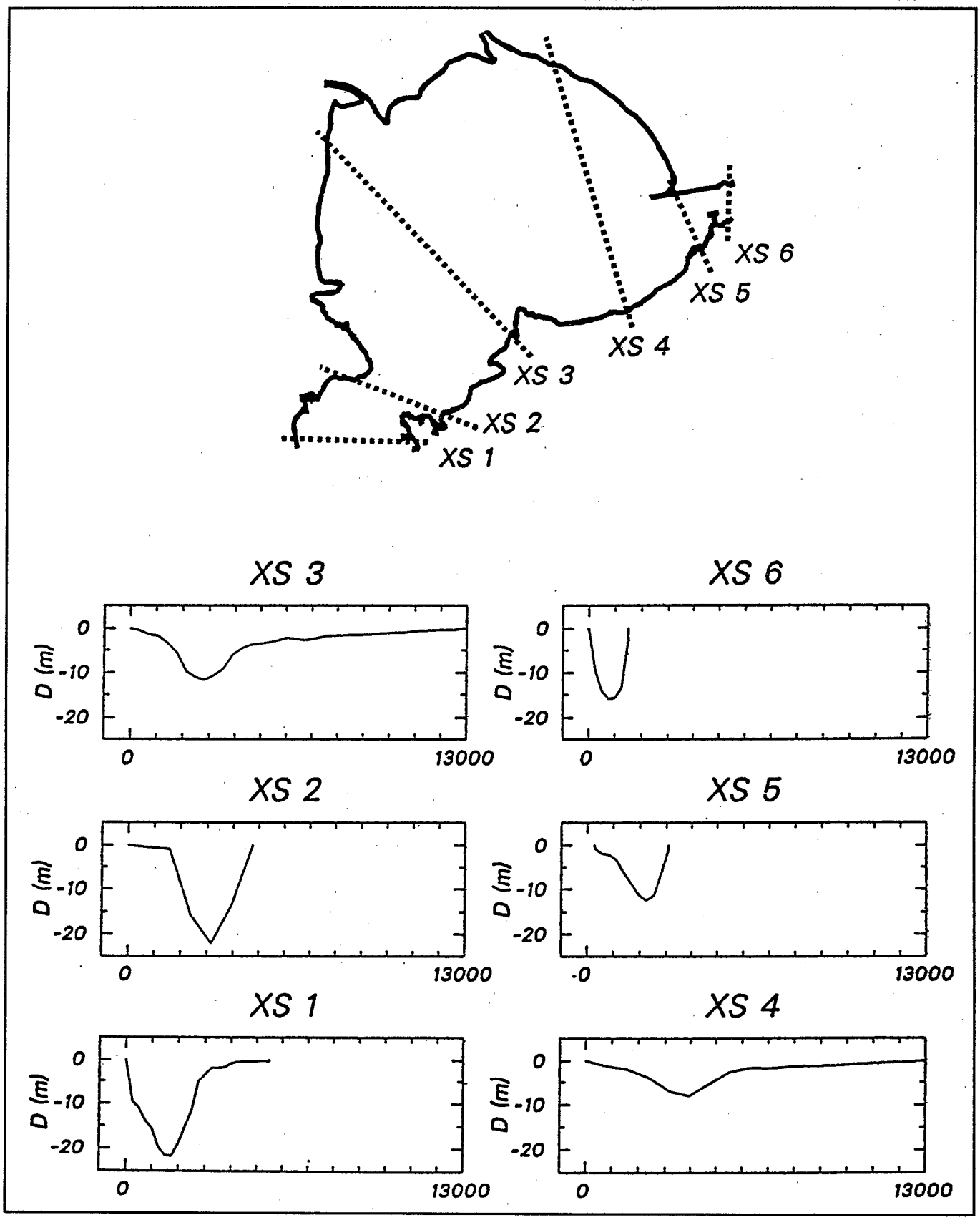

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Figure 106
NON-TIDAL VELOCITY DISTRIBUTIONS AT SIX CROSS SECTIONS IN SAN PABLO BAY FOR A NEAP TIDE CALCULATED USING A 3-DIMENSIONAL MODEL (EHSM3D)

