Attachment #1

American Fisheries Society Symposium 39:281–295, 2004

Evaluating Entrainment Vulnerability to Agricultural Irrigation Diversions: A Comparison among Open-Water Fishes

Matthew L. Nobriga[*], Zoltan Matica, and Zachary P. Hymanson[1]

Aquatic Ecology Section, California Department of Water Resources
3251 S Street, Sacramento, California 95816-7017, USA

Abstract.—In July 2000 and 2001, we sampled adjacent screened and unscreened agricultural irrigation diversions in the Sacramento River, California to (1) evaluate the effectiveness of a custom fish screen for excluding four open-water fishes: native delta smelt *Hypomesus transpacificus* and alien threadfin shad *Dorosoma petenense*, inland silverside *Menidia beryllina*, and striped bass *Morone saxatilis*; and (2) examine factors affecting entrainment of each species. We also compiled trawl and beach seine data from contemporaneous monitoring programs to make inferences about microhabitat use by these fishes and its implications for entrainment vulnerability. The fish screen reduced entrainment of each species by 99% or more and excluded many fish less than 25 mm, the approximate minimum length it was designed to exclude. Tidal and diel influences on entrainment through the unscreened diversion were observed, but diel cycles appeared to be more important, as most entrainment occurred at night or during crepuscular periods. Except for delta smelt, our results suggested that open-water fishes may undergo ontogenetic changes in vulnerability to unscreened irrigation diversions. Fishes entrained during daylight (threadfin shad and striped bass) averaged only 15–16 mm in length. At night, average lengths of entrained threadfin shad and inland silverside were 22–25 mm, even though larvae continued to be entrained. Similarly, a diel influence on striped bass entrainment was observed only in 2000, when individuals larger than 20 mm were consistently collected. No striped bass were collected at sizes greater than 35 mm, even though larger individuals occupied the study area. We found no evidence of size-related changes in delta smelt vulnerability to entrainment, but the monitoring data indicated that delta smelt were abundant offshore, whereas the other three species were most abundant nearshore. We think that low and inconsistent entrainment of delta smelt reflected (1) predominantly offshore habitat use by delta smelt, and (2) the relatively small hydrodynamic influence of the diversion.

Introduction

Humans divert water from aquatic ecosystems for numerous reasons, and not surprisingly, water diversion is often considered a major stressor of aquatic resources (Dadswell and Rulifson 1994; Kingsford 2000). The Sacramento–San Joaquin Delta is no exception; aquatic ecosystem impacts attributable to State Water Project (SWP) and Central Valley Project (CVP) operations have been widely reported (Stevens and Miller 1983; Arthur et al. 1996; Bennett and Moyle 1996). Although SWP and CVP diversions are by far the largest in the system; more than 2,200 additional diversions are used to irrigate crops grown within the delta (Herren and Kawasaki 2001). All of these irrigation diversions are shore-based, and almost all are small (30–60-cm pipe diameter), operate via pumps or gravity flow, and lack fish screens. Like SWP and CVP diversions,

---

[*] Corresponding author: mnobriga@water.ca.gov

[1] Present address: California Bay-Delta Authority, 650 Capitol Mall, Sacramento, California 95814, USA

fish losses to delta irrigation diversions have been a concern for many years (Hallock and Van Woert 1959).

As a component of a comprehensive fisheries restoration strategy, the CALFED Bay-Delta Program (CALFED 2000), a state and federal resource agency collaboration to manage the San Francisco Estuary, considered retrofitting many or all delta irrigation diversions with fish screens. One species hypothesized to benefit from fish screens was the threatened delta smelt *Hypomesus transpacificus*. Delta smelt have been found in samples of delta irrigation diversions, as well as larger wetland management diversions downstream. However, previous studies either (1) did not quantify the volumes of water diverted (Hallock and Van Woert 1959; Pickard et al. 1982), or (2) did not sample at times when, or locations where, delta smelt were abundant (Spaar 1994; Cook and Buffaloe 1998). Delta smelt primarily occur in large open-water habitats, but early life stages move downstream through delta channels (Moyle et al. 1992) where irrigation diversions are concentrated (Herren and Kawasaki 2001). At smaller spatial scales, delta smelt distribution can be influenced by tidal and diel cycles (Aasen 1999; Bennett et al. 2002), which also may influence vulnerability to shore-based diversions.

Examining multiple species responses to similar situations often provides additional context and insight into the response of a target species (Swanson et al. 2000; Bennett et al. 2002). We compared entrainment dynamics and habitat use of delta smelt to two ecologically similar but alien, small (typically <100-mm adult size), open-water fishes (Moyle 2002), threadfin shad *Dorosoma petenense* and inland silverside *Menidia beryllina*, and a third alien species, striped bass *Morone saxatilis*. Although adult striped bass are large piscivores, larvae and young juveniles have habitat requirements that are similar to delta smelt (Bennett and Moyle 1996). In this paper, we address the following questions: (1) what is the efficiency of fish screens for small open-water fishes? (2) is entrainment through an unscreened diversion influenced by tidal and/or diel cycles, and if so, do entrainment dynamics differ among species? (3) does fish size influence entrainment vulnerability? and (4) did delta smelt, threadfin shad, striped bass and/or inland silverside occur in different microhabitats, and if so, do these differences help explain entrainment vulnerability and entrainment dynamics?

Methods

We sampled for fishes entrained at the California Department of Water Resources' (CDWR) Horseshoe Bend diversion facility on the lower Sacramento River, California (Figure 1). The Horseshoe Bend facility consists of three 61-cm-diameter pipes that operate as siphon diversions. After priming, diversion flows are controlled both by valves in the pipes and differences in water elevations on the river and island sides of its levee. Therefore, changes in tidal stage affect the volume of water flowing through the diversions. The two upstream-most diversions at the Horseshoe Bend facility were screened by CDWR in 1997 and 1998. The fish screens, which were designed to exclude delta smelt larger than 25 mm, are cylindrical, stainless steel, 1.5 m long with 2.4-mm mesh, and have a maximum approach velocity of 6 cm/s. The U.S. Fish and Wildlife Service adopted this approach velocity criterion for delta fish screens specifically to protect delta smelt, which, in a laboratory setting, are vulnerable to impingement even at low velocities (Swanson et al. 2001). The downstream-most diversion is unscreened and is not used during normal irrigation operations. During our sampling, the unscreened diversion and the screened diversion closest to it were operated simultaneously. The mouths of these diversions were at equal depth (1.5 m below mean low water) and are 2.3 m apart.

