■ Interagency Ecological Program for the San Francisco Estuary ■

IEP NEWSLETTER

VOLUME 13, NUMBER 4, FALL 2000

CONTENTS

OF INTEREST TO MANAGERS

Chuck Armor, DFG
carmor@delta.dfg.ca.gov

- **Mitten Crabs.** p 4. May and Brown describe Chinese mitten crab distribution in the San Joaquin River drainage and found no crabs at any of the sites sampled. This suggests there are fewer mitten crabs in the San Joaquin drainage this year than in past years, and associated problems with large mitten crab numbers at the CVP and SWP facilities may be less this year.

- **Striped Bass and Delta Smelt Fish Abundance Indices.** p 8–10. Gartz reports on the status of various fish species of special interest, which is a mixture of good and bad news. The striped bass 38-mm index was set at 5.5, twice the 1999 index of 2.2, and the highest index since 1996. The townet survey index for delta smelt decreased from 11.9 in 1999 to 8.0 in 2000. Catch indices for longfin smelt and starry flounder are both significantly lower this year than in previous years.

- **Sherman Island Agricultural Diversion Evaluation.** p 11. Nobriga and Matica observed a large increase in the fish diverted by an unscreened diversion during the incoming tide at night. This suggests management of diversion periods may be an effective tool to reduce fish entrainment into Delta agricultural diversions. Additional work is planned when delta smelt and young salmon are present next year.

- **Fish Diet Analysis from Suisun Marsh Points to Implications for the San Francisco Estuary.** p 21–27. Feyrer and Matern compare the diets of five important species of fish and found in Suisun Marsh between 1987 and 1999 found a significant change in their diets, mostly due to the large decrease of the mysid shrimp, *Neomysis mercedis* in the Suisun Marsh. Potential implications of this change are discussed.

- **Pesticides in Delta Smelt Habitat.** p 27–33. In 1999 numerous pesticides were detected in areas inhabited by larval and small juvenile delta smelt. Moon and others compare 1998 and 1999 pesticide data from the Delta to demonstrate that the mixture, concentrations, and distributions of pesticides found in delta smelt habitat is strongly influenced by a number of factors, including river discharge and CVP and SWP diversions.

Potential Mercury Problems with Delta Restoration Sites. p 34–44. Slotton and others report spatial differences in Delta mercury levels are most closely related to proximity to upstream sources, such as the Yolo Bypass and Cosumnes River, as well as residual sediments from California's Gold Rush era. Areas with organic-rich vegetated wetland tracts had a higher potential to convert mercury into a form accumulated by the biota; however, this did not necessarily result in higher accumulation in organisms tested. This information along with other findings will be critical to the selection and restoration of sites within the Delta. One additional finding was the identification of an area of high mercury bioaccumulation between the confluence of the Sacramento and San Joaquin rivers and Carquinez Strait.

- **Effects of *Potamocorbula* on the Estuarine Food Web.** p 45–54. Since the decline in zooplankton abundance and the concurrent rise in the exotic clam *Potamocorbula* was detected in the estuary in 1986, the nature of the interactions between the exotic clam and the zooplankton community has been poorly understood. Kimmerer and Peñalva discusses the results of a number of laboratory and field experiments that provide some insight to the direct and indirect effects of *Potamocorbula* on the zooplankton community.

- **Mortality Rates of Largemouth Bass.** p 54–60. Largemouth bass mortality rates have traditionally been calculated using tag return data. Schaffter presents tag return data from 1980–1984 and compares natural and angler mortality rates in the Delta to other waters in the State. Delta largemouth bass mortality rates were lower than those estimated for several major reservoirs in the State. Although his analysis was complicated by a shift in the Delta largemouth bass recreational fishery to a "catch and release" fishery, such a shift gives insights into Delta recreation priorities.

A Note from the New ESO Chief

Barbara McDonnell, DWR
bmcdonne@water.ca.gov

This is the first issue of the *IEP Newsletter* to be published since I was appointed Chief of the DWR Environmental Services Office on August 1. I want to take this opportunity to introduce myself to those of you whom I have not worked with in the past and to say “hello” to all my old friends. I am very pleased to lead such an outstanding group of scientists and engineers who provide such a key component to the management of the estuary. As a rather classically trained aquatic ecologist, I have an appreciation for the daunting task of managing a diverse group of native and non-native species that inhabit the estuary for at least a part of their life history.

I will strive to further the role of the Environmental Services Office in the scientific endeavors of the Interagency Ecological Program, particularly in its certain role of importance within the overall CALFED Science Program. I also pledge to continue the tradition of putting the best scientific information forward to the decision-makers as we learn more about target species and their habitat requirements. I look forward to meeting all of you at venues such as the CALFED Science Conference, the Annual IEP Workshop, and other events. If you wish to contact me, my e-mail address is bmcdonne@water.ca.gov.

First CALFED Science Conference a Huge Success!

Zach Hymanson, DWR
zachary@water.ca.gov

The first CALFED Science Conference, held October 3–5, 2000 in Sacramento, California, was a huge success. Eight hundred twenty-five registered participants heard over 125 oral presentations and viewed nearly 100 poster presentations. The following comment from one participant summarized the thoughts of many, “. . .overall the highest proportion of high-quality talks and posters I have seen at any conference. . .”

Topics of the conference considered large-scale factors, such as climate variability; regional factors, such as hydrodynamics and effects of contaminants; and local factors, such as fish screens and invasive species. The unifying theme was to provide a forum for the presentation of scientific information and ideas relevant to CALFED goals and objectives. Abstracts from the conference, as well as a brief management summary, will be available at the conference web site, which can be accessed at http://www.iep.water.ca.gov/calfed/sciconf/.

The success of this conference ensures that future CALFED science conferences will occur. One likely scenario is that the CALFED Science Conference and the State of the Estuary Conference will occur in alternate years. The next State of the Estuary Conference is scheduled to occur in October 2001. Congratulations to all the members of the conference coordinating committee on a job well done!

INTERAGENCY ECOLOGICAL PROGRAM QUARTERLY HIGHLIGHTS—FALL 2000

YOLO BYPASS STUDY

Ted Sommer and Bill Harrell, DWR
tsommer@water.ca.gov

The Yolo Bypass program includes sampling for fish, food web organisms, water quality, and contaminants. As in 1998 and 1999, we operated a rotary screw trap and conducted beach seine hauls during winter and spring. Sampling was most intensive from mid-February through mid-March, the period of inundation. Salmon were the dominant native fish collected from winter through mid-spring, after which splittail became abundant. Splittail production appeared much higher than in 1999, but not as substantial as the record year class in 1998. To provide additional information about floodplain salmon residence time, growth, and survival, coded wire tagged salmon were released during the main flow pulse. We are still analyzing data collected from this experimental release. Fyke trapping was added this year as a study component to examine adult fish migration through the floodplain. We found that migration of adult splittail, blackfish, salmon, and suckers was associated with early flow pulses through the perennial toe drain channel. Adult fall-run, winter-run, and spring-run chinook salmon and sturgeon were all captured during periods when there was inadequate flow for upstream passage through Fremont Weir. Based on our observations, we believe that Fremont Weir comprises a major fish passage issue in the lower Sacramento Valley.

Zooplankton and drift invertebrate sampling continued as part of baseline food web monitoring. Chlorophyll monitoring was added to our sampling program to examine the hypothesis that the floodplain is a net source of phytoplankton. Fluorometry and grab samples demonstrated that Yolo Bypass chlorophyll levels were much higher than the adjacent Sacramento River, particularly during descending hydrographs. Anke Mueller-Solger (UC Davis) used floodplain water samples in bioassays to determine the relative quality of this material for zooplankton. Another new study component was stable isotope analyses of food web organisms. We collected samples from multiple trophic levels to test the hypothesis that the floodplain food web is different than the adjacent Sacramento River. Laboratory processing of the samples has not been completed. In addition to the biological studies, Larry Schemel (USGS) completed water quality sampling of the Yolo Bypass tributaries and outflow, with emphasis on the drainage period. Kathy Kuivila (USGS) will conduct pesticide analyses of water samples collected from different hydrologic “bands” in the floodplain.

CHINESE MITTEN CRAB HABITAT USE IN THE SAN JOAQUIN RIVER DRAINAGE

Jason May and Larry Brown, USGS,
jasonmay@usgs.gov

The initial objective of this study was to determine habitat use of the Chinese mitten crab in the San Joaquin River drainage upstream of the Delta. Juvenile mitten crabs are believed to use riverine habitats as rearing habitat. Monthly sampling began in early June at two sites, the San Joaquin River near Vernalis and the Merced River at George Hatfield State Park, just upstream of the confluence with the San Joaquin River. The primary sampling method is traps baited with sardines, fished for approximately 24 hours. At each location, two sets of three traps were used in up to five habitat types, including backwater, main channel, emergent vegetation, woody debris, and riprap.

No mitten crabs were captured at the Merced River or San Joaquin River sites from June 6–8 and June 28–30. The San Joaquin River near Mossdale was also sampled on July 6–7, August 4–5, and August 30–31, with no crabs captured. The traps were effective at capturing a variety of other organisms, including crayfish, channel catfish, and black bullhead. This suggests the traps will be effective when mitten crabs are present. Qualitative sampling with seines and backpack electrofishing also failed to capture mitten crabs. After consultation with the IEP management team, the focus of the study has been shifted to determine the presence of mitten crabs at various locations in Suisun Marsh, with sampling also continuing at the San Joaquin River near Mossdale. The first sampling effort in Suisun Marsh occurred from August 30–31. Trapping efforts in Peytonia Slough, Boyton Slough, and a side channel of Suisun Slough resulted in no crabs captured. Fish captured included yellowfin goby, prickly sculpin, and black bullhead. Sampling is planned to continue through November.

LARVAL FISH SAMPLING AT NORTH BAY AQUEDUCT

Andy Rockriver, DFG
arockriv@delta.dfg.ca.gov

The North Bay Aqueduct (NBA) larval fish monitoring program was completed July 14. Approximately 55,000 larval fish, representing at least 23 species, were collected from eight North Delta sampling stations. For the first time since 1995, the most abundant species was not prickly sculpin. Striped bass, typically the second or third most abundant species, was the most abundant at 55.7% of the total catch (30,883 fish: a new record). Prickly sculpin was second at 36.2% of the total catch.

As usual, from mid-February to May, prickly sculpins dominated the catch. However, by the end of May, sculpin numbers dwindled and larval striped bass numbers skyrocketed. In early June, striped bass reached their maximum density of 1,860 fish per 200 m^3. By the end of June, the striped bass passed through the area and the numbers decreased.

This year we also saw a record number of wakasagi and a relatively large number of delta smelt. More wakasagi were caught this year (100) than the five previous years combined (65). Wakasagi were found primarily in Miner Slough. Wakasagi were found in water temperatures ranging from 11 to 18 °C. Delta smelt numbers were high relative to previous years. A total of 309 delta smelt was caught, compared to 27 in each of the last two years. Most delta smelt were caught in the sampling stations around Prospect Island. A few were caught in Barker and Lindsey sloughs. Delta smelt were found in water temperatures ranging from 11 to 23 °C.

The criteria for restricting NBA pumping was triggered on four occasions: once in April, twice in May, and once in June. NBA pumping is restricted to a five-day running average of 65 cfs when the weighted mean of delta smelt caught in Barker Slough exceeds 1.0. Although we were unable to report delta smelt catch within 72 hours, due to the higher priority of 20-mm survey and the unexpected high catch of striped bass, the delay in reporting did not result in NBA exceeding the 65 cfs pumping restriction. For more information about the North Bay Aqueduct monitoring program, access the web site at www.delta.dfg.ca.gov/data/nba/2000.

KNIGHTS LANDING JUVENILE SALMONID MONITORING

Bill Snider, DFG
bsnider @dfg2.ca.gov

Juvenile salmonid emigration monitoring at Knights Landing continued through the summer (July and August 2000). No juvenile salmonids were collected during this period.

During the quarter, we completed reports summarizing the results of monitoring at Knights Landing during the 1996–1997 and 1997–1998 monitoring periods.

DISSOLVED OXYGEN LEVELS IN THE STOCKTON SHIP CHANNEL

Casey Ralston, DWR
cralston@water.ca.gov

Dissolved oxygen concentrations in the Stockton Ship Channel are closely monitored during the late summer and early fall of each year because levels can drop below 5.0 mg/L, especially in the eastern portion of the channel. The dissolved oxygen decrease in this area is apparently due to low San Joaquin River inflows, warm water temperatures, high biochemical oxygen demand (BOD), reduced tidal circulation, and intermittent reverse flow conditions in the San Joaquin River past Stockton. Low dissolved oxygen levels can cause physiological stress to fish and inhibit upstream migration of salmon.

Monitoring of dissolved oxygen levels in the Stockton Ship Channel was conducted three times between August 14 and September 12, 2000, by vessel (the *San Carlos*). Sampling will continue through September, October, and November, depending on dissolved oxygen levels recorded. During each of the monitoring runs, 14 sites were sampled from Prisoner's Point in the central Delta to the Stockton Turning Basin. Dissolved oxygen and water temperature data were collected for each site at the top and bottom of the water column during ebb slack tide using traditional discrete methods (Winkler titration) and continuous monitoring methods (Hydrolab DS-3 multiparameter surveyor, Seabird 9/11 multiparameter sensor).

As in previous years, dissolved oxygen levels in the western portion of the ship channel from Prisoner's Point to Disappointment Slough were relatively high and stable throughout the study period, ranging from 7.0 to 10.4 mg/L.

In the central portion of the channel from Columbia Cut to Fourteen Mile Slough, dissolved oxygen concentrations dropped to levels approaching or below 5.0 mg/L in August. However, September monitoring results suggest the dissolved oxygen sag may be dissipating and dissolved oxygen levels are recovering earlier than expected. In the eastern portion of the channel from Buckley Cove to the eastern end of Rough and Ready Island, the dissolved oxygen depression is less pronounced. While a few values approached the 5.0 mg/L standard, the dissolved oxygen levels were variable and the majority measured greater than 6.0 mg/L.

Monitoring by vessel in the eastern channel is supplemented by an automated multiparameter water quality recording station near Burns Cutoff at the western end of Rough and Ready Island. The continuous monitor captures diel variation in dissolved oxygen levels. Early morning concentrations are often lower than values recorded later in the day. However, with the exception of one week in August, even the depressed early morning values measured above 5 mg/L. During the week of August 14–19, 2000, the continuous monitor recorded several values in the 4 to 5 mg/L range, indicating that the sag reached farther eastward than suggested by discrete sampling methods.

A slight decrease in water temperatures (20.6 to 23.9 °C) and maintenance of adequate San Joaquin River inflows (average daily inflows past Vernalis of approximately 2,000 cfs) appear to be contributing to the maintenance of acceptable dissolved oxygen levels in the channel.

Delta Flows Measurement

Richard N. Oltmann, USGS
rnoltman@usgs.gov

All 12 stations of the continuous flow-monitoring network successfully collected data through the quarter.

On September 5, six UL-ADCPs were deployed in the vicinity of the Delta Cross Channel (DCC) near Walnut Grove as part of an investigation into alternative means of operating the DCC gates to minimize effects on emigrating Sacramento River salmon and water quality in the south and central Delta. The UL-ADCPs will be deployed for at least three months; but may be retrieved and redeployed after three months depending upon flow conditions.

Three UL-ADCPs were deployed in the Sacramento River at the junction with the DCC to provide continuous velocity-profile data to monitor how the hydrodynamics at the junction varies with the operation of the gates and how the velocity variations might affect fish passage. UL-ADCPs were also deployed in the DCC and the North Fork and South Fork of the Mokelumne River. They will be flow calibrated with numerous flow measurements made with a DL-ADCP flow measuring system. The UL-ADCP flows, in combination with flow data from the existing UVMs located on the Sacramento River upstream of the DCC and downstream of Georgiana Slough, will provide the flow data to determine all of the necessary flow splits in the vicinity of the DCC.

The hydrodynamic work described above will be done jointly by USGS and DWR's Central District. Several fish movement studies will also be conducted during the deployment period, including release and recapture of spray-dyed salmon smolts, tracking of radio tagged salmon, and the use of hydroacoustics to determine fish distribution.

Juvenile Salmon Monitoring

Rick Burmester, USFWS
rbrmest@delta.dfg.ca.gov

Juvenile salmon monitoring efforts were reduced to summer background sampling (July through September). San Joaquin River beach seining has continued through the summer with three sites sampled once per week. No chinook have been detected at these sites so far this summer. Lower Sacramento River and Delta area seining continued, with one winter run captured at Clarksburg on August 22 (39 mm), and two fall run captured at Wimpy's on September 18 (132 and 162 mm). During the same period in 1999, three fall run were captured. Juvenile chinook have not been detected in the San Francisco Bay area seine since April 3.

Midwater trawling at Sacramento continued, and one 90 mm fall-run chinook salmon was captured on July 26. Between July and August 1999, 14 fall run and one late-fall run were captured.

Trawling effort at Chipps Island decreased below scheduled summer sampling, due mostly to delta smelt take limitations. Chinook captured since July 1 include eight fall run, and three adults of an unknown race. During the same period last year, one late-fall, two fall run, and three adults were captured.

Sampling efforts will increase starting October 1. Kodiak trawling at Sacramento will be conducted three days per week. Chipps Island trawling will be conducted three days per week, and will increase to seven days per week during CWT studies in December and January. Kodiak trawling at Mossdale will start on November 1 provided water levels are high enough.

On October 17, the Sacramento area beach seine will begin, with sampling conducted three days per week. On November 1, all lower San Joaquin River beach seine sites will be sampled, provided there is enough flow to access the sites that can only be reached by boat. All other beach seine sites will continue to be conducted once per week.

For a thorough review of the season's catches, see the juvenile salmon monitoring summary report on the Internet at http://165.235.108.8/usfws/monitoring/report.asp.

NEOMYSIS AND ZOOPLANKTON

Jim Orsi, DFG
jorsi@delta.dfg.ca.gov

As usual, *Neomysis mercedis* reached its highest abundance in spring. The maximum concentration found in April was slightly more than 1 m^{-3} in the Suisun Marsh sloughs. Abundance was higher in May; the maximum was 10 m^{-3} in the lower San Joaquin River and 8 m^{-3} in Suisun Slough. These values are only fractions of historical levels. On the other hand, the introduced *Acanthomysis bowmani* was abundant and reached 361 m^{-3} at Martinez and 277 m^{-3} in the low salinity zone. These are record highs for this species and compare with historical *N. mercedis* maxima.

Limnoithona tetraspina (introduced) was the most abundant copepod, reaching highest concentrations in western Suisun Bay and in Carquinez Strait. The maximum was 157,461 m^{-3} at Martinez in May. *Eurytemora affinis* was widely distributed, but did not exceed more than a few hundred per cubic meter at any location. *Pseudodiaptomus forbesi* (introduced) was also widely distributed and more abundant than *E. affinis*. It reached a maximum abundance of 2,527 m^{-3} in Disappointment Slough. The native *Diaptomus* and *Cyclops* and the exotic *Sinocalanus doerrii* were not abundant, but the native *Acartia* reached 35,206 m^{-3} in Carquinez Strait. This is the highest value recorded in several years. Cladocerans were not abundant except in the San Joaquin River at Stockton in April. Rotifers were only moderately abundant.

Summer zooplankton abundance showed unusual features. *Eurytemora* was still present in July at station S42 in Suisun Slough and appeared in August in the San Joaquin River at Stockton. It is highly unusual to find *Eurytemora* anywhere in July and August. Its presence at Stockton illustrates the upstream shift in its distribution that began in the late 1980s. (See article on page 14 for more information.) *Limnoithona tetraspina* was the most abundant copepod. Its abundance was typical of past years with maxima at 20,000 to 30,000 m^{-3}. *Pseudodiaptomus forbesi* was the second most abundant copepod and showed typical summer concentrations of a few thousand per cubic meter. On the other hand, *Acartiella* abundance was very low, only a few occurred per cubic meter and at only one station per month. This introduced species has been declining since 1998. The abundance of *Diaptomus* and *Cyclops* was very low.

Bosmina bloomed at the San Joaquin River near Stockton in June, reaching 21,000 m^{-3}, ten times higher than usual. A phytoplankton bloom may have been the cause. Cladocerans other than *Bosmina* were not abundant. Rotifer abundance was unusually low during all months.

Mysid shrimp catches were typical of summer. *Neomysis mercedis* abundance was very low in June and was zero in July and August. *Acanthomysis bowmani* was abundant in June and became more abundant in July and August. Peak abundance was 480 m^{-3}: the highest ever recorded in July in Suisun Slough. In August the distribution was disjunct with high concentrations at widespread locations: >100 m^{-3} in Montezuma and Suisun sloughs and in the San Joaquin River at Stockton, and low abundance at all other locations.

ROCK SLOUGH MONITORING PROGRAM

Jerry Morinaka, DFG
jmorinak@delta.dfg.ca.gov

A sieve-net was used to sample fish entrainment once a week at the Rock Slough intake of the Contra Costa Canal in early July. The storage unit located at the sampling site was broken into in late July, and all of the monitoring program's sampling equipment was stolen. While a replacement net was made, monitoring continued once a week using a smaller sieve-net. Very few fish were caught in August and September with the replacement net, due in part to the large amounts of *Melosira* entering the intake channel that reduced the effectiveness of the sampling net. The early phases of construction of the new fish screen facility has been postponed until 2001; therefore, the sieve-net sampling will remain scheduled for once a week through the end of the year.

OLD RIVER FISH SCREEN FACILITY (LOS VAQUEROS) MONITORING PROGRAM

Jerry Morinaka, DFG
jmorinak@delta.dfg.ca.gov

A sieve-net was used to sample fish entrainment three times a week behind the fish screens at the Old River Fish Screen Facility in early July. Frequency of sampling shifted to once a week for the remainder of July, August, and September. Sieve-net sampling in front of the facility was discontinued in early July. Five species of small juvenile fish were captured in the sieve-net behind the fish screens in July. White catfish, *Ameiurus catus* (mean length: 15 mm FL), was the predominant small juvenile fish species captured. Fish captured behind the fish screens in August and September were large juvenile and adult fish that were most likely entrained at the larval and small juvenile life stages and grew up downstream of the screen.

TOWNET SURVEY

Russ Gartz, DFG
rgartz@delta.dfg.ca.gov

The townet survey (TNS) staff conducted four, biweekly surveys in 2000: survey 1 (June 23–27), survey 2 (July 7–11), survey 3 (July 21–25), and survey 4 (August 04–08). Each survey lasted five days and sampled 32 stations with up to three, ten minute, oblique tows. Indices of abundance were calculated using 31 stations.

Results from surveys 1–3 are reported here (data from survey 4 have yet to complete quality assurance and quality control procedures), and are restricted to young-of-the-year (YOY) fish. For striped bass (*Morone saxatilis*), YOY included all bass ≤99 mm FL. For delta smelt (*Hypomesus transpacificus*), YOY included all smelt ≤69 mm FL. No striped bass >99 mm FL and only five delta smelt >69 mm FL were caught during surveys 1–3.

Striped Bass. The TNS calculates an annual index of abundance for striped bass when the average size is 38.1 mm FL (Chadwick 1964; Turner and Chadwick 1972), attained during surveys 2 and 3 in 2000 (Table 1). The annual index of abundance was interpolated from the log-transformed indices and "set" at 5.5 on July 18, 2000. Although the 2000 index is more than twice the 1999 index of 2.2 and above 5.0 for the first time since 1996, it is well below the highest index of 117.2 in 1965 (Figure 1). The 2000 index may indicate an increase in the stock, as it is more than double the average index from 1996–1999 (1.9). However, there are insufficient data to determine if the stock is recovering.

Table 1 Mean length, standard deviation, sample size, and survey indices for striped bass and delta smelt during townet surveys 1–3, 2000

	Survey 1	*Survey 2*	*Survey 3*
Striped bass			
Mean length (mm FL)	21.9	30.0	42.9
SD (mm)	7.0	9.8	12.5
N	958	547	149
Survey index	15.5	13.1	3.3
Delta smelt			
Mean length (mm FL)	31.7	33.2	41.0
SD (mm)	7.3	8.3	8.0
N	186	227	213
Survey index	7.8	8.1	7.8

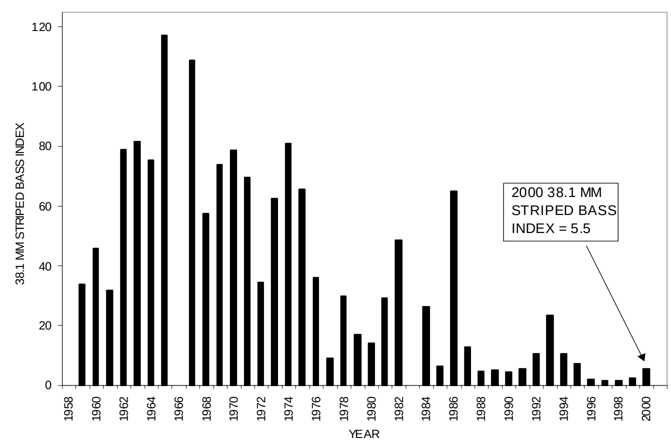

Figure 1 Midsummer townet survey indices of abundance (at 38.1 mm FL) for striped bass from 1959–2000. Note no survey was conducted in 1966, no index was calculated in 1983, and the index was estimated in 1995.

Distribution of striped bass during the 2000 TNS showed little variation between surveys (Table 2). Striped bass were found predominately in Montezuma Slough, Suisun Bay, and the Sacramento and San Joaquin rivers, with the highest percentage of the survey index in Montezuma Slough during any survey (Table 2).

Table 2 Percentage of survey index by area for striped bass and delta smelt for townet surveys 1–3, 2000

Species and area	*Survey 1*	*Survey 2*	*Survey 3*
Striped bass			
Montezuma Slough	27.2	29.9	35.2
Suisun Bay	24.6	18.1	15.6
Sacramento River	18.4	24.0	20.8
San Joaquin River	18.2	26.3	24.3
East Delta	9.3	1.8	4.2
South Delta	2.2	0.0	0.0
Delta smelt			
Montezuma Slough	0.8	1.4	1.2
Suisun Bay	25.0	28.4	77.0
Sacramento River	68.6	68.6	17.5
San Joaquin River	5.8	1.6	4.4
East Delta	0.2	0.0	0.0
South Delta	0.0	0.0	0.0

Delta Smelt. The TNS calculates the annual index of abundance for delta smelt differently than for striped bass. The annual index is the average of the survey indices for the first two surveys. The delta smelt TNS index for 2000 is 8.0; somewhat lower than the 1999 index of 11.9 (Figure 2).

Distribution of delta smelt shifted from the Sacramento River to Suisun Bay as the 2000 TNS progressed (Table 2). Combined, these two areas accounted for 93.6% to 97% of the survey index.

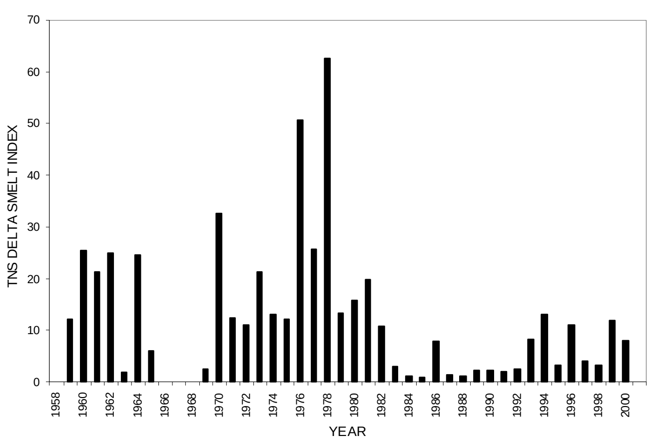

Figure 2 Midsummer townet survey indices of abundance for delta smelt from 1959–2000. Note no indices are available from 1966–1968.

References

Chadwick HK. 1964. Annual abundance of young striped bass, *Roccus saxatilis,* in the Sacramento-San Joaquin Delta, California. California Fish and Game 50(2):69–99.

Turner JL, Chadwick HK. 1972. Distribution and abundance of young-of-the-year striped bass, *Morone saxatilis,* in relation to river flow in the Sacramento-San Joaquin Estuary. Trans Am Fish Soc 101(3):442–52.

REAL TIME MONITORING

Kevan Urquhart, DFG
kurquhar@delta.dfg.ca.gov

The real-time monitoring (RTM) program was successfully concluded on June 30. The RTM project work team met in August to discuss the proposed 2001 program, and approved it with one additional special study. We were unable to complete the special study proposed for 2000 to evaluate the efficiency of a larger Kodiak trawl compared to the standard one in use by the IEP due to inadequate lead time.

Four special studies are planned for 2001. Two will evaluate a larger Kodiak trawl and 20-mm townet compared to the standard sized gear, and two others will evaluate increased effort over two separate weeks, targeting high and low fish density for the standard gears at the Sacramento River near Sherwood Harbor, and various South Delta stations, respectively. These studies have been designed in response to questions about whether sufficient sampling is being conducted at key sites, or whether larger gear would increase sampling efficiency and decrease the number of zero data values. Both of these issues could be contributing to the lack of strong predictive correlations to date between field data and salvage for splittail, salmonids, and delta smelt.

DETERMINATION OF ADULT DELTA SMELT HATCH DATES USING MICROSTRUCTURAL OTOLITH ANALYSIS

Lenny Grimaldo, DWR; Matt Nobriga, DWR; and Anna Holmes, DFG
lgrimald@water.ca.gov

The purpose of this project was to examine the feasibility of aging pre-adult delta smelt to determine individual hatch dates and to determine whether the distribution of hatch dates can be correlated with such environmental variables as food availability, temperature, or exports.

Transverse sections were taken of the otoliths of 100 adult delta smelt collected during the 1998 fall midwater trawl survey. Of these 100 sectioned otoliths, only five had circulli (daily rings) that could be confidently counted from the core to the outer edge. The majority of the remaining 95 otoliths were not readable beyond 100 circulli because the rings near the outer edge became indistinguishable. Although previous studies have shown daily circulli can be counted on otoliths of juvenile delta smelt, this study suggests daily counts on otoliths of adult delta smelt are not feasible using standard sectioning techniques.

SAN FRANCISCO BAY FISHERIES MONITORING

Kathy Hieb, DFG
khieb@delta.dfg.ca.gov

IEP has been sampling fishes and macroinvertebrates in San Francisco Bay monthly since 1980. Water temperature is one of the key factors controlling seasonal movements of species in the bay. As temperatures reach an annual maximum in July, August, or September, several species including Pacific herring and English sole, migrate from South and San Pablo bays to Central Bay, and some of these begin their annual emigration to the nearshore coastal area. Age 0+ English sole, a species that uses the bay as a nursery for its first year, were widely distributed from South to San Pablo bays in June. By July, they were no longer collected in South Bay, and few were collected in San Pablo Bay. In August, all English sole were collected in Central Bay.

Dungeness crab were widely distributed from South to San Pablo bays in July, but were collected only at our station south of the Dumbarton Bridge in August and were no longer collected anywhere in South Bay in September. Meanwhile, their distribution continued to expand upstream to Carquinez Strait and Suisun Bay through the summer. From May to September, we collected 520 age-0 Dungeness crab, similar to the 1999 catch for this period (491), and the highest catch since 1988.

