LIFE HISTORY OF FALL-RUN JUVENILE CHINOOK SALMON, *ONCORHYNCHUS TSHAWYTSCHA*, IN THE SACRAMENTO-SAN JOAQUIN ESTUARY, CALIFORNIA

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Abstract: The Sacramento-San Joaquin Estuary is one of the largest on the Pacific Coast and supports a variety of anadromous species. Fall-run chinook salmon, the dominant race in the system, utilize the estuary for rearing and migration. Fry (<70 mm) rear in the estuary for about 2 months, primarily in the upper freshwater Delta. Brackish water bays are used primarily as a migration corridor by smolts (> 70 mm). Chinook in more northern estuaries appear to make greater use of brackish water for rearing. Peak fry rearing (February to March) and smolt migration (April to June) occurs two to three months earlier in the Sacramento-San Joaquin than in most northern estuaries. This reflects earlier spawning and high summer temperatures that force juveniles from the lower river and Delta. Fry abundance and distribution in the estuary are influenced by the magnitude and timing of river flows. Growth rates during estuarine rearing range from 0.4 to 1.2 mm day^{-1} and are similar to other Pacific Coast estuaries. Chinook diet also is similar to other west coast estuaries and is dominated by dipterans, cladocerans, copepods, and amphipods. Survival during smolt outmigration is greater in the lower bays than in the Delta. Survival through the Delta in June is inversely related to water temperature and directly related to river flow as suggested for some northern systems. Alteration of the timing, magnitude, and distribution of flow in the Sacramento-San Joaquin Estuary has a major impact on juvenile chinook survival. Hatcheries produce about 26 million fall-run smolts annually with most released during May and June in upstream and estuarine waters.

Introduction

The Sacramento-San Joaquin River system has one of the largest estuaries along the Pacific Coast (Fig. 1). The major anadromous species it supports include striped bass, *Morone saxatilis*; American shad, *Alosa sapidissima*; white sturgeon, *Acipenser transmontanus*; steelhead trout, *Salmo gairdneri*; and chinook salmon, *Oncorhynchus tshawytscha* (Kelley 1966).

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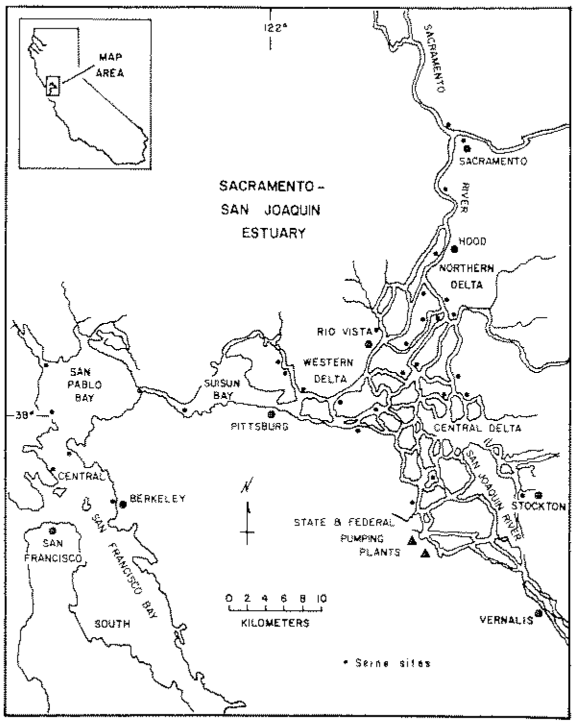

Figure 1. The Sacramento-San Joaquin Estuary, California.

Chinook salmon in this system are at the southern limit of their range. Only the more northern Columbia River system produces more chinook than California's Central Valley streams. Over 90% of the Valley's chinook salmon spawn in the Sacramento River system.

Four major runs (fall, late fall, winter, and spring), identified by the season in which upstream migration occurs, spawn in the Sacramento drainage. The fall-run is the largest numerically (the 1968 to 1978 average number of spawners was 199,000), comprising about 80% of the Sacramento drainage stock. The San Joaquin system supports a fall-run that has averaged less than 4,000 spawners in recent years (1973 to 1978). Fall-run chinook have received the most study.

Chinook populations in the Sacramento-San Joaquin drainages have declined by about 70% since 1953 (Hoopaugh and Knutson 1979). This decline is attributed primarily to the development of water resources through the construction of dams and water diversion projects during the last 40 years. Such development has caused extensive loss and alteration of spawning, rearing, and migration habitat in upstream and estuarine environments. The influence of harvest rates on the decline of chinook in California is unknown.

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Description of Study Area

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Three salmon hatcheries located on the American and Feather rivers (State) and on Battle Creek (Federal) were built to mitigate losses of habitat due to water development. All three emphasize production of fall-run chinook. The two State hatcheries release their total fall-run production of about 12 million salmon/year directly into the estuary, while the Federal production (about 14 million annually) is released in the upper Sacramento River and Battle Creek. Hatchery releases are made from mid-May through June. The relative contribution of hatchery produced young to adult stocks is presently unknown.

The objective of this paper is to describe the rearing of fry in the estuary and the migration of smolts through the estuary to the ocean and to compare our observations, where possible, with observations on fall-run chinook in other estuaries from northern California to British Columbia. Most of the data presented in this paper were collected as part of a cooperative study of the Sacramento-San Joaquin Estuary conducted by the California Departments of Fish and Game and Water Resources, the U. S. Fish and Wildlife Service, and the U. S. Bureau of Reclamation. Our chinook salmon studies were designed to assess the impacts of water diversions from the estuary upon chinook salmon survival and to provide information to help correct negative impacts.