Samples were collected from 1207 hours on 12 July 2000 to 0736 hours on 14 July 2000 and from 1728 hours on 9 July 2001 to 0750 hours on 11 July 2001. These dates were chosen to (1) sample when observed delta smelt abundance was high in the lower Sacramento River, (2) sample at a time when irrigation water demand was sufficient to allow for extended continuous sampling, and (3) allow separation between tidal and diel influences on fish entrainment. During 2000, peak tidal stages occurred in the middle of the night and

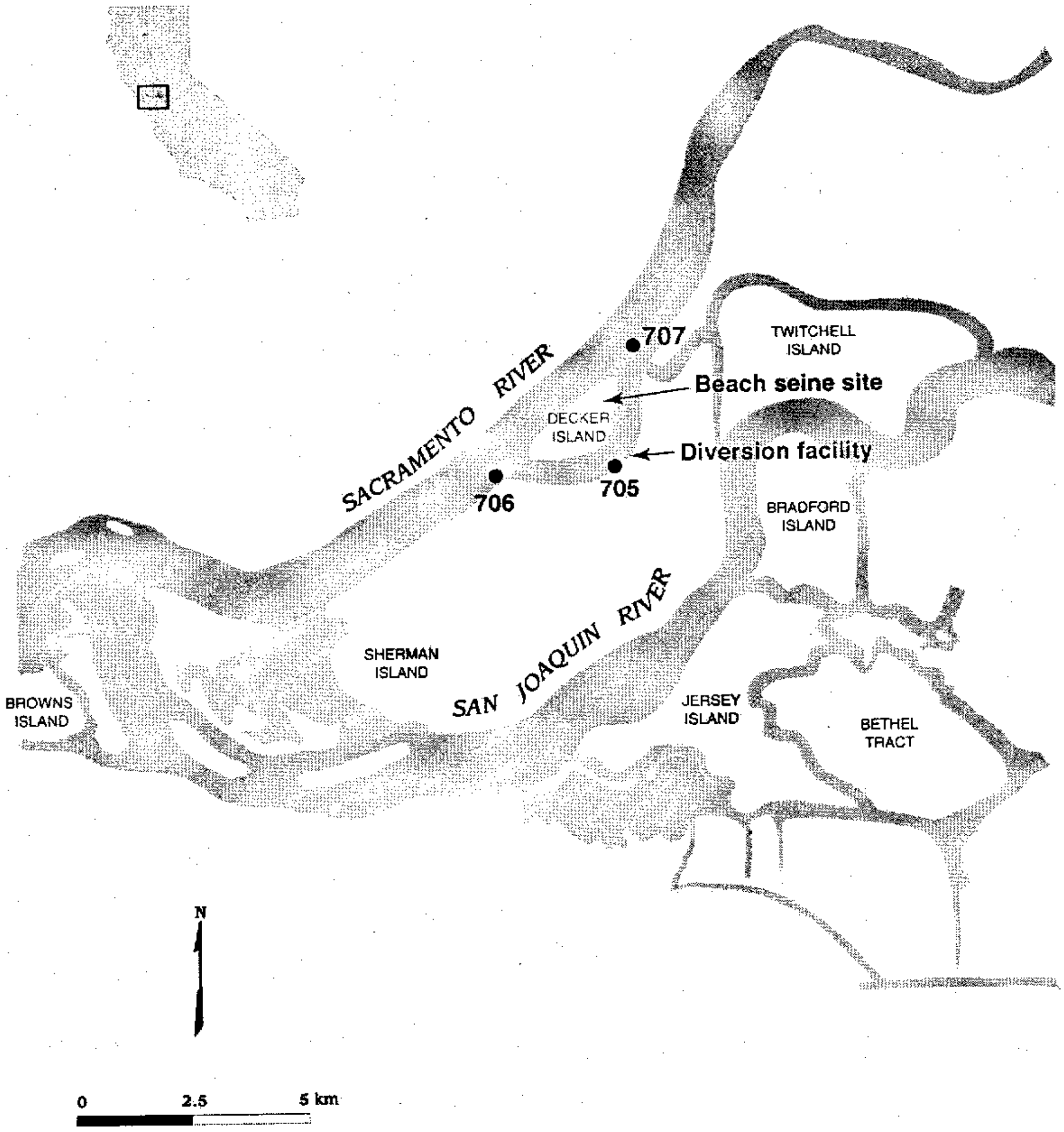

FIGURE 1. Sacramento–San Joaquin Delta, California and the location of the Horseshoe Bend diversion facility, beach seine sampling site, and 20-mm Delta Smelt Survey trawl stations 705–707.

mid-morning. During 2001, peak tidal stages occurred around sunset and sunrise.

Fish were collected using two 1.6-mm-mesh hooped plankton nets. The nets were attached to the diversion outfall pipes via coupling rings, so that when engaged, they sampled 100% of the diverted flow. Net contents were collected at approximately hourly intervals. No samples were collected between 2148 hours and 0022 hours on 12–13 July 2000 because personnel were unavailable. At the end of each sampling interval, nets were retrieved and cod end contents were placed into separate buckets. When possible, fish larger than or equal to 25 mm total length (TL), or fork length (FL) if the caudal fin was forked, were measured and identified to species on site. All fish that could not be identified on site were preserved in 10% formalin and identified in the laboratory. All smelt regardless of length were preserved and identified in the laboratory. In 2000, only length ranges from each sample were recorded for fishes other than delta smelt. In 2001, up to 50 randomly selected individuals of each species from each preserved sample were measured for TL. When more than 50 individuals of a species were present in a sample, the remaining individuals were tallied but not measured. The volume of water sampled during each interval was estimated using General Oceanics propeller flowmeters. Water temperature (°C) in the irrigation canal was measured with most net samples.

To address the first study question, we summarized the catch and length range of each species from screened and unscreened diversion samples. Differences in screened and unscreened diversion catches were examined qualitatively. To address the second study question, we used two approaches based on the unscreened diversion samples. During our sampling, flow through the diversions varied with changes in tidal stage and valve adjustments made by the local water manager. We hypothesized entrainment through the unscreened diversion might be influenced by diversion flow variation (or a correlate like water velocity at the intake). To test this hypothesis, we ranked the raw catch data for each species each year based on mean flow through the diversion (m^3/s). We used randomization tests (Haddon 2001) to compare mean catches among the upper and lower 50% of diversion flows. Each randomization test compared an observed mean catch difference at low versus high diversion flows to a probability distribution of catch differences derived by randomly resampling the combined dataset 1,000 times. The reported *P*-values represent the proportion of randomly derived mean differences that equaled or exceeded the observed mean differences. The significance level chosen for the tests was $P < 0.05$. For inland silverside in 2001, only nighttime catch data were used, which resulted in an uneven number of observations in the low and high diversion flow groups. To be certain that we did not come to an erroneous conclusion, we tested the inland silverside data three ways: (1) the median data point was placed in the "low" volume diverted category, (2) the median data point was placed in the "high" volume diverted category, and (3) the median data point was removed. We reported the results as a range of *P*-values.

We also explored potential tidal and diel influences on entrainment through the unscreened diversion with scatterplots (not shown) and analysis of covariance (ANCOVA) using four explanatory variables (Table 1): catch per unit effort (CPUE) = tidal flow + absolute value of tidal flow + day–night + crepuscular + ε. Explanatory variables were considered significant if the probability of their *t*-statistic (coefficient divided by its standard error) was less than 0.05. Prior to statistical analysis, catch data were transformed to CPUE as number of fish per 10,000 m^3 of water diverted, then further transformed to $\ln(\text{CPUE} + 1)$.