Age-0 longfin smelt started to move upstream from San Pablo Bay in July, and in August fish were collected in the lower Sacramento River, near Sherman and Decker islands. Central Bay catches decreased in September, as some fish most likely moved from the Bay to the nearshore areas. Our combined otter and midwater trawl age-0 catch was 873 for May through September, which is much lower than either the 1998 catch (2,923) or 1999 catch (4,804) for the same months.

The 2000 age-0 starry flounder catch was also lower than recent years. Only seven age-0 fish were collected through September, which is our lowest catch since 1992, when no age-0 fish were collected. Catches were relatively high from 1996 to 1999, as we collected between 127 and 226 age-0 fish annually. The 1998 and 1999 year classes have been more common in the bay this year than the 2000 year class. We collected two starry flounder >400 mm TL this summer; in the past ten years, we collected only six fish >400 mm TL, while from 1980–1989 we collected 184 starry flounder >400 mm TL.

The introduced goby, *Tridentiger barbatus*, was first collected in the San Joaquin River near Antioch in November 1997. About 65 have been collected from San Pablo Bay to Chipps Island since then. In September 2000, ten small *T. barbatus* were collected in the Sacramento River near Sherman Lake and another five were collected in the Sacramento River near Decker Island. Thirteen of these 15 fish were only 15 to 20 mm TL. These are the smallest *T. barbatus* known to have been collected in the estuary. In contrast, all the larger (>70 mm TL) *T. barbatus* have been collected in Suisun Bay. Intermediate sized fish have been widely distributed from San Pablo Bay to the western Delta, although all the *T. barbatus* collected upstream of Chipps Island were <40 mm TL.

Also of interest, in August we collected the first downstream migrating adult Chinese mitten crabs of the season in Honker Bay and the lower Sacramento and San Joaquin rivers. In September, we also collected a few mitten crabs in Suisun Bay. The sex ratio was almost equal among the crabs collected in August (five females, six males) and September (six females, five males).

In July, we began to identify "jellyfish" in the field, using John Rees' recently developed key. We collected *Aurelia* spp. and *Polyorchis penicillatus* in Central and San Pablo bays and large numbers of the introduced *Maeotias marginata* in Suisun, Grizzly, and Honker bays in August and September.

SHERMAN ISLAND AGRICULTURAL DIVERSION EVALUATION

Matt Nobriga and Zoltan Matica, DWR
mnobriga@water.ca.gov

We sampled the relative abundance and species composition of fishes entrained in side-by-side diversion siphons in Horseshoe Bend on the lower Sacramento River. The Horseshoe Bend facility consists of two screened 24-inch diversion pipes and one unscreened 24-inch pipe. During this evaluation, only one of the screened siphons and the unscreened siphon were operated. The siphons were sampled simultaneously using modified fyke nets (1600 µm mesh) which fit completely over the outfall side of the pipes so that all water coming through the siphons was filtered before entering the irrigation canal. Flow through the pipes was estimated using General Oceanics flowmeters set in the mouth of each net. The diversions were continuously sampled from 0944 on July 12, 2000 to 0637 on July 14, 2000. The nets were checked approximately every hour for a total of 37 paired samples.

The fish and mitten crab catch is shown in Table 1. Young-of-the-year shimofuri goby, yellowfin goby, and striped bass were the dominant species in the catch, with hundreds of individuals of each collected during the survey. Only 12 delta smelt and one splittail were collected, an insufficient catch to discern individual trends for these species.

Overall, fish density (CPUE, expressed as total fish per cubic meter of water sampled) was much lower in the screened diversion than in the unscreened diversion (Figure 1). Eighty-one percent of the screened diversion samples had no fish catch (not even larvae). In contrast, all 37 unscreened samples contained at least one fish. All 12 delta smelt and the splittail were caught in the unscreened diversion.

Fish catch in the unscreened diversion showed an obvious day-night trend (Figure 1), with noticeably higher CPUE during the night. The data also suggest a tidal effect on catch, with CPUE increasing during rising tides, peaking near the maximum high tide, and declining thereafter. However, this trend was only apparent at night. If springtime agricultural irrigation needs are sufficient, DWR plans to repeat this evaluation next April or May when both young-of-the-year chinook salmon and delta smelt are present in the western Delta.

Table 1 Total fish collected in the screened and unscreened diversion siphons at Sherman Island, July 12–14, 2000

Common name	*Scientific name*	*Number collected*
shimofuri goby	*Tridentiger bifasciatus*	452
yellowfin goby	*Acanthogobius flavimanus*	333
striped bass	*Morone saxatilis*	302
threadfin shad	*Dorosoma petenense*	60
white catfish	*Ameiurus catus*	32
delta smelt	*Hypomesus transpacificus*	12
tule perch	*Hysterocarpus traski*	10
rainwater killifish	*Lucania parva*	10
American shad	*Alosa sapidissima*	7
channel catfish	*Ictalurus punctatus*	6
black crappie	*Pomoxis nigromaculatus*	4
lamprey ammocoete	*Lampetra spp.*	3
prickly sculpin	*Cottus asper*	3
largemouth bass	*Micropterus salmoides*	2
goldfish	*Carassius auratus*	2
starry flounder	*Platichthys stellatus*	2
splittail	*Pogonichthys macrolepidotus*	1
mosquitofish	*Gambusia affinis*	1
Sacramento blackfish	*Orthodon microlepidotus*	1
bigscale logperch	*Percina macrolepida*	1
Chinese mitten crab	*Eriocheir sinensis*	1

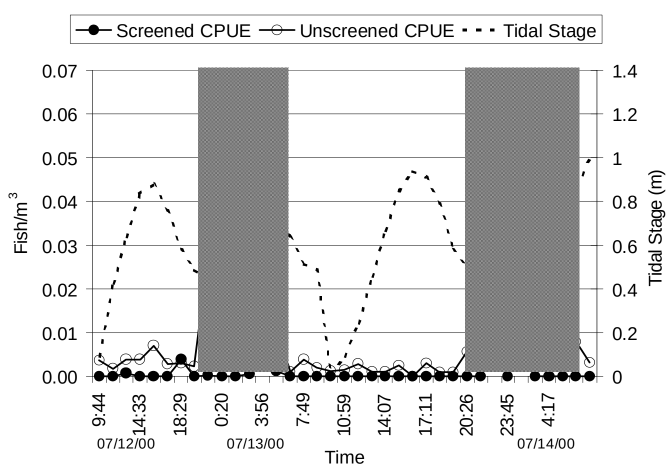

Figure 1 Fish density in screened and unscreened diversions at Horseshoe Bend and tidal stage at Threemile Slough, July 12–14, 2000. The periods between sunrise and sunset are shaded gray. Except for 16 of the white catfish, all fish were young-of-the-year.

SPLITTAIL INVESTIGATIONS

Randall D. Baxter, DFG
rbaxter@delta.dfg.ca.gov

Data collection began in July to document the shallow water habitat associations of juvenile splittail in the Sacramento River. The 9.5-km study area chosen stretches from the upstream limit of the Sutter Bypass confluence downstream to about 4 km below the Feather River confluence. Both physical and biological factors contributed to the selection of this study area. The shoreline configuration results from both natural and man-made features: willow, cottonwood, oak, and other trees reinforce some banks, whereas riprap and rock wing-deflectors protect others. Proximity to potential splittail spawning areas in the lower Sutter Bypass improved the likelihood of encountering juvenile splittail during the summer. Early sampling reinforced this belief (see *IEP Newsletter* spring 2000). Initially, both beach seining and boat electrofishing were planned to sample fish, but scheduling conflicts prevented use of the electrofishing boat.

The first steps, habitat characterization and mapping, began in early July after a delay due to backordered equipment. Sixty-four shoreline reaches were categorized as one of five habitat types based upon river current and channel characteristics: cove and backwater, eddy, inside edge, outside edge, and straight edge.

Daily fish sampling goals were to seine two sites within each of five habitats, one of each habitat type. Sampling order and habitats were randomly selected with replacement for sampling each day. Within habitats, sample sites were located using random numbers as a proportion of the known habitat length and measuring from the downstream boundary to the top with a differentially corrected GPS. Up to four randomly selected sites were evaluated for seining suitability for each sample in each habitat. The first two suitable sites were sampled with a 20-m x 1.8-m seine (about 6-mm mesh) set from a boat. If none of the first four sites was suitable, a sample was skipped and the process was repeated. If none of the second four sites was suitable, the second sample and the habitat was skipped. In a few cases, no suitable seining locations were found and the habitat was dropped from sampling. In addition to recording species caught and fish lengths for each habitat, we are also tracking how many alternate sites were evaluated before sampling occurred, whether sampling was effective (cobble bottoms lift the lead-line and reduce effectiveness) and the time necessary to conduct this type of sampling.

Fish sampling has been challenging due to currents and bottom materials (riprap, tree limbs, or mud). Only two splittail have been caught since random sampling began in August (juveniles are big and fast). Splittail numbers will probably not be sufficient to evaluate habitat associations based on this sampling. Our sampling has detected good numbers of threadfin shad across all habitat types. Wakasagi were common in eddies below the confluence of the Feather River in August, but have rarely been caught in early September. Sacramento suckers and Sacramento pikeminnows have been the dominant native fishes collected. A few tule perch and prickly sculpin have also been collected. Flow reductions and periodically decreasing water levels that began the first of September have reduced noticeably the numbers of fish caught in shallow water. A full report will occur in a future *IEP Newsletter* article.

SHALLOW WATER HABITAT METHODS AND PREDATION STUDIES

Mike Chotkowski, USBR; and Matt Nobriga, DWR
mnobriga@water.ca.gov

The Shallow Water Habitat Methods Project. The 2000 field season, which extended from late May through September, is complete. We have done preliminary work with minnow seine, block net (seine depleted), and boat-mounted electrofishing sampling methods. Most progress has been made with the seine; an article discussing some properties of this gear on sandy shores will be submitted for the winter 2001 *IEP Newsletter.*

Predation Project. The laboratory work (mainly gut content work ups) for the project is just beginning, and is expected to extend through the end of the year. This work relies on the methods project to provide most of the specimens. In addition, several days per month are being devoted to collecting paired samples of the nearshore fish fauna (daytime) and likely piscivores (late day, dusk, evening) from fixed sites in the Delta. Nearshore faunal samples are being collected using the seine or blocknets, while likely predators are being collected by gillnet. A large number of fishes has been collected this year for study.

An Extensive *Microcystis aeruginosa* Bloom returns to the Delta

M. Scott Waller, DWR
swaller@water.ca.gov

Microcystis aeruginosa, a blue-green algae with the potential to clog filters and cause taste and odor in drinking water, returned to the Delta in 2000. While conducting compliance monitoring in mid-July, field staff observed initial patches of an algal bloom in the South Delta. The bloom was characterized by green, irregularly shaped flakes, approximately one-quarter to three inches in diameter, floating on or near the water surface. Grab samples were collected and phytoplankton analysis confirmed the organism as *M. aeruginosa*. A similar bloom spread extensively throughout the central and southern Delta during the late summer and early fall of 1999.

Because the alga is known to produce toxins called microcystins and has the potential to adversely affect water supply and water treatment facilities, staff conducted a follow up special study on July 27 that included 15 stations throughout the central and southern Delta (the area leading to Clifton Court forebay and ultimately to the Banks Pumping Plant). Phytoplankton samples were collected for identification, and *M. aeruginosa* was found in all samples, with the highest concentrations observed in Old River between Sand Mound Slough and Rock Slough. A dense distribution also existed at Light 5 in the Stockton Ship Channel and at the juncture of the San Joaquin and Mokelumne rivers. Nutrient analysis, fluorometry, timed tows, and chlorophyll extractions were conducted to quantify the intensity of the bloom. Phytoplankton samples collected during subsequent monitoring also confirmed the presence of *M. aeruginosa* in the Sacramento River at Collinsville and in Benicia Harbor.

Water quality conditions similar to those that contributed to the formation of the bloom in 1999 returned this year. During both years there was a high nutrient input from a wet spring followed by a dry summer with warm water temperatures and high water clarity. These conditions evidently play a crucial role in determining bloom potentials. Adequate nutrient (specifically nitrogen) loading during a wet spring followed by low discharge (low flushing) conditions in late summer and early fall dictate the magnitude and persistence of blooms (Paerl 1987). Water quality in the interior Delta is typically influenced by low summer and fall stream inflow, longer residence times than regions in the Sacramento and San Joaquin rivers, and higher phytoplankton biomass (Lehman 1996). Lower levels of total suspended solids in the study area may have also led to the increased light penetration measured throughout most of the interior Delta from late spring to early summer. These factors, combined with higher than normal water temperatures and increased nutrients in the water column, may have contributed to the formation of the algal bloom.

References

Paerl HW. 1987. Dynamics of blue-green algal (*Microcystis aeruginosa*) blooms in the Lower Neuse River, North Carolina: Causative factors and potential controls. Water Resources Research Institute of the University of North Carolina, Report No. 229.

Lehman PW. 1996. Water quality conditions in the Sacramento-San Joaquin Delta, 1970–1993. p 31–42, 80.

DSM2 Project Work Team Update

Chris Enright, DWR
cenright@water.ca.gov

The Delta Simulation Model 2 (DSM2) project work team is nearing completion of a two-year, multi-agency and stakeholder effort to improve the calibration of the DSM2 model based on improved bathymetry and Delta flow measurement data. Participants include staff from USGS, USBR, DWR, Metropolitan Water District, and Contra Costa Water District. The team has completed calibration of the hydrodynamics portion of the model and is working on the salinity module calibration. The team conducted 57 hydrodynamics calibration runs, each considering four, two-week historical periods between 1988 and 1998. The team employs conference calls and a web site to conduct its day-to-day work.

A complete accounting of the calibration process is documented at http://www.iep.water.ca.gov/dsm2pwt. By clicking on the text “Run 57” within the web site you may view the results of the final hydrodynamics calibration run with comparisons of model flow and water level output to field data.

The team expects to complete the salinity transport module calibration in October. A long-term verification, final report, and user guide will be also be produced to help users of model results interpret modeling study output. Participation by several modeling experts through an interagency team approach has yielded a superior model calibration and generated trust and common understanding about the model and its appropriate use for planning and project operation.

PAPER ACCEPTED FOR JOURNAL PUBLICATION

STRUCTURES TO PREVENT THE SPREAD OF NUISANCE FISH FROM LAKE DAVIS, CALIFORNIA

Lauren Buffaloe, DWR
buffaloe@water.ca.gov

Kudos to Douglas Rischbieter of the California Department of Water Resources, Division of Planning and Local Assistance. Doug's paper "Structures to prevent the spread of nuisance fish from Lake Davis, California," was published in the *North American Journal of Fisheries Management*[1]. The abstract appears below.

Methods to contain the spread of nuisance or otherwise undesirable fish species are relatively limited. I describe an unconventional method used to help restrict the movement of northern pike *Esox lucius* from a mountain reservoir into downstream water. Reservoir managers designed, installed, and monitored steel structures ("graters") that served to increase the likelihood that fish entrained in discharge from Lake Davis (Plumas County, Calfornia) would incur fatal trauma. Seven species of fish, cumulatively hundreds of individuals, were observed killed by the graters. Injuries induced included dismemberment, lacerations, abrasions, and contusions. No failures to induce fatal trauma to entrained fish were observed, though a few crayfish *Pacifasticus* spp. remained alive after only partial dismemberment. The graters were fabricated from commercially available steel and sized to fit over 10-inch and 30-inch discharge ports of the outlet works. Reservoir and fishery managers could adapt these designs for use at a variety of other outlet facilities where interim measures are desired to contain the spread of nuisance fish.

Limited reprints of the paper are available by contacting Doug by e-mail at dougr@water.ca.gov.

1. Full reference: Rischbieter D. 2000. Structures to prevent the spread of nuisance fish from Lake Davis, California. North Am J Fish Manage 20:784–790.

NEWS FROM AROUND THE ESTUARY

FRESHWATER INVASION OF *EURYTEMORA AFFINIS*

James J. Orsi, DFG
jorsi@delta.dfg.ca.gov

Eurytemora affinis (*Eurytemora*) is a copepod and a preferred food for larval striped bass and delta smelt. It has undergone a long-term decline throughout the estuary which became severe in 1988, two years after the arrival of the Asian clam, *Potamocorbula amurensis* (Kimmerer and others 1994). *Eurytemora* is now abundant only in winter and spring and is virtually absent from May or June to November. The summer collapse is system-wide; it disappears from the Napa River (A. Rockriver, personal communication, see "Note"), Cache Slough, Suisun Bay, and the Delta. *Eurytemora* was originally a brackish water species that reached highest abundance in the low salinity zone (LSZ) (0.6 to 6.0 psu, 1.0 to 10.6 mS/cm), but in 1986, it began an invasion of fresh water. This copepod also has invaded fresh water in other locations such as the Great Lakes, the Mississippi Valley, and Holland (Lee and Bell 1999). Nowhere else, however, has there been a long-term monitoring program in place to document an invasion.

Data from stations 92, the San Joaquin River at Stockton, and M10, Disappointment Slough, show the freshwater movement (Figure 1). The mean abundance at these two stations was combined for (1) March through May and (2) June-August and calculated and plotted for each year from 1972 through 1999. Mean *Eurytemora* abundance was $<10\ m^{-3}$ in both periods from 1972 to 1985. In spring 1986, abundance surged to $>50\ m^{-3}$ and to a peak of $>1{,}000\ m^{-3}$ in spring 1994. It remained high in springs of subsequent years with the exception of 1998. Abundance was higher in the springs of dry years after 1986 (1987–1992 and 1994) than in wet years, but abundance in wet years was much higher after 1986 than before 1987. Summer abundance also rose in 1986 and 1987 but declined in 1988 and remained low thereafter. The summer decline after 1987 has not yet been explained.

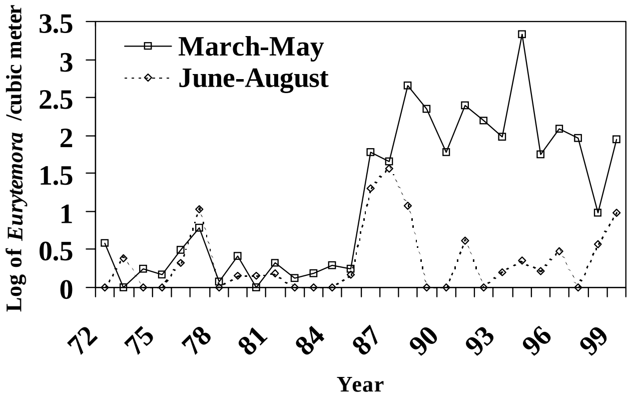

Figure 1 Mean March–May and June–August *Eurytemora* abundance (per m^3) in Disappointment Slough and in the San Joaquin River at Stockton, 1972–1999

Before 1986, *Eurytemora* abundance was highest in Suisun Bay at mean specific conductance (ECs) of almost 4.0 mS/cm (Figure 2). After 1986, *Eurytemora* abundance was low at these ECs and was highest at Stockton in fresh water (Figure 3). This indicates that not only has *Eurytemora* invaded fresh water, but that conditions at Stockton are more favorable than farther downstream even in stretches of the San Joaquin River that contain fresh water. Although chlorophyll is higher at Stockton than in the rest of the San Joaquin River and in Suisun Bay, chlorophyll was even higher at Stockton in the early 1970s when *Eurytemora* was rare. What happened in 1986 to cause the increase in *Eurytemora* at Stockton is unknown.

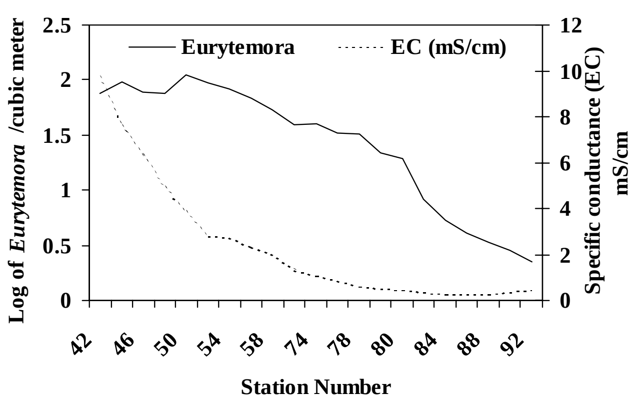

Figure 2 Mean spring *Eurytemora* abundance (per m^3) at each Suisun Bay and San Joaquin River station from Martinez (42) to Stockton (92), 1972–1985

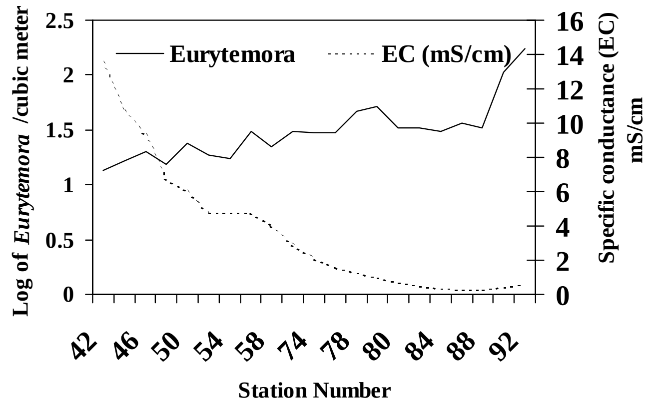

Figure 3 Mean spring *Eurytemora* abundance (per m^3) at each Suisun Bay and San Joaquin River station from Martinez (42) to Stockton (92), 1986–1999

Freshwater invasions by *Eurytemora* in other areas have been sudden events apparently caused by introductions as happened in the Great Lakes and in Mississippi Valley reservoirs (Lee and Bell 1999). The situation in the estuary is different in that *Eurytemora* has always been present at the interface between salt and fresh water. “Always” may mean for a considerable stretch of geological time if *Eurytemora* is native to the estuary, or for only somewhat more than a century if it was inadvertently introduced along with striped bass or American shad. The sudden increase in fresh water in 1986 suggests that something “new” happened, that is, an unprecedented event that enabled *Eurytemora* to become and remain more abundant in fresh water.

REFERENCES

Kimmerer WJ, Gartside E, Orsi JJ. 1994. Predation by an introduced clam as the likely cause of substantial declines in zooplankton of San Francisco Bay. Marine Ecology Progress Series 113:81–93.

Lee C, Bell MA. 1999. Causes and consequences of recent freshwater invasions by saltwater animals. Trends in Ecology and Evolution 14:284–8.

NOTE

Andy Rockriver (California Department of Fish and Game). 20-mm survey database.

CONTRIBUTED PAPERS

MYSID SHRIMPS IN SUISUN MARSH

Stephanie M. Carlson and Scott A. Matern
Department of Wildlife, Fish, and Conservation Biology
University of California, Davis
samatern@juno.edu

INTRODUCTION

Mysid shrimp belong to the malacostracan order Mysidacea, and are often called opossum shrimp due to the ventral brood pouch where they carry their young (Orsi and Mecum 1996). On a survey of San Francisco and San Pablo bays in 1912 and 1913, Tattersall (1932) identified five species of mysids: *Neomysis mercedis*, *N. rayi*, *N. kadiakensis*, *N. costata* (now *Holmesmysis costata*), and *N. macropsis* (now *Alienacanthomysis macropsis*). Of the five mysids originally identified by Tattersall, all but *N. rayi* were caught in 1977 (Orsi and Knutson 1979).

Mysids are important components of estuarine food webs as both producers and consumers (Roast and others 1998). These shrimps are a common prey item of numerous fish species of the San Francisco Estuary, including yellowfin goby (*Acanthogobius flavimanus*; Feyrer 1999), striped bass (*Morone saxatilis*; Stevens 1966; Thomas 1967), Sacramento splittail (*Pogonichthys macrolepidotus*; Daniels and Moyle 1983; Herbold 1987), chinook salmon (*Oncorhynchus tshawytscha*; Sasaki 1966), warmouth (*Chaenobryttus gulosus*; Turner 1966a), white catfish (*Ictalurus catus*; Turner 1966b), prickly sculpin (*Cottus asper*; Feyrer 1999), black crappie (*Pomoxis nigromaculatus*; Turner 1966a), starry flounder (*Platichthys stellatus*; Herbold 1987; Feyrer 1999), green sturgeon (*Acipenser medirostris*; Radtke 1966) and white sturgeon (*Acipenser transmontanus*; Radtke 1966). Mysid shrimp also comprise a significant portion of the diets of two caridean shrimp existing in the estuary, *Crangon franciscorum* and *Palaemon macrodactylus* (Sitts and Knight 1979).

Recent decreases in mysid abundance in fish diets in the San Francisco Estuary, and specifically Suisun Marsh, are probably related to the introduction of the Asian clam, *Potamocorbula amurensis* (Feyrer 1999). The Asian clam was first detected in 1986 and by 1987 had become abundant (Kimmerer and others 1994; Nichols and others). By 1988, within its range, chlorophyll levels and the abundance of three copepods had decreased by 53% to 91% (Kimmerer and others 1994). The primary result is that the clam now controls the lower strands of the food webs in Suisun Bay, the western Delta, and possibly San Pablo Bay (Orsi 1996). Because the clam removes so much of the phytoplankton from the estuary, it may have indirectly created a competitive advantage for the recently introduced Asian mysid, *Acanthomysis bowmani*. *Acanthomysis bowmani* appears better adapted to surviving at low food concentrations than the native mysid, *N. mercedis*, as shown by increasing abundance, while *N. mercedis* has been decreasing (Orsi 1996).

Neomysis mercedis ranges from Prince William Sound, Alaska to below Point Conception, California (Orsi and Knutson 1979). Within the San Francisco Estuary, *N. mercedis* reaches its highest abundance in the western Delta and Suisun Bay (Orsi and Knutson 1979; Orsi 1999), where it is an important component of estuarine food webs (Siegfried and Kopache 1980). This mysid was historically the most important and most common prey item of young-of-the-year (YOY) striped bass (Stevens 1966). Herbold (1987) found that many of the common fish species of Suisun Marsh preyed on *N. mercedis* during periods of high mysid abundance.

The Asian mysid, *A. bowmani*, was probably introduced to the San Francisco Estuary via ballast water dumping (Modlin and Orsi 1997). *Acanthomysis bowmani* was rare in 1992 and 1993 and became more abundant than *N. mercedis* in 1994–1996 (Orsi 1997), but it has yet to achieve the abundance shown by *N. mercedis* in the 1970s and most of the 1980s (Orsi 1999). *Acanthomysis bowmani* appears to be more euryhaline than *N. mercedis* (Orsi 1997). In 1992–1996, *N. mercedis* abundance peaked in May though June while *A. bowmani* abundance peaked in June through September (Orsi 1997). Because *A. bowmani* is found in greater abundance in late summer and early fall than the native mysid (Orsi 1997), it may actually benefit YOY striped bass that are not big enough to prey on mysids in spring. In addition, *A. bowmani* is smaller than *N. mercedis* (Orsi 1997), possibly making it more available to YOY striped bass (Bennett and Moyle 1996).

Both *A. bowmani* and *N. mercedis* are concentrated in the low salinity zone (0.4 to 0.6 psu) and Suisun Marsh, where they may compete for food. Indeed, the decline of the native mysid in 1994, the first year that *A. bowmani* was abundant, suggests competition (Orsi 1997).

Many of the possible competitive advantages *A. bowmani* holds over *N. mercedis* are linked to reproduction and fecundity issues. The eggs of *N. mercedis* are 1.2 times as large as those of *A. bowmani*, and therefore develop more slowly. The alien mysid carries more eggs at a given length and is able to reproduce at a smaller size than *N. mercedis*. A combination of these factors may give *A. bowmani* a competitive advantage (Orsi 1997). Because egg development time and thus birth rate are related to temperature, *A. bowmani* may have a greater advantage at higher temperatures (J. Orsi, personal communication, see "Note").

Acanthomysis bowmani appears to be replacing *N. mercedis* in the San Francisco Estuary (Feyrer 1999). Because of the importance of Suisun Marsh as a nursery for many species of fish, and the historical importance of *N. mercedis* in the diet of many juvenile fish, the introduction of *A. bowmani* may be affecting the estuarine food web. This study was designed to determine abundance of the mysid shrimp species of Suisun Marsh and to examine the responses of these species to several environmental variables.

MATERIALS AND METHODS

Field Collection

Zooplankton from Suisun Marsh was sampled via Tucker trawls in coordination with the larval fish sampling conducted by the University of California Davis (UCD). Weekly collections were made beginning February 4, 1999, and ended on May 6, 1999, when IEP managers concerned about delta smelt take levels terminated sampling. A 505-micron mesh net (3-m long with a 0.362-m^2 mouth opening) mounted on a sled was towed at approximately 4 km/h. Three replicate, five-minute tows were performed in each of the following sloughs: Suisun, Spring Branch, Denverton, Nurse, and Cordelia. During each of the 15 tows, environmental data including tidal stage, temperature (°C), salinity (‰), specific conductance (µS) and water transparency (Secchi depth in cm) were recorded. Zooplankton samples were preserved in the field in a 5% formalin solution combined with Rose Bengal dye.

Mysid Identification

Using a dissecting scope, mysids were identified to species based on differences in telson morphology. The total number of mysids in each sample were counted and identified unless the samples were very large. For samples with greater than 200 mysids, a subsample of 100 was identified, and the results extrapolated to estimate the total of each species.

Data Analysis

Canonical correspondence analysis (CCA) is a direct gradient analysis that handles intercorrelated environmental variables and quantitative noise in species catch data exceptionally well (Palmer 1993). It linearly combines the environmental variables so as to maximally separate the species niches along a series of ordination axes. Subsequent axes are uncorrelated with those previously extracted and each provides less additional species niche separation (ter Braak 1986; ter Braak and Verdonschot 1995). Points representing sites and species (weighted averages) can then be plotted against the first two ordination axes, resulting in an ordination diagram. In these diagrams the environmental variables can be represented by arrows; the length of each arrow is proportional to the importance of that variable in separating species niches and the direction of each arrow indicates the axis along which values for that variable increase in the diagram (ter Braak 1986).

In this study, the CANOCO software package was used to perform a CCA relating log(x+1) transformed mysid catch data to the following environmental variables: time of day, temperature, salinity, specific conductance, Secchi depth, tide direction, and date. Before the analysis, species and environmental data from the three replicate samples in each slough were pooled. Then, using forward selection, the environmental variable explaining the most variation in mysid catch was tested for significance ($P < 0.05$). If significant, it was included in the model and the next environmental variable was tested. Selection continued until a variable failed the test of significance.

RESULTS AND DISCUSSION

Five mysid shrimp species were found in Suisun Marsh: *N. mercedis*, *N. kadiakensis*, *Acanthomysis bowmani*, *Alienacanthomysis macropsis*, and one distinct but still unidentified species. Only results for the four identified species are reported here. Significant environmental variables were date, Secchi depth, and temperature. The first CCA ordination axis (eigenvalue = 0.121) explained 16.1% of the variance in the species data and the second CCA ordination axis (eigenvalue = 0.063) explained an additional 8.4% of the variance.

Environmental Variables. While some of the environmental variables changed appreciably during the sampling period (temperature min. = 8.5 °C, max. = 20.5 °C, mean = 12.8 °C), others showed little change (salinity min. = 0.2‰, max. = 2.1‰, mean = 0.8 ‰). The ordination diagrams (Figures 1 and 2) indicate that date and temperature were positively correlated. The arrow for Secchi depth, pointing nearly in the opposite direction, indicates that water clarity generally decreased as the season progressed.

Site Scores. As expected, there was a distinct trend with time (Figure 1). Samples collected early in the season are on the right and progressively later samples are further to the left, in the direction of the date arrow. There were no obvious trends among sloughs, suggesting that during the course of this study there was little spatial heterogeneity in environmental conditions or catch within Suisun Marsh.