Description of Study Area

The Sacramento-San Joaquin Estuary consists of the tidally influenced, freshwater Delta where the Sacramento and San Joaquin rivers join, and a series of downstream embayments, Suisun, San Pablo, and San Francisco Bays (Fig. 1).

The Delta covers about 300,000 ha of land and water. It consists of 1130 km of navigable, freshwater channels and 30 large leveed islands used for farming. Some channels are edged by narrow stretches of freshwater marsh, but most have steep banks of mud or riprap. Delta levees are generally covered by riparian vegetation. Channel widths vary from 50 m to 1.5 km and generally are less than 15 m deep. Annual Delta water temperatures range from 6 to 28°C. Turbidity is high, particularly in the spring, with secchi readings usually less than 0.5 m. Tidal action reaches to the upstream limits of the Delta but the upper edge of the salinity gradient only extends to the western Delta-Suisun Bay area.

The bays downstream from the Delta cover 124,000 ha. Their average depth is 6.1 m although most are less than 2 m deep at low tide. Much of the shore-line is industrialized, but considerable salt and brackish marshland still remains in Suisun, northern San Pablo, and southern San Francisco Bays. Annual surface water temperatures range from 9 to 21°C and salinities range from 28 to 34‰ at the entrance to the ocean and from 0 to 10‰ in Suisun Bay. Kelley (1966), Turner and Kelley (1966), and Conomos (1979) provide more detailed descriptions of the physical and biological characteristics of the estuary.

Water resource project operations in California have altered the distribution, seasonality, and magnitude of flows in the estuary. The historical annual flow passing through the estuary from its 163,000 km^2 drainage basin averaged about 41,000 hectometers^3 in 1900, but consumptive uses upstream and diversions from the Delta by 1960 reduced that flow by about one-half (Kelley 1966).

The Delta is the pivot point in the transfer of water from northern California to southern California. The major out-of-basin diversions (exports) are made via the Federal and State Water Project pumping plants in the southern Delta (Fig. 1). Typical export rates substantially exceed the flow in the San Joaquin River, hence most of its flow goes to the pumps. Also, the San Joaquin River flow to the Delta has been decreased greatly by upstream dam construction. Remaining export needs are met by diversions of Sacramento River water. Part of the flow passes through the central Delta but, due to channel volume limitations, at higher export rates water is drawn upstream to the pumps via the western San Joaquin River. Such net upstream flows are typical in the spring, except in wet years, and in the summer and fall of all years (Chadwick et al. 1977). Future water development plans include construction of additional upstream storage reservoirs and additional export from the Delta.

Definitions and Methods

Fry

We define "fry" as the life stage of salmon (<70 mm) between emergence from the spawning gravel to the completion of upstream or estuarine rearing.

Seasonal abundance and spatial distribution of fry in the estuary were measured by weekly seine surveys at 36 stations during daylight hours (Fig. 1). Delta stations were sampled from 1977 to 1981 while the bays were sampled in 1980 and 1981. The bag seine used was 15.2 by 1.2 m (3.2 mm mesh). Salmon captured were measured to the nearest millimeter fork length (FL). Water temperature and salinities were recorded at all stations. Flow records were provided by the State Department of Water Resources. Each year was classified relative to the amount of unimpaired river runoff that occurred in the Central Valley drainage. These classifications vary from critical, dry, below normal, above normal, to wet, and are determined by the State Water Resources Control Board.

Residence times and growth rates of fry were determined from mark-recapture data in 1980 and 1981. Hatchery fry (40 to 50 mm) were marked with half-sized coded wire nose tags (Jefferts et al. 1963) and by removing the adipose fin. Size variation within each marked release group was small; the standard deviation ranged from 0.05 to 0.1 times that of mean length. One

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Smolt

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Results and Discussion

Fry Rearing

a. Seasonality and Distributi

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Recruitment of small fry to
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hundred thousand fish per site were released each year in February below Red Bluff (302 km upstream of Sacramento) in the upper Sacramento River, at two sites in the northern Delta, and at Berkeley in San Francisco Bay (Fig. 1). Recoveries of marked fish were made in our seine and trawl surveys (see below).

We performed stomach analyses of 540 chinook fry collected in the Delta in 1979 and 189 fish collected in San Pablo and San Franciso Bays in 1980.

Smolt

Smolts are older salmon (≥70 mm) that are physiologically adapted to enter salt water and are migrating to the ocean.

The timing of smolt migration was estimated by sampling twice weekly during daylight near Pittsburg (Fig. 1) with a 9.1 by 7.9 m (3.2 mm mesh, cod end) midwater trawl. Samples were taken in April through June from 1978 to 1981 and from October, 1979, to March, 1980.

Survival and migration rates through the Delta were estimated from mark-recapture data. Smolts were marked by fin clips in 1969 to 1971, spray dye in 1976 and 1977, and coded wire nose tags in 1978 to 1981. Releases were made in June in the Sacramento River at Sacramento and Suisun Bay (Fig. 1). Recovery of marked smolts from the Sacramento release site in trawl catches at Hood and at Pittsburg from 1976 to 1981 provided estimates of smolt migration rate and smolt survival in the Delta. Survival between Hood and Pittsburg was defined as the ratio of the recovery rate of marked smolts at Pittsburg divided by the recovery rate at Hood. The recovery rates were corrected for sampling effort in time and space.

Recovery of marked adults from the ocean sport and commercial fisheries from 1969 to 1971 and 1978 to 1980 provided an independent estimate of smolt survival through the Delta characterized by larger sample sizes than from Delta trawling. Survival through the Delta between Sacramento and Suisun Bay from adult tag returns was defined as the ratio of the recovery rate of marked salmon from the Sacramento release divided by the recovery rate of marked salmon released in Suisun Bay. We assumed marked salmon behaved similarly to unmarked salmon and that they had similar catchability.