We used several summaries of fish length data to examine the influence of length on entrainment through the unscreened diversion. First, we tested for day–night differences in the sizes of delta smelt, striped bass, and threadfin shad entrained through the unscreened diversion using the Haddon (2001) randomization technique described above. Samples were grouped into "day" or "night" as described in Table 1. Only 2001 data were used to test day–night length differences of striped bass and threadfin shad because only length ranges were recorded in 2000. More than 1,000 threadfin shad were measured in 2001, but most were collected at night, so length differences were tested using random subsamples of 50 fish collected during daylight and 50 fish collected at night. Length data for striped bass in 2001 and delta smelt in both years were taken for all individuals collected, so subsampling was not necessary. Next, we assessed interannual differences in the size of striped bass entrained using cumulative frequency plots of maximum lengths recorded from each sample. We were limited to this technique because of the incomplete length data in 2000. Lastly, we compared length frequency data for striped bass and threadfin shad from the unscreened diversion to length frequencies from beach seine (30 m × 1.5 m, 3.2 mm mesh) data collected along about 1 km of beach on the bank opposite the diversion facility (Figure 1). The data were summarized from six hauls taken from 1620 to 2044 hours on 29 June 2001, and four hauls taken from 1657 to

TABLE 1. Explanatory variables used in analyses of covariance of factors influencing fish entrainment through the unscreened diversion at Horseshoe Bend, 12–14 July 2000 and 9–11 July 2001.

	Tidal flow	Absolute value of tidal flow	Day–night	Crepuscular
Data source	DSM-2[a]	DSM-2[a]	software[b]	software[b]
Definition	Estimated flow (m^3/s) in Horseshoe Bend converted from 15-min interval to average per sample; (+) values are ebb flows and (–) values are flood flows	Same as above but without directional component; flow estimates ranged from 6.25–476 m^3/s in 2000 to 12.6–445 m^3/s in 2001	daytime = 51–100% sample taken after sunrise and before sunset	51–100% of sample taken ± 2 h of sunset or sunrise
Interpretation	(+) coefficient: highest entrain- during ebb tides; (–) coefficient: highest entrainment during flood tides	(+) coefficient: highest entrain- at high tidal flows regardless of flow direction; (–) coefficient: highest entrain- during slack tides	(+) coefficient: highest entrainment at night; (–) coefficient: highest entrainment during day	(+) coefficient: highest entrainment during crepuscular periods; (–) coefficient: highest entrainment during midday or midnight

[a] California Department of Water Resources Delta Simulation Model-2 (Culberson et al. 2004, this volume)

[b] Tides & Currents 2.2©, Nautical Software, Beaverton, Oregon.

1844 hours on 27 July 2001. Note the mesh size of the seine was twice that of the diversion nets. Thus, quantitative comparisons of CPUE among gear types are not appropriate.

To address study question four, we compiled relative abundance data for delta smelt, threadfin shad, striped bass, and inland silverside from fish monitoring programs that sampled in and near Horseshoe Bend near the time of our diversion sampling. We compared relative offshore abundance of each species based on a mid-channel trawling survey, the 20-mm Delta Smelt Survey, which also uses a 1.6-mm-mesh net (Dege and Brown 2004, this volume, provide further details). We used mean CPUE (fish/10,000 m^3 of water sampled ± SE) from the three stations nearest the diversion facility (Figure 1). These three stations are within the tidal excursion range (2–5 km; CDWR, unpublished data) of the diversion intakes, so it was theoretically possible for fish inhabiting the area bounded by the three stations to be transported to the point of diversion with each tidal cycle. In addition, we used the beach seine data described above to compare relative nearshore abundances of the four species. These represent the best available distribution data in terms of proximity to our sampling, both geographically and temporally.

Results

We sampled more than 115,000 m^3 of diverted water in more than 33 h of sampling each year (Table 2). We intended to have flows evenly distributed through the screened and unscreened diversions, but flow through the unscreened diversion actually comprised about two-thirds of the total volume diverted during both years. Mean flows through both diversions were 10–20% higher in 2001. Mean

TABLE 2. Summary of sampling effort at the Horseshoe Bend diversion facility, 12–14 July 2000 and 9–11 July 2001.

	Screened diversion		Unscreened diversion	
	2000	2001	2000	2001
No. of samples	36	34	36	34
Volume sampled (m³)	41,242	40,651	78,420	92,419
Mean flow (m³/s ± SD)	0.28 ± 0.15	0.31 ± 0.10	0.61 ± 0.06	0.75 ± 0.14
Flow range (m³/s)	0.031–0.50	0.15–0.45	0.40–0.71	0.45–1.0
Total sampling time (h)	37.9	35.3	35.5	33.6
Mean sample duration (min ± SD)	65 ± 13	61 ± 8	59 ± 6	58 ± 8
Mean time between samples (min ± SD)	5 ± 3	6 ± 3	9 ± 3	8 ± 4

water temperatures (±SE) were similar in both years: 20 ± 1°C in 2000 and 22 ± 1°C in 2001.

The Horseshoe Bend fish screen was very effective at reducing entrainment of small open-water fishes (Table 3). In 2000, we collected 300 striped bass, 59 threadfin shad, and 12 delta smelt from 36 unscreened diversion samples, but only 2 striped bass, 1 threadfin shad, and no delta smelt from 36 screened diversion samples. No inland silverside were collected in 2000. In 2001, we collected 7,824 threadfin shad, 160 inland silverside, 115 striped bass, and 31 delta smelt from 34 unscreened diversion samples. Only 17 threadfin shad, 3 striped bass, and no inland silverside or delta smelt were collected from the 34 screened diversion samples. All of the striped bass and threadfin shad entrained through the screened diversion were less than 25 mm. In contrast, all four species were collected at sizes greater than 25 mm in unscreened diversion samples.

Entrainment rates from the unscreened diversion were not consistent among samples (Figure 2). Peak entrainment of each species was staggered in time, but most entrainment occurred at night or during crepuscular periods. The most extreme diel difference was observed for inland silverside, 100% of which were entrained at night. Of the four species we examined, striped bass was the only one whose entrainment was influenced by flow through the unscreened diversion (Table 4).

Statistical relationships between CPUE in the unscreened diversion samples and the tidal-diel variables were generally inconsistent among years (Table 5). However, threadfin shad was an exception. In both 2000 and 2001, threadfin shad entrainment was significantly higher at night and negatively correlated with tidal flow. Scatterplots (not shown) showed the inverse correlations with tidal flow were driven by nighttime samples, whereas the additional correlation with abso-

TABLE 3. Numbers of threadfin shad, inland silverside, striped bass, and delta smelt collected, and their length ranges from screened and unscreened diversion samples in Horseshoe Bend, 12–14 July 2000 and 9–11 July 2001.

