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State of California
The Resources Agency
DEPARTMENT OF WATER RESOURCES
Northern District

WATER TEMPERATURE EFFECTS ON CHINOOK SALMON
(*Oncorhynchus tshawytscha*)
With Emphasis on the Sacramento River

A Literature Review

National Marine Fisheries Service
Southwest Region, HCB
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FOREWORD

Water temperatures in the Sacramento River are critical to the survival and perpetuation of chinook salmon. Requirements for adults are different than those for eggs and juveniles. Temperatures may directly affect the fish, or may affect fish indirectly through effects on other environmental factors such as food organisms or predators. Required temperatures may also differ for different races of salmon in the same or different drainages.

Accurate knowledge of temperature requirements for chinook salmon in the Sacramento River is essential for efforts currently planned for restoration of the species. This report reviews published literature on temperature requirements of chinook salmon. Emphasis has been placed on requirements of fish in the Sacramento River. Recommendations are included to gather the data necessary for a complete understanding of the temperature requirements for all life stages of each of the four runs of chinook salmon occurring in the river.

This report was reviewed by fishery biologists in Region II of the Department of Fish and Game, who also kindly provided unpublished data.

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Introduction

Specific water temperature requirements of chinook salmon (*Oncorhynchus tshawytscha*) are often cited by fisheries biologists for determining effects from various water development projects. Desirable water temperatures are reported to vary for the different life stages of chinook salmon, and are often different in different geographic regions.

Water development projects on the Sacramento River have altered temperature conditions which may at certain times or localities be unfavorable to particular life stages of chinook salmon. Migration and survival of adult fish have been linked to critical temperature limits (Bell 1973). Exposure of ripe adults and eggs to water temperatures in excess of 56°F is commonly assumed to incur greater than normal losses and abnormalities of young fish (Morat and Richardson 1983, Weidlein 1971, Dunham 1968).

A literature review was undertaken at the request of engineers in the Northern District of the Department of Water Resources to clarify the temperature requirements and effects for the various life stages of chinook salmon in the Sacramento River.

Significant Findings

The activities of fish are controlled by temperatures in the aquatic environment. Extremes of temperature, whether hot or cold, produce adverse effects in fish. The tolerance of fish to temperature extremes varies with the life stage, whether egg, fry, fingerling, smolt, or adult. In addition to direct effects of temperature on fish, indirect effects due to temperature also occur that can limit fish populations. Such effects include altered food abundance and conversion efficiency, increased predation, temperature-mediated disease, dissolved oxygen, and increased toxicity of various compounds.

Temperature Regime

Construction of Shasta Dam in 1943 produced water temperatures in the Sacramento River immediately downstream of the dam that were cooler than previously occurred during the summer, but somewhat warmer than normal in the fall. The limited data available show that, during normal hydrologic years, river water temperatures may range up to 55°F at Keswick Dam, 58°F at Balls Ferry, 59°F below the Red Bluff Diversion Dam, and 61°F at Hamilton City.

Water temperatures during the second year of drought in 1977 ranged up to 66 °F even at the upper locations. River temperatures normally begin to decline in October, remain uniform from December through March, and begin to increase in April. Increased releases from Shasta Dam tend to maintain cooler river temperatures, while deepening of the thermocline and drawdown of the water level in the reservoir tend to increase river temperatures during late summer.

Races of Chinook Salmon

Four distinct races comprising separate upstream runs of chinook salmon occur in the Sacramento River, with sufficient overlap so that adult immigration and spawning, egg hatching, and juvenile emigration each occur nearly year round. The early fall run begins as early as July in the lower river reaches and peaks at the Red Bluff Diversion Dam in late September. The late fall run begins in mid-October and peaks at Red Bluff in January. The winter run migrates upstream from December through July. Upstream migration of the spring run occurs from March through November. Spawning activity peaks a month or two following the peak migration of each run past Red Bluff. The time required for eggs to hatch is dependent on water temperatures. Peak hatching occurs from two and a half to four and a half months following peak spawning activity. Fry migrate shortly after hatching or may remain in the river during the summer and emigrate as smolts in the fall.

Spawning Locations

Immediately following completion of Shasta Dam, the primary spawning area became the reach of river between Balls Ferry and Keswick Dam. However, coinciding with several additional water-diversion facilities completed between 1963 and 1966, increasing numbers of salmon have been spawning in downstream reaches. By 1976, spawning activity was nearly uniform in the reaches from Balls Ferry to Keswick, Red Bluff to Balls Ferry, and Hamilton City to Red Bluff. More recent data show that the reach from Hamilton City to Red Bluff receives more spawning activity than do both upper reaches combined.

Temperature Requirements

Water temperature has a direct effect on survival of chinook salmon adults, eggs, fry, and fingerlings. The period from mid-May through September may contain temperature conditions most adverse to some life stage from the various races. During drought conditions, water temperatures may not be suitable for maximum survival of any of the life stages of the various runs.

Adults. Adult immigrants have exhibited poor survival when held at hatcheries at water temperatures greater than 60°F or less than 38°F. Water temperatures to which adult fish are exposed also affect unspawned eggs. Adults held at water temperatures greater than 60°F or less than 38°F have produced eggs less viable than those produced by fish held in water between 38°F to 60°F.

Eggs. Egg incubation temperatures also contribute to loss of egg vitality. Eggs incubated at constant water temperatures greater than 60°F or less than 38°F have suffered high mortalities. Survival increases, however, for eggs taken at high water temperatures but incubated at temperatures that gradually decline to the mid-forty to mid-fifty degree range. Highest survival has been found in eggs from fish from the Sacramento River when incubated at temperatures ranging from 53°F to 57.5°F. Tolerance of eggs to lethal cold water temperatures increases with incubation time at temperatures above the lethal limit. Temperatures as cold as 35°F could be tolerated once the 128-cell stage in egg development has occurred in warmer incubation temperatures, which requires about six days at 42.5°F. The cause of death from adverse water temperatures in incompletely developed egg embryos may be lack of cellular coordination between growth and differentiation of organs or altered order of differentiation that fails to produce a functioning organism.

Fry. Adverse effects from high holding or incubating temperatures may not become apparent until after the egg stage of development. Eggs taken from adults at high temperatures, but apparently successfully incubated at lower temperatures, have produced fry that subsequently succumb, even though reared at much cooler temperatures. Incubation temperatures greater than 60°F have produced high mortalities in fry able to develop past the egg stage. Though producing low egg mortality in fish from the Sacramento River, constant water temperatures in the range of 55°F to 57.5°F produced sac-fry mortalities in excess of 50 percent. Mortalities in fry were reduced to low levels when eggs were incubated at constant temperatures of from 50°F to 55°F, or under declining temperatures from initial incubation temperatures ranging up to 60°F. Coagulated yolks were found in many of the fry that succumbed due to high egg incubation temperatures. The greatest mortality of fry from early incubation of eggs at unfavorably high temperatures occurs during the transition period from complete yolk absorption to active feeding. Abnormal physiological development during the egg stage apparently prevents the successful transition to active feeding by the fry stage.

Fingerlings. Latent effects in the fingerling stage from high egg incubation temperatures are either non-existent, the affected individuals having succumbed during the fry to fingerling transition, or uninvestigated. Fingerling chinook salmon have a preferred temperature range of 53.6°F to 57.2°F. Maximum growth occurs at 55°F. Acclimation to higher temperatures increases the maximum temperature that can be tolerated up to the lethal limit, at which warmer acclimation temperatures have no effect. The upper lethal temperature for long-term exposure for fish in the Sacramento River has been determined to be 78.5°F, though higher temperatures can be tolerated for brief periods. Delayed mortality may occur in fish briefly exposed to high temperatures. Mortality may result from the direct effects of exposure to high temperatures or indirect effects, such as loss of equilibrium that increases susceptibility of the fish to predation.

Migration. Both adult and juvenile migrations are affected by water temperatures. The upstream migration of adults to the San Joaquin River from the Delta has been prevented by water temperatures above 70°F. Upstream migration of adults resumed when temperatures cooled to 65°F.

The transformation of non-migratory chinook parr into migratory smolts with increased seawater tolerance occurs in association with elevated gill (Na and K) adenosinetriphosphatase activity. Temperatures greater than 55°F inhibit adenosinetriphosphatase activity in steelhead trout (*Salmo gairdneri gairdneri*), while temperatures between 54°F and 59°F inhibit activity in coho salmon (*Oncorhynchus kisutch*). Although specific temperature limits have not been determined for chinook salmon, a maximum temperature of 54°F for all species of salmonids has been recommended to maintain migratory response and seawater adaptation in juveniles.

Meristic Features. Morphological characteristics, which often are used to distinguish between races, can vary with temperature of water used for egg incubation. The numbers of both normal and abnormal vertebrae increase, while dorsal and anal fin rays decrease, as temperatures approach the extremes of the range suitable for incubation.

Indirect Effects

Water temperatures preferred by chinook salmon create environmental conditions that favor continued survival of the species. Deviation from the preferred temperature range, however, may favor other species or create environmental conditions unsuitable for chinook salmon.

Food and Growth. Juvenile chinook salmon feed primarily on drifting aquatic organisms, especially chironomids, mayflies, stoneflies, and caddisflies. Water temperatures affect the types, abundance, and availability of aquatic organisms, and hence the food supply of juvenile salmonids. The diversity of aquatic organisms decreases as water temperature increases. Species tolerant of warm temperatures may increase in abundance, but such species generally are not those that enter the drift. In addition to direct effects, warmer water temperatures may affect aquatic organisms indirectly through habitat degradation, such as increased trapping of silt due to increased growths of filamentous algae.

Higher water temperatures increase metabolic rates and food requirements. Fry produced from eggs incubated at warmer temperatures, even though within the preferred temperature range of 53.6°F to 57.3°F selected by juveniles, may hatch sooner but are smaller than those produced at lower temperatures. This occurs because of increased maintenance costs and lower yolk conversion efficiencies at the higher temperatures. Growth of fingerlings in hatcheries may be greater at temperatures slightly higher than the preferred range selected by fish, but requires a higher ration level for maintenance and growth. In natural streams, increased temperatures may decrease food availability and subsequently decrease growth rate and survival of fish. Competition for food may increase from other species better adapted to warmer conditions. When food is limited by water temperature or competition, additional losses of juvenile salmon may occur from predation or downstream displacement as the fish leave the more sheltered areas to forage for prey in deeper water.

Predation. Warm water temperatures may increase losses of young chinook salmon to predators by adversely affecting the performance of young salmon or enhancing habitat conditions favorable to predatory fishes. The most important predatory fishes in the Sacramento River include largemouth bass (Micropterus salmoides), striped bass (Morone saxatilis), Sacramento squawfish (Ptychocheilus grandis). and steelhead trout. Large numbers of squawfish congregate below the Red Bluff Diversion Dam, where salmon migrants, confused by backwater currents, may become easy prey. Mass movements at night by emigrating salmon avoid the prime feeding hours of many predators, cause predators to become confused in selection of prey, and limit the availability of emigrants for consumption.

Disease. Chinook salmon are susceptible to a variety of diseases, many of which have specific temperature requirements. While certain diseases are more prevalent in cold water, most of the more important diseases afflicting chinook salmon increase in virulence as temperatures increase. Water temperatures greater than 56°F favor bacteria causing columnaris and furunculosis, while temperatures greater than 65°F favor the protozoan causing ichthyophthiriosis (or ich). A common fungus infecting fish, Saprolegnia parasitica, occurs over a wide range of temperatures, but develops most rapidly at higher temperatures. Among the important diseases that develop under cooler water conditions are kidney disease and infectious hematopoietic necrosis (also referred to as Sacramento River Chinook Disease). Both diseases have optimum temperature requirements in the 45°F to 50°F range. Although most disease organisms are active within a rather narrow temperature range, the protozoan Ceratomyxa shasta first becomes infective at temperatures of about 50°F but increases in virulence as temperatures increase. Many other diseases affect chinook salmon, but temperature requirements of the causative agents are not well understood.

Oxygen. Oxygen requirements of fish depend on metabolic rates, which are highest in the egg stage and decrease through successive developmental stages, but increase in response to increasing water temperatures. Insufficient oxygen levels can result in high embryo mortality, delayed egg hatching, developmental abnormalities, reduced growth of sac-fry, and reduced scope for activity of fingerlings.

