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Journal
San Francisco Estuary and Watershed Science, 7(2)

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Publication Date
2009

DOI
https://doi.org/10.15447/sfews.2009v7iss2art1

DECEMBER 2009

SAN FRANCISCO ESTUARY & WATERSHED SCIENCE
Published by the California Bay-Delta Authority Science Program and the John Muir Institute of the Environment

Nearshore Areas Used by Chinook Salmon Fry, *Oncorhynchus tshawytscha,* in the Northwestern Sacramento-San Joaquin Delta, California

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ABSTRACT

We report the geographic distribution and the densities and catch rates of Chinook salmon fry, *Oncorhynchus tshawytscha,* in different substrata and nearshore zones in the northwestern Sacramento-San Joaquin Delta of the San Francisco Estuary, California, USA. Nearshore zones in the freshwater, tidally influenced northwestern delta are dominated by riprap, and contain sparse sections of tule beds, beaches, and riparian zones. We sampled at six beach seine sites and eight electrofishing sites during winter 2001 along the Sacramento River, Steamboat Slough, Miner Slough, Prospect Island Marsh, Prospect Slough, and Liberty Island Marsh. Overall, fry densities were higher on the Sacramento River and Steamboat Slough and lower in Liberty Island and Prospect Island marshes. Chinook fry were significantly larger in the Sacramento River than in Steamboat Slough during March. Densities of Chinook fry were higher in shallow beaches than in riprap nearshore zones. Fry densities also increased with Secchi depth and richness of non-native species, suggesting increased predation risk. Shallow nearshore environments in conveyance channels such as Steamboat Slough and the Sacramento River seem important for rearing Chinook salmon fry. Conversely, riprap in these channels was less used by fry. Evaluating potential impacts of habitat quality on growth and survival of fry seems key to successful conservation and restoration efforts in the delta.

KEYWORDS

Fry, Chinook salmon, delta, habitat, rearing, estuary, beach seine, electrofishing.

INTRODUCTION

Many estuaries have been shown to provide important nursery habitat for salmon fry, especially Chinook salmon, *Oncorhynchus tshawytscha.* (Reimers 1971; Levy and Northcote 1981; Healey 1980, 1991). Habitat alteration can severely reduce the value of estuarine nursery habitats for salmon (Healey 1980, 1991; Levy and Northcote 1981). California's Sacramento-San Joaquin Delta (Figure 1) is a highly modified estuary and its importance as a nursery habitat for Chinook salmon fry has not been well studied. The length of time different races of Chinook salmon fry spend rearing and preparing for ocean entry varies in the delta but is most protracted in fall-run, lasting from several weeks to months (Kjelson and others 1982). The relative contribution of delta-reared fry to adult production is unknown but may have been substantial under natural conditions (Brown 2003). Thus, an assessment of the value and use of delta habitats by Chinook salmon fry is needed.

Past juvenile Chinook salmon sampling in the delta has been concentrated on or adjacent to the Sacramento River and in the eastern delta (Brandes and McLain 2001). Fry diverted into the eastern delta from the Sacramento River experience low survival (Brandes and McLain 2001). The northwest delta offers an alternative salmon migration route to the ocean that may contain better habitat for Chinook salmon fry than the mainstem Sacramento River or interior delta. Our goal in this study was to describe the geographic distribution and to compare the densities of Chinook salmon fry in different habitats and nearshore zones in the northwest delta during winter 2001. In particular we were concerned with how Chinook salmon fry responded to riprap, which is widely used for bank stabilization in the delta. Elsewhere, riprap has been shown to be detrimental to salmon (Chapman and Knudsen 1980; Garland and others 2002; Schmetterling and others 2001). In addition, we describe the length composition of Chinook salmon fry and the co-occurring species of fish in the different areas sampled. Our results identify areas of Chinook salmon fry concentration and serve as a baseline against which to assess future research and monitoring in the northwest delta.

Description of Study Area

Peak outflow in the delta typically occurs between January and March and tends to coincide with the presence of fry (Kjelson and others 1982). The northwest delta consists of sloughs, channels, and flooded islands. Water circulation in these habitats is influenced by both tides and Sacramento River Basin outflow. Nearshore habitats in the northwest delta are dominated by riprap, interspersed with small tule beds, beaches, and riparian zones, some with instream woody debris. Low water visibility was evident throughout the studied period (mean Secchi disk depth = 0.46 m, range: 0.21 to 0.85 m).

