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Species Profiles: Life Histories and Environmental Requirements of Coastal Fishes and Invertebrates (Pacific Southwest)

CHINOOK SALMON

Fish and Wildlife Service
U.S. Department of the Interior

Coastal Ecology Group
Waterways Experiment Station
U.S. Army Corps of Engineers

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CHINOOK SALMON

by

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PREFACE

This species profile is one of a series on coastal aquatic organisms, principally fish, of sport, commercial, or ecological importance. The profiles are designed to provide coastal managers, engineers, and biologists with a brief comprehensive sketch of the biological characteristics and environmental requirements of the species and to describe how populations of the species may be expected to react to environmental changes caused by coastal development. Each profile has sections on taxonomy, life history, ecological role, environmental requirements, and economic importance, if applicable. A three-ring binder is used for this series so that new profiles can be added as they are prepared. This project is jointly planned and financed by the U.S. Army Corps of Engineers and the U.S. Fish and Wildlife Service.

Suggestions or questions regarding this report should be directed to one of the following addresses.

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CONVERSION TABLE

Metric to U.S. Customary

Multiply	By	To Obtain
millimeters (mm)	0.03937	inches
centimeters (cm)	0.3937	inches
meters (m)	3.281	feet
kilometers (km)	0.6214	miles
square meters (m^2)	10.76	square feet
square kilometers (km^2)	0.3861	square miles
hectares (ha)	2.471	acres
liters (l)	0.2642	gallons
cubic meters (m^3)	35.31	cubic feet
cubic meters	0.0008110	acre-feet
milligrams (mg)	0.00003527	ounces
grams (g)	0.03527	ounces
kilograms (kg)	2.205	pounds
metric tons (t)	2205.0	pounds
metric tons	1.102	short tons
kilocalories (kcal)	3.968	British thermal units
Celsius degrees	1.8(°C) + 32	Fahrenheit degrees

U.S. Customary to Metric

Multiply	By	To Obtain
inches	25.40	millimeters
inches	2.54	centimeters
feet (ft)	0.3048	meters
fathoms	1.829	meters
miles (mi)	1.609	kilometers
nautical miles (nmi)	1.852	kilometers
square feet (ft^2)	0.0929	square meters
acres	0.4047	hectares
square miles (mi^2)	2.590	square kilometers
gallons (gal)	3.785	liters
cubic feet (ft^3)	0.02831	cubic meters
acre-feet	1233.0	cubic meters
cunces (oz)	28.35	grams
pounds (lb)	0.4536	kilograms
short tons (ton)	0.9072	metric tons
British thermal units (Btu)	0.2520	kilocalories
Fahrenheit degrees	0.5556(°F - 32)	Celsius degrees

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ACKNOWLEDGMENTS

We are grateful for reviews by Richard J. Hallock and Kenneth A. Hashagen, Jr., California Department of Fish and Game.

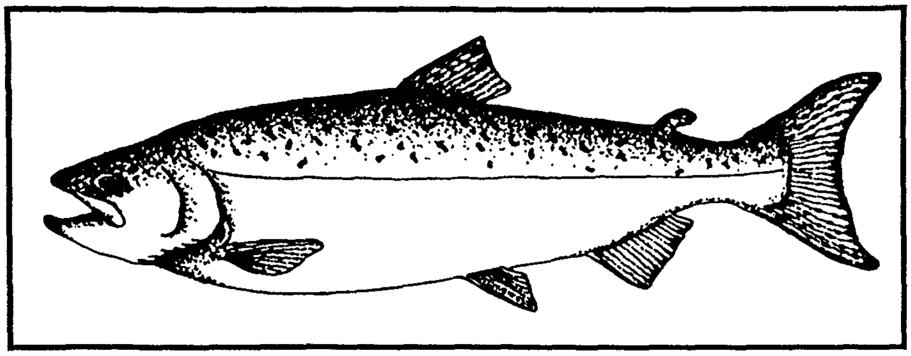

Figure 1. Chinook salmon.

CHINOOK SALMON

NOMENCLATURE/TAXONOMY/RANGE

Scientific name . . . . . Oncorhynchus tshawytscha (Walbaum) (Figure 1).
Preferred common name . . . . Chinook salmon
Other common names . . . . King, king salmon, tyee, quinnat, spring salmon.
Class . . . . Osteichthyes
Order . . . . Salmoniformes
Family . . . . Salmonidae

Geographic range: Spawning populations of chinook salmon in North America are distributed from the Sacramento-San Joaquin River system in central California north to Point Hope, Alaska. Asian populations are distributed from Japan north to the Anadyr River, USSR. Introductions of young chinook salmon have established spawning populations and fisheries in rivers tributary to South Island, New Zealand, and the U.S. Laurentian Great Lakes. The major rivers in California that support spawning runs of chinook salmon are shown in Figure 2.

MORPHOLOGY/IDENTIFICATION AIDS

The following descriptions were taken from McConnell and Snyder (1972), Hart (1973), and Moyle (1976). Fin rays: Dorsal 10-14, anal 13-19, pelvic 10-11, and pectoral 14-19. The caudal fin is moderately forked; adipose is stout and prominent; a free-tipped flesh appendage inserts just above the pelvic. Cycloid scales, 130-165 pored scales on lateral line, 131-158 in rows above. Number of branchiostegal rays each side of jaw, 13-19; gill rakers rough and widely spaced, 6-10 on lower half of first gill arch; pyloric caeca, 120-185.

