■ Interagency Ecological Program for the San Francisco Estuary ■

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News from Around the Estuary

Contributed Papers

CALFED Corner

Meeting Review

OF INTEREST TO MANAGERS

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A provocative article by Jassby and others (page 18) compares and contrasts the environments and concerns driving key restoration issues in Lake Tahoe and the Sacramento-San Joaquin Delta. This article clearly illustrates how the nature of these systems and our imposed values lead to opportunities and conflicts in achieving meaningful results.

An informative article by Knowles and Cayan (page 23) presents model results used to estimate the effects of global climate change on temperature, snowpack, and runoff in the Sacramento-San Joaquin watershed. Potential salinity changes in San Pablo bay are also presented. Under the "business-as-usual" circumstances examined, increased temperatures would result in diminished snowpack, earlier water runoff, and increased salinity levels in the Estuary between late spring and fall. While the full effect of these changes may be a century away, the growing body of evidence presented by these researchers and several others clearly shows we need to plan now for the effects of climate changes.

Nobriga and Cadrett (page 30) examine available steelhead catch data from three monitoring programs to address four questions of management interest. The results reveal some interesting differences between hatchery and wild steelhead. Several topics for further investigation also are identified.

Young and others (page 38) report on a study to determine if significant stress is detectable in delta smelt handled during setup for other experiments. Delta smelt are notoriously sensitive to handling by humans and the results of this study corroborate empirical information from the field. These results have implications for interpreting larger studies designed to examine the ability of delta smelt and other species of concern to avoid impingement on fish screens.

Kurth and Nobriga (page 40) provide results of a study describing the diet composition and patterns in larval splittail. Two types of prey dominated the diets of larval splittail. Prey size increased with larval size, but the percentage of empty guts decreased with larval size. This study provides information useful to understanding the early life history of splittail and the factors that may limit this life stage.

Feyrer (page 42) examines data collected over eight years to characterize fish assemblages in the south Delta and their associations with environmental variables. Results show introduced species dominate all locations sampled. River flow and water temperature seemed to exert the most influence over the structure of the fish assemblages, and fish assemblages were consistently different each year. This information will be useful in developing strategies under CALFED's South Delta Improvement Program.

Taylor (page 46) provides an overview of the process developed by the CALFED Science Program for oversight and review of the Environmental Water Account (EWA) Program. The EWA is a four-year pilot program intended to provide water that benefits fish species of concern at no cost to CVP and SWP water supplies. The expectations for the EWA are quite high and its implementation will test the ability of scientists, managers, and policy makers to work together to effect meaningful change. The process described by Taylor is key to the overall effort.

A succinct summary of the 2001 PACLIM (Pacific Climate) workshop is provided by Dettinger (page 51) and is of interest to all California residents. Presentations at the workshop provided a "picture of California's long-term climatic history that includes significant epic 'droughty' periods spanning hundreds of years." Evidence was also presented that California's prehistory included extremely large floods, substantially larger than those occurring within the historical record. Several competing plausible explanations for the origins of California's paleoclimatic variations were presented, but the exact origins remain uncertain. "As a result, the ability to predict the recurrence of such disasters is minimal."

IEP QUARTERLY HIGHLIGHTS: APRIL–JUNE 2001

Splittail Investigations

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Work during the spring quarter concentrated on completing a draft report on splittail larvae abundance and distribution based on the1988–1994 striped bass egg and larva sampling, revising an unpublished report assessing gear effectiveness and habitat use of juvenile splittail in the Sacramento and San Joaquin rivers, and extracting and processing splittail otoliths and fin rays for age determination.

In 1994, Johnson Wang identified and measured splittail larvae from the archived ichthyoplankton samples collected from 1988 to 1994 by the Striped Bass Egg and Larva Survey. He summarized this information by collection date and sampling station in an unpublished draft IEP Technical Report. Catch and length data were corrected for sampling effort and associated with environmental measurements recorded for the same period. Information was developed on seasonal abundance and distribution of larvae and the influence of river stage and temperature on the temporal abundance of splittail larvae at selected locations. A draft will be sent out for Project Work Team review in July.

The 1996 Resident Fishes PWT white paper is being edited so that it can be published as a section of an IEP Technical Report. The paper reports on summer 1995 efforts to assess gear effectiveness for collecting juvenile splittail and to document their use of riverine habitats. This sampling documented extended young-of-the-year splittail use of river habitats through summer and fall 1995, and suggested they underwent a distribution shift from being generally edge-oriented to primarily inhabiting eddies through summer and fall.

Splittail aging work progressed to the steps leading up to the actual "reading" of structures. Otoliths, dorsal rays, and pectoral rays have been removed. All structures have been cataloged; mounting and reading protocols were written and practiced; and a subset of forty structure-sets was selected for reading and comparison. The selected structures were derived from 250- to 425-mm total length (TL) splittail. The four splittail ≥400 mm TL were as large or larger than any previously used for age determination and could provide an older maximum age for splittail. We will complete the reading of these structures by early August and complete a report by late fall.

Adult Salmon Passage in the Stockton Deepwater Ship Channel

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During the fall of 2000, we tagged 112 adult chinook salmon in the Lower San Joaquin River with sonic tags. The objective was to determine if salmon passed through the Stockton Deepwater Ship Channel during periods of low dissolved oxygen levels or elevated water temperatures. This research was a continuation of a study by Hallock and others (1970) during 1964–1967.

Adult chinook salmon were tagged in the Lower San Joaquin River at Prisoners Point and at channel marker 26 near Eddo's Boat Harbor. After the fish were released, three mobile (boat) routes and eleven fixed telemetry stations were used to follow salmon movements. Boat tracking routes were San Joaquin River from Mossdale to channel marker 26, Old River, Middle River, and the north Delta including the Delta Cross Channel. Most mobile-tracking efforts were concentrated in the Stockton Deepwater Ship Channel. Two of the fixed stations were located in the Stockton Deepwater Ship Channel. Fish passage was detected on the Sacramento, San Joaquin, Old, Middle, and Mokelumne rivers, Delta Cross Channel, and Georgiana Slough.

Water quality was monitored at the tagging locations, during mobile monitoring, and at predetermined sites around the Delta. These data, along with water quality data obtained by the Department of Water Resources, will be used in the analysis. Since DWR operates a continuous monitoring station at Rough and Ready Island in the Stockton Deep Water Ship Channel, we will be able to determine water quality conditions at the times of salmon passage.

Analysis of fish movement and water quality data is proceeding. Seventy-three of the 112 fish tagged have been accounted for. Most of the fish tracked during the mobile hydrophone monitoring were found near the tagging site at Prisoners Point. Apparently, some salmon remained in the tagging vicinity for up to one week prior to moving upstream. Most of the tracking data came from the fixed telemetry stations. Of the 73 fish detected 43 passed the exit monitoring site on the Sacramento River at Hood, two were detected in the Mokelumne River at Woodbridge Dam, and nine at Mossdale on the San Joaquin River. The remaining nineteen salmon were detected at other supplemental stations, but not at exit stations. We believe these fish died in the river, regurgitated the tag, were caught by predators or fishermen, or passed the exit stations undetected. Salmon passage through the Stockton Deepwater Ship Channel will not be reported until data analysis is completed.

We will continue sonic tagging of adult fish in the San Joaquin River from fall 2001 through spring 2002. Our objective is to determine the possible effects of control gate operations at the Delta Cross Channel on the upstream movements of adult migratory salmon, white sturgeon, and striped bass. Most of our fixed telemetry stations will be located in the north Delta, but we will have exit-point stations on the Sacramento, San Joaquin, and Mokelumne rivers.

References

Hallock RJ, Elwell RF, Fry DH, Jr. 1970. Migration of adult king salmon *Oncorhynchus tshawytscha* in the San Joaquin Delta as demonstrated by the use of sonic tags. Fish Bulletin 151. Department of Fish and Game.

2001 Delta Smelt and Splittail Transportation and Release

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We initiated an extensive ongoing literature search this past year, exploring all aspects of handling and transport, including various alternative methods of handling and transport, aeration techniques, circulation techniques, history of fish transport, and use of anesthetics to improve survival.

The 2001 literature review is focusing on primary and secondary fish stress indicators such as cortisol, glucose, and lactate found in blood plasma after exposure to stressors. The literature review and research being conducted at the John E. Skinner Fish Protective Facility in Byron, California, will be used to design pilot experiments. These pilot physiology experiments will explore the impact of the facility on stress indicator levels in delta smelt, splittail, and other species that are endangered, threatened, or are of special concern.

A series of pilot transport and handling mortality experiments was conducted in April through July of 2000 at the Skinner Fish Protective Facility. During the experiments various juvenile species including splittail, American shad, delta smelt, and longfin smelt were used to test handling losses independent of transport losses. After the experiments, fish were placed into 300-gallon recovery tanks to observe mortality. Fish mortality counts for transport and handling experiments were recorded immediately following the experiments, at 24 h, and at 48 h. The sample size of these experiments varied between 50 to 100 fish. Dissolved oxygen, temperature, and visibility were also recorded. Data analysis is underway.

In May, experiments on transport and handling were postponed temporarily and will resume in July, along with pilot experiments to sample fish stress indicators found in the blood plasma. The methods developed during the pilot study may be used in future studies to improve fish survival during transport, handling and release at the Skinner Fish Protective Facility and other fish facilities.

Also, efforts were begun in June to sample fish in Clifton Court Forebay to observe pre-fish facility stress indicator levels in target fish species. A 30-foot beach seine is being used to obtain fish. If successful, the results from pre-facility fish sampling will be used to compare the potential stress of target fish by comparing pre- and post- fish facility exposure stress indicator levels. Sampling efforts to collect data on pre-test fish will continue and will be concurrent with transport and release experiments at the Skinner Fish Protective Facility. If efforts to sample in Clifton Court Forebay are limited by pumping schedules at the Banks Pumping Plant, alternative sampling sites in the nearby Delta will be used.

Suisun Marsh Salinity Control Gates

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During fall 2001 the Suisun Marsh Salinity Control Steering Group considered several options for improving fish passage at the Suisun Marsh Salinity Control Gates. After examining each option, we chose a study design involving opening the existing boat lock to form a vertical passageway as the most feasible and cost effective. This study is a continuation of the 1998-1999 adult salmon migration study in Montezuma Slough.

As in previous studies, adult fall-run chinook salmon will be implanted with ultrasonic transmitters, released downstream of the control gates and their upstream migration monitored during three operational configurations of the gates. During Full Open Operation (Phase I), the flashboards are out, the gates fixed in the up position, and the boat lock closed. During Full Bore Operation with Mitigation Modifications (Phase II), the flashboards are in, the gates tidally operated, and the boat lock held open. During Full Bore Operation (Phase III), the flashboards are in, the gates tidally operated, and the boat lock closed. From September 24 to November 2 salmon will be captured, tagged, and released at intervals beginning with the start of each operational phase. The passage rates of tagged fish including the total number and the time it takes the fish to pass through the gates during each operational phase will be examined to determine if the mitigation measure resulted in a significant improvement in adult salmon passage rates.

Developing a Diagnostic Key for Discriminating Osmerid Larvae

Lenny Grimaldo (DWR), lgrimald@water.ca.gov; Linda Rivard (DWR); Lisa Lynch (DFG); Johnson Wang (National Environmental Scientists); Bradd Baskerville-Bridges (UCD); and Brent Bridges (USBR)

Collection continues of morphometric measurements from larval delta smelt and wakasagi cultured during spring 2000. Our objective is to determine the most useful set of characteristics to distinguish larval delta smelt from wakasagi. Our preliminary data suggest oil globule size, eye depth, intestine diameter, intestine length, nape depth, and head depth are among the key characters that can be used to discriminate these two species during their larval phase. After all the measurements are completed, we will attempt to quantify our observations to determine the variability among characters and between species. If significant ranges of variability can be separated between the two species, we will develop a key composing at least three characters per ontogenetic phase at the conclusion of the study.

Delta Smelt Culture Update: Availability of Juveniles

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and Joan Lindberg (UCD)

In November and December 2000, we collected 1,129 delta smelt from the Sacramento-San Joaquin Estuary near Decker Island. Initial fatalities decreased dramatically within 72 h and were considered due to transport stress. Survival after 72 h was 70%. We collected 200,000 eggs during the spawning season (February–May), yielding over 100,000 larvae.

The major obstacle in rearing delta smelt has been the production of juveniles due to high mortality during the larval period. We have made significant progress this year and have achieved up to 60% survival to 60 days post hatch (18 mm).

We have provided smelt to researchers for various experiments:

- larval key identification (Grimaldo, DWR);
- otolith study (Bennett, UC Davis);
- histopathology (Bennett, UC Davis); and
- predation study (Bennett, UC Davis).

In addition, other projects have requested delta smelt for investigation:

- fish treadmill study (Cech, UC Davis);
- exposure experiment (Bennett, UC Davis);

- competition and feeding experiments (Kimmerer and Bennett, UC Davis); and
- testing of fish friendly pumps and new fish screens (USBR, Tracy fish facility).

Delta Smelt Monitoring

Andrew Rockriver (DFG), arockriv@delta.dfg.ca.gov; and Michael Dege (DFG)

In spring 2001, delta smelt spawned upstream of the Sacramento-San Joaquin confluence, specifically in the central and north Delta. The highest catch of adult delta smelt from the last Spring Midwater Trawl Survey in March occurred in the South Fork of the Mokelumne River. In April, Real-Time Monitoring Program staff caught larval delta smelt using light traps in the South Fork of the Mokelumne River, suggesting spawning did occur in the area. Larval delta smelt were also caught by 20-mm Survey staff in the central Delta. North Bay Aqueduct (NBA) Survey staff caught a large number of larval delta smelt in the north Delta.

To date 924 delta smelt were caught in the first seven 20-mm surveys. This is roughly 44% of the number of delta smelt caught during the first 7 surveys in 2000. In the first three surveys of this year (end of March through April), larval delta smelt were caught in low numbers throughout the Delta. By survey 4 and 5 (beginning of May), the relative delta smelt distribution began shifting towards the central Delta. In June, the distribution shifted towards the lower Sacramento and San Joaquin rivers. Since the smelt are reaching a size that the 20-mm net can no longer effectively sample and salvage of delta smelt has declined at the CVP and SWP; we anticipate that the last survey (9) will occur the second week of July.

Salvage of adult delta smelt from the State Water Project and Central Valley Project was moderately high in February of this year. Adult delta smelt salvage declined towards the end of March. In the subsequent months, salvage of juvenile delta smelt remained low. However, the “yellow light” level of concern for delta smelt salvage was exceeded for about three weeks, from late May to early June. The “red light” level was not exceeded. The low salvage of juvenile delta smelt was due in part to the relatively low abundance and central distribution, low water exports, and warm south Delta water temperatures. Because salvage was low, no special 20-mm surveys were conducted this year.

The 2001 NBA Survey was initiated on February 15 and will continue through July 15. The catch of delta smelt by the NBA Survey has been the largest since the survey was started in 1995. So far, 541 delta smelt have been sampled with two weeks of monitoring left. Nearly half of these fish came from station 723 in the Sacramento Deep Water Ship Channel, near the confluence of Miner and Cache sloughs. High delta smelt catch appeared with the onset of sampling, remained consistent through early April, and spiked again in early May. With the increased catch of delta smelt, the NBA pumping facility has been periodically under operating restrictions. Following the trend of delta smelt, longfin smelt catch has also increased from 12 fish last year to 2,386 fish this year. Conversely, wakasagi catch has decreased from 100 to 11 fish. For more information on NBA or the 20-mm surveys, visit http://www.delta.dfg.ca.gov.

Sherman Island Agricultural Diversion Evaluation

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This IEP study element samples the relative abundance and species composition of fishes entrained by diversion siphons in Horseshoe Bend on the lower Sacramento River. In particular, the effects of tidal and diel cycles on fish entrainment are being investigated. The Horseshoe Bend facility consists of two, screened, 24-inch diversion pipes and an unscreened 24-inch pipe. A screened and unscreened siphon will be sampled simultaneously using modified fyke nets (1600 µm mesh) that fit completely over the outfall side of the pipes such that all of the water coming through the siphons will be filtered by the nets before entering the irrigation canal.

Last year we conducted continuous sampling for a 43.5-h period. A similar effort is planned for July 9–11. We timed this year’s sampling to coincide with high tide periods around sunset to contrast with last year’s sampling, when high tides occurred in the middle of the night.

Chinese Mitten Crab Reporting and Monitoring Program

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A full color brochure is now available that summarizes the identification of the Chinese mitten crab and provides contact information to report sightings. The brochure was mailed out to marinas, bait shops, county agriculture offices, U.C. cooperative extensions, flood control and water conservation districts, reclamation districts, levee districts, and several federal and State agencies in thirteen counties. Since the induction of the reporting system, reports of sightings in the Central Valley, Delta and tributaries around the San Francisco Bay region have been received. These include Colusa National Wildlife Refuge, Bear River, Feather River, Yolo Bypass, Cosumnes River, Fourteen-Mile Slough, Irrigation Ditch in Oakdale, and Sonoma Creek. Monitoring in these areas will begin this summer and the results will be published in this newsletter next spring.

A letter was sent out to the project work team leaders asking for help to report sightings of the mitten crab from their field personnel. Your help is still greatly needed to make this reporting system a success. If you are interested in receiving copies of the brochure you can email me at the above address or visit the website at http://www.delta.dfg.ca.gov/mittencrab/sighting.asp.

Delta Hydrodynamics

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Head of Old River Barrier Study

The CDFG, DWR, USFWS, and USGS monitored the hydrodynamics and fish passage on the San Joaquin River at the head of Old River barrier during the spring VAMP period. The USGS deployed 3 upward-looking, acoustic Doppler current profilers (UL-ADCP) on the San Joaquin River in the vicinity of the rock barrier at the head of Old River to obtain high resolution velocity profile data at the junction. In addition, UL-ADCPs were deployed in the San Joaquin River above and below the junction. Discharge measurements, collected by DWR, will be used to flow calibrate these two sites. Data from the two San Joaquin River sites and the long-term DWR station located on Old River will be used to understand how the flows are partitioned between the San Joaquin River and Old River for a 3-month period involving 3 stages: before barrier installation, while the barrier was in place, and after the barrier was removed. We will recover all of the UL-ADCP meters in early July.

Additionally, two fish passage studies were conducted during late-April and early-May. Mike Simpson coordinated the deployment of acoustic arrays across the San Joaquin River and across the Old River barrier. Salmon smolts were released at Mossdale; 1 to 2 hours later, the smolts arrived in the barrier region. The equipment successfully tracked smolt and potential predator movement through the barrier region. To our knowledge this is the first time this type of equipment has been used to monitor salmon smolt movement in the Delta and the results are encouraging.

Flow Network Summary

On April 23, vandals completely removed the transducers and mounting racks from the Middle River at Bacon Island ultrasonic velocity meter (UVM) station. On June 6, the station was restored and a sideward-looking acoustic Doppler current profiler (SL-ADCP) was installed in place of the original UVM. We have not yet established a new rating for this station; therefore, flow data are not yet available. In addition to using the SL-ADCP technology to collect an index velocity, a third, upward-looking beam measures the stage at the station. The stage readings are currently erratic and we are investigating several possible remedies.

The UVM at the San Joaquin River at Stockton had many problems during this period that lead to a questionable record over much of the quarter. Ultimately both the UVM electronics and the transducers were replaced at Stockton and the data recovery rate has improved. The Dutch Slough UVM collected erroneous data May 6–13 due to misaligned transducers and weak battery power. There were some periods of poor data acquisition from the San Joaquin River at Jersey Point in early April due to mechanical troubles with the UVM that have since been corrected. The SL-ADCP in Old River at Highway 4 collected poor data during May 22–26.

Neomysis–Zooplankton Study

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For the most part, the abundance of mysids and other zooplankton did not differ appreciably from last year. Exceptions to this statement are the introduced mysid shrimp, *Acanthomysis bowmani*, which was much more abundant last year than this and the rotifer, *Keratella*, which showed exceptionally high abundance in April of this year. *Keratella* achieved a concentration of 224,000 individuals per cubic meter in the San Joaquin River at Stockton. This is the highest concentration any rotifer has reached in many years. Peak abundance of *A. bowmani* this spring reached 30 to 50 individuals per cubic meter in the Sacramento River at Sherman Island during the May survey. On the other hand, peak abundance of the native mysid, *Neomysis mercedis*, occurred at the same time and location, but at a level of only 12 individuals per cubic meter.

The established patterns of numerical dominance by certain species did not change this spring. Dominant spring species have been the copepods *Limnoithona tetraspina*, *Eurytemora affinis*, and *Pseudodiaptomus forbesi* and the mysid, *Acanthomysis bowmani*. All are introduced species with the possible exception of *E. affini*s, which may be native.

Species reached their spring maxima at only a few locations—the San Joaquin River at Stockton (*Keratella*, *Diaptomus*, *Daphnia*), Disappointment Slough (*E. affinis*, *Cyclops*, *Bosmina*, *Polyarthra*, *Synchaeta*, other rotifers), the Sacramento River at Sherman Island (*A. bowmani*, *N. mercedis*, *Sinocalanus doerrii*, *P. forbesi*), and in Montezuma Slough (*L. tetraspina*).

Delta Resident Shoreline Fish Sampling

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In April, the Department of Fish and Game started the new Delta Resident Shoreline Fishes Monitoring Element. This survey is a modification of three previous resident fish surveys: (1) a Delta-wide stratified random survey that sampled 10 locations monthly from May 1980 to April 1983; (2) a Delta-wide monthly survey at 15 fixed locations in 1984; and (3) a 1995, 1997, and 1999 survey at 20, fixed, 1-km locations sampled in February, April, June, and August.

The new resident fish monitoring survey samples monthly at 15, randomly selected, 0.5-km sites. These sites are stratified among 5 regions of the Delta: 4 sites each in the east and central Delta, 3 sites in the south Delta, and 2 sites each in the north and west Delta. Shoreline habitat types are sampled separately at each site. Physical variables (water temperature, transparency, water velocity, and insolation) are measured at each site and stomach contents are removed from a subsample of fishes collected. These diet data will be used to explore trophic interactions in the Delta shoreline fish community.

In April and May, 1,683 fishes representing 30 species were captured. Stomach contents from 837 fishes (27 species) were collected using gastric lavage or dissection.

In addition, 400 largemouth bass (*Micropterus salmoides*) were tagged with disk-dangler tags to estimate survival, catch rate, and angling and natural mortality rates. These fish were tagged at both the random sites and at other locations throughout the Delta.

Juvenile Salmon Monitoring

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From January through June, we conducted beach seining on the lower Sacramento River, at the three Delta area sites, and the San Francisco–San Pablo Bay sites. On February 14, we discontinued the intensive Sacramento area beach seine survey for the season. We suspended the San Joaquin River beach seine upstream of Mossdale on June 22 due to low flows and difficulties accessing sites by boat. For historical consistency during the fall run emigration season, midwater trawling replaced Kodiak trawling at Sacramento on March 26, and will continue through September. At Mossdale, shallow water delayed the start of Kodiak trawling until February 13. DFG (Region 4) assumed this effort beginning March 19, and continued for the rest of the quarter. We conducted Chipps Island trawling throughout both quarters with a doubling of daily effort between May 3 and June 2 as part of VAMP survival experiments.

We first collected winter-run-sized fish in the lower Sacramento River beach seine on November 1 but did not collect them again until January 12, when the first large peak of 50 were captured. In response to this influx of fish, the Delta Cross Channel gates (DCC) were closed for four days. A second peak above Sacramento occurred on January 24 and the DCC gates were closed for six days starting January 25. We began to catch winter run on January 22 in the Chipps Island trawl, and observed a peak period of emigration from February 26 through March 26. We observed only one fish in the Sacramento area after March 21 (on April 13), and detected the last winter run leaving the Delta at Chipps Island on May 6. Total catch of winter run in the lower Sacramento River beach seine was highest since seining began there and the second highest in the Delta area seines for the same period.

We first collected fall- and spring-run-sized chinook fry in the Delta at Sacramento on December 22; the last was captured in this area on June 19. The peak period of emigration was from January 25 through March 8. Chipps Island capture of these emigrants was from February 28 through June 15, with a peak on May 10. Also, 6 fry were captured by beach seine in the San Francisco–San Pablo Bay between May 3 and 21. These fish were captured as far west as San Quentin Beach and Paradise Beach, and represented the lowest catch and the fourth consecutive year of declining numbers since seining was resumed there in 1997.