The oxygen content of water is inversely related to temperature, varying at saturation from 11.3 mg O_2/L at 50 F to 9.0 mg O_2/L at 70°F. An oxygen level of 6 mg/L is required by salmon, so that at temperatures tolerated by salmon, oxygen levels at saturation should be adequate. However, higher temperatures increase organic decomposition and respiration rates of aquatic organisms, which may remove sufficient oxygen from the water to create conditions unsuitable for salmon. Growths of aquatic plants, stimulated by warmer water temperatures, trap sediments which impede the flow of oxygen-carrying water to gravels. Loss of fish or eggs may occur from reduced levels of oxygen in water and gravels.

<u>Metals</u>. Toxic trace metals, primarily copper, zinc, and cadmium, leaching from abandoned mining operations in the Spring Creek drainage, have caused numerous fish kills in the Sacramento River. Though increasing temperatures generally increase the toxic effects of metals, little research has been conducted with chinook salmon. Increasing temperatures appear to reduce survival time of chinook salmon at the lethal levels of metal contamination rather than to decrease the metal concentration that results in death.

Implications for Chinook Salmon in the Sacramento River

Chinook salmon from widely isolated streams have developed into separate races with differing water temperature tolerances and preferences. Within the Sacramento River, four races of chinook salmon exist. Whether differences occur for temperature tolerances and preferences among the races is unknown. Races of salmon were not specified for which temperature tolerances and preferences were determined. Sufficient overlap exists in specific life stages of chinook salmon that determination of race used in previous studies cannot be determined.

Water temperature requirements vary with the developmental stage of chinook salmon, in addition to the possibility of race. The available data suggest that for adult chinook salmon in the Sacramento River, the maximum temperature for successful upstream migration should be less than 65°F. Maximum temperature for maintenance of adults in the river while eggs are maturing should be less than 60°F but greater than 37°F. Eggs can be exposed for a short period to initial water temperatures as high as 60°F, with a gradual decline to temperatures in the upper forty to mid-fifty degree range. Eggs should not be exposed to temperatures below 40°F until the 128-cell stage of development has occurred, after which eggs can tolerate temperatures as low as 35°F. The preferred temperature range, both for egg incubation and rearing of fry, is between 53°F and 57.5°F. The preferred temperature range for fingerlings also lies between 53°F and 57.5°F, with a maximum tolerated temperature of 78.5°F. However, prior to and during seaward migration, young chinook salmon should not be exposed to water temperatures greater than 54°F.

Very limited temperature data are available for the Sacramento River. Complete temperature records from Keswick Dam to Hamilton City are available only from 1983 and 1986 to the present. Water temperatures in the upper Sacramento River during 1983 and 1986 were suitable for the upstream migration of adult chinook salmon, which occurs throughout the year. Temperatures in June prior to increased flow releases from Shasta Dam exceeded the suggested temperature maximum for brief periods at the lowest portion of the spawning area, which ranges from Hamilton City to Keswick Dam. High water temperatures during June may affect adults comprising the end of the winter run or the beginning of the spring run of chinook salmon.

Proper water temperatures for the maturation of viable eggs in adult fish were available throughout 1983 and 1986 in the upper spawning reach ranging from Balls Ferry to Keswick Dam. Temperatures exceeded the optimum limit of 60°F during late May to early June and again in mid-September in the lower portion of the middle reach ranging from the Red Bluff Diversion Dam to Balls Ferry. Unsuitable water temperatures were present for maturation of eggs in adult fish during this same period in the entire lower spawning reach ranging from Hamilton City to the Red Bluff Diversion Dam. At least some portion of the lower spawning reach was unsuitable for holding adult fish from mid-May to October. Warm temperatures during these periods in the lower spawning reach could impact the early fall, winter, and spring runs of fish.

Water temperatures suitable for egg incubation existed in all spawning reaches, except in the lower reach from mid-May through September. Eggs of the late fall, winter, and spring runs of fish could be affected by the high water temperatures. Preferred water temperatures for egg incubation as well as fry rearing, however, were present year round only in the upper spawning reach and the upper portion of the middle spawning reach. The lower portion of the middle reach and the lower reach did not contain preferred temperatures from mid-May through mid-October, affecting the late fall, winter, and spring runs of fish.

Preferred temperatures of fingerlings also existed year round only in the upper reach and upper portion of the middle reach, though temperatures in all three reaches were within those tolerated by chinook fingerlings. Water temperatures recommended for successful seaward migration were not available in any reach at certain times of the year. Temperatures exceeded the limit in both the entire lower and middle reaches from mid-April to mid-November and in the upper reach during October. From May to late September or early October, temperatures in the lower Sacramento River would be expected to be even warmer than those in the upper reaches. At least some portion of every race of chinook salmon in the Sacramento River may be affected by water temperatures that exceed recommended limits for successful emigration.

During severe drought conditions, water temperatures may not be suitable in any reach for the various life stages. In 1977, the second year of a two-year drought, water temperatures exceeded the requirements for every stage of the chinook salmon in the entire river from July to mid-October. Temperatures did not cool to preferred levels for eggs, fry, and fingerlings until early November.

Recommendations

Water temperatures obviously to a large degree affect survival of chinook salmon in the Sacramento River. Water temperatures may not be suitable for specific life stages at all times in all areas of the river. Relatively little information is available to determine the temperature regime in the Sacramento River, especially during dry years. Also, little information is available to determine the effects of various temperatures on the different life stages of each of the four races of chinook salmon in the Sacramento River. Several intensive studies are recommended so that the effects can be determined of water temperature on chinook salmon in the Sacramento River.

Temperature data must be developed and maintained for the Sacramento River from Shasta Dam to the Delta. Presently, ten temperature recorders maintained by the Department of Water Resources are located between Keswick Dam and Hamilton City. These have been in place since May 1986 and are expected to be maintained through June 1988. However, two years of data do not provide the long-term information needed to assess changes in river temperatures through dry, wet, and normal water years or changing operations of Shasta Dam or other water facilities. Temperature data are needed below Shasta Dam to assess warming rates to Keswick Dam and the effects on temperatures from diversions from the Spring Creek Debris Dam and the Trinity River. The U. S. Geological Survey maintains thermograph records near Grimes and Freeport on the Sacramento River, which should provide adequate data for the lower part of the river. Provisions should be made to provide for long-term maintenance of the ten temperature recorders between Hamilton City and Keswick Dam, with additional recorders placed immediately below Shasta Dam, in Keswick Reservoir above Spring Creek, and at the mouth of Spring Creek.

Temperature requirements for eggs, fry, and fingerlings from the Sacramento River have been investigated. However, the race of fish investigated is unknown, and differences in temperature requirements may exist. Temperature requirements for each stage of each race of chinook salmon in the Sacramento River should be determined.

Determinations of preferred and tolerated temperatures have used diurnally constant water temperatures. Natural temperatures in the Sacramento River fluctuate on a diurnal cycle. Effects of diurnal fluctuations on preferred and tolerated temperatures should be investigated.

A trend has developed for increasing numbers of chinook salmon to spawn in lower reaches of the Sacramento River. Temperature conditions may not be suitable for all life stages of the salmon during the entire year in these areas of the river. The proportions of each race spawning in various reaches of the river should continue to be investigated.

Data developed for chinook salmon from different areas of the West Coast tend to show that eggs can develop normally when initially exposed to temperatures approaching 60°F that subsequently decline to the mid-forty to mid-fifty degree range. No information is available to determine the effects on egg and subsequent fry development when exposed to increasing water temperatures. Eggs of winter-run fish, and possibly those of the late fall run, are exposed to rising temperatures during incubation and fry development in the Sacramento River. The effects from rising water temperatures in the Sacramento River on eggs and fry of the late fall- and winter-run fish should be investigated.

Seaward migratory behavior of steelhead trout and coho salmon has been found to be inhibited in juvenile fish at temperatures greater than 54°F. Temperatures inhibiting the migratory response of chinook salmon juveniles have not been determined. Temperatures in the Sacramento River may often exceed those found to inhibit migratory response of some salmonids. The effects of water temperature on migratory response of chinook salmon juveniles in the Sacramento River should be determined.

Literature Review

Water temperatures in the Sacramento River have been modified by various water storage and transfer facilities. Chinook salmon, which had developed different races in response to the natural temperature regime, have undergone serious population declines since construction of the water projects.

Upper Sacramento River Temperature Regime

Since the beginning of impoundment of the Sacramento River in December 1943, maximum daily water temperatures for some distance downstream from Shasta Dam (Figure 1) have become cooler than normal in the summer and somewhat warmer than normal in late fall or early winter. Comparison of the limited data collected from the Anderson-Cottonwood Irrigation District dam in 1939 to that collected at Balls Ferry in 1946 (Table 1) shows that, following impoundment, average daily maximum river temperatures became cooler by 8.9°F in May, 13.0°F in June, 16.1°F in July, 14.5°F in August, 7.1°F in September, and 1.6°F in October, but warmer by 3.1°F in November. Comparison of data from Balls Ferry collected in 1941 to that collected in 1946 (Moffett 1949) shows temperatures to have become cooler by 15.8°F in August, 5.9°F in September, and 0.2°F in October. Data collected from Balls Ferry in 1986 (DWR, unpublished data) show that river temperatures were slightly warmer than those found in 1946, with corresponding lesser reductions in summer temperatures and greater increases in fall temperatures. Water temperatures at Balls Ferry were warmer in 1986 than in 1946 by 3.4°F in May, 2.3°F in June, 2.2°F in July, 1.9°F in August, 0.4°F in September, 0.6°F in October, and 1.1°F in November. Data are insufficient to determine whether the warmer water temperatures are due to increased utilization of Shasta Reservoir or to annual thermal variation.

Data for the Sacramento River, although deficient, show that recent water temperatures in early October during normal hydrologic years have ranged up to 55°F downstream from Keswick Dam, 58°F at Balls Ferry, 59°F below the Red Bluff Diversion Dam, and 61°F at Hamilton City (Figure 2). During 1976, the first year of a two-year drought, water temperatures in early October ranged up

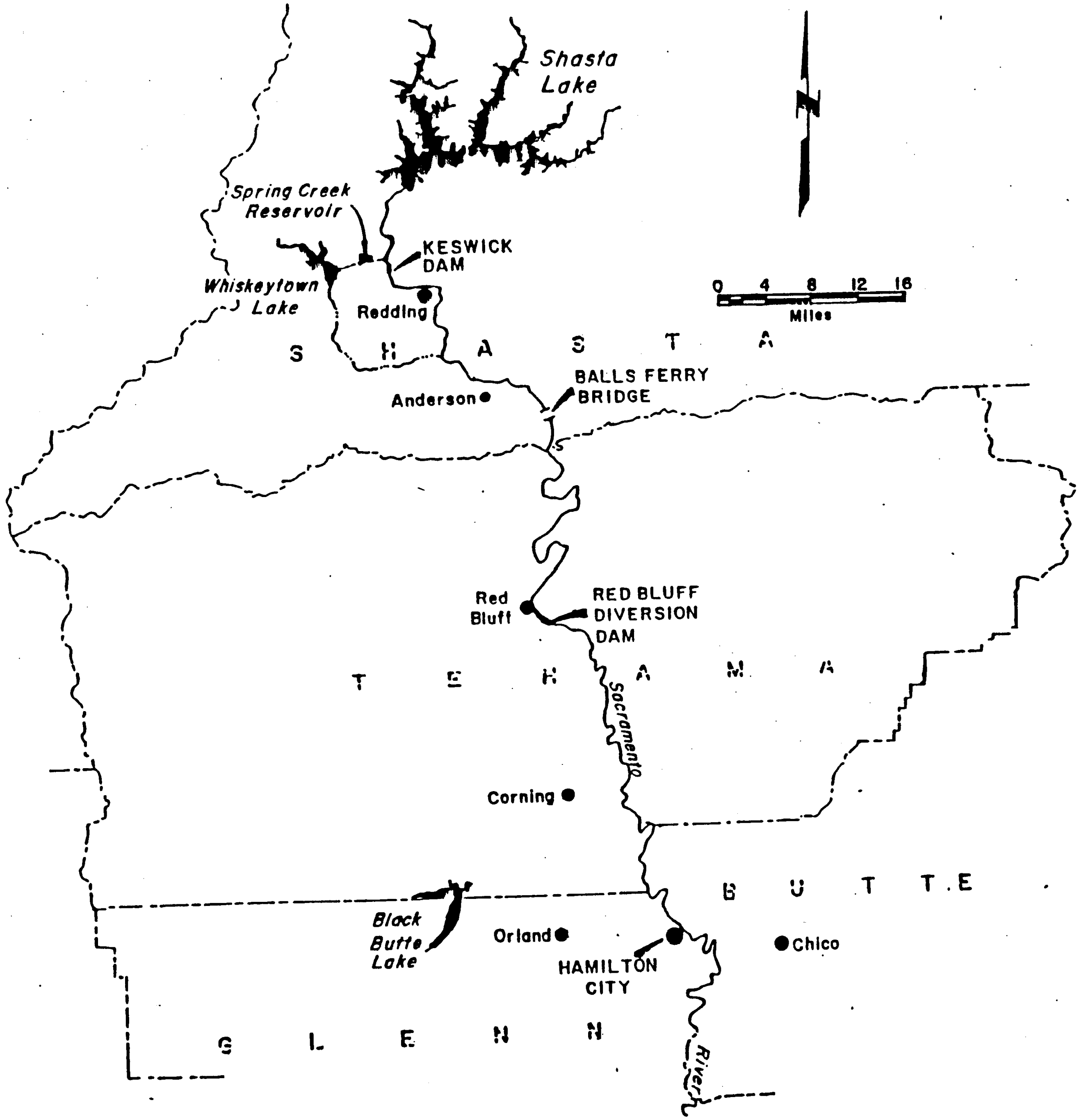

Figure I. Location of the Sacramento River in Northern California.