Results and Discussion

Fry Rearing

a. Seasonality and Distribution

Fry abundance in the estuary was usually greatest between February and March (Table 1). Previous salmon surveys in the Delta using fyke nets and seines to capture downstream migrants also showed similar peaks in fry abundance (Rutter 1903; Hatton 1940).

Recruitment of small fry to the Delta occurred during January to March of each year and was reflected by the small increase in mean length and

Table 1. Mean monthly catch (fish per haul) of chinook salmon fry collected by seine in the northern Sacramento-San Joaquin Delta during a variety of water years between 1977 and 1981. Average coefficient of variation (C.V.) for mean monthly catch was 208%.

	Water year classification				
Month	*1977* *Critical*	*1978* *Wet*	*1979* *Dry*	*1980* *Wet*	*1981* *Dry*
Jan	0.1	15.3	23.5	13.7	5.7
Feb	0.0	25.3	50.8	19.9	20.5
Mar	0.2	22.4	45.6	20.1	10.8
Apr	1.2	7.5	12.8	8.0	11.1
May	6.6	1.3	6.9	1.2	1.2
Jun	3.1	0.7	1.1	1.2	0.6

relatively constant minimum length of fry in the samples (Fig. 2). Similar curves were observed from 1978 to 1980. Emergence of fall-run fry from upstream spawning gravel extended for about three months, which supports this interpretation.

Number of fry in the estuary was influenced by egg deposition and environmental conditions during spawning, incubation, and rearing. Peak catches of fry in the Delta followed major runoff periods (Fig. 3). Low catches in 1977 reflected drought conditions that provided poor spawning and incubation conditions and low runoff after fry emergence. In contrast, 1979 and 1980

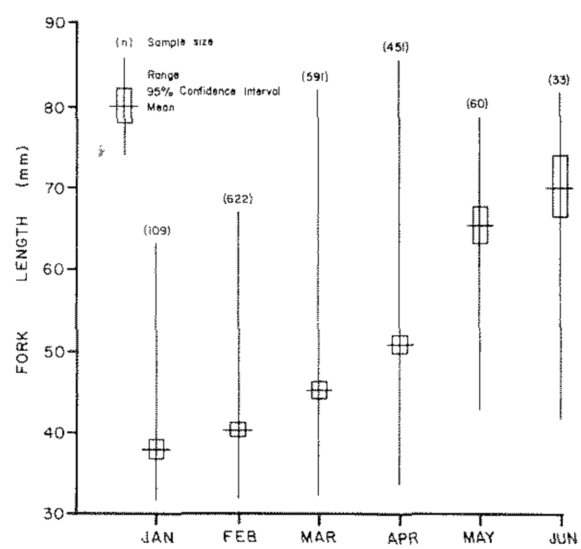

Figure 2. Average size of juvenile chinook salmon collected by seine in the Sacramento-San Joaquin Delta between 1978 and 1981.

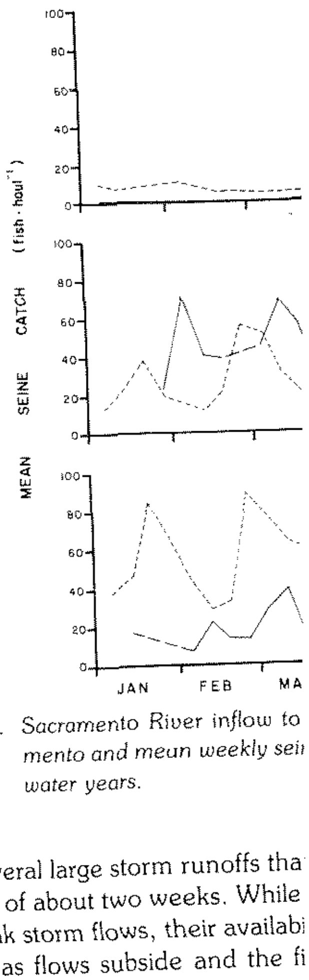

Figure 3. Sacramento River inflow to mento and mean weekly sei water years.

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Distribution of fry in the estu 1980 and 1981 fry were most n However, during 1980 (a wet yea lected as far downstream as centr year), only a few individual fry w haul).

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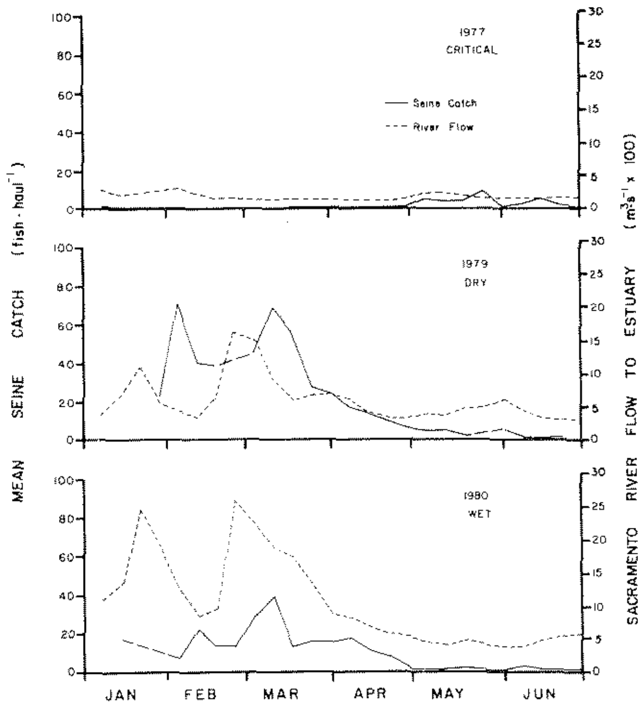

Figure 3. Sacramento River inflow to the Sacramento-San Joaquin Delta at Sacramento and mean weekly seine catches of chinook salmon fry for a variety of water years.

had several large storm runoffs that were followed by high catches of fry after a delay of about two weeks. While the fry may actually enter the estuary with the peak storm flows, their availability to be sampled along the shore may increase as flows subside and the fish concentrate along the shoreline. Even though 1979 was a drier year than 1980, influence of the storm flows on peak fry abundance in the Delta was apparent.