We first detected fall-run-sized juveniles from the San Joaquin system entering the Delta at Mossdale on February 13 with catches continuing through June 16. Catches in the Mossdale Kodiak trawl were the highest over the last 5-year period with peak periods of emigration occurring between April 16–27 and May 16–24.

Since 1997, the first year that all Central Valley hatchery steelhead production was marked, catches of wild (not adipose fin clipped) steelhead have continued to decline in the Delta area. Three wild steelhead were captured in the Sacramento River and Delta area beach seines between February 13 and March 22 (29 mm to 300 mm). Another 29-mm wild steelhead fry was captured on the Mokelumne River at Wimpy's on May 8. The Sacramento trawls captured 7 wild steelhead from January 13 through May 10 (198 mm to 300 mm). At Chipps Island, 41 wild steelhead were captured from January 17 through June 8 (172 mm to 360 mm). Between February 13 and April 24, the Mossdale Kodiak trawl catches increased from 1 in 1997 to 7 wild steelhead this year (247 mm to 272 mm).

On May 30, we conducted beach seining for the first time on the San Joaquin River National Wildlife Refuge west of the confluence of the Tuolumne and San Joaquin rivers. This sampling was conducted to establish a baseline of the fish present on the refuge prior to future plans to flood some of the refuge in wet years. Juvenile fish found included carp (the most abundant species), inland silverside, red shiner, fathead minnow, mosquitofish, bluegill, and logperch.

Delta Smelt Egg Deposition Study

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During this year's delta smelt spawning season, another attempt was carried out to sample eggs from the wild to identify spawning habitat. As with past attempts in the Delta (Chotkowski and others 2000; Aasen personal communication) artificial substrates were deployed in areas described as spawning habitat. This year's approach was similar to previous attempts except the area, duration, and frequency of sampling were increased to improve the chance of encounter.

The artificial substrates used in this study consisted of 30.5 x 30.5 cm ceramic tiles attached to a 3- or 6-meter nylon line with an identification float. Each tile, line, and float made up an individual sampling unit or "string" and could be strategically placed in various shallow water microhabitats under investigation. Site locations and microhabitats were determined from literature descriptions, past and present larval fish studies, and personal communications.

Sampling began on February 8 and ended on May 4. During the early part of February when the Delta water temperature fluctuated around 12 °C, strings were deployment in the San Joaquin River, North Fork Mokelumne River, Miner Slough, Prospect Slough and Cache Slough. At each location, two sampling sites were selected where 15 to 20 strings could be set in shallow (<3 m) microhabitats of interest. An additional 5 strings were set in deeper water (>3 m) adjacent to the area covered by the shallow set. Strings were fished for a period of 3 to 10 days, depending on the temperature of the water and related incubation period of developing eggs from cultured fish.

With nearly 1,500 individual string sets covering very little (approximately 0.00005%) of the Delta's surface area, only 2 fish eggs were collected. One unknown fish egg from the South Fork Mokelumne River on April 23 and one threadfin shad egg from Miner Slough on May 4. One consistent problem with this study and the previous studies was the siltation of the artificial substrates. This seemed to be a problem at all locations throughout the duration of the study. In an attempt to reduce siltation, substrates were suspended off the bottom from overhanging structures (when available) and positioned upright or on end. In most cases, these techniques did reduce siltation and the aforementioned threadfin shad egg was collected on one of the suspended strings.

Later this year, the Delta Smelt Investigations PWT will propose a new study to sample delta smelt eggs from the wild using a combination of shallow water techniques that will emphasize suspended structures and associated edge zones.

References

Chotkowski M, Baxter R, Nobriga M, Grimaldo L. 2000. Shallow Water Methods Project. Interagency Ecological Program for the Sacramento-San Joaquin Estuary. IEP Newsletter 13(2):6–7.

Notes

Aasen, Geir. Department of Fish and Game. Personal conversation in 2001.

San Francisco Bay Fisheries Monitoring

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The IEP, through DFG's San Francisco Bay Study, has been sampling fishes and macroinvertebrates in the San Francisco Bay monthly since 1980. San Francisco Bay is situated in a transition zone between cold-temperate fauna (north of Pt. Blanco) and subtropical fauna (south of Pt. Conception) where both faunas coexist. This spring, San Francisco Bay catches of age-0 lingcod, cabezon, and kelp greenling, all cold water species, were the highest for the study period. Other cold water fauna, including Dungeness crab, Pacific herring, and English sole, appear to have very strong year classes (see below). Although the last El Niño event ended in 1998, we also collected Pacific sardine, queenfish, and California grunion, all subtropical species, over the past few months.

Spring catches are a preliminary indication of year class strength for many species, although we often use at least 6 months' data to calculate the annual abundance indices. The first age-0 Dungeness crabs of the year were collected in May, with a May-June total of 1,339 crabs. This is the highest May-June catch since 1988, which had the highest annual abundance index for the entire study period. In May and June 2001, age-0 Dungeness crabs were concentrated in the channel from northern South Bay to lower San Pablo Bay. The highest catch was at our Alcatraz Island station, where we collected 781 crabs in June. We also collected 252 crabs at our lower San Pablo Bay channel station and over 100 crabs at our lower San Pablo Bay shoal station.

The age-0 Pacific herring April-June 2001 catch was slightly higher than the 2000 catch for the same months. It appears that the Pacific herring annual abundance index will be at least as high as in 2000, which had the highest index since 1986. This year most age-0 Pacific herring were collected in Central and San Pablo bays, with a few fish as far upstream as Suisun Bay and Chipps Island.

English sole catches were a record high this year with over 1,700 fish collected in one tow in May and almost 1,200 fish collected in one tow in June at the same Central Bay station. In these 2 tows we collected more English sole than the total number from at all our stations in all years except for 2000. 2001 will undoubtedly be the third consecutive year with a record high English sole abundance index. If below average ocean temperatures and strong upwelling continues for several more years, we should see even higher numbers of some cold water species in the Bay. For more information about west coast ocean conditions, please see the NOAA El Niño Watch page (http://cwatchwc.ucsd.edu/elnino.html). The Central Coast regional sea surface temperature anomaly can be found at http://cwatchwc.ucsd.edu/time_series.html.

Errata

An errata occurred in the last issue (spring 2001) of the *IEP Newsletter*'s "Long-term Status and Trends" section. In Kathy Hieb's article on San Francisco Bay Species (page 21), the third sentence in the second paragraph should have reported the following ocean temperature data:

"In the Gulf of the Farallones, the lowest monthly anomaly was –0.8 °C in July 2000, compared to –2.1 °C in June 1999."

Data for June 1999 was incorrectly reported as 2.1 °C.

Upper Estuary Chinese Mitten Crab Research Projects

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Two research projects are focused on Chinese mitten crabs in the Sacramento-San Joaquin Delta; one investigates mitten crab habitat use, and the other the effects of mitten crabs on the benthic invertebrate community. The field data collection phase of the habitat use study ended in early July 2001. During the spring months, crab catch remained low at most of the sites (Frank's Tract and False River, Old River and Connection Slough, and Middle River at Five Fingers), but increased at the Horseshoe Bend site. Because of the low catch rates at the interior sites, the May and June sampling effort was concentrated at the Horseshoe Bend site. A report is scheduled for completion by December 2001.

The enclosure phase of the benthos study began in May 2001. Each enclosure trial consists of 10 enclosures: 5 enclosures containing 2 crabs and 5 empty enclosures (control group). The enclosures remain in place for approximately 12 to 14 days (set and retrieved during minus tides). To determine the effect of the crabs on the benthos, we collect substrate core samples (containing benthic invertebrates) before and after the enclosure trials. Core samples are taken for each treatment (enclosures with crabs, without crabs and outside of enclosures). Two study sites were selected to conduct the enclosure trials: Sherman Lake and Frank's Tract. We will conduct enclosure trials monthly through May 2002.

Yolo Bypass Floodplain Study

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We completed seasonal sampling of the Yolo Bypass floodplain in June. Despite no flooding from the Sacramento River, we captured a total of 18 unmarked "wild" juvenile chinook salmon in screw trap sampling. We presume that many of these fish originated from Cache or Putah creeks, although some may have strayed upstream from the Sacramento River. Data on other species are still being analyzed; however, it is obvious that there was little production of young splittail compared to the previous four years. This result is not surprising given the relatively "dry" hydrology in 2001. In addition to the floodplain work, we completed a study of splittail reproduction and rearing in a model floodplain wetland at the Yolo Basin Wildlife Area Headquarters. The study confirmed that splittail can be induced to spawn in a dry year if they are provided with suitable floodplain habitat. Snorkel observations of juveniles yielded valuable data on the distribution and behavior of young splittail. These results could be relevant to design and implement restoration projects to benefit splittail. We have written a draft paper on the study and will be distributing the manuscript for IEP review.

NEWS FROM AROUND THE ESTUARY

First Observation of an Exotic Water Flea, *Daphnia lumholtzi,* in the Delta

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The water flea *Daphnia lumholtzi* is native to Africa, Asia, and Australia and recently invaded the US. It was first observed in the southeastern US about 10 years ago (Havel and Hebert 1993). Since then, it has been found in many lentic and lotic water bodies across the eastern part of the continent (Figure 1). It has become especially common in warm (up to approx. 30 ºC) reservoirs in mid to late summer (Work and Gophen 1999). During the rest of the year the species persists in the form of ephippia (resting stage, Figure 2). In this article I report the first observation of *D. lumholtzi* in the Sacramento-San Joaquin Delta and discuss its potential implications.

I found several *D. lumholtzi* specimens in zooplankton samples from Clifton Court Forebay collected during a CALFED sampling cruise on July 21, 1999. Subsequent identification by several zooplankton experts confirmed the species as *Daphnia lumholtzi*. This is the only observation of this species in the Delta and only the second observation in a western US state. No further CALFED zooplankton sampling was conducted in Clifton Court Forebay after July 1999 and there is no IEP zooplankton monitoring station in or near Clifton Court. It is currently unknown if *D. lumholtzi* has become established in Clifton Court Forebay and possibly elsewhere in the Delta, and what its ecological effects might be. It is also not known if it has spread southward via the Delta-Mendota Canal or the California Aqueduct.

Figure 1 ***D. lumholtzi*** **distribution in the US before Delta observations.** Map created by the Nonindigenous Aquatic Species (NAS) information resource for the United States Geological Survey, http://nas.er.usgs.gov/.

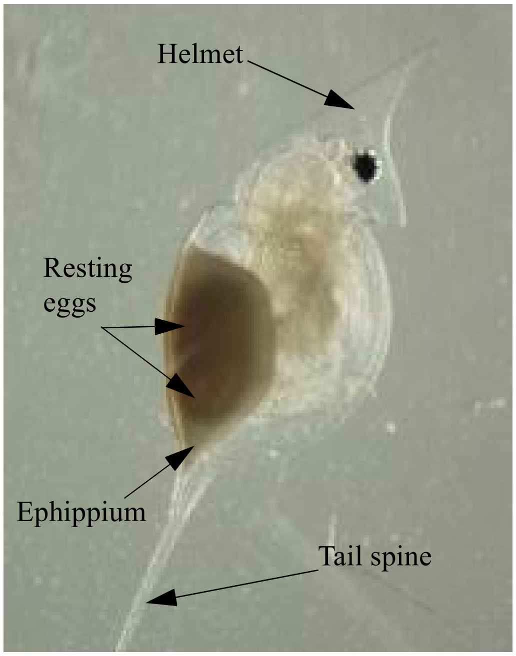

Figure 2 ***D. lumholtzi*** **with two resting eggs encased in the chitinous ephippium.** The ephippium is a thick, resistant part of the dorsal carapace of sexual females and develops in response to unfavorable conditions such as crowding, lack of food, or oxygen depletion. The ephippium with the two resting eggs is shed when the female molts. The eggs can remain viable for up to 50 years. Photo: Anke Mueller-Solger, DWR.

D. lumholtzi is well known for its ability to develop long tail spines and helmets (head spines) as well as elongated, pointed fornices (Figure 3). Mature females have been shown to reach up to 5.6 mm in total body length with the tail and head spines contributing 68% (3.8 mm) of the total length (Sorensen and Sterner 1992). Spine length increases in the presence of predators (Tollrian 1994), insecticides (Hanazato and Dodson 1993), and warmer water temperatures (Sharma and Dattagupta 1985). Crowding and colder temperatures reduce spine length (Burns 2000). Very high temperatures result in helmet deformation and mortality (Work and Gophen 1995).

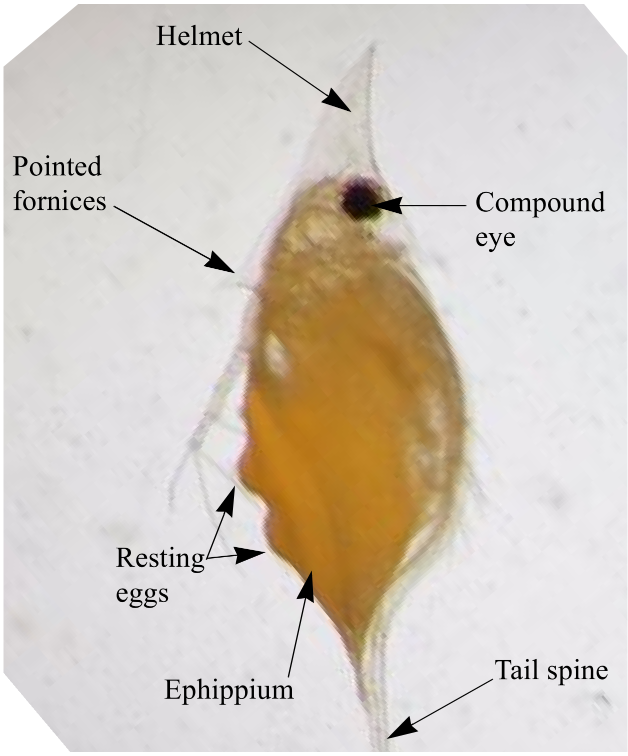

Figure 3 The *D. lumholtzi* shown here has a relatively short helmet. This specimen is the offspring of one of the original Clifton Court organisms raised in a batch culture. The helmet length decreased under culture conditions (20 °C, *Scenedesmus* as food), possibly due to crowding. Under different conditions, the helmet can be three times as long. Note the pointed, elongated fornices and the protruding resting eggs in the encasing ephippium. Photo: Anke Mueller-Solger, DWR.

D. lumholtzi often coexists with zooplanktivorous predators such as small fish and predatory invertebrates. The long tail and head spines and possibly the unusually pointed fornices protect this species against predation by fish smaller than about 50 mm in length (Kolar and Wahl 1998; Lester and Luecke 2001). In contrast, *D. lumholtzi* can be a preferred prey species for larger fishes. Sometimes *D. lumholtzi* also exhibits nocturnal vertical migration, thus avoiding visual predators (Davidson and Kelso 1997).

Introduction of *D. lumholtzi* into pelagic food webs can have severe ecological implications. Due to its high temperature tolerance and protection against predation, *D. lumholtzi* may have a competitive advantage over native zooplankton species in warm water bodies with high predator densities. In the Delta, this might be the case in summer in warm water as found in Clifton Court Forebay in summer. The high turbidity in the Delta affords these large cladocerans additional protection against visual predators. If *D. lumholtzi* became a dominant species in the Delta, small fishes such as juvenile salmon and delta smelt might suffer food shortages. However, such direct negative effects of *D. lumholtzi* on native fish larvae in the Delta may be limited because most native fish larvae occur in early spring and *D. lumholtzi* populations typically peak in late summer. On the other hand, there may be substantial and possibly equally harmful indirect effects such as those observed by Kolar and others (1997): Within very few years after the invasion of Lake Springfield, Illinois, by *D. lumholtzi*, the zooplankton community composition shifted from cladocerans to copepods in spring. According to Kolar and others (1997), this shift may have resulted from *D. lumholtzi*'s ability to avoid predation and outcompete native cladocerans in late summer, leading to less overwintering adults of native cladocera and in consequence a smaller pool of reproductive individuals the next spring.

It is currently unclear how and from where *D. lumholtzi* invaded Clifton Court Forebay. Populations in the eastern U.S. were possibly introduced together with nile perch imported from Africa in the early 1980s (Havel and Hebert 1993). It would be interesting to know if the Clifton Court population migrated westward across the entire US (as other invasive invertebrates such as the zebra mussel might also do) or if it invaded Clifton Court directly from Asia or Australia. Genetic comparisons with other US, Asian, Australian, and African populations would help answer this question. Furthermore, the current population dynamics and distribution of *D. lumholtzi* in the Delta need to be investigated and compared to those of other aquatic species in the Delta to assess possible ecological effects. If the *D. lumholtzi* population is in fact expanding, the effects on fish species in the Delta should be investigated in more detail. Zooplankton field sampling aimed at detecting *D. lumholtzi* will be conducted in and around Clifton Court Forebay this summer by DWR scientists.

Acknowledgements

I thank the CALFED POC research team headed by Jim Cloern (USGS) for sampling assistance and Doerthe Mueller-Navarra (UCD), Jim Orsi (DFG), and Ralph Tollrian (U. Muenchen, Germany) for providing independent species identifications.

References

Burns CW. 2000. Crowding-induced changes in growth, reproduction and morphology of *Daphnia*. Freshwater Biology 43:19–29.

Davidson NL, Kelso WE. 1997. The exotic Daphnid, *Daphnia lumholtzi*, in a Louisiana River-Swamp. J Freshwater Ecol 12: 431–5.

Hanazato T, Dodson SI. 1993. Morphological responses of four species of cyclomorphic Daphnia to a short-term exposure to the insecticide carbaryl. J Plankton Res 15:1087–95.

Havel JE, Hebert PDN. 1993. *Daphnia lumholtzi* in North America: another exotic zooplankter. Limnol Oceanog 38:1823–7.

Kolar CS, Boase JC, Clapp DF, Wahl DH. 1997. Potential effect of invasion by an exotic zooplankter, *Daphnia lumholtzi*. J Freshwater Ecol 12:521–30.

Kolar CS, Wahl DH. 1998. Daphnid morphology deters fish predators. Oecologia 116:556-564.

Lester O, Flinders J, Luecke C. 2001. Invasion of the exotic cladoceran *Daphnia lumholtzi* to Willard Bay, Utah: alteration of the pelagic food web. Poster presentation, American Society of Limnology and Oceanography 2001 Aquatic Sciences Meeting, Albuquerque, NM.

Sharma MP, Dattagupta AK. 1985. Cyclomorphosis in *Daphnia lumholtzi* (Crustacea: Cladocera): an intermittent species from a subtropical water body. Proceedings of the Indian National Science Academy Part B Biological Sciences 50:170–3.

Sorensen KH, Sterner RW. 1992. Extreme cyclomorphosis in *Daphnia lumholtzi*. Freshwater Biol 28:257–62.

Tollrian R. 1992. Fish-kairomone induced morphological changes in *Daphnia lumholtzi* (Sars). Archiv fuer Hydrobiologie 130: 69–75.

Work, K, Gophen, M. 1995. The invasion of *Daphnia lumholtzi* (SARS) into Lake Texoma (USA). Archiv fuer Hydrobiologie 133: 287–303.

Work K, Gophen, M. 1999. Environmental variability and the population dynamics of the exotic Daphnia lumholtzi and native zooplankton in Lake Texoma, U.S.A. Hydrobiologia 405: 11–23.

Preliminary Validation of Daily Otolith Ring Deposition in Juvenile Splittail

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In recent years, otolith microstructure has been increasingly used as a tool to analyze fish age and growth rates, providing insight into issues such as life history diversity and habitat preferences. We conducted a pilot study to determine whether otoliths could be used to study juvenile splittail ecology. Our preliminary study results suggest (1) oxytetracycline (OTC) is an effective method to mark juvenile splittail otoliths and (2) otolith rings are deposited on a daily basis in fish ranging in size from 18 to 22 mm fork length.

The experiment was conducted in a 0.1-ha model floodplain wetland constructed at the DFG Yolo Wildlife Area Headquarters, immediately adjacent to the Yolo Wildlife Area. The juvenile splittail used in the study were offspring of adults that were planted in the pond during February 2001 to study adult spawning behavior and habitat associations of larvae and juveniles (Sommer and others forthcoming).

Our basic approach was to double immersion mark the juvenile splittail in OTC-treated pond water 6 days apart. We collected 26 juvenile splittail (mean standard length = 21.3 mm; standard deviation = 1.2) from the pond by dipnet for the experiment. Each immersion treatment lasted 2 hours and OTC concentrations varied from 400 to 800 mg/L. Environmental conditions were nearly identical during each immersion marking attempt. Between the attempted markings, splittail were held in 0.5-m^3 enclosures in the pond. Splittail were sacrificed 24 hours after the final marking attempt to obtain their otoliths. Preliminary results indicate that the OTC successfully marked splittail otoliths and that otoliths produced daily increments in fish ranging in size from 18 to 22 mm FL (Figure 1). Daily otolith increments were validated by the number of days between marks matching the number of rings between marks.

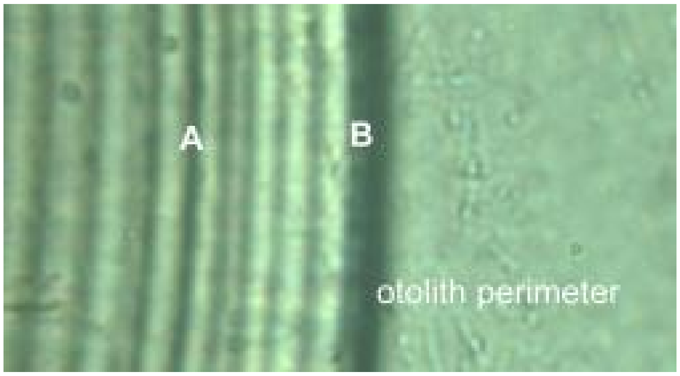

Figure 1 Image of a juvenile splittail otolith showing two tetracycline marks. The number of rings between marks matched the number of days between marks. A = first mark, B = second mark. Note that the final two circuli, located at the otolith perimeter, are difficult to distinguish in this photograph.

We plan to conduct a similar, yet more robust, experiment next year and submit the results for journal publication. With the validation of daily otolith increments, we also plan to conduct a comparative age and growth study of juvenile splittail in different habitats of the San Francisco Estuary.

We thank R. Baxter (DFG) for supplying the OTC, D. Feliz and M. Schiedt (DFG) for allowing us to use the wetland demonstration pond, and especially Jim Hobbs (UCD) and Bill Bennett (UCD) for help with the otoliths.

Reference

Sommer T, Conrad L, G. O'Leary, F. Feyrer, B. Harrell. In prep. Spawning and Rearing of Splittail in a Model Floodplain Wetland.

The Chinese Mitten Crab (*Eriocheir sinensis*) in Great Britain

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The present explosion of the Chinese mitten crab population in the Sacramento-San Joaquin Estuary area lends greater significance to the development of the mitten crab population in Great Britain.

Species Spread Until Today

Despite the well known population explosion which occurred in Continental Europe during the 1930s (Peters 1933, 1938), there were only two sightings of the mitten crab in Britain during this period. The first record is from 1935 in the River Thames (Harold 1935) followed by a further sighting in a reservoir in central England in 1949 (Wall and Limbed 1983). During the next 25 years, while the Chinese mitten crab was present over most of northern Europe no further findings were recorded in Britain. The reasons for the absence of mitten crabs in Britain during this time can be only speculated upon, but seems incongruous in view of the volume of shipping and Britain's proximity to continental Europe. One might argue that some peculiarities of British river systems could prevent introduction or that pollution levels were too high, but neither argument finds support.

This changed during the 1970s when the first new specimen from the River Thames was recorded. In 1973, three specimens were caught in the intake screens of a power station (Ingle and Andrews 1976). Since then a consistent number were caught annually until 1992 when the number of animals caught increased markedly, a trend that prevailed until at least 1996 when this monitoring project finished. At the same time the distribution and number of sightings along the River Thames started to increase (Clark and others 1998). Today there is a large established population in the Thames with burrows in every suitable bank from the estuary up to 60 km inland in some areas; this causes detrimental effects on those banks (Dutton and Conroy 1998). *Eriocheir sinensis* also has reached many tributaries of the Thames, causing concern about its effect on the already endangered native crayfish *Austropotamobius pallipes*. This species is already under pressure from the introduced signal crayfish *Pacifastacus leniusculus* (Holdich 1999).