Species Scores. The ordination diagram for species scores (Figure 2) and the graph of weekly mysid densities (Figure 3) both show that the four identified mysids exhibited peaks in abundance at different times. *Alienacanthomysis macropsis* appeared early in the season (just three individuals), followed by *N. kadiakensis* (264 individuals). The two most abundant species, *A. bowmani* (2,880 individuals) and *N. mercedis* (4,298 individuals) both peaked later in the season, but the proximity of their species scores to the origin indicates that both species were found in many samples (and thus under a wide variety of the environmental conditions measured during this study). The proximity of the species scores of *A. bowmani* and *N. mercedis* to each other is also noteworthy; these species responded similarly to the environmental conditions present in Suisun Marsh during the sampling period.

Thus, it appears that, at least under the limited range of environmental conditions present during this study, the abundant native and alien mysids responded similarly to environmental conditions. Those variables typically had similar effects throughout the entire marsh. More sampling, under more diverse environmental conditions, would greatly aid in identifying niche differences between the mysid shrimps of Suisun Marsh.

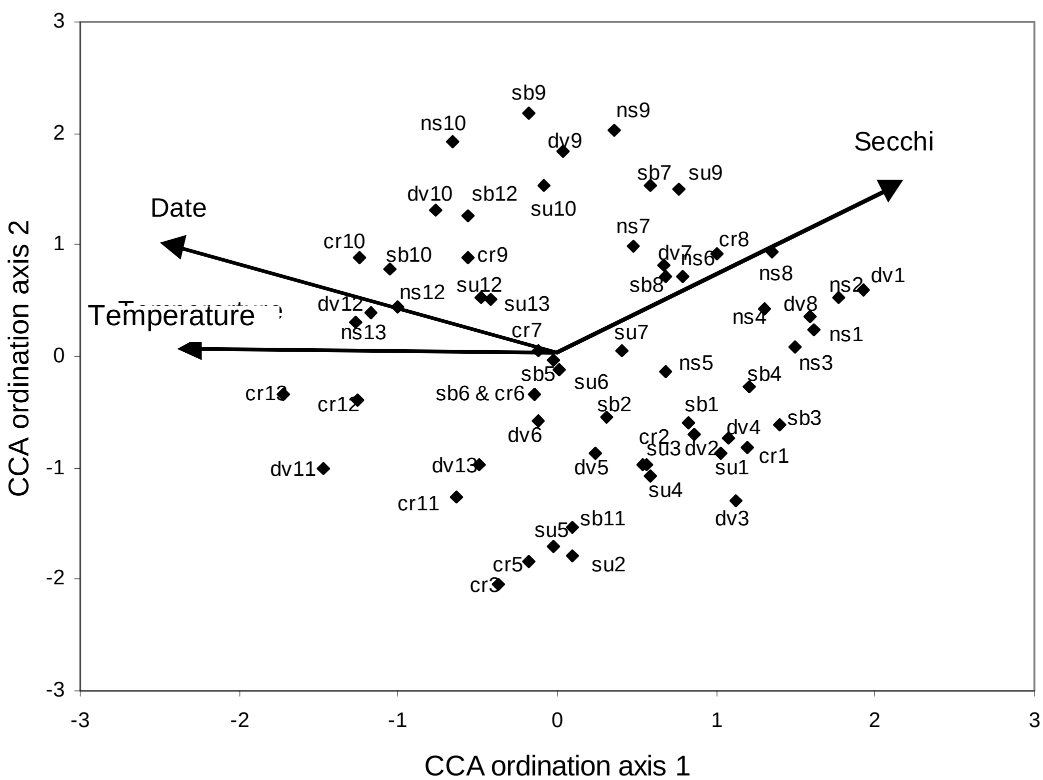

Figure 1 CCA ordination diagram for sites. Sites are designated by a two-letter abbreviation for the slough (cr = Cordelia, dv = Denverton, ns = Nurse, sb = Spring Branch, su = Suisun) followed by a number indicating the sampling week.

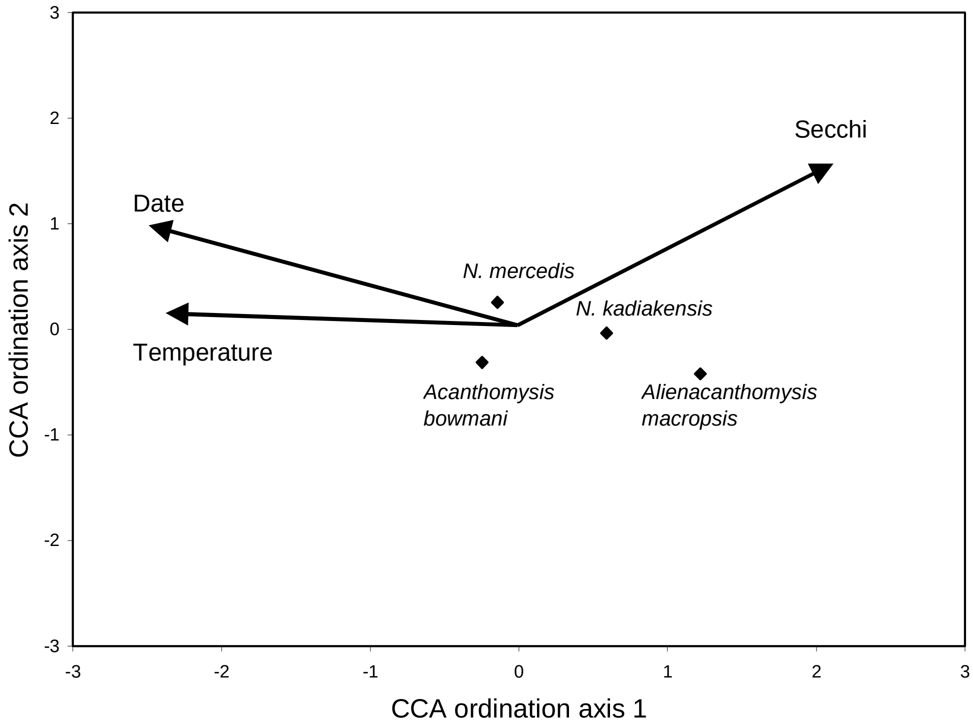

Figure 2 CCA ordination diagram for mysid shrimp species

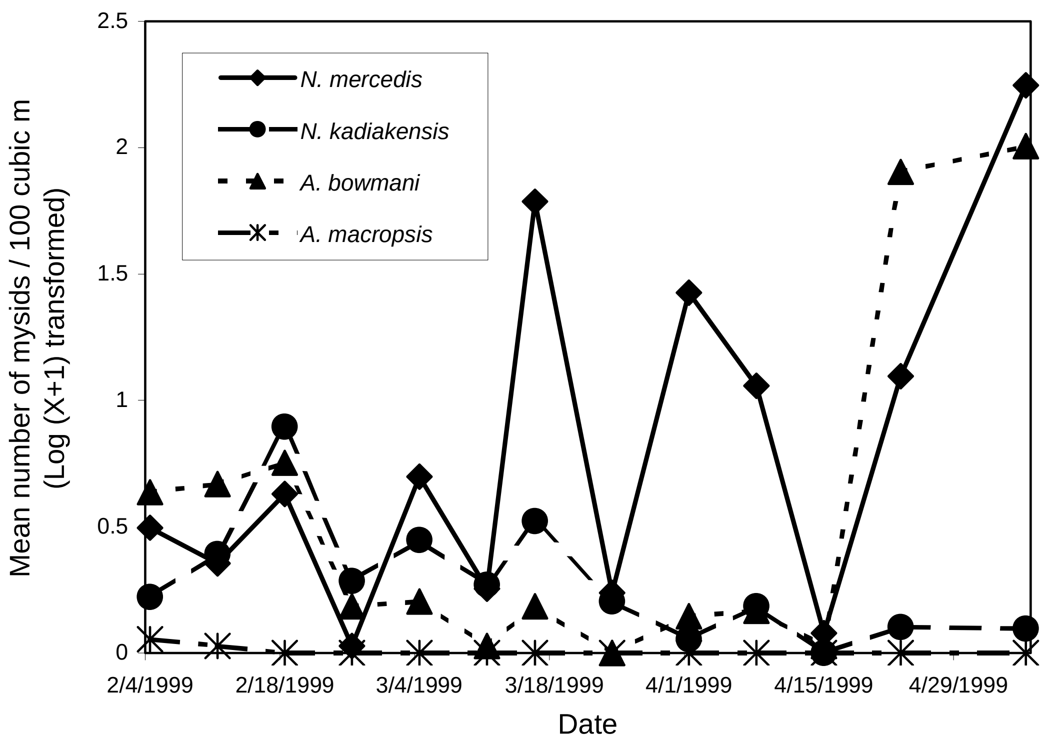

Figure 3 Mysid shrimp catch in Suisun Marsh, February 4 through May 6, 1999. Points represent log (X+1) transformed weekly mean densities (mysids per 100 m^3).

ACKNOWLEDGEMENTS

Peter Moyle and Jim Orsi provided helpful comments on the manuscript. Financial support was provided by DWR (grant B-81568 to Peter Moyle).

REFERENCES

Bennett WA, Moyle PB. 1996. Where have all the fishes gone? Interactive factors producing fish declines in the Sacramento-San Joaquin Estuary. In: Hollibaugh JT, editor. San Francisco Bay: the ecosystem. San Francisco (CA): American Association for the Advancement of Science, Pacific Division. p 519–42.

Daniels RA, Moyle PB. 1983. Life history of splittail (Cyprinidae: *Pogonichthys macrolepidotus*) in the Sacramento-San Joaquin estuary. Fishery Bulletin 81:647–54.

Feyrer F. 1999. Feeding ecology of Suisun Marsh fishes [MS thesis]. California State University, Sacramento. 60 p.

Herbold B. 1987. Patterns of co-occurrence and resource use in a non-coevolved assemblage of fished [Ph.D. dissertation]. University of California, Davis. 81 p.

Kimmerer WJ, Gartside E, Orsi JJ. 1994. Predation by an introduced clam as the likely cause of substantial declines in zooplankton of San Francisco Bay. Mar Ecol Prog Ser 113:81–93.

Modlin RF, Orsi JJ. 1997. *Acanthomysis bowmani*, a new species, and *A. aspera* Ii, Mysidacea newly reported from the Sacramento-San Joaquin Estuary, California (Crustacea: Mysidae). Proc Biol Society Washington 110:439–46.

Nichols FH, Thompson JK, Schemel LE. 1990. Remarkable invasion of San Francisco Bay (California, USA) by the Asian clam Potamocorbula amurensis. II. Displacement of a former community. Mar Ecol Prog Ser 66:95–101.

Orsi JJ. 1996. Shifts in mysid shrimp relative abundance. Interagency Ecological Program for the San Francisco Estuary. IEP Newsletter 8(2):3.

Orsi JJ. 1997. Relative abundance and some aspects of the biology of native and introduced mysid shrimp in Suisun Bay and the Delta. Interagency Ecological Program for the San Francisco Estuary. IEP Newsletter 10(3):13–4.

Orsi JJ. 1999. Long-term trends in mysid shrimp and zooplankton. Interagency Ecological Program for the San Francisco Estuary. IEP Newsletter 12(2):13–5.

Orsi JJ, Knutson AC, Jr. 1979. The role of mysid shrimp in the Sacramento-San Joaquin Estuary and factors affecting their abundance and distribution. In: Conomos TJ, Leviton AE, Berson M, editors. San Francisco Bay: the urbanized estuary. San Francisco (CA): American Association for the Advancement of Science, Pacific Division. p 401–8.

Orsi JJ, Mecum WL. 1996. Food limitation as the probable cause of a long-term decline in the abundance of *Neomysis mercedis* the opossum shrimp in the Sacramento-San Joaquin Estuary. In: Hollibaugh JT, editor. San Francisco Bay: the ecosystem. San Francisco (CA): American Association for the Advancement of Science, Pacific Division. p 375–401.

Palmer MW. 1993. Putting things in even better order: the advantages of canonical correspondence analysis. Ecology 74:2215–30.

Radtke LD. 1966. Distribution of smelt, juvenile sturgeon, and starry flounder in the Sacramento-San Joaquin Delta with observations on food of sturgeon. California Department of Fish and Game. Fish Bulletin 136:115–26.

Roast SD, Thompson RS, Widdows J, Jones MB. 1998. Mysids and environmental monitoring: a case for their use in estuaries. Marine and Freshwater Research 49:827–32.

Sasaki S. 1966. Distribution and food habits of King Salmon, *Oncorhynchus tshawytscha*, and steelhead rainbow trout, *Salmo gairdnerii*, in the Sacramento-San Joaquin Delta. California Department of Fish and Game. Fish Bulletin 136:108–14.

Siegfried CA, Kopache ME. 1980. Feeding of *Neomysis mercedis* (Holmes). Biol Bull 159:193–205.

Sitts RM, Knight AW. 1979. Predation by the estuarine shrimps *Crangon franciscorum* Stimpson and *Palaemon macrodactylus* Rathbun. Biol Bull 156:356–68.

Stevens DE. 1966. Food habits of striped bass, *Roccus saxatilis*, in the Sacramento-San Joaquin Delta. California Department of Fish and Game. Fish Bulletin 136:68–96.

Tattersall WM. 1932. Contributions to a knowledge of the Mysidacea of California: II. The Mysidacea collected during the survey of San Francisco Bay by the *U.S.S. Albatross* in 1914. University of California Publications in Zoology 37:315–47.

ter Braak CJF. 1986. Canonical correspondence analysis: a new eigenvector technique for multivariate direct gradient analysis. Ecology 67:1167–79.

ter Braak CJF, Verdonschot PFM. 1995. Canonical correspondence analysis and related multivariate methods in aquatic ecology. Aquat Sci 57:255–89.

Thomas JL. 1967. The diet of juvenile and adult striped bass, *Roccus saxatilis*, in the Sacramento-San Joaquin river system. California Fish and Game 53:49–62.

Turner JL. 1966a. Distribution and food habits of centrarchid fishes in the Sacramento-San Joaquin Delta. California Department of Fish and Game. Fish Bulletin 136:144–53.

Turner JL. 1966b. Distribution and food habits of ictalurid fishes in the Sacramento-San Joaquin Delta. California Department of Fish and Game. Fish Bulletin 136:130–43.

NOTE

Jim Orsi (California Department of Fish and Game). E-mail correspondence with the senior author on January 18, 2000.

CHANGES IN FISH DIETS IN THE SAN FRANCISCO ESTUARY FOLLOWING THE INVASION OF THE CLAM *POTAMOCORBULA AMURENSIS*

Frederick Feyrer, Sacramento State University, and Scott A. Matern, University of California, Davis
ffeyrer@water.ca.gov

Harboring over 200 exotic species, many resulting from the transfer of ballast water, the San Francisco Estuary has been called the most invaded aquatic ecosystem in North America (Cohen and Carlton 1995). Ecological changes stemming from exotic species have irreversibly altered the estuary's food web. The 1986 introduction of the Asian clam *Potamocorbula amurensis* is of particular concern because it has contributed to declines of 80% or more in lower level trophic organisms such as phytoplankton, zooplankton, and the opossum shrimp *Neomysis mercedis* (Kimmerer and others 1994; Kimmerer and Orsi 1996; Orsi and Mecum 1996).

Because of their importance as a food resource for fish, the decline in abundance of zooplankton and mysids may have important implications for fish populations in the estuary. Bennett and Moyle (1996) suggested the effects of exotic species and the resulting food web alterations may be important factors associated with the dramatic declines in fish abundance observed in the estuary.

In this study, we tested the hypothesis that the trophic ecology of fishes in the estuary did not change following the *P. amurensis* invasion. We examined the food habits, feeding incidence, and stomach fullness of five resident fishes during 1998 and compared our observations to those of Herbold (1987), a very similar study conducted before the *P. amurensis* invasion.

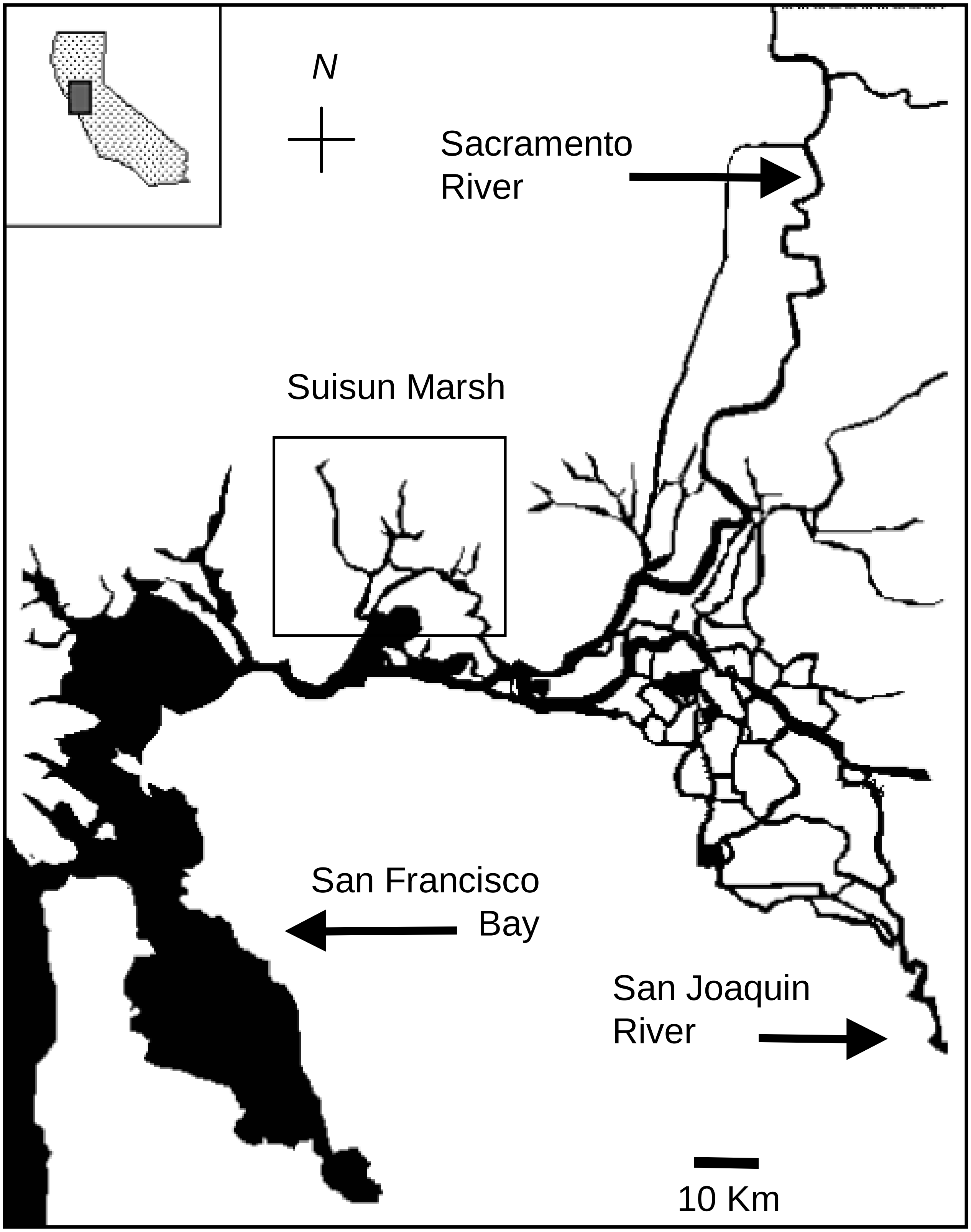

Figure 1 The San Francisco Estuary and Suisun Marsh

MATERIALS AND METHODS

Field Sampling

Fishes were collected bi-monthly by otter trawl between March 1998 and January 1999 for diet analysis during the ongoing (from 1979 to the present) UC Davis Suisun Marsh Fish Survey (area map shown in Figure 1). We examined the stomach contents of three native species—splittail *Pogonichthys macrolepidotus,* tule perch *Hysterocarpus traski*, prickly sculpin *Cottus asper*; and two introduced species—striped bass *Morone saxatilis*, and yellowfin goby *Acanthogobius flavimanus*. These species were targeted because they have comprised 70% of the total annual catch in Suisun Marsh from 1994 through 1998 (P.B. Moyle, UC Davis unpublished data), and because they were also common before the *P. amurensis* invasion.

Laboratory Methods

We measured fish standard length (SL) to the nearest millimeter and weight to the nearest 0.001 g. The stomach contents of each fish were enumerated separately to the lowest practical taxon, and weighed wet to the nearest 0.0001 g on an electronic balance. For splittail and yellowfin gobies, which lack true stomachs, we examined contents of the digestive tract to the first 180-degree bend to be consistent with Herbold (1987).

Data Analysis

Prey items were summarized by their percent composition of total prey biomass (%M) and their frequency of occurrence (%FO) in stomachs. We calculated %M as the proportional contribution of a particular food item to the total prey biomass for a particular fish species and %FO as the proportion of individuals (of a fish species) that contained a particular food item. We compared our food habits data to those of Herbold (1987), who examined fish diets from 1979–1982 and collected specimens exactly as described above.

Schoener's (1970) similarity coefficient (c) was used as a descriptive statistic to compare overall diet similarity of each fish species between the two studies:

$$c = 1 - 0.5\left(\sum_{i=1}^{n} \left|p_{xi} - p_{yi}\right|\right)$$

where p_{xi} is the mass (g) proportion of resource i for species x in our study, p_{yi} is the mass (g) proportion of resource i for species x in the previous study, and n is the number of resources. We chose coefficient values ≥0.60 to indicate high similarity. The original data from the previous study were obtained to calculate and compare a relative measure of stomach fullness (SL/stomach contents weight) between studies by Student's *t*-test. These data were also used to calculate and compare feeding incidence (percent of stomachs with prey) and the %FO and %M of mysids for each fish species between studies using chi-square analysis with Yates correction for continuity (Zar 1999). Because we were investigating overall population and community diet trends, the data were summarized over all size ranges of each species and across the full period of each study.

We obtained annual mysid abundance data from the Department of Fish and Game's (DFG) *Neomysis*-Zooplankton Survey, and with correlation analysis compared mysid abundance in Suisun Marsh to that of the estuary as a whole from 1979–1999, the time frame encompassing both studies.

RESULTS

Overall, the most important prey items in our study were amphipods (*Gammarus* and *Corophium*), fish (*Gasterosteus aculeatus*), annelids, and mysids (*N. mercedis* and *Acanthomysis bowmani*) (Table 1). Splittail diet was dominated by unidentified material, probably detritus, but also contained mollusks and small numbers of copepods. The mollusks included gastropods and the exotic bivalves *Corbicula fluminea* and *P. amurensis*. Tule perch diet consisted almost exclusively of *Corophium* amphipods. Prickly sculpin diet consisted mostly of *Gammarus* and *Corophium* amphipods, but also small numbers of isopods and unidentified fish prey. Yellowfin goby diet was also dominated by *Corophium* and *Gammarus* amphipods, but small numbers of mysids (*A. bowmani*) and annelids were present as well. Striped bass diet consisted mostly of mysids (predominately *N. mercedis*), fish (*G. aculeatus*), and amphipods (*Corophium* and *Gammarus*).

Diet similarity between the two studies was high for prickly sculpin (0.69), striped bass (0.67), and tule perch (0.60) but not for yellowfin goby (0.31) or splittail (0.43). In our study, stomach fullness was significantly lower for prickly sculpin and higher for tule perch than in the previous study (Table 2). Additionally in our study, feeding incidence was significantly higher for both prickly sculpin and yellowfin goby, and lower for tule perch (Table 2).

Table 1 Food habits of Suisun Marsh fishes, March 1998 through January 1999[a]

Species	*SPT*		*TP*		*PSC*		*YFG*		*SB*	
N	70		44		51		37		113	
SL mean (mm)	164		98		59		104		122	
SL range (mm)	58–310		63–137		29–105		60–198		57–240	
# empty	11		14		1		9		9	
Food items	%FO	%M	%FO	%M	%FO	%M	%FO	%M	%FO	%M
Plant material	1	1	---	---	---	---	5	1	1	1
Hydroida	---	---	---	---	4	1	3	1	1	1
Nematoda	3	1	---	---	6	1	---	---	---	---
Molluska	11	34	---	---	---	---	5	1	---	---
Annelida	1	1	5	2	---	---	11	10	6	9
Cladocera	7	4	11	3	---	---	---	---	18	1
Gammarus	6	1	16	1	80	43	65	51	35	7
Corophium	6	6	27	79	57	12	43	27	28	4
Copepoda	10	8	---	---	---	---	---	---	---	---
N. mercedis	3	1	---	---	3	1	---	---	36	12
A. bowmani	---	---	---	---	3	---	8	1	12	6
N. kadiakensis	---	---	---	---	---	---	---	---	4	1
Unid. Mysidae	---	---	---	1	2	---	---	1	21	6
Isopoda	3	1	7	1	25	19	---	---	5	2
Chironomidae	1	1	---	---	---	---	8	1	---	---
Fish	---	---	---	---	8	19	---	---	18	43
Unidentified	28	43	7	14	37	5	14	6	21	4

[a] SPT = splittail, TP = tule perch, PSC = prickly sculpin, YFG = yellowfin goby, SB = striped bass. %FO = frequency of occurrence, %M = percent of total prey biomass. Dashes indicate the food item was not present.

Table 2 Summary statistics for Suisun Marsh fish diets compared between Herbold (1987) and the present study[a]

Variable	*SPT*	*TP*	*PSC*	*YFG*	*SB*
SL mean (mm)					
Herbold (1987)	143	93	63	106	98
Present study	164	98	59	104	122
SL range (mm)					
Herbold (1987)	59–277	62–137	24–133	60–142	24–206
Present study	58–310	63–137	29–105	60–198	57–240
Stomach fullness (*t*-test: * indicates $P \leq 0.05$)					
Herbold (1987)	0.11	0.10*	0.20*	0.10	0.24
Present study	0.14	0.39	0.09	0.07	0.24
% FO mysids (chi-square: * indicates $P \leq 0.05$)					
Herbold (1987)	42*	13*	34*	52*	84*
Present study	3	2	10	11	11
% M mysids (chi-square: * indicates $P \leq 0.05$)					
Herbold (1987)	20*	45*	5*	50*	88*
Present study	1	1	1	2	25

[a] Acronyms and symbols as in Table 1.

The %FO and %M of mysids for each fish species was significantly lower in our study than in the previous study (chi-square, $P < 0.05$) (Table 2). The declines in the dietary importance of mysids were dramatic in that mysids were practically absent from the diet of most species in our study. Averaged across all five fish species, mysids declined in %FO from 45% to 7% and in %M from 42% to 6%. Striped bass was the only species in our study that continued to exploit mysids as a major food resource, yet they also the exhibited the sharpest declines in %FO and %M from the previous study: differences of 73% and 63%, respectively. The DFG *Neomysis*-zooplankton survey data indicated that annual mysid abundance measured in Suisun Marsh was highly correlated with mysid abundance measured estuary-wide (Figure 2).

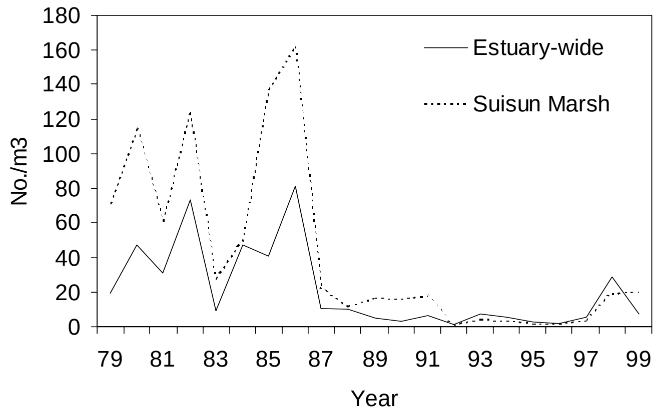

Figure 2 Mean annual abundance of mysids calculated for the San Francisco Estuary (Estuary-wide) and for Suisun Marsh. Mysid abundance in Suisun Marsh was highly correlated with mysid abundance throughout the estuary (r = 0.91, P < 0.001).

DISCUSSION

Our observations of fish diets in Suisun Marsh during the two study periods suggest (1) overall, the slected fish consumed similar prey, and (2) there was a significant decline in the dietary importance of mysids following the *P. amurensis* invasion.

Suisun Marsh fishes generally exploited the same major prey taxa during the two study periods. The finding of significant amounts of unidentified material in the diet of splittail was expected based upon the results of previous studies (Caywood 1974; Daniels and Moyle 1983; Herbold 1987). However, splittail predation on *P. amurensis* was a surprise because only white sturgeon *Acipenser transmontanus*, was previously shown to ingest the exotic clam (Peterson 1997). Thus far, only native fish species have been found to prey upon *P. amurensis*. We found that amphipods were the dominant prey for prickly sculpin, tule perch, and yellowfin goby. This is consistent with previous studies (Turner 1966; Herbold 1987) with the exception of yellowfin goby, which formerly fed predominately on mysids (Herbold 1987). Striped bass diet also largely resembled that documented in previous studies in the estuary with mysids, amphipods, and fish prey being the most important food items (Stevens 1966; Thomas 1967; Herbold 1987).

Statistically significant declines in both %FO and %M for each of the five fish species we examined strongly suggests mysids declined in dietary importance for fishes in the estuary after the *P. amurensis* invasion. Before attributing the decreased dietary importance of mysids to *P. amurensis*, one must consider potential sources of bias that may confound comparisons between the two studies. The most conspicuous sources of bias include variables associated with the sampling methods, the size range of fishes examined, and that we compared fish diets in Suisun Marsh to estuary-wide mysid abundance levels. Fishes examined in each study were collected year-round under the range of a single long-term sampling program. Thus, both studies sampled during daylight hours, with the same sampling gear, and among the same sampling locations within the marsh, thereby reducing biases associated with sampling. The size range of each fish species we examined overlapped that of Herbold (1987), thereby reducing size-specific biases (Table 2). Finally, we showed with the DFG *Neomysis*-zooplankton survey data that mysid abundance in Suisun Marsh followed a nearly identical trend to that previously published for the entire estuary (Figure 2).

Our observations of decreased dietary importance of mysids for fishes, provides the first evidence that *P. amurensis* has affected the highest trophic levels in the estuary and documents that an invading bivalve has altered the feeding ecology of fishes in a river-dominated estuary. Although the link between decreased dietary importance of mysids and declines in fish abundance in the estuary is unclear, the change in diet may have important bioenergetic implications affecting fish populations. Kimmerer and others (2000) found a significant negative relationship between the abundance of striped bass and the abundance of mysids, suggesting that the diet shift we observed following the mysid abundance decline may be one of several potential factors promoting density-dependent population declines in striped bass (Kimmerer and others 2000). Another possible response to the diet shift may be decreased reproductive output. Diet and fecundity observations of splittail suggest this hypothesis merits investigation. Daniels and Moyle (1983) estimated the fecundity of a subset of the splittail examined in Herbold's (1987) diet study. Feyrer and Baxter (1998) found that fecundity was significantly lower for splittail collected throughout the estuary in 1997 (after the *P. amurensis* invasion) when compared to Daniels and Moyle (1983) (before the *P. amurensis* invasion). This potential decreased reproductive output may be due in part to a dramatic diet shift observed for splittail. Herbold (1987) found splittail to selectively prey on mysids year-round, whereas our study found mysids conspicuously absent year-round from the splittail diet after the mysid abundance decline.