Distribution of fry in the estuary also appears related to storm runoff. In 1980 and 1981 fry were most numerous in the northern Delta (Table 2). However, during 1980 (a wet year), some fry (1.15 fish per haul) were collected as far downstream as central San Francisco Bay, while in 1981 (a dry year), only a few individual fry were seen in the brackish bays (0.01 fish per haul).

Low numbers of fry were observed in the central or western Delta in both years (Table 2). Low numbers in the central Delta suggest that fry moving into the northern Delta via the Sacramento River tend to remain in its channel as opposed to moving off into the smaller channels leading to the central Delta. Some of the fry caught in the central Delta probably represent small populations moving out of the San Joaquin. Lack of many fry in the

Table 2. Mean number of fish per haul of chinook salmon fry collected by seine at varied locations in the Sacramento-San Joaquin Estuary from January to April during 1980 and 1981.

Year	Northern Delta	Central Delta	Western Delta	San Francisco and San Pablo Bays
1980	14.37	2.11	3.0	1.15
1981	12.44	2.41	0.5	0.01

western Delta in 1981 probably indicated a lack of sufficient flow to transport them to that location.

The spatial distribution of fry in the Delta channels changes from day to night and with an increase in body size. Seining has revealed that smaller fry are found in shallow water near the shoreline during daylight, but at night the number caught by seine decreases suggesting that they move offshore (Schaffter 1980). Trawling studies have revealed that the size of juvenile salmon increases toward the center of the channel (Wickwire and Stevens 1971). Wickwire and Stevens' studies also indicated that larger fry and smolts were concentrated in the upper 3 m of the water column by day and were more randomly distributed vertically at night.

b. Residence Time

The residence time of marked fry rearing in the Delta was as long as 64 days in 1980 and 52 days in 1981, based on 32 fry recovered in 1980 and 51 recoveries in 1981. Some fish remained in the immediate vicinity of the release site for up to 36 days in 1980 and 49 days in 1981. For comparison, the residence time of marked fry rearing in the upper Sacramento River below Red Bluff was as long as 78 days, based on 11 recoveries.

Four marked fry of the group released at Berkeley in San Francisco Bay during 1980 were recovered 14 days later at a point 7 km west of Berkeley. The small number of recoveries and short residence time may reflect the large amount of shoreline and relatively small sampling effort we expended in San Francisco Bay. No recoveries were made in the Bay after the 1981 release, nor were any wild fry collected. Possibly Bay salinities were adverse during 1981. Low freshwater runoff resulted in salinities of about 24‰ at Berkeley that year compared to 18‰ in 1980. Wagner et al. (1969) found that chinook fry of the size we released are not able to survive immediate release into water of 25‰ salinity, but could withstand salinities up to 20‰.

c. Growth

Fry growth rates in the Delta were estimated from marked fry recoveries. Average growth was 0.86 mm day^{-1} (range, 0.57 to 1.23) for 1980, and 0.53 mm day^{-1} (range, 0.40 to 0.69) for 1981 (Fig. 4). Average growth

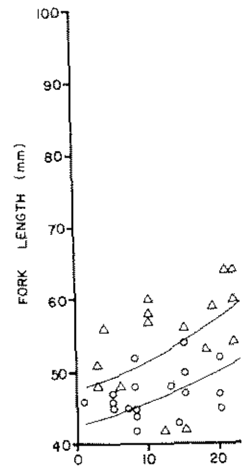

Figure 4. Growth curves for coded- captured in the Sacramer April during 1980 (triangl equations for 1980 and 1 and log Y = 1.629 + 0.

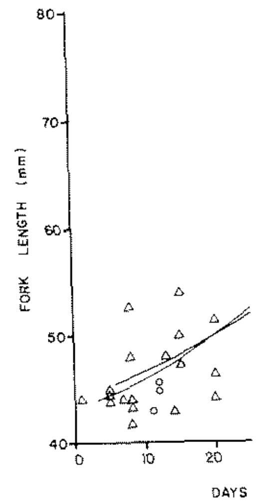

Figure 5. Growth curves for code recaptured in the Sacram per Sacramento River (ci of release) and April 26 regression equations for Sacramento River are: lo 1.647 + 0.0026X, r =

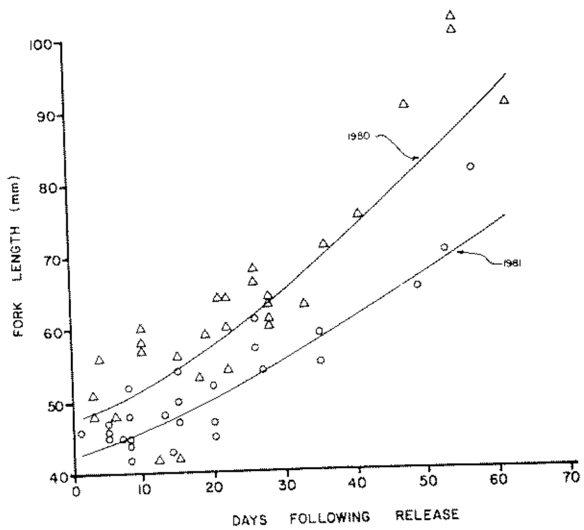

Figure 4. *Growth curves for coded-wire tagged chinook salmon fry released and recaptured in the Sacramento-San Joaquin Estuary between February and April during 1980 (triangles) and 1981 (circles). The curvilinear regression equations for 1980 and 1981 are: log Y = 1.662 + 0.0054X, r = 0.89 and log Y = 1.629 + 0.0041X, r = 0.89, respectively.*