Table 1. Maximum daily water temperatures in the Sacramento River at the Anderson-Cottonwood Irrigation District (ACID) Dam and Balls Ferry (modified from Moffett 1949; 1986 data from DWR thermographs).

Day	MAY ACID Dam 1939	MAY Balls Ferry 1946	MAY Balls Ferry 1986	JUNE ACID Dam 1939	JUNE Balls Ferry 1946	JUNE Balls Ferry 1986	JULY ACID Dam 1939	JULY Balls Ferry 1946	JULY Balls Ferry 1986
1	59	-	52	66	55	59	70	55	56
2	60	-	51	66	55	58	69	55	57
3	60	-	51	66	55	58	69	55	58
4	60	-	52	65	54	57	68	55	57
5	61	-	52	63	53	57	68	55	57
6	61	-	52	64	-	57	69	55	57
7	62	-	53	65	54	57	70	55	56
8	63	-	54	66	53	57	70	55	57
9	64	-	54	67	53	57	70	54	57
10	64	-	54	68	53	57	72	55	57
11	63	-	54	69	54	56	72	55	58
12	64	-	56	70	54	56	72	55	57
13	63	-	54	70	54	56	72	55	58
14	64	-	53	69	-	56	72	55	58
15	64	-	55	66	54	56	70	53	57
16	64	-	56	62	54	56	71	54	57
17	64	54	57	62	54	56	71	55	56
18	63	53	57	62	54	55	71	55	56
19	62	54	57	64	54	55	70	55	56
20	60	53	57	66	55	55	70	55	57
21	57	53	56	68	55	55	71	55	57
22	56	53	56	69	55	56	71	55	57
23	56	54	56	68	52	56	72	55	56
24	60	54	57	68	53	56	72	55	57
25	62	55	58	69	54	56	72	54	57
26	65	55	58	70	54	54	72	-	57
27	66	55	58	70	54	55	72	-	57
28	66	54	58	70	54	56	72	-	57
29	69	51	58	70	53	56	73	-	57
30	70	52	58	70	54	56	73	-	57
31	66	-	58	-	-	-	73	-	58
Ave	62.5	53.6	57.0	66.9	53.9	56.2	70.9	54.8	57.0

Day	AUGUST ACID Dam 1939	AUGUST Balls Ferry 1941	AUGUST Balls Ferry 1946	AUGUST Balls Ferry 1986	SEPTEMBER ACID Dam 1939	SEPTEMBER Balls Ferry 1941	SEPTEMBER Balls Ferry 1946	SEPTEMBER Balls Ferry 1986
1	73	72	-	58	65	64	56	57
2	73	73	-	58	65	65	55	58
3	72	72	-	58	65	66	55	57
4	72	72	55	58	66	67	55	58
5	71	73	55	58	64	-	55	58
6	71	72	54	58	65	-	56	58
7	71	72	55	58	64	-	56	59
8	71	72	55	57	64	-	56	58
9	71	72	55	57	63	-	56	58
10	71	71	55	57	63	-	56	58
11	70	71	55	57	64	-	56	58
12	70	69	55	57	64	65	56	56
13	70	72	55	57	62	64	56	57
14	70	72	55	57	62	64	56	56
15	70	74	55	56	62	64	56	54
16	70	73	-	57	62	64	56	54
17	70	72	54	57	62	64	56	56
18	70	72	55	57	62	60	56	55
19	70	72	54	57	64	60	57	57
20	69	72	55	56	64	59	-	57
21	69	72	55	56	65	59	57	57
22	69	71	55	56	66	59	58	58
23	68	70	54	56	65	60	58	57
24	69	70	55	56	65	60	57	56
25	69	70	56	56	63	61	57	54
26	68	70	56	55	62	62	58	56
27	66	68	56	57	61	62	58	56
28	66	67	56	57	62	62	59	57
29	66	66	55	57	62	62	57	57
30	64	65	55	57	63	61	57	57
31	65	65	55	57	-	-	-	-
Ave	69.5	70.8	55.0	56.9	63.5	62.3	56.4	56.8

Day	OCTOBER ACID Dam 1939	OCTOBER Balls Ferry 1941	OCTOBER Balls Ferry 1946	OCTOBER Balls Ferry 1986	NOVEMBER ACID Dam 1939	NOVEMBER Balls Ferry 1946	NOVEMBER Balls Ferry 1986
1	62	60	57	56	55	55	56
2	60	61	57	57	54	53	56
3	59	61	55	57	54	54	56
4	58	59	56	58	54	55	56
5	58	58	-	57	52	54	56
6	57	58	-	57	52	54	55
7	58	56	-	57	52	54	54
8	57	56	-	57	51	54	54
9	58	56	-	57	51	54	55
10	59	56	-	56	51	54	55
11	59	55	-	56	50	53	55
12	59	54	-	56	50	-	55
13	59	55	-	56	50	54	55
14	58	55	-	56	50	55	54
15	58	55	-	56	49	54	55
16	57	56	-	55	48	54	55
17	56	57	-	56	48	54	55
18	56	56	-	56	-	54	55
19	56	55	-	56	-	54	55
20	56	56	-	56	49	51	54
21	-	55	56	56	48	52	54
22	58	54	55	56	49	53	54
23	57	51	57	54	-	52	54
24	55	50	57	55	49	51	53
25	53	48	57	56	46	-	52
26	51	-	55	56	-	-	-
27	54	-	54	57	-	-	-
28	56	-	54	55	-	-	-
29	56	-	54	55	-	-	-
30	56	-	54	56	-	-	-
31	56	-	55	55	-	-	-
Ave	57.1	55.7	55.5	56.1	50.5	53.6	54.7

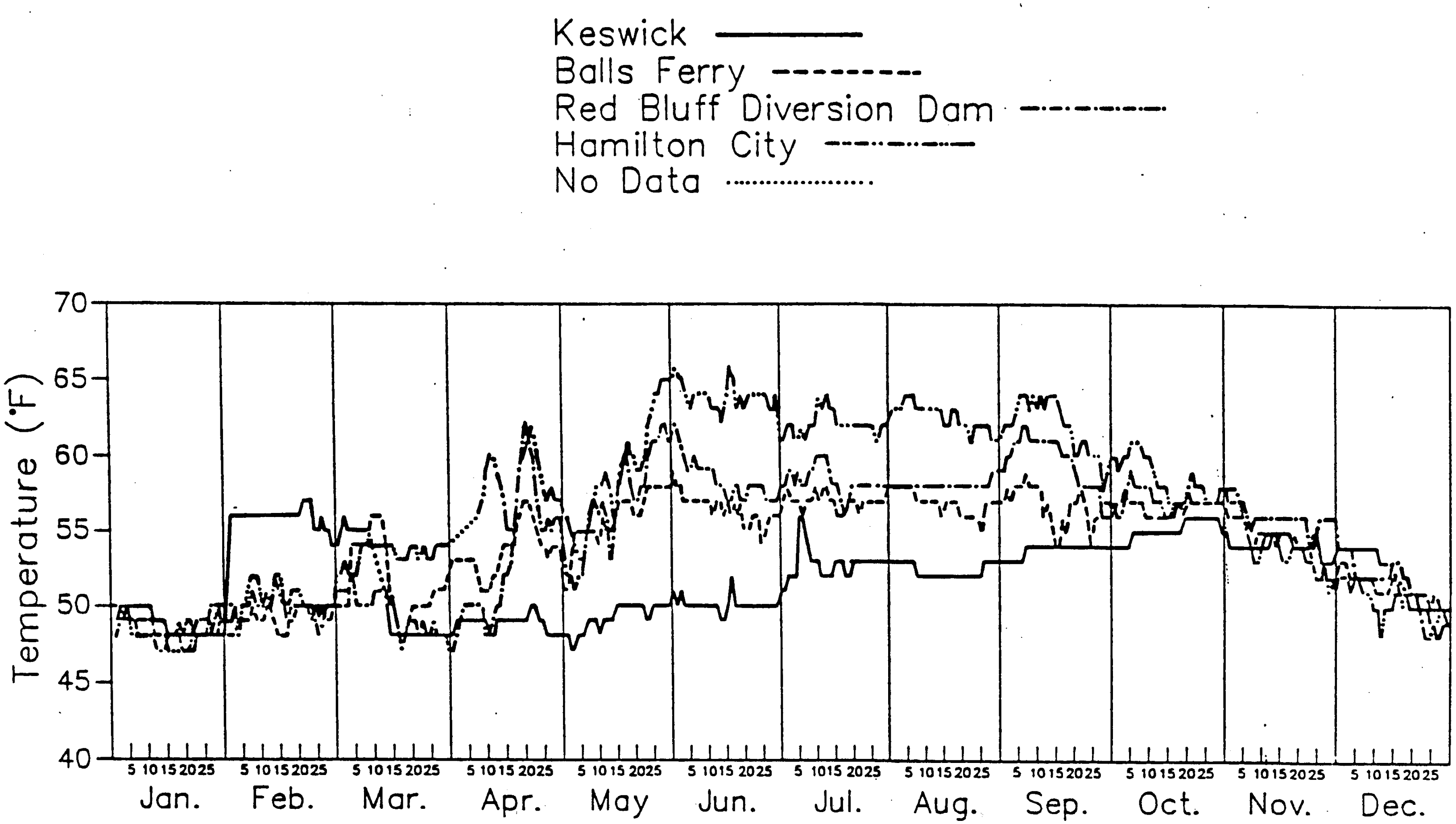

Figure 2. Annual variation in maximum water temperatures at four locations on the Sacramento River (data from 1983 and 1986 D.W.R. thermograph records).

to 59°F below Keswick Dam, 62°F at Balls Ferry, and 64°F below the diversion dam (DFG and USFWS, unpublished data). During early October 1977, water temperatures ranged from 64°F to 66°F between Keswick Dam and the Red Bluff Diversion Dam. Water temperatures during normal hydrologic years may remain elevated into early November, but decline to the mid to low fifty degree range by the middle of the month. Temperatures become fairly uniform throughout the river by December, fluctuating between the upper forty to low fifty degree range through March. Increases begin to occur in April, reaching temperatures by June as high as 51°F below Keswick Dam, 59°F at Balls Ferry, 62°F below the diversion dam, and 66°F at Hamilton City. Higher releases from Shasta Dam beginning in late spring maintain cool water temperatures during the summer. Temperatures gradually increase, however, in the upper river by late summer as warmer water is released from Shasta Dam. These higher temperatures are caused by deepening of the thermocline and drawdown of the reservoir level.

The warmer late fall and winter water temperatures present following completion of Shasta Dam were thought to be beneficial in accelerating the development of eggs in the gravels, advancing the time of seaward migration of smolts and increasing the production of macroinvertebrates utilized as food by the fish (Moffett 1949). However, more recent studies have shown that warmer water temperatures may also have detrimental effects on egg development, smoltification, benthic productivity, and other facets related to survival of chinook salmon.