The Yolo Bypass is a 59,000-acre flood bypass on the west side of the Sacramento River (Jones & Stokes 2001; Figure 1). Portions of the Yolo Bypass that are flooded in winter and early spring provide spawning and nursery habitat for Chinook salmon and many other species (Sommer and others 2001a, 2001b, 2005). Historical records indicate the Yolo Bypass was flooded during 71% of years since 1935 (Jones & Stokes 2001). When conveying floodwaters in high-flow years, the Yolo Bypass empties back into the Sacramento River approximately three kilometers upstream of Rio Vista. Liberty Island and Prospect Island, Cache, Prospect and Lindsey sloughs, and the Yolo Bypass toe drain are located in the southern reach of the bypass (Figure 1). All these are inundated by tidal action and subject to flooding since the State of California acquired easements to flood Liberty and Prospect islands as part of routine Yolo Bypass operations (hereafter, these areas will be referred to as island marshes). The easements restrict the heights of the levees that were built around the islands and the type of vegetation the islands can support. As part of a normal flooding event in the bypass, the levees surrounding Liberty Island were overtopped and the island was inundated in 1998. In addition, the southern tip of Liberty Island was breached in 1990 to restore its full tidal action (T. Harvey, Stones Lake National Wildlife Refuge, pers. comm., 2004). The effects of such flooding on juvenile salmon distribution and abundance have not been reported.

METHODS

Fish were sampled by beach seine and electrofishing at several sites in four different areas (Sacramento River, Steamboat Slough, Miner Slough and the Liberty Island–Prospect Island complex, Figure 1, Table 1). Sample sites within each area were chosen to represent four different shoreline habitats (riprap,

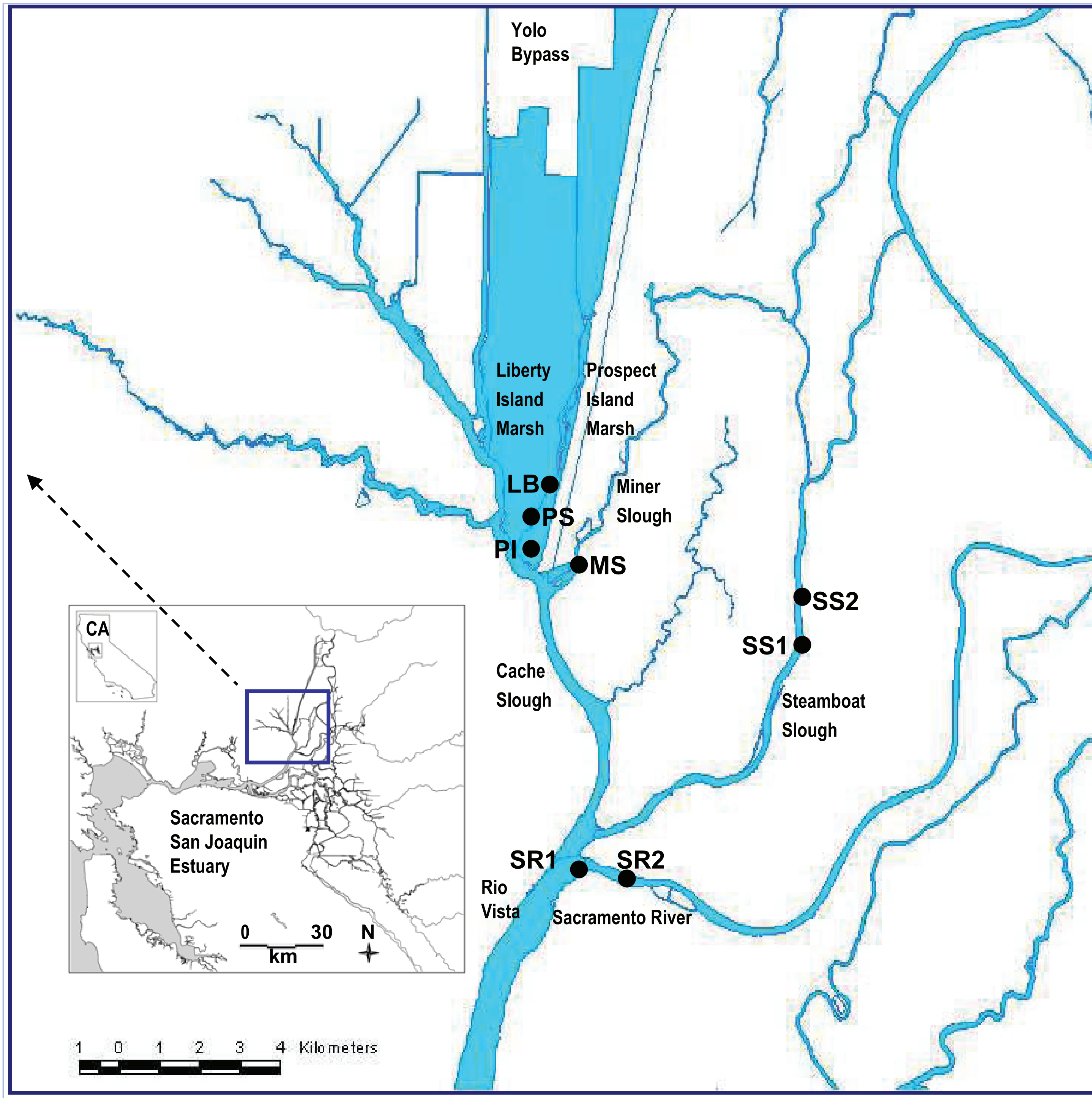

Figure 1 Site locations for electrofishing and beach seining in the northwestern Sacramento-San Joaquin Delta from January through March 2001. South portion of the Yolo Bypass is also indicated.