On a national scale a similar trend has been observed, though some of these sightings were reported without specimens provided. In 1976 the first specimen was caught from the River Humber. The population showed a steady increase over the next two decades (Clark 1984; Clark and Rainbow 1996). Moreover the distribution across the whole country also increased over this period; there were two sightings in the 1970s, 5 in the 1980s and by the 1990s the Chinese mitten crab had spread to 17 river systems. In two estuaries, the Thames and the Humber, there are well established populations, as seen in Figure 1.

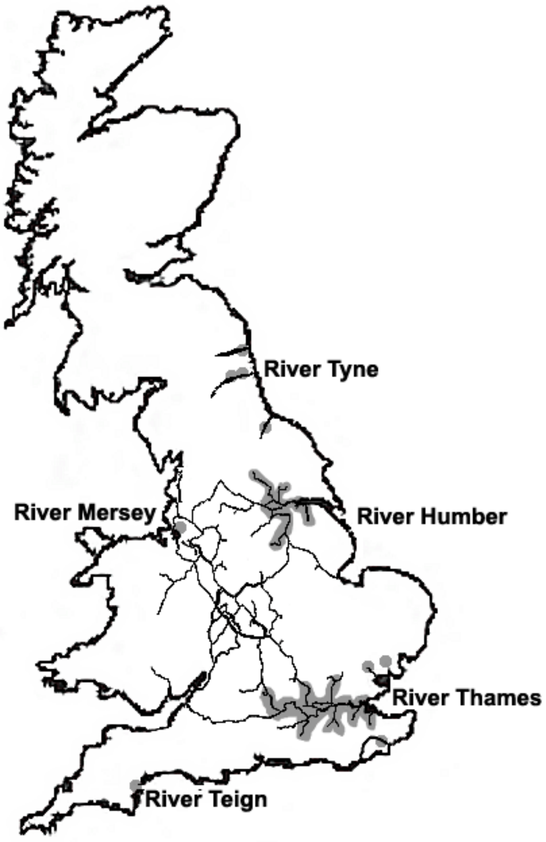

Figure 1: The distribution of Chinese mitten crab in Britain; ● single report; ▨ known population.

Despite their wide distribution along most of the east coast, the density of the population has only reached a nuisance level in the River Thames.

Ongoing and Future Research

Current research into the distribution of Chinese mitten crab in Britain has highlighted a need for monitoring. Therefore it is difficult to tell at which level the population is spreading or increasing. This is now being addressed at a local level through a continuous sampling program in the River Tyne by the author. Efforts to secure funding for a national monitoring program are ongoing. Another aim of the sampling program is to obtain tissue samples from around Britain to determine if there has been a single introduction event into Britain, from where it spread, or if this is more of a continuous process with populations in different river systems being introduced from various locations. By obtaining samples from a variety of populations outside Britain we want to determine and compare the source of the British population with animals from continental Europe, China, as well as San Francisco Bay.

These data are essential to model the mechanisms, speed, and ways of spreading and make predictions for future effects. Since the data available at the moment is insufficient to comment on the extent of the invasion, population levels and accordingly the invasive potential of *E. sinensis*.

For additional information see the website http://www.students.ncl.ac.uk/lief-matthias.herborg/.

References

Clark P. 1984. Recent records of alien crabs in Britain. Naturalist (Doncaster) 109(970):111–2.

Clark P, Rainbow P. 1996. The Chinese mitten crab in the Thames catchment. 000208370, Environment Agency Report.

Clark PF. et al. 1998. The alien Chinese mitten crab *Eriocheir sinensis* (Crustacea: Decapoda: Brachyura), in the Thames catchment. J Mar Biol Assoc UK 78:1215–21.

Dutton CD, Conroy C. 1998. Effects of burrowing Chinese mitten crabs (*Eriocheir sinensis*) on the Thames Tideway. Environment Agency Report.

Harold CHH. 1935. Thirtieth annual report on the results of the chemical and bacteriological examination of the London Waters for the 12 months ending 31 December 1935. Metropolitan Water Board London. 101 p.

Holdich DM. 1999. The negative effects of established crayfish introductions. Crustacean (11):31–43.

Ingle RW, Andrews MJ. 1976. Chinese mitten crab reappears in Britain. Nature 263:638.

Peters N. 1933. Lebenskundlicher Teil. In: Peters N, Panning A, Schnakenbeck W, editors. *Die chinesische Wollhandkrabbe* (*Eriocheir sinensis* H. Milne-Edwards) *in Deutschland. Zoologischer Anzeiger.* Leipzig: Akademische Verlagsgesellschaft MBH. p 59–155.

Peters N. 1938. *Ausbreitung und Verbreitung der chinesischen Wollhandkrabbe* (*Eriocheir sinensis* H. Milne-Edwards) *in Europa im Jahre* 1933 *bis* 1935. *Mitteilungen aus dem Hamburgischen Zoologischen Museum und Institut* 47:1–31.

Wall C, Limbed M. 1983. A Yorkshire record of the Chinese mitten crab. Naturalist 108:147.

CONTRIBUTED PAPERS

Tahoe and the Delta: Some Fundamental Differences in Conservation and Restoration Issues

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Introduction

In the Sierra Nevada Mountains to the east of the San Francisco Estuary lies another important body of water — Lake Tahoe—that has undergone remarkable systemic changes over the past few decades. Like the watershed of the Sacramento-San Joaquin River Delta ("Delta"), the Tahoe Basin is also the focus of a major rehabilitation effort involving many federal and State agencies. Moreover, the two rehabilitation efforts both are characterized by unusually large budgets, a time span of decades, and numerous economic and political uncertainties that must accompany such expensive, long-term projects. Although not part of the Delta watershed—Tahoe drains through the Truckee River past Reno to Pyramid Lake in Nevada—the Tahoe Basin resembles Sierra Nevada watersheds that do drain into the Delta. Issues confronting the Tahoe Basin therefore overlap with those confronting the Delta watershed.

Here, we compare the challenges at Tahoe with those for the Delta to understand fundamental characteristics that differentiate the two systems with regard to assessment and restoration. The two systems collectively represent a large number of ecological phenomena and environmental issues, and so a comprehensive treatment cannot be undertaken here. Rather, we concentrate on a few fundamental differences: the general nature of the restoration issues, environmental variability, and system response times. A more detailed description of the Tahoe Basin focusing on limnological issues can be found in a recent publication (Jassby and others 2001). Two recent reports, one specifically on the Tahoe Basin (USDA Forest Service and others 2000) and another on the larger Sierra Nevada landscape (SNEP 1996), offer a wide-ranging overview of environmental problems involving Lake Tahoe. In addition, the U.S. Environmental Protection Agency has sponsored a decade-long Center for Ecological Health Research (CEHR) at the University of California at Davis, including one program focusing on Sierra Nevada watersheds. A final synthesis of CEHR research will be forthcoming in the next year. Contemporary Delta issues are covered in breadth by the recent CALFED EIS/EIR documents (CALFED 2000).

Differences in Restoration Issues

Role of Nutrient and Mineral Inputs

The complexity of restoration issues for the Tahoe Basin is far less than for the Delta. In fact, the majority of the issues at Tahoe are concerned with the flow of nutrients and mineral particles into and through the Basin. To understand why this is the case for Tahoe, and not for the Delta, it is instructive to compare the morphometry of the two water bodies and watersheds. From this viewpoint, Lake Tahoe and the Delta are remarkably different. It is true that the two have surface areas of the same magnitude, but the resemblance ends there (Table 1). The major differences stem from two features: Lake Tahoe's unusually large depth (the eighth deepest freshwater body in the world) and its relatively small watershed. On the one hand, Tahoe is 55 times deeper than the Delta, which leads to a volume more than 100 times that of the Delta. The water in Lake Tahoe at any time could provide about nine years of average Delta inflow. On the other hand, its watershed is more than 200 times smaller than that of the Delta. Together, these two features imply that the watershed area to water volume ratio is much lower for Tahoe than the Delta, by a huge factor of almost 26,000. A simplified but useful view is that the small watershed provides a small load of nutrients, whereas the large water volume provides a large dilution of these nutrients. The effect is accentuated due to the largely granitic and forested watershed at Lake Tahoe, which has a relatively low yield of nutrients per unit area compared to other rock and vegetation types.

Table 1 Lake Tahoe and the Delta are similar in surface area but differ markedly in other morphometric and hydrological characteristics

Parameters measured	*Tahoe*	*Delta*[a]
Surface area (km^2)	501	215
Volume (km^3)	157	1.23
Maximum depth (m)	505	26.7
Mean depth (m)	313	5.7
Watershed area (km^2)	800	163,000
Hydraulic residence time (yr)	650	0.0693

[a] Not including Clifton Court Forebay, Sacramento River upstream of Freeport, and San Joaquin River more than 5 km upstream of the head of Old River.

The concentrations of nutrients and mineral suspensoids, and the potential phytoplankton biomass, are therefore unusually low in the lake, leading to Tahoe's well-known clarity and Secchi depths that still occasionally exceed 30 m. This unique water clarity has been declining at an average rate of about 0.25 m/yr over the past four decades, however, due to inputs of both nutrients and mineral particles from the atmosphere and an increasingly urbanized watershed. The major impetus of restoration in the Tahoe Basin is to halt and reverse the clarity decline by controlling nutrient and mineral inputs.

The Delta, by contrast, is relatively rich in nutrients and mineral suspensoids, partly because of morphometry but also because of agricultural drainage, human and animal wastewater, and the legacy of hydraulic mining. Phytoplankton biomass (a median of ca. 4 mg/L chlorophyll *a*) is ten times higher than at Tahoe and total suspended solids (a median of ca. 25 mg/L TSS) are a hundred times higher. Water clarity has never been remarkably high, and its protection for aesthetic reasons is not relevant. Moreover, phytoplankton nutrients are in great excess in the Delta and nutrient control is unlikely to have any affect on growth rates (the same is not true for the Bay and coastal ocean). Rather, phytoplankton growth rates are controlled primarily by mineral suspensoids through their effect on light availability.

Conceptualization of Restoration Issues

It is true that there are many problems—including many analogous problems—in both watersheds. The Delta, however, reflecting the size and diversity of its watershed, is not dominated so strongly by one issue. Moreover, the issues do not easily lend themselves to some kind of unifying conceptualization. The primary CALFED objectives of ecosystem quality, water supply, water quality, and levee protection encompass a large and disparate collection of issues. Even within a single objective such as water quality, the list of significant issues is long and diverse: dissolved oxygen depletion, drinking water quality, mercury in fish, currently-used pesticides in surface waters, organochlorine pesticide residues, salinity and selenium in drainage water, and heavy-metal and sediment loading. This relative complexity has an important consequence: It takes a much greater intellectual effort to grasp the breadth of the Delta restoration effort, and correspondingly fewer people might be willing to make the effort. The result can be an unfortunate parochial quality to the way we view our stake in Delta restoration.

Tahoe concerns have been somewhat more unified, as represented by the rallying cry: "Keep Tahoe Blue." In fact, there are many environmental issues other than water clarity in the Tahoe Basin, including air quality, protection of old-growth forest and riparian habitats, tree disease, fire management, biodiversity and invasive species, and organic micropollutants (MTBE) in the lake. Almost all of these concerns, however, have some aspect that ties them to water clarity. Consider air quality, for example. Atmospheric deposition of nitrogen and phosphorus constitutes a major source of algal nutrient loading to the lake. Measures to control ozone and other atmospheric pollutants should simultaneously lower nitrogen and phosphorous deposition, because the sources overlap. Similarly, invasive aquatic species may have significance through their effects on native species, but they also alter the lake's food web. The manner in which sinking particles are packaged—smaller or larger, less dense or more dense—depends on the structure of the food web above the primary producer level. Sinking losses, in turn, profoundly affect the mass balances of nutrients and inorganic particles in Lake Tahoe.

The connectedness of environmental issues at Lake Tahoe can be grasped in terms of a "stocks and flows" diagram, that is, a diagram that illustrates storage and movement of materials in the basin (Figure 1). Separate major goals are associated with each "stock": good air quality in the case of the airshed; forest integrity and biodiversity in the case of the watershed; and water clarity in the case of the lake itself. Yet the flow of materials among these components emphasizes their close linkage;

management of one material (for example, ozone) in one component affects the flows of other materials (such as nitrogen) between components. Moreover, the most important management activities can also be incorporated into the diagram by depicting where they impinge on flows. Thus, although there are exceptions, most concerns and management options can be summarized in one picture.

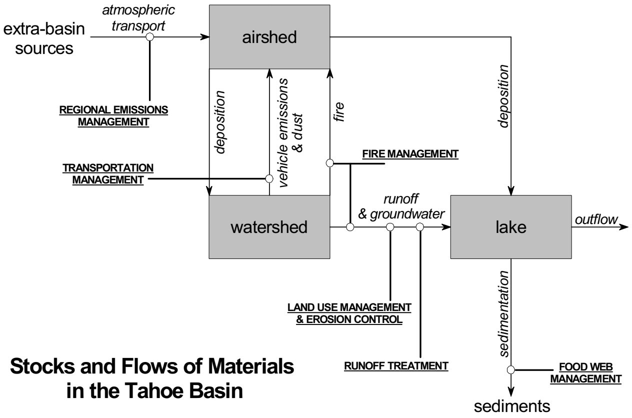

Figure 1 Problems in the air, land and water of the Tahoe Basin are connected by the flows of materials. Actions to address almost any environmental problem also have an impact on water clarity through modification of nutrient and mineral particle loading

Conflicts Between Management Endpoints

The diversity of issues suggests the opportunity for conflicting aims in both systems, yet we would expect this to be more frequent in the Delta. Phytoplankton biomass provides an example of conflicting management endpoints sometimes encountered in the Delta, and much less so at Tahoe. Although water clarity per se is not central to Delta restoration, phytoplankton is an issue for other reasons. On the one hand, phytoplankton biomass appears to be in relatively short supply in certain Delta habitats such as river channels, restricting the growth rates of primary consumers such as zooplankton and perhaps, through them, organisms at higher trophic levels. Higher phytoplankton biomass is therefore desirable from the viewpoint of increasing food supply to certain desirable fishes in the Delta. On the other hand, phytoplankton biomass contributes to dissolved oxygen depletion in the Stockton Deep Water Ship Channel, forming a barrier at times to chinook salmon immigrating through the San Joaquin River. Phytoplankton is also a drinking water concern, insofar as it contributes to the formation of harmful disinfection byproducts, undesirable taste and odors, and chronic toxicity. Lower phytoplankton biomass is accordingly desirable from the viewpoints of maintaining fish migration routes and delivering safe drinking water. Large-scale watershed management for nutrient and particle inputs therefore has complicated consequences for the Delta. Reducing these inputs could actually increase phytoplankton growth rates because of increased light availability, beneficial for the food supply (although this depends on the resulting phytoplankton quality as well as quantity) but deleterious for dissolved oxygen conditions as well as perhaps for drinking water quality.

There is less opportunity for such conflicts at Tahoe because the system provides fewer functions that could be in conflict. In the Delta, for example, the Deep Water Shipping Channel provides at least three services: a conduit for commercial shipping, a receptor for wastewater effluent, and a pathway for salmon migration. Dredging of the channel for shipping changes the morphometry in a way that is more conducive to dissolved oxygen depletion; wastewater effluent is a source of BOD and ammonia contributing to dissolved oxygen depletion; and chinook salmon migration may be impaired as a result. In the Tahoe Basin, on the other hand, commercial shipping in the area is by road and wastewater effluent is transported out of the basin.

Differences in Environmental Variability

Spatial Variability

A further reason for reduced management conflicts at Tahoe is the relative lack of spatial heterogeneity. A resource such as phytoplankton, for example, is less likely to be playing a beneficial role in one subregion and a deleterious one in another; rather, phenomena tend to be systemwide. Phenomena at different places in the lake are displaced in time, but on an annual basis there is a remarkable similarity between nutrient conditions, for example, at the near-shore "Index" station and the "Mid-lake" station, which are 20 km apart.

Water quality and biota monitoring is therefore far simpler in Lake Tahoe compared to the Delta. Even the "open water" of the Delta is composed of numerous habitats, including river channels, flooded islands and shallow lakes, and sloughs, all of which are well-represented. Tahoe is essentially a lake dominated by its pelagic region. The littoral zone and wetlands are locally important but they do not appear to control lakewide properties. This difference implies a much less complicated sampling regime for characterizing Tahoe's waters. In fact, the single nearshore station ("Index Station") appears to be adequate for capturing dynamics of water clarity, nutrient chemistry, and primary producers. In contrast, some sort of stratified sampling scheme is essential for the Delta, with each habitat covered separately.

Both systems have instrumental records going back to the 1960s. At Tahoe, research was initially funded through the National Science Foundation and uncertain from year to year. As a result, only the Secchi depth and primary productivity (^{14}C uptake) time series were collected continuously at high resolution (approximately every 12 days). The length, resolution, and consistency of these series, however, are unique. Moreover, because of the relative spatial homogeneity of Lake Tahoe and the fewer management issues, these two time series have been invaluable in characterizing long-term change lakewide and revealing the underlying mechanisms.

The instrumental records for the Delta are remarkable in their breadth and length, encompassing water quality, plankton, and fish abundance with commendable consistency (although this consistency has broken down somewhat in the last few years and threatens the continuity of the records). The temporal resolution (monthly) is somewhat less than at Tahoe but the number of variables and stations render this dataset unique. The greater sampling effort in the Delta is necessary because spatial heterogeneity makes it more difficult to characterize and understand long-term change. Water quality and plankton are dependent on the salinity field, which shifts from year to year (and, of course, at other time scales) depending on the flow regime. A single station may be a poor indicator of systemwide change because of the extra interannual variability imposed by this shifting salinity field. The spatial variability combined with lateral water movements essentially renders records "noisier" at individual stations and it is preferable to aggregate the data over subregions or on a Deltawide basis to determine systemic trends. It is not clear, however, how effective the station network in the Delta is for subregional or systemwide averaging.

One monitoring goal that is more difficult at Tahoe is the determination of nutrient and mineral particle budgets. Nutrients enter the lake through 63 streams, intervening areas between the streams, groundwater, and the atmosphere in a spatially heterogeneous pattern. The Delta receives most materials from the Sacramento and San Joaquin rivers. Moreover, the identification and management of nutrient and mineral sources is at the core of Tahoe restoration, whereas it is not so central for the Delta. The number of different subwatersheds in the Tahoe Basin opens the door, in principle, to an understanding of how land use and mitigation practices influence nutrient yields, but it also entails a large monitoring burden. Fortunately, a 20-year stream monitoring effort has reached the point where a nutrient budget can be constructed with some confidence.

Temporal Variability

Temporal variability is intimately linked to spatial variability. As pointed out above, the interannual variability in flow regime combined with the spatial variability in water quality makes individual station records noisy with respect to long-term trends. On a shorter time scale, tidally-driven changes add yet another and quite serious source of variability to Delta samples not found in Lake Tahoe. An attempt has been made to remove this scale of variability at individual stations by sampling at the same tidal stage. Unfortunately, this design introduces distortions for systemwide averaging because the entire Delta is portrayed at the same tidal stage in the same "snap-shot." On the other hand, apart from the few cases where remote sensing can play a role, the time needed to sample throughout the Delta implies that all snapshots will have tidally induced uncertainty. The recent implementation of continuous monitoring sensors obviates problems of tidal variability at those sites but they are not widely distributed enough for systemwide or subregional averaging. Nonetheless, there is hope that a cleverly used combination of continuous and discrete sampling can reduce the bias and uncertainty in the historical sampling design.

Another advantage of the Tahoe time series is inherently lower interannual variability due to the long hydraulic residence time (Table 1). The amount of nutrients entering the lake in any year is small compared to storage within the lake water. A single year's loading therefore does not have much affect on water quality, except during extreme events such as the 1983 El Niño-

Southern Oscillation. Tahoe does have a unique source of interannual variability. This deep lake does not mix completely to the bottom every year, which leads to an annually variable upwelling of nutrients and subsequent year-to-year variability in primary production and clarity. Even with this additional source, however, interannual variability is low compared to the Delta. During 1976–1995, for example, the annual deviation from the long-term trend averaged 29% for systemwide Delta chlorophyll *a* and only 3.6% for Tahoe Secchi depth. One consequence is that it is easier to identify longer-term trends at Tahoe, which implies that management can in principle respond faster to problems in Tahoe than the Delta.

Differences in Response Time

Although the long hydraulic residence time may enable easier identification of trends at Tahoe, it also implies that the lake does not respond as quickly to remedial measures. The hydraulic residence time for Lake Tahoe is 650 yr, compared to the average 25 d residence time for the Delta. Flushing of materials is therefore a major phenomenon in understanding the balance of materials and organisms in the Delta, whereas it is unimportant at Tahoe except for highly conservative substances over centennial time scales. Sinking rather than flushing loss drives material balances at Tahoe. But even the sinking-related residence times are large, on the order of 30 to 50 years for both nitrogen and phosphorus and currently uncertain for the mineral contributions to clarity losses. These long residence times at Tahoe mean that concentrations of nutrients and clay particles will not respond quickly to watershed management.

Adaptive management of water clarity is therefore a challenging undertaking at Tahoe. Without understanding these response times, it is easy for the public and even scientists to misinterpret the slow pace of recovery and to arrive at erroneous conclusions. This occurred in the early years of other lake restoration programs when internal loading of phosphorus kept nutrient concentrations unexpectedly high and delayed recovery after external phosphorus loading was reduced. Certain restoration activities in the Delta will also take a long time to mature, although the response times are still probably less than those of Tahoe.

In both cases, the long response times mean that we must seek intermediate indicators that respond faster than our ultimate endpoints. In the case of Tahoe, for example, we understand that lake clarity ultimately depends on nutrient and particle loading from many individual watersheds, and that these in turn depend on yields that are linked to land use and vegetation cover. Therefore, an objective assessment of how small-scale watershed management influences nutrient and particle yields must be the foundation of adaptive management in the Basin. But this requires a sound understanding of mechanisms linking the intermediate to ultimate goals. At Tahoe, there are still outstanding questions about the nature of particles responsible for clarity loss, especially the size of the relevant mineral suspensoids, and so the intermediate indicators cannot be completely defined. There are many more examples from the Delta and our main challenge is to provide this understanding of mechanisms in a practical fashion—affordable and timely.

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References

[CALFED] CALFED Bay-Delta Program. 2000. Executive summary: final programmatic Environmental Impact Statement, Environmental Impact Report. Sacramento (CA): CALFED Bay-Delta Program. 25 p.

Jassby AD, Goldman CR, Reuter JE, Richards RC, Heyvaert AC. 2001. Lake Tahoe: diagnosis and rehabilitation of a large mountain lake. In: Munawar M, Hecky RE, editors. Exploring the great lakes of the world: food-web, health and integrity. Leiden (Netherlands): Backhuys Publishers.

[SNEP] Sierra Nevada Ecosystem Project Science Team and Consultants. 1996. Sierra Nevada Ecosystem Project, Final report to Congress, vol. I, assessment summaries and management strategies. Davis (CA): University of California, Centers for Water and Wildland Resources. 209 p.

USDA Forest Service, Tahoe Regional Planning Agency, University of California at Davis, University of Nevada at Reno, and Desert Research Institute. 2000. The Lake Tahoe watershed assessment: executive summary. Washington (DC): US GPO. 15 p.

Global Climate Change: Potential Effects on the Sacramento–San Joaquin Watershed and the San Francisco Estuary

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Introduction

In light of mounting evidence of anthropogenic warming of the Earth's oceans and atmosphere (NRC 2001) the consequences of projected future global and regional warming for the Bay-Delta estuary and its watershed need to be carefully evaluated. California's heavy dependence on reservoirs and snowpack for flood prevention and freshwater storage makes it especially vulnerable to projected hydrologic changes.

From December through March, the Bay-Delta watershed receives an average 30 to 40 km^3 (about 24 to 32 maf[1]) of freshwater as rain and snow. California depends on artificial storage (reservoirs) and natural storage (snowpack) to help make this supply last the rest of the year. Snowpack alone delays an average of 40% of the annual supply until after April 1 (Roos 1989). Highly variable winter and spring runoff is managed as a flood hazard, meaning it is released from reservoirs as quickly as necessary to maintain sufficient flood control storage space. After April, the management goal is reservoir recharge, accumulating the steady stream of snowmelt runoff for distribution later in the year.

