Effects of Hydroelectric Dam Operations on the Restoration Potential of Snake River Fall Chinook Salmon (*Oncorhynchus tshawytscha*) Spawning Habitat

Final Report

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Summary

This report describes research conducted by the Pacific Northwest National Laboratory for the Bonneville Power Administration (BPA) as part of the Fish and Wildlife Program directed by the Northwest Power and Conservation Council. The study evaluated the restoration potential of Snake River fall Chinook salmon spawning habitat within the impounded lower Snake River. The objective of the research was to determine if hydroelectric dam operations could be modified, within existing system constraints (e.g., minimum to normal pool levels; without partial removal of a dam structure), to increase the amount of available fall Chinook salmon spawning habitat in the lower Snake River.

Empirical and modeled physical habitat data were used to compare potential fall Chinook salmon spawning habitat in the Snake River, under current and modified dam operations, with the analogous physical characteristics of an existing fall Chinook salmon spawning area in the Columbia River. The two Snake River study areas included the Ice Harbor Dam tailrace downstream to the Highway 12 bridge and the Lower Granite Dam tailrace downstream approximately 12 river kilometers. These areas represent tailwater habitat (i.e., riverine segments extending from a dam downstream to the backwater influence from the next dam downstream). We used a reference site, indicative of current fall Chinook salmon spawning areas in tailwater habitat, against which to compare the physical characteristics of each study site. The reference site for tailwater habitats was the section extending downstream from the Wanapum Dam tailrace on the Columbia River. Fall Chinook salmon spawning habitat use data, including water depth, velocity, substrate size and channelbed slope, from the Wanapum reference area were used to define spawning habitat suitability based on these variables. Fall Chinook salmon spawning habitat suitability of the Snake River study areas was estimated by applying the Wanapum reference reach habitat suitability criteria to measured and modeled habitat data from the Snake River study areas. Channel morphology data from the Wanapum reference reach and the Snake River study areas were evaluated to identify geomorphically suitable fall Chinook salmon spawning habitat.

The results of this study indicate that a majority of the Ice Harbor and Lower Granite study areas contain suitable fall Chinook salmon spawning habitat under existing hydrosystem operations. However, a large majority of the currently available fall Chinook salmon spawning habitat in the Ice Harbor and Lower Granite study areas is of low quality. The potential for increasing, through modifications to hydrosystem operations (i.e., minimum pool elevation of the next downstream dam), the quantity or quality of fall Chinook salmon spawning habitat appears to be limited. Estimates of the amount of potential fall Chinook salmon spawning habitat in the Ice Harbor study area decreased as the McNary Dam forebay elevation was lowered from normal to minimum pool elevation. Estimates of the amount of potential fall Chinook salmon spawning habitat in the Lower Granite study area increased as the Little Goose Dam forebay elevation was lowered from normal to minimum pool elevation; however, 97% of the available habitat was categorized within the range of lowest quality. In both the Ice Harbor and Lower Granite study areas, water velocity appears to be more of a limiting factor than water depth for fall Chinook salmon spawning habitat, with both study areas dominated by low-magnitude water velocity. The geomorphic suitability of both study areas appears to be compromised for fall Chinook salmon spawning habitat, with the Ice Harbor study area lacking significant bedforms along the longitudinal thalweg profile and the Lower Granite study area lacking cross-sectional topographic diversity.

To increase the quantity of available fall Chinook salmon spawning habitat in the Ice Harbor and Lower Granite study area, modifications to hydroelectric dam operations beyond those evaluated in this study likely would be necessary. Modifications may include operational and structural changes, such as lowering downstream dam forebay elevations to less than minimum pool. There is a large amount of uncertainty as to whether or not such modifications could increase the quantity of available fall Chinook salmon spawning habitat in the Ice Harbor and Lower Granite study area. The results from this study provide some certainty that the quantity and quality of fall Chinook salmon spawning habitat within the lower Snake River are not likely to be increased within the existing hydroelectric dam operations.

Acknowledgments

We thank Jonathan McCloud (BPA) as the contracting officer's technical representative providing oversight of this project. Special gratitude is given to Grant County PUD and the U.S. Army Corps of Engineers Walla Walla District for providing data from the Wanapum and Snake River study areas, respectively. We thank PNNL staff Corey Duberstein, Fenton Khan, Bob Mueller, Katie Murray, Jennifer Panther, Cynthia Rakowski, Scott Titzler, Cherylyn Tunnicliffe, Jessica Vucelick, and Abby Welch for their work on this project.

Contents

Figures

Tables

1.0 Introduction

Development of hydroelectric dams in the Columbia River basin has contributed to the declining abundance of fall Chinook salmon (*Oncorhynchus tshawytscha*) through conversion of rivers to reservoirs and blocked access to historic spawning areas (Dauble et al. 2003). Populations of Snake River fall Chinook salmon have declined to the point that they now are protected under the Endangered Species Act (57 FR 14653). The decline of fall Chinook salmon has prompted management and regulatory agencies to consider actions directed at recovering lost salmon spawning areas, including dam removal, reservoir drawdown, and reintroduction into blocked historic habitat (Dauble et al. 2003; Hanrahan et al. 2004, 2005; Groves and Chandler 2005), as well as expanding existing salmon spawning areas. Because hydroelectric dams impound the majority of the Snake River, the potential exists for increasing mainstem natural production of fall Chinook salmon by increasing the amount of riverine habitat available for spawning and rearing through operational or structural changes of selected hydroelectric dams.

Fall Chinook salmon historically spawned in the mainstem of the Snake River as far upstream as Salmon Falls at river kilometer (rkm) 925 (Dauble et al. 2003). Access to the upper river was blocked in the late 19th and early 20th century by the construction of a series of hydroelectric dams. Swan Falls Dam (rkm 737) was constructed in 1901 and was the upstream terminus for Chinook salmon until the construction of Brownlee Dam (rkm 459) in 1958. Shortly after Brownlee Dam was built, construction was completed on Oxbow Dam (rkm 439) in 1961 and Hells Canyon Dam (rkm 399) in 1967. Brownlee, Oxbow, and Hells Canyon dams form what is now referred to as the Hells Canyon Complex, operated by the Idaho Power Company (IPC). Subsequent to the completion of the Hells Canyon Complex of dams, available Snake River fall Chinook salmon spawning habitat was reduced further by the construction of four hydroelectric dams on the lower Snake River. Ice Harbor Dam (rkm 16) was constructed in 1962, followed by Lower Monumental Dam (rkm 67) in 1969, Little Goose Dam (rkm 113) in 1970, and Lower Granite Dam (rkm 173) in 1975. Completion of the four lower Snake River dams converted 240 rkm of riverine environment into a series of low-velocity impoundments.

Remaining spawning areas for Snake River fall Chinook salmon are largely limited to the Hells Canyon Reach of the Snake River (rkm 240–399). A few fall Chinook salmon (<10 redds per year) also spawn downstream of Lower Granite and Little Goose dams (Dauble et al. 1999; Mueller 2007), where the tailrace environment provides some resemblance of riverine habitat. The presence of these tailrace satellite populations suggests that there is the potential for increasing the spawning habitat use of these locations, if the amount of available spawning habitat can be increased.

This research evaluated the restoration potential of Snake River fall Chinook salmon spawning habitat. The studies addressed two research questions: "Are there sections not currently used by spawning fall Chinook salmon within the impounded lower Snake River that possess the physical characteristics for potentially suitable fall Chinook spawning habitat?" and "Can hydrosystem operations affecting these sections be adjusted such that the sections closely resemble the physical characteristics of current fall Chinook salmon spawning areas in similar physical settings?" The objective of this research was to determine if hydroelectric dam operations could be modified, within existing system constraints (e.g., minimum to normal pool levels; without partial removal of a dam structure), to increase the amount of available fall Chinook salmon spawning habitat in the lower Snake River.

2.0 Methods

Research efforts were focused at two study sites in the lower Snake River: 1) the Ice Harbor Dam tailrace downstream to the Highway 12 bridge and 2) the Lower Granite Dam tailrace downstream approximately 12 rkm. Previous studies indicated that these two areas have the highest potential for restoring Snake River fall Chinook salmon spawning habitat (Dauble et al. 2003). These areas represent tailwater habitat (i.e., riverine segments extending from a dam downstream to the backwater influence from the next dam downstream). We used a reference site, indicative of current fall Chinook salmon spawning areas in tailwater habitat, against which to compare the physical characteristics of each study site. The reference site for tailwater habitats was the section extending downstream from the Wanapum Dam tailrace on the Columbia River. Escapement estimates for recent years indicate more than 9,000 adult fall Chinook salmon return to this area, accounting for more than 2,100 redds within a 5-km section of river (Grant PUD, personal communication).

2.1 Wanapum Reference Area

Fall Chinook salmon spawning habitat was evaluated from Wanapum Dam downstream to Crab Creek, which is the downstream extent of fall Chinook salmon spawning (Figure 2.1) on the Columbia River. The study area shoreline is characterized by arid shrub-steppe ecotypes with low vegetative cover. Near-shore habitat throughout the study area consists of basalt bedrock formations, unconsolidated basalt, and unconsolidated cobble/gravel.

Spawning habitat suitability was quantified within the reference area using suitability indices. Characterization of channel morphology and hydraulic modeling required creation of a three-dimensional surface of channel bed elevations (bathymetry). Suitability criteria were based on empirical and modeled measurements of depth, substrate, velocity, and channel bed slope of fall Chinook salmon redds from the Wanapum tailrace. A hydraulic model was used to predict how habitat suitability changed with discharge. For the modeling, the suitability indices of individual characteristics were combined into one composite index to assess relative habitat quality for the entire project area.

2.1.1 Bathymetry

The development of a bathymetry dataset for the Wanapum tailrace (Priest Rapids pool) involved the compilation of new and existing data. The following datasets were acquired and processed into the final bathymetric dataset.

Data were acquired from a light detection and ranging (LiDAR) data collection effort performed in 2002 and encompassed the full pool length of Priest Rapids, extending from rkm 635 to rkm 666. Data were provided by the LiDAR contractor (3Di, Inc.) in an ASCII text file format and were extracted and processed into a vector GIS format using a specially developed UNIX Bourne shell script. The data have a ground spacing (resolution) of approximately 4 meters. LiDAR data were used to build out-shore terrestrial areas (including in-stream islands) in the bathymetric dataset.

Figure 2.1. Wanapum Reference Area Extending from Wanapum Dam Downstream to Crab Creek

Bathymetry data originally collected by Sverdrup for other forebay/tailrace studies were acquired and incorporated into the data processing. The data were provided in the form of spot elevations and contour data. The data were concentrated primarily at the Priest Rapids Dam tailrace and the Wanapum Dam forebay and tailrace. Approximate resolution of the dataset is 1-2 meters.

PNNL collected bathymetry data in the form of vector spot elevations to fill in areas with little or no existing data in the Priest Rapids pool. Data were collected using an Innerspace 455 single-beam, survey-grade, echo sounder with an 8-degree transducer, operating at 208 kHz, and a manufacturer's stated vertical accuracy of 3.05 cm. The echo sounder was coupled and synchronized with a real-time differentially corrected submeter Global Positioning System receiver (Trimble ProXR) providing horizontal positioning and depth values. Vertical positioning was established using piezometers positioned throughout the Priest Rapids pool. The piezometers were surveyed in to allow for the measurement of an accurate water surface elevation, and logger results were extrapolated by time and space to establish a true pool bottom elevation.

Data were processed primarily using a geographic information system (GIS) software package, Arc/INFO v. 8.1.2, from Environmental Systems Research Institute, Inc. (ESRI). As indicated previously, LiDAR data were preprocessed using a customized data extraction script and then incorporated into the GIS. The various data sources were brought into a common projection and horizontal/vertical datum before surface generation was performed. Prior to surface processing, raw dataset elevations were compared for a measure of quality control. Vector elevation data were then compiled into a three-dimensional surface using a triangulated irregular network (TIN) methodology. Several iterations of this processing were performed to eliminate data anomalies. The final TIN was converted into a regularly spaced raster using a nearest-neighbor type of interpolation. The output resolution of the dataset is approximately 3 x 3 meters. This surface was used to create the computational mesh for the two-dimensional hydrodynamic model.

2.1.2 Hydrodynamic Model

Depth-averaged water velocities downstream of Wanapum Dam were simulated using the hydrodynamic and water quality model MASS2 (Modular Aquatic Simulation System 2-D). MASS2 is an unsteady, two-dimensional model that simulates hydrodynamics and water quality in rivers and estuaries for subcritical and supercritical flow regimes (Perkins and Richmond 2004a, 2004b). The model uses a structured multi-block, boundary-fitted, curvilinear computational mesh to represent the river geometry. The blocks may be of varying resolution that allows the simulation of complex river or estuary systems. Finite-volume methods (Patankar 1980) are used to discretize and solve the conservation equations for mass, momentum, and water quality constituents. The model is computationally efficient; it has been used to simulate flow conditions over long reaches (10 to 120 rkm) at high spatial resolution (cells sizes are typically 3 to 50 m) and high temporal resolution (on the order of 30 seconds).

Gridgen (Pointwise, Inc., Fort Worth, Texas) was used to develop the computational mesh for each study reach. Bottom elevations for each mesh cell were determined from continuous, three-dimensional, raster-based bathymetric surfaces for each reach. The computational mesh extends from Wanapum Dam, the upstream inflow boundary, to Priest Rapids Dam, where the downstream stage boundary is specified. The mesh contains 18 blocks with a total of 96,512 cells. The lateral resolution ranged from 3 to 218 m and averaged 12 m. The longitudinal resolution ranged from 4 to 172 m and averaged 17 m, with smaller mesh cells representing regions of particular interest. The variable mesh size increases computational efficiency by using increased resolution only in areas of interest.

The input boundary conditions required for MASS2 are river discharge at the upstream boundary and water surface elevation (stage) at the downstream boundary. Hourly discharges from Wanapum Dam and hourly forebay elevations from Priest Rapids Dam were obtained for the fall Chinook salmon spawning period of October 2000. These data were used to calculate the 10, 50, and 90% percent exceedence values for discharge (Q_{10}, Q_{50}, Q_{90}, respectively) and forebay elevation during October 2000 (Table 2.1). These values were used to specify the upstream inflow and downstream water elevation for the MASS2 model of the Wanapum reference area.

Table 2.1. Columbia River Fall Chinook Salmon Spawning Season Scenarios Used for Upstream (inflow) and Downstream (stage) Boundary Conditions for the MASS2 Model of the Wanapum Reference Area. The exceedence discharge is the volumetric flow rate (cfs) that was equaled or exceeded 10, 50, and 90% of the time (Q_{10}, Q_{50}, Q_{90}, respectively). The exceedence forebay elevation (ft) is that which was equaled or exceeded 10, 50, and 90% of the time (Q_{10}, Q_{50}, Q_{90}, respectively).

Boundary Condition	**Exceedance** **Q_{10}**	 **Q_{50}**	 **Q_{90}**
Wanapum inflow (cfs)	120,600	75,000	38,500
Priest Rapids forebay elevation (ft)	487	486	484.4

Note: the volumetric discharge unit $ft^3 s^{-1}$ (cfs) is the standard unit of discharge used by regional water management agencies, and is used throughout this report; similarly, forebay elevations are given in units of feet.

The Wanapum tailrace was a new application of MASS2, and model results were validated by comparing simulated depth-averaged velocity, both magnitude and direction, with observations from acoustic Doppler current profiling. The simulated depth-averaged velocity magnitude and directions were in reasonable agreement with the measurements. The mean absolute velocity error was 0.62 ft s^{-1}. After the model was validated, steady-state simulations were run for the specified boundary conditions. Simulations provided water velocities and depths at a resolution corresponding to the computational mesh. MASS2 simulation results were exported to the GIS database as Arc/Info grids.

2.1.3 Substrate

Grain-size distribution was determined using Wolman pebble counts in areas sufficiently shallow to wade; in areas too deep to wade, we used an underwater video camera to determine grain size. Pebble counts were distributed evenly, and points selected at random from within the selected polygon. A distance of approximately 30 meters between points was used. Points were collected below the high-water mark and marked with a Trimble ProXR GPS. Pebble count sample locations were determined randomly using a consistent selection method. The exact location of each grain was always the same relative to the observer—for example, the first grain encountered in front of the observer's left boot. If the observer reached down to that point and contacted two grains, the grain on the left would be used each time, and so forth. After a grain was selected, the size class was determined using a metal template with holes representing ½ phi size classes. We recorded the largest size class for which the grain would not pass through the template.

The underwater video system consisted of a high-sensitivity remote camera (Sony Model HVM-352) attached to a weighted platform. Recordings were made using a digital 8-mm recorder (Sony Model GV-D800) located on the survey vessel. Two high-resolution monitors were used during the surveys for better viewing of the video obtained by the remote camera. An integrated video/tow cable attached to a manual winch with slip ring mechanism was used to raise and lower the camera sled to the desired depth. The camera was mounted on a diving sled platform containing two downward-pointing lasers, providing reference scale within each video image. Positional data were recorded using a Trimble ProXRS DGPS (real-time differentially corrected) receiver controlled with Trimble Aspen or TerraSync. From each location where video images were recorded to determine the riverbed grain size, underwater video tapes were reviewed and one grain randomly selected for analysis. The random selection process followed arbitrary rules similar to the process of selecting a grain for a pebble count (i.e., if the reference laser falls between two grains, always select the one from the same side, etc.). The intermediate (B) axis of each grain was measured using Optimus software to determine its length.

Ten equal-area polygons were established to define the reference study site in the Wanapum Dam tailrace area. Within the polygon coverage, an evenly distributed 10-m spacing point coverage was created to assist with data collection. The point coverage was loaded into Aspen and used as a navigational reference to collect each data point.

Several indices of substrate composition provide means of evaluating the quality of spawning gravels. The geometric mean (d_g) provides a measure of central tendency, while emphasizing the extremes of the distribution rather than the median (Kondolf 2000). The geometric mean (d_g) is determined by

$$d_g = (d_{84} \text{ x } d_{16})^{0.5} \tag{2.1}$$

The symbols d_{84} and d_{16} represent the grain size (in millimeters) at which 84% and 16% of the sampled grains were finer than. The geometric sorting coefficient (s_g) is an indication of the sorting (or grouping) of similarly sized particles (Kondolf 2000). When particles of all sizes are well mixed together (also known as dispersion), s_g values increase. Conversely, when particles of the same size are grouped together (i.e., a deposit is well sorted by particle size classes), s_g values decrease. The geometric sorting coefficient is determined by

$$s_g = (d_{84} / d_{16})^{0.5} \tag{2.2}$$

The Fredle index (F_i) combines central tendency (d_g) with a different sorting coefficient (s_t). The Fredle sorting coefficient (s_t) is similar to s_g, except uses d_{25} and d_{75} instead of d_{16} and d_{84}. The Fredle index is a concise measure of d_g and s_g, is common in the literature (Kondolf 2000), and is thus a useful tool for comparing results to the literature. The Fredle index is determined by

$$F_i = d_g / s_t = [(d_{84} \text{ x } d_{16})^{0.5}]/[(d_{75}/d_{25})^{0.5}] \tag{2.3}$$

A total of 4,974 underwater video substrate images were processed for the Wanapum Dam tailrace reference area. For each point where an image was processed, a grain size was determined and entered into a GIS. Grain-size sorting indices (e.g., d_g, S_g, and F_i) were computed for each polygon.

2.1.4 Channel Morphology

The MASS2 model output was imported into a GIS database for analysis of hydraulic geometry at closely spaced cross sections. Model results were extracted from 85 cross-sections spaced 50–100 m apart throughout the study area. The hydraulic geometry at these cross sections was estimated with a steady discharge of 120,600 cfs and a Priest Rapids Dam forebay elevation of 487 ft. At each cross section, the model results were used to calculate the top width, mean depth, and depth at individual stations spaced 3 m apart along a cross section. These data were used to calculate the ratio of width to mean depth (*F*, an index of channel shape) and the ratio of maximum depth to mean depth (*d**, an index of cross-section asymmetry) for each cross section. When considered simultaneously, these two indices summarize a continuum of cross-sectional channel form that ranges from narrow and deep triangular channels to wide and shallow rectangular channels (Figure 2.2). To categorize each cross section within this continuum, we assigned each cross section into one of four categories based on the combined *F* and *d** values (Table 2.2).

Quantifying the channel morphology of existing spawning areas involved identifying the longitudinal bedforms where fall Chinook salmon spawning occurs. The analysis of the longitudinal bedform profile

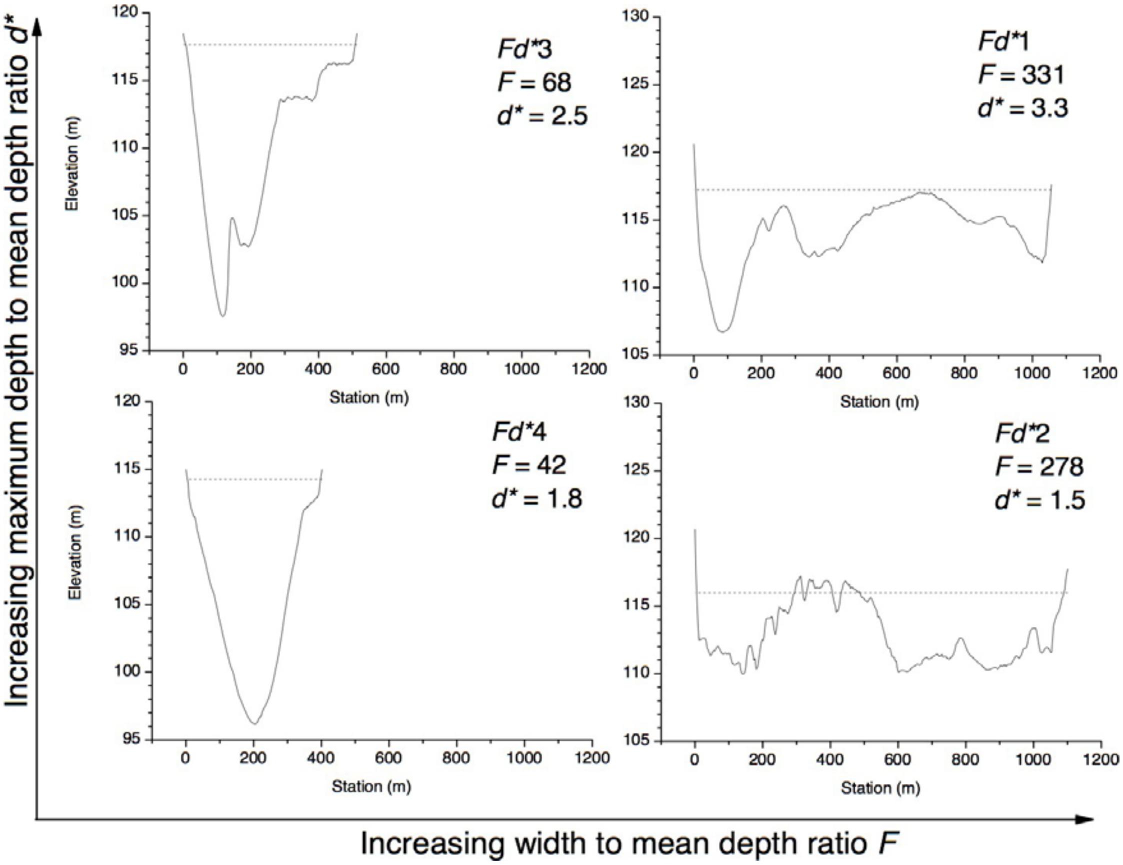

Figure 2.2. The Continuum of Cross-Sectional Channel Form Based on the Combination of Width to Mean Depth Ratio *F* and Maximum Depth to Mean Depth Ratio *d**. These cross-section plots of bed elevation (solid line) and water surface elevation (dashed line) at a total discharge of 120,600 cfs, represent the extremes of the *F* and *d** values for the sampled cross sections. All cross sections are plotted at the same scale. The vertical exaggeration is 40x.

Table 2.2. Criteria for Categorizing Cross Sections Based on *F* and *d**

Fd* **Category**	**Definition**	**Description**
1	$F >= 100$ and $d^* >= 2.0$	Cross section is typically asymmetrical, wide, with part shallow bar deepening into a V-shaped deep thalweg
2	$F >= 100$ and $d^* < 2.0$	Cross section is symmetrical, wide, and with relatively uniform shallow depths
3	$F < 100$ and $d^* >= 2.0$	Cross section is asymmetrical, narrow, with part shallow bar deepening into a V-shaped thalweg
4	$F < 100$ and $d^* < 2.0$	Cross section is symmetrical, narrow, and relatively uniformly deep

was completed using sequential bed elevation data from the thalweg of the river based on the created bathymetry surface. Thalweg points from each of the 85 cross sections were used in a bedform differencing technique to identify pools and riffles (O'Neill and Abrahams 1984). Application of the technique resulted in identification of the thalweg points that were either riffle crests or pool bottoms. After riffle crests and pool bottoms were identified, two additional analyses were completed to classify where the remaining thalweg points were located relative to the riffle crests and pool bottoms. First, the thalweg points were determined to be in riffles or pools based on their riffle proximity index (*RPI*):

$$RPI \ = \ 1 - \frac{rcelev \text{ - } tpelev}{rcelev \text{ - } pbelev} \tag{2.4}$$

where *rcelev* = nearest riffle crest elevation, *tpelev* = thalweg point elevation, and *pbelev* = nearest pool bottom elevation (Hanrahan 2006). The *RPI* ranges from 0.0 to 1.0, where thalweg points with an *RPI* greater than 0.50 were categorized as being in riffles, while the remaining points were categorized as being in pools. Second, all thalweg points were categorized as being located in one of four areas along the longitudinal profile: 1) upstream side of riffle crests, 2) downstream side of riffle crests, 3) upstream side of pool bottoms, and 4) downstream side of pool bottoms.

Fall Chinook salmon spawning locations were incorporated into the GIS database for an analysis of their spatial relationship with bedform types. GIS overlay techniques were used to code all cross sections and thalweg points as spawning or non-spawning, depending on their proximity to the observed spawning locations. Cross-tabulation tables and Pearson's chi-square (χ^2) test statistic were used to test the null hypothesis that spawning habitat use was independent of bedform category ($\alpha = 0.05$). Wald-Wolfowitz runs test was used to test the null hypothesis that thalweg points in spawning and non-spawning areas had the same mean *RPI* ($\alpha = 0.05$). Similar channel morphology data from other fall Chinook salmon spawning habitat reference locations in the Columbia and Snake rivers were used for comparative purposes (Geist et al. 2006; Hanrahan 2007a).

2.1.5 Fall Chinook Salmon Spawning Habitat

The results from each MASS2 model run were imported into the GIS database, providing hydraulic data (e.g., depth and velocity) for each node in the study area. A continuous surface for each hydraulic variable was created using an inverse distance weighting interpolation between nodes. The interpolated value of individual "habitat cells" (Payne and Lapointe 1997) was determined by a linearly weighted average of the three nearest nodes of each cell. The weight was a function of inverse distance, such that nearby sampling points had more influence on the interpolated value. The resulting surfaces for depth and velocity had cell sizes of 9 m^2 (3 m x 3 m) and were used to estimate potential spawning habitat. A habitat cell size of 3 m was chosen to estimate hydraulic conditions at a fine scale relative to channel size (mean widths ~300 to 800 m), particularly near the shorelines. Each habitat cell (i.e., 9 m^2) was assumed to represent depth and velocity conditions of a hydraulically uniform area of river.

Once the physical channel characteristics were assessed and the hydraulic modeling was completed, spawning habitat suitability was assessed by comparing suitability criteria developed from characteristics of habitat cells in spawning areas to the entire population of habitat cells that were available for spawning. Habitat suitability criteria were formulated using a combination of empirical measurements of habitat use based on substrate, slope, depth and velocity at the location of individual redds and modeled data (Table 2.3). As previously described, depth and velocity values were modeled for each habitat cell for all nine model scenarios and pooled for analyses. Channel bed slopes were calculated for all habitat cells as described above. Available substrate was determined using empirical measurements made at geomorphic units within the entire study area. Substrate summary statistics based on the distribution within each geomorphic unit were used to categorize individual geomorphic units as "suitable" or "not suitable." A unit (and consequently a habitat cell within that unit) was categorized as suitable for substrate if

1. The d_g, d_{84}, and d_{75} values (i.e., grain size in millimeters) were within the criteria defining the size range of suitable fall Chinook spawning substrate (Table 2.5).

2. The unit lacked an appreciable amount of fine sediment as indicated by strongly negatively skewed grain-size distributions (Kondolf and Wolman 1993; Kondolf 2000).

Once depth, velocity, substrate, and slope were assigned to each habitat cell, the cell was classified as either suitable or not suitable for fall Chinook spawning habitat (i.e., a binary classification). To be suitable, all of the characteristics of habitat cells had to fall within the criteria range (Table 2.3).

Table 2.3. Criteria Defining Suitable Fall Chinook Salmon Spawning Habitat. Criteria were based on empirical data measured at individual redds, as well as modeled hydraulic data within habitat cells that contained at least one fall Chinook redd.

Variable	Values
Depth	0.30–11.50 m
Velocity	0.10–2.25 $m \cdot s^{-1}$
Substrate	20–270 mm
Channel bed slope	0.0–7.0 %

Suitable habitat was classified further for quality by assigning habitat suitability index (SI) values (weights) to each cell of suitable spawning habitat, thereby partitioning the suitable habitat into categories ranging from low to high quality. Habitat modeling with suitability curves typically requires the use of suitability criteria originating within the river of interest (Bovee 1995). We developed our depth, velocity, and channel bed slope SI curves based on data from the Wanapum tailrace using the modeled data and measured data from redds. We completed a frequency analysis with the depth, velocity, and slope data, resulting in probability-of-use values (SI curves) for a range of hydraulic conditions (Bovee and Cochnauer 1977; Bovee 1995). The SI curves represented weighted criteria, where a value of 1.0 indicated the optimum condition for a given hydraulic variable (Figure 2.3). Because the measured data from redds were biased toward the extremes of the depth and velocity distributions, the SI curves were

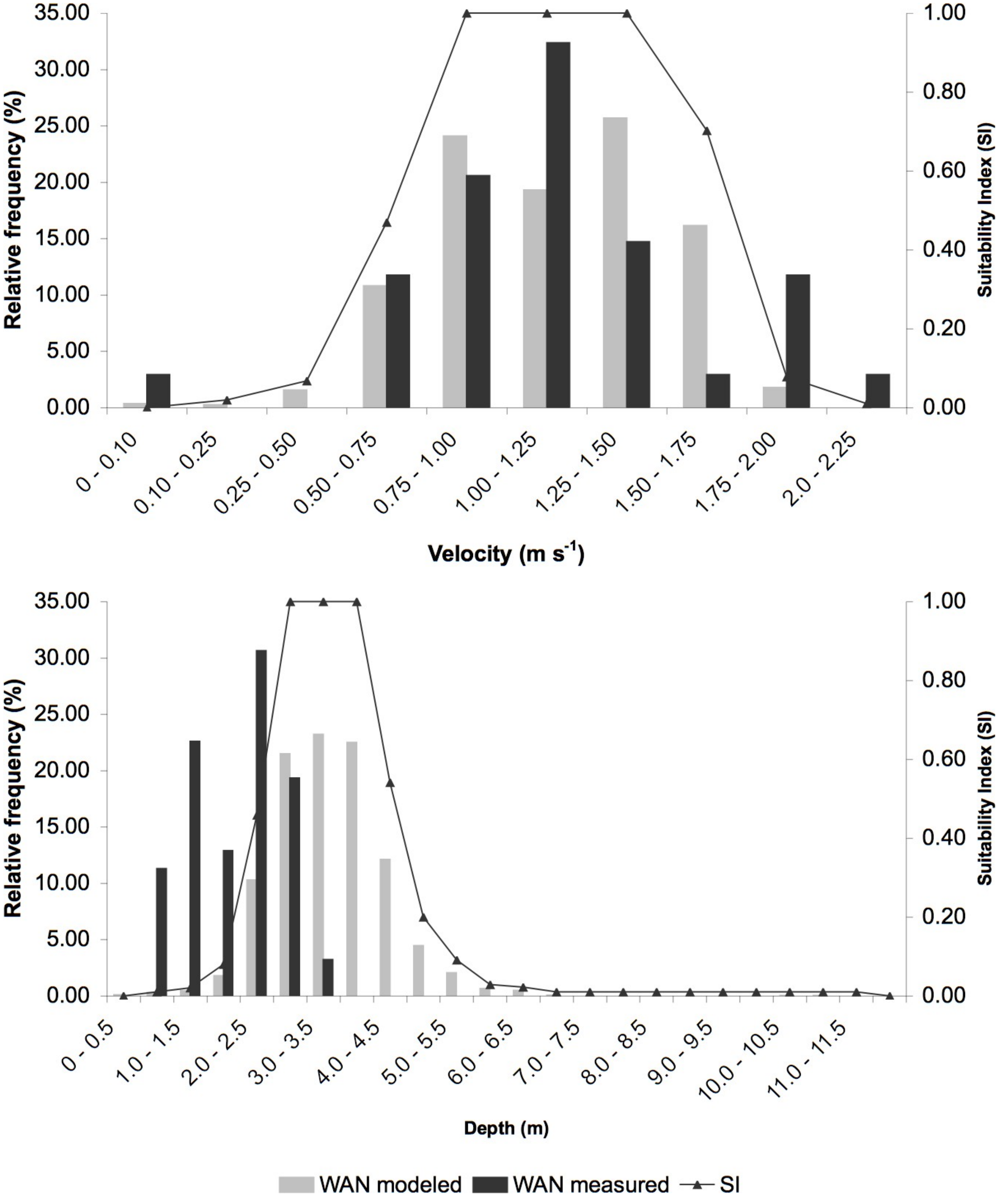

Figure 2.3. Velocity (top panel) and Depth (bottom panel) at Fall Chinook Salmon Redds in the Wanapum Reference Area. The resulting suitability curves were based on modeled (*n* = 47,227 cells) and empirical observations (*n* = 62 redds).

adjusted at the lower and upper ends to eliminate any artificial bimodal distributions. The SI curves were adjusted through range and optimum analysis (Bovee and Cochnauer 1977); however, the depth and velocity values were always assigned an SI value less than or equal to the nearest value from the original SI curve.

2.2 Ice Harbor and Lower Granite Study Areas

Fall Chinook salmon spawning habitat was evaluated at two study areas of the lower Snake River: 1) the Ice Harbor Dam tailrace downstream to the Highway 12 bridge and 2) the Lower Granite Dam tailrace downstream approximately 12 rkm (Figure 2.4). The study area shoreline is characterized by arid shrub-steppe ecotypes with low vegetative cover. Near-shore habitat throughout the study area consists of basalt bedrock formations, unconsolidated basalt, and unconsolidated cobble/gravel.

Spawning habitat suitability was quantified within the study areas using suitability indices derived from the Wanapum reference area. Predictions of spawning habitat suitability for both study areas were made by comparing characteristics of channel morphology and hydraulics to suitability criteria from redds in the Wanapum tailrace. Characterization of channel morphology and hydraulic modeling required the creation of a three-dimensional surface of channel bed elevations (bathymetry). A hydraulic model was used to predict how habitat suitability changed with discharge. For the modeling, the suitability indices of individual characteristics were combined into one composite index to assess relative habitat quality for the entire project area.

2.2.1 Bathymetry

A continuous three-dimensional, raster-based bathymetric dataset was required to develop the computational mesh used by the MASS2 hydrodynamic model and to describe the physical habitat characteristics for each reach in the study. New hydrographic surveys were conducted at the tailraces of Ice Harbor and Lower Granite dams to supplement existing bathymetric data used in previous hydrodynamic models of these reaches.

Bathymetric data were collected using an Innerspace 455 single-beam, survey-grade, echo sounder with an 8-degree transducer, operating at 208 kHz, and a manufacturer's stated vertical accuracy of 3.05 cm. Positioning and depth data were collected and saved on a rate of one measurement per second. Horizontal and vertical position of the echo sounder was derived using a Trimble 5800 Real-Time Kinematic Global Positioning System (RTK-GPS) receiver providing the most efficient and accurate data possible for the survey. The horizontal and vertical accuracy of the RTK-GPS was calculated to be less than 4 cm and was verified using other known and published benchmarks from the Washington State Department of Transportation, U.S. Army Corps of Engineers, and the National Geodetic Survey. The RTK-GPS antenna and integrated receiver was mounted on a fixed-length survey pole above the echo sounder transducer. To calculate a true bottom elevation, the echo-sounder reported depth and survey pole length were subtracted on-the-fly from the synced RTK-GPS elevations.

The hydrographic survey was conducted in the tailrace areas of Ice Harbor Dam on February 2–4, 2005, and extended from rkm 3.8 (Highway 12 bridge) to rkm 13.8. The surveys for the Lower Granite Dam tailrace were conducted on February 7–9, 2005, and extended from rkm 160 to rkm 170.

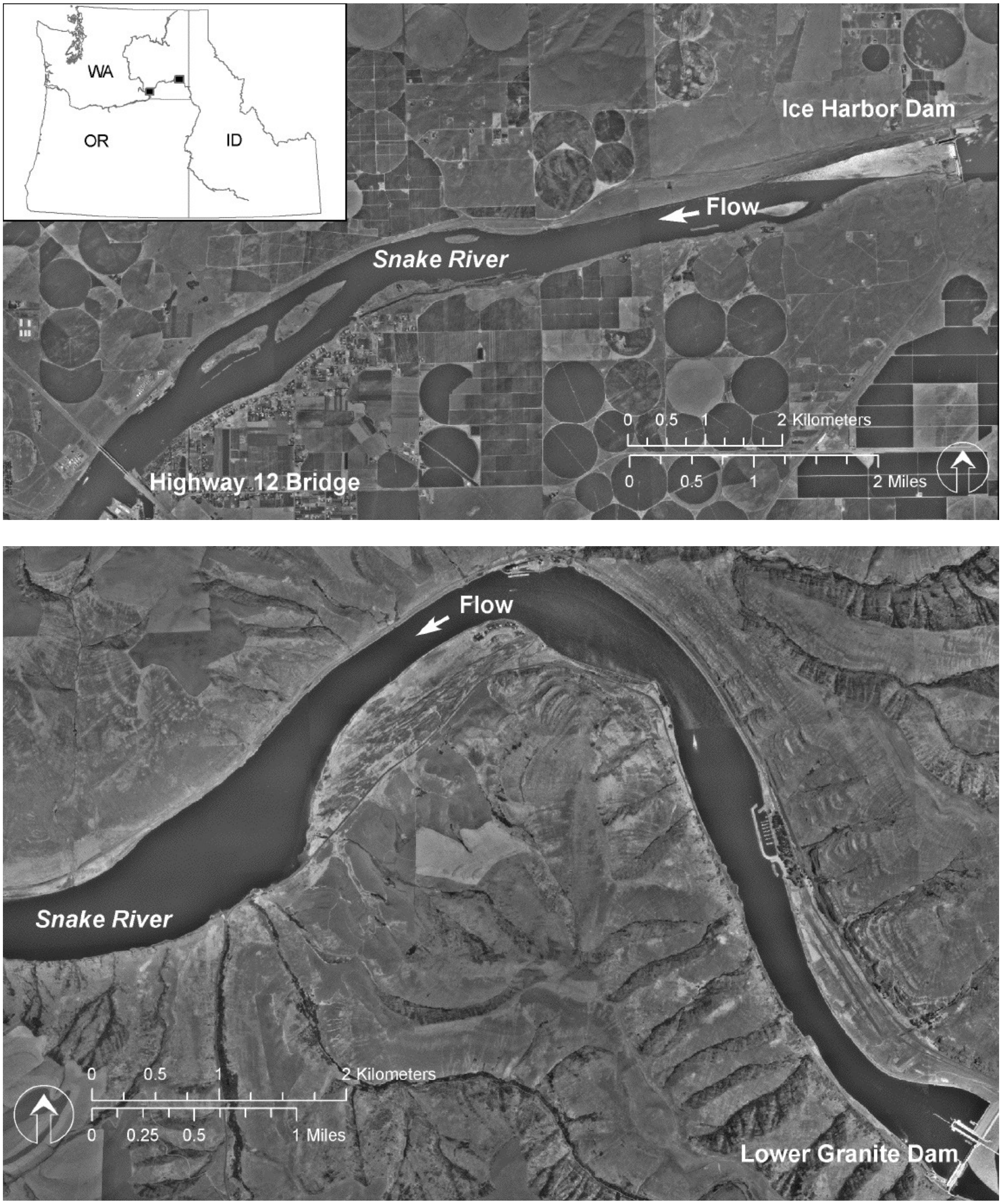

Figure 2.4. Study Areas in the Lower Snake River, Washington. The Ice Harbor study area (top panel) extended from Ice Harbor Dam downstream to near the Highway 12 Bridge (approximately river kilometer (rkm) 2 to rkm 16). The Lower Granite study area (bottom panel) extended from Lower Granite Dam downstream 12 rkm (approximately rkm 161 to rkm 173).

For the Ice Harbor Dam tailrace, the RTK-GPS base station was set at the National Geodetic Survey (NGS) benchmark “SA2465” on the deck of the dam. This is a horizontal order “A” and vertical order “3” benchmark with a relative horizontal accuracy of 5 mm and a relative vertical accuracy of 3 mm. The RTK-GPS base station was verified with Washington State Department of Transportation benchmark “Sacajawea 2/Monument ID 30” at the northeast side of the Snake River Highway 12 bridge.

For the Lower Granite Dam survey, NGS benchmark “RZ1892” on the deck of the dam was used as a base station for the tailrace hydrographic survey. This benchmark is a part of the High Accuracy Reference Network and is published as a horizontal order “B” and vertical order “3” benchmark with a relative horizontal accuracy of 8 mm and a relative vertical accuracy of 3 mm. The base station was verified with the U.S. Army Corps of Engineers reference mark “39+52.98” also located on the dam platform. A new benchmark was established upstream of the Almota port and was verified back to the original reference benchmarks.

As a verification of the elevation data collected with the RTK-GPS/echo-sounder system, three pressure sensors were deployed and surveyed-in at the upstream, middle, and downstream location of each survey area to track possible water level changes. These data were then used independently without the RTK-GPS vertical data to determine a bottom elevation. The bathymetric data were collected in a pattern of lateral transects (perpendicular to flow direction) that were preplanned using ArcGIS software with digital orthophotography and existing bathymetry data. In the field, the preplanned transects were loaded and viewed in real time using Trimble’s HydroPro navigation and data collection software. The distance between transects was 51.8 m and 305 m in alternating orders at the Ice Harbor Dam tailrace, and 51.8 m at the Lower Granite Dam tailrace. The varying transect widths were determined by using existing bathymetric data, allowing for the collection of data where none currently existed. To test for the data quality of our hydrographic survey, all existing bathymetric data were overlapped with the current survey and later tested for mean differences (determined to be no greater than 20 cm in both tailraces). Data from a total 187 transects were collected at Lower Granite Dam tailrace and 149 transects at Ice Harbor Dam. Tables 2.4 and 2.5 reference source data and dates of collection for both Ice Harbor and Lower Granite tailraces.

Table 2.4. Bathymetry Data Downstream from Ice Harbor Dam

Name	Data Source	Year
Ice Harbor Tailrace Survey	USACE Walla Walla	1993
Port Survey	USACE Walla Walla	1995
Sediment Range Survey	USACE Walla Walla	1997
Navigation Channel Survey	USACE Walla Walla	2002
PNNL Survey	PNNL	2005

Table 2.5. Bathymetry Data Downstream from Lower Granite Dam

Name	Data Source	Year
Sediment Range Survey	USACE Walla Walla	1987
Navigation Channel Survey	USACE Walla Walla	1992
Lower Granite Tailrace Survey	USACE Walla Walla	2003
PNNL Survey	PNNL	2005

The bathymetric data for the 2005 fieldwork was processed using Golden Software's Surfer and ESRI's ArcGIS 9.x software. The 2005 dataset was divided into sections with similar flow orientations and processed using an anisotropic kriging technique, which generates a stream-wise surface grid from an irregular set of point data. This procedure ultimately provided a set of contour lines that would then be used generate a raster-based bathymetric surface. The use of anisotropic kriging has been found to minimize typical sinkhole and hillock effects that are commonly found when processing transect data, often leaving regions between data points with a higher elevations than actually observed (e.g., bullseye effect) or other miscellaneous data interpolation anomalies. Each stream section that was processed was verified for conformity with adjacent sections and if necessary, suspect data points were eliminated and data were reprocessed. The individual stream sections were assembled into the two tailrace reaches, and a final surface with a resolution of 1.52 x 1.52 m was created using an inverse distance weighting (IDW) technique that combined the anisotropic kriging-generated contour lines, survey point data, other available sources of bathymetry, and U.S. Geological Survey 10-m digital elevation models (DEM) to represent the surrounding terrestrial topography of the two tailrace areas. IDW is an interpolation technique that estimates cell values in the raster that have been weighted so that the farther a point is from the cell being evaluated, the less important it is in calculating the value of a cell. The final bathymetric surface grids were used for the hydrodynamic model MASS2.

2.2.2 Hydrodynamic Model

Depth-averaged water velocities downstream of Ice Harbor and Lower Granite Dams were simulated using the hydrodynamic and water quality model MASS2 described above. The Ice Harbor and Lower Granite Dam tailrace reaches were subsections of existing MASS2 models that originally encompassed larger river reaches that were configured and validated for the U.S. Army Corps of Engineers dissolved gas abatement study (Richmond et al. 1999). These existing model configurations were used as the starting point for this work.

