



Evaluation of Anadromous Fish Potential Within the Mainstem Snake River, Downstream of the Hells Canyon Complex of Reservoirs

Phil Groves
Editor

**Technical Report
Appendix E.3.1-3**

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Physical Habitat and Water Quality Criteria for Chinook Salmon Associated with the Hells Canyon Complex

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Appendix E. 3.1-3
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Chapter 2

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ABSTRACT

To accurately model and estimate habitat availability for a given life history stage of a fish species, investigators need to understand the parameters influencing habitat use (Bovee 1986). Physical habitat attributes such as depth, water velocity, substrate composition, water temperature, and dissolved oxygen (DO) are primary, measurable factors that influence where and when fall chinook salmon spawn. These factors also influence the success of incubation and rearing (Raleigh et al. 1986). Water temperature and DO are also primary factors that indicate how successfully adult and juvenile chinook salmon can move through a particular migratory corridor. We also determined that water temperature and DO function together to affect the quality of habitat for chinook salmon (Davis 1975, Raleigh et al. 1986, Glass et al. 2001).

Physical habitat criteria for migrating juvenile and adult salmon were determined from peer-reviewed literature. Data collected during ten years of spawning surveys, and from peer-reviewed literature, were used to develop physical habitat criteria for spawning fall chinook salmon. Data collected by the U.S. Geological Survey, and peer-reviewed literature, were used to develop physical habitat criteria for rearing juvenile fall chinook.

In general, optimal water temperatures for all stages of chinook salmon life histories were found to be between about 9 and 15 °C. However, temperatures as low as 1 °C, and as high as 21 °C can be suitable for both adults and juveniles during rearing and migration, depending on acclimation temperatures. As well, we determined that water temperatures as low as 5 °C and as high as 16 °C can be suitable for spawning fall chinook salmon.

For all life stages, optimal DO levels were determined to be above 76% saturation at temperatures of 16 °C or lower. Suitable DO levels were determined to be between about 40 and 76% saturation when temperatures are 16 °C or lower. At higher temperatures, DO requirements increase for both optimal and suitable levels.

Physical habitat requirements for spawning fall chinook salmon include depths between 0.2 and 6.5 m, mean water-column velocities between 0.6 and 1.7 m/s, and substrate sizes between 2.6 and 15.0 cm long axis length. Based on our observations, it is our opinion that velocity and substrate size are more important than depth in determining the relative value of habitat for spawning. Physical habitat requirements for rearing fall chinook salmon include areas within 5.0 m of the shore, substrates of less than 22.5 cm long axis length, mean water-column velocities less than 0.4 m/s, and lateral shoreline slopes less than 40%.

1. INTRODUCTION

Wild stocks of Snake River chinook salmon (*Oncorhynchus tshawytscha*) declined in abundance from about 1965 to 1976. Several factors contributed to their decline, including exploitation, impeded migration, predation, and habitat loss (Irving and Bjornn 1981). After construction of the Hells Canyon Complex (HCC) of hydroelectric projects (Brownlee, Oxbow, and Hells Canyon dams) from 1958 to 1967, dams barred the chinooks' access to their historical habitat upstream of river kilometer (RKM) 398.6. Additional dams constructed by the U.S. Army Corps of Engineers (COE) in the lower river between 1961 and 1975 inundated habitat downstream of RKM 239.8. Because of these projects, present-day spawning, incubation, and rearing of fall chinook salmon occur primarily in the free-flowing reach of the mainstem Snake River (hereafter referred to as the Snake River) between Hells Canyon Dam (RKM 398.6) and Asotin, Washington (RKM 234.9). Limited habitat associated with these life history stages also exists in the lower portions of major Snake River tributaries, including the Clearwater, Grande Ronde, Imnaha, Tucannon, and Salmon rivers, and the tailraces of the lower four Snake River dams. Migratory conditions (temperature, dissolved oxygen [DO], and flow volume particularly) for spring or summer chinook salmon (both as adults and juveniles) within the Snake River have been altered because of upstream and downstream hydroelectric projects, and changing land-use practices.

In 1992, the National Marine Fisheries Service (NMFS) listed fall chinook and spring/summer chinook salmon as threatened under the Endangered Species Act (ESA) (NMFS 1992). Following that decision, research has primarily focused on quantifying available habitat for fall chinook salmon within the Snake River in comparison with regulated discharges from the HCC. Through the HCC relicensing process, Idaho Power Company (IPC) has also undertaken the task of assessing how operating the three-dam complex might affect conditions for all races of chinook salmon within the Snake River's migratory corridor. To accurately model and estimate habitat availability for a given life history stage of a fish species, investigators need to understand the parameters influencing habitat use (Bovee 1986). Physical habitat attributes such as depth, water velocity, substrate composition, water temperature, and DO are primary, measurable factors that influence where and when fall chinook salmon spawn. These factors also influence the success of incubation and rearing (Raleigh et al. 1986). Water temperature and DO are also primary factors that indicate how successfully adult and juvenile chinook salmon can move through a particular migratory corridor. However, the relative importance of these and other possible parameters (such as groundwater upwelling) is poorly understood (Crisp and Carling 1989).

The history of the development of use-criteria for spawning habitat of fall chinook salmon is particularly interesting. Within the Pacific Northwest, these fish generally spawn within the large mainstem Columbia and Snake Rivers (Haas 1965, Irving and Bjornn 1981). Initial work to describe the spawning habitat that fall chinook salmon use was conducted on small river systems (Chapman 1943, Burner 1951, Briggs 1953, Chambers et al. 1955). The geomorphology of these small river systems probably limited the range of available habitat. Chambers et al. (1955), in comparing information from the Columbia River and two smaller rivers, concluded that the Columbia River mainstem stocks used predominantly faster water velocities and greater depths.

However, they were unable to measure habitat attributes where fall chinook salmon were observed spawning at depths greater than 2.4 meters (m). Smith (1973) and Raleigh et al. (1986) integrated data from numerous studies conducted throughout the Pacific Northwest and California and redefined criteria for describing fall chinook salmon spawning habitat. These authors compensated for the uncertainty in depth distribution used by fall chinook salmon in large rivers by using a minimum depth, with no maximum. However, the velocity distribution both authors developed continued to represent data from small river systems. Later studies on the Columbia River by Chapman et al. (1986) and Swan (1989) described fall chinook salmon spawning where depths were approximately 10 m and velocities were as high as 2.0 m per second (m/s). But because of highly fluctuating flows within their study area during the spawning period, measurements representing microhabitat at specific redd construction sites were either broadly generalized or not obtained. As a result, habitat criteria within a larger river were not quantitatively described.

These previous studies lacked adequate criteria for modeling spawning habitat use by fall chinook salmon. Because the historical criteria could be interpreted various ways, the results from any modeling efforts would be difficult to analyze. This uncertainty emphasized the need for developing appropriate values for the principal habitat attributes before proceeding with a modeling process. We specifically sought to describe the distribution of depth, mean water-column velocity, substrate-level water velocity, surficial-substrate particle size, and temperature that spawning fall chinook salmon need. These attributes were of particular interest because of their utility for instream flow modeling. Regulated flow operations within the Snake River, a large mainstem river, provided stable hydraulic conditions for evaluating habitat use over a wide range of habitat variables during the fall chinook salmon spawning period.

Habitat variables associated with adult fall chinook are similarly important for rearing juveniles. Water velocity, substrate, depth, temperature, and DO are all important when describing habitat requirements. However, incubating embryos are affected more by water temperature and DO, as well as the porosity and accumulation of fine materials within the incubation environment (Raleigh et al. 1986).

General criteria corresponding to incubation and rearing have been developed and reported in peer-reviewed literature. It is difficult to sample and test a species having status under the ESA. For that reason, we used a synthesis of various study results from peer-reviewed literature to develop appropriate criteria for describing the habitat of incubating and rearing fall chinook salmon within the Snake River downstream of the HCC. Existing, peer-reviewed literature was also used to develop a series of relational tables that describe risks associated with water temperature and DO, as well as how those factors affect migrating adult and juvenile chinook salmon.