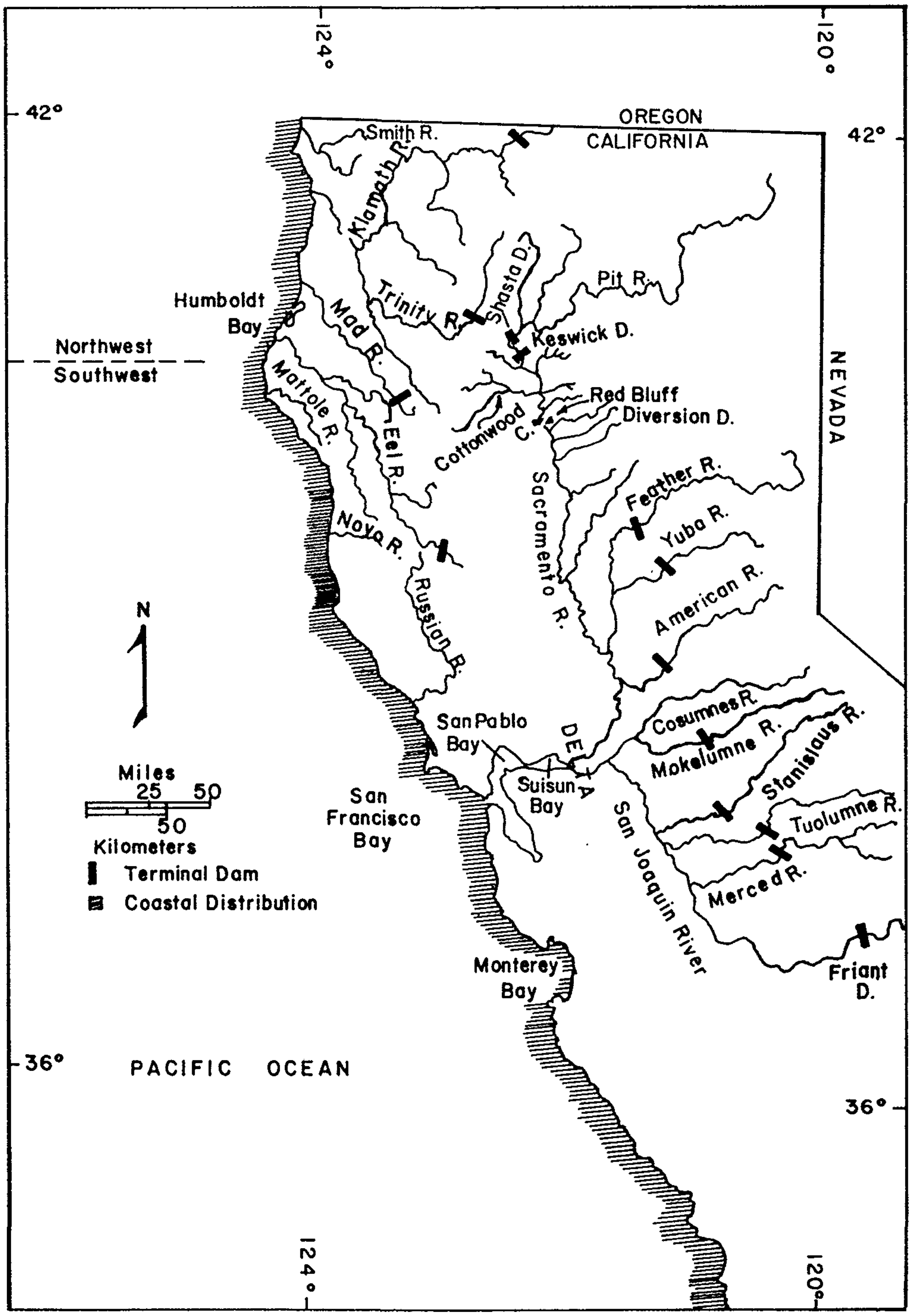

Figure 2. The major rivers in the Pacific Southwest that support spawning runs of chinook salmon.

The adult has prominent irregular black spots on back, upper sides, dorsal fin, and both lobes of caudal fin. Spawning males develop moderately hooked jaws and dark olive to red skin. Lower jaw gum-line is solid black. Juveniles are closest in appearance to coho salmon (*O. kisutch*), but are distinguished by 6 to 12 parr marks that are wider than the interstices; the anal fin is unpigmented between rays and the anterior tip is not distinctly elongated; the adipose is pigmented on upper surface, clear below; and the pyloric caeca count is diagnostic (>120, but <90 in coho salmon.)

REASON FOR INCLUSION IN SERIES

The chinook salmon supports valuable commercial and sport fisheries in the Pacific Southwest. This species accounted for over 69% of the salmon caught along the California coast from 1971 through 1983, according to the Pacific Fishery Management Council (PFMC 1984). Chinook fry and smolts spend a portion of their early life in estuaries where growth is rapid.

LIFE HISTORY

Upstream Migration

Chinook salmon spawning runs in the Sacramento-San Joaquin River system produce over 50% of the annual ocean harvest of chinook salmon in California (PFMC 1984). Runs in the Sacramento River above the Red Bluff Diversion Dam are composed of four populations, divided as follows (1971-81 means): fall 54%, late fall 14%, winter 21%, and spring 11% (Reavis 1983).

The separation of chinook salmon spawning populations is based on the times of the upstream migration of adults, spawning, and the downstream migration of juveniles (Figure 3). External physical appearance, time of gonadal development, and location of spawning grounds are additional factors. Chinook salmon runs in the fall and late fall spawn in the mainstem or tributaries shortly after they reach their spawning grounds. Those in the winter and spring runs may remain in deep pools near their spawning grounds for as long as 5 months before their eggs ripen and spawning begins (Hallock and Fry 1967).

Terminal dams in the Sacramento-San Joaquin River system (Figure 2), which lack fish-passage facilities, have altered the relative composition of the four spawning populations of chinook salmon. Until the construction of Shasta Dam in 1942, the winter run of chinook salmon spawned in upper Sacramento River tributaries and was believed to be of minor importance. After 1942, water released from the dam created favorable spawning temperatures in the mainstem Sacramento River for winter-run chinook salmon and their numbers increased (Slater 1963). Spring-run chinook salmon,

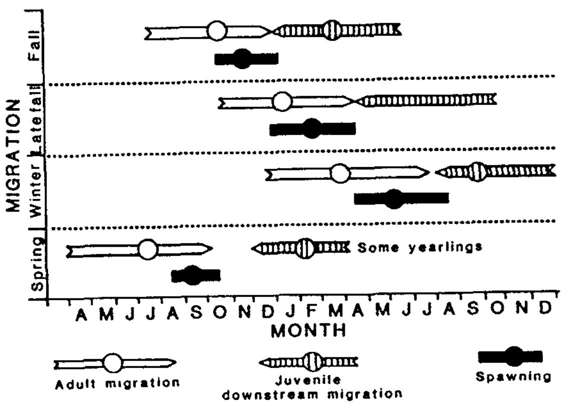

Figure 3. Adult migration, spawning, and juvenile downstream migration of chinook slamon in the Sacramento River at Red Bluff Diversion Dam, California; circles indicate peak activity (Hallock 1983).

however, were unable to adapt to the loss of their headwater spawning grounds and their numbers decreased.

The construction of Friant Dam on the San Joaquin River in 1939 blocked the spring-run of chinook salmon from their spawning grounds and they have all but disappeared (Hallock et al. 1970; California Department of Fish and Game 1971). Now (1971-84) only a fall-run population remains and averages only 10% of the fall-run of chinook salmon in the Sacramento River (Figure 4).

Spring-run chinook salmon also ascend the Eel and Klamath River systems to spawn but have contributed less than 5% of all chinook salmon produced in California. Chinook salmon spawning runs have decreased in all California rivers, especiallv in the Sacramento and San Joaquin Rivers (Figure 4).

The release of gonadal or thyroid hormones in adult salmon may stimulate upstream migration by modifying fish behavior in response to external variables that influence migration (Hoar 1953). An increase in the volume of stream flow is the

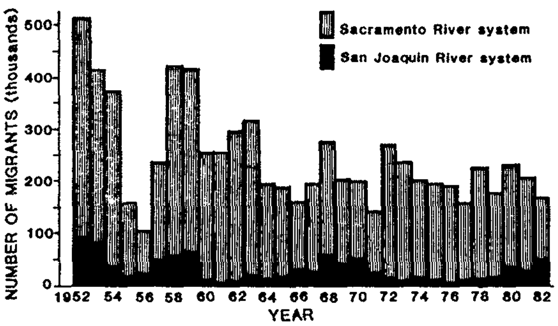

Figure 4. The estimated number of fall-run chinook salmon (may include some spring-run fish) that returned yearly to the Sacramento and San Joaquin Rivers to spawn in 1953-83 (data from Taylor 1974; Reavis 1983; PFMC 1984).

most frequently cited environmental stimulus to upstream migration, but this relation is most evident in small rivers (Banks 1969). Changes in atmospheric pressure, water turbidity, water temperature, and dissolved oxygen are also known to influence upstream migration.