Gridgen was used to develop the computational mesh for each study reach. Bottom elevations for each mesh cell were determined from continuous, three-dimensional, raster-based bathymetric surfaces for each reach. The Ice Harbor tailrace model extended from Ice Harbor Dam downstream to just upstream of the confluence with the Columbia River and consisted of 104,837 cells. The lateral resolution ranged from 1 to 16 m and averaged 9 m. The longitudinal resolution ranged from 3 to 15 m and averaged 7.5 m. The Lower Granite tailrace model covered the area from Lower Granite Dam downstream to rkm 160 using a mesh with 74,955 cells. The lateral resolution ranged from 3 to 24 m and averaged 8 m. The longitudinal resolution ranged from 5 to 20 m and averaged 10 m.

The input boundary conditions required for MASS2 are river discharge at the upstream boundary and water surface elevation (stage) at the downstream boundary. Inflow discharges for the Snake River MASS2 simulations of the Ice Harbor and Lower Granite tailraces were determined using 1975 to 2004 operations records at Ice Harbor and Lower Granite (North Pacific Water Management Division, Northwestern Division, U.S. Army Corps of Engineers, see www.nwd-wc.usace.army.mil). Review of the data revealed that the Lower Granite annual average discharge was higher than that at Ice Harbor during several years. Therefore, only the Ice Harbor discharge data were used in the subsequent analysis.

Inflow discharges to be modeled were developed for a range of water year types, including wet, normal, and dry. A wet or dry water year does not necessarily mean a corresponding wet or dry fall Chinook salmon spawning season occurred in that year. To better represent the range of flow conditions, the annual records were ranked based on the average discharge during the fall Chinook salmon spawning season. Ranking the data in this manner yielded the following classification: 2002 (dry), 1990 (normal), and 1984 (wet). For each of these types of fall Chinook salmon spawning seasons, a discharge that was exceeded 10, 50, and 90% of the time (Q_{10}, Q_{50}, Q_{90}, respectively) was computed (Table 2.6), representing a range of discharges from high flow (Q_{10}) to low flow (Q_{90}). These discharges were used as inflow conditions to both tailraces.

Table 2.6. Snake River Fall Chinook Salmon Spawning Season Discharges (cfs) Used As Upstream Inflow Conditions to the MASS2 Models of the Lower Granite and Ice Harbor Tailraces. The exceedence discharge is the volumetric flow rate (cfs) that was equaled or exceeded 10, 50, and 90% of the time (Q_{10}, Q_{50}, Q_{90}, respectively).

	Discharge (cfs) for Each Exceedance (%)		
Type of Spawning Season	**Q_{10}**	**Q_{50}**	**Q_{90}**
Wet	52,000	44,000	34,500
Normal	34,500	21,700	19,100
Dry	18,200	15,300	12,600

The MASS2 models of the Lower Granite and Ice Harbor tailraces covered a reach that did not extend downstream to the forebay of the next downstream dam. The required downstream stage was supplied by the one-dimensional MASS1 model previously applied to these sections of the river (Richmond et al. 2000). MASS1 simulations used the upstream discharges specified in Table 2.6 and the forebay elevations shown in Table 2.7. The computed stage at the appropriate locations were extracted and used as downstream boundary conditions for the MASS2 simulations.

Table 2.7. Forebay Elevations Used in the MASS1 Simulations to Determine the Downstream Water Surface Elevation To Be Used in the MASS2 Simulations

Dam	Normal Forebay Elevation (ft)	Minimum Operating Elevation (ft)
Little Goose	638.0	633.0
McNary	340.0	335.0

In the Ice Harbor and Lower Granite tailraces, previous MASS2 validation simulations documented in Richmond et al. (1999) show that the model accurately represents the spatial and temporal distributions of the simulated hydrodynamics. Water surface elevations and velocities compared favorably with measured tailwater elevations at both dams and velocities measured using an acoustic Doppler current profiler.

After the model was validated, steady-state simulations were run for the conditions specified. Simulations provided water velocities and depths at a resolution corresponding to the computational mesh. MASS2 simulation results for the Lower Granite and Ice Harbor reaches were exported to the GIS database as Arc/Info grids.

In summary, hydraulic conditions at the Ice Harbor and Lower Granite study areas were estimated for the fall Chinook salmon spawning period by modeling three discharges (low, median, high) during three different water year types (dry, normal, wet) under both current operating conditions (normal forebay elevation of the next downstream dam) and modified operating conditions (minimum forebay elevation of the next downstream dam).

2.2.3 Substrate

Substrate sampling in the Ice Harbor and Lower Granite dam tailraces was completed using the same methods described above. In the Lower Granite and Ice Harbor tailrace areas, previous modeling results were used to select sampling locations that could not be ruled out as potentially suitable habitat based on depth or velocity. Riverbed bathymetry was then used to create polygons that represented distinct geomorphic features within the channel (i.e., a lateral bar). Nine polygons were established using a 35-m suggested point spacing.

A total of 2,178 underwater video images were processed to produce grain-size data collected from the Lower Granite and Ice Harbor tailraces. In addition, 193 grains were measured using pebble counts in the Ice Harbor tailrace to augment underwater video data in shallow locations. The geometric mean (d_g), geometric sorting coefficient (S_g), and the Fredle index (F_i) were determined for the Lower Granite and Ice Harbor study areas.

2.2.4 Channel Morphology

The MASS2 model output was imported into a GIS database for analysis of hydraulic geometry at closely spaced cross sections. Model results were extracted from 133 cross sections spaced 50–100 m apart throughout the Ice Harbor Dam tailrace and 161 cross sections spaced 50–100 m apart throughout the Lower Granite Dam tailrace. The hydraulic geometry at these cross sections was estimated with a steady discharge of 21,700 cfs and normal forebay elevations of the next downstream dam. The same methods described for the Wanapum reference area were used to quantify the channel morphology at the Snake River tailrace sites.

2.2.5 Fall Chinook Salmon Spawning Habitat

The results from each MASS2 model run were imported into the GIS database, providing hydraulic data (e.g., depth and velocity) for each node in the study areas. As with the Wanapum reference area, a continuous surface for each hydraulic variable was created using an inverse distance weighting interpolation between nodes. The resulting surfaces for depth and velocity had cell sizes of 9 m^2 (3 m x 3 m) and were used to estimate potential fall Chinook salmon spawning habitat.

The habitat suitability modeling proceeded by assigning SI values derived from the Wanapum reference area (described above) to the habitat cells based on depth, velocity, and channel bed slope for each discharge scenario; the substrate values were assigned SI values of either 1.0 or 0.0, based on the values in Table 2.3, and included in the calculation of the composite SI (CI) for the study areas. The CI was calculated as the geometric mean of the input variables:

$$CI = (SI_1 \times SI_2 \times \ldots SI_n)^{1/n} \tag{2.5}$$

where SI_n is the suitability index value for variable n, and n is the number of input variables. Calculating the CI based on geometric mean allows for compensatory relationships among variables but not as much as the arithmetic mean (USFWS 1981). For example, if the SI value of one variable is 0.0, the geometric mean will calculate the CI as 0, meaning that if one variable is outside the range of suitable criteria, the other variables cannot compensate for it. The resulting CI for each discharge scenario represents the weighted suitability of the study area, where a value of 1.0 indicates optimum potential fall Chinook spawning habitat.

3.0 Results

3.1 Fall Chinook Salmon Spawning Habitat Availability

3.1.1 Ice Harbor

Under the current hydrosystem operations (i.e., normal pool elevation of McNary Dam forebay), the estimate of total potential fall Chinook salmon spawning habitat in the study area ranged from 316 to 489 ha, depending on the discharge regime from Ice Harbor Dam. The discharge representing the median hourly flow during the fall Chinook salmon spawning period (i.e., the Q_{50} flow) of a normal water year resulted in a potential spawning habitat estimate of 415 ha, or 67% of the total study area (Table 3.1). The quantity of potential spawning habitat increased as the discharge regime increased from low flow (Q_{90}) to high flow (Q_{10}), and as water availability increased from dry to wet water years (Table 3.1). The greatest amount of potential spawning habitat is available under the high discharge (Q_{10}) during a wet water year, when 489 ha (78%) is potentially suitable (Table 3.1).

Table 3.1. Quantity and Relative Percentage of Potential Spawning Habitat for Each Discharge Scenario at the Ice Harbor Dam Study Area

		Q_{10}		**Q_{50}**		**Q_{90}**	
Pool Level	**Water Year**	**ha**	**%**	**ha**	**%**	**ha**	**%**
Minimum Pool	Dry	281.7	60.1	264.4	57.6	242.0	53.5
	Normal	346.3	68.5	298.8	62.5	284.7	60.4
	Wet	404.8	73.5	388.5	72.1	347.5	68.6
Normal Pool	Dry	393.1	64.0	351.8	57.4	315.9	51.8
	Normal	463.6	74.6	414.6	67.3	396.5	64.5
	Wet	489.0	78.2	481.3	77.1	464.1	74.7

Under the current hydrosystem operations, the estimates of composite suitability index (SI) indicated that the majority of potential spawning habitat is of low quality. For the Q_{50} discharge during a normal water year, 79% of the potential spawning habitat had an SI value ≤ 0.50, or less than half the optimal index (1.0) of other fall Chinook salmon spawning areas in the Columbia Basin (Table 3.2, Figure 3.1). For this same flow regime, high quality habitat ($SI > 0.75$) accounted for 0.2% (1 ha) of the total potential spawning habitat within the study area. Most of the higher-quality ($SI > 0.5$) potential spawning habitat is located on lateral bars away from the navigation channel (Figure 3.1). The amount of high-quality potential spawning habitat increased as the discharge regime increased from low flow (Q_{90}) to high flow (Q_{10}) and as water availability increased from dry to wet water years (Table 3.2). The greatest amount of high-quality potential habitat is available under the high discharge (Q_{10}) during a wet water year, when 14% (70 ha) of the potential habitat has an SI value > 0.75 (Table 3.2, Figure 3.2).

Under the current hydrosystem operations, and within the potential spawning habitat, water depths toward the shallow end of the suitable range and water velocities toward the slower end of the suitable range comprise a significant portion of the available habitat. For example, during the Q_{50} discharge of a normal water year 36% of the potential spawning habitat is in water depths less than 2 m, while 89% of those areas contain water velocities less than 0.5 m s^{-1} (Figures 3.3 and 3.4). Water velocity appears to be

Table 3.2. Suitability Index (SI) Summary of the Quantity and Relative Percentage of Potential Spawning Habitat at the Ice Harbor Dam Study Area Based on a Normal Operating Pool Level at McNary Dam

Discharge Regime	Water Year	Suitability Index								Total Suitable Area (ha)
		0.01-0.25		0.26-0.50		0.51-0.75		0.76-1.0		
		ha	%	ha	%	ha	%	ha	%	
Q_{10}	Dry	283.1	72.0	41.8	10.6	67.7	17.2	0.5	0.1	393.1
	Normal	252.1	54.4	86.0	18.6	98.3	21.2	27.2	5.9	463.6
	Wet	218.0	44.6	108.9	22.3	92.5	18.9	69.7	14.2	489.0
Q_{50}	Dry	287.5	81.7	37.8	10.7	26.3	7.5	0.2	0.0	351.8
	Normal	271.1	65.4	56.9	13.7	85.6	20.7	1.0	0.2	414.6
	Wet	236.5	49.1	96.3	20.0	100.1	20.8	48.3	10.0	481.3
Q_{90}	Dry	273.0	86.4	35.2	11.1	7.3	2.3	0.5	0.2	315.9
	Normal	281.6	71.0	43.8	11.0	70.5	17.8	0.6	0.2	396.5
	Wet	251.8	54.3	86.1	18.5	98.0	21.1	28.2	6.1	464.1

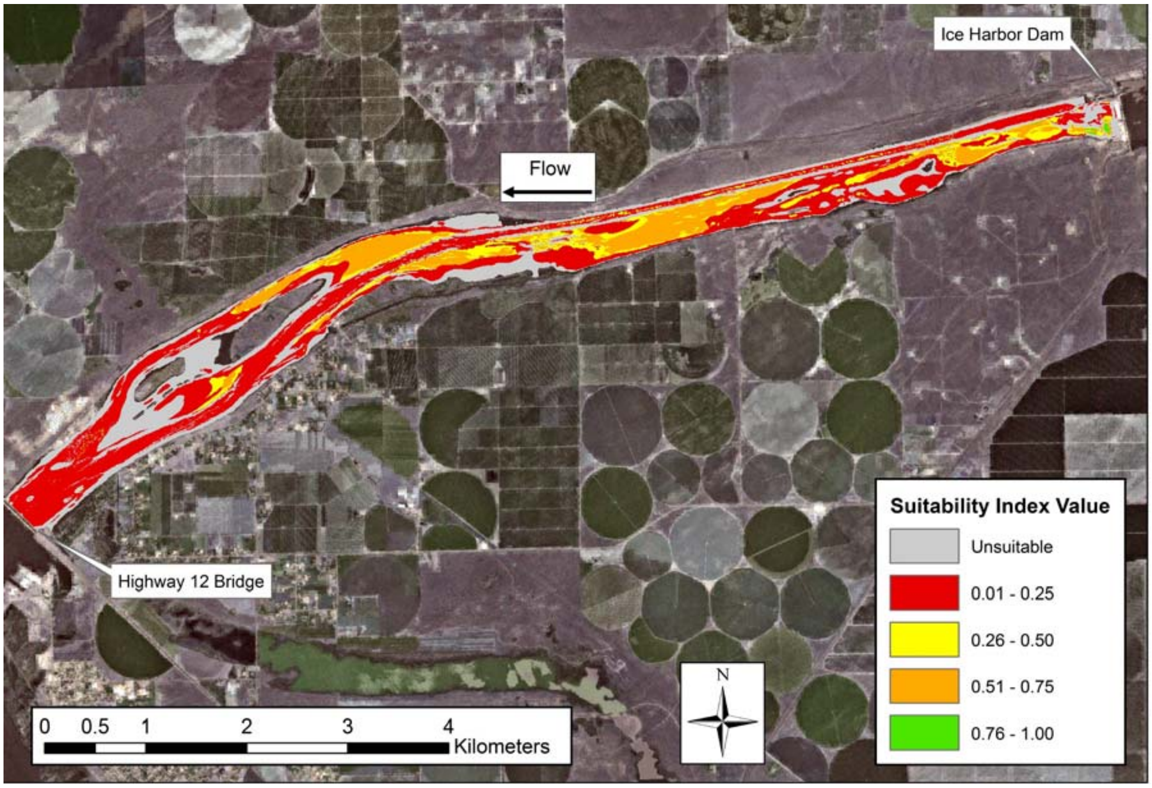

Figure 3.1. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 50% Exceedance Discharge (21.7 kcfs) During a Normal Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0). The navigation channel begins just downstream from Ice Harbor Dam along the north side of the river.

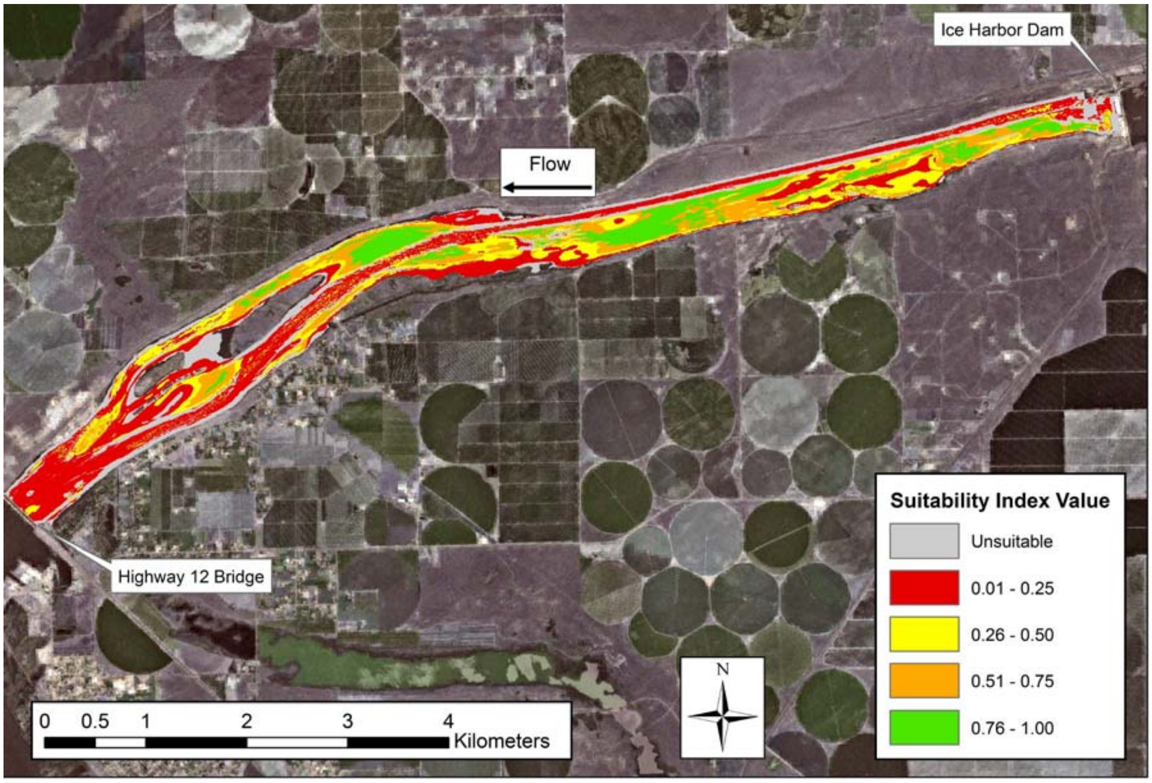

Figure 3.2. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 10% Exceedance Discharge (52.0 kcfs) During a Wet Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

more of a limiting factor than water depth, as 26% of the potential spawning habitat is within the optimal water depth range of 2.0–4.0 m (Figure 3.3). However, another 26% of the potential spawning habitat is in the very low suitability water depth range of 6.0–11.5 m, much of which is located in the navigation channel (Figures 3.3 and 3.5). Nearly all of the potential spawning habitat with water velocities within the optimal range (0.7–1.5 m s^{-1}) is also located within the navigation channel (Figure 3.6), and not within areas of optimal water depths.

Under modified hydrosystem operations (i.e., minimum pool elevation of McNary Dam forebay), the estimate of total potential fall Chinook salmon spawning habitat in the study area ranged from 242 to 405 ha, depending on the discharge regime from Ice Harbor Dam. The Q_{50} discharge during a normal water year resulted in a potential spawning habitat estimate of 299 ha, or 63% of the total study area (Table 3.1). This estimate of potential spawning habitat under modified hydrosystem operations represents a 28% (116 ha) decrease from the potential spawning habitat (415 ha) available for the same Q_{50} discharge under current hydrosystem operations (Table 3.1). A similar reduction (17–28%) in the quantity of potential spawning habitat was observed for all discharges and water years as the pool elevation of McNary Dam forebay was lowered from normal to minimum pool elevation.

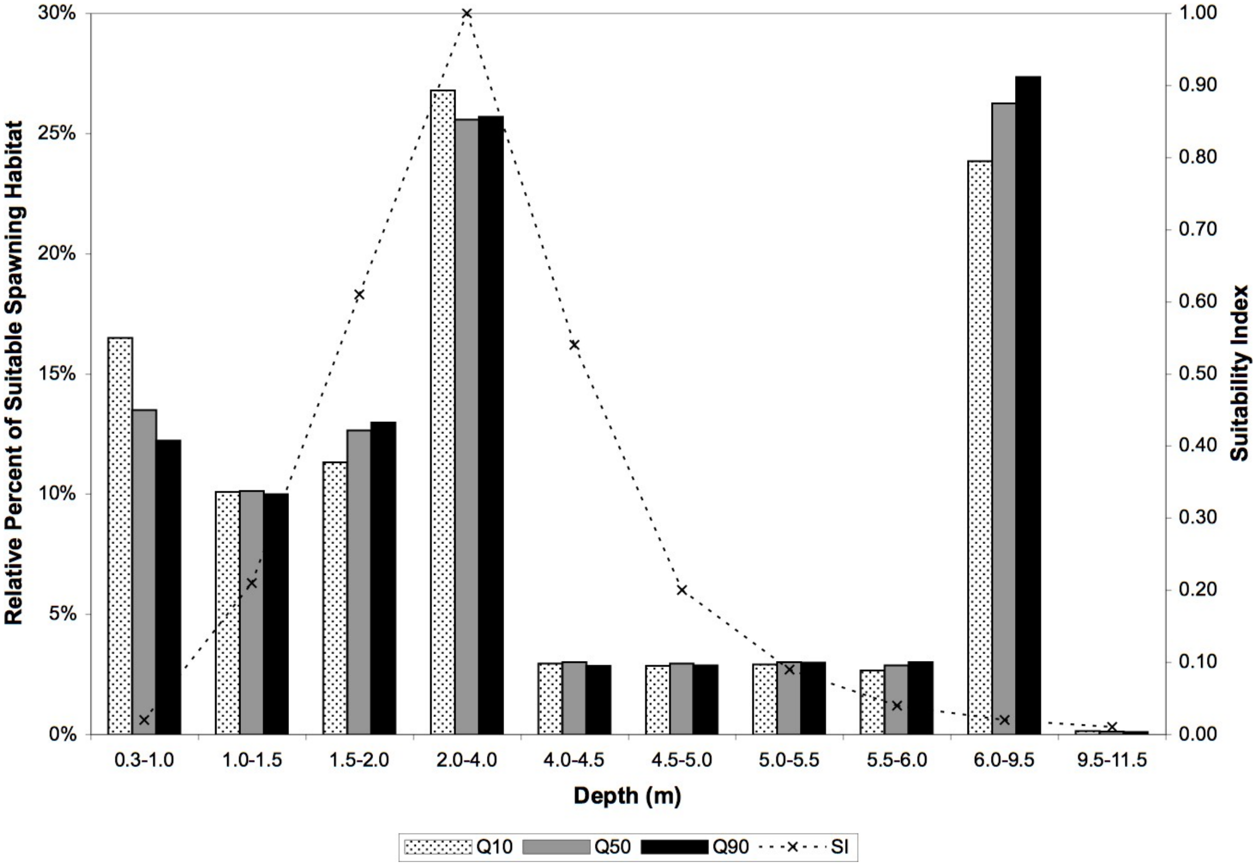

Figure 3.3. Depth Within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Ice Harbor Dam, During a Normal Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

Under modified hydrosystem operations, the estimates of composite suitability index (SI) indicated that the majority of potential spawning habitat is of low quality. For the Q_{50} discharge during a normal water year, 88% of the potential spawning habitat had an SI value ≤ 0.50, or less than half the optimal index (1.0) (Table 3.3, Figure 3.7). For this same flow regime, high quality habitat (SI > 0.75) accounted for 0.9% (2.6 ha) of the total potential spawning habitat within the study area. This estimate of high-quality potential spawning habitat under modified hydrosystem operations represents a 1.6-ha increase from the high-quality potential spawning habitat (1 ha) available for the same Q_{50} discharge under current hydrosystem operations. However, for nearly all discharges and all water years, the quantity of potential fall Chinook salmon spawning habitat with an SI value > 0.50 was larger under current hydrosystem operations (normal pool) than under modified hydrosystem operations (minimum pool). The difference between current and modified hydrosystem operations in the quantity of potential spawning habitat with an SI value >0.50 ranged from 9 to 57 ha (Tables 3.2 and 3.3).

Under modified hydrosystem operations, and within the potential spawning habitat, water depths toward the shallow end of the suitable range and water velocities toward the slower end of the suitable range comprise a significant portion of the available habitat. For example, during the Q_{50} discharge of a normal water year, 41% of the potential spawning habitat is in water depths less than 2 m, while 67% of

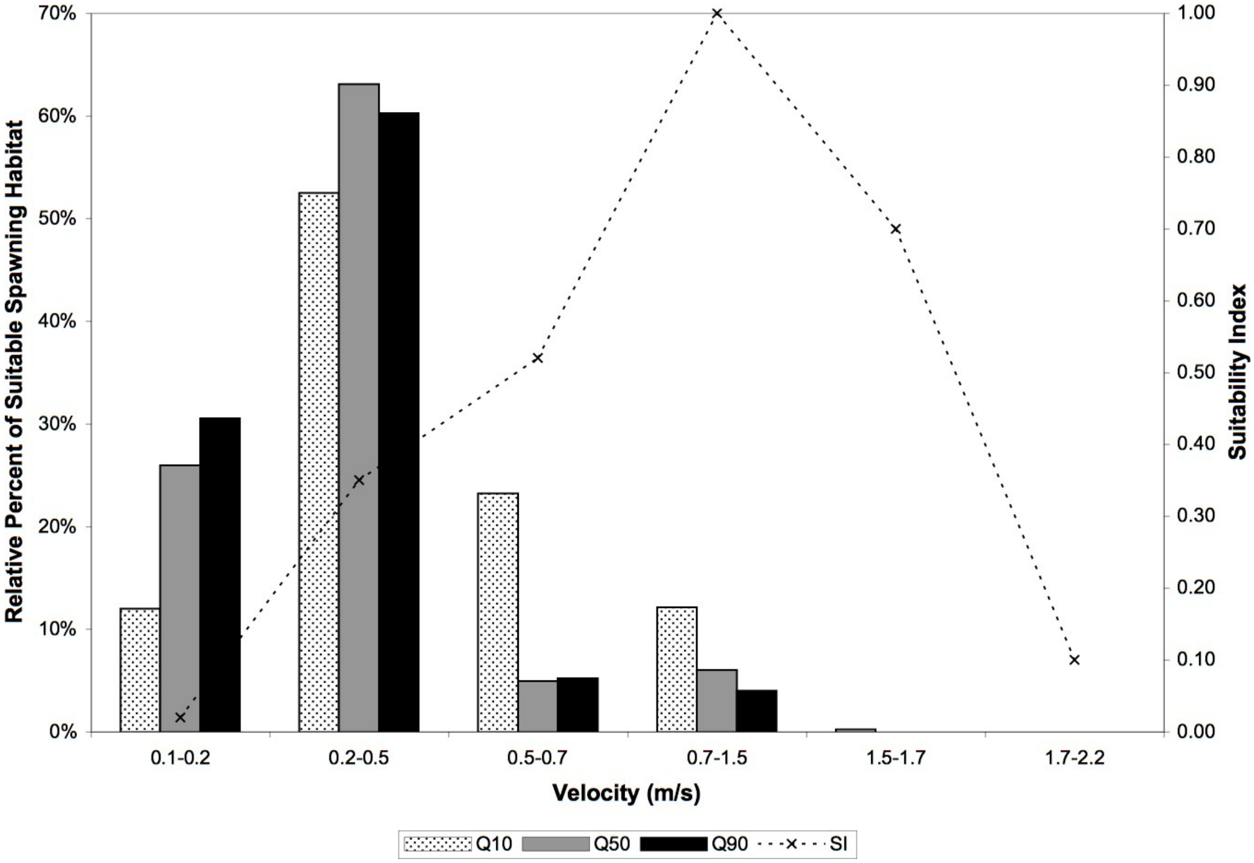

Figure 3.4. Velocity Within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Ice Harbor Dam, During a Normal Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

those areas contain water velocities less than 0.5 m s^{-1} (Figures 3.8 and 3.9). The change in hydrosystem operations from normal to minimum pool elevation of McNary Dam forebay resulted in an increase in shallow water spawning habitat, and an increase in water velocities within the optimal range of 0.7–1.5 m s^{-1}. Nevertheless, water velocity appears to be more of a limiting factor than water depth, as only 0.2% of the potential spawning habitat contains water velocities greater than 1.5 m s^{-1} (Figure 3.9). Nearly all of the potential spawning habitat with water velocities within the optimal range of 0.7–1.5 m s^{-1} is located within the navigation channel (Figure 3.10), which is largely comprised of low suitability water depths exceeding 5.0 m (Figures 3.8 and 3.11).

3.1.2 Lower Granite

Under the current hydrosystem operations (i.e., normal pool elevation of Little Goose Dam forebay), the estimate of total potential fall Chinook salmon spawning habitat in the study area ranged from 86 to 313 ha, depending on the discharge regime from Lower Granite Dam. The discharge representing the median hourly flow during the fall Chinook salmon spawning period (i.e., the Q_{50} flow) of a normal water year resulted in a potential spawning habitat estimate of 272 ha, or 50% of the total study area (Table 3.4). The quantity of potential spawning habitat increased as the discharge regime increased from low flow

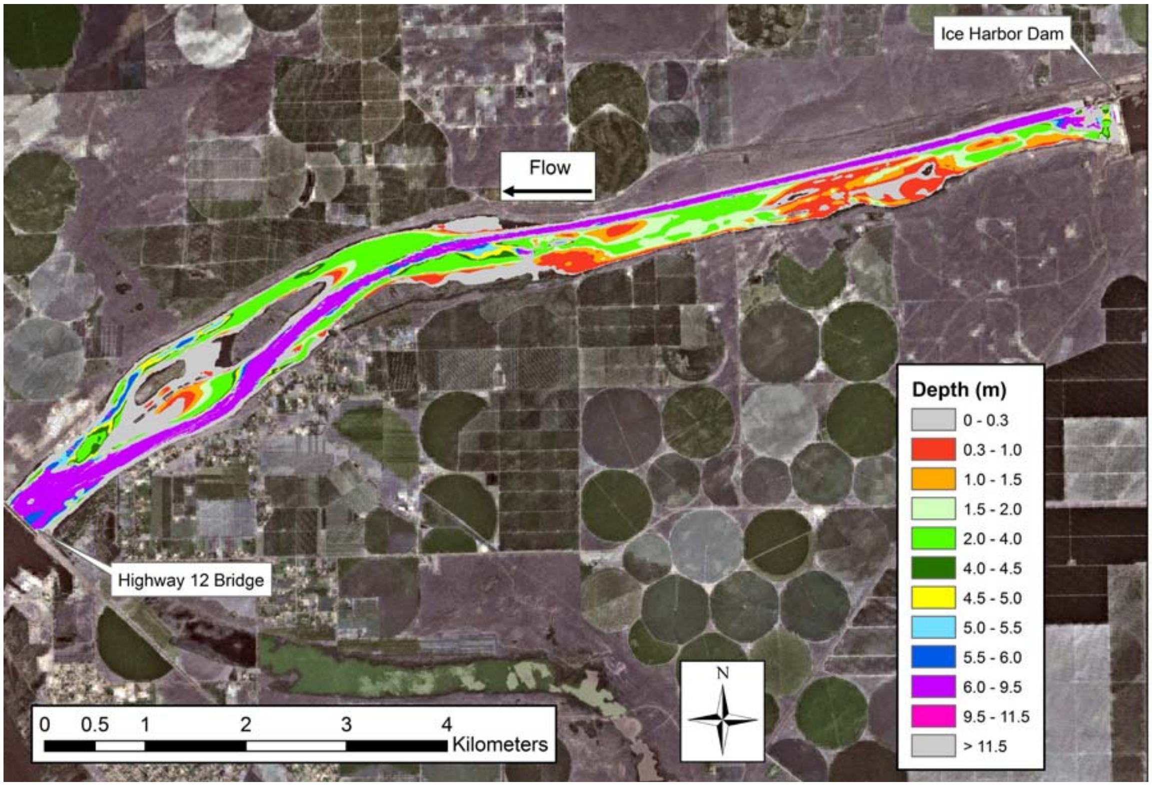

Figure 3.5. Depth Within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Ice Harbor Dam, Based on a 50% Exceedance Discharge (21.7 kcfs) During a Normal Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria. Much of the low suitability, deep water potential spawning habitat is located within the navigation channel.

(Q_{90}) to high flow (Q_{10}), and as water availability increased from dry to wet water years (Table 3.4). The greatest amount of potential spawning habitat is available under the high discharge (Q_{10}) during a wet water year, when 313 ha (57%) is potentially suitable (Table 3.4).

Under the current hydrosystem operations, the estimates of composite suitability index (SI) indicated that the majority of potential spawning habitat is of very low quality. For the Q_{50} discharge during a normal water year, 99% of the potential spawning habitat had an SI value ≤ 0.25, or less than one-fourth the optimal index (1.0) of other fall Chinook salmon spawning areas in the Columbia Basin (Table 3.5, Figure 3.12). For this same flow regime, all of the remaining potential spawning habitat within the study area (<1%, 1.6 ha) had an SI value within the range 0.25–0.50; none of the potential spawning habitat had an SI value > 0.50 (Table 3.5). The amount of high quality potential spawning habitat increased as the discharge regime increased from low flow (Q_{90}) to high flow (Q_{10}) and as water availability increased from dry to wet water years (Table 3.5). The greatest amount of high-quality potential habitat is available under the high discharge (Q_{10}) during a wet water year, when 1.4% (4.3 ha) of the potential habitat has an SI value > 0.50 (Table 3.5, Figure 3.13).

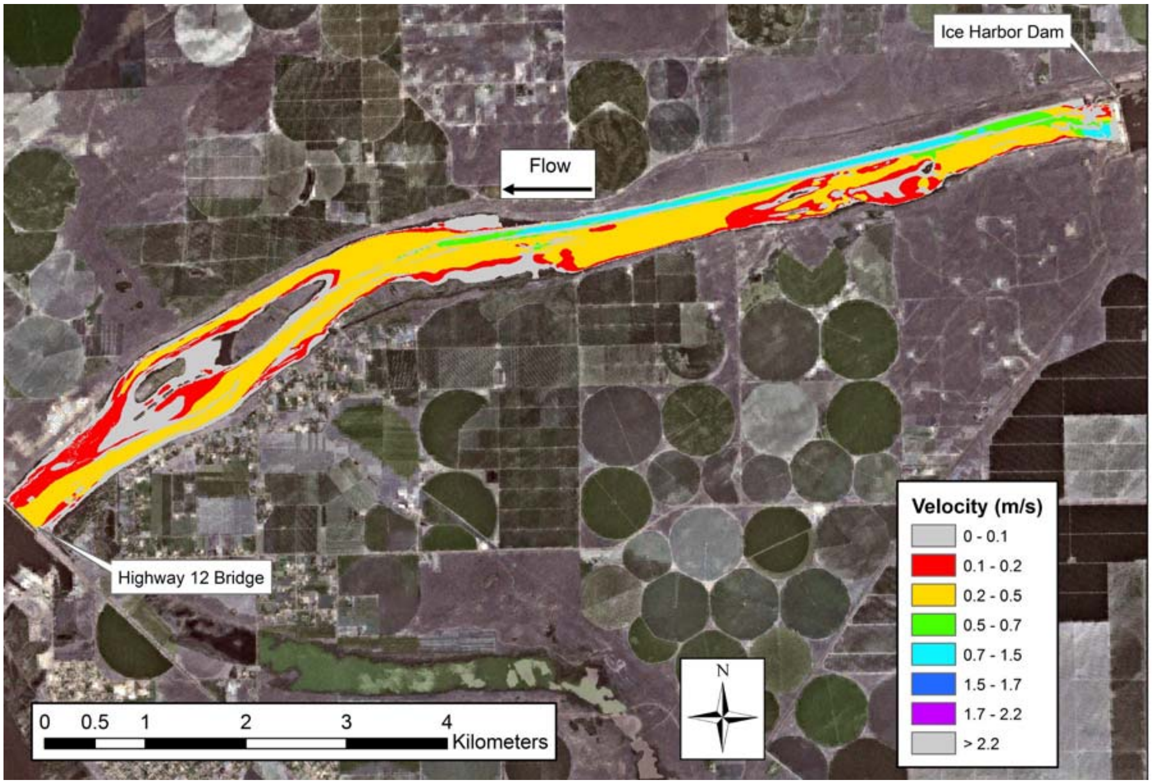

Figure 3.6. Velocity Within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Ice Harbor Dam, Based on a 50% Exceedance Discharge (21.7 kcfs) During a Normal Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria. Much of the potential spawning habitat with water velocities within the optimal range (0.7–1.5 m s^{-1}) is located within the navigation channel.

Under the current hydrosystem operations, and within the potential spawning habitat, water depths toward the deeper end of the suitable range and water velocities toward the slower end of the suitable range comprise a significant portion of the available habitat. For example, during the Q_{50} discharge of a normal water year, 88% of the potential spawning habitat is in water depths greater than 6.0 m, while 64% of those areas contain water velocities less than 0.2 m s^{-1} (Figures 3.14 and 3.15). Water velocity appears to be more of a limiting factor than water depth, as less than 0.1% of the potential spawning habitat contains water velocities greater than 0.7 m s^{-1} (Figure 3.15). Nearly all of the potential spawning habitat with the greatest water velocities available (>0.2 m s^{-1}) is located where low-suitability water depths exceed 6.0 m (Figures 3.16 and 3.17). In much of the shallower lateral and mid-channel bar areas with more suitable water depths (2.0–4.0 m), water velocities are on the lower end of the suitability range (0.1–0.2 m s^{-1}) (Figures 3.16 and 3.17).

Under modified hydrosystem operations (i.e., minimum pool elevation of Little Goose Dam forebay), the estimate of total potential fall Chinook salmon spawning habitat in the study area ranged from 181 to 356 ha, depending on the discharge regime from Lower Granite Dam. The Q_{50} discharge during a normal water year resulted in a potential spawning habitat estimate of 327 ha, or 61% of the total study area (Table 3.4). This estimate of potential spawning habitat under modified hydrosystem operations represents a 20% (55 ha) increase from the potential spawning habitat (272 ha) available for the same Q_{50}

Table 3.3. Suitability Index (SI) Summary of the Quantity and Relative Percentage of Potential Spawning Habitat at the Ice Harbor Dam Study Area Based on a Minimum Operating Pool Level at McNary Dam

Discharge Regime	Water Year	Suitability Index 0.01-0.25 ha	 %	 0.26-0.50 ha	 %	 0.51-0.75 ha	 %	 0.76-1.0 ha	 %	Total Suitable Area (ha)
Q_{10}	Dry	175.7	62.4	80.1	28.4	24.8	8.8	1.1	0.4	281.7
	Normal	167.5	48.4	110.6	31.9	55.7	16.1	12.6	3.6	346.3
	Wet	162.2	40.1	100.7	24.9	76.0	18.8	65.9	16.3	404.8
Q_{50}	Dry	176.4	66.7	70.6	26.7	17.0	6.4	0.5	0.2	264.4
	Normal	175.3	58.7	87.2	29.2	33.6	11.3	2.6	0.9	298.8
	Wet	169.7	43.7	109.9	28.3	68.8	17.7	40.1	10.3	388.5
Q_{90}	Dry	174.6	72.2	56.3	23.3	10.5	4.3	0.6	0.2	242.0
	Normal	175.2	61.5	82.1	28.8	26.0	9.1	1.4	0.5	284.7
	Wet	167.4	48.2	111.0	31.9	56.0	16.1	13.1	3.8	347.5

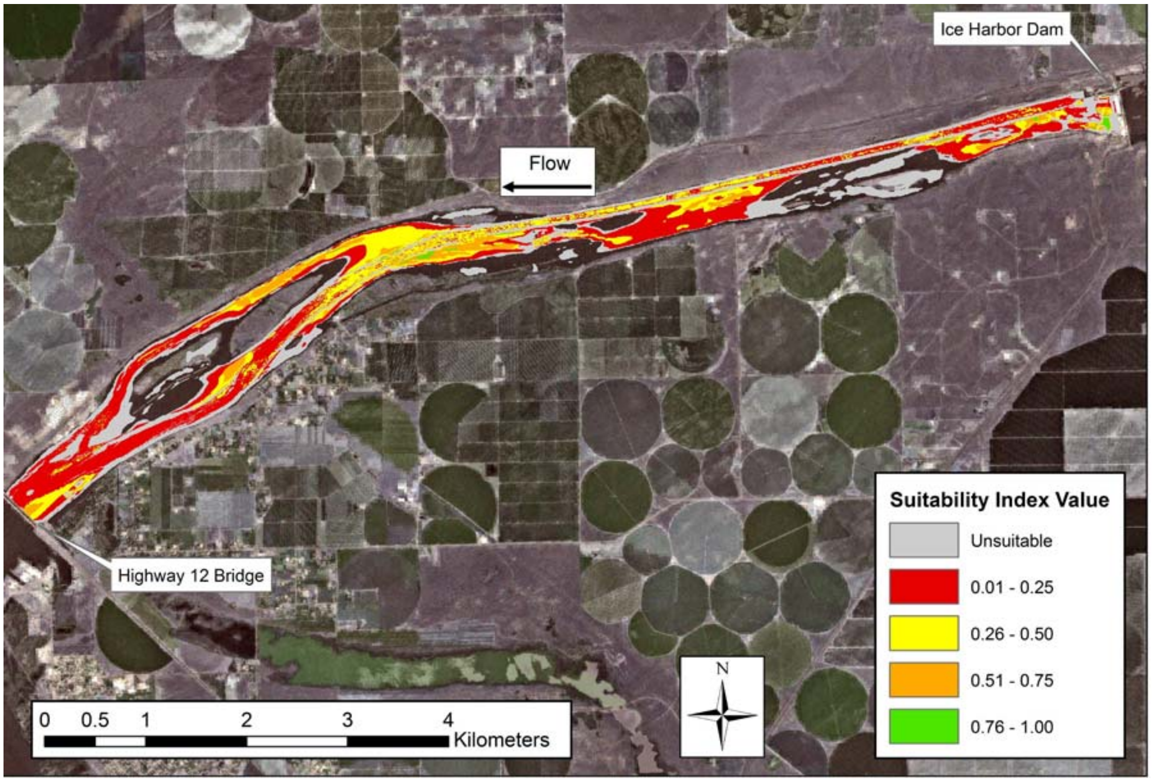

Figure 3.7. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 50% Exceedance Discharge (21.7 kcfs) During a Normal Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

discharge under current hydrosystem operations (Table 3.4). An increase in the quantity of potential spawning habitat was observed for all discharges and water years as the pool elevation of Little Goose Dam forebay was lowered from normal to minimum pool elevation. The corresponding estimates from the Q_{50} discharge resulted in the potential spawning habitat area increasing for all water years, with the percentage increase ranging 14%–73% (Table 3.4). Under the low flow (Q_{90}) during a dry water year, the potential spawning habitat more than doubled when Little Goose Dam forebay was lowered from normal to minimum pool elevation (Table 3.4).

Under modified hydrosystem operations, the estimates of composite suitability index (SI) indicated that the majority of potential spawning habitat remains low quality. For the Q_{50} discharge during a normal water year, 96.6% of the potential spawning habitat had an SI value ≤ 0.25, or less than one-fourth the optimal index (1.0) (Table 3.6, Figure 3.18). For this same flow regime, 3.1% (10 ha) of the remaining potential spawning habitat within the study area had an SI value within the range 0.25–0.50; 0.3% (1.1 ha) of the potential spawning habitat had an SI value > 0.50 (Table 3.6). This estimate of potential spawning habitat within the SI range 0.25–0.75 represents a 9.5-ha increase under modified hydrosystem operations from the potential spawning habitat available for the same Q_{50} discharge under current hydrosystem operations (Tables 3.5 and 3.6). For all discharges and all water years, the quantity of potential fall Chinook salmon spawning habitat with an SI value > 0.50 was larger under modified hydrosystem operations (minimum pool) than under current hydrosystem operations (normal pool). The difference between current and modified hydrosystem operations in the quantity of potential spawning habitat with an SI value > 0.50 ranged from 0.2 to 15.5 ha (Tables 3.5 and 3.6).

Under modified hydrosystem operations, and within the potential spawning habitat, water depths toward the deeper end of the suitable range and water velocities toward the slower end of the suitable range continue to comprise a significant portion of the available habitat. For example, during the Q_{50} discharge of a normal water year, 70% of the potential spawning habitat is in water depths greater than 6.0 m, while 53% of those areas contain water velocities less than 0.2 m s^{-1} (Figures 3.19 and 3.20). The change in hydrosystem operations from normal to minimum pool elevation of Little Goose Dam forebay resulted in an increase in shallower water spawning habitat and an increase in water velocities within the range of 0.2–0.5 m s^{-1}. Nevertheless, water velocity continues to be more of a limiting factor than water depth, as less than 0.1% of the potential spawning habitat contains water velocities greater than 0.7 m s^{-1} (Figure 3.20). Nearly all of the potential spawning habitat with the greatest water velocities available (>0.2 m s^{-1}) is located where low-suitability water depths exceed 6.0 m (Figures 3.22 and 3.23). In much of the shallower lateral and mid-channel bar areas with more suitable water depths (2.0–4.0 m), water velocities are on the lower end of the suitability range (0.1–0.2 m s^{-1}) (Figures 3.22 and 3.23).

