■ Interagency Ecological Program for the San Francisco Estuary ■

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■

Of Interest to Managers

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As part of our goal to provide timely information to managers, the winter 2006 issue of the IEP newsletter includes new survey information on sturgeon, a species of recent concern in the estuary. Marty Gingras' Quarterly Highlight reports that recent white sturgeon abundance estimates are 8,000-17,000 adults, dramatically lower than peak levels of 142,000 adults less than a decade ago. This decline already has resulted in a rapid response from DFG including changes in fishing regulations and management actions such as increased efforts on poaching enforcement.

Managers may also be interested to learn that studies by IEP's Yolo Bypass research program recently discovered a new invertebrate species in the floodplain. The Yolo Bypass project had already revealed that the floodplain is an important "food bank" for the estuary, providing good rearing habitat for native fishes. The new study focused on chironomids, a group of flies (midge) that represent one of the most important food sources for young fish in the estuary. The Yolo Bypass team reports that a never-before-described species dominates the invertebrate drift during flood events. The identification of the new chironomid species was made by Dr. Peter Cranston, one of the world's experts on this taxonomic group.

One of the feature articles in the winter 2006 newsletter is an analysis of fish facility salvage data by Zach Hymanson and Larry Brown. Their objective was to evaluate the whether recent Environmental Water Account (EWA) efforts during spring helped to reduce entrainment losses of delta smelt. Their exhaustive analysis concluded that EWA-funded export curtailments during the spring ("VAMP shoulder period") reduced losses of delta smelt. Their report includes a synthesis of the factors that cause extreme numbers of smelt to be collected at the State Water Project screens. Hymanson and Brown hypothesize that seasonal outflow, water temperature, and spawning distribution patterns are key factors that set the stage of major entrainment events.

Two articles by FWS staff provide an update on efforts to improve sampling methods for Delta fishes, and to synthesize IEP monitoring data. The major findings of their studies included the following: 1) current daytime trawling efforts may underestimate salmon migration during periods when many fish are moving at night; and 2) trawl and beach seine data suggest that autumn Delta fish assemblages have been relatively consistent since 1995.

Dr. Inge Werner and colleagues report efforts to rear an invertebrate, the estuarine amphipod Gammarus, in the laboratory. The goal was to determine whether this local species could be used in bioassays to test the toxicity of Delta sediments and water samples. Dr. Werner's study collected key information about the laboratory requirements of the species. They concluded that the amphipod is a promising species for toxicity testing.

IEP QUARTERLY HIGHLIGHTS

DAYFLOW Update 2005

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The DAYFLOW database has been extended to include water year 2005. Below are highlights of this year's effort:

•A preliminary 2005 DAYFLOW data set was provided to the Pelagic Organism Decline (POD) group in early October 2005. Several minor Delta inflow data sets were not included in the Delta outflow estimate at that time because data had not yet been received from data collectors.

•This year's DAYFLOW output was delayed due to slow provision of flow data from some data collectors. The DAYFLOW process includes requesting and receiving the official flow station input data from responsible agencies before flow estimates are computed. The stations and responsible agencies that provide flow data for DAYFLOW estimates are listed below:

- USGS (Cosumnes, Sacramento, Yolo Bypass, San Joaquin)
- EBMUD (Mokelumne)
- DWR-O&M (CCFI, Barker pumping, Stockton precipitation)
- DWR-CD (Sacramento Weir and French Camp Slough)
- USBR-CVP Operations (DXC times/status, CVP pumping, Contra Costa pumpings, Putah South Canal
- USACOE (Calaveras)

•French Camp Slough flow was ultimately NOT included in water year 2005 DAYFLOW computation because input data was not provided by Central District DWR as the program does not currently have funded support. French Camp Slough flows fluctuate seasonally as shown in Figure 1 (water year 2004, a "Below Normal" year). Delta outflow, and other parameters calculated in Dayflow, will therefore be biased low by approximately these amounts. There are other east side tributaries in the Delta that have never been measured and included in Dayflow. Thus, we would expect DAYFLOW estimate of Delta outflow would be biased consistently low. We believe, however, that the greatest source of uncertainty in the Delta outflow estimate continues to be Delta agriculture consumptive use.

•DAYFLOW data users can usually answer most questions by referencing the extensive documentation on the DAYFLOW web site (http://www.iep.ca.gov/dayflow)

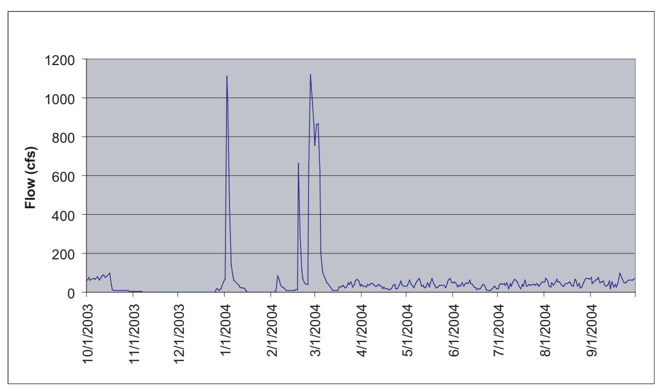

Figure 1 WY 2004 French Camp Slough Flow

New Invertebrate Species Discovered in Yolo Bypass

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Larvae from the invertebrate Chironomidae comprise a major portion of the insect drift in tributaries to the San Francisco Estuary (Sommer et al. 2004). Since 1998, we have been studying how chironomids support young Chinook salmon, a fish that seasonally migrates into the Yolo Bypass during high flow events (Sommer et al. 2001). The 24,000 hectare-Yolo Bypass is the primary floodplain of the Sacramento River. Our research has shown that the seasonal floodplain habitat produces higher levels of chironomids than the adjacent Sacramento River, resulting in better salmon feeding, faster growth, and perhaps improved survival.

One of our big challenges in the fish project is that there are often many different species of chironomids present in ponds or wetlands, each with a complicated life cycle. In late 2004 and early 2005, we conducted studies to try and identify some of the major groups of chironomids and their habitats. Our sampling in different parts of the Yolo Bypass included: 1) dip netting of insects in ponds and seasonal wetlands; 2) rehydration of seasonally dried floodplain soils in the laboratory; 3) drift netting of insect drift in Yolo Bypass tributaries (e.g. Putah and Cache creeks); and 4) drift netting of insect drift in different parts of the floodplain.

One of the biggest surprises in this study was that the chironomid fauna during flood events was dominated by a single species. Moreover, Dr. Peter Cranston (UC Davis) determined that this was a "new" species, not previously reported in the scientific literature. We were particularly impressed at the discovery of a new species so close to major universities and a large metropolitan area. The description of the new species *Hydrobaenus 'saetheri'* will appear shortly in the Bulletin of the Ohio Biological Survey (Cranston et al. 2006).

We are presently working on a report of the life cycle and sources of *Hydrobaenus*. Our research revealed that cocoons formed by young larvae of this species remain dormant in Yolo Bypass soils, likely for long periods. Winter flood events cause hatching of these cocoons, rapidly generating high densities of chironmid larvae in the inundated Yolo Bypass. After the aquatic life stage, *Hydrobaenus* emerges from the water as flying adults, which is when most people notice them. The adults survive only for a short period before laying eggs and the cycle repeats itself, depending on the flood cycle. Note that these adults are true midges, not one of the other families of "biting midges" that occur in the valley during warmer months.

Because of the difficulty in doing this work, we focused our efforts on early winter, when young salmon often use the floodplain as a nursery. Hence, we have yet to describe the range of wetland chironomids that occur throughout the year. However, we have good reason to believe that the fauna would differ substantially as we found that perennial ponds in the wildlife area harbored different species than the rewetted soils we sampled.

Acknowlegements

This project was supported with funding from the CALFED Ecosystem Restoration Program. We are particularly indebted to: Chris Hogle and Laura Carpenter for help in the field; Wayne Fields and Michelle Domingeuz for laboratory assistance; Paul Lutes and Peter Moyle for laboratory facilities; and Ted Grosholz for advice on study design. Dave Feliz graciously provided access to different parts of the Yolo Wildlife Area for field sampling.

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2005 Adult Sturgeon Population Study

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The adult sturgeon population study uses mark-recapture methods to develop information on the absolute abundance, harvest rate, and survival rate of anadromous white sturgeon and (to a lesser degree) green sturgeon in the San Francisco Estuary. This information is used directly to assess the suitability of fishing regulations and contributes to the understanding of how sturgeon populations respond to environmental conditions.

Using both multiple-census and Petersen methods, we estimate abundance of sturgeon >102 cm TL, the minimum legal size limit established before 1990. Prior to initiation of a pilot sturgeon creel survey this year, all data for calculation of abundance has been from the catch during estimate-year and subsequent-year tagging. Harvest rate is from the number of tags returned to us by the public within one year of application and the number of tags applied. Survival rate is calculated from the catch curve during tagging and/or from tags returned to us by the public.

Field staff catch sturgeon in San Pablo Bay with a 366-m, variable-mesh, drift trammel net and attach a disk-dangler reward tag to the dorsal fin of sturgeon meeting health and size criteria. They identify sturgeon to species, then measure, tag, and release fish that are outwardly healthy and injury-free.

Prior to this year, only healthy legal-sized sturgeon, presently 117-183 cm total length, were tagged. To address an expected decline in legal-sized white sturgeon and a paucity of information on green sturgeon, this year all captured sturgeon were to be tagged.

We tagged sturgeon from September 7 through October 27, 2005. Crew of the R/V *New Alosa* set nets on 25 days; fished nets 117 hours; tagged 171 legal-sized white sturgeon, 110 sub-legal-sized white sturgeon, and 2 super-legal-sized white sturgeon; recaptured two tagged white sturgeon tagged in 2005 and one sturgeon tagged in 2002; and tagged 14 green sturgeon of which seven were legal-sized and seven were sub-legal-sized.

Using a multiple-census calculation, estimated abundance of white sturgeon >102 cm TL in San Pablo Bay was approximately 8,000-17,000. Since 1997 the multiple-census estimates have ranged from 85-190% of the corresponding Petersen estimates.

Although this is not a catch per unit effort (CPUE) study *per se*, trends in overall sturgeon CPUE (fish/net-hour) during tagging and estimated sturgeon abundance are positively correlated. Catch per unit effort of legal-sized white sturgeon was ~1.4, much lower than 1998-2002 CPUE (min = 2.4, max = 8.6, average = 5.4). In contrast, CPUE of sublegal-sized white sturgeon was ~0.9, within the range of 1998-2002 CPUE (min = 0.8, max = 2.2, average = 1.4).

As in all previous study years, we could not calculate abundance of green sturgeon. The white sturgeon:green sturgeon catch ratio was 21 for fish => 102 cm FL and was 16 for fish <102 cm FL. Both of these ratios are within the range of values from the sixteen previous similar tagging efforts.

Schaffter and Kohlhorst (1999) predicted a substantial decline in legal-sized white sturgeon abundance from a high of 142,000 (this value was subsequently revised upward) in 1997, due in large part to poor spawning success during the late 1980's through the early 1990's. Abundance estimates from 2001-2002 and the new abundance and CPUE data suggest the prediction was accurate. Schaffter and Kohlhorst also predicted strong recruitment late in the present decade due to a series of 'wet years starting in 1993'. From the new length frequency and CPUE data, there is some sign of increased recruitment to the fishery attributable to fish spawned in the mid-1990's.

Tagging CPUE was very low this year and is likely to be low for several years, so without mitigations we anticipate relatively low-quality harvest rate data and abundance data for several years. The pilot sturgeon creel survey, any additional tagging effort (e.g., tagging in 2006-2007; using two boats; tagging in August), tagging in other water bodies, tagging all caught fish, and additional outreach to anglers will somewhat mitigate for low CPUE during tagging.

Given that the San Francisco Estuary adult white sturgeon population appears to be the result (primarily) of occasional strong year-classes and harvest, managing sturgeon harvest during any period of expected low abundance suggests the use of additional caution. To that end, we have begun outreach to stakeholders in the fishery to discuss short- and long-term potential management objectives and regulation changes.

References

Schaffter, R.G., and D.W. Kohlhorst. 1999. Status of white sturgeon in the Sacramento-San Joaquin Estuary. California Fish and Game 85:37-41.

2005 Adult Striped Bass Population Study

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Using a slightly modified Petersen method, we estimate abundance of adult striped bass (stratified by age and sex) in the estuary from mark and recapture of striped bass => 42 cm fork length (FL). From the mid-1960s through 1994, we tagged annually. During much of the 1990's, we tagged on alternate (even-numbered) years. We've tagged annually since 2002. The long time series helps managers and stakeholders understand how the striped bass population responds to environmental conditions and harvest.

We use fyke traps and drifting gill-nets to capture striped bass during their spring spawning migrations in the Sacramento and San Joaquin rivers. Field staff tag legal-sized healthy fish and release them immediately after collecting scales and recording length and sex. We also monitor fish captured and recaptured during the recreational harvest and subsequent-year tagging and use that information to calculate abundance.

We calculate annual abundance once all (or nearly all) observed fish are assigned an age by laboratory staff who interpret growth patterns on scales. Abundance estimates for a given tagging season are first calculated from that summer's creel sample and we later update prior abundance estimates as substantial blocks of information (e.g., from subsequent creel surveys and tagging) become available.

During April and May this year, staff captured striped bass in fyke traps deployed near Knights Landing and in drifting gill-nets deployed near Antioch from the R/V *New Alosa.* The fyke trap crew tended traps on 29 days, observed 4687 legal-sized striped bass, tagged 4142 striped bass, and recaptured 25 tagged striped bass. The *New Alosa* crew set nets on 26 days, observed 1865 legal-sized striped bass, tagged 1734 striped bass, and recaptured 7 tagged striped bass. For additional information on either effort, contact us for the pertinent Cruise Report(s).

Sampling by fyke trap was record-breaking (or nearly so) in a number of respects (e.g., average number of fish tagged per day and total fish tagged), although adversely affected by rapidly-changing river stage and damage to some traps by poachers. This result was due in large part to a number of changes (most were first implemented last year and refined this year) which allow us to set and tend more traps per unit time. The most important changes are that (1) crews now include three taggers and a boat operator, (2) we no longer attempt to remove every fish from every trap every day, and (3) we now set and tend traps seven days per week.

We used the rapidly-changing river conditions this year to learn about deploying and tending fyke traps across a wide range of conditions. By tactically re-rigging and deploying traps at increasingly high river stages this year, we learned that it is feasible to set and tend traps at river stages from 16-37 feet (37 feet is flood monitoring stage at Knight's Landing). We also learned that striped bass in large numbers are susceptible to the traps at those stages. Setting and tending traps had previously been limited to maximum stages in the 20-foot range, so we anticipate operating the traps during more of the striped bass migration in future years.

Fish captured in 2002 and 2003 have been aged and estimates of striped bass abundance during those years are forthcoming this year, as are updates of certain prior abundance estimates. We are now ageing fish captured in 2004 and 2005. Due to adjustments we've made in laboratory procedures and that we plan to make in data processing, we expect to generate abundance estimates and updates more frequently than in prior years.

Regional Trends in Fish Assemblage Stability and Diversity Based on Fall Seine and Trawl Sampling, 1995-2005 September – December.

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Background

As part of the Interagency Ecological Program, the Delta Juvenile Fish Monitoring Program at the Stockton Fish and Wildlife Office has used beach seines, Kodiak (KDTR) and mid-water (MWTR) trawls to monitor the relative abundance and distribution of juvenile Chinook salmon (*Oncorhynchus tshawytscha)* and other juvenile fish species in the Sacramento-San Joaquin River Delta and Bays. This article reports total fish catch for the sampling period during September 1 and December 31, 2005. In addition, as a follow up to Wichman and Hanni (2005) and Hanni (2005), this article examines fish assemblage stability and diversity during September-December across an eleven-year period (1995-2005).

Methods

All sampling locations previously have been described in Wichman and Hanni (2005). STFWO divides the Sacramento-San Joaquin River Delta and Bays into six different regions (Figure 1): (1) Lower Sacramento River, (2) North Delta, (3) Central Delta, (4) South Delta, (5) San Joaquin River, and (6) San Francisco and San Pablo Bays. Trawling locations are located at Sherwood Harbor on the Sacramento River (Region 2), Chipps Island in Suisun Bay (Region 3), and Mossdale on the San Joaquin River (Region 5). Juvenile fish were collected during September-December of each year over the eleven year period with few exceptions. Beach seine sampling in Regions 5 and 6 was not conducted throughout the year until 1999 and 1998, respectively. Trawl volume was not recorded at all trawl locations until 1997. Included in this report are trawls where only volume was recorded. Mossdale KDTRs were not conducted during September-December until 1998. In 2000, no trawls were conducted at Mossdale. In addition, MWTRs at Sherwood Harbor were only conducted during the first month of the reporting period (September) and KDTRs were conducted for the remaining three months (October-December). Unmarked salmon (those without a clipped adipose fin) were assigned a race according to Fisher (1992). All salmon catch data were converted to CPUE to compare among samples, where effort is the volume of water sampled.

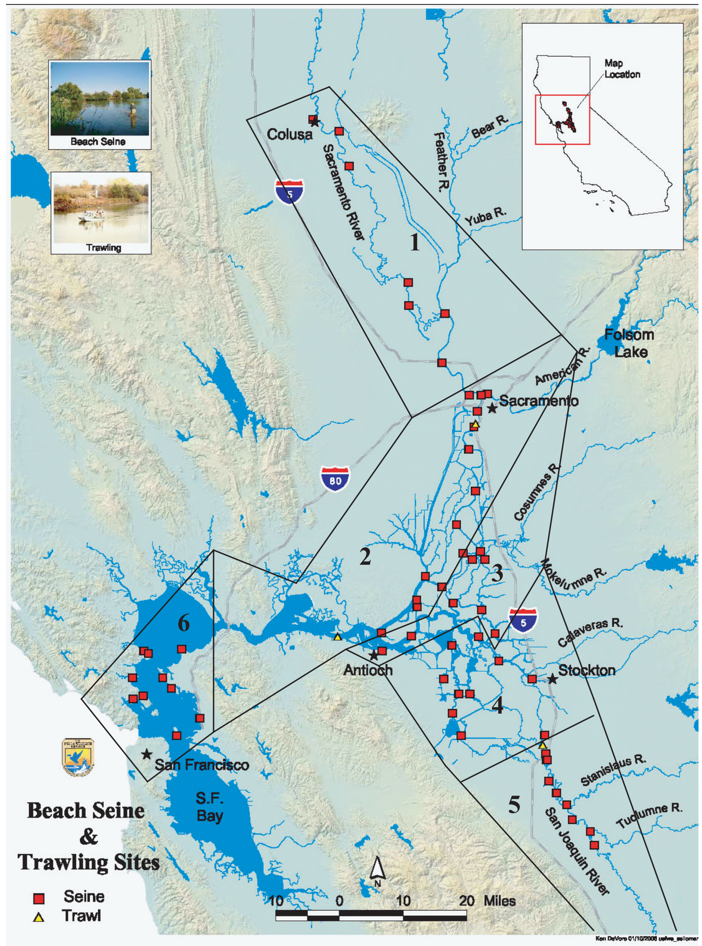

Figure 1 2005 Stockton Fish and Wildlife Sampling Regions and Locations

Kendall's coefficient of concordance with tied ranks, W_c (Zar 1984 was used to investigate fish assemblage stability through time at each trawl location and beach seine region. To calculate W_c, species were ranked by CPUE within a region for each year. Ties were handled by giving each tied species the average rank. Next, W_c was calculated (Wichman & Hanni 2005). Values of this coefficient range between 0 (no consistency in species ranks among years) and 1 (complete consistency in species ranks among years).

Simpson's Indices of Diversity were calculated for each year to determine diversity trends for each trawl location and beach seine region through time (Krebs 1989). These indices account for richness and evenness of fish species within the assemblage and denotes the probability that randomly sampled individuals will belong to different species. Variance calculations for Simpson's Index of Diversity were computed from Grundmann et al. (2001). To determine whether there were linear changes in diversity through time, separate regression analyses on diversity through time for each beach seine region or trawl location were performed. For further descriptions on these techniques, see Wichman and Hanni (2005) and Hanni (2005).

Results

Beach Seines

Chinook Salmon September 1 – December 31, 2005

We captured 2,003 unmarked Chinook salmon in beach seines during the four month reporting period. The majority of salmon captured were fall-run size (n = 1,179) from Regions 1, 2, and 3 (Table 1). Only two fall-run were captured in Region 5 and no salmon were captured in Regions 4 and 6. All eight of the marked salmon during the sampling period were recovered in Regions 1, 2, and 3. Only one adult salmon was captured in Region 1. Based on size criteria, a total of 10 late-fall, 328 spring-run, and 485 winter-run salmon were captured in Regions 1,2 and 3 combined.

Trawls

Chinook Salmon September 1 – December 31, 2005

A total of 204 unmarked Chinook salmon were captured in trawls during the reporting period (Table 2). The majority were winter- (n = 68) and fall-run size (n = 67) at Sherwood Harbor KDTR. We caught 117 marked Chinook salmon in trawls, 97% of which were captured at Chipps Island MWTR in December (n = 113). The marked salmon originated from various releases made by the Coleman National Fish Hatchery in December 2005.

Table 1 Regional catch and CPUE of unmarked and marked Chinook salmon captured from beach seining activities conducted from September 1 - December 31, 2005. All unmarked fish were classified into races based on size.