sand–mud beach, tule, riparian, Table 1). Nearshore habitat types follow Cowardin and others (1979): tule (emergent wetland class), riprap (rocky shore class), sand–mud beach (unconsolidated class), and riparian (forested wetland class).

Seine

Seining was done along six shoreline sites between January 11 and March 30, 2001 (Figure 1, Table 1). The majority of nearshore habitats in the northwest delta consists of riprap and the first sites of sand-mud encountered traveling upstream from Cache Slough were selected for seining. Nearby riprap zones were then selected for seining for comparative purposes. A total of 78 hauls was made during daylight hours on beach and riprap substrates. Fifty-four hauls were made with a 15 m x 1.2 m (50 ft x 4 ft) 3-mm (1/8-inch) delta square mesh beach seine with a 1.2 m (4 ft) long bag. Fifteen round plastic rollers were attached to the beach seine lead line (Peanut style mudroller), reducing lead line resistance when pulling the net across mud and riprap, and enabling seining on substrata previously inaccessible in rocky or vegetated areas. For gear comparison purposes, 24 supplemental hauls were also made with a 30 m x 1.2 m (100 ft x 4 ft) 3-mm (1/8-inch) delta square mesh beach seine with a 1.2 m (4 ft) long bag.

Sites were sampled by boat between 8:00 AM and 3:00 PM. One seine haul was conducted during each visit to a site whenever weather conditions allowed. Upon arrival at a sampling site, the boat was moored a minimum of 25 m upstream or downstream from the sampling site. Environmental variables potentially related to fish, such as shoreline slope, substrate hardness, Secchi depth, water temperature, vegetation density, and riparian vegetation occurrence (Table 2) were recorded prior to sampling fish. After pulling the beach seine, fish were placed immediately in a tub for processing. All fish captured were identified and measured by fork length and released immediately.

All sample site information, shoreline habitat descriptions, and number and size of fry captured were entered into the Interagency Ecological Program database and all entries were checked for accuracy before analysis started. Fish density and percent occurrence (determined by presence divided by number of hauls) were computed for all fish encountered in beach seining. Miner Slough and Liberty Island–Prospect Island complex areas were combined due to their low overall fish density.

Density of fish (D, in catch per m^3) in seine hauls was computed as:

$$D = \frac{C}{(0.5)ZWL} \tag{1}$$

Where C is the number of collected fish, Z is the maximum depth of the seine haul in meters, W is the distance each haul is taken from shore in meters, and L is the length of the seine haul in meters. Z is multiplied by 0.5 to calculate the volume of water filtered per haul from depth zero to Z.

Fry density (D) was also computed for the 24 supplementary hauls conducted in sand-mud substrates with the 30 m beach seine. However, due to the absence of experimental mudrollers in the 30-m seine, no sampling over riprap surfaces was attempted. We found no differences in catch density between the 30-m and 15-m seines when sampling sand-mud substrates. Thirty-meter and 15-m seine results were, therefore, combined for analyses related to fry density and size distribution. Fry densities were converted to three categories for multinomial logistic regression (MLR) analysis (Systat 2004):

1. ($D = 0$)
2. ($0 < D < 0.1$)
3. ($D \geq 0.1$).

We combined fry lengths from individual samples into monthly box plots to assess possible ontogenic differences in habitat use among northwest delta areas. Due to low catches in Miner Slough and Liberty Island Marsh, the significance of differences in monthly mean lengths was only assessed in the Sacramento River and Steamboat Slough by means of *t*-tests. Differences in fry density among the four

Table 1 Catch of Chinook salmon fry in the northwestern Sacramento-San Joaquin Delta in winter 2001