Sacramento River Chinook Salmon

Four distinct runs of chinook salmon are recognized in the Sacramento River (Burns 1978), with considerable overlap in migration and spawning (Figure 3). The early fall run is the largest and begins migrating through the Delta to the Sacramento River as early as mid-July. The peak migration past the Red Bluff Diversion Dam occurs in late September (Haley et al. 1972). Spawning begins in October and continues into early January. The eggs hatch from early January to April, with downstream migration of juvenile salmon occurring immediately following hatching (F. Fisher, California Department of Fish and Game, pers. comm.). The late fall run is the second largest. The run begins the upstream migration in mid-October, with peak numbers of fish passing the Red Bluff Diversion Dam in January. Spawning occurs from late January to early April. Eggs hatch from late March to June, with emigration of fry

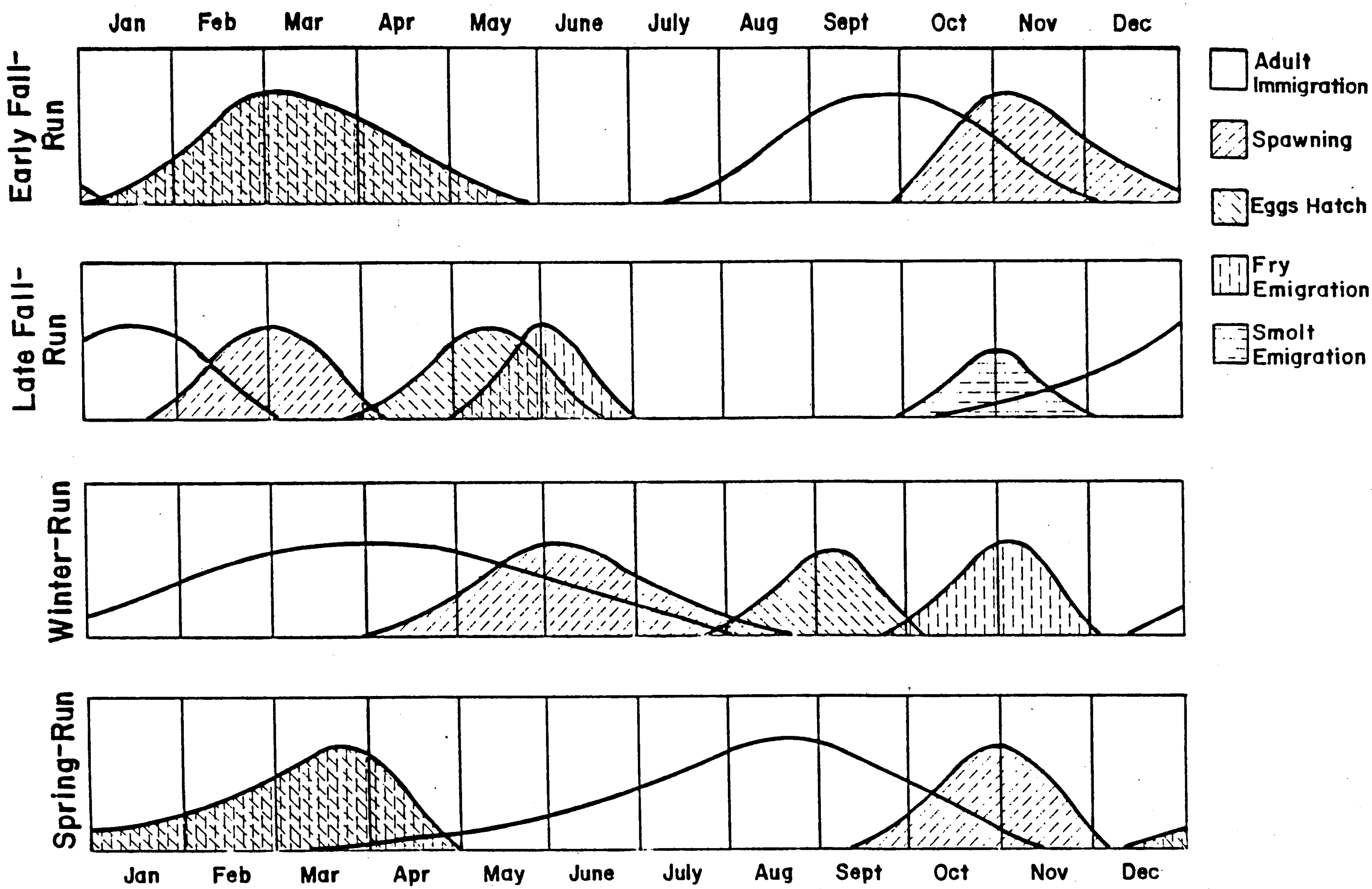

Figure 3. Timing of life stages of the four runs of chinook salmon in the Sacramento River (from Haley et al. 1972, Moyle 1976, Burns 1978, and F. Fisher, pers. comm.).

peaking in May and June (Moyle 1976). Some fry remain in the river through the summer to emigrate as smolts in October and November (F. Fisher, pers. comm.). The winter run had been the second largest in abundance but in recent years has experienced significant declines. This run, which now ranks third in abundance, migrates upstream from December through July. Spawning occurs from April to mid-August. Eggs hatch from late July through September, with downstream migration of juveniles occurring from September to December (Slater 1963). Spring-run fish are the least abundant. Upstream migration occurs from March through November, with migrants remaining in the river over summer to spawn in the fall from September through November (F. Fisher, pers. comm.). Eggs hatch and juveniles emigrate from December through April.

Construction of Shasta and Keswick Dams has blocked since 1942 approximately 50 percent of the spawning and nursery habitat previously available to chinook salmon in the Sacramento River (Moffett 1949). Efficient use by spawning salmon of gravels downstream of the damsite was not possible prior to the construction of Shasta Dam, except by late fall-run fish, because of low streamflow and high water temperature. Temperature conditions were dramatically improved in the river downstream from Shasta Dam following its completion, allowing successful holding and spawning by fall-, winter-, and spring-run chinook salmon primarily between Balls Ferry and Keswick Dam.

Additional water diversion facilities were constructed during the 1960s (Burns 1978). Diversion into Keswick Reservoir from the Trinity River was begun in 1963. The Spring Creek Debris Dam, which regulates the discharge of toxic mine wastes into Keswick Reservoir, also became operational in 1963. The Red Bluff Diversion Dam became operational in 1966. In addition, numerous bank-protection projects involving riprap have been and continue to be conducted. The cumulative effect of these projects is believed to have altered chinook salmon runs in the upper river through streamflow manipulation, loss of spawning gravels, heavy metal pollution, inadequate fish passage at the Red Bluff Diversion Dam, and altered water temperatures (Burns 1978).

The primary spawning areas of chinook salmon in the Sacramento River have shifted downstream since completion of water diversion facilities in the 1960s. Prior to construction of the Red Bluff Diversion Dam in 1966, nearly 76 percent of spawning activity occurred upstream of Balls Ferry, 19 percent occurred between Balls Ferry and Red Bluff, and only 5 percent occurred between Red Bluff and Hamilton City (Burns 1978). Since 1966, spawning activity has exhibited a gradual decline in the river above Balls Ferry, but has increased in the lower two reaches. From 1971 to 1976, spawning activity above Balls Ferry amounted to less than 38 percent of the total, while from Red Bluff to Balls Ferry and below Red Bluff, spawning activity increased to 28 percent and 33 percent, respectively. Data compiled in more recent years show that over half the spawning activity of chinook salmon occurs downstream from Red Bluff (F. Fisher, pers. comm.).

Temperature Tolerance

Recognition occurred as early as 1936 that the various life stages of Pacific Coast salmonid species had different temperature tolerances (Davidson and Hutchinson 1938). While adult Pacific salmon of an unspecified species were observed to migrate through estuaries and streams with temperatures as high as 80.6°F, eggs of salmon in Washington were found to experience excessive mortalities when incubated at temperatures lying outside the range of 39°F to 52°F (Donaldson, unpublished, cited in Davidson and Hutchinson 1938). Optimum temperatures for fry of the species of salmon studied shifted to a range between 55°F to 62.6°F. Temperatures above or below this range resulted in retarded growth and excessive mortality, which increased with variance from the optimum range.

Brett (1952) found that the temperature tolerance range of juvenile Pacific salmon differed with the species and acclimation temperature. Increasing acclimation temperatures resulted in increasing upper lethal temperatures until the ultimate upper lethal temperature was reached, at which point acclimation to higher temperatures had no effect on increasing the upper temperature resistance. Increasing acclimation temperatures also increased the lower temperature threshold that the young fish could tolerate. For juvenile chinook salmon in Canada aged three to six months, the ultimate upper lethal temperature was 77°F (Figure 4). The lower lethal temperature ranged from near 32°F for fish acclimated to very low temperatures to 45°F for fish acclimated to a temperature of 73.4°F. For acclimation temperatures ranging from 50°F to 73.4°F, fish selected preferred temperatures within the narrow range from 53.6°F to 57.2°F.

Studies conducted by Johnson and Brice (1953) in Oregon showed that chinook salmon eggs were even less tolerant of high temperatures than were juveniles. Eggs incubated at water temperatures over 60°F suffered high

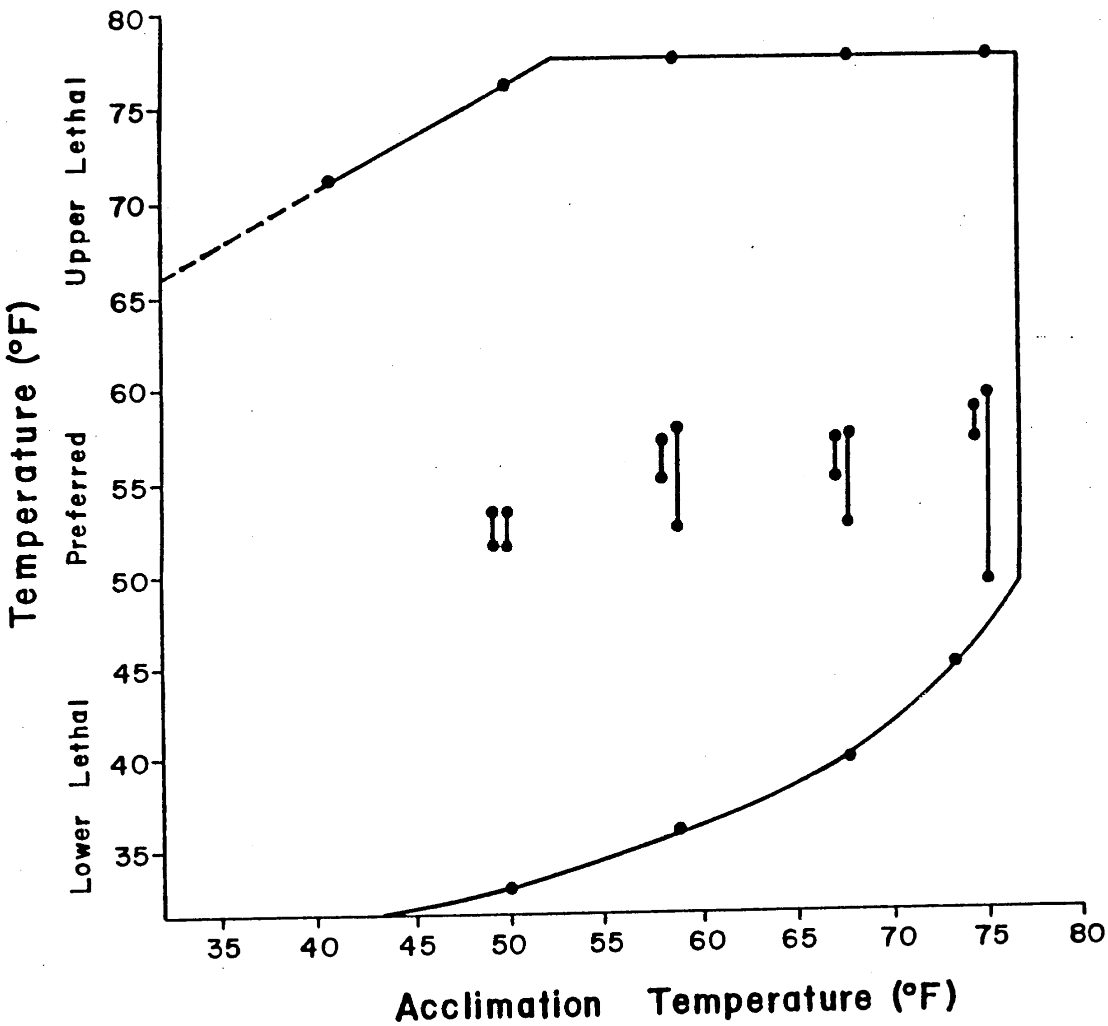

Figure 4. Temperature tolerance of juvenile chinook salmon (modified from Brett 1952).

mortalities, with complete mortality occurring at temperatures above 65°F. Mortalities continued to be greater for sac-fry and fingerling stages of fish that were hatched from eggs incubated at high temperatures, even though rearing temperatures were cooler. Coagulated yolk disease, in which a portion of the yolk coagulates and cannot be absorbed by the fry, was responsible for much of the mortality. Egg, fry, and fingerling stages progressed normally with little mortality for lots held in water where the daily mean temperatures were less than 54°F.