Region # and Name	Total volume (m^3)	Adult	CPUE	Fall	CPUE	Late Fall	CPUE	Spring	CPUE	Winter	CPUE	Marked	CPUE
1. Lower Sacramento R.	6405.5	1	0.00016	481	0.07509	7	0.00109	183	0.02857	246	0.03840	1	0.00016
2. North Delta	13092.40005	0	0	545	0.04163	2	0.00015	141	0.01077	226	0.01726	6	0.00046
3. Central Delta	7111.9	0	0	151	0.02123	1	0.00014	4	0.00056	13	0.00183	1	0.00014
4. South Delta	7886.1	0	0	0	0	0	0	0	0	0	0	0	0
5. San Joaquin R.	1781.2	0	0	2	0.00112	0	0	0	0	0	0	0	0
6. San Francisco & San Pablo Bays	5679	0	0	0	0	0	0	0	0	0	0	0	0
Total		1		1,179		10		328		485		8	

Table 2 Catch and CPUE of unmarked and marked Chinook salmon captured at each trawling location from September 1 through December 31, 2005. Unmarked fish were classified into races based on size.

Location	Volume (m3)	Adult	CPUE	Fall	CPUE	Late Fall	CPUE	Spring	CPUE	Winter	CPUE	Marked	CPUE
Chipps Island mid-water trawl	13318808	8	6.007 x 10-7	2	1.502 x 10-7	25	1.877 x 10-6	0	0	4	3.003 x 10-7	113	8.484 x 10-6
Mossdale Kodiak trawl	3495136.919	0	0	1	2.861 x 10-7	0	0	0	0	0	0	1	2.861 x 10-7
Sherwood Harbor mid-water trawl	646057.9357	0	0	0	0	0	0	0	0	0	0	0	0
Sherwood Harbor Kodiak trawl	3052792.638	1	3.276 x 10-7	67	204537106.7	1	4.889 x 10-9	27	5522501881	68	1.231 x 10-8	3	243639788.9
Totals		9		70		26		27		72		117	

Fish Assemblage Summary - Beach Seine Samples

We conducted 959 beach seine samples (volume = 41,956 m^3) for the reporting period, yielding 76,823 fish from 45 species (Table 3). The most abundant fish species captured in beach seine samples were inland silverside (*Menidia beryllina*, n = 51,394) and red shiner (*Cyprinella lutrensis*, n = 8,946), both non-natives. Species of concern captured from beach seine sampling included winter-run size Chinook salmon (n = 485), Sacramento splittail (*Pogonichthys macrolepidotus*, n = 8), and delta smelt (*Hypomesus transpacificus*, n = 1). The dominant fish fauna (defined as all species comprising 75% or more of the relative abundance) in each beach seine region or trawl location was comprised of one to four species (Table 3).

Regions 1 and 5 exhibited the strongest fish assemblage stability through time (W_c = 0.80 and 0.79 respectively). Moderate assemblage stability was observed for Regions 2, 3, and 4 (W_c = 0.75, 0.68, and 0.70, respectively), while the lowest assemblage stability was observed in Region 6 (W_c = 0.62).

Statistically significant linear declines in fish diversity from 1995-2005 were observed in Regions 2 (r^2 = 0.53, p = 0.012) and 3 (r^2 = 0.52, p = 0.012, Figure 2). Region 6 had a marginal decline in diversity (r^2 = 0.41, p = 0.085). A non-significant increase in diversity was observed in Region 4 (r^2 = 0.22, p = 0.145). Diversity did not change through time in Regions 1 and 5.

Fish Assemblage Summary - Trawl Samples

During the four-month reporting period (September-December) in 2005, we conducted 1,617 trawls (est. vol. 20,512,795 m^3) yielding 54,025 fish from 34 different species. Chipps Island MWTR yielded 52,282 fish from 23 species. Mossdale KDTR captured 1,254 individuals from 21 species. Sherwood Harbor MWTR yielded 75 individuals from eight species, while KDTR captured 415 individuals from 20 species. American shad was the most dominant species captured (n = 48,104), 89% of which were caught at Chipps Island. Species of concern included delta smelt (n = 83) and Sacramento splittail (n = 66), both of which were captured exclusively at Chipps Island. There were also 72 winter-run size salmon captured by trawling; 68 were caught in the Sherwood Harbor KDTR and four in the Chipps Island MWTR. The dominant fish fauna (species comprising 75% or more of the relative abundance) was comprised of one to six species within a region (Table 3).

Mossdale and Chipps Island trawls exhibited the strongest assemblage stability (W_c = 0.74 and 0.73, respectively). Sherwood Harbor KDTR had moderate assemblage stability (W_c=0.57), while Sherwood Harbor MWTR showed the lowest stability with in the fish assemblage (W_c=0.28).

Diversity declined through time at Chipps Island (R^2 = 0.67, p = 0.007), but did not change at any other trawl locations (Figure 2).

Table 3 Species that comprise greater than 75% of the fishes captured within each beach seine region and trawl sample area from September 1 - December 31, 2005.

	Species	*(n)*	*% of total fish captured*	*Total # Fish Captured*	*Total # Species*
Beach Seine Region					
1. Lower Sacramento River (n = 7 sites)	Inland Silverside	5,616	55%		
	Golden Shiner	1,347	13%		
	Chinook Salmon (fall)	481	5%		
	Fathead Minnow	447	4%		
	TOTAL	7,891	78%	10,176	33
2. North Delta (n = 10 sites)	Inland Silverside	18,113	89%		
	TOTAL	18,113	89%	20,459	32
3. Central Delta (n = 9 sites)	Inland Silverside	8,185	83%		
	TOTAL	8,185	83%	9,831	28
4. South Delta (n = 8 sites)	Inland Silverside	15,033	69%		
	Threadfin Shad	3,614	17%		
	TOTAL	18,647	85%	21,813	18
5. San Joaquin River (n = 10 sites)	Red Shiner	6,164	54%		
	Inland Silverside	4,435	39%		
	TOTAL	10,599	94%	11,321	17
6. San Francisco and San Pablo Bays (n = 9 sites)	Topsmelt	3,154	98%		
	TOTAL	3,154	98%	3,223	12
Trawl Location					
Chipps Island	American Shad	4,800	53%		
	Threadfin Shad	2,433	27%		
	TOTAL	7,233	80%	9,082	23
Mossdale	Threadfin Shad	676	54%		
	Inland Silverside	287	23%		
	TOTAL	963	77%	1,254	21
Sherwood Harbor (mid-water)	American Shad	66	88%		
	TOTAL	66	88%	75	8
Sherwood Harbor (kodiak)	Chinook Salmon (winter)	68	16%		
	Chinook Salmon (fall)	67	16%		
	Theadfin Shad	67	16%		
	Inland Silverside	66	16%		
	American Shad	30	7%		
	Chinook Salmon (spring)	27	7%		
	TOTAL	325	78%	415	20

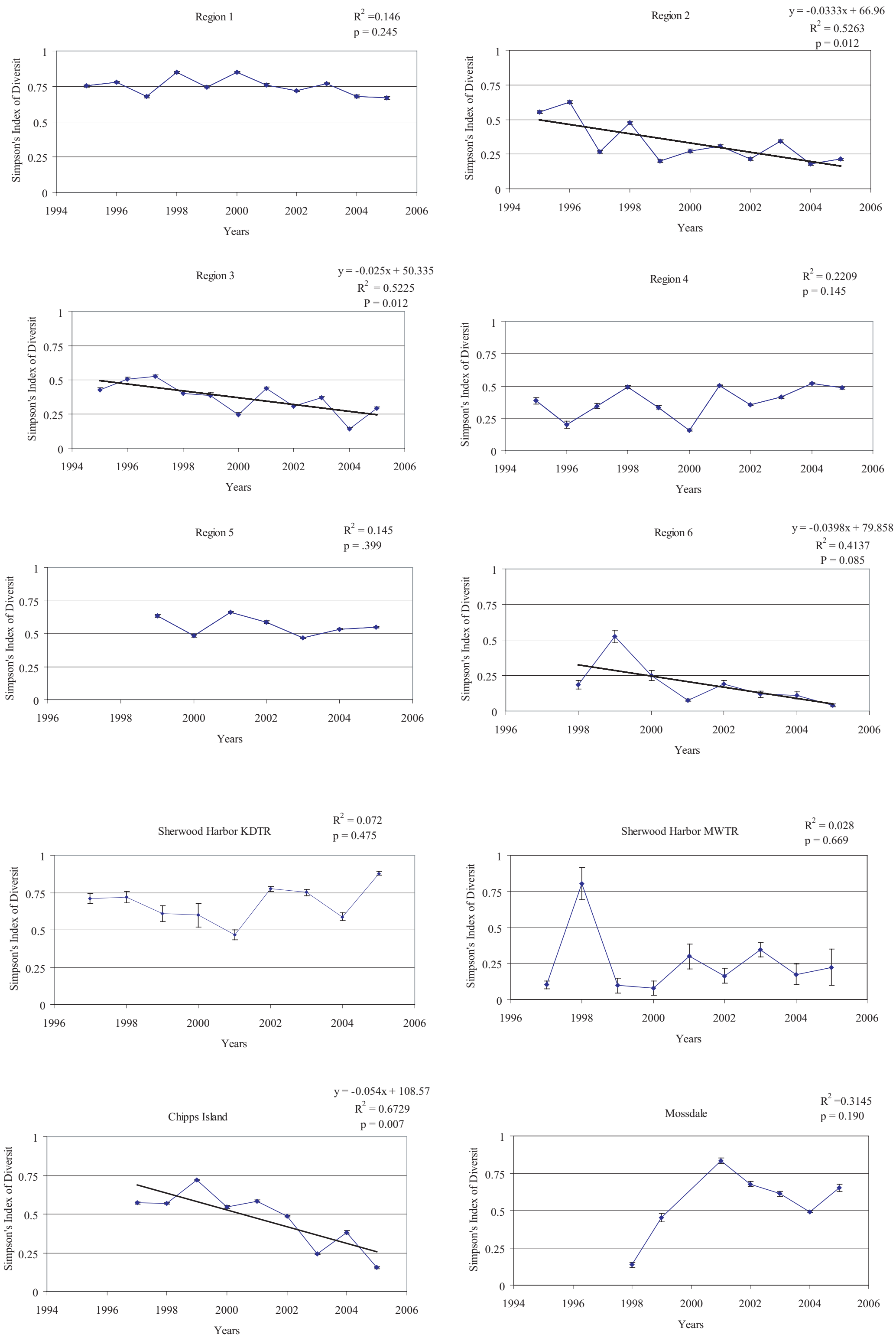

Figure 2 Graphs of Simpson's Index of Diversity over the previous 8 to 11 years for each beach seine and trawl location during the reporting period of September 1 through December 31, 2005.

Discussion

Fish assemblages in most regions and trawl locations remained fairly stable through time during fall months, as indicated by the relatively high values of Kendall's W_c. As discussed previously (Wichman and Hanni 2005), these values show that ranks in CPUE among species are consistent among years. Although the W_c values for fall (September-December) differ slightly from summer (May-August) and winter (January-April) values, the seasonal fish assemblages appear to be stable, at least during the study period. (Wichman and Hanni 2005*,* Hanni 2005). One exception is Sherwood Harbor MWTR, where the low W_c value indicates a relative lack of stability in the fish community assemblage through time. This lack of stability is related to the abundance ranks of individual species fluctuating drastically through time. There were 21 different species captured over the 9 years examined. Although American shad consistently received the highest abundance rank (21) among species each year, the abundance ranks assigned to other species captured fluctuated greatly. For example, in 2002, the abundance of threadfin shad was ranked eighth, yet in the following year, their abundance was ranked 20^{th}.

In the current study, a significant decline in diversity, measured as species evenness, was observed in Regions 2 and 3, and a marginally significant decline in diversity was observed in Region 6 (Figure 2). The decrease in diversity through time in these regions may be attributed to changes in the number of dominant species through time (Table 3). In each of these regions, the number of dominant species decreased from multiple species in the early years of sampling to just one dominant species in 2005.

Hanni (2005) found a decrease in diversity through time in Regions 5 and 6 during the summer months of sampling. However, the reasons for this change in diversity through time appear to be more complicated than in the current study (Hanni, 2005).

Species diversity did not significantly change through time in three of the four trawl locations in fall months. There was a clear decline in diversity at Chipps Island (Figure 2). This decline is likely related to the shift in the number of dominant species through time from many to one, American shad (Table 3).

Hanni (2005*)* found no significant change in diversity through time at any trawl location during summer sampling. Differences in diversity trends between fall and spring may be due to the presence of different dominant species. For example, fall-run Chinook salmon, which composed up to 74% of all individuals caught in summer months, are extremely rare in fall months.

Further investigations into native and non-native dynamics between years may provide better insight into long term species diversity and assemblage stability. A common consequence of successful invasions by non-native species is the local extinction of native species competing for common resources (Moyle 2002).

Acknowledgements

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Delta Smelt Broodfish Collection, Fall 2005

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Sub-adult delta smelt were collected by lampara net in the lower Sacramento River in the fall of 2005, under state and federal permits for production of cultured animals in 2006. This year, the smelt appeared to be concentrated near the confluence of the Sacramento and San Joaquin Rivers with highest densities on the western Sacramento River bank across from Sherman Lake (near Channel marker 11). The sub-adults appeared to occupy a more restricted area in 2005 compared to the last several years of collecting with our gear. Delta smelt were collected efficiently after finding their location, and by-catch was mainly threadfin shad and American shad (Tables 1 and 2). The collected smelt were collected as part of a contract with the Department of Water Resources to provide several thousand juvenile and adult cultured smelt for the Capture, Handling, Transportation, and Release (CHTR) study conducted by the Department of Fish and Game.

Table 1 Collection and survival of delta smelt broodfish

			% Survival after capture and transport						
Collection date	*Number of Sets*	*Total collected*	*24 hours*	*48 hours*	*72 hours*	*Total fish after 72 hours*	*sample size n=*	*Average Length*	*Weight*
11/21/05	14	46	80.4	80.4	80.4	37	9	52	1.18
11/22/05	20	124	99.2	98.4	98.4	122	1	58	1.54
11/23/06	17	578	58.1	55.5	55.2	319	26	54	1.37
12/7/05	20	1033	95.5	94.6	94.5	962	67	53	1.33
12/9/05	9	516	92.8	91.7	91.5	472	27	53	1.22
Total take	2297								
Total remaining after 72 hrs						1912			
Average % survival after 72 hrs					83.2				

Table 2 Incidental take caught in the lampara net while collecting delta smelt

Species	*Collection Dates*					
	11/21/05	11/22/05	11/23/05	12/7/05	12/9/05	Totals
Alosa sapidissima,American shad	41	117	266	47	4	475
Dorosoma petenense,Threadfin shad	2	1	26	416	108	553
Hypomesus nipponensis,Wakasagi smelt	0	2	0	0	0	2
Menidia beryllina,Inland Silverside	2	3	16	21	10	52
Morone saxatilis,Striped bass	0	0	0	3	1	4
Pogonichthys macrolepidotus,Splittail	0	0	0	2	1	3
Spirinchus thaleichthys,Longfin smelt	1	0	10	6	4	21

Contributed Papers

Life Cycle Observations and the Effect of Temperature and Salinity on Survival and Growth of the Estuarine Amphipod *Gammarus daiberi* (Amphipoda)

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Introduction

Gammarus daiberi was first described in 1969 (Bousfield 1969) as an estuarine amphipod, indigenous in the Delaware- and Chesapeake Bay. In the Sacramento-San Joaquin Delta, the species was first documented in 1983 (Cohen & Carlton 1995), and has since established itself in the Western and Central Delta as well as in Suisun Bay. As a member of the family Gammaridae, *G. daiberi* has two pairs of gnathopods, which are modified pereopods. The second gnathopod is larger than the first. *G. daiberi* has a small accessory flagellum attached to each pair of first antennae. The species is characterized by the long setae on his pereopods, gnathopods and, most importantly, on both antennas. These setae, especially the ones on the first antennae, distinguish *G. daiberi* from its closest relatives *G. tigrinus* and *G. fasciatus.* Although it is now a common species in the Sacramento-San Joaquin Delta, and an abundant and important part of the estuarine food chain (Lee II et al. 2003, Toft et al. 2003), little is known about its life cycle and ecological needs. The species prefers the oligo- to mesohaline salinity range typical for estuarine species. Highest population densities are reached in the pelagic and benthic habitats during spring and summertime; it is nearly absent in the pelagic zone and lives mostly on the bottom during the winter months (Bousfield 1969). Resident fish species including juvenile striped bass (*Morone saxatillis*) (Hymanson et al. 1994), Sacramento splittail (*Pogonichthys macrolepidotus*), largemouth bass (*Micropterus salmoides*), bluegill (*Lepomis macrochirus*), and tule perch (*Hysterocarpus traski*) (Toft 2000) use *G. daiberi* as a food source.

The ultimate objective of this study was to evaluate the suitability of *G. daiberi* as a candidate resident species for testing the toxicity of sediments and water samples from the Delta. However, in order to measure the impacts of environmental stressors on a particular species, as well as successfully maintain animals in the laboratory, more information was needed about the organism's life cycle and its tolerance to potential natural stressors. Here, we present out data on important elements of *G. daiberi*'s life cycle, and the species' optimum salinity and temperature ranges.

Methods

Animal Source and Treatment

Animals were collected with a kick net (Turtose, mesh size 0.5mm) and two sieves (Nalgene, mesh size 0.5 mm and 2 mm in the Sacramento-San Joaquin Delta at the western end of Twichel Island, and near Ryer Island and Boynton Slough between June 6 and August 21, 2000. Water temperatures at collection sites were 20.8-25.2°C, conductivity ranged from 438-8610 µS/cm, O_2 concentrations were 6.3-9.9 mg/L, and pH 7.7-9.0. Highest densities of *G. daiberi* were present at salinities ranging from 3-5 ppt. Animals were transported to the laboratory and transferred to aquaria containing Sierra Spring Water (Suntory Water Group, Atlanta, GE, USA) adjusted to a salinity of 3 ppt using Instant Ocean (Aquarium Systems, Mentor, OH USA). They were maintained at 20°C±1°C and a light:dark cycle of 16h:8h (800-1000 Lux). Organic detritus and plants from the collection sites were used as substrate. The holding water was aerated and renewed at least twice a month. Animals were fed with approx. 0.1 g of Tetramin flakes (Pfitzer, New York, NY, USA) every other day. One group was maintained in laboratory culture for nearly two months, while another was maintained in the laboratory for >6 months and considered to be more acclimated to laboratory conditions.

Weight measurements

To obtain reproducible and gender-specific wet weights of single animals, 45 amphipod pairs were separated during the precopular stage, and individual animals were dried carefully on a paper towel and weighed (Mettler scale, model H54). Females were separated into embryo bearing and non-embryo bearing groups and weighed. The wet weight change of females due to molting, spawning, or both molting and spawning was obtained by measuring the weight of individuals before and after a 7-day holding period. To validate the accuracy of our weighing method, 20 wet weight measurements and the corresponding dry weights were compared. Amphipods were weighed then dried overnight at 90°C in a drying oven (Fisher Scientific, Hampton, NH, Canada). Dry weights were measured and correlated with wet weights obtained for single animals prior to the drying procedure. There was good agreement between the two data sets (r^2= 0.947) indicating that our method to measure wet weights of amphipods was accurate.

Determination of optimum ranges for salinity and temperature

Mortality and wet weight measurements were used to determine optimum salinity and temperature ranges for *G. daiberi*. A range of temperatures (5, 10, 20, 25 and 35^{o}C) and a range of salinities (0.1, 0.3, 5, 15, 20, 25 ppt) were tested in two 7-day experiments. Ten randomly selected animals were weighed then transferred to one of five replicate 500-ml Pyrex beakers per temperature or salinity treatment. Initial weights per ten animals ranged from 25.7-51.4 mg. Each beaker contained 400 ml aerated control water. During exposure experiments, amphipods were fed each day with approximately 0.01g Tetramin flakes per beaker, and maintained at a light:dark cycle of 16h:8h. During both exposure experiments, dead animals were removed daily, and the number of surviving amphipods was determined after 7 days. Wet weight of each group of amphipods was measured and divided by the number of animals. Percent weight change was calculated based on the average individual weight per animal at initiation of the experiment and after 7 days.

Life history

For life history observations, amphipods were kept in 500 ml Pyrex beakers filled with 400 ml of aerated control water (20^{o}C, 3 ppt). In order to ensure that the chosen animals were unfertilized females, 50 single females with embryos were placed into beakers until they released their offspring. These females were then moved individually to 20 ml glass vials (Kimble Glass Inc., Vineland, NJ USA) containing 15 ml of water and a single male. The male was removed after fertilization indicated by a break-up of the pre-copular position. Amphipods were fed directly after being moved into the scintillation vial, and again, after removal of the male. We recorded the average duration of the pre-copular stage, the time between fertilization and release of neonates, and the number of offspring. Newly hatched neonates were transferred to a 500 ml beaker containing 400 ml of aerated water. Ground Tetramin flakes were added every other day, and approximately 70% of the water was renewed once a week. For these neonates, we recorded the time until the first successful fertilization (time to reach sexual maturity), indicated by the break-up of the pre-copular position.

Results and Discussion

Weight measurements

As in most gammarid amphipods, males were significantly larger than females ($p<0.001$). There were no significant differences between wet weights of females with or without eggs (Table 1). However, the effects of spawning, molting and combined molting and spawning on wet weight of females were significant ($p<0.05$; Figure 1).

Table 1 Weight measurements of individual male and *female G. daiberi*.