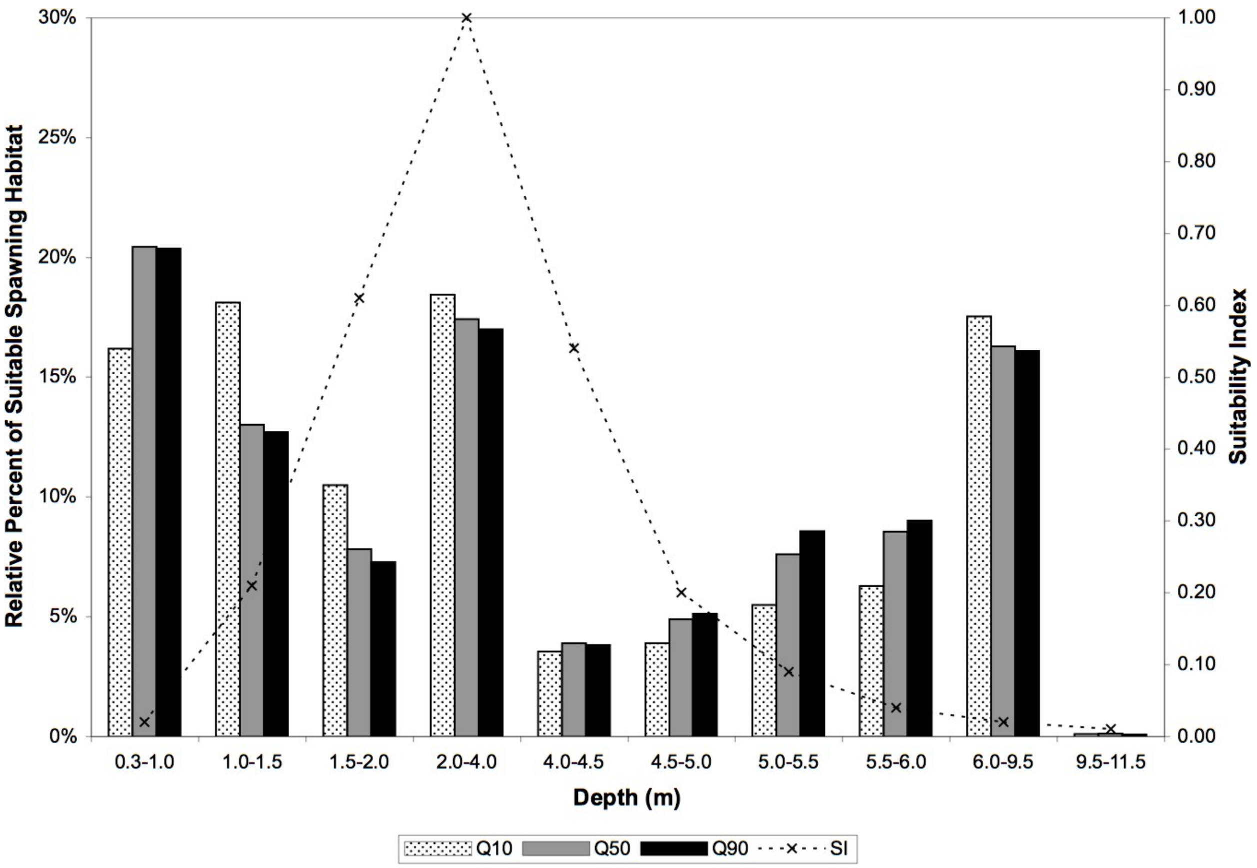

Figure 3.8. Depth Within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Ice Harbor Dam, During a Normal Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

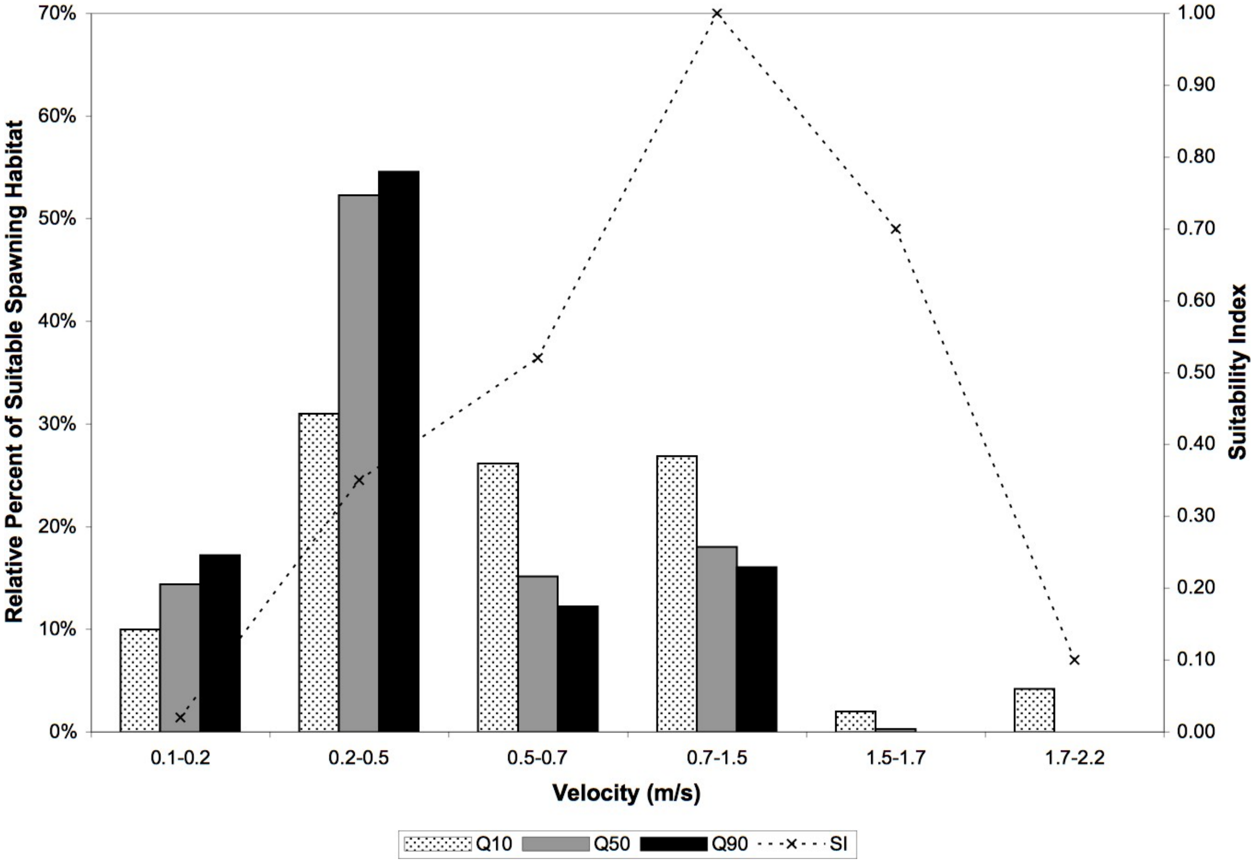

Figure 3.9. Velocity Within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Ice Harbor Dam, During a Normal Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

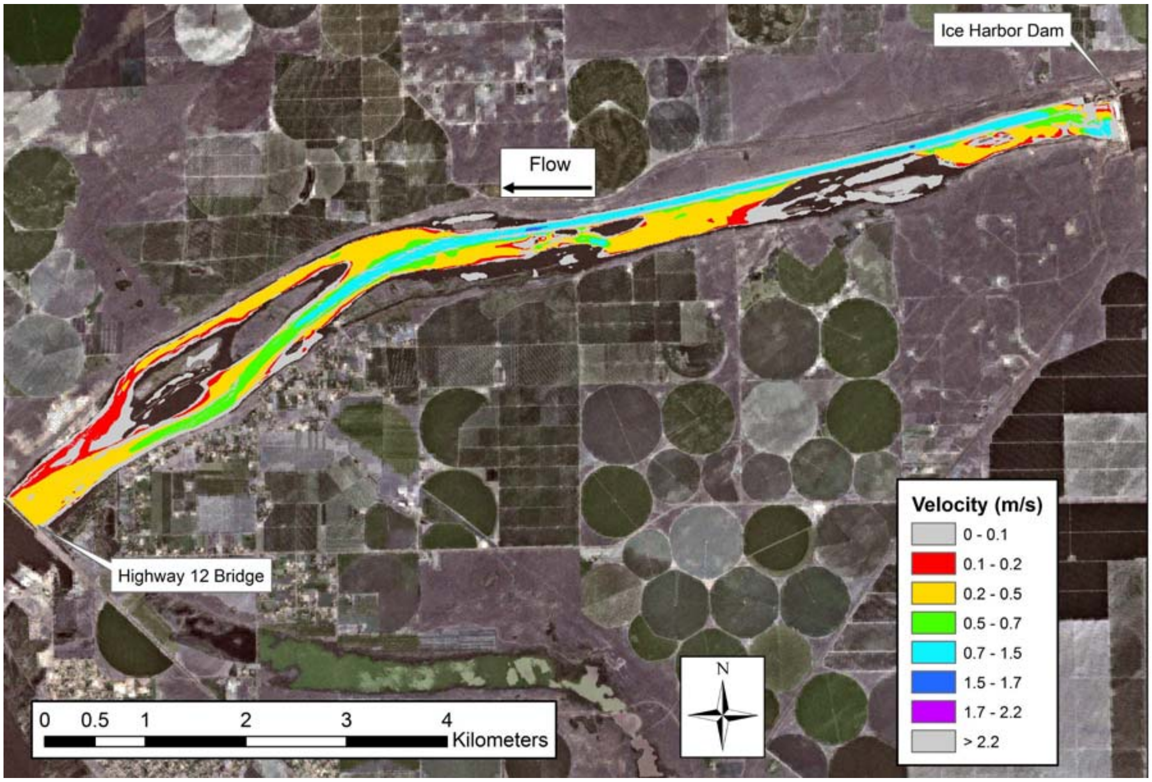

Figure 3.10. Velocity Within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Ice Harbor Dam, Based on a 50% Exceedance Discharge (21.7 kcfs) During a Normal Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria. Much of the potential spawning habitat with water velocities within the optimal range (0.7–1.5 m s^{-1}) is located within the navigation channel.

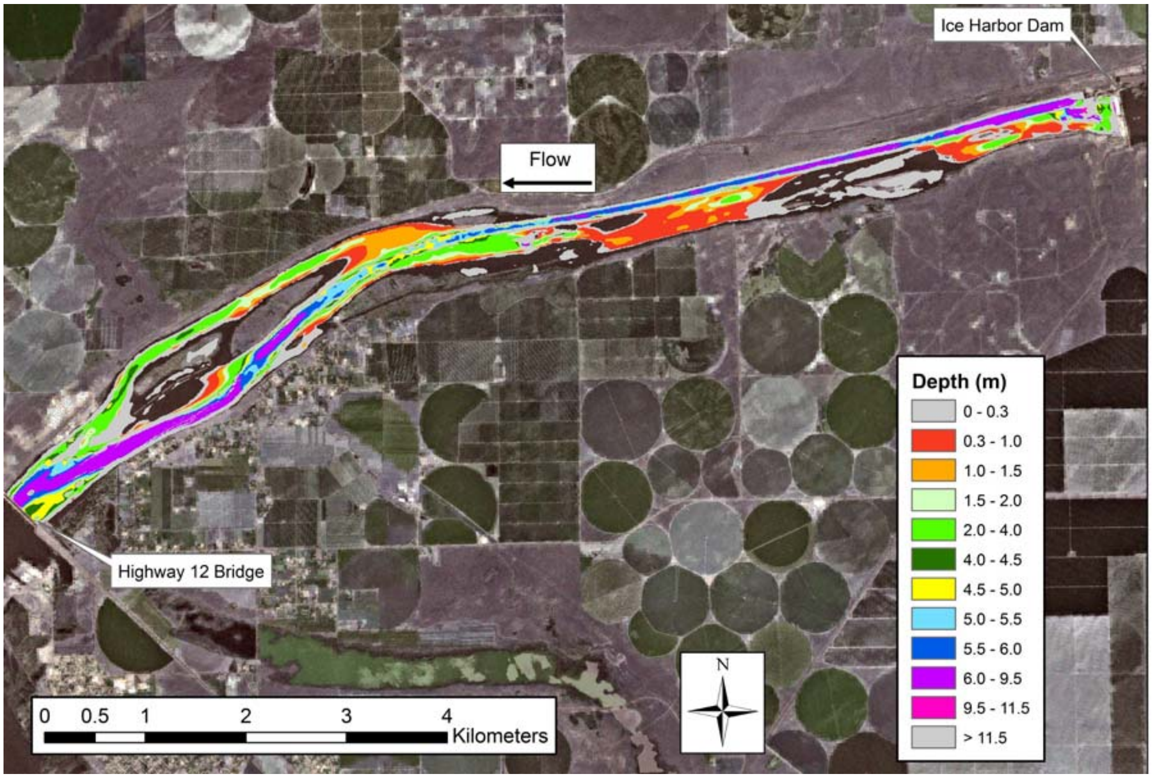

Figure 3.11. Depth Within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Ice Harbor Dam, Based on a 50% Exceedance Discharge (21.7 kcfs) During a Normal Water Year, With the McNary Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria. Much of the low suitability, deep water potential spawning habitat is located within the navigation channel.

Table 3.4. Quantity and Relative Percentage of Potential Spawning Habitat for Each Discharge Scenario at the Lower Granite Dam Study Area

		Q_{10}		Q_{50}		Q_{90}	
Pool Level	**Water Year**	**ha**	**%**	**ha**	**%**	**ha**	**%**
Minimum Pool	Dry	289.7	54.0	239.0	44.6	180.7	33.7
	Normal	346.7	64.6	327.1	61.0	307.8	57.4
	Wet	355.9	66.2	354.4	66.0	347.7	64.8
Normal Pool	Dry	201.0	36.9	138.2	25.3	86.1	15.8
	Normal	303.1	55.6	271.6	49.8	204.4	37.5
	Wet	312.7	57.3	311.3	57.1	301.5	55.3

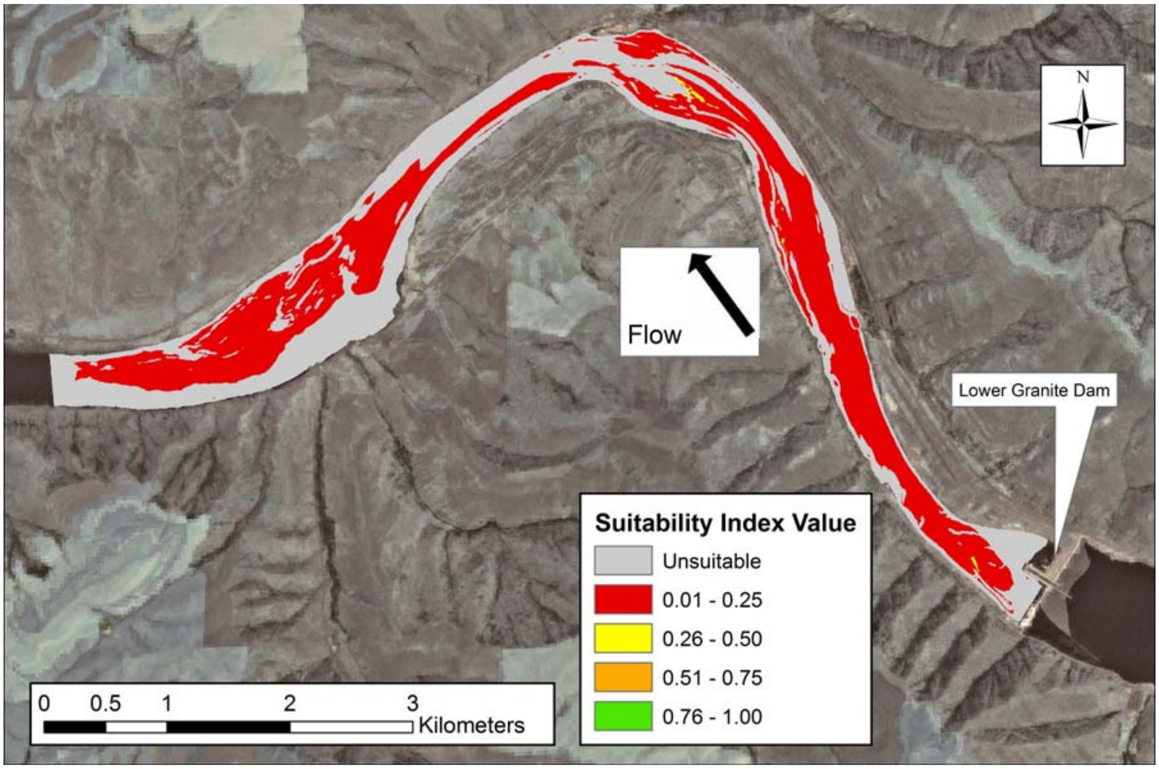

Figure 3.12. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 50% Exceedance Discharge (21.7 kcfs) During a Normal Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

Table 3.5. Suitability Index (SI) Summary of the Quantity and Relative Percentage of Potential Spawning Habitat at the Lower Granite Dam Study Area Based on a Normal Operating Pool Level at Little Goose Dam

Discharge Regime	Water Year	Suitability Index 0.01-0.25 ha	%	0.26-0.50 ha	%	0.51-0.75 ha	%	0.76-1.0 ha	%	Total Suitable Area (ha)
Q_{10}	Dry	200.3	99.6	0.7	0.4	0.0	0.0	0.0	0.0	201.0
	Normal	291.9	96.3	9.6	3.2	1.5	0.5	0.0	0.0	303.1
	Wet	291.2	93.1	17.2	5.5	4.3	1.4	0.0	0.0	312.7
Q_{50}	Dry	137.8	99.7	0.4	0.3	0.0	0.0	0.0	0.0	138.2
	Normal	270.0	99.4	1.6	0.6	0.0	0.0	0.0	0.0	271.6
	Wet	292.8	94.1	15.1	4.9	3.3	1.1	0.0	0.0	311.3
Q_{90}	Dry	85.9	99.8	0.2	0.2	0.0	0.0	0.0	0.0	86.1
	Normal	203.7	99.6	0.7	0.4	0.0	0.0	0.0	0.0	204.4
	Wet	291.5	96.7	8.5	2.8	1.6	0.5	0.0	0.0	301.5

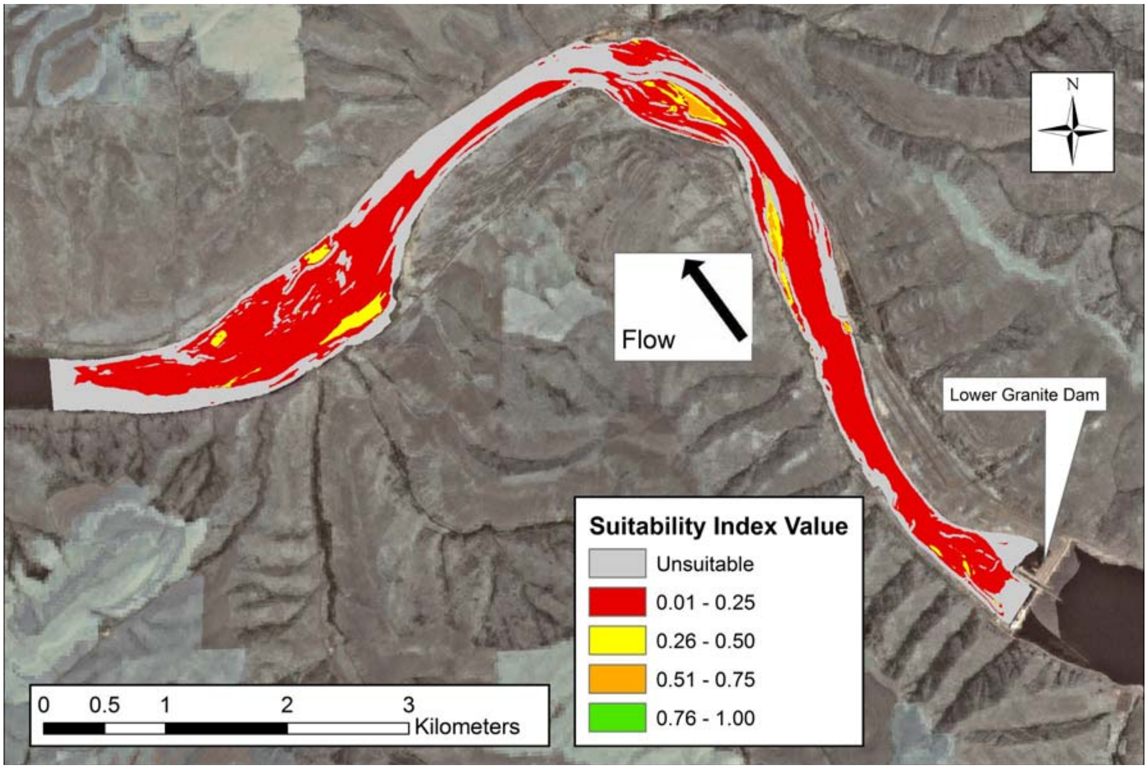

Figure 3.13. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 10% Exceedance Discharge (52.0 kcfs) During a Wet Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

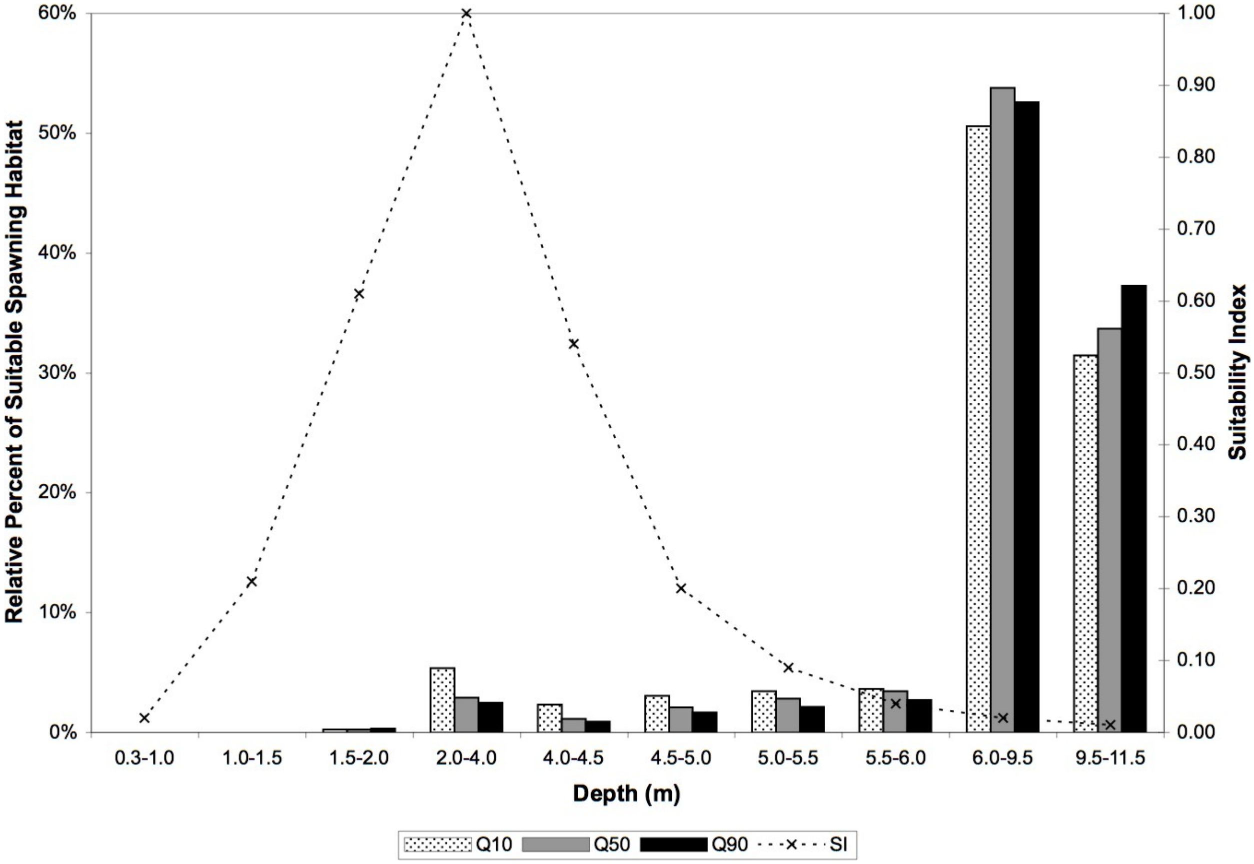

Figure 3.14. Depth Within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Lower Granite Dam, During a Normal Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

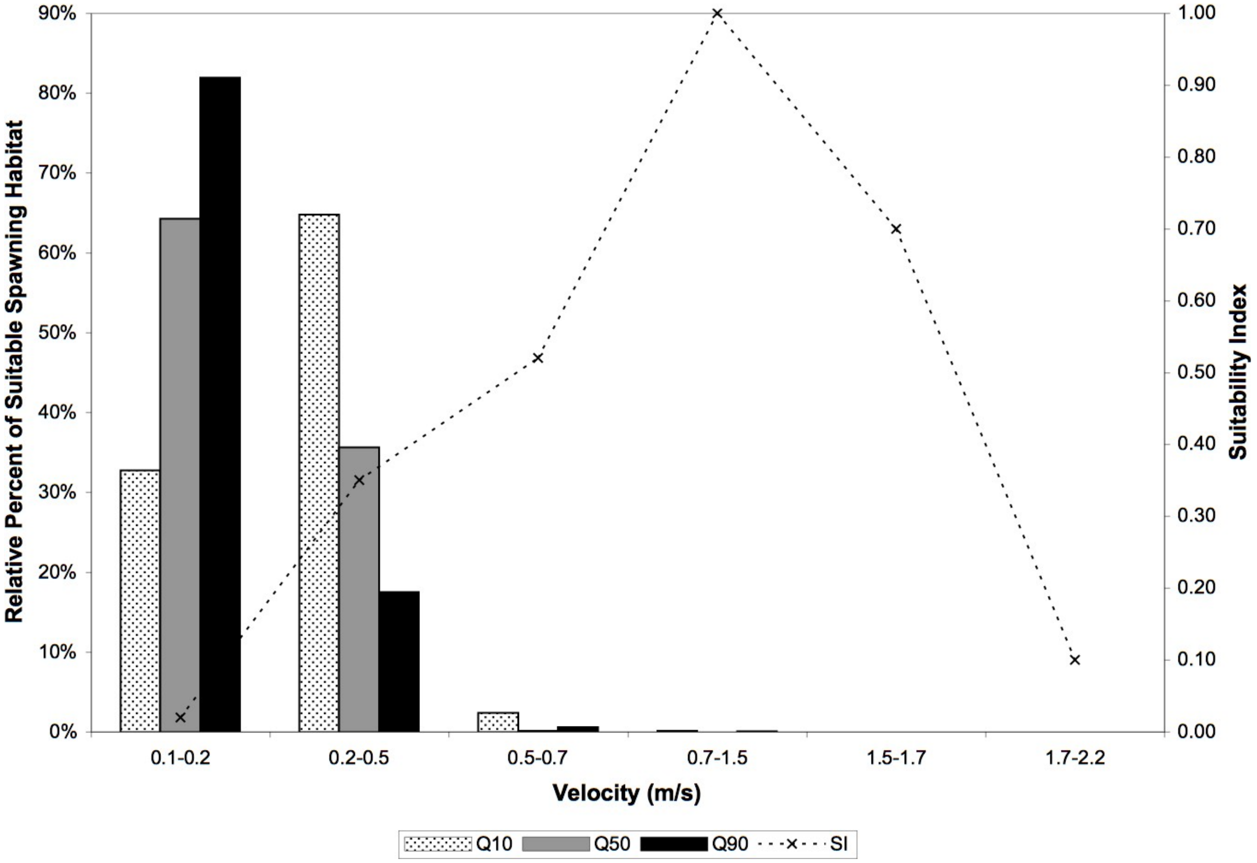

Figure 3.15. Velocity Within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Lower Granite Dam, During a Normal Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

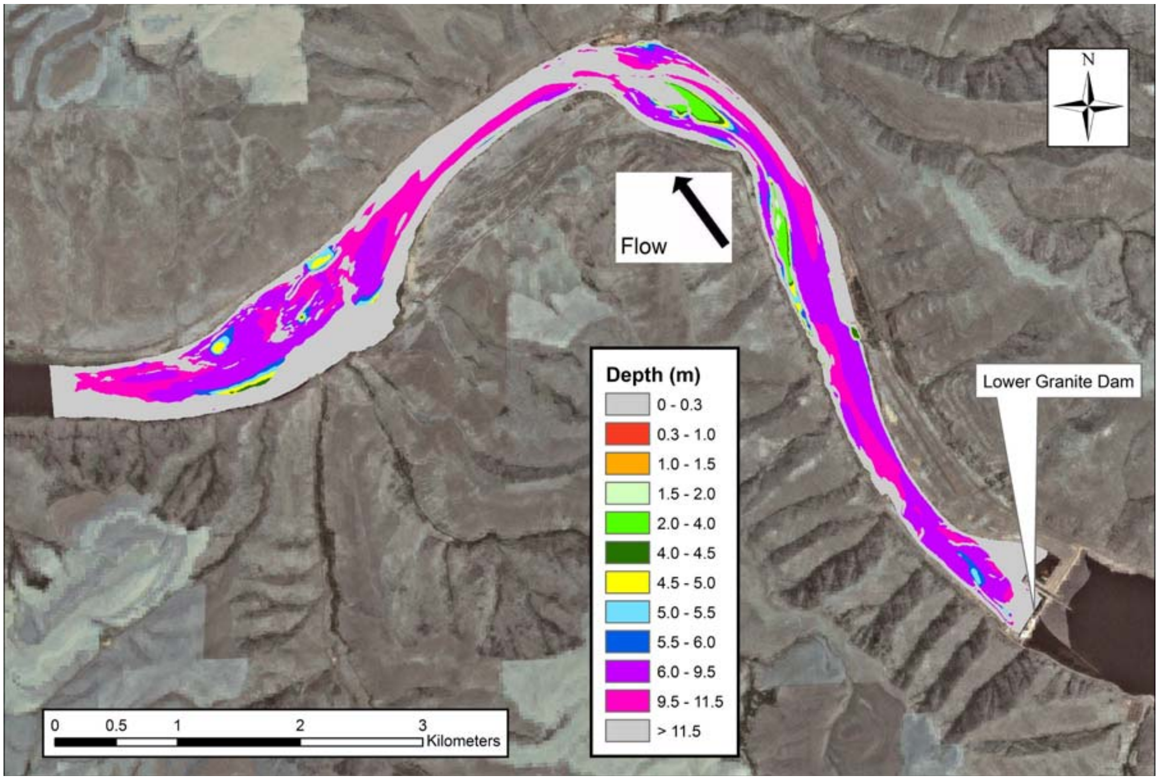

Figure 3.16. Depth Within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Lower Granite Dam, Based on a 50% Exceedance Discharge (21.7 kcfs) During a Normal Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

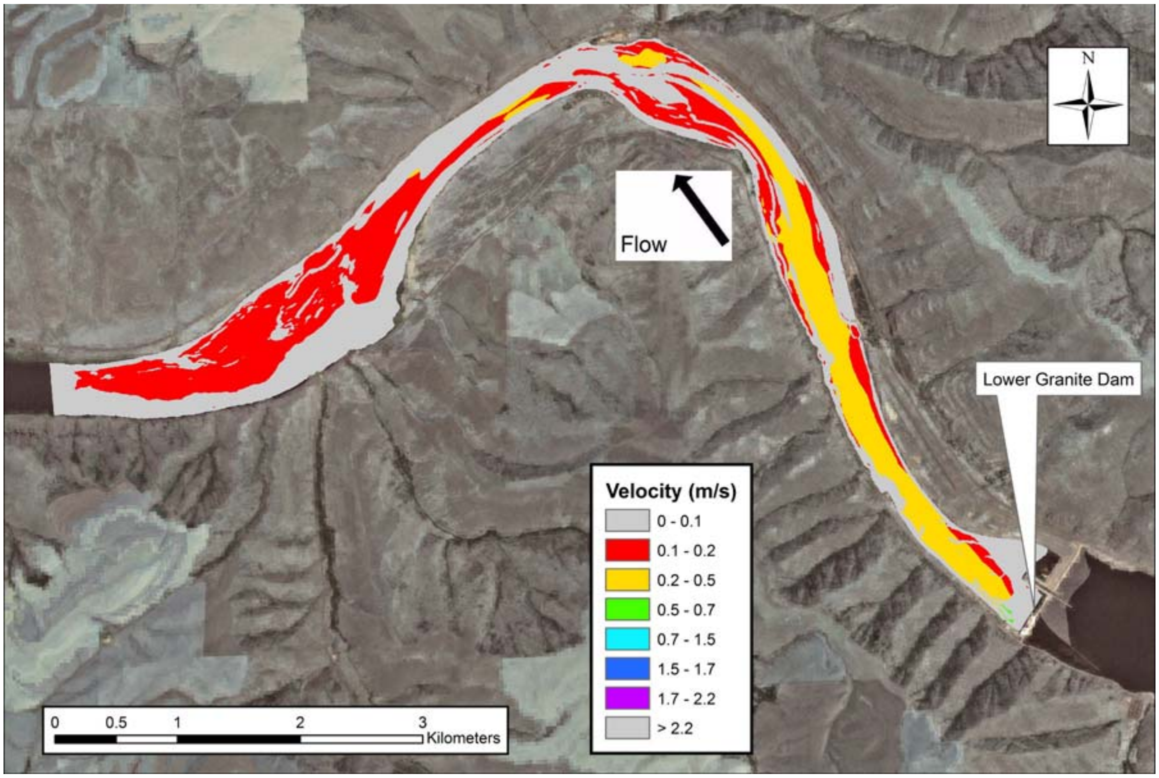

Figure 3.17. Velocity Within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Lower Granite Dam, Based on a 50% Exceedance Discharge (21.7 kcfs) During a Normal Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

Table 3.6. Suitability Index (SI) Summary of the Quantity and Relative Percentage of Potential Spawning Habitat at the Lower Granite Dam Study Area Based on a Minimum Operating Pool Level at Little Goose Dam

Discharge Regime	Water Year	Suitability Index 0.01-0.25 ha	%	0.26-0.50 ha	%	0.51-0.75 ha	%	0.76-1.0 ha	%	Total Suitable Area (ha)
Q_{10}	Dry	283.3	97.8	5.3	1.8	1.0	0.3	0.0	0.0	289.7
	Normal	312.7	90.2	27.8	8.0	6.2	1.8	0.1	0.0	346.7
	Wet	289.5	81.3	46.7	13.1	19.3	5.4	0.5	0.1	355.9
Q_{50}	Dry	235.0	98.3	3.3	1.4	0.7	0.3	0.0	0.0	239.0
	Normal	315.9	96.6	10.0	3.1	1.1	0.3	0.0	0.0	327.1
	Wet	298.8	84.3	40.6	11.5	14.9	4.2	0.1	0.0	354.4
Q_{90}	Dry	179.0	99.1	1.5	0.8	0.2	0.1	0.0	0.0	180.7
	Normal	300.2	97.5	6.5	2.1	1.1	0.4	0.0	0.0	307.8
	Wet	311.9	89.7	29.0	8.3	6.7	1.9	0.1	0.0	347.7

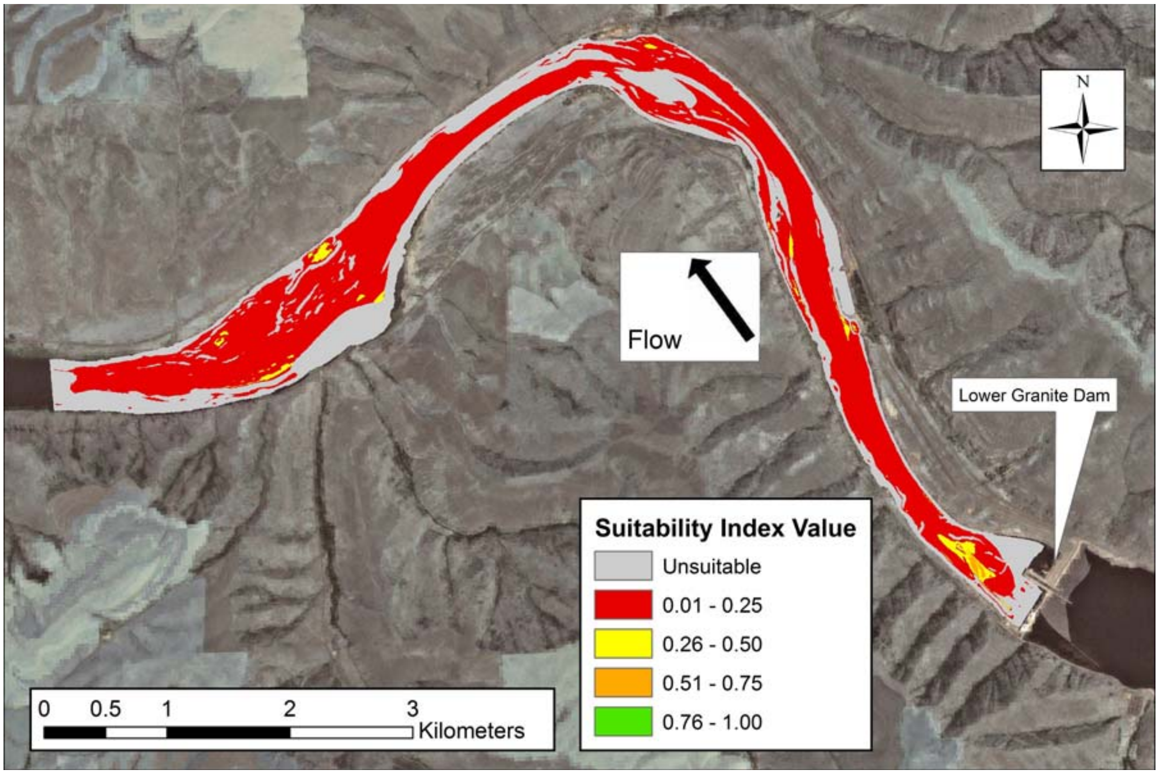

Figure 3.18. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 50% Exceedance Discharge (21.7 kcfs) During a Normal Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

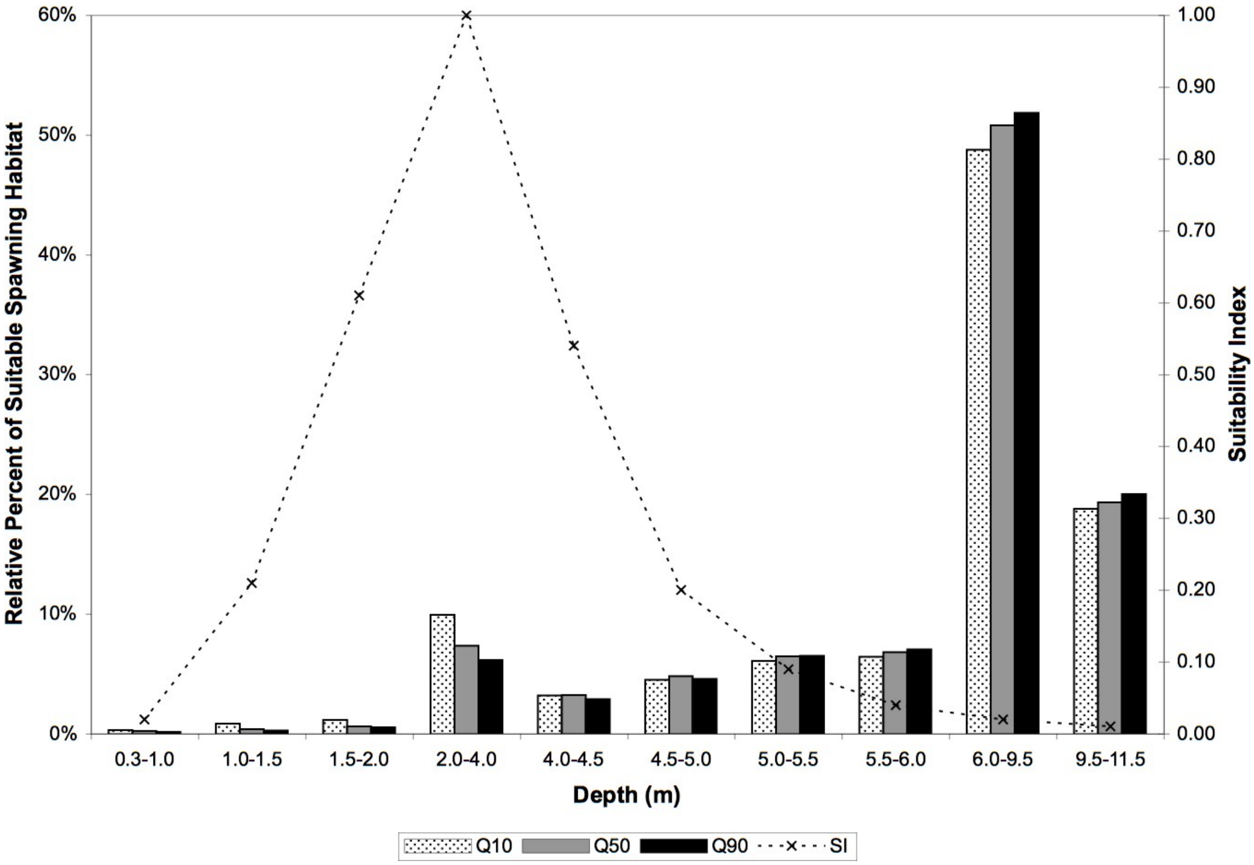

Figure 3.19. Depth Within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Lower Granite Dam, During a Normal Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

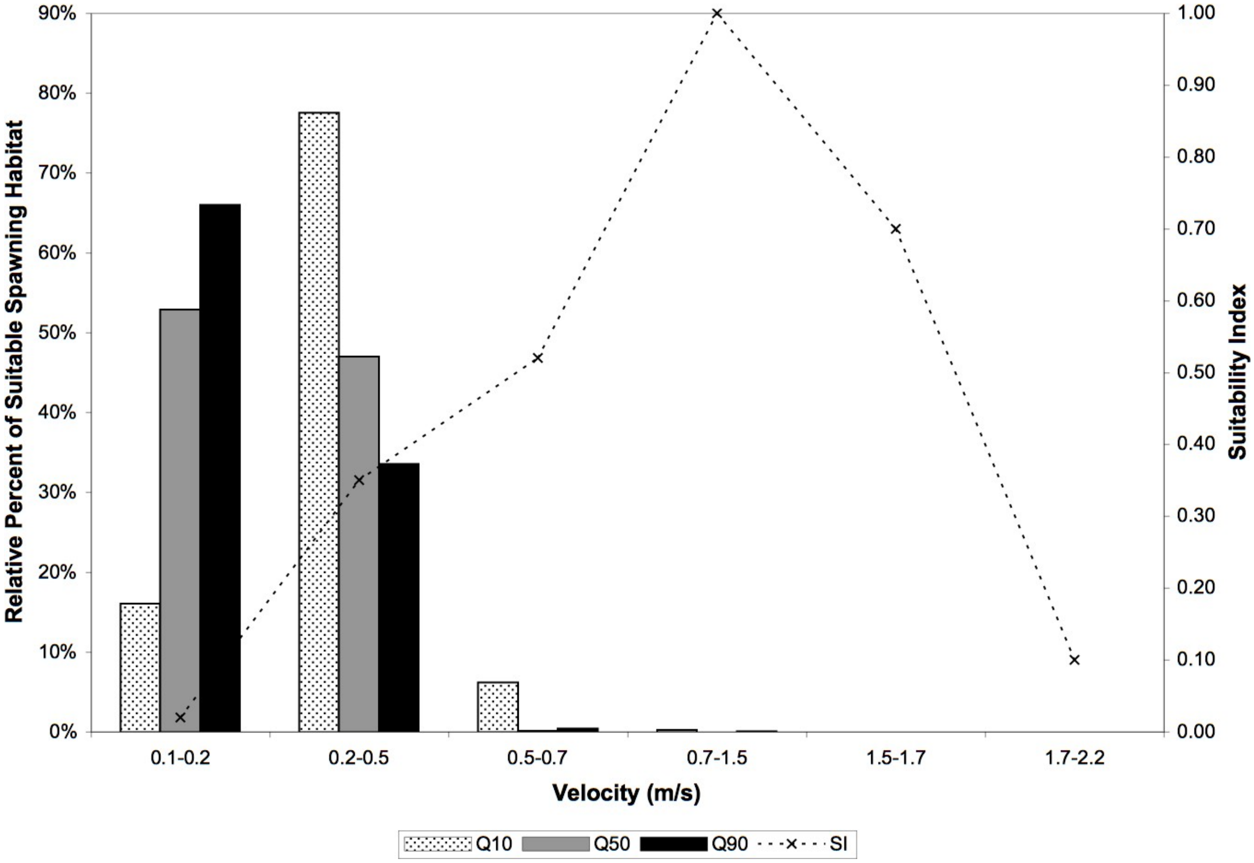

Figure 3.20. Velocity Within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Lower Granite Dam, During a Normal Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

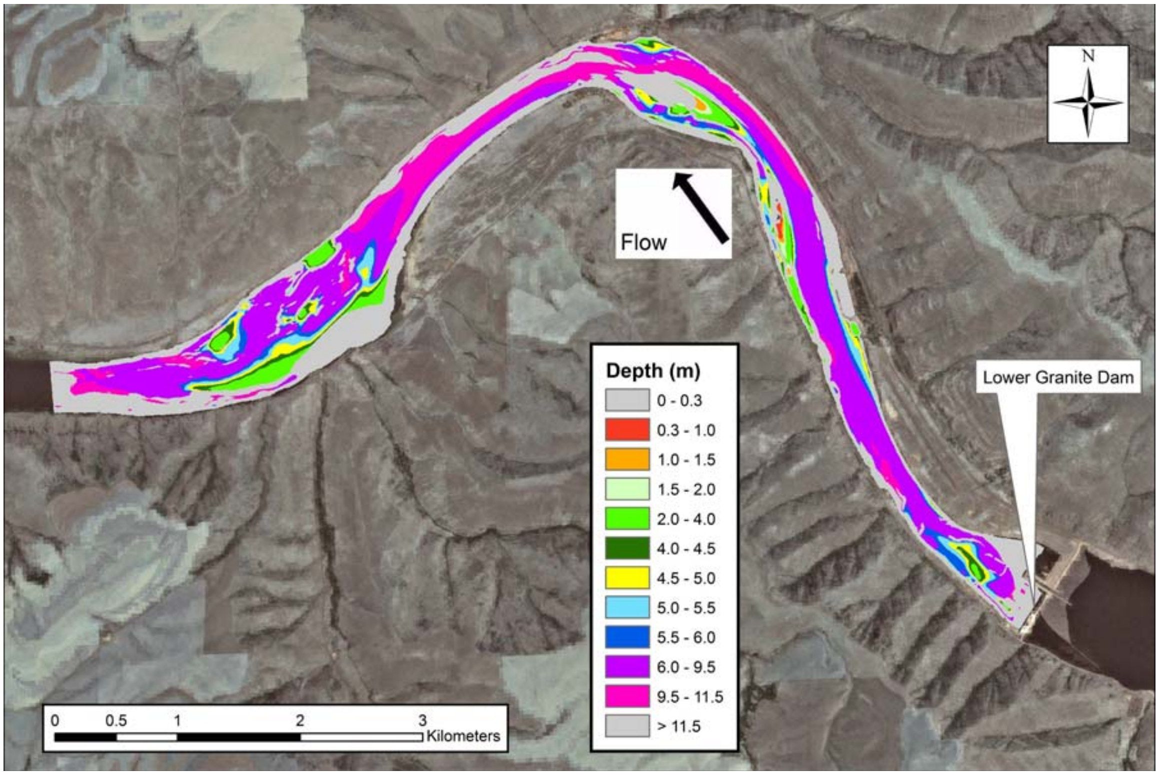

Figure 3.21. Depth Within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Lower Granite Dam, Based on a 50% Exceedance Discharge (21.7 kcfs) During a Normal Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

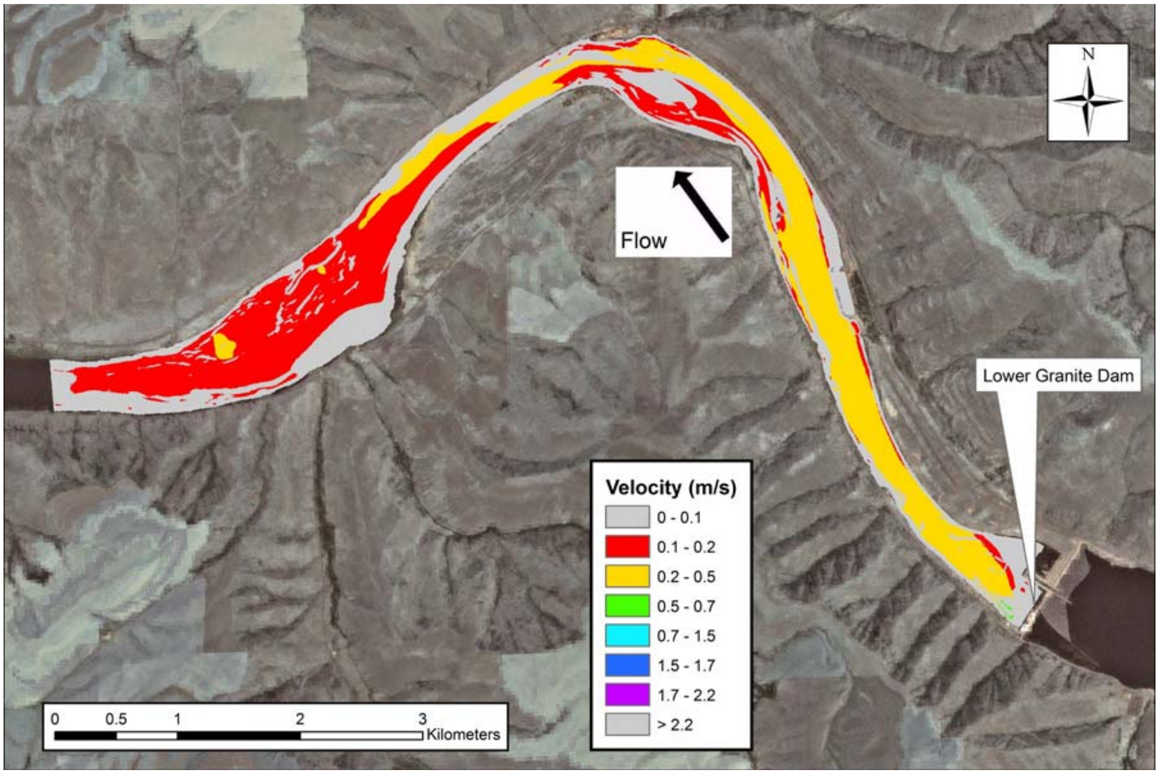

Figure 3.22. Velocity Within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Lower Granite Dam, Based on a 50% Exceedance Discharge (21.7 kcfs) During a Normal Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

3.2 Channel Morphology

3.2.1 Reference Locations

Results from the analyses of thalweg points in the Wanapum study area indicated that spawning locations were more likely to occur near riffle crests than elsewhere along the longitudinal profile. The cross-tabulation analysis indicated that spawning habitat use was dependent on bed form type ($\chi^2 = 10.1$, $df = 3$, $P = 0.02$). The upstream and downstream sides of riffle crests contained 26% and 42% of the spawning habitat use, respectively (Table 3.7). The remaining spawning habitat use occurred on the upstream (32%) ends of pools, while no spawning occurred on the downstream ends of pools.