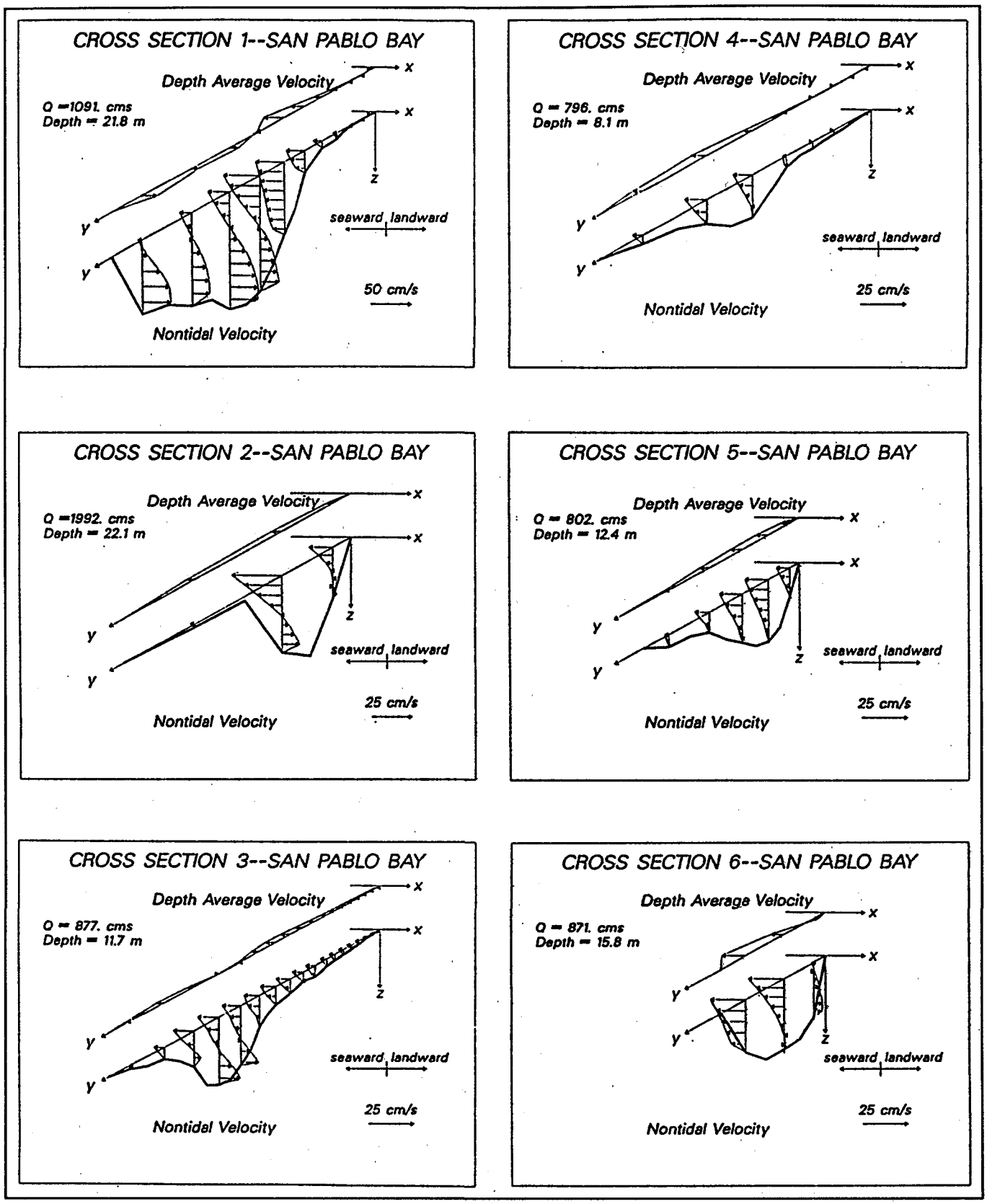

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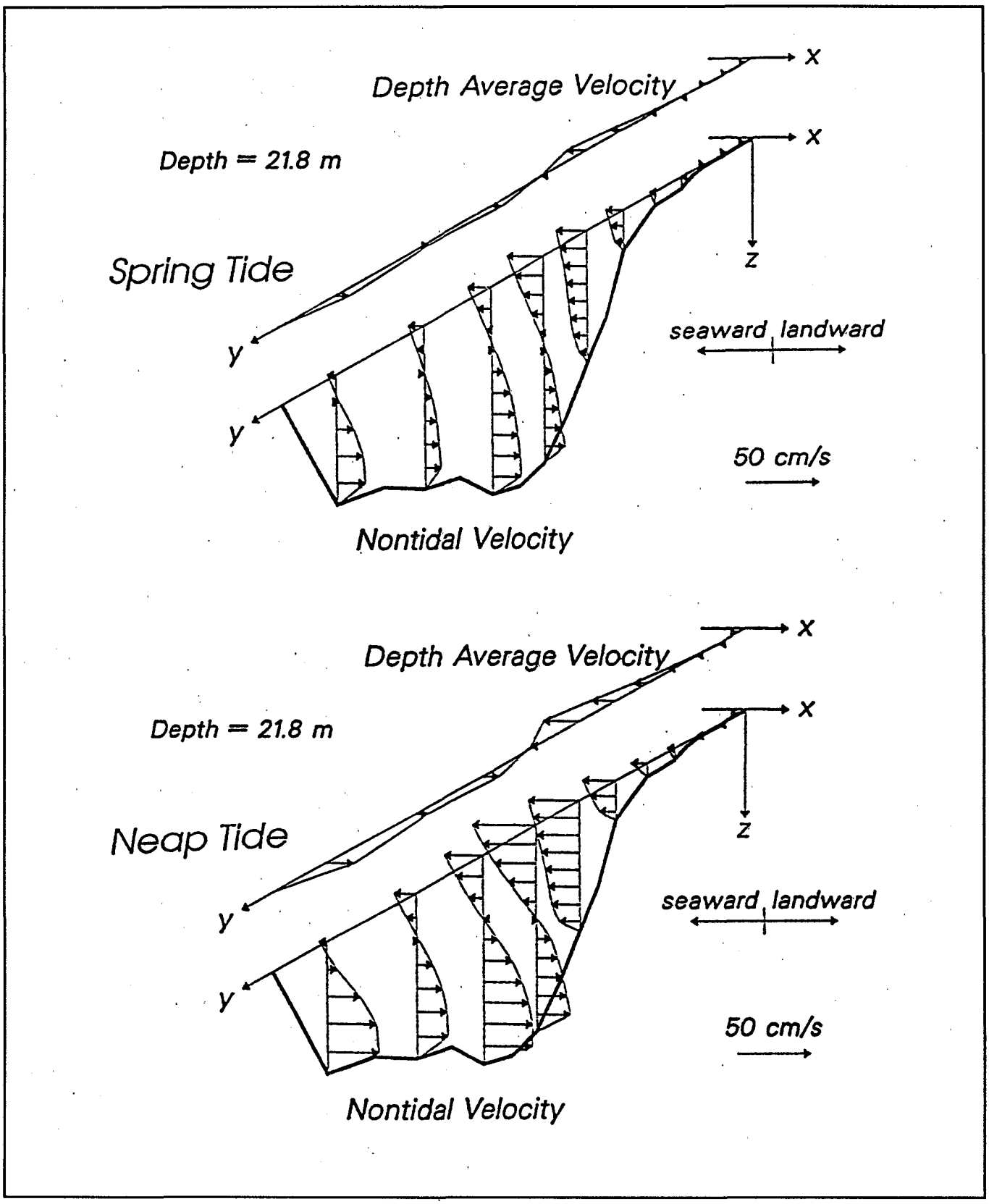
Figure 107
COMPARISON OF NON-TIDAL VELOCITY DISTRIBUTIONS DURING SPRING AND NEAP TIDES AT CROSS SECTION 1 IN SAN PABLO BAY



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TRIM3D Model

TRIM3D is a new 3-dimensional model under development by Vincenzo Casulli of Italy in collaboration with USGS in Menlo Park. An early version of the model (without a salt transport equation or density-gradient forcing) has already been set up on San Francisco Bay, and a number of simulations have been made (Casulli and Cheng 1991). The model is mentioned here because it is being evaluated for use in future 3-dimensional modeling applications on the bay, along with EHSM3D and ECOM-si.

TRIM3D is a semi-implicit, finite-difference model, similar to ECOM-si except for some differences in the manner in which the semi-implicit solution strategy is implemented. TRIM3D uses a slightly more "elegant" numerical approach that should result in computational savings.

The most significant difference between TRIM3D and the other two models is that it does not implement the sigma-coordinate transformation of the vertical coordinate. It is formulated using a "level-plane" approach in which the dependent variables are defined in horizontal layers that are fixed in space and do not follow the motion of the water surface. The level-plane approach saves many grid points when modeling an estuary like San Francisco Bay, because only one or a few layers are needed to represent shallow areas. A sigma-coordinate model uses the same number of layers regardless of the depth of water. In San Francisco Bay this leads to "over-resolution" in the shallow portions of the bay that are largely well-mixed and that can be represented adequately by very few layers.

Experience so far with TRIM3D has shown it is extremely efficient. It has a wetting and drying capability and has been vectorized for super computer applications. A shortcoming of the model is that it does not have a sophisticated turbulence sub model. It is also limited to a rectangular mesh in the horizontal plane. Since the model is new, it has not undergone extensive testing.

Discussion

As noted above, EHSM3D has been the 3-dimensional model used on the hydrodynamic study so far. It will not be used, however, for the planned whole-bay application because it is too slow. Also, the model is difficult to apply because of coding errors in the computer program and difficulties in obtaining stable solutions with the numerical solution scheme. Because the model is poorly documented, it has also been difficult to understand and modify the coding.

To replace EHSM3D, both ECOM-si and TRIM3D are being considered. There are some advantages and disadvantages to each of these models. The primary advantage of ECOM-si is that it has evolved from the well-known and respected ECOM model, which has been used and tested on many applications and numerical experiments. It is well established that ECOM can reproduce the important hydrodynamic processes in a variety of estuarine types. Although ECOM-si has many new lines of coding, it has been shown to agree with ECOM solutions on a number of test problems. ECOM-si also has a very advanced turbulence submodel that may eventually prove useful for applications to San Francisco Bay in trying to model vertical distributions of velocity and salinity. Availability of a curvilinear grid with ECOM-si is also a potentially useful feature.

As part of the HydroQual contract, ECOM-si was set-up on San Pablo Bay using the same grid and input data as EHSM3D. A number of simulations were made with both models to compare computer costs. Results showed ECOM-si is 2 to 4 times faster than EHSM 3D when time steps are identical with both models. Since ECOM-si should, in general, be capable of running larger time steps than EHSM3D (by a factor of perhaps 5), we can expect a speed-up with ECOM-si of from 10 to 20 times over EHSM3D. On a super computer the speed-up is even more dramatic because of the vectorized coding in ECOM-si.

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A disadvantage of ECOM-si is that it is a code, like EHSM3D, developed by someone not a member of the modeling team. There is always a steep learning curve for using an unfamiliar code. In addition, the computer code itself might be difficult to modify. Experience has shown efficiency of applying a model improves dramatically when a code has been developed by the model's user. Although TRIM3D was not developed by the modeling team, significant portions of the code have been developed by USGS in Menlo Park. Thus, information on the code can be communicated efficiently to the modeling team.

Probably the greatest advantage of TRIM-3D, is that it is the most computationally efficient of the three models. Not only is it programmed efficiently using the latest numerical techniques, but it is also formulated with a "level-plane" concept of layers that is most appropriate for use on San Francisco Bay. By using a level-plane grid instead of the more common sigma-coordinate grid, it is possible to reduce by as much as 75 percent the number of 3-dimensional grid points required in the model. Overall, we estimate that TRIM3D will be about 5 times faster than ECOM-si and from 50 to 100 times faster than EHSM3D.

The most significant disadvantage of TRIM-3D is that it is not completed. Although a version of the model is now working, it does not have a salt transport equation or a baroclinic term. These will be needed before realistic simulations of San Francisco Bay can begin. Plans call for TRIM3D to be completed by fall 1992. If that deadline is met, it should be ready for applications to the whole bay, scheduled to begin in October 1993. It is likely that more testing of TRIM3D will be needed because it is a new model. The turbulence model may have to be upgraded as well.

Verification Data for 3-Dimensional Model of Carquinez Strait

With the recent increase in development and application of 3-dimensional hydrodynamic models in hydraulic engineering, a need exists for well-documented and widely-available datasets to use in verification of 3-dimensional model codes. Since many 3-dimensional model codes have been developed and tested on specific problems, in many instances they have received only limited verification. Analytical, idealized, physical model, and field datasets are needed so that model solutions can be compared with known solutions or measured data.

Described below is a field dataset collected between December 1990 and April 1991 in Carquinez Strait and intended for use in verifying a 3-dimensional model. The data include measurements of water level, salinity, and temperature needed for defining open boundary and initial conditions, as well as measurements of wind for surface forcing. In addition, velocity, salinity, and temperature profile data are available at interior cross sections of the strait for use in model verification. One particularly attractive feature of the dataset is that velocity data are available from two ADCP *(acoustic Doppler current profiler)* systems. Velocity data from ADCP systems have not been widely available for purposes of a 3-dimensional model verification.