	Mean Wet Weight ± SD (n) [mg]
Male	12.30 ± 2.00* (45)
Female, total	5.30 ± 1.30 (45)
Female, embryo bearing	6.07 ± 1.17
Female, non-embryo bearing	5.50 ± 1.34

** significantly different (p<0.001)*

Temperature tolerance

G. daiberi tolerates temperatures from <5^{o}C to approximately 25^{o}C (Figure 2), with an optimum temperature of 20^{o}C . Although growth was highest at 25^{o}C, mortality was also higher at this temperature than at 5-20^{o}C (5-10% mortality at 5-20^{o}C; 28% mortality at 25^{o}C). The increase in mortality at 25^{o}C was statistically significant when compared to amphipods exposed to 10^{o}C. There were no surviving animals at 35^{o}C. Survival was highest at 10°C and 20°C. Growth was negative at 10°C and 5°C.

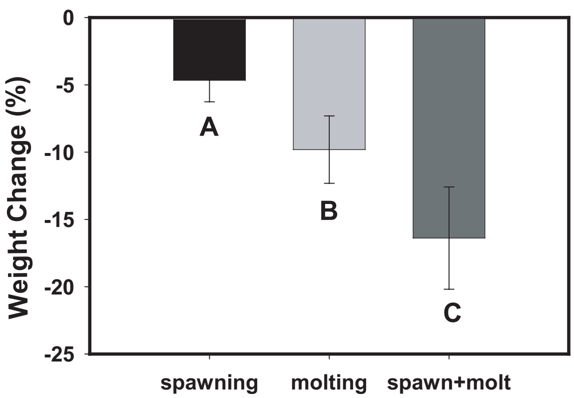

Figure 1 Weight loss of female *G. daiberi* due to spawning, molting or both. Shown are mean percentages of initial weight and standard deviation (n=3-5). A, B, C identify significantly different groups (p<0.05).

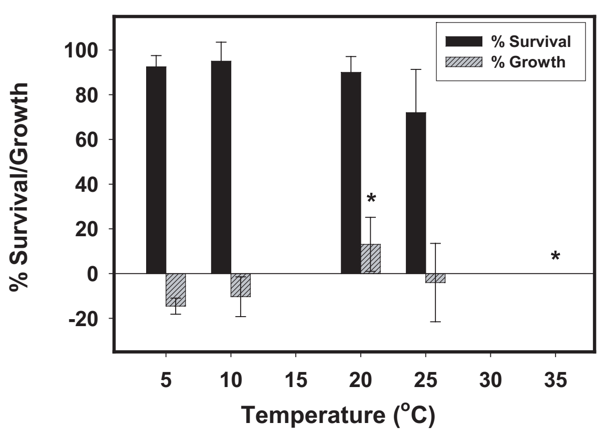

Figure 2 Mean percent survival and percent wet weight change (± standard deviation, n=4-5) of *G. daiberi* after 7-day exposures to a range of temperatures (from 20ºC). *Growth/survival in this group was significantly (p<0.05) different from all other groups.

Salinity tolerance

G. daiberi is well adapted to estuarine salinity conditions, but cannot survive prolonged periods in freshwater. Percent survival was zero at 0.1 ppt, but almost all (92%) animals survived a 7-day exposure to 0.3 ppt (Figure 3). Mean survival was highest (100% ± 0) at 5 ppt, and showed a tendency to decrease with increasing salinity 97.5% at 15 ppt, 94% at 20 ppt, and 92% at 25 ppt, but survival in these groups was not statistically different. Growth appeared to be a more sensitive indicator of salinity stress than mortality. Although 92% of animals survived exposure to 0.3 ppt, growth at this salinity was significantly less than in other exposure groups with the exception of the 15 ppt group. We do not have an explanation for the low and highly variable growth results at 15 ppt. Animals grew best at a salinity of 20 ppt.

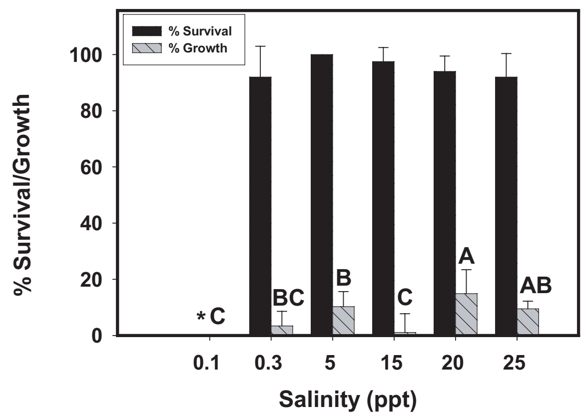

Figure 3 Mean percent survival and percent wet weight change (± standard deviation, n=4-5) of *G. daiberi* after 7-day exposures to a range of salinities (from 3 ppt). *Survival in this group was significantly (p<0.05) different from all other groups; A, B, C identify significantly different groups (p<0.05).

Fecundity and reproductive cycle

Knowing the frequency of reproduction as well as the fecundity of a particular species is important for maintaining animal cultures as well as for assessing population level effects in the field. In *G. daiberi*, the duration of the pre-copular phase, which was observed for 42 mating pairs, was 1 to 4 days. Data were variable, most likely a consequence of the variability in female molting time before fertilization. Our life cycle observations were performed on animals from two different groups. One was maintained in laboratory culture for nearly two months, while the other was maintained in the laboratory for >6 months and considered to be more adapted to laboratory conditions. A comparison of the data collected for the two populations showed no significant difference in the average number of offspring. For the "less acclimated" group, the number of offspring ranged from 2 to 7 with an average of 4.4 ± 1.6 (n=12), while the average number of offspring was 7.0 ± 4.8 (n=25) in the "more acclimated" group, with a range of 1 to 19 neonates (Figure 4). Approximately 20% of females produced more than 10 neonates per reproductive cycle. There was a significant difference between groups in embryo maturation time. For animals from the 2-month-old, "less acclimated" culture, the period between fertilization and release of neonates was 9 ± 0 days (n = 12). In the second, more acclimatized culture, it took only 8 ± 0 days (n = 25) from fertilization to release of neonates.

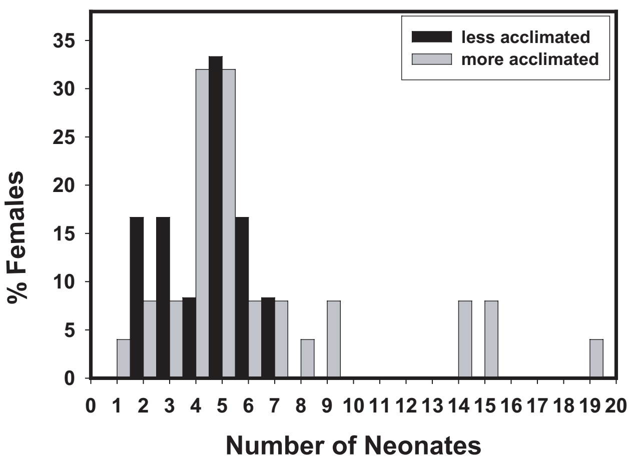

Figure 4 Fecundity (number of neonates) in one reproductive cycle of *G. daiberi* females selected from two laboratory cultures (2 and 6+ months of acclimation). Bars represent percentages of females that produced x number of neonates.

Summary and Conclusions

For this study, amphipods were collected from the Sacramento-San Joaquin Delta, and growth and mortality were used as endpoints to determine optimal ranges of salinity and temperature. In addition, body weights of males and females were measured, as well as life cycle parameters such as the average duration of the precopular phase, time between fertilization and release of neonates, the average number of offspring, and the time for neonates to reach sexual maturity. As in other gammarids, males (average weight: 12.3±2.0 mg) were significantly heavier than females (average weight: 5.3±1.3 mg). The duration of the precopular phase ranged from one to four days in both groups. Time between fertilization and neonate release was 8-9 days. The acclimation period to laboratory conditions influenced fecundity. Average fecundity was 4.4 ±1.6 neonates per female in a less acclimated group, and 7.0 ±4.8 neonates in a more acclimated group. Neonates reached sexual maturity, defined as the time from release as neonates until the first precopular stage, after 37 days. We conclude that the relatively constant maturation period and fecundity of the females, and the ability to quantify embryos in the living female, as well as observe the development of embryos *in vivo,* make *G. daiberi* a promising candidate for its use in toxicity studies. In particular, the species shows promise for evaluating the potential impacts of reproductive and developmental toxins. In addition, we developed a method to measure growth in single animals, and demonstrated that growth in this species was a sensitive sublethal indicator of stress.

Acknowledgments

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Temporal Patterns in Catch Rates of Juvenile Chinook Salmon and Trawl Net Efficiencies in the Lower Sacramento River

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Introduction

A full understanding of spatial and temporal patterns in distribution and abundance of a species is vital to making well informed decisions regarding management of the species (Walters 1991, Gerber et al. 1999, Forney 2000). U.S. Fish and Wildlife Service (USFWS) has monitored populations of juvenile Chinook salmon, *Oncorhynchus tshawytscha*, throughout the San Francisco Bay Delta Estuary (hereafter, "Delta") since the early 1970's. A primary purpose of the monitoring program is to provide managers of Delta water operations with information on patterns in distribution and abundance of migrating juvenile Chinook salmon that allows them to make informed decisions about water operations. Until now, efforts to determine salmon abundance have been conducted primarily during morning to mid-day hours with few exceptions (see San Joaquin River Group Authority 2005). However, there is growing evidence that juvenile salmonids in other regions exhibit complex diel patterns in activity levels (Sagar and Glova 1988, Ledgerwood et al. 1991, Fraser et al. 1993, 1995, Fraser and Metcalfe 1997, Hiscock et al. 2002, Reebs 2002, Johnston et al. 2004). These studies have found that salmon are primarily diurnal during spring and summer months but primarily nocturnal during fall and winter months. Given these complex temporal patterns in activity level of salmonids, it is important to determine whether juvenile Chinook salmon exhibit similar diel activity patterns in areas sampled by the USFWS. The existence of such patterns may have implications for the accuracy of our estimates of salmon abundance at different times of year.

Sampling techniques used to gain information on patterns in distribution and abundance of an organism often do not fully account for all individuals in a given area, leading to less accurate abundance estimates. For example, a lack of fish catch by a given sampling gear does not necessarily signify that the fish is not present. The fish may indeed be present, but the net is not efficient in successfully capturing the individual. The fish may be just outside the sampling area or be able to avoid or pass through the sampling gear. One approach to partition these two potential explanations for lack of catch -- fish presence versus sampling efficiency -- is to observe fish behavior *in situ* via radio telemetry (Hiscock et al. 2002, Pollock et al. 2004), hydroacoustics (United States Bureau of Reclamation 2004), or snorkel surveys. When these techniques are impractical, one may calculate efficiency of the sampling technique by estimating the proportion of fish that are caught from a known number of fish. This efficiency rate provides a correction factor for future catches (Wickwire and Stevens 1966).

The purpose of this study was to evaluate the accuracy of sampling procedures conducted by the USFWS to ensure that we are providing the best information possible to water operators for management decisions. By timing our sampling with scheduled hatchery releases of tagged juvenile Chinook salmon, we addressed two goals: (1) to examine whether diel patterns in catch per unit effort

(CPUE) differed between spring and late fall sampling periods, and (2) to determine catch efficiencies of midwater and Kodiak trawl nets on the Sacramento River. To address the first goal, we sampled continually for ~24 hours after hatchery releases in spring and late fall to recover released individuals. In addition, we collected data on juvenile Chinook salmon from outside of the release to compare diel patterns in CPUE of released salmon to those of non-released salmon. To address the second goal, we calculated the proportion of released salmon available for capture that were caught in midwater and Kodiak trawl nets.

Methods

Study site

Sampling was conducted along a 3.2 km stretch of the Sacramento River near Sherwood Harbor (River Mile [RM] 55). River width through this stretch ranges from 142-182 m. Tides in the area are semi-diurnal.

Sampling

Fish were captured in spring using a midwater trawl net and in late fall using a Kodiak trawl net. Twenty minute trawls were conducted on a near continuous basis during six periods, three in spring (05/15/03-05/16/03, 04/15/05-04/16/05, and 04/29/05-04/30/05) and three in late fall (12/03/02-12/04/02, 12/05/03-12/06/03, and 12/06/04-12/07/04). All trawls were conducted in the center of the river in an upstream direction. Water temperature was recorded at the beginning of all trawls whereas water turbidity was measured using a Secchi disk at the beginning of daytime trawls only. River flow data for the Sacramento River at Freeport was obtained from the California Department of Water Resources data exchange (California Department of Water Resources 2005).

Trawling was timed in coordination with hatchery releases of coded wire tagged (CWT) juvenile Chinook salmon at the Broderick boat ramp in West Sacramento, 7.25 km upstream of the sampling area. Sampling began near the time of each release and continued for approximately 24 hours. CWT fish released in spring were all fall-run Chinook salmon from the Feather River Hatchery (Table 1). Fish released in late fall were late fall-run Chinook salmon from Coleman National Fish Hatchery. Fish were not released in relation to a specific tidal stage.

Table 1 Hatchery release information for coded wire tagged Chinook salmon associated with the current study.

Release date	*Release time*	*# of fish released*	*Sampling period*
Late fall			
12/3/02	1420	69,490	12/3/02, 2036 to 12/4/02, 1352
12/5/03	1215	30,738	12/5/03, 1248 to 12/6/03, 1356
	1515	33,809	
12/6/04	1115	25,279	12/6/04, 1138 to 12/7/04, 0746
	1625	25,482	
Spring			
5/15/03	1045	50,284	5/15/03,1155 to 5/16/03, 1158
4/15/05	1234	51,144	4/15/05,1234 to 4/16/05, 1154
4/29/05	1210	51,390	4/29/05,1241 to 4/30/05, 1203

A midwater trawl net was used during spring sampling. The net fishes the top 1.8 m of the water column and is 4.6 m wide. The net is composed of six panels, each decreasing in mesh size (0.32-20.32 cm, USFWS 2003) towards a cod end. When deployed, two metal bottom depressors sink and spread the net at the bottom lead line while a second pair of metal hydrofoils, attached to floats, spread the top of the net at the surface. The net is fished 30.5 m behind the boat.

A larger Kodiak trawl net was used during late fall sampling. The net fishes the top 1.8 m of the water column and is 7.5 m wide when fully extended. A 1.8 m bar attached to the front of each wing keeps the lead line at a constant depth. The net is made of variable mesh and is composed of four panels, each decreasing in mesh size (0.32-2.54 cm) towards a cod end. The cod end is capped with an aluminum live box (33 X 33 X 26 cm) with baffles that protect enclosed fish from flow pressure to minimize fish mortality. The net is fished 30.5 m behind two boats.

After each trawl, all Chinook salmon were counted to race, while all other fish were counted to species. Race of all CWT salmon was determined from release information provided by hatcheries. Race of untagged salmon was determined using length-at-date criteria (Greene 1992). We also measured the fork lengths of =50 salmon from each race and =30 individuals from each other species. Diel patterns are reported here for Chinook salmon only. For our analysis, salmon were categorized as (1) targeted, which were individuals from the associated hatchery release, or (2) non-targeted, which were all other salmon, including those from other CWT releases not associated with our study. All salmon with a clipped adipose fin were returned to the laboratory and examined for presence of a CWT. If present, the CWT was extracted and the tag code was read and recorded. All other fish caught were released.

Catch per unit effort (in fish/m^3) of each trawl was calculated as:

$$CPUE = \frac{catch\ per\ tow}{volume\ through\ net} \quad (1)$$

Trawl nets do not always open completely while under tow, causing net mouth area to vary within and among tows. This issue has been addressed previously by calculating mean net mouth area for each net type (Midwater trawl = 5.08 m^2, Kodiak trawl = 12.54 m^2; USFWS 2003), which we used in our calculations. Volume during each trawl was calculated by converting rotations of a General Oceanics mechanical flow meter (model #2030) attached to the boat using the net mouth area and standard equations. All CPUE calculations were multiplied by 10,000 for ease of presentation.

Net Efficiency

We calculated net efficiency for each release, $NE_{release}$, as:

$$NE_{release} = \frac{N_{recovered}}{N_{available}} \quad (2)$$

where $N_{recovered}$ = number of salmon captured in the trawl net, $N_{available}$ = number of salmon available for capture. Because we sampled during only a portion of time of the entire sampling period, p_{time}, and on only a portion of the width of the river, p_{width}, not all fish released were available for capture by nets. Therefore, we corrected the number of fish from the release to gain a more accurate estimate of $N_{available}$, which was calculated as:

$$N_{available} = N_{release} \times p_{time} \times p_{width} \quad (3)$$

where $N_{release}$ = number of salmon released upstream. p_{time} was calculated as:

$$p_{time} = \frac{t_{sampled}}{t_{total}} \quad (4)$$

where $t_{sampled}$ = amount of time sampled (when net was in the water), and t_{total} = total time during which trawls were conducted ($t_{sampled}$ and time when net was out of the water). p_{width} was calculated as:

$$p_{width} = \frac{w_{net}}{w_{channel}} \quad (5)$$

where w_{net} = width of trawl net, and $w_{channel}$ = average channel width in sampling area.

These calculations were based on several assumptions: (1) all released salmon moved downstream from the release site to the sample site; (2) channel depth is uniform across the width of the channel; and (3) fish were uniformly distributed through time and space during sampling. Although it is probable that none of these assumptions were met completely, this calculation provides the best estimate of net efficiency currently available.

All trawls were categorized as occurring in one of three times periods: diurnal, nocturnal, and crepuscular, which we define here as the periods between first daylight and sunrise and between sunset and last daylight. These times were taken from Tidelog for Northern California (1996-2005). When a trawl was conducted during two time periods, it was categorized as the period during which the majority of time was spent. If a trawl was conducted during two time periods equally, it was categorized as the first time period.

Data Analysis

We conducted nested analyses of variance (ANOVAs) to determine whether temperature or flow rates varied among time period, among sample dates, or between seasons. In the analyses, sample date was nested within season and time period was nested within sample date within season. Because turbidity was measured during diurnal hours only, we could not determine whether it varied among time periods. Instead, we conducted a nested ANOVA to determine whether turbidity varied between seasons or among dates nested within seasons.

For CPUE, separate analyses were conducted for targeted and non-targeted salmon. Because data severely violated the assumption of normality (Shapiro-Wilkes test; $p < 0.001$), a nonparametric analysis was required. We analyzed CPUE data separately by season because dates were nested within season, and to our knowledge, a nonparametric nested ANOVA with a block design and unequal replication among cells within blocks does not exist. Therefore, for each season separately, we conducted a non-parametric ANOVA using the Mack-Skillings (Mack and Skillings 1980; Skillings and Mack 1981) procedure to determine whether there were differences in CPUE among times of day. This procedure allows unequal replication among cells within blocks (in our study, cells = time period and blocks = dates) and the resulting test statistic, the MS-statistic, can be compared to a two-way distribution.

To determine whether flow rate influenced the speed at which released fish travel down stream and, hence, the timing of their capture, we conducted two linear regressions: flow rate versus time between fish release and first catch, and flow rate versus time between fish release and peak CPUE.

To determine whether there were differences in fork length of targeted or non-targeted salmon among seasons, sample dates, and time period, we conducted parametric nested ANOVAs where date was nested within season and time period was nested within date nested within season. Assumptions of normality and homoscedasticity were not critically violated.

All parametric statistical analyses were conducted in SYSTAT 11 or JMP 5.1. The Mack-Skillings nonparametric analyses for CPUE data were conducted by hand.

Results

Physical Variables

Water temperature was significantly higher during spring sampling periods (16.6 ± 0.9° C) than during late fall sampling periods (10.7 ± 0.2° C; MS = 990.90, $F_{1,243} = 19651$, $P < 0.0001$; Figure 1A). Temperatures varied significantly among dates within season (MS = 90.07, $F_{4,243} = 1786$, $P < 0.0001$) and among time periods within date within season (MS = 0.24, $F_{12,243} = 4.729$, $P < 0.0001$). Temperatures during the day were ~1° C higher than those during crepuscular and night periods.

Flow rates were significantly higher during spring sampling (24596 ± 1024 cfs) than during late fall sampling (12388 ± 554 cfs; MS = 3.28×10^9, $F_{1,125} = 450.149$, $p < 0.0001$; Figure 1B). Flow rates also varied significantly among sample dates within season (MS = 7.23×10^8, $F_{4,125} = 99.317$, $p < 0.0001$) and among time period within sample dates within season (MS = 2.82×10^7, $F_{4,125} = 3.873$, $p < 0.0001$). Daytime flows were ~1300 cfs higher than crepuscular and night time flows.

Turbidity levels were significantly higher (i.e., Secchi readings were lower) during spring sampling periods (Secchi: 0.75 ± 0.02 m) than during late fall sampling periods (Secchi: 0.99 ± 0.03 m; MS = 2.22, $F_{1,136} = 894.2$, $p < 0.0001$; Figure 1C). Turbidity also varied significantly among sample dates within season (MS = 1.52, $F_{4,136} = 611.9$, $p < 0.0001$) and among time periods within sample dates within season. Turbidity and flow rates were positively correlated ($r = 0.87$, $n = 6$, $p = 0.03$).