Year	Species	Screened	FL (mm)	Unscreened	FL (mm)
2000	Threadfin shad	1	19	59	13–59
	Inland silverside	0	–	0	–
	Striped bass	2	11–18	300	13–33
	Delta smelt	0	–	12	19–30
2001	Threadfin shad	17	10–22	7,824	9–42
	Inland silverside	0	–	160	15–37
	Striped bass	3	12–16	115	9–35
	Delta smelt	0	–	31	16–45

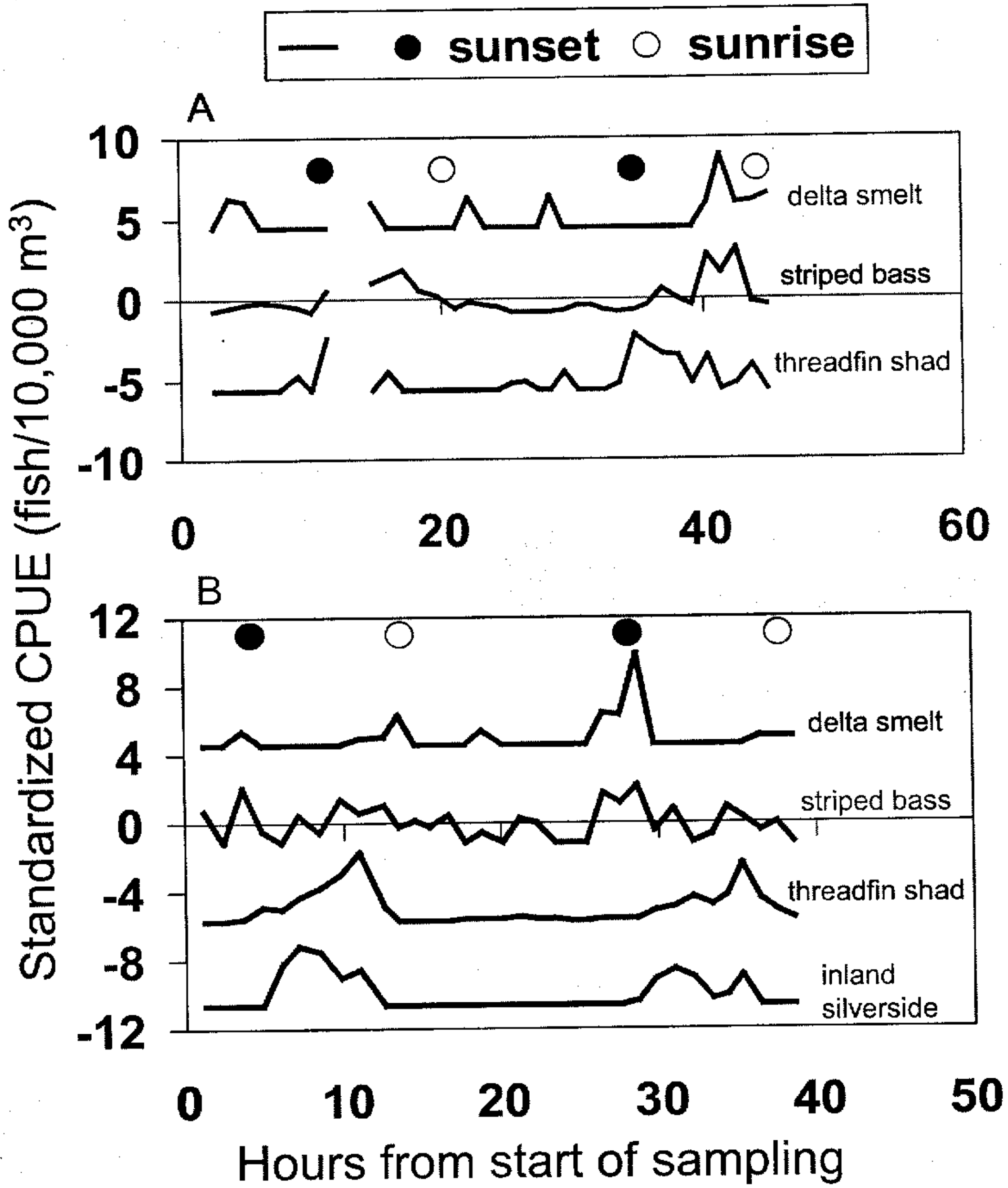

FIGURE 2. Time series of delta smelt, striped bass, threadfin shad, and inland silverside collected per 10,000 m^3 of water sampled (CPUE) from the unscreened irrigation diversion at Horseshoe Bend: (A) 12–14 July 2000, and (B) 9–11 July 2001. CPUE for each species was standardized using Z-scores to facilitate interspecies comparisons. Constants were added to or subtracted from the Z-scores to allow visual separation of the time series, so the absolute values of the *y*-axis have no meaning. The gaps in the 2000 time series represent the gap in sampling when personnel were unavailable.

lute value of tidal flow in 2001 resulted from peak daytime entrainment around slack tides. In 2000, the entrainment of striped bass also was significantly higher at night, but in contrast with threadfin shad, striped bass entrainment was positively correlated with tidal flow.

TABLE 4. Probabilities that there were no significant differences in numbers of fish entrained through the unscreened diversion at Horseshoe Bend between the lower and higher 50% of diversion flows (m^3/s). Probabilities were derived from randomization tests using 1,000 iterations.

Species	2000	2001
Threadfin shad	0.09	0.22
Inland silverside	–	0.07–0.25
Striped bass	0.03	0.000
Delta smelt	0.06	0.61

In 2001, the tidal-diel variables were unable to explain any of the variation in striped bass entrainment. As mentioned above, all inland silverside were collected at night in 2001. Both the day–night (+ coefficient) and crepuscular (– coefficient) variables were significant for inland silverside. This resulted from maximum entrainment near the middle of the night, as opposed to crepuscular periods (Figure 2). Delta smelt entrainment was weakly positively correlated with tidal flow in 2000 (Table 5). In 2001, delta smelt were entrained significantly more often during crepuscular periods. In both years, delta smelt entrainment had a conspicuous peak (Figure 2). This likely had a large influence on statistical results, as evidenced by the low adjusted R^2 in both delta smelt ANCOVA models (Table 5).

Three of four species showed influences of body size on their vulnerability to entrainment through the unscreened diversion. Because no inland silverside were collected during daytime, it may be inferred that "larger" sizes were vulnerable at night when their mean length was 25 mm. In addition, size of threadfin shad entrained increased at night (randomization test; $P < 0.001$). During daylight, mean TL of threadfin shad entrained was 16 mm, but at night, mean TL increased to 22 mm. In 2001, the mean length of striped bass entrained did not differ between day and night (daytime mean = 15 mm; nighttime mean = 16 mm; $P = 0.49$). However, in 2000 when striped bass entrainment was associated with tidal-diel cycles (Table 5), most samples included striped bass larger than or equal to 24 mm (Figure 3). In contrast, during 2001 when entrainment was not related to tidal-diel cycles (Table 5), few samples included striped bass larger than 20 mm (Figure 3). Only delta smelt showed no evidence of length-based vulnerability to entrainment. Delta smelt length did not differ significantly between day and night in 2000 (daytime mean = 23 mm; nighttime mean = 28 mm; $P = 0.06$) or 2001 (daytime mean = 28 mm; nighttime mean = 29 mm; $P = 0.51$).

Although the 1.6-mm-mesh diversion net retained smaller fishes than the 3.2-mm-mesh beach seine, all but the largest size-classes of threadfin shad and inland silverside collected by seining in Horseshoe Bend in June and July 2001 also were collected from unscreened diversion samples (Figure 4A and B). In contrast, the beach seine data showed that striped bass much larger than the maximum size entrained in the unscreened diversion were present in nearshore habitats of Horseshoe Bend (Figure 4C).

In both years, delta smelt and striped bass were more abundant than threadfin shad and inland silverside in midchannel trawl surveys (Figure 5). In addition, delta smelt had by far the lowest relative abundance in the nearshore beach seine surveys. These data suggest a predominantly offshore distribution for delta smelt, predominantly nearshore distributions for inland silverside and threadfin shad, and a ubiquitous distribution for striped bass.