Seymour (1956) also found complete mortality of chinook eggs from the Sacramento River when incubated at constant water temperatures of 65°F or higher, as well as at 34°F (Figure 5). High egg mortality and complete sac-fry mortality occurred at constant incubation and rearing temperatures of 60°F and 62.5°F. Although exhibiting low egg mortality at constant temperatures of 55°F and 57.5°F, sac-fry mortality exceeded 50 percent. Between constant temperatures of 40°F and 55°F, low mortality rates were found for all developmental stages. Mortality rates of the egg stage were drastically reduced when incubated under declining temperature conditions. Mortality, however, was still excessive, ranging up to 40 percent, for eggs incubated at an initial temperature of 65°F and a final temperature of 60°F. Egg mortality was low for all lots incubated at initial temperatures of 45°F to 60°F. Tolerance of eggs to otherwise low lethal temperatures increased with length of incubation at temperatures ranging from 48°F to 55°F (Figure 6). Experiments were discontinued upon hatching of the eggs so that the effects of declining temperatures on sac-fry were not determined. Cause of death of sac-fry and fingerlings at higher temperatures was hypothesized to occur as a result of aberrations in sequential physiological development. High sac-fry mortalities occur because the physiological processes required for survival are unable to develop at the high incubation temperatures. The most prevalent abnormalities in fry from egg incubation temperatures of 60°F or greater were developmental deficiencies, weak body structure, serous fluid, spinal curvature, and shortened body. Growth rates were greatest for fish reared at 55°F and declined at higher and lower temperatures (Figure 7).

Mortality to the eyed stage was found to be higher in groups of eggs taken from fish when water temperatures in the American River were high (Hinze, Culver, and Rice 1956). As river temperatures declined through the fall from the mid-sixty to low fifty degree range, successively greater survival of eggs

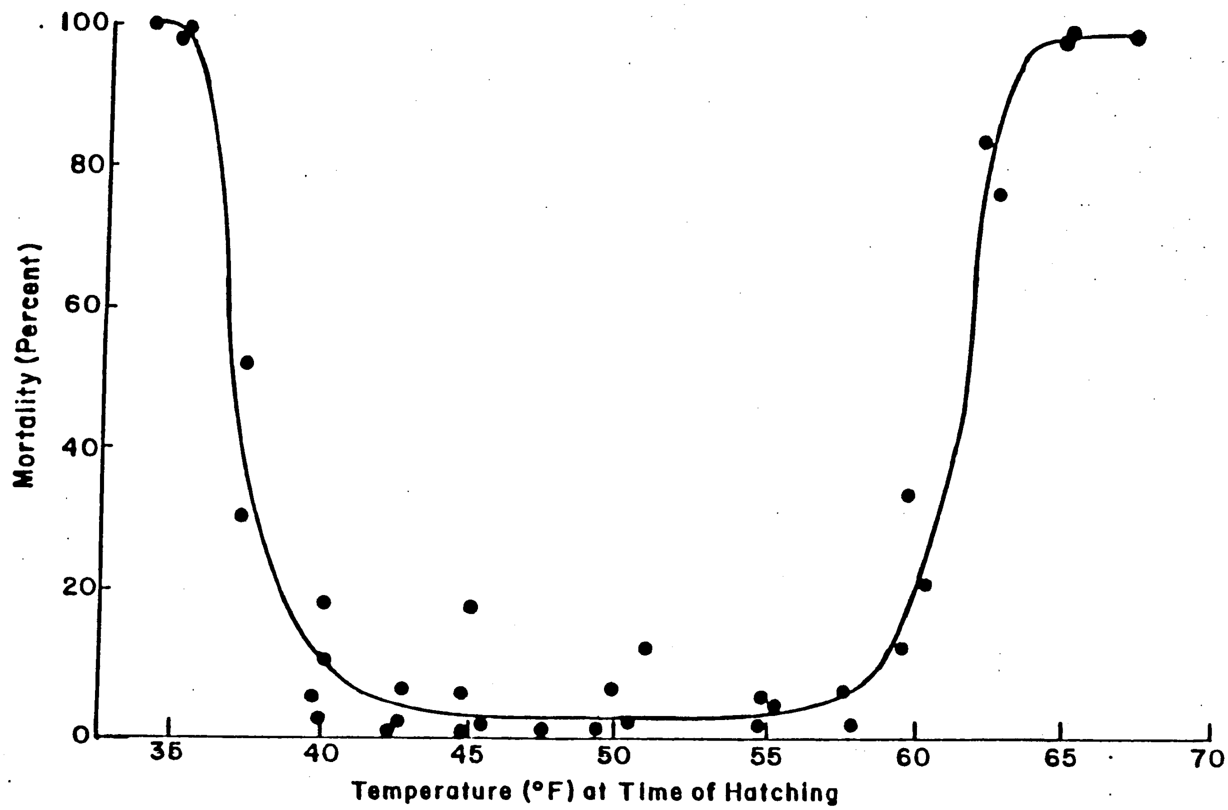

Figure 5. Effects of incubation temperature on mortality of chinook salmon (Oncorhynchus tshawytscha) eggs (from Seymour 1956).

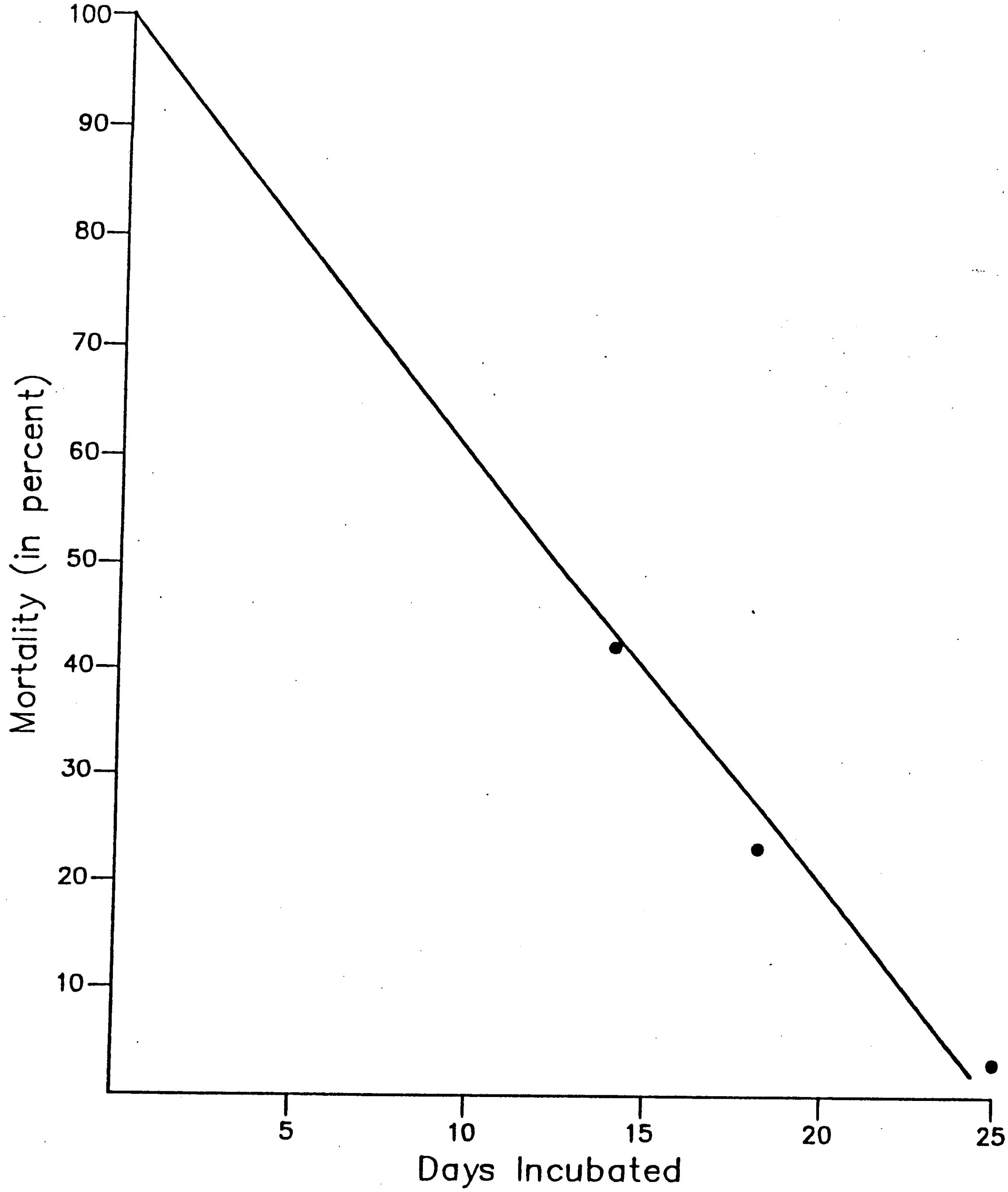

Figure 6. Susceptibility of chinook eggs to exposure of 34 °F water after various days of incubation at temperatures ranging from 48 °F to 55 °F (data from Seymour 1956).

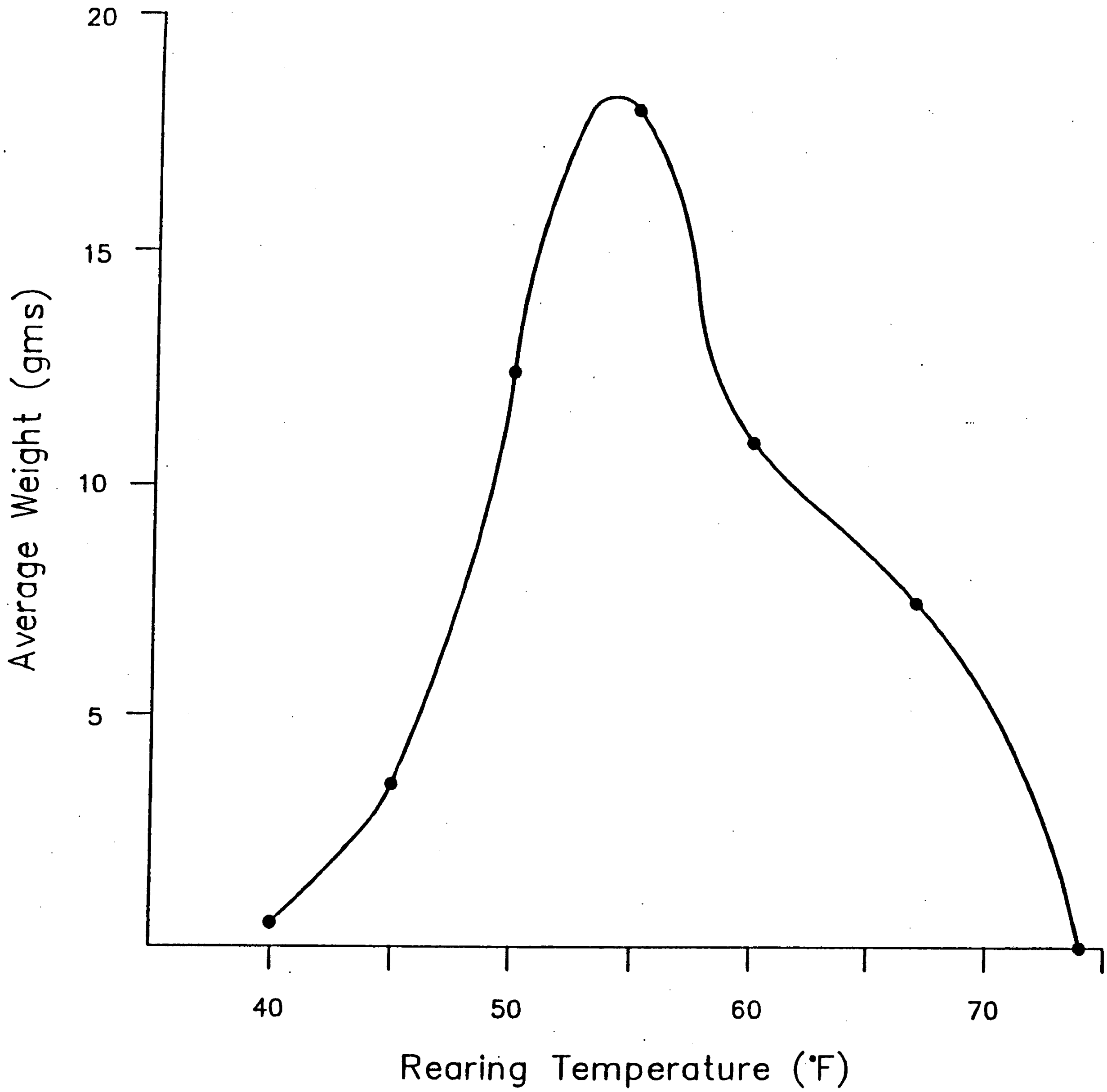

Figure 7. Relationship between rearing temperature and growth for 46 weeks (data from Seymour 1956).

occurred. Greatest survival occurred in eggs taken from fish when water temperature was in the 53°F to 54°F range (Figure 8). Greater mortality of sac-fry, due to coagulated yolk, was found in groups of fish hatched from eggs initially incubated at warm temperatures. Conclusions were that water temperatures greater than 60°F decrease egg survival and contribute to coagulated yolk in sac-fry. Exposure of adult fish to high temperatures was hypothesized to affect the unspawned eggs.