Low dissolved oxygen and high water temperatures inhibited upstream movement of fall-run chinook salmon in the San Joaquin River (Hallock et al. 1970). Most adult chinook salmon migrate upstream during the day (Needham et al. 1940; Banks 1969). Fall-run chinook typically migrate upstream at a rate of 5 to 14.5 km/day (Gray and Haynes 1979; Heifetz 1982).

The homing of salmon to their parent stream after entering freshwater is well documented and is attributable to olfactory cues that are specific for each location and are "learned" by the juvenile salmon shortly before they migrate to the sea (Hasler and Wisby 1951; Hasler and Scholz 1983). Genetic history may also influence homing success (Bams 1976).

Salmon do not usually feed after entering freshwater and severe atrophy of the digestive system sets in before spawning begins.

Spawning

The female chinook salmon usually chooses a nesting site in gravel deposits at the lower lip of a pool just above a riffle (Burner 1951; Briggs 1953). The female makes a redd (an area containing several individual nests) by turning on her side and repeatedly flexing her body and tail to force gravel and fine sediment into the water column; these sediments are deposited a short distance downstream. The completed nest forms an oval depression with a mound of gravel located immediately downstream.

During spawning, a dominant male salmon accompanies the female and aggressively chases away other males attempting to enter the redd area. The eggs and sperm are released into the nest by the female and male simultaneously. Usually one or more males will position themselves alongside the female opposite the dominant male and release sperm. By the end of the spawning, as many as 10 to 12 male salmon may have attempted to spawn with a single female (Briggs 1953; Vronskiy 1972).

After the eggs are released, the female usually moves just upstream and repeats the nest building and the spawning act. The fertilized eggs are buried 20 to 60 cm below the gravel surface with the excavation material from the new nest (Briggs 1953; Vronskiy 1972). The female will repeat the process several times before spawning is completed. Each completed redd may contain several nests; the overall size of the redd is directly related to the size of fish and inversely related to the size of the substrate particles, water velocity, and density of spawners (Burner 1951; Vronskiy 1972). Female chinook salmon sometimes dig false redds (but do not deposit eggs there) before and after they build true redds (Briggs 1953).

Each female may spawn over a period of 5 to 14 days. Unlike females of other salmon species, female chinook salmon may defend the redd from intruding females for 5 to 9 days after spawning (Briggs 1953; Vronskiy 1972).

After spawning, the salmon deteriorate rapidly, exhibiting large open wounds and heavy fungal infection. Life expectancy after spawning is 2 to 4 weeks (Briggs 1953).

Eggs and Alevins

Fecundity varies greatly among chinook salmon of different populations. For example, fecundity of fall-run chinook salmon averages 3,634 eggs per female in the Klamath River but 7,295 eggs in Sacramento River fish. Difference in female size alone cannot account for the variation in fecundity (Healey and Heard 1984).

Chinook salmon eggs are large: 6.3 to 7.9 mm in diameter (Rounsefell 1957) and 0.35 to 0.40 grams in weight (Leitritz and Lewis 1980).

The length of time required for hatching is inversely related to water temperature. Chinook salmon eggs have been successfully incubated and hatched at water temperatures of 4^{0} to 16^{0} C; however, lower temperatures can be tolerated in the later stages of embryonic development (Combs and Burrows 1957; Combs 1965; Piper et al. 1982).

Chinook salmon eggs are particularly vulnerable to shock injury. Injury can result from gravel movement caused by bottom scouring, mechanical impaction, or superimposed spawning activity. Other causes of egg mortality are low dissolved oxygen, high concentrations of toxic chemicals, excessively high water temperatures, infestations with fungi or oligochaetes, predation by insects or fish, and heavy sedimentation. Under poor conditions the mortality of eggs may be as high as 95% (Wales and Coots 1954; Gangmark and Bakkala 1960). Under ideal conditions the mortality of the eggs may be as low as 10% (Briggs 1953).

After hatching, alevins (yolk-sac larvae) remain in the gravel interstices for a month or longer, during which time they exhibit the following three major distributional phases: a deeper submergence, a resting period, and an upward emergence (Dill 1969). Salmonid alevins are negatively phototactic and positively geotactic and thigmotactic; these characteristics serve to encourage further submergence into the gravel and prevent premature emergence (Godin 1981). After deeper submergence, alevins remain relatively inactive unless forced to disperse in response to excessive levels of carbon dioxide or metabolic waste (Dill 1969), or to avoid desiccation during low flow (Fast et al. 1981).

As the yolk sac is absorbed, alevins develop positive rheotactic and phototactic responses and begin an upward migration in the gravel (Dill 1969). Intra-gravel movement of alevins is governed by gravel size, interstitial spacing, rate of water flow, dissolved gases, and water temperature (Dill 1969; Godin 1981).

Fry and Smolts

Chinook salmon fry usually emerge from the gravel at night, probably as an antipredation measure (Bams 1969), and spend 1 to 18 months in freshwater. After emerging, most chinook salmon fry immediately disperse downstream, possibly because of their new nondemersal habits and loss of visual contact with the stream substrate (Reimers 1973). Diurnal dispersion has been observed during increases in water turbidity and temperature (Rutter 1904; Thomas 1975). After emergence, the fry develop neutral buoyancy, begin exogenous feeding, and develop social behavior (Bams 1969).

Chinook salmon fry in streams change habitats as they grow older. Lister and Genoe (1970) generalized changes in order as follows: "initial hiding, possibly in the gravel; association with bank cover; appearance along open shorelines; and finally, movement into higher velocity locations along the stream margin or farther out from shore." After the initial hiding period, chinook salmon fry seek fine substrates and low water velocities, progressively moving into deeper, faster, and rockier habitats (Lister and Genoe 1970; Everest and Chapman 1972). Overwintering spring-run chinook juveniles hide under large rocks and debris, a habitat shift apparently triggered by low water temperature (Chapman and Bjornn 1969).

As the fry begin to smolt[1], they become silvery and slimmer and change their behavior; their territorial instincts break down, and they usually emigrate in schools downstream to the ocean.

The osmoregulatory changes that allow tolerance of saltwater are somewhat more complex in chinook salmon than in coho salmon or steelhead trout (Salmo gairdneri) (National Marine Fishery Service 1979; Zaugg 1981). Unlike the fry of other salmonids, those of chinook salmon tolerate high levels of serum chlorides and are able to rapidly acclimate to high salinities. As the fry age in freshwater, their tolerance to salinity gradually increases, and some enter estuaries without first developing the morphological characteristics of a smolt (Hoar 1976). The degree of salinity tolerance depends somewhat on prior acclimation, but fish size and growth rate have been identified in several studies as factors affecting salinity tolerance. The saltwater tolerance of larger fish of a given age is known to exceed that of smaller ones. Ewing et al. (1980), who monitored gill (Na^+-K^+) - ATPase activity as an indicator of seawater readiness, found activity to be lower among slower-growing fish; faster-growing fish had either a more fully functional osmoregulatory system or

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[1]Smolt is a silvery juvenile, tolerant of seawater, migrating toward the ocean; fry may live in estuaries with moderate salinities, but generally do not enter the ocean. A parr is a pre-smolt stage with vertical bars (parr marks) on the sides.

one that was capable of faster acclimation to higher salinities (Wagner et al. 1969). Most investigators agree that the parr-smolt transformation involves an endogenous rhythm affected by fish size and growth rate and environmental cues that include temperature, photoperiod, and lunar cycle (Ewing et al. 1979; Grau 1981).