Discussion

This study provided the longest continuous monitoring of fish entrainment at a delta agricultural diversion facility to date. Generally, our results suggest that entrainment risk was strongly influenced by the presence or absence of a fish screen and by species-specific behavioral traits. In general, diel cycles appeared to influence entrainment more than tidal cycles or the tidally influenced variations in diversion flows. We acknowledge that our results may not be representative of entrainment dynamics at other delta diversions.

Relative to the unscreened diversion, the screened diversion excluded more than or equal to 99% of all four species (both years combined). This result was interesting because most fish entrained through the unscreened diversion were less than or equal to 25 mm and therefore could have theoretically passed through the screened diversion as well. Be-

TABLE 5. ANCOVA models for factors influencing entrainment of delta smelt, threadfin shad, striped bass, and inland silverside collected from samples of an unscreened diversion in Horseshoe Bend, 12–14 July 2000 and 9–11 July 2001. Asterisks denote probabilities less than 0.05.

Year	Species	Predictor	Coefficient	SE coefficient	*P*
2000	Delta smelt	Constant	0.454	0.576	0.44
		Day–night	0.231	0.291	0.43
		Crepuscular	−0.0766	0.286	0.79
		Tidal flow (m^3/s)	1.00×10^{-3}	4.47×10^{-4}	0.03*
		Absolute value of tidal flow	-9.07×10^{-4}	1.06×10^{-3}	0.40
		Adjusted R^2	0.05		
	Threadfin shad	Constant	−1.77	0.764	0.03*
		Day–night	1.54	0.386	<0.001*
		Crepuscular	0.593	0.379	0.13
		Tidal flow (m^3/s)	-1.96×10^{-3}	5.93×10^{-4}	0.002*
		Absolute value of tidal flow	2.51×10^{-4}	1.41×10^{-3}	0.86
		Adjusted R^2	0.43		
	Striped bass	Constant	0.590	0.661	0.38
		Day–night	1.90	0.334	<0.001*
		Crepuscular	−0.567	0.328	0.09
		Tidal flow (m^3/s)	2.24×10^{-3}	5.13×10^{-4}	<0.001*
		Absolute value of tidal flow	1.83×10^{-4}	1.22×10^{-3}	0.88
		Adjusted R^2	0.64		
2001	Delta smelt	Constant	−0.364	0.810	0.66
		Day–night	−0.227	0.319	0.48
		Crepuscular	1.19	0.332	0.001*
		Tidal flow (m^3/s)	1.83×10^{-5}	5.69×10^{-4}	0.98
		Absolute value of tidal flow	-1.22×10^{-3}	1.33×10^{-3}	0.37
		Adjusted R^2	0.28		
	Threadfin shad	Constant	1.49	0.962	0.13
		Day–night	3.35	0.379	<0.001*
		Crepuscular	−0.0985	0.395	0.81
		Tidal flow (m^3/s)	-1.79×10^{-3}	6.76×10^{-4}	0.01*
		Absolute value of tidal flow	-3.64×10^{-3}	1.58×10^{-3}	0.03*
		Adjusted R^2	0.73		
	Striped bass	Constant	0.215	1.14	0.85
		Day–night	0.578	0.450	0.21
		Crepuscular	0.700	0.469	0.15
		Tidal flow (m^3/s)	-1.37×10^{-4}	8.03×10^{-4}	0.87
		Absolute value of tidal flow	-1.13×10^{-4}	1.87×10^{-3}	0.95
		Adjusted R^2	0.0		
	Inland silverside	Constant	−0.882	0.876	0.32
		Day–night	2.78	0.345	<0.001*
		Crepuscular	−1.06	0.359	0.006*
		Tidal flow (m^3/s)	4.01×10^{-4}	6.15×10^{-4}	0.52
		Absolute value of tidal flow	-1.56×10^{-3}	1.44×10^{-3}	0.29
		Adjusted R^2		0.68	

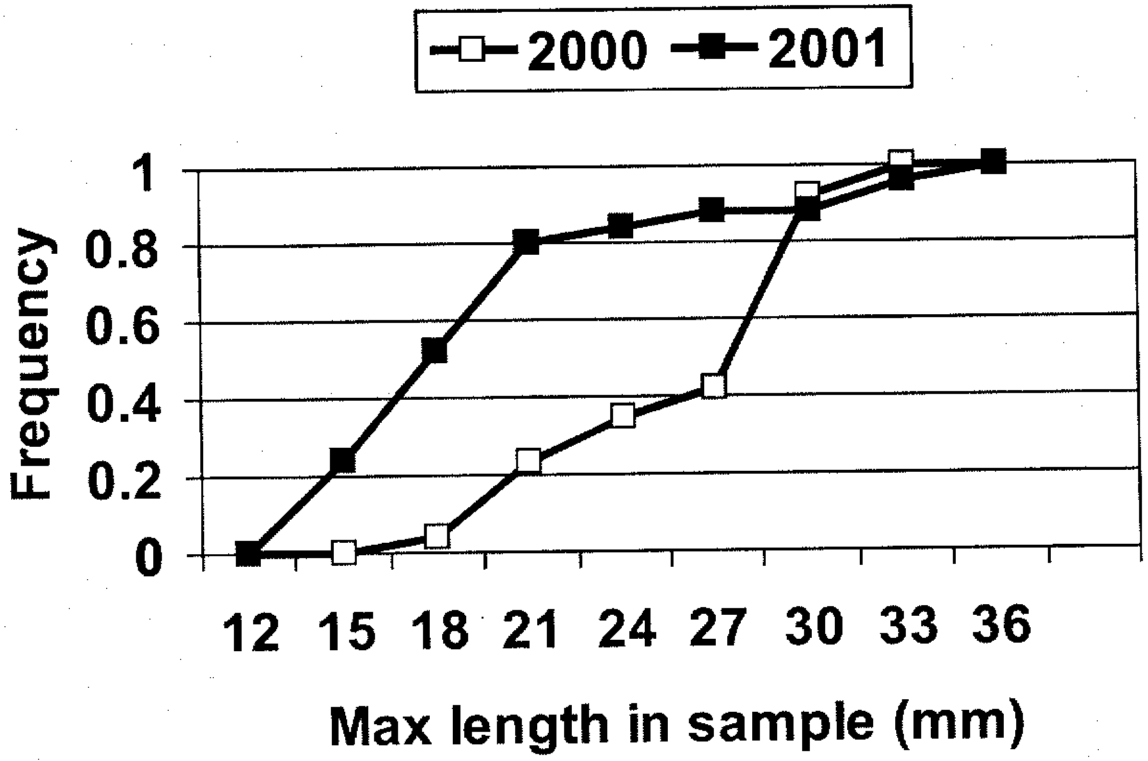

FIGURE 3. Cumulative frequency plots of the maximum lengths of striped bass (mm total length) from unscreened diversion samples at Horseshoe Bend, 12–14 July 2000 and 9–11 July 2001. Summaries are based on *N* = 26 samples in 2000 and *N* = 25 samples in 2001.

cause the screen excluded most larval (10–20 mm) threadfin shad, which are morphologically similar to larval delta smelt (Wang 1986), we suspect that during normal irrigation operations, virtually all equivalently sized delta smelt also are excluded from diverted water at Horseshoe Bend. Because CDWR has installed identical screens on four other lower Sacramento River irrigation diversions, delta smelt less than 25 mm may have more protection from entrainment into these diversions than anticipated.