Table 3.7. Summary Frequency Table of Four Bedform Types in Fall Chinook Salmon Spawning and Non-Spawning Areas. Points along the longitudinal profile were categorized as being on the upstream (proximal) or downstream (distal) side of a riffle crest or pool bottom. The data included all thalweg points in spawning areas ($N = 19$), and a random sample of thalweg points in non-spawning areas ($N = 20$). The cross tabulation analysis indicated that spawning habitat use was dependent on bedform type ($\chi^2 = 10.1$, $df = 3$, $P = 0.02$).

	Riffle Proximal	**Riffle Distal**	**Pool Proximal**	**Pool Distal**
Spawning				
Count	5	8	6	0
Frequency	26%	42%	32%	0%
Non-spawning				
Count	6	5	3	6
Frequency	30%	25%	15%	30%

The majority of spawning areas occurred at elevations in the transition zone between riffle and pool bedforms. The median riffle proximity index (*RPI*) for all spawning areas was 0.51, which is 51% of the elevation difference between the nearest riffle crest and pool bottom (Figure 3.23). The Barge Dock Bar spawning locations (typically containing over 90% of the fall Chinook salmon redds in the area) are situated exclusively on a riffle bedform, with a median *RPI* = 0.54 (Figure 3.24). Results from the Wald-Wolfowitz runs test indicated that the mean *RPI* in the Barge Dock Bar spawning area was significantly larger than the mean *RPI* in non-spawning areas ($z = -2.08$, $P = 0.04$) (Figure 3.25).

Within the Wanapum study area, three riffle bedforms were identified (Figure 3.26). All of the bedforms are large, with 15 m of riverbed elevation change along the thalweg over the length of the study area. The slopes of individual bedforms ranged from 0.004 to 0.01 (Table 3.8). The bedform slopes on the upstream and downstream side of the Barge Dock Bar (rkm 666.5–667.5) are 0.01 and 0.008, respectively. The dimensions of these bedforms are similar to those of the other fall Chinook salmon spawning habitat reference locations in the Columbia and Snake rivers. The tolerance value *T* (used in the bedform differencing technique to distinguish bedforms from local undulations of smaller magnitude in the riverbed profile) at the reference locations ranges from 2.5 m to 3.9 m (Table 3.8). The bedform slopes in the Hanford Reach of the Columbia River range from 0.002 to 0.009, while those in the Hells Canyon Reach of the Snake River are much larger, ranging from 0.001 to 0.156 (Table 3.8).

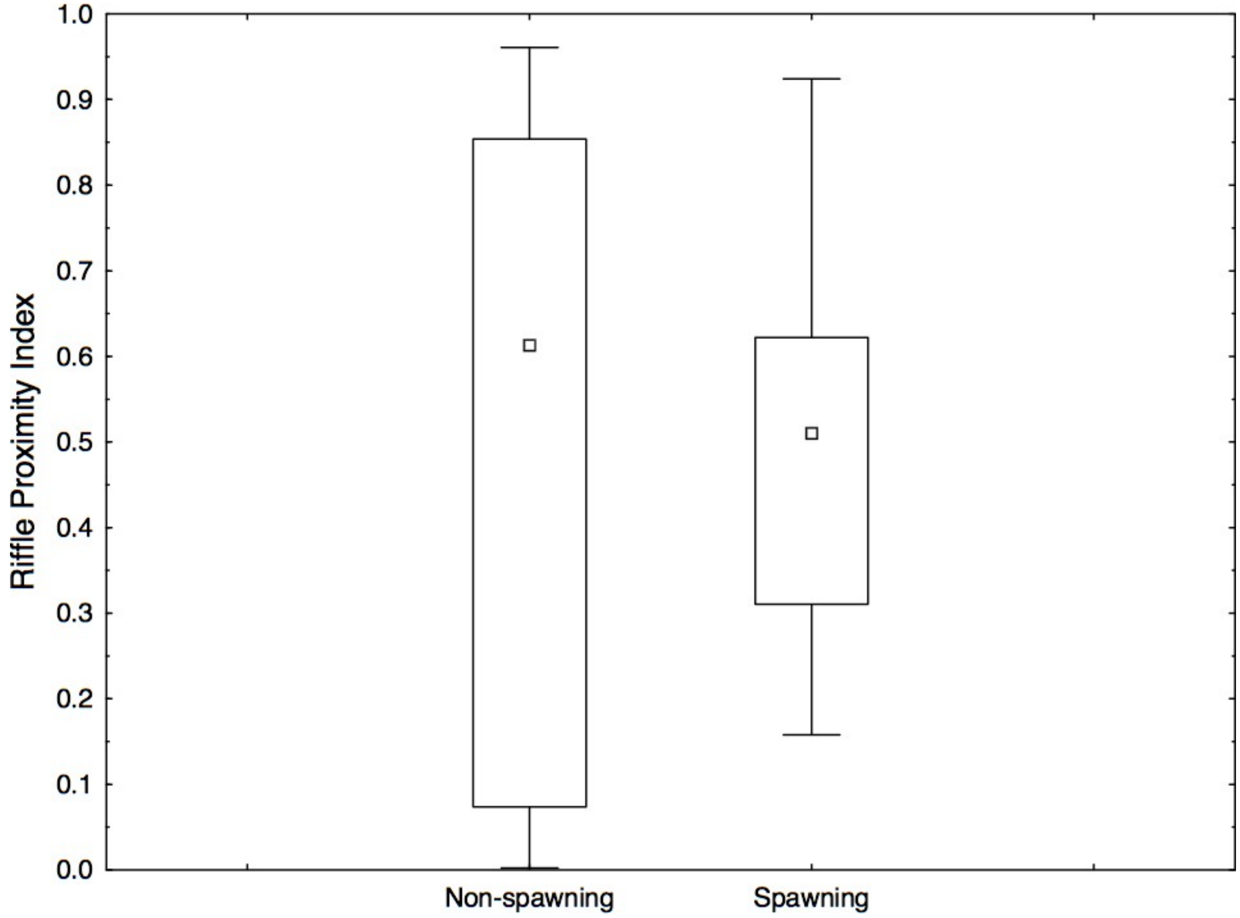

Figure 3.23. Riffle Proximity Index (*RPI)* for Fall Chinook Salmon Spawning and Non-Spawning Locations. The boxplots indicate the median (small box), surrounded by the 25th and 75th percentiles (large box), and extend to the 10th and 90th percentiles (whiskers) of observed values.

Within the Wanapum study area, 93% of the fall Chinook salmon spawning areas were located at cross sections with large width-to-depth ratios (*Fd*1* and *Fd*2*, Table 16). The majority (75%) of the cross sections containing spawning areas were asymmetrical from bank to bank (*Fd*1*), with part of the transect containing a shallow bar that deepened into a V-shaped deep thalweg. A remaining 18% of the cross sections containing spawning areas were symmetrical from bank to bank, with large width-to-depth ratios (*Fd*2*) (Table 3.9).

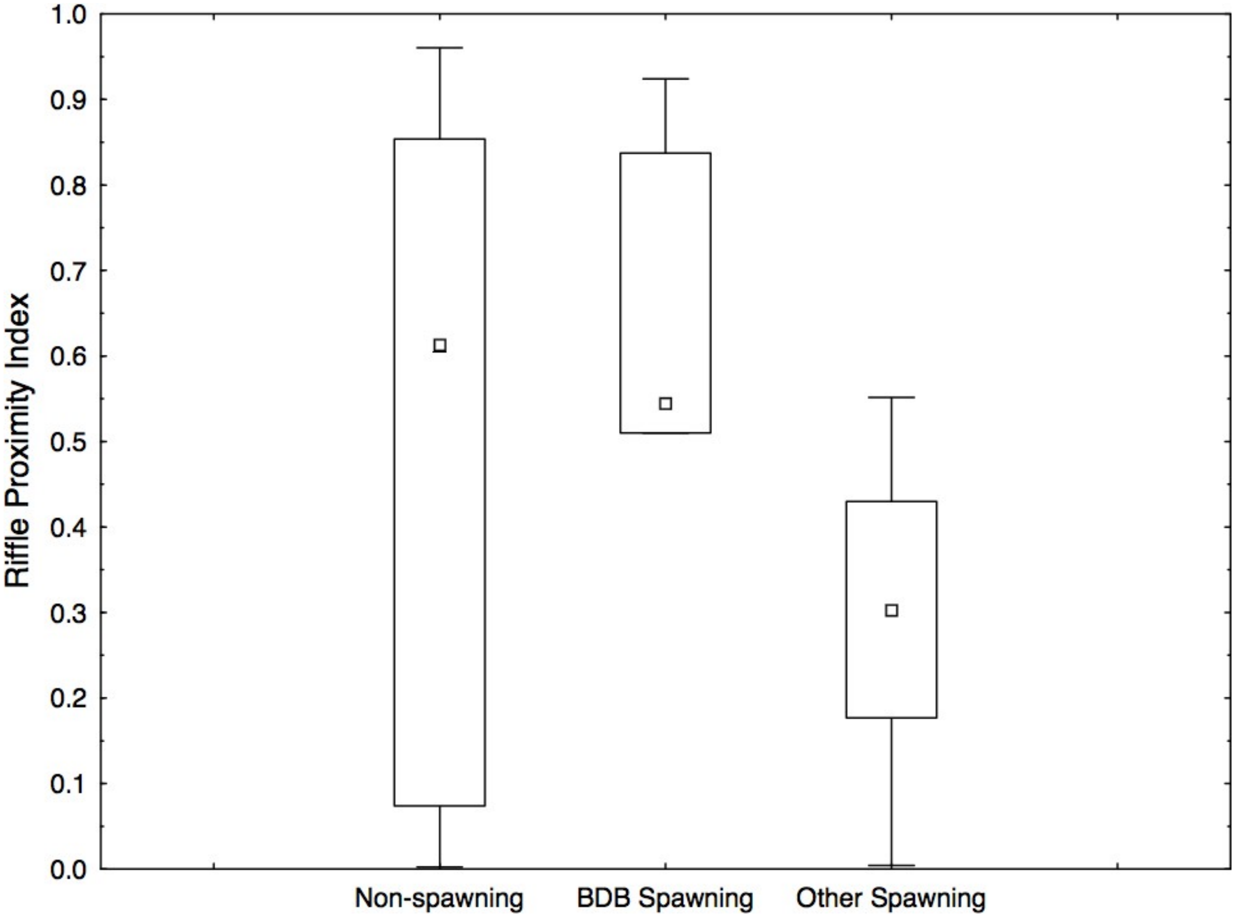

Figure 3.24. Riffle Proximity Index (*RPI*) for Fall Chinook Salmon Spawning Locations (on the Barge Dock Bar (BDB) and elsewhere) and Non-Spawning Locations. The boxplots indicate the median (small box), surrounded by the 25th and 75th percentiles (large box), and extend to the 10th and 90th percentiles (whiskers) of observed values. More than 90% of fall Chinook salmon redds in the study area are located on the Barge Dock Bar.

3.2.2 Ice Harbor and Lower Granite

Bedforms identified in the Ice Harbor and Lower Granite study areas were much smaller than those in the reference locations. In the Ice Harbor study area there was approximately 3.5 m of riverbed elevation change along the thalweg over the 12 km study area (Figure 3.27), markedly smaller than the 15.0 m of riverbed elevation change in the Wanapum reference location (Figure 3.26). In the Lower Granite study area, there was approximately 8.0 m of riverbed elevation change along the thalweg over the 13 km study

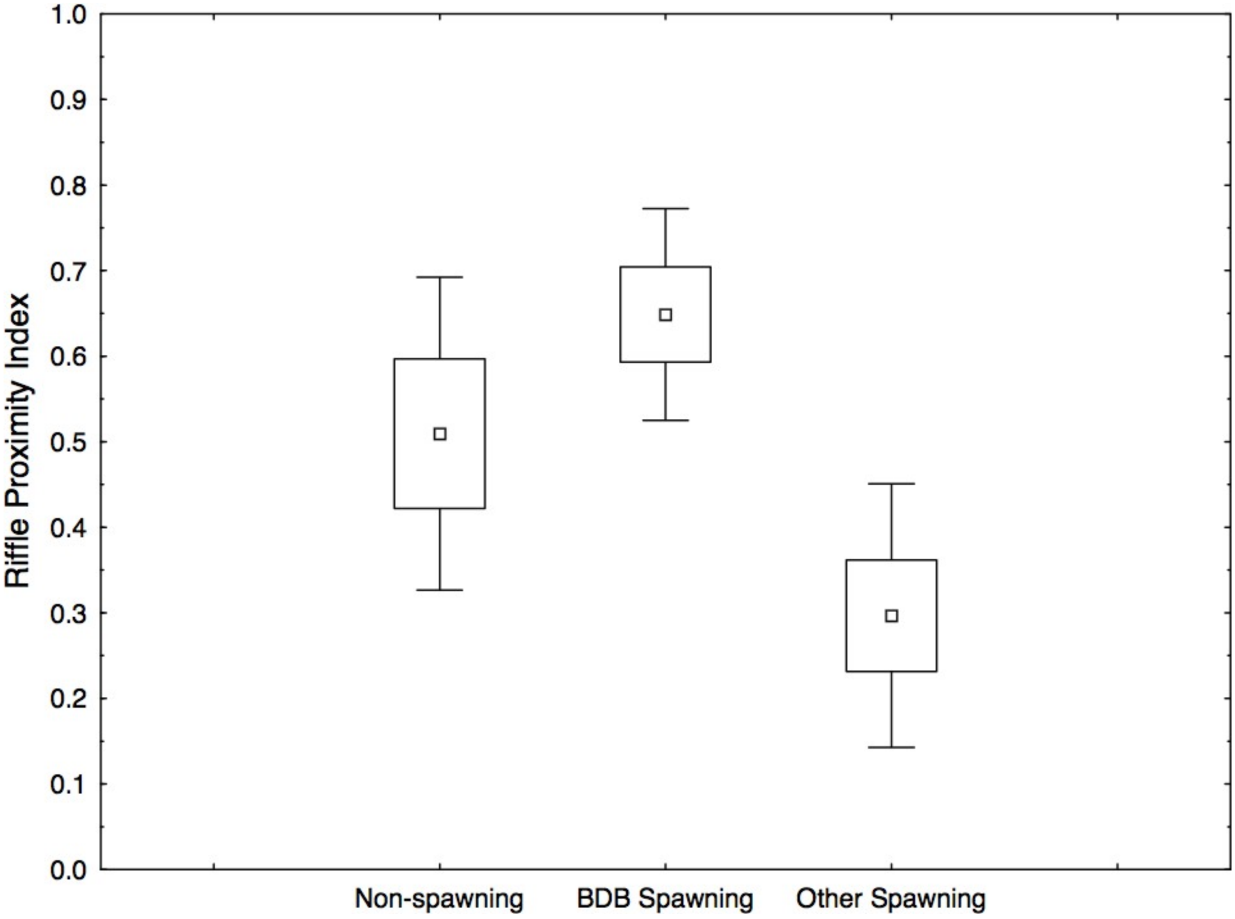

Figure 3.25. Estimates of the Mean Riffle Proximity Index (*RPI*) were Significantly Larger in Fall Chinook Salmon Spawning Locations on the Barge Dock Bar (BDB) that in Non-Spawning Locations ($P = 0.04$). The boxplots indicate the mean (small box), surrounded by the standard error of the mean (large box), and extend to the 95% confidence interval (whiskers). More than 90% of fall Chinook salmon redds in the study area are located on the Barge Dock Bar.

area (Figure 3.28). There was so little topographic relief along the thalweg of the Ice Harbor study area that the calculated bedform tolerance value (*T*) specific to the study area was too small (1.1 m) to identify any bedforms. With *T* values applied from the Lower Granite study area (2.1 m) and Hanford Reach reference location (2.5 m), there were 2 and 1 riffle crests, respectively, identified in the Ice Harbor study area (Figure 3.27). The local bedform slope of these riffles was much smaller than those in the reference locations, with the maximum bedform slope in the Ice Harbor study area being less than the minimum bedform slope in the reference locations (Tables 3.8 and 3.10). Local bedform slopes in the Lower Granite study area were similar to those of the reference locations, with mean and maximum slopes larger in the Lower Granite study area than in the Wanapum and Hanford Reach reference locations (Tables 3.8 and Table 3.10).

The cross-section channel morphology at the Ice Harbor study area was very different from that at the Lower Granite study area. Within the Ice Harbor study area, 86% of the sampled cross sections contained large width-to-depth ratios (*Fd*1* and *Fd*2*, Table 3.11). The majority (73%) of the Ice Harbor sampled

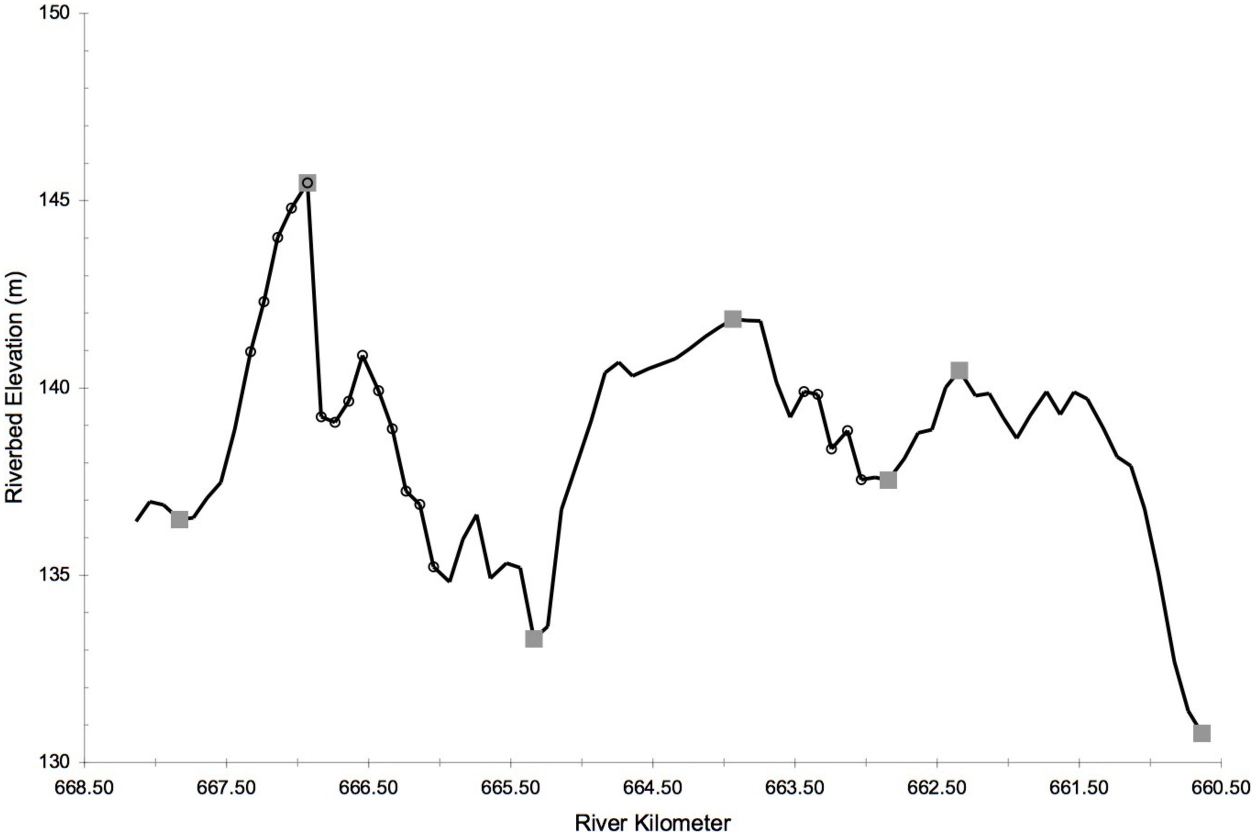

Figure 3.26. Pool and Riffle Bedforms (■) Along the Longitudinal Riverbed Profile Within the Wanapum Study Area Located in the Columbia River. Most (68%) fall Chinook salmon spawning (○) occurred on riffle bedforms.

Table 3.8. Riverbed Morphology Characteristics of Reference Fall Chinook Salmon Spawning Areas in the Columbia River (Wanapum and Hanford Reach) and Snake River (Hells Canyon). The tolerance value (*T*, m) is used in the bedform differencing technique to distinguish bedforms (riffle crests and pool bottoms) from local undulations of small magnitude in the riverbed profile. The change in elevation between adjacent riffle crests and pool bottoms is identified as bedform slope (unitless). Reach slope (unitless) indicates the change in riverbed elevation throughout the identified river reach.

		Bedform Slope			
Location	**T (m)**	**Min**	**Mean**	**Max**	**Reach Slope**
Wanapum	2.8	0.004	0.007	0.010	0.0002
Hanford Reach	2.5	0.002	0.004	0.009	0.0004
Hells Canyon	3.9	0.001	0.040	0.156	0.0020(a) 0.0010(b) 0.0007(c)

(a,b,c) Upper, middle, and lower reach, respectively. See Hanrahan (2007b) for details.

Table 3.9. Classification Summary of Sampled Cross Sections in the Wanapum Study Area

Fd* **Category**	**Count**	**Relative Frequency (%)**	**% Spawning**
1	44	52	75
2	22	26	18
3	8	9	<4
4	11	13	<4

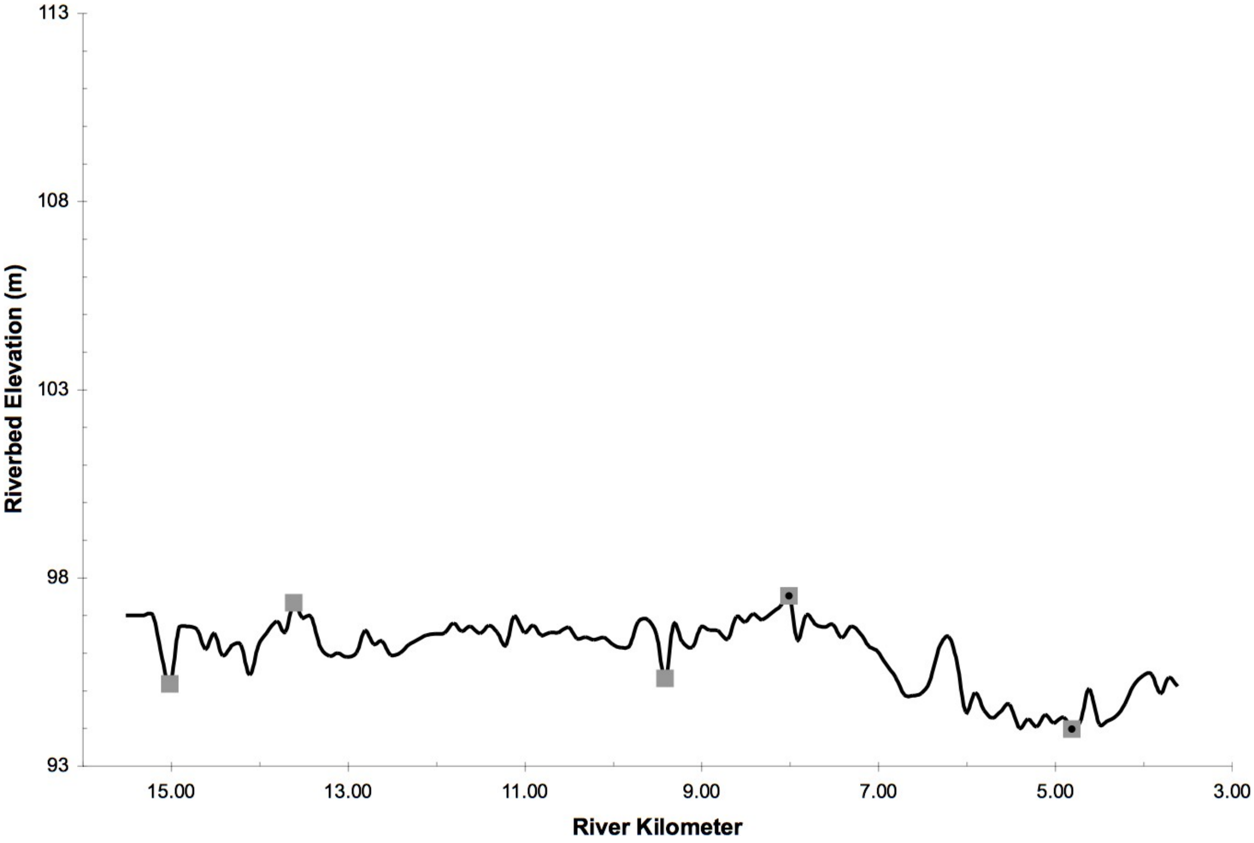

Figure 3.27. Pool and Riffle Bedforms Along the Longitudinal Riverbed Profile Within the Ice Harbor Study Area Located in the Snake River. Bedforms were identified based on tolerance values (*T*) calculated from the Lower Granite study area (2.1 m, ■) and the Hanford Reach reference location (2.5 m, ●).

cross sections were asymmetrical from bank to bank (*Fd*1*), with part of the transect containing a shallow bar that deepened into a V-shaped deep thalweg. The next most frequent cross section type in the Ice Harbor study area was symmetrical from bank to bank, with large width-to-depth ratios (*Fd*2*) (Table 3.8). Within the Lower Granite study area, only 18% of the sampled cross sections contained large width-to-depth ratios (*Fd*1* and *Fd*2*, Table 3.8). The majority (82%) of the Lower Granite sampled cross sections were symmetrical, narrow, and relatively uniformly deep (*Fd*4*) (Table 3.8). The cross section channel morphology at the Ice Harbor study area was very similar to that of the Wanapum reference location (Table 3.9).

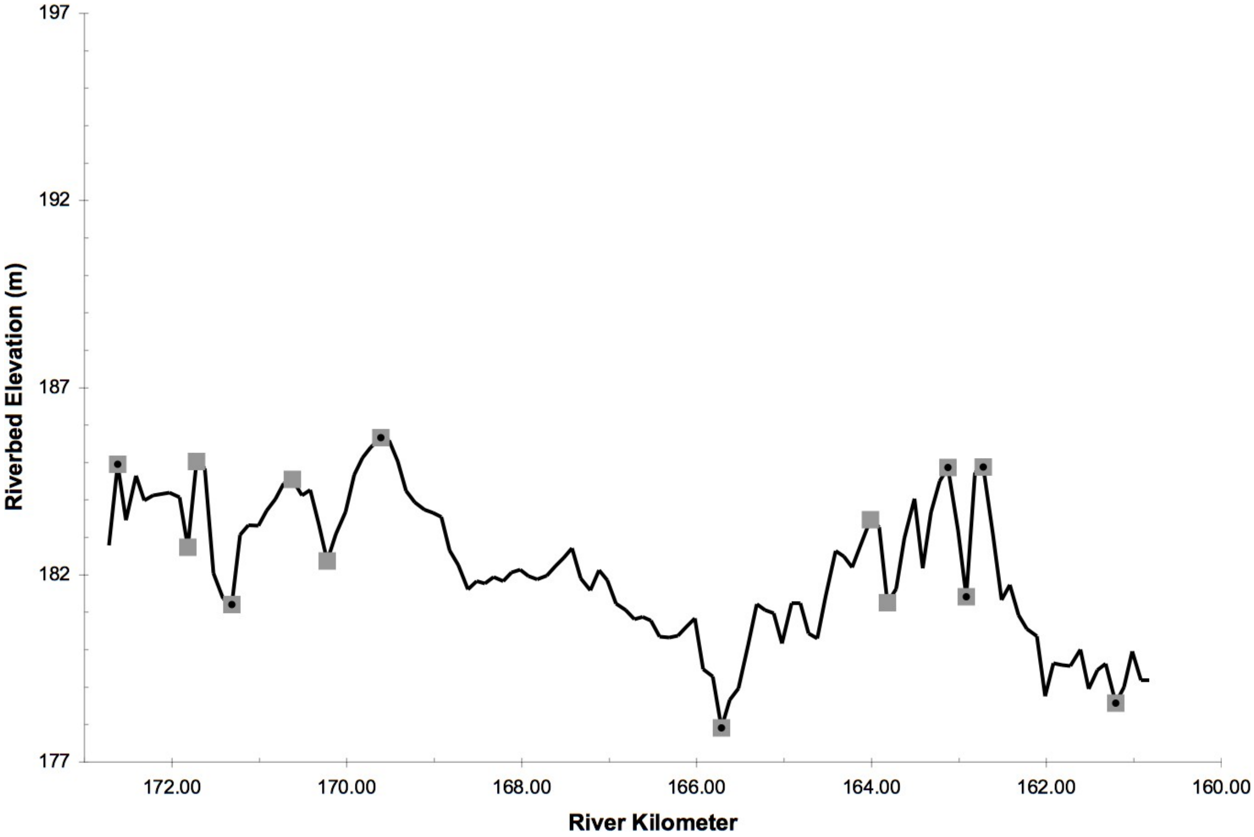

Figure 3.28. Pool and Riffle Bedforms Along the Longitudinal Riverbed Profile Within the Lower Granite Study Area Located in the Snake River. Bedforms were identified based on tolerance values (*T*) calculated from the Lower Granite study area (2.1 m, ■) and the Hanford Reach reference location (2.5 m, ●).

Table 3.10. Riverbed Morphology Characteristics of the Ice Harbor and Lower Granite Study Areas. The tolerance value (*T*, m) is used in the bedform differencing technique to distinguish bedforms (riffle crests and pool bottoms) from local undulations of small magnitude in the riverbed profile. The change in elevation between adjacent riffle crests and pool bottoms is identified as bedform slope (unitless). Reach slope (unitless) indicates the change in riverbed elevation throughout the identified river reach.

		Bedform Slope			
Location	**T (m)**	**Min**	**Mean**	**Max**	**Reach Slope**
Ice Harbor	1.1[a]				0.0002
	2.1[b]	0.0005	0.001	0.002	
	2.5[c]	0.001	0.001	0.001	
Lower Granite	2.1[b]	0.002	0.009	0.024	0.0003
	2.5[c]	0.002	0.007	0.018	

(a) The calculated bedform tolerance value (*T*) for the Ice Harbor study area was too small to identify any bedforms.
(b) Bedform slopes calculated from bedforms identified with the Lower Granite *T* value of 2.1 m.
(c) Bedform slopes calculated from bedforms identified with the Hanford Reach *T* value of 2.5 m.

Table 3.11. Geomorphic Classification Summary of Sampled Cross Sections in the Ice Harbor and Lower Granite Study Areas

Study Area	***Fd**** **Category**	**Count**	**Relative Frequency (%)**
Ice Harbor	1	88	73
	2	15	13
	3	3	<3
	4	14	<12
Lower Granite	1	1	<1
	2	21	18
	3	0	0
	4	98	82

4.0 Discussion

The results of this study indicate that a majority of the Ice Harbor and Lower Granite study areas contain suitable fall Chinook salmon spawning habitat under existing hydrosystem operations. However, a large majority of the currently available fall Chinook salmon spawning habitat in the Ice Harbor and Lower Granite study areas is of low quality. The potential for increasing, through modifications to hydrosystem operations (i.e., minimum pool elevation of the next downstream dam), the quantity or quality of fall Chinook salmon spawning habitat appears to be limited. Estimates of the amount of potential fall Chinook salmon spawning habitat in the Ice Harbor study area decreased as the McNary Dam forebay elevation was lowered from normal to minimum pool elevation. Estimates of the amount of potential fall Chinook salmon spawning habitat in the Lower Granite study area increased as the Little Goose Dam forebay elevation was lowered from normal to minimum pool elevation; however, 97% of the available habitat was categorized within the range of lowest quality. In both the Ice Harbor and Lower Granite study areas, water velocity appears to be more of a limiting factor for fall Chinook salmon spawning habitat than water depth, with both study areas dominated by low-magnitude water velocity. The geomorphic suitability of both study areas appears to be compromised for fall Chinook salmon spawning habitat, with the Ice Harbor study area lacking significant bedforms along the longitudinal thalweg profile and the Lower Granite study area lacking cross-sectional topographic diversity.

The results from the modeling of potential fall Chinook spawning habitat availability suggest that the primary limiting physical factors in the Ice Harbor and Lower Granite study areas are the hydraulic characteristics of water depth and velocity. The large amount of shallow water fall Chinook salmon spawning habitat in the Ice Harbor study area is considered low quality, and becomes dewatered or outside the fall Chinook salmon spawning suitability range when the McNary Dam forebay elevation is lowered to minimum pool. On the contrary, much of the Lower Granite study area contains deep water near the upper end of the fall Chinook salmon spawning habitat suitability range, and this habitat remains relatively deep even when the Little Goose forebay elevation is lowered to minimum pool.

Some researchers have suggested that water depth alone does not limit spawning habitat use by Chinook salmon (Chapman et al. 1986). While this may be true, studies of deep water fall Chinook spawning in the Columbia River have not documented redds deeper than approximately 11 m (Chapman et al. 1986; Swan 1989), and researchers in the Snake River noted that no fall Chinook redds were deeper than 6.5 m, even though searches for redds in suitable habitat frequently occurred in deeper water (Groves and Chandler 1999). One reason may be that visual cues related to mate recognition and substrate differentiation would be reduced at depths greater than light penetration levels (Geist and Dauble 1998). Whether the lack of documented redds in water depths greater than 11 m is a function of habitat selection or sampling methodology is unknown. Indeed, Swan (1989) concluded that up to 80% of fall Chinook spawning in the Hanford Reach may occur in water too deep to sample by aerial observation.

Regardless of water depths *beyond* those within the suitability criteria, areas estimated as potential spawning habitat are dominated by water depths on the deeper end of the suitable range and water velocities toward the slower end of the suitable range. In contrast, within one spawning area of the Hanford Reach, 80% of the habitat within fall Chinook redd clusters contained water velocities of 1.4–2.0 m s^{-1} and water depths of 2.0–4.0 m (Geist et al. 2000). Additional data from Hanford Reach redds (N = 230, PNNL, unpublished data) indicate that only 10.5% of the redds were constructed in water depths > 4.0 m, while 29% of those redds were located in water velocities ≤0.75 m s^{-1}. Conversely, 43%

of the redds were in water depths between 2–3 m, and 58% of the redds were in areas of the water velocities from of 0.75–1.25 m s^{-1}. Fall Chinook redds in the Snake River were observed in average water depth of 2.8 m and average water velocity of 1.1 m s^{-1}. In deep water fall Chinook spawning habitat in the Columbia River, near bottom water velocities at redds averaged 1.75 m s^{-1} (Swan 1989), and 0.93–1.13 m s^{-1} over a range of discharges (Chapman et al. 1986).

Results from the hydrodynamic modeling indicate that the lack of water velocity of sufficiently large magnitude is more of a limiting factor in the Lower Granite study area than the Ice Harbor study area. For all the modeled scenarios in the Lower Granite study area, less than 1% of the suitable fall Chinook salmon spawning habitat contained water velocity greater than 0.7 m s^{-1}. While the Ice Harbor study area contains more potential fall Chinook salmon spawning habitat with water velocity within the optimal range of 0.7–1.5 m s^{-1}, nearly this entire higher velocity habitat is located within the navigation channel. The fall Chinook salmon spawning habitat suitability of these higher-velocity areas is compromised, as the navigation channel contains deep-water habitat beyond the optimal water depths and lacks the longitudinal bedforms along the thalweg typically associated with fall Chinook salmon spawning (Hanrahan 2007a).

Research from the Wanapum reference reach, and elsewhere within the Columbia River basin, indicates that fall Chinook salmon spawning is associated with significant bedforms along the longitudinal riverbed profile. The results from the Wanapum reference reach indicate that most fall Chinook salmon spawning occurs in riffles and at a vertical location near the riffle crest elevation. This location corresponds to the transitional area between pools and riffles, an important habitat area where many salmon species tend to prefer to spawn (Bjornn and Reiser 1991). Owing to localized variations in sediment transport rates, these transitional areas are depositional zones that are often associated with the formation of bars (lateral, midchannel, point) and islands. Previous researchers have observed salmon spawning locations to be associated with depositional ‘response’ reaches (Montgomery et al. 1999; Moir et al. 2004), especially near the upstream end of bars and islands (Dauble and Watson 1997; Geist and Dauble 1998; Coulombre-Pontbriand and Lapointe 2004). The results reported here corroborate these earlier findings and quantify the location along the longitudinal profile where Chinook salmon spawning occurs. By quantifying the two-dimensional location (vertical and longitudinal) of salmon spawning areas, these findings complement previous planform mapping of fall Chinook salmon spawning areas. Dauble and Geist (2000) reported that Chinook salmon spawning in the Hanford Reach of the Columbia River and the Hells Canyon Reach of the Snake River was associated with the presence of bars that were mapped along 1.6-km river segments. Based on planform mapping of morphological channel types (bar, fan, glide, pool, rapid, riffle), Groves and Chandler (2002) observed that most fall Chinook salmon spawning in the Snake River occurred in riffles. Hanrahan (2007) quantified the relationship between Snake River fall Chinook salmon spawning and channel morphology, reporting that 84% of the spawning occurred in riffles and at a vertical location within 80% of the riffle crest elevation. Similar findings were reported for Hanford Reach fall Chinook salmon spawning areas, where most spawning occurred in riffles and at a vertical location within 80% of the riffle crest elevation (Geist et al. 2006).

Although channelbed substrate is not a primary limiting factor of fall Chinook spawning habitat within the study areas, it is likely a contributing factor due largely to hydraulic conditions rather than grain-size composition. The hydraulic conditions within the potential spawning areas, especially in the Lower Granite study area, are likely not sufficient to initiate channelbed movement, or to sustain periodic sediment transport and deposition necessary to maintain a substrate matrix dominated by coarse gravel and cobble with a relative small percentage of sand and finer material (i.e., typical salmonid spawning substrate). Our substrate surveys adequately characterized the overall grain-size distribution of each geomorphic unit, but we did not map small-scale changes in substrate composition within a sampling unit. In general, site-scale evaluations of geomorphic competency (e.g., sediment transport), substrate quality (e.g., permeability, %fines), and surface water–groundwater interactions (e.g., riverbed pore water velocity) were not completed for this study, all of which are important components in determining habitat quality of spawning sites.

Uncertainties in our estimates of potential habitat arise from the suitability index (SI) curves we used for calculating suitability of a spawning area. The suitability criteria for depth, velocity, substrate, and channelbed slope were compiled for the fall Chinook salmon spawning areas of the Wanapum reference reach, which represents a tailwater habitat physical setting similar to that of the Ice Harbor and Lower Granite study areas. To create the depth and velocity SI curves, we used data from more than 62 redds and 47,000 spawning habitat cells in the Wanapum reference reach. These data were evaluated for consistency with depth and velocity data from studies of all major fall Chinook salmon spawning areas within the mainstem Columbia and Snake rivers (Chapman et al. 1986; Swan 1989; Geist et al. 1997; reviewed in Geist and Dauble 1998; Groves and Chandler 1999; Geist et al. 2000). Collectively, these data best represent the entire range of conditions within which fall Chinook salmon spawn within the mainstem Columbia and Snake rivers. While the SI curves represent the best available to date, the proportion of fall Chinook selected spawning areas with these microhabitat characteristics (i.e., depth/velocity combinations) relative to the total availability of microhabitat is not known. Nevertheless, we believe the suitability index modeling produced estimates of potential spawning habitat within acceptable ranges.

While approximately 65% and 50% of the Ice Harbor and Lower Granite study areas, respectively, contain suitable fall Chinook salmon spawning habitat, it is very unlikely that most of this habitat would be used, even if adult escapement were increased considerably. Estimating the redd capacity of a river reach based on potentially suitable habitat leads to a high degree of uncertainty. Much of the variability in habitat and capacity estimates may result from a general lack of understanding of the habitat conditions influencing fall Chinook spawning. Observations from studies in the Columbia and Snake rivers indicate that spawning fall Chinook salmon utilize a relatively small proportion of seemingly suitable habitat within a contiguous area (Swan 1989; Dauble and Watson 1990, 1997; Geist and Dauble 1998; Geist et al. 2000; Visser 2002). Research from the Hanford Reach of the Columbia River indicates that fall Chinook salmon spawn in distinct clusters within areas predicted by habitat models, or other methods, to be suitable (Dauble and Watson 1997; Geist et al. 2000; Visser 2002). Indeed, fall Chinook redds have been observed aggregated in clusters, even though apparently suitable spawning habitat was widely distributed (Dauble and Watson 1990). To account for proportional use of suitable habitat, previous estimates of redd capacity considered that only 5–30% of suitable fall Chinook salmon habitat would actually be used (Hanrahan et al. 2004; Geist et al. 2006).