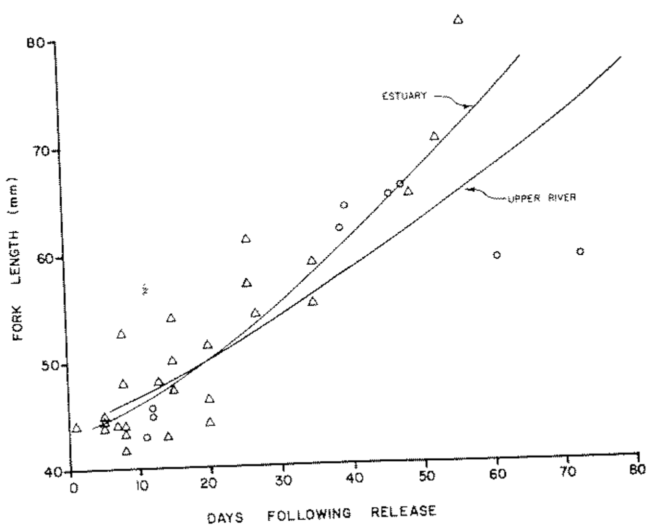

Figure 5. *Growth curves for coded-wire tagged chinook salmon fry released and recaptured in the Sacramento-San Joaquin Estuary (triangles) and the upper Sacramento River (circles), respectively, between February 6 (first date of release) and April 26 (last date of recapture), 1981. The curvilinear regression equations for the Sacramento-San Joaquin Estuary and upper Sacramento River are: log Y = 1.629 + 0.0041X, r = 0.89 and log Y = 1.647 + 0.0026X, r = 0.78, respectively.*

rates for fry rearing in the upper Sacramento River in 1981 (Fig. 5) were estimated at 0.33 mm day^{-1} (range, 0.26 to 0.40). Growth curves in Fig. 4 did not have slopes that were significantly different ($T = 0.13$, $df = 59$), while those in Fig. 5 did ($T = -2.37$, $df = 35$, $p<0.05$), suggesting that fry reared in the estuary grew faster than those reared upriver. The curves in Fig. 4 are separated slightly since mean length at release in 1981 was about 5 mm less than that in 1980. Growth rate of marked fry from our 1980 San Francisco Bay release was about 1.01 mm day^{-1} during the two weeks between release and recovery.

d. Diet

Crustacea and insects dominated chinook fry stomach contents, with an increase in crustacea ingestion downstream (Table 3). Cladocera and diptera were consumed frequently in the Delta, while in brackish San Pablo and San Francisco Bays, consumption of copepods, amphipods, and fish larvae increased. Similar food habits were described for older fry and smolts in Delta studies by Rutter (1903), Ganssle (1966), and Sasaki (1966).

Table 3. Taxonomic composition, percent numerical occurrence and percent frequency of occurrence of prey items in the stomachs of juvenile chinook salmon from upper (1979) and lower (1980) Sacramento-San Joaquin Estuary.

Taxa	*Upper Estuary (Delta)*		*Lower Estuary (San Pablo and San Francisco Bays)*	
	% numerical occurrence	*% frequency of occurrence*	*% numerical occurrence*	*% frequency of occurrence*
Crustacea	75	89	88	85
Cladocera	66	76	62	59
Copepoda	8	49	20	34
Amphipoda	1	22	4	41
Other (Mysidacea)	1	<1	2	7
Insecta	24	93	11	65
Diptera	17	89	4	44
Homoptera	3	23	5	33
Plecoptera	<1	6	–	–
Other (Coleoptera)	3	<1	2	5
Miscellaneous (Fish Larvae)	<1	<1	1	13

Smolt Migration

a. Timing and Size

Peak abundance of smolts April and mid-June (Fig. 6; Ganss The average size of smolts passin through June remained very coı varied somewhat between years (Schaffter 1980).

Other investigators have reț migration, with few young salmon mer (Rutter 1903; Sasaki 1966). I summer may be caused by greate lower Sacramento and San Joaqu September during most years. Sur channels usually peak around 22° 12 to 14°C (Brett 1952).

A small secondary peak in s Bays during fall months. Midwate

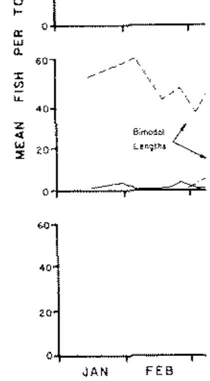

Figure 6. Mean weekly catch and si on midwater trawls at Pitts Estuary. Average coefficie weekly catch and size, res

Smolt Migration

a. Timing and Size

Peak abundance of smolts in the Delta and Bays occurred between April and mid-June (Fig. 6; Ganssle 1966; Messersmith 1966; Aplin 1967). The average size of smolts passing through the Delta and Bays from April through June remained very constant in each year, although mean size varied somewhat between years (Fig. 6; Ganssle 1966; Messersmith 1966; Schaffter 1980).

Other investigators have reported identical results for peak smolt outmigration, with few young salmon seen in the Delta or Bays during the summer (Rutter 1903; Sasaki 1966). Lack of young salmon in the estuary during summer may be caused by greater than optimum water temperatures in the lower Sacramento and San Joaquin rivers and in the Delta from mid-June to September during most years. Summer water temperatures in the main Delta channels usually peak around 22°C. Young chinook prefer temperatures of 12 to 14°C (Brett 1952).