Carquinez Strait

Carquinez Strait is a good site for testing a 3-dimensional model because the geometry is relatively uncomplicated, yet the hydrodynamics are complex. The strait is an S-shaped tidal channel, about 10 kilometers long by 2 kilometers wide, located in the northern reach of San Francisco Bay (Figure 108). Tides in the strait have a range of about 1.5 meters, and tidal velocities are high (>2 meters/second during spring tides). Freshwater inflows to San Francisco Bay set up both longitudinal and vertical salinity gradients in the strait that affect hydrodynamic

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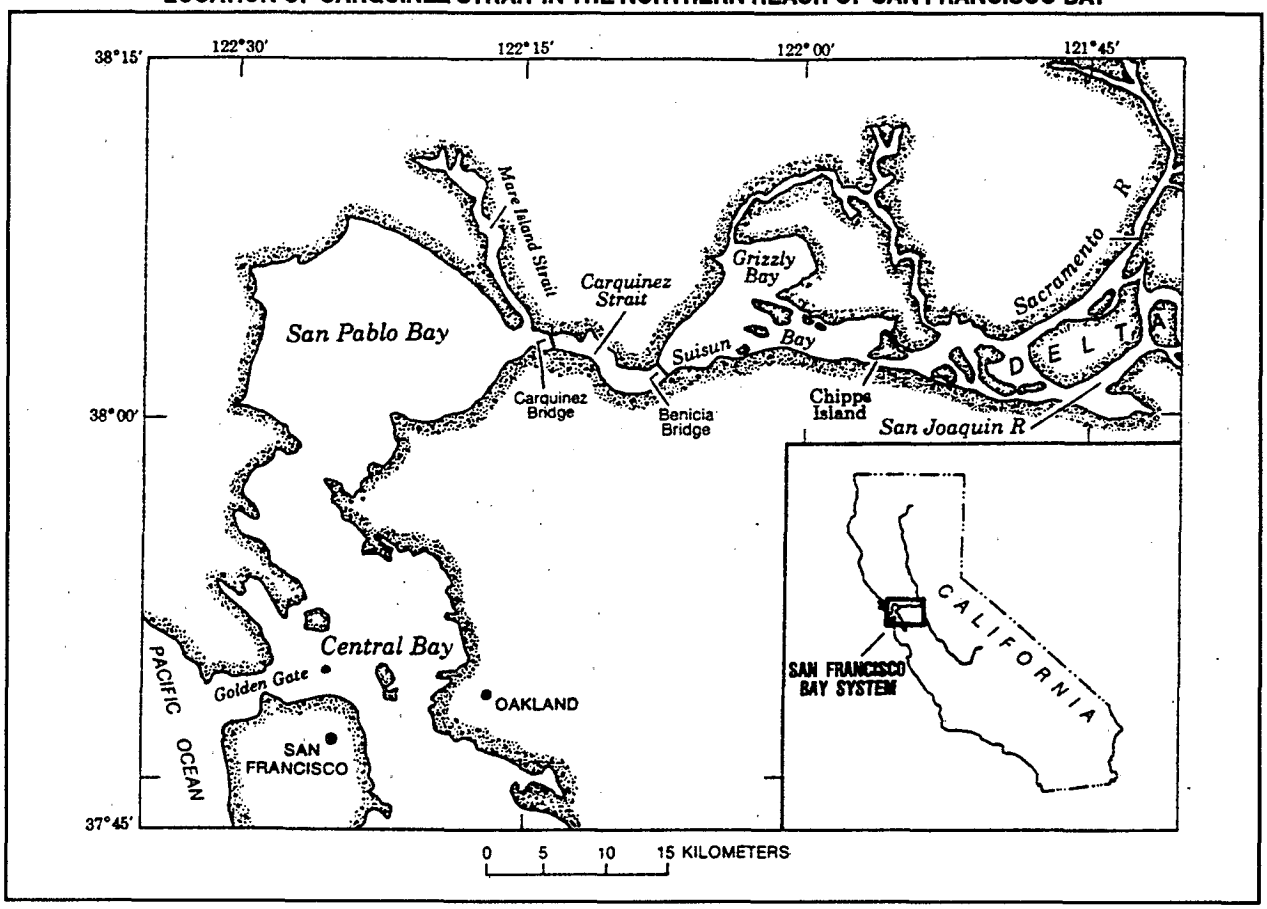
Figure 108
LOCATION OF CARQUINEZ STRAIT IN THE NORTHERN REACH OF SAN FRANCISCO BAY



circulations. Smith and others (1991) recently described the density-driven gravitational circulation observed in the strait during conditions of low freshwater inflow. Gravitational circulation and vertical salinity stratification were found to vary fortnightly over the spring/neap tidal cycle. Attempting to simulate these processes will be a challenging test case for baroclinic 3-dimensional models and should prove useful to compare and evaluate the performance of various formulations of turbulence submodels used in 3-dimensional models for simulating the vertical turbulent mixing.

The detailed bathymetry of the strait has been digitized from nautical charts and is available in a computerized database. The bathymetry is illustrated in Figure 109, with eight cross sections chosen as sites for data collection. Since bottom elevations were taken from nautical charts, the cross sections do not reflect the significant sand dunes observed at many locations in the strait. Dunes in the strait range in height from 0.3 meter to as large as 6 meters in the deepest location.

Boundary Conditions

Time series of water level, salinity, and temperature were collected at 15-minute intervals at shore stations at the ends of the Carquinez Strait. These data can be used as modeling boundary conditions (Figure 109). Salinity data were collected at two depths at each station. Temperature data were collected at two depths at the west station and one depth at the east station. Salinity and temperature profiles were also collected across the boundaries on four dates so the lateral variation in salinity and temperature could be examined relative to values measured at the shoreline. These profiling data were collected during periods of inflow to the strait so as to be most useful in deriving salinity boundary conditions.

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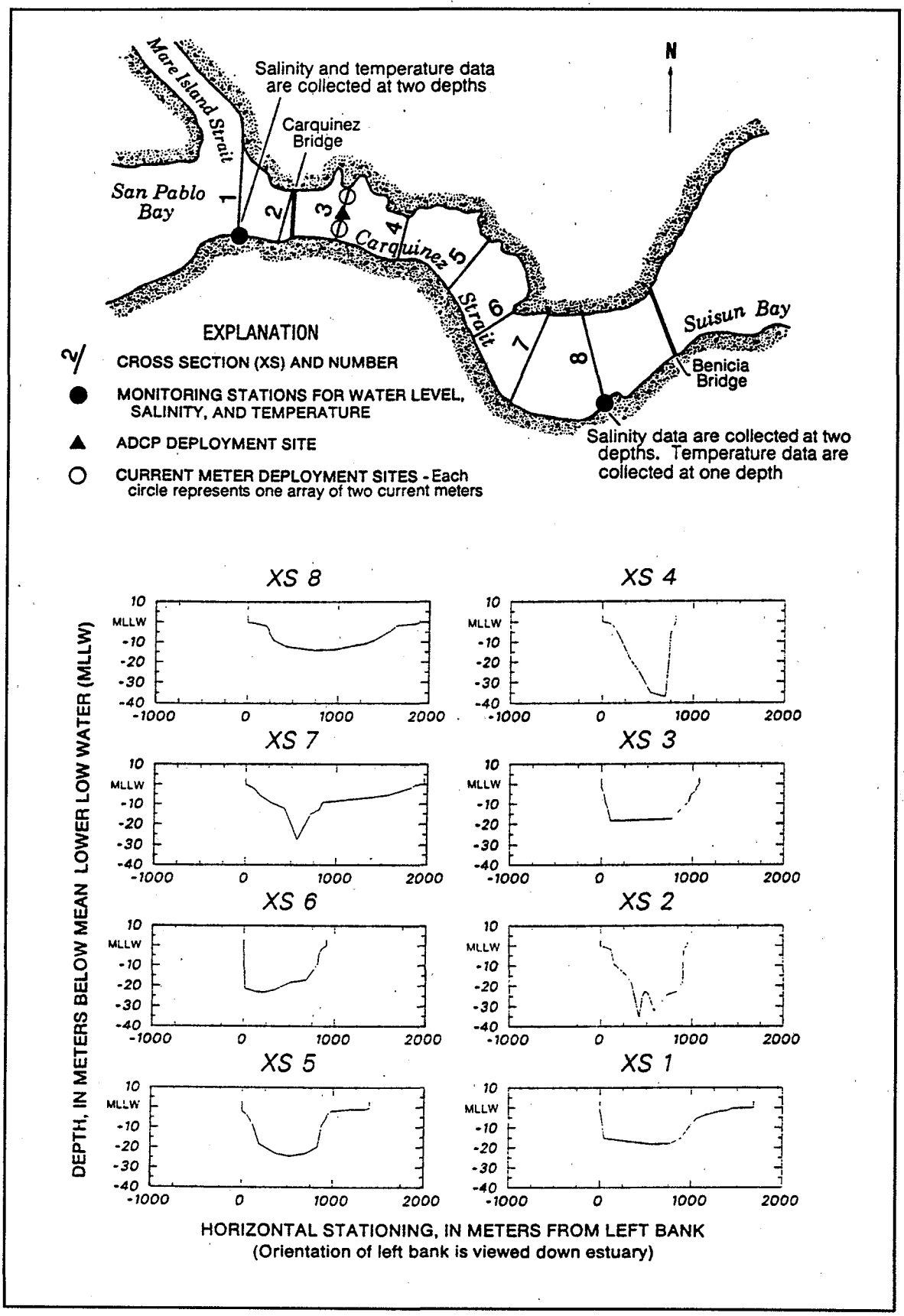
Figure 109
LOCATIONS OF DATA COLLECTION SITES AND CROSS SECTIONS OF CARQUINEZ STRAIT AND BATHYMETRIC PROFILES OF THE CROSS SECTIONS



Initial Conditions

At the start of the study, December 18, 1990, salinity and temperature profiles were collected at cross sections 1, 3, 4, 5, 7, and 8, shown in Figure 109. Three profiles were collected at equally-spaced points along each cross section. These profiles can be used in defining initial conditions for a model.

Wind Data

Fifteen-minute data of wind speed and direction were collected at a site in San Pablo Bay about 8 kilometers west of cross section 1. Atmospheric pressure data were also collected.