Gear	Location	Site	Substrate	Samples	Catch
15-m Beach Seine					
	Sacramento River	SR1	Sand/mud	3	37
	Sacramento River	SR2	Sand/mud	7	118
	Sacramento River	SR2	Riprap	9	1
	Steamboat Slough	SS1	Sand/mud	5	107
	Steamboat Slough	SS1	Riprap	1	0
	Steamboat Slough	SS2	Sand/mud	5	60
	Steamboat Slough	SS2	Riprap	7	5
	Miner Slough	MS	Riprap	6	12
	Liberty Island Marsh	LB	Sand/mud	11	18
		Total		54	358
30-m Beach Seine					
	Sacramento River	SR1	Sand/mud	5	43
	Sacramento River	SR2	Sand/mud	8	120
	Steamboat Slough	SS1	Sand/mud	6	30
	Steamboat Slough	SS2	Sand/mud	5	53
		Total		24	246
Electrofishing					
	Sacramento River	SR1	Beach	1	2
	Sacramento River	SR1	Tule	3	15
	Sacramento River	SR2	Riparian	4	22
	Sacramento River	SR2	Riprap	3	8
	Sacramento River	SR2	Beach	2	25
	Steamboat Slough	SS1	Riparian	2	13
	Steamboat Slough	SS1	Tule	2	7
	Steamboat Slough	SS1	Beach	1	2
	Steamboat Slough	SS2	Riprap	2	16
	Steamboat Slough	SS2	Beach	2	37
	Miner Slough	MS	Riparian	2	8
	Miner Slough	MS	Riprap	1	0
	Miner Slough	MS	Tule	1	6
	Liberty Island Marsh	LB	Beach	3	3
	Prospect Island Marsh	PI	Riparian	1	1
	Prospect Island Marsh	PI	Tule	1	0
	Prospect Slough	PS	Riprap	1	4
	Prospect Slough	PS	Tule	1	3
		Total		33	172

Table 2 Means of physical and biotic variables recorded at each sampling site in relation to three density levels (D) from beach seining for Chinook salmon fry: 1 ($D = 0$ /m^3); 2 ($0 < D < 0.10$ / m^3); 3 ($D \geq 0.10$ /m^3). Type of variables: quantitative (A), qualitative (B). Rho^2 denotes McFadden's Rho-squared.

Variable	Variable Type	D 1	D 2	D 3	Rho^2
Physical					
Shoreline slope[a, b]	A	0.20	0.15	0.12	0.04
Substrate hardness[a]	B[d]	2.27	1.58	1.24	0.11
Secchi depth (m)[a]	A	0.37	0.23	0.49	0.13
Water temperature (°C)	A	10.79	11.32	11.91	0.01
Biotic					
Richness, native fish[c]	A	0.17	0.29	0.35	0.01
Richness, introduced fish[a]	A	0.47	1.03	1.18	0.06
Density, native fish[c]	A	11.81	11.23	6.95	0.01
Density, introduced fish	A	0.37	0.10	0.19	0.01
Vegetation density	B[e]	1.03	1.10	1.06	0.01
Occurrence riparian - woody debris	B[f]	1.07	1.13	1.23	0.02

[a] *LR-P < 0.05 (p-value of likelihood ratio statistic)*
[b] *Shoreline slope = Z ÷ L (See Equation 1).*
[c] *Excludes Chinook salmon fry.*
[d] *Substrate hardness: mud = 1; sand = 2; riprap = 3.*
[e] *Vegetation density: low = 1; medium = 2; high = 3.*
[f] *Riparian vegetation and/or woody debris: absent = 1; present = 2.*

areas and between sand-mud and riprap substrates (categorical variables) were evaluated using MLR models (Systat 2004). MLR models were also used to evaluate relations between fry densities and physical and biotic variables (Table 2).

Electrofishing

Electrofishing was done along eight shoreline sites between March 12 and 16, 2001 (Figure 1, Table 1). Fishing was conducted with an 18-ft Smith-Root flat hauled aluminum boat equipped with DC Smith-Root electrofishing gear and a Honda 5.0 GPP generator (6 to 8 A of electricity pulsed at 60 pulses/second). Each electrofishing site was large enough to include a variety of nearshore zones per kilometer. Shoreline distance sampled depended on the length of each type of shoreline zone and ranged from 30 m to 500 m (mean = 163 m).

The first site was randomly selected prior to sampling between the hours of 7:00 AM and 3:00 PM to avoid biases associated with sampling frequency and order. The electrofishing boat idled as close as possible along the shoreline while floating downstream with the current. Occasionally the boat was put in gear to adjust position. Two biologists on the bow of the boat with long handled nets removed all shocked fish and placed them in the live well. At the end of the sample, all fish species were identified, measured, and released immediately downstream of the boat. The only salmon fry counted were those found floating on the top of the water to reduce possible biases affecting visibility and detection.

Catch of Chinook salmon fry and other species at each sample site was standardized as catch/minute shocking and this variable was used to compare catch rates among areas and nearshore zones (Reynolds 1996). Catch rates in the four areas were compared among the four types of nearshore habitats. Three fry catch rate levels (CR) in fry/minute were assigned: $CR = 0$; $0 > CR < 2$ and $CR \geq 2$. Each catch rate was used in MLR models to compare differences among the four areas and four nearshore habitats (categorical variables).