5.0 Conclusions

The modifications to hydroelectric dam operations that were evaluated in this study are unlikely to increase the quantity of available fall Chinook salmon spawning habitat in the Ice Harbor and Lower Granite study areas. Lowering the McNary Dam forebay elevation from normal pool to minimum pool will result in a net loss of available fall Chinook salmon spawning habitat in the Ice Harbor study area, as formerly suitable habitat becomes dewatered. Lowering the Little Goose Dam forebay elevation from normal pool to minimum pool will result in a small net increase in available fall Chinook salmon spawning habitat in the Lower Granite study area. However, the modest increase in available habitat in the Lower Granite study area should be tempered by the finding that 81–99% of this habitat (depending on discharge regime and water year type) is characterized as being of the lowest quality available. While the change in hydroelectric dam operations may elicit some improvement in hydraulic conditions within the study areas, the geomorphic suitability of both study areas appears to be compromised for fall Chinook salmon spawning habitat, with the Ice Harbor study area lacking significant bedforms along the longitudinal thalweg profile and the Lower Granite study area lacking cross-sectional topographic diversity.

To increase the quantity of available fall Chinook salmon spawning habitat in the Ice Harbor and Lower Granite study area, modifications to hydroelectric dam operations beyond those evaluated in this study likely would be necessary. Modifications may include operational and structural changes, such as lowering downstream dam forebay elevations to less than minimum pool. There is a large amount of uncertainty as to whether or not such modifications could increase the quantity of available fall Chinook salmon spawning habitat in the Ice Harbor and Lower Granite study area. The results from this study provide some certainty that the quantity and quality of fall Chinook salmon spawning habitat within the lower Snake River are not likely to be increased within the existing hydroelectric dam operations.

6.0 References

57 FR 14653). April 22, 1992. “Endangered and Threatened Species; Threatened Status for Snake River Spring/Summer Chinook Salmon, Threatened Status for Snake River Fall Chinook Salmon.” *Federal Register*, National Marine Fisheries Service, pp. 14653-14663.

Bjornn TC and DW Reiser. 1991. “Habitat Requirements of Salmonids in Streams.” In *Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats*, WR Meehan (ed). AFS Special Publication 19, American Fisheries Society, Bethesda, Maryland.

Bovee KD. 1995. *A Comprehensive Overview of the Instream Flow Incremental Methodology*. IF 250, National Biological Service, Fort Collins, Colorado.

Bovee KD and T Cochnauer. 1977. *Development and Evaluation of Weighted-Criteria, Probability-of-Use Curves for Instream Flow Assessments*. Instream Flow Information Paper No. 3, FWS/OBS-77/63, U.S. Fish and Wildlife Service, Fort Collins, Colorado.

Chapman DW, DE Weitkamp, TL Welsh, MB Dell, and TH Schadt. 1986. “Effects of River Flow on the Distribution of Chinook Salmon Redds.” *Transactions of the American Fisheries Society* 115:537-547.

Dauble DD and DR Geist. 2000. “Comparison of Mainstem Spawning Habitats for Two Populations of Fall Chinook Salmon in the Columbia River Basin.” *Regulated Rivers: Research and Management* 16:345-361.

Dauble DD and DG Watson. 1990. *Spawning and Abundance of Fall Chinook Salmon (Oncorhynchus tshawytscha) in the Hanford Reach of the Columbia River, 1948-1988*. DOE/BP-62611-16, Bonneville Power Administration, Portland, Oregon.

Dauble DD and DG Watson. 1997. “Status of Fall Chinook Salmon Populations in the Mid-Columbia River, 1948-1992.” *North American Journal of Fisheries Management* 17:283-300.

Dauble DD, TP Hanrahan, DR Geist, and MJ Parsley. 2003. “Impacts of the Columbia River Hydroelectric System on Main-Stem Habitats of Fall Chinook Salmon.” *North American Journal of Fisheries Management* 23:641-659.

Geist DR and DD Dauble. 1998. “Redd Site Selection and Spawning Habitat Use by Fall Chinook Salmon: The Importance of Geomorphic Features in Large Rivers.” *Environmental Management* 22:655-669.

Geist DR, DD Dauble, and Visser. 1997. *The Development of a Spawning Habitat Model to Aid in Recovery Plans for Snake River Fall Chinook Salmon. Fiscal Year 1995 and 1996 Progress Report.* Bonneville Power Administration, Portland, Oregon.

Geist D, J Jones, CJ Murray, and DD Dauble. 2000. "Suitability Criteria Analyzed at the Spatial Scale of Redd Clusters Improved Estimates of Fall Chinook Salmon (*Oncorhynchus tshawytscha*) Spawning Habitat Use in the Hanford Reach, Columbia River." *Canadian Journal of Fisheries and Aquatic Sciences* 57:1636-1646.

Geist DR, EV Arntzen, YJ Chien, TP Hanrahan, CJ Murray, WA Perkins, MC Richmond, and Y Xie. 2006. *Spawning Habitat Studies of Hanford Reach Fall Chinook Salmon (Oncorhynchus tshawytscha).* Bonneville Power Administration, Portland, Oregon.

Groves PA and JA Chandler. 1999. "Spawning Habitat Used by Fall Chinook Salmon in the Snake River." *North American Journal of Fisheries Management* 19:912-922.

Groves PA and JA Chandler. 2002. *The Quality and Availability of Fall Chinook Salmon Spawning and Incubation Habitat Downstream of the Hells Canyon Complex*. Technical Report Appendix E.3.1.3 to FERC Relicensing Application, Idaho Power Company, Boise, Idaho.

Groves PA and JA Chandler. 2005. "Habitat Quality of Historic Snake River Fall Chinook Salmon Spawning Locations and Implications for Incubation Survival: Part 2, Intra-Gravel Water Quality." *River Research and Applications* 21:469-483.

Hanrahan TP. 2007a. "Bedform Morphology of Salmon Spawning Areas in a Large Gravel-Bed River. *Geomorphology* 86:529-536.

Hanrahan TP. 2007b. "Effects of river discharge on hyporheic exchange flows in salmon spawning areas of a large gravel-bed river. *Hydrological Processes* DOI: 10.1002/hyp.6605.

Hanrahan TP, DD Dauble, and DR Geist. 2004. "An Estimate of Chinook Salmon (*Oncorhynchus tshawytscha*) Spawning Habitat and Redd Capacity Upstream of a Migration Barrier in the Upper Columbia River." *Canadian Journal of Fisheries and Aquatic Sciences* 61:23-33.

Hanrahan TP, DR Geist, and EV Arntzen. 2005. "Habitat Quality of Historic Snake River Fall Chinook Salmon Spawning Locations and Implications for Incubation Survival: Part 1, Substrate Quality." *River Research and Applications* 25:455-467.

Kondolf GM. 2000. "Assessing Salmonid Spawning Gravel Quality." *Transactions of the American Fisheries Society* 129:262-281.

Kondolf GM and MG Wolman. 1993. "The Sizes of Salmonid Spawning Gravels." *Water Resources Research* 29:2275-2285.

Moir HJ, CN Gibbins, C Soulsby, and J Webb. 2004. "Linking Geomorphic Characteristics to Spatial Patterns of Spawning Activity and Discharge Use by Atlantic Salmon (*Salmo salar L.*)." *Geomorphology* 60:21-35.

Montgomery DR, EM Beamer, GR Pess, and TP Quinn. 1999. "Channel Type and Salmonid Spawning Distribution and Abundance." *Canadian Journal of Fisheries and Aquatic Sciences* 56:377-387.

O'Neill MP and AD Abrahams. 1984. "Objective Identification of Pools and Riffles." *Water Resources Research* 20:921-926.

Patankar S. 1980. *Numerical Heat Transfer and Fluid Flow*. Hemisphere, New York.

Payne BA and MF Lapointe. 1997. "Channel Morphology and Lateral Stability: Effects on Distribution of Spawning and Rearing Habitat for Atlantic Salmon in a Wandering Cobble-Bed River." *Canadian Journal of Fisheries and Aquatic Sciences* 54:2627-2636.

Perkins WA and MC Richmond. 2004a. *MASS2, Modular Aquatic Simulation System in Two Dimensions: Theory and Numerical Methods*. PNNL-14820-1, Pacific Northwest National Laboratory, Richland, Washington.

Perkins WA and MC Richmond. 2004b. *MASS2, Modular Aquatic Simulation System in Two Dimensions: User Guide and Reference*. PNNL-14820-2, Pacific Northwest National Laboratory, Richland, Washington.

Richmond MC, WA Perkins, and Y Chien. 2000. *Numerical Model Analysis of System-Wide Dissolved Gas Abatement Alternatives*. PNWD-3245, Battelle–Pacific Northwest Division, Richland, Washington.

Richmond MC, WA Perkins, and TD Scheibe. 1999. *Two-Dimensional Hydrodynamic, Water Quality, and Fish Exposure Modeling of the Columbia and Snake Rivers. Part 1: Summary and Model Formulation*. U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington.

Swan GA. 1989. "Chinook Salmon Spawning Surveys in Deep Waters of a Large, Regulated River." *Regulated Rivers: Research and Management* 4:355-370.

USFWS (U.S. Fish and Wildlife Service). 1981. *Standards for the Development of Habitat Suitability Index Models*. 103 ESM, Division of Ecological Services, U.S. Fish and Wildlife Service, Washington, D.C.

Visser RH, DD Dauble, and DR Geist. 2002. "Use of Aerial Photography to Monitor Fall Chinook Salmon Spawning in the Columbia River." *Transactions of the American Fisheries Society* 131:1173-1179.

Appendix A

Maps of Fall Chinook Salmon Spawning Habitat Suitability

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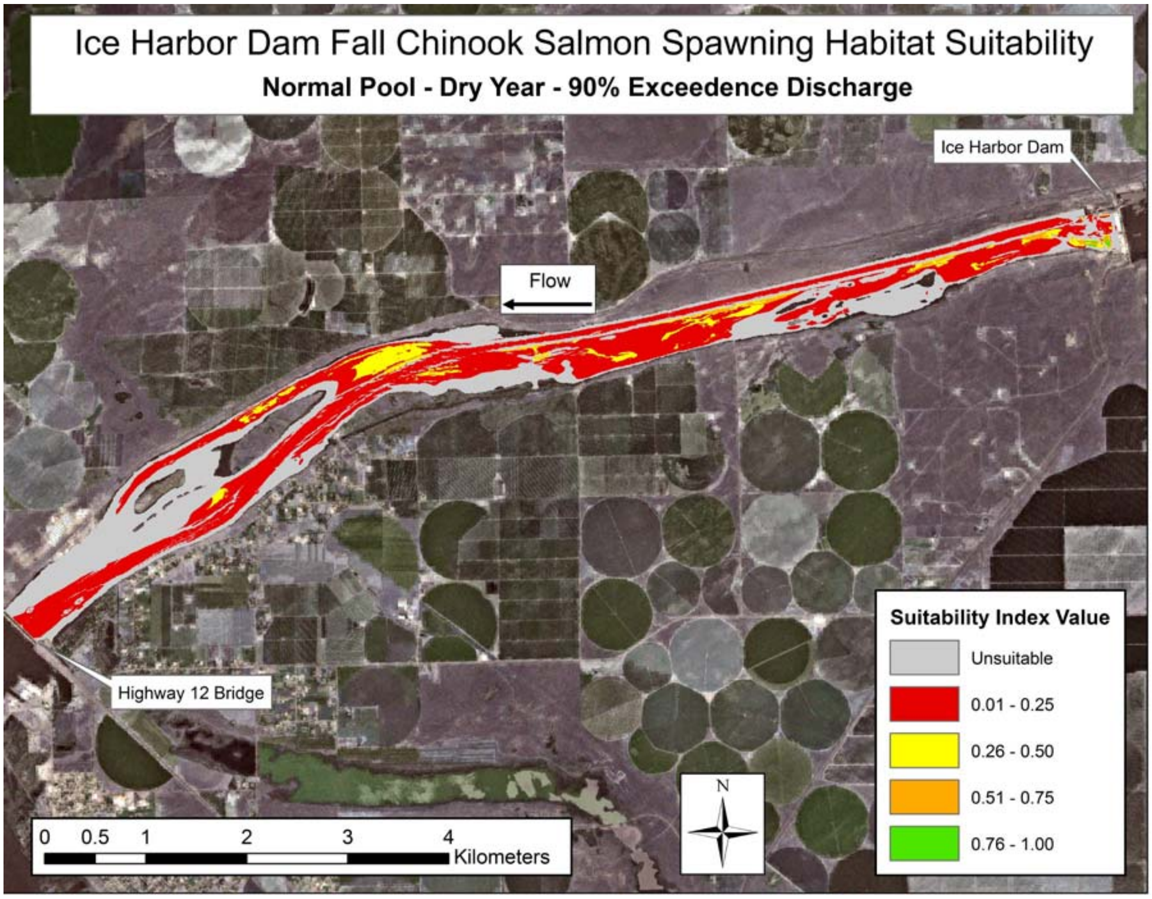

Figure A.1. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 90% Exceedence Discharge (12.6 kcfs) During a Dry Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

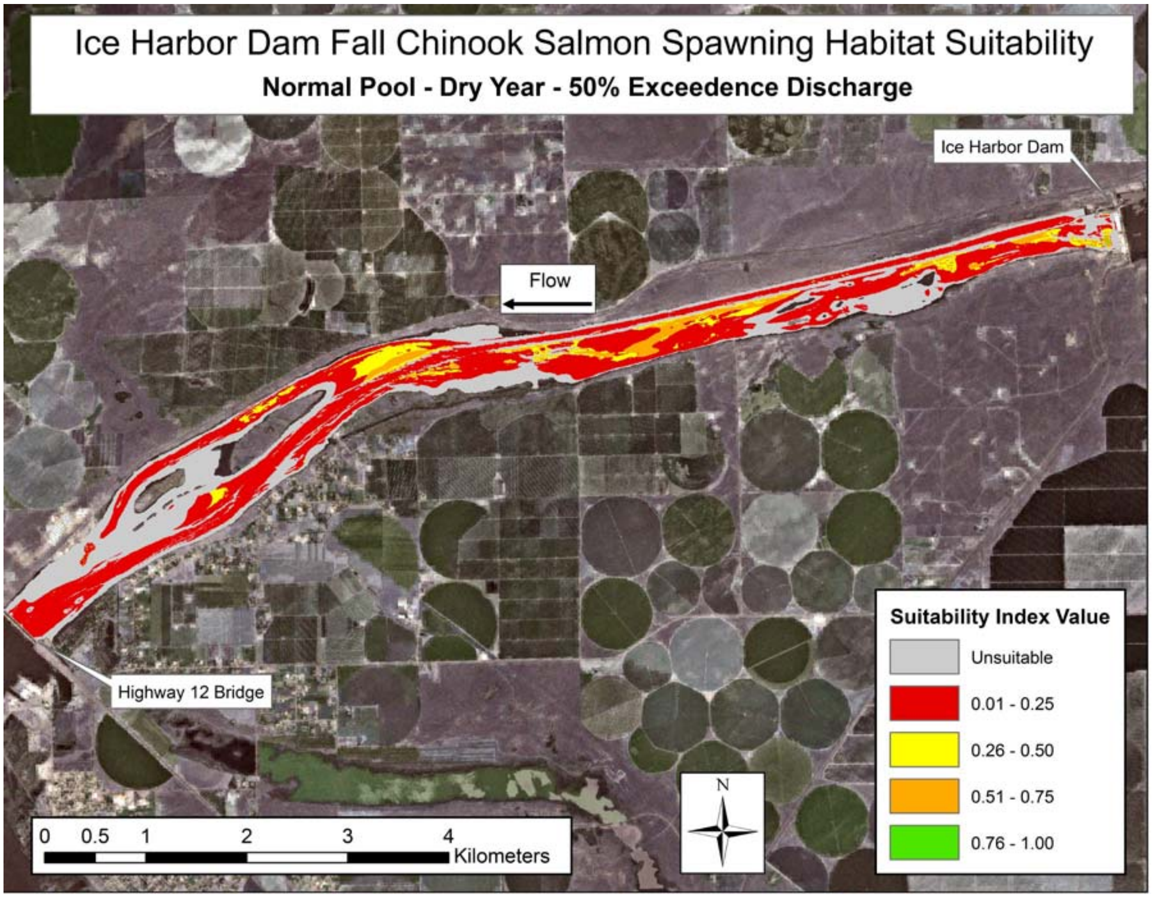

Figure A.2. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 50% Exceedence Discharge (15.3 kcfs) During a Dry Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

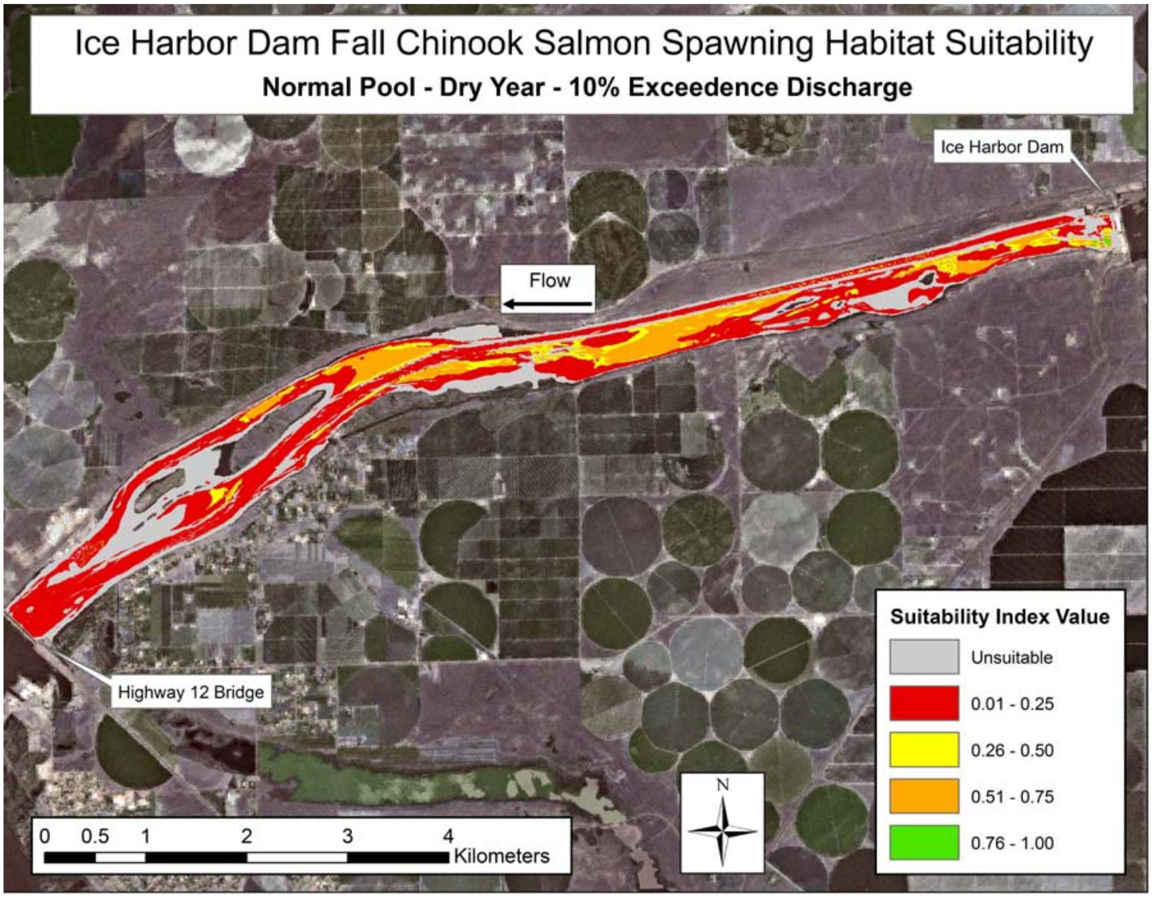

Figure A.3. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 10% Exceedence Discharge (18.2 kcfs) During a Dry Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

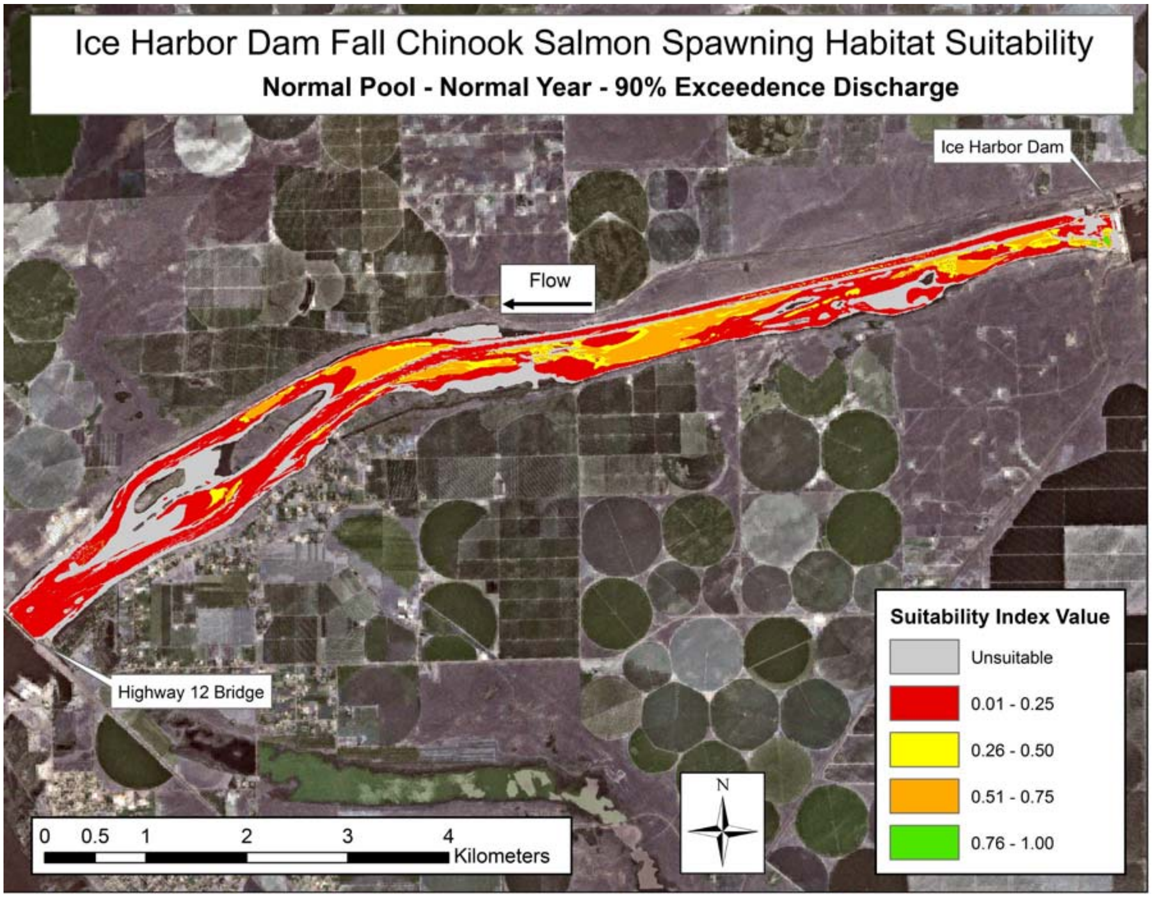

Figure A.4. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 90% Exceedence Discharge (19.1 kcfs) During a Normal Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

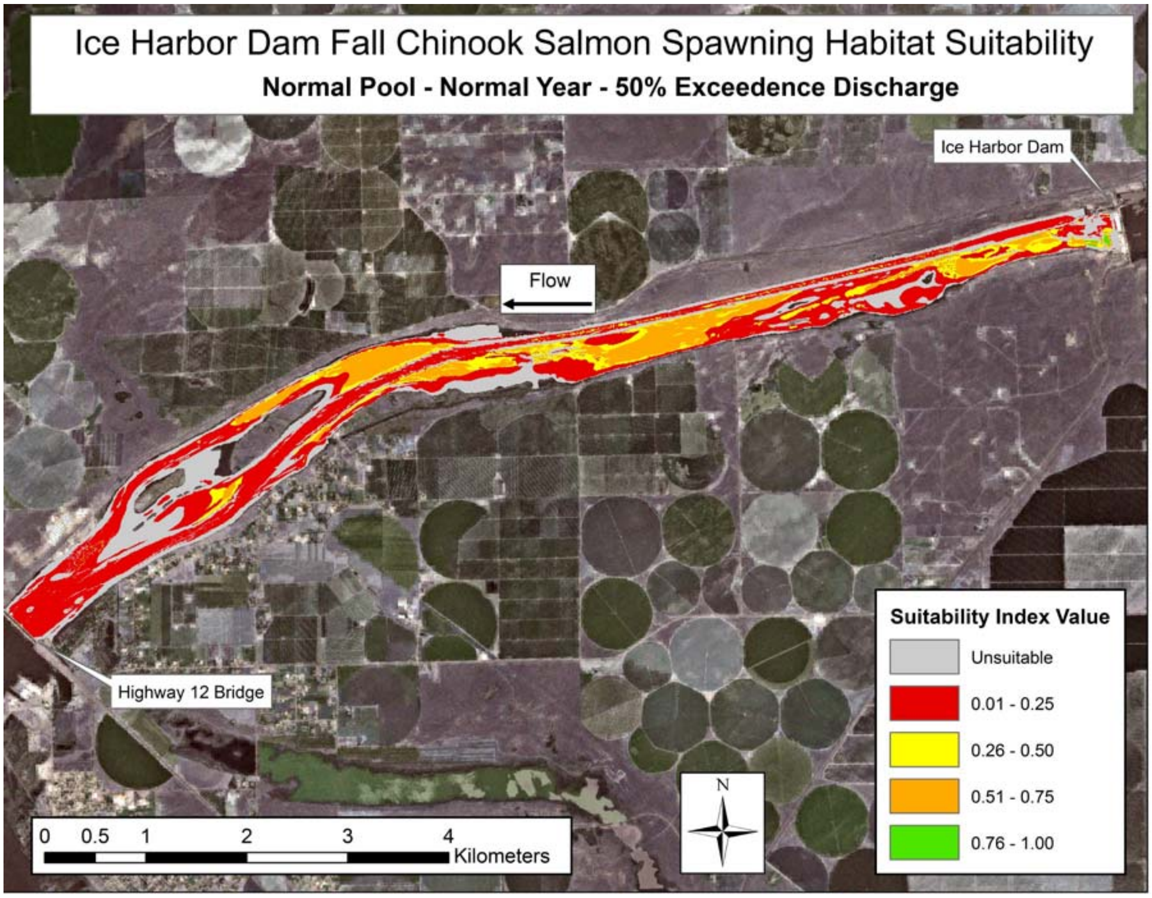

Figure A.5. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 50% Exceedence Discharge (21.7 kcfs) During a Normal Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

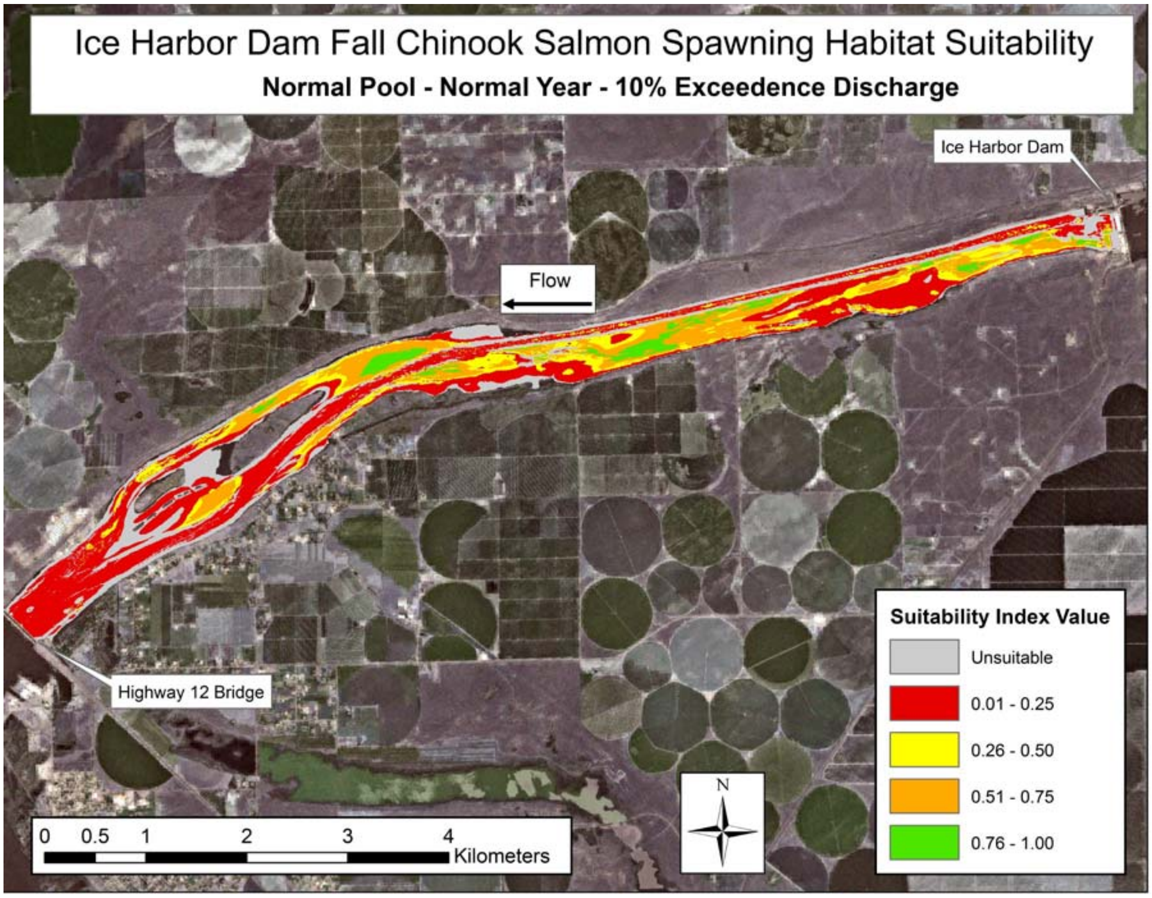

Figure A.6. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 10% Exceedence Discharge (34.5 kcfs) During a Normal Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

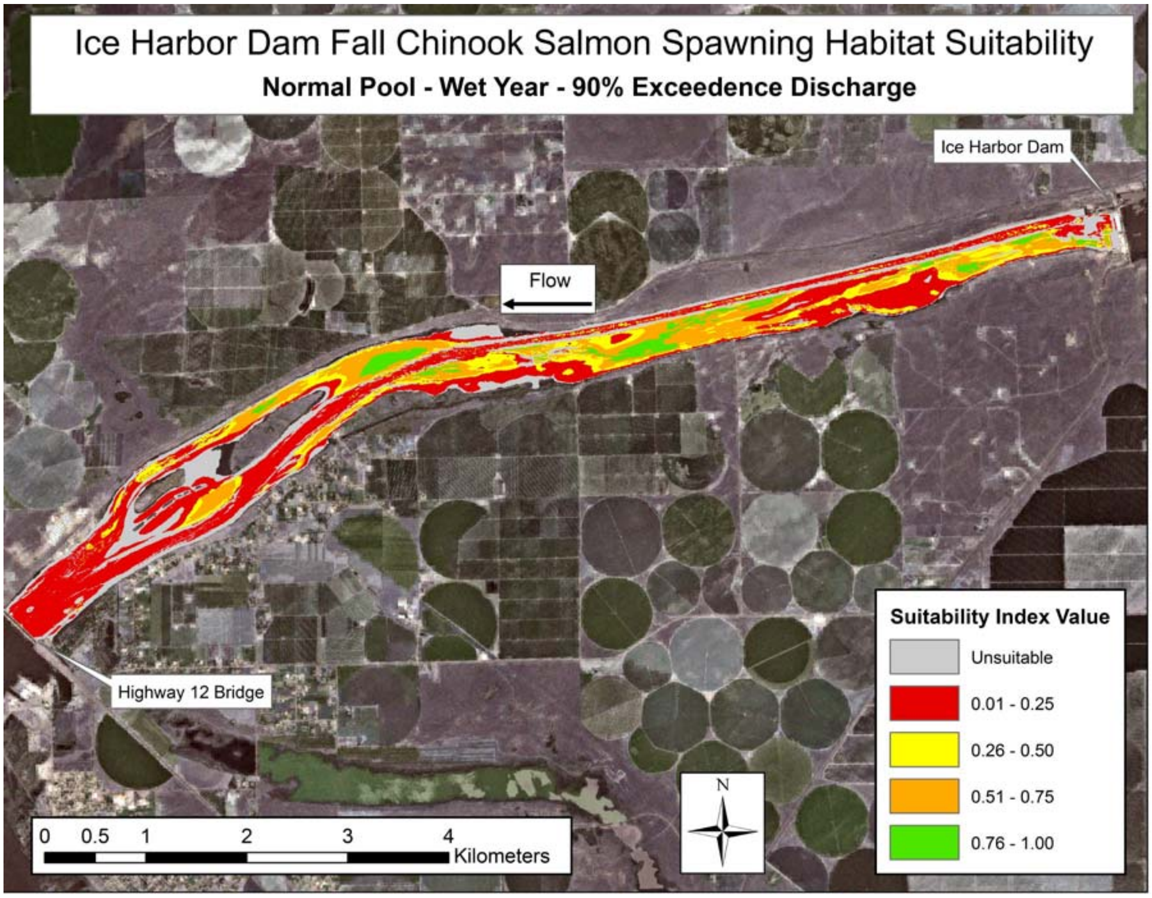

Figure A.7. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 90% Exceedence Discharge (34.5 kcfs) During a Wet Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

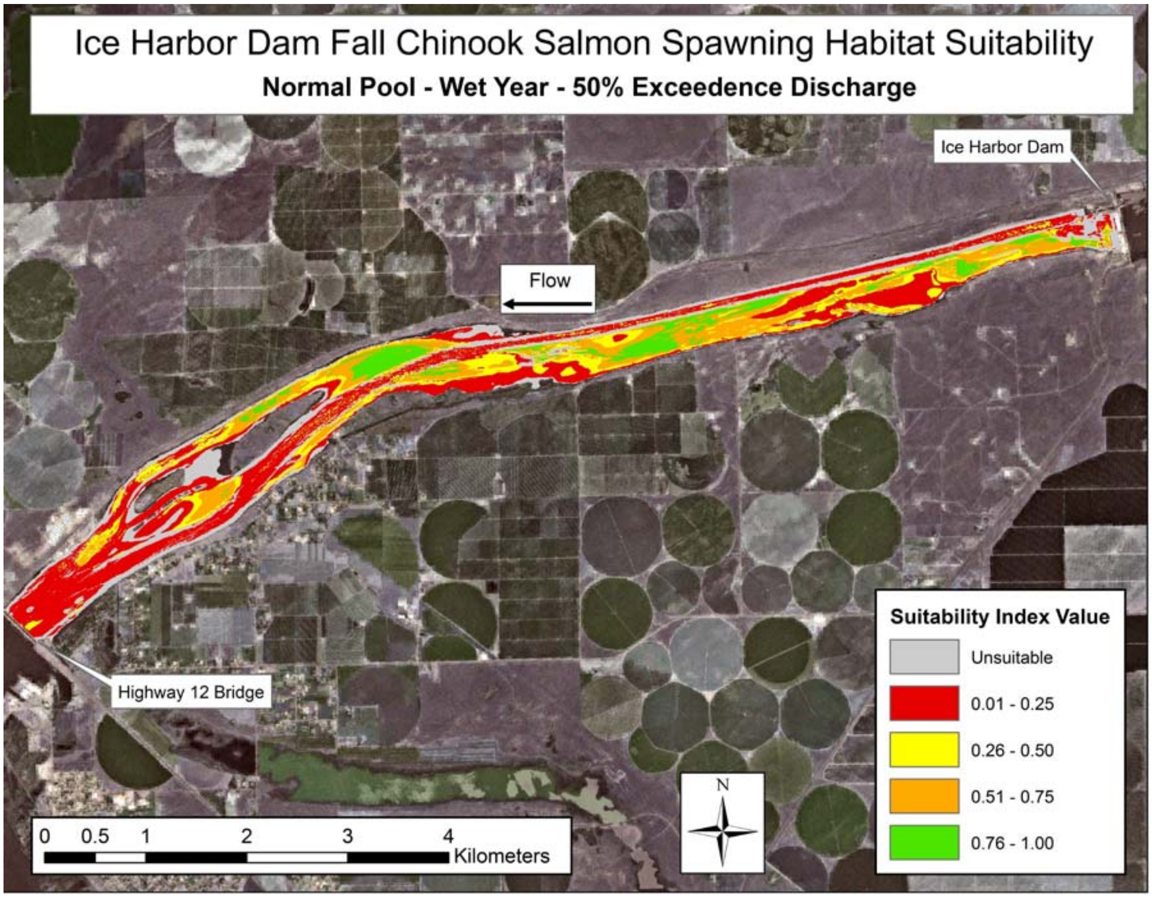

Figure A.8. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 50% Exceedence Discharge (44.0 kcfs) During a Wet Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

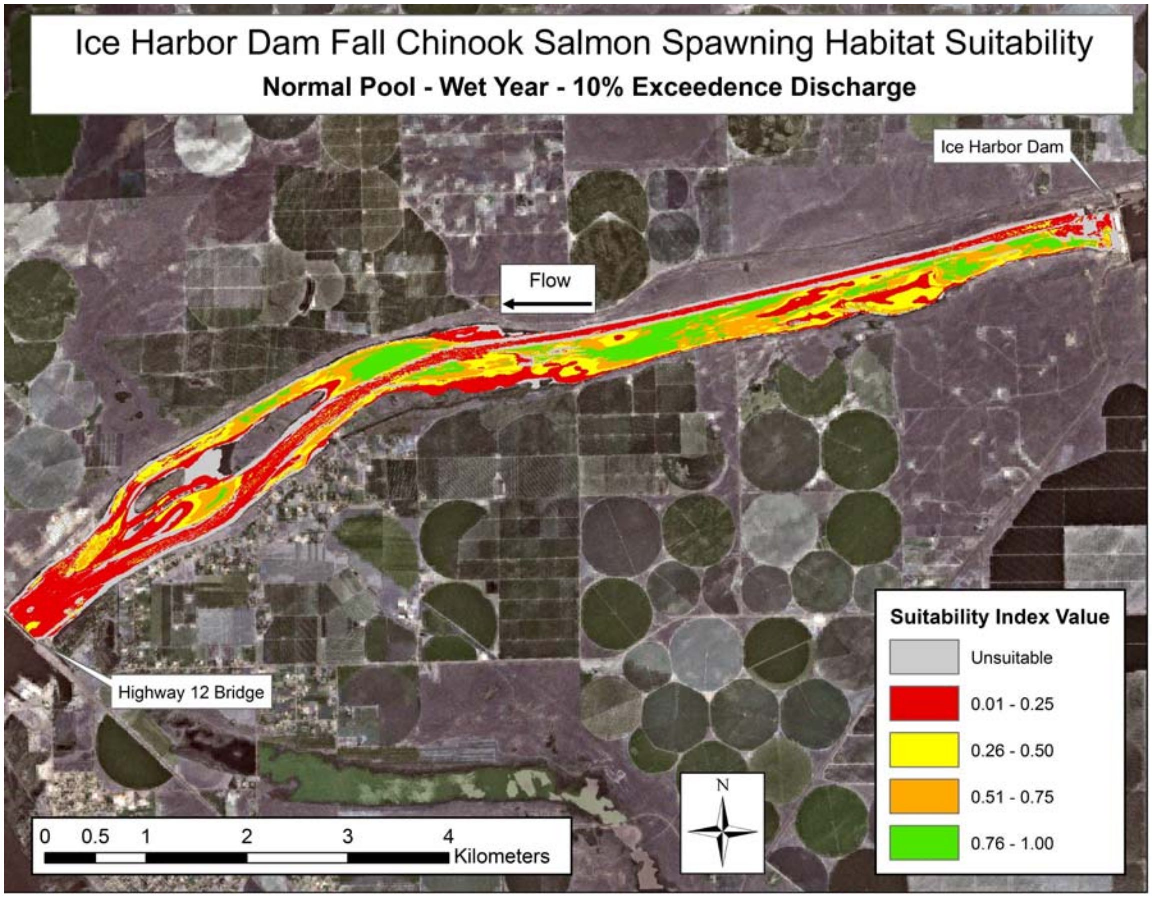

Figure A.9. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 10% Exceedence Discharge (52.0 kcfs) During a Wet Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

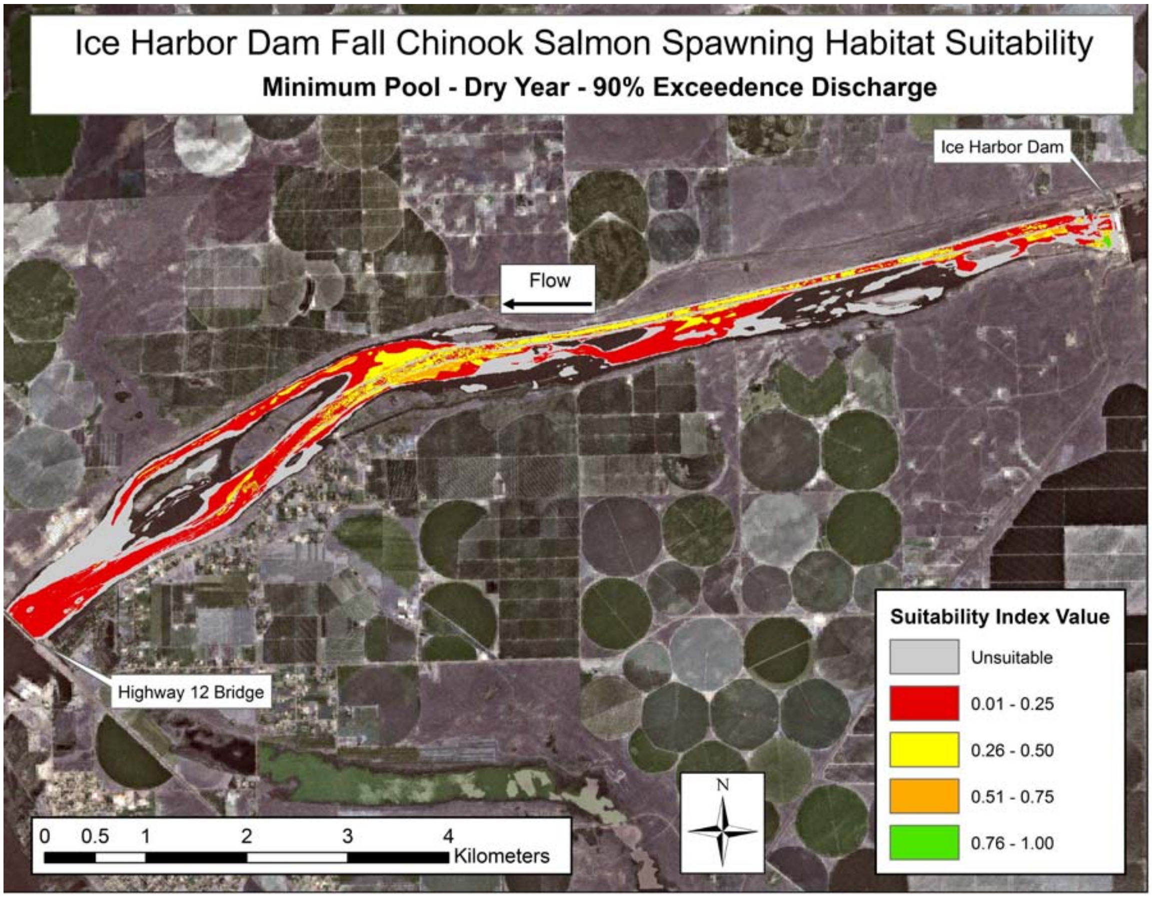

Figure A.10. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 90% Exceedence Discharge (12.6 kcfs) During a Dry Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