Warmer conditions would reduce the volume of the snowpack, contributing to higher flood peaks during the rainy season and reduced warm-season flows after April. Possible precursory signs of a warming trend include a long-term decrease in the fraction of bay inflows arriving in the spring (Roos 1991; Aguado and others 1992; Wahl 1992; Dettinger and Cayan 1995), earlier onset of spring plant blooms and of the initial spring snowmelt runoff pulse (Peterson and others 2000; Cayan and others 2001), and increased spring salinity in the estuary (Peterson and others 1995; Knowles 2000).

A sustained warming trend would alter hydrologic conditions throughout the watershed, consequently changing the annual salinity cycle of the estuary. The amount of snowpack reduction would determine the level of effect on the economies and ecosystems that depend on this freshwater supply. This article presents new estimates of warming-induced changes in snowpack and streamflow throughout the watershed, and of changes in estuarine salinity, for the remainder of this century.

Methods

The Parallel Climate Model (PCM) is a numerical model of the global climate system that couples atmospheric, land surface, oceanic and sea-ice components (Washington and others 2000). It has recently been shown to accurately reproduce an observed long-term rise in the temperature of the world's oceans (Barnett and others 2001) and otherwise produces climate simulations that compare favorably to observations. In California, this model projects a near-surface air temperature increase of just over 2 °C during the course of the 21st century, in response to a hypothesized "business-as-usual" buildup of greenhouse gases in the atmosphere. This is a relatively small warming in comparison to most other climate models (see Gleick 2000).

While there is a consensus among global models in the occurrence and approximate magnitude of temperature increase, precipitation is a much more variable process. In response to the projected 21st century greenhouse-gas buildup, the PCM projects relatively little

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[1] million acre-feet.

overall change in the amount of precipitation California receives (Figure 1). During the recent National Climate Change Impacts Assessment (Felzer 1999), however, other models have forecasted increases. Thus, the magnitude and even the direction of possible precipitation changes in California remains an area of considerable uncertainty. Because of the great uncertainty shrouding precipitation projection at present, we focus here solely on the effect of temperature change on the Bay-Delta estuary and watershed, with the implicit assumption that the PCM forecast of (essentially) no precipitation trend is accurate.

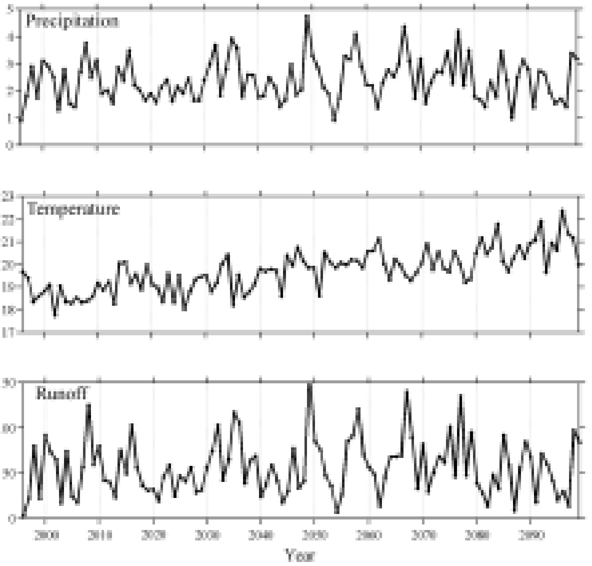

Figure 1 Downscaled PCM-simulated watershed-averaged precipitation and temperature and simulated total watershed runoff for WY 1995-2099

To isolate the effects of temperature increase, simulated temperatures from a 1995–2099 PCM run were used to generate monthly temperature anomalies averaged over the periods 2020–2039, 2050–2069, and 2080–2099, relative to 1995–2005 monthly averages. The resulting values represent estimates of average monthly temperature changes over the Bay-Delta watershed for the years 2030, 2060 and 2090, relative to present conditions. These 3 sets of 12 monthly mean anomalies were added separately to historical temperature data from water years (WY) 1965–1987. Along with the adjusted temperature time series, historical (unchanged) precipitation data from the same 1965–1987 period were used as forcing input to a hydrologic model of the Bay-Delta watershed, resulting in three simulations of watershed snowpack and streamflow representing the watershed's hydrologic behavior under 2030, 2060, and 2090 temperature regimes. A fourth control simulation was performed using unchanged WY 1965–1987 precipitation and temperature to represent the watershed's present hydrologic regime.

The Bay-Delta watershed model (BDWM) used for these simulations is a physically based, soil moisture accounting model with a daily time step and a horizontal resolution of 4 km (Knowles 2000). The snow component of this model is an adaptation of the Utah Energy Balance (UEB) snow model (Tarboton and Luce 1996), which has been shown to accurately reproduce Sierran snowpack variability. The BDWM reproduces observed streamflow variations throughout the watershed with sufficient accuracy to indicate that it contains a valid representation of the physical processes generating this variability. An important feature of the model is that it is not calibrated to any particular historical hydrologic regime, making it particularly well suited for studies of climate change.

The final step in these simulations was to use output from the BDWM runs to estimate changes in total watershed outflow (Delta outflow) in 2030, 2060 and 2090, relative to present conditions. These simulated changes in Delta outflow were added to historical, observation-based estimates of outflow (DWR 1999) to generate estimates of freshwater inflows to the estuary that would occur under the projected increases in temperature. The implicit assumption that management effects on Delta outflow would be the same under the projected warmed conditions as they have been under recent historical conditions is of course an oversimplification; limitations of this assumption are addressed below. Adjusted Delta outflow time series were used to drive 3 simulations of estuarine salinity from WY 1965–1987. These simulations correspond to the three climate change simulations of the watershed; a corresponding fourth control simulation using unchanged 1965–1987 inflows was also performed.

The Uncles-Peterson (U-P) estuarine model, an advective-diffusive intertidal box model of San Francisco Bay with a daily time step, was used to perform these simulations. This model has been applied in several previous studies of the San Francisco Bay and has been shown to accurately reproduce salinities at weekly to interannual time scales over a wide range of flow regimes (Peterson and others 1995; Knowles and others 1997; Knowles and others 1998). The simulated salinity values provide a rough estimate of the effect of the projected temperature change on estuarine salinity in 2030, 2060, and 2090, relative to present conditions.

Results

Interannual Variability

Before examining the broad trends that result from the simulations described above, it is useful to first consider the interannual variability present in the climate simulation. Statistically downscaled PCM precipitation and temperature were used to drive the BDWM model over the period WY 1995–2099. The downscaling method used was developed by M. Dettinger (personal communication) and is a simple but robust means of translating the approximately 250 km PCM output onto the 4 km grid of the 140,000 km^2 BDWM domain. The resulting watershed-averaged precipitation and temperatures and total watershed outflow (Figure 1) reveal strong interannual variability of the same magnitude observed in California historically (Namias 1978; Cayan and others 1999). Among the PCM's distinguishing features is its high-resolution treatment of the tropical ocean, which gives a relatively realistic depiction of the El Niño-Southern Oscillation process and other interannual variability (Washington and others 2000). The long-term rise in temperature associated with anthropogenic change is also clearly evident (Figure 1, middle). Though no long-term trend in precipitation is apparent, decadal to interdecadal variability is evident (Figure 1, top), also consistent with observed historical behavior (Cayan and others 1998; Dettinger and others 1998).

Thus these simulations suggest strong interannual and decadal variability (including very wet years, droughts, and relatively cold and hot years), will continue to occur in the coming century much as has been observed to occur in California in the instrumental record. The subject of the present study, however, is the background of slower hydrologic change that would underlie these variations.

Snowpack Changes

Simulated snowpack under warmed conditions depicts a severe loss of snow as indicated by changes in the snow water equivalent (SWE) by 2090 (Figure 2). By 2030, the watershed-averaged temperature is projected, under the business-as-usual scenario, to rise by about 0.6 °C, resulting in a minor reduction in snowpack at lower elevations. April SWE, typically the snowpack's annual apex, is reduced by only 5% compared to present conditions. However, an increase of 1.6 °C by 2060 causes the loss of over one-third of the total April snowpack. This loss is focused in mid to lower elevations, since snowpack there is more sensitive to temperature changes than at higher, colder elevations. Regionally, this means that the northern Sierra and Cascades experience the greatest loss. Note that since overall precipitation is conserved in this projection, the lost snowpack appears instead as early runoff.

By 2090, average temperatures are projected to have increased 2.1 °C, resulting in a loss of one-half of the watershed's total April snowpack. Again, the loss is most severe in the northern Sierra and Cascades, which would lose 66% of their April snowpack, but the southern Sierra would also be strongly affected, losing 43% of their April snowpack.

Outflow Changes

The loss of snowpack indicated above would have large effects on streamflows throughout the watershed. The mean annual (water year) hydrographs of the total outflow from the northern and southern headwaters (Figure 3) for 2030, 2060, and 2090 reflect the changing flow patterns in these two regions. In general, the loss of snowpack results in higher runoff peaks before April and reduced snowmelt-driven flows in subsequent months.

As with the relatively unchanged 2030 snowpack, projected 2030 outflows are very similar to present conditions. By 2060, both the northern (Sacramento) and the southern (Cosumnes, Mokelumne, and San Joaquin) headwaters show the effect of reduced snowpack, with the largest effect in the north. The April–July fraction of total annual flow is reduced from 0.36 in 2030 to 0.26 in 2060. Combined with the smaller reduction in the south, this represents over 3 km^3 (about 2.5 maf) of runoff shifting from post-April 1 to pre-April 1 flows.

By 2090, both regions show significantly affected hydrographs, with a loss of 1.2 km^3 April–July runoff in the south and 4.4 km^3 in the north, for a total loss of 5.6 km^3 (about 4.5 maf). This lost snowmelt runoff appears instead as increased flood peaks during the earlier portions of the hydrographs.

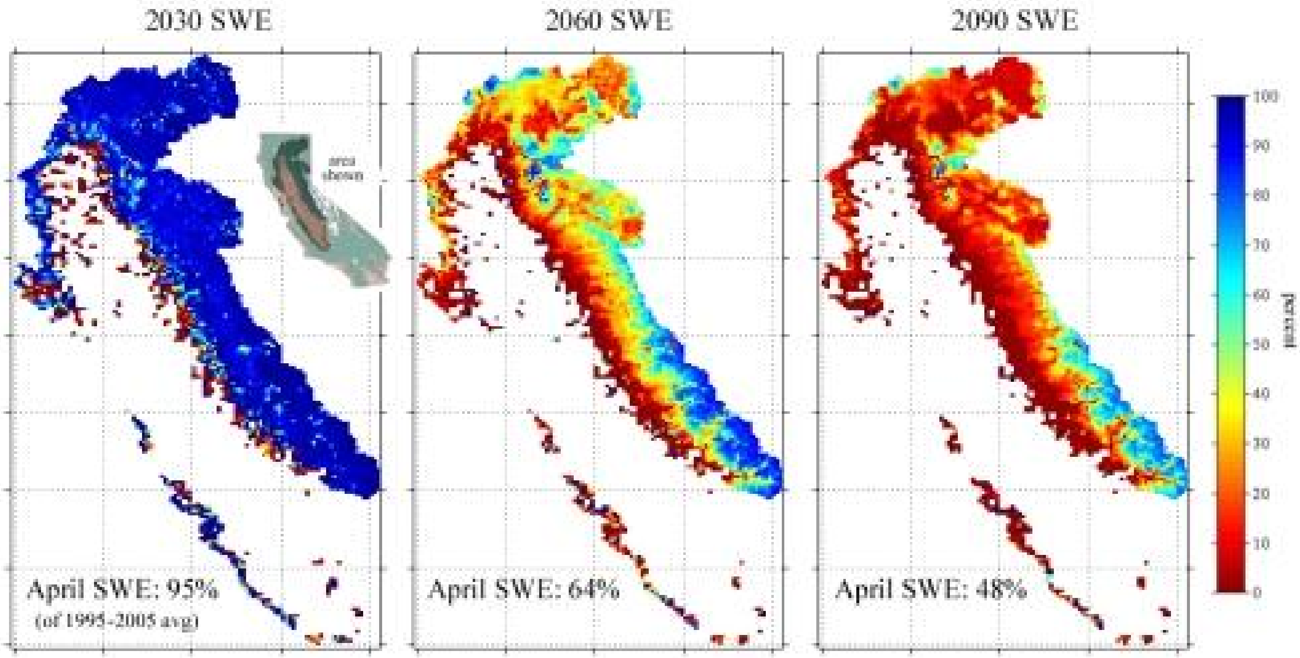

Figure 2 Simulated snow water equivalent (SWE) under a projected temperature increase for the periods 2020-2039, 2050-2069 and 2080-2099, expressed as a percentage of average 1995-2005 SWE

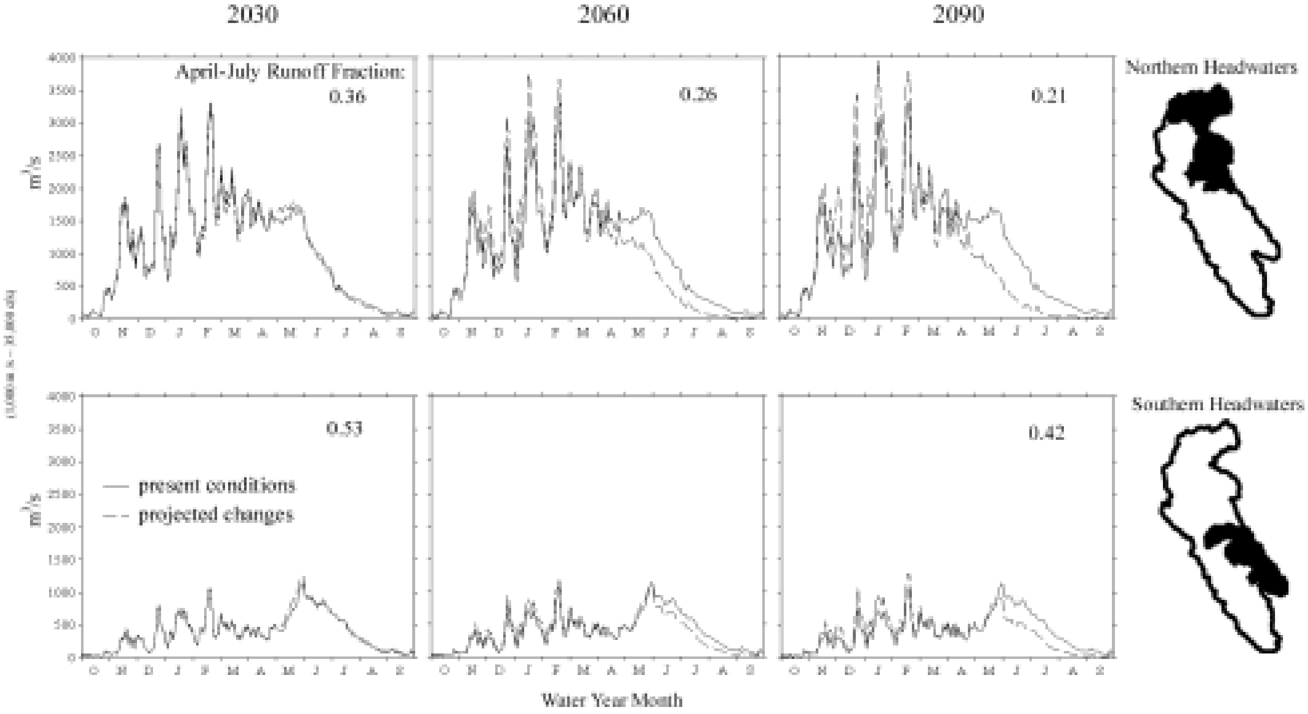

Figure 3 Simulated mean annual hydrographs of northern and southern headwater regions for the same periods as Figure 2

Salinity Changes

Seasonal to interdecadal variations in San Francisco Bay salinity can be explained almost entirely by variations in freshwater inflow from the watershed (Knowles 2000). Among the factors associated with global change, changing inflow patterns are likely to have a large effect in the estuary. With the simplifying assumption that reservoirs would not change their operating procedures in response to climate change, and neglecting the effects of sea level rise, the simulated changes in total watershed outflow were used to model the effect of warming on salinity in the estuary.

While increased December–March runoff would lead to a fresher estuary, reduced snowmelt runoff in the subsequent months would allow tidal action to mix seawater into the estuary more quickly, resulting in higher salinities during late spring, summer, and fall. The mean annual cycle of simulated San Pablo Bay salinity for present and projected future conditions (Figure 4) indicate that average salinities could be 2 to 5 psu higher for May through September.

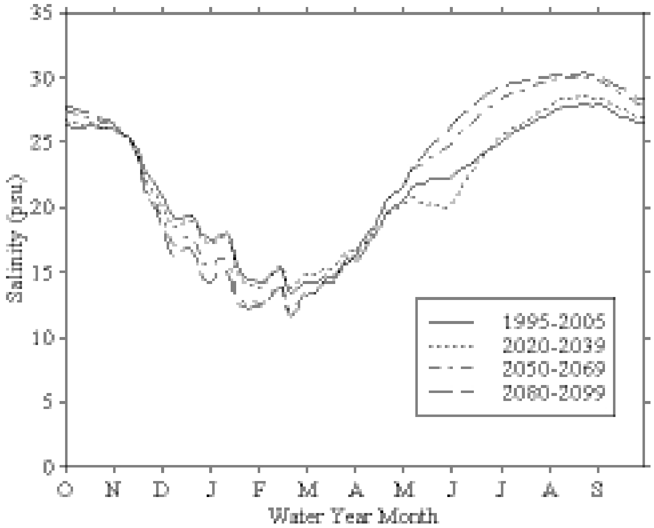

Figure 4 Simulated San Pablo Bay mean annual salinity cycles for periods 1995-2005, 2020-2039, 2050-2069 and 2080-2099. Differences result from changes in total watershed outflow simulated by the watershed model as depicted in the hydrographs of Figure 3.

However, actual salinity changes resulting from the projected temperature increase might in fact be quite different than those shown here, since these estuarine simulations incorporate historical Delta outflows (see "Methods") which are adjusted by the simulated Delta outflow changes resulting from higher temperatures. The resulting outflow time series used in these simulations contain the effects of historical management strategies, which would invariably differ from future management strategies intended to mitigate the hydrologic effects of warming.

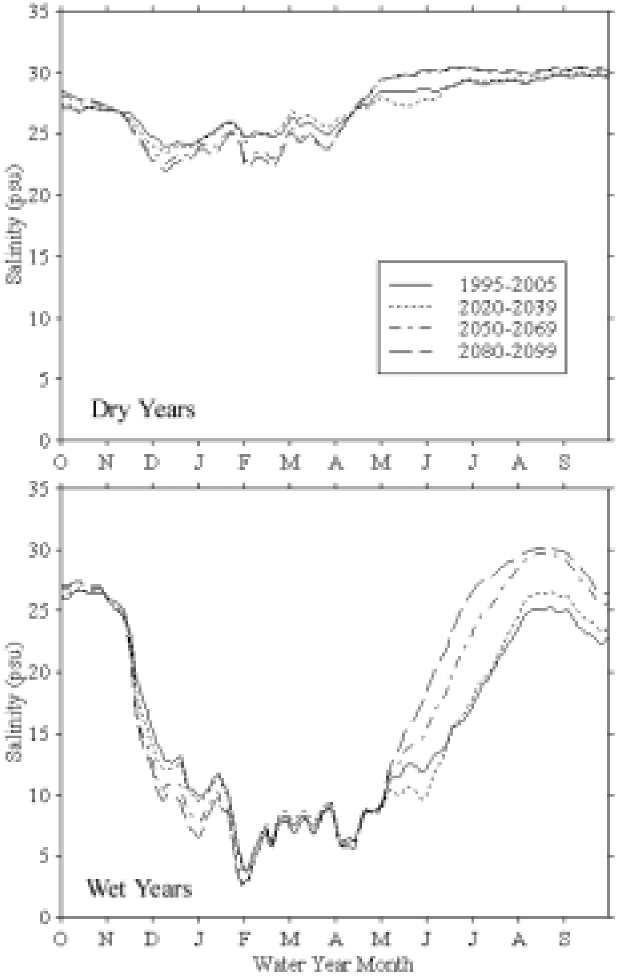

Figure 5 Simulated warming-induced changes in San Pablo Bay mean annual salinity cycle for extreme wet and dry years

To permit a more comprehensive assessment of the potential changes, composites were produced of the 5 wettest and driest years of the simulations used to generate the salinity change estimates (Figure 5). In dry years (Figure 5, top), estimates of salinity change between 2000 and 2090 conditions are on the order of 1 to 3 psu. However, dry year conditions would actually leave reservoirs with more space to mitigate the hydrologic effects of temperature change. As a result, it may be likely that during dry years, salinity effects could be even less than shown by these simulations.

Conversely, wet years (Figure 5, bottom) bring precisely the type of conditions that would handicap the reservoirs' ability to mitigate change. The need for increased flood control capacity, combined with severely reduced snowmelt runoff, could severely limit the options of water managers. The resulting lower-than-historical dry season freshwater reserves could result in salinity increases greater than the 5 to 9 psu shown here.

Discussion

Under the business-as-usual temperature increase scenario examined here, the diminished snowpack and earlier runoff of water that is currently used to recharge California reservoirs would bring adverse effects to estuarine and watershed ecosystems and all who depend on the freshwater supply infrastructure. This water would runoff during the rainy season, greatly increasing the potential for flooding. During the dry season, lower streamflows and increased salinities would affect many species that depend on the estuary and rivers. The risk of contamination of freshwater supplies by salinity intrusion would also be greater. Also, the estuarine simulations presented here do not include the effect of sea level rise, which is projected to proceed at a rate of 50 cm over the next 100 years (IPCC 2001), an acceleration of the recent historical rate of 23 cm per century (Flick 1998). This effect is likely to add to the salinity increase seen in the simulations presented here (Williams 1985). The increased possibility of levee failure that would result from higher wet season flows and increased sea level could have additional effects.

The estimates of hydrologic change presented here agree well with the results of previous studies of the potential effects of climate change in this watershed (Gleick 1987; Roos 1989; Lettenmaier and Gan 1990; Jeton and others 1996; Gleick and Chalecki 1999). These results are also supported by recent simulations with much finer scale models of the upper Merced, Carson, and North Fork American rivers under the same climatic changes, which show similar losses of snowpack in those basins (M. Dettinger, personal communication).

It is important to recognize that this study represents one possible climate change scenario. As discussed earlier, there is general consensus regarding the occurrence of a temperature increase. However, the range of warming estimates from the various climate models is large—from 1 to 6 °C over the next 100 years (IPCC 2001). Clearly, a smaller increase than the approximately 2 °C used in the present study would lessen the effects on snow, streamflow and salinity discussed above, while the higher increases projected by some climate models would magnify these effects. Changes in precipitation as a result of global climate change are far less certain than the change in temperature. Consequently, there is considerable uncertainty in the hydrologic consequences of climate change. Using the U.S. National Assessment scenario (HadCM2 climate model) results of a 50% increase in California precipitation over the next century, Wilby and Dettinger (2000) have shown that a precipitation increase of this magnitude would restore snowpack volume in the watershed's higher elevations to near-present conditions even with a projected temperature increase of 3 °C. The potential for rainy season flooding under this scenario, however, would be increased considerably more than in the constant-precipitation scenario presented here. Thus, a range of potential hydrologic effects could result from climate change, while some consequences, such as increased flooding potential, are quite likely under most scenarios.

This study illustrates the distribution of the very sensitive response of snowpack and streamflow throughout the watershed, and the propagation of that response into the San Francisco Bay-Delta estuary with an associated change in salinities. The hydrologic and water quality changes exhibited are substantial, even though the PCM's projected temperature change of about 2 °C per century is relatively conservative. These results emphasize that California's strong reliance on natural and artificial storage of freshwater will make adjusting to the hydrologic changes that seem likely to occur in the coming century a difficult challenge.

Acknowledgements

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References

Aguado E, Cayan D, Riddle L, Roos M. 1992. Climatic fluctuations and the timing of West Coast streamflow. J Climate 5:1468–83.

Barnett TP, Pierce DW, Schnur R. 2001. Detection of anthropogenic climate change in the world's oceans, Science 292:270–74.