2. STUDY AREA

For purposes of collecting information on fall chinook salmon spawning, we conducted surveys along the 165-kilometer (km)-long, free-flowing reach of the Snake River between Asotin and the Hells Canyon Dam. This river reach flows north from the Hells Canyon Dam and is bounded

on the east by Idaho, and on the west by Oregon and Washington. Within this study area, three distinct segments were identified based on the river's physical characteristics, such as gradient, discharge, temperature, channel width, and turbidity.

The upper segment, approximately 95 km long, runs from the Hells Canyon Dam downstream to the confluence of the Salmon River (RKM 303.0). This segment has a narrow channel with an average river gradient of 0.2%, short and deep pools, and numerous rapids of high and low gradient. Since 1991, flows during the spawning season (from about mid-October through mid-December) have been held steady. In accordance with the IPC interim protective flow plan, the spawning flow is established as the minimum discharge until fry emergence is estimated to be complete (usually by early May to early June of the following year). As a result of these flows, the turbidity within the upper segment remains relatively low and constant, generally less than 2.0 nephelometric turbidity units (ntu) from late October through early December.

The middle segment, approximately 32 km long, runs north from RKM 303.0 to the confluence of the Grande Ronde River (RKM 271.5). This segment could be termed a transitional zone, as the average river gradient is 0.2% within the upper third, but then abruptly drops to about 0.07% as the narrow and steep-banked channel widens near RKM 289.7. During the fall spawning period, the daily mean flow is slightly higher, but relatively stable, due to influences from the Salmon River. Turbidity within the middle segment, also influenced by the Salmon River, is usually more variable, with observed extremes during our surveys of between 1.0 and 11.0 ntu.

The lower segment stretches approximately 38 km downstream from the Grande Ronde River confluence. Throughout this segment, the river gradient remains low, around 0.07%, and the river channel remains wide, with gently sloping shorelines. This lower segment can also be characterized as having long, deep pools and runs and low-gradient rapids. Because of compounded influence from the Salmon and Grande Ronde rivers, the discharge and turbidity within this segment during the fall spawning period is higher and more variable than in the upper segments. During the spawning period, observed turbidity has ranged between 0.7 and 13.2 ntu.

In the fall (October through December), the water temperature within the upper segment tends to be slightly warmer than in the middle and lower segments. By about mid-January through early March, the temperature throughout the entire reach (from the Hells Canyon Dam downstream to Asotin) is virtually the same. Finally, in early spring (March through mid-June), the water temperature in the upper segment is slightly cooler than in the middle and lower segments. This thermal disjunction results from a combination of reservoir buffering at Brownlee and the quantity of water provided from the Salmon River.

3. METHODS

3.1. Adult Migration: Temperature and Dissolved Oxygen

We obtained values for temperature and DO from peer-reviewed literature. Those values are discussed in the results section of this chapter (section 4). We developed criteria that could be

used to describe habitat suitability for adult chinook salmon migrating through the Snake River, downstream of the Hells Canyon Dam. The temperature criteria could be used alone, but DO criteria were dependent on ambient temperature. Combining these two criteria helped characterize how water quality conditions might affect the success of an organism (*i.e.*, whether it could remain stress-free and healthy) and the likelihood of an organism completing a particular portion of its life history. We use suitability curves that we developed for our models to describe the Snake River corridor's suitability during the adult chinook salmon's known migration periods.

3.2. Spawning Habitat

Methods for most of this section were previously reported in Groves and Chandler (1999). In this report we restate the methods for obtaining redd locations and attributes. During the 1993, 1994, and 1995 spawning seasons, we collected values for depth, mean-column and near-bottom water velocities, and substrate at identified redds. Using data collected during the spawning seasons of 1991 through 2000, we developed water temperature values associated with spawning. We developed DO criteria through a synthesis of literature-reported values associated with spawning chinook salmon.

3.2.1. Location of Redds

Primarily, we used aerial surveys to locate redds. However, water turbidity, cloud cover, and surface turbulence limited the depth at which redds were visible to approximately 3 m. Because redds of fall chinook salmon had been reported in the Columbia River at depths to about 10 m, we used remote video searches to expand the aerial surveys of potential deep-water spawning areas. Turbidity within the Snake River can be quite low (< 4.0 ntu), providing good to excellent conditions for underwater videography (Groves 1993, Groves and Garcia 1998). We classified the redds identified during aerial surveys (depth ≤ 3.0 m) as shallow, and those located by video searches (depth > 3.0 m) as deep. Habitat-use data were collected at all redds located during the 1993 through 1995 spawning seasons.

We conducted weekly aerial surveys during the spawning season (mid-October through mid-December). Flights began at Asotin and covered the entire length of the free-flowing Snake River upstream to Hells Canyon Dam. We used a three-seat helicopter (center pilot seat and two outboard observers) operated at an altitude lower than 200 m above water level, cruising at approximately 70 km per hour (Mendel et al. 1992, Connor et al. 1993, Groves 1993, Garcia et al. 1999). Redd locations were noted on a COE navigation chart of the Snake River.

During summer 1992, we used underwater videography to locate potential deep-water spawning areas deeper than 3.0 m and containing patches of gravel or cobble substrate (2.5–15.0 centimeters [cm], long axis length). We inspected all pool tail-out areas, deeper zones contiguous with known shallow spawning sites, as well as deep runs exhibiting laminar flow patterns. Throughout the three study reaches we identified 89 sites that contained potential spawning substrate at depths greater than 3.0 m.

The underwater video system consisted of a remote, submersible camera (attached to a hydraulic weight) that was fastened to a video camcorder and monitor (Groves and Garcia 1998). A manually operated, calibrated winch controlled the height of the camera over the river bottom. To reduce disturbance to spawning adults, we waited until mid-November (when spawning activity began to decline) to initiate video searches. Each year we determined how many sites we could search within the time constraints of the spawning season, and then we randomly selected sites from the pool of 89 deep-water areas. In cooperation with the U.S. Fish and Wildlife Service (USFWS), we searched 50 sites in 1993, 73 in 1994, and 42 in 1995 (Garcia et al. 2000).

Typical deep-water searches consisted of a succession of cross-channel transects viewed serially upstream throughout the site. We maintained the distance between transects at approximately 10.0 m by visually orienting to natural shoreline landmarks. Each transect was considered complete if depth decreased to less than 3.0 m or increased to greater than 11.0 m (the limit of our visibility), or if the substrate no longer met the defined criteria (size range 2.5–15.0 cm). To more accurately estimate substrate size, we kept the camera approximately 0.6 m above the bottom and placed a clear Mylar reference grid over the monitor screen. In 1994 and 1995, we monitored search patterns using a surveying instrument to record several positions along each transect. The instrument was very useful for relocating redds if we drifted off of position during data collection.

Throughout the spawning period, we monitored flows and documented any significant changes ($>\pm 10\%$) in discharge and stage. We compared these measurements to measurements taken during redd construction. We obtained discharge data from U.S. Geological Survey (USGS) gauges at Hells Canyon Dam (RKM 398.6), Anatone (RKM 269.7), and White Bird on the Salmon River.

3.2.2. Redd Attributes (Spawning)

We measured depth, velocity, and substrate directly upstream of, but adjacent to, the pit portion of redds. We assumed that this data represented conditions before the redds were constructed and the substrate was modified (Reiser and Wesche 1977, Grost et al. 1990, Thurow and King 1994). We only took measurements near completed redds, evidenced by well-defined pits and tailspill and by clean substrate. In 1993, we collected data as redds were identified. But during 1994 and 1995, we collected data in early December to further minimize disturbance to spawning fish.