Current Measurements

Throughout the study period, an upward-looking ADCP was deployed near the centerline of cross section 3, as shown in Figure 109. The instrument continuously collected velocity profiles at 10-minute intervals, with velocities given at 1-meter depth intervals over 75 percent of the depth. The profiles have been reduced into time series of two horizontal velocity components for each depth interval and have been low-pass filtered to compute Eulerian residual currents. During a model verification, both tidal and residual currents should be compared with those derived from the numerical simulations.

In addition to the ADCP measurements, two arrays of two conventional current meters were deployed on both sides of the ADCP (Figure 109). The data were collected at 2-minute intervals and averaged to 30 minutes for storage.

At the instrumented cross section, velocity profiling using a vessel-mounted (downward-looking) ADCP was conducted at half-hour intervals during four tidal cycles to determine cross-sectional distributions of velocity during both flooding and ebbing flows and with spring and neap tidal conditions. Velocity distributions were also integrated as the research vessel traversed the strait to determine the cross-sectionally averaged flows. (Techniques to determine the integrated flow are described in Simpson and Oltmann [1990]). A total of 43 flow measurements were made; maximum tidal flow was 17,200 m^3/s.

Salinity and Temperature Profiling

Salinity and temperature profiling was performed concurrently with the ADCP velocity profiling described above. Velocity profiles were collected each half hour as the research vessel headed north across the channel, and salinity and temperature profiles were collected as the vessel returned south. During each southerly traverse, five salinity and temperature profiles were collected, at about equally spaced intervals over the cross section. As noted above, the profiling was performed on four tidal cycles. In addition to the above measurements, eight sets of salinity and temperature profiling data were collected over a 6-hour period spanning a transition from flood to ebb tide on January 29, 1991. Each of the eight datasets consists of three profiles at each of three cross sections (3, 5, and 7).

The data should be useful for formulating a test case for use in verifying 3-dimensional baroclinic models. The detailed synoptic observations of velocity, salinity, and temperature distributions across the strait at cross section 3, combined with the long-term continuous measurements with the upward-looking ADCP, represent one of the most complete datasets of its kind.

Analysis of Tide and Salinity Time Series

Once a model has been validated with data for San Francisco Bay, it can be applied to address specific questions. Many questions, however, are hypothetical and require simulations of conditions that have never actually occurred. This situation creates the need for hypothetical boundary conditions that are realistic and consistent with each other. Such boundary conditions can be generated by separating sea level and salinity time series near model boundaries into components that result from tides, inflow, and

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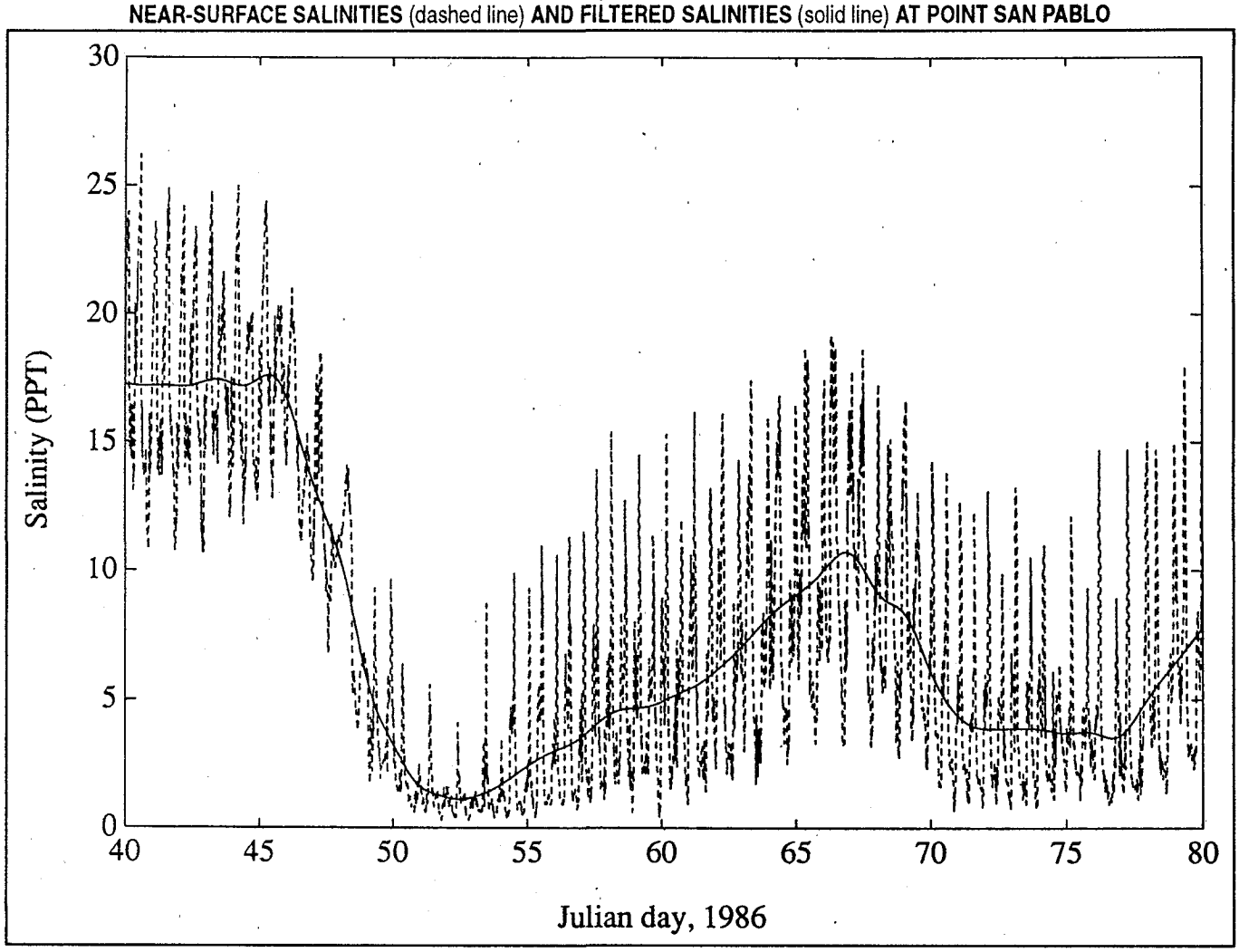
other physical forcings. Appropriate hypothetical boundary conditions then can be assembled from these components.

These analyses involve use of the techniques of digital filtering and principal components analysis and will be presented in future reports. What follows are some illustrations of the significant spring/neap (fortnightly) and annual cycles of tidal energy in San Francisco Bay, and how delta discharge in combination with the spring/neap tidal cycle can influence vertical salinity stratification in the bay.

In the following examples, tide and salinity data have been filtered using a Godin tidal filter (Godin 1972) to remove tidal variations while preserving longer-period variations. The effect of applying a Godin filter to a time series is illustrated in Figure 110, which shows filtered and unfiltered salinities at Point San Pablo. The filtering process is similar to a moving average, except the average is weighted to avoid fictitious cycles (aliasing of tidal frequencies into lower frequencies) in the results. The resultant time series remains between extremes of the original time series and varies more slowly. The filtered time series would be a tidal mean if the unfiltered time series contained only tidal effects. In the example shown, the filtered time series shows primarily the effect of the arrival of low-salinity water from a runoff event.

USGS and DWR operate continuous monitoring stations throughout San Francisco Bay (Figure 111) that provide the hydrographic time series being analyzed. Near-surface and near-bottom salinities are

Figure 110
NEAR-SURFACE SALINITIES (dashed line) **AND FILTERED SALINITIES** (solid line) **AT POINT SAN PABLO**