[DWR] California Department of Water Resources. 1999. DAYFLOW data, available at http://iep.water.ca.gov/dayflow/data.

Cayan DR, Dettinger MD, Diaz HF, Graham NE. 1998. Decadal variability of precipitation over western North America. J Climate 11:3148–66.

Cayan DR, Kammerdiener SA, Dettinger MD, Caprio JM, Peterson DH. 2001. Changes in the onset of spring in the western United States. Bull Am Meteorol Soc 82:399–415.

Cayan DR, Redmond KT, Riddle LG. 1999. ENSO and hydrologic extremes in the western United States. J Climate 12:2881–93.

Dettinger MD, Cayan DR. 1995. Large-scale atmospheric forcing of recent trends toward early snowmelt runoff in California. J Climate 8:606–23.

Dettinger MD, Cayan DR, Diaz HF, Meko DM. 1998. North-south precipitation patterns in western North America on interannual-to-decadal timescales. J Climate 11:3095–111.

Felzer B. 1999. Hydrological implications of GCM results for the US National Assessment. In: AWRA, editor. Specialty Conference on Potential Consequences of Climate Variability and Change to Water Resources of the United States. Atlanta, GA. p 69–72.

Flick RE. 1998. Comparison of California tides, storm surges, and mean sea level during the El Nino winters of 1982–83 and 1997–98, shore and beach. J Am Shore Beach Pres Assoc 66:7–11.

Gleick PH. 1987. The development and testing of a water balance model for climate impact assessment: modeling the Sacramento basin. Water Resources Research 23:1049–61.

Gleick PH. 2000. Water: the potential consequences of climate variability and change for the water resources of the United States. National Water Assessment Group for the US Global Change Research Program.

Gleick PH, Chalecki EL. 1999. The impacts of climatic changes for water resources of the Colorado and Sacramento-San Joaquin River Basins, J Am Water Res Assoc 35:1429–41.

IPCC. Climate change 2001: impacts, adaptation and vulnerability. Geneva, Switzerland: World Meteorological Organization.

Jeton AE, Dettinger MD, Smith JL. 1996. Potential effects of climate change on streamflow, eastern and western slopes of the Sierra Nevada, California and Nevada. US Geological Survey Earth Science Information Center Open-File Report. Denver (CO): USGS. 44 p.

Knowles N. 2000. Modeling the hydroclimate of the San Francisco Bay-Delta estuary and watershed [PhD dissertation]. University of California, San Diego, La Jolla. Available at http://meteora.ucsd.edu/~knowles/html/SFBayHydroclimate.html.

Knowles N, Cayan D, Ingram L, Peterson DH, Uncles RJ. 1997. Diagnosing the flood of 1997 in San Francisco Bay with observations and model results. Interagency Ecological Program for the San Francisco Estuary. IEP Newsletter 10 (3):28–31.

Knowles N, Cayan D, Peterson DH, Uncles RJ. 1998. Simulated effects of delta outflow on the bay: 1998 compared to other years. Interagency Ecological Program for the San Francisco Estuary. IEP Newsletter 11:29–31.

Lettenmaier DP, Gan TY. 1990. Hydrologic sensitivities of the Sacramento-San Joaquin River basin, California, to Global Warming. Water Resources Research 26:69–86.

Namias J. 1978. Multiple causes of the North American abnormal winter 1976–77. Monthly Weather Rev 106:279–95.

[NRC] National Research Council. 2001. Climate change: an analysis of some key questions. Washington, DC: National Acad Pr.

Peterson D, Cayan D, Dileo J, Noble M, Dettinger M. 1995. The role of climate in estuarine variability. Am Sci 83:58–67.

Peterson DH, Smith RE, Dettinger MD, Cayan DR, Riddle L. 2000. An organized signal in snowmelt runoff over the western United States. J Am Water Res Assoc 36:421–32.

Roos M. 1989. Possible climate change and its impact on water supply in California. Oceans ‘89 Conference. Seattle (WA): Institute of Electricity and Electronic Engineering.

Roos M. 1991. A trend of decreasing snowmelt runoff in northern California. In: Proceedings of the 59th Western Snow Conference; Juneau, AK. p 29–36.

Tarboton DG, Luce CH. 1996. Utah energy balance snow accumulation and melt model (UEB): computer model technical description and users guide. Utah Water Research Laboratory and USDA Forest Service Intermountain Research Station.

Wahl KL. 1992. Evaluation of trends in runoff in the Western United States. In: Managing water resources during global change. Reno (NV): Am Water Res Assoc. p 701–10.

Washington WM, Weatherly JW, Meehl GA, Semtner AJ, Bettge TW, Craig AP, Strand WG, Arblaster J, Wayland VB, James R, Zhang Y. 2000. Parallel climate model (PCM) control and transient simulations. Climate Dynamics 16:755–74.

Wilby RL, Dettinger MD. 2000. Streamflow changes in the Sierra Nevada, California, simulated using statistically downscaled general circulation model output. In: McLaren S, Kniveton D, editors. Linking climate change to land surface change. Kluwer Academic. p 99–121.

Williams P. 1985. An overview of the impact of accelerated sea level rise on San Francisco Bay. Project No. 256. San Francisco (CA): Philip Williams & Assoc.

Notes

Dettinger M. (Scripps Institution of Oceanography and US Geological Survey). Verbal communications with Noah Knowles in June 2001.

Differences Among Hatchery and Wild Steelhead: Evidence from Delta Fish Monitoring Programs

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Introduction

Steelhead is the name generally used for anadromous rainbow trout, *Oncorhynchus mykiss*. The Central Valley steelhead Evolutionarily Significant Unit (ESU) was listed as threatened in 1998 (NMFS 1998). Beginning in water year 1997-98, the four Central Valley hatcheries that produce steelhead (Coleman National Fish Hatchery, Feather River Hatchery, Nimbus Hatchery, and Mokelumne River Fish Installation) began marking all hatchery steelhead with an adipose fin-clip. This permits differentiation of hatchery and wild steelhead, allowing for life history comparisons among them. For the purpose of this paper “hatchery” steelhead are defined as those lacking an adipose fin, and “wild” steelhead are those with an adipose fin present. It should be noted that these terms are approximate since small percentages of hatchery fish probably go unmarked due to human error. In addition, some wild fish are the progeny of hatchery fish that spawned naturally. This paper presents an initial exploratory analysis to address the following questions:

1. What proportion of emigrating Central Valley steelhead are of hatchery origin?
2. Are life history differences among hatchery and wild steelhead discernible in the available Delta monitoring data?
3. What factor(s) affect the salvage of hatchery and wild steelhead at the CVP and SWP fish facilities?

4. What percentages of emigrating hatchery and wild steelhead smolts are salvaged at the CVP and SWP fish facilities?

Methods

Fish Sampling

Fish recoveries are reported from three locations, the USFWS Stockton Fish and Wildlife Office Chipps Island Midwater Trawl (Chipps), the State Water Project's Skinner Fish Protective Facility (SWP), and the Central Valley Project's Tracy Fish Collection Facility (CVP). We used data from all three sources beginning August 1, 1997, to coincide with the beginning of the period in which all hatchery steelhead were adipose fin-clipped. Our analysis extends through July 31, 2000, for Chipps and through May 31, 2001, for both the SWP and CVP, which represents the most current data available.

Chipps has been in operation since 1976 (Kjelson and others 1982). Collection methods are described in detail in Brandes and McLain (2001); but briefly, the survey usually conducts ten 20-minute surface tows per day between 1 and 7 days per week. Between August 1997 and July 2000, some sampling at Chipps occurred in all months except July and August 1998. To compare the relative abundance of hatchery and wild steelhead, daily catch per unit effort (CPUE) was calculated as the number of fish collected per 10,000 cubic meters of water sampled.

SWP fish samples are typically taken for 20 minutes every two hours throughout the day and night. Sample duration may vary due to high fish counts, extremely low fish counts or low flows. Samples at the CVP are taken for 10 minutes every two hours on the even hour. The duration of fish counts at the CVP are much more regular than SWP fish counts and vary little throughout the year. SWP and CVP data also were converted to daily CPUE (number of fish per acre-foot of water exported).

Statistical Analysis

The contribution of hatchery fish to emigrating Central Valley steelhead was estimated by calculating the percentage of mean daily steelhead CPUE comprised of hatchery fish each year in each sampling program.

We compared two aspects of life history for hatchery and wild steelhead—size structure and emigration timing. First we looked for evidence of size differences. We constructed annual (August of the first year through July of the next) length frequency histograms of hatchery and wild steelhead collected at Chipps and qualitatively examined them for obvious differences. Then we performed a two-way ANOVA on the fork length (FL) data, using year of collection and mark (adipose fin-clipped or not) as factors. Based on the length frequency histograms, we randomly subsampled fish < 330 mm to provide equal sample sizes (n = 48) within treatments. Most steelhead greater than 330 mm were clearly age classes that represented returning adults rather than emigrating smolts. We also examined the seasonal size structure of wild steelhead collected at Chipps by plotting the monthly mean fork lengths of wild smolts and the individual fork lengths of wild adults versus month of collection. Due to highly fluctuating and often small sample sizes, the seasonal length data were only qualitatively examined.

We examined emigration timing in two ways. First, we constructed annual (August through July) plots of daily CPUE of hatchery and wild steelhead at Chipps and daily Delta outflow from DAYFLOW (http://iep.water.ca.gov/). Emigration patterns of hatchery and wild steelhead were compared qualitatively to each other and to Delta outflow. Second, we plotted cumulative annual CPUE of hatchery and wild steelhead versus surface water temperature measured at Chipps.

We examined factors associated with steelhead salvage using monthly data for January through June 1998–2000, and January through May 2001 (the most current data available). We chose this period because virtually all steelhead salvage occurs during January through June (DWR and USBR 2000). Relationships of total monthly salvage of hatchery and wild steelhead at the SWP and CVP and total monthly SWP and CVP exports were analyzed using linear regression techniques. All salvage data were natural log transformed prior to statistical analysis.

We estimated the percentage of the hatchery and wild steelhead smolts that were salvaged as follows. Estimates of the number of hatchery steelhead released each year from 1998 to 2000 were obtained from Marty Kjelson (personal communication). We assumed zero mortality from point of release to Chipps Island, then used the proportion of hatchery fish CPUE collected at Chipps to derive a population estimate of wild steelhead smolts:

[hatchery smolts released ÷ proportion of hatchery fish at Chipps] – hatchery smolts released

The percent of hatchery and wild steelhead salvaged were estimated using the formula below:

[Combined CVP and SWP salvage ÷ population estimate] × 100

Results

The contribution of hatchery steelhead has varied considerably among monitoring programs and years (Table 1). Hatchery steelhead generally contributed a higher percentage to trawl catches (63% to 77%) than to salvage at the SWP and CVP fish facilities (3% to 62%).

Table 1 Percentage of steelhead catch per unit effort comprised of hatchery fish in Delta monitoring surveys. Years were defined as August 1 through July 31. Numbers of hatchery steelhead the CPUE calculations were based on are in parentheses.

Year	*1997–1998*	*1998–1999*	*1999–2000*	*2000–2001*
USFWS Trawl at Chipps Island	63 (112)	76 (171)	77 (142)	---
CVP Fish Facilities	41 (336)	3 (70)	41 (1,291)	62[a] (2,976)
SWP Fish Facilities	54 (36)	11 (117)	62 (4,139)	61[a] (5,261)

[a] Only extends through May in 2001.

Most steelhead collected at Chipps have ranged from 180 to 280 mm fork length (FL), with smaller and larger individuals collected occasionally (Figure 1). Although differences in hatchery and wild fork lengths were not striking, mean fork lengths of steelhead smolts varied significantly among years (Table 2; $F = 4.6$; $P = 0.01$), differing up to 12 mm interannually. In addition, hatchery steelhead were slightly, but significantly larger than their wild counterparts ($F = 4.6$; $P = 0.03$). There was no significant interaction between year and mark ($F = 1.7$; $P = 0.19$). The residuals from the ANOVA did not differ substantially from normality. Variances were homogeneous among years, but variance differed among hatchery and wild fork lengths.

Table 2 Results of two-way ANOVA on steelhead fork length data from the USFWS Chipps Island Trawl. The ANOVA tested for differences among water years (1997-2000) and mark (adipose fin-clipped or not). Results were based on 48 randomly selected observations from each year-mark combination. Years were defined as August 1 through July 31.

Source	*DF*	*SS*	*MS*	*F*	*P*
Year	2	7,528	3,764	4.64	0.01
Mark	1	3,720	3,720	4.59	0.03
Year X Mark	2	2,747	1,374	1.69	0.19
Error	282	228,716	811		
Total	287	242,711			
Mean fork lengths (mm)					
1997–1998 = 218.2					
1998–1999 = 226.3					
1999–2000 = 230.5					
Hatchery = 228.6					
Wild = 221.4					

On a monthly basis, wild steelhead adults were occasionally collected at Chipps during winter, spring, and summer (Figure 2). One 515-mm steelhead was collected in April 1998 and two steelhead estimated to be 800 mm were collected in July 1999. These are the only wild fish not shown in Figure 2. Monthly mean fork lengths of smolts at Chipps were sometimes higher in the spring than in the late fall, but monthly mean fork lengths did not show consistent trends during the primary spring emigration period.

During the winter of all years, CPUE of hatchery steelhead peaked during or shortly after the first increase in Delta outflow following their release, then tended to taper off throughout the spring (Figure 3). In contrast, CPUE of the unclipped fish was generally low, but relatively consistent, extending from late fall through early summer. No wild steelhead were collected in fall 1999, although sampling did occur. Emigration timing did not appear to be related to Delta outflow in wild fish.

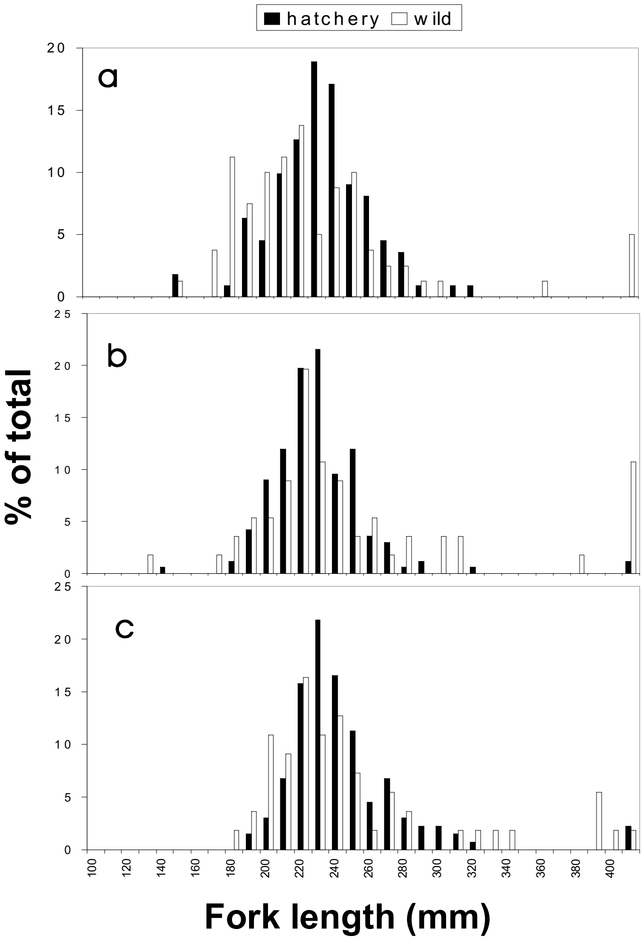

Figure 1 Length frequency distributions of hatchery and wild steelhead collected in the USFWS Chipps Island Trawl, August 1 through July 31: (a) 1997–1998; (b) 1998–1999; (c) 1999–2000.

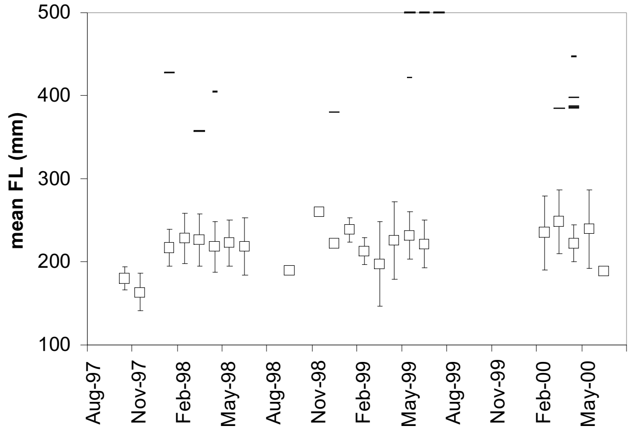

Figure 2 Mean monthly fork lengths (mm) +/- 1 standard deviation for wild steelhead from the USFWS Chipps Island Trawl Survey. Dashes represent individual observations of wild adult steelhead that were not included in the calculations of mean length. Three observations of adult fish larger than 500 mm FL are not shown (see text).

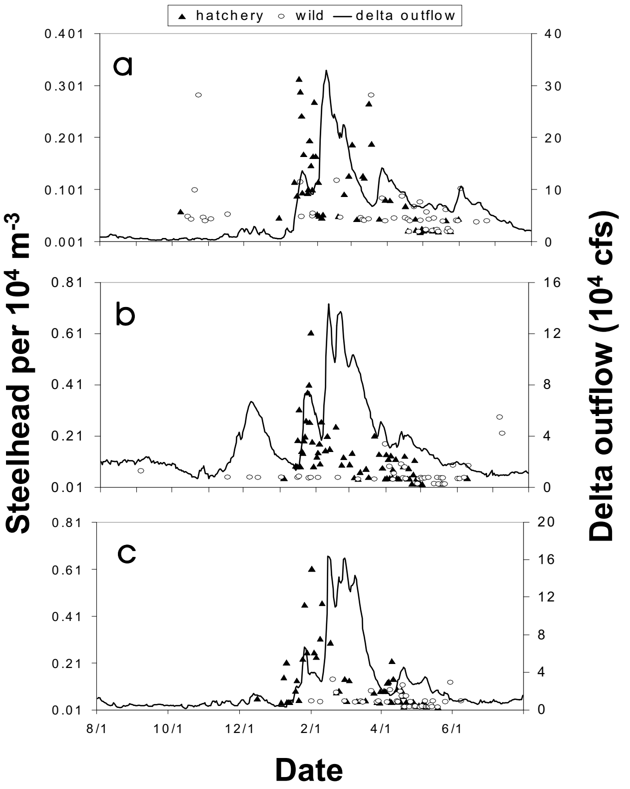

Figure 3 Temporal distribution of hatchery and wild steelhead per 10,000 m^3 of water sampled by the USFWS Chipps Island Trawl and total Delta outflow from DAYFLOW for (a) August 1, 1997 through July 31, 1998; (b) August 1, 1998 through July 31, 1999; and (c) August 1, 1999 through July 31, 2000.

The differences in emigration timing of hatchery and wild steelhead past Chipps Island are particularly clear in plots of cumulative percentage of CPUE versus water temperature (Figure 4). In each of the three years analyzed, about 50% of the hatchery fish CPUE occurred at temperatures less than or equal to about 10 °C (50 °F). In contrast, the temperature at which about 50% of the wild steelhead CPUE occurred was between 15 °C and 16 °C (about 60 °F). Virtually all smolts had emigrated by the time water temperatures reached 20 °C (68 °F).

During the primary steelhead salvage season (January through June), total monthly steelhead salvage at SWP has been highly correlated ($r^2 = 0.63$; $P < 0.0001$) with total monthly SWP exports (Table 3; Figure 5a). This relationship has not been significantly different ($P = 0.10$) for hatchery and wild fish at the SWP. The small slope coefficient reflects an association of large differences in exports with much smaller changes in steelhead salvage.

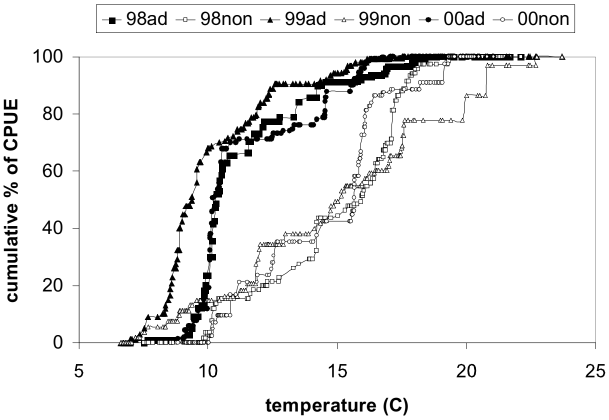

Figure 4 Cumulative percentage of steelhead per 10,000 m^3 in the USFWS Chipps Island Trawl versus surface water temperature at Chipps Island. Solid symbols represent hatchery fish and open symbols represent wild fish.

Table 3 Results of linear regression of total monthly SWP exports versus natural log transformed total monthly SWP steelhead salvage (+ the constant 1) for January through June 1998-2000 and January through May 2001. Mark (adipose fin clipped or not) was included as a covariate.

Coefficients	*Value*	*Standard error*	*t value*	*P*
Intercept	0.912	0.381	2.39	0.02
Slope	<0.0001[a]	<0.0001[a]	8.46	<0.0001[a]
Mark	0.387	0.233	1.66	0.10
Degrees of freedom	43			
Multiple r^2	0.63			

[a] Software output as 0.0000.

The division of the salvage data into monthly groups results in samples that cannot be considered truly independent. (An assumption of linear regression analysis is that the samples are independent.) To address the issue of independent samples, we also did a series of linear regressions using the data for the same month among years (Table 4). This provided independence of the observations at the expense of sample size (There are only 4 seasons of data in which all hatchery-produced steelhead have been adipose fin-clipped.) Despite the low sample sizes, the export-salvage relationships for hatchery fish in the months of January through March, and for wild fish during the months of January through April, all had $r^2 \geq 0.81$ and $P \leq 0.10$. All slope coefficients were small, similar to the result in Table 3. Therefore, we suggest the export-salvage relationship at SWP is probably not spurious.

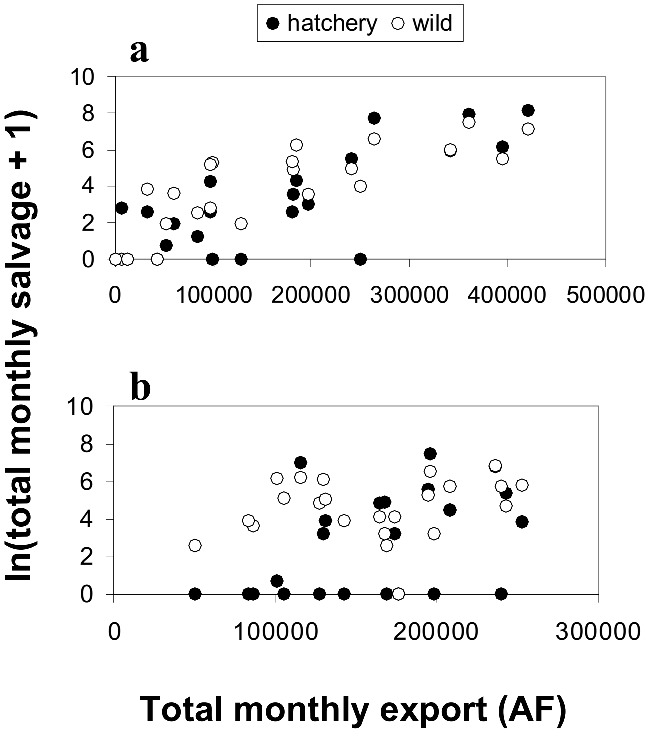

Figure 5 Scatterplots of (a) total monthly SWP exports and total monthly SWP steelhead salvage for January through June, 1998-2000 and January through May 2001; and (b) total monthly CVP exports and total monthly CVP steelhead salvage for January through June 1998–2000 and January through May 2001.

Table 4 Linear regression results for total monthly SWP exports versus natural log transformed total monthly SWP steelhead salvage (+ the constant 1) by month, 1998 through 2001.

Month	*Mark*	*Slope (× 10^{-5})*	r^2	*P*
January	AdClip	1.6	0.85	0.08
	NoClip	1.0	0.86	0.07
February	AdClip	1.7	0.81	0.10
	NoClip	1.7	0.91	0.05
March	AdClip	2.1	0.96	0.02
	NoClip	1.9	0.92	0.04
April	AdClip	1.7	0.54	0.27
	NoClip	3.0	0.85	0.08
May	AdClip	-0.4	0.008	0.91
	NoClip	3.0	0.22	0.53
June[a]	AdClip	-0.9	0.60	0.44
	NoClip	0.3	0.09	0.80

[a] Data for 2001 were not available.