We suggest that the ability of this fish assemblage to maintain foraging success (solely in terms of feeding incidence and stomach fullness), through a major decline of a dominant food resource stems from consistent historical experiences of resource seasonality. Historically, mysids have exhibited a predictable pattern of seasonal abundance in Suisun Marsh where abundance is high from January through June and low from July through December (Moyle and others 1986). Distinct feeding strategies were exhibited by native and introduced fishes to deal with the seasonality of mysids; natives generally narrowed their diet to alternative prey items while introduced species increased their dietary diversity (Herbold 1987). The uses of these seasonal strategies on a more continual basis has likely enabled Suisun Marsh fishes to maintain successful foraging.

The results of this study, with additional in-progress analyses further investigating the consequences of the diet shift, are being prepared for a manuscript that will be submitted to a peer-reviewed journal.

ACKNOWLEDGEMENTS

We thank the following individuals for their help with various aspects of this study: W. Avery, R. Baxter, J. Cech, J. Feyrer, B. Herbold, P. Moyle, M. Nobriga, T. Sommer, and D. Vanicek. J. Orsi provided the DFG mysid abundance data. The UC Davis Suisun Marsh Fish Survey is supported annually by DWR.

REFERENCES

Bennett WA, Moyle PB. 1996. Where have all the fishes gone? Interactive factors producing fish declines in the Sacramento-San Joaquin Estuary. In: Hollibaugh JT, editor. San Francisco Bay: the ecosystem. San Francisco (CA): American Association for the Advancement of Science, Pacific Division. p 519–42.

Caywood ML. 1974. Contributions to the life history of the splittail *Pogonichthys macrolepidotus* (Ayers) [M.S. thesis]. California State University, Sacramento.

Cohen AN, Carlton JT. 1995. Non-indigenous aquatic species in a United States estuary: a case study of the biological invasions of the San Francisco Bay and Delta. Report prepared for the U.S. Fish and Wildlife Service. Washington, D.C.

Daniels RA, Moyle PB. 1983. Life history of the Sacramento splittail (Cyprinidae: *Pogonichthys macrolepidotus*) in the Sacramento-San Joaquin Estuary. Fisheries Bulletin 81:647–54.

Feyrer F, Baxter R. 1998. Splittail fecundity and egg size. California Fish and Game 84:119–26.

Herbold B. 1987. Patterns of co-occurrence and resource use in a non-coevolved assemblage of fishes [Ph.D. dissertation]. University of California, Davis.

Kimmerer WJ, Cowan JH, Miller LW, Rose KA. 2000. Analysis of an estuarine striped bass (*Morone saxatilis*) population: influence of density-dependent mortality between metamorphosis and recruitment. Can J Fish Aquat Sci 57:478–86.

Kimmerer WJ, Gartside JE, Orsi JJ. 1994. Predation by an introduced clam as the likely cause of substantial declines in zooplankton of San Francisco Bay. Mar Ecol Prog Ser 113:81–93.

Kimmerer WJ, Orsi JJ. 1996. Changes in the zooplankton of the San Francisco Bay Estuary since the introduction of the clam *Potamocorbula amurensis*. In Hollibaugh JT, editor. San Francisco Bay: the ecosystem. San Francisco (CA): American Association for the Advancement of Science, Pacific Division. p 403–24.

Moyle PB, Daniels RA, Herbold B, Baltz DM. 1986. Patterns in the distribution and abundance of a noncoevolved assemblage of estuarine fishes in California. Fishery Bulletin 84:105–17.

Orsi JJ, Mecum WL. 1996. Food limitation as the probable cause of a long-term decline in the abundance of *Neomysis mercedis* the opossum shrimp in the Sacramento-San Joaquin estuary. In: Hollibaugh JT, editor. San Francisco Bay: the ecosystem. San Francisco (CA): American Association for the Advancement of Science, Pacific Division. p 375–401.

Peterson H. 1997. Clam stuffed sturgeon. Interagency Ecological Program for the San Francisco Estuary. IEP Newsletter 10(1):21.

Schoener T. 1970. Non-synchronous spatial overlap of lizards in patchy habitats. Ecology 51:408–18.

Stevens DE. 1966. Food habits of striped bass, *Roccus saxatilis*, in the Sacramento-San Joaquin Delta. In: Turner JL, Kelley DW, compilers. Ecological studies of the Sacramento-San Joaquin Estuary. Part II. California Department of Fish and Game. Fish Bulletin 136. p 68–93.

Thomas JL. 1967. The diet of juvenile and adult striped bass, *Roccus saxatilis*, in the Sacramento-San Joaquin River system. California Fish and Game 53:49–62.

Turner JL. 1966. Distribution of threadfin shad, *Dorosoma petenense*; tule perch, *Hysterocarpus traski*; sculpin spp. and crayfish spp. in the Sacramento-San Joaquin Delta. In: Turner JL, Kelley DW, compilers. Ecological studies of the Sacramento-San Joaquin Estuary. Part II. California Department of Fish and Game. Fish Bulletin 136. p 160–8.

Zar JH. 1999. Biostatistical analysis. 4th edition. Upper Saddle River (NJ): Prentice Hall, Inc.

EXPOSURE OF DELTA SMELT TO DISSOLVED PESTICIDES IN 1998 AND 1999

G. Edward Moon, Kathryn Kuivila, Catherine Ruhl, and David Schoellhamer, U.S. Geological Survey

INTRODUCTION

Delta smelt is a threatened species in the San Francisco Bay Estuary. Pesticide toxicity is a possible cause for the need to list this fish (Bennett and Moyle 1996; Moyle and others 1996). Numerous pesticides are transported into the estuary from area rivers (MacCoy and others 1995). However, there are minimal data to document the presence, or absence, of pesticides within delta smelt habitat, especially during their vulnerable early life stages. This study, conducted by the U.S. Geological Survey (USGS), documents the occurrence of pesticides within delta smelt habitat; specifically, the length and variability of their potential exposure to multiple dissolved pesticides.

This article reviews delta smelt habitat and early life stages followed by an explanation of the study design for assessing pesticide exposure. Results show the co-occurrence of multiple pesticides and delta smelt in their native habitat; these results are presented within the context of possible toxic effects to delta smelt. Finally, the annual variability of pesticide distributions is discussed.

DELTA SMELT LIFE STAGES AND HABITATS

For the purpose of discussion in this article, two delta smelt life stages are of primary interest. The first is the larval stage when delta smelt are incapable of extensive swimming. The second is the juvenile stage when delta smelt are relatively motile.

Delta smelt typically spawn in shallow areas during early spring. Delta smelt are known to spawn throughout the Sacramento-San Joaquin Delta (Moyle and others 1992, 1996). While spawning locations vary from year to year and depend on environmental conditions, one primary location is the northwestern Delta, including Cache and Lindsey sloughs (Figure 1).

The movements of newly hatched larvae are controlled primaritly by tidal currents. This implies that exposure of delta smelt larvae to pesticides is greatly controlled by residence time. In the tidal currents the larvae can be expected to behave generally as particles; therefore, the residence time of a particle within a particular slug of water can be used as a model of exposure time. In this study, residence times were calculated from measured velocities in Cache and Lindsey sloughs and in the Sacramento River at Rio Vista using Lagrangian particle tracking. In the main channel of Lindsey Slough, residence times were five to ten times longer than in the main channel of the Sacramento River at Rio Vista (USGS unpublished data 1999). Residence times are likely to be even longer in the shallower channel edges and in the upstream sections of the sloughs. Many of the larvae likely reside in side sloughs, such as Cache and Lindsey sloughs (Moyle and others 1992, 1996), where residence time is longer than in the main river channels. Co-occurrence of pesticides and larvae in these habitats result in a long exposure time of developing larvae to pesticides.

As delta smelt mature and become better swimmers, the juveniles tend to move downstream and congregate in waters having a salinity of about 2 ppt (Moyle and others 1992, 1996). These 2-ppt waters typically lie in Suisun Bay or near the confluence of the Sacramento and San Joaquin rivers (Jassby and others 1995; Gartner and Burau 1999) (Figure 1).

STUDY DESIGN

To document pesticide exposure to the two early life stages of delta smelt, sampling was done in two parts. Samples were taken during 1998 and 1999 from a variety of sites within the Suisun Bay and the Delta. All samples were analyzed for pesticides using the methods described in Crepeau and others (2000).

Samples were collected at a fixed time interval from the Delta sites in conjunction with the 20-mm delta smelt surveys taken by the California Department of Fish and Game (DFG). These concurrent samplings allowed for direct comparison of pesticide concentrations and fish abundances. Samples were collected biweekly at five Delta sites in 1998 and ten Delta sites in 1999, from late April to late June, when larvae were expected to occur (Figure 1).

Samples were collected from Suisun Bay during periods of 2-ppt salinity when juveniles were expected to occur (June to August). Two sites where salinities of 2 ppt routinely occur were selected: Mallard Island and the Reserve Fleet (Gartner and Burau 1999) (Figure 1). Autosamplers were programmed to collect no more than one sample per day on the ebb tide as the 2-ppt waters passed their respective locations. Due to equipment difficulties, samples were not collected successfully from Suisun Bay in 1998. During the study period, salinities of 2 ppt occurred consistently at Mallard Island, but only intermittently at the Reserve Fleet in 1999 (USGS unpublished data 1999), so samples were collected only from Mallard Island.

MULTIPLE PESTICIDES IN DELTA SMELT HABITAT

In 1998 and 1999, the waters within the Delta and the confluence contained many different pesticides (Table 1). Of the 147 samples collected, all samples contained at least two pesticides, the median number of pesticides detected per sample was four and the maximum number of pesticides detected per sample was eight (Figure 2). Overall, the distributions of the number of pesticides detected in different samples were similar for 1998 and 1999 (USGS unpublished data 1998, 1999).

The complexity of the pesticide mixture in delta smelt habitat is illustrated further by examining the list of the individual pesticides (Table 1). Ten pesticides were detected in 1998 and 12 were detected in 1999. The frequency of detection and maximum concentration of each pesticide are shown in Table 1. Metolachlor was the most frequently detected pesticide, with detection in 98% of all samples. Other frequently detected pesticides included molinate, simazine, and thiobencarb with percent detections of 76%, 93%, and 70%, respectively. The pesticides EPTC, molinate, and thiobencarb had maximum concentrations of 7,700 ng/L, 2,500 ng/L, and 330 ng/L, respectively.

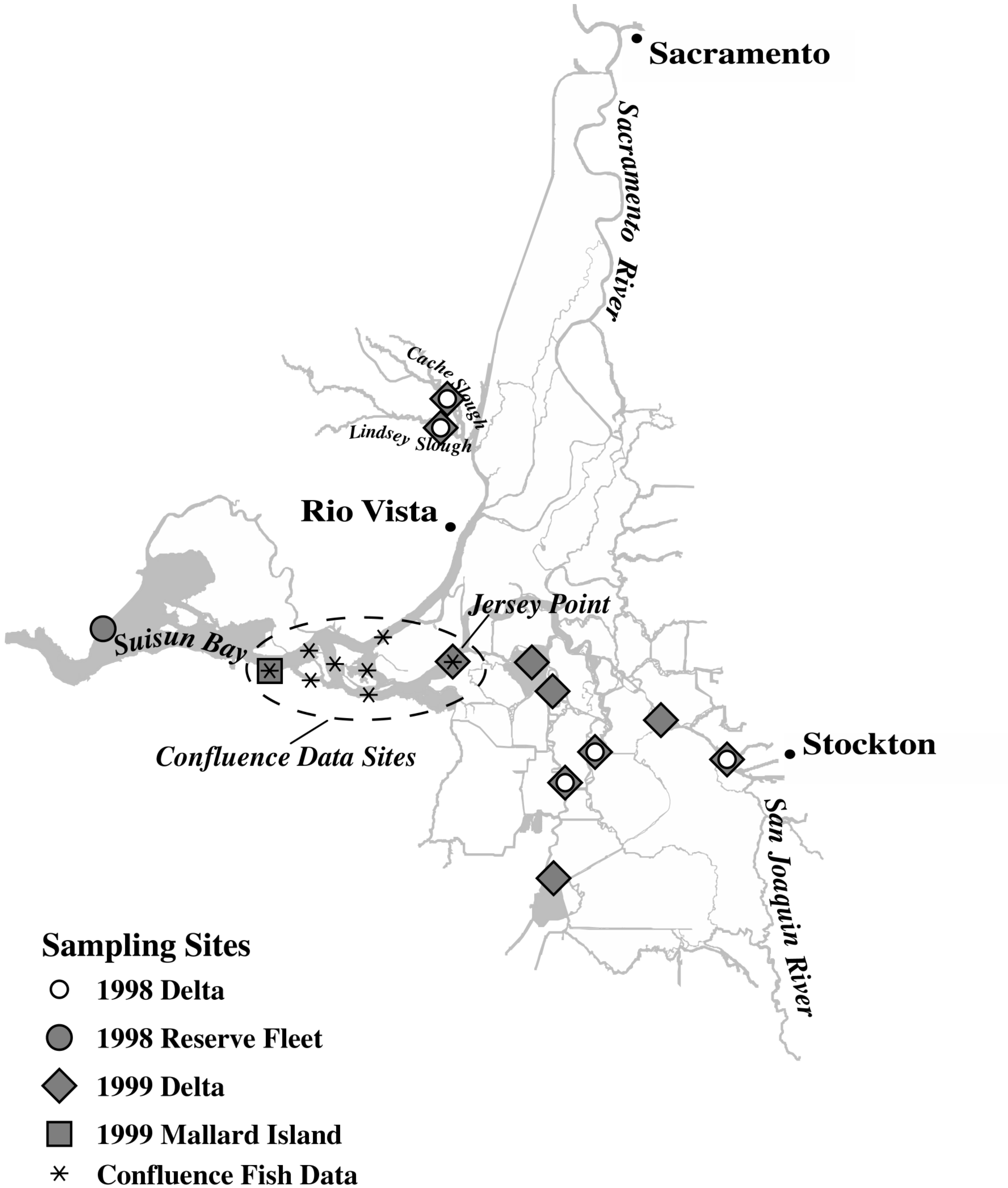

Figure 1 Map of sampling locations

Table 1 List of pesticides detected

	Samples Detected[a] (%)		*Maximum Concentration (ng/L)*	
Pesticide	*1998*	*1999*	*1998*	*1999*
Alachlor	0	2	---[b]	56
Atrazine	10	7	43	24
Carbaryl	0	5	---[b]	210
Carbofuran	50	29	30	82
Diazinon	18	0	46	---[b]
EPTC	45	29	1500	7700
Metolachlor	100	96	210	210
Molinate	25	76	2500	440
Pebulate	13	1	140	84
Simazine	93	41	68	64
Sulfotep	0	24	---[b]	120
Thiobencarb	13	70	330	150
Trifluralin	20	14	8	65

[a] Percent values given are the percent of samples in which each pesticide was detected in each year. In 1998 n = 40, in 1999 n = 107

[b] Dashes indicate the constituent was not detected.

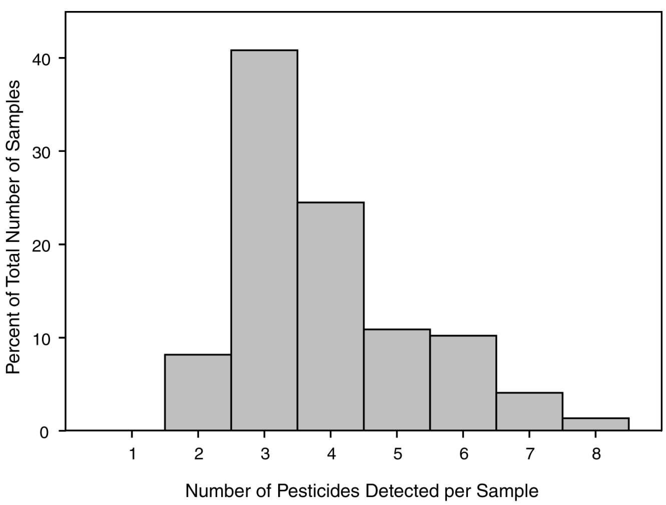

Figure 2 Number pesticides detected per sample. This graph shows a plot of the relative number of samples containing different numbers of pesticides in 1998 and 1999.

EXPOSURE OF DELTA SMELT TO MULTIPLE PESTICIDES

Multiple pesticides occurred within delta smelt habitat; however, the question of interest was, “Are delta smelt exposed to these pesticides?” To answer this question, fish densities from the 20-mm survey for delta smelt, which catches both larval and juvenile delta smelt, were compared with pesticide concentrations from this study.

In 1998, few delta smelt were caught by DFG at the sites with concurrent pesticide sampling by the USGS. In 1998, high spring outflows centered the delta smelt population downstream in Suisun Bay (Sweetnam 1999). Because delta smelt were not present at the pesticide sampling sites in 1998, no estimate could be made of their exposure to pesticides.

In 1999, the 20-mm survey found that delta smelt were present at the pesticide sampling sites. Comparison of the delta smelt densities and pesticide concentrations show that delta smelt were exposed to pesticides in 1999 (Figure 3). Examination of the data for the San Joaquin River at Jersey Point (Figure 1) revealed that fish abundances and pesticide concentrations were very similar to those observed at the confluence. Therefore, the data from Jersey Point were excluded from the Delta data (Figure 3A) and grouped with the confluence data (Figure 3B) for purposes of interpretation. In Figure 3A, the fish densities at each of the remaining nine Delta sites were averaged for each sampling date. The total pesticide concentration at each site for each sampling date was calculated as the sum of individual pesticide concentrations. The total pesticide concentrations were averaged across the nine Delta sites for each sampling date to give the pesticide data in Figure 3A. The highest densities of delta smelt were present at the Delta sites from May 10 through June 7 (Figure 3A). During this time, fish co-occurred with the pesticides with the highest concentrations detected on May 10. Extremely high concentrations of EPTC (7,700 ng/L and 4,300 ng/L) detected at two sites within the Delta strongly influenced the high total pesticide concentration on May 10. Even without EPTC, however, pesticide concentrations were elevated throughout the period that delta smelt were present in the Delta.

As the juvenile delta smelt migrated toward and congregated in the confluence, they were exposed to elevated concentrations of dissolved pesticides for an additional one to two months (Figure 3B). Fish densities in Figure 3B were an average of the densities at the nine DFG sites within the confluence area (Figure 1) and pesticide concentrations are total pesticide concentrations from Jersey Point and Mallard Island. The timing of the peak fish abundance at the confluence sites lagged the Delta sites by two weeks, with the largest number of delta smelt being found on June 21. As in the Delta, the highest densities of delta smelt co-occurred with the highest concentrations of dissolved pesticides. The rise and fall of pesticide concentrations was comprised primarily of the rice pesticides molinate and thiobencarb (USGS unpublished data 1999).

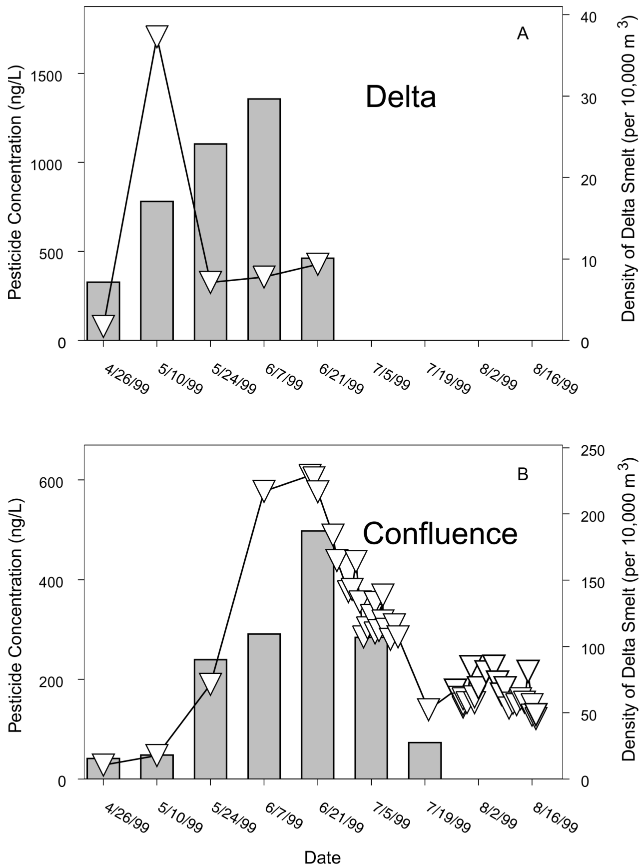

Figure 3 Co-occurrence of pesticides and delta smelt. These graphs contain both a line plot of pesticide concentrations and a bar plot of density of delta smelt in the Delta (A) and in the confluence (B). See text for calculation methods.

Previous studies (Bennett 1996) have suggested the timing of pesticide pulses is offset from fish abundance and exposure to pesticides is not important. Bennett (1996) found that the maximum densities of striped bass larvae and concentrations of molinate did not occur concurrently; however, he noted that his two data sets were not sampled concurrently and suggested future studies should be designed accordingly. Our study did conduct concurrent sampling and found that delta smelt were exposed to a complex mixture of dissolved pesticides in 1999.

The maximum concentrations for each pesticide (Table 1) were well below the LC50 values for most fish species (Tomlin 1997); therefore, it is unlikely that even the mixtures of pesticides observed in 1999 caused acute toxicity to delta smelt. However, chronic exposure to individual and multiple pesticides may hinder growth rate, reproduction, and swimming performance (Rand 1995). Indirect effects of pesticide exposure, such as alteration of delta smelt diet, also are possible (Rand 1995). Information on chronic pesticide exposure is needed to fully evaluate the environmental effects of pesticides on the delta smelt population.

Annual Variability of Pesticide Distribution

Multiple pesticides were detected in delta smelt habitat in 1998 and 1999; however, there was considerable variability in the maximum concentration and distribution of the pesticides. The pesticides alachlor, carbaryl, and sulfotep were not detected in 1998 but were detected in 1999 (Table 1). Conversely, diazinon was detected in 1998 but not in 1999 (Table 1). Several other pesticides were detected both years, but at very different concentrations. The maximum concentrations of EPTC and trifluralin were five and eight times higher, respectively, in 1999 than in 1998. In contrast, the concentrations of molinate and thiobencarb were approximately five times and two times lower, respectively, in 1999 than 1998. The differences in concentrations of pesticides may be due to variations in the amount applied or in the timing of sampling relative to application. The two pesticides molinate and thiobencarb are applied to rice, and the observed differences in concentration have been explained previously by variations in the actual holding time of water on rice fields before release (Crepeau and Kuivila 2000).

The spatial distribution of pesticides also varied from year to year. In 1998, the concentrations of molinate and thiobencarb peaked at 2,500 ng/L and 330 ng/L, respectively, in Cache and Lindsey sloughs. However, these pesticides were not detected at any other Delta sites in 1998 (USGS unpublished data 1998). In 1999, however, the concentrations of molinate and thiobencarb in the central Delta sites were very similar to those in Cache and Lindsey sloughs (USGS unpublished data 1999). This difference in pesticide distribution between the two years can be explained by the effect of Delta hydrodynamics on pesticides originating from the Sacramento River watershed (Figure 4).

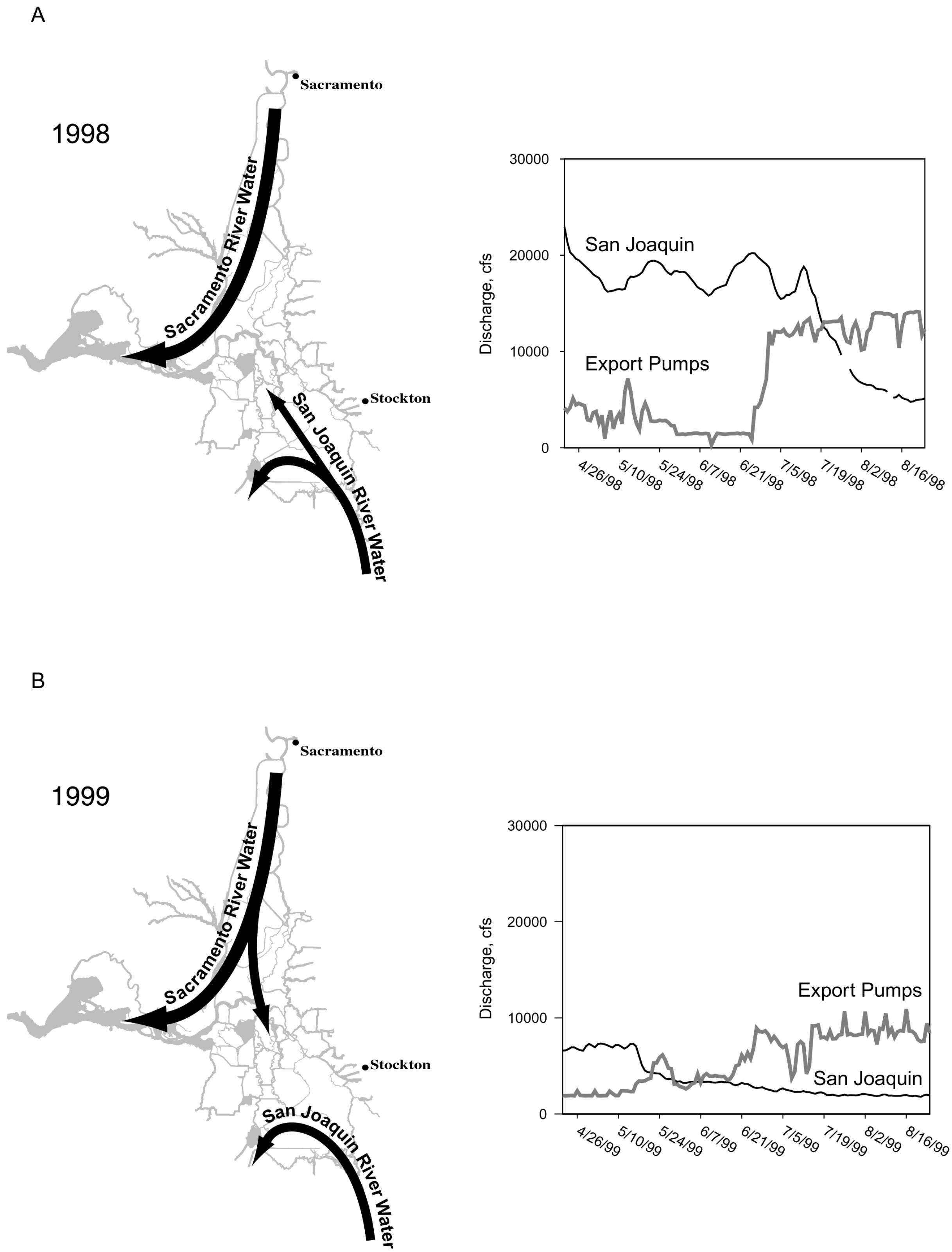

Figure 4 Transport of water and pesticides through the Delta in 1998 (A) and 1999 (B). This figure depicts the Sacramento and San Joaquin River discharges and water project exports.

In 1998, San Joaquin River flow was high relative to the export pumping by the State and federal water projects; therefore, flow from the San Joaquin River was sufficient to supply the pumps and the amount of Sacramento River water drawn into the central Delta was minimal until late July (Figure 4A). Conversely, during spring 1999, export pumping rates at times equaled or exceeded discharge from the San Joaquin River beginning in mid-May (Figure 4B). This resulted in Sacramento River water with its associated pesticide load being drawn into the central Delta in 1999. The observed variability in pesticide concentrations and distributions from year to year is evidence that caution is needed when extrapolating and estimating long-term exposure of delta smelt to pesticides without actually measuring both fish abundance and pesticide concentrations.

SUMMARY AND CONCLUSIONS

In 1998 and 1999, a complex mixture of pesticides was detected in delta smelt habitat. Furthermore, delta smelt were exposed to this complex mixture of pesticides in 1999 for extended periods during their larval and juvenile stages. The observed annual and spatial variability of pesticide concentrations suggest pesticide concentrations from one year cannot be realistically extrapolated into future years. Future studies of delta smelt exposure to pesticides should be designed accordingly. The environmental effects of pesticides on the delta smelt population cannot be evaluated fully until more data are available on the sublethal and indirect effects of chronic exposure of delta smelt larvae and juveniles to complex mixtures of pesticides.

REFERENCES

Bennett WA. 1996. Framework for evaluating pesticide effects on fish populations. Interagency Ecological Program for the San Francisco Estuary. IEP Newsletter 8:2.

Bennett WA, Moyle PB. 1996. Where have all the fishes gone? Interactive factors producing fish declines in the Sacramento-San Joaquin Estuary. In: Hollibaugh JT, editor. San Francisco Bay: the ecosystem. San Francisco (CA): American Association for the Advancement of Science, Pacific Division.

Crepeau KL, Baker LM, Kuivila KM. 2000. Method of analysis and quality-assurance practices for determination of pesticides in water by solid-phase extraction and capillary-column gas chromatography/mass spectrometry at the U.S. Geological Survey California District Organic Chemistry Laboratory, 1996–1999. U.S. Geological Survey Open-File Report 00–229.

Crepeau KL, Kuivila KM. 2000. Rice pesticide concentrations in the Colusa Basin Drain and the Sacramento River, California, 1990–1993. J Environ Qual 29:926–35.

Gartner JW, Burau JR. 1999. Hydrodynamic measurements in Suisun Bay, California, 1992–93. U.S. Geological Survey Water-Resources Investigations Report 99–4049.

Jassby AD, Kimmerer WJ, Monismith SG, Armor C, Cloern JE, Powell TM, Schubel JR, Vendlinski TJ. 1995. Isohaline position as a habitat indicator for estuarine populations. Ecol App 5:272–89.

MacCoy D, Crepeau KL, Kuivila KM. 1995. Dissolved pesticide data for the San Joaquin River at Vernalis and the Sacramento River at Sacramento, California, 1991–94. U.S. Geological Survey Open-File Report 95–110.

Moyle PB, Herbold B, Stevens DE, Miller LW. 1992. Life history and status of delta smelt in the Sacramento-San Joaquin Estuary, California. Trans Am Fish Soc 121:67–77.

Moyle PB, Pine R, Brown LR, Hanson CH, Herbold B, Lentz KM, Meng L, Smith JJ, Sweetnam DA, Winternitz L. 1996. Recovery plan for the Sacramento-San Joaquin Delta native Fishes. U.S. Department of the Interior Fish and Wildlife Service, 15–46.

Rand GM. 1995. Fundamentals of aquatic toxicology: effects, environmental fate, and risk assessment. 2nd edition. London: Taylor and Frances.

Sweetnam DA. 1999. Delta smelt investigations. Interagency Ecological Program for the San Francisco Estuary. IEP Newsletter 12(2):25–8.

Tomlin CDS. 1997. The pesticide manual. 11th edition. Farnham (UK): British Crop Protection Council.