A small secondary peak in smolt abundance occurred in the Delta and Bays during fall months. Midwater trawling has yielded a few salmon around

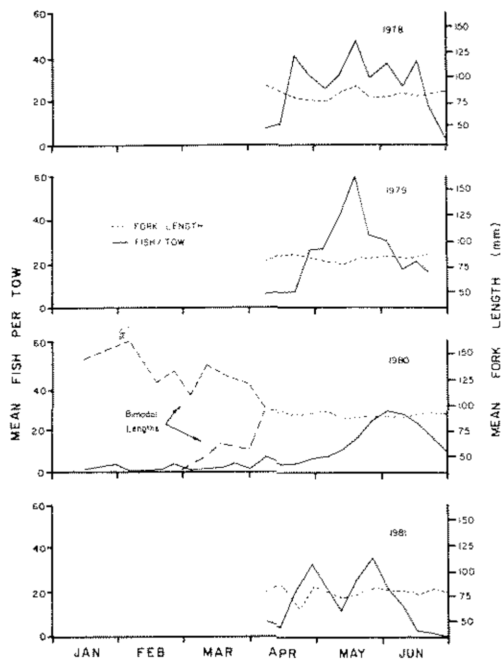

Figure 6. Mean weekly catch and size of chinook salmon for 1978 and 1981 based on midwater trawls at Pittsburg, California in the Sacramento-San Joaquin Estuary. Average coefficient of variation equals 70% and 13% for mean weekly catch and size, respectively.

90 to 200 mm long, apparently from fall and late fall runs that have over-summered in cooler waters upstream from the Delta. Some of these fish also represent yearling hatchery releases.

b. Rate of Migration

The constant size of smolts throughout the Delta and lower bays and mark-recapture data indicate that smolts move through the estuary quickly. Similar sized smolts (94 to 100 mm) were observed in the ocean by Snyder (1924) which further supports this conclusion. Weisbart (1968) and Wagner et al. (1969) found that juvenile chinook could tolerate full sea water upon reaching a size of 70 mm, slightly smaller than the mean sizes we observed during the peak out-migration period (Fig. 6).

Our 1976 to 1980 mark-recapture data based on smolt released at Sacramento and recovered at Pittsburg indicate that smolt migrate through the Delta from 10 to 18 km day^{-1}. At this rate smolts could pass through the estuary (about 172 km from Sacramento to San Francisco) within 10 to 17 days. Salmon trawling planned for 1982 in San Francisco Bay will attempt to recover marked smolts released that year at Sacramento so that migration and growth rates can be estimated for the brackish portion of the estuary. Wickwire and Stevens (1971) estimated smolt migration at 8, 12 and 24 km day^{-1} in April, May, and June, respectively, as water temperatures rose.

c. Survival

Our mark-recapture studies have shown that survival is lower for smolts migrating through the Delta than through the lower estuary. Ocean recoveries (n = 718) of marked smolts released in Suisun Bay in June of 1978 were about 80 times greater than those of the smolts released at Sacramento (n = 9), yet the migration distance for the Sacramento released fish was only twice that traveled by those released in Suisun Bay. We assume that ocean survival was the same for both release groups.

Survival in the Delta appears to be influenced by water temperatures and/or river flow rate. Temperature of water entering the Delta at Sacramento is influenced by the magnitude of flow and ambient air temperature (Rowell 1972). Smolt survival (based on our ocean recovery data on marked adults) decreased as flow rates decreased and temperatures increased for marked fish released in June ($p<0.01$, $R^2 = 0.97$, df = 4; Fig. 7). Temperatures and flow rates were so closely related during the release periods that it was not possible to separate their individual impacts on smolt survival. However, using our trawl recovery data of marked smolts at Pittsburg, temperature alone was related to smolt survival during June ($p<0.05$, $r = -0.86$, df = 5; Fig. 8). Our ocean and trawl recovery data indicated that almost total mortality was experienced by migrant smolts in June of 1978 (Figs. 7 and 8) and 1981 (Fig. 8) when temperatures were about 23°C.

Operations of State and Federal pumping plants in the south Delta influence survival of smolts during their migration. Records of smolts collected

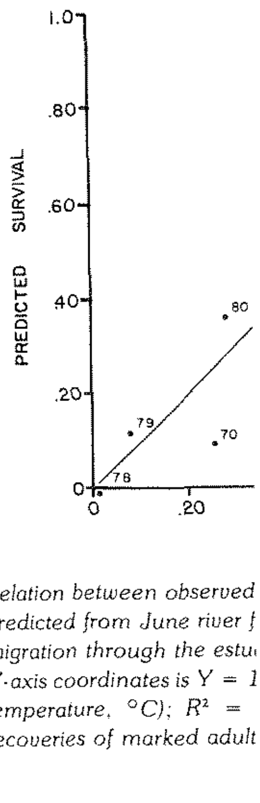

Figure 7. Relation between observed predicted from June river f migration through the estu Y-axis coordinates is Y = 1 temperature, °C); R^2 = recoveries of marked adult

at pumping plant fish screens in smolts are drawn to the screens these screens are returned to the pumps, but handling and transpo to 35% (dependent on size) are While the number of salmon c 200,000 fish) represent a small fr tion, more fish probably are drawn Our earlier mark-recapture studie northern Delta channels on a di lower survival than those released the most direct route to the ocea smolts have occurred from th municipal diversions in the estuar main unscreened and in total ac Van Woert 1959).