We used frequency histograms to describe the distribution of depth, mean water-column velocity, bottom velocity, substrate, and temperature associated with redds. Depth was consistently measured at all redds. But because sampling in deep water was difficult, we measured velocity and substrate more frequently at shallow redds. Because depth was the most consistent parameter we measured, we used it to examine the possibility of bias within the other habitat attributes. We used a Kolmogorov-Smirnov test to determine whether the depth distribution of redds, where a habitat attribute was measured, differed from the depth distribution of all redds. If we found a depth-related bias, we used a t-test to determine whether a difference for the other attributes existed between shallow and deep-water redds. We used a chi-square test for differences in distribution of substrate categories between shallow and deep-water redds. We used SAS (1989) software to analyze all statistics. We did not attempt to produce preference

curves by correcting use observations with availability data. Collecting habitat availability data was considered difficult within a system as large as the Snake River. Also, given the depauperate population and the regional experts' consensus that ample spawning habitat is available, we assumed that fish would use optimum habitat.

3.2.2.1. Depth

Data collection methods differed based on the relative depth of redds. We measured very shallow redds (< 0.6 m) with a standard wading rod. For deeper redds, we measured from a boat with a calibrated sounding cable.

3.2.2.2. Velocity

We used a Marsh-McBirney (model 2000) meter to measure water-column and bottom velocities at redds. If redd depths were less than or equal to 0.91 m water-column velocities were measured at 0.60-depth. If redds were deeper than 0.91 m, a mean water-column velocity was calculated from measurements obtained at 0.2 and 0.8 the depth of the redds (Orth 1983). Bottom velocities were measured approximately 0.20 m above the substrate to describe the conditions spawning fish encounter. Although bottom velocities more accurately represent conditions for spawning fall chinook salmon, mean water-column velocity was also included to help model in-stream flow.

3.2.2.3. Substrate

We used the remote underwater video camera (held 0.6 m above the river bottom) to measure substrate at both shallow and deep redds (Groves 1993, Groves and Garcia 1998). Positioning the camera at a constant distance above the substrate, we used a referenced measuring rule or Mylar grid to determine particle size classes. Later, we displayed substrate recordings on a 30-cm monitor. Then we measured dominant and subdominant particle sizes along their longest axis and classified them according to an expanded Brusven (1977) scale. Our particle size classes included sand-pebble (< 0.6 cm; class 0), small gravel (0.6–2.5 cm; class 1), medium gravel (2.6–5.0 cm; class 2), large gravel (5.1–7.5 cm; class 3), small cobble (7.6–15.0 cm; class 4), large cobble (15.1–22.5 cm; class 5), small boulder (22.6–30.0 cm; class 6), medium boulder (30.1–60.0 cm; class 7), large boulder (> 60.0 cm; class 8), and bedrock (class 9). We detected a slight distortion in size (about +20%) in the images. The distortion was caused by the type of lens we used, but only the extreme outside edges of the viewable area were distorted. We therefore restricted our representative measuring area to the central portion of the image. The size class that filled more than 55% of the video image was considered dominant, and the next most abundant was subdominant.

3.2.2.4. Temperature

We used electronic thermographs (Ryan Corporation and Onset Computer Corporation) throughout the study area to collect water temperatures associated with redd construction. We spaced nine thermographs at approximately 16-km intervals along the main Snake River corridor, and three more within the first 2 km of the main tributaries. Each monitor recorded data hourly. We used the mean water temperature for the week preceding redd construction to describe the spawning temperature at each redd. Redds were excluded from the temperature

analysis if the week of their construction was unknown (primarily deep redds). Generally, we used the thermograph located closest to each redd for estimating temperature.

3.2.2.5. Dissolved Oxygen

DO values associated with chinook salmon spawning were obtained from literature. We conducted a careful synthesis and developed criteria for defining and describing suitable spawning habitat for fall chinook salmon within the mainstem Snake River downstream of the Hells Canyon Dam. The suitability curve that we developed is dependent on water temperature and provides a more realistic interpretation of how water quality will affect the spawning environment.

3.3. Incubation and Early Rearing

It was not feasible to collect data to describe the success of fall chinook incubation. Because these fish are listed and protected under the ESA, it was not advisable to sample or otherwise disturb them during this critical life period. Methods that would have been useful for describing the success of this life stage may have required unnecessary and unacceptable levels of direct “take” (in the form of mortality) prohibited under the ESA. Chandler et al. (2001) and Groves and Chandler (2001), describe the physical incubation environment matrix (substrate particle size distribution and porosity) upstream and downstream of the Hells Canyon Complex, respectively, and how project operations may affect its function in relationship with incubation success. Therefore, this section (and corresponding results) will specifically address only the rearing life stage of juvenile fall chinook salmon.

3.3.1. Depth, Velocity, Slope, and Substrate

Water depth, mean column velocity, shoreline slope, and substrate types associated with juvenile fall chinook rearing within the Hanford Reach of the Columbia River have been previously reported by Key et al. (1996), Garland and Tiffan (1999), and Garland et al. (2001). Their criteria have been assumed to be representative of juveniles rearing within the Snake River (K. Tiffan, USGS, personal communication). Calibrated hydraulic models of the Snake River will use those criteria to determine whether (and to what degree) HCC operations impact the rearing life stage of fall chinook salmon.

3.3.2. Temperature and Dissolved Oxygen

Temperature and DO values, which we obtained from peer-reviewed literature, are discussed in the results section of this chapter. We developed curves to help describe the suitability of the habitat for rearing juvenile fall, spring, or summer chinook salmon within (and migrating through) the mainstem Snake River, downstream of the Hells Canyon Dam. Based on a combination of water temperature and DO, the curves are most realistic in describing how existing conditions might affect the suitability of habitat for sustaining healthy organisms.

4. RESULTS AND DISCUSSION

4.1. Adult Migration: Temperature and Dissolved Oxygen

Temperature and DO function together to determine the quality of habitat for migrating adult chinook salmon (Davis 1975, Raleigh et al. 1986, Glass et al. 2001). Generally, as the water temperature increases, an organism's respiratory and metabolic activity, as well as oxygen demand, also increase. If insufficient oxygen is available to maintain respiratory and metabolic activity, stress develops and causes increased susceptibility to disorientation, predation, disease, or failure of physiological systems—resulting, finally, in death. The physics of water's ability to contain dissolved gasses, such as oxygen, at varying temperatures can exacerbate these problems. As water temperature increases, the amount of a dissolved gas that water can contain decreases. So, while respiratory and metabolic activity of organisms (fish) increase as water temperature increases, the amount of available oxygen decreases. Temperature also affects the efficiency of enzymatic and other physiological processes occurring within an organism. For fish, as well as invertebrates, this is particularly important because they are poikilothermic and incapable of maintaining a constant, efficient body temperature.

Various values of temperature and DO lethal limits, tolerances, preferences, and optima have been presented in the literature from laboratory and field studies. Coutant (1977), citing Spigarelli (1975), reported 17.3 °C as the upper temperature preference of migrating adult chinook salmon. Kilgour et al. (1985) acknowledged that the upper incipient lethal temperature (UILT) for adult chinook was dependent on acclimation temperature and that as the acclimation temperature increased, so did the UILT. However, even at the highest acclimation temperatures (20.0 and 24.0 °C) the UILT remained constant at 25.1 °C. Raleigh et al. (1986) produced suitability index graphs that indicated 8.0 to 12.0 °C as optimum for pre-spawning adults, with 0 and 24.0 °C as the lower and upper limits, respectively. Karr et al. (1992) described a range of temperatures useful for delineating bounds of resistance, tolerance, and optima for adult chinook salmon migrating within the Columbia River Basin specifically. They indicated that resistance, the temperature at which biological functions become impaired and when organisms may die from prolonged exposure, was apparent at temperatures lower than 5.6 and greater than 20.0 °C. The lower and upper temperature tolerance ranges, which are generally associated with normal biological functions, were documented as being between 5.6 to 6.7 and 15.6 to 20.0 °C, respectively. The optimum temperature range that was reported in their document was between 6.7 and 15.6 °C. Glass et al. (2001) reviewed various reports and concluded that the optimum temperature range for migrating adult summer and fall chinook was between 12.0 and 21.0 °C. Also, they reported that thermal blocks to migration developed as water temperatures increased to 21.1 °C, but speculated that thermal differences between two streams might actually serve as the functional barrier. Their thermal suitability index curve was similar to that described by Raleigh et al. (1986), except that they extended the optimum temperature for fall chinook to 21.0 °C and abruptly forced all temperatures above that point to un-suitable. Hallock et al. (1970) reported that chinook salmon migrating through the San Joaquin River would not move through areas where DO was less than 4.5 milligrams per liter (mg/l), or when temperatures were greater than 17.7 °C. They also noted that the salmon migration did not appear to be impeded as long as the DO levels were greater than 5.0 mg/l. Davis (1975) presented a comprehensive synthesis of

DO criteria for Canadian fish, including chinook salmon. He determined that at water temperatures between 15.0 and 25.0 °C, DO levels greater than 6.5 mg/l were necessary for the majority of a population to exist without adverse physiological or behavioral effects. Within the same temperature bounds, lengthy periods of exposure to DO levels between 6.5 and 4.0 mg/l could induce serious deleterious effects to the majority of a population.