DELTA WETLANDS RESTORATION AND THE MERCURY QUESTION: YEAR 2 FINDINGS OF THE CALFED UC DAVIS DELTA MERCURY STUDY

Darell G. Slotton[1], Thomas H. Suchanek[2], and Shaun M. Ayers[1]
[1]Dept. of Environmental Science and Policy
[2]Dept. of Wildlife, Fish and Conservation Biology
University of California, Davis
dgslotton@ucdavis.edu

ABSTRACT

Field and laboratory measures were developed for the determination of relative sediment mercury methylation potential and biotic mercury accumulation in the Sacramento-San Joaquin Delta. Mercury bioaccumulation was investigated at over 60 varied sites. Methylation potential experiments found flooded wetland sediments to exhibit between 200% and 3,000% greater potential to convert inorganic mercury to methyl mercury than sediments of adjacent channels and flats. However, biological findings to date suggest wetlands restoration projects may result in localized mercury bioaccumulation at levels similar to, but not necessarily greater than, general levels within their surrounding Delta region. Delta regions with elevated biotic mercury concentrations included areas fed by inflows from the Cosumnes River, Yolo Bypass and, to a lesser extent, Sacramento River. The Central and South Delta were markedly lower, despite high signals in some southern tributaries and the presence of numerous flooded tracts in the Central Delta. One of the most important new findings was the identification of an extensive additional zone of elevated mercury bioaccumulation in the West Delta between the Sacramento-San Joaquin confluence and Carquinez Strait. Possible mechanisms are discussed.

BACKGROUND

Mercury contamination is one of the primary water quality issues in the San Francisco Bay-Delta watershed. This is the result, in large part, of the Gold Rush era legacy of extensive mercury use in Sierra Nevada gold mining, as well as the now abandoned mercury mines in the California coast ranges that supplied this mercury. It is clear that both regions remain major sources of ongoing mercury contamination, both locally and downstream (Slotton and others 1995, 1997, 1998, 1999; Suchanek and others 1997; Foe and Croyle 1998; Domagalski 1998; Roth and others 2000). The relative effect of that mercury loading is dependent on how much is converted to methyl mercury, the form which bioconcentrates through food webs and can lead to neurological damage in top consumers. International mercury research during the past decade has found that wetland habitats can be sites of significantly elevated mercury methylation (Rudd 1995). This is not surprising, as methyl mercury production is known to be stimulated by sulfate-reducing and other bacteria, which typically occupy the zone just below the oxic-anoxic interface in aquatic systems. Organic-rich and potentially sulfate-rich wetlands can provide optimal habitat for these microbes.

Our UC Davis study is investigating mercury methylation and bioaccumulation patterns throughout the Sacramento-San Joaquin Delta system. This research focuses on habitat-specific and site-specific measures of these phenomena. Thus, while mercury concentrations in edible fish species is perhaps the primary ultimate concern, our project targets more sedentary and short-lived lower trophic level biota, as well as surficial sediment chemistry, as localized indicators of relative mercury exposure. A primary goal is to provide management recommendations that address the mercury question with regard to wetland restoration projects. In the first year of this ongoing research, initial results suggested flooded Delta tracts—in a variety of configurations—may not, in fact, lead to locally elevated levels of mercury bioaccumulation (Suchanek and others 1999). Instead, first year results indicated that spatial differences in Delta mercury bioaccumulation may be linked most closely to proximity to upstream sources such as the Yolo Bypass and the Cosumnes River. Within Delta subregions, preliminary results suggested biotic mercury might be quite uniform, irrespective of habitat.

In the second year of the project, reported here, we used surficial sediments and carefully chosen bioindicator organisms to comprehensively sample the entire Delta, with comparable protocols and collections at over 60 sampling sites. We also conducted laboratory experiments to investigate the mercury methylating potential of sediments from key locations and micro-habitats. The results of this ongoing work provide a new picture of mercury dynamics in the Delta.

METHODS

Sampling sites were chosen to be representative of important Delta subregions and habitat types, with a particular focus on flooded tracts across a range of ages. Sampling was conducted throughout the fall of 1999. Fish were collected with a variety of seines. Crayfish were collected with baited traps. Clams were generally taken by hand during low tides. Sediment samples were taken from the top centimeter of undisturbed grab samples, primarily collected using an Ekman grab sampler. Biota and sediment samples were placed immediately on ice in the field, within secure clean containers, for transport to the UC Davis laboratories. Fish were cleaned, identified, and sorted within 24 hours of collection, then frozen with water in Ziploc bags to avoid freezer desiccation. Fish were weighed and measured prior to processing. Clams were maintained live in clean water, which was changed twice daily for four days to purge them of all major gut contents and associated sediment, and were then frozen for storage. Crayfish were also stored frozen.

Crayfish tail muscle and clam soft tissues were excised with a clean scalpel prior to analysis. Crayfish digestive tracts were removed. Biota samples were dried at 60 °C, ground, and powdered. Both individual and composite samples were used. Small fish were prepared whole body, as were the clams (minus shells). Crayfish mercury was analyzed in tail muscle. Percentage moisture was determined for all sample types to allow conversion of wet or dry weight analytical results. UC Davis analysis of total mercury used dry biota samples and fresh, wet sediment. Clam composite samples typically used 10 to 25 purged individuals within the optimal size range. Inland silverside composites contained a minimum of six and typically 30 to 40 individuals in the key size range.

Samples were digested in 2:1 sulfuric:nitric acid under pressure (capped vessels) at approximately 90 °C for one hour, and then for two additional hours, uncapped, with the addition of potassium permanganate and potassium persulfate. Mercury was analyzed using a FIMS cold vapor atomic absorption system. Sediment and biota moisture percentage was determined with oven drying and sequential weighings. Sediment loss on ignition was determined with sequential weighings and 475 °C muffle furnace ashing. Laboratory experiments using sediment slurries to estimate maximal potential methyl mercury production rates were conducted with 2:1 mixtures of site water:site sediment (top 1 cm). Mixtures were spiked with mercury chloride to 1.00 µg Hg g^{-1}. After placing identical aliquots into multiple incubation chambers and sparging to uniform anoxia with nitrogen, samples were incubated at 22 °C for varying lengths of time. Individual methylation experiments were stopped by freezing at defined endpoints. Methyl mercury concentrations were analyzed by Battelle Marine Science Laboratories in Sequim, Washington.

SECOND YEAR RESULTS

Mercury in Sediment

Surficial sediments (top 1 cm) were collected at most of the fall 1999 biota stations. Dry weight, whole-sediment Delta mercury concentrations all occurred within a range of 0.01 to 0.33 µg Hg g^{-1}. Particle size varied dramatically in these samples, from fine clay and silt in depositional areas to coarse sand in some of the more erosional locations. Metals, including mercury, tend to be most concentrated in fine grained particles (Theis and others 1988; Roth and others 2000). Future sampling rounds will normalize to grain size and a variety of other sediment parameters. The whole-sediment mercury values are useful, however, as they represent the environment the organisms are exposed to. Greatest concentrations occurred at North Delta and East Delta inflow regions and in depositional regions where finest particle sizes dominated. This particularly included West Delta sites (0.18 to 0.33 µg Hg g^{-1}), with moderate levels interspersed within the Central Delta (0.08 to 0.26 µg Hg g^{-1}). South Delta sites were uniformly low in total mercury (0.02 to 0.15 µg Hg g^{-1}).

Potential Methyl Mercury Production from Sediments: Experimental Results

Initially, we attempted to quantify methyl mercury efflux from Delta sediments into overlying water. In laboratory core-tube experiments, we found that the changes in aqueous methyl mercury levels were too low for accurate measurement within our project constraints. Subsequently, we chose an alternate technique which provided excellent detection levels and results. Laboratory slurry experiments introduced spike additions of reactive inorganic mercury (mercury chloride) to Delta sediment samples and measured the methyl mercury production that resulted over a 16-day period. These measurements of “methylation potential” determine not what is naturally produced from a given sediment, but that sediment’s propensity to methylate inorganic mercury if it is presented in a bioavailable form. Results from the Delta have been enlightening.

Figure 2 represents time series methylation data from a representative experimental set. Following identical spike additions to 1.00 µg Hg g^{-1}, sediments from three different representative habitat types at the Cosumnes River all reached a maximum methyl mercury balance within two days. Peak concentrations differed in the three representative sediments, though all rose well above initial levels. Methyl mercury subsequently declined in the coarsest, mid-channel sample after day two. In the most organic-rich sediment, taken from a depositional, well-vegetated, off-channel marsh, methyl mercury persisted at maximal levels for six additional days beyond the initial rise. In the intermediate sediment, taken from a depositional (but not marsh) environment, peak levels persisted for through day four, an intermediate length of time. In all three sediments, following maximal initial methyl mercury concentrations, levels maintained at approximately 50% of peak levels (well above baseline) for at least 8 to 16 days. The experimental declines from peak levels may be indicative of a demethylating phase.

The magnitude of the methyl mercury production peak was lowest in the coarse, mid-channel sediment (90 ng Hg g^{-1}, baseline = 10), intermediate in the off-channel depositional zone sediment (130 ng Hg g^{-1}, baseline = 20), and notably greatest in the lower marsh sediment (390 ng Hg g^{-1}, baseline = 30). Figure 3 displays reduced data from this and other representative Delta marsh habitats and their respective non-marsh controls in units of peak methyl mercury concentrations during identical methylation potential experiments. Sediments from the Cosumnes River, Liberty Island in the North Delta, and Venice Cut Island in the Central Delta all demonstrated dramatically elevated levels of mercury methylation potential in the more organic-rich, heavily vegetated, flooded wetland sediments, relative to adjacent non-marsh controls. In the North Delta, while absolute levels were much lower, the difference in peak methyl mercury response to spike additions of inorganic mercury was 39 ng Hg g^{-1} (marsh) and 2 ng Hg g^{-1} (submerged island flats). Much of the North Delta is characterized by sandy sediments and turbid water that does not readily promote macrophyte development. Cosumnes region concentrations, as noted above, were ten times greater at 399 ng Hg g^{-1} (marsh) and 93 ng g^{-1} (channel). At Venice Cut Island, representative of peat-based Central Delta flooded tracts, the maximum methyl mercury concentration in spiked flooded peat material was an astounding 1,077 ng Hg g^{-1}, with 34 ng Hg g^{-1} in the adjacent control (submerged island flats). In all paired tests, flooded wetland sediments exhibited between 200% and 3,000% greater mercury methylation potential than adjacent channels and flats.

Choosing Appropriate Bioindicator Species

In the first year collections, we found that many locally abundant small fish and macro-invertebrate species had relatively limited ranges throughout the Delta. While these will be useful bioindicators of local food web dynamics, we needed organisms which exhibited strong site fidelity and could be taken from a wide variety of Delta locations and habitats. Our prime candidates were Asiatic clams (*Corbicula fluminea*), signal crayfish (*Pacifasticus leniusculus*), and inland silversides (*Menidia beryllina*). One major focus during the past year was the study of individual variation in mercury levels, within each of the primary sample types, from identical locales. To be most useful in describing potential spatial and inter-habitat variation in Delta mercury bioavailability, low levels of within-site variation were needed in the monitoring organisms. In Figures 4, 5, and 6, typical within-site mercury variability in individuals of each of the three types of biota is displayed in size versus mercury plots.

Crayfish (*Pacifasticus leniusculus*, Figure 4) were found to have unacceptably high levels of within-site variability in tail muscle mercury concentration. This was likely a function of a highly variable, opportunistic diet and the co-occurrence of widely varying age classes. Individual variability was frequently equal to or greater than the spatial and habitat related mercury variability. There was no apparent size range that was free of this high variability. This was unfortunate as, otherwise, crayfish could be ideal candidates as bioindicator species. They accumulate mercury to high concentrations, similar to predatory fish, but maintain highly localized home ranges.

The variability of mercury concentration in Asiatic clams (*Corbicula fluminea*, Figure 5) was very low in the smaller size classes from most locations investigated. Among the fall 1999 samples, whole body mercury concentration in individuals <28 mm (maximum shell diameter) were quite consistent. Above this size at a number of sites tested, individual variability increased significantly. We attributed this to age structure and sexual maturity. Larger fall clams demonstrated a significant variation in body mass, likely a function of reproductive energy needs and spawning. Individuals which metabolized much of their body mass were left with similar mercury body burdens but elevated concentrations. Based on these findings, we chose 15- to 27-mm *Corbicula* as one of our two primary Delta-wide mercury bioindicators.

Inland silversides (*Menidia beryllina*, Figure 6) were found to behave primarily as annuals in the Delta, as is the case in other parts of California. Fall silversides were typically very consistent in same-site, individual, whole body mercury concentration at sizes of about 45 to 75 mm. Above this size, individual mercury concentrations were often significantly more variable. Our interpretation, supported by field observation of Delta silverside life history, is that fall individuals less than about 75 mm are the young of the year. Larger individuals consist primarily of over-wintering fish from the previous year. We chose 45 to 75 mm silversides as our second Delta-wide mercury bioindicator.

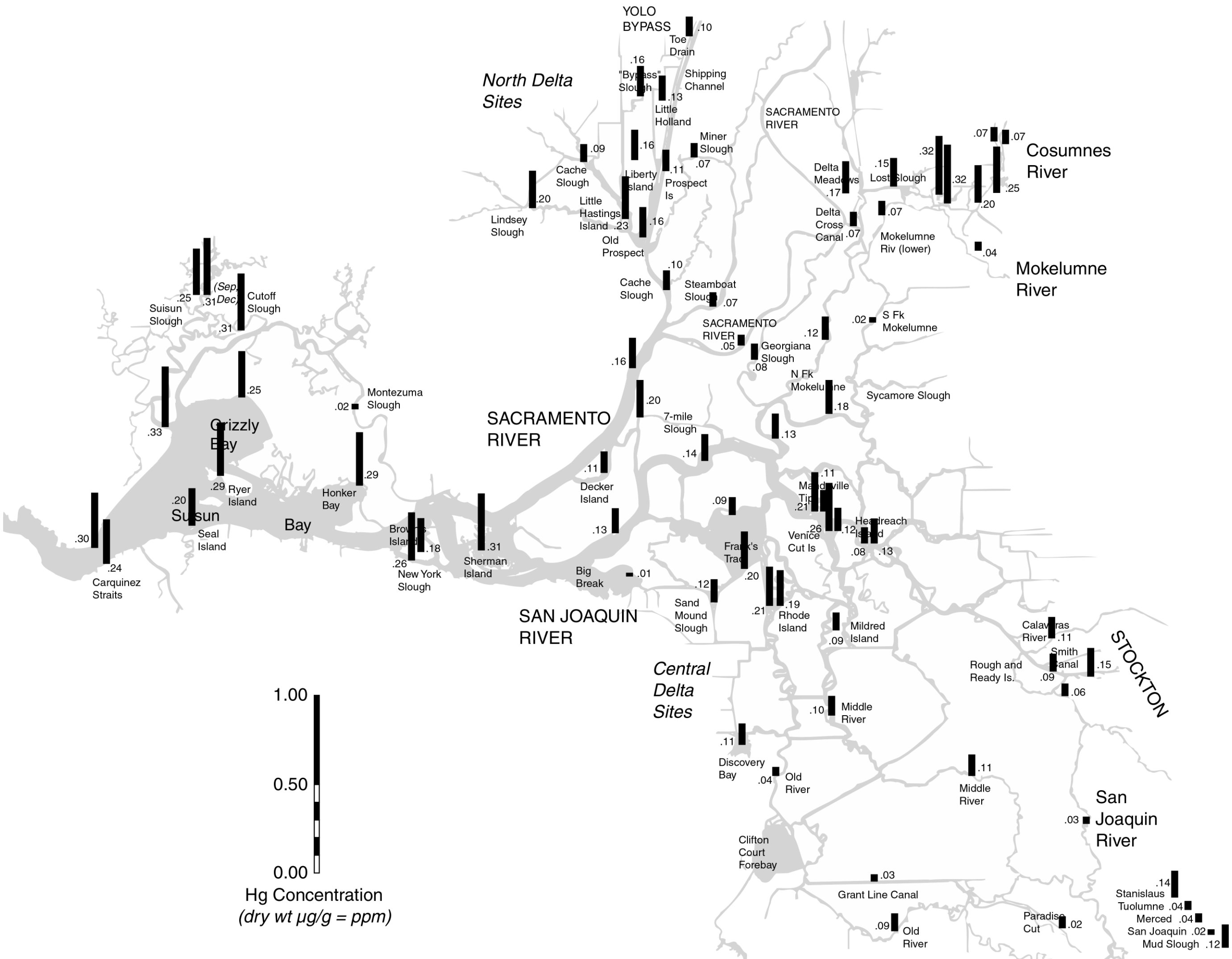

Figure 1 Surficial whole-sediment mercury spatial distribution. Fall 1999 collections; top 1 cm.

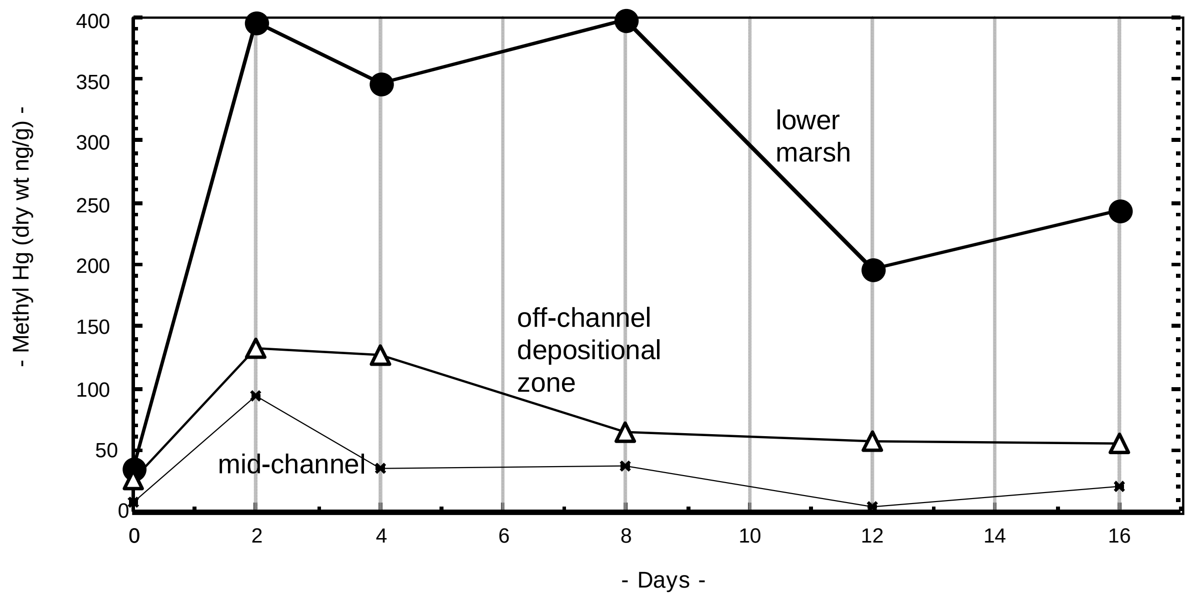

Figure 2 Time course of methyl mercury concentration in spiked laboratory sediment slurry incubations. Cosumnes region sediment slurries; 2:1 mixtures of site water:site sediment; inorganic mercury added to 1.00 µg Hg g^{-1}; anoxic incubations at 22 °C.

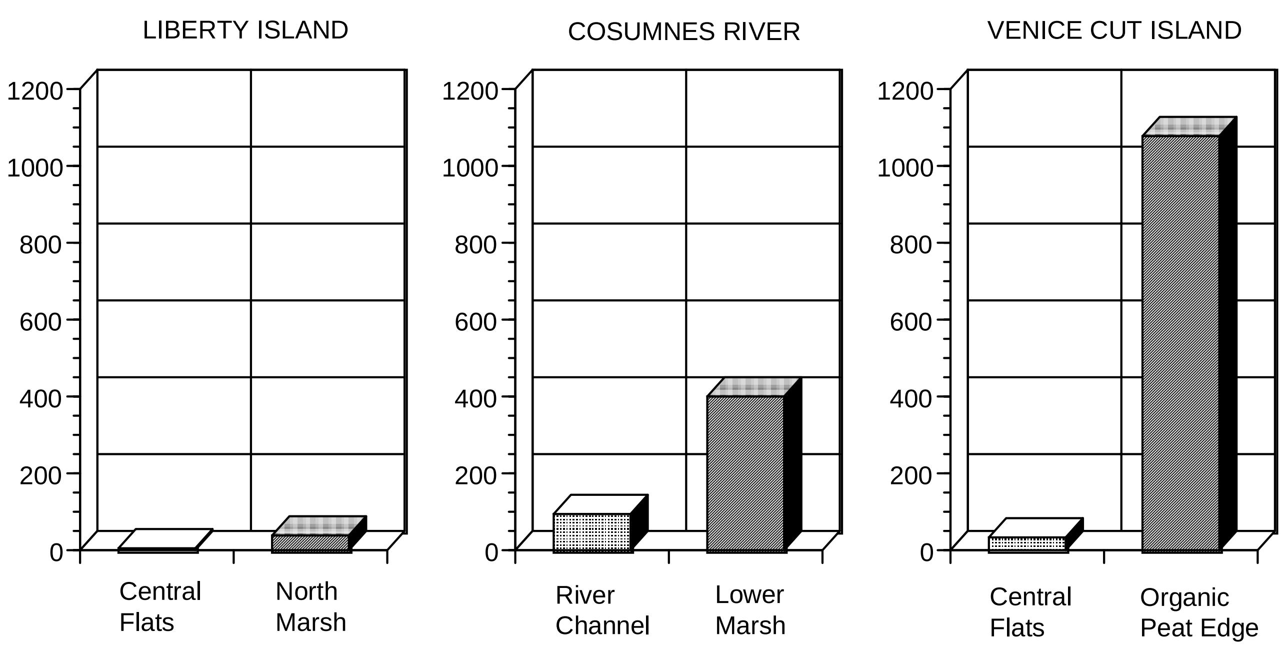

Figure 3 Relative mercury methylation potential of Delta marsh habitats vs. adjacent aquatic habitat. Mean maximum methyl mercury concentrations in inorganic mercury addition experiments to 1.00 µg Hg g^{-1}; methyl mercury concentrations in dry wt ng Hg g^{-1}.

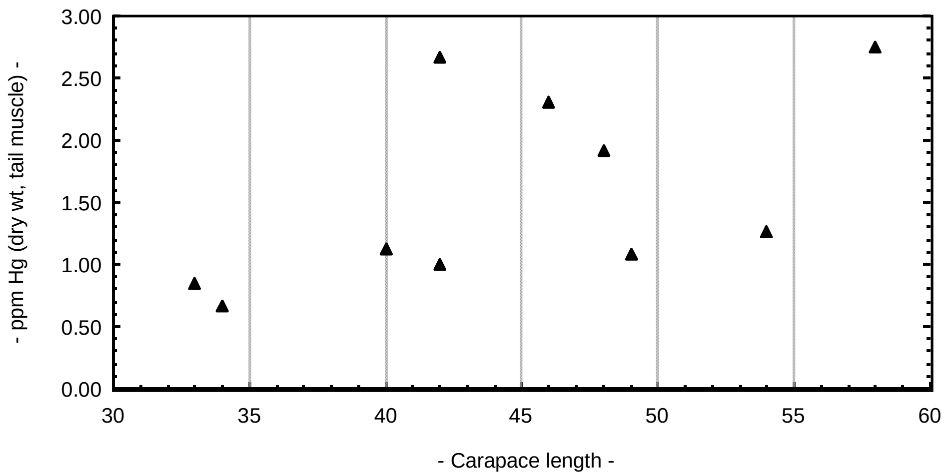

Figure 4 Individual mercury variability in signal crayfish, *Pacifasticus leniusculus*. Sacramento River at Isleton, December 9, 1999; tail muscle with gut removed.

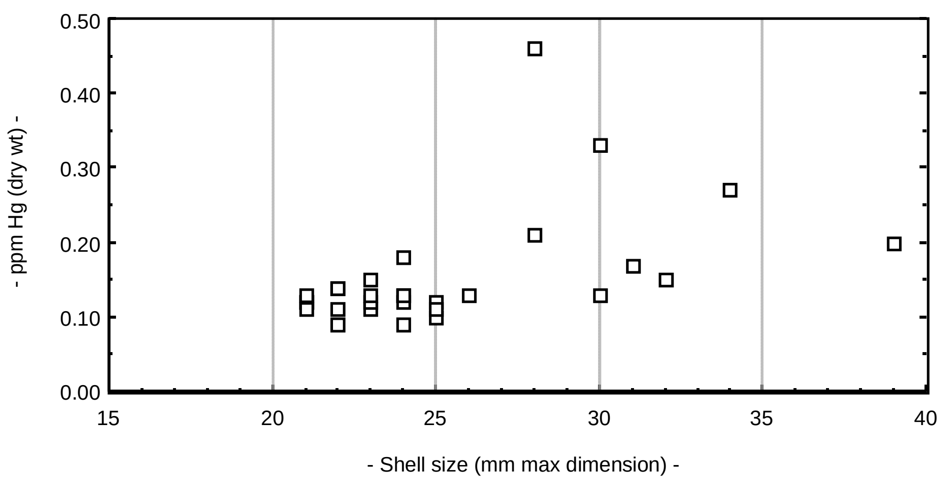

Figure 5 Individual mercury variability in the Asiatic clam, *Corbicula fluminea*. Cosumnes North Slough, October 26, 1999; whole body clams were purged four days before analysis.

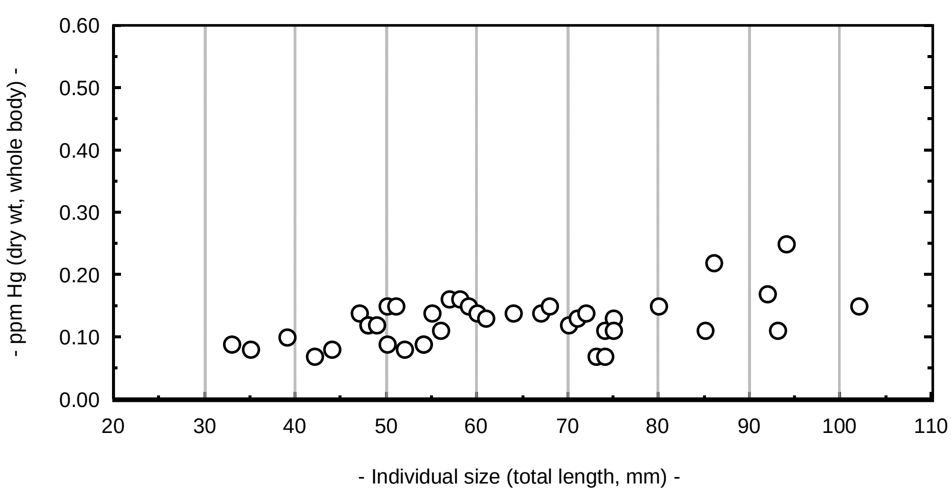

Figure 6 Individual mercury variability in inland silverside *Menidia beryllina*. Mildred Island, November 9, 1999.

Mercury in Clams (*Corbicula fluminea*)

Figure 7 shows mercury concentrations in 15- to 27-mm *Corbicula* from multi-individual, whole body composites taken consistently throughout the Delta. *Corbicula* mercury concentrations were relatively elevated in the Cosumnes and Mokelumne rivers (0.34 to 0.38 µg Hg g^{-1}) and moderately elevated in downstream channels carrying their water (0.18 to 0.26 µg Hg g^{-1}). Sacramento River inflows (0.15 to 0.22 µg Hg g^{-1}) and North Delta sites exposed to Yolo Bypass flows had similar levels (0.14 to 0.29 µg Hg g^{-1}). Clams from the Stanislaus (0.34 µg Hg g^{-1}), Tuolumne (0.20 µg Hg g^{-1}), and Merced (0.17 µg Hg g^{-1}) rivers were also elevated to varying degrees. Clams from the entire South Delta region were consistently low (0.0 to 0.16 µg Hg g^{-1}), except for one outlier from Old River south of Clifton Court Forebay (0.35 µg Hg g^{-1}). The Central Delta region, with its many flooded tracts, demonstrated clam mercury concentrations similar to those in the inflows at sites north of Mildred Island (0.16 to 0.35 µg Hg g^{-1}).

Throughout the Delta, there was no indication of localized increases in mercury concentrations of *Corbicula* as a function of habitat. Flooded wetland tracts consistently exhibited mercury levels that were similar to those from control sites within the same subregion. In paired collections (inside and outside flooded tracts) from Venice Cut and Rhode islands, concentrations were not statistically different.

Notably, the highest overall values in the *Corbicula* mercury data set were recorded at West Delta and Suisun Bay sites between Ryer Island to the west and Big Break, Gallagher Slough, and Sand Mound Slough to the east. Throughout this region, *Corbicula* mercury concentrations were between 0.32 and 1.08 µg Hg g^{-1}. Composites of another bivalve, *Potamocorbula amurensis*, taken at the upstream side of Carquinez Strait, were also relatively high (0.37 to 0.42 µg Hg g^{-1}). Suisun Slough and Grizzly Bay (0.15 to 0.26 µg Hg g^{-1}) did not appear to be the source of elevated West Delta and Suisun Bay mercury bioaccumulation.

Mercury in Inland Silversides (*Menidia beryllina*)

Figure 8 displays inland silverside mercury from 45 to 75 mm, multi-individual, whole body composites taken at 64 sites throughout the Delta. These small, schooling fish accumulate mercury over a larger region than the clams, likely integrating mercury across each flooded tract or slough, thus, being more representative of average mercury conditions at each site. As a result, the silverside data set grades very evenly from site to adjacent site and provides perhaps the best broad spatial measure to date of relative mercury bioavailability to fishes throughout the Delta. Additionally, mercury bioaccumulation in small fishes is dominated by methyl mercury (similar to large fishes), whereas bivalve mercury bioaccumulation may include substantial amounts of inorganic mercury (Brenda Lasorsa, personal communication, see “Notes”). Thus, the silverside data set may be the better indicator of relative methyl mercury exposure. Ongoing work will directly determine the methyl mercury component in our primary indicator organisms.

Mercury concentrations in silversides were consistently elevated in the Cosumnes and Mokelumne rivers (0.30 to 0.55 µg Hg g^{-1}) and the North Delta sites exposed to Yolo Bypass flows (0.18 to 0.46 µg Hg g^{-1}), with highest regional levels closest to the undiluted inflows. Elevated to a lesser extent were the channels carrying Sacramento River water (Sacramento River, Steamboat and Georgiana sloughs, Delta Cross Canal), which had very similar mercury levels in silversides at 0.21 to 0.28 µg Hg g^{-1}. Collections in the target size class were not possible in the Stanislaus, Tuolumne, or Merced rivers, but composites from the San Joaquin River upstream of the Merced (0.79 µg Hg g^{-1}) and from Mud Slough at Kesterson Reserve (0.69 µg Hg g^{-1}) contained the highest mercury levels in silversides of the survey. However, as in the clams, this did not translate into elevated levels downstream in the South Delta. Silversides from the entire south and central portions of the Delta were uniformly low in mercury (0.08 to 019 µg Hg g^{-1}) relative to the inflow values.

As with clams, silversides demonstrated little or no localized elevation in mercury concentrations in relation to flooded wetland habitats. Fish from large, relatively isolated flooded tracts in the North Delta such as Liberty Island (0.29 µg Hg g^{-1}) and Little Holland Tract (0.18 µg Hg g^{-1}) were not elevated over control samples from adjacent and regional channel and slough sites (0.21 to 0.46 µg Hg g^{-1}). The Central Delta, with its prevalence of flooded tracts, also showed no relative increase in silverside mercury concentration in flooded tracts compared to control sites, with all concentrations throughout the region being uniformly low relative to inflow sites and the West Delta. In fact, the Central Delta demonstrated the lowest levels of silverside mercury bioaccumulation in the entire system.