Downstream Migration

Juvenile chinook salmon form two major groups (Gilbert 1913): those that migrate to the ocean early in their first year of life (ocean-type) and those that overwinter in freshwater before entering the ocean (stream-type). Fall-run chinook salmon are typically ocean-type and emigrate downstream to estuaries as fry shortly after they emerge or as smolts (Reimers 1973; Kjelson et al. 1982). Juvenile chinook salmon of the spring-run characteristically are stream-type and emigrate as yearlings in early spring (Schaffter 1980). Winter-run chinook salmon fry emerge in the summer and emigrate during fall, when they are 4 to 7 months old (Slater 1963). The periods of peak abundance of migrating juvenile chinook salmon in the Sacramento River are shown in Figure 3.

Chinook salmon juveniles usually emigrate in the upper 2 m of water in daylight, but swim deeper and disperse after dark (CDFG 1975; Schaffter 1980). The larger migrants tend to concentrate in midstream where current velocities are greatest (Schaffter 1980). As spring progresses, the vertical distribution of emigrants is increased as they disperse and inhabit deeper water (Wickmire and Stevens 1971). Increases in streamflow and turbidity also have been observed to increase the vertical and horizontal distribution of migrants (Hallock and Van Woert 1959). Fry migrate slower than smolts, a characteristic attributable to their preference of slower velocity streambank areas or their orientation; they face upstream, whereas smolts swim downstream (Schaffter 1980). Estimates of the migration rates of fry and smolts average 1.6 km/day in the mainstream (Rutter 1904; Wickmire and Stevens 1971; Kjelson et al. 1982). The time of year, water temperature, streamflow, and fish size are all factors influencing the time and speed of downstream migration.

Estuarine Residence

Several early life history patterns of fall-run chinook salmon in a coastal Oregon river were reported by Reimers (1973). Most fish emigrated into the estuary in the spring as fry 2 to 3 months old (50-69 mm long). Some fry entered the ocean in mid-summer, but others remained in the estuary an additional 2 to 4 months and entered the ocean in the fall (90 to 119 mm long). From scale analysis of returning adults, Reimers (1973) concluded that the survival of fish that remained in the estuary until fall was greater than that of migrants that left the estuary in mid-summer.

Other juvenile chinook salmon migration patterns, according to Reimers (1973), include fish that go directly into the ocean from freshwater. Newly emerged fry may directly enter the ocean; juveniles (70-85 mm long) sometimes pass directly into the sea during fall freshets; and yearlings (100-130 mm long) may enter in the spring.

Two principal movements of juvenile fall-run chinook salmon into the Sacramento-San Joaquin Estuary (the Delta and Suisun, San Pablo, and San Francisco Bays) have been identified (Kjelson et al. 1982). Fry (40-50 mm long) began entering the estuary in January and peaked in abundance in February and March; most stayed in the upper estuary's freshwater channels (the Delta). A later emigration of chinook smolts (80-90 mm long) occurred from April to June; the fish moved quickly through the Delta and Suisun and San Pablo Bays. Chinook salmon smolts typically use estuaries only as migrational corridors to the ocean (Reimers 1973; Kjelson et al. 1982; Simenstad 1983), whereas fry remain in the estuary until they become larger and environmental conditions stimulate them to move into the ocean.

Estimates of chinook fry residence time in northwestern U.S. and Canadian estuaries ranged from 10 days to 2 months (Shepard 1981). Probable factors that affected their length of stay in estuaries were fish size, population density, prey abundance, habitat suitability, freshwater inflow (particularly abrupt increases), and water temperature (Reimers 1973; Shepard 1981; Kjelson et al. 1982; Simenstad 1983).

Chinook salmon fry (30-50 mm long) in estuaries characteristically feed in schools in littoral or shallow sublittoral habitats such as saltmarshes, mudflats, and other intertidal areas. The feeding habits of chinook salmon fry are regulated largely by the tidal cycle. For example, during flood tide, fry move from small tidal channels into near-shore marshes (Healey 1980, 1982). Nocturnal onshore movements for feeding have also been described for chinook salmon fry (Myers 1980; Cannon 1982). Larger fry and smolts congregate in surface waters of main and subsidiary channels and move into shallow sublittoral zones to feed. Occasionally they enter blind tidal channels, but their stay appears to be transitory (Shepard 1981; Simenstad 1983). The composition of the substrate in estuaries inhabited by salmon is commonly mud, silt, and sand, and less frequently, coarser materials (Forsberg et al. 1977; Healey 1980).

The distribution of chinook salmon fry in the Sacramento-San Joaquin Estuary seemed to be regulated by freshwater inflow during the downstream migration (Kjelson and Raquel 1981). In years of high freshwater inflow, the fry inhabited both upper freshwater channels (the Delta) and the brackish waters of Suisun Bay and San Pablo Bay. In years of low flow, most of the fry were restricted to the upper Delta. Spring discharge also affects survival of fry in estuaries. High freshwater inflow may reduce the mortality of chinook salmon fry and smolts caused by high water temperatures, water diversion, and predation.

Sand sills frequently form at the mouths of small coastal streams in northern California; these cause lower tidal movement and salinities than those found in larger open estuaries. In such a stream, further emigration is prevented by the sill and the growth and mortality of juveniles are affected by the size of the estuary and the population density of chinook and their predators (Reimers 1973). A strong relation between chinook salmon abundance and availability of suitable habitat suggests that estuarine land "reclamation" may substantially reduce the biological carrying capacity of the estuary (Levy and Northcote 1982). Also, land management practices (levees, stream channeling and breaking sand sills) that reduce estuarine trapping of incoming allochthonous materials may reduce the detritus-based food web believed to be necessary to maintain an abundance of juvenile salmon (Sibert et al. 1978; Healey 1982).

<u>Oceanic Residence</u>

Upon entering the ocean, most of the chinook salmon smolts from the Sacramento-San Joaquin Estuary migrate northward, but a spring fishery for chinook salmon south of San Francisco Bay at Monterey is evidence that there is some southward migration (Snyder 1931). The extent of northward movement fluctuates considerably, depending on ocean environmental conditions, food availability, and race. For example, in a mark and recovery study, over 50% of the 1949 year-class of fall-run chinook salmon from the Sacramento River were caught north of the Oregon border, but in a following study 90% were caught south of there (Jensen 1971). Analyses of Pacific coast catch data (sport and commercial) suggest that fall-run chinook salmon spend most, if not all, of their oceanic life near shore, relatively close to their home river. Spring-run chinook salmon often leave nearshore waters in their first year of life and seek out more northerly high seas areas (Hartt 1980; Healey 1983).