Using information from the various sources cited in previous paragraphs, we first developed a suitability curve for water temperature alone (Figure 1). The temperature curve indicates that while suitability exists at temperatures between 1.0 and 22.0 °C, optimum temperatures are found between 9.0 and 14.0 °C. However, the final suitability of the habitat is also dependent on the DO levels found at any specific temperature. The curve developed for DO indicates a range, at any given temperature, where suitable oxygen saturation exists (Figure 2). Two curves are presented that show both lethal and optimal saturation levels for DO at any given temperature along the x-axis (lower and upper lines, respectively, in Figure 2). In general, we found that at temperatures lower than 16.0 °C, optimal DO saturation should be greater than about 76% saturation. At temperatures lower than 16.0 °C, suitable habitat exists at DO levels between about 38 and 76% saturation; however, reduced growth and some alteration in behavior could occur. We found that as temperature increased above 16.0 °C, the optimal limit increased rapidly, indicating that a higher saturation of oxygen is necessary to enable normal growth and behavior. The lower lethal limit also increased to 50% saturation at 24.0 °C, and to 54% saturation when water temperature climbed to 28.0 °C (Figure 2), indicating that DO saturation must increase as water temperature increases for the habitat to remain suitable.

4.2. Spawning Habitat

4.2.1. Location of Redds

Aerial surveys from 1993 to 1995 indicated that spawning of fall chinook salmon in the Snake River began during the last week of October, peaked by mid-November, and concluded by the second week of December. Discharge in the reach upstream of the Salmon River confluence varied little (3%) between the period of initial spawning activity and data collection. Discharge within the Snake River downstream of the Salmon and the Grande Ronde rivers has more potential to vary because of natural influences. During 1993 and 1994, discharge in the middle and lower reaches varied no more than 6% during the spawning and data collection periods. Within the lower river reach, when flows varied by 6% from the time of redd construction to habitat measurement, only 11 redds were subjected to minor changes in depth (± 0.08 m) and velocity (± 0.15 m/s) (W.P. Connor, USFWS, personal communication). Because of an unusual flood event in 1995, we were unable to collect data from redds downstream of the Salmon River; however, the potential number of redds missed was not deemed significant.

Using a combination of aerial and underwater video observations, we identified 127 redds in 1993, 67 in 1994, and 71 in 1995 (Garcia et al. 1999, Groves 2001). Redds located at depths greater than 3.0 m comprised 53% of the total in 1993, 24% in 1994, and 42% in 1995.

4.2.2. Redd Attributes

4.2.2.1. Depth

The depth measured at 205 redds varied between 0.2–6.5 m, with a mean of 2.8 m. From 1993 to 1995, no redds deeper than 6.5 m were observed in the Snake River, even though searches of suitable habitat occurred frequently below that depth. However, more recent searches within the Snake River have detected redds at depths as great as 8.5 m. In total, about an equal number of redds were observed at depths less than and greater than 3 m.

When we were developing the suitability criteria curve, we took into account that our survey methods were probably biased toward the shallow end of the depth spectrum. The reason for the bias is that aerial surveys cover very close to 100% of the entire reach, while deep video searches are extremely limited in the amount of area they can actually observe. We also took into account the fact that active deep-water spawning was observed close to sites where shallow-water spawning had occurred in the past (although shallow-water spawning was not occurring at the time of sampling) and that deep-water spawning was observed throughout the Snake River before spawning at known shallow-water spawning sites occurred. Because of these observations, we assigned reasonable criteria to the deeper bins. The resultant curve continues to indicate that useable habitat can be found at depths between 0.2 and 6.5 m, which basically describes a binary suitability continuum (Figure 3).

4.2.2.2. Velocity

Mean water-column velocity over redds ranged from 0.4 to 2.1 m/s, with a mean of 1.1 m/s (Figure 4). The depth distribution of redds, where mean water-column velocity was measured, differed significantly ($P < 0.01$) from all redds sampled. However, we detected no significant difference ($P = 0.29$) in the distribution of velocity between shallow and deep-water redds, suggesting a low probability of bias from excluding some deeper redds. As a specific point of interest, there was no relationship between depth and mean water-column velocity measured at redds ($n = 145$, $r^2 = 0.02$, $P = 0.14$).

Bottom velocity (0.2 m above the substrate) ranged between 0.1 and 2.0 m/s, with a mean of 1.0 m/s (Figure 5). The depth distribution of redds where bottom velocity was recorded did not differ from that of all redds ($P = 0.45$), and the distribution of bottom velocity at shallow redds did not differ from that of deep-water redds ($P = 0.73$). As with mean water-column measurements, no relationship existed between depth and the substrate-level water velocity measured at redds ($n = 164$, $r^2 < 0.01$, $P = 0.91$). However, a significant relationship existed between bottom velocity and mean water-column velocity ($n = 140$, $r^2 = 0.68$, $P < 0.001$).

Because near-bottom velocities are closely dependent on mean water-column velocity and because hydraulic models poorly estimate near-bottom velocities, we determined that the mean water-column velocity parameter could be used without reference to a bottom velocity codeterminant, and would provide acceptable results within our modeling. We also determined that, when appropriate, we could present more conservative habitat model results by eliminating the lower and higher velocity bins and estimating habitat availability based on a binary mean water-column velocity parameter of 0.6 to 1.7 m/s.

4.2.2.3. Substrate

Dominant and subdominant substrate types were classified at 112 redds during the spawning seasons of 1993, 1994, and 1995. The majority of redds (77%) occurred in medium- to large-sized gravel. Large gravel (5.1–7.5 cm; class 3) was the dominant substrate type found at redds, comprising 48% of the sample. Medium gravel (2.6–5.0 cm; class 2) made up the dominant substrate type at 29% of redds, while small cobble (7.6–15.0 cm; class 4) was dominant at 21% of redds (Figure 6). Considering that only 2 observations of dominant substrate were smaller or larger than the range of particle sizes observed between 2.6 and 15.0 cm, we determined that the dominant substrate parameter could be conservatively viewed as having binary suitability.

The subdominant substrate types we observed at the sampled redds were generally within one class (above or below) of the observed dominant substrate. Overall, there were a few more observations of smaller (small gravel, 0.6–2.5 cm), and larger (large cobble, 15.1–22.5 cm) substrate types as subdominant around and within redds (Figure 7). Substrate combinations (dominant and subdominant) observed at redds mostly comprised large and medium gravel (23%), large gravel and small cobble (21%), medium and large gravel (17%), and small cobble and large gravel (14%). In general, the substrate composition in areas where redds were located was fairly homogenous in size distribution. The depth distribution of redds where substrate was classified differed significantly ($P < 0.01$) from the overall redd depth distribution. However, the distribution of dominant substrate observed at shallow and deep-water redds did not differ significantly ($P = 0.94$), nor did the distribution of combined dominant and subdominant substrates ($P = 0.28$), suggesting a low probability of depth-related bias in substrate frequencies.

Regarding substrate type, our final model analyses were determined using only the dominant, binary substrate parameter (2.6–15.0 cm size range; classes 2, 3, and 4). This decision was based on our observations that indicated substrate types around redds were generally homogenous, and because the collection of the modeling data only reflected a dominant substrate type.