In addition to entrainment, impingement on fish screens is another concern for delta smelt (Swanson et al. 2001). However, we do not know whether delta smelt or other fishes impinged on the screened diversion during our sampling. Long-term debris accumulation or biofouling, due to algal growth, small woody debris, and so on, could result in impingement of fish if the fouling reduced the nominal mesh size sufficiently to increase water velocities at unfouled sections. However, we think that the very low catches of fish less than 25 mm in the screened diversion samples are evidence that impingement did not often occur. Our rationale is that it is unlikely that large numbers of fish less than 25 mm could impinge without eventually passing through because they would most likely contact unimpeded high velocity sections and be pulled through the screen.

We found evidence that fish entrainment risk at Horseshoe Bend was inversely related to fish length. With the exception of delta smelt, which is discussed in detail below, fishes entrained during daylight (threadfin shad and striped bass) were typically larvae or postlarvae averaging 15–16 mm. At night, average lengths of entrained threadfin shad and inland silverside were 22–25 mm, even though larvae continued to be entrained, and a significant diel influence on striped bass was only observed in 2000 when individuals larger than 20 mm were consistently collected. Thus, it appears that larval fishes (<20 mm) were

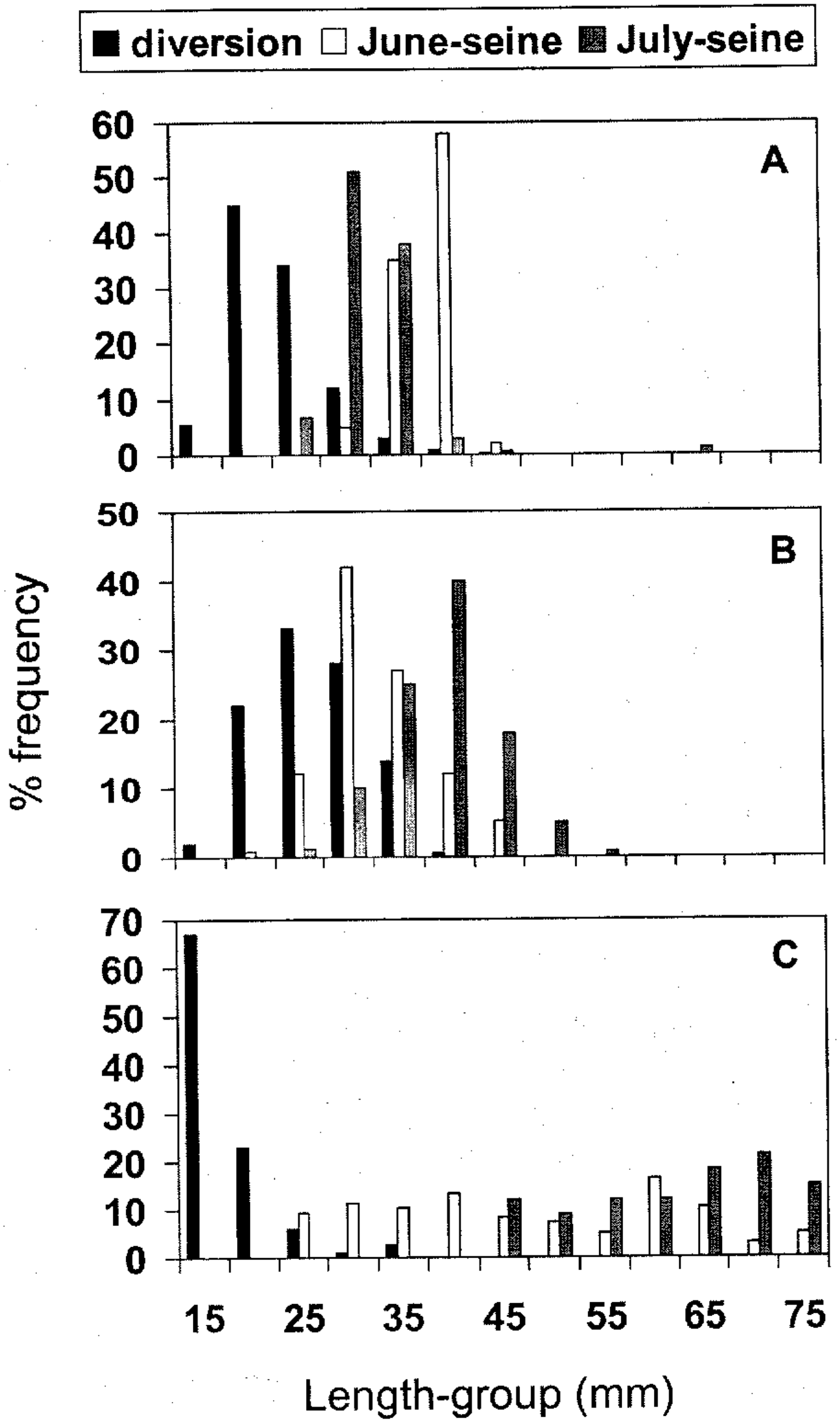

FIGURE 4. Standardized length frequencies of (A) threadfin shad, (B) inland silverside, and (C) striped bass from unscreened diversion samples at Horseshoe Bend, 12–14 July 2000 and 9–11 July 2001, and beach seine samples in Horseshoe Bend on 29 June 2001 and 27 July 2001. Gear mesh sizes differed so quantitative comparisons are not appropriate. Striped bass larger than 75 mm were collected, but were not shown to improve the clarity of the chart.