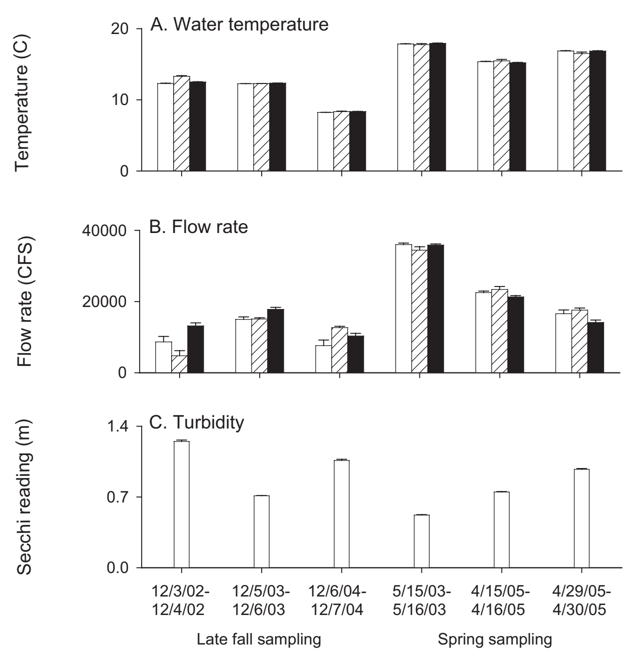

Figure 1 Summary of (A) temperature, (B) flow rates, and (C) turbidity during each sampling period. A higher secchi reading corresponds to lower turbidity. Turbidity readings were conducted during daylight hours only.

Catch Per Unit Effort

There were 1312 fish from 16 species captured in 286 tows and 95.23 hours of sampling (Table 2). A total of 557 fish were caught in late fall sampling periods and 755 fish were caught in spring sampling periods. Chinook salmon were most abundant, accounting for 73.4% of all captured fish. Of the 963 Chinook salmon captured, 598 (62.1%) were targeted. Of both targeted and non-targeted salmon, late fall-run was the most abundant race captured in late fall, although one winter-run was also caught. Fall-run salmon were the most abundant race captured in spring, although 11 spring-run and one late fall-run fish were also caught. Besides Chinook salmon, only threadfin shad and inland silversides represented >1% of total fish counts.

Table 2 Total catches by species during each sampling period. Percentage of total catch within a sampling period is indicated in parentheses.

	Late fall			*Spring*			
Species	*12/3/02-12/4/02*	*12/5/03-12/6/03*	*12/6/04-12/7/04*	*5/15/03-5/16/03*	*4/15/05-4/16/05*	*4/29/05-4/30/05*	Total
Chinook salmon, *O. tshawytscha* (targeted)	130 (78.8)	31 (38.3)	53 (17.0)	188 (46.2)	175 (62.3)	21 (31.3)	598 (45.6)
Chinook salmon, *O. tshawytscha* (non-targeted)	0	3 (3.7)	1 (0.3)	217 (53.3)	102 (36.3)	42 (62.7)	365 (27.8)
Threadfin shad, *Dorosoma* petenense	28 (17.0)	35 (43.2)	238 (76.5)	0	1 (0.4)	0	302 (23.0)
Inland silverside, *Menidia beryllina*	2 (1.2)	2 (2.5)	12 (3.9)	0	0	0	16 (1.2)
Rainbow trout/Steelhead, O. mykiss	0	0	1 (0.3)	0	2 (0.7)	2 (3.0)	5 (0.4)
American shad, *Alosa sapidissima*	2 (1.2)	0	0	1 (0.3)	1 (0.4)	0	4 (0.3)
Channel catfish, *Ictalurus* punctatus	1 (0.6)	2 (2.5)	0	0	0	1 (1.5)	4 (0.3)
River lamprey, *Lampetra ayresii*	2 (1.2)	0	2 (0.6)	0	0	0	4 (0.3)
Yellowfin goby, *Acanthogobius flavimanus*	0	0	3 (1.0)	0	0	0	3 (0.2)
Bluegill, *Lepomis macrochirus*	0	1 (1.2)	1 0.3)	0	0	0	2 (0.2)
Common carp, *Cyprinus carpio*	0	2 (2.5)	0	0	0	0	2 (0.2)
Wakasagi, *Hypomesus* nipponensis	0	2 (2.5)	0	0	0	0	2 (0.2)
Black crappie, *Pomoxis* nigromaculatus	0	1 (1.2)	0	0	0	0	1 (0.1)
Fathead minnow, *Pimephales promelas*	0	1 (1.2)	0	0	0	0	1 (0.1)
Golden shiner, *Notemigonus* crysoleucas	0	0	0	0	0	1 (1.5)	1 (0.1)
Striped bass, *Morone saxatilis*	0	0	0	1 (0.3)	0	0	1 (0.1)
White crappie, P. annularis	0	1 (1.2)0	0 0	0	0	0	1 (0.1)
Total	165	81	311	407	281	67	1312

We excluded the first 12 trawls on 12/3/02 (between 1358 and 1857h) because the net was fished incorrectly. Despite this, there were clear diel patterns in mean CPUE of targeted salmon, and these patterns switched between seasons (Figure 2). In late fall, CPUE was significantly greater at night than during diurnal and crepuscular hours (MS-statistic = 9.1; $p < 0.001$). We caught 95.3% of all targeted salmon at night, 1.4% during the day, and 3.3%

during crepuscular periods. In spring, CPUE was highest during the day and lowest at night (MS-statistic = 189.4; $p < 0.001$). We caught 94.6% of all targeted salmon in spring during the day, 2.1% during crepuscular periods, and 3.4% at night.

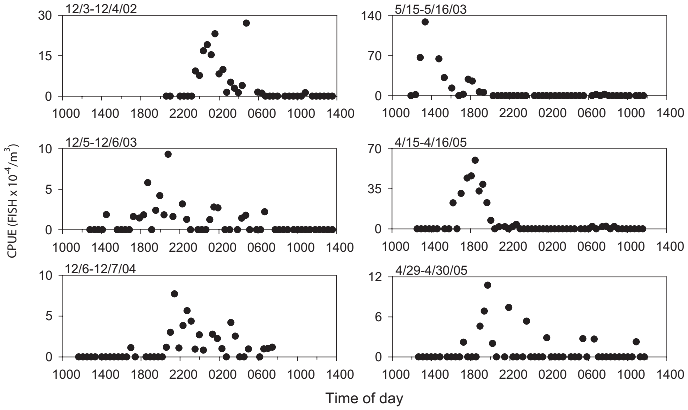

Figure 2 Catch per unit effort (CPUE) of targeted juvenile Chinook salmon from hatchery releases. Clear regions = day; striped regions = crepuscular hours; cross-hatched = night. Arrows indicate release times. Note change in scale among panels. The first 12 trawls on 12/3/02 (between 1358 and 1857h) were excluded because the net was fished incorrectly.

Non-targeted salmon comprised 27.8% of all fish caught in trawls (Table 2). Only four salmon were captured during the three late fall sampling periods combined, precluding formal statistical analysis (Figure 3). Two of these fish were caught at night and two were caught during the day. Therefore, no clear diel patterns in CPUE of non-targeted salmon during late fall could be detected. In spring, CPUE was greater during the day and lowest at night (MS-statistic = 200.7, $p < 0.001$). We caught 84.3% of all non-targeted salmon in the spring during the day, 7.0% during crepuscular periods, and 2.3% at night. This pattern is similar to CPUE of targeted fish in spring, but the reverse pattern of CPUE of targeted fish in late fall.

The relationship between flow rate and time between the release and first catch of targeted fish is not statistically significant, although the trend indicates that higher flow rates reduce the time between the release and first catch ($R^2 = 0.60$; $p = 0.13$; Figure 4). There was a highly significant negative relationship between flow rate and time until peak CPUE ($R^2 = 0.97$; $p = 0.002$).

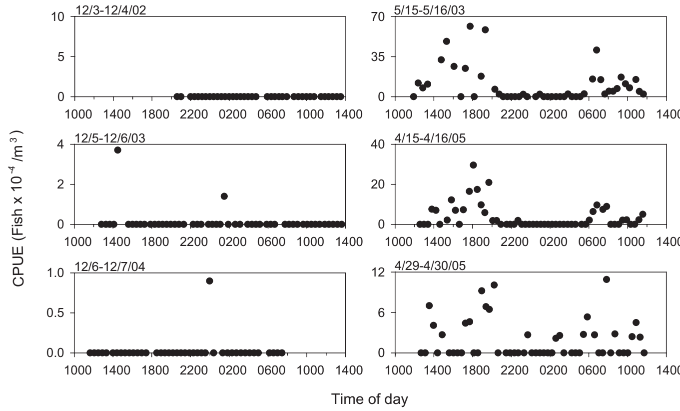

Figure 3 Catch per unit effort (CPUE) of non-targeted juvenile Chinook salmon (i.e., untagged salmon and tagged salmon from an unassociated release). Clear regions = day; striped regions = crepuscular hours; cross-hatched = night. Note change in scale among panels. The first 12 trawls on 12/3/02 (between 1358 and 1857h) were excluded because the net was fished incorrectly.

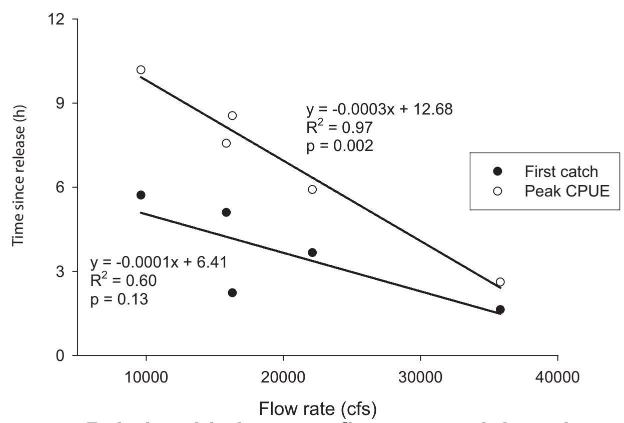

Figure 4 Relationship between flow rate and time since fish release until first catch (darkened circles), and time since fish release until peak CPUE (open circles).

Fork lengths

Mean fork length of targeted salmon was larger during late fall sampling (121.70 ± 1.19 mm) than during spring sampling (80.24 ± 0.57 mm; MS = 19236.97, $F_{1,595} = 128.1$, $p < 0.0001$; Figure 5A). Mean fork lengths differed among days within season (MS = 1209.06, $F_{4,595} = 8.1$, $p < 0.0001$) and among time periods nested within day nested within season (MS = 694.32, $F_{10,595} = 4.6$, $p < 0.0001$), although there were no clear patterns among time periods or dates within seasons.

Mean fork length of non-targeted salmon varied by season (MS = 2961.86, $F_{1,342} = 52.70$, $p < 0.0001$, Figure

5B). Mean fork length was 113.0 ± 15.7 mm in late fall and 76.7 ± 0.5 mm during spring sampling. Mean fork lengths also varied among sample date within season (MS = 650.47, $F_{3,342} = 11.57$, $p < 0.0001$) and among time period nested within sample date within season (MS = 534.91, $F_{7,342} = 9.52$, $p < 0.0001$), although, as with targeted salmon, there were no consistent patterns among time periods or dates within season.

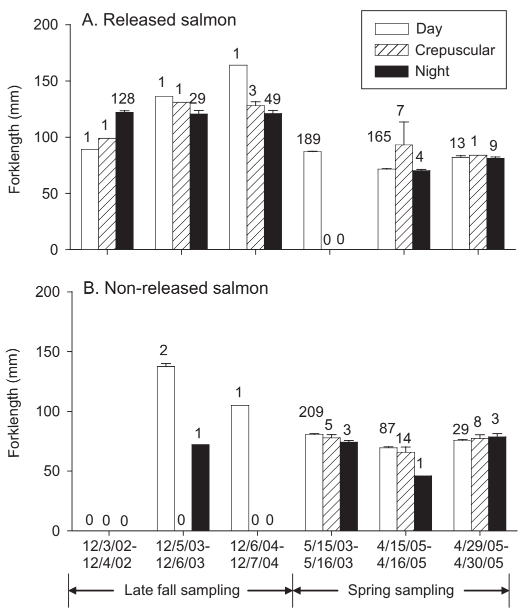

Figure 5 Mean fork length (±1 SE) of (A) targeted and (B) non-targted juvenile Chinook salmon caught in trawls during sampling. Numbers above bars indicate number of fish upon which means were based.

Net Efficiency

Mean efficiency of the midwater trawl net was 0.034 ± 0.007 and values ranged from 0.015-0.054 (Table 3). Mean efficiency of the Kodiak trawl net was 0.122 ± 0.031 and values ranged from 0.019-0.195. There was no statistically significant difference between gear types ($t_4 = 1.628$, $p = 0.18$), although the trend indicates that the Kodiak trawl net was much more efficient than the midwater trawl net. A power analysis indicates that the statistical power was 0.57 and that, given the variances we found, at $\alpha = 0.05$, we must conduct a minimum of five sample dates from each trawl type to obtain the generally accepted statistical power of 0.80.

Table 3 Efficiency ($NE_{release}$) of midwater and Kodiak trawl nets used at Sacramento.

Midwater trawl (Late fall)		*Kodiak trawl (Spring)*	
Sample dates	*NErelease*	*Sample dates*	*NErelease*
12/3-12/4/02	0.054	5/15-5/16/03	0.195
12/5-12/6/03	0.015	4/15-4/16/05	0.151
12/6-12/7/04	0.032	4/29-4/30/05	0.019
Mean	0.034	Mean	0.122
(SE)	(0.007)	(SE)	(0.031)

Discussion

Although not statistically significant, the Kodiak trawl net was four times as efficient as the midwater trawl net during our sampling (Table 3). Noel (1980) found that Kodiak trawls are more efficient than midwater trawls, concluding that the use of two boats during Kodiak trawls will herd fish into the net, increasing net efficiency. Further, the largest mesh size of the midwater trawl net (20.32 cm) used in spring is eight times greater than that of the Kodiak trawl net (2.54 cm) used in late fall. This larger mesh size increases the ability of fish to slip through the mesh, which would reduce the efficiency of the midwater trawl net. Also, the Kodiak trawl net is 2.6 m wider than the midwater trawl net, requiring fish to travel a longer horizontal distance if they attempt to escape from the net. These latter two explanations are confounded, however, by other differences between late fall and spring, such as fish length, turbidity, and water temperature (Figures 1, 5).

CPUE of targeted juvenile Chinook salmon in spring sampling periods was significantly greater during the day and significantly greater at night during late fall sampling periods (Figure 2). Although these patterns are consistent with those observed in other salmonid studies (Sagar and Glova 1988, Ledgerwood et al. 1991, Fraser et al. 1993, 1995, Fraser and Metcalfe 1997, Hiscock et al. 2002, Johnston et al. 2004), it appears that they were driven primarily by flow rate and time of day of the fish release (Figure 4). Flow rate explained 60% and 97% of the variation in time since the release until first fish catch and peak CPUE, respectively. As a result, it is not reasonable to consider CPUE of targeted salmon in this study in assessing diel patterns in CPUE, regardless of their consistency with other studies. This relationship between timing of fish capture suggests that the timing of the release will influence the timing of fish capture.

CPUE of non-targeted juvenile Chinook salmon in spring sampling periods was significantly greater during the day, consistent with other studies, although low catches of non-targeted salmon in late fall (n = 4 fish) precluded formal analysis to evaluate diel patterns in CPUE with confidence (Figure 3). To properly assess diel patterns of CPUE in late fall, sampling efforts must be increased to catch a sufficient number of non-targeted salmon.

There have been six additional surveys over 24 hour periods conducted for or by USFWS since 1996 in the Delta to which we can compare to our findings (Table 4). Although we conducted no formal statistical analysis on these data, CPUE of Chinook salmon in spring surveys was generally greatest during the day and crepuscular hours and lowest at night. CPUE of Chinook salmon in fall/late-fall surveys was generally greatest during nocturnal and crepuscular hours and lowest during the day. High CPUE during crepuscular periods may be due to spillover from other time periods. In fact, in the two spring surveys where CPUE was greatest during crepuscular periods, CPUE during the day was approximately three times greater than that of night time. In the fall sampling date where CPUE was greatest during crepuscular periods, CPUE at night was nearly 69 times greater than CPUE during the day. The seasonal shift in diel patterns in these surveys is largely consistent with those in other studies (Sagar and Glova 1988, Ledgerwood et al. 1991, Fraser et al. 1993, 1995, Fraser and Metcalfe 1997, Hiscock et al. 2002, Johnston et al. 2004). Also, patterns in CPUE during spring are consistent with those of non-targeted salmon in the current study, although we were unable to compare fall patterns owing to low catches in our study.

Many factors differ between fall and spring sampling periods that may contribute to the shift in diel CPUE patterns between seasons (Table 4). First, temperature has been recognized as an important factor responsible for the shift in diel activity level by other species of salmon (Fraser et al. 1993, 1995). Fraser et al. (1993) showed that, under laboratory conditions, juvenile Atlantic salmon (*Salmo salar*) change from diurnal to nocturnal with a decrease in water temperature. A threshold temperature of ~8-12° C has been suggested previously, below which salmonids switch from diurnal to nocturnal activity patterns (Gibson 1978, Fraser et al. 1993, 1995). A plausible mechanism for the temperature-dependent shift in activity levels involves a trade-off between foraging efficiency and predation risk (Fraser et al. 1993, 1995). When temperatures decrease, the metabolism of these exothermic organisms is reduced. A lower metabolism reduces their mobility, increasing their risk of predation because they are less able to escape predation from endothermic predators (e.g., birds and aquatic mammals). A lower metabolism also reduces energy requirements of a salmon. As a result, they can "afford" to forage during nocturnal hours when foraging efficiency is reduced (reduced foraging efficiency of salmonids at night has been demonstrated by Fraser and Metcalfe 1997). In warmer conditions, fish metabolism is higher and, thus, energy requirements are higher. As a result, salmon must forage during the day when their foraging efficiency is greater, despite higher predation risk. Spring patterns in the current study are consistent with this hypothesis (Figure 1), although we cannot determine the influence of temperature in late fall because of low fish counts. However, seasonal patterns in CPUE of salmon from other DJFMP studies appear to be independent of water temperature (Table 4).

A second difference between late fall and spring that may influence seasonal patterns in CPUE is photoperiod. In the current study, there were nearly four hours of additional daylight during spring sampling periods compared to late fall sampling periods (Figure 2). In the other USFWS studies, there were between three and four hours of additional daylight during spring sampling periods compared to fall sampling periods (Table 4). Fraser et al. (1993) found no effect of photoperiod on *S. salar* activity levels, although Clarke et al. (1985) found that photoperiod influences the seasonal cycle of seawater adaptation in juvenile *S. salar*. However, we cannot reject this hypothesis because, to our knowledge, the effect of light regimes has not been empirically tested on Chinook salmon activity levels.

Table 4 Summary table of other studies associated with the USFWS conducted over a 24 h period. Mean (±1 SE) values of water temperature, daylight hours, turbidity, and CPUE were calculated across the entire sample period. Time period with the highest CPUE for each study is indicated with an asterisk (*).

							Mean CPUE (Fish X 10-4/m3)		
Study site	*Dates*	*Gear type*	*Predominant race*	*Mean water temperature (C)*	*Mean daylight hours (h)*	*Mean turbidity (m)*	*Day*	*Crepuscular*	*Night*
Georgiana Slough	4/29/96-5/2/96	Kodiak trawl	Fall	16.90 (0.12)	13:46 (0:01)	0.79 (0.01)	336.52 (32.18)	525.30* (105.31)	121.73 (19.12)
Walnut Grove	4/29/96-5/2/96	Kodiak trawl	Fall	16.76 (0.10)	13:46 (0:01)	0.80 (0.01)	157.16 (13.78)	162.75* (68.62)	53.96 (10.54)
Jersey Point[a]	4/29/97-5/15/97	Kodiak trawl	Fall	17.97 (0.13)	13:58 (0:02)	0.58 (0.01)	20.56* (12.86)	6.09 (0.97)	0.72 (0.09)
Delta Cross Channel[b]	10/29/01-11/1/01	Mid-water trawl	Late fall	18.21 (0.03)	10:39 (0:02)	1.35 (0.01)	0.04 (0.02)	1.44 (0.59)	1.54* (0.37)
Sacramento River, RM 27[b]	10/29/01-11/1/01	Mid-water trawl	Late fall	15.57 (0.02)	10:39 (0.02)	1.36 (0.01)	0.18 (0.05)	13.12* (3.80)	12.40 (1.47)
Chipps	12/11/03-12/12/03	Mid-water trawl	Late fall	11.47 (0.05)	9:36 (0:01)	0.66 (0.02)	0.19 (0.09)	0.25 (0.14)	0.71* (0.15)

a. Data collected by Hanson Environmental for DJFMP

b. From Hansen (2004)

Third, the type of trawl net may influence seasonal patterns in CPUE. A Kodiak trawl employs two boats that herd fish into the net (Noel 1980), whereas a midwater trawl uses one boat. Further, the Kodiak trawl net is larger and its mesh size is smaller than midwater trawls. Although McLain (1998) found that these differences between nets influence catch/tow, size of fish caught, and volume of water sampled, there is no plausible reason why the difference in net type would cause differences in diel patterns in CPUE. Regardless, data from other USFWS studies do not refute this hypothesis (Table 4). Until an experimental evaluation of diel patterns of CPUE is conducted for Kodiak and midwater trawls simultaneously (*sensu* McLain 1998), the hypothesis that gear type influences seasonal patterns in CPUE cannot be rejected.