4.2.2.4. Temperature

Since 1991, IPC has been collecting water temperature data downstream of the HCC during the fall chinook spawning period. (We assumed that the timing of observed spawning in shallow water was representative of spawning at all depths throughout the water column.) We used this data to assess ambient water temperatures associated with initiation and cessation of spawning activity. We also used this data to develop a temperature criteria curve representing suitability downstream of the HCC. The overall distribution of mean weekly water temperatures obtained for 1020 redds during 1991 through 2000 ranged from 17.3 to 5.0 °C, with a mean of 12.1 °C (Figure 8). Water temperatures during the weeks of spawning initiation and completion have averaged 13.9 °C and 8.3 °C, respectively. While we have observed initial redd construction when water temperatures were above 17.0 °C, we must keep these observations in perspective—there have been only three years when redd construction began before temperatures dropped below 16.0 °C (Groves 2001). We should also emphasize that for any specific year, the percentage of redds observed when temperatures have been above 16.0 °C has never been greater than 1.5%. Based on our observations, we assigned no suitability to temperatures lower than 5.0 and greater than 16.0 °C. We found optimal temperatures for spawning to be between 11.0 and 14.0 °C (Figure 8).

4.2.2.5. Dissolved Oxygen

We assumed that DO criteria for spawning fall chinook salmon were similar to those developed for migrating adult chinook salmon. Peer-reviewed literature about actual oxygen requirements for spawning fall chinook salmon was unavailable. We assumed that both migration and nest-building activities would require a similar need for oxygen. We determined that optimal values for DO would be above 76% saturation at temperatures lower than 16 °C (Figure 2). At temperatures lower than 16.0 °C, suitable habitat exists at DO levels between about 38 and 76% saturation. We found that as temperature increased above 16.0 °C, the optimal limit increased rapidly, indicating that a higher saturation of oxygen is necessary to enable normal growth and behavior. The lower lethal limit also increased, to 50% saturation at 24 °C and to 54% saturation when water temperature climbs to 28 °C, indicating that DO saturation must increase as water temperature increases for the habitat to remain suitable.

4.3. Rearing

4.3.1. Depth, Velocity, Slope, and Substrate

Very little information is available about rearing habitat in the mainstem Snake River for juvenile fall chinook salmon. Key et al. (1996) used beach seines to investigate habitat use of juvenile fall chinook in the Snake River. Unfortunately, their results were subject to bias because the sampling gear limited the ability to sample all habitat types present. More recently, Garland and Tiffan (1999) compared habitat use of juvenile fall chinook rearing in the Snake River and the Hanford Reach of the Columbia River. Their methods used point electro-fishing and were designed to allow sampling over all habitat types. Their final conclusions were that habitat use was similar between the Snake River and the Hanford Reach of the Columbia River and that the primary determinants of fish presence were lateral substrate gradient (< 20%) and water velocity (< 0.35 m/s). While most of the juvenile fall chinook that were collected in both systems were detected over sandy substrates, the researchers reported that all types of substrates were used. The researchers didn't specifically mention depth, except that collections were greatest in shallow areas near the shore, similar to observations of Bennett et al. (1993) for fall chinook rearing within the Little Goose Reservoir.

The criteria we applied to our models were based on data collected by Garland and Tiffan (1999) and Garland et al. (2001), and used by Tiffan et al. (2001), for both the Hanford Reach of the Columbia River, and from within the free-flowing Snake River downstream of the Hells Canyon Dam. In their final analyses, they determined that a depth mask to 1.5 m should first be applied, indicating that suitable habitat would be within the littoral zone at depths less than 1.5 m. They also concluded that a substrate mask should be applied to eliminate from consideration all substrates bigger than large cobble. Finally, they determined through logistic regression that suitable habitat would be located where water velocity was < 0.4 m/s and bottom slope was < 40%. We adopted these indices and decided to use specific masks within our two-dimensional hydraulic site models to indicate littoral areas to a depth of 1.5 m (at modeled discharges) that had substrates of large cobble and smaller, water velocity of < 0.4 m/s, and bottom slopes < 40%. Those areas could then be calculated and compared across a range of discharges and operational

scenarios. A separate, reach-wide analysis was conducted using a one-dimensional hydraulic model with the suitability determinants of littoral depth, substrate type, and bottom slope (Chandler et al. 2002). These habitat criteria values proved satisfactory for biologists conducting similar research within the Columbia River (K. Tiffan, USGS, personal communication).

4.3.2. Temperature and Dissolved Oxygen

As well as for adults, temperature and DO function together in determining the quality of habitat for juvenile rearing and migrating chinook salmon. As the water temperature increases, an organism's respiratory and metabolic activity, as well as oxygen demand, increase. If insufficient oxygen is available to maintain respiratory and metabolic activity, stress develops and increases susceptibility to disorientation, predation, disease, or failure of physiological systems—resulting, finally, in death. The physics of water's ability to contain dissolved gasses, such as oxygen, at varying temperatures can exacerbate these problems. As water temperature increases, the amount of a dissolved gas that water can contain decreases. So, while respiratory and metabolic activity of organisms (fish) increase as water temperature increases, the amount of available oxygen decreases. Temperature also affects the efficiency of enzymatic processes occurring within an organism. Within fish, as well as invertebrates, this is particularly important because they are poikilothermic and incapable of maintaining a constant, efficient, body temperature.

At temperatures lower than about 8.0 °C, Raleigh et al. (1986) noted that chinook salmon fry tended to re-enter the gravel; however, Barton and Schreck (1987) noted that at temperatures as low as 7.5 °C, no stress parameters were present in the blood of sampled chinook fry. These data indicate that while the suitability of habitat may be lowered at temperatures lower than 8.0 °C, they are not necessarily lethal or harmful. Various authors have reported optimal thermal ranges, and their findings mostly indicate that juvenile chinook salmon prefer temperatures in a range between about 11.0 and 14.0 °C (Brett 1952, Ferguson 1958, Coutant 1977). However, Raleigh et al. (1986) reported that a temperature range between 12.0 and 18.0 °C was optimal. Again, any preferred range, as well as upper tolerance and lethal limits, is somewhat dependent on the thermal regime in which fish are acclimated. Biologists sampling juvenile fall chinook salmon rearing within the Snake River downstream of Hells Canyon Dam report that their catch per unit effort decreases rapidly as water temperatures increase above about 16.0 °C (B. Connor, USFWS, Orofino, ID, personal communication). Raleigh et al. (1986) reported reduced growth in chinook juveniles at temperatures greater than 19.0 °C; Barton and Schreck (1987) began to observe stress within juvenile chinook salmon subjected to temperatures greater than 21.0 °C. These data suggest that suitability is decreased at temperatures above at least 19.0 °C. Finally, temperatures greater than 24.0 °C have been reported as lethal to juvenile chinook salmon (Brett 1952). Based on the information reported from these various sources, we developed a water temperature suitability curve for rearing juvenile chinook salmon (Figure 9). A slightly modified curve was prepared for migratory juvenile chinook salmon (Figure 10). The difference in these two curves is that the lower end of the optimal range for migration has been reduced from 11.0 to 9.0 °C. This alteration is based partly on the hypothesis that rearing juveniles have an optimum growth range (growth tends to fall off at lower temperatures), whereas migratory juvenile chinook are generally not feeding and growing.

Within the literature, low values of oxygen saturation were found to be more limiting during periods of warmer water temperatures. Raleigh et al. (1986), citing Bustard (1983), reported that winter mortality was observed when fish were subjected to lengthy periods of low DO levels (below 3.0 mg/l) at temperatures lower than 5.0 °C (equivalent to about 20% saturation). Davis (1975) noted that oxygen levels lower than 4.5 mg/l were avoided only during summer months. Katz et al. (1959) reported that at 20 °C, with an oxygen concentration of 2.84 mg/l (31% saturation), juvenile chinook salmon were unable to maintain swimming against a current of approximately 0.8 ft/s. Finally, Davis (1975) recommended that at temperatures greater than 23.0 °C oxygen levels should be in excess of 90% saturation to provide a high level of protection. In general, higher levels of DO (either measured as mg/l or % saturation) are required as water temperature increases. Our DO suitability curve is identical for both rearing and migratory juvenile chinook salmon and relates the percentage of oxygen saturation to water temperature (Figure 11).