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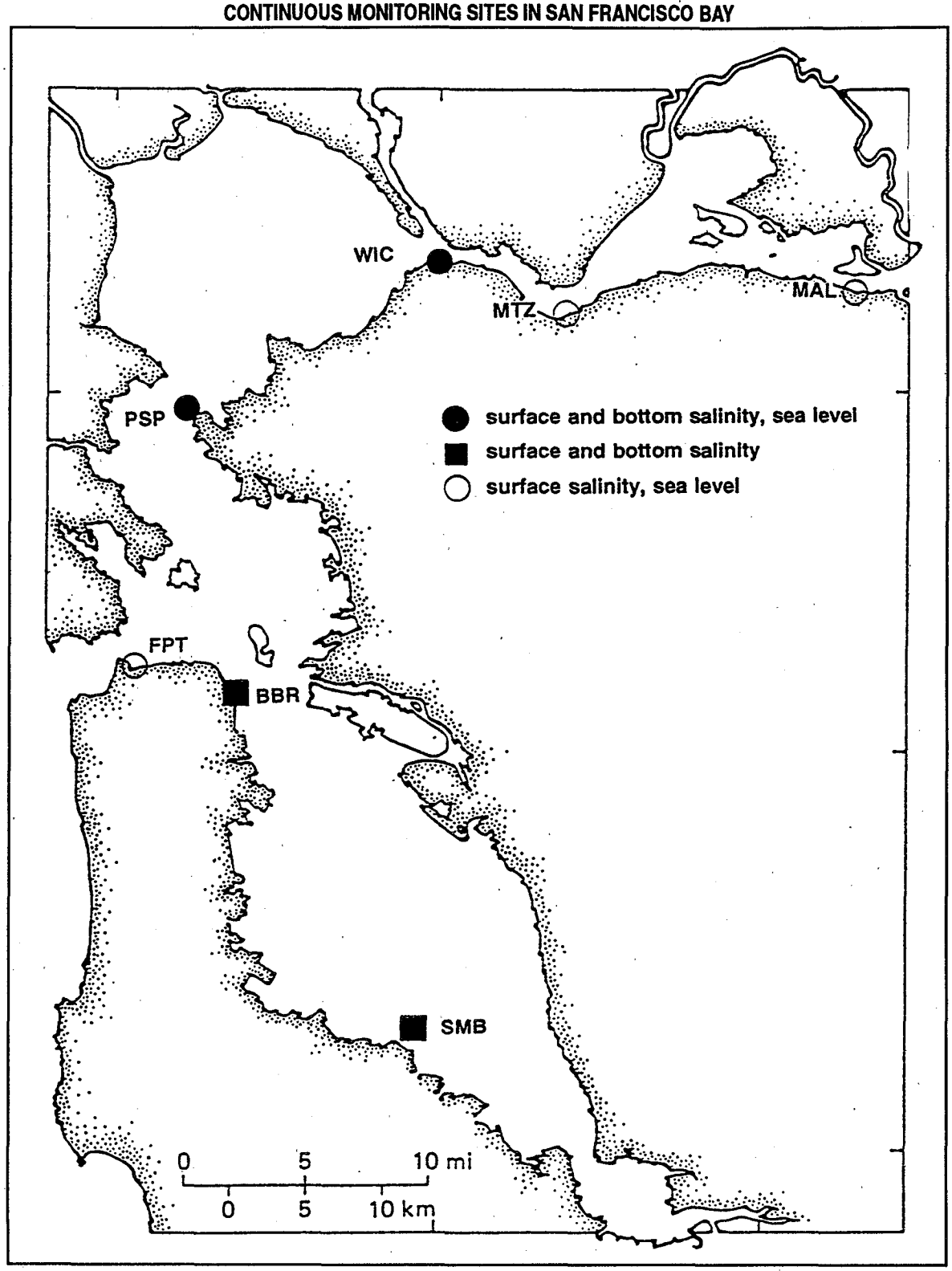
determined from temperature and conductivity data collected at Mallard Island, Martinez, Wickland Oil Pier, Point San Pablo, Pier 24 (west end of the Bay Bridge), and in the channel at San Mateo Bridge. In addition, surface salinities are determined at Fort Point. Similarly, sea level (water level) data are recorded at all except the South Bay sites. Most of these time series extend back to the mid- or early 1980s.

Figure 111
LOCATIONS AND DATA COLLECTED BY USGS AND DWR AT CONTINUOUS MONITORING SITES IN SAN FRANCISCO BAY



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Spring / Neap and Annual Cycles of Tidal Energy

Energy for mixing in San Francisco Bay is derived primarily from tides, meteorological forces, and freshwater inflow. A useful measure of energy for producing currents and mixing is the RMS (root-mean-square) tide height. As the name suggests, RMS tide height is a time series found by calculating the square root of the mean squared deviations of tide heights from mean tide. In this case it was computed as:

RMS tide height = SQRT< Godin[(tide height – annual mean tide height)^2]>,

where tide height is the data time series of sea level, and where the Godin tidal filter is used to compute the mean in RMS. The effective sample interval of RMS tide height is about one day, although the calculation procedure produces the same sample interval as the tide heights. Spring/neap tidal variations in San Francisco Bay dominate the RMS tide height, but variations from atmospheric pressure variations and wind stress on the bay and local coastal ocean are also present.

Variations in RMS tide heights for calendar year 1989 are shown in Figures 112-115 for the five water level monitoring stations in the North Bay (Figure 111). On each graph, a horizontal line is drawn showing the annual mean RMS value computed by simple averaging of the time series. The most apparent variations in RMS about the mean are the fortnightly oscillations due to the spring/neap tidal cycle. This strong spring/neap variability in tides causes a corresponding spring/neap variability in tidal currents in the bay that plays an important role in mixing. The spring/neap variability is greatest at the Golden Gate before the incoming tides are modified by bay geometry or the increased friction from shallow bay water. Progressing up-estuary from the Golden Gate, spring tide amplitudes continuously decrease, while neap tide amplitudes increase slightly up to Carquinez Strait, then decrease through the strait and Suisun Bay. The annual mean RMS value remains relatively constant between 0.55 and 0.57 meter up to Carquinez Strait and then drops off markedly through the strait and Suisun Bay.

Figure 112
ROOT-MEAN-SQUARE TIDE HEIGHTS FOR 1989 COMPUTED FROM SEA LEVEL DATA COLLECTED AT MALLARD ISLAND (solid) AND MARTINEZ (dotted)

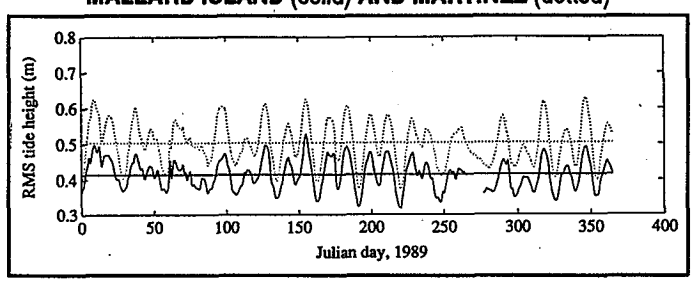


Figure 113
ROOT-MEAN-SQUARE TIDE HEIGHTS FOR 1989 COMPUTED FROM SEA LEVEL DATA COLLECTED AT SELBY (WICKLAND OIL PIER)

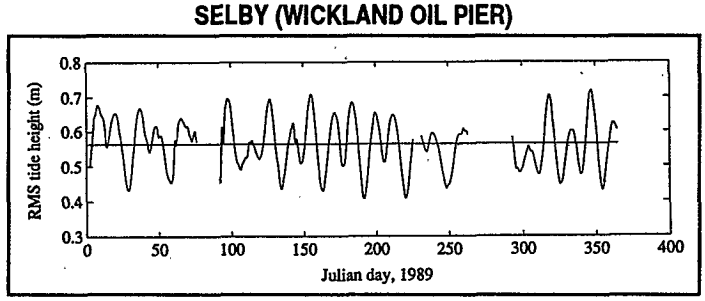


Figure 114
ROOT-MEAN-SQUARE TIDE HEIGHTS FOR 1989 COMPUTED FROM SEA LEVEL DATA COLLECTED AT POINT SAN PABLO

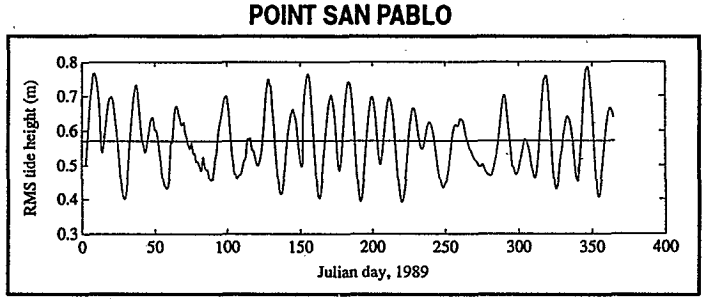
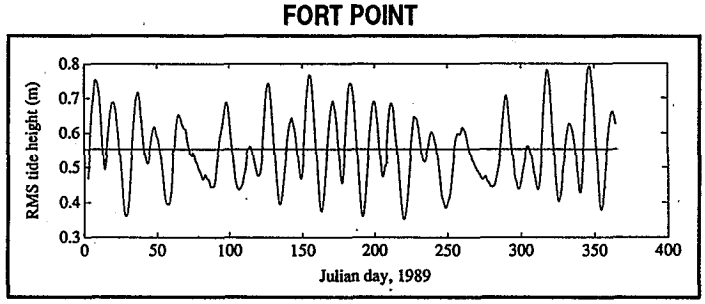