RESULTS

Seine

Seventeen species of juvenile fishes were collected in beach seines (Table 3), including 604 fall-run Chinook salmon (Table 1). Most commonly captured species with relatively highest densities included fall-run Chinook salmon, the invasives inland silverside and yellowfin goby, and the native Sacramento pikeminnow. Delta smelt and threadfin shad were both relatively abundant and common in the Liberty Island–Prospect Island complex and Minor Slough area but rare elsewhere. Small numbers of winter- and spring-run races of Chinook were captured, as were some hatchery tagged Chinook (Table 3). Other species were widely distributed, but were captured at relatively low densities.

Chinook salmon fry densities differed significantly among the four areas (MLR, LR test, $P < 0.005$), being highest in Steamboat Slough (131/1,000 m^3), intermediate in the Sacramento River (73/1,000 m^3), and lowest in the Miner Slough, Liberty Prospect complex (36/1,000 m^3) (Table 3). Densities showed an increasing trend between January and March in Sacramento River and Steamboat Slough areas, but not in Miner Slough and Liberty Island Marsh. Fry densities were higher in beach (sand-mud) substrata than in riprap substrata (MLR, LR test, $P < 0.005$), particularly in the Sacramento River and Steamboat Slough (Figure 2). Although the Sacramento River is a major downstream migration route for Chinook salmon fry, none were found in Sacramento River riprap.

Mean fry fork lengths increased from 39 mm in January to 44 mm in March (Figure 3). Fork lengths were similar in the Sacramento River and Steamboat Slough in January and February ($P > 0.70$) but in March, Steamboat Slough fry were significantly smaller than Sacramento River fry ($P < 0.001$, Figure 3).

Environmental factors significantly associated with Chinook salmon fry density levels included, in decreasing fitting order: Secchi depth (positive); substrate hardness (negative); richness of introduced (non-native) fish (positive) and shoreline slope (negative). Fry density also increased with richness of native fishes but the difference was not significant. Highest fry density levels tended to be associated with low substrate hardness and shoreline slope and with high Secchi depth and richness of introduced

Table 3 Fish density and percent occurrence of all fish in 15-m and 30-m beach seining in the northwestern Sacramento San Joaquin Delta in winter 2001

		Density (number/m^3) x 1,000				% Occurrence (presence/number of hauls)			
Common Name	**Scientific Name**	**All**	**Sacra-R**	**Steam-S**	**Mi-Pr-Li**	**All**	**Sacra-R**	**Steam-S**	**Mi-Pr-Li**
Inland silverside (I)	*Menidia beryllina*	214.43	411.34	112.81	34.68	51	52	57	41
Chinook salmon, fall-run (N)	*Oncorhynchus tshawytscha*	87.07	73.26	130.53	35.59	60	48	77	53
Yellowfin goby (I)	*Acanthogobius flavimanus*	7.31	16.71	0.67	2.45	18	32	3	18
Sacramento pikeminnow (N)	*Ptychocheilus grandis*	2.56	0.92	4.44	2.24	13	10	13	24
Delta smelt (N)	*Hypomesus transpacificus*	1.73	1.03	1.05	4.20	8	3	7	18
Chinook salmon, hatchery-tagged (N)	*Oncorhynchus tshawytscha*	0.97	0.12	1.87	0.96	10	6	13	12
Threadfin shad (I)	*Dorosoma petenense*	0.90	0.36	0.30	2.96	6	3	3	18
Sacramento sucker (N)	*Catostomus occidentalis*	0.62	0.00	1.26	0.00	3	0	7	0
Sacramento splittail (N)	*Pogonichthys macrolepidotus*	0.54	1.03	0.00	0.58	3	3	0	6
White crappie (I)	*Pomoxis annularis*	0.49	0.00	0.00	2.24	1	0	0	6
Fathead minnow (I)	*Pimephales promelas*	0.41	0.20	0.87	0.00	3	3	3	0
Rainbow trout, hatchery (N)	*Oncorhynchus mykiss*	0.40	0.61	0.00	0.73	3	3	0	6
Chinook salmon, winter-run (N)	*Oncorhynchus tshawytscha*	0.40	0.69	0.00	0.57	3	3	0	6
Shimofuri gobi (I)	*Tridentiger bifasciatus*	0.19	0.16	0.00	0.57	3	3	0	6
Chinook salmon, spring-run (N)	*Oncorhynchus tshawytscha*	0.18	0.16	0.00	0.54	3	3	0	6
Largemouth bass (I)	*Micropterus salmoides*	0.16	0.00	0.41	0.00	1	0	3	0
Rainbow trout (N)	*Oncorhynchus mykiss*	0.12	0.00	0.31	0.00	1	0	3	0
Western mosquitofish (I)	*Gambusia affinis*	0.11	0.00	0.00	0.52	1	0	0	6
Pacific lamprey (N)	*Lampetra tridentata*	0.11	0.27	0.00	0.00	1	3	0	0
Golden shiner (I)	*Notemigonus crysoleucas*	0.11	0.27	0.00	0.00	1	3	0	0