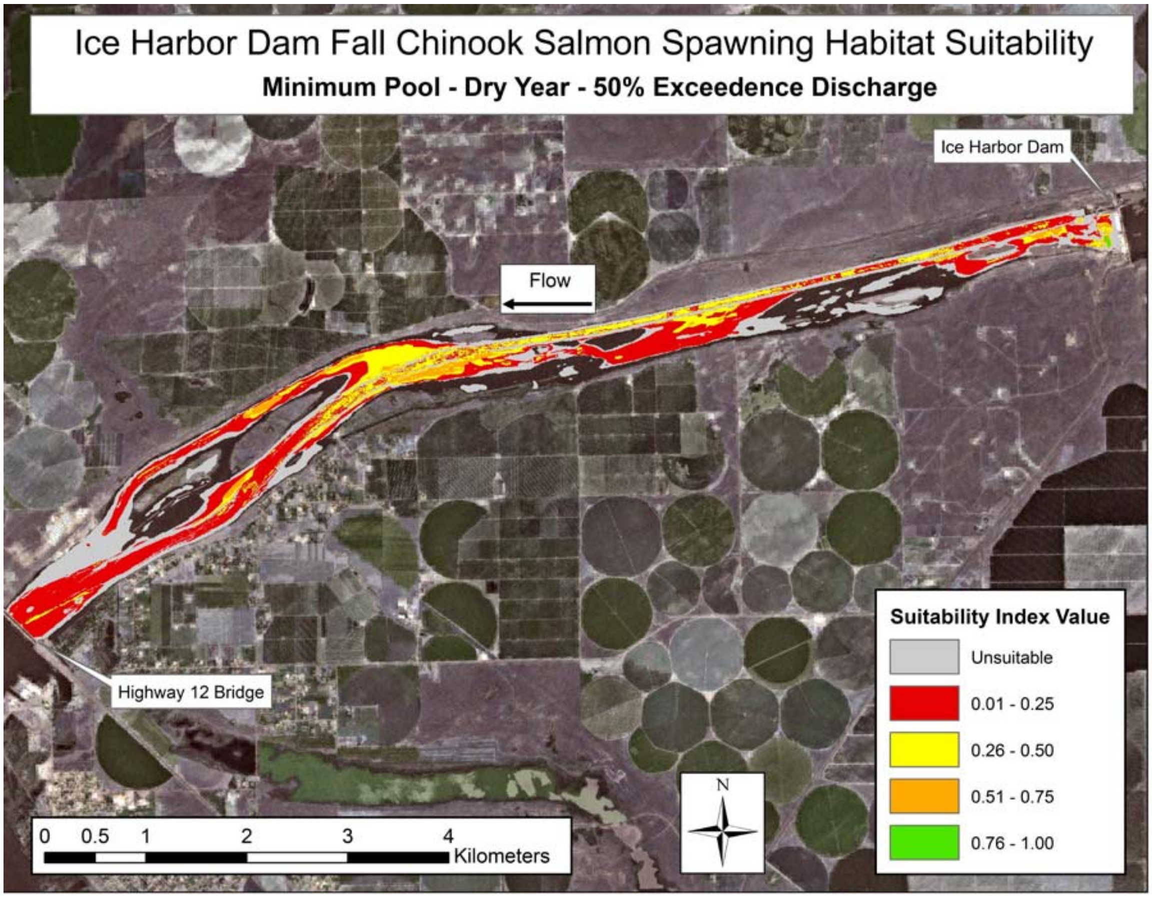

Figure A.11. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 50% Exceedence Discharge (15.3 kcfs) During a Dry Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

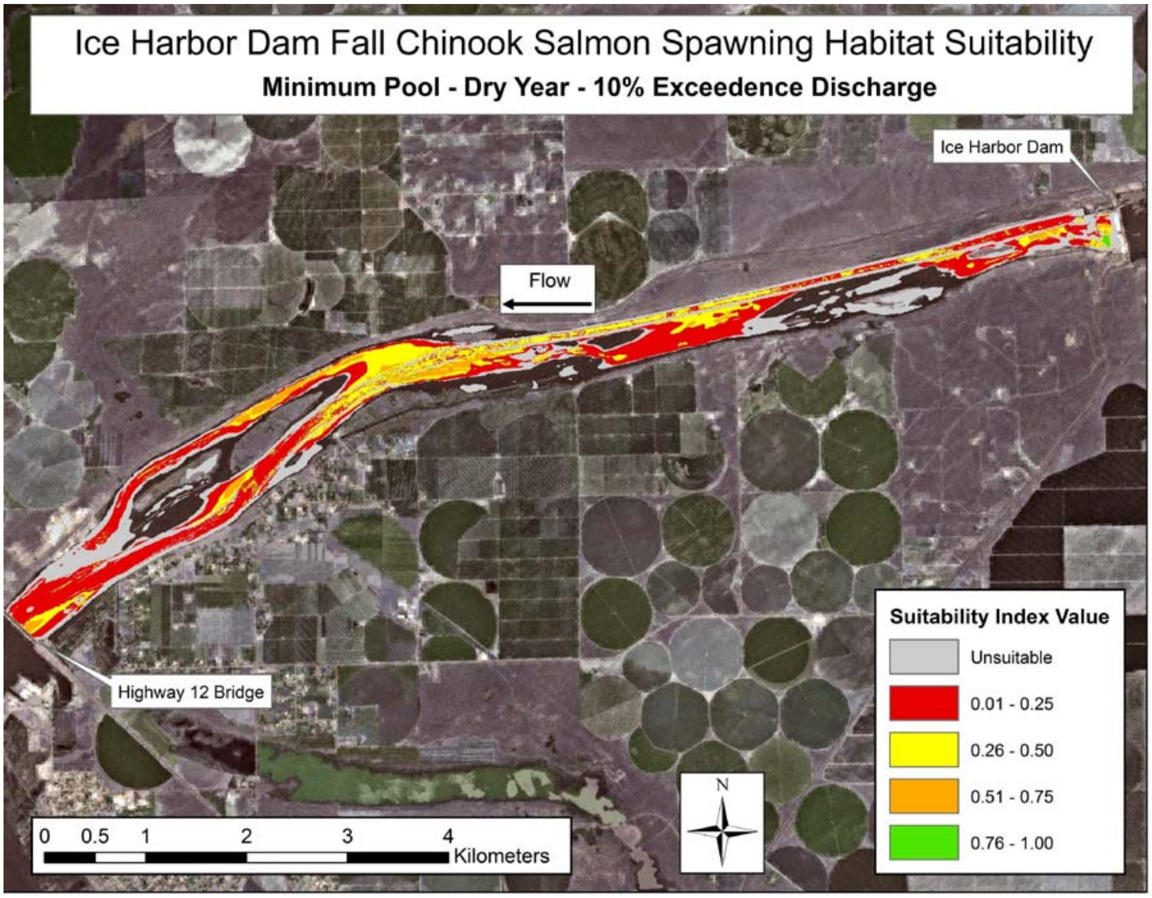

Figure A.12. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 10% Exceedence Discharge (18.2 kcfs) During a Dry Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

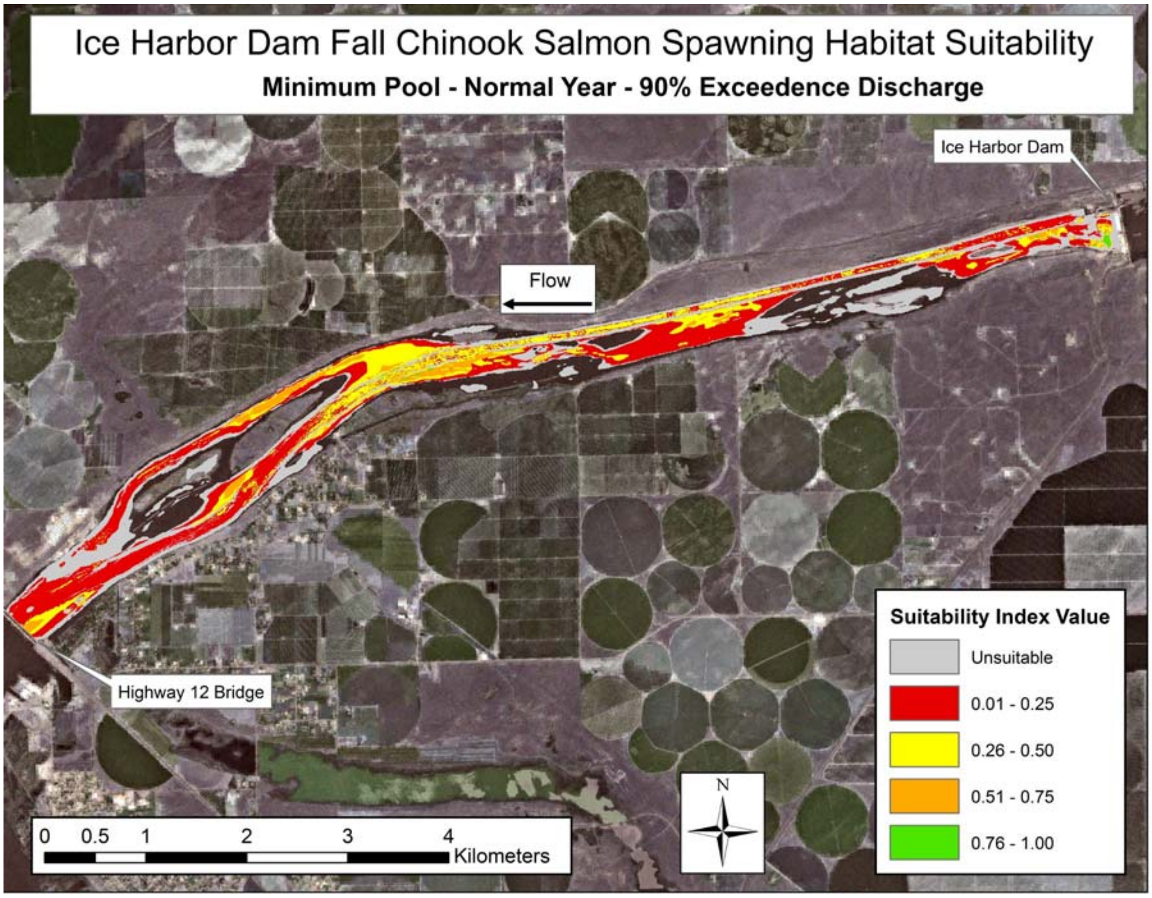

Figure A.13. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 90% Exceedence Discharge (19.1 kcfs) During a Normal Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

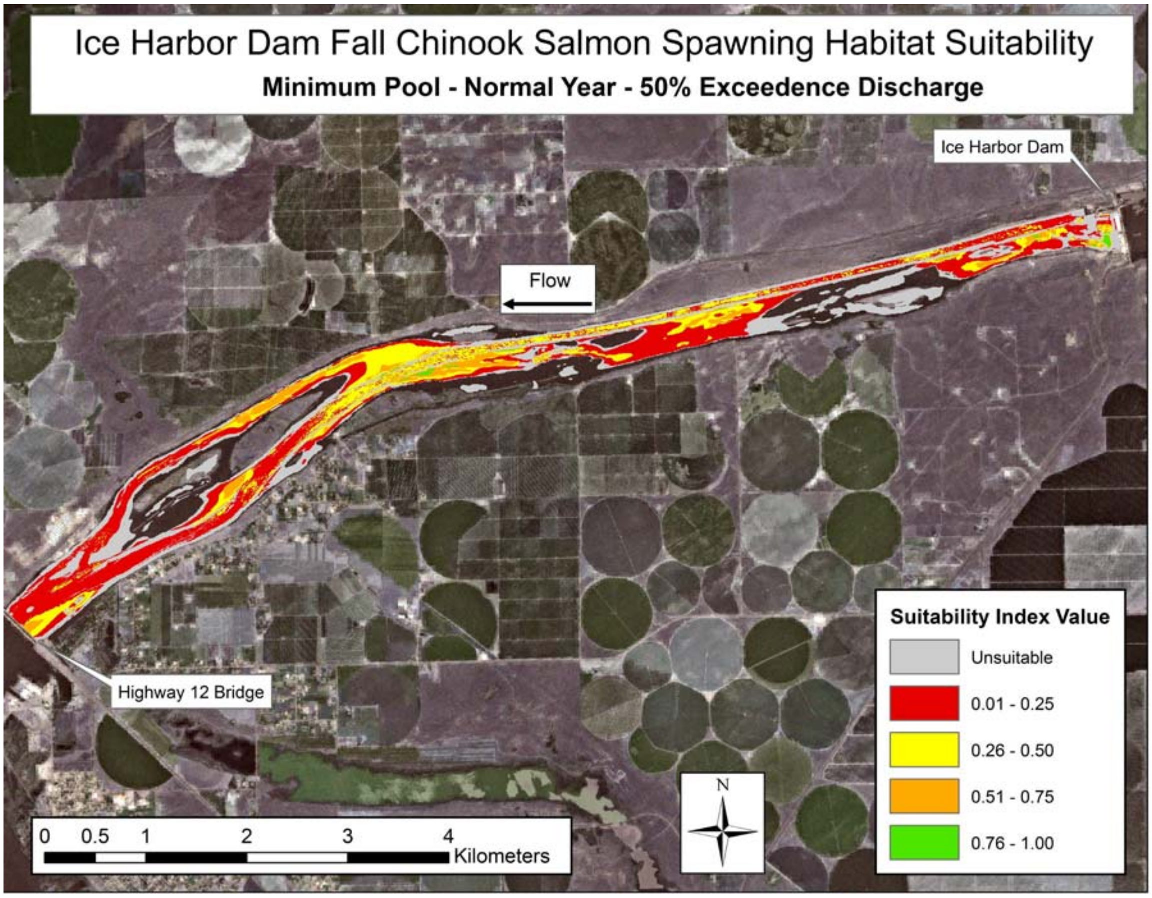

Figure A.14. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 50% Exceedence Discharge (21.7 kcfs) During a Normal Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

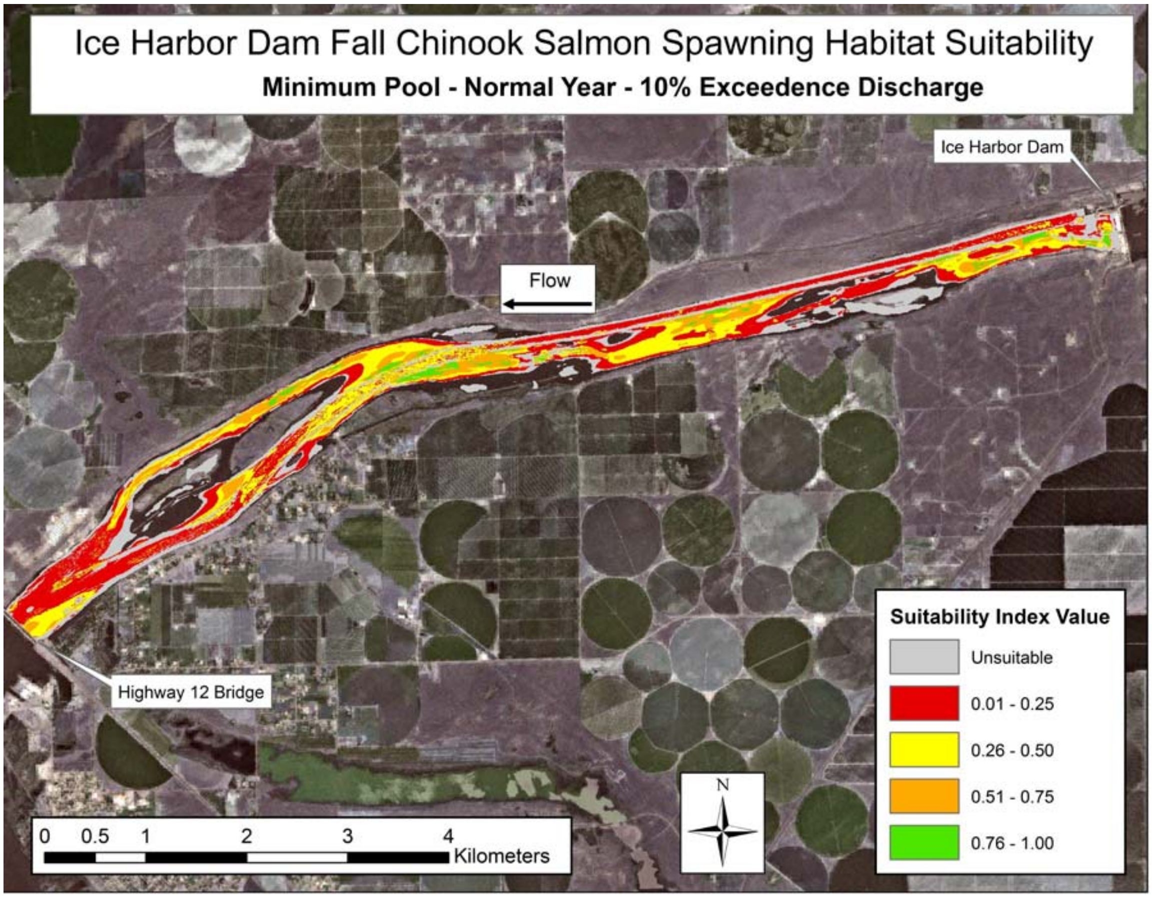

Figure A.15. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 10% Exceedence Discharge (34.5 kcfs) During a Normal Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

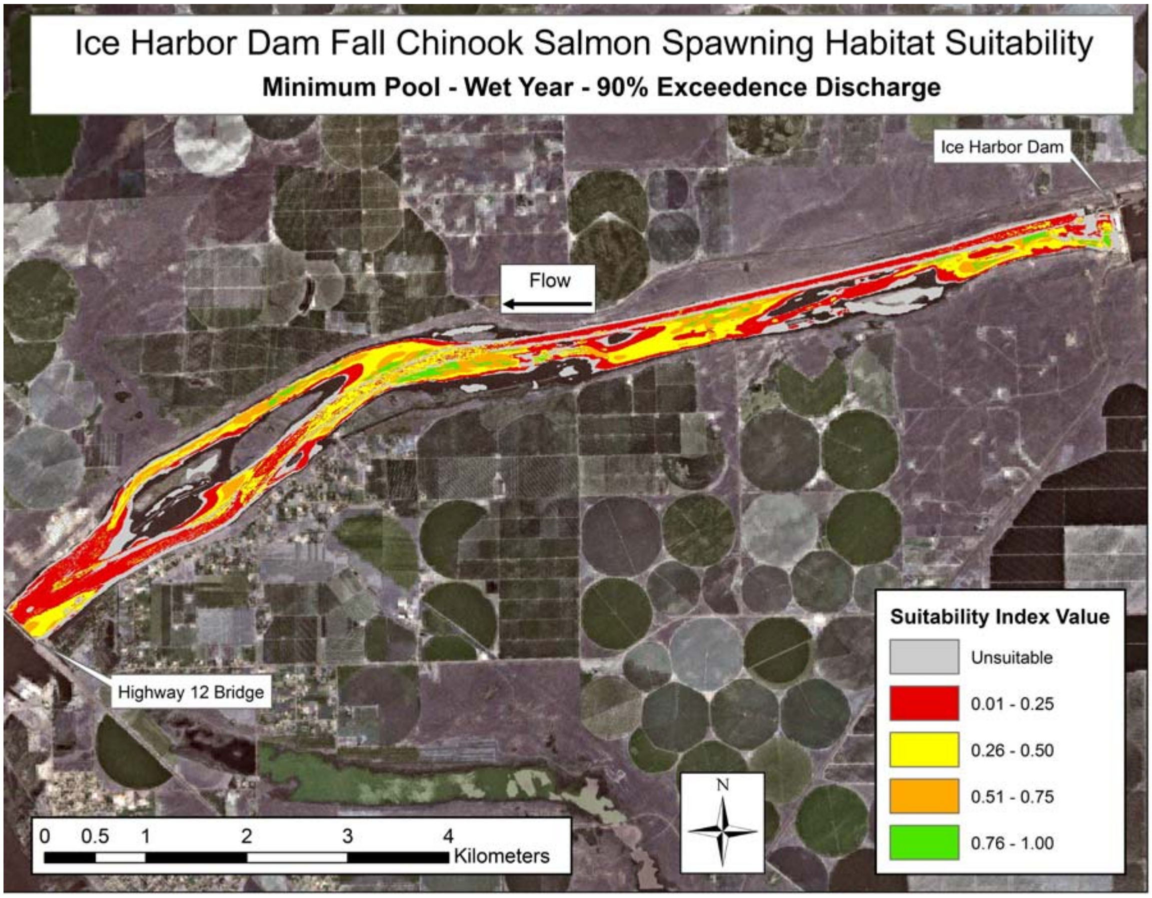

Figure A.16. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 90% Exceedence Discharge (34.5 kcfs) During a Wet Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

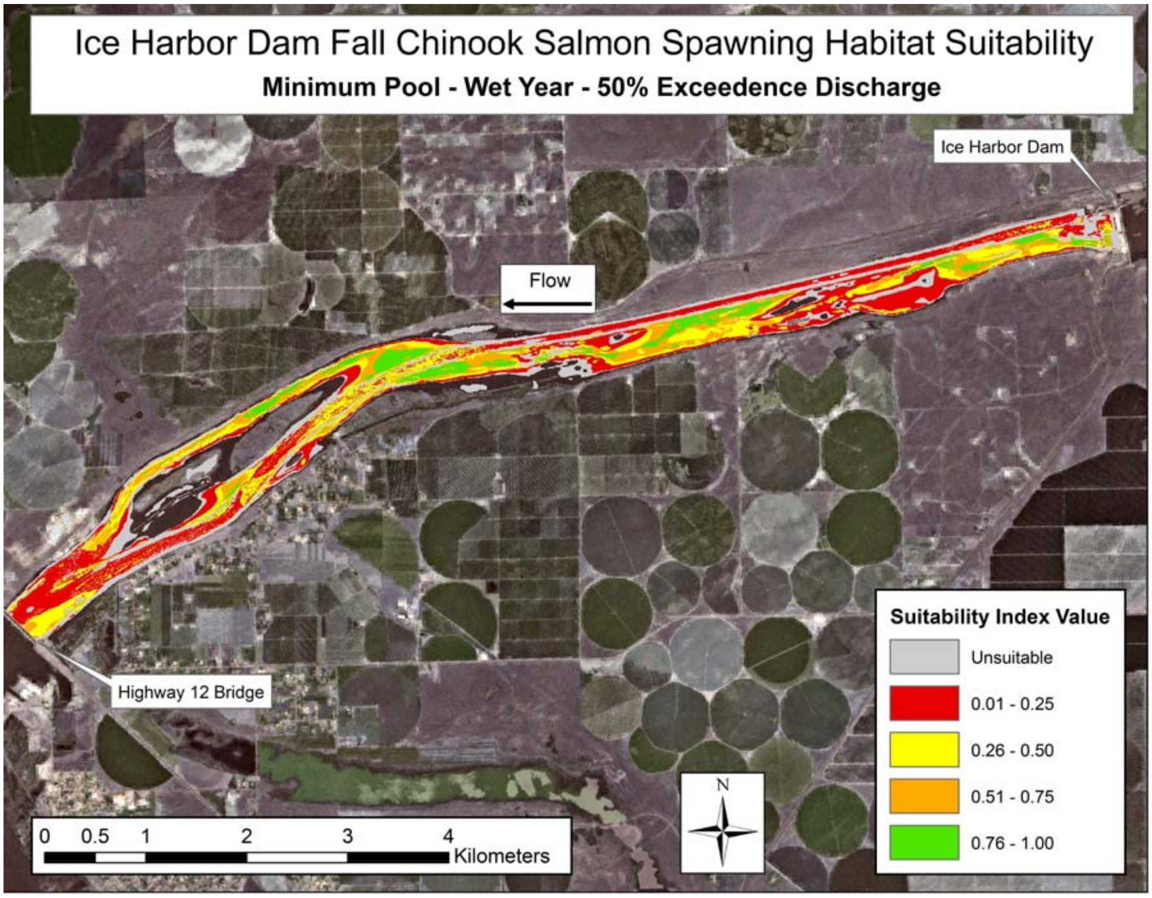

Figure A.17. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 50% Exceedence Discharge (44.0 kcfs) During a Wet Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

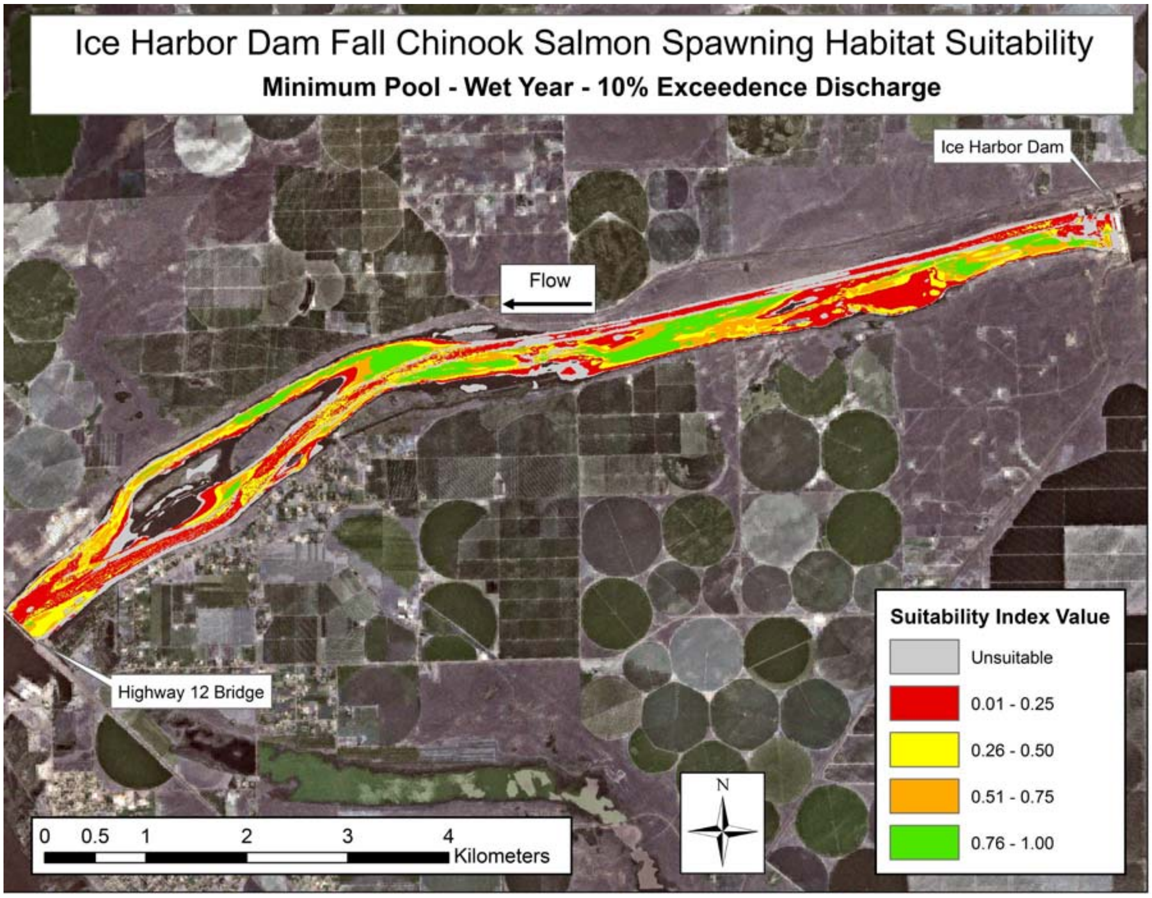

Figure A.18. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 10% Exceedence Discharge (52.0 kcfs) During a Wet Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

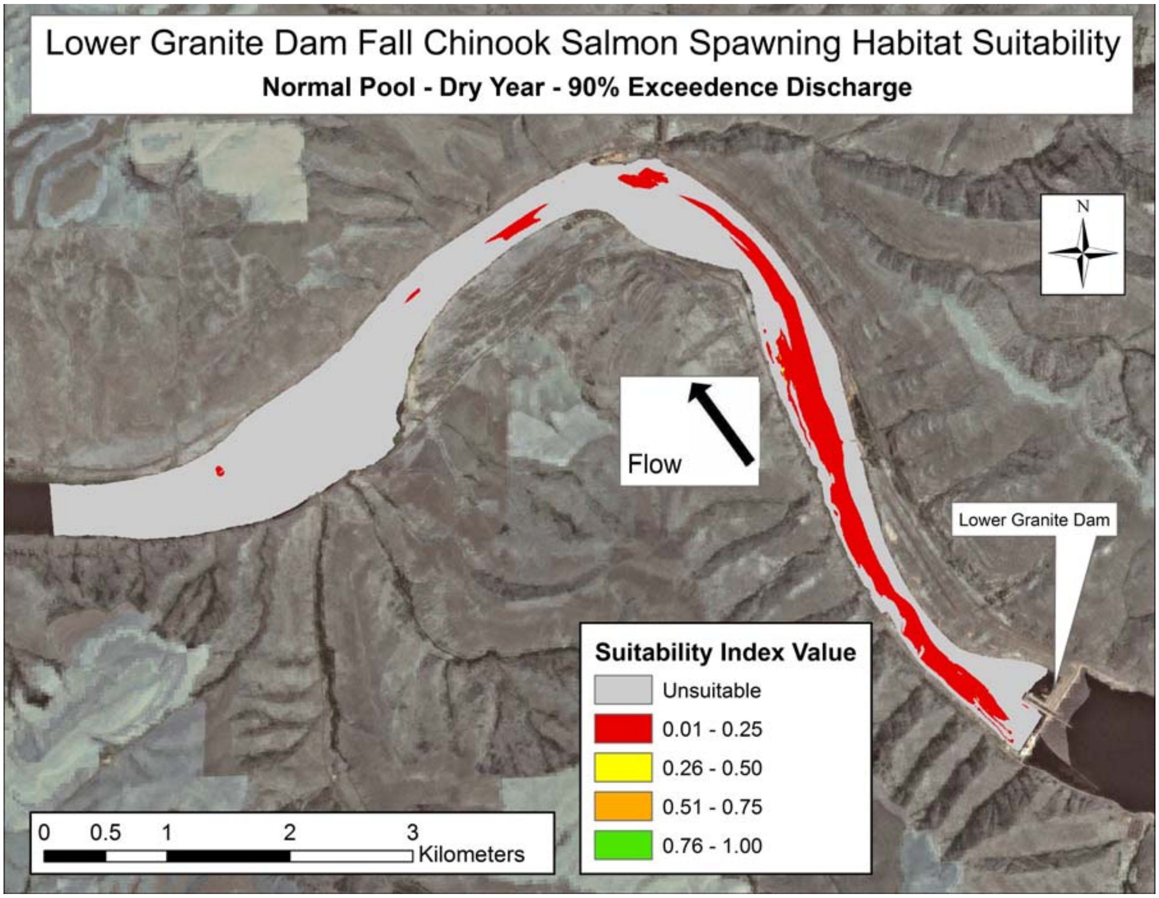

Figure A.19. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 90% Exceedence Discharge (12.6 kcfs) During a Dry Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

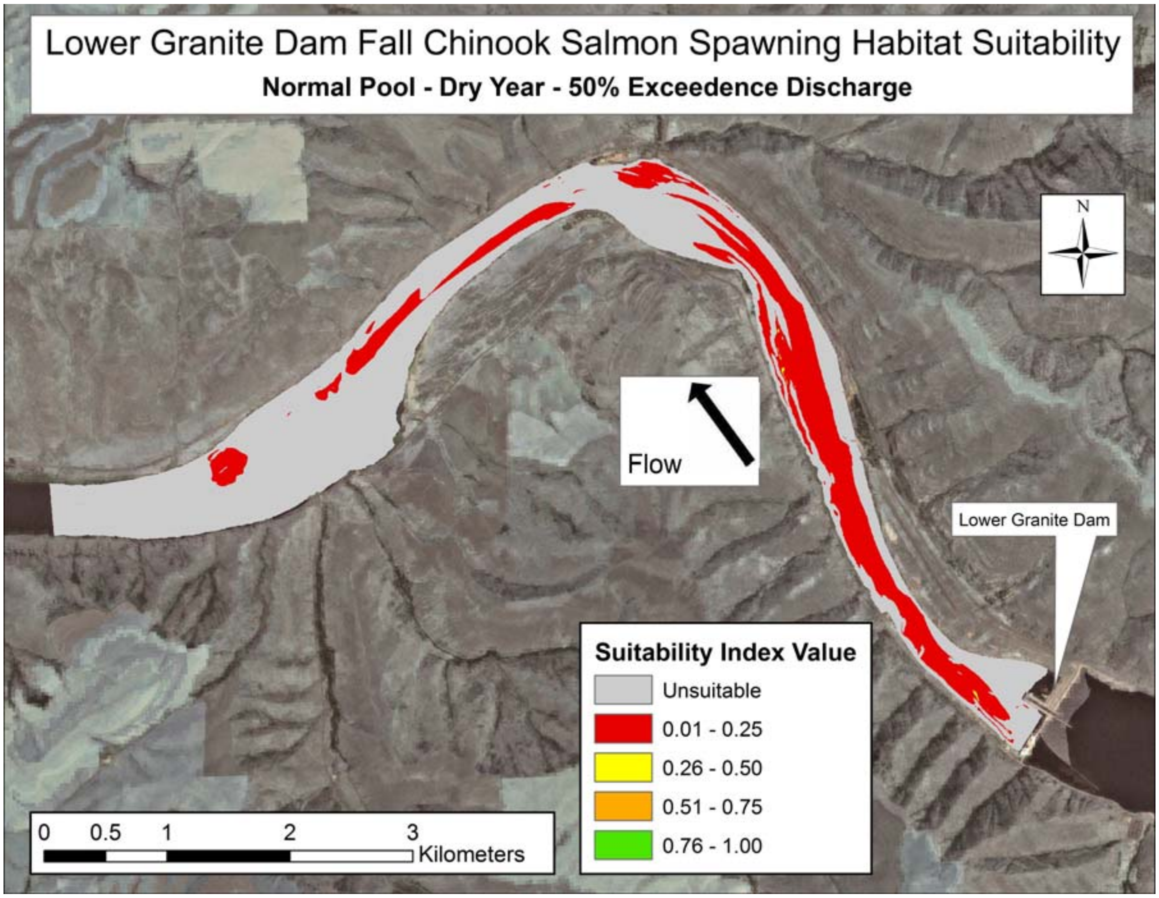

Figure A.20. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 50% Exceedence Discharge (15.3 kcfs) During a Dry Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

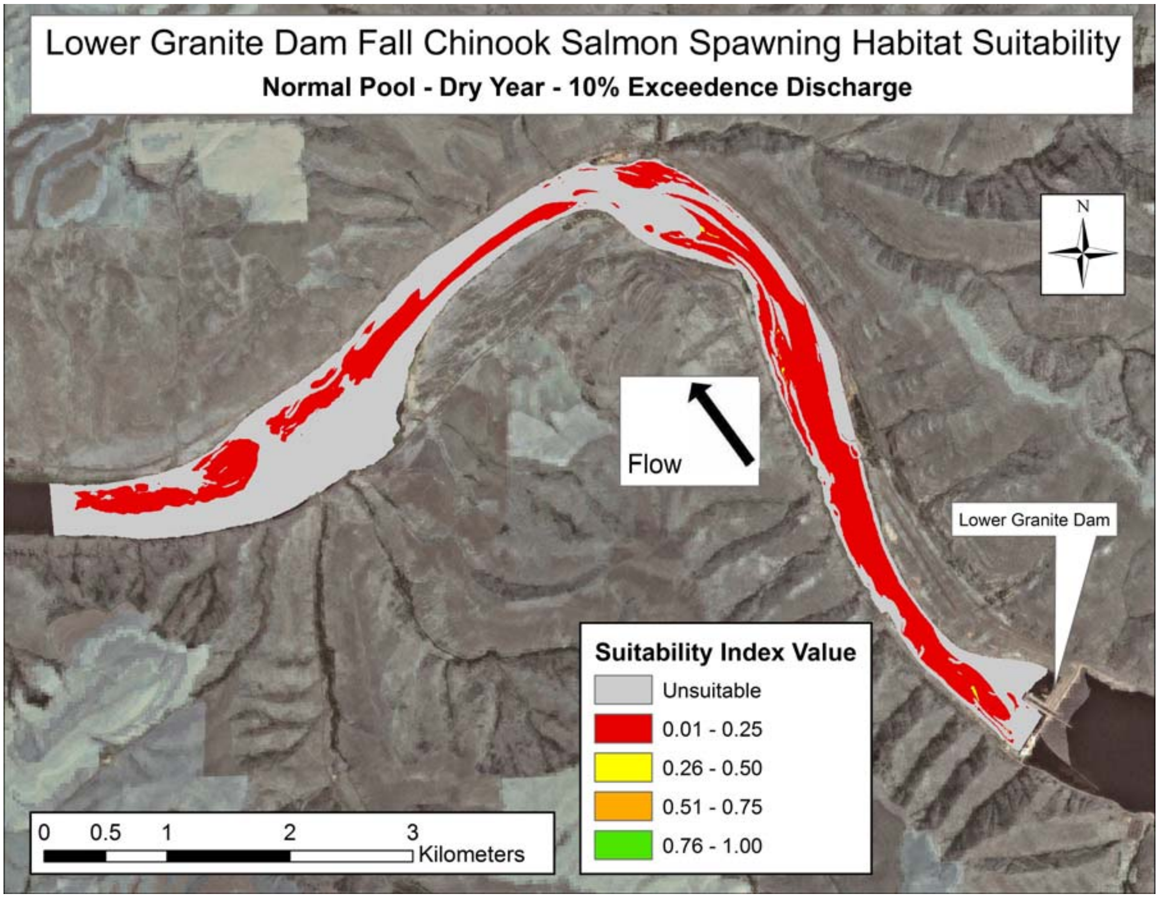

Figure A.21. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 10% Exceedence Discharge (18.2 kcfs) During a Dry Water Year, with the Little Goose Dam Forebay at Normal Pool elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

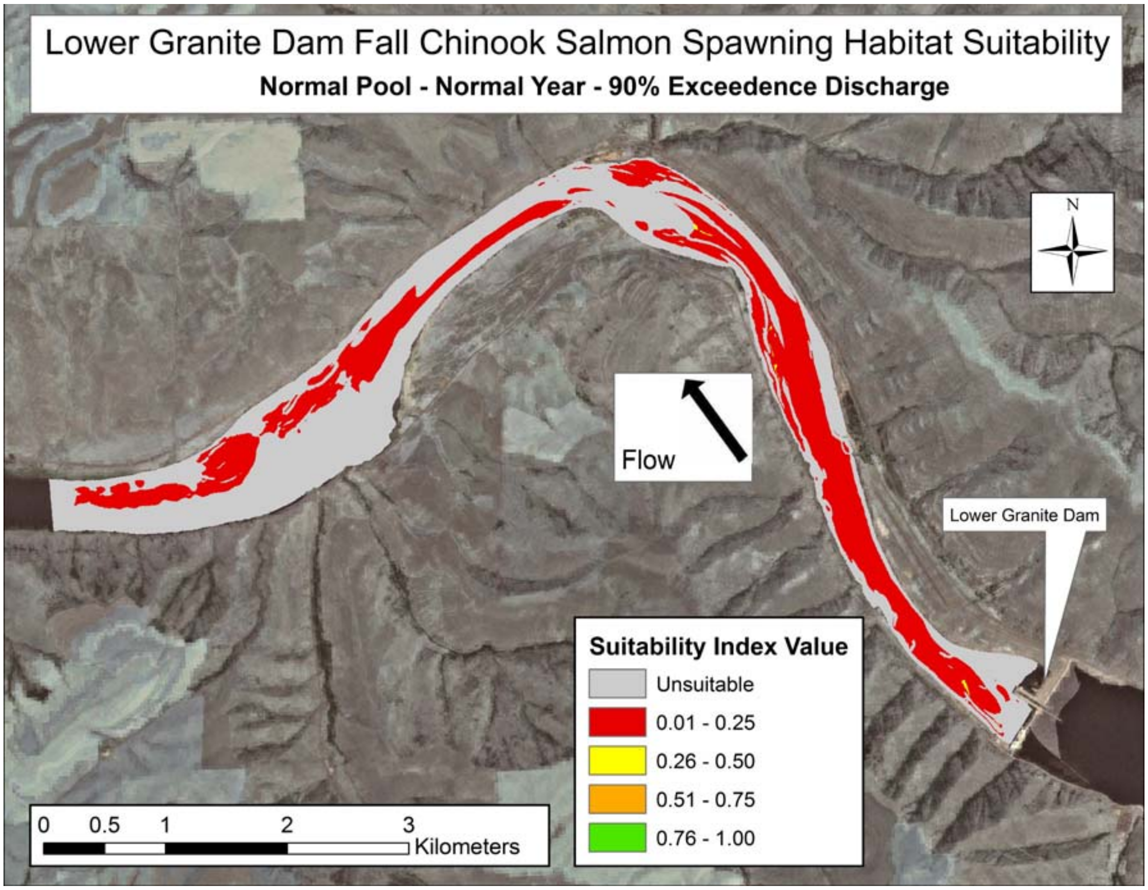

Figure A.22. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 90% Exceedence Discharge (19.1 kcfs) During a Normal Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

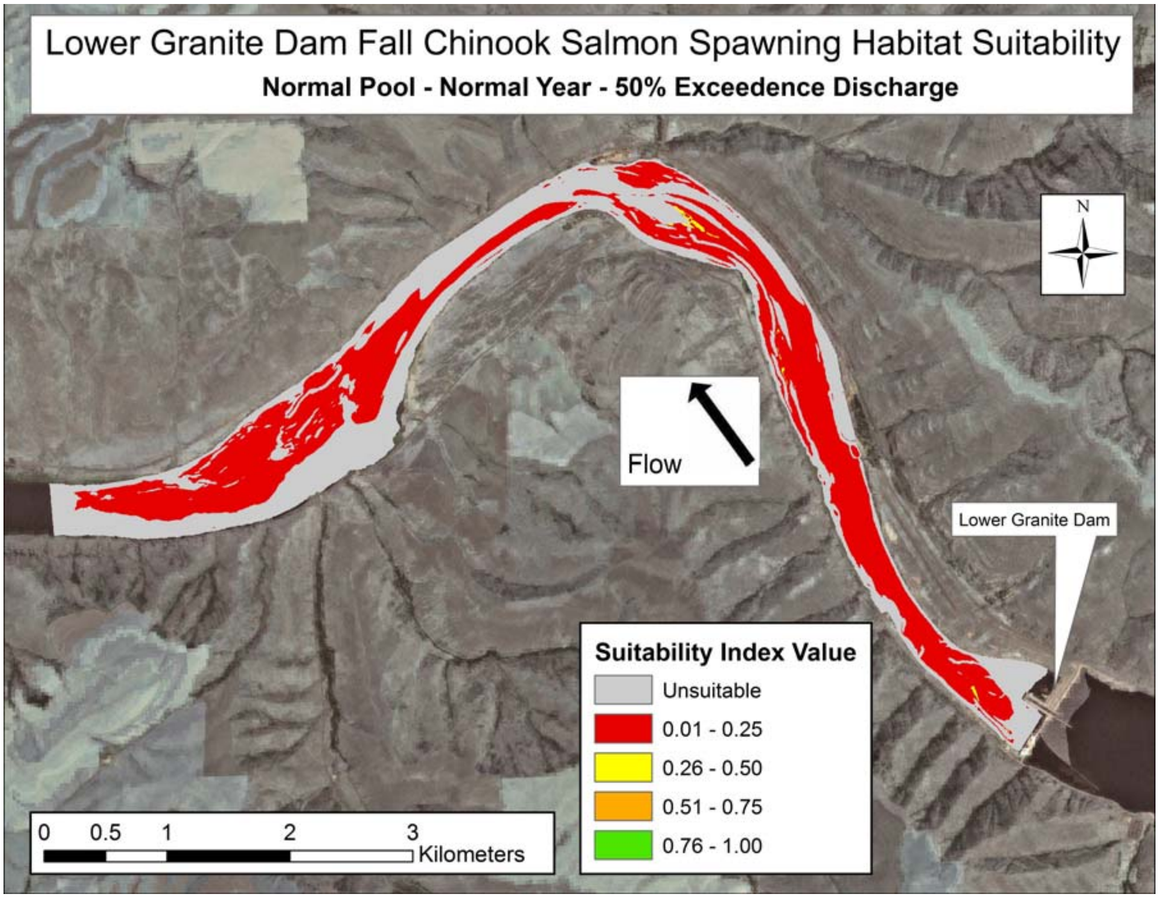

Figure A.23. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 50% Exceedence Discharge (21.7 kcfs) During a Normal Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

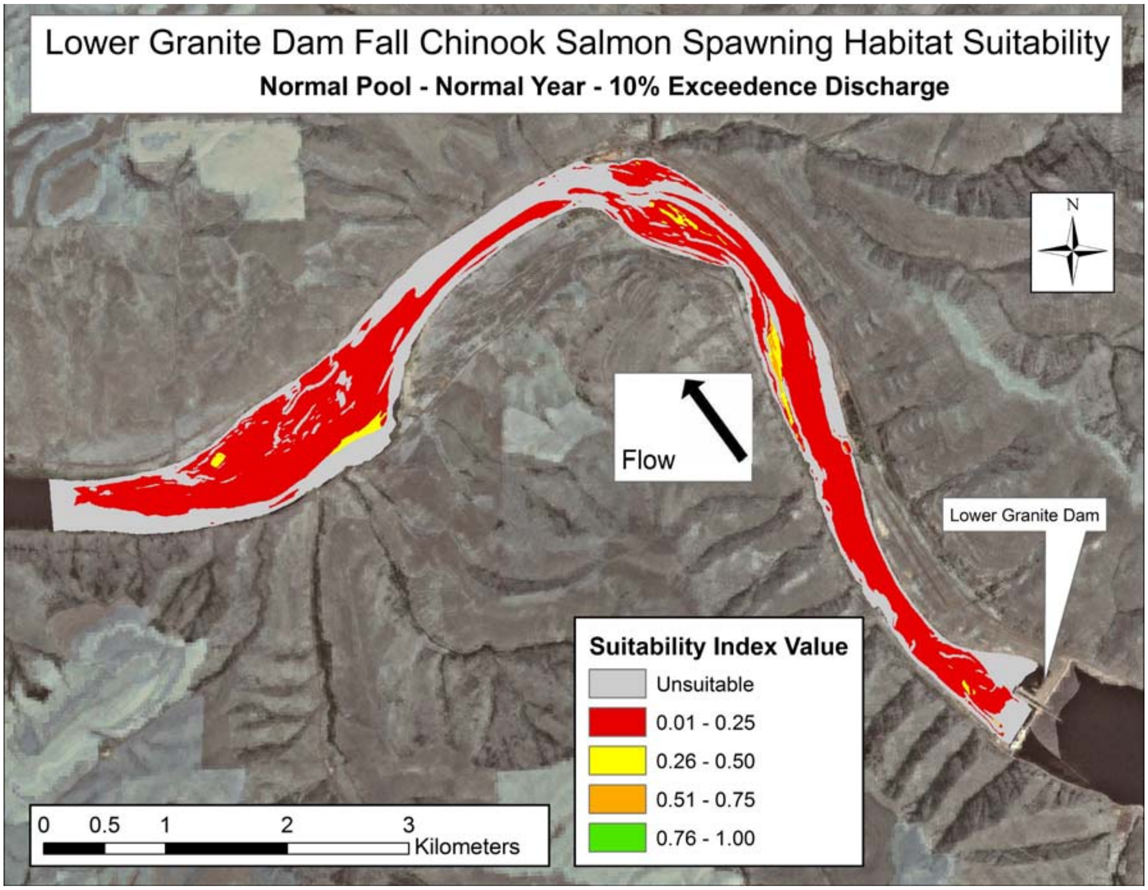

Figure A24. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 10% Exceedence Discharge (34.5 kcfs) During a Normal Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