Figure 115
ROOT-MEAN-SQUARE TIDE HEIGHTS FOR 1989 COMPUTED FROM SEA LEVEL DATA COLLECTED AT FORT POINT



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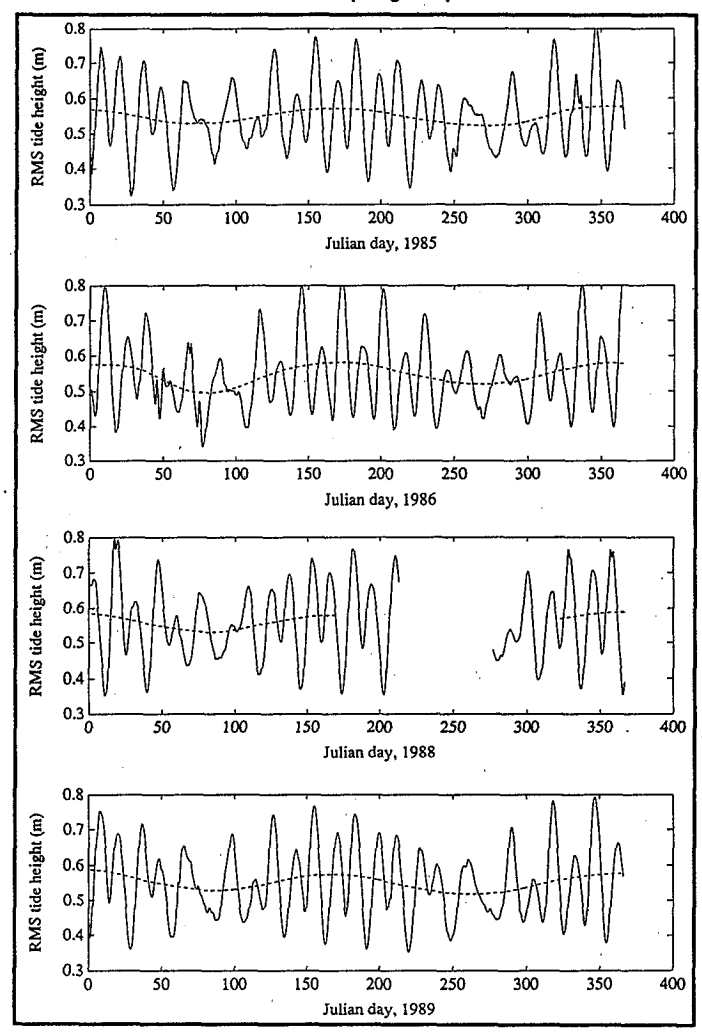
As the tide wave propagates into San Francisco Bay, there are competing tendencies for the wave height to both amplify and dissipate. The wave height tends to amplify as its energy funnels into shallower water and becomes confined within a greatly reduced depth. Wave reflection off shorelines such as in San Pablo Bay may also serve to amplify the wave height. The wave height tends to dissipate mostly due to the increased frictional effects in shallow water and energy losses at constrictions such as San Pablo and Carquinez straits. Friction and constriction losses have the greatest effect when tidal currents are large. This most likely explains the decrease in tidal amplitudes proceeding landward on spring tides. During neap tides, when tidal currents are small, friction and constriction losses are less important, and the slight amplification of the tide wave as it progresses up through San Pablo Bay is probably due to the greater importance of geometry effects.

Further evident in Figures 112-115 is an annual cycle in the tides that is present at all five measuring sites but is most significant at the seaward sites. Large-amplitude spring tides and small-amplitude neap tides occur during June and July (days 152-212) and December and January (days 335-365 and 1-31). Small-amplitude spring tides and large-amplitude neap tides occurred during March (days 60-90) and in late September and early October (days 260-280).

Timing of spring and neap tidal maxima and minima varies slightly from year to year, but the annual cycle repeats itself each year, as illustrated in Figure 116, with data from years 1985, 1986, 1988, and 1989 at the Golden Gate (Fort Point). For each of the years, the cycle of winter and summer as periods of high spring/low neap tides and spring and fall as periods of low spring/high neap tides is present (with the one exception of spring 1986, when the weakest neap tide of the year occurred during March).

The dashed line in Figure 116 is the result of applying a spring/neap filter (a Godin filter for daily data that removes cycles with periods shorter than 30 days) to the RMS tide height. This time series illustrates that spring and fall are also seasons of lower than average overall tidal energy. These seasons may be periods when salinity stratification and gravitational circulation are maintained for longer periods.

Figure 116
ROOT-MEAN-SQUARE TIDE HEIGHTS FOR 1985, 1986, 1988, AND 1989 COMPUTED FROM SEA LEVEL DATA COLLECTED AT FORT POINT
Dashed lines represent RMS tide heights filtered with a spring/neap filter.



Effects of Freshwater Inflow and Tidal Energy on Salinity Stratification

During most water years, several winter runoff events into San Francisco Bay reduce salinities and increase vertical salinity stratification. The stratification and low salinities persist until the event recedes and tidal mixing returns the bay to antecedent

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conditions. The degree of stratification is influenced by the water buoyancy of the runoff and by the amount of vertical mixing derived from the energy of the tides. Cloern (1984), Walters and others (1985), and Smith and others (1991) have discussed the effect of the spring/neap cycle of the tidal energy on vertical stratification. Stratification is greater during neap tides because of smaller vertical mixing. The effect of the annual cycle of the tides is difficult to identify clearly, but it is likely that salinity stratification can be maintained for longer periods during the spring and fall at the time of the annual minima in tidal energy (as calculated with the spring/neap filter above).

An example of the response of mean salinities at the Wickland (Selby) site to a mid-sized runoff event during the spring of 1989 is shown in Figures 117-120. Salinities measured at both surface and mid-depth sensors (Figure 117) decreased by more than 15 ppt during March (days 60-91) and did not recover to previous levels until July, even though runoff subsided early in April (Figure 118. Mean stratification between sensors rose to more than 1 ppt/ meter and remained above 0.2 ppt/meter at least until the end of April (Figure 119).

Any effect of the spring/neap tidal cycle on stratification is not clear in Figure 119 because of missing data after the event and generally low stratification before the event. The effect is quite clear, however, during February 1986, the largest runoff event ever recorded for the bay monitoring stations, and one of the largest events in the historical record. Delta discharges peaked during the third week of February (Figure 121) at nearly 18,000 m^3/s (about 630,000 ft^3/s). Salinities in the bay decreased rapidly during that week (Figure 122-124) and did not recover completely until summer.

Mean salinity stratification in the water column between sensors increased in response to the inflow of fresh water (Figures 125-127), and subsequently the degree of stratification varied inversely with the amount of tidal energy available to mix the water column (Figure 128). Minima of tidal energy occurred during neap tides on days 47, 61, 77, 92, and 106 (shown as vertical lines in Figures 125-128). These minima often preceded maximum values of the mean stratification by a few days.

Figure 117
FILTERED SALINITIES AT UPPER (solid) AND LOWER (dotted) SENSORS AT SELBY (WICKLAND OIL PIER)

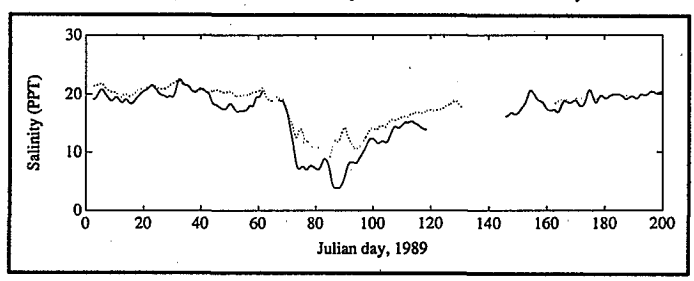

Figure 118
7-DAY RUNNING MEANS OF DELTA DISCHARGE (DAYFLOW) ESTIMATES, 1989

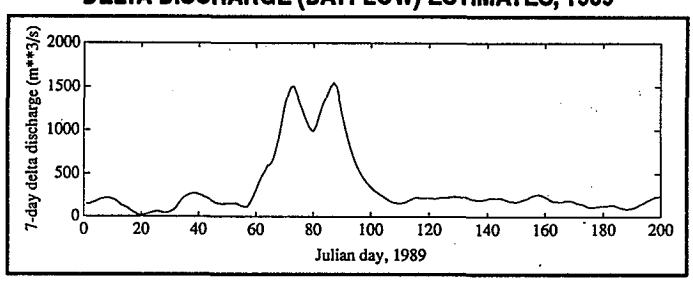

Figure 119
STRATIFICATION BETWEEN SENSORS AT SELBY

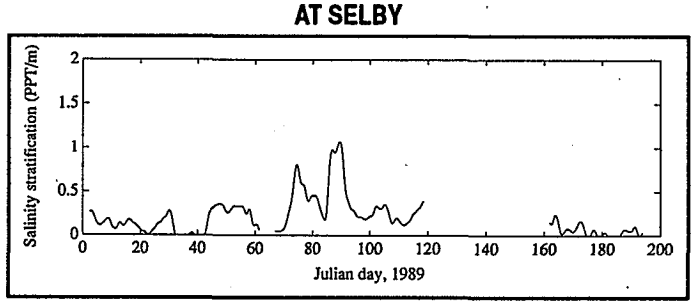

Figure 120
ROOT-MEAN-SQUARE TIDE HEIGHTS AT SELBY (dotted) AND FORT POINT (solid)

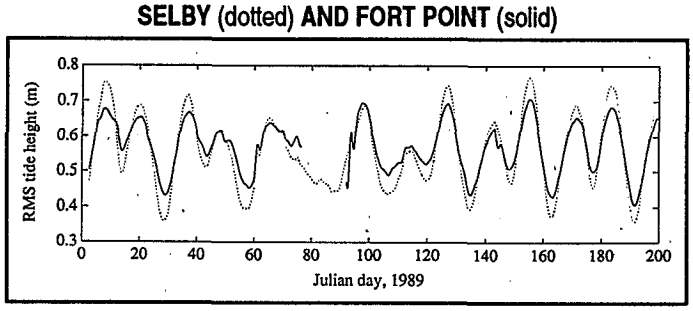

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Figure 121
DAILY DISCHARGE (DAYFLOW) ESTIMATES, 1986