Fourth, late fall-run salmon were the dominant race caught during fall sampling, whereas fall-run salmon were the dominant race caught during spring sampling (Table 4). Late fall-run juveniles are generally larger than fall-run juveniles (Figure 5) because they overwinter upstream and become smolts as yearlings. Larger fish tend to be less active, possibly because digestive rates are lower for larger fish, and, therefore, may not need to forage during the day (Brett and Groves 1979, Hiscock et al. 2002). Thus, seasonal patterns in CPUE observed in Table 4 may have been caused, at least in part, by the presence of different races of salmon at different times of year.

Fifth, variation in turbidity between seasons may influence patterns in CPUE between seasons. Net avoidance by fish should be more difficult when turbidity is higher (i.e., visibility is lower), resulting in higher CPUE during the day. However, because light levels have little influence on the reactive distance of fishes in highly turbid waters (Benfield and Minello 1996), this difficulty in net avoidance, and, thus, CPUE, should not vary significantly throughout a 24 h cycle in high turbidity conditions. In the current study, turbidity was high in spring (Figure 1C). However, CPUE of non-targeted salmon varied significantly during the day (Figure 3). Further, there were clear diel patterns in CPUE of salmon in even higher turbidity conditions at Jersey Point and Chipps (Table 4). Therefore, the hypothesis that turbidity drives seasonal patterns in CPUE is not supported by these studies.

Determining the mechanisms driving seasonal changes in diel patterns of CPUE of Chinook salmon is important 30because it would allow us to adjust timing of our sampling to obtain the best estimate of actual salmon abundance. At present, we generally sample only during morning and midday hours throughout the year, and conduct Kodiak trawls from October through March and mid-water trawls from April through September at Sacramento. As a result, we may be underestimating fish abundances during periods when fish are predominantly nocturnal and overestimating fish abundances during periods when fish are predominantly diurnal. Thus, by determining the causes of diel patterns in salmon activity levels, we may be able to provide more accurate estimates of salmon abundance in the Delta. The actual cause of these patterns likely involves a combination of above hypotheses and possibly others not discussed. We recommend controlled laboratory experiments similar to Fraser et al. (1993) to evaluate these mechanisms. Despite inherent problems with altering fish behavior in an artificial setting, we could more easily partition the effects of these hypothesized factors on intra-annual shifts in diel patterns that can then be followed up with field investigations. Further, we recommend additional 24-hour sampling of non-released salmon at multiple times of year to determine how diel patterns vary intra-annually.

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Fulfilling a Paradoxical Mandate: Can the Environmental Water Account Ensure the Reliability of Freshwater Exports from the Sacramento-San Joaquin Delta and Simultaneously Protect Delta Smelt (*Hypomesus transpacificus*) from Excessive Entrainment?

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Introduction

The San Francisco Estuary (SFE) is often defined by its extremes. It is considered one of the most urbanized estuaries in the world (Conomos 1979, Nichols et al. 1986), and one of the most invaded estuaries in the United States, with hundreds of aquatic nonindigenous species established throughout the system (Cohen and Carlton 1995, Dill and Cordone 1997, Kimmerer and Orsi 1996). It is also one of the most managed estuaries, particularly in relation to freshwater inflow, water circulation, and water quality (Jassby and Powell 1994, CSWRCB 1995, Arthur et al. 1996, Kimmerer 2002). Despite this high level of disturbance, the SFE is one of the most valuable natural resources in the western United States (CALFED 2000). The SFE provides important habitat for numerous native plant and animal species, many of special concern, as well as several species with sport and commercial value (CALFED 2000). Conserving and restoring estuarine habitat and natural resources is a pressing and complex challenge for the responsible government agencies because human water needs continue to increase in concert with continuing urbanization of the watershed.

The Sacramento-San Joaquin Delta (Delta) is the focus of several ongoing management challenges in the SFE. The Delta (Figure 1) is the eastern, landward portion of the SFE, where major efforts are underway to simultaneously maintain and improve ecosystem services (e.g., reliable and ample water supplies for municipal, industrial, and agricultural use, pollution abatement, and flood control) and ecosystem functions (e.g., provision of high quality habitat for native species, nutrient and carbon cycling, and biomass production). Roe and van Eten (2002) refer to this simultaneous pursuit as the "paradoxical mandate" due to inherent, fundamental conflicts in simultaneously improving conditions for human use (ecosystem services) and improving habitat conditions and processes (ecosystem functions). In this paper, we examine one set of actions taken to achieve the paradoxical mandate of maintaining the reliability of water deliveries from the two major Delta export projects (the California State Water Project (SWP) and the Federal Central Valley Project (CVP)), while simultaneously protecting the threatened delta smelt (*Hypomesus transpacificus*) from excessive water export entrainment. Note that since February 2005, different incidental take levels have been used as a result of a new USFWS biological opinion.

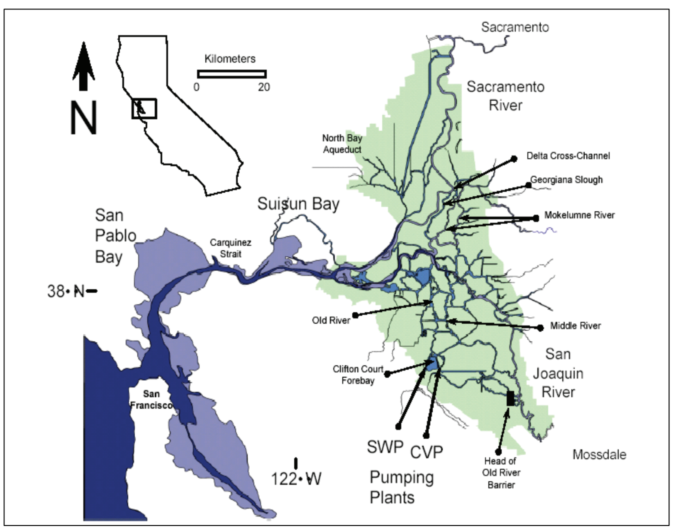


Figure 1 Geographic components of the San Francisco Estuary, California, USA and locations of important features. The Sacramento-San Joaquin Delta is the shaded area to the east of Suisun Bay. The USGS Old River flow monitoring station is located approximately at the arrowhead indicating Old River.

The delta smelt has attracted much interest since it was listed as a threatened species under the State and Federal endangered species acts in 1993 (USFWS 1993, Sweetnam et al. 1993). Much of the research has centered on understanding delta smelt ecology and population biology in relation to factors that might limit its abundance and distribution (Herbold et al. 1992, Moyle et al. 1992, Sweetnam 1999, Kuivila et al. 2002, Bennett 2005). Long-term SWP and CVP export operations are considered an important limiting factor because these operations result in direct entrainment loss and have hydrodynamic effects thought to adversely affect rearing conditions , Sweetnam et al. 1991, CDWR and USBR 1994, USBR 2004).

In 1995, the U.S. Fish and Wildlife Service (USFWS) issued a biological opinion evaluating the long-term adverse effects of SWP and CVP operations on delta smelt (USFWS 1995b). The biological opinion presented an overall package of reasonable and prudent measures considered necessary to ensure that long-term SWP and CVP operations were unlikely to jeopardize the continued existence of delta smelt. The reasonable and prudent measures included various existing agreements and regulations in conjunction with several new terms and conditions (USFWS 1995b). The biological opinion includes levels of incidental take (Table 1) that serve as one of the principal metrics the USFWS uses to determine if SWP and CVP operations are resulting in potential, unanticipated jeopardy to delta smelt.

Between 1995 and 2000 delta smelt incidental take levels were exceeded in at least one month, in four out of six years (Table 2). These events led to unanticipated and uncompensated reductions in SWP and CVP water exports (for example see, Nobriga et al. 2000 and 2001), and suggested to the USFWS that long-term water project operations were continuing to jeopardize the species through excessive entrainment losses. By 1999 it was clear that additional efforts were needed to ensure the reliability of water exports, while simultaneously protecting delta smelt.

Table 1 Combined (SWP + CVP) authorized incidental take levels of delta smelt for each month by water year type (USFWS 1995b). Monthly values are averages of the upper quartile of delta smelt collected each month at SWP and CVP salvage facilities from 1980 to 1992. Water year (WY) types (above normal or below normal) are based on hydrologic forecasts that predict with 90% confidence the total inflow to the Delta between October 1 and September 30. Methods for estimating the number of delta-smelt collected at the salvage facilities are described in the Materials and Methods section.

Months	*Above Normal WY*	*Below Normal WY*
January	5,397	13,354
February	7,188	10,910
March	6,979	5,368
April	2,378	12,345
May	9,769	55,227
June	10,709	47,245
July	9,617	35,550
August	4,818	25,889
September	1,329	1,978
October	11,990	6,440
November	3,330	2,001
December	733	8,052

Table 2 Combined (CVP + SWP) monthly (March - July) collections of delta smelt at the two salvage facilities from 1995 through 2004. Values in bold type exceed the monthly incidental take levels authorized by USFWS (see Table 1). AN, above normal water year; BN, below normal water year.

Year	*March*	*April*	*May*	*June*	*July*
1995(AN)	16	24	0	0	0
1996(AN)	155	111	**30,399**	9,465	148
1997(AN)	1,730	1,159	**32,828**	7,876	228
1998(AN)	592	48	4	66	124
1999(AN)	564	410	**58,929**	**73,368**	**19,822**
2000(AN)	2,746	1,746	**49,401**	**49,124**	1,513
2001(BN)	3,748	519	13,134	2,325	6
2002(BN)	225	372	47,361	11,926	24
2003(BN)	483	492	16,216	9,580	12
2004(BN)	2,267	276	5,239	6,416	18

In 2001, the Environmental Water Account (EWA) was initiated in part to address the chronic springtime conflict between SWP and CVP water project exports and the episodes of apparent high delta smelt entrainment losses. The EWA is a cooperative water management program with the dual purpose of protecting fish in the Delta through environmentally beneficial changes in SWP and CVP water operations, while improving water supply reliability by ensuring water users are fully compensated for these changes (CALFED 2000). During its first four years of operation, the EWA program used approximately 1.3 billion m^3 (1.054 million acre-feet) of water assets, at a total cost of approximately $139 million in public funding (White and Poage 2004, J. White, CDFG, pers. comm.), with a gross average cost of $1.07 10-m^{-3}. By comparison, contractors receiving water from the SWP paid an overall average of $1.24 10-m^{-3} in 2001 (CDWR 2004).

Three agencies charged with management of aquatic living resources in California—California Department of Fish and Game (CDFG), U.S. Fish and Wildlife Service, and NOAA Fisheries—determine the use of EWA water assets. Use of EWA assets has most commonly involved curtailing SWP and CVP water exports from the Delta to reduce entrainment loss of fish species of concern (e.g., delta smelt or winter-run Chinook salmon; White and Poage 2004). In this paper we examine EWA actions to reduce SWP and CVP exports in the last two weeks of May between 2001 and 2004. This application of EWA water is called the "shoulder-on-VAMP" because it extends the one-month curtailment of Delta exports undertaken as part of an adaptive management experiment, the Vernalis Adaptive Management Plan (VAMP) (SJRG 2004). The shoulder-on-VAMP export curtailment is thought to reduce direct SWP and CVP entrainment of young delta smelt, and improve hydraulic conditions for young delta smelt emigrating from the interior Delta to rearing areas in Suisun Bay, Suisun Marsh, and the lower Sacramento River (Figure 1, Poage 2004). Specifically, this article addresses two questions:

1. What effect does the shoulder-on-VAMP export curtailment have on young delta smelt?

2. What combination of physical conditions in the Delta (flows, transport, temperature) result in extreme entrainment events of young delta smelt?

Study Area

The SWP and CVP operate to export water out of the Delta to supply agriculture and municipal needs in central and southern California. The SWP and CVP water export facilities are located in the southern Delta (Figure 1). Total annual exports of the two projects ranged from 5.65 to 7.58 billion m^3 between 1995 and 2004. Although the SWP and CVP are operated for the same general purpose, there are important differences in the physical features and operations of each project. Head works of the CVP (Figure 2) include: 1) a diversion canal from Old River; 2) debris barriers at the entrance to the canal; 3) fish salvage facilities situated near the diversion canal entrance; and 4) a pumping plant which lifts water from the diversion canal into the Delta-Mendota aqueduct. The CVP must continually pump at or near design capacity (~125 $m^3 s^{-1}$) to fulfill its water delivery contracts.

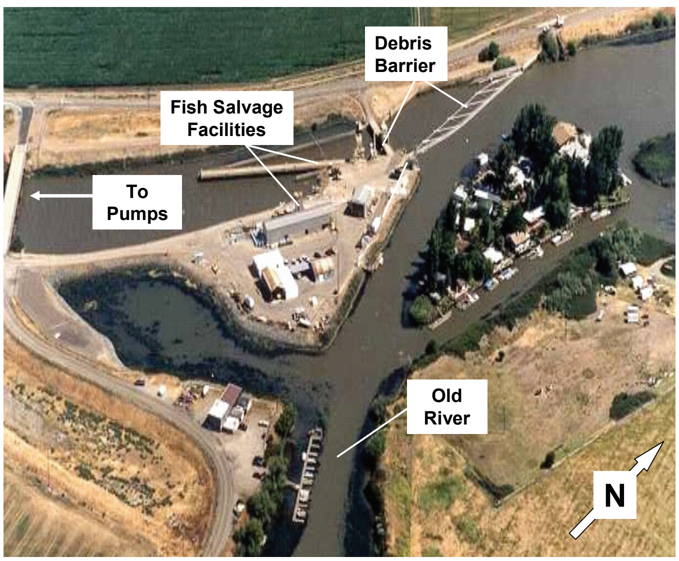


Figure 2 Aerial photograph of the Central Valley Project Delta water export facilities (CVP) head works. See Figure 1 for the general location of the CVP. The CVP export pumps are outside of this photograph.

The SWP head works (Figure 3) include: 1) five radial gates, which regulate water diversion from Old River into Clifton Court Forebay (CCF), a 37-million-m^3 regulating reservoir; 2) an approach canal from CCF to the pumping plant; 3) the SWP fish salvage facilities; and 4) the pumping plant that lifts water into Bethany reservoir, the headwater reservoir for the California aqueduct. The presence of CCF allows the SWP to operate very differently from the CVP. Unlike the CVP, where some level of diversion is continuously occurring, SWP operators divert water into CCF from the Delta at discrete times of optimal tidal conditions (generally just before or after high tide). Water can be pumped out of CCF to meet water demands before, during, or after these diversions. The SWP head works remove the problems associated with pumping under a varying tidal head and allow operators to take advantage of the daily variations in power costs.

The export rate of either project is limited by physical features (e.g., water capacity of the Delta-Mendota canal for the CVP or CCF storage capacity for the SWP) and a variety of regulations designed to minimize degradation of water levels and water quality (CSWRCB 2000) and limit fish entrainment loss (USFWS 1995).

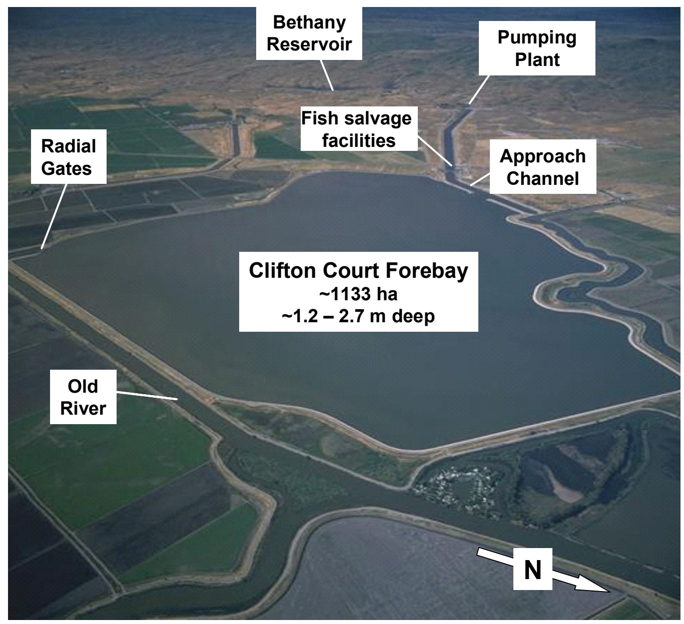


Figure 3 Aerial photograph of the California State Water Project Delta water export facilities (SWP) head works. See Figure 1 for the general location of the SWP.

The purpose of the fish salvage facilities is to reduce the loss of fish entrained in CVP or SWP water destined for export south of the Delta. Diverted water passes through sets of louvers that help to divert fish into holding tanks. Fish in the holding tanks are periodically transferred into tanker trucks, transported away from the SWP and CVP and released into the Delta. These processes are collectively referred to as "fish salvage" or "salvage." The number of fish collected in fish salvage facilities at the SWP and CVP serves as the only routine quantitative measure of incidental take and fish entrainment in State and Federal water diversions. Additional details on fish salvage are available in Brown et al. (1996).

Before fish protection became an important consideration, springtime operations of the CVP and SWP were focused on directly providing water to contractors and to filling San Luis Reservoir, a large storage reservoir, to the south of the facilities. High springtime pumping rates are possible because snowmelt runoff from the Sierra Nevada flows into the Delta at this time of year. Water stored in San Luis Reservoir is used to provide water to contractors later in the year when river inflows to the Delta are relatively low. As already mentioned, the biological opinions for delta smelt and other listed species could necessitate unanticipated and uncompensated export reductions, thereby introducing uncertainty into the ability of the CVP and SWP to fulfill springtime contractual obligations and fill San Luis Reservoir to meet later obligations. The EWA shoulder-on-VAMP action restricts spring-time exports to predetermined levels. However, EWA fully compensates these export reductions by allowing greater pumping rates before and after imposition of export restrictions, along with water marketing and water transfer activities to fulfill water contract obligations (CALFED 2000, White and Poage 2004).

Between 2001 and 2004 the annual shoulder-on-VAMP export curtailment represented a substantial use of available EWA water (Table 3). Variations in the amount of EWA water used by the shoulder-on-VAMP export curtailment depended on the duration of the curtailment, and more importantly, on estimates of water export levels that would have occurred in the absence of the curtailment. These estimates depend on the annual delivery commitments of the water projects and the delivery schedule (T. Pettit, CDWR, pers. comm.). The shoulder-on-VAMP export curtailment always ended by May 31st. Overall, the shoulder-on-VAMP export curtailments consumed approximately 42% of all EWA water devoted to fish protection actions between 2001 and 2004.

Table 3 Total amount of water available in the Environmental Water Account (EWA) annually for all actions taken to protect fish (EWA Fish Actions), and amounts of EWA water applied annually to the VAMP export curtailment (VAMP Actions) and shoulder-on-VAMP export curtailment (Shoulder Actions). All values are m3 (× 1,000). Values in parentheses are percentages of EWA fish action water consumed by each type of action.

Year	*EWA Fish Actions*	*VAMP Actions*	*Shoulder Actions*
2001	357.7	53.04 (15)	18.50 (5)
2002	360.2	55.51 (15)	162.8 (45)
2003	429.3	39.47 (9)	240.5 (56)
2004	153.0	24.67 (16)	128.3 (84)
4-year Total	1,300.2	172.7 (13)	550.2 (42)

Methods and Materials

Study organism

The delta smelt is endemic to the low-salinity and freshwater regions of the San Francisco Estuary (Moyle 2002, Bennett 2005). This relatively small planktivore is semelparous, reproducing in late winter and spring in the freshwater regions of the Sacramento-San Joaquin Delta and Suisun Bay (Figure 1; Moyle 2002). In the field, spawning is believed to occur at temperatures between 15°C and 20°C during spring tides (Bennett 2005). Fertilized eggs produce adhesive stalks allowing eggs to develop while attached to demersal substrates (Mager et al. 2003). In laboratory studies, Mager et al. (2003) found embryo development and hatching take 11 – 13 days (at 14.8 – 16ºC), while larval development including swim bladder inflation and fin differentiation takes 60 – 70 days (at 16 – 17ºC). Delta smelt larvae are 5-mm in length at hatch and average growth rates in the laboratory are ~ 0.4 mm day^{-1} (B. Bridges, UCD, pers. comm.). Larvae and juveniles rear in fresh and brackish water areas of the Estuary (Moyle 2002). In this article, "young delta smelt" includes the larval and early juvenile life stages.

Delta smelt occupy a relatively narrow range of temperature conditions, even compared to the closely related wakasagi (*Hypomesus nipponensis)* (Swanson et al. 2000). Delta smelt acclimated to 17°C had upper and lower critical thermal maxima of 25.4°C and 7.5°C, respectively (Swanson et al. 2000). In the field, delta smelt have been observed at temperatures ranging from 6°C and 28°C (Moyle 2002); however, the vast majority of delta smelt (>90%) have been captured at temperatures <22°C (Bennett 2005).

Data sources

We used data on SWP and CVP export rates to document water project operations. These data are maintained as part of the fish salvage database and are available from the CDFG at http://www.delta.dfg.ca.gov/Data/Salvage/. Export rates are reported as daily averages and export volumes as total volume per day. For the CVP, daily average export rates are a relatively accurate measure of the export rate at any time throughout the day because the export rate is generally constant over the entire day. This is not the case at the SWP, because diversions out of the Delta into CCF only occur over a portion of the day when the radial gates are open, ranging from 1 to 17 hours. For example, to achieve a daily average export rate of ~42.5 $m^3 s^{-1}$ during the shoulder-on-VAMP export curtailment, the diversion rate into CCF might range from 122 $m^3 s^{-1}$ to 208 $m^3 s^{-1}$ over a 5-hour period or it might range from 40 $m^3 s^{-1}$ to 110 $m^3 s^{-1}$ over an 8-hour period.