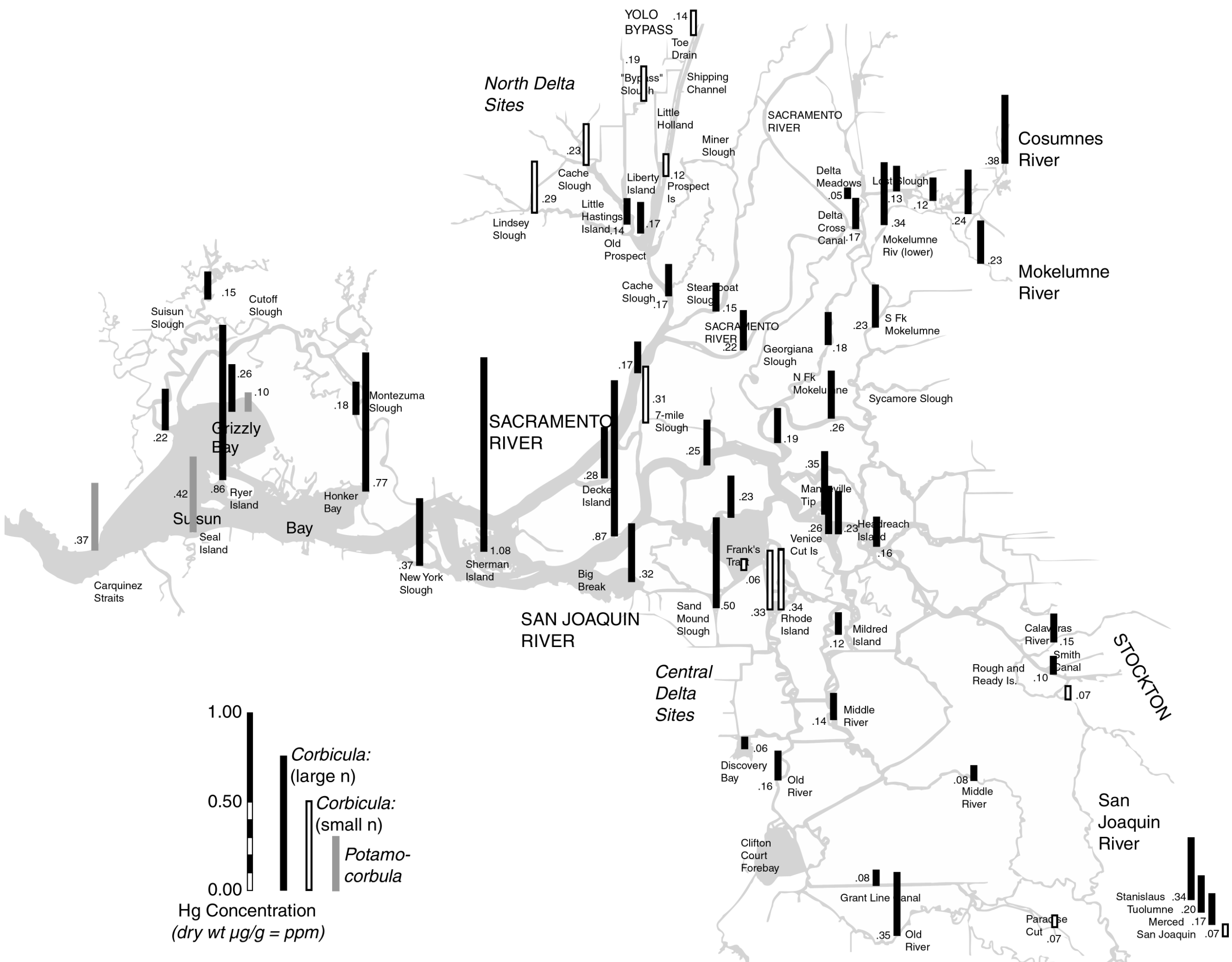

Figure 7 Mercury spatial distribution of the Asiatic clam, *Corbicula fluminea*. Fall 1999 collections; 15 to 27 mm, multi-individual composites; clams purged four days before analysis; "small *n*" ≤ 5.

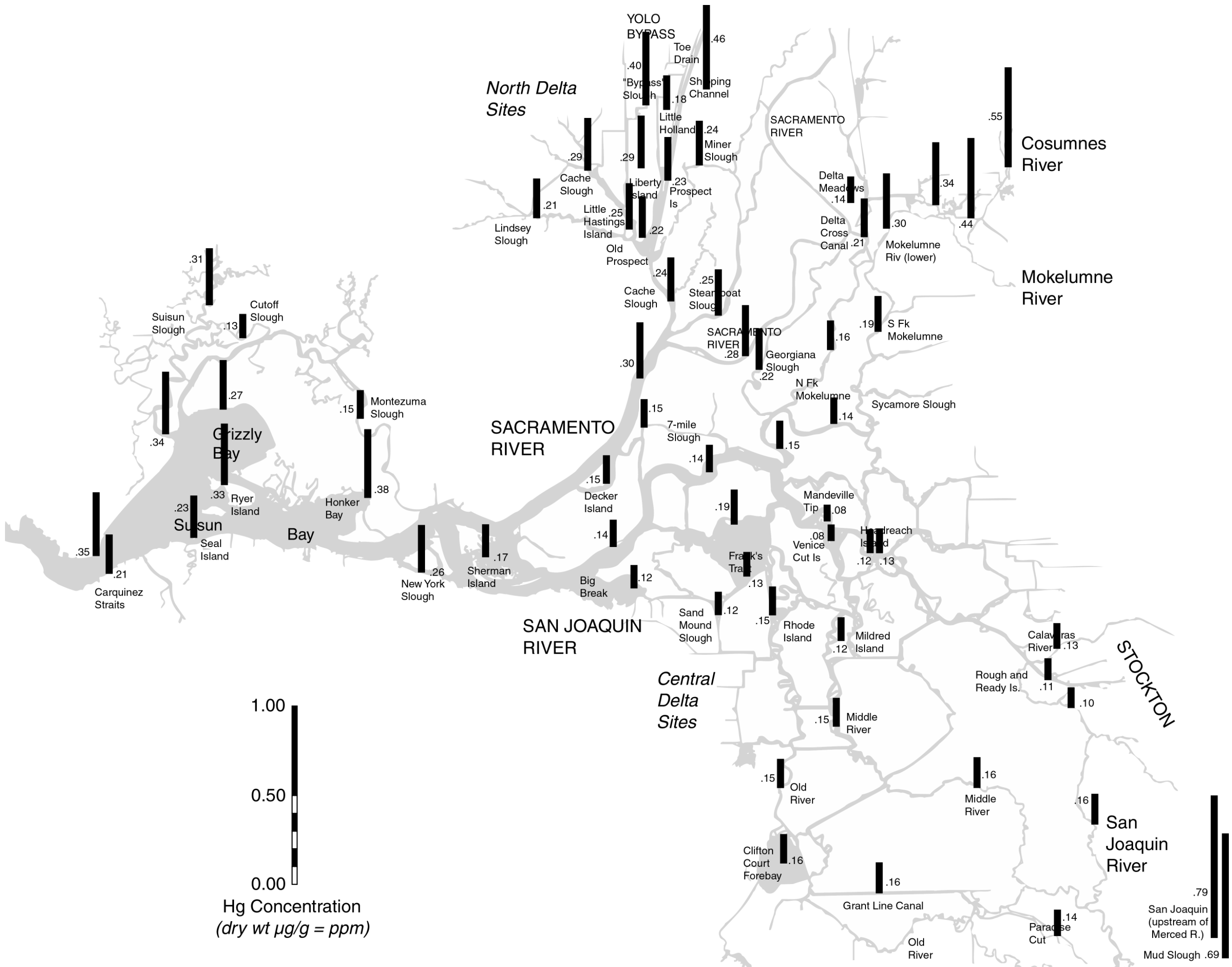

Figure 8 Mercury spatial distribution of inland silverside, *Menidia beryllina*. Fall 1999 collections; 45 to 75 mm, multi-individual composites; $n \geq 6$; whole body dry wt µg Hg g^{-1}.

Inland silversides in the West Delta and Suisun Bay again showed a distinct signal of increased mercury bioaccumulation relative to the Central Delta. While increases were not as apparent as those seen in the clams (Sand Mound Slough, Gallagher Slough, Big Break, Sherman Lake: 0.12 to 0.17 µg Hg g^{-1}), silversides from west of the Sacramento-San Joaquin confluence to the Carquinez Strait exhibited elevated levels similar to those of the northern and eastern inflow regions at 0.21 to 0.38 µg Hg g^{-1}.

Conclusions and Implications for Delta Wetlands Restoration

For problem levels of methyl mercury to accumulate in fish, several factors must interact. There must be a source of inorganic mercury that is bioavailable to mercury methylating bacteria. There must be conditions that promote the methylation of this mercury. And, finally, the methyl mercury that is produced must move efficiently into and up through aquatic food webs. It is clear, from this study and upstream studies preceding it, that the Bay-Delta system contains a significant watershed source of mercury, largely linked to historic mining. Results to date suggest the Cosumnes River, Yolo Bypass, and Sacramento River are primary ongoing sources, with additional elevated inflows in some of the San Joaquin tributaries. This is in addition to the depositional mercury within the system that has presumably accumulated since the Gold Rush period. The methylation experiments indicate that flooded Delta wetland sediments have the strong potential to methylate bioavailable inorganic mercury. Preliminary results suggest methylation potential is proportional to the level of wetland ecological development. The bioindicator data show marked differences in localized mercury bioaccumulation across the Delta, with several regions of elevated mercury uptake that may be of particular concern. However, these elevated mercury bioaccumulation zones do not appear to directly correspond with tract flooding and wetland restoration. Within each Delta region, mercury bioaccumulation was typically similar in marsh, sand and mud flat, and channel and slough habitats. One possibility is that regional mercury bioavailability may be largely a function of methylation in flooded marsh zones, with this methyl mercury being subsequently distributed throughout all adjacent aquatic habitats as a result of vigorous tidal mixing. However, we found the Central Delta, with a preponderance of flooded tracts and a demonstrated high mercury methylating potential, was the lowest fish mercury bioaccumulation region of all, indicating several potentially competing processes may be involved in the dynamics of mercury bioaccumulation associated with flooded tracts.

Consistent with preliminary findings from 1998–1999, the 1999–2000 results reported here suggest relative mercury bioaccumulation may be more closely linked to location within the Delta than habitat type. This may be a function of proximity to inflowing sources, methylation efficiency, methyl mercury bioaccumulation efficiency, or food web complexity. Ongoing research is examining these and other factors. Delta regions with elevated mercury accumulation in localized bioindicators included areas fed by inflows from the Cosumnes River, Yolo Bypass and, to a lesser extent, Sacramento River. The Central and South Delta were markedly lower, despite high signals in some southern tributaries. One of the most important new findings of this year's research was the identification of an extensive additional zone of elevated mercury bioaccumulation in the West Delta between the Sacramento-San Joaquin confluence and Carquinez Strait.

The West Delta region encompasses the estuary entrapment zone, where fresh and salt water meet and inorganic and organic particulates typically accumulate. Several inter-related mechanisms may play a role in the apparent West Delta elevated biotic mercury phenomenon, including (1) the localized accumulation of organic and fine-grained inorganic material, promoting general bacterial activity and increased food web complexity, (2) sulfate increases associated with the transition to salinity, supporting sulfate-reducing bacteria, and (3) chemistry of the neutral form of mercury in this transition zone, which has been hypothesized to be optimal for cross-membrane transport into methylating bacteria (Mark Marvin Di Pasquale and Cynthia Gilmour, personal communications, see "Notes").

The configuration and magnitude of water diversion operations within the Delta can be expected to play an important, ongoing role in the mercury dynamics of the different regions, influencing the location of the entrapment zone, the re-distribution of elevated mercury inflows, and the re-distribution of within-Delta methyl mercury production.

Findings to date suggest organic-rich, vegetated wetland tracts have dramatically greater potential to methylate mercury than adjacent channel or flats habitat. However, this does not appear to result in localized increases in mercury accumulation in organisms. Mercury levels in bioindicator organisms showed regional trends, apparently related to inflow sources and differences in mercury cycling dynamics. Results to date suggest that wetlands restoration projects may result in localized mercury bioaccumulation at levels similar to, but not necessarily greater than, general levels within their surrounding Delta sub-region. Nevertheless, high methylation potential, flooded wetland habitat may be the primary source of methyl mercury production in the overall system: further work is being done to look at the specific contribution of flooded tracts. Careful monitoring will be essential to assess the actual effects of new wetlands restoration projects.

FUTURE WORK

Ongoing UC Davis CALFED research on Delta mercury dynamics includes:

- Determination of the methyl mercury component of total mercury in the bioindicator organisms and the spatial pattern of biotic methyl mercury and methyl:total mercury ratio.

- Investigation of possible seasonal and inter-annual variation in Delta mercury methylation and bioaccumulation at 12 representative index locations (May, August, November).

- Paired flooded tract and adjacent channel or slough sediment sampling at primary existing flooded tracts. Methyl mercury absolute concentration and methyl/total ratio are key variables, with additional comparisons of potentially driving variables including particle size, percentage moisture, percentage organic matter, sulfide, sulfate, pH, and dissolved organic carbon.

- Methylation potential experiments across the salinity gradient, including Franks Tract, Sherman Island, Grizzly Bay, and San Pablo Bay.

- Mercury bioaccumulation in additional species.

- Stable isotope investigations of food web structure.

Acknowledgements

The authors gratefully thank past and present members of the UC Davis Delta mercury research team, including Ron Weyand and Anne Liston who carefully prepared and analyzed the bulk of the samples reported here, Chance MacDonald and Professor Douglas Nelson for their work with the sediment slurry experiments, and Brenda Johnson. Additional thanks to numerous agency personnel who provided a variety of help and advice, including Chris Foe, Curtis and Jackie Hagen, Mark Stephenson, and Lenny Grimaldo. Funding for this research is provided by the CALFED Bay-Delta Program under Contract No. 97–C05 to the University of California, Davis.

References

Domagalski J. 1998. Occurrence and transport of total mercury and methyl mercury in the Sacramento River Basin, California. J Geochem Exp 64:277–91.

Rudd JWM 1995. Sources of methyl mercury to freshwater ecosystems: a review. Water Air Soil Poll 80:697–713.

Foe C, Croyle W. 1998. Mercury concentrations and loads from the Sacramento River and from Cache Creek to the Sacramento-San Joaquin Delta estuary. Central Valley Regional Water Quality Control Board staff report. 101 p.

Roth DA, Taylor HE, Peart DB, Antweiler RC, Domagalski JL, Dileanis PD, Alpers CN. 2000. Distribution of inorganic mercury in Sacramento River water and suspended colloidal sediment material. Archives of Environmental Contamination and Toxicology. Forthcoming.

Slotton DG, Ayers SM, Reuter JE, Goldman CR. 1995. Gold mining impacts on food chain mercury in northwestern Sierra Nevada streams. Technical Completion Report for the University of California Water Resources Center, Project W–816. 46 p.

Slotton DG, Ayers SM, Reuter JE, Goldman CR. 1997. Cache Creek watershed preliminary mercury assessment, using benthic macro-invertebrates. Final Report for the Central Valley Regional Water Quality Control Board and the National Science Foundation. 36 p.

Slotton DG, Ayers SM, Reuter JE. 1998. Marsh Creek watershed mercury assessment project: third year (1997) baseline data report with 3-yr review of selected data. Report for Contra Costa County. 62 p.

Slotton DG, Ayers SM, Reuter JE, Goldman CR. 1999. Lower Putah Creek 1997–1998 mercury biological distribution study. Report for the Department of Environmental Health and Safety, University of California, Davis. 59 p.

Suchanek TH, Richerson PJ, Mullen LJ, Brister LL, Becker JC, Maxson A, Slotton DG. 1997. The role of the Sulphur Bank Mercury Mine site (and associated hydrogeological processes) in the dynamics of mercury transport and bioaccumulation within the Clear Lake aquatic ecosystem. A report prepared for the USEPA, Region IX Superfund Program. 479 p.

Suchanek TH, Slotton DG, Ayers SM, Johnson B, Nelson DC. 1999. Effects of wetlands restoration on the production of methyl mercury in the San Francisco Bay-Delta system: preliminary results. Interagency Ecological Program for the San Francisco Estuary. IEP Newsletter 12(3):19–24.

Theis TL, Young TC, DePinto JV. 1988. Factors affecting metal partitioning during resuspension of sediments from the Detroit River. J Great Lakes Research 14(2):216–26.

Notes

Cynthia Gilmour (Academy of Natural Sciences, Estuarine Research Center, St. Leonard, Maryland). Telephone conversation on July 15, 2000.

Brenda Lasorsa (Battelle Marine Sciences Laboratory, Sequim Washington). Telephone conversation on August 14, 2000.

Mark Marvin Di Pasquale (US Geological Survey, Menlo Park). In-person conversation on March 20, 2000.

POTAMOCORBULA REVISITED: RESULTS OF EXPERIMENTAL AND FIELD WORK ON THE EFFECT OF CLAMS ON ESTUARINE FOOD WEBS

Wim Kimmerer and Carolina Peñalva
Romberg Tiburon Center
San Francisco State University
kimmerer@sfsu.edu

ABSTRACT

This article is a progress report on an IEP-funded study of the effects of *Potamocorbula amurensis* on the zooplankton of the San Francisco Estuary. We present results of experiments on ingestion of copepod nauplii by the clams, using copepod species common in the lower estuary. Results show that copepods avoided ingestion by clams in about 50% of encounters. These results, together with results from an EPA-funded study showing high sensitivity of reproductive rate to food supply, suggest that the decline in abundance of *Acartia* spp. may be due to competition with *P. amurensis*. However, the relative importance of each still needs to be determined through modeling studies. Field studies were also conducted to investigate the population dynamics of copepods in the low salinity zone during spring. These results suggest recruitment failure of *Eurytemora affinis* may have been due both to reduced egg production and reduced survival of nauplii. However, the copepod *Pseudodiaptomus forbesi* is probably neither an important predator nor competitor of *E. affinis*. The dynamics of *P. forbesi* also suggest a decline in production and survival of nauplii in late spring, so that the population becomes older during late spring to summer. Modeling studies will also be used to investigate these changes.

INTRODUCTION

The clam *Potamocorbula amurensis* has become the poster-child for introduced species in the estuary. Since its spread throughout the northern estuary in 1987, it has had apparent direct or indirect effects on phytoplankton (Alpine and Cloern 1992; Kimmerer and Orsi 1996), bacteria (Werner and Hollibaugh 1993), zooplankton (Kimmerer and others 1994; Kimmerer and Orsi 1996), mysids (Orsi and Mecum 1996), benthos (Nichols and others 1990; Carlton and others 1990), and possibly fish (Kimmerer 1998).

The effects of *P. amurensis* on zooplankton include a severe reduction in abundance of the copepod *Eurytemora affinis*, previously the numerical dominant in the low-salinity zone in summer. The near-absence of this copepod from this region in summers since 1987 was attributed to inadvertent predation by the clams on the nauplius larvae of the copepods (Kimmerer and others 1994). *Eurytemora affinis* has been replaced in summer by two introduced copepods: *Pseudodiaptomus forbesi*, which is similar in size and general life history; and *Limnoithona tetraspina*, a very small and extremely abundant cyclopoid copepod whose life history is poorly known.

Concurrent with the decline in copepods of the Low Salinity Zone, abundance of *Acartia* spp. declined in the lower estuary. This ubiquitous genus includes *A. tonsa*, *A. californiensis*, and the numerical dominant, an unidentified species of the subgenus *Acartiura* (referred to previously as *A. clausi*; Ambler and others 1985). This decline was noted in the IEP monitoring data (Kimmerer and Orsi 1996), but sampling for these species is inadequate since most of the population is seaward of the area covered by IEP sampling. The decline in *Acartia* spp. was corroborated in a comparison of recent (1997–1999) zooplankton data with data collected in 1978–1981 (Kimmerer and others 1999). Declines were noted only in the shallower regions of San Pablo Bay and South Bay, suggesting a possible effect of *P. amurensis*. However, the mechanism for such declines has not been established. The recent sampling also revealed an increase in abundance of the small, introduced cyclopoid copepod *Oithona davisae*, which has surpassed *Acartia* spp. as the most abundant copepod of the lower estuary.

Potential mechanisms for effects of clams on copepods are illustrated in Figure 1. Clams may either consume nauplii or free-floating eggs. Predatory effect is likely to be greater on nauplii because of their much longer duration in the water column, although nauplii can avoid clam siphons and may also avoid the bottom. In addition, clams may reduce the food supply causing food limitation in one or more life stages. Typically in broadcast spawners reproduction is most sensitive to food limitation (Berggreen and others 1988), although that may not be true for egg-carriers, some of which have a lower reproductive rate that is insensitive to food limitation (Fancett and Kimmerer 1985). To determine the likely mechanisms for clam effects requires an estimate of the predatory effect of clams on eggs and nauplii, an estimate of the degree of food limitation of either reproductive or development rates, and a population dynamics model with which to compare the magnitudes of these effects.

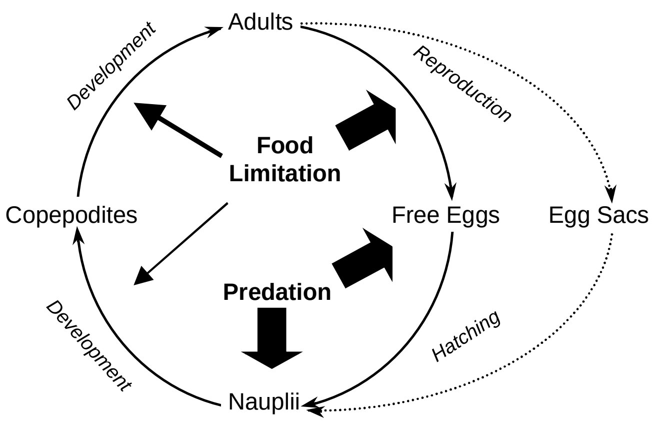

Figure 1 Schematic diagram of copepod life cycle showing potential influences of *P. amurensis* on life cycle. Copepods may broadcast spawn free-floating eggs (*Acartia* spp.), or they may carry eggs in egg sacs (*Eurytemora*, *Pseudodiaptomus*, *Oithona*), in which case eggs are invulnerable to ingestion by clam siphons. Nauplii are more or less vulnerable depending on their escape responses. Food limitation is likely to be most severe in reproduction, less so in development of copepodite (juvenile) stages, and least in nauplii.

This report presents data from the first year of a two-year study funded by IEP. The purpose of the study is to investigate further the mechanisms by which *P. amurensis* may have caused reductions in abundance of zooplankton important in fish diets, and why some zooplankton species have become abundant in spite of low chlorophyll concentration in most years. Ultimately, we hope to understand how productivity of lower trophic levels of the estuary has changed. During the first year we have conducted investigations to provide partial answers to the following questions:

1. What is the mechanism by which *Acartia* spp. has declined?

2. Is there any evidence for a direct competitive interaction among zooplankton species?

3. By what mechanism have the “replacement species” been able to maintain their abundance in spite of high and varying abundance of *P. amurensis*?

4. What is the cause of the annual patterns of abundance in which *Eurytemora affinis* declines sharply in late spring?

The general approach to question 1 was to conduct grazing experiments to investigate the vulnerability of copepod nauplii to ingestion by clams. We addressed questions 2–4 by estimating population parameters of the two key copepod species of the low salinity zone in spring 1999 using a sampling interval of (usually) one week. Measurements made under other funding provide important input to this project, including estimates of abundance in the lower estuary during 1997–1999 (Kimmerer and others 1999) and egg production rates of key zooplankton species measured in an EPA-funded project (Kimmerer unpublished).

METHODS

Predation Experiments. The general approach was to incubate samples containing small zooplankton in one-liter beakers containing *P. amurensis* and in control beakers, and observing differences in the abundance of zooplankton in the beakers. We also conducted “artificial predation” experiments, in which clam siphons were mimicked by fine-bore tubes used to siphon water out of the beakers. In some experiments we combined these techniques, since the artificial predation experiments presumably did not cause the loss of any zooplankton.

Clams were collected at various sites in the northern San Francisco Estuary. Clams were held either in mesh bags off the seawall at the Romberg Tiburon Center, in beakers with periodic additions of cultured phytoplankton, or in a refrigerator. Refrigerated clams were brought to experimental temperature at least 24 hours before experiments began. When salinity changes were necessary the salinity was altered by gradual dilution over a period of up to five days, depending on the amount of change needed. For each experiment, clams were selected in groups of 2 to 20 (median 4) depending on size to provide approximately the same total weight of clams in each experimental beaker. Total live weight of clams in experimental containers ranged from 0.9 to 1.8 g (median 1.0).

Water for experiments was collected by dipping from the surface with a bucket at various stations in Central Bay to Suisun Bay, depending on the target species and the salinity distribution. Zooplankton were collected either with brief, gentle net tows (50-µm mesh) or by concentrating about 100 liters of surface water using upward filtration through a 50-µm mesh, then an 80 µm mesh and diluting the 50- to 80-µm fraction to 15 to 20 liters until the experiment began. For the experiments reported here we collected samples in Central Bay, targeting the copepods *Acartia* spp. and *Oithona davisae*. However, the abundance of nauplii of these copepods, and of other zooplankton, was unpredictable and not always sufficient for a robust estimate of grazing rate or escape response. We diluted samples as needed to obtain a final abundance of roughly 100 nauplii L^{-1}. Between 30 and 191 (median 121) nauplii were recovered from control containers.

Predation experiments were conducted in one-liter beakers with magnetic stirrers running at low speed (about 100 rpm). Experiments were run in dim light at normal room temperature, which ranged from 17 to 25 °C, between 0 and 6 °C above the temperature at which the zooplankton was collected. Initial samples were not taken since initial abundance is not needed for the calculation of grazing rate (see below). Experiments were started by suspending clams in the beakers in small plexiglass cylinders with 500-µm mesh bottoms. Control beakers contained no clams, and beakers were assigned randomly to treatments. After 4 to 24 hours the contents of the beakers were rinsed and concentrated through a 35-µm mesh and preserved in 2% formaldehyde. The entire contents of samples from experimental and control containers were counted and identified to as low a taxonomic level as practicable. Nauplii were identified to species but not to stage.

In some experiments, either in conjunction with clam grazing or separately, we constructed artificial clam siphons using silicone tubing of 0.55 mm inside diameter. These tubes were set up as siphons with approximately one meter of head, which resulted in a flow rate of about 45 ml h^{-1}. One to four siphons removed water from each beaker without clams into separate beakers, until approximately 800 ml had been transferred. We then removed zooplankton from the paired beakers as above. In experiments with clams the results from paired beakers with siphons were used both to provide data on vulnerability to capture by siphons and, with data from paired beakers combined, as controls for the containers with clams.

To calculate the ability of nauplii to escape ingestion in clam siphons required estimates of grazing rate on particles without an escape response. To accomplish this, in some experiments we measured *in vivo* fluorescence using a Turner Designs model 11 fluorometer over the first two to four hours of the experiment to allow for an estimate of grazing rate on phytoplankton. In experiments in which the fluorometer was not used, we calculated grazing rate using uptake of either rotifers or tintinnid ciliates, neither of which has an observable response to suction by siphons. The assumption of no escape response was tested in some experiments in which fluorescence was measured and there were sufficient rotifers or tintinnids for a comparison.

Calculations. The experimental objective was to determine Pe, the probability that an organism encountering a siphon will escape entrainment. Assumptions of the method are as follows: (1) an organism encountering a siphon may respond with an escape reaction that moves it from its current volume element *dV* to any other volume element in the beaker, and this movement is random; (2) clam grazing rate and probability of escaping are constant during the experiment; and (3) mortality not due to clam siphons occurs at the same rate in all beakers.

The probability that an organism in a small volume element *dV* will be entrained during time interval *dt* is:

$$P(entrain) = (1 - P_e)\frac{dV}{V} \qquad (1)$$

where *V* is the volume of the container. The rate of decrease of organisms *N* in the beaker is then:

$$\frac{dN}{dt} = -R\frac{N}{V(t)}(1 - P_e) - mN \qquad (2)$$

where *R* is the clearance rate (volume $time^{-1}$, taking into account filtration efficiency), and *m* is the non-clam mortality rate. In the control beakers *R* is 0, and since *m* is assumed constant the final abundance in the control beakers is related to *m* by integrating equation (2) with *R* = 0:

$$C_c = C_0 e^{-mt} \qquad (3)$$

where C_C and C_0 are control and initial concentrations respectively. In an artificial predation experiment the number removed and the number remaining are known, so controls are unnecessary and P_e can be computed by integration as:

$$\hat{P}_e = 1 - \frac{\ln(N_f / N_T)}{\ln(V_f / V_T)} \qquad (4)$$

where P_e is the estimate of escape probability in a given beaker, N_T is the sum of abundance in the two beakers, N_f is the final number in the beaker being siphoned from, and V_T is the combined volume and V_f the final volume in the beaker being siphoned from. Note that unlike a true probability, P_e can exceed the range (0,1) because of experimental error and biases (discussed below).

In a clam predation experiment both the number of organisms removed and the siphoning rate are unknown, so controls must be used to determine the number lost and only the clearance rate is calculated. The siphoning rate must be determined indirectly so that the probability of escaping capture can be determined. Integrating equation (2) and substituting equation (3) gives:

$$R_i(1 - \hat{P}_{ei}) = \frac{V_i}{T}\ln\frac{N_i}{V_i C_c} \qquad (5)$$

where the left-hand term is the clearance rate, the subscript *i* refers to individual experimental beakers, and C_C is the mean concentration of the selected taxon in the control beakers. Then the siphoning rate *R* must be determined by assuming some taxon not to have an escape response, in which case P_e is zero. For this purpose we used either total chlorophyll fluorescence as a proxy for phytoplankton abundance, or abundance of rotifers or tintinnids when they were sufficiently abundant, calculated *R* for each beaker (with P_e set to 0), then used that value of *R* to calculate P_e for the other taxa.

For fluorescence, the mortality rate *m* in equation (2) could be negative indicating growth, but is still accounted for by measurements on controls. We took several measurements over the course of the experiments. The slope of log fluorescence, divided by control means for each sample to correct for growth or mortality in the absence of clams, was substituted into equation (2) to obtain *R/V* directly. In most cases the decline of fluorescence in the experimental containers flattened after one to two hours, presumably either because the remaining chlorophyll was unavailable to the clams or because some chlorophyll-containing particles were released in pseudofeces or feces. The clams continued pumping water, with no observed change in behavior, throughout the experiments. Thus the initial decline in fluorescence probably provided a good measure of *R* throughout the experiments.

Population Abundance Study. We sampled for population characteristics of copepods common in the low salinity zone (LSZ; Kimmerer and others 1998), specifically *Eurytemora affinis* and *Pseudodiaptomus forbesi*. Duplicate samples were collected from May through July 1999 using a 50 µm mesh net with a flow meter, hauled vertically from near the bottom to the surface. Zooplankton were preserved in 2% to 5% formaldehyde. In the laboratory, subsamples were taken and copepods were identified to species and the following life stages: nauplii (all stages grouped), copepodite stages 1–5, and adults. In the same and some duplicate samples, the proportion of females carrying eggs was determined, and random subsamples of ten ovigerous females from each sample were examined to determine the number of eggs each was carrying. These data were used to compute the egg ratio, that is, the total number of eggs per female in the samples.