An upper temperature threshold between 57.5°F and 60°F was established for chinook salmon eggs in Washington incubated at constant water temperatures (Combs and Burrows 1957). The lower temperature threshold at which excessive mortalities occurred was determined to lie between 40°F and 42.5°F. Causes of death at either high or low temperature extremes were theorized to be lack of coordination between growth and organic differentiation within the embryo or dislocations in the order of differentiation brought about by the unfavorable temperatures.

Indications of early embryonic damage becoming manifested at later stages of development were found by Olson and Foster (1957). Chinook salmon eggs from the Columbia River were incubated at initial temperatures of 52.9°F, 56.9°F, 59.0°F, 60.9°F, and 65.2°F. Incubation temperatures subsequently followed normal seasonal patterns (Figure 9). Mortalities were similar between groups whose eggs were initially incubated at temperatures ranging from 52.9°F to 60.9°F. Mortalities at each stage ranged from 6.4 to 8.7 percent for eggs, 1.1 to 2.0 percent for fry, and 0.0 to 7.0 percent for fingerlings. Total mortality ranged from 7.8 to 16.1 percent. Mortality of each stage for the initial incubation temperature of 65.2°F was 10.8 percent for eggs, 45.9 percent for fry, and 56.4 percent for fingerlings. Total mortality was 79.0 percent. The greatest mortality occurred during the latter part of the fry stage and just after feeding had begun in the fingerling stage. Water temperatures during the fry and fingerling stages ranged from 43°F to 54°F and, therefore, should not have been unfavorable. Abnormal development during early incubation of eggs at unfavorably high temperatures is implicated in contributing to mortality in later stages of development.

Additional evidence of adverse effects on viability of chinook salmon eggs from exposure of mature female fish to warm water temperatures in the American River was provided by Hinze (1959). Eggs taken from mature fish subjected to prolonged exposure to water temperatures between 60°F and 62°F,

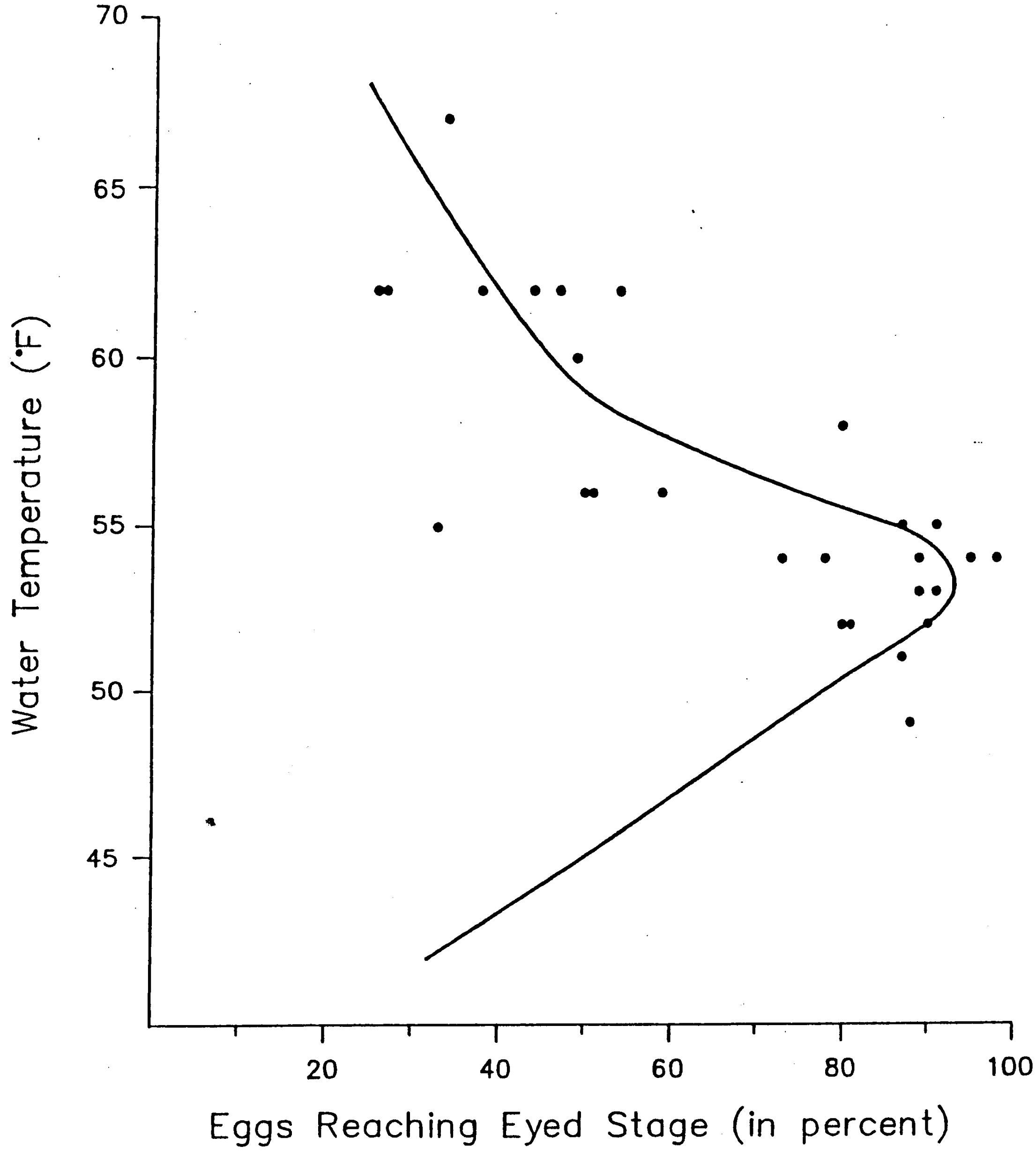

Figure 8. Relationship between temperature at which adult fish are taken and survival of eggs to eyed stage.

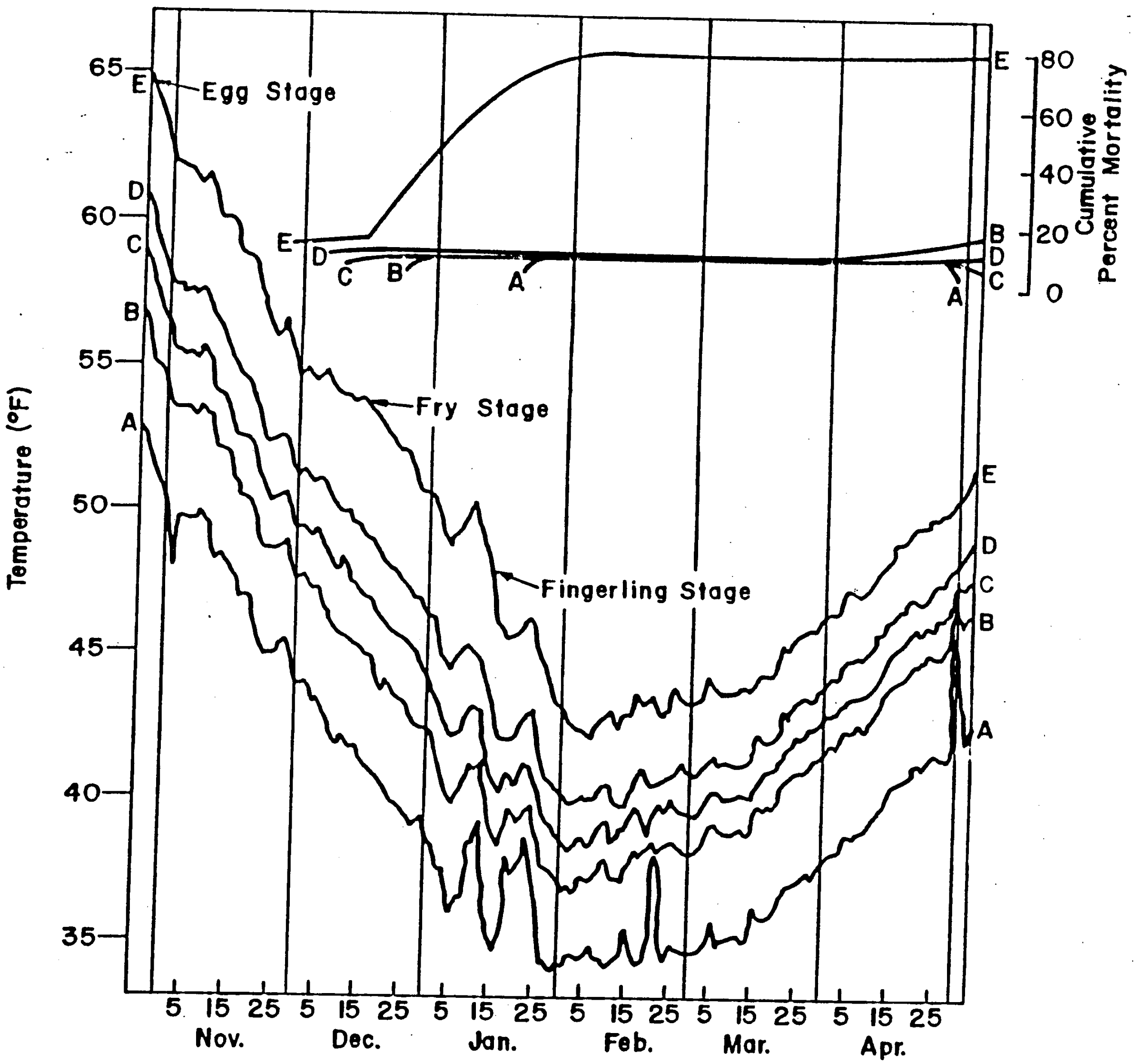

Figure 9. Daily average temperatures and resulting cumulative mortalities plotted at semimonthly intervals after hatching (from Olson and Foster 1957).

but incubated at 55°F to 56°F, had 70 percent survival to the eyed stage, while eggs taken and incubated at 55°F to 59°F water temperatures yielded 80 percent survival. No eggs survived to the eyed stage that were taken and incubated in water warmer than 62°F or colder than 38°F, while only 50 percent survived when taken and incubated in water between 60°F and 62°F. Survival of adult fish was also poor when held in water warmer than 59°F or colder than 38°F. Little difference in heat tolerance of eggs was found between American River and Klamath River stocks.

Water temperatures of 35°F could be tolerated by chinook salmon eggs once the 128-cell stage of development had been reached while reared in warmer water (Combs 1965). Survival was similar between groups of eggs incubated at a constant temperature of 42.5°F and those incubated for six days to the 128-cell stage in 42.5°F water and then subjected to 35°F water for the remainder of the incubation period. Mortalities were significantly greater for eggs not reaching the 128-cell stage before subjection to the colder water, and increased inversely with stage of development.