In contrast to the SWP, total monthly export has been a poor predictor of total monthly steelhead salvage at CVP (Figure 5b). However, CVP export combined with SWP salvage explained 63% of the variability in CVP salvage (Table 5). In contrast to salvage at SWP, the hatchery and wild steelhead salvaged at the CVP showed significantly different responses to CVP exports and SWP salvage, with stronger correlations for the hatchery fish.

Table 5 Final result of a stepwise linear regression of total monthly CVP exports, total monthly SWP exports, and natural log transformed total monthly SWP steelhead salvage (+ the constant 1) versus natural log transformed total monthly CVP steelhead salvage (+ the constant 1) for January through June 1998-2000 and January through May 2001. Mark (adipose fin clipped or not) was included as a covariate. Total monthly SWP exports was removed during the stepwise procedure.

Coefficients	*Value*	*Standard error*	*t value*	*P*
Intercept	0.193	0.721	0.268	0.79
Slope of exports	<0.0001[a]	<0.0001[a]	2.05	0.047
Slope of SWP salvage	0.589	0.093	6.35	<0.0001[a]
Mark	0.73	0.229	3.18	0.003
Degrees of freedom	42			
Multiple R^2	0.63			

[a] Software output as 0.0000.

The currently available data suggest salvage represents small percentages of hatchery and wild steelhead smolts (Table 6). The estimated percentages of hatchery smolts in combined (CVP and SWP) salvage ranged from 0.01% to 0.4% from 1998 through 2000. The estimated percentages of wild steelhead smolts salvaged were higher, but were still less than 1% in each year.

Table 6 Estimates of the percentage of emigrating hatchery and wild steelhead smolts salvaged at the CVP and SWP fish facilities and the data used to derive the estimates. H = Hatchery, W = Wild.

	Combined salvage		*Proportion of Chipps CPUE that was hatchery fish*	*No. of hatchery fish released*	*Est. of wild population size*	*Fish salvaged (%)*	
Year	*H*	*W*				*H*	*W*
1997–1998	372	424	0.63	1,121,151	658,453	0.033	0.064
1998–1999	187	2292	0.76	1,509,482	476,679	0.012	0.48
1999–2000	5430	3862	0.77	1,382,884	413,069	0.39	0.93

Discussion

What proportion of emigrating Central Valley steelhead are of hatchery origin?

We think Chipps, which indicated hatchery fish comprise about two-thirds to three-fourths of Central Valley steelhead smolts (Table 1), provides the best currently available estimate of the proportion of emigrating steelhead that is hatchery produced each year. The Chipps Island sampling site is immediately downstream of the confluence of the Sacramento and San Joaquin rivers and thus provides a measure of all steelhead entering or leaving the Central Valley watersheds. In addition, steelhead from both the Sacramento and San Joaquin basins are sampled. Finally, Chipps is sampled nearly year-round, which is important for understanding steelhead migration patterns (Shapovalov and Taft 1954; McEwan 2001).

Unfortunately, even catches at Chipps Island may provide a biased estimate of the proportion of hatchery steelhead. Collis and others (2001) found hatchery steelhead were sometimes more vulnerable than wild steelhead to Caspian tern (*Sterna caspia*) predation in the Columbia River Estuary. They attributed this to a tendency of hatchery fish to be more surface-oriented than their wild counterparts. If Central Valley hatchery steelhead are more surface-oriented than wild steelhead, the relative abundance of hatchery fish may be overestimated at Chipps since it is a surface trawling program. Determining whether catches at Chipps Island accurately reflect the relative abundance of hatchery and wild steelhead may be the highest priority research question for steelhead in the Delta. If it is determined that Chipps does not accurately depict the relative abundance of hatchery-produced fish, then a monitoring program which does should be developed or a correction factor should be applied.

As suggested by McEwan (2001), the proportion of the population that is hatchery produced has probably increased due to both increases in hatchery production and declines in wild stocks. Hallock and others (1961, as cited in McEwan 2001) reported hatchery fish contributed an average of 12% to the adult Central Valley steelhead population during the 1950s. The Chipps estimate is not directly comparable to Hallock and others' (1961) data since the hatchery and wild smolts may have different survival rates in the ocean. However, bay-ocean mortality of the hatchery fish would have to be substantially higher than wild fish mortality for adult ratios to approach those estimated during the 1950s.

Are life history differences among hatchery and wild steelhead discernible in the available Delta monitoring data?

Hatchery and wild steelhead differ in length, emigration timing, and responses to Delta outflow and water temperature. Although mean lengths of hatchery and wild steelhead were significantly different, interannual length variation was greater, suggesting length differences among hatchery and wild fish may not be ecologically significant. Qualitatively, the length frequencies of wild steelhead appeared to show some multimodality. Multimodality can arise in two ways: (1) from emigration of different age-classes and (2) as a result of growth differences among same age individuals (Shapovalov and Taft 1954). DFG biologists are currently studying this and other life history aspects of Central Valley steelhead.

An interesting observation from the length frequencies of wild steelhead collected at Chipps Island is that no young-of-year (YOY) Central Valley steelhead use the estuary downstream of Chipps. Most YOY steelhead appear to leave the Feather River before summer at sizes <50 mm (B. Cavallo, personal communication). Since these young steelhead apparently do not move into the estuary, it would be interesting to determine whether they find upstream habitats in which to rear or whether they are excess production with little hope for survival.

Hatchery steelhead have an earlier, more peaked emigration than their wild counterparts. Data from the Pacific States Marine Fisheries Commission's Regional Mark Information System database indicate that all coded-wire-tagged Central Valley steelhead released between 1998 and 2000 were released between January 1 and February 17 each year. This suggests the emigration timing of hatchery fish is related to their release date. Since the hatchery fish have never been in a river system before, we speculate they tend to be readily dispersed downstream once outflow increases.

In contrast, wild steelhead did not respond to outflow (Figure 3), which is consistent with Shapovalov and Taft's (1954) observations of wild steelhead in Santa Cruz County. Since outflow does not appear to be a consistent emigration cue for wild steelhead, we suggest wild smolts may use water temperature as a migration cue. Wild smolts emigrated at warmer temperatures than hatchery steelhead (Figure 4), but we do not think this represents a physiological difference among them. It is more likely the wild steelhead were responding to increasing temperature, whereas many hatchery fish were passively transported downstream following their release in January or February.

What factor(s) affect the salvage of hatchery and wild steelhead at the CVP and SWP fish facilities?

On a monthly basis, total export is the best predictor of steelhead salvage at SWP. In contrast, monthly export is a poor predictor of steelhead salvage at CVP. Steelhead salvage at both facilities is correlated. One hypothesis is that increased pumping is associated with increased entrainment of steelhead into the south Delta. Once there, the steelhead are salvaged at both facilities. We do not suggest this is the only mechanism affecting steelhead salvage. Other factors like residence time in the Delta or the specifics of emigration timing from different river basins may also be important.

The assessment of factors affecting steelhead salvage will benefit from additional years of data, which will alleviate the low sample size problem associated with the statistically more defensible months among years version of the analysis (Table 4). With only 4 data points, the salvage-export relationships must be nearly perfect (that is, have an $r^2 \approx 1.0$) to be significant at the standard $\alpha = 0.05$ level. Nonetheless, preliminarily strong ($P \leq 0.10$ with 4 observations) salvage-export relationships for hatchery fish during January through March and wild fish during January through April coincide with their general patterns of emigration (Figure 3).

What percentages of emigrating hatchery and wild steelhead smolts are salvaged at the CVP and SWP fish facilities?

Based on the currently available data, steelhead salvage appears to represent entrainment of < 1% of the estimated numbers of emigrating smolts, but there are several reasons these estimates may be biased low. For instance, there are confounding factors at the facilities like pre-screen loss and louver efficiency. Although the correlation between SWP and CVP salvage does not seem consistent with the hypothesis of significant pre-screen loss across Clifton Court Forebay, pre-screen loss of steelhead should nonetheless be studied. Steelhead screening efficiency at SWP is unknown (J. Morinaka, personal communication), but louver efficiency at the CVP was recently found to be 100% for steelhead smolts (*n* = 22 individuals; L. Hess personal communication). Although this suggests screen efficiencies for steelhead may be high, more study is warranted. In addition to confounding factors at the facilities, our abundance estimate of wild steelhead is sensitive to assumptions about catches at Chipps, including equivalent gear efficiency for hatchery and wild fish and low mortality of hatchery fish upstream of Chipps.

We conclude that fish and water operations managers should not treat hatchery steelhead as surrogates for wild steelhead. In addition, we suggest the following null hypotheses as priority research topics for steelhead in the Delta:

- Chipps monitoring provides an unbiased estimate of the relative abundance of hatchery and wild steelhead.
- There is no difference in Delta residence time among hatchery and wild steelhead.
- SWP and CVP salvage provide accurate estimates of the magnitude of steelhead entrainment into the south Delta.

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References

Brandes PL, McLain JS. 2001. Juvenile chinook salmon abundance, distribution, and survival in the Sacramento-San Joaquin Estuary. In: Brown RL, editor. Contributions to the biology of Central Valley salmonids. Fish Bulletin 179. Sacramento (CA): California Department of Fish and Game. Forthcoming.

Collis K, Roby DD, Craig DP, Ryan BA, Ledgerwood RD. 2001. Colonial waterbird predation on juvenile salmonids tagged with passive integrated transponders in the Columbia River Estuary: vulnerability of different salmonid species, stocks, and rearing types. Transactions of the American Fisheries Society 130: 385-396.

[DWR and USBR] California Department of Water Resources, US Bureau of Reclamation. 2000. Biological assessment: effects of the Central Valley Project and State Water Project Operations from April 2000 through March 2001 on steelhead and spring-run chinook salmon.

Hallock RJ, Van Woert WF, Shapovalov L. 1961. An evaluation of stocking hatchery-reared steelhead rainbow trout (*Salmo gairdnerii gairdnerii*) in the Sacramento River system. Fish Bulletin 114. Sacramento (CA): California Department of Fish and Game.

Kjelson MA, Raquel PF, Fisher FW. 1982. Life history of fall-run juvenile chinook salmon, *Oncorhynchus tshawytscha*, in the Sacramento-San Joaquin Estuary, California. In: Kennedy VS, editor. Estuarine comparisons. New York: Academic Press.

McEwan DR. 2001. Central Valley steelhead. In: Brown RL, editor. Contributions to the biology of Central Valley salmonids. Fish Bulletin 179. Sacramento (CA): California Department of Fish and Game. Forthcoming.

[NMFS] National Marine Fisheries Service. 1998. Final rule: notice of determination. Endangered and threatened species; threatened status for two ESUs of steelhead in Washington, Oregon, and California. Federal Register 63:13347–71.

Shapovalov L, Taft AC. 1954. The life histories of the steelhead rainbow trout (*Salmo gairdneri gairdneri*) and silver salmon (*Oncorhynchus kisutch*) with special reference to Waddell Creek, California, and recommendations regarding their management. Fish Bulletin 98. Sacramento (CA): California Department of Fish and Game.

Notes

Lloyd Hess. (US Bureau of Reclamation). Personal communication with M. Nobriga on

Jerry Morinaka (California Department of Fish and Game). Personal communication with M. Nobriga on

Responses and Recovery in Delta Smelt Exposed to Handling Stress During Fish Treadmill Experiments at Winter Temperature

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Introduction

Young and small native fishes in the Sacramento-San Joaquin Delta system may be vulnerable to more than 2,000 water diversions distributed throughout the Sacramento-San Joaquin Delta system (Herren and Kawasaki forthcoming). Fish screen installation has been identified as a means to reduce direct mortality associated with water diversions. However, screen designs and operations have not been thoroughly tested using the species being protected. Thus, Fish Treadmill experiments are conducted to quantitatively evaluate behavior and performance of selected Delta and riverine species near a fish screen (Frink and others 1998). In any Fish Treadmill experiment, the fish are subjected to stress, including (1) pre-experiment fish collection; (2) transport to the experimental apparatus (Fish Treadmill); (3) release from the transport container; (4) exposure to the 3-m diameter wedge-wire fish screen with 2.3 mm vertical bar spacing in a 62-cm wide swim channel; and (5) collection after the 2-h experiment. This study was conducted to quantitatively measure the stress responses and recovery of delta smelt (6 to 8 cm standard length, SL) subjected to this handling stress at 12 °C. We chose delta smelt (*Hypomesus transpacificus*) because, based on preliminary experiments, they are the most sensitive fish compared to our other priority fish species (splittail, chinook salmon, steelhead, and green sturgeon).

Methods

Delta smelt collected from various sites in the Sacramento-San Joaquin Delta from August to October 1999 were kept at 15 to 17 °C during 10-day prophylactic treatments of nitrofurazone and formalin-malachite green solutions immediately after fish collection. After treatments, fish were acclimated to 19 °C and maintained at this temperature for at least one week before being used in Fish Treadmill experiments in September to November 1999. After having being assessed for injury 48 h post-experiment, the fish were pooled and acclimated to 12 °C in December and kept at this temperature before being used in January 2000 for this study.

Before the start of the experiment (about 0.5 h pre-experiment), four fish were randomly selected (via quick dip-netting) from the pre-experiment tank and sampled through caudal transection. Blood was collected using heparinized hematocrit tubes that were immediately centrifuged for 5 min at 11,500 rpm to separate blood cells from plasma, and percent red blood cells was read using the hematocrit reader. The hematocrit tubes were then scored between the plasma and the blood cells, snapped at the score, and the plasma collected into a freezer vial. After the plasma pH (immersible micro-electrode) was read, the plasma samples were then frozen for later cortisol analyses (ELISA, Munro and Stabenfeldt 1984). After resting samples were taken, 20 randomly selected fish were individually collected with a soft net and a small plastic cup (so the fish were never out of the water) and gently placed into the 20-cm diameter transport container with about 3 liters of water. The fish were then brought to the Fish Treadmill and released from the bottom of the container into the 62-cm wide swim channel with 50 to 60-cm water depth (minimal water flow). Immediately after release four fish were collected for blood sampling. Fish were left in the swim channel and after half an hour, another four fish were sampled. The rest of the fish were left until the end of the 2-h experimental period, at which time another four fish were sampled. Four fish were left in the Fish Treadmill for the half hour post-experiment sampling, and another 4 fish were collected and placed in individual containers. The containers were then placed in a holding tank for the 2-h post-experiment sampling. The experiments were replicated 5 times.

Results

Our results (Figure 1) show that delta smelt mean cortisol and hematocrit levels significantly increased immediately after release into the Fish Treadmill swim channel (0 h post-release) indicating a significant stress response due to pre-experiment fish collection and transport. At 0.5 h after release, delta smelt mean cortisol level peaked indicating additional stress response from release and exposure to the swim channel and the fish screen. However, mean delta smelt cortisol and hematocrit levels decreased after 2-h exposure to the swim channel and the fish screen (0 h post-experiment) to levels that were not significantly different from resting levels, indicating fish recovery from stress within 2 h of exposure in the test channel. At 0.5 h post-experiment, delta smelt mean cortisol level significantly increased indicating that post-experiment fish collection was stressful to delta smelt. However, the second peak's mean value did not reach as high a value as the first peak's mean value. Further, although the 0.5 h post-experiment hematocrit showed an upward trend, it did not significantly exceed the resting value. At 2 h post-experiment, mean cortisol level decreased and was not significantly different from resting level indicating that a 2-h post-experiment period was sufficient for recovery. Throughout the experiment, plasma pH did not change significantly indicating insignificant acidosis, although the lowest mean value occurred after the second handling stress (0.5 h post-experiment).

Conclusions

1. Pre-experiment fish collection and transport elicited significant stress responses in delta smelt at 12 °C.
2. Exposure to the Fish Treadmill swim channel and fish screen may have resulted in additional stress to the fish.
3. Delta smelt recovered from stress resulting from pre-experiment fish collection, transport, release, and exposure to the swim channel and fish screen within 2 hours.
4. Post-experiment fish collection resulted in significant stress responses in delta smelt.
5. Delta smelt recovered from post-experiment fish collection within 2 hours.

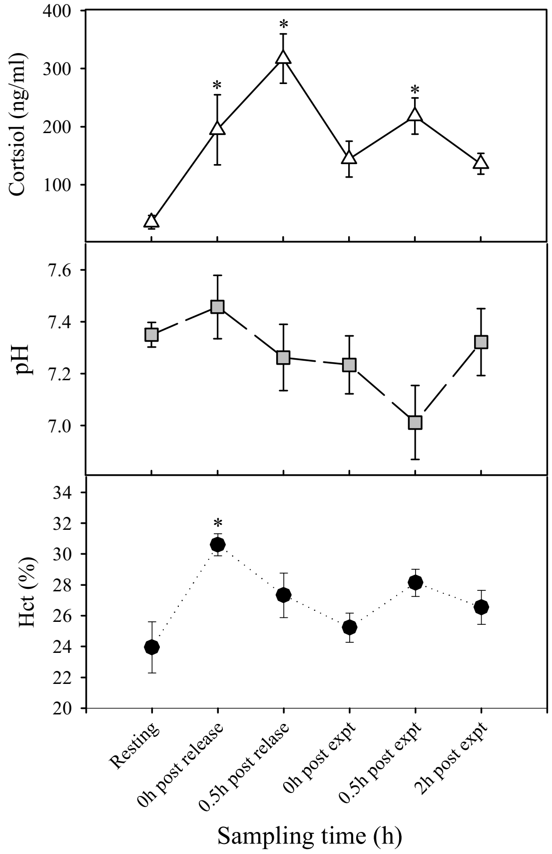

Figure 1 Delta smelt mean (± standard error of the mean) plasma cortisol, plasma pH and hematocrit levels at different sampling times. Asterisk (*) indicates significantly higher than resting level.

Acknowledgements

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S. San Julian (all DFG); N. West, M. Kondratieff, V. Metcalf, J. Andersen, L. Sickafoose, K. Sesser, K. Thorne, E. Hamilton, and K. Kirchner (all UCD).

References

Frink T, Swanson C, Young PS, Fujimura B, Mayr S, Cech JJ Jr, Kavvas ML. 1998. UC Davis fish treadmill investigations update. Interagency Ecological Program for the Sacramento-San Joaquin Estuary. IEP Newsletter 11(4):37–8.

Herren J, Kawasaki S. Inventory of water diversions in four geographic areas in California. In: Brown RL, editor. Contributions to the biology of Central Valley salmonids. Fish Bulletin 179. Sacramento (CA): California Department of Fish and Game. Forthcoming.

Munro CJ, Stabenfeldt G. 1984. Development of a cortisol enzyme immunoassay in plasma. Clin Chem 31:956.

Food Habits of Larval Splittail

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Introduction

Splittail, *Pogonichthys macrolepidotus*, a cyprinid endemic to the Sacramento-San Joaquin Delta, is now listed as threatened by the US Fish and Wildlife Service. The listing process prompted several studies, which have improved our understanding of the relationship between spilttail life history and their environment (Meng and Moyle 1995; Sommer and others 1997; DWR 1998). However, many important aspects of splittail early life history remain unknown. This study was initiated to provide information on the food habits of larval splittail. The objectives were (1) to describe the diet composition; (2) to determine the relative importance of specific prey items; and (3) to identify ontogenetic diet shifts occurring through the larval and early juvenile life stages.

Methods

Larval splittail were collected by the California Department of Fish and Game (DFG) 20-mm Survey and North Bay Aqueduct Larval Survey from February to July 1998 (hereafter, 20-mm and NBA). For the NBA, a 10-minute stepped-oblique tow from bottom to top was made at each station with an egg and larval net (505 micron mesh) mounted on a sled. Sampling stations are located in Cache Slough and some of its tributaries. Samples from the 20-mm survey are collected throughout the Delta in a similar manner, however with a 1600 micron mesh net. More specific information concerning the sampling methods for the 20-mm and NBA surveys can be found online at http://www.delta.dfg.ca.gov/. DFG also collected splittail with light traps on the Sutter Bypass, a floodplain of the Sacramento River. DFG personnel preserved all samples in 10% formalin and performed the larval fish identification.

The standard lengths of 141 preserved larval splittail were measured to the nearest 0.1 mm. Gut content analysis on the larvae was performed by first removing the entire digestive tract. Then, the section from the esophageal sphincter to the first 180° bend was examined. If an intestinal bend had not developed, the entire gut was examined. Contents were identified to the lowest practical taxon. Average prey length was determined by measuring up to ten individuals of each prey type. Dry weight estimates for each taxon were calculated from prey lengths, using regression equations from Sommer and others (2001).

To examine ontogenic diet shifts, larvae were divided into three arbitrary size-classes (≤ 8.9, 9.0 to 14.9, and ≥ 15.0). Diet for each size class was analyzed as an index of relative importance (IRI). The index was calculated as follows: IRI = (percent numeric composition + percent weight composition) x percent frequency of occurrence. Mean prey biomass and the percentage of larvae with empty guts was also calculated.

Results

Gut content analysis revealed that larval splittail fed primarily on cladocerans, (56% of diet by dry weight), chironomid larvae (40%) and copepods (4%). Rotifers comprised less than 1% of the diet by weight. Other items encountered infrequently included diatoms, detritus and terrestrial insects.

Cladocerans (mostly *Daphnia*) were important components of all larval splittail size classes from the Sacramento-San Joaquin Delta (Figure 1). Chironomid larvae became a more important food item as splittail grew, whereas copepods (mostly cyclopoid copepodids) began to disappear from the diet. As larval splittail grew, their guts contained more prey biomass (Figure 2).

Roughly 30% of the larvae examined had no food in their guts (Table 1). The percentage of larvae with empty guts appears to be size dependent, with half (58%) of the empty guts occurring in the smallest size class.

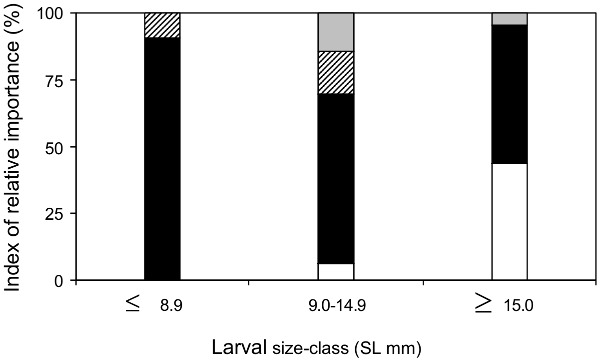

Figure 1 Larval splittail diet from March to July 1998 in Sacramento-San Joaquin Delta. Diet is reported as an index of relative importance (see text). Chironomidae larvae (open bars), Cladocera (solid bars), Copepoda (striped bars) and Rotifera (shaded bars) are displayed for each larval size-class. SL is standard length.

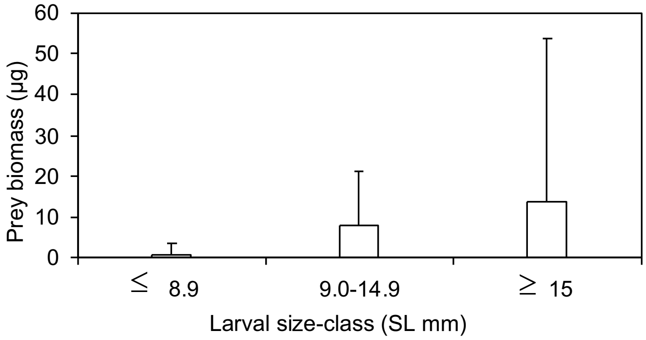

Figure 2 Feeding success of larval splittail from the Sacramento-San Joaquin Delta in 1998. Prey biomass is calculated from the estimated prey weight of gut contents. Mean and standard errors are shown.

Table 1 Percent of empty guts encountered per size-class of splittail larvae collected in the Sacramento–San Joaquin Delta between March and July 1998

Larval size class (SL, mm)	*Empty guts (%)*	*N*
≤ 8.9	50	38
9.0 to 14.9	22	23
≥ 15.0	16	50

Discussion

Diet Composition

Cladocerans and chironomid larvae were the dominant prey type of larval splittail, perhaps as a result of selective foraging or overall abundance. Without appropriate prey abundance data the distinction cannot be determined. Regardless of prey abundance, it appears larval splittail are precocial feeders able to consume a wide variety of prey types and sizes.