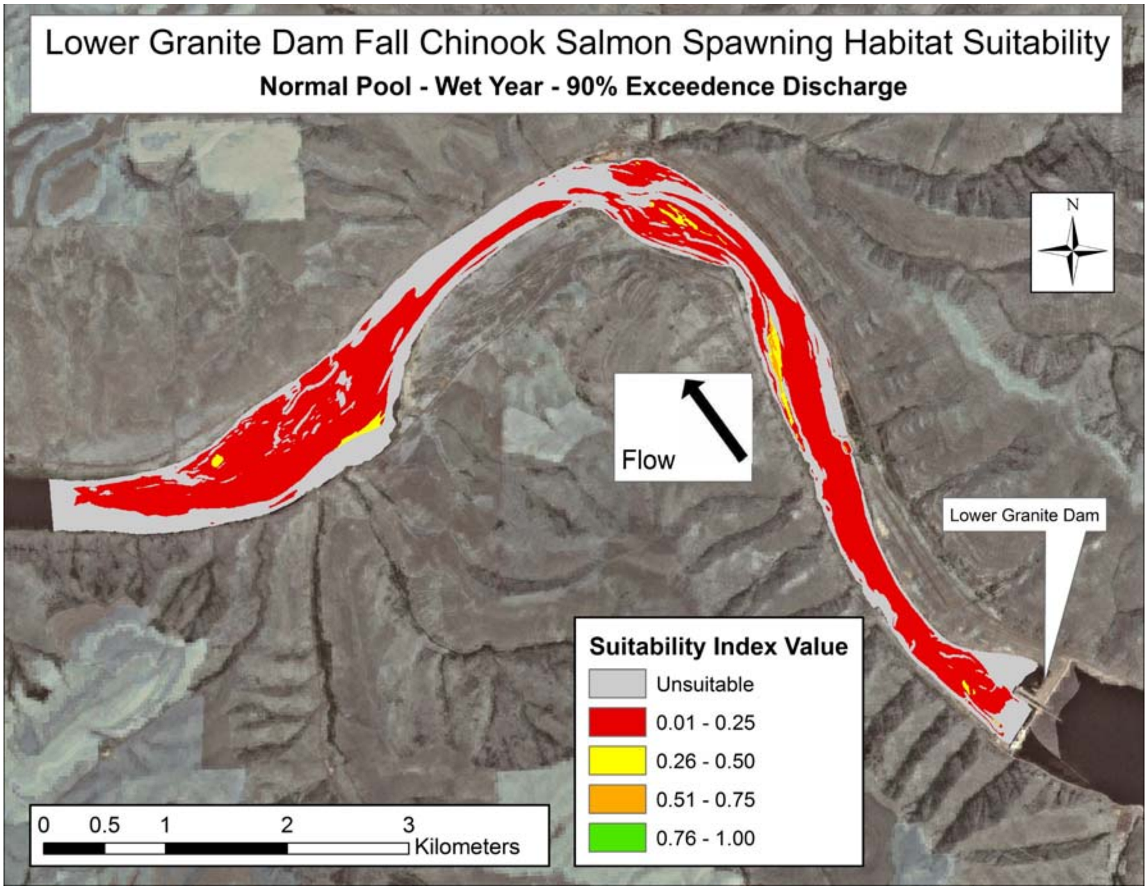

Figure A.25. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 90% Exceedence Discharge (34.5 kcfs) During a Wet Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

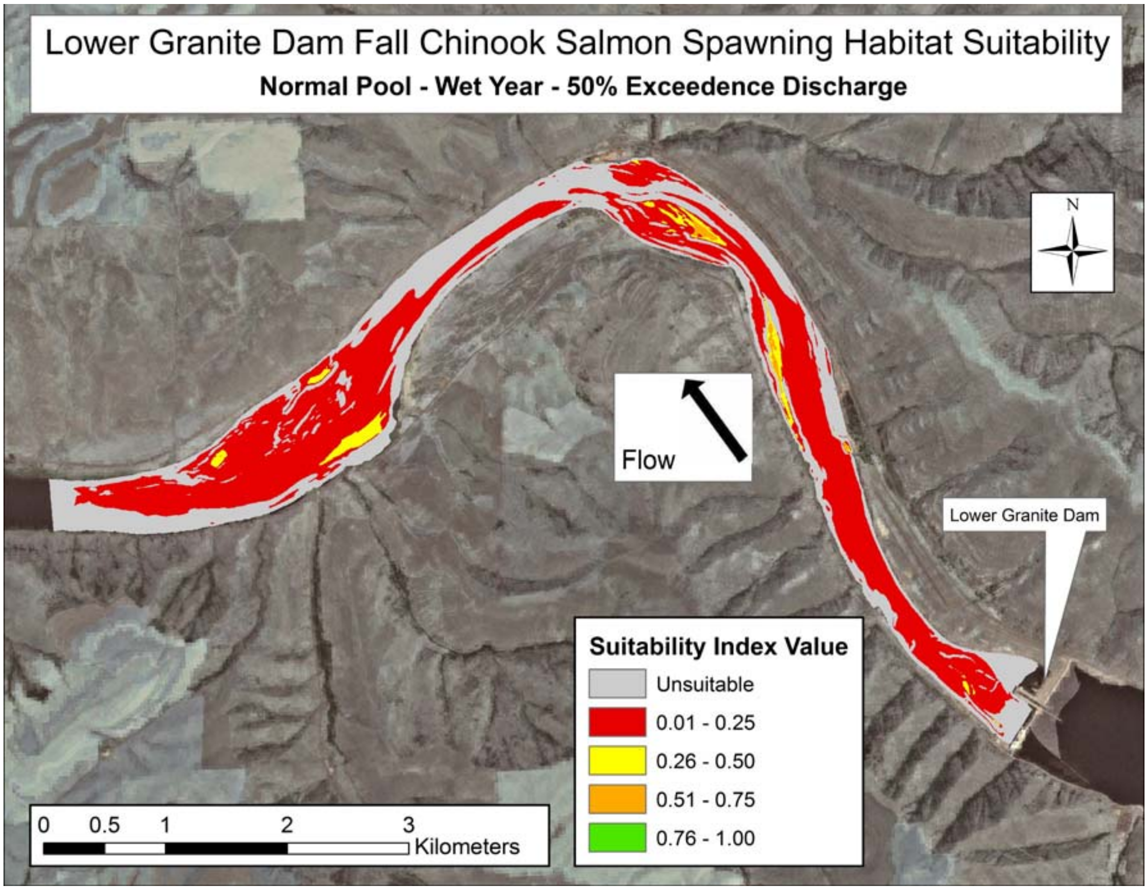

Figure A.26. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 50% Exceedence Discharge (44.0 kcfs) During a Wet Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

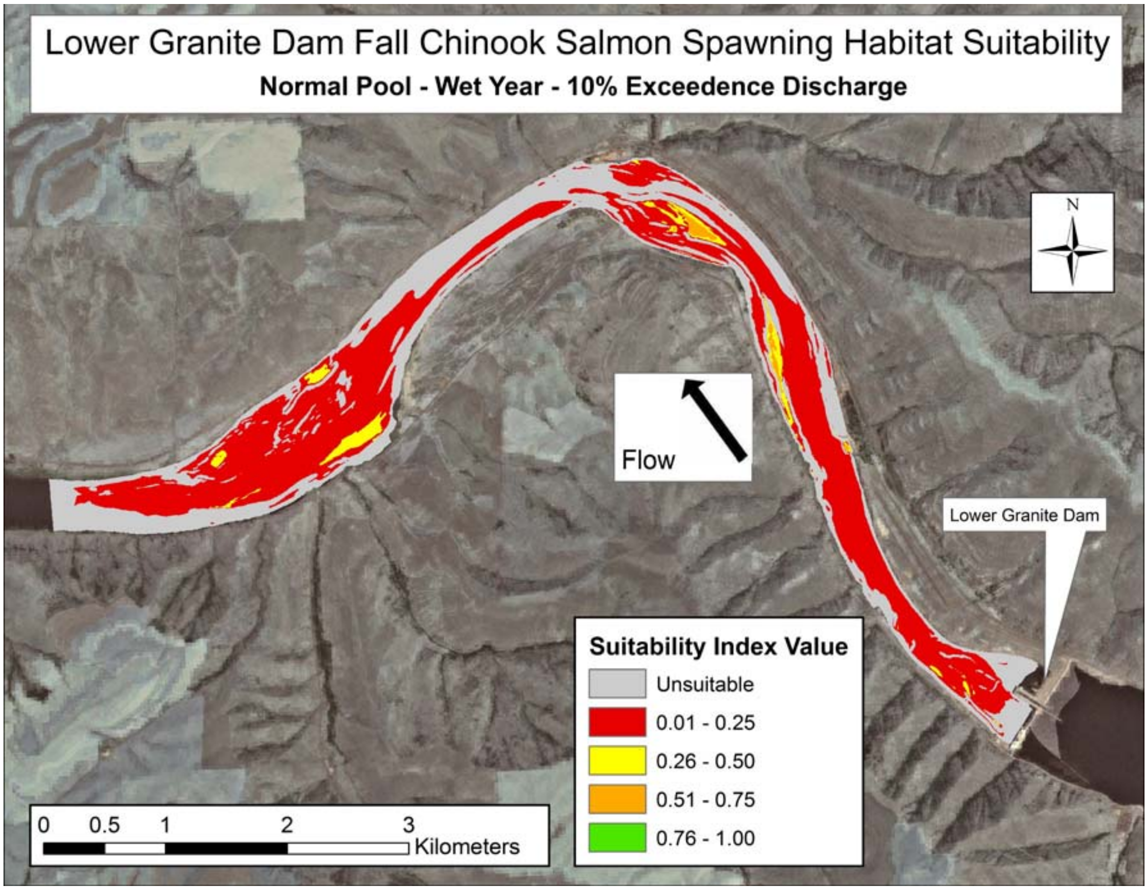

Figure A.27. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 10% Exceedence Discharge (52.0 kcfs) During a Wet Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

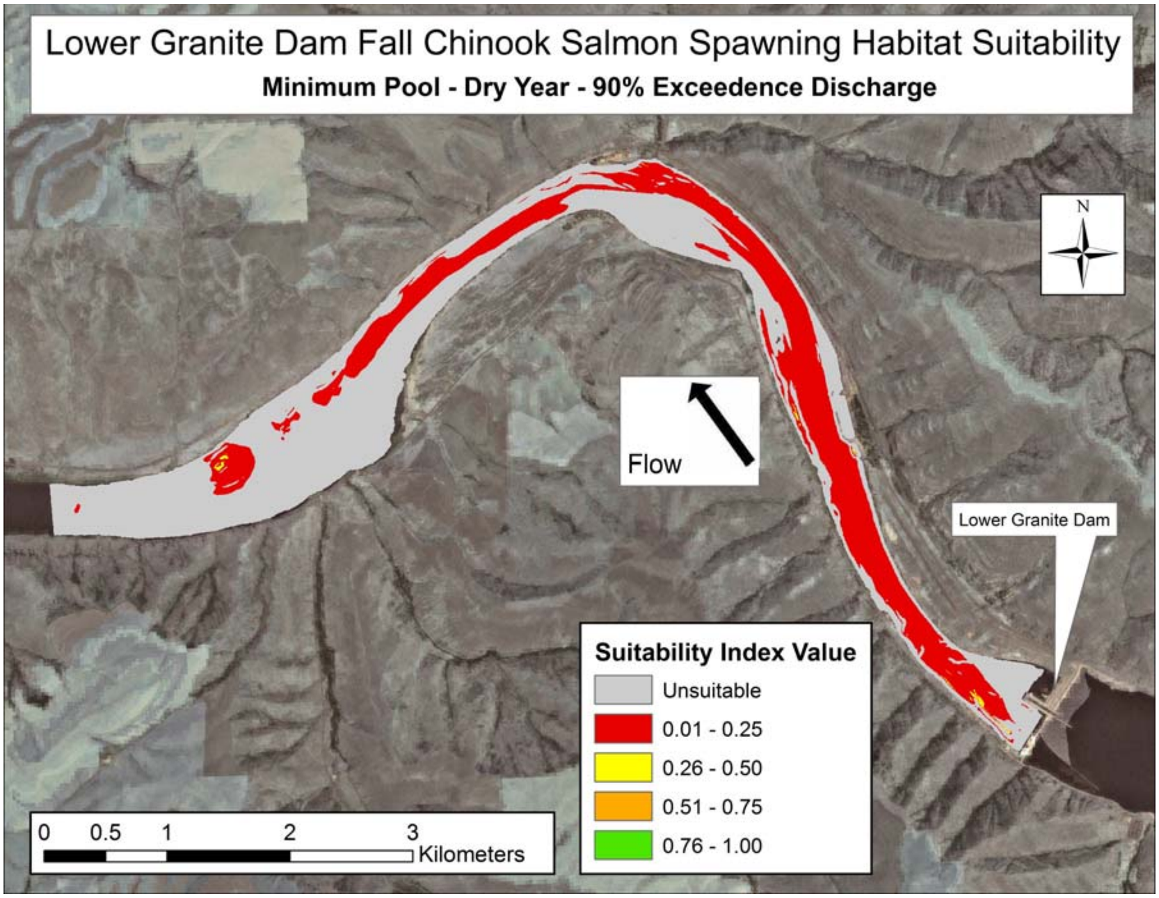

Figure A.28. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 90% Exceedence Discharge (12.6 kcfs) During a Dry Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

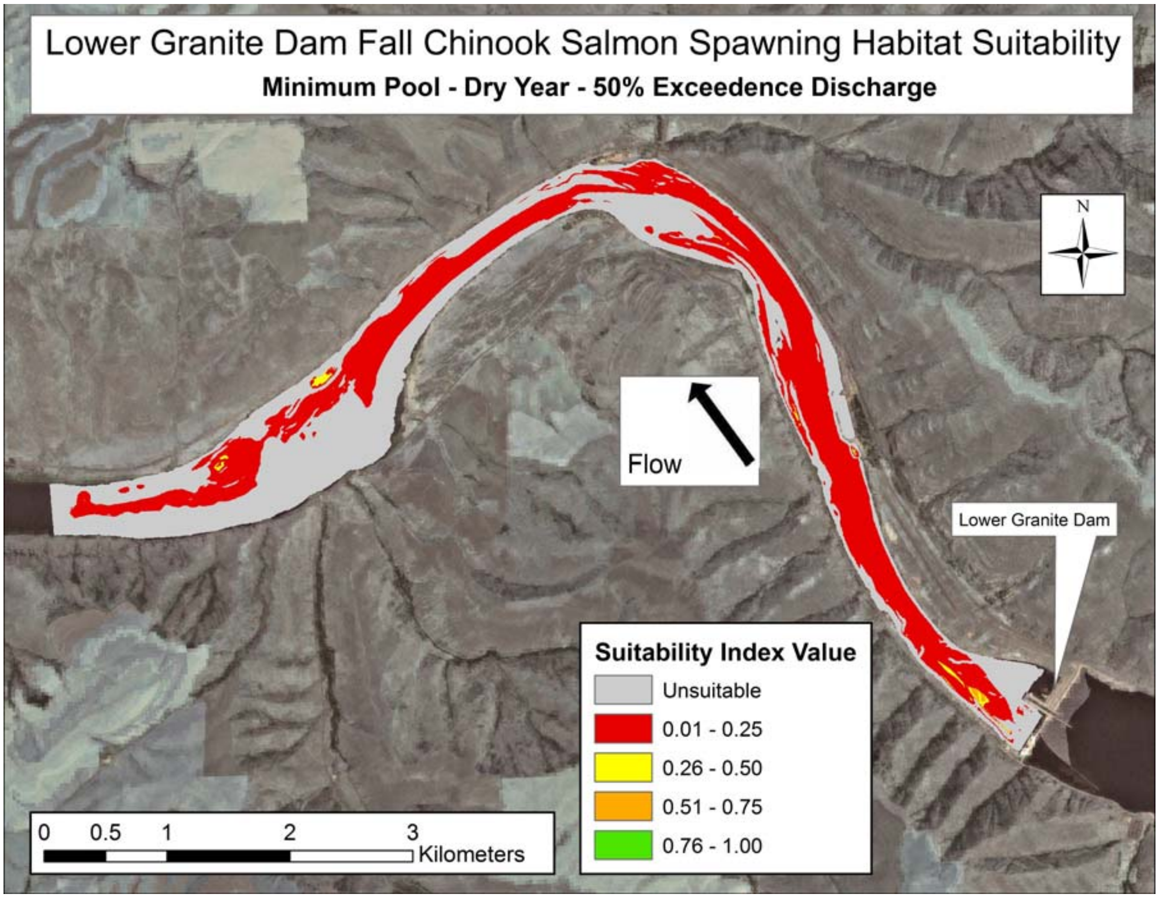

Figure A.29. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 50% Exceedence Discharge (15.3 kcfs) During a Dry Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

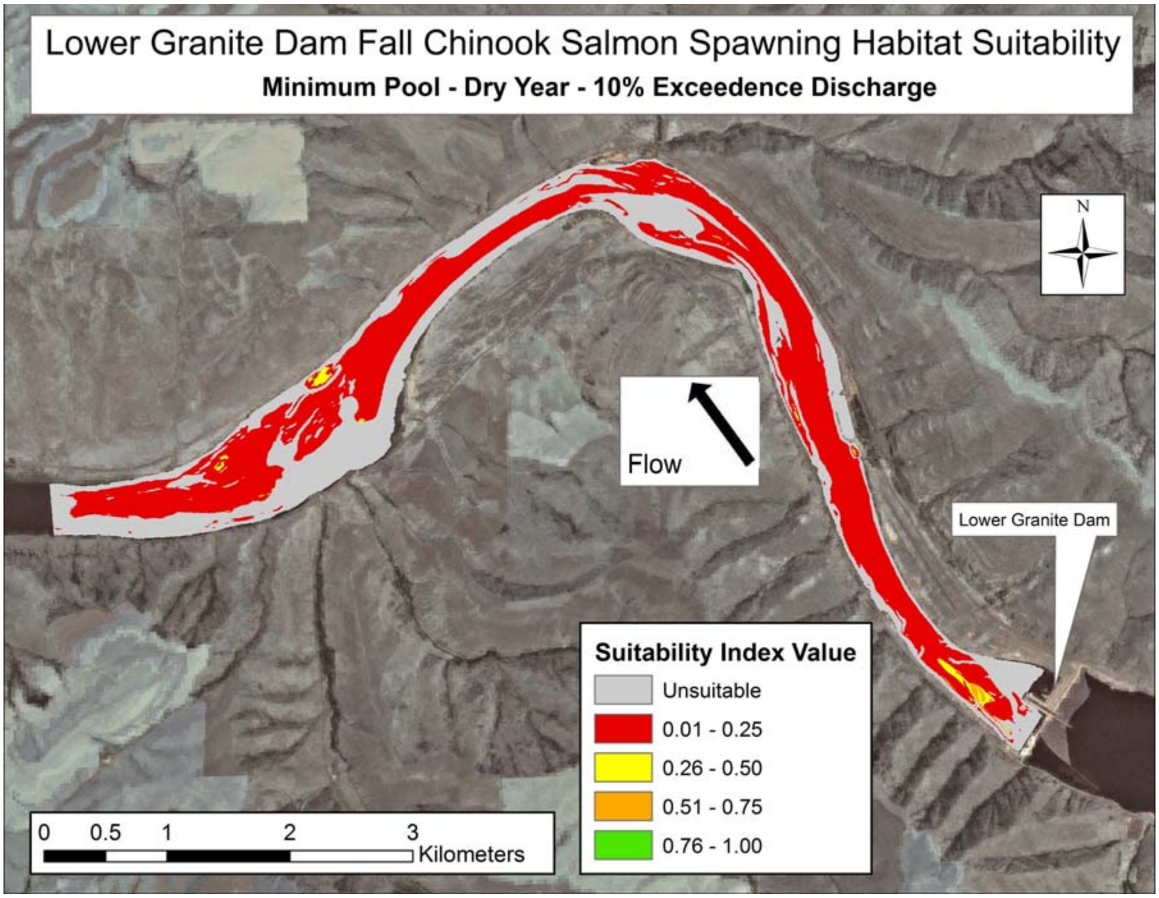

Figure A.30. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 10% Exceedence Discharge (18.2 kcfs) During a Dry Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

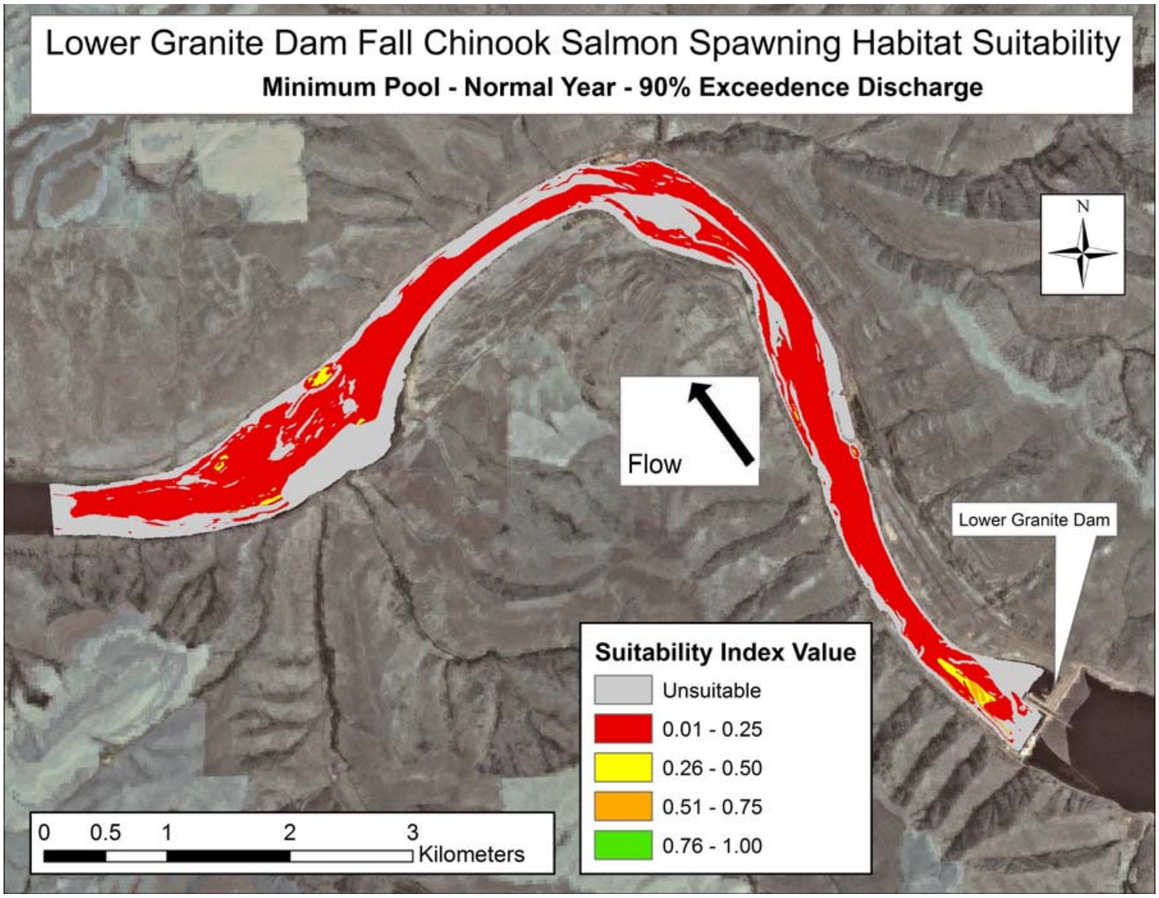

Figure A.31. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 90% Exceedence Discharge (19.1 kcfs) During a Normal Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

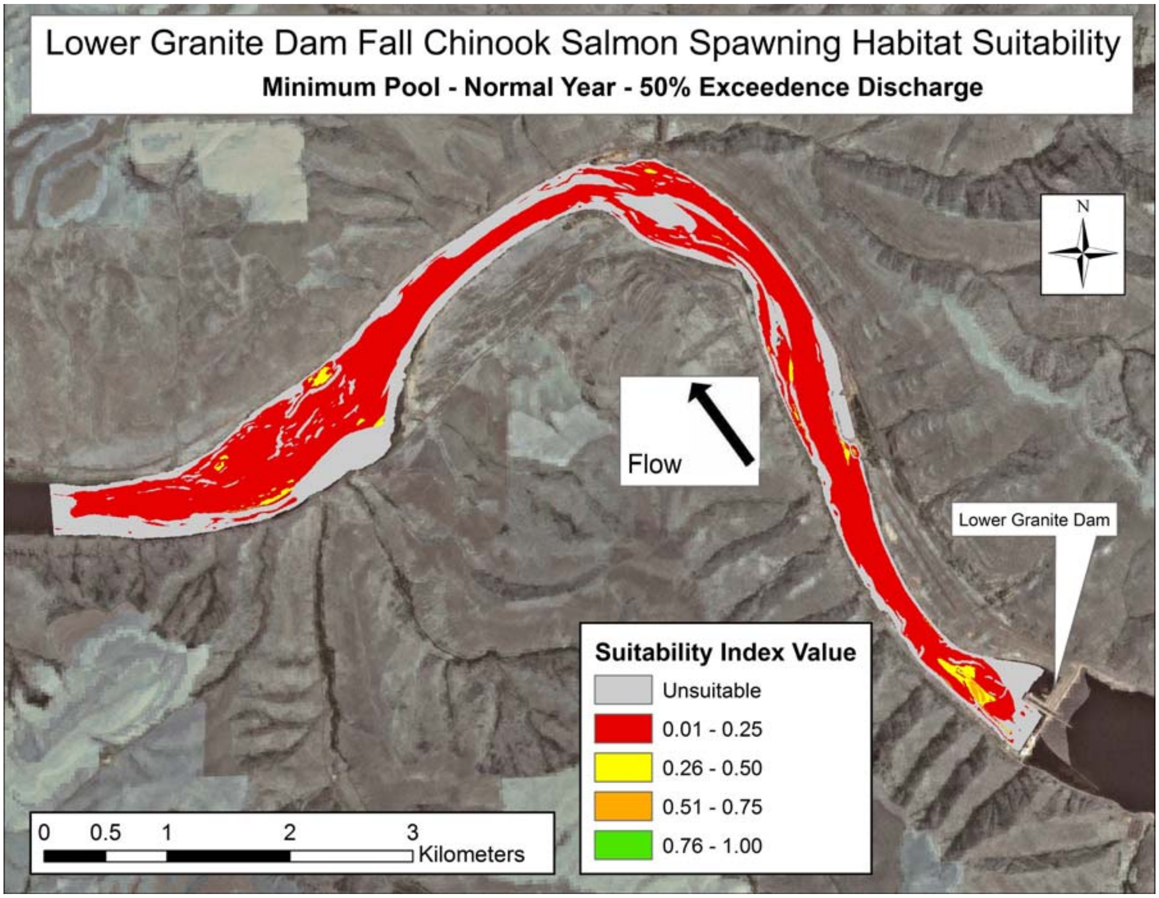

Figure A.32. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 50% Exceedence Discharge (21.7 kcfs) During a Normal Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

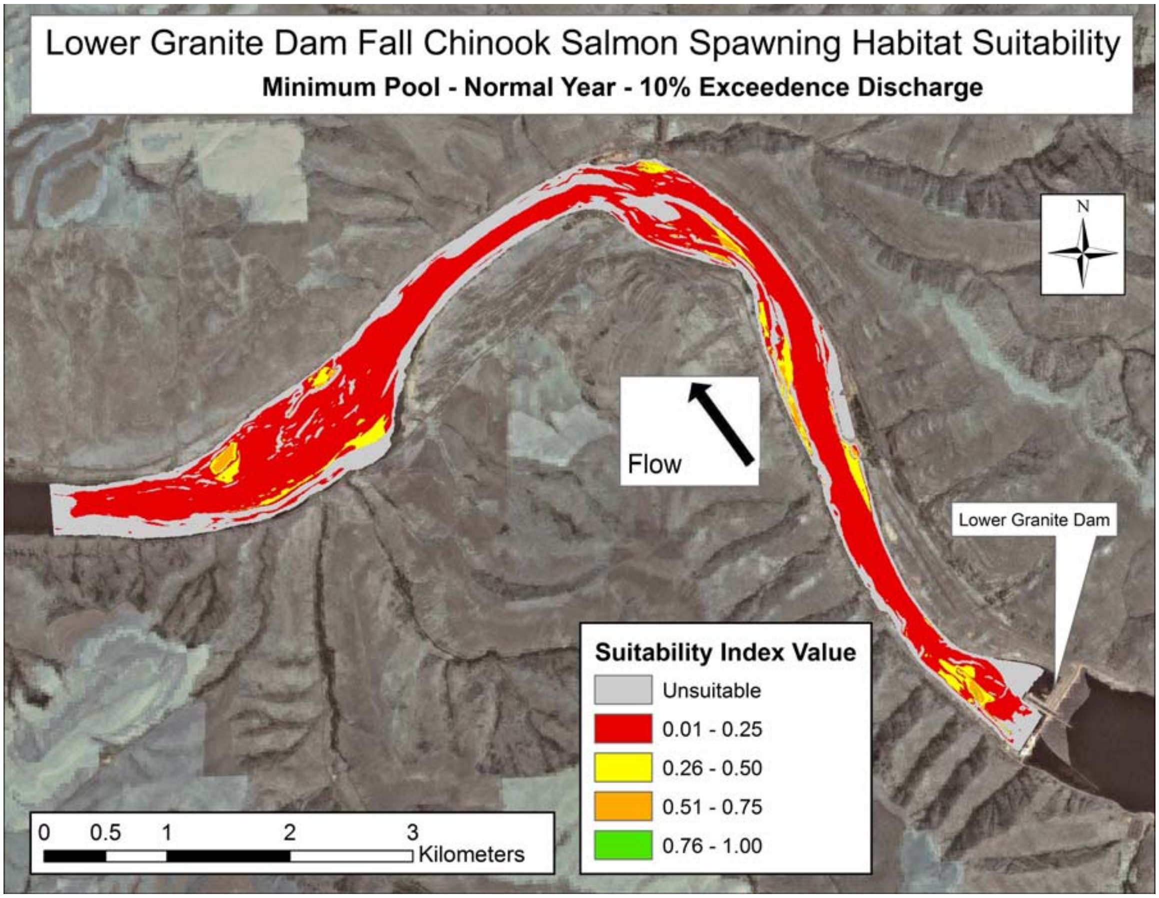

Figure A.33. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 10% Exceedence Discharge (34.5 kcfs) During a Normal Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

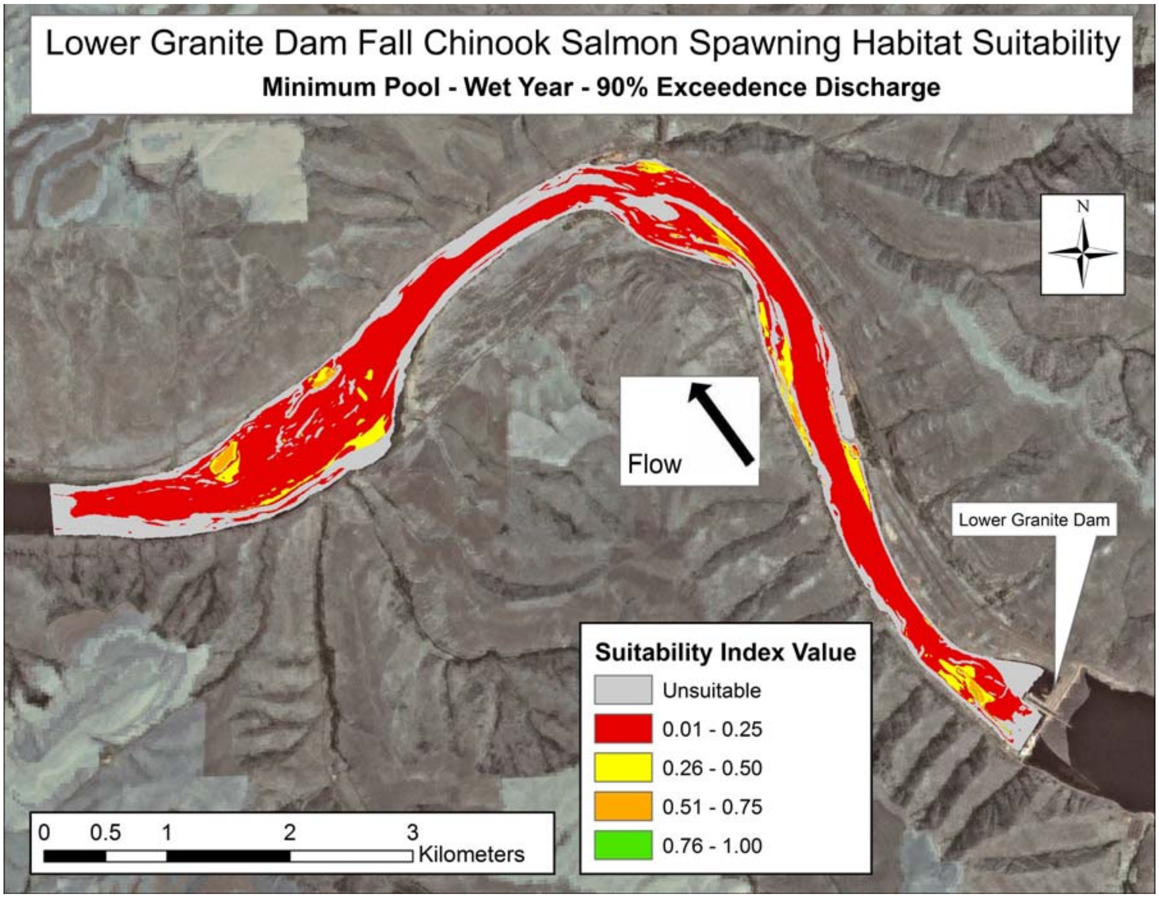

Figure A.34. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 90% Exceedence Discharge (34.5 kcfs) During a Wet Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

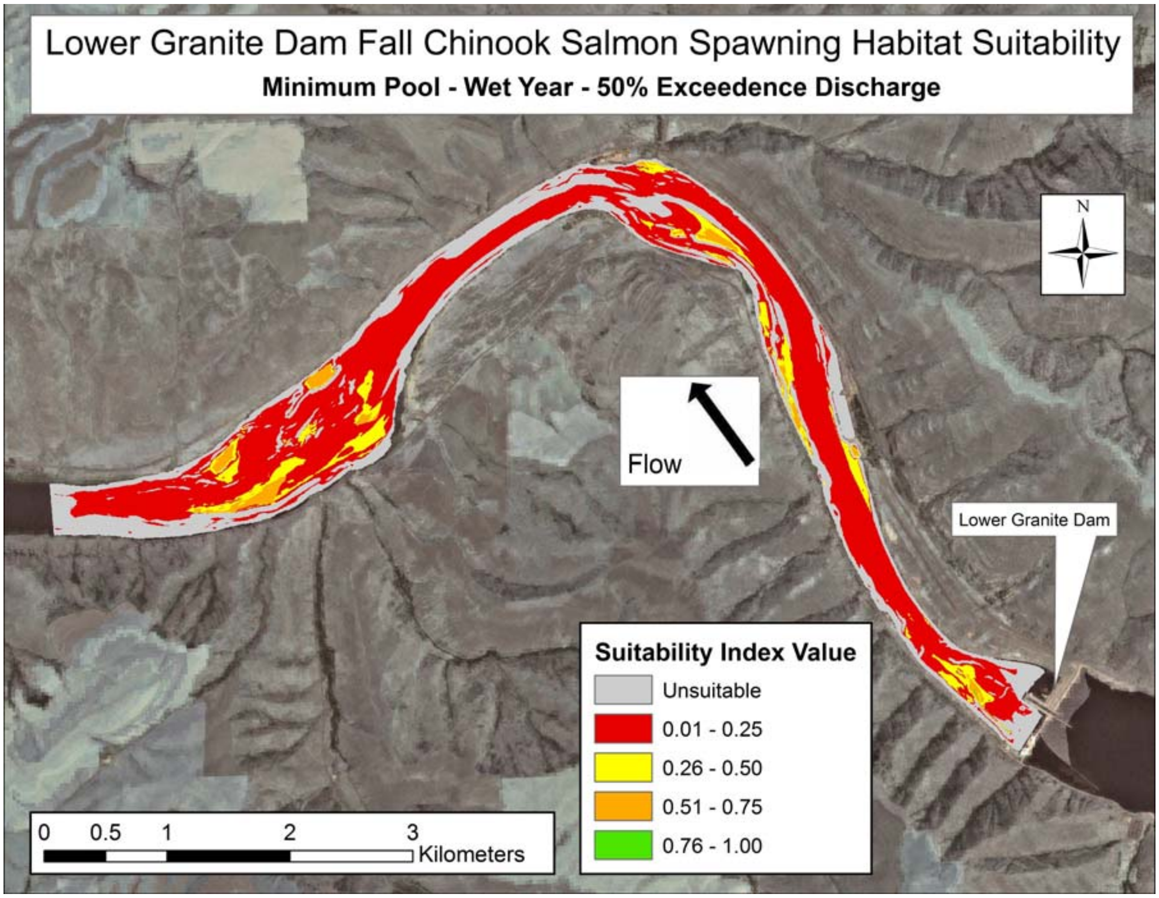

Figure A.35. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 50% Exceedence Discharge (44.0 kcfs) During a Wet Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

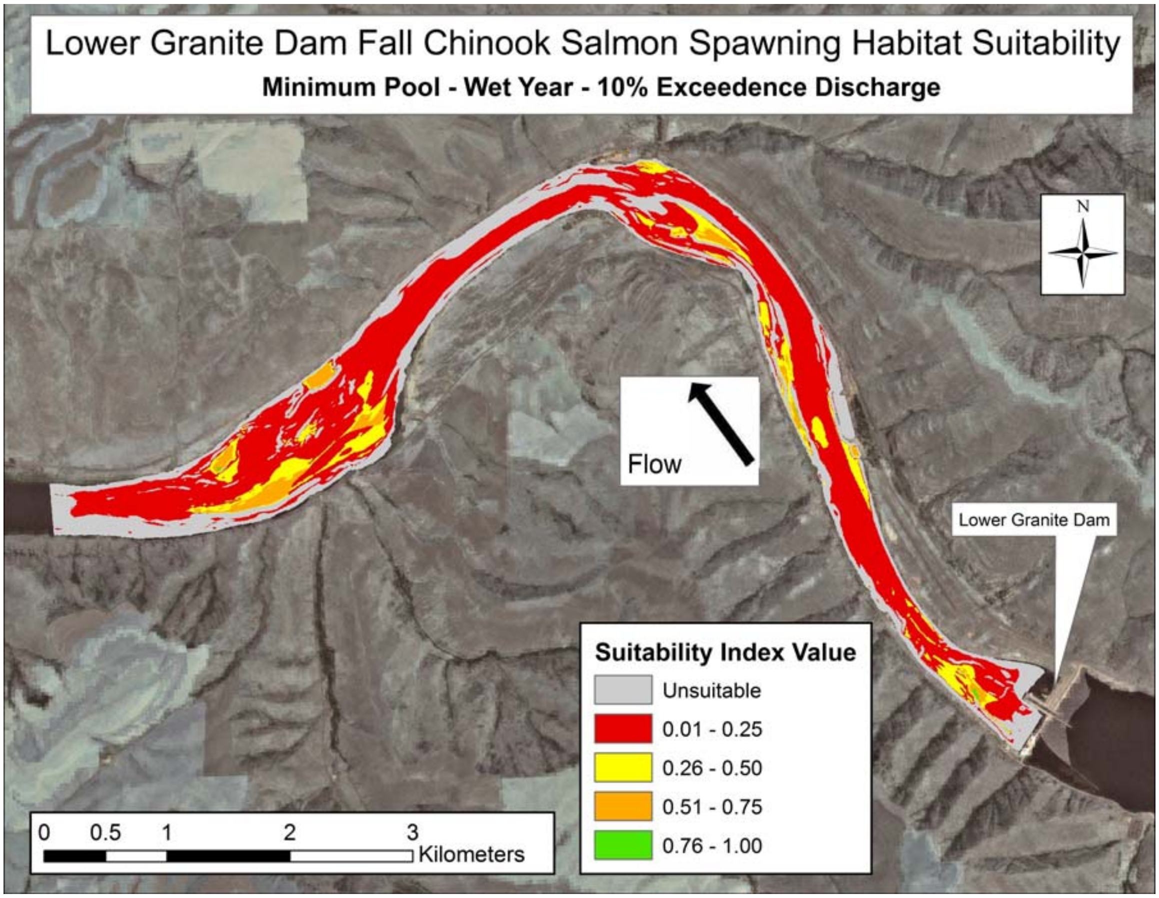

Figure A.36. Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 10% Exceedence Discharge (52.0 kcfs) During a Wet Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

Appendix B

Model Results of Depth, Velocity, and Suitability Index Values within Suitable Spawning Habitat

Appendix B

Model Results of Depth, Velocity, and Suitability Index Values within Suitable Spawning Habitat

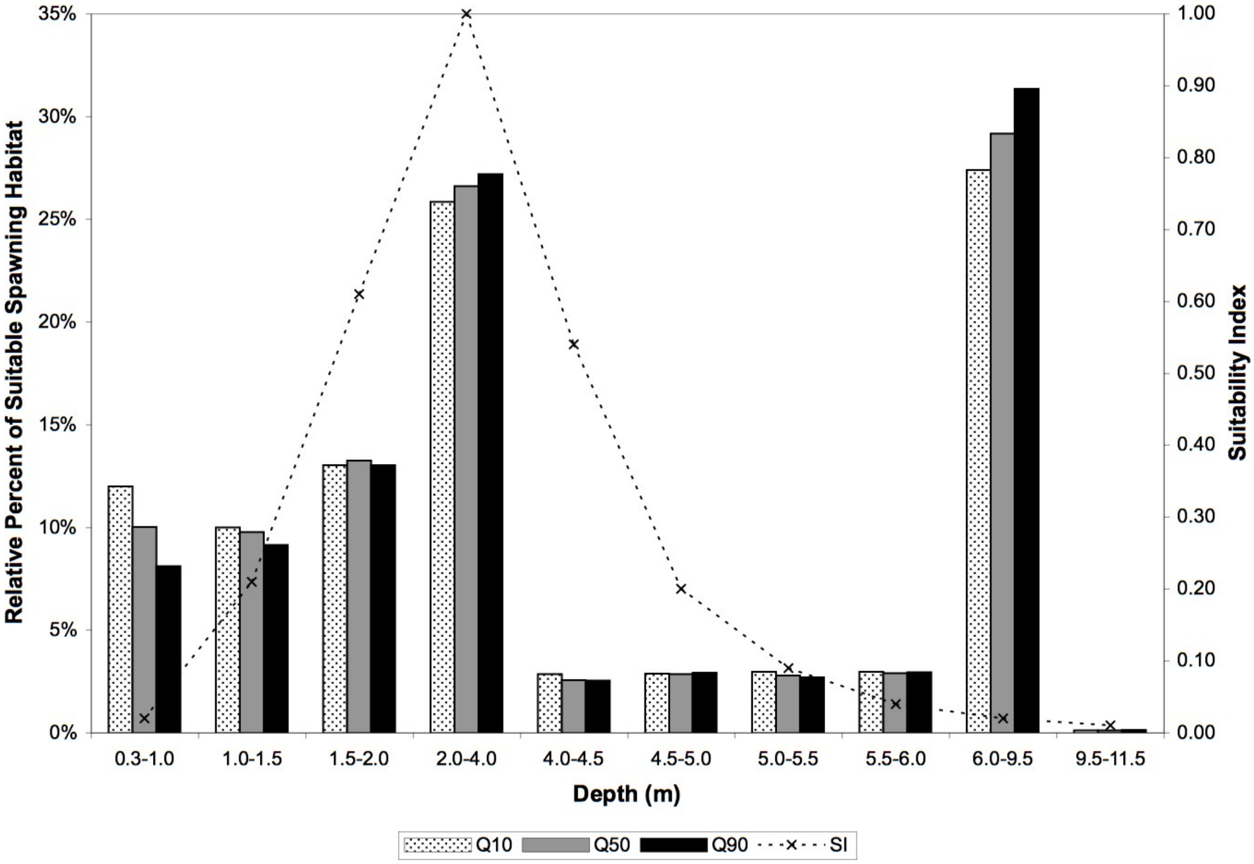

Figure B.1. Depth within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Ice Harbor Dam, with the McNary Dam Forebay at Normal Pool Elevation, During a Dry Water Year. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