Demographic characteristics of copepods can usually be determined in one of two ways: by cohort analysis, or by steady-state analysis in cases where reproduction is more or less continuous. Neither method proved suitable: both species have transitory life history patterns, but cohorts were not detectable in the data for either. The data are reported here, and we are exploring a cohort model for estimating the key population parameters of stage-specific mortality (which may be related to the abundance of *P. amurensis*), and for estimating the rate at which copepods are hatching from eggs in the sediments.

RESULTS

In addition to several pilot experiments and tests of alternative methods, not reported here, we completed seven experiments in which either clam predation, artificial predation, or both were used to examine the response of the target species and life stages (Table 1).

Zooplankton taxa were generally less abundant in experimental than in control containers, indicating consumption by clams (Figure 2). Rotifers and tintinnids were much less abundant, relative to the controls, than any of the copepods examined.

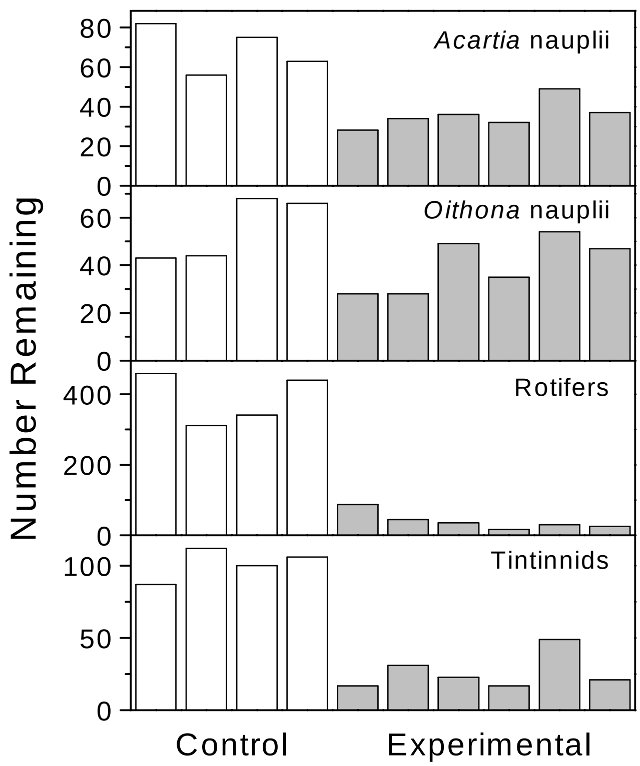

Figure 2 Results of experiment of August 25, 1999. Bars give the number of animals remaining in control (clear bars) and experimental (shaded bars) beakers. Differences between control and experimental containers are assumed to be due to ingestion by clams.

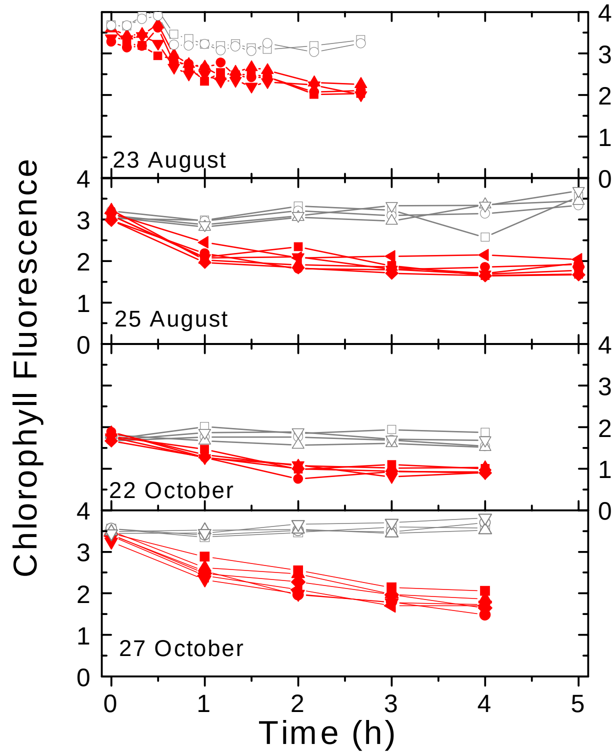

Figure 3 Time course of chlorophyll fluorescence during four experiments in control (open symbols) and experimental (filled symbols) beakers. Fluorescence is in uncalibrated units, presumed proportional to chlorophyll concentration within a given experiment.

Table 1 Summary of experiments conducted and analyzed to date[a]

Experiment	*1*	*2*	*3*	*4*	*5*	*6*	*7*
Date	Jul 28	Aug 5	Aug 10	Aug 19	Aug 25	Oct 22	Oct 27
Type	A	AC	AC	C	C	C	AC
Temp. (°C)	17	18	18	24	25	22	18
Fluorescence					Y	Y	Y
Acartia nauplii	Y	Y	Y	Y	Y	Y	Y*
Oithona nauplii	Y	Y	Y	Y	Y	Y	Y
Oithona juveniles	Y	Y*	Y	Y*	Y	Y	Y*
Rotifers	Y	Ref		Y	Y		
Tintinnids			Ref	Ref	Y	Y	Y

a All dates are 1999. "Type" refers to **A**rtificial predation or **C**lam predation experiments, or both. Fluorescence indicates whether chlorophyll fluorescence was used to estimate grazing rate; if not, either rotifers or tintinnids were used, as indicated by "Ref" in their respective rows. Rows with taxon names indicate whether escape response was determined for each taxon in each experiment. Asterisks indicate that numbers of organisms in control beakers were low, so results are less reliable than in other experiments.

Chlorophyll fluorescence was measured during experiments 5–7 and at short intervals during a preliminary experiment on August 23, 1999 (Figure 3). In all of these experiments there was evidence that the rate of decrease in fluorescence in the experimental containers, presumably due to clam grazing, fell off after the first hour or two of the experiment. Therefore only the first hour of data was used to estimate the grazing flow rate *R*.

Figure 4 gives an example of estimates of P_e based on data in Figure 2. The nauplii of the two copepods had positive escape responses, indicating that they were successfully evading clam siphons at least part of the time. Escape responses of rotifers were negative. This could indicate that rotifers are more vulnerable to ingestion than phytoplankton, or that the rate of decline of fluorescence was underestimated; in this experiment the rate of decline of fluorescence essentially ended at one hour, and may have ended earlier (Figure 3). Escape responses of tintinnids appeared to be negligible.

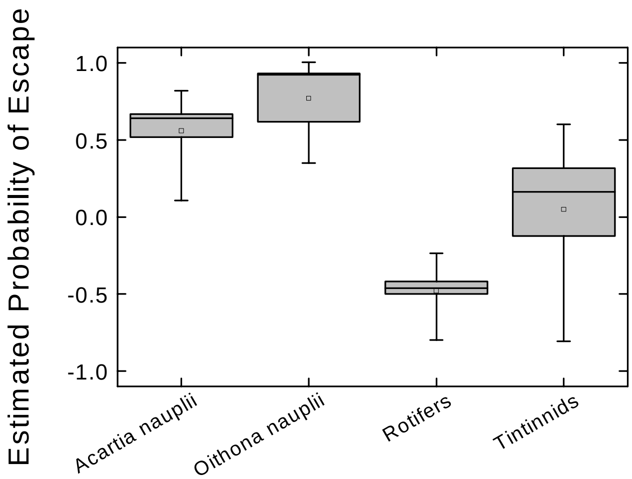

Figure 4 Boxplot summarizing results of August 25, 1999 clam predation experiment. Boxplot shows the median (horizontal line), mean (square), 25th and 75th percentiles (limits of bar) and maximum and minimum (ends of whiskers). Based on the data shown in Figure 2, this gives P_e for the four taxa included in this experiment.

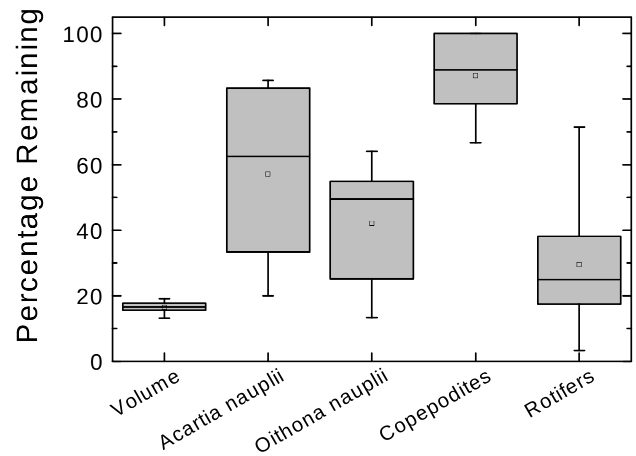

Figure 5 Boxplot summarizing results of artificial predation experiment of July 28, 1999. Symbols summarize the percentage of water volume and the percentage of each group of organisms remaining in beakers from which about 80% of the water was siphoned out. Boxplot symbols as in Figure 4.

Artificial predation experiments were interpreted in relation to the proportion of volume siphoned out of the experimental beakers (Figure 5). The expectation was that animals with a weak escape response would be transferred in proportion to their abundance. Again, nauplii of both copepod species showed evidence of avoiding the siphon. Copepodites seemed very resistant to being siphoned, which is not surprising given their larger size and stronger swimming ability. Rotifers were siphoned roughly in proportion to their abundance (Figure 5).

Results of the two kinds of experiments are summarized in Figure 6 and Tables 2 and 3. Copepod nauplii had positive P_e in nearly all cases (the single very low value for *Acartia* nauplii was for a sample with only three nauplii remaining). Rotifers and tintinnids had P_e values that varied widely around zero.

Results of clam predation experiments show that on average, the copepod nauplii and copepodites had strong escape responses with P_e very different from zero (but not 1; Table 2). Rotifers and tintinnids on average had no escape response. However, among the experiments there were significant differences in P_e for *Oithona* nauplii, rotifers, and tintinnids. These differences could not be explained by experimental conditions such as weight or number of clams, temperature, or duration of the experiment.

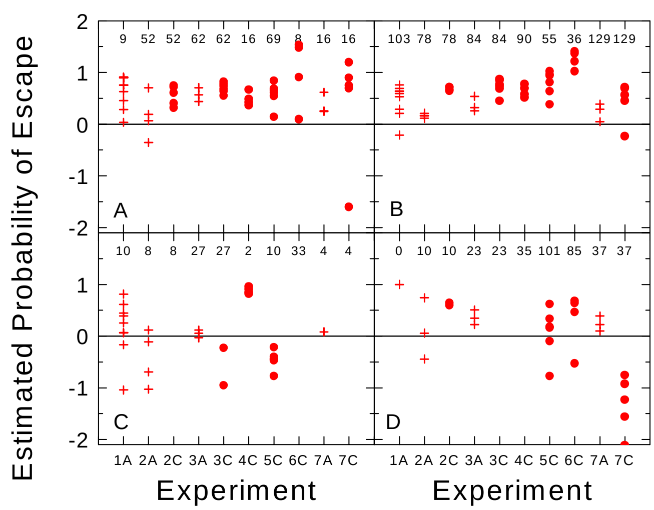

Figure 6 Summary of results of all experiments. Artificial predation experiments are indicated by crosses and by the experiment identifier #A, where # is the experiment number; clam predation experiments are indicated by circles and #C. Each symbol gives P_e for a single experimental beaker. Numbers at top within each figure give the mean number of organisms in the controls; note that numbers in experimental treatments were often much smaller. A, *Acartia* nauplii; B, *Oithona* nauplii; C, rotifers; and D, tintinnids.

Table 2 Summary of predation experiments with clams[a]

Taxon	P_e	*Dates*
Acartia nauplii	0.64 ± 0.10	6 dates; no difference
Oithona nauplii	0.92 ± 0.06	6 dates; significantly different
Oithona copepodites	0.89 ± 0.07	5 dates; no difference
Rotifers	–0.05 ± 0.10	3 dates; significantly different
Tintinnids	–0.01 ± 0.30	4 dates; significantly different

[a] Values given are grand mean probability of escape with 95% confidence interval, based on a robust weighted analysis of variance vs. date, in which the weighting factor was the square root of the mean number of zooplankton of each species in the controls.

Table 3 Summary of artificial predation experiments[a]

Taxon	P_e	*Dates (total = 3)*
Acartia nauplii	0.44 ± 0.16	No difference
Oithona nauplii	0.36 ± 0.13	No difference
Oithona copepodites	0.71 ± 0.06	Significantly different
Rotifers	–0.06 ± 0.25	No difference
Tintinnids	0.25 ± 0.20	No difference

[a] Notes as in Table 2.

Results of artificial predation experiments were generally similar to those of clam predation experiments, except that P_e values of copepods were generally lower, and tintinnids appeared to have a small positive P_e value (Table 3). The differences between clam and artificial predation experiments were tested using robust analysis of variance in a comparison of all three experiments where both methods were used. These differences were statistically significant for *Acartia* nauplii ($P < 0.02$) and *Oithona* nauplii ($P < 0.0001$), but not for *Oithona* copepodites ($P > 0.1$) or rotifers ($P > 0.1$). Escape responses of tintinnids differed between the two types of experiments in experiments 2 and 7, but in opposite directions.

Population Abundance Study. The two copepods, *Eurytemora affinis* and *Pseudodiaptomus forbesi*, had very different patterns of abundance in spring 1999. *E. affinis* was most abundant at the beginning of the study in early May (Figure 7). As in most copepod populations, the bulk of the population comprised nauplii early in the study. In June and July, abundance fell off rapidly as it has done in spring of previous years, beginning around the end of May (Julian day 151). The decline coincided with a reduction in egg ratio, which is related to egg production rate, and in the proportion of nauplii in the population. By mid-June the *E. affinis* population consisted almost entirely of adults.

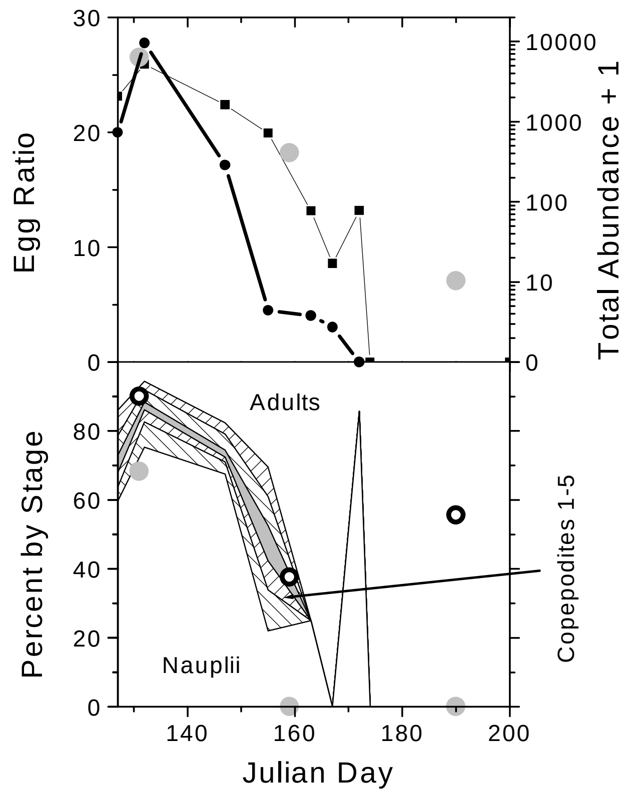

Figure 7 ***Eurytemora affinis*** **in spring 1999.** Top, total abundance (squares, right axis) and egg ratio (circles, left axis). Bottom, relative abundance (percent) by life stage including nauplii, copepodite stages I-V, and adults. Circles give data from IEP zooplankton sampling: total abundance (top) and relative abundance (bottom) of nauplii (solid) and of nauplii plus copepodites (open).

P. forbesi was much less abundant than *E. affinis* in early May, with very few adults in the population (Figure 8). Initially the egg ratio of the females was low, but by the end of May it was nearly 10 eggs per female, still lower than the egg ratio of *E. affinis*. After that the egg ratio of *P. forbesi* declined, and until *E. affinis* disappeared from the plankton its egg ratio remained above that of *P. forbesi*. Abundance of *P. forbesi* reached a plateau of about 2,000 to 5,000 m^{-3} beginning in mid-June. During the entire period the proportion of nauplii in the population declined, and that of adults increased. The proportion of copepodite stages was higher than that of *E. affinis* for most of the sampling period.

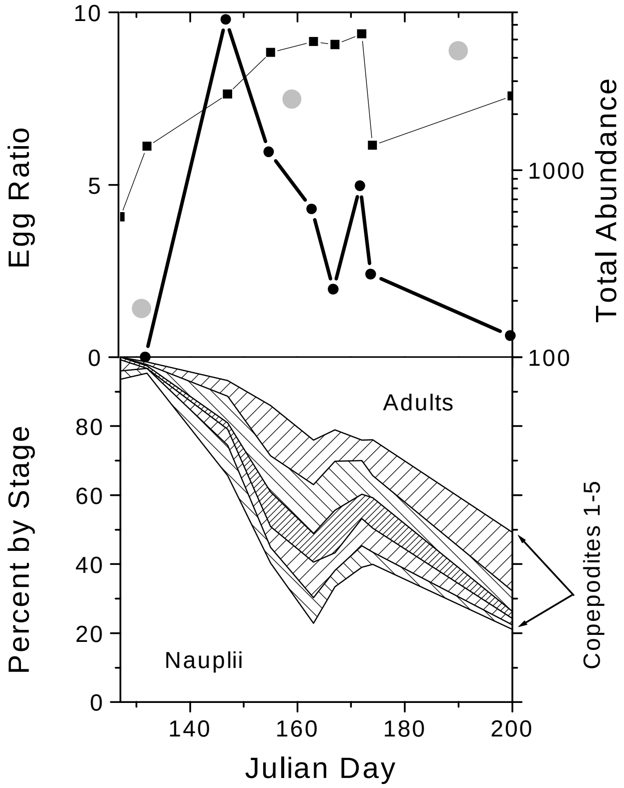

Figure 8 As in Figure 7 for *Pseudodiaptomus forbesi*. Abundance data from IEP surveys did not include nauplii, so relative abundance is not given and total abundance excludes nauplii. Symbols as in Figure 7.

DISCUSSION

The experiments on escape responses gave somewhat conflicting results in terms of P_e, the estimated probability of escaping the siphons. For one thing, there were differences among experiments not explained by experimental conditions, and differences between results of paired clam and artificial predation experiments. In the clam experiments these may be partially explained by the data used to estimate the siphoning rate of the clams, which may have introduced bias into the experiments. In addition, the artificial siphons appeared to be better able than clam siphons to capture both nauplii and copepodites (Tables 2 and 3).

Nevertheless, the overall result is clear: nauplii of both *Acartia* and *O. davisae* have moderately strong escape responses that enable them to avoid ingestion in clam siphons. Thus, if they are exposed to predation by the clams through their seasonal and vertical distribution, ingestion rate should be considerably less than that of inert particles.

If predation on *Acartia* nauplii is low, how have they been affected? Egg production rate of *Acartia* has been measured monthly in San Pablo Bay and Central Bay from November 1999 to September 2000, was found to be food limited most of the time, and sensitive to chlorophyll concentration. Thus, the low chlorophyll values throughout the summer, which have been attributed to *P. amurensis*, may prevent *Acartia* from increasing its population size.

In the upper estuary, we observed the seasonal decline in *Eurytemora affinis* and increase in *Pseudodiaptomus forbesi* during spring 1999. The decline in *E. affinis* was clearly due to recruitment failure, as the proportion of nauplii in the population became progressively lower and that of adults higher. Near the end of the sampling period the population was low and declining, and consisted almost entirely of adults. Based on the proportions of copepodite (juvenile) stages in the population it is unlikely that they suffered a decline in survival. In contrast to previous results (Kimmerer and others 1994), the egg production rate of *E. affinis* declined through the period. Thus, there appeared to have been at least some food limitation. In addition, the rapid decline in proportion of nauplii in the population suggests a strong effect of clam predation, although the relative magnitudes of predation and low reproductive rate cannot be distinguished in these data.

During the same time *P. forbesi* went through its seasonal transient, increasing in abundance through the early spring and leveling off in summer. However, this leveling off did not occur in a steady-state mode as expected. Instead, it involved a continuous shift from a high proportion of nauplii to about 50% adults by the end of the period. This shift coincided with a reduction in egg ratio (and therefore reproductive rate) to a very low value. Thus, this population also appeared to be senescing. The main difference between the two copepod populations seems to be that the mortality of adult *P. forbesi* appears to be very low, while that of *E. affinis* appears higher. These differences are being explored through population modeling.

A key question is the influence of *P. forbesi* on *E. affinis*. This can be crudely estimated through the use of literature data on copepod growth and growth efficiency. Using stage-specific growth rates for *P. marinus* at 20 °C from Uye and others (1983), and assuming a 50% gross growth efficiency, I calculated stage-specific ingestion rates, then used observed abundance to determine total ingestion of the *P. forbesi* population. I then assumed a carbon:chlorophyll ratio of 50 to estimate chlorophyll (Chl) ingestion rates. The mean chlorophyll in the June IEP zooplankton survey for samples taken in the low salinity zone was 4.5 µg Chl L^{-1}. At their highest abundance the copepods were consuming less than 2% of this chlorophyll daily, a negligible proportion given the high turnover rate of phytoplankton. If grazing by *P. forbesi* were equally effective on the nauplii of *E. affinis*, the mortality of nauplii due to this grazing would be also less than 2% per day, but the decline in *E. affinis* nauplii was closer to 20% per day (Figure 7). Furthermore, the nauplii are probably consumed at a lower rate than chlorophyll. Thus, it is unlikely that *P. forbesi* had either a competitive or a predatory effect on *E. affinis* during spring 1999.

During the sampling period, abundance of *P. amurensis* based on IEP data was above 1000 m^{-2} at three of four stations in the northern estuary near where copepods were collected (Figure 9). Clams were absent at station D4 at the confluence of the Sacramento and San Joaquin rivers, and in the Delta. X2 averaged 64, 69, and 75 km during May, June, and July, respectively. Thus, assuming these copepod populations were centered at a salinity of about 2 psu (Kimmerer and others 1998), they would have been exposed to a declining population of clams over time, with abundance on the order of 100 to 1,000 m^{-2} in May, and less than 100 m^{-2} in July. The magnitude of the predation effect is difficult to estimate without considering the extent of the tidal excursion and the size (and therefore filtration rate) of the clams. However, the clams were probably smaller early in the season than late.

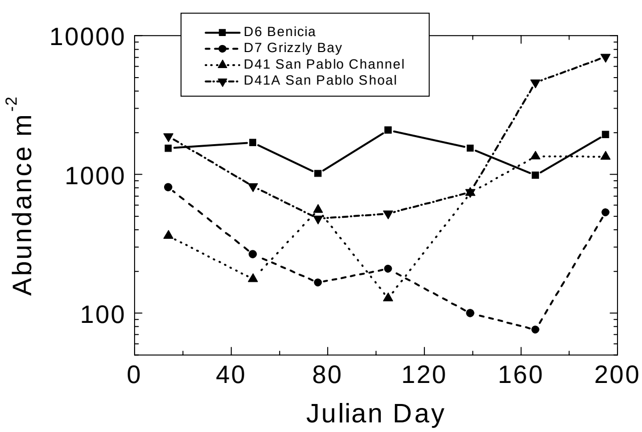

Figure 9 Abundance of *Potamocorbula amurensis* from the IEP survey for spring 1999

These results will be explored, and the relative effects of predation and food limitation estimated, using a model of copepod population dynamics now being developed.

Acknowledgments

Funding for this study was provided by IEP. We thank Jeff McLain and the U.S. Fish and Wildlife Service Chipps Island sampling crew for taking zooplankton samples for us. We thank Nissa Ferm for laboratory assistance, and Randy Brown for just about everything.

References

Alpine AE, Cloern JE. 1992. Trophic interactions and direct physical effects control phytoplankton biomass and production in an estuary. Limnology and Oceanography 37:946–55.

Ambler JW, Cloern JE, Hutchinson A. 1985. Seasonal cycles of zooplankton from San Francisco Bay. Hydrobiologia 129:177–97.

Berggreen U, Hansen B, Kiorboe T. 1988. Food size spectra, ingestion and growth of the copepod *Acartia tonsa* during development: implications for determination of copepod production. Marine Biology 99:341–52.

Carlton JT, Thompson JK, Schemel LE, Nichols FH. 1990. Remarkable invasion of San Francisco Bay (California, USA) by the Asian clam *Potamocorbula amurensis*. 1. Introduction and dispersal. Mar Ecol Prog Ser 66:81–94.

Fancett MS, Kimmerer WJ. 1985. Vertical migration of the demersal copepod *Pseudodiaptomus* as a means of predator avoidance. J Exp Mar Biol Ecol 88:31–43.

Kimmerer W. 1998. A summary of the current state of the X2 relationships. Interagency Ecological Program for the San Francisco Estuary. IEP Newsletter 11(4):14–25

Kimmerer WJ, Orsi JJ. 1996. Causes of long-term declines in zooplankton in the San Francisco Bay estuary since 1987. In: Hollibaugh JT, editor. San Francisco Bay: the ecosystem. San Francisco (CA): American Association for the Advancement of Science, Pacific Division. p 403–24.

Kimmerer WJ, Gartside E, Orsi JJ. 1994. Predation by an introduced clam as the probable cause of substantial declines in zooplankton in San Francisco Bay. Mar Ecol Prog Ser 113:81–93.

Kimmerer WJ, Burau JR, Bennett WA. 1998. Tidally-oriented vertical migration and position maintenance of zooplankton in a temperate estuary. Limnology and Oceanography 43:1697–1709.

Kimmerer W, Peñalva C, Bolens S, Avent S, Cordell J. 1999. Zooplankton in the lower San Francisco Estuary. Interagency Ecological Program for the San Francisco Estuary. IEP Newsletter 12(2):15–8.

Nichols FH, Thompson JK, Schemel LE. 1990. Remarkable invasion of San Francisco Bay (California, USA) by the Asian clam *Potamocorbula amurensis*. 2. Displacement of a former community. Mar Ecol Prog Ser 66:95–101.

Orsi JJ, Mecum WL. 1996. Food limitation as the probable cause of a long-term decline in the abundance of *Neomysis mercedis* the opossum shrimp in the Sacramento-San Joaquin Estuary. In: Hollibaugh JT, editor. San Francisco Bay: the ecosystem. San Francisco (CA): American Association for the Advancement of Science, Pacific Division. p 375–401.

Uye, S.-I., Y. Iwai, and S. Kasahara. 1983. Growth and production of the inshore marine copepod Pseudodiaptomus marinus in the central part of the Inland Sea of Japan. Marine Biology 73:91–8.

Werner I, Hollibaugh JT. 1993. *Potamocorbula amurensis*–comparison of clearance rates and assimilation efficiencies for phytoplankton and bacterioplankton. Limnology and Oceanography 38:949–64.

MORTALITY RATES OF LARGEMOUTH BASS IN THE SACRAMENTO-SAN JOAQUIN DELTA, 1980 THROUGH 1984

Raymond G. Schaffter, DFG
rschafft@delta.dfg.ca.gov

INTRODUCTION

In 1980, the Department of Fish and Game conducted a four-year resident fish study as part of the Interagency Ecological Program. This was the first Delta-wide study of non-migratory species conducted by electrofishing, an efficient method of sampling shallow water shoreline zones. We determined how environmental variables and habitat types were associated with resident fish abundance (Urquhart 1987), and tagged largemouth bass (*Micropterus salmoides*) to determine largemouth bass survival, and angling and natural mortality rates. The growing effect of a "catch and release" strategy (beginning to be practiced by bass anglers) on fishing mortality was unforeseen at the beginning of the study. This report compares survival rates of largemouth bass in the early 1980s as determined by tag returns and by age composition, a method of survival estimation free from biases of tag return studies when a catch and release fishery is present.

METHODS

Largemouth bass tagged for mortality estimates were collected by electrofishing during three related surveys: (1) a Delta-wide stratified random resident fish survey from May 1980 to April 1983; (2) a Delta-wide monthly resident fish survey at 15 locations during 1984, and (3) a dedicated tagging survey during June and July of each year, 1980 through 1984, which concentrated on east and central Delta locations where largemouth bass were most abundant (Figure 1). Although there was no minimum size limit for largemouth bass in the Delta during tagging, only healthy, 200 mm fork length (FL) bass were tagged with $10 reward disc-dangler tags (Kimsey 1956; Chadwick 1966). All tag returns were acknowledged with the reward and a card. Missing recovery information, such as date and location of capture, was requested with an enclosed postpaid return card. If the date of capture was not given in the return letter or follow-up postcard, a capture date of the 15th of the month preceding the return was usually assumed. Although not part of the study design, if an angler volunteered information that the fish was released, it was noted. The tag return year was the number of days from release to recapture of each fish divided by 365.25 days.

I divided the overall tag-return matrix at 294-mm fork length, corresponding to the now current 305-mm total length (TL) minimum size limit by using the total length-fork length conversion of Shultz and Vanicek (1974). This length corresponds to the near universal 12-inch total length minimum size limit now in effect for the Delta and most other California waters. The two resultant tag-return matrices were tested for similarity with the chi-square testing row and block totals used in calculating survival rates (Brownie and others 1985). Chi-square tests of returned vs. not returned tags were also used to evaluate potential biases in other tagging variables.

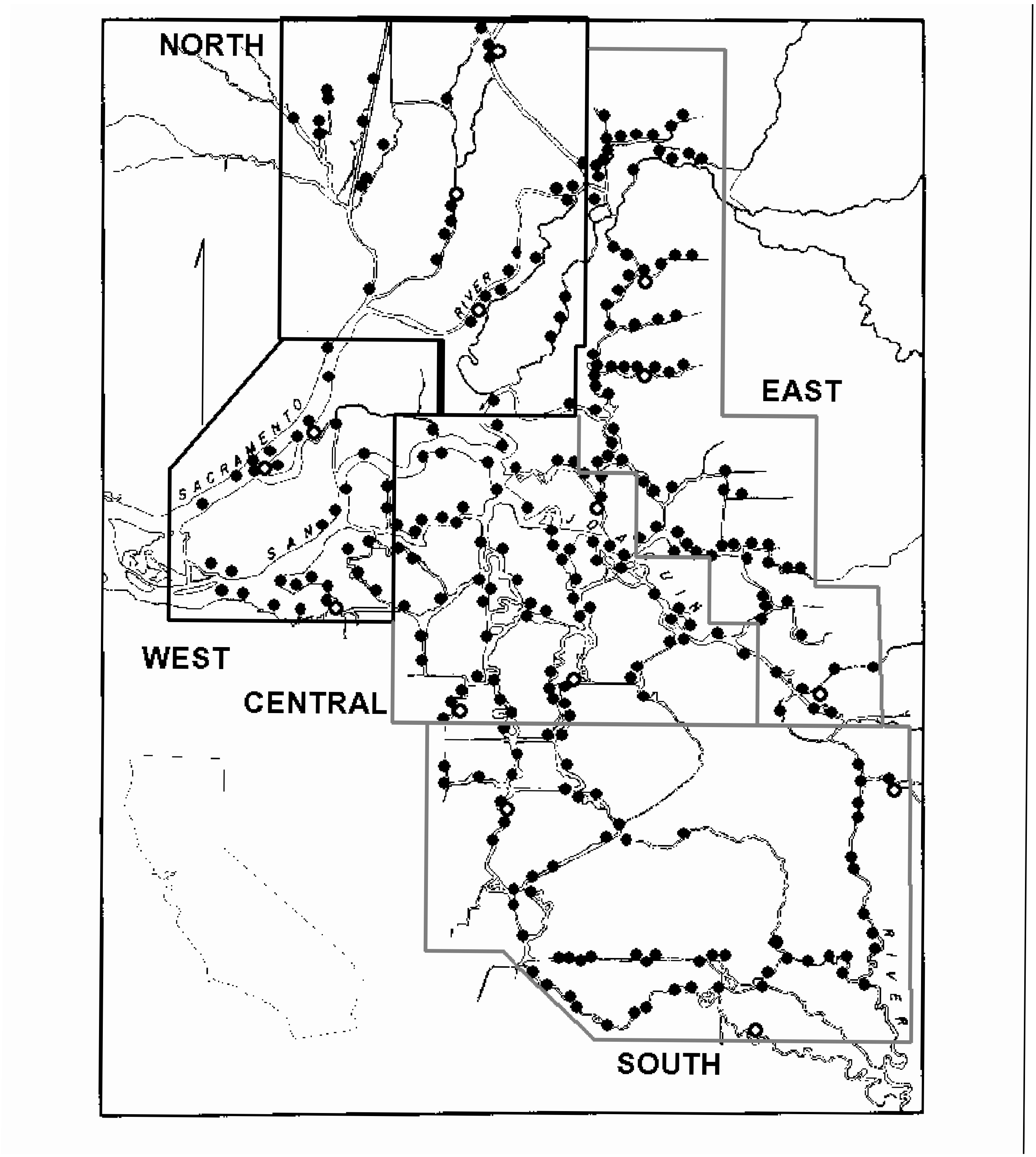

Figure 1 Largemouth bass sampling sites in the Sacramento-San Joaquin Delta. Closed circles denote sampling sites for the 1980–1983 resident fish survey, open circles denote 1984 sample sites during the 1984 resident fish survey. Irregular polygons represent Delta regions used in resident fish surveys and dedicated bass tagging.