Male and female chinook salmon usually spawn when they are 3 to 4 years old. Two-year-old male spawners (commonly called "jacks") usually make up 10% to 25% of the spawning run in California waters. Yearling male chinook salmon may mature before they emigrate to the ocean (Rutter 1904; Rich 1920).

Factors that account for the return of adult salmonids to their natal streams are among the most perplexing and least understood facets of salmon biology. The consensus of salmon biologists is that high seas navigation is innately controlled, and that the role of extrinsic environmental factors increases in importance as the salmon approach their home estuary (Brannon 1981). Orientation in marine waters is believed to involve magnetic and celestial information, interpreted by the innate latitudinal and calendar senses of the fishes (Brannon 1981; Quinn 1981). The length of day, rate of change of day length, sun position, and light polarization are suggested cues. Nearshore migration may be enhanced by onshore winds that concentrate river water close to shore where olfactory cues further guide the salmon (Banks 1969).

GROWTH

Chinook salmon fry newly emerged from the redd are 35 to 44 mm long and weigh as much as 0.5 g (Rich 1920). Fry grew 0.26 to 0.40 mm/day (mean 0.33 mm/day) in the upper Sacramento River, but during the same period, 0.40 to 0.69 mm/day (mean = 0.53 mm/day) in the estuary (Kjelson et al. 1982). Growth rates generally increase in estuaries (Rich 1920; Reimers 1973). In more northern estuaries, growth ranged from 0.37 to 1.32 mm/day (Shepard 1981). The rate of growth of chinook salmon further accelerates when they enter the ocean. Fall-run chinook salmon smolts average 8 cm total length (TL) when they leave the Sacramento-San Joaquin Estuary and are as long as 30 cm by the end of their first year (Jensen 1971). The average lengths of chinook salmon of different ages are shown in Table 1.

The average weights of salmon are greatest just before they migrate into the river to spawn. They lose 15% to 20% of their body weight during upstream migration in large river systems and an additional 10% to 15% during spawning (Rutter 1904).

Table 1. Mean total length (cm) and (in parentheses) percent composition at each age of fall-run chinook salmon in the California commercial troll fishery, 1970-72 (from Denega 1973).

Year	Age in years[a] 1	2	3	4	5
1970	34.0	45.7 (32)	68.6 (50)	83.8 (17)	99.9 (1)
1971	32.3	48.3 (11)	68.6 (60)	83.8 (28)	99.1 (1)
1972	-	43.2 (21)	68.6 (46)	81.3 (32)	96.5 (1)

[a]Lengths at age 1 were derived from back calculation of scale.

THE FISHERY

The California commercial salmon fishery began along the Sacramento River in the mid-1800's. By 1881, 20 canneries were processing over 10 million pounds of chinook salmon from the Sacramento and San Joaquin Rivers. Two years later the fishery collapsed, presumably as a result of over-fishing and the loss of spawning habitat from gold mining operations (Frey 1971; Jensen 1971). Gill nets were the most efficient means of catching salmon in the rivers, but as catches declined in the late 1800's, some fishermen began trolling in off-shore waters. The California ocean troll fishery began near Monterey in the 1880's and near Eureka and Crescent City in 1916 (Frey 1971). Chinook salmon caught in the ocean constituted an increasing proportion of the commercial salmon catch because the major northern California rivers were closed to commercial salmon fishing from 1919 to 1933. The commercial salmon fisheries in the Sacramento and San Joaquin Rivers closed in 1957. Annual chinook salmon catches in California were highest in 1918-19 and 1945-46 (over 13 million pounds each year); record low landings of less than 4 million pounds were reported for 1938-39, 1941, 1958 and 1983. A summary of the annual California ocean sport and commercial troll catches for selected years from 1940 to 1983 is shown in Table 2.

All of the commercial salmon now landed in California waters are caught by ocean trolling. Annually, an average of 4,800 salmon trolling boats expended 75,000 fishing days from 1978 to 1983 (PFMC 1984). Sport-fishing in the ocean has flourished since World War II and now contributes about 21% of the California catch. The ocean sport fishery in California supported an average of 193,000 angler trips annually between 1971 and 1983 (PFMC 1984).

Table 2. The number of chinook salmon in the sport fishery and the weight and value (all in thousands) of chinook salmon in the commercial fisheries of California, 1940-83 (data from National Marine Fisheries Service 1940-75 and Pacific Fishery Management Council 1984).

Sport fishery		Commercial	
Year	Numbers	Pounds	Dollars
1940	7[a]	5,156[a]	411
1945	--	7,912	1,446
1950	56[a]	5,861	1,572
1955	129[a]	9,317	3,266
1960	38[a]	5,996	3,242
1965	60	7,397	4,132
1970	148	5,266	4,421
1975	104	5,781	6,123
1980	86	5,907	13,149
1983	62	2,308	4,609

[a]May include some coho salmon.

The Sacramento River and several other northern coastal rivers in California support a substantial sport fishery for chinook salmon. From 1977 to 1981, the average sport catch of fall-run chinook salmon in the Sacramento River was 1.8% of the total estimated run (Hoopaugh and Knutson 1979; Knutson 1980; Reavis 1981a, 1981b, 1983). The sport catch of the remaining three stocks averaged 1.8% of the late fall run, 1.7% of the winter run, and 2.5% of the spring run. The salmon sport fishery in the Klamath River is estimated to compose up to 13% of the total chinook salmon run and 7% of the total ocean sport and commercial catches of Klamath River fish (U.S. Fish and Wildlife Service 1980, 1981, 1982, 1983, 1984).

The economic value of the Pacific coast salmon fishery is of great importance, ranking second in quantity and value in the entire 1983

U.S. marine catch (NMFS 1984). The estimated value of California's commercial chinook salmon fishery is shown in Table 2. The dollar value of commercial salmon depends on fish size and dockside ex-vessel price (Wahle et al. 1974). In 1983, ex-vessel prices per pound ranged from $1.40 for small salmon less than 8 lb to $2.25 for fish larger than 12 lb (PFMC 1984). The exact value of the ocean sport salmon fishery is difficult to ascertain, but an estimate of the net economic sport value of a chinook salmon is $63.00 per fish. Chinook salmon caught in rivers are estimated to be worth $28.00 per fish (Mathews and Brown 1970).

According to Wright (1981), the salmon fishery needs to be regulated for optimum yield. He suggested that optimum yield may be reached by using area and season closures, minimum size limits, and gear restrictions. A more direct method would be through the establishment of limited entry or catch quotas. Catch quotas have been instituted in Oregon and Washington, and recently the California legislature has joined Oregon and Washington in an attempt to limit the entry of new fishing boats into the existing fleet (PFMC 1984).