To better understand SWP water diversion dynamics and its potential effects on delta smelt entrainment, we calculated hourly diversion rates into CCF. We used a spreadsheet model developed by CDWR to calculate hourly diversion rates for the March 1 – July 1 period in the years 2001 – 2004. This spreadsheet calculates hourly inflow through the radial gates into CCF based on measured values of water stage inside and outside of the radial gates and the height to which each of the five radial gates is raised. This spreadsheet is available from the CDWR at http://www.iep.ca.gov/dsm2pwt/dsm2pwt.html. The data used to populate the spreadsheet are available at http://iep.water.ca.gov/cgi-bin/dss/dss1.pl?station=CHWST000.

Fish salvage processes at the SWP and CVP include regular sampling to estimate the number, species, and length of fish collected. A multiplier based on the proportion of the pumping interval sampled is used to expand the number of individual fish collected in a sample to arrive at estimates of "expanded salvage" or "salvage" for the entire pumping interval. For example, if export pumping occurs for 120 minutes and a 10-minute sample is taken during that 120-minute interval, then the expansion multiplier is 120/10 = 12. Generally, a 10-minute sample is collected every two hours of export pumping. Expanded salvage values are summed over the day to yield an estimate of total daily salvage for each fish species collected. For delta smelt, this total daily salvage value is also used as the daily estimate of incidental take. Fish length (total length) is measured and recorded by species for a subset of fish collected during each sampling interval. The size of the subset varies depending on the number of individuals collected. These data and the associated operational data (e.g., export rate, water temperature, and time of day) are managed by CDFG. Brown et al. (1996) provides more information about the salvage facilities and the sampling program.

Analyses presented in this paper use daily total salvage data collected at the SWP and CVP over the period of interest. Delta smelt salvage data collected prior to 1993 are not considered due to limited confidence in the accuracy of these data (S. Foss, CDFG, pers. comm.). Historical fish salvage data are available from CDFG at http://www.delta.dfg.ca.gov/Data/Salvage/.

Although enumeration of delta smelt collected at the CVP and SWP fish salvage facilities is the only quantitative estimate of fish entrainment at these diversions, neither facility is able to routinely collect and enumerate delta smelt less than 20 mm total length (Figure 4) due to physical and process limitations (S. Foss, CDFG, pers. comm.). Annual estimates of delta smelt spawning period indicate that larval delta smelt between 5 and 20 mm are in Delta waters, including water exported from the Delta, in the April – May period of most years (Bennett 2005). Thus, the existing salvage operations provide an incomplete estimate of young delta smelt entrainment in the SWP and CVP diversions. Although understanding the factors driving extreme entrainment events is a purpose of this paper, the available data only permit investigation of the factors responsible for extreme salvage events. Therefore, the second question addressed in this article was modified to focus on the combination of physical conditions that result in extreme salvage events.

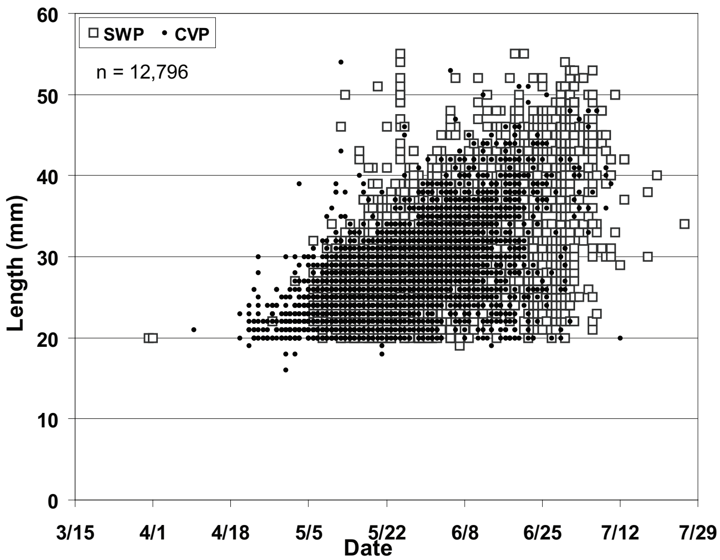


Figure 4 Length of young delta smelt collected at the SWP and CVP fish salvage facilities from 1995 through 2003. Reported lengths are total length measurements from a subset of fish collected during each sampling event.

The distribution of larval delta smelt was estimated using monitoring data from CDFG 20-mm survey. This survey started in 1995 and is designed primarily to sample young-of-year delta smelt (Dege and Brown 2004). The survey collects samples throughout the upper SFE (from San Pablo Bay through the Delta, Figure 1) providing abundance and distribution estimates every two weeks in the spring and summer. Dege and Brown (2004) provide more details about the 20-mm survey. The 20-mm survey data are available from CDFG at http://www.delta.dfg.ca.gov/data/20mm/. Estimates of daily Delta outflow are available from CDWR at http://www.iep.ca.gov/dayflow/index.html. These estimates were used to assess relationships between Delta outflow and distribution of young delta smelt.

The California Department of Water Resources (CDWR) continuously monitors water temperature at several locations in the Delta. For this study, we used average daily water temperature data collected at the SWP Harvey O. Banks pumping plant, because we wanted to examine the relationship between delta smelt salvage levels and water temperatures at the SWP. Water temperature data are available from the CDWR California Data Exchange Center at http://cdec.water.ca.gov/cgi-progs/selectO-MWQ.

Hydrodynamic variables (e.g., water stage and velocity) are continuously monitored at several locations in the Delta by the U.S. Geological Survey (USGS). Analyses in this paper use average daily river flow data in Old River at Bacon Island (Figure 1) as an indication of the timing and magnitude of SWP and CVP operational effects on interior Delta hydraulics. Delta hydrodynamics data are available from the USGS at http://baydelta.wr.usgs.gov/. Ruhl and Simpson (2005) provide details on the instrumentation and methods used to collect and process daily river flow data in the Sacramento-San Joaquin Delta.

Analyses

We first examined delta smelt salvage data from May through June in the years 1994 through 2004 to evaluate differences in delta smelt salvage levels between the CVP and SWP. Log-transformed mean daily delta smelt salvage and mean daily delta smelt salvage density (number of fish 10,000-m^{-3} of water exported) at the SWP and CVP were analyzed using a two-factor, fixed effects ANOVA. The factors in the ANOVA model were year, facility (SWP or CVP), and year x facility interaction.

We then examined patterns and relationships among long-term data sets of delta smelt salvage at the SWP and CVP and temporally associated environmental variables (i.e., water temperature, water export rates, and flow in Old River) for selected years. We focus on the period between March 1 and July 1, because this is the time when young delta smelt occur in the central and southern Delta and when episodes of high incidental take at the SWP and CVP typically occur (Table 2). Data from the March 1 to July 1 timeframe were divided into four periods for analysis: 1) the 31-day period prior to the VAMP export curtailment (Pre-VAMP); 2) the 31-day VAMP export curtailment period (VAMP); 3) the 11 to 16-day shoulder-on-VAMP export curtailment period (Shoulder); and 4) the 31-day period after the shoulder-on-VAMP export curtailment (Post-Shoulder). We included all four years in which the shoulder-on-VAMP export curtailment occurred (2001 – 2004). For comparative purposes, we also examined two years (1993 and 2000) in which the shoulder-on-VAMP export curtailment did not occur. We included 1993 because it was a year of relatively limited export curtailment (an approximately three-week export curtailment did occur in the spring) and relatively high numbers of young delta smelt occurred in the central and south Delta. We included 2000 because it was the first year of the VAMP export curtailment (SJRG 2000), and the only year when a VAMP export curtailment occurred without a shoulder-on-VAMP. Comparisons were made by visual examination of plots of export rates, Old River flow, salvage rate, and water temperature for each year.

We used a linear extrapolation of fish salvage to estimate the annual reduction in CVP and SWP salvage of young delta smelt resulting from the shoulder-on-VAMP export curtailment. Specifically, the average density of young delta smelt (number of fish/m^3 d^{-1}) estimated at each salvage facility during the shoulder-on-VAMP export curtailment period was multiplied by the amount of water that would have been exported if the curtailment had not occurred. The result is an estimate of the number of fish potentially salvaged if the shoulder-on-VAMP export curtailment did not occur. A linear extrapolation of fish salvage at the CVP facilities is considered a reasonable first order approximation of shoulder-on-VAMP export effects, given the relatively constant pumping rates and lack of features (e.g., a forebay) that could result in the retention or accumulation of young delta smelt. There is greater uncertainty associated with a linear extrapolation of fish salvage at the SWP facilities, given the spatial and temporal separation between water diversions and water pumping, and the possibility of retention or accumulation of young delta smelt in CCF. The major assumptions in these extrapolations are: 1) the density of young delta smelt collected at the salvage facility does not change under different export rates or volumes; and 2) pre-salvage mortality of entrained delta smelt is negligible.

To better understand how SWP operations might affect delta smelt entrainment we examined how hourly inflow rate and hours of gate opening (duration of diversion) differed between the four periods of interest (Pre-VAMP, VAMP, Shoulder, and Post-Shoulders). Mean inflow rates and mean durations of diversion among the four periods were analyzed using a two-factor, fixed effects ANOVA. The factors in the ANOVA model were year, period, and year x period interaction. A Tukey multiple comparison test was used for pair-wise comparisons.

Finally, we investigated the relationship between the distribution of larval delta smelt and freshwater outflow from the Delta. Catch of delta smelt during the first four 20-mm surveys of each year (1995 – 2004) were combined to estimate the proportion of young delta smelt in the southeast Delta just prior to the May-June salvage period. These estimates were compared to estimates of mid-March through mid-May Delta outflow to determine if there was any relationship between springtime outflow and the resulting distribution of young delta smelt.

Results

Between 1994 and 2004, most young delta smelt were collected during the months of May and June at both the SWP and CVP salvage facilities (Table 2). Delta smelt salvage and salvage density differed significantly between facilities ($F_{1,1342} = 17.1$; $P < 0.001$ and $F_{1,1342} = 25.5$; $P < 0.001$, respectively) and among years ($F_{10,1342} = 50.9$; $P < 0.001$ and $F_{10,1342} = 31.3$; $P < 0.001$, respectively), with significant interactions of facilities and years ($F_{10,1342} = 5.4$; $P < 0.001$ and $F_{10,1342} = 7.7$; $P < 0.001$, respectively). In general, salvage and salvage density were highest at the SWP (Figure 5). The interaction of facilities and years was associated with high salvage and salvage density at the CVP during 1996 and relatively equal salvage and salvage density at the CVP and SWP in 1997, 2003, and 2004. Overall, the ANOVA results support the idea that extreme salvage events of young delta smelt were often driven by salvage events at the SWP. For this reason, we focused subsequent analyses on young delta smelt salvage at the SWP.

The VAMP and shoulder-on-VAMP export curtailments resulted in substantial changes in interior Delta hydraulics as indicated by changes in the direction and magnitude of daily average net flow in Old River (Figures 6A, 7A, 8A, and 9A). Old River flow was less negative and sometimes slightly positive (i.e., the magnitude of export-mediated reverse flow was reduced) throughout each of the export curtailment events. Note that these flows represent the net flows after tidal flows have been filtered out. Ruhl and Simpson (2005) provide more detail on this concept.

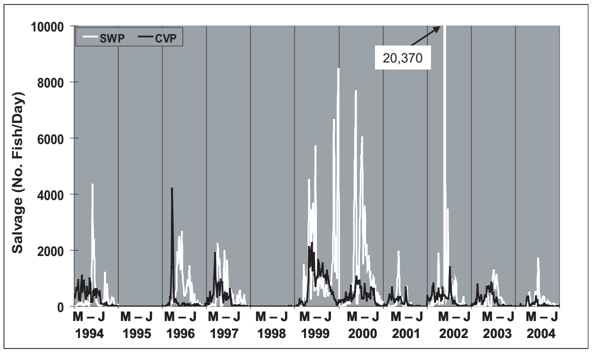


Figure 5B.

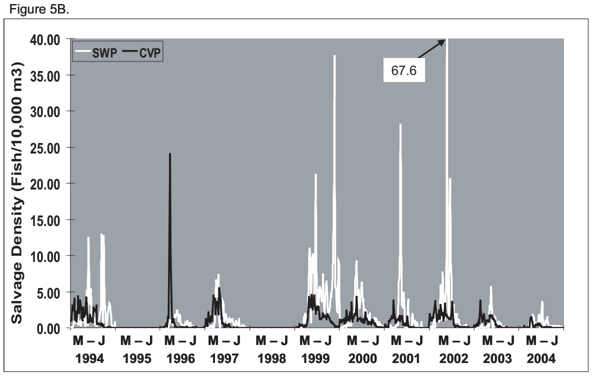


Figure 5A Number of delta smelt collected daily at the SWP and CVP salvage facilities in May and June from 1994 through 2004.

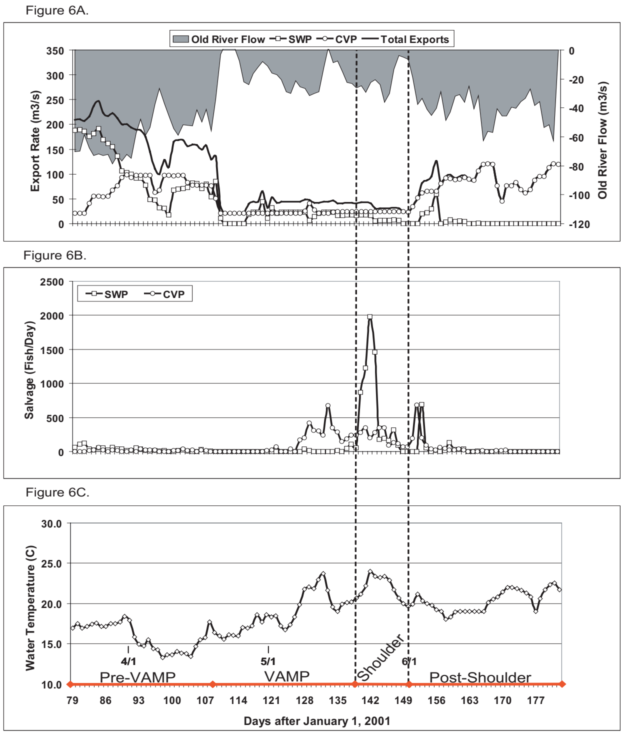
Figure 5B Daily delta smelt salvage density (fish 10,000 m-3) at the SWP and CVP facilities in May and June from 1994 through 2004.

The VAMP and shoulder-on-VAMP export curtailments varied somewhat among the four years (Figures 6A, 7A, 8A, and 9A). Overall, export rates were most uniform during the 2001 and 2002 curtailment periods. Export rates were generally lowest in 2001 and 2002, although the shoulder-on-VAMP curtailment period only extended for 11 days in 2001 compared to 16 days in the other years. The level of export curtailment was reduced near the end of the shoulder-on-VAMP action in 2003 and 2004. The export curtailment was reduced in 2003 due to concern that water costs could exceed available EWA assets and the high cost of repayment (White and Poage 2004). The export curtailment was reduced in 2004 after 20-mm survey data indicated young delta smelt were emigrating from the Delta, reducing the concern over excessive entrainment (V. Poage, USFWS, pers. comm.). The shoulder-on-VAMP export curtailment ended on May 31st in each of the four years. Consistency among years in the ending date was driven primarily by the availability and allocation of EWA assets (V. Poage, USFWS, pers. comm.).

Abrupt increases in SWP salvage of young delta smelt occurred in the May-June period of all years in which the shoulder-on-VAMP export curtailment occurred, although the magnitude and duration of the increase varied among years (Figures 6B, 7B, 8B, and 9B). Extreme SWP salvage of young delta smelt occurred during (2001 and 2002), or immediately after (2003 and 2004) the shoulder-on-VAMP export curtailment. Abrupt increases in CVP salvage of young delta smelt also occurred in the May-June period, although the timing and duration often differed from the SWP events. Appreciable salvage of young delta smelt generally occurred first at the CVP. Extreme SWP salvage events in any one-year were two to twenty times larger than extreme CVP salvage events.

Between 2001 and 2004, extreme SWP salvage of young delta smelt occurred when water temperatures inside CCF were at or increasing above 20°C (Figures 6C, 7C, 8C, and 9C). In all years except 2002, the highest levels of daily SWP salvage occurred when water temperatures were consistently 20°C or greater for the second time between March 1 and July 1. In 2002, the highest levels of daily SWP salvage occurred when water temperatures were warming to 20°C for the first time in the March to July period.

Patterns observed in 1993 and 2000 were consistent with patterns observed from 2001 through 2004 (Figures 10 and 11). Abrupt increases in SWP salvage of young delta smelt occurred in the May-June period after a period of export curtailment. Extreme SWP salvage events of young delta smelt differed from CVP salvage events in timing and duration. Extreme SWP salvage events were four to eight times larger than peak CVP salvage. And, abrupt increases in SWP salvage of young delta smelt generally occurred when water temperatures inside CCF were at or increasing above 20×C. An exception occurred in June 1993 when two, one-day increases in SWP salvage of young delta smelt occurred when daily average water temperatures were 19°C.



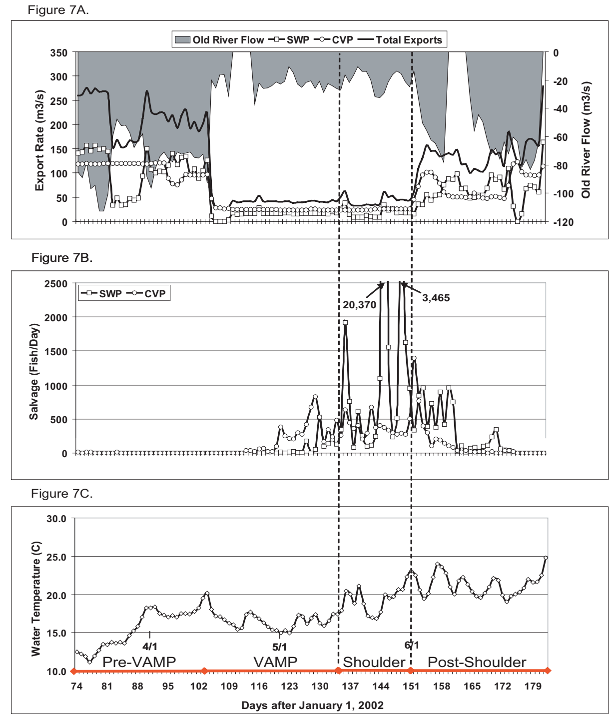


Figure 6A Daily export rate at the SWP and CVP Delta export facilities, total (SWP + CVP) daily export rate, and daily average flow in Old River between March and July 2001. Daily values are presented for four periods described in the Methods and Materials section. The x-axis values are Julian days as listed in figure 6C.

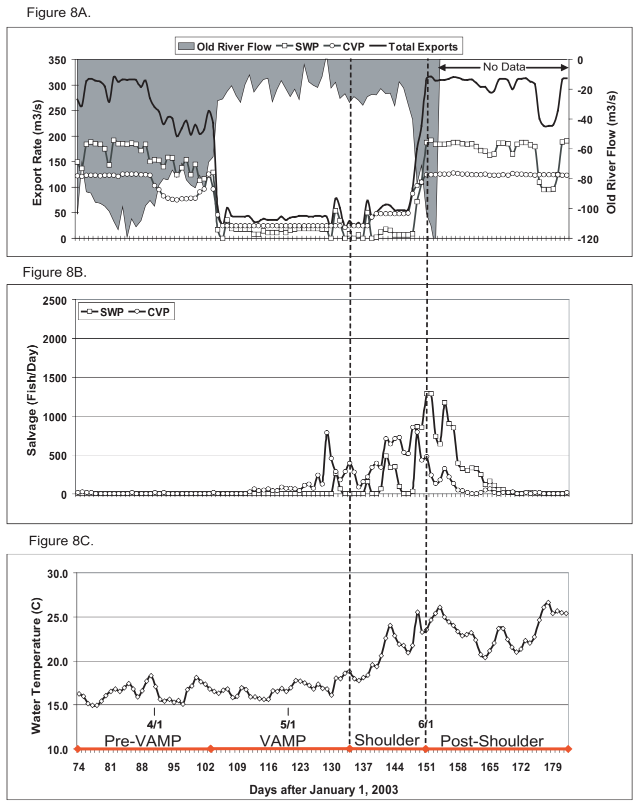
Figure 6B Daily number of delta smelt collected at the SWP and CVP salvage facilities between March and July 2001. Daily values are presented for four periods described in the Methods and Materials section. The x-axis values are Julian days as listed in figure 6C.

Figure 6C Daily average water temperature at the SWP Harvey O. Banks pumping plant between March and July 2001. The pumping plant receives water from Clifton Court Forebay and these data are used to indicate water temperatures in the Forebay. Daily values are presented for four periods described in the Methods and Materials section. The x-axis values are Julian days.

Figure 7A Daily export rate at the SWP and CVP Delta export facilities, total (SWP + CVP) daily export rate, and daily average flow in Old River between March and July 2002. Daily values are presented for four periods described in the Methods and Materials section. The x-axis values are Julian days as listed in figure 7C.

Figure 7B Daily number of delta smelt collected at the SWP and CVP salvage facilities between March and July 2002. Daily values are presented for four periods described in the Methods and Materials section. The x-axis values are Julian days as listed in figure 7C.