Estuarine Comparisons and

We now review some of th

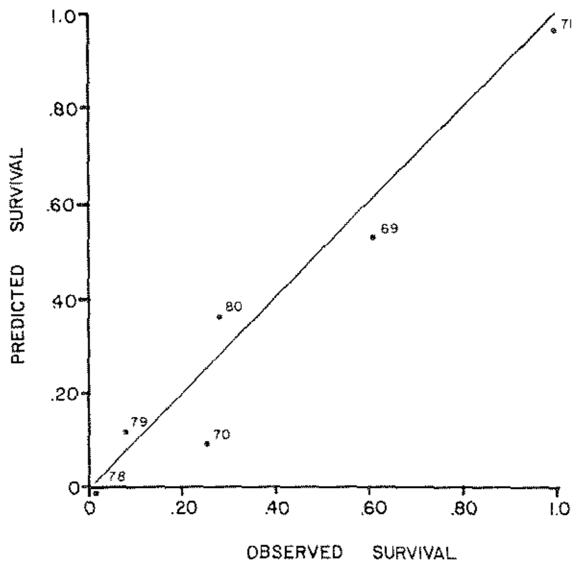

Figure 7. *Relation between observed survival of chinook salmon smolts and survival predicted from June river flows and June water temperatures during June migration through the estuary. The regression equation used to obtain the Y-axis coordinates is* $Y = 1.81 + 0.0008$ *(river flow,* $m^3 s^{-1}$*)* $- 0.09$ *(water temperature,* $^{\circ}C$*);* $R^2 = 0.95$*. Survival estimates are based on ocean recoveries of marked adults.*

at pumping plant fish screens indicate that as water exports increase more smolts are drawn to the screens (Kjelson et al. 1981). Salmon collected at these screens are returned to the western Delta out of the influence of the pumps, but handling and transport mortality average 58%. An additional 10 to 35% (dependent on size) are lost through the screens (Skinner 1974). While the number of salmon observed at the pumps each year (about 200,000 fish) represent a small fraction of the estimated total smolt production, more fish probably are drawn out of their normal migration path and die. Our earlier mark-recapture studies in 1976 indicated that smolts released in northern Delta channels on a direct path to the south Delta pumps had a lower survival than those released in the Sacramento River which represented the most direct route to the ocean (Kjelson et al. 1981). Additional losses of smolts have occurred from the numerous agricultural, industrial, and municipal diversions in the estuary and upper river systems. Most of these remain unscreened and in total account for considerable losses (Hallock and Van Woert 1959).

Estuarine Comparisons and Summary

We now review some of the readily available literature on life histories

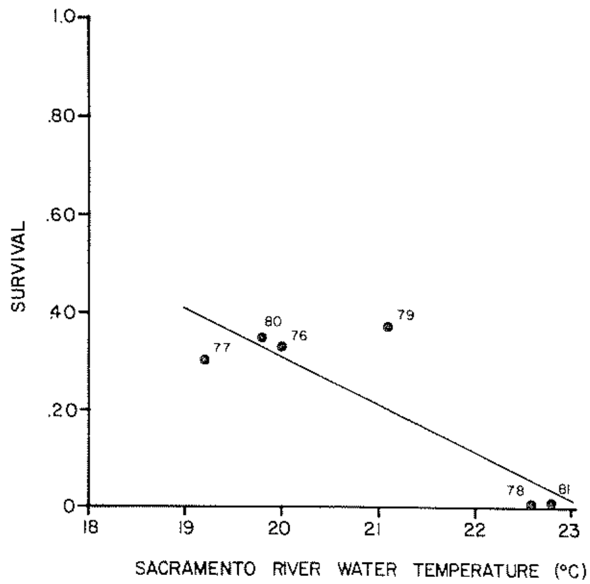

Figure 8. Linear regression between chinook salmon June smolt survival during migration through the Sacramento-San Joaquin Delta and mean June water temperature at Sacramento. Survival estimates are based on mid-water trawl recoveries in the Delta of marked smolts released at Sacramento. Regression equation is: $\hat{S} = 2.28 - 0.10$ (water temperature, °C), $r = -0.86$.

of juvenile fall run chinook salmon in estuaries from northern California to British Columbia. There are a few unique differences and some similarities in salmon life history and their habitats between the Sacramento-San Joaquin Estuary and those further north. Chinook salmon life histories between estuarine systems are highly variable.

Physical Environment

Most estuaries further north which have been studied are much smaller than the Sacramento-San Joaquin Estuary (Reimers 1973; Healey 1980). In absolute terms, most of these smaller systems have little or no tidally influenced delta and limited tidal marshes and mudflats (Healey 1980; Fish and Wildlife Service 1981). Salinity gradients are narrow and river gradients steep making transition from fresh to salt water relatively abrupt compared to that seen in the Sacramento-San Joaquin system and to some extent the Columbia River Estuary. Some estuaries such as in the Mad and Sixes Rivers in California and Oregon have a sill or sand bar that forms across the mouth and restricts exchange with the ocean during low runoff periods (Taniguchi 1970; Reimers 1973). Lower river and estuarine water temperatures can be limiting to chinook residence in summer in estuaries from British Columbia to California.

Seasonal Abundance

Estuarine fry rearing and :
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than further north. Chinook fry
northern estuaries in April and Ma
numbers are highest between Ju
Wildlife Service 1981). Earlier us
by salmon appears related to sp
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1980).