High hatching success of chinook eggs from the Mokelumne River, taken at the upper limit of thermal tolerance found in eggs from more northern latitudes, led to the early conclusion that a strain of fish had developed which could tolerate higher water temperatures (Groh and Menchen 1970, Jewett and Menchen 1970). Eggs taken from fish during 1965 and 1966 and initially incubated at water temperatures as high as 61°F produced survival rates through the early fry stage ranging from 69.4 to 88.3 percent. Eggs taken from fish during 1967 and initially incubated at water temperatures of 61°F to 62°F also had high survival rates to hatching, ranging from 67.5 to 90.6 percent (Jewett 1970). However, significant mortality occurred during the late fry stage, decreasing survival rates to 28.6 to 32.3 percent. As with fish from more northern latitudes, apparently some abnormal physiological development prevents successful transition from the yolk-absorption stage of the fry to the feeding stage of the fingerling in many of the fish initially incubated at high water temperatures.

Juvenile salmon migrating from the upper reaches of natal streams to the ocean may be exposed to river reaches containing significantly higher temperatures. Orsi (1971) investigated the effects on chinook fingerlings from the Sacramento River to temperature increases at various acclimation temperatures. Higher acclimation temperatures produced higher tolerated temperatures until an upper lethal level was reached, at which point higher acclimation temperatures were ineffective in increasing the tolerated temperatures. The lethal level at which half the fish died when exposed for 48 hours was found to be 70°F for fish acclimated to 60°F and rose only to 76.8°F for fish acclimated to 70°F. All fish exposed to 80°F died within eight hours. The upper lethal temperature at which half the subjected fish died was determined by interpolation of data to be 78.5°F. However, juvenile salmonids may tolerate higher temperatures for brief periods. Fingerlings acclimated to 73°F suffered 100 percent mortality when exposed to 87°F water for six minutes, but only 30 percent mortality when exposed for two minutes. Fish acclimated to 70°F suffered 100 percent mortality when exposed to 88°F water for four to six minutes, but only 10 percent mortality at 84°F. Mortality of fish acclimated to 65°F and exposed to 83°F water for four to six minutes was 50 percent. Delayed mortality at acclimation temperatures following brief exposure to higher temperatures may have occurred, but was difficult to assess because of handling injuries or fungal infections, though the latter are more likely to occur at higher temperatures. Brief exposure to high temperatures can produce loss of equilibrium, which under natural conditions can result in mortality from predators that are attracted to the more vulnerable fish.

The effects of water temperature on chinook salmon eggs and fry in the upper Sacramento River were investigated by Healey (1979). Eggs and fry maintained between 60°F and 63°F suffered from 80 to 88 percent mortality. Mortality was nearly equally divided between egg and fry stages for all three groups of eggs spawned on September 24, October 22, and November 9, 1976. The high mortality was primarily due to coagulated yolks. Mortalities to the fingerling stage ranged from 13 to 31 percent for two other groups of eggs spawned on September 24 that were exposed to declining temperatures ranging from an initial temperature of 60°F to final temperatures of 45°F and 50°F. Mortalities to the fingerling stage for groups of eggs spawned on October 22 and November 9 ranged from 3 to 10 percent for initial incubation temperatures between 53°F and 57.5°F. Mortalities in the egg stage were highest in the groups spawned on September 24 and lowest in the groups spawned on November 9. River temperatures prevailing while adult salmon were maturing were felt to have affected the quality of eggs later produced. River temperatures during September were higher than 60°F.

Salmon Migration

Both immigration of adult and emigration of juvenile chinook salmon may be affected by water temperatures. Migratory response to water temperatures also may vary with the different races of chinook salmon. Water temperatures as high as 76°F in the lower Klamath River apparently have not affected the upstream migration of adult salmon (Dunham 1968), but temperatures above 70°F in the San Joaquin River prevented salmon from migrating upstream from the Delta (Hallock et al. 1970). Salmon resumed their upstream migrations when temperatures declined to 65°F.

Seaward migration of young salmonids is preceded by the biochemical and physiological transformation of non-migrating parr into migratory smolts (Hoar 1976). Smolts are characterized externally by silvery color and streamlined body form. Internally, changes occur in guanine deposition, lipid composition, ionic constituents, and gill (Na and K) adenosinetriphosphatase (ATPase) activity (Ewing et al. 1979). Increases in gill (Na and K) ATPase activity have been associated with seawater tolerance in steelhead trout (*Salmo gairdneri gairdneri*) and coho salmon (*Oncorhynchus kisutch*) (Zaugg and McLain 1970 and 1972, Zaugg et al. 1972, Adams et al. 1973 and 1975, Zaugg and Wagner 1973). Increasing levels of gill (Na and K) ATPase activity in the spring have been associated with increasing photoperiod rather than increasing water temperatures. However, cooler water temperatures have been found to delay the onset of increased gill (Na and K) ATPase activity, while warmer temperatures have been found to decrease the period of activity. Water temperatures in excess of 55°F inhibit formation and decrease activity of gill (Na and K) ATPase in steelhead trout, with concomitant reduced migratory behavior and seawater survival (Zaugg and Wagner 1973, Adams et al. 1975). Gill (Na and K) ATPase activity in coho salmon was inhibited at 59°F (Zaugg and McLain 1976), but effects of lower experimental temperatures were not clear. Fish reared at 54°F experienced greater gill (Na and K) activity than those reared at 46°F during the first year of study, but activity levels were lower at 54°F during the second year (Ewing et al. 1979). Greater activity at 54°F than at 46°F during the first year was thought to be a result of increased growth of fish at the warmer temperatures. The temperature limit that inhibits gill (Na and K) ATPase activity in coho salmon was felt to lie between 54°F and 59°F.

Chinook salmon have also been found to undergo smolt transformation with increased seawater tolerance in association with elevated gill (Na and K) ATPase activity (Zaugg and McLain 1972). Unlike coho salmon, however, which migrate during the spring as yearlings, chinook salmon migrate during various times of the year at different ages. The bulk of chinook salmon in the Sacramento River migrate soon after the fry emerge from the gravels. Emigration of fry occurs for the early fall run from January through May, for the late fall run from May through June, for the winter run from September through November, and for the spring run from December through April (Haley et al. 1972, Moyle 1976, Burns 1978, and F. Fisher, pers. comm.). A small number of juvenile chinook salmon may spend up to a year in the Sacramento River.
In contrast, peak movement of juvenile chinook salmon in the Rogue River in Oregon occurs during October, with smaller migrations in May and the following October (Ewing et al. 1979). Elevated gill (Na and K) ATPase activity has been associated with each peak in migratory behavior. Water temperatures critical for gill (Na and K) ATPase activity in juvenile chinook salmon have not been determined, but water temperatures less than 54°F have been suggested to prevent desmoltification (Wedemeyer et al. 1980).

Meristic Characteristics

Races of fish within the same species have often been determined from slight differences in morphology, particularly in the number of vertebrae. Chinook salmon from four separate drainages, including the Sacramento River drainage, were found to possess a significantly different number of veretebrae (Seymour 1956, 1959). Furthermore, the number of vertebrae increased as egg-incubating temperatures approached the lower or upper extremes of a temperature range of 39°F to 62°F. The number of abnormal vertebrae followed the same pattern, with fewest abnormalities near the center of the temperature range and increasing abnormalities at either extreme. The number of dorsal and anal fin rays followed an opposite pattern, with the greatest number of rays near the center of the temperature range.

Food and Growth

Juvenile salmon feed primarily on drifting organisms (Becker 1973). Aquatic organisms comprising the major portion of the drift usually include chironomids (Chironomidae), mayflies (Ephemeroptera), stoneflies (Plecoptera), and caddisflies (Trichoptera) (Bisson and Davis 1976, Davis 1974). In the Sacramento River, chironomids and baetid mayflies were the dominant species ingested by juvenile salmon (Schaffter et al. 1982). Aphids (Aphididae) were an important food group from a terrestrial source.

Maintenance of adequate food supplies during the instream rearing period is critical to the survival of juvenile salmon, which greatly influences the number of returning adults (Beak Consultants 1976). Water temperatures affect the types, quantities, and availability as food of aquatic organisms. The diversity of organisms generally decreases as temperatures increase. Species tolerant of warmer conditions may increase in density, but these species usually are not ones that predominantly enter the drift and are therefore largely unavailable to juvenile salmonids (Davis 1974). Some species, such as baetid mayflies and some caddisflies, may exhibit increasing drift tendencies with increasing water temperatures (Wojtalik and Waters 1970, Waters 1969) but offer insufficient biomass to compensate for the loss at higher temperatures of other drifting forms. As well as direct adverse effects of elevated temperatures on many species of aquatic organisms, community declines can be attributed to habitat degradation from increased silt deposits associated with increased growths of filamentous algae (Bisson and Davis 1976).

Increasing stream temperatures increase the metabolic rate of fish and, hence, the ration levels required for maintenance and growth (Hughes et al. 1978, Bisson and Davis 1976). However, since increasing stream temperatures often result in decreased availability of food organisms, growth rate and survival of fish may decrease. Production in a model stream averaged 65 percent higher at 53.6°F than at 60.8°F (Bisson and Davis 1976). Production differences were due to reduced growth and survival in the warmer stream.

Commensurate with increased metabolic demand and decreased food availability at higher temperatures is increased competition for food from other fish species adapted to warmer conditions, further compounding the food supply problem and growth and survival of juvenile salmon. When food supplies become limiting, either from the effects of competition or adverse temperatures, salmon fry must leave sheltered areas near banks where they usually forage to enter the less protective deeper waters in search of invertebrate drift. Juvenile salmonids become more susceptible to predation in open waters and during early displacement downstream, with resultant decreased survival (Beak Consultants 1976).

Rearing at warmer water temperatures favors faster developmental times, which lead to earlier hatching and commencement of feeding (Olson and Foster 1957, Heming 1982). However, fry produced in warmer water are smaller than those produced in cooler water at similar stages of development because those subject to warmer water exhibit poorer yolk conversion efficiency (Olson, Nakatani, and Meekin 1970). Warmer temperatures increase maintenance costs, thereby diverting energy reserves of the yolk from growth. The smaller fish produced from earlier hatching and emergence may be weaker, poorer swimmers, more susceptible to predation, and possess decreased foraging abilities.

Preferred temperatures of fish have often been considered optimum for rearing of fish in hatcheries. Although the preferred range of chinook juveniles ranges from 53.6°F to 57.3°F (Brett 1952), eggs incubated at 54°F produced smaller and poorer surviving fry than those incubated at temperatures ranging as low as 43°F (Heming 1982). Preferred temperatures also may not be optimum for growth. Weight gains of chinook fingerlings were consistently greater at a constant rearing temperature of 60°F than at temperatures of 50°F or 55°F (Banks, Fowler, and Elliott 1971). Weight gains of fish reared at 65°F were only slightly greater than those reared at 60°F, but were not consistently greater, and the fish were more susceptible to diseases.

<u>Predators</u>

Warm water temperatures may increase losses of young chinook salmon to predators by adversely affecting the performance of young salmon or by increasing habitat conditions favorable to predators. Young salmon subjected to thermal stress may exhibit behavioral characteristics that increase the rate of discovery by predators (Coutant 1973). Such characteristics include disorientation, erratic bursts of swimming activity, and an unnatural posture. Decreased responsiveness of stressed fish is another behavioral modification which may reduce the ability to recognize predators and take evasive action.

Several predatory fish species prey on young chinook salmon in the Sacramento River. Some of the more important predators include largemouth bass (<u>Micropterus</u> <u>salmoides</u>), striped bass (<u>Morone</u> <u>saxatilis</u>), Sacramento squawfish

(Ptychocheilus grandis), and steelhead trout. Spawning of these species occurs in the spring as water temperatures begin to rise. Spawning migrations of striped bass and Sacramento squawfish begin in April and peak during May and June (Moyle 1976). Large numbers of migrating squawfish congregate below the Red Bluff Diversion Dam before moving upstream to spawn (Vondracek and Moyle 1983). Young salmon migrating downstream may become confused and disoriented immediately below the diversion dam because of backwater currents, becoming easy prey for squawfish (Hall 1977). Predation, however, by the primarily dusk- and dawn-feeding squawfish is reduced in juvenile salmon through migration at night (Brown and Moyle 1981). Heaviest predation of hatchery-reared juvenile salmon occurs when the fish are released during the daytime. The inexperienced migrants, however, quickly learn predator avoidance responses. Around 80 percent of hatchery-reared fish migrate past the diversion dam the first night after release, with the remainder passing the second night. Such mass movements of both natural and hatchery-reared migrants reduce predation by squawfish and other predators through confusion and satiation. Sudden large numbers of prey cause predators to forage ineffectively, and the sacrifice of a few prey satisfies the daily appetite of predators, allowing most of the others to pass unharmed.