5. SUMMARY

IPC biologists developed chinook salmon criteria curves that can help describe habitat suitability downstream of the HCC. These curves can apply to various operational scenarios and protection, mitigation, or enhancement measures for adult migration and spawning, as well as juvenile rearing and migration. The biologists developed criteria for water temperature for migration, spawning, and rearing; DO for migration, spawning, and rearing; spawning depth; water velocity for spawning and rearing; substrate use for spawning and rearing; rearing distance from shore; and rearing use of lateral substrate surface slope.

In general, the criteria indicate the following conditions:

1. Suitable temperature for migrating adult chinook is from 1 to 8 °C, as well as 15 to 21 °C.
2. Optimal temperature for migrating adult chinook is between 8 and 15 °C.
3. Suitable temperature for spawning fall chinook is from 5 to 10 °C, as well as 15 to 16 °C.
4. Optimal temperature for spawning fall chinook is between 10 and 15 °C.
5. Suitable temperature for rearing fall chinook is from 1 to 10 °C, as well as 15 to 21 °C.
6. Optimal temperature for rearing fall chinook is between 10 and 15 °C.
7. Suitable temperature for migrating juvenile chinook is from 1 to 8 °C, as well as 15 to 21 °C.
8. Optimal temperature for migrating juvenile chinook is between 8 and 15 °C.

9. For all life stages, optimal DO levels are above 76% saturation at temperatures of 16 °C or lower.
10. For all life stages, suitable DO levels are between about 40 and 76% saturation when temperatures are 16 °C or lower.
11. At higher temperatures, DO requirements increase for both optimal and suitable levels.
12. Physical habitat requirements for spawning fall chinook salmon include depths between 0.2 and 6.5 m, mean water-column velocities between 0.6 and 1.7 m/s, and substrate sizes between 2.6 and 15.0 cm long axis length.
13. Physical habitat requirements for rearing fall chinook salmon include areas within the littoral zone to depths of 1.5 m, and having substrates of less than 22.5 cm long axis length, mean water-column velocities less than 0.4 m/s, and lateral shoreline slopes less than 40%.

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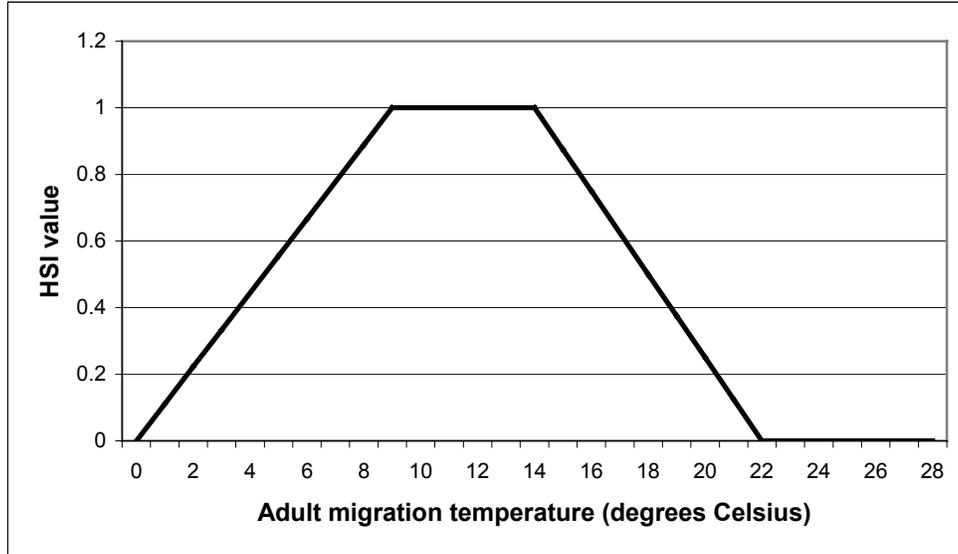


Figure 1. Water temperature criteria for habitat suitability developed for migrating adult chinook salmon.

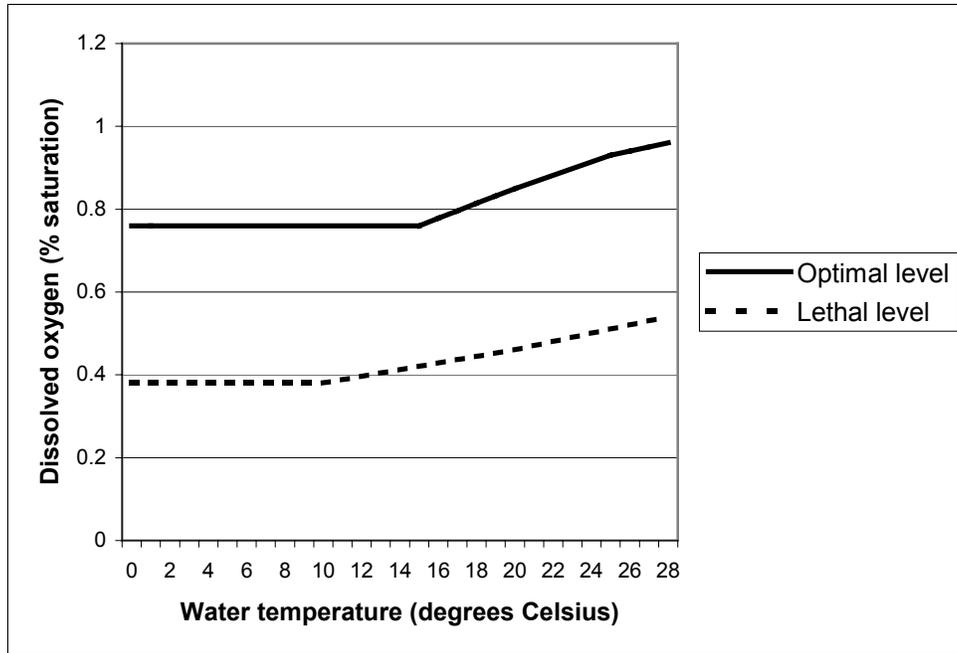


Figure 2. DO optimal and lethal bounds (dependent on water temperature), which were developed for adult migrating and spawning chinook salmon. DO saturation levels between the upper and lower bounds represent suitable conditions that might result in slight reduced, non-lethal activity or other behavior changes.

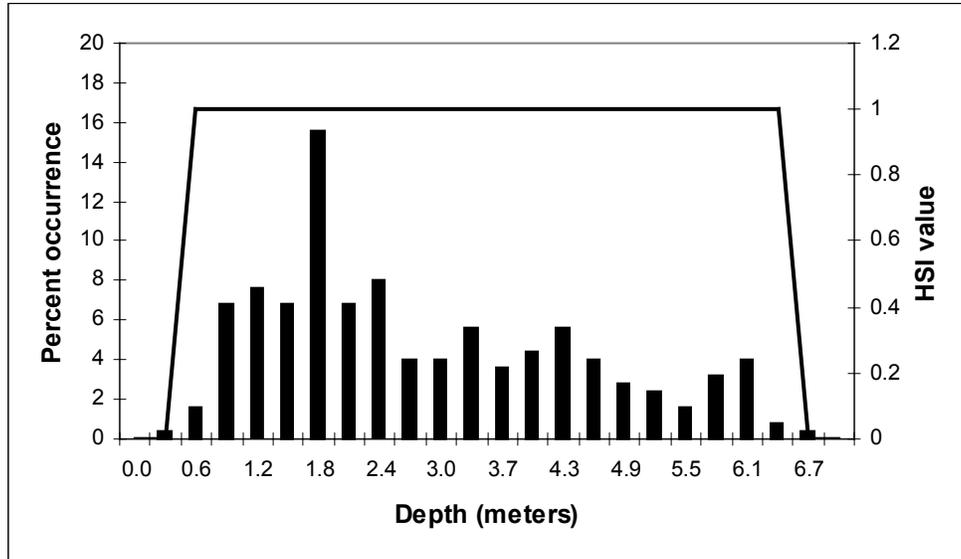


Figure 3. Frequency distribution and resultant habitat suitability criteria of water depth measured at fall chinook salmon redds in the Snake River during 1993–1995 spawning periods.