N = native, I = introduced species
All = Sacramento area, Steamboat Slough, Prospect Island Marsh, Liberty Island Marsh, and Minor Slough
Sacra-R = Sacramento area
Steam-S = Steamboat Slough
Mi-Pr-Li = Prospect Island Marsh, Liberty Island Marsh, and Minor Slough

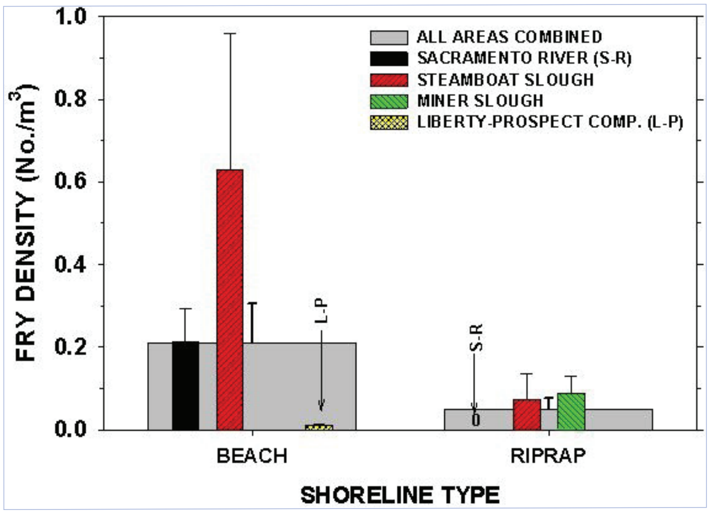

Figure 2 Densities of Chinook salmon fry sampled on beach (mud, sand) and riprap substrata in the northwestern Sacramento-San Joaquin Delta using a 15-m long beach seine. T bars denote standard error of mean densities. No fry (denoted as 0) were found in riprap in the Sacramento River. No beach and riprap shorelines were found or were accessible to seining in Miner Slough and Liberty-Prospect complex, respectively.

fish (Table 2). MLR models including both Secchi depth and substrate hardness (or richness of introduced fish) showed greatly improved fit over individual variables (McFadden's Rho^2 ≥ 0.20), particularly when estimating fry density from Secchi depth and substrate hardness (McFadden's Rho^2 = 0.34, LR-P < 0.001).

Electrofishing

Catch rates of fry by electrofishing did not differ significantly among areas (MLR, LR test, $P > 0.05$, Table 4). A total of six predatory species of fish greater than 260 mm FL was captured during electrofish sampling. Catches of predatory species were highest in the Sacramento River and lowest in Steamboat Slough sampling sites, however, overall predatory fish captures were low (Table 4).