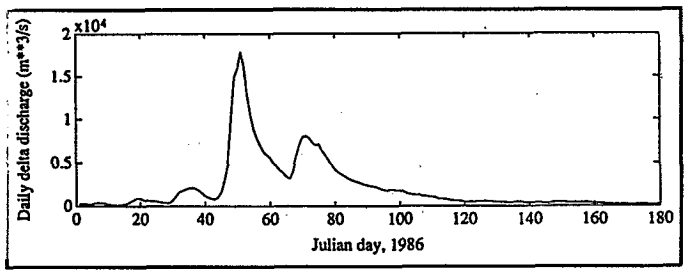


Figure 122
UPPER (solid) AND LOWER (dotted) FILTERED SALINITIES AT MALLARD ISLAND, MARTINEZ, AND POINT SAN PABLO

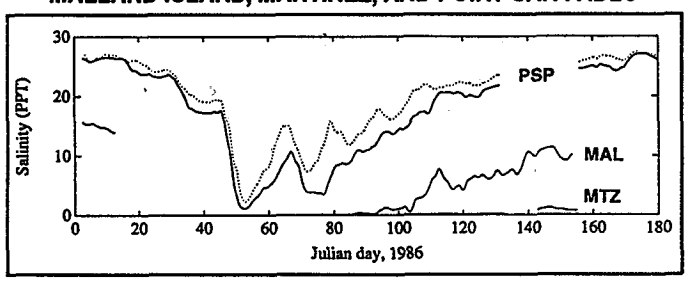


Figure 123
UPPER (solid) AND LOWER (dotted) FILTERED SALINITIES AT BAY BRIDGE

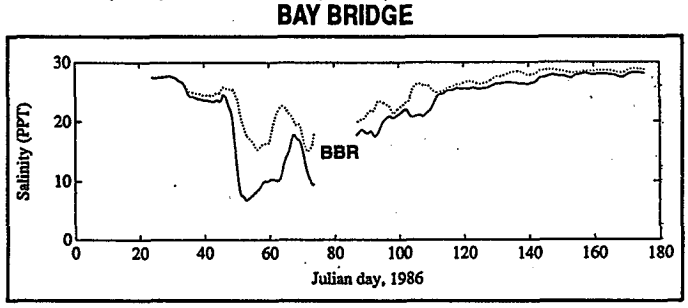


Figure 124
UPPER (solid) AND LOWER (dotted) FILTERED SALINITIES AT SAN MATEO BRIDGE

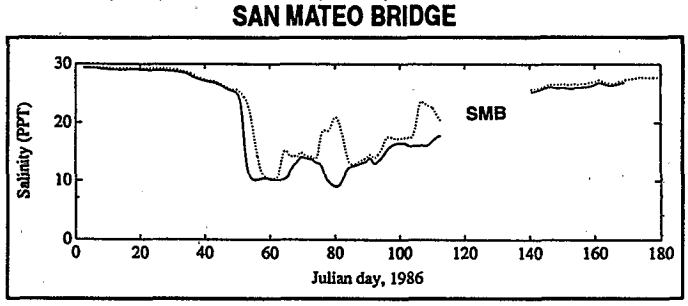


Figure 125
FILTERED SALINITY STRATIFICATION AT POINT SAN PABLO
Vertical lines locate times of minimum RMS tide heights at San Mateo Bridge.

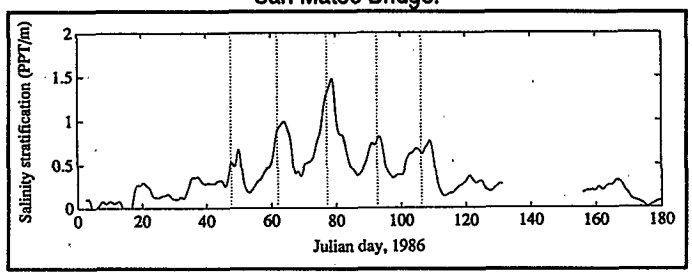


Figure 126
FILTERED SALINITY STRATIFICATION AT BAY BRIDGE
Vertical lines locate times of minimum RMS tide heights at San Mateo Bridge.

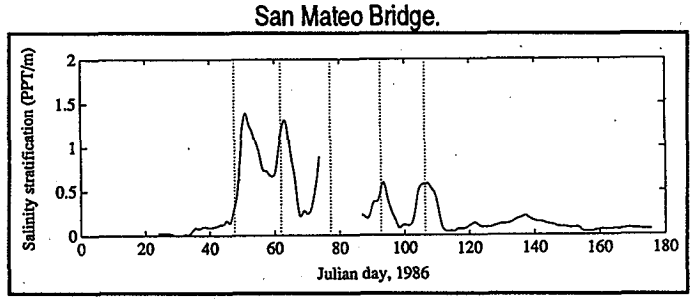


Figure 127
FILTERED SALINITY STRATIFICATION AT SAN MATEO BRIDGE
Vertical lines locate times of minimum RMS tide heights at San Mateo Bridge.)

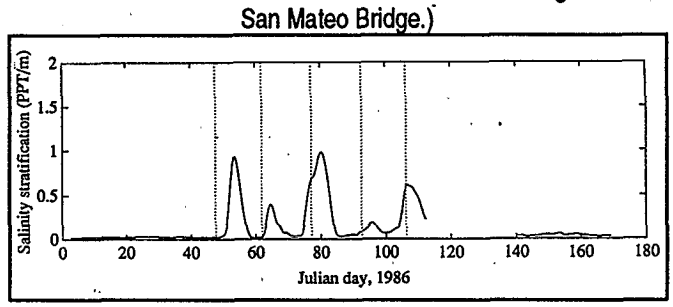
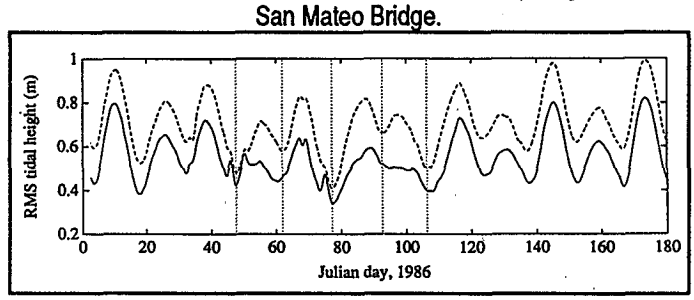


Figure 128
ROOT-MEAN-SQUARE TIDE HEIGHTS AT FORT POINT (solid) AND SAN MATEO BRIDGE (dashed)
Vertical lines locate times of minimum RMS tide heights at San Mateo Bridge.



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Finally, three facts indicate that low-salinity water passed from the delta through the northern bay and into South Bay on the surface, as has been described previously (McCulloch and others 1979).

- Salinities decreased at ever later dates, moving south from Point San Pablo to the San Mateo Bridge. Salinities began decreasing on Julian day 45 at Point San Pablo, day 46 at the Bay Bridge, and day 51 at San Mateo Bridge; salinities reached minima at these sites on days 52, 54, and 55, respectively.
- Bottom salinities in South Bay dropped no lower than 10 to 15 ppt, although the runoff event introduced an amount of fresh water greater than the volume of the entire bay.
- Salinities at the lower sensors in South Bay decreased later than at the upper sensors by a few days.

All of this evidence points to a delta source of fresh water that penetrated into South Bay on the surface and that mixed downward in the water column during subsequent spring tides.

Vessel-Mounted Flow Measurement System for the Sacramento-San Joaquin Delta

Earlier annual reports described a flow-measurement system under development that uses a narrow-band ADCP *(acoustic Doppler current profiler)* mounted in the bottom of a boat. Making a flow measurement in the time needed for the boat to cross a channel was the objective. This system has now been completed (Simpson and Oltmann 1991). Summarized below are accuracy tests of the ADCP and flow-measurement system and some initial applications.

Velocity Measurement With an ADCP

An ADCP operates using an array of four transducers that continuously transmit short acoustic pulses or "pings" into the water column beneath the instrument at angles inclined 30 degrees from vertical. Part of the transmitted sound from each ping is reflected backward or is "back scattered" to the transducers from sound scatterers in the water.

The sound scatterers are small suspended particles or plankton that occur everywhere in a water body and move at the same velocity as the water. The frequency of the back scattered sound is Doppler-shifted to a higher or lower frequency by an amount that is a direct function of the relative velocity between the scatterers and the transducer assembly.

Water velocities are first computed as components along each beam axis and later converted on a shipboard computer to three orthogonal components in the north, east, and vertical directions. Normally, only the two horizontal components are saved. Because the ADCP samples back-scattered sound from each beam at 0.1-second intervals, water velocities can be resolved at depth intervals of 1 meter, called bins. Measurements are made over the middle three-fourths of the water column when water depths are at least 4 meters. The velocity measured for each bin is considered as the average water velocity through the 1-meter horizontal slice of the water column bounded by the four acoustic beams.

Using a separate acoustic pulse, the velocity of the channel bottom relative to the ADCP, which is equivalent to the vessel velocity, is also determined and is referred to as bottom tracking. The vessel velocity is used to compute water velocities relative to an earth-based reference frame. For a further description of ADCP operation, refer to RD Instruments (1989).

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Accuracy of ADCP Velocity Measurements

Shortly after delivery of the ADCP, accuracy of the system was tested in the field. The first test was on Lake Berryessa, where the instrument was operated from a houseboat navigated over a strait-line course of precisely-measured distance. The ADCP system was used to estimate distance traveled by the houseboat using bottom-tracking data. Distances calculated from the ADCP during 13 test runs, carried out using various boat speeds and two directions of travel, agreed to an average of 1.9 percent with the known distance. ADCP-measured water velocities in the lake were used to quantitatively estimate a short-term random error of the instrument. Water velocities detected by the ADCP could be attributed to random error of the instrument, because water in the lake was motionless during windless conditions. This random error was evaluated for various averaging periods of the profiler data. The error using a 1-second averaging period was 6.5 cm/s, but for a 20-second averaging period it was reduced to 2.3 cm/s. Further averaging reduced the error still more. Simpson (1986) presented complete results of the testing in the form of a curve relating measurement error to averaging period.