I determined tag recovery (a surrogate for angler mortality [u]) and survival (S) rates using the maximum likelihood models of Brownie and others (1985), which fit data to a series of four less restrictive models and provide goodness-of-fit chi-square tests between calculated and actual returns for each model. For a brief synopsis of these models see Schaffter (1997). Natural mortality (v) was estimated by subtracting angling mortality (u) from total mortality (1–S).

Preliminary analyses of tag return data indicated that late returns of some tags were causing rejection of fit with all models. For this reason, tag returns were reviewed to identify tags which may have been kept for some time before being returned. If a fourth- through seventh-year tag was returned with two or more recent tags, and no capture information was supplied for it, either with the tag or in response to follow-up prepaid postcard inquiry, the late return tag was deleted from the tagged and returned data sets. Because of lack of evidence of non or other late angler response, a 100% return on all other $10 reward tags was assumed. For accurate estimation of angler mortality, these models require the assumption that all tags are returned and all angler caught fish are a component of angler mortality (u).

To estimate the potential effect of catch and release fishing on the calculated angling mortality rate, I used a survival rate based on age composition. I used a superset of the age data included in the Delta largemouth bass growth data (Schaffter 1998) that contained all bass that had age agreement by two readers, or in case of conflicts, resolved by a third reader, to provide an alternate estimate of survival (S) by the method of Robson and Chapman (1961) for fish at ages 4 through 12. To estimate revised angler mortality (u) because of catch and release, I used the average natural mortality estimate (v), obtained from the mark-return Brownie and others models. To gain information on the catch and release fishery, I computed the proportion of first year returns for each tag year that were accompanied with a voluntary statement of release of the caught fish, then tested the mean lengths at time of tagging of fish released vs. fish whose tag return letters did not state the disposition of the fish.

RESULTS

Differences between ratios of returned vs. non-returned tags by 20-mm size intervals from 200 to 440 mm FL were highly significant (X^2 = 52.41, 12 df, P < 0.001) with under-returns from the 200 to 219 mm FL size interval contributing 26.07 to the total chi-square. Hence, fish from the 200 to 219 mm FL size interval were deleted from additional mark-recapture analyses. Although differences still existed when all remaining 20-mm groups were present, return vs. non-returned tag ratios were similar for four size groups from 220 and 294 mm (X^2 = 5.97, 3 df, P = 0.11) and nine size groups from 295 to 439 mm FL and 440 mm FL. (X^2 = 4.40, 8 df, P = 0.82).

Tag-return matrices for bass 220 to 294 mm FL and bass 295 mm FL were significantly different (X^2 = 24.26, 11 df, P = 0.01) and were analyzed separately. After removing 15 fish from the tag and return matrices because of questionable recapture and return dates, two final tag-return matrices covering five years of tagging and seven years of recovery were used for mortality estimates (Table 1).

The least restrictive maximum likelihood model that fit the data for larger fish (>294 mm TL) was model 2 (X^2 = 16.50, 12 df, P = 0.169), which allows recovery rates (surrogate of u) to vary between tag years, but finds no difference in annual survival (S) between tag years (Table 2). Largemouth bass 220 to 294 mm FL fit the less restrictive model 3 (X^2 = 23.83, 18 df, P = 0.16), which features constant recovery and survival rates between years. But model 3 was nearly rejected in favor of model 2 (X^2 = 11.64, 6 df, P = 0.07). For comparisons of annual catch levels and parallelism of results, model 2 was also selected for small fish (Table 2). The average tag recovery rate through the seven recovery years for fish <295 mm FL was 0.26 (95% CI = 0.23 to 0.29) and the average survival rate (S) was 0.40 (95% CI = 0.35 to 0.45), corresponding to a total mortality rate (A) of 0.60 (95% CI = 0.55 to 0.65) (Table 2). For larger fish, 295 mm FL, the tag recovery rate was 0.33 (95% CI = 0.30 to 0.36) and average survival rate (S) was 0.33 (95% CI = 0.28 to 0.37), corresponding to a total mortality rate of 0.66 (95% CI = 0.63 to 0.70) (Table 2).

The Robson-Chapman estimate for survival (S) for ages 4 through 12 was 0.50 (95% CI = 0.48 to 0.53) corresponding to an annual total mortality rate (A) of 0.50 (95% CI = 0.47 to 0.52) (Table 2). The associated chi-square value testing for full recruitment of the youngest age group (4) relative to older age groups was 0.362 with 1 df (P = 0.55). Using the 0.33 average natural mortality rate from maximum likelihood estimates, the angler mortality rate (u) was 0.17 (Table 2). The difference between maximum likelihood harvest of largemouth bass >294 mm FL and age composition harvest was 0.16 or 52% of the maximum likelihood estimate, suggesting about 50% of largemouth bass were released after capture during the study.

Table 1 Tag and return matrices for five years of tagging and seven years of returns of largemouth bass in the Sacramento-San Joaquin Delta

Largemouth bass 220–294 mm FL		Recaptures made and reported in year						
Year tagged	Number tagged	1	2	3	4	5	6	7
1980	101	28	10	0	1	1	0	0
1981	219		49	29	10	6	0	1
1982	272			70	30	8	3	1
1983	261				68	29	11	2
1984	501					133	32	14
Largemouth bass ≥295 mm FL		Recaptures made and reported in year						
Year tagged	Number tagged	1	2	3	4	5	6	7
1980	157	55	18	5	1	3	0	0
1981	232		77	18	9	2	0	2
1982	197			72	23	12	2	0
1983	226				77	15	5	5
1984	310					100	22	3

Table 2 Angler harvest (*u*), total annual mortality (*A*) calculated as 1-survival (*S*), and annual natural mortality (*v*) calculated as *A-u* of largemouth bass in the Sacramento-San Joaquin Delta[a]

	Mortality		
Year	*Angler (u)*	*Total (A)*	*Natural (v)*
Largemouth bass 220–294 mm FL			
1980	0.26	0.60	0.34
1981	0.23	0.60	0.37
1982	0.26	0.60	0.34
1983	0.27	0.60	0.33
1984	0.27	0.60	0.33
Mean	0.26	0.60	0.34
95%CI	0.23–0.29	0.55–0.65	0.32–0.37
Largemouth bass >294 mm FL			
1980	0.35	0.66	0.31
1981	0.32	0.66	0.34
1982	0.34	0.66	0.32
1983	0.33	0.66	0.33
1984	0.31	0.66	0.35
Mean	0.33	0.66	0.33
95%CI	0.30–0.36	0.63–0.70	0.30–0.36
Largemouth bass ages 4–12			
1980–1984	0.17	0.50	0.33
95%CI		0.47–0.52	

[a] Maximum likelihood estimates were derived from the Model 2 of Brownie and others (1985) which assumes constant survival rate, but annually varying tag recovery rate (angling mortality). Age based mortality estimate was derived from the method of Robson and Chapman (1961) and the mean value of natural mortality (*v*) from maximum likelihood methods was used to determine fishing mortality (*u*).

The portion of anglers who volunteered in their tag-return letters that they released fish increased steadily from 6% to 20% (Table 3) through the five years of tagging. With the exception of 1980, the average length at tagging of fish released by anglers tended to be smaller than those caught by anglers who did not volunteer the disposition of their fish, although this size difference was significant only in 1983 and almost disappeared in 1984.

Table 3 Portion by year of first year tag returns released alive after removing the tag[a]

Year	*Portion released*	*$\bar{x}$ FL (mm) released*	*$\bar{x}$ FL (mm) unknown*	*t*	*df*	*P*
1980	0.06	329	317	0.47	82	0.63
1981	0.10	278	316	–1.88	139	0.06
1982	0.12	276	304	–1.84	150	0.07
1983	0.16	269	303	–2.56	156	0.01
1984	0.20	284	286	–0.28	253	0.78

[a] Fork lengths are mean fork lengths at time of tagging of fish released and fish with release status unknown. The probability is the significance of a two-tailed *t*-test, pooled variance, between mean length at tagging of released and unknown release status fish.

DISCUSSION

Two sources of error which affect the estimate of fishing mortality may not have been well controlled: angler response to the $10 reward tags and the effect of catch and release fishing. Angler harvest, as determined by voluntary return of tags, remained remarkably stable throughout the five-year tagging study with no declining trend. Both Schaffter (1997) and Stevens and others (1985) noted declines in the response to non-reward tags in the Sacramento-San Joaquin Delta following two or more years of tagging thousands of fish annually, but it was assumed that the combination of a $10 reward and the relatively small number of fish tagged would make the recovery of a tagged largemouth bass an infrequent enough event to maintain angler interest. These factors suggest the rate of angler encounter with a tagged fish was relative to the number of fish tagged and was fairly constant throughout the five-year tagging study with little change in angler response to the $10 reward tags. However, a decline in angler return rates coupled with an increase in angler capture rates over time due to increased fishing effort, could mimic a steady-state harvest condition. I cannot evaluate this with existing data.

Undoubtedly some reward tags were not returned or were retained by anglers for some period of time until they had accumulated tags and the total value of all tags in their possession became sufficient to respond. Non-response, or never returning tags, does reduce the estimate of angler harvest, but, assuming a constant rate of non-response, has no effect on calculated survival rates. Late returns both reduce the estimates of angler harvest and increase the estimates of survival because they indicate an angler caught fish was alive longer than it actually was. Late returns also cause lack of fit with maximum likelihood tag recovery models, which assume previously tagged fish are caught, depending on their availability, at the same rate as newly tagged fish during the same time interval. If smaller fish were not fully vulnerable to the fishery, the return rates of available second and later years tags would be higher than tags of newly tagged fish, mimicking a situation of delayed tag returns. The differences between tag recovery based survival rates between small and large fish indicate that some mechanism other than constant lower return rates for smaller fish was present. However, it cannot be determined if reduced return rates of recently tagged fish was due to differential size-related angler response or directed fishing effort towards larger bass by anglers using lures, baits, and fishing methods favoring larger fish. The deletion of fourth- through seventh-year tags returned when batched with newer tags and no capture information and, therefore, excluded from the analysis, tended to reduce effects of extreme cases of late response on both survival rates and model fit.

With some unknown level of catch and release fishery occurring, however, the problem becomes how to differentiate between the survival rate of fish tags and the survival rate of fish.

The steadily increasing portion of anglers who volunteered that they had released their tagged catch indicate that a significant percentage of tagged fish captured was being released, and that this percentage was probably increasing throughout the tagging study. Although some anglers, perhaps used to fishing in area reservoirs where a 305 mm minimum size limit was then in effect, may not have been aware than no size limit existed in the Delta, many anglers were releasing fish that exceeded this length. By 1984, when 40 anglers volunteered that they had released their tagged fish (after removing and returning the tag), the mean size at tagging of released and release status unknown fish was nearly identical (Table 3).

The age-derived survival rate of tagged largemouth bass, which was not subject to any of the uncertainties of a tag and recapture study, is probably more accurate. As the sample included most tagged bass collected over five years, it reduced irregularities in age classes due to random variations in year-class strength (Ricker 1975). Only 12% of the four-year-old bass and a single five-year-old bass were smaller than the 295 mm FL cutoff level between small and large fish at time of tagging, making this population segment similar to the 295 mm FL population segment of the mark-recapture sample. The non-overlapping 95% confidence limits of the two survival estimates strongly suggest the mark and recapture estimates were measuring the life spans of fish tags rather than actual fish.

Delta largemouth bass mortality rates, whether estimated by tag returns or age composition, were lower than those derived by tagging studies from Shasta (Van Woert 1980) and Folsom lakes and Merle Collins Reservoir (Table 4) where, by the 1960s and early 1970s, anglers were removing nearly 50% of the "catchable" largemouth bass annually. There may be two possibilities for this relatively low exploitation in the Delta. Bass anglers may have been slow to recognize the potential of largemouth bass fishing within the Delta. Many reservoir bass anglers may not have considered fishing in the Delta until the 1976–1977 drought closed boat ramps at many area reservoirs and "forced" bass anglers to fish in the Delta. Secondly, the Delta contains far more inshore and relatively shallow largemouth bass habitat than most area reservoirs and can provide habitat for greater numbers of largemouth bass. The Delta contains over 1,100 km of channels considered navigable and 2,200 km of shoreline (Kelley 1966) in addition to numerous shallow flooded islands. Because of the large amount of bass habitat available, anglers may have fished the Delta less intensely than they fished northern California reservoirs.

Unlike fluctuating reservoirs, where rapid spring drawdown can dewater relatively shallow largemouth bass nests, Delta water level fluctuations are largely tidal, reaching a maximum fluctuation of only about one meter during spring tidal cycles (Kelley 1966). This is not considered a hindrance to successful largemouth bass spawning. Abundant cover is provided by submerged and emergent aquatic vegetation in sluggish water areas such as dead-end sloughs, oxbows, and flooded islands (Urquhart 1987). This combination of widespread adequate spawning and early rearing habitat insures a steady supply of young bass. Although growth rates of Delta bass are much slower than that found in most California reservoirs (Schaffter 1998), a relatively high and increasing level of catch and release fishing suggests the Delta will continue to provide opportunity for largemouth bass fishing.

While tag-recapture studies will continue to estimate angler use of largemouth bass, they are probably no longer good estimators of mortality rates for this species. Although we now request release information from anglers returning tags, as the portion of anglers releasing fish increases, the number of tags left to measure actual mortality rates is reduced. Recent tagging indicates that now approximately 90% of largemouth bass caught in the Delta are released. Hence, we will probably have to rely on age composition for future mortality estimates.

Table 4 Largemouth bass survival (*S*), total mortality (*A*), angler mortality (*u*) and natural mortality (*v*) estimates from California waters

Body of water	*S*	*A*	*u*	*v*	*Source*
Clear Lake	0.44	0.56	0.20	0.36	Kimsey 1957
Sutherland Reservoir[a]	0.41	0.59	0.37	0.22	La Faunce and others 1964
Folsom Lake	0.11	0.89	0.40	0.49	Rawstron 1967
El Capitan Reservoir[b]	0.38[c]	0.62	0.46	0.16	Bottroff and Lembeck 1978
	0.71[d]	0.29	0.19	0.10	
Lower Otay Reservoir[b]	0.43[d]	0.57	0.43	0.14	Bottroff and Lembeck 1978
Merle Collins Reservoir[e]	0.18	0.82	0.53	0.29	Rawstron and Hashagen 1972
Folsom Lake[f]			0.47		Rawstron and Reavis 1974
Lake Berryessa[f]			0.58		Rawstron and Reavis 1974
Lake Shasta	0.22	0.78	0.50	0.22	Van Woert 1980
Sacramento-San Joaquin Delta	0.40[g]	0.60	0.26	0.34	Present study
	0.34[h]	0.66	0.33	0.33	Present study
	0.50[i]	0.50	0.17	0.33	Present study

[a] Average values, four years with disk-dangler tags.
[b] Average values, two-year study with fin clip marks and creel census recovery.
[c] *Micropterus salmoides salmoides* (northern largemouth bass).
[d] *M. s. floridanus* (Florida largemouth bass).
[e] Average values, five-year study with disk-dangler tags.
[f] First year returns only.
[g] Largemouth bass 220–294 mm FL only.
[h] Largemouth bass ≥ 295 mm FL only.
[i] Largemouth bass age 4–12, age composition estimate.

REFERENCES

Bottroff LJ, Lembeck ME. 1978. Fishery trends in reservoirs of San Diego County, California, following the introduction of Florida largemouth bass, *Micropterus salmoides floridanus*. California Fish and Game 64:4–23.

Brownie C, Anderson DR, Burnham KP, Robson DS. 1985. Statistical inference from band recovery data—a handbook. U.S. Fish and Wildlife Service Resource Publication No. 156. Washington, DC.

Chadwick HK. 1966. Fish marking. In: Calhoun A, editor. Inland fisheries management. Sacramento (CA): California Department of Fish and Game. p 18–40.

Kelley DW. 1966. Description of the Sacramento-San Joaquin Estuary. In: Kelley DW, editor. Ecological studies of the Sacramento-San Joaquin Estuary. California Department of Fish and Game, Fish Bulletin 133. Sacramento (CA): California Department of Fish and Game. p 8-17.

Kimsey JB. 1956. Largemouth bass tagging. California Fish and Game 42:337–48.

Kimsey JB. 1957. Largemouth bass tagging at Clear Lake, California. California Fish and Game 43:111–8.

La Faunce DA, Kimsey JB, Chadwick HK. 1964. The fishery at Sutherland Reservoir, San Diego County, California. California Fish and Game 50:271–91.

Rawstron RR. 1967. Harvest, mortality and movement of selected warmwater fishes in Folsom Lake, California. California Fish and Game 53:40–8.

Rawstron RR, Hashagen KA. 1972. Mortality and survival of tagged largemouth bass (*Micropterus salmoides*) at Merle Collins Reservoir. California Fish and Game 58:221–30.

Rawstron RR, Reavis RA. 1974. First year harvest rates of largemouth bass at Folsom Lake and Lake Berryessa, California. California Fish and Game 60:52–3.

Ricker WE. 1975. Computation and interpretation of biological statistics of fish populations. Bulletin 191:113–6. Ottawa, Canada: Fisheries Research Board of Canada.

Robson DS, Chapman DG. 1961. Catch curves and mortality rates. Trans Am Fish Soc 93:181–9.

Schaffter RG. 1997. Mortality rates of white catfish in California's Sacramento-San Joaquin Delta. California Fish and Game 83:45–56.

Schaffter RG. 1998. Growth of largemouth bass in the Sacramento-San Joaquin Delta. Interagency Ecological Program for the San Francisco Estuary. IEP Newsletter 11(3):27–30.

Schultze RF, Vanicek CD. 1974. Age and growth of largemouth bass in California farm ponds. California Fish and Game 60:94–6.

Stevens DE, Kohlhorst DW, Miller LW, Kelley DW. 1985. The decline of striped bass in the Sacramento-San Joaquin Estuary, California. Trans Am Fish Soc 114:12–30.

Urquhart KAF. 1987. Associations between environmental factors and the abundance and distribution of resident fishes in the Sacramento-San Joaquin Delta. Exhibit 24, entered by the California Department of Fish and Game for the State Water Resources Control Board 1987 Water Quality/Water Rights Proceeding on the San Francisco Bay/Sacramento-San Joaquin Delta. Stockton (CA): California Department of Fish and Game.

Van Woert WF. 1980. Exploitation, natural mortality, and survival of smallmouth bass and largemouth bass in Shasta Lake, California. California Fish and Game 66:163–71.

ANNUAL INTERAGENCY ECOLOGICAL PROGRAM AND BAY-DELTA MODELING FORUM WORKSHOPS

Zach Hymanson, DWR
zachary@water.ca.gov

The 2001 Interagency Ecological Program workshop will be held February 28 through March 2, at the Asilomar Conference Center in Pacific Grove, California. The IEP workshop will provide information on a number of projects through oral presentations, posters, and panel discussions. As in previous years, the IEP workshop will overlap with the Bay-Delta Modeling Forum workshop, held February 27–28, so you may attend all or part of both workshops.

The IEP workshop planning committee is now formulating a draft agenda, with the intent of having a final agenda available in early December. You may view the final agenda at the IEP website (www.iep.ca.gov). However, due to procedural changes at Asilomar, the deadline for workshop registration occurs earlier on November 21, 2000. Registration forms will be available in October. Check the IEP website for registration forms and the latest information about the workshop agenda.

Poster presentations will again be an important part of the workshop. Titles for all poster presentations will be included in the agenda. If you plan to present a poster, please contact Peggy Lehman (plehman@water.ca.gov) with your title. Please e-mail Zach Hymanson at zachary@water.ca.gov for additional information about the IEP workshop; John Williams can be reached at jgwill@dcn.davis.ca.us for additional information about the Bay-Delta Modeling Forum workshop.

ARE WE READY FOR A CALIFORNIA ESTUARINE RESEARCH SOCIETY?

The Estuarine Research Federation (ERF), the largest international scientific society dedicated to the study and management of estuaries and associated watersheds and coasts, will hold its next (16th) Biennial Research Conference at St. Petersburg, Florida, November 4–8, 2001. The year leading up to this meeting may be a good time to consider forming a new society affiliated with ERF.

ERF is an independent society and a federation of five regional affiliated societies: New England Estuarine Research Society, Atlantic Estuarine Research Society, Southeastern Estuarine Research Society, Gulf Estuarine Research Society, and Pacific Estuarine Research Society (PERS).

For many years, California members of ERF and PERS have discussed the possibility of forming a California affiliate of ERF: the California Estuarine Research Society. Randy Brown (rbrown@water.ca.gov), Wim Kimmerer (kimmerer@sfsu.edu), and Fred Nichols (fnichols@usgs.gov) welcome your thoughts about forming such a society. We envision that it could meet concurrently with, or co-sponsor, our existing conferences such as the IEP Annual Workshop, the State of the Estuary Conference, and the CALFED Science Conference. Advantages would be greater recognition of Bay area research and management at the international level; better integration with outside or national organizations; and increased opportunities for participation in Bay area activities by talented students and postdoctoral associates.

Information about ERF and the 2001 conference can be found at http://erf.org/. Abstracts will be due next spring. The conference will be held concurrently with the 7th International Conference on Estuarine and Coastal Modeling. Conference themes include: detecting estuarine change; measuring estuarine health; temperate and tropical comparisons; marine restoration and conservation; essential fish habitat—new perspectives on habitat use and trophic interactions; combining science and management to solve estuarine problems; technological advances—applications to estuarine science; modeling estuarine processes; and ecological impacts of invasive species and disease.

Articles Published in Volume 13 of the *IEP Newsletter*

Number 1, Winter 2000

Predictions and predications from a visiting Chinese mitten crab expert—*T. Vedhuizen*

Natural and human influences on freshwater flows and salinity in the San Francisco Bay-Delta and watershed—*N. Knowles*

Recent historical evidence of centrarchid increases and tule perch decrease in the Delta—*M. Nobriga and M. Chotkowski*

Survival of juvenile chinook salmon tagged with biotelemetry transmitters—*D. Killam*

Tidal marsh study—*K. Hieb and S. DeLeón*

The tow-net survey abundance index for delta smelt revisited—*L. Miller*

Update of delta smelt culture with an emphasis on larval feeding behavior—*J. Lindberg, B. Baskerville-Bridges, and S. Doroshov*

Similarities between hatchery reared delta smelt and wild wakasagi from the Sacramento-San Joaquin Delta—*J. Wang*

A comparison of fall Stockton Ship Channel dissolved oxygen levels in years with low, moderate, and high inflows—*S. Hayes and J. Lee*

Examining the relative predation risks of juvenile chinook salmon in shallow water habitat: the effect of submerged aquatic vegetation—*L. Grimaldo, C. Peregrin, and R. Miller*

Number 2, Spring 2000

Recent research on the hydrodynamics of the Sacramento-San Joaquin River Delta and North San Francisco Bay—*J. Burau, S. Monismith, M. Stacey, R. Oltmann, J. Lacy, and D. Schoellhamer*

Environmental factors influencing the distribution and salvage of young delta smelt: a comparison of factors occurring in 1996 and 1999—*M. Nobriga, Z. Hymanson, and R. Oltmann*

Number 3, Summer 2000

Vamp 2000 fish investigations—*C. Hanson*

The Chinese mitten crab as a potential host for human parasitic lung flukes in the San Francisco Bay Estuary—*M. Walter and C. Culver*

Reproduction in the Chinese mitten crab, *Eriocheir sinensis*—*B. Tsukimura and A. Toste*

Specific conductance, water temperature, and water level data from San Francisco Bay, California, water year 1999—*P. Buchanan*

Primary food resources in the Sacramento-San Joaquin Delta—*A. Jassby and J. Cloern*

Floodplain rearing may enhance growth and survival of juvenile chinook salmon in the Sacramento River—*T. Sommer, M. Nobriga, B. Harrell, W. Batham, and R. Kurth*

Monitoring the distribution and migration of delta smelt (*Hypomesus transpacificus*): are additional midwater trawl stations useful?—*R. Gartz*

The Sacramento-San Joaquin Delta largemouth bass fishery—*D. Lee*

Estimating population level effects on salmon smolts and estuarine species for environmental requirements affecting Delta water project opertations—*B.J. Miller*

Number 4, Fall 2000

Freshwater invasion of *Eurytemora affinis*—*J. Orsi*

Mysid shrimps in Suisun Marsh—*S. Carlson and S. Matern*

Changes in fish diets in the San Francisco Estuary following the invasion of the clam *Potamocorbula amurensis*—*F. Feyrer and S. Matern*

Exposure of delta smelt to dissolved pesticides in 1998 and 1999—*E. Moon, K. Kuivila, C. Ruhl, and D. Schoellhamer*

Delta wetlands restoration and the mercury question: year 2 findings of the CALFED UC Davis Delta Mercury Study—*D. Slotton, T. Suchanek, and S. Ayers*

Potamocorbula revisited: results of experimental and field qork on the effect of clams on estuarine food webs—*W. Kimmerer and C. Peñalva*

Mortality rates of largemouth bass in the Sacramento-San Joaquin Delta, 1980 through 1984—*R. Schaffter*

DELTA WATER PROJECT OPERATIONS

Kate Le, DWR
kle@water.ca.gov

From April through September 2000, San Joaquin River flow ranged between 2,000 and 6,600 cfs, Sacramento flow ranged between 1,300 and 34,000 cfs, and the Net Delta Outflow Index ranged between 3,000 and 46,000 cfs (Figure 1). The increase in Net Delta Outflow in mid-April was due to reduced pumping at both water projects. Combined exports at Banks (SWP) and Tracy (CVP) during the same period varied from a low of about 1,000 cfs to a high of about 11,000 cfs (Figure 2).

From mid-April to mid-May both projects reduced pumping in support of the Vernalis Adaptive Management Program. The decreased pumping at Tracy during this time was likely for maintenance. Due to delta smelt presence near the SWP intake in late May, the USFWS asked DWR to ramp exports as a (b)(2) action. To "pay" for this action, the CVP increased pumping through mid-June for the SWP. After July 1, both projects pumped full bore. The SWP was granted approval by the U.S. Army Corps of Engineers to pump an additional 500 cfs through September for fishery related "make-up" water. Decreases in Banks pumping occurred during late summer and fall for a variety of reasons:

- Late June—compliance with standards (X2 and agricultural concerns)
- Early August—weed treatment
- Mid-August—K-rail installation and maintenance
- Early September—maintenance at the intake gates
- Late September—maintenance at Banks

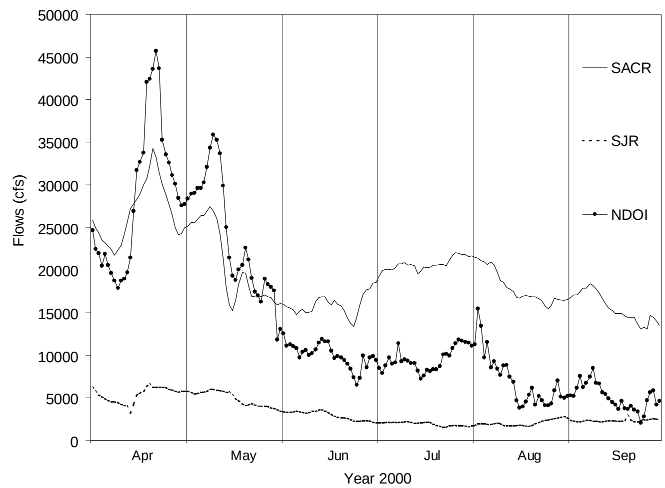

Figure 1 Flow (cfs) in the San Joaquin and Sacramento rivers and Net Delta Outflow Index from April through September 2000

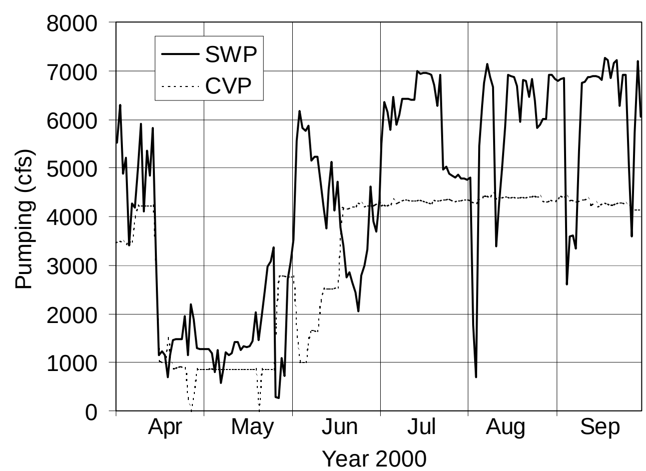

Figure 2 SWP and CVP exports (cfs) from April through September 2000

■ Interagency Ecological Program for the San Francisco Estuary ■

IEP NEWSLETTER

3251 S Street
Sacramento, CA 95816-7017

For information about the Interagency Ecological Program, log on to our website at http://www.iep.water.ca.gov. Readers are encouraged to submit brief articles or ideas for articles. Correspondence, including submissions for publication, requests for copies, and mailing list changes should be addressed to Lauren Buffaloe, California Department of Water Resources, 3251 S Street, Sacramento, CA, 95816-7017.

■ Interagency Ecological Program for the San Francisco Estuary ■

IEP NEWSLETTER

The Interagency Ecological Program for the San Francisco Estuary
is a cooperative effort of the following agencies:

California Department of Water Resources
State Water Resources Control Board
US Bureau of Reclamation
US Army Corps of Engineers
California Department of Fish and Game
US Fish and Wildlife Service
US Geological Survey
US Environmental Protection Agency

National Marine Fisheries Service

BEFORE CITING INFORMATION HEREIN,
CONSIDER THAT ARTICLES HAVE NOT RECEIVED PEER REVIEW.