The magnitude of the chinook salmon fishery has probably contributed to the decline in abundance of the species. Ricker (1980, 1981) attributed the apparent decrease in size and age at maturity of chinook salmon stocks to the huge salmon catch in the commercial troll fishery along the Pacific coast. Since the 1920's, the average weight of troll-caught chinook has decreased significantly (some 2.5 kg in British Columbia waters from 1951 to 1975), and mean age at maturity for returning adults has decreased from 4 years to 3 years. Ricker (1980) stated that trends in ocean temperatures are not known to be responsible for the age and size decreases, but offers several other possible explanations:

1. The increased intensity of the troll fishery has resulted in more salmon being caught early in the season and at a smaller size.

2. The ocean catch has been so large that fewer salmon survive to older ages and young fish make up a bulk of the catch (i.e., the "fishing-up effect").

3. The excessive removal of late-maturing salmon favors reproduction of smaller, early-maturing fish.

The increased proportion of younger fish in the spawning population had been recognized earlier by Warner et al. (1961) for the Sacramento River and by Junge and Phinney (1963) for the Columbia River.

Current California stocks of chinook salmon are heavily supplemented by hatchery fish that are released as fry or fingerlings (large fry to yearlings). Now being evaluated are the survival of hatchery-reared salmon and their contribution to the offshore fishery, returns to the hatchery in relation to fish size at the time of release and the distance from the point of release to the ocean (Sholes and Hallock 1979; Kjelson et al. 1982). Production of chinook salmon (State and Federal hatcheries) in California from 1971 to 1981 is shown in Table 3.

ECOLOGICAL ROLE

Competition

Competition for spawning gravels between chinook salmon and other anadromous species is limited because of the chinook salmon's preference for spawning grounds in mainstem or large tributary streams and their early period of upstream migration and spawning. Downstream disperson of newly emerged salmonid fry is a density adjustment mechanism and may

Table 3. The numbers (thousands) and weight (thousands of pounds) of juvenile fall-run chinook salmon raised in State and Federal hatcheries and released in California rivers from 1971 to 1981 (data from California Department of Fish and Game 1972-84 and U.S. Fish and Wildlife Service 1970-81).

Year	State Number	State Weight	Federal Number	Federal Weight
1971	37,845	413	8,186	118
1972	28,793	446	12,360	115
1973	23,384	452	10,971	114
1974	15,115	371	12,518	113
1975	27,039	443	7,205	27
1976	24,947	456	8,544	104
1977	24,723	535	10,129	116
1978	14,598	335	8,719	84
1979	16,187	555	7,411[a]	117[a]
1980	20,133	677	16,951	229
1981	34,850	650	16,060	138

[a]Includes some winter-run chinook salmon.

result in cohabitation of chinook salmon fry with juvenile steelhead trout or coho salmon (Reimers 1973). Juvenile chinook salmon, like other stream-dwelling salmonids, are territorial, and competition for food and space may result when they live in the same waters with other salmonids. Fry of chinook salmon and coho salmon select similar habitat, and coho salmon are the more aggressive of the two species (Lister and Genoe 1970; Stein et al. 1972). The aggression and territoriality of salmon fry appear to be influenced by current velocity, and are subdued in large pools and estuaries where schooling is common (Reimers 1968). Intraspecific dominance is largely governed by fish size (Chapman 1962; Reimers 1968).

The early downstream migration of ocean-type chinook salmon fry reduces contact with other species, but large introductions of hatchery-reared coho salmon may encourage premature emigration of chinook salmon fry from freshwater into estuarine or oceanic waters and could reduce growth and survival of the chinook salmon migrants (Stein et al. 1972). Myers (1980) reported a large degree of feeding overlap in estuaries between wild chinook juveniles and hatchery-released coho salmon and hypothesized a high potential for competition. Stream-type chinook salmon live in freshwater for up to a year and frequently occur with juvenile steelhead trout. The selection of different habitats by the two species reduces competition for space or food (Everest and Chapman 1972).

Upon entering the estuary, chinook salmon fry and smolts are confronted with a sizable assemblage of potential competitors. High population densities of chinook salmon within estuaries increase intraspecific competition and may result in reduced summer growth and early ocean entry (Reimers 1973). Shepherd (1981) reported that fishes in estuaries known to eat the same food as that preferred by chinook salmon are coho salmon, chum salmon (_O. keta_), pink salmon (_O. gorbuscha_), steelhead trout, cutthroat trout (_Salmo clarki_), Dolly Varden (_Salvilinus malma_), threespine stickleback (_Gasterosteus aculeatus_), shiner perch (_Cymatogaster aggregata_), starry flounder (_Platichthys stellatus_), prickly sculpin (_Cottus asper_), Pacific staghorn sculpin (_Leptocottus armatus_), and Pacific herring (_Clupea harengus_). Other potential competitors in the Sacramento-San Joaquin Delta are juvenile Sacramento squawfish (_Ptychocheilus grandis_) and Delta smelt (_Hypomesus transpacificus_) (Schaffter 1980).

The greatest competitors of chinook salmon in the ocean are probably other Pacific salmon, particularly during peak abundance in nearshore waters. Evidence of marine density-dependent survival was noted by Peterman (1978) for northern Pacific salmon stocks, but the ocean proper probably does not seriously limit salmon production (Walters et al. 1978). Analysis of food resources of the northern Pacific Ocean suggests that the supply of food for salmon is nonlimiting (Rothschild 1972).

Predation

Predation on salmon eggs usually is not a major cause of mortality because the eggs are in the substrate. Predation on chinook salmon fry may be high when they begin their downstream migration. When salmon are concentrated above or below dams or water diversion structures, some are easy prey to piscivorous birds such as belted kingfishers (Ceryle alcyon), herons (Ardeidae), and mergansers (Mergus spp.), and larger salmonids, sculpins, Sacramento squawfish, and striped bass (Morone saxatilis). Hatchery-released fingerling chinook salmon and steelhead trout in Sacramento River tributaries prey heavily on the smaller wild chinook salmon fry (Sholes and Hallock 1979; Menchen 1981).

Predation by larger salmonids on chinook salmon fry and smolts may be substantial in estuaries. Coho salmon smolts are known to be highly piscivorous during outmigration (Parker 1968), and predation by coho salmon and other predators may significantly reduce survival of hatchery-released salmon fry or smolts (Peterman and Gatto 1978). Other estuarine predators include mergansers, cormorants (Phalacrocorax spp.), grebes (Podicipedidae), loons (Gavia spp.), and ospreys (Pandion haliaetus).

The extent of high seas predation is unknown, but loss of salmon to northern fur seals (Callorhinus spp.) may range from 2 million to 60 million salmon annually (Peterman 1978). The salmon shark (Lamna ditropis) is another high-seas predator. Nearshore predators are cormorants, ospreys, sea lions (Eumetopias jubatus and Zalophus californianus), harbor seals (Phoca vitulina), blue sharks (Prionace glauca), and lampreys (Lampetra spp.).