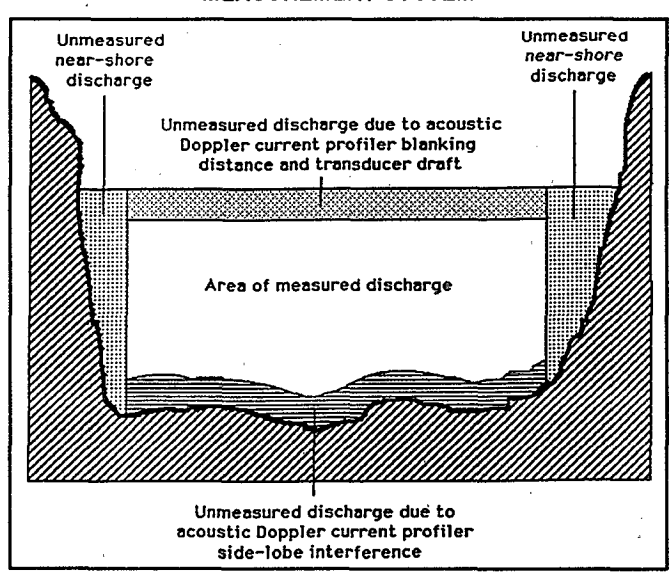
A second test of the instrument was done under moving water conditions (>100 cm/s) at two locations on the Sacramento River and one on the San Joaquin River. Velocities were measured by the ADCP from an anchored vessel and then compared with those measured with Price AA and electromagnetic current meters. Results showed ADCP measurement errors in moving water were essentially equal to those in still water during the lake tests (Simpson 1986).

Accuracy specifications determined by the tests were in overall agreement with those supplied by the manufacturer. The conclusion was that the ADCP is accurate for current measurements as long as an averaging period of 20 seconds or more is used.

Development and Use of the Flow Measurement System

USGS began development of an ADCP-based flow measurement system in October 1987. A computer program was written that uses velocity profiles and bottom track data from the ADCP and water-depth data provided by a sonic sounder to integrate flow as the profiler is transported across a channel in the bottom of a vessel. Procedures were incorporated into the computer program to estimate flow in unmeasured portions of the channel cross section (Figure 129).

Figure 129
SKETCH OF MEASURED AND UNMEASURED DISCHARGE AREAS FOR A TYPICAL RIVER CROSS SECTION USING AN ACOUSTIC DOPPLER DISCHARGE MEASUREMENT SYSTEM



Comparisons of flow measurements made with the ADCP-based system to flows determined by a calibrated ultrasonic velocity meter *(UVM)* in the Sacramento River at Freeport revealed average differences of less than 2 percent (Figure 130) (Simpson and Oltmann 1991). The system, called "Acoustic Doppler Discharge Measurement System" *(ADDMS)*, was then used for a variety of purposes.

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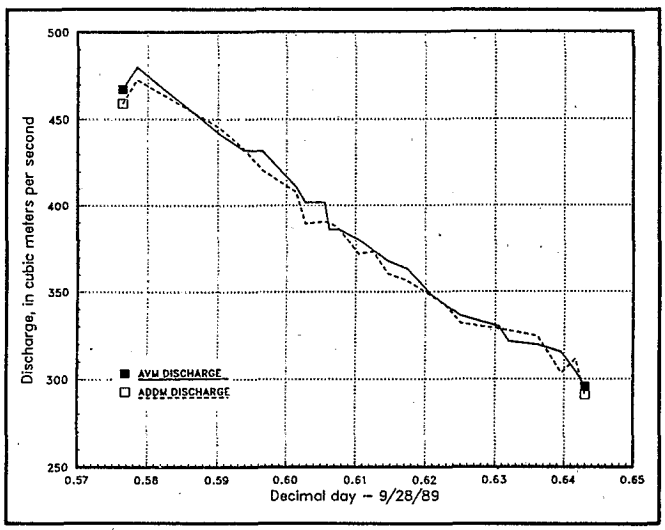
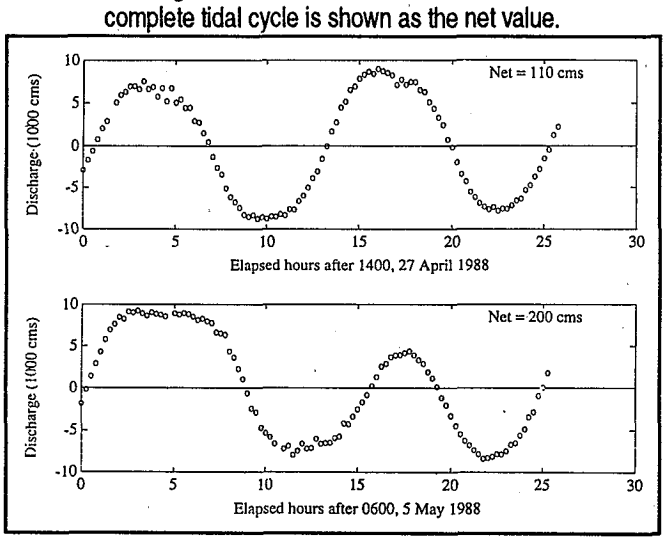
Figure 130
RELATIONSHIP OF DISCHARGES MEASURED AT SACRAMENTO RIVER NEAR FREEPORT WITH ULTRASONIC VELOCITY METER AND ACOUSTIC DOPPLER DISCHARGE MEASUREMENT SYSTEM



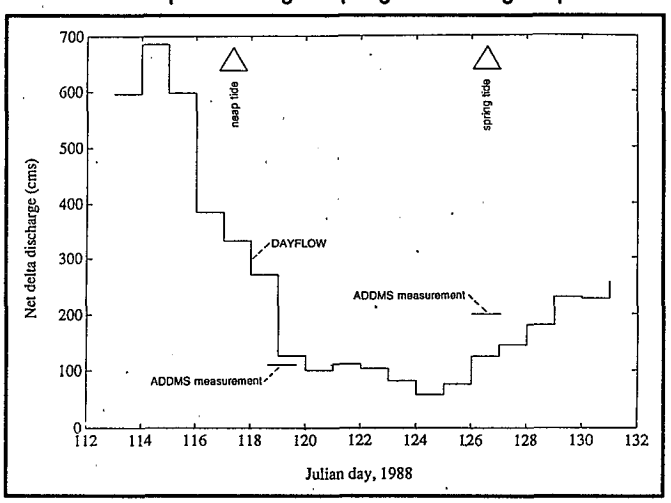
ADDMS was used to measure tidal flows at Chipps Island every 15 minutes over complete tidal cycles during April and May 1988 (Figure 131). The measurements were integrated over the entire tidal cycle to obtain estimates of net delta discharge.

Figure 131
DISCHARGES MEASURED BY ACOUSTIC DOPPLER DISCHARGE MEASUREMENT SYSTEM AT CHIPPS ISLAND
Integration of the measurements over a complete tidal cycle is shown as the net value.



Computed net discharge for the first tidal cycle was 110 m^3/s, as compared to DAYFLOW estimates of 270 and 125 m^3/s on April 27-28 (Figure 132). For the second tidal cycle, the measurements yielded 200 m^3/s compared to DAYFLOW estimates of 125 and 145 m^3/s on May 5-6.

Figure 132
COMPARISON OF DAYFLOW ESTIMATES OF NET DELTA DISCHARGE WITH INTEGRATED ADDMS MEASUREMENTS AT CHIPPS ISLAND
Arrow heads mark the days of the weakest neap and strongest spring tides during the period.



These differences are well within the differences to be expected, because DAYFLOW calculations do not take into account the tides or travel time of water through the delta. In particular, the ADDMS estimates of net delta discharge are expected to be less than the DAYFLOW estimate during neap tides and greater during spring tides because tidal processes reduce net seaward flow during neap tides and enlarge net seaward flow during spring tides (Walters and others 1985). Although the differences between the ADDMS estimates and DAYFLOW are consistent with this observation (Figure 132), a longer time series of measurements would be necessary to draw any concrete conclusions.

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Current meters were moored near the measurement section for a 30-day period surrounding the ADDMS measurements, with the objective of developing a correlation that could extend the ADDMS measurements in time. These longer flow time series would then permit a more realistic comparison with DAYFLOW estimates. Data storage failures in the current meters prevented completion of this part of the study.

Subsequently, ADDMS was used to calibrate UVMs at delta sites on Old River and Middle River and for making a large number of individual flow measurements in an area including these sites. These data were used successfully to calibrate a network flow model of the area. In this case, model calibration would not have been possible with water level data because surveying techniques are inadequate to define gage datums with sufficient accuracy. These efforts are described by Simpson and Oltmann (1991). The availability of ADDMS now permits measurement of flow with UVMs at other delta sites where calibration would be infeasible otherwise.

ADDMS has proven to be a fast and accurate method for measuring discharge in the bay and delta in channels 4 meters deep or greater. Measurements with this system can be made in a fraction of the time needed for conventional current meter measuring techniques. The path of the vessel across the channel need not be a straight line, nor are any shore-based navigational aids or tag lines required for positioning the vessel. ADDMS can be used successfully in many locations where measurements using conventional methods are not feasible.

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