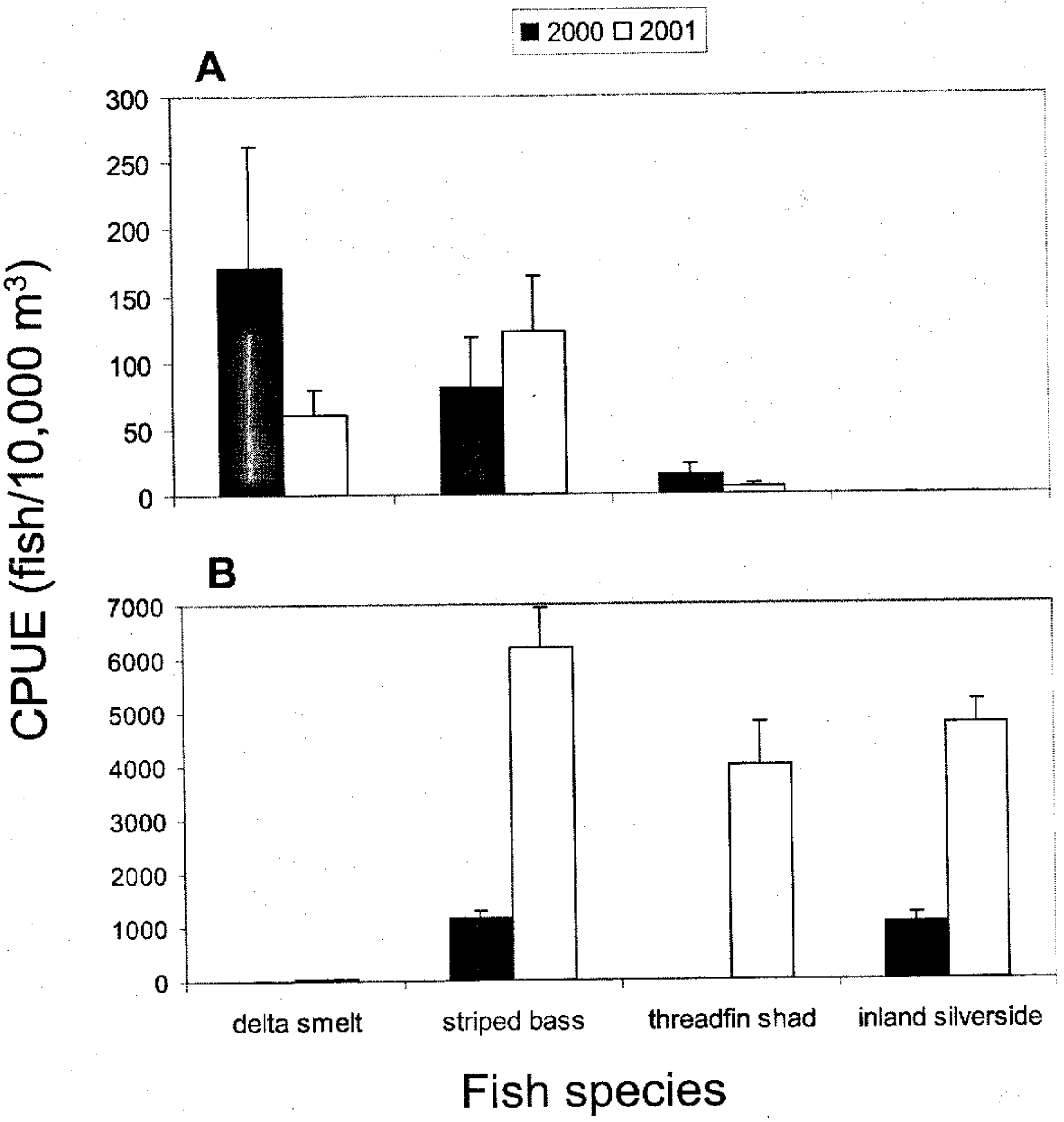

FIGURE 5. Average catch per unit effort (+SE) of delta smelt, striped bass, threadfin shad, and inland silverside from Interagency Ecological Program monitoring surveys. (A) stations 705–707 of 20-mm delta smelt survey 9 in 2000 and stations 705–707 of 20-mm delta smelt survey 8 in 2001 (survey described in detail by Dege and Brown 2004), (B) beach seine surveys in Horseshoe Bend, 11–12 July 2000 and 29 June 2001.

consistently vulnerable to entrainment, whereas early juvenile fishes (>20 mm) were principally vulnerable at night. This is consistent with expectations based on studies of other fishes. Swimming ability increases with length in young fishes (Hunter 1981), which would tend to reduce vulnerability as they grew. Also, Atlantic herring *Clupea harengus* have been shown to school less, swim more slowly, and show less response to sound in the dark (Blaxter and Batty 1987).

Few open-water fishes larger than 35 mm were entrained through the unscreened diversion (Figure 4). For threadfin shad and inland silverside, we cannot be certain if this reflected a continued decline in entrainment risk with increasing length because beach seine catches were not dominated by size-classes larger than those being entrained. In contrast, no striped bass larger than 35 mm were collected from diversion samples, even though much larger individuals occupied Horseshoe Bend. This suggests that striped bass entrainment risk may approach zero early in the juvenile stage. We emphasize that this hypothesis is a generalization regarding a probabilistic phenomenon. Striped bass as large as 124 mm have been reported from other studies of irrigation diversions in the delta (Cook and Buffaloe 1998), and therefore, even considerably larger individuals have some vulnerability to entrainment. Unfortunately, meaningful comparison with the Cook and Buffaloe (1998) data on striped bass and other species is not possible because they did not present length data for individual species or effort data for individual sites.

Despite the lack of evidence for length-based changes in entrainment vulnerability of delta smelt, we collected only 43 delta smelt during 69 h of sampling 170,839 m^3 of unscreened water (both years combined). The low delta smelt catch did not appear to be due to low abundance in the vicinity of the diversion. In 2000 and 2001, 44% and 50% of the total delta smelt CPUE from the 20-mm Delta Smelt Survey's 41 stations was collected from the 3 stations nearest the diversion, suggesting that substantial proportions of the delta smelt standing stock were within the tidal excursion range of the diversion. It is possible that tidal and river flows could have transported delta smelt downstream away from the diversion, particularly in 2001 when distribution data preceded diversion data by nearly 2 weeks. However, large proportions of the delta smelt population rear in the lower Sacramento River throughout the summer, particularly in dry years like 2001 (Moyle et al. 1992; Sweetnam 1999). We think the low numbers entrained reflect the offshore distribution of delta smelt and the small hydrodynamic influence of the Horseshoe Bend diversion.

This hypothesis is supported by consideration of diversion influence relative to tidal influence in Horseshoe Bend. The maximum volume of water that we estimated was diverted during one of our approximately hourly samples was 3,870 m^3. During our sampling, peak flood and ebb flows through Horseshoe Bend removed 3,870 m^3 of water in an estimated 8–9 s (CDWR, unpublished data). Further, at mean low water when there was no tidal exchange, Horseshoe Bend retained an estimated 5.4 million m^3 of water. Clearly, the diversion had a very small influence on Horseshoe Bend hydrodynamics and therefore the movement of delta smelt and other fishes.

Results from the present study suggest entrainment losses are strongly affected by fish habitat use, size, and diel behavior. A detailed understanding of these factors could help fisheries managers (1) prioritize locations for fish screens, (2) recommend strategies that reduce entrainment losses at unscreened diversions, and (3) improve the performance of coupled hydrodynamic-particle tracking models. Additional research is needed to better understand the effect of hydrodynamics in particular. Although our results suggested a relatively small role of tidal dynamics, additional sampling is needed in channels with different volumes and tidal regimes. For example, we expect that the hydrodynamic influences of irrigation diversions are lower in large delta channels (e.g., main-stem Sacramento and San Joaquin rivers) and flooded agricultural islands than in Horseshoe Bend, which has considerably less volume (CDWR, unpublished data). Irrigation diversions also must have larger hydrodynamic influences in delta channels that are smaller than Horseshoe Bend. Spatiotemporally expanded studies of the horizontal and vertical distribution of young delta smelt over tidal-diel cycles also are needed. Delta smelt move into shallow water to facilitate retention in low salinity zone embayments of the western delta and areas downstream (Aasen 1999; Bennett et al. 2002), but tidally oriented inshore movement was not observed in a delta channel (Aasen 1999). Further, Grimaldo et al. (2004, this volume) found that most delta smelt larvae in the central delta occurred in offshore habitats. To resolve these apparent disparities between delta channels and estuarine embayments, we recommend coupling behavioral studies with simultaneous monitoring studies of channel and diversion hydrodynamics. Ultimately, a modeling approach will probably be needed to confirm that a large-scale screening program for delta irrigation diversions is an effective component of a comprehensive restoration strategy for delta smelt and other species.