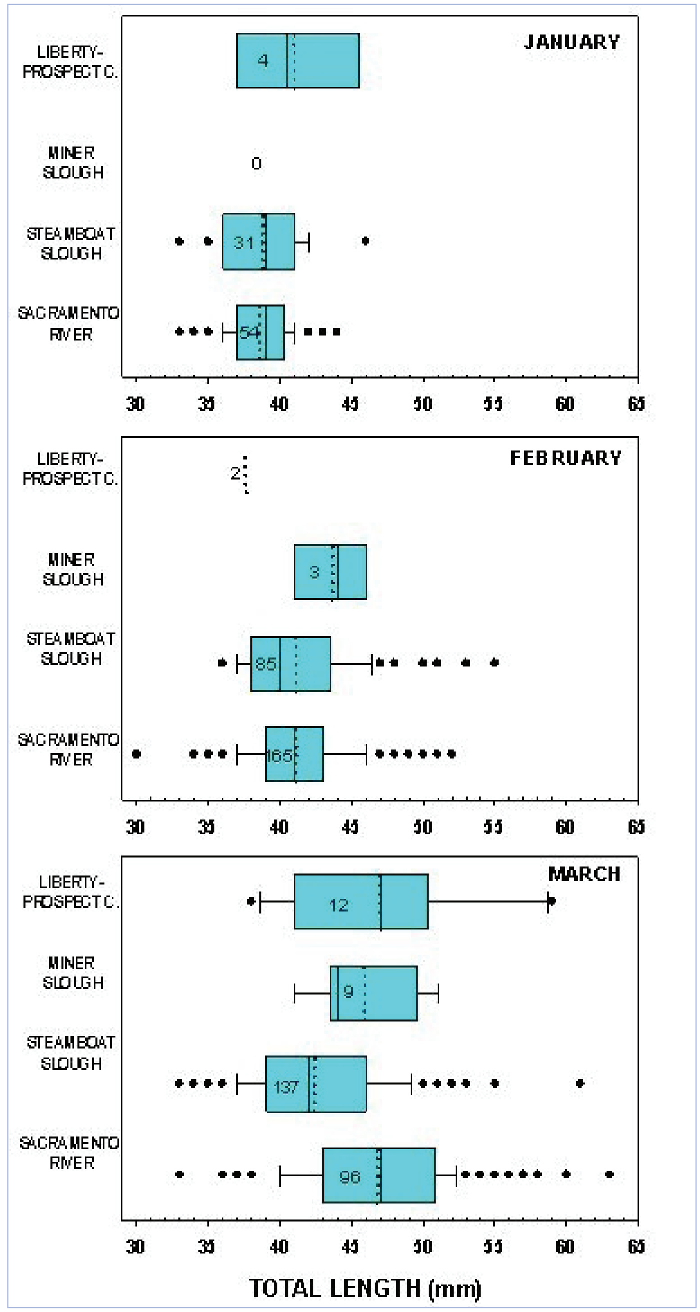

Figure 3 Box plots for the size distribution of Chinook salmon fry caught with beach seine in the northwestern Sacramento-San Joaquin Delta from January to March 2001. Vertical lines in boxes denote the mean (dotted) and median (solid). Points outside the whiskers include all outliers. Number of fish is indicated in boxes (unless < 3).

DISCUSSION

Chinook salmon fry and other species were captured throughout the sampling areas but generally in low abundance (Table 3). By far the most abundant species in beach seine samples was the introduced inland silverside, *Menidia beryllina*, which averaged 214/1,000 m^3. Fall-run Chinook salmon were the second most abundant species at 87/1,000 m^3. All other species averaged less than 10/1,000 m^3 and many were much less abundant.

Electrofishing and seining results showed higher Chinook salmon fry densities in Sacramento River and Steamboat Slough, compared to Miner Slough and Liberty Island Marsh (Tables 3 and 4). This result suggests that the marshy habitats at the downstream end of Yolo Bypass were little used by Chinook fry in 2001. This particular distribution of Chinook fry may be a reflection of the water year. Sacramento Basin outflow during the winter 2001 study period was relatively low, and flows into the Yolo Bypass were negligible. The Yolo Bypass appears to be important as salmon nursery habitat during years of high flow. Sommer and others (2001a, 2005) reported the presence of juvenile salmon at low densities throughout the Yolo Bypass during 1998 and 1999. In these two years, the bypass was wetted and fish grew faster than those in the river channels. They suggested that the Yolo Bypass provides better rearing and migration habitat for juvenile Chinook salmon than adjacent river channels, such as the Sacramento River. Moreover, the Yolo Bypass, when fully wetted, contained significantly more low-velocity habitat known to be selected by young Chinook salmon.

Highest fry density levels were associated with low substrate hardness and shoreline slope and with high Secchi depth and richness of other fish species (Table 2, Figure 2). It is possible that the irregular surface of riprap resulted in an underestimate of Chinook salmon fry densities from beach seining in that habitat. Catch rates of fry by electrofishing were also lower in riprap, although the difference was not significant. Consistently lower fry densities in riprap than in beach (sand-mud) substrates suggests that riprap may be less used by fry. Higher densities of juvenile salmon have been consistently reported in non-riprapped areas rather than in riprapped areas elsewhere in the U.S. West Coast, suggesting higher affinity for non-riprapped habitat (Knudsen and Dilley 1987; Schmetterling and others 2001; Beamer and Henderson 1998). Sommer and others (2005),

Table 4 Catch rate and percent occurrence of Chinook salmon fry and predatory fish captured by electrofishing in the northwestern Sacramento-San Joaquin Delta in winter 2001

		Catch Rate (number/minute)				Percent Occurrence (presence/number of attempts)			
Common Name	**Scientific Name**	**All**	**Sacra-R**	**Steam-S**	**Mi-Pr-Li**	**All**	**Sacra-R**	**Steam-S**	**Mi-Pr-Li**
Chinook salmon (N)	*Oncorhynchus tshawystcha*	1.72	1.74	3.01	0.65	82	92	100	55
Sacramento pikeminnow (N)	*Ptychocheilus grandis*	0.12	0.19	0.00	0.12	27	39	0	0
Striped bass (I)	*Morone saxatilis*	0.04	0.02	0.00	0.09	9	8	0	0
Largemouth bass (I)	*Micropterus salmoides*	0.02	0.00	0.07	0.02	9	0	22	9
Smallmouth bass (I)	*Micropterus dolomieui*	0.02	0.06	0.00	0.00	3	8	0	0
Rainbow trout, hatchery (N)	*Oncorhynchus mykiss*	0.01	0.03	0.00	0.00	3	8	0	0
Spotted bass (I)	*Micropterus punctulatus*	0.01	0.00	0.00	0.02	3	0	0	9

N = native, I = introduced species
All = Sacramento area, Steamboat Slough, Prospect Island Marsh, Liberty Island Marsh, and Minor Slough
Sacra-R = Sacramento area
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however, did not find any evidence that fry avoided hard substrates in the Yolo Bypass.