Diseases

Chinook salmon are susceptible to a number of diseases. Some diseases are specific for certain life stages, while others can infect fish at any stage of the life cycle. While some diseases may be directly lethal, others may simply impair the activities of afflicted fish, which may then lead to greater susceptibility to predators or other diseases, slower growth, impaired reproductive potential, and other behavioral abnormalities. Pathogenic organisms include viruses, bacteria, protozoa, fungi, and parasitic worms. Many of these disease agents have specific temperature preferences at which they are active or most infectious. Fish already under stress from warm water temperatures may be more easily infected by pathogens.

Columnaris disease infects both adult and juvenile chinook salmon. The causative agent is a myxobacterium called Chondrococcus columnaris (Wood 1979), which may also be referred to as Cytophaga columnaris (Snieszko 1958a) or Bacillus columnaris (Fish and Rucker 1943). The bacterium readily enters fish through external skin injuries, but also easily infects uninjured skin and gill tissues. Lesions form on the gills, which in advanced cases of infection may completely erode the gill epithelium. Lesions on the body begin as circular eroded areas which become hemorrhagic and spread to cover large areas of the body, particularly the head region. Infections become most prevalent as water temperatures rise above 56°F (Ordal and Pacha 1963, Leitritz 1959). Two strains of the bacteria occur which differ in virulence and temperature requirements. The low virulent strain attacks both body and gill tissues, producing extensive lesions prior to death of the fish. The high virulent strain attacks primarily the gills and results in death of the fish with much less apparent tissue damage. Outbreaks of the high virulent strain occur as water temperatures reach 60°F, while temperatures approaching 70°F trigger the low virulent strain. During years of high water temperatures, columnaris disease can cause significant mortalities among adult salmon prior to spawning. In years with cooler water temperatures, greater numbers of adult salmon may survive to spawn, but significant losses of juveniles may occur as water temperatures rise in the spring.

The myxobacterium Cytophaga psychrophila causes cold-water disease primarily in coho salmon, but also has affected chinook salmon (Wood 1979). The bacteria cause rupturing of the yolk in sac-fry and lesions behind the dorsal or adipose fins in older fry, which may eventually result in complete loss of the tail and death of the fish. The optimum temperature for the bacterium is 40°F to 50°F, but, at least among sac-fry, increases in severity with rises in temperatures up to 60°F.

A bacterium known as Corynebacterium causes kidney disease (Wood 1979). As the disease name implies, the focus of infection is the kidney, but other organs can also be affected, including the liver, spleen, and heart. Affected tissues gradually break down, leading to death of the fish. The disease occurs over a wide range of temperatures. At temperatures between 45°F to 50°F, the incubation period of the bacterium is 60 to 90 days, while at temperatures greater than 52°F, the incubation period is reduced to 30 to 35 days.

Furunculosis is another bacterial disease affecting both adult and juvenile salmon. The disease is caused by Aeromonas salmonicida (Wood 1979), which was previously known as Bacterium salmonicida (Snieszko 1958b). The disease causes the formation of purple, reddish, or iridescent blue areas beneath the skin which may ulcerate. The dorsal fin becomes frayed, and the gills may show hemorrhaged areas (Leitritz 1959). Internally, inflamed areas occur inside the body wall, among the visceral fat, and along the hind gut. Production of a toxin by the bacteria destroys the immune system of the fish, which then allows a generalized bacterial infection to occur that eventually kills the fish. Transmission of the bacteria is through water from other infected fish, with rough fish usually harboring the disease. The optimum temperature range of the disease is 56°F to 70°F. At temperatures below 45°F, infection becomes latent.

An important viral disease thought to be limited to the Sacramento and Mokelumne River drainages is the Sacramento River Chinook Disease (Wingfield and Chan 1970). However, the same virus has been found to cause similar disease symptoms in fish in other states and is now known as infectious hematopoietic necrosis or IHN (Wood 1979). Disease symptoms in infected fish appear in the sac-fry or fingerling stages until the fingerlings have grown to about three inches in length (Parisot and Pelnar 1962). Symptoms of infection include exophthalmia, lethargy, erratic behavior, and subdermal hemorrhages (Bell 1973). High mortalities result from infection. Disease outbreak is temperature dependent. The optimum temperature for the virus is 50°F. Temperatures near 45°F will initiate viral infections, but infections decrease as water temperatures approach 55°F. Temperatures greater than 55°F inhibit or inactivate the virus.

The ciliated protozoan Ichthyophthirius multifilis is parasitic under the epithelial layers of the gills, fins, and skin of fish (Wood 1979). Young salmon infected by the protozoan become listless. Severe losses at hatcheries have occurred on occasion. The optimum temperature for the protozoan is between 77°F and 80°F, but serious outbreaks among salmon generally occur in the range of 65°F to 70°F.

The protozoan Ceratomyxa shasta is an internal parasite, infesting various tissues including the liver, kidney, spleen, and muscle of fish (Wood 1979). Death of infected fish occurs in as little as 20 to 30 days. Temperatures above 50°F to 53°F appear necessary to initiate infection, and disease intensity increases with warmer water temperatures.

A common fungus affecting fish is Saprolegnia parasitica (Wood 1979). The fungus normally enters and develops on injured areas or areas where the protective slime has been rubbed from the fish. The fungus kills surrounding tissues and spreads to form large necrotic areas. The fungus occurs over a wide range of temperatures but develops most rapidly in warm water.

Many other diseases cause losses of fish. Specific temperature requirements of many of the disease agents are not well understood.

Dissolved Oxygen

The oxygen content of water is critical to all developmental stages of chinook salmon. Dissolved oxygen requirements are determined by the metabolic rate and thus are highest in the egg stage and decrease through successive developmental stages (Elliott 1969). Inadequate water flow past eggs or flow with insufficient dissolved oxygen causes high embryo mortalities, delay of egg hatching, developmental abnormalities, and reduced growth of sac-fry (Davis 1975, Silver et al. 1963). The developing embryo responds to reduced oxygen levels by a reduction in respiration rate, which subsequently leads to reduced growth and developmental rates. Severe oxygen restrictions cause the embryo to die, while less severe restrictions may result in abnormal sac-fry that are small and weak. Such fish may not compete well with normal fry and may be more prone to succumb to predation. Activities, including feeding and swimming abilities, of later stages may also be impaired with reduced oxygen levels.

In laboratory studies, eggs incubated at 52°F with a dissolved oxygen level of 1.6 mg/L exhibited grossly abnormal development and failed to hatch (Silver et al. 1963). Eggs incubated with dissolved oxygen levels ranging from 2.5 mg/L to 11.7 mg/L had hatching successes ranging from 92.3 to 100 percent. Embryos increased in size with increasing dissolved oxygen levels, while time to hatching decreased. Post-hatching survival was depressed at the lowest oxygen level but increased with increasing velocity of water at all dissolved oxygen levels. Embryos were also larger at higher water velocities, illustrating that adequate oxygen supplies can be maintained by increased water velocity when oxygen concentrations are low.

Fingerling chinook salmon were found to suffer losses of swimming performance at oxygen concentrations less than saturation (Davis et al. 1963). Exposure to dissolved oxygen levels of 7, 6, 5, 4, and 3 mg/L resulted in reduction of maximum sustained swimming speeds by about 10, 14, 20, 27, and 38 percent of that found at saturation.

Dissolved oxygen levels can be affected by temperature both directly and indirectly. The solubility of oxygen in water varies inversely with temperature. At a water temperature of 50°F, the maximum concentration of oxygen that can dissolve in water is 11.3 mg/L at sea level, while at 55°F, 60°F, 65°F, and 70°F, solubilities are reduced to 10.6, 10.0, 9.5, and 9.0 mg/L, respectively. Since dissolved oxygen at a minimum concentration of 6.0 mg/L is adequate for salmon (Davis 1975), the direct effects of temperature on dissolved oxygen should not be adverse to their survival. Temperature indirectly affects dissolved oxygen concentrations by affecting the rate of organic decomposition, rate of respiration of aquatic organisms, and the growth of aquatic plants. Both decomposition and respiration remove oxygen from water. Higher temperatures cause rates of decomposition and respiration to increase, which result in increased removal of oxygen from the water. Insufficient flows to meet oxygen demands may result in reduction of oxygen levels below those required to maintain salmonids. Growths of aquatic plants, primarily filamentous algae, trap sediments from flowing water (Bisson and Davis 1976). As the growth of plants increases, stimulated by higher temperatures, sufficient sediments may be trapped to impede the flow of oxygenated water through gravels containing eggs. Loss of eggs may then occur due to inadequate oxygen supply or poor cleansing of metabolic wastes produced by the eggs (Gangmark 1960, Wickett 1954).

Trace Metals

Numerous fish kills have occurred in the Sacramento River between Keswick Reservoir and Balls Ferry due to trace metals contained in acid mine wastes from the Spring Creek drainage (USFWS 1959, Nordstrom 1977). Elevated concentrations of aluminum, cadmium, chromium, copper, iron, nickel, and zinc in the Sacramento River below Keswick Dam occur from discharges from Spring Creek (Wilson et al. 1981). Tolerance limits for juvenile chinook salmon have been determined for copper, zinc, and cadmium (Hazel and Meith 1970, Finlayson and Verrue 1980 and 1981). Fry were less resistant than eggs to the toxic effects of the metals and experienced reduced growth at sub-lethal levels.

Within the limits of thermal tolerance, water temperature may modify the toxic effects of a trace metal, altering the minimum lethal concentration or survival time in a lethal concentration. Little research, however, has been conducted to determine the effects of temperature on metal toxicity to salmon. From the limited studies conducted using a variety of freshwater fishes, it appears that increasing temperature influences toxicities of copper, zinc, and cadmium very little (Cairns et al. 1975). The effect of these metals is to reduce survival time of fish at lethal levels rather than to decrease the concentration that causes lethality.

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CONVERSION FACTORS

Quantity	To Convert from Metric Unit	To Customary Unit	Multiply Metric Unit By	To Convert to Metric Unit Multiply Customary Unit By
Length	millimetres (mm)	inches (in)	0.03937	25.4
	centimetres (cm) for snow depth	inches (in)	0.3937	2.54
	metres (m)	feet (ft)	3.2808	0.3048
	kilometres (km)	miles (mi)	0.62139	1.6093
Area	square millimetres (mm^2)	square inches (in^2)	0.00155	645.16
	square metres (m^2)	square feet (ft^2)	10.764	0.092903
	hectares (ha)	acres (ac)	2.4710	0.40469
	square kilometres (km^2)	square miles (mi^2)	0.3861	2.590
Volume	litres (L)	gallons (gal)	0.26417	3.7854
	megalitres	million gallons (10^6 gal)	0.26417	3.7854
	cubic metres (m^3)	cubic feet (ft^3)	35.315	0.028317
	cubic metres (m^3)	cubic yards (yd^3)	1.308	0.76455
	cubic dekametres (dam^3)	acre-feet (ac-ft)	0.8107	1.2335
Flow	cubic metres per second (m^3/s)	cubic feet per second (ft^3/s)	35.315	0.028317
	litres per minute (L/min)	gallons per minute (gal/min)	0.26417	3.7854
	litres per day (L/day)	gallons per day (gal/day)	0.26417	3.7854
	megalitres per day (ML/day)	million gallons per day (mgd)	0.26417	3.7854
	cubic dekametres per day (dam^3/day)	acre-feet per day (ac-ft/day)	0.8107	1.2335
Mass	kilograms (kg)	pounds (lb)	2.2046	0.45359
	megagrams (Mg)	tons (short, 2,000 lb)	1.1023	0.90718
Velocity	metres per second (m/s)	feet per second (ft/s)	3.2808	0.3048
Power	kilowatts (kW)	horsepower (hp)	1.3405	0.746
Pressure	kilopascals (kPa)	pounds per square inch (psi)	0.14505	6.8948
	kilopascals (kPa)	feet head of water	0.33456	2.989
Specific Capacity	litres per minute per metre drawdown	gallons per minute per foot drawdown	0.08052	12.419
Concentration	milligrams per litre (mg/L)	parts per million (ppm)	1.0	1.0
Electrical Conductivity	microsiemens per centimetre (uS/cm)	micromhos per centimetre	1.0	1.0
Temperature	degrees Celsius (°C)	degrees Fahrenheit (°F)	(1.8 × °C)+32	(°F−32)/1.8