Rearing Environment

Information from the Pacifi
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(Reimers 1973; Healey 1980). Ir
estuarine rearing occurs in the fr
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and British Columbia (Healey 19
abundant in the shallow water,
migrant smolts are found further

Residence Time and Migration Rate

Chinook fry in the Sacrame
to two months which may be sl
Healey (1980) estimated an ave
Estuary (British Columbia), but s

Smolt migration rates app
rates ranging from 6 to 24 km
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km day^{-1} in Columbia River E
Sacramento-San Joaquin, that r
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Growth

Observations of estuarin
systems. Our measurements in t
from 0.40 to 1.23 mm day^{-1} whi
Sixes River (Oregon). Sibert (19

Seasonal Abundance

Estuarine fry rearing and smolt outmigration by fall-run chinook is about two to three months earlier in the Sacramento-San Joaquin Estuary than further north. Chinook fry appear to be most abundant in the more northern estuaries in April and May (Healey 1980; Puckett 1977) while smolt numbers are highest between June and August (Reimers 1973; Fish and Wildlife Service 1981). Earlier use of the Sacramento-San Joaquin Estuary by salmon appears related to spawning times and the fact they are at the southernmost limit of the chinook range where warmer summer water temperatures in the upper estuary force the salmon to leave. Fall-run spawning in the Sacramento-San Joaquin peaks in October; in some systems further north, it is later by about one month (Reimers 1973). Warm summer water temperature also causes salmon to move out of the main river channel into the estuary in Oregon and British Columbia (Reimers 1973; Healey 1980).

Rearing Environment

Information from the Pacific northwest indicates that estuarine rearing by chinook occurs in both fresh (tidally influenced) and brackish water habitat (Reimers 1973; Healey 1980). In the Sacramento-San Joaquin system most estuarine rearing occurs in the freshwater Delta supplemented by fry rearing in the brackish water bays during high runoff years. The number of fry present in the estuary is influenced, in part, by river flow magnitude both in the Sacramento-San Joaquin system, as well as in Washington (Wetherall 1970) and British Columbia (Healey 1980). Young chinook fry appear to be most abundant in the shallow water, shoreline habitat, while older fry and outmigrant smolts are found further offshore in most Pacific estuarine systems.

Residence Time and Migration Rate

Chinook fry in the Sacramento-San Joaquin Estuary reside there for up to two months which may be slightly longer than in systems further north. Healey (1980) estimated an average residence time of 25 days in Nanaimo Estuary (British Columbia), but some fish remained much longer.

Smolt migration rates appear similar for most estuaries. We estimated rates ranging from 6 to 24 km day^{-1} indicating that movement through the estuary was fairly rapid. Dawley et al. (1981) found an average rate of 6 to 21 km day^{-1} in Columbia River Estuary and also found, as we did in the Sacramento-San Joaquin, that migration rates were higher in the upper river and that estuarine migration rates increased as water temperatures rose.

Growth

Observations of estuarine growth rates varied between different systems. Our measurements in the Sacramento-San Joaquin Estuary ranged from 0.40 to 1.23 mm day^{-1} while Reimers (1973) reported 1.0 mm day^{-1} for Sixes River (Oregon). Sibert (1975) and Healey (1980) estimated growth of

0.71 (smolts) to 1.32 mm day^{-1} (fry) for the Nanaimo River Estuary (British Columbia).

Intermediate circuli spacing on chinook scales, attributed to brackish water estuarine growth by older juveniles (>100 mm), was observed in Columbia River (Rich 1922), in Klamath River (Snyder 1931), and in Sixes River (Reimers 1973). We did not see such a pattern on juvenile and adult scales from chinook in the Sacramento-San Joaquin system. This apparently reflects either lack of significant brackish water rearing by older juveniles in the lower Sacramento-San Joaquin Estuary or similar river and estuarine growth rates.

Diet

Young chinook in the estuaries from northern California to British Columbia appear to consume prey similar to those in the Sacramento-San Joaquin (Herrmann 1971; Lipovsky 1977; Healey 1980). Stomach contents were dominated by copepods, cladocera, amphipods, mysids, insects, and some fish larvae.

Survival

Wetherall (1970) found juvenile chinook survival rates in Green River (Washington) between 37 and 99%; they increased as river flow rates increased. Reimers (1973) provided evidence that there was a survival advantage for extended juvenile chinook residence in Sixes River Estuary. Argue et al. (1979) found that a greater fraction of the chinook smolt population in the Cowichan-Koksilah Estuary (British Columbia) originated from fry that reared exclusively in the estuary. Van Hyning (1973) suggested that the number of adult chinook returning to spawn in Columbia River increased as the May estuarine water temperature decreased during juvenile outmigration. We found that smolt survival during outmigration was better in the lower estuary than in the Delta and that temperature and possibly flow rate influenced survival in the Delta.

Physical and Biological Stresses

Juvenile chinook in more northern estuaries are exposed to somewhat different environmental alterations than those in the Sacramento-San Joaquin Estuary. Salmon in the Pacific northwest estuaries experience the impacts of the lumbering industry, while in the Sacramento-San Joaquin Delta there are no lumbering activities and the greater impacts come from water diversion activities.

Potential problems of exceeding estuarine rearing capacity through hatchery releases have been emphasized by various investigators in the northwest (Reimers 1973; Iwamoto and Salo 1977; Meyer 1979). Hatchery production of multi-races of salmon in Columbia River and Puget Sound systems has been much larger than that in the Sacramento-San Joaquin drainages. Dawley et al. (1981) reports that Columbia River has approximately 150

million young salmon released eacl
The problem of exceeding estuarine
Sacramento-San Joaquin (hatcher
nually), but as yet has not been st

Acknowledgments

We wish to thank the Young Adult
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assistance in field sampling and laboratory a
Stevens, D. Vogel, and T. Yocom for thei

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million young salmon released each year that must pass through the estuary. The problem of exceeding estuarine rearing capacity is of some concern in the Sacramento-San Joaquin (hatchery releases total about 26 million smolts annually), but as yet has not been studied.

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