Diet Shifts with Larval Size

There was a size-related change in the diet of larval splittail. In general, as larvae increased in size, so did the size of their prey. This was likely a function of prey size and fish morphology, larger mouths enabling larvae to capture larger prey. Ontogenetic diet shifts have been reported for many other larval fish species (Goshorn and Epifanio 1991; Nobriga 1998). In larval cyprinids of the River Great Ouse, England, Garner (1996) found a similar shift from small prey (rotifers and diatoms) to larger cladocerans and chironomids.

There was a decrease in the number of empty guts with increasing size-class. The smallest larvae had higher proportions of small, rapidly digested prey, which may explain the higher frequency of guts without food (Sutela and Huusko 2000). Also small larvae have fewer prey to select from and are therefore more vulnerable to low prey abundances (Gadomski and Peterson 1988). Goshorn and Epifanio (1991) stated that due to possible factors such as inadequate food supply and relatively poorer foraging ability, it is likely younger weakfish larvae were less successful at obtaining food than older larvae.

Acknowledgements

This study would have not been completed if it were not for the valuable contributions of Ted Sommer, Randy Baxter and Zach Hymanson. Special thanks are also owed to the Department of Fish and Game, Central Valley Bay-Delta Branch. Funding was provided by the IEP.

References

[DWR] California Department of Water Resources. 1998. Preliminary results of 1998 Yolo Bypass studies. Prepared by California Department of Water Resources, Environmental Services Office for National Marine Fisheries Service, Endangered Species Division. September 1998.

Gadomski DM, Petersen JH. 1988. Effects of food deprivation on the larvae of two flatfishes. Mar Ecol Prog Ser 44:103–11.

Garner P. 1996. Microhabitat use and diet of 0+ cyprinid fishes in a lentic, regulated reach of the River Great Ouse, England. J Fish Biol 48:367–82.

Goshorn DM, Epifanio CE. 1991. Diet of larval weakfish and prey abundance in Delaware Bay. Trans Am Fish Soc 120:684–92.

Meng L, Moyle PB. 1995. Status of splittail in the Sacramento-San Joaquin estuary. Trans Am Fish Soc 124:538–49.

Merz JE, Vanicek CD. 1996. Comparative feeding habits of juvenile chinook salmon, steelhead, and Sacramento squawfish in the lower American River, California. California Fish and Game 82:149–59.

Nobriga MN. 1998. Trends in the food habits of larval delta smelt, *Hypomesus transpacificus*, in the Sacrameto-San Joaquin Estuary [master's thesis]. California State University, Sacramento.

Sommer TR, Nobriga ML, Harrell WC, Batham W, Kimmerer WJ. 2001. Floodplain rearing of juvenile chinook salmon: evidence of enhanced growth and survival. Can J Fish Aquat Sci 58:325–33.

Sommer T, Baxter R, Herbold B. 1997. Resilience of splittail in the Sacramento-San Joaquin estuary. Trans Am Fish Soc 126:96–76.

Sutela T, Huusko A. 2000. Varying resistance of zooplankton prey to digestion: implications for quantifying larval fish diets. Trans Am Fish Soc 129:545–51.

Fish Assemblage Structure and Associations with Environmental Variables in the Southern Sacramento-San Joaquin Delta

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Introduction

This article presents the preliminary results of a community analysis conducted on data collected as part of the South Delta Temporary Barriers Resident Fishes Monitoring Program. The monitoring program has been funded by DWR and implemented by DFG Bay-Delta since 1992 as part of the mitigation requirements for DWR's South Delta Temporary Barriers Program. This monitoring program was originally started to investigate the effects of the barriers on resident fishes but has developed into a useful tool for describing trends in fish communities of the south Delta. Mike Healey, formerly of DFG Bay-Delta, was instrumental in the collection of these data. I will be working with Mike to publish these results in a journal. My goals for this article are to (1) document faunal composition, including the status of native species, (2) determine the relative importance of environmental variables structuring fish assemblages, and (3) examine spatial and temporal (year-to-year) variation in fish assemblage structure within the south Delta.

Methods

Data Collection

Fishes were sampled in the south Delta over an eight-year period, 1992–1999. Initially, sampling was conducted monthly, April 1992 to November 1995. Thereafter sampling was conducted monthly during the following periods: April–November 1996, March–November 1997, March–October 1998, and March–September 1999. Sampling was conducted at 11 permanent stations: 3 stations each within Old River, Middle River, Grant Line Canal, and 2 stations in the San Joaquin River. The San Joaquin River stations were sampled only during 1992–1995, while all other stations were sampled each year. Each station was sampled by boat (equipped with pulsed AC electroshocking gear) after dusk along bank transects approximately 500 m in length. Each station was sampled at least once per month, except when equipment failed or logistical problems arose. A total of 909 samples was obtained over the study period. All fishes captured were identified to species, measured for fork length (mm), and released alive after sampling was completed. Fish catch data from this study are available in raw form from the IEP website at http://iep.water.ca.gov/.

Four environmental variables were measured each time fish were sampled, water temperature (°C), specific conductance (µS), turbidity (NTU), dissolved oxygen (mg/L). Tidally averaged daily flow (m^3/s) was obtained from the DWR CALSIM Hydrology Model (courtesy of Parviz Nader, DWR) (Table 1).

Table 1 Environmental variable average values and standard deviation (in parentheses) for the four sampling regions in the south Delta, 1992–1999

Variable	*Middle R.*	*Old R.*	*Grant Line Canal*	*San Joaquin R.*
Flow (m^3/s)	5.8 (9.0)	10.2 (14.8)	57.5 (66.22)	104.5 (146.1)
Water temperature (°C)	19.3 (5.1)	18.8 (4.7)	19.1 (4.5)	18.1 (5.3)
Specific conductance (uS)	406 (181)	609 (271)	543 (248)	676 (305)
Turbidity (NTU)	13.8 (11.8)	14.4 (10.4)	17.6 (11.3)	19.5 (17.7)
Dissolved oxygen (mg/L)	7.9 (1.5)	7.6 (1.5)	7.9 (1.4)	8.9 (1.6)

Data Analysis

I used canonical correspondence analysis (CCA) by means of the CANOCO software program (ter Braak and Smilauer 1998) to investigate associations of fish assemblages with environmental variables (Legendre and Legendre 2000). CCA is a multivariate direct ordination technique that extracts synthetic environmental gradients that maximize niche separation within species assemblages, thereby facilitating the interpretation of how species abundances relate to environmental variables. To reduce the influence of rare taxa, I limited the analysis to species that occurred in at least 10% of all samples. Non-transformed species proportional abundance data and all five environmental variables (centered and standardized) for each sample were initially included in the analysis. I used the forward selection procedure with Monte Carlo simulations (199 permutations) to constrain the final model to only included environmental variables significant at $P < 0.05$ (ter Braak and Smilauer 1998).

I used detrended correspondence analysis (DCA) to investigate spatial (location: slough compared to river) and temporal (annual) variation in fish assemblage structure. DCA is an indirect eigenvector ordination technique based upon reciprocal averaging that corrects for the "arch effect" observed in correspondence analysis (Gausch 1982; Legendre and Legendre 2000). Primary gradients within communities are effectively displayed by DCA, and species turnover rates can be inferred by scaling the axes to standard deviation units of sample scores, 50% turnover in species composition occurs over approximately one standard deviation (Gausch 1982). I limited the DCA analysis to data collected from April through September, the only months sampled in all years. Species proportional abundance data were summarized by location and year for this analysis, and as with the CCA, only species that occurred in at least 10% of the total samples were included. I used detrending by segments with the CANOCO software program (ter Braak and Smilauer 1998) and therefore only interpreted scores along axis one of the DCA ordination diagram are ecologically meaningful (Legendre and Legendre 2000).

Results and Discussion

Over the study period, 70,939 fishes representing 33 species were collected (Table 2). Only eight native species were captured, none of which represented greater than 0.5% of the total catch. The most common species were bluegill, redear sunfish, white catfish, and largemouth bass, which comprised over 65% of the total catch, and each occurred in at least 79% of the total samples.

The forward selection procedure resulted in the retention of all five environmental variables in the final CCA model. The first two CCA axes explained a total of 87.9% of the variation in the species environment relation

(71.4% and 16.5%, respectively, Table 3). Inter-set correlations indicated that river flow and water temperature were important gradients for the first two CCA axes (Table 3).

Table 2 Taxa, code, status (I = introduced, N = native), total number, and percent number (if greater than 1%) of fishes captured in the south Delta, 1992–1999

Taxa	*Code*	*Status*	*Number (%)*
Bluegill, *Lepomis macrochirus*	BG	I	19,820 (28)
Redear sunfish, *Lepomis microlophus*	RSF	I	9,521 (13)
White catfish, *Ameiurus catus*	WCF	I	9,088 (13)
Largemouth bass, *Micropterus salmoides*	LMB	I	7,950 (11)
Golden shiner, *Notemigonus crysoleucas*	GS	I	5,393 (8)
Striped bass, *Morone saxatilis*	SB	I	5,043 (7)
Inland silverside, *Menidia beryllina*	ISS	I	4,262 (6)
Threadfin shad, *Dorosoma petenense*	TFS	I	3,589 (5)
Common carp, *Cyprinus carpio*	CP	I	1,726 (2)
Channel catfish, *Ictalurus punctatus*	CCF	I	712 (1)
Yellowfin goby, *Acanthogobius flavimanus*	YFG	I	497 (1)
Chinook salmon, *Oncorhynchus tshawytscha*	CS	N	390
Tule perch, *Hysterocarpus traski*	TP	N	384
Warmouth, *Lepomis gulosus*	WMB	I	313
Sacramento sucker, *Catostomus occidentalis*	SSU	N	278
Goldfish, *Carassius auratus*	GF	I	256
Sacramento blackfish, *Orthodon microlepidotus*	SB	N	238
Black crappie, *Pomoxis nigromaculatus*	BC	I	226
Shimofuri goby, *Tridentiger bifasciatus*	SG	I	192
Brown bullhead, *Ameiurus nebulosus*	BB	I	186
Bigscale logperch, *Percina macrolepida*	LP	I	180
Green sunfish, *Lepomis cyanellus*	GS	I	138
Smallmouth bass, *Micropterus dolomieui*	SB	I	138
Splittail, *Pogonichthys macrolepidotus*	SPT	N	94
Mosquitofish, *Gambusia affinis*	GAM	I	67
American shad, *Alosa sapidissima*	AS	I	63
Prickly sculpin, *Cottus asper*	PS	N	60
Sacramento pikeminnow, *Ptychocheleius grandis*	SP	N	55
Black bullhead, *Ameiurus melas*	BLB	I	43
Fathead minnow, *Pimephales promelas*	FM	I	18
Red shiner, *Cyprinella lutrensis*	RSH	I	13
White crappie, *Pomoxis annularis*	WC	I	4
Steelhead, *Oncorhynchus mykiss*	STH	N	2

Table 3 Summary statistics for the canonical correspondence analysis of fish abundance and environmental variables. Total Inertia = 1.63.

Variable	*Axis 1*	*Axis 2*
Eigenvalue	0.122	0.028
Species-environment correlation	0.601	0.448
Cumulative percentage of variation		
Explained by species only	7.5	9.2
Explained by species & env. var.	71.4	87.9
Inter-set correlations with axes		
River flow	0.361	0.230
Temperature	0.380	-0.331
Specific conductance	0.086	0.111
Turbidity	0.191	0.150
Dissolved oxygen	0.077	-0.054

The ordination plot of species associations with environmental variables (Figure 1) indicated that native species (tule perch and Sacramento sucker) were associated with conditions of increasing river flow and turbidity. Several of the non-native species (most notably striped bass and white catfish) were also associated with increasing river flow, however the majority appeared to be associated with intermediate flow and water temperature.

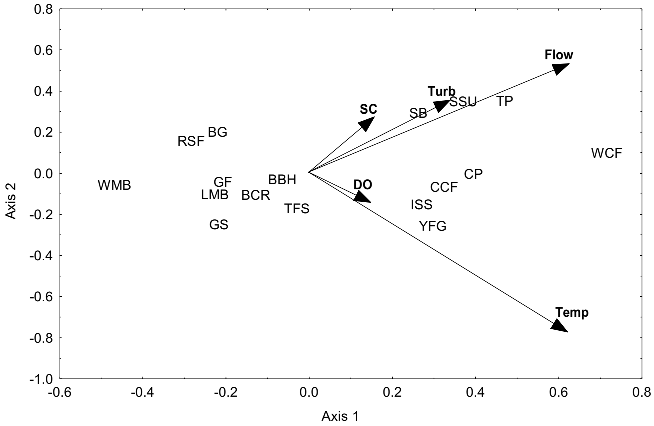

Figure 1 Plot of canonical correspondence analysis showing species scores and the importance of environmental variables (arrows). Species codes as in Table 2. Scores for LMB and GF were moved slightly to make them readable on the plot. Temp = water temperature, DO = dissolved oxygen, SC = specific conductance, Turb = turbidity, Flow = river flow.

The first axis of the DCA ordination analysis explained 45.2% of the variance of the annual fish community data (eigenvalue = 0.23) with a gradient length of 1.6 standard deviation units. Site scores along axis one of the DCA ordination diagram (Figure 2) indicated that variation in fish assemblage structure was greater among locations within years than within locations among years. This suggests fish assemblages were consistently different each year. Site scores suggested fish assemblages within each location were primarily clustered along an environmental gradient of river flow. Locations clustered along a Middle River–Old River–Grant Line Canal–San Joaquin River gradient every year. The greatest separation among locations was between the San Joaquin River and the three other sloughs. Species scores also suggested locations clustered along an environmental gradient of river flow (Figure 2, bottom). Species shown to be associated with river flow by CCA were clustered in the same region of the DCA plot as the locations with the highest river flow.

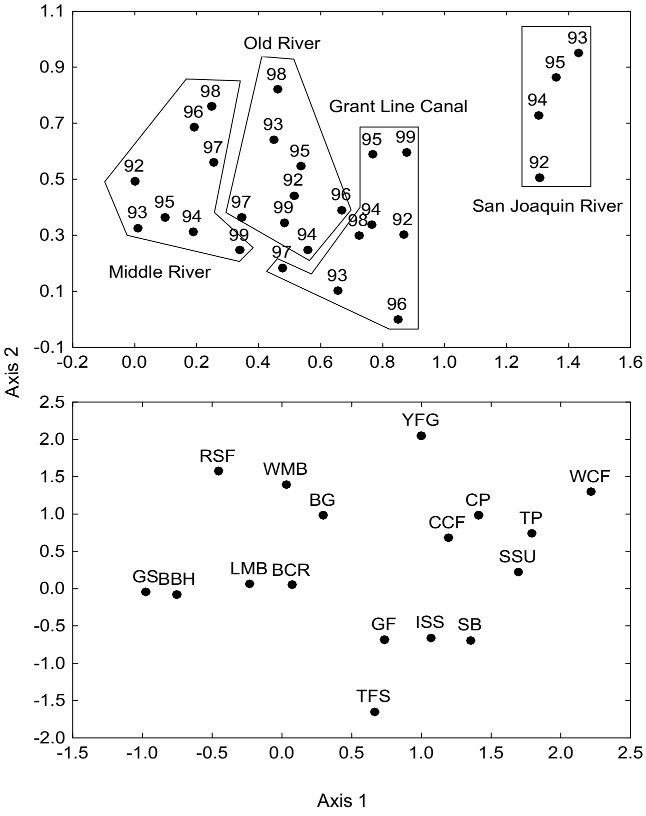

Figure 2 Plot of detrended correspondence analysis showing site scores (top) and species scores (bottom) along the first axis. Site scores are coded by year and are enclosed to facilitate interpretation. Species codes as in Table 2. The scales are different in each diagram to facilitate interpretation.

In summary, spatially distinct locations in the southern Sacramento-San Joaquin Delta were sampled over an 8-year period, 1992–1999, to characterize fish assemblages and their associations with environmental variables. Fish assemblages were primarily structured along environmental gradients of river flow and water temperature. Native fishes were most abundant during conditions of increasing river flow, while non-native fishes were most abundant primarily during conditions of moderate water temperature and river flow. Variation in fish assemblage structure was greater among locations within years than within locations among years, which suggested fish assemblages were consistently different each year. Differences in fish assemblages among locations were consistent with differences in river flow among the locations.

References

Gauch HG. 1982. Multivariate analysis in community ecology. Cambridge: Cambridge Univ Pr.

Legendre P, Legendre L. 2000. Numerical ecology. Developments in environmental modelling, 20. Elseveier Science.

ter Braak CJF, Smilauer P. 1998. CANOCO reference manual and user's guide to CANOCO for Windows: software for canonical community ordination (version 4). Ithaca: Microcomputer Power.

CALFED CORNER

Science and the CALFED Bay-Delta Program's Environmental Water Account

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Science Program's Oversight Role

The CALFED Science Program is responsible for developing and using performance measures for the Environmental Water Account (EWA), giving advice about technical aspects of day-to-day operations (including special circumstances when "Tier 3" water may be used), and evaluating the overall effect of the program.

Science Program's Oversight Goals

The Science Program's goals for oversight of the EWA are to (1) contribute to open dialog between scientists, managers, and stakeholders; (2) incorporate external scientific advice, scientific review, and aspects of adaptive management into the EWA process; (3) develop information that will continuously improve and expand upon the knowledge base used by resource managers; (4) provide unbiased feedback about measurable responses associated with flow and/or operations changes; and (5) provide an annual, broad evaluation of EWA relative to its original goals.

These oversight goals do not include judgments about whether the EWA is a policy failure or success, or whether the science used in EWA is good or bad. The political success of the EWA program is ultimately a decision that rests with the CALFED Policy Group.

Oversight Strategy

The strategy to achieve the oversight goals uses two questions as focal points:

- What measures will allow us to evaluate the (a) environmental benefits and (b) the supply reliability benefits of EWA activities annually, over multiple years, and over decades?

- How do we incorporate scientific review and adaptive management into the operations planning and implementation of the EWA?

Formulating answers involves different mixes of expertise, analysis and synthesis, different time frames, and several iterations of review. The process depicted in Figure 1 accommodates different needs, while maintaining connections between the people working on different aspects of scientific oversight.

There are two concurrent processes (Figure 1). In an annual process, resource agency biologists and water operations managers (the Water Operations Management Team or WOMT) develop plans for acquiring, storing, conveying, and using EWA water. As more or less water becomes available and as endangered fish species move into vulnerable reaches, agency staff make decisions about EWA water, such as how much, where and when to use it. This work takes place within short time schedules and is based on professional knowledge developed by interagency staff. The Science Program has contracted two senior scientists (EWA Advisors) to work collaboratively with the WOMT biologists to document the rationale for water use, facilitate the transfer of information among scientists involved in the EWA, and advise effective use of science in the EWA process. The work of the advisors is designed to foster adaptive management and integrate scientific review into the day-to-day activities of the program. In addition, at the end of every year, the plans, decisions, and their effects will be reviewed by an independent panel of scientists (Delta Science Panel). The panel is chosen and convened by the Lead Scientist, who will set the scope for their review.

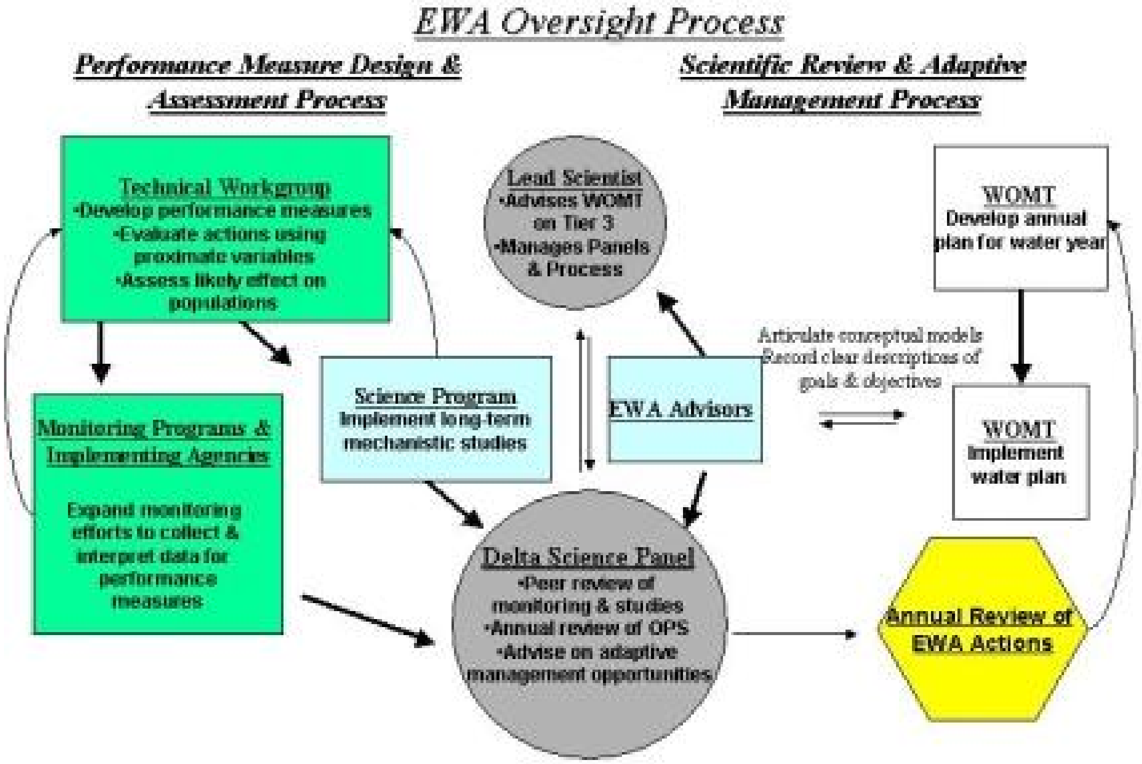

Figure 1 EWA oversight process

The second process (left side of the diagram) focuses on measuring the environmental and water supply benefits associated with flow and/or operational changes effected by use of EWA assets. These measures will ultimately be used to assess EWA performance.

Two groups of agency and independent scientists (the Technical Workgroup), are charged with identifying what kinds of ecosystem responses to changes in flow and/or operations we can currently measure with confidence and what research we now need to develop better metrics to capture more subtle and longer-term effects. One group is focusing on delta smelt and changes in exports and Delta flows; the second group is focusing on salmonids. Biologists within WOMT are working simultaneously on similar questions. The Science Program and the senior advisors help facilitate communication between the groups. When the workgroups have finished analyzing existing data, they will forward their analyses and recommendations for monitoring and research to the Lead Scientist. After peer review the Science Program will work with existing monitoring programs to implement the monitoring recommendations and initiate a call for proposals for the recommended research.

Thus, outside scientific advice and review plays a critical role in EWA by

- linking the two processes;
- ensuring that decisions, conceptual models, and working hypotheses are clearly articulated before annual peer reviews happen (Working Advisors);
- facilitating open lines of communication among agency scientists;
- expressing information needs and defining research strategies;
- identifying where existing information may help test working hypotheses;
- initiating research that will specifically test working hypotheses; and
- evaluating the overall technical activities and outcomes of EWA activities.

Details about the processes, the scientists involved, the status of work underway, and preliminary schedules for workshops and reviews are described in the following sections.

Performance Measure Design and Assessment Process

Ecological Measures

Although it is widely accepted that restoration of fish populations (especially species of concern) is the ultimate goal of EWA and other "environmental water" programs (for example, "b(2)" water under the CVPIA)[1], realistically, many populations will either take a decade or so to respond, or it will take a decade of data to recognize a response. However, there may be biological responses that are sensitive to short-term changes in flow and potentially indicative of longer-term population changes. There are probably also physical, chemical, and perhaps biological responses that will be indicative of whether flow and operational changes are making a difference.

The Science Program has formed a working group of agency and academic scientists to help design and implement performance measures for environmental water use. The Technical Workgroup is charged with collaborating with the scientific community to

- develop measures of EWA effects based on existing data;
- recommend studies that may yield new measures through focused, short-term research;
- evaluate EWA actions and the degree to which this evaluation is possible using proximate variables; and
- assess the likely effect of environmental water use on the variables we are ultimately concerned about (such as fish population size).