Figure 7C Daily average water temperature at the SWP Harvey O. Banks pumping plant between March and July 2003. The pumping plant receives water from Clifton Court Forebay and these data are used to indicate water temperatures in the Forebay. Daily values are presented for four periods described in the Methods and Materials section. The x-axis values are Julian days.



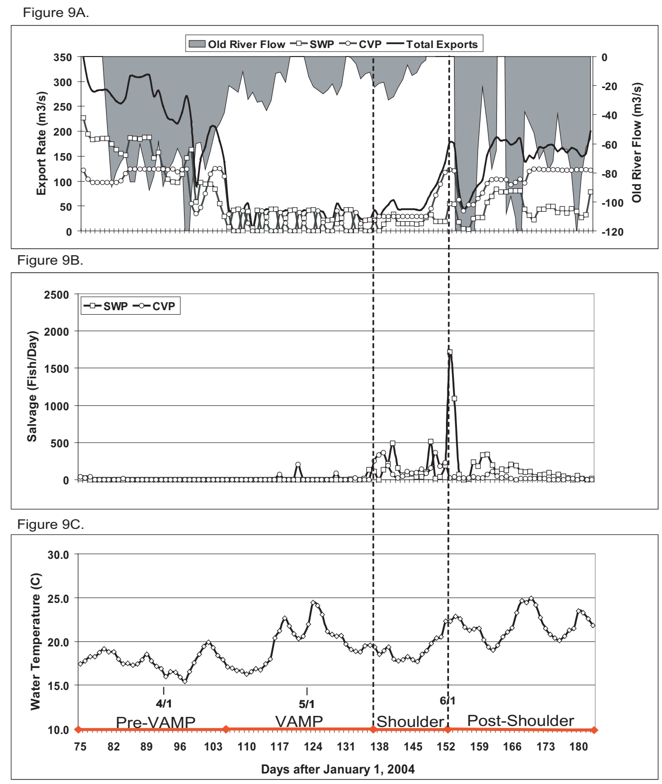


Figure 8A Daily export rate at the SWP and CVP Delta export facilities, total (SWP + CVP) daily export rate, and daily average flow in Old River between March and July 2003. Daily values are presented for four periods described in the Methods and Materials section. The x-axis values are Julian days as listed in figure 8C.

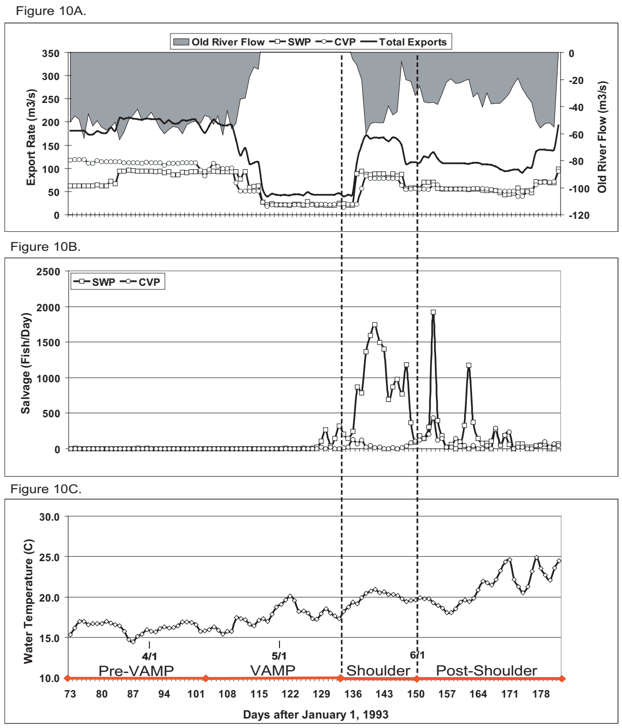
Figure 8B Daily number of delta smelt collected at the SWP and CVP salvage facilities between March and July 2003. Daily values are presented for four periods described in the Methods and Materials section. The x-axis values are Julian days as listed in figure 8C.

Figure 8C Daily average water temperature at the SWP Harvey O. Banks pumping plant between March and July 2003. The pumping plant receives water from Clifton Court Forebay and these data are used to indicate water temperatures in the Forebay. Daily values are presented for four periods described in the Methods and Materials section. The x-axis values are Julian days.

Figure 9A Daily export rate at the SWP and CVP Delta export facilities and total (SWP + CVP) daily export rate between March and July 2004. Data for daily average flow in Old River were not available at the writing of this paper. Daily values are presented for four periods described in the Methods and Materials section. The x-axis values are Julian days as listed in figure 9C.

Figure 9B Daily number of delta smelt collected at the SWP and CVP salvage facilities between March and July 2004. Daily values are presented for four periods described in the Methods and Materials section. The x-axis values are Julian days as listed in figure 9C.

Figure 9C Daily average water temperature at the SWP Harvey O. Banks pumping plant between March and July 2004. The pumping plant receives water from Clifton Court Forebay and these data are used to indicate water temperatures in the Forebay. Daily values are presented for four periods described in the Methods and Materials section. The x-axis values are Julian days.



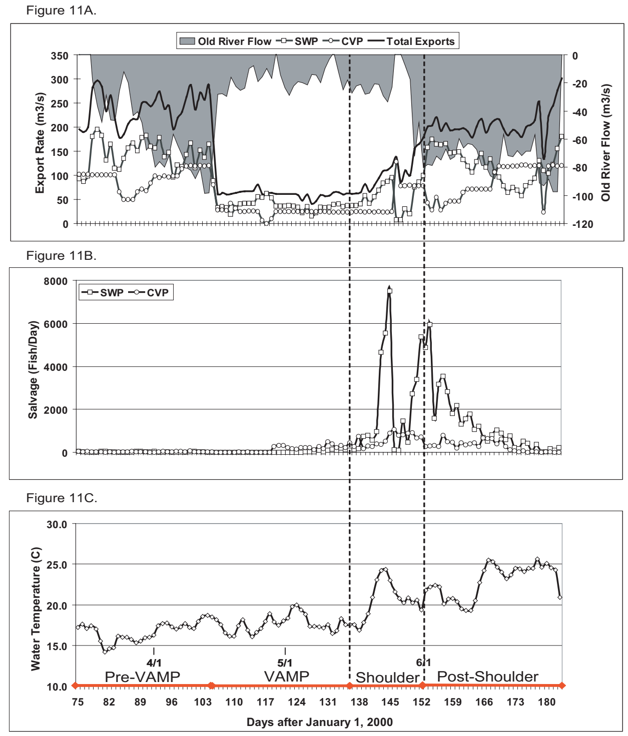


Figure 10A Daily export rate at the SWP and CVP Delta export facilities, total (SWP + CVP) daily export rate, and daily average flow in Old River between March and July 1993. Daily values are presented for four periods to facilitate comparison with 2001 - 2004 data. The x-axis values are Julian days as listed in figure 10C.

Figure 10B Daily number of delta smelt collected at the SWP and CVP salvage facilities between March and July 1993. Daily values are presented for four periods to facilitate comparison with 2001 - 2004 data. The x-axis values are Julian days as listed in figure 10C.

Figure 10C Daily average water temperature at the SWP Harvey O. Banks pumping plant between March and July 1993. The pumping plant receives water from Clifton Court Forebay and these data are used to indicate water temperatures in the Forebay. Daily values are presented for four periods to facilitate comparison with 2001 - 2004 data. The x-axis values are Julian days.

Figure 11A Daily export rate at the SWP and CVP Delta export facilities, total (SWP + CVP) daily export rate, and daily average flow in Old River between March and July 2000. Daily values are presented for four periods to facilitate comparison with 2001 - 2004 data. The x-axis values are Julian days as listed in figure 11C.

Figure 11B Daily number of delta smelt collected at the SWP and CVP salvage facilities between March and July 2000. Daily values are presented for four periods to facilitate comparison with 2001 - 2004 data. Note change in Y-axis scale compared to similar figures for other years. The x-axis values are Julian days as listed in figure 11C.

Figure 11C Daily average water temperature at the SWP Harvey O. Banks pumping plant between March and July 2000. The pumping plant receives water from Clifton Court Forebay and these data are used to indicate water temperatures in the Forebay. Daily values are presented for four periods to facilitate comparison with 2001 - 2004 data. The x-axis values are Julian days.

Our estimates suggest the shoulders-on-VAMP export curtailment reduced CVP and SWP salvage of young delta smelt in each year between 2001 and 2004 (Table 4). The estimated amount of salvage reduction varied among years due to differences in both salvage density and the estimated increase in exports that would have occurred in the absence of the shoulder-on-VAMP curtailment. Over the four year period, the estimates suggest that without the shoulder-on-VAMP young delta smelt salvage would have more than doubled at the CVP and more than tripled at the SWP due mainly to increased salvage estimates for 2002.

Table 4 Actual and estimated salvage of young delta smelt at the CVP and SWP during the shoulder-on-VAMP export curtailment period in 2001 - 2004. Actual salvage is the sum of reported daily values during the curtailment period. Mean salvage density (fish m^{-3} d^{-1}) is the mean of daily salvage densities derived from reported values of daily salvage and daily exports during the curtailment period. Estimated export (m^3) is the estimated volume of water (T. Pettit, CDWR, pers. comm.) that would have been exported by the CVP or SWP over the shoulder-on-VAMP period if the export curtailment did not occur. Estimated salvage for each year is calculated as: (mean salvage density)×(estimated exports). Salvage difference is the difference between estimated salvage and actual salvage.

Year	*Actual Salvage*	*Mean Salvage Density*	*Estimated Export*	*Estimated Salvage*	*Salvage Difference*
		CVP			
2001	2,208	0.93×10^{-4}	48,772,086	4,536	2,328
2002	6,144	1.80×10^{-4}	119,921,349	21,586	15,442
2003	7,896	1.06×10^{-4}	111,387,638	11,807	3,911
2004	2,724	0.57×10^{-4}	120,707,799	6,880	4,156
4-Yr. Total	18,972	--	--	44,809	25,837
		SWP			
2001	5,613	5.94×10^{-4}	28,842,184	17,132	11,519
2002	33,899	9.94×10^{-4}	103,313,097	102,693	68,794
2003	4,506	$1.08 \text{ X } 10^{-4}$	261,025,546	28,191	23,685
2004	2,257	0.75×10^{-4}	83,835,037	6,288	4,031
4-Yr. Total	*46,275*	--	--	*154,304*	*108,029*

Average hourly diversion rates into CCF were very different from the generally reported daily average values. During the VAMP and shoulder-on-VAMP export curtailment periods, the total combined (CVP + SWP) export rate was targeted to average ~43 m^3 s^{-1} over a 24-hour period. In most years, the CVP and SWP are operated to achieve an equal export rate, meaning the SWP export rate averages ~21.5 m^3 s^{-1} over a 24-hour period during curtailment events. However, calculated values for the SWP during the export curtailment periods show mean diversion rates ranged from ~79 m^3 s^{-1} over a mean diversion duration of seven hours in 2001 to ~212 m^3 s^{-1} over a mean diversion duration of five hours in 2003 (Table 5). During periods when export curtailments are not in effect, the SWP can routinely divert water at a maximum mean rate of ~189 m^3 s^{-1} over a 24-hour period. However, calculated values during the pre-VAMP and post-shoulder period show mean SWP diversion rates ranged from ~149 m^3 s^{-1} over a mean diversion duration of five hours in 2001 to ~284 m^3 s^{-1} over a mean diversion duration of 15 hours in 2003. It was not uncommon for mean pumping rates to differ substantially from mean diversion rates within any of the periods examined (Table 5). Overall, calculations of estimated diversion rates into CCF suggest very high diversion rates are common and hourly diversion rates can deviate substantially from 24-hour averages.

Table 5 Summary statistics for SWP operations during four periods in the years 2001 - 2004. See Methods and Materials for specifics on the four periods examined in this study. Mean pumping rate is the volume of water pumped out of Clifton Court Forebay averaged over the time pumping occurred each day during the period of interest. Mean diversion rate is the rate of water inflow into Clifton Court averaged over the time the radial gates were open during the period of interest. Mean diversion duration is the average number of hours the radial gates were open during the period of interest. Percentage of days open is the percentage of days during each period in which the Clifton Court Forebay radial gates were open for at least one hour. Mean rates are expressed as m3 s-1 ± 1 SD (standard deviation). Mean duration is hours ± 1 SD.

Period	*Mean Pumping Rate (± SD)*	*Mean Diversion Rate (± SD)*	*Mean Diversion Duration (± SD)*	*Percentage of Days Open*
		2001		
Pre-VAMP (31 days)	99.7 (± 75.7)	261 (± 108)	10 (± 4.6)	100
VAMP (31 days)	17.4 (± 23.7)	153 (± 102)	4 (± 2.7)	97
Shoulder (11 days)	5.82 (± 13.8)	78.7 (± 82.7)	7 (± 3.0)	73
Post-shoulder (31 days)	4.32 (± 16.3)	149 (± 134)	5 (± 6.3)	35
		2002		
Pre-VAMP (31 days)	100 (± 74.1)	244 (± 104)	11 (± 4.0)	100
VAMP (31 days)	15.4 (± 23.7)	205 (± 110)	3 (± 1.1)	100
Shoulder (16 days)	17.8 (± 28.2)	112 (± 58.8)	5 (± 2.2)	100
Post-shoulder (31 days)	62.1 (± 65.9)	214 (±128)	9 (± 2.8)	100
		2003		
Pre-VAMP (31 days)	151 (± 68.8)	266 (± 107)	15 (± 2.8)	100
VAMP (31 days)	16.0 (± 30.1)	167 (± 101)	3 (± 1.6)	97
Shoulder (16 days)	31.3 (± 61.2)	212 (± 111)	5 (± 5.0)	100
Post-shoulder (31 days)	157 (± 63.6)	284 (± 111)	15 (± 3.1)	100
		2004		
Pre-VAMP (31 days)	138 (± 66.0)	237 (± 110)	14 (± 4.1)	100
VAMP (31 days)	22.8 (± 21.2)	153 (± 104)	5 (± 2.5)	100
Shoulder (16 days)	18.5 (± 27.0)	154 (± 106)	3 (± 1.5)	94
Post-shoulder (31 days)	43.5 (± 55.8)	158 (± 134)	8 (± 3.5)	97

Mean diversion rates into CCF differed significantly among years ($F_{3,3296} = 41.5$; $P < 0.001$) and periods ($F_{3,3296} = 125.5$; $P < 0.001$). Mean diversion rates into CCF were lower during the VAMP and shoulder-on-VAMP export curtailment periods compared to the Pre-VAMP period, although the amount of reduction was inconsistent among years and across periods (Table 5). These inconsistencies caused a significant interaction ($F_{9,3296} = 18.9$; $P < 0.001$). Tukey multiple comparison tests of main effects indicated that diversion rates were highest in 2003. Mean diversion rates were slightly higher in 2002 compared to 2004. Diversion rates were similar in 2001 and 2004. All pair wise comparisons of periods were significant but diversion rates tended to be much higher during the Pre-VAMP and Post-shoulder periods compared to lower diversion rates during the VAMP and shoulder-on-VAMP periods (Table 5).

The mean duration of diversion into CCF differed significantly among years ($F_{3,386} = 16.4$; $P < 0.001$) and among periods ($F_{3,386} = 158.4$; $P < 0.001$). In general, the duration of diversion was lowest during VAMP and shoulder-on-VAMP (Table 5) but exceptions to the general pattern resulted in a significant interaction ($F_{9,386} = 12.8$; $P < 0.001$). Tukey multiple comparison tests indicated that the VAMP and shoulder-on-VAMP periods (fewer hours open) did not differ from each other but differed from the pre-VAMP and post-shoulder periods (more hours open). Duration of gate opening was greatest in 2003 with the other years being lower and not significantly different from each other.

Examination of the data for the individual variables (i.e., water stage, height of gate opening, and duration of gate opening) used to calculate diversion rate suggested SWP project operators mainly control inflow into CCF by adjusting the duration of gate opening and secondarily adjusting the rate of inflow by manipulating the extent to which the individual gates are open and the time of day the gates are open in relation to water stage across the gates. Thus, both the magnitude and duration of diversion events into CCF must be considered when examining entrainment dynamics at the SWP.

Between 2001 and 2004 the SWP diverted water into CCF almost every day between March 1 and July 1 (Table 5). The only substantial exception was in 2001, when repairs to the aqueduct lining necessitated a complete shutdown of the pumps removing water from the CCF during much of June. Daily diversions into CCF and daily pumping out of CCF represent normal SWP operations whether export curtailments occur or not.

The proportion of young delta smelt in the southeast Delta during spring ranged from zero to 57% between 1995 and 2004 (Figure 12). Young delta smelt occurred in the southeast delta whenever average daily Delta outflow was < 1,500 $m^3 s^{-1}$ during the mid-March to mid-May period. The proportion of delta smelt in the southeast Delta ranged from 10% to 57% in the years when combined (CVP + SWP) salvage exceeded the authorized incidental take level (Table 2), and these proportions generally bracketed the proportions of young delta smelt estimated to occur in the southeast delta in 2001 through 2004.

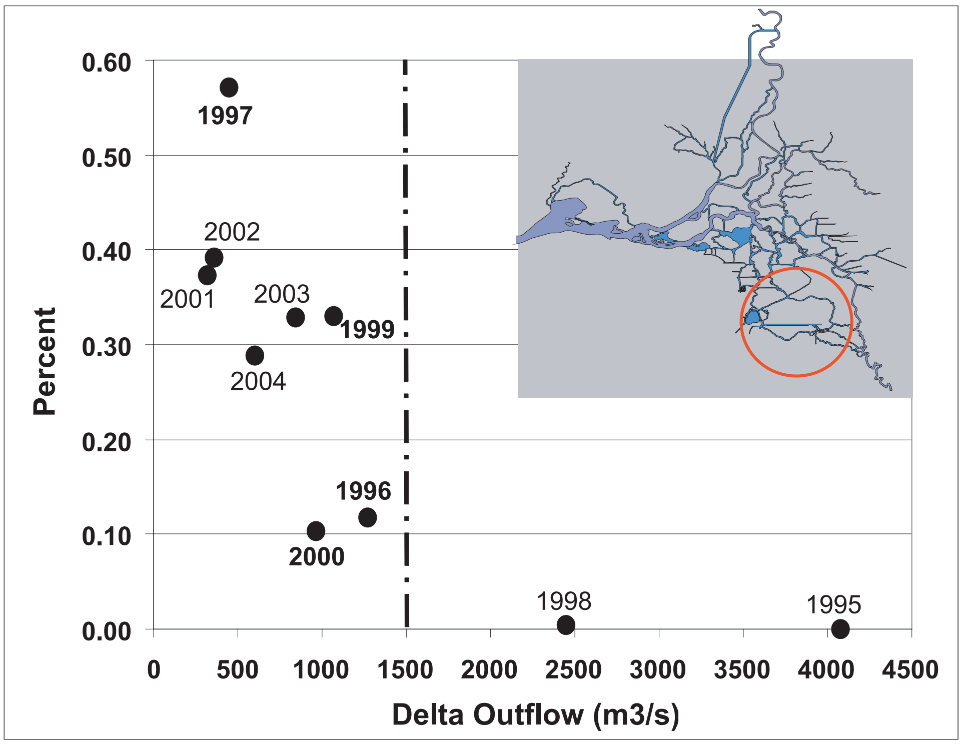


Figure 12 Percentage of young delta smelt estimated to occur in the southeastern Delta (indicated by the circle) after the first four 20-mm surveys versus mean daily Delta outflow from mid-March to mid-May. Year labels are provided for each data point and bold labels indicate years when the USFWS authorized incidental take level for delta smelt was exceeded.

Discussion

The EWA was able to fully compensate for all SWP and CVP export curtailments during spring 2001 – 2004 (White and Poage 2004, J. White, CDFG, pers. comm.), so the mandate of ensuring the reliability of SWP and CVP water deliveries was fully met. The remainder of this discussion focuses on the second part of the paradoxical mandate. Did the EWA actions protect young delta smelt from excessive export entrainment? Specifically, we attempt to answer the two questions posed at the beginning of the paper.

1.What affect does the shoulder-on-VAMP export curtailment have on young delta smelt?

At a qualitative level, it seems reasonable to conclude that shoulder-on-VAMP export curtailments reduced the export entrainment of young delta smelt. Reducing the amount of water diverted from the Delta during the time young delta smelt are present in the Delta should generally result in concurrent reductions in fish entrainment. Our estimates suggest that young delta smelt salvage was reduced substantially at both the CVP and SWP during the two-week shoulder-on-VAMP export curtailment undertaken in 2001 through 2004. However, the utility of these numbers is severely limited by the untested assumptions underlying linear extrapolations of salvage, the lack of information on sampling variability, and at the SWP, the unknown effects of the spatial and temporal separation between water diversions into CCF and export pumping out of CCF. We do not have estimates of the total number of individuals in the population or the affected life stages (e.g., juvenile population size), so we cannot quantify the relative population-level effects of the incidental take as estimated by salvage. Further, we do not fully understand the relationship between salvage and entrainment for young delta smelt, so we do not know if the estimated reductions in salvage translate directly into a similar level of reduction in entrainment. Overall, we conclude that the shoulder-on-VAMP export curtailments likely decreased entrainment of young delta smelt as intended. However, the quantitative information does not exist to determine if the shoulder-on-VAMP significantly enhances the abundance of the delta smelt population as a whole.