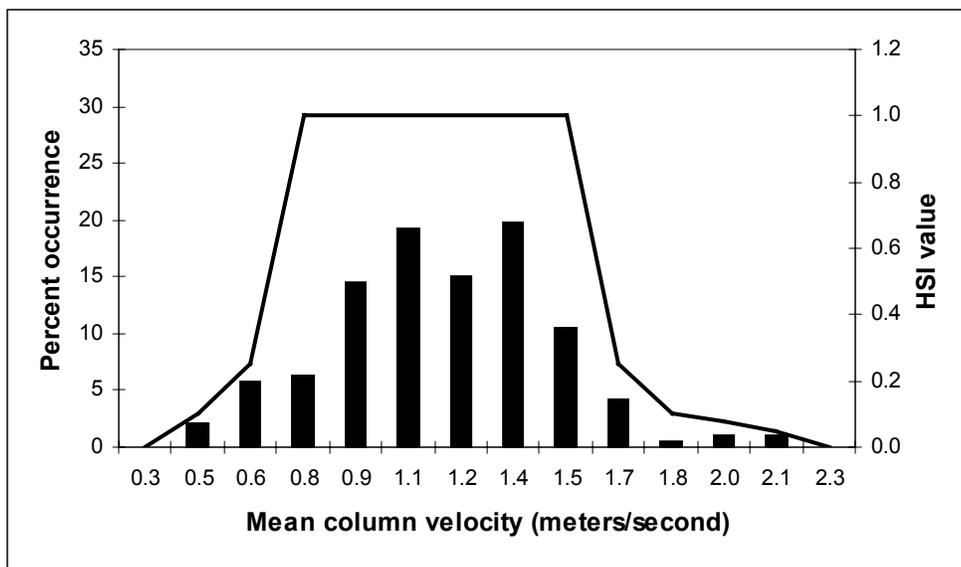


Figure 4. Frequency distribution and resultant habitat suitability criteria of mean water-column velocity measured at fall chinook salmon redds in the Snake River during 1993–1995 spawning periods.

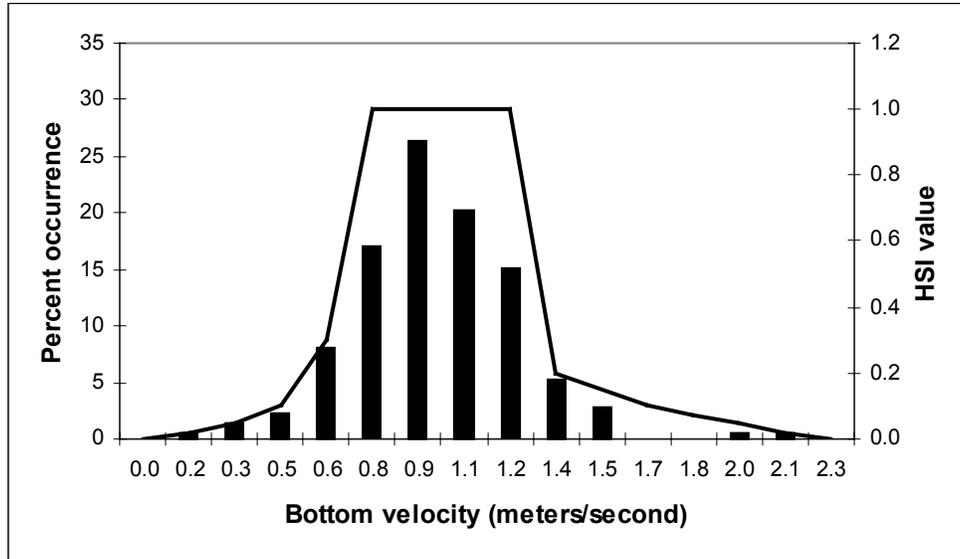


Figure 5. Frequency distribution and resultant habitat suitability criteria of near-bottom water velocity measured at fall chinook salmon redds in the Snake River during 1993–1995 spawning periods.

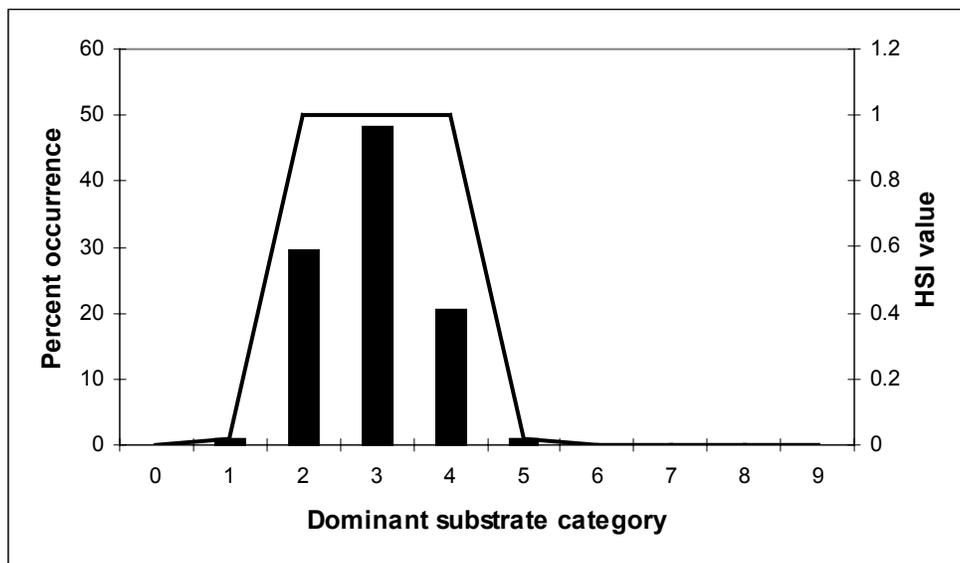


Figure 6. Frequency distribution and resultant habitat suitability criteria of dominant substrate types recorded at fall chinook salmon redds in the Snake River during 1993–1995 spawning periods.

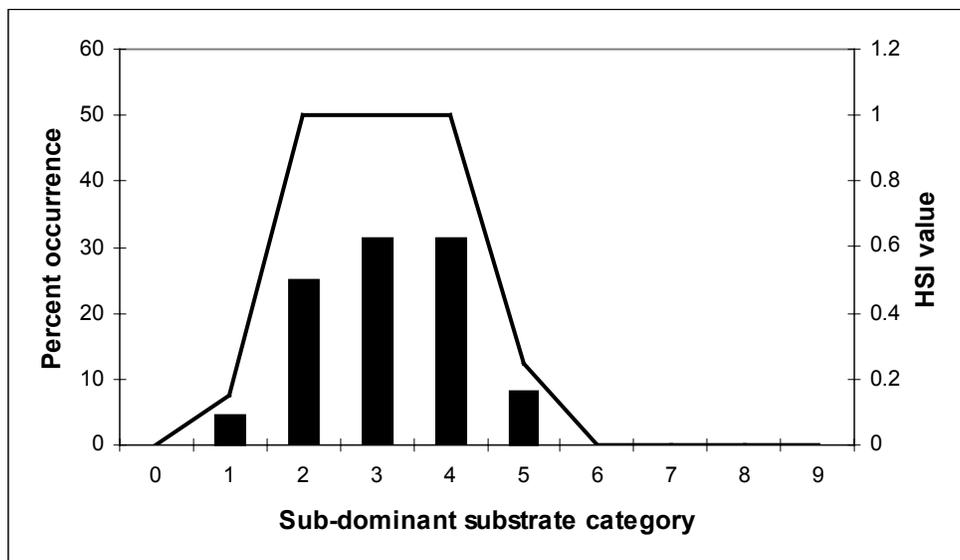


Figure 7. Frequency distribution and resultant habitat suitability criteria of subdominant substrate types recorded at fall chinook salmon redds in the Snake River during 1993–1995 spawning periods.