An important goal is to have the most robust data and information available before the 2005 program evaluation. To that end, the Science Program is seeking help from the Technical Workgroup to implement monitoring and studies supporting simple performance measures quickly while work continues on the longer-term measures.

Technical Workgroup Members

Organizer: Dr. Bruce Herbold, US EPA

Delta Subgroup

Dr. Cathy Lawrence, UCD
Kevin Fleming, DFG
Dr. Mike Chotkowski, USBR
Chris Enright, DWR
Jon Burau, USGS
Zach Hymanson, DWR
Mike Fris, USFWS

Watershed Subgroup

Dr. Tim Horner, CSUS
Erwin Vanniewuwenhuyse, USFWS
Dr. Mike Chotkowski, USBR
Beth Campbell, NMFS

The Technical Work Group is organized as two subgroups. One subgroup is focusing on delta smelt and changes in distribution, abundance, and salvage. The second subgroup is focusing on conceptual models for salmonids and water use in the upper watersheds. We expect the workgroups will provide a combination of detailed analyses of existing data, suggestions for detailed adaptive management studies of environmental water use in specific locations, and recommendations for research to test working assumptions or build knowledge about environmental processes. The CALFED EWA and Watershed Programs, the VAMP, and AFRP are seeking similar opportunities and are natural partners for experiments. In keeping with standard

General Questions Posed to the Technical Workgroup

1. What physical and chemical features will change in response to shifts in exports and flows?
2. What physical and chemical features may be good proximate variables for biological responses?
3. How do the direct impacts of the projects affect abundance and distribution of different life stages of the species of concern?
4. What are the trade-offs between using EWA for different species at different times and places?

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[1] The Science Program will not be distinguishing between different kinds of environmental water in the process of designing performance measures and evaluating system responses. Once the system responses are known and related to quantity and timing of flow and operational changes, the relative benefits of different kinds of environmental water can be calculated.

practice, the Science Program will have these products peer reviewed.

Supply Reliability Measures

Supply reliability performance measures, like those associated with environmental responses, must also be defined for the EWA. The Science Program has retained a consultant to examine the full range of definitions of reliability. These will include considerations of hydrologic variability, operational reliability of the water delivery system, new flexibility in the supply structure created through system interties, planned storage, water marketing, and changes in the overall flexibility of the system resulting from a combination of avoided demand through water conservation and increasing flexibility of the delivery system. Like the Technical Workgroup, the consultant will review, analyze, and compare existing reliability information and metrics, along with reviewing metrics used in other industries and situations. The consultant will make recommendations to the Science Program about the design of supply reliability performance measures and basic data needed to support them. These recommendations also will undergo peer review.

Scientific Review and Adaptive Management Process

The Science Program's strategy for incorporating adaptive management into the EWA on a day-to-day basis is to place senior scientists in roles that form a bridge between the management and scientific communities (EWA Advisors) and to organize an annual peer review of the EWA (Figure 1).

Current Focus of the Delta Subworkgroup

- Building conceptual models outlining mechanistic relationships between salvage at the export facilities, delta smelt abundance, and hydrologic conditions (tidal, San Joaquin flows, etc.)
- Exploring the relationships between delta smelt distribution and abundance, hydrodynamics and water quality using existing datasets.

EWA Advisors

The Scientific Program's charge to the EWA Advisors is to

- Collaborate with management agency biologists to clarify the state of scientific and professional knowledge regarding the goals, objectives, and effects of environmental water use, and associated conceptual models and working hypotheses;
- Collaborate with resource agency engineers and CALFED EWA program staff to maintain a balanced, clear record of actions and justification;
- Facilitate information flow between the Technical Workgroup and the WOMT;
- Advise WOMT, the Lead Scientist, and the Technical Workgroup about needs for new science and opportunities to implement adaptive management; and
- Provide information to the panel conducting the annual review (Delta Science Panel).

The Advisors provide a critical link between agency scientists responsible for managing special status species and the scientific community. Their roles complement the tasks undertaken by the Technical Workgroup and the peer reviewers.

The Annual EWA Peer Review

The final piece of the EWA oversight process is the annual peer review. This will take place each year near the end of the water operations cycle but before the development of the next year's EWA plan (November 1). The first peer review panel meeting has been tentatively scheduled for the third week in October 2001. The purpose of this review is to provide

- unbiased feedback on any measured responses associated with flow or operations changes;
- peer review of the conceptual models, synthesis papers, and data analyses conducted or used during the year;

- recommendations on approaches for advancing knowledge in key areas, including performance measures and testing key working assumptions;
- an opportunity to highlight new knowledge developed by the Technical Workgroup and other researchers;
- recommendations on the institutional design of the EWA; and
- an opportunity for the WOMT to identify key information needs.

The Science Program and the WOMT share responsibility for the annual peer review. The Lead Scientist will organize an evaluation panel comprised of scientific experts who represent a balance between those with detailed knowledge about the Delta and water operations and outside scientists who can bring experiences and knowledge from other areas to bear on local questions. The Lead Scientist will also design the overall charge to the panel and specific questions for different experts.

WOMT and CALFED EWA staff is responsible for providing written information for panel members before the review meeting. Those written reports should include documentation about decisions to buy and use water, the rationale behind each decision, conceptual models, goals, and objectives linking use of the water to environmental benefits, and summaries of the state of knowledge that inform EWA decisions. These documents, along with other supporting information such as a water gaming exercise and feedback directly from the EWA Advisors, must be available to the panel no later than mid-September.

Sample Issues
Collaboratively Addressed by WOMT Biologists and EWA Advisors

- Justification for individual EWA actions
- Adult salmonid population trends and working hypotheses of factors driving observed trends
- Description of how production estimates are calculated
- Description of the basis for take limits and derivation of take numbers
- Ocean conditions and effects on escapement
- Discriminating between races of juvenile salmon

CALFED & IEP Delta Smelt Workshop Planned for September

Randy Brown, (DWR, retired)
rl_brown@pacbell.net

CALFED and the IEP are organizing a delta smelt workshop for September 7, 2001, at a site to be announced. Zach Hymanson (DWR) is working with DFG's Kevin Fleming to develop an agenda. The CALFED contact person is Lenny Grimaldo and he can contacted at lgrimald@water.ca.gov for more information. Since seating will be limited, attendance at this workshop is by invitation only.

Although the agenda is under development, the workshop is expected to cover delta smelt protection through CALFED's Environmental Water Account, conceptual models of delta smelt life history and research and monitoring needs. I will be preparing a workshop summary report for the CALFED Science Program and for distribution to interested parties. An abbreviated summary will likely be in the fall issue of the *IEP Newsletter.*

Droughts, Epic Droughts and Droughty Centuries—Lessons from California's Paleoclimatic Record: A PACLIM 2001 Meeting Report

Michael Dettinger (USGS), mddettin@usgs.gov

During the early 1990s (but echoing studies by S.T. Harding at the University of California, from as early as the 1930s), several lines of paleoclimate evidence in and around the Sierra Nevada Range have provided the water community in California with some real horror stories. By studying ancient tree stumps submerged in Lake Tahoe and Tenaya Lake, stumps that were emerging from Mono Lake during its recent decline, and stumps that were exhumed in the Walker River bed during the floods of 1997, paleoclimatologists like Scott Stine of California State University, Hayward, assembled a picture of epic droughts in the central Sierra Nevada during the medieval period. These droughts had to be severe to drop water levels in the lakes and rivers low enough for the trees to grow in the first place, and then had to last for hundreds of years to explain tree-ring counts in these sizeable stumps. Worse yet, the evidence suggested at least two such epic droughts, one ending close to 1100 and the other close to 1350. These epic droughts challenged paleoclimatologists, as well as modern climatologists and hydrologists, to understand and, ultimately, to determine the likelihood that such droughts might recur in the foreseeable future. The first challenge, however, was to verify that such droughts were more than local events and as extreme as suggested.

At this year's Pacific Climate (PACLIM) Workshop, held March 18–21, 2001, at Asilomar (Pacific Grove, Calif.), special sessions brought together scientists to compare paleoclimatic reconstructions of ancient droughts and pluvial (wet) epidodes to try to determine the nature of decadal and centennial climate fluctuations in western North America, with emphasis on California. A companion session brought together modern climatologists to report on the latest explanations (and evidence) for decadal climate variations during the instrumental era of the 20th century.

PACLIM is an annual workshop that, since 1983, has brought together specialists from diverse fields, including physical, social, and biological sciences, to discuss and investigate climate and climate effects in the eastern Pacific and western America. This year's PACLIM was sponsored by the U.S. Geological Survey, NOAA Office of Global Programs, California Department of Water Resources, and, for the first time, the CALFED Science Program. In addition to the presentations summarized here, sessions at this year's PACLIM covered topics as varied as the North American monsoon system; recent economic and political effects of California's climate variations, including a presentation on climate and CALFED by Sam Luoma (U.S. Geological Survey, Menlo Park); and research into daily-to-seasonal weather variations. Information about this year's and next year's meetings can be found at http://meteora.ucsd.edu/paclim/.

Prehistoric Droughts and Floods

Recent developments and comparisons of paleoclimatic time series from a variety of sources and settings in the California region were an important focus of this year's PACLIM. Sediment layers from the offshore Santa Barbara Basin and Gulf of California; isotopic, chemical, and paleomagnetic signatures in cores from Pyramid Lake in northwestern Nevada; and tree rings from numerous locales around the western states—along with many other paleomarkers from ocean sediments, marshes, and lakes, and other sources—were analyzed to develop high-resolution paleoclimate reconstructions (often cataloging year-by-year climate variations). The overall picture of decadal and centennial climate variations in California during the last several millenia that emerged from comparison of these various reconstructions is that long-term decades to centuries-long excursions of California's climate, and in particular, of its precipitation regimes, have indeed occurred in the not-too-distant past (for example, during medieval times).

For example, Larry Benson (USGS, Boulder, Colo.) reported that major oscillations in the water balance of Pyramid Lake have occurred irregularly but, on average, about every 150 years during the last 8,000 years. Among the paleodroughts that affected the lake were the medieval epic droughts inferred elsewhere in the Sierra Nevada. A major relocation of Anasazi populations in the Four Corners region occurred in the middle of the second of these prolonged droughty periods, which took place in the 1280s. Numerical simulations of the lake's water balance (as inferred from the geochemical variations in its sediments) suggest extended droughts could have involved greater than 30% reductions in the wetness of the Sierra Nevada, on average, over multidecade and even century time scales. Remarkably close, but quite independent, corroboration of many of these paleoclimatic changes came from Douglas Kennett's (California State University, Long Beach) report on the formanifera and geochemistry of ocean sediments from the Santa Barbara Basin. The Santa Barbara Basin sediments indicate important sea-surface temperature variations along the California coast over the last several thousands of years that coincided with droughts and wet periods identified far inland in White Mountains bristlecone tree rings. Malcolm Hughes (The University of Arizona Laboratory of Tree-Ring Research) used new precipitation-sensitive tree-ring reconstructions, each over 1,000 years long, from around the West to show long-term droughts in exquisite detail. In the Southwest, the 1950s drought ranked as probably the most extensive intense decadal-scale drought in the last 1,000 years, but closer to home, the medieval droughts (especially the later one) was clearly evident in the tree rings. Similarly, Lisa Graumlich (Montana State University) found evidence of persistent (but not unbroken) drought conditions in 1,000-year tree-ring reconstructions from the Greater Yellowstone Region. David Meko (The University of Arizona Laboratory of Tree-Ring Research) and others showed evidence that the epic medieval droughts coincided with wet intervals farther north in Oregon, perhaps indicating persistent reroutings of storm tracks to the north of California during the drought periods.

Each of these climate reconstructions also included sustained, wetter-than-normal intervals of durations comparable, in some cases, to the epic droughts. Ominously, several of the climate reconstructions presented showed that the 20th century has yielded fewer droughts in California than in previous centuries. At the wet hydrologic extreme, past megafloods in coastal southern California were inferred from distinctive clay-rich layers in the Santa Barbara Basin. Megafloods occurred in 212 AD, 440 AD, and 1418 AD, and 1650 AD, according to Arndt Schimmelmann (Indiana University). To put these episodes in perspective, Schimmelmann noted that historical wet years have left no signs comparable to these prehistoric megafloods.

Overall, the intercomparisons of paleoclimate reconstructions presented at the workshop suggest epic droughts (decades and centuries long) did afflict central California during the last several millennia, including, in particular, the medieval droughts. The drought periods were vastly longer than we have experienced, but not necessarily more severe than historical droughts. There are tantalizing suggestions of almost periodic recurrences of some of the inferred droughts, with periods ranging from 20 to 150 years and more. The general consensus from the PACLIM Workshop, was that these droughts should not be envisioned as unbroken spells of uninterrupted dryness, but rather as extended intervals during which droughts were significantly more common. The "six-year" drought in California during the late 1980s and early 1990s may provide a much reduced model for such droughts; that drought was broken by a year of normal wetness at its midpoint and occurred despite year-to-year changes in the large-scale climate state (for example, El Niño conditions, La Niña conditions, and in-between conditions prevailed at various times during the course of this event). Thus it may be best to imagine that the epic droughts corresponded to long intervals with greater-than-normal propensities towards drought in California, quite possibly with droughts more persistent than usual. Thus these dry intervals probably reflect prolonged shifts to more droughty conditions rather than single "continuous droughts." Finally, Malcolm Hughes concluded that the various paleorecords presented at this year's PACLIM, along with many others, are now mature enough to support a major case study of one or both of the medieval droughts in far greater detail than has previously been possible. A wide range of paleoclimate indicators from the entire western North American region can now be brought together to provide constraints on the conditions, spatial extent, and persistence of those droughts, as well as compare these paleodroughts. Such comparisons would provide a much clearer depiction of epic droughts in California than is possible in a single workshop.

Modern Decades-long Climate Fluctuations

In an attempt to understand the climate mechanisms that might drive such long-term fluctuations, particularly in the Pacific Ocean basin and western Americas, several climatologists were asked to present some of the most recent views of decadal climate processes in the Pacific. Michael Evans (Harvard University) and Mark Lyford (University of Wyoming) used regional syntheses of paleoclimatic reconstructions to argue that the paleoclimatic versions of decadal and centennial climate variations form climate patterns that are recognizable in the modern climate system. Evans argued, in particular, that paleoclimatic reconstructions of decade-scale El Niño-Southern Oscillation (ENSO)-like climate variations show much the same pattern as that associated with current ENSO-like variations; furthermore, those variations are so symmetric around the equator in the Pacific Ocean basin that they must be of tropical origins. David Pierce (Scripps Institution of Oceanography) and Matthew Newman (Climate Diagnostics Center, Boulder, Colo.) used climate-model simulations and the last century of records of year-to-year and decadal climate variations to draw much the same conclusion: the decadal variations of Pacific, and thus western North American, climate witnessed during the last 50 years are driven by slow variations in the chaotic evolution of tropical Pacific ENSO episodes, with some amplification of the decadal parts by the long, slow responses of the extratropical Pacific Ocean to those year-to-year ENSO variations. In this view of the decadal variations of the Pacific climate, the decadal (and longer) climate spells are artifacts of slowly varying but essentially random variations of the global climate, termed "red-noise climates." The conclusions of these speakers reflect a growing belief among many climatologists that the so-called Pacific Decadal Oscillation (PDO) has its roots in the tropics, rather than reflecting independent climatic oscillations from the extratropical North Pacific. The PDO remains an interesting index to correlate to and reconstruct back through time; however the predictability of the PDO is limited.

Others at the workshop, notably David Keeling (Scripps Institution of Oceanography) and Alan Hunt (Pacific Northwest Laboratory), were more inclined to explain the long-term climate variations in terms of slow "external" forcings, like tidal mixing of the deep ocean, solar-irradiance variations, or greenhouse gas accumulations. At this workshop, the least popular among explanations of decadal climate variations were various, previously proposed extratropical ocean-air mechanisms. The chaotic-tropics versus external-forcings camps continue to debate the sources of decadal to centennial climate variability as this article is published (and probably for a long time to come).

Summary

This year's PACLIM Workshop presented a picture of California's long-term climatic history that includes significant epic "droughty" periods spanning hundreds of years, with water balance deficits as large as any we have suffered historically. Wetter-than-normal periods have also persisted at times in California prehistory, and extremely large floods during the last 2,000 years occasionally have left their marks offshore. Although competing plausible explanations for the origins of California's long decadal to centennial paleoclimate variations have been offered, the origins remain uncertain—especially since it is not clear that we have ever seen even mild versions of this form of climate variation in our time in California. As a result, our ability to predict the recurrence of such disasters is minimal. We can, however, advise that such events have happened before and thus may happen again.

ANNOUNCEMENTS

Dan Odenweller: Stepping off the Treadmill

By Randy Brown

Last month Dan Odenweller, DFG's fish screen expert for the past three decades or so, effectively retired from State service. Although he will officially be on the payroll for the next few months, Dan will be using accumulated vacation hours and will rarely be seen in the office.

I first worked with Dan in the late 1970s on fish screen clogging and cleaning studies designed to help construct and operate a peripheral canal. We were then challenged to come up with a conceptual design for the entire screening facility with Dan handling the biological side and DWR working mainly on the engineering aspects. Although in 1982 voters decided against the canal, the work he led as chair of the Interagency Fish Facilities team has been invaluable in helping design other screens and in shaping the current thinking about new screens for the federal and State south Delta intakes.

After 1982, under Dan's direction the Delta fish facilities program focused on some very tough issues surrounding operation of the State Water Project's John E. Skinner Fish Protective Facility. His staff conducted studies on fish losses to predators in Clifton Court Forebay and in the intake channels as well as losses during the salvage process itself. This information has been used to develop more fish friendly operational procedures, as the basis for DWR's 4-pumps mitigation agreements, salmonid and delta smelt take limits and to consider water allocation pursuant to CALFED's Environmental Water Account. He was also actively involved in successfully pushing for construction and testing of a fish treadmill at UC Davis to help evaluate fish responses to screens.

Lately Dan has been actively working with CALFED, the individual water agencies and stakeholders to plan for even more fish friendly intake facilities in the south Delta. These facilities could result in a complete rescreening of both intakes. The costs, perhaps approaching one billion dollars, and benefits to fish require that the facilities be carefully thought out before proceeding.

In talking to Dan at the recent salmonid EWA workshop, it appears that he is considering remaining active in the local fish facilities arena. I hope he does in that it is rare to find his combination of intimate knowledge (from the 1960s when John Skinner and Herb Hyde first studied the DWR intake), dedication and biological insight. In any event, I am sure I speak for the bay/delta community in thanking Dan for all his efforts and wish him well in retirement—or hopefully—semi-retirement.

A Call for Comments on New Estuarine Research Federation Affiliate Bylaws

Randy Brown (DWR, retired), rl_brown@pacbell.net

For several months now Wim Kimmerer, Fred Nichols, and I have discussed the formation of the California Estuarine Research Society (CERS). This society would be the newest affiliate of the Estuarine Research Federation. We have announced it at meetings, published a brief IEP newsletter article about it, and discussed it with several members of the California coastal and estuarine research community.

Now it is time to take the next step. We offer proposed bylaws for your review. Please find them at Wim's website, http://online.sfsu.edu/~kimmerer. Send any comments to Wim at kimmerer@sfsu.edu with courtesy copies (cc) to Fred Nichols at fnichols@pacbell.net and me at rl_brown@pacbell.net.

We will accept any and all comments and incorporate them where we can. Once the bylaws have been completed, we will incorporate the society and solicit membership. We would like to finish this process, hold society elections, set up a membership process and a web page, and petition ERF for affiliate status in time to announce all this at the November ERF meeting in Florida.

DELTA WATER PROJECT OPERATIONS

Kate Le (DWR), kle@water.ca.gov

From April through June 2001, San Joaquin River flow ranged between 43 and 142 m^3/s (1,500 and 5,000 cfs), Sacramento flow ranged between 198 and 397 m^3/s (7,000 and 14,000 cfs), and the Net Delta Outflow Index (NDOI) ranged between 198 and 595 m^3/s (7,000 and 21,000 cfs) (Figure 1). NDOI peaked in early and mid-April due to precipitation and export reductions. Reductions from both projects were for Vernalis Adaptive Management Program (VAMP) action, which usually begins sometime in April and lasts for about one month. The increase in San Joaquin River flow from mid-April through mid-June was a result of VAMP action.

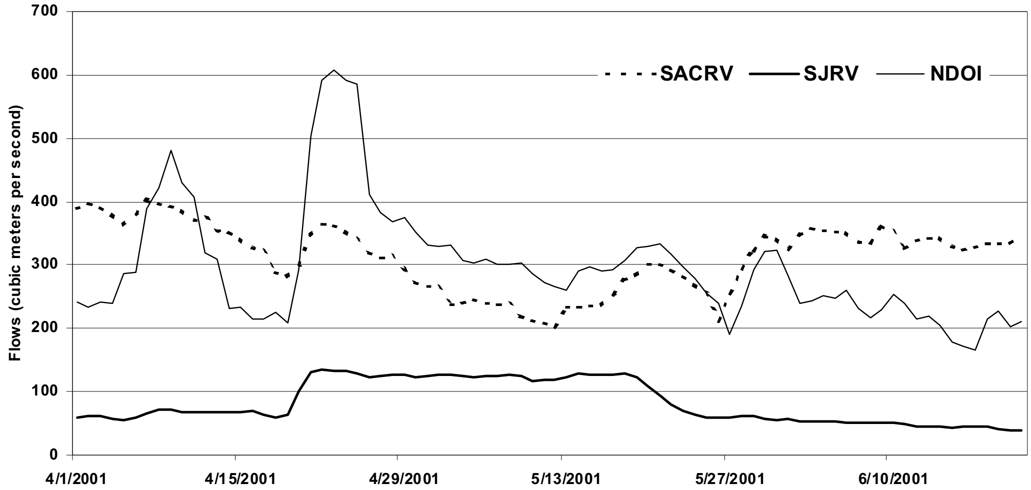

Figure 1 April through June 2001 Sacramento River, San Joaquin River, and Net Delta Outflow Index

Export reductions at both projects in early April were due to maintenance at the CVP and fish protection action at the SWP as shown in Figure 2. Both projects curtailed exports in mid-April through mid-May for VAMP. CVP exports increased in early June whereas SWP remained low due to higher delta smelt salvage. Additionally, the Environmental Water Account (EWA) was used to ensure the SWP pumping remained low for fish protection. From June 12 through the end of June, SWP pumping was shut down to repair an aqueduct leak.

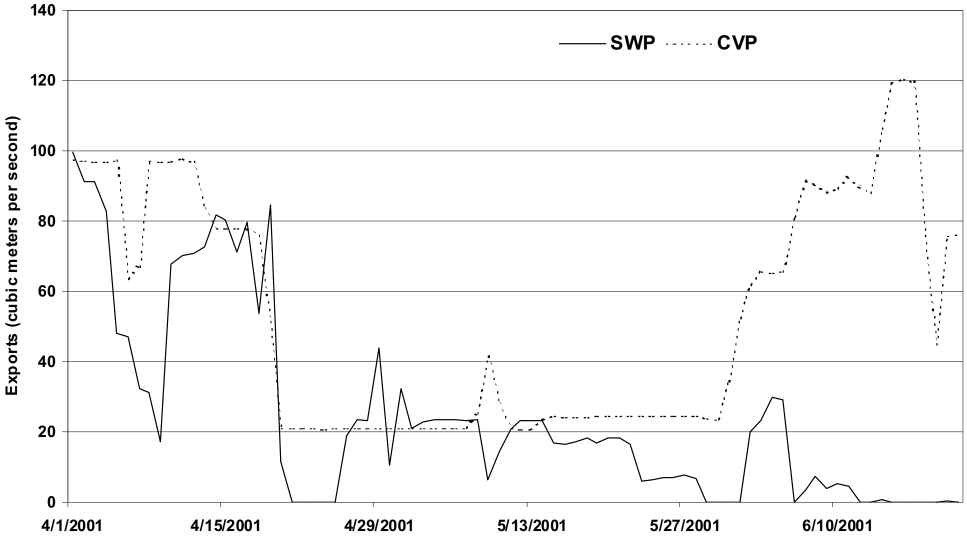

Figure 2 April through June 2001 State Water Project and Central Valley Project exports

■ Interagency Ecological Program for the San Francisco Estuary ■

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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.

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US Fish and Wildlife Service
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