The positive association between fry density and Secchi depth suggests that fry prefer less turbid water, which is not surprising for a visually feeding fish. Gregory and Northcote (1993) found that Chinook fry fed most effectively at intermediate turbidity levels and speculated that at intermediate turbidity fry could still see their prey but were somewhat protected from predation. Gregory and Levings (1998) subsequently confirmed that salmon fry were less subject to predation at higher turbidity. The positive association between fry density and species richness suggests that certain habitats are generally attractive to small fish and that not only Chinook but other species are congregating in these areas as well. This could be problematic for Chinook fry as a number of introduced species prey upon them. However, predator abundance was generally low in the habitats sampled (Table 4).

From January through March of the study period, fry increased about 5 mm in average length. This is a slow rate of increase in size over time compared with other estuaries (Healey 1991) but it is likely that the estuary population of fry was continually being supplemented by small fry from upstream. MacFarlane and Norton (2002) also found relatively slow growth of juvenile Chinook salmon in the Sacramento–San Joaquin Estuary compared to other estuaries and relative to juvenile growth in the ocean. Chinook salmon fry were significantly larger in the Sacramento River than in Steamboat Slough during March. This may indicate that the Sacramento River is utilized more by actively migrating juvenile Chinook salmon at this time and the channels to the west are utilized more by rearing fry. Research on salmon habitat use in other Pacific Coast estuaries suggests a general transition of fry from shallow, slower-velocity nearshore areas, to deeper, faster moving water as they grow (Everst and Chapman 1972; Brandes and McLain 2001; Garland and others 2002), and this behavior may have influenced the size composition of our catches.

Although our results suggest that salmon fry select beach (sand-mud) substrates over riprap, and that other habitat factors such as slope and species richness also play a role, more focused studies are needed to evaluate the relative benefits of different shoreline zones and substrate types (e.g., growth potential, food availability, predation risk, water quality, residence time). Sommer and others (2001a) observed enhanced food production and increased juvenile Chinook salmon growth in the flooded Yolo Bypass. Despite the low density Chinook fry we observed in Liberty and Prospect Island marshes and Miner Slough, it is conceivable that these areas contribute more to juvenile fish production than our results suggest. The negative association between fry density and shoreline slope suggests that shallow nearshore areas could contribute more to juvenile fish production than deeper nearshore areas commonly found in conveyance channels (such as the Sacramento River) despite the high average abundance of fry in Sacramento River sites. Remaining shallow nearshore environments in Steamboat Slough and the Sacramento River could be especially important for Chinook fry rearing during low flows when extensive floodplain areas like the Yolo Bypass are not accessible to fry. Shallow habitats in Liberty Island and Prospect Island marshes may also be valuable transition zones for juvenile Chinook salmon exiting the Yolo Bypass during wet years.

Our results represent only one small additional step toward a sufficient understanding of how Chinook fry use the Sacramento–San Joaquin Delta. For example, the relatively high densities of Chinook fry in Steamboat Slough need to be evaluated relative to other regions of the delta and the mainstem Sacramento River. Synoptic surveys are needed to assess salmon distribution and habitat use under different outflow conditions. The effects of our growing understanding of the complex tidal circulation in the delta on salmon distribution and migration need to be investigated. More knowledge of the relative quality of different habitat types within the delta is needed to assist with restoration (Grimaldo and others 2000). Particular emphasis should be placed on ways to enhance the habitat value of riprap as this is such a dominant nearshore habitat in the delta and will continue to be a primary means of flood control and levee stabilization. The transient nature of Chinook salmon and the lack of sampling gears to evaluate the various habitats in the delta make assessments of habitat choices by fish difficult (Brown 2003). Nevertheless, effective management of the species and its habitat in the delta requires a fuller understanding of Chinook salmon in the delta.

ACKNOWLEDGEMENTS

The authors acknowledge support of this work from the Interagency Ecological Program. Dr. Russell Bellmer and Larry Hansen, U.S. Fish and Wildlife Service, and Dr. Ted Sommer, California Department of Water Resources, provided guidance and important critical reviews of the manuscript. Dr. Mike Chotkowski, U.S. Bureau of Reclamation, was instrumental in developing this research project. Allie Stover, U.S. Fish and Wildlife Service, assisted with literature searches and editing. Dr. David Brown, Louisiana State University, provided statistical guidance. The authors also would like to thank the Associate Editor, Dr. Michael Healey, for his invaluable assistance, and two anonymous peer reviewers whose comments greatly improved the manuscript.

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