Food

Chinook salmon tend to be more opportunistic feeders than other salmonids (Healey 1982). Fry in streams feed extensively on drift insects (Rutter 1904), but zooplankton are more heavily eaten in main river systems and estuaries. Adult and juvenile dipteran insects and crustacean zooplankters -- especially Cladocera and Copepoda -- are principal food items of chinook fry in the Sacramento River and the Sacramento-San Joaquin Estuary (Figure 5). Smolts feed on gammarid amphipods and larval fish in brackish waters; larger and older smolts select larger crustaceans (Corophium and Neomysis) and fish as food (Cannon 1982). The shift from shallow epibenthic prey to larger, often pelagic species reflects the movement of juveniles from shallow littoral habitats into deeper river and tidal channels as they increase in size. Food consumed by marine dwelling juveniles consists primarily of fish, crustaceans, and insects (Snyder 1924). Marine prey of adult chinook salmon are pelagic crustaceans such as krill (euphausiids), larval crabs, and fish (Figure 5).

ENVIRONMENTAL REQUIREMENTS

Temperature

Chinook salmon are coldwater fish but they are more tolerant of higher water temperatures than other Pacific salmon (Brett 1952). Optimum, tolerable, and lethal water temperatures for different life stages of chinook salmon are given in Table 4. Excessively abrupt water temperature changes may kill fish even within

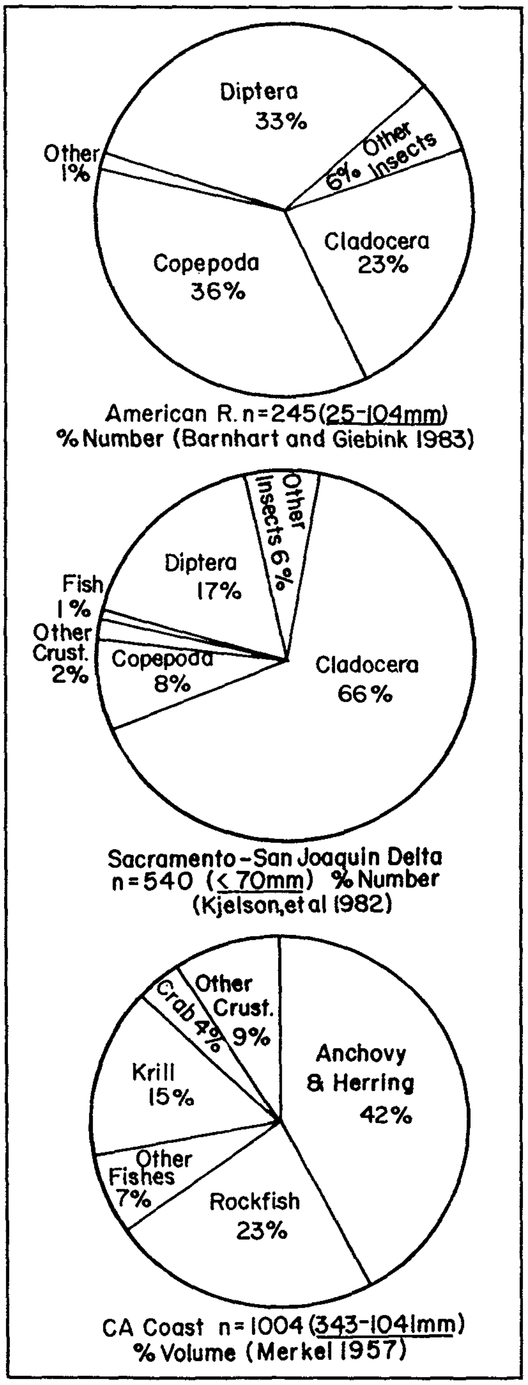

Figure 5. Stomach contents of chinook salmon of different lengths (in parentheses) and habitats.

tolerated ranges. In the Delta, water temperatures that exceed 23° C are lethal to most chinook smolts (Kjelson et al. 1982).

Salinity

Among the Pacific salmons, juvenile chinook salmon are most tolerant of changing salinities. Shortly after hatching, the alevins tolerate moderate salinities (15 ppt), and at 100 days of age and at a mean length of 65 mm, they tolerate full-strength seawater (Wagner et al. 1969). Salinity tolerance can be broadened by acclimation and is increased by the size of the fish and rate of growth. Despite a high tolerance for high salinities, studies in the Sacramento-San Joaquin Estuary and in southern Canadian estuaries suggested an apparent preference of low salinity water by chinook salmon fry (Healey 1982; Kjelson et al. 1982). The salinity requirements of juvenile chinook salmon are listed in Table 4. Adult salmon tolerate rapid salinity changes.

Dissolved Oxygen

The dissolved oxygen (DO) requirements of chinook salmon embryos are unclear, but Alderdice et al. (1958) observed an increase in oxygen demand by chum salmon embryos as they neared hatching. The effects of DO concentrations below the saturation level on salmonids include delayed or premature hatching (depending on the timing of low DO in the egg development process); abnormal embryo development; reduced size and strength at hatching; reduced growth, feeding, and swimming ability; and increased susceptability to disease, predation, and toxic contaminants (Orsi 1967; Davis 1975). The DO requirements of chinook salmon may change at various life stages (Table 4).

Table 4. Temperature, salinity, and dissolved oxygen requirements for several life stages of chinook salmon.

Environmental factor	Life stage	Limits: Optimal	Limits: Tolerance	Limits: Lethal	Comments
Temperature (°C)	Adult upstream migration		51-67°F 10.6-19.4[a] 3.3-13.3[a]		Fall-run chinook Spring-run chinook
	Spawning		42-57 F 5.6-13.9[b]		
	Egg incubation		42-58 F 5.8-14.2[c]	< 0.6[c]	Eggs survive near freezing after initial development to 128 cell stage at 5°C.[d]
	Juvenile rearing	12-13[e]		< 0.8[e] >25.1[e]	Acclimated at 10°C Acclimated at 24°C
Salinity (ppt)	Juvenile rearing			>15[f]	At 10 days post-hatch
				>30[f]	At yolk-sac absorption (with acclimation) or at 100 days post hatch (without acclimation)
Dissolved oxygen (mg/l)	Adult upstream migration		>5.0[b]		
	Egg incubation	Saturation		< 1.6[g]	As percent saturation decreases, growth decreases and abnormalities and mortality increase.
	Juvenile rearing		>4.5[h]		Avoidance at 16-25°C.
			>3.0[h]		Avoidance at 8-18°C.

[a]Bell (1973).
[b]Reiser and Bjornn (1979).
[c]Combs and Burrows (1957).
[d]Piper et al. (1982).
[e]Brett (1952).
[f]Wagner et al. (1969).
[g]Silver et al. (1963).
[h]Whitmore et al. (1960).

Substrate

Substrate requirements are fairly rigid for successful spawning and egg incubation. Chinook salmon spawn over a substrate of unconsolidated materials of the appropriate size and adequate intragravel water flow, with proper stream depth, current velocity, and bottom contour. The requirements for spawning and rearing of chinook salmon are described in Table 5. Chinook salmon fry tend to prefer soft substrates, possibly because of the preferred low water velocities there, but fry also inhabit areas of gravel, cobble, or bedrock in either streams or estuaries (Everest and Chapman 1972; Healey 1980). Juvenile spring-run salmon that overwinter in streams are known to seek coarse substrates (cobble or boulder) for protection against heavy winter and spring flows (Chapman and Bjornn 1969).