Acknowledgments

This study was conducted under the auspices of the Interagency Ecological Program (IEP), a cooperative San Francisco Estuary research effort. We thank B. McDonnell, R. Brown, S. Ford, J. Andrew, R. Churchwell, and T. Frink who facilitated IEP support. We thank V. Afentoulis, F. Feyrer, L. Grimaldo, B. Harrell, S. Itoga, M. Kirkland, J. Long, M. McGee, G. O'Leary, A. Seesholtz, T. Veldhuizen, and S. Zeug for assistance in the field. We gratefully acknowledge J. C. S. Wang, L. Lynch, and T. Rouse for larval fish identification and C. Enright and K. Le for hydrodynamic data. Finally, we thank R. Brown, W. Bennett, J. Orsi, S. Foss, and D. Odenweller for comments that improved the manuscript.

References

Aasen, G. A. 1999. Juvenile delta smelt use of shallow-water and channel habitats in California's Sacramento-San Joaquin Estuary. California Fish and Game 85:161–169.

Arthur, J. F., M. D. Ball, and M. Y. Baughman. 1996. Summary of federal and state water project environmental impacts in the San Francisco Bay-Delta Estuary, California. Pages 445–495 *in* J. T. Hollibaugh, editor. San Francisco Bay: the ecosystem. American Association for the Advancement of Science, San Francisco.

Bennett, W. A., and P. B. Moyle. 1996. Where have all the fishes gone? Interactive factors producing fish declines in the Sacramento-San Joaquin Estuary. Pages 519–542 *in* J. T. Hollibaugh, editor. San Francisco Bay: the ecosystem. American Association for the Advancement of Science, San Francisco.

Bennett, W. A., W. J. Kimmerer, and J. R. Burau. 2002. Plasticity in vertical migration by native and exotic estuarine fishes in a dynamic low-salinity zone. Limnology and Oceanography 47:1496–1507.

Blaxter, J. H. S., and R. S. Batty. 1987. Comparisons of herring behaviour in the light and dark: changes in activity and responses to sound. Journal of the Marine Biological Association of the United Kingdom 67:849–860.

CALFED. 2000. Programmatic Record of Decision. August 28, 2000. CALFED Bay-Delta Program. Sacramento, California. Available online at http://www.calfed.water.ca.gov/current/ROD.html.

Cook, L., and L. Buffaloe. 1998. Delta agricultural diversion evaluation summary report, 1993–1995. California Department of Water Resources, Interagency Ecological Program, Technical Report 61, Sacramento, California.

Culberson, S. D., C. B. Harrison, C. Enright, and M. L. Nobriga. 2004. Sensitivity of larval fish transport to location, timing, and behavior using a particle tracking model in Suisun Marsh, California. Pages 257–267 *in* F. Feyrer, L. R. Brown, R. L. Brown, and J. J. Orsi, editors. Early life history of fishes in the San Francisco Estuary and watershed. American Fisheries Society, Symposium 39, Bethesda, Maryland.

Dadswell, M. J., and R. A. Rulifson. 1994. Macrotidal estuaries: a region of collision between migratory marine animals and tidal power development. Biological Journal of the Linnaean Society 51:93–113.

Dege, M., and L. Brown. 2004. Effect of outflow on spring and summertime distribution and abundance of larval and juvenile fishes in the upper San Francisco Estuary. Pages 49–65 *in* F. Feyrer, L. R. Brown, R. L. Brown, and J. J. Orsi, editors. Early life history of fishes in the San Francisco Estuary and watershed. American Fisheries Society, Symposium 39, Bethesda, Maryland.

Grimaldo, L. F., R. E. Miller, C. M. Peregrin, and Z. P. Hymanson. 2004. Spatial and temporal distribution of native and alien ichthyoplankton in three habitat types of the Sacramento–San Joaquin Delta. Pages 81–96 *in* F. Feyrer, L. R. Brown, R. L. Brown, and J. J. Orsi, editors. Early life history of fishes in the San Francisco Estuary and watershed. American Fisheries Society, Symposium 39, Bethesda, Maryland.

Haddon, M. 2001. Modeling and quantitative methods in fisheries. Chapman and Hall/CRC, Boca Raton, Florida.

Hallock, R. J., and W. F. Van Woert. 1959. A survey of anadromous fish losses in irrigation diversions from the Sacramento and San Joaquin rivers. California Fish and Game 45:227–296.

Herren, J. R., and S. S. Kawasaki. 2001. Inventory of water diversions in four geographic areas in California's Central Valley. Pages 343–355 *in* R. L. Brown, editor. Contributions to the biology of Central Valley salmonids, Volume 2. California Department of Fish and Game, Fish Bulletin 179, Sacramento, California.

Hunter, J. R. 1981. Feeding ecology and predation of marine fish larvae. Pages 33–77 *in* R. Lasker, editor. Marine fish larvae: morphology, ecology, and relation to fisheries. University of Washington Press, Seattle.

Kingsford, R. T. 2000. Ecological impacts of dams, water diversions, and river management on floodplain wetlands in Australia. Austral Ecology 25:109–127.

Moyle, P. B., B. Herbold, D. E. Stevens, and L. W. Miller. 1992. Life history and status of delta smelt in the Sacramento–San Joaquin Estuary, California. Transactions of the American Fisheries Society 121:67–77.

Moyle, P. B. 2002. Inland fishes of California. Revised and expanded. University of California Press, Berkeley.

Pickard, A., A. Baracco, and R. Kano. 1982. Occurrence, abundance, and size of fish at the Roaring River Slough intake, Suisun Marsh, California during the 1980–81 and the 1981–82 diversion seasons. California Department of Water Resources, Interagency Ecological Program, Technical Report 3, Sacramento, California.

Spaar, S. 1994. Delta agricultural diversion evaluation 1992 pilot study. California Department of Water Resources, Interagency Ecological Program, Technical Report 37, Sacramento, California.

Stevens, D. E., and L. W. Miller. 1983. Effects of river flow on abundance of young chinook salmon, American shad, longfin smelt, and delta smelt in the Sacramento-San Joaquin River system. North American Journal of Fisheries Management 3:425–437.

Swanson, C., T. Reid, P. S. Young, and J. J. Cech, Jr. 2000. Comparative environmental tolerances of threatened delta smelt (*Hypomesus transpacificus*) and introduced wakasagi (*H. nipponensis*) in an altered California estuary. Oecologia 123:384–390.

Swanson, C., P. S. Young, S. Chun, T. Chen, T. MacColl, L. Kanemoto, and J. J. Cech, Jr. 2001. Fish treadmill-developed fish screen criteria for native Sacramento-San Joaquin watershed fishes. Part 2. Biological studies. Final report to the CALFED Bay-Delta Restoration Program, CALFED project #99-N02, Sacramento, California.

Sweetnam, D. A. 1999. Status of delta smelt in the Sacramento-San Joaquin Estuary. California Fish and Game 85:22–27.

Wang, J. C. S. 1986. Fishes of the Sacramento-San Joaquin Estuary and adjacent waters, California: a guide to the early life histories. California Department of Water Resources, Interagency Ecological Program, Technical Report 9, Sacramento, California.