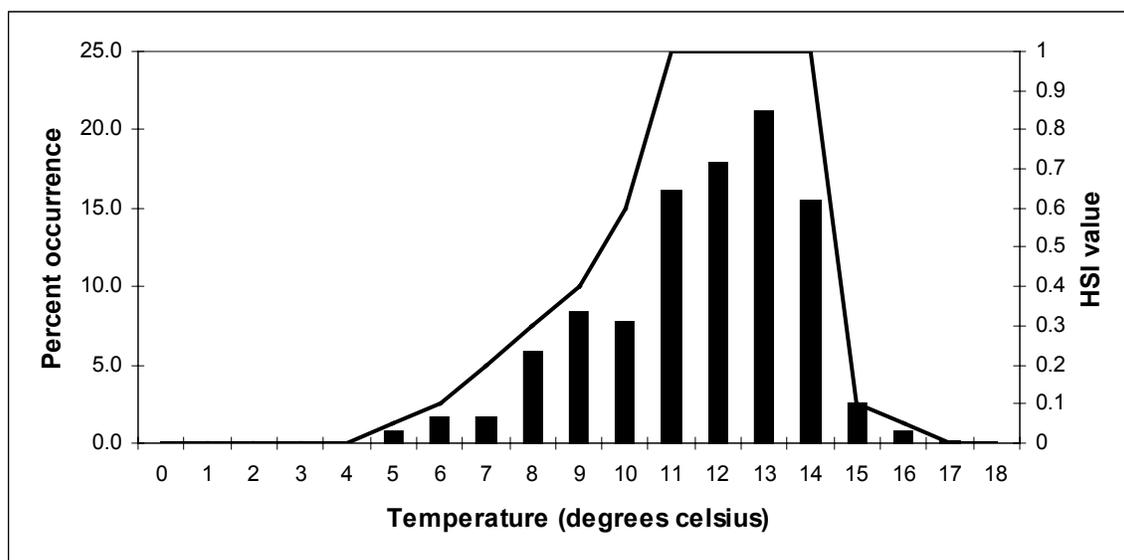


Figure 8. Frequency histogram and developed habitat suitability values of water temperature associated with observed fall chinook spawning activity within the Snake River, 1991–2000.

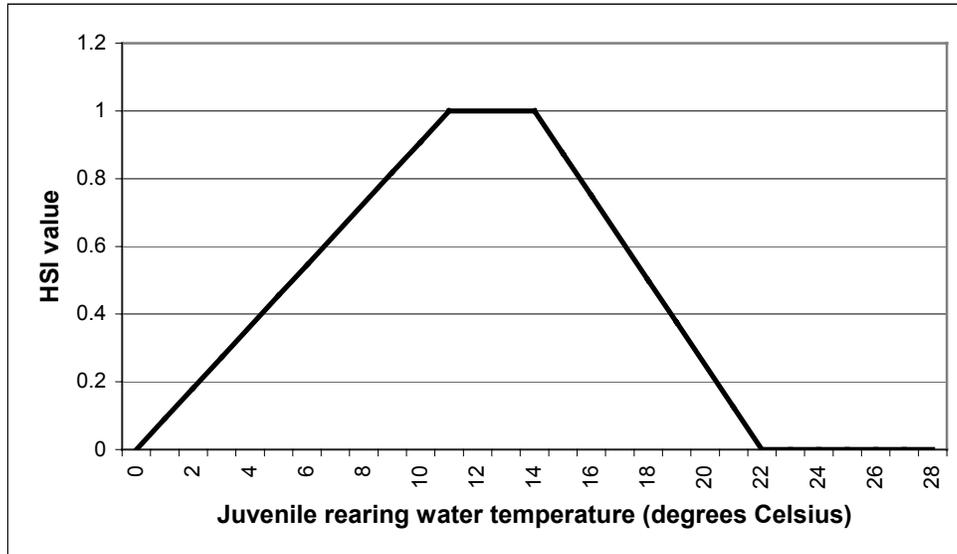


Figure 9. Water temperature criteria for habitat suitability developed for juvenile, rearing chinook salmon.

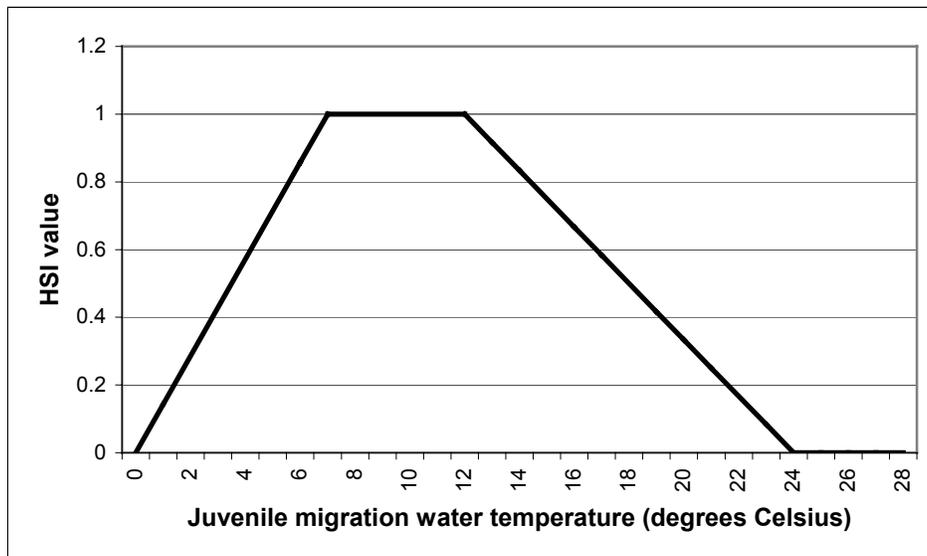


Figure 10. Water temperature criteria for habitat suitability developed for migrating juvenile chinook salmon.

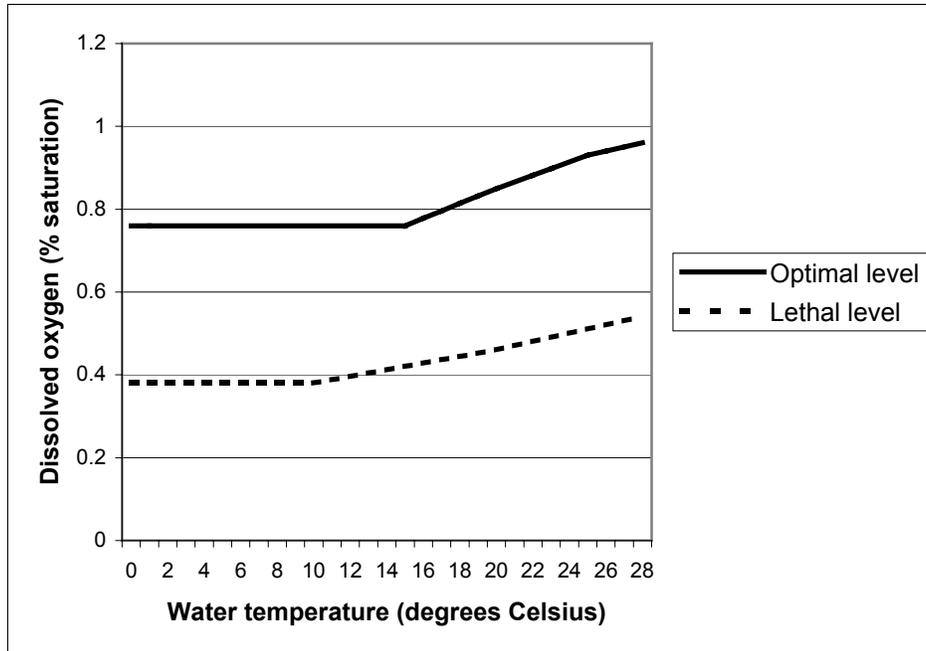


Figure 11. DO optimal and lethal bounds (dependent on water temperature), developed for juvenile rearing and for migrating chinook salmon. DO saturation levels between the upper and lower bounds represent suitable conditions that might result in slight reduced, non-lethal growth or behavior changes.

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