The greatest threat to the substrate quality is the accumulation of fine sediments on spawning gravels and food-producing areas (Cordone and Kelley 1961). Excessive sedimentation clogs gravel interstices and reduces

Table 5. Habitat requirements of several life stages of chinook salmon.

Environmental factor	Life stage	Limits: Optimal	Limits: Tolerance	Comments
Substrate size (cm)	Spawning[a]	1.3-10.2		80% 1.3-5.1 cm, 20%>5.1 cm
	Juvenile rearing[b]	silt	silt-rubble	
Depth (m)[c]	Adult upstream migration		$\geq$ 0.24	
	Spawning	> 0.24		
	Juvenile rearing	0.3-1.22		
Water velocity (m/s)	Adult upstream migration		$\leq$ 2.4[c]	Sustained current maximum
			$\leq$ 6.1[d]	Obstacle current maximum
	Spawning[c]	0.3-0.91		90%-95% confidence interval
	Juvenile rearing[c]	0.06-0.24		

[a]Bell (1973).
[b]Everest and Chapman (1972).
[c]Thompson (1972).
[d]Weaver (1963).

intragravel water flow, which is essential for the transport of oxygen to, and metabolic wastes from, incubating egg surfaces. Heavy sedimentation may also trap alevins in the gravel, causing suffocation or starvation. Sedimentation of rocky substrates also reduces the available habitat for food organisms and reduces fish escape cover.

Depth

Minimum depths are necessary to assure successful upstream migration of adult salmon. During low flow, riffles may be too shallow for adult passage. Thompson (1972) developed methods by which critical areas are identified and adequate passage flows are estimated. Depth is important in spawning site selection because it affects the hydraulic "head" and intragravel flow. Chinook salmon are reported to spawn at depths up to 10 m in large rivers (Chapman 1943), but generally favor depths less than 3 m. Depth criteria for migrating and spawning chinook are listed in Table 5. Depth preference of stream-dwelling juvenile chinook salmon is about 1 m and may be influenced by water velocity, instream cover, fish size, and the abundance of predators and competitors. Chinook salmon fry and smolts in estuaries favor surface waters in shallow flats or deepwater channels.

Water Movement

Adequate current velocities are required to assist the female in nest excavation and for intra-gravel flow. Gangmark and Bakkala (1960) found significant increases in mortality of chinook salmon eggs when intragravel flow rates dropped below 60 cm/h. Juvenile chinook salmon in streams and estuaries select low velocity habitats, but in streams the fry will seek faster waters as they grow larger and most select locations adjacent to higher velocities where prey abundance is greater (Everest and Chapman 1972). Current velocity preferences for spawners and juveniles are given in Table 5. The cruising, sustained, and darting speeds of adult chinook salmon are about 1.1, 3.3, and 6.8 m/s, respectively (Bell 1973). Maximum speeds depend on fish size, water temperature, dissolved oxygen concentrations, and stage of maturity.

The estimation of streamflow requirements for juvenile salmonids is extremely complex due to the interaction of numerous physical, chemical, and biological factors. The Instream Flow Incremental Methodology (IFIM) was developed by the USFWS Cooperative Instream Flow Service Group to predict the effects of a decline in flow and space on freshwater fish populations (Bovee 1982). This procedure, a hydraulic simulation model that incorporates fish age and species-specific habitat preference data, is in use throughout the western United States. Flow requirements for chinook salmon in large rivers are complex, but several studies have associated high survival of downstream migrants with high discharges in the spring (Wetherall 1970; CDFG 1975; Kjelson and Raquel 1981; Kjelson et al. 1982). Survival of chinook salmon smolts in the Sacramento River was highly correlated ($r = .94$) with freshwater inflow in the spring and estuarine water temperatures (Kjelson et al. 1982). Various data support the view that years of high freshwater inflow in the San Joaquin River result in greater return of spawning adults 2.5 years later (CDFG 1975; Kjelson and Raquel 1981).

Turbidity

Juvenile salmonids are capable of tolerating turbidity as high as 1,000 ppm, but reductions of primary food production and feeding efficiency are likely at much lower turbidities (Bell 1973). The migration of adult salmon may be inhibited at turbidities of 4,000 ppm (Bell

1973), and chinook salmon are reported to avoid turbid waters if given a choice (Cordone and Kelley 1961). Direct harm to fish by excessive suspended sediments is probably rare in nature and can be combatted in part by mucous secretions that flush gill membranes. Abrasion and clogging of gill lamellae may result under extreme turbidities and are related to the size and hardness of the suspended material (Cordone and Kelley 1961). Prolonged exposure to highly turbid waters may cause thickening of gill lamellae, which reduces oxygen-carbon dioxide exchange efficiency resulting in an increase in vulnerability to disease (Bell 1973). Silt deposits are more damaging to salmon than silt suspended in the water column.

Heavy Metals

Acid-mine wastes from the Spring Creek drainage have caused numerous kills of chinook salmon, steelhead trout, and other species in the Sacramento River between Keswick Dam and Cottonwood Creek (a distance of 33 river mi) (USFWS 1959; Prokopovich 1965; Nordstrom 1977). Of the four most abundant metals in the mine waste, copper and zinc are extremely toxic to chinook salmon. Since 1963, the wastes have been collected in Spring Creek Reservoir and metered into Keswick Reservoir at levels thought to be safe for anadromous fish (Finlayson and Ashuckian 1979). In 1978, new interim release schedules proposed by Wilson (1978) allow for maximum dissolved copper and zinc concentrations of 5 µg/l and 64 µg/l, respectively (Finlayson and Verrue 1980). Recently the water quality program to partially control metal concentrations in the Sacramento River (from acid-mine wastes from Spring Creek) has curtailed the number of fish kills (Wilson et al. 1981). The sublethal effects on chinook salmon and other fish species caused by chronic exposure to the metals are not known.

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16. Abstract (Limit: 200 words)

Species profiles are literature summaries of the taxonomy, morphology, distribution, abundance, life history, and environmental requirements of coastal aquatic species. They are prepared to assist in environmental impact assessment. The chinook salmon (Oncorhynchus tshawytscha) is a valuable sport and commercial fish species and accounted for over 69% of the salmon caught off the California coast from 1971 through 1983. Chinook salmon spawning runs in the Sacramento River, the major producer of chinook salmon in California, are divided into fall, late fall, winter, and spring runs. Other coastal rivers have fall and spring runs of chinook or only a fall run. After hatching, the sac-fry live in the gravel for a month or longer before they emerge as fry. Some fry migrate immediately to saltwater, others remain 2 to 12 months in freshwater before migrating. They remain in the ocean from 1 to 7 years; most females mature and return to freshwater to spawn after 2 to 4 years at sea. Some males return to spawn after only 1 year in the ocean, but most return after 2 to 4 years. All chinook salmon die after they reenter freshwater, whether they spawn or not.

17. Document Analysis a. Descriptors

Fishes
Estuaries
Growth
Animal migrations

b. Identifiers/Open-Ended Terms

Habitat requirements
Life history
Chinook salmon
Oncorhynchus tshawytscha
Salinity requirements
Temperature requirements

c. COSATI Field/Group

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