Maximizing the benefit of export reductions for young delta smelt requires explicit consideration of the temporal relationships between biological processes and water project operation schedules. Specifically, delta smelt might accrue greater benefits if the onset and duration of export curtailments coincided with the onset and duration of the spawning period. Bennett (2005) indicates that delta smelt spawning occurs in the temperature range of 15°C to 20°C on spring tides. Tidal cycles are well known and water temperature is easily monitored. These two physical variables might serve as useful indicators of the onset of delta smelt spawning and as a trigger for export curtailments. Reducing exports early in the spawning period could minimize the adverse effects of SWP and CVP diversions on south Delta hydraulics at a time when developing larvae are most vulnerable to hydrodynamic influences.

Previous evaluations of measures to protect delta smelt from excessive entrainment loss (e.g., Poage 2004, or Nobriga et al. 2001) generally compared actual salvage levels to the USFWS authorized incidental take levels (i.e., Table 2 vs. Table 1). If salvage levels stay below the authorized incidental take levels then it is generally concluded that excessive export entrainment loss was avoided. The major drawback of this evaluation—besides not knowing the quantitative relationship between entrainment and salvage— is that events in any year are compared only to average historical salvage. Such comparisons are of limited value for an annual species that is susceptible to large fluctuations in abundance among years and life stages (Bennett 2005). More recent efforts have focused on developing evaluation criteria to determine if a shoulder-on-VAMP export curtailment should occur in any given year (Poage 2004). These criteria include: 1) the index of adult abundance in the previous year; 2) the relative abundance of young delta smelt in the southern Delta; 3) delta smelt salvage levels; 4) hydrologic conditions; and 5) length of spawning period estimated from Delta water temperatures. Yet, with the exception of salvage levels, none of these criteria have been routinely used to assess the effectiveness of measures specifically designed to protect delta smelt.

It will be difficult to conduct more sophisticated assessments of protective measures like the shoulder-on-VAMP until several underlying knowledge limitations are addressed. Key limitations include: 1) the inability of the SWP and CVP facilities to quantify the salvage of young delta smelt < 20 mm; 2) the unknown quantitative relationship between fish salvage and fish entrainment; 3) the inability to define and locate delta smelt spawning habitat; and 4) limited knowledge regarding the movement and distribution of young delta smelt while rearing in the Delta.

Use of an existing particle tracking model coupled with fish distribution information from the delta smelt 20-mm survey could help to address some of the knowledge limitations mentioned above. The particle tracking model uses inputs of physical conditions derived from a one-dimensional hydrodynamic simulation model of the Delta to track the movement and re-distribution of individual particles. The particles can behave passively (i.e., neutrally buoyant) or include basic behavior (e.g., diel vertical migration). Routinely using this model to evaluate different operational scenarios could help to understand how SWP and CVP operations might affect young delta smelt distribution.

Another approach for improving the assessment of protective measures is to directly estimate fish entrainment through repeated sampling of water at the point of diversion and the surrounding area directly affected by exports. Evaluating this sort of entrainment estimate relative to estimates of the total life stage population obtained by the same sampling methods could provide estimates of the proportion of the population affected by water project entrainment. These sorts of estimates have already been made using data from the 20-mm survey (BJ Miller pers. comm.), but the underlying sampling design requires further optimization to increase the overall sampling frequency and increase the catch efficiency of delta smelt less than 20 mm in length.

2.What combination of physical conditions in the Delta (flows, transport, temperature) results in extreme salvage events of young delta smelt?

Since the listing of delta smelt in 1993, Delta hydrology and the effects of SWP and CVP exports on interior Delta hydraulics have figured prominently in several conceptual models used to describe the physical conditions that result in extreme salvage events (Herbold et al. 1992, USFWS 1995a, b). More recently, Dege and Brown (2004) found that the distribution of young delta smelt relative to a fixed geographic point (i.e., the Golden Gate Bridge) differed significantly with annual outflow conditions. The distribution shifted upstream under low outflow conditions and downstream under high outflow conditions. Once in the Delta, the alteration of interior Delta hydraulics by SWP and CVP operations is thought to inhibit the ability of delta smelt to emigrate from the Delta resulting in direct entrainment losses as well as an increased potential for indirect losses due to increased localized predation, food limitation, increased exposure to small agricultural water diversion facilities, or increased exposure to pollutants. This conceptual model provides much of the basis for the shoulder-on-VAMP export curtailment (Poage 2004).

Our results combined with the results of other recent studies (e.g., Dege and Brown 2004, Bennett 2005) suggest a conceptual model for the combination of physical conditions that give rise to extreme salvage events of young delta smelt (Figure 13). The conceptual model described here is based on the premise that extreme salvage events of young delta smelt are a function of the integrated response of the species to environmental conditions that vary in time and space (Figure 13).

Springtime Delta outflow is the initial environmental factor to consider because adult immigration into the Delta and dispersal to spawning areas is thought to occur largely in response to Delta outflow conditions. This process likely operates on a time scale of weeks to months. Our data (Figure 12) suggest springtime Delta outflow operates like a switch to affect spawning location. When average daily mid-March to mid-May Delta outflow is < 1,500 $m^3 s^{-1}$, some portion of the adult population moves into the southern Delta to spawn. When average daily mid-March to mid-May Delta outflow is > 1,500 $m^3 s^{-1}$ little or no spawning occurs in the southern Delta. The distribution of spawning adults in response to springtime Delta outflow is considered a primary factor in determining the initial distribution of delta smelt larvae.

Once adult delta smelt have moved into the Delta, water temperature becomes important to determining if an extreme salvage event could occur. Bennett (2005) indicates that spawning occurs in the temperature range of 15°C to 20°C on spring tides. Bennett (2005) shows that the onset and duration of the spawning period varies among years and is strongly influenced by large-scale climate events (i.e., El Niño or La Niña events), which affect precipitation and spring water temperatures. During El Niño events, the spawning period is generally shorter because water temperatures increase rapidly. Because Delta water temperatures are mainly driven by ambient air temperature, water temperature has a relatively broad spatial effect throughout the Delta (Kimmerer 2004). The effects of increasing water temperature on delta smelt spawning probably operate on a time scale of weeks.

The timing of delta smelt spawning and rearing in relation to changes in water export conditions are key to determining how interior delta hydraulics affect initial larval distribution and subsequent entrainment. If spawning occurs relatively early (March and April) then a relatively smaller proportion of the larval rearing period will occur under low export conditions afforded by the VAMP (mid-April to mid-May) and shoulder-on-VAMP (mid-May to June) export curtailments. If spawning occurs relatively late (April and May) then a relatively greater proportion of the larval rearing period will occur during the period of export curtailments.

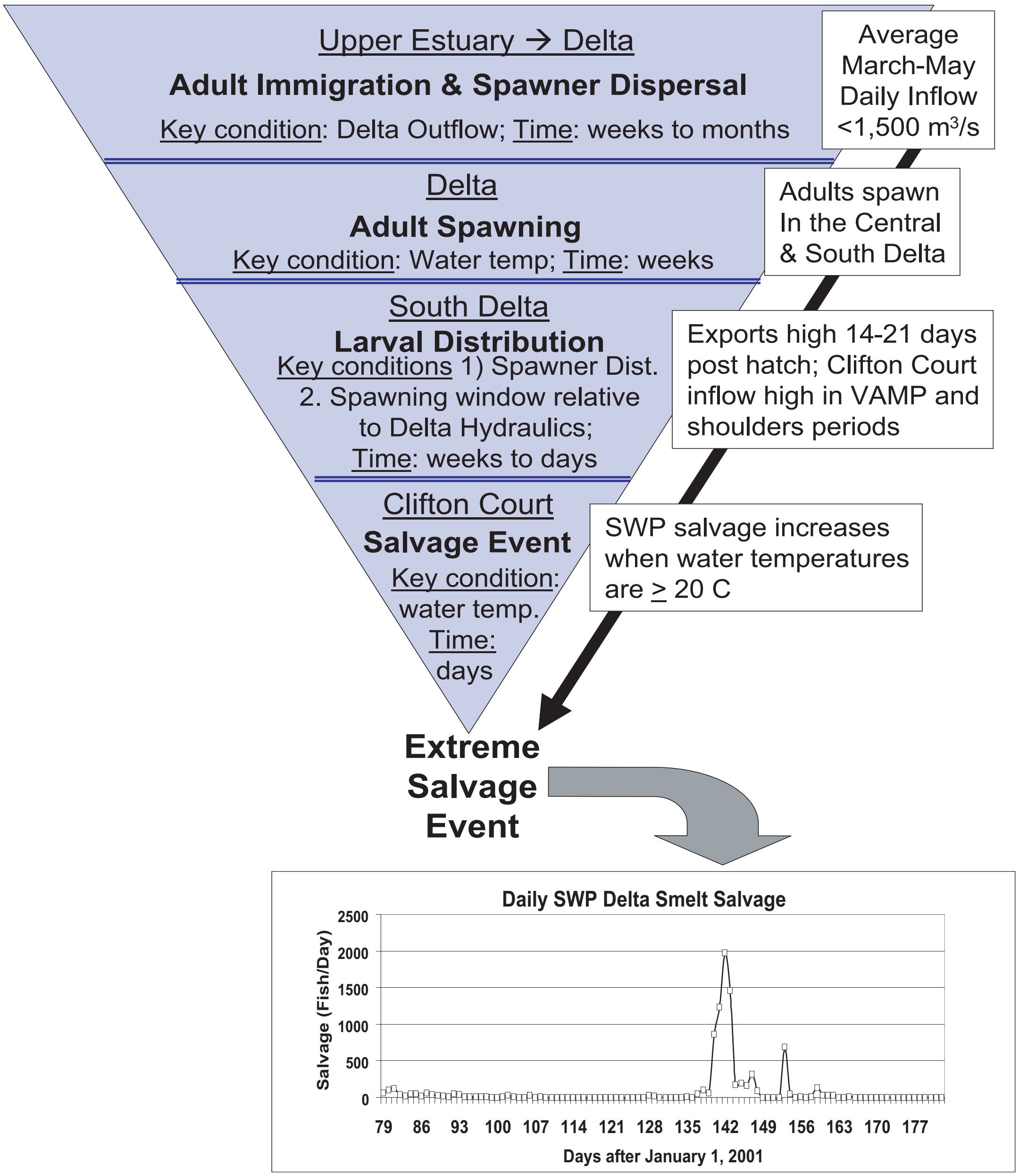


Figure 13 Conceptual model including the regions, events, key conditions, and timeframe of events thought important in the processes leading to extreme salvage events of young delta smelt at the SWP. Text listed in the right-hand boxes provides brief descriptions of the steps in the overall scenario thought to result in an extreme salvage event.

Water temperature changes through the larval rearing period are thought to be the final environmental factor important to determining if an extreme salvage event occurs at the SWP. Extreme SWP salvage events of young delta smelt consistently occurred when water temperatures inside CCF are ≥ 20 ºC, while SWP exports may be either high or low. We suggest increasing water temperatures motivate young delta smelt residing in CCF to seek out other locations with cooler waters before temperatures approach lethal levels around 25°C. Initiation of juvenile emigration at about 20°C is consistent with the observation that few delta smelt are captured at temperatures > 22°C (Bennett 2005). It is during periods of active movement that young delta smelt become most susceptible to salvage at the SWP facilities. Increasing water temperatures would affect young delta smelt occurring throughout the Delta, but the temporal effect initially motivating a fish response (e.g., emigration to cooler downstream waters) is thought to occur on the order of days.

Our conceptual model provides a good fit to the data and observations provided in this article, but the importance of extreme salvage events to the population biology of delta smelt remains unknown. Several reasons for this have been mentioned earlier but the differences in magnitude of salvage events between the CVP and SWP are another issue that complicates our understanding of the importance of entrainment. Differences in design and operation suggest the CVP is much more likely to sample ambient conditions indicating that there are aspects of SWP design and operation that result in elevated salvage levels. One hypothesis is that salvage events at the SWP may be enhanced by the accumulation of young delta smelt (< 20 mm) in CCF.

Accumulation of young delta smelt in CCF could occur as a result of several processes, including: 1) entrainment during diversions into CCF; 2) successful spawning in CCF; or 3) a combination of the two. Young delta smelt in CCF would have to accumulate at rates greater than the combined rates of mortality due to predation and removal by export pumping for any of these processes to result in a net accumulation. Although the data needed to test this hypothesis do not exist, several pieces of information suggest it is plausible. First, diversion rates and associated water velocities into CCF remain high even during periods of export curtailment. Although the duration of diversion events is reduced during export curtailments, there is little doubt the rates of diversion are sufficient to entrain young delta smelt into CCF throughout the VAMP and shoulder-on-VAMP export curtailment period. Meanwhile, export pumping out of CCF is reduced during the curtailment period, so there is likely a reduction in the transport of young delta smelt out of CCF. Second, the SWP and CVP salvage patterns between March 1 and July 1 in 2001 through 2004 often showed that appreciable salvage of young delta smelt first occurred at the CVP. This delay in salvage increases at the SWP may be an indication of the continuing accumulation of young delta smelt in the CCF without appreciable loss due to export pumping removal.

Additional research is needed to test and verify the cause-effect relationships between changes in environmental variables (i.e., Delta inflow, SWP and CVP export operations, and water temperature) and the responses of delta smelt. Critical information needs include:

- Verify calculated estimates of inflow rates into CCF with in-situ measurements.
- Quantitatively estimate SWP and CVP entrainment of young delta smelt through field sampling outside the primary points of diversion.
- Determine if a predictable quantitative relationship exists between SWP and CVP entrainment and salvage of young delta smelt.
- Verify if young delta smelt do accumulate in CCF and determine the sources (i.e., entrainment, spawning, or both) of any accumulation.
- Conduct experiments to estimate the magnitude of delta smelt mortality in CCF.
- Begin rigorous use of an existing particle-tracking model to develop a better understanding of how entrainment risk might change under different SWP and CVP water project operations. Use of the existing model should be coupled with efforts to improve the capabilities of the underlying hydrodynamic model to simulate physical processes in a geographically complex Delta, and allowing the particles to exhibit more complex behavior.
- Conduct mesocosm studies to understand how young delta smelt respond to changes in hydraulics and water temperature.

Management agencies will continue to take actions using EWA water assets to achieve the paradoxical mandate of ensuring the reliability of SWP and CVP water deliveries, while simultaneously protecting young delta smelt and other fishes from excessive export entrainment. Results presented here indicate the shoulder-on-VAMP actions have achieved some measure of success in satisfying this mandate. However, the results of this study suggest actions focused on protecting young delta smelt might provide more benefit if the timing and duration of the export curtailment are more closely aligned with the spawning period. Springtime water temperatures appear to be an effective indicator of the delta smelt spawning period and may also be important in triggering emigration. Timing export curtailment events around key water temperatures may help to maximize the protective benefits of these events. The limited water available from the EWA means actions must be tactical and capitalize on events associated with key biological processes in order to maximize long-term effectiveness.

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DELTA WATER PROJECT OPERATIONS

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During the October through December 2005 period (Figure 1), San Joaquin River flow ranged between 53 and 320 cubic meters per second (1,859 cfs and 11,288 cfs), Sacramento flow ranged between 313 and 2480 cubic meters per second (11,000 cfs to 87,718 cfs), and the Net Delta Outflow Index (NDOI) ranged between 74 and 4870 cubic meters per second (2,625 cfs and 172,000 cfs). River flows and outflow were stable and remained below 20,000 cfs in October and November. However, in December flows only remained below 20,000 cfs between the period of December 7 and 19; outside of this period, all flows increased sharply as a result of large storm events in December. The first peak occurred around December 5; Sacramento and NDOI were above 600 cubic meters per second (21,180 cfs), whereas San Joaquin was stable at about 58 cubic meters per second (2,048 cfs). The second and most impressive peak occurred on December 31; Sacramento flow was about 2,100 cubic meters per second (75,000 cfs), NDOI was about 4,800 cubic meters per second (172,000 cfs), and San Joaquin was about 320 cubic meters per second (11,300 cfs). All flows ended the year at relatively high levels.

Exports during the October through December 2005 period at CVP were stable, whereas SWP exports were more variable. CVP pumping was about 125 cubic meters per second, but SWP pumping varied between 70 and 170 cubic meters per second (Figure 2). Highlights of SWP pumping during the October through December period are listed below:

- Mid-October through mid-November: EI ratio controlling
- Decreased pumping on 11/15/05, 12/4/05, and 12/17/05 to meet water quality standards
- Increased pumping on December 20 and thereafter to above 189 cubic meters per second (+6680 cfs + 1/3 Vernalis flow)

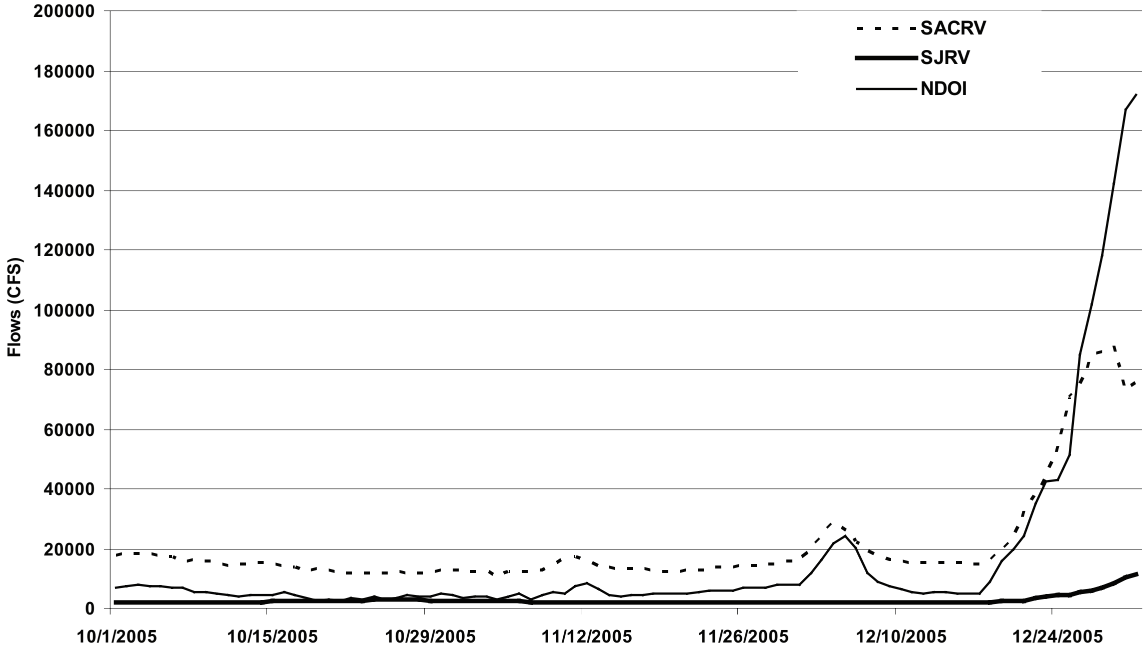

Figure 1 October through December 2005 Sacramento River, San Joaquin River, and Net Delta Outflow Index

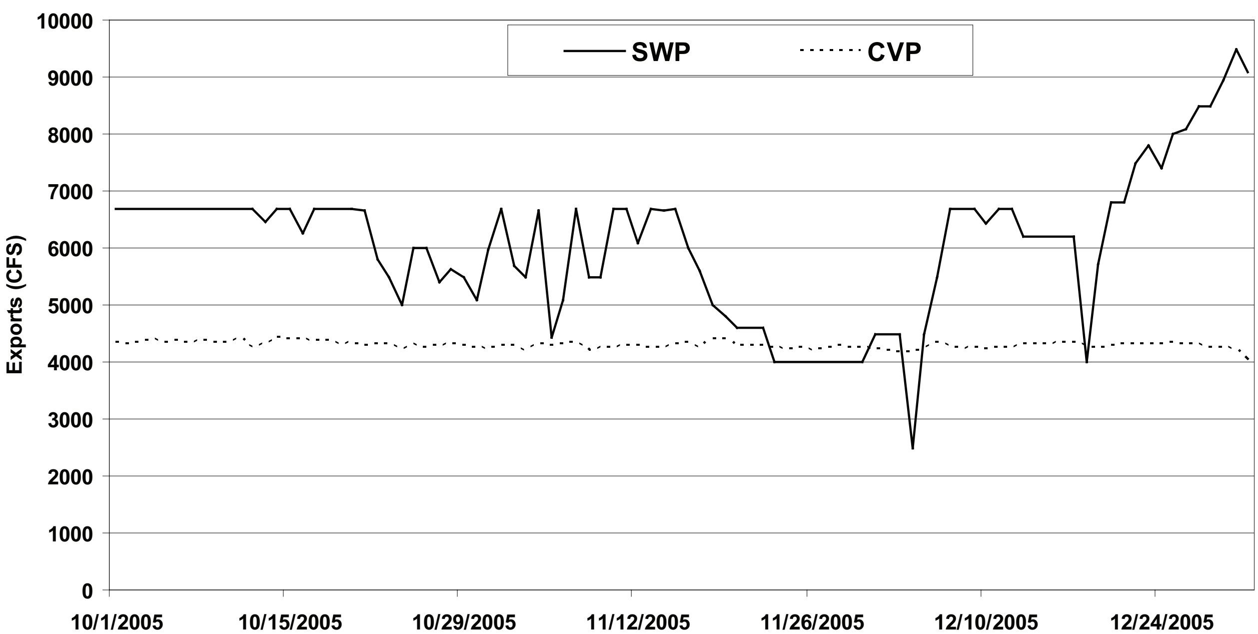

Figure 2 October through December 2005 State Water Project and Central Valley Project pumping

■ Interagency Ecological Program for the San Francisco Estuary ■

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