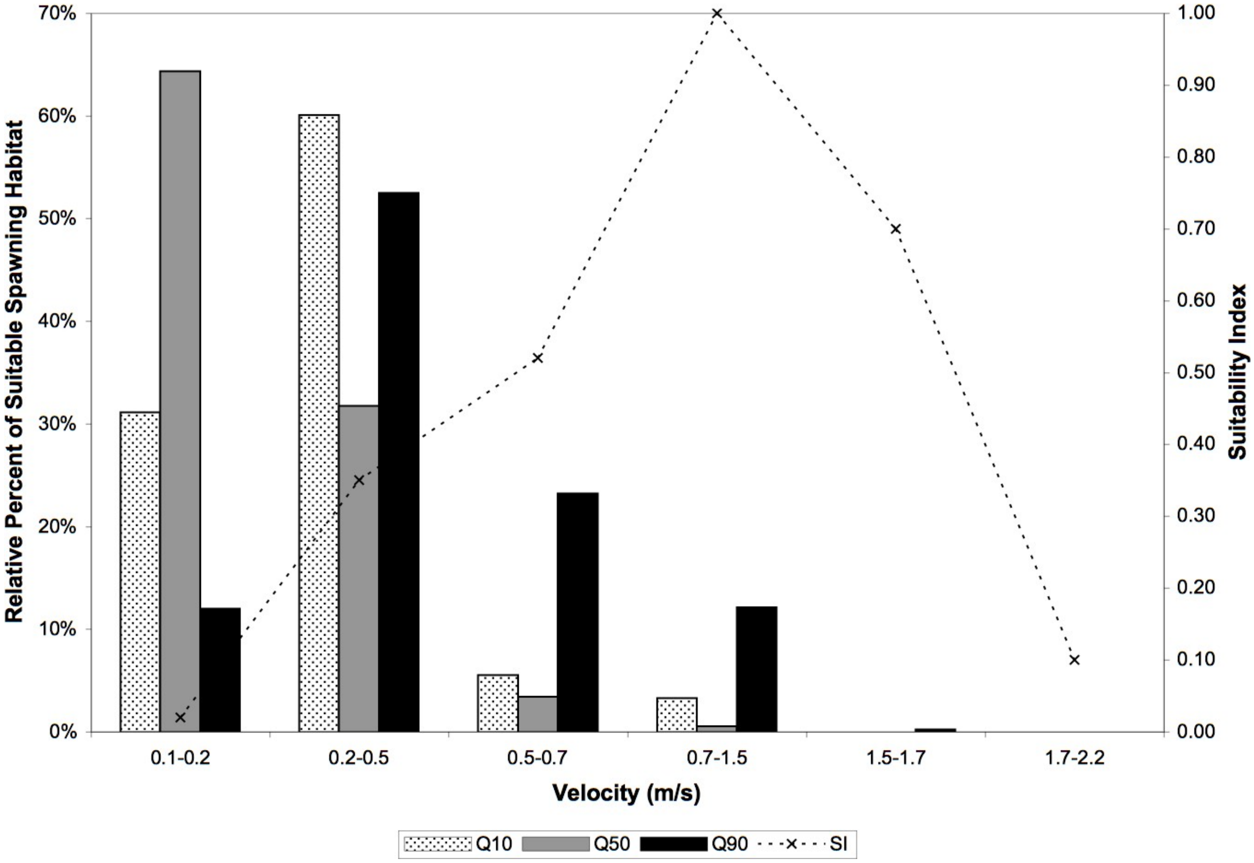

Figure B.2. Velocity within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Ice Harbor Dam, with the McNary Dam Forebay at Normal Pool Elevation, During a Dry Water Year. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

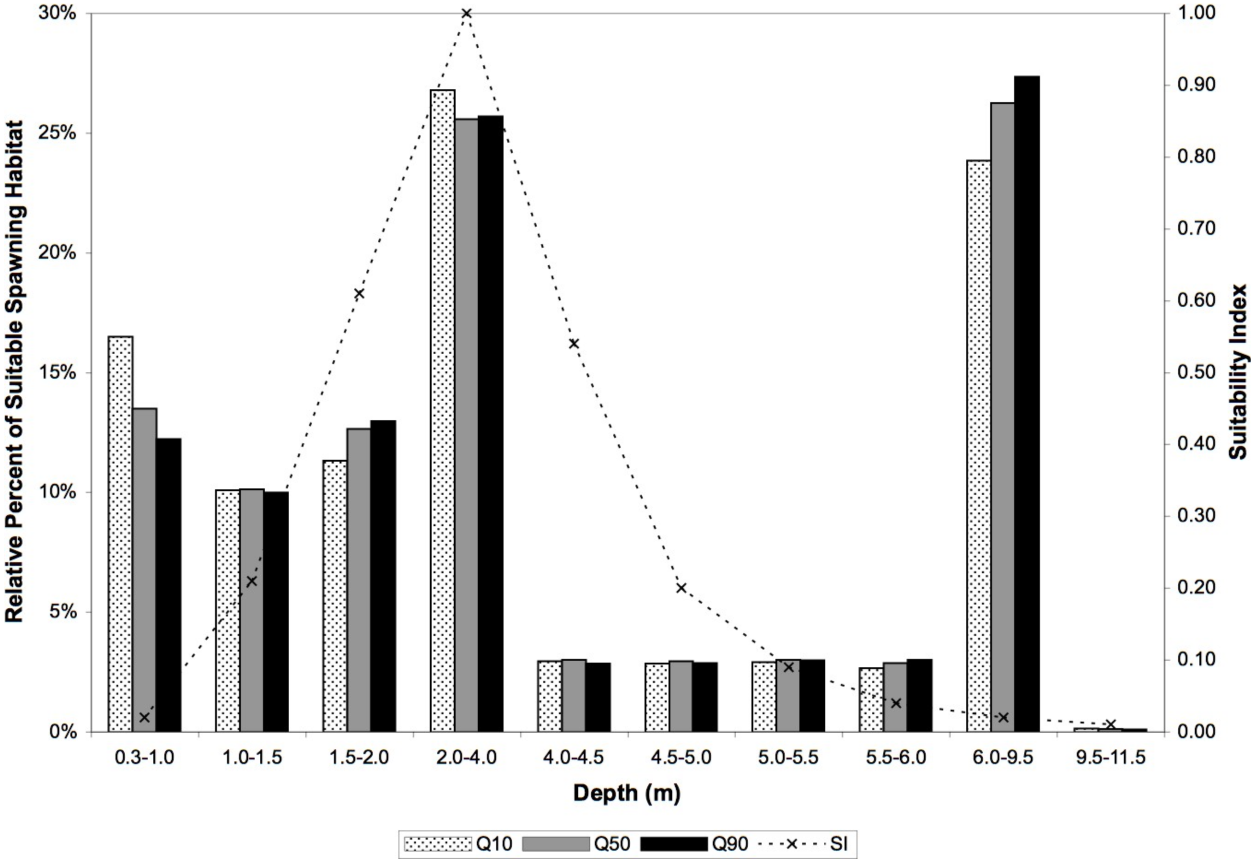

Figure B.3. Depth within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Ice Harbor Dam, with the McNary Dam Forebay at Normal Pool Elevation, During a Normal Water Year. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

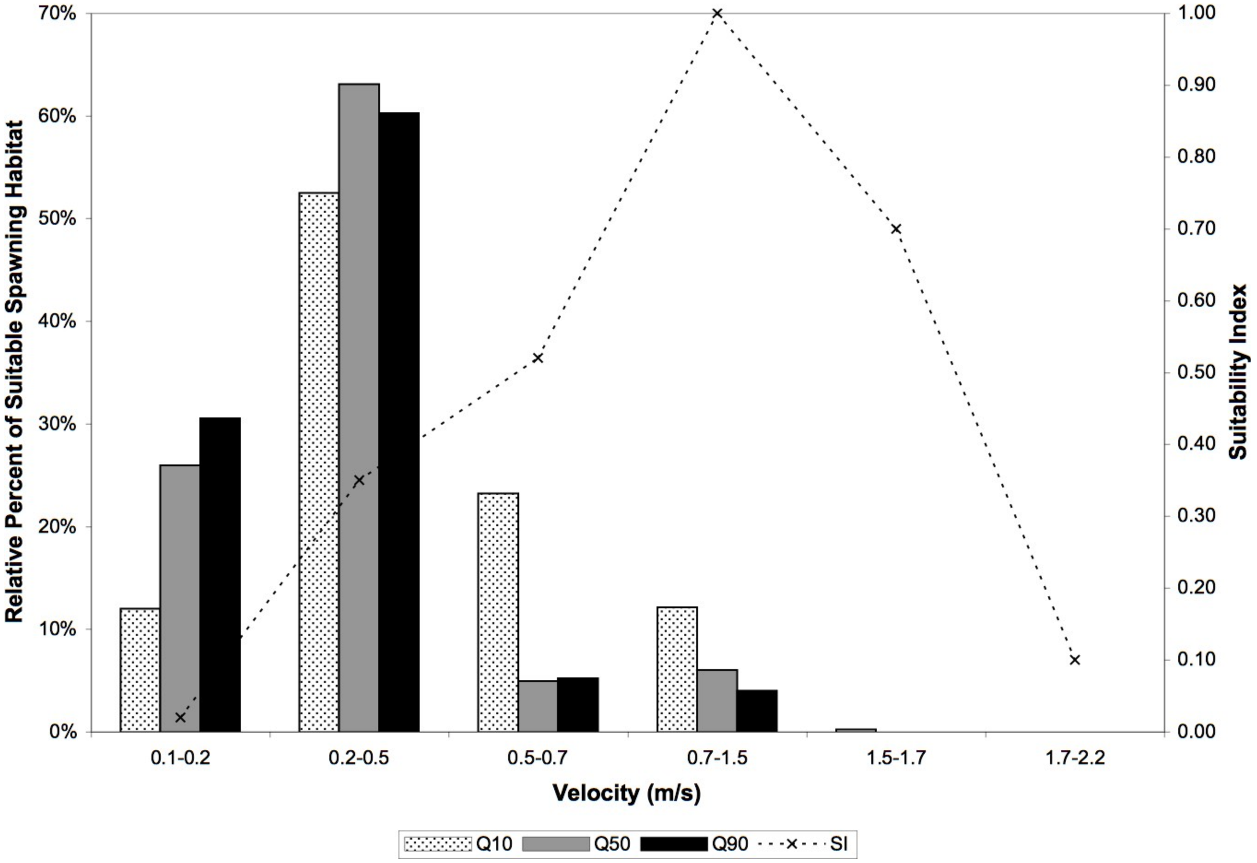

Figure B.4. Velocity within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Ice Harbor Dam, with the McNary Dam Forebay at Normal Pool Elevation, During a Normal Water Year. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

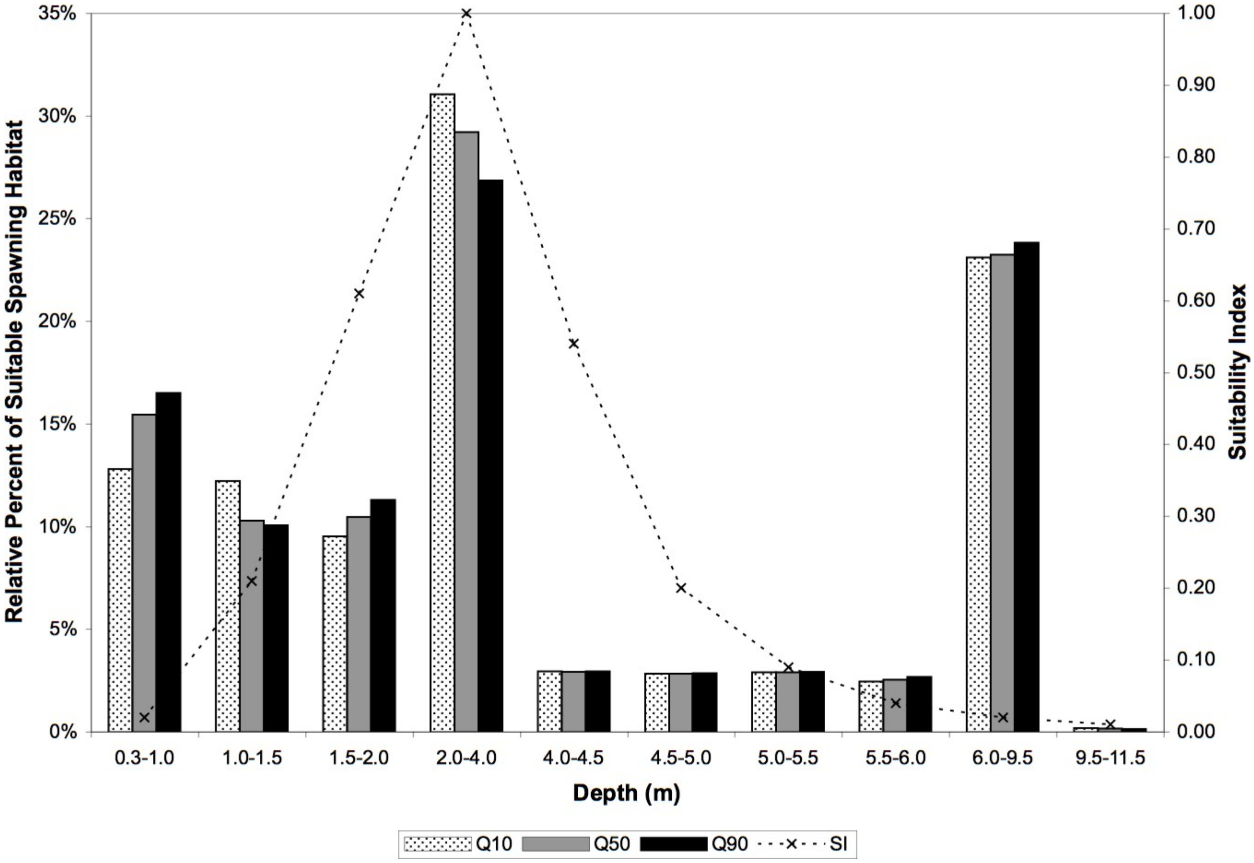

Figure B.5. Depth within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Ice Harbor Dam, with the McNary Dam Forebay at Normal Pool Elevation, During a Wet Water Year. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

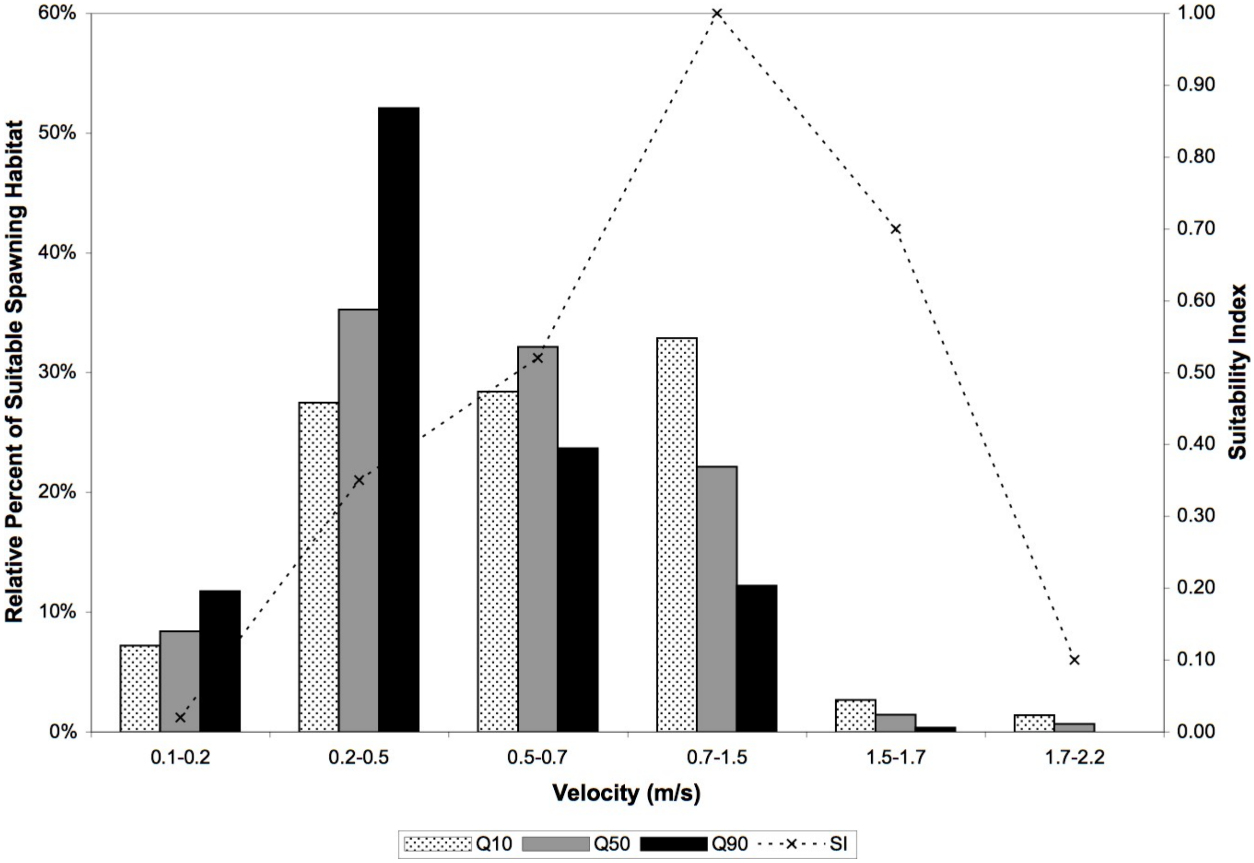

Figure B.6. Velocity within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Ice Harbor Dam, with the McNary Dam Forebay at Normal Pool Elevation, During a Wet Water Year. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

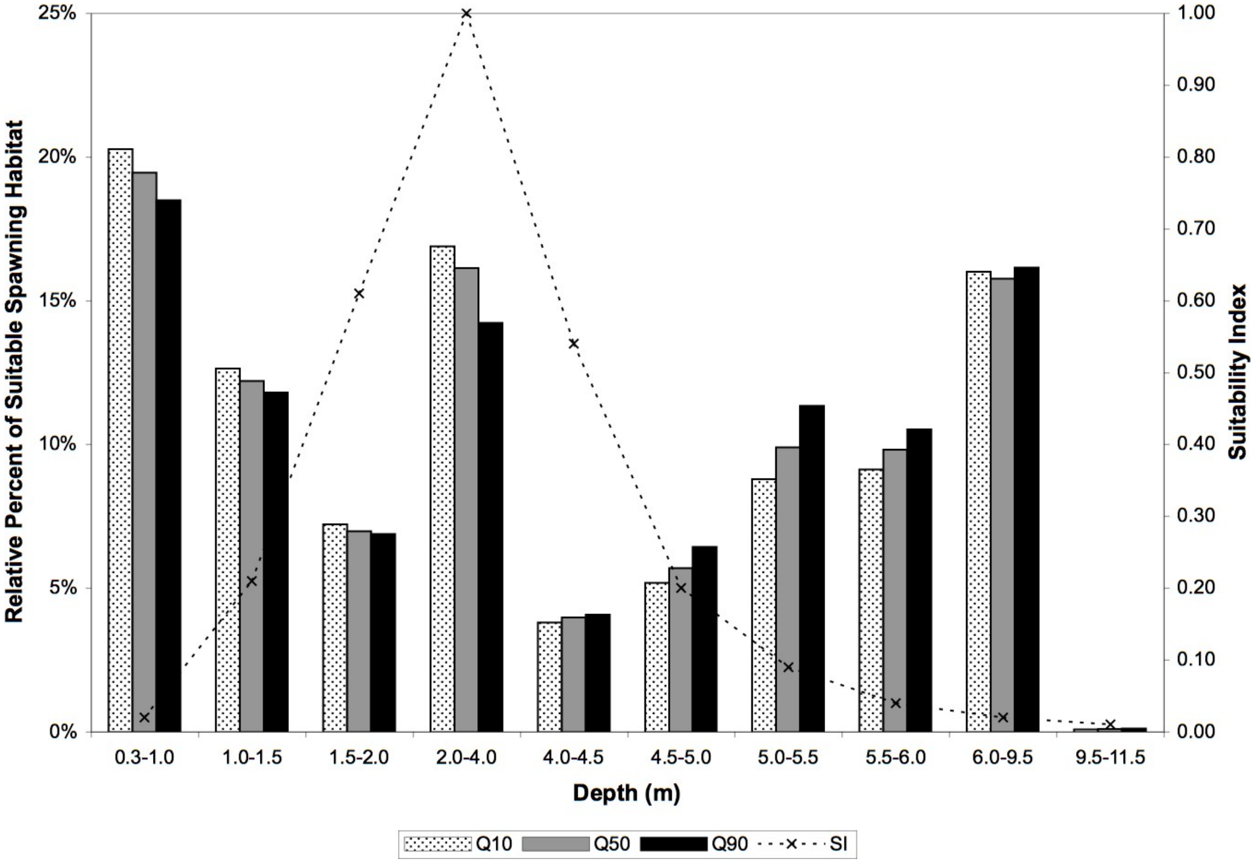

Figure B.7. Depth within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Ice Harbor Dam, with the McNary Dam Forebay at Minimum Pool Elevation, During a dry Water Year. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

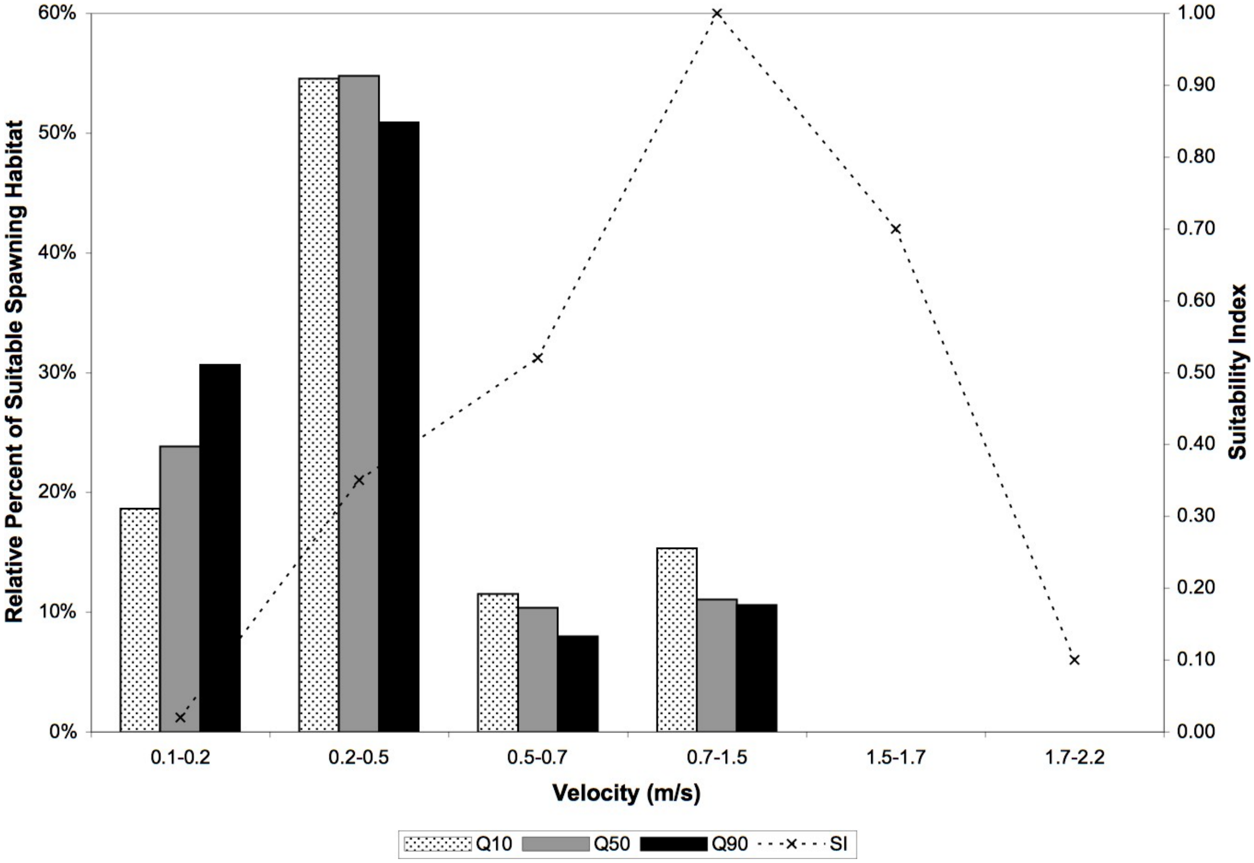

Figure B.8. Velocity within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Ice Harbor Dam, with the McNary Dam Forebay at Minimum Pool Elevation, During a Dry Water Year. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

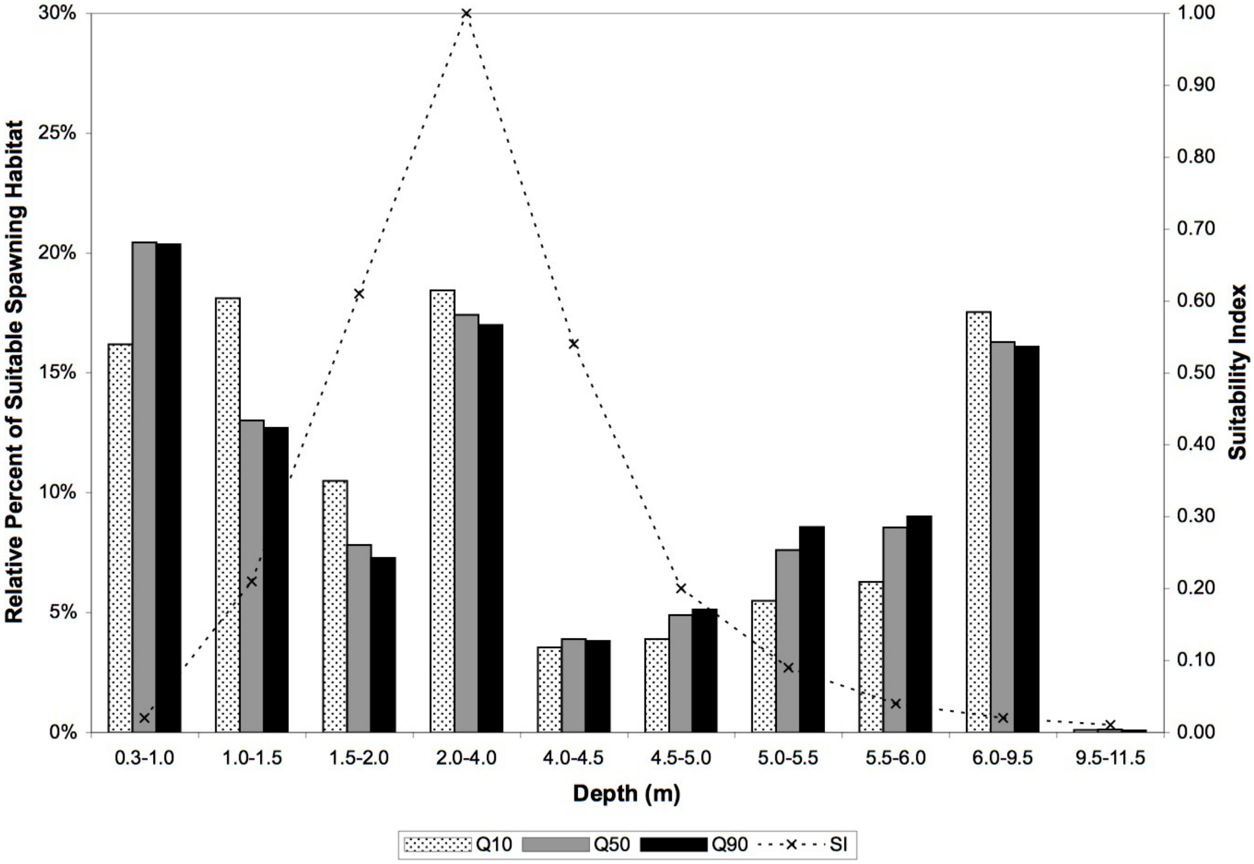

Figure B.9. Depth within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Ice Harbor Dam, with the McNary Dam Forebay at Minimum Pool Elevation, During a Normal Water Year. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

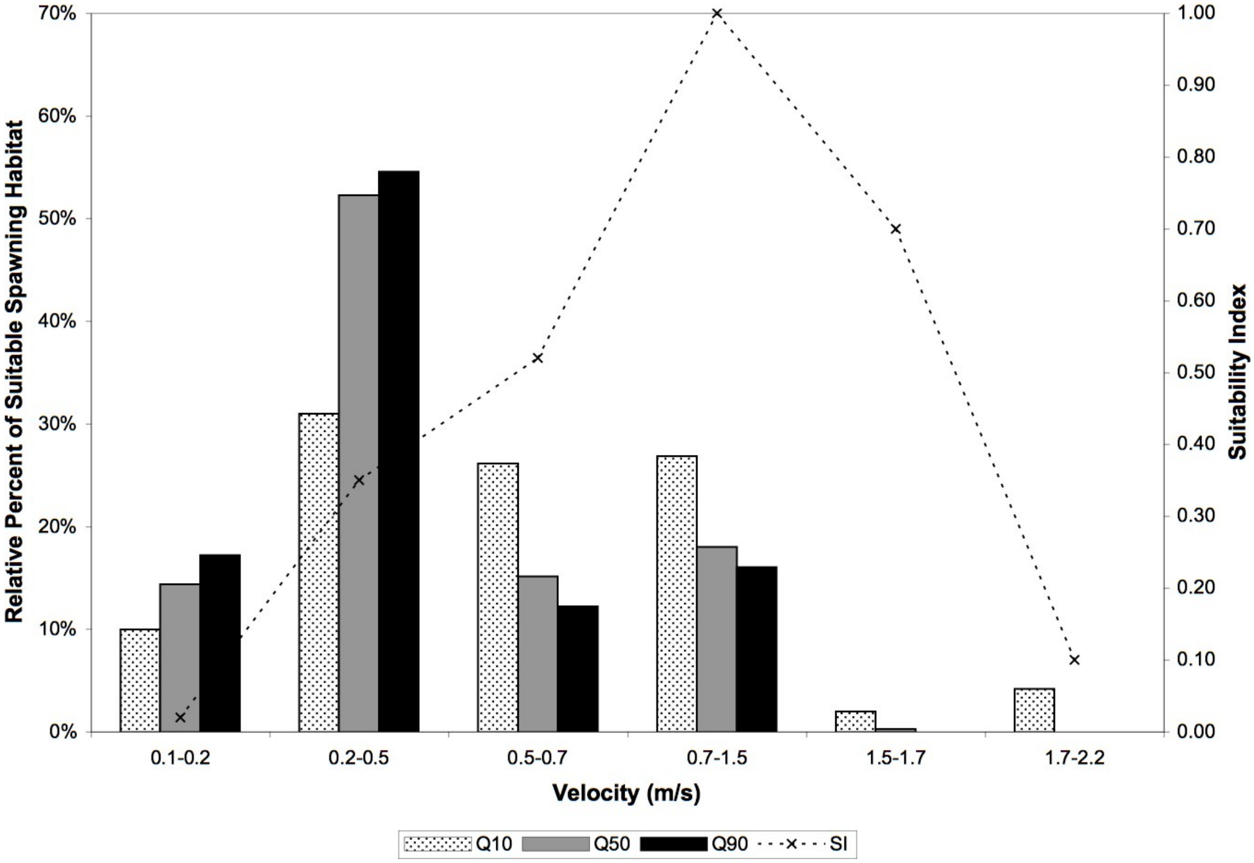

Figure B.10. Velocity within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Ice Harbor Dam, with the McNary Dam Forebay at Minimum Pool Elevation, During a Normal Water ear. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

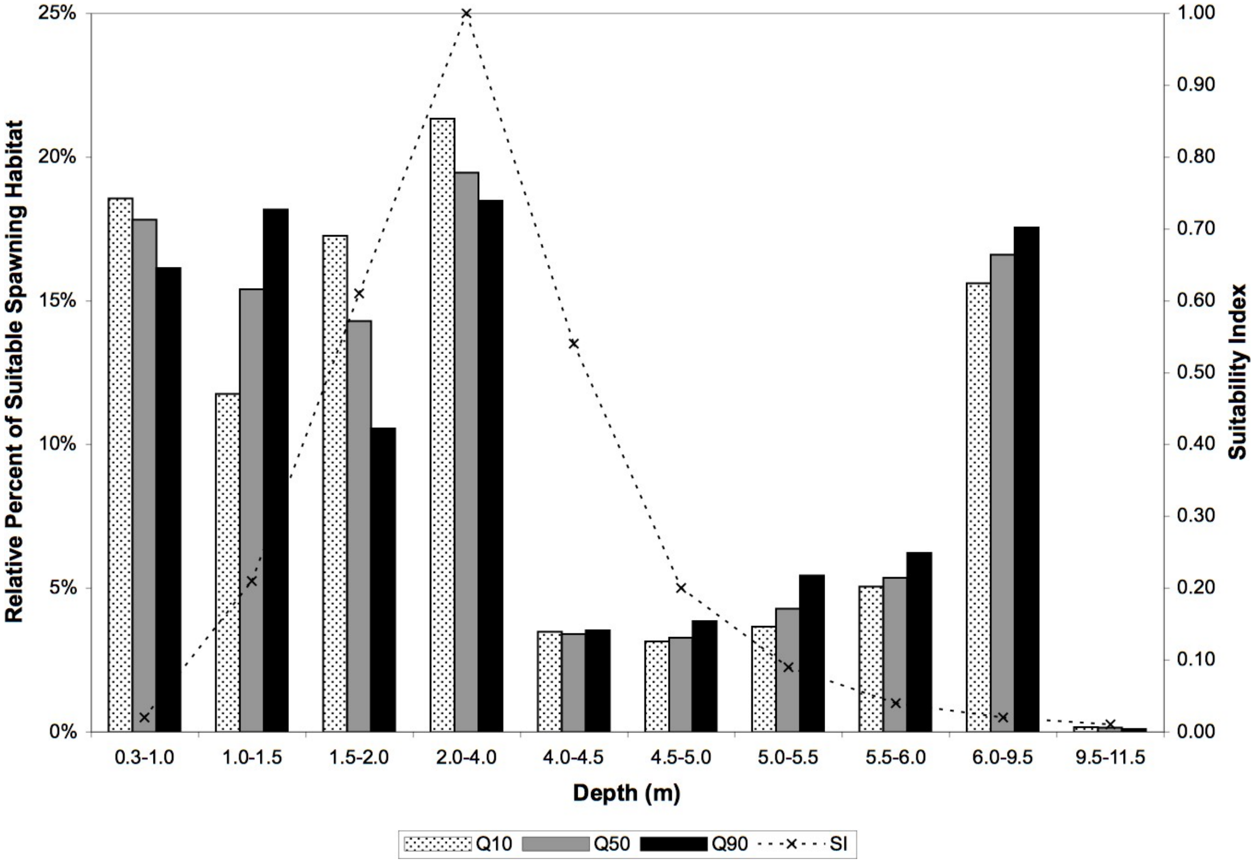

Figure B.11. Depth within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Ice Harbor Dam, with the McNary Dam Forebay at Minimum Pool Elevation, during a Wet Water Year. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

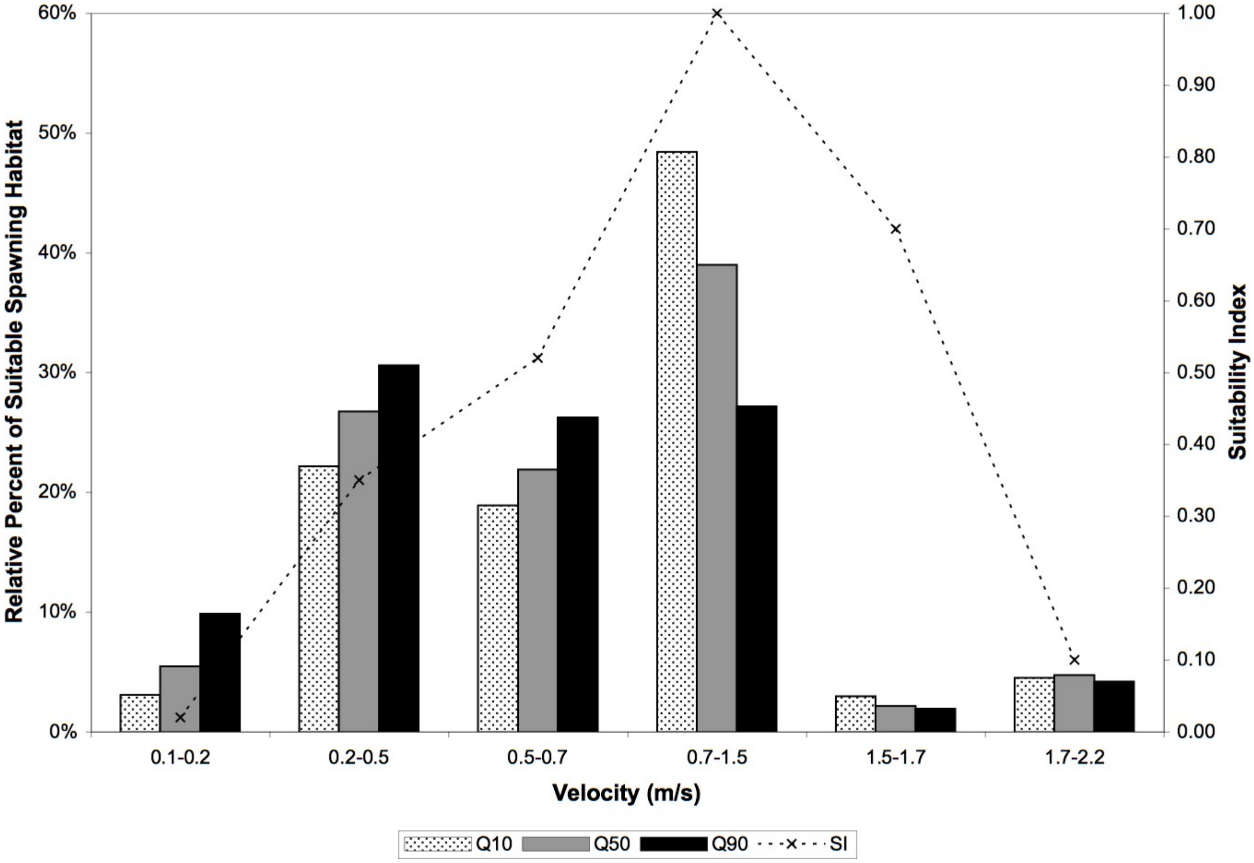

Figure B.12. Velocity within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Ice Harbor Dam, with the McNary Dam Forebay at Minimum Pool Elevation, During a Wet Water Year. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

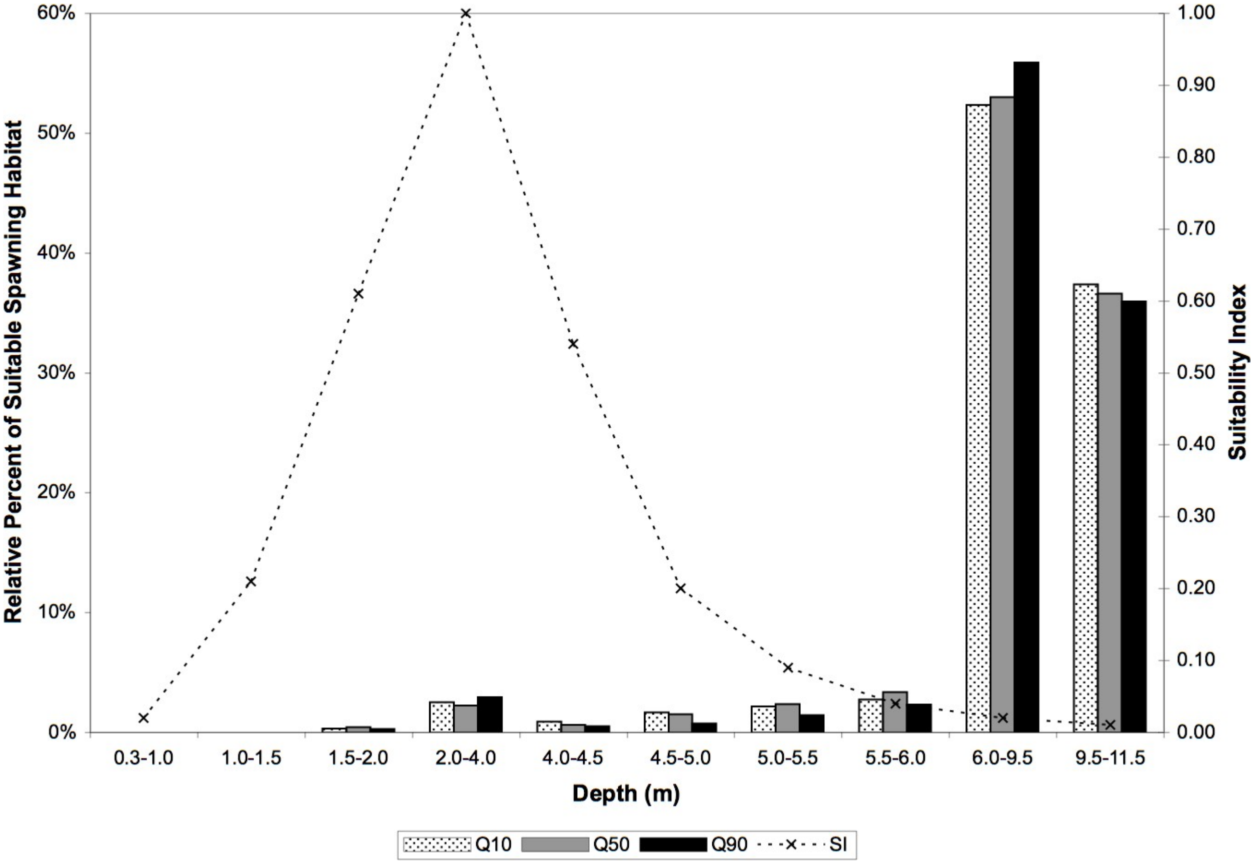

Figure B.13. Depth within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Lower Granite Dam, with the Little Goose Dam Forebay at Normal Pool Elevation, During a Dry Water Year. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

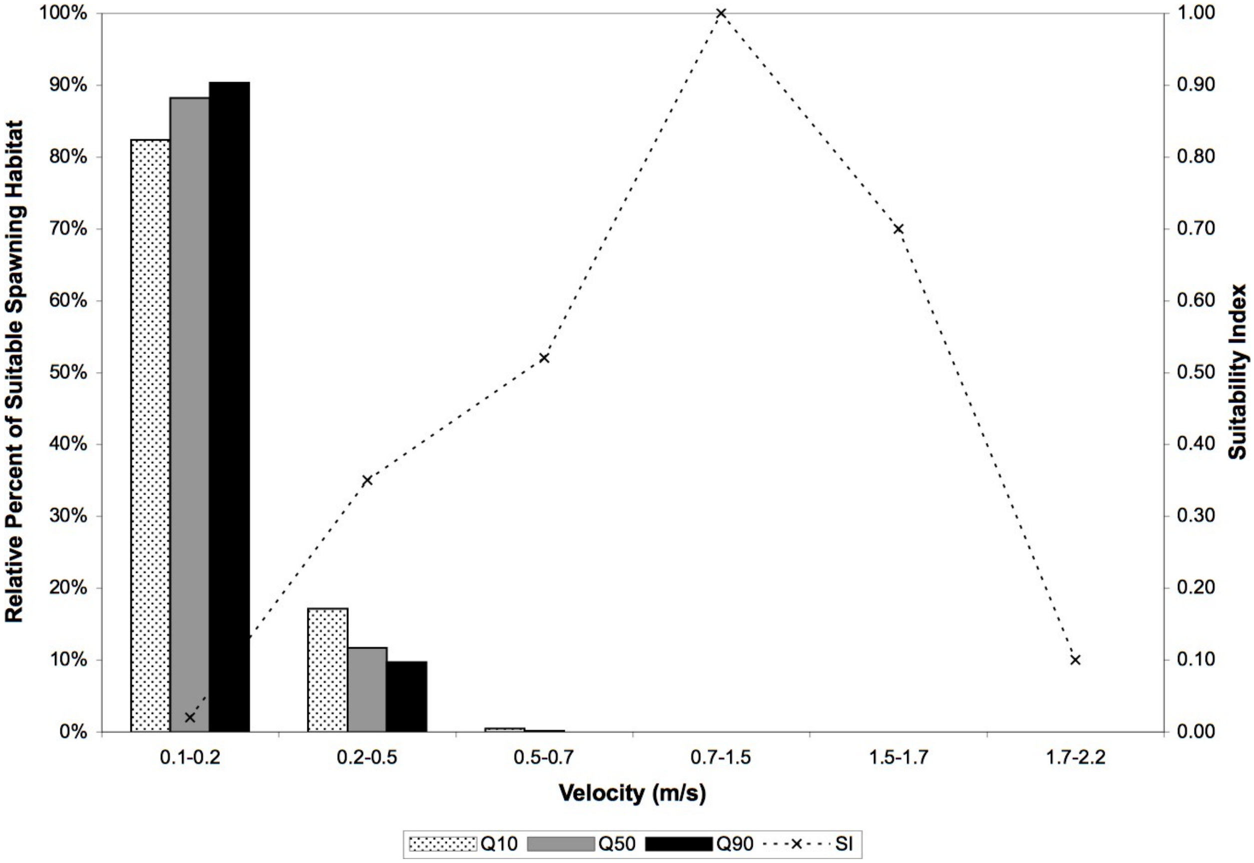

Figure B.14. Velocity within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Lower Granite Dam, with the Little Goose Dam Forebay at Normal Pool Elevation, During a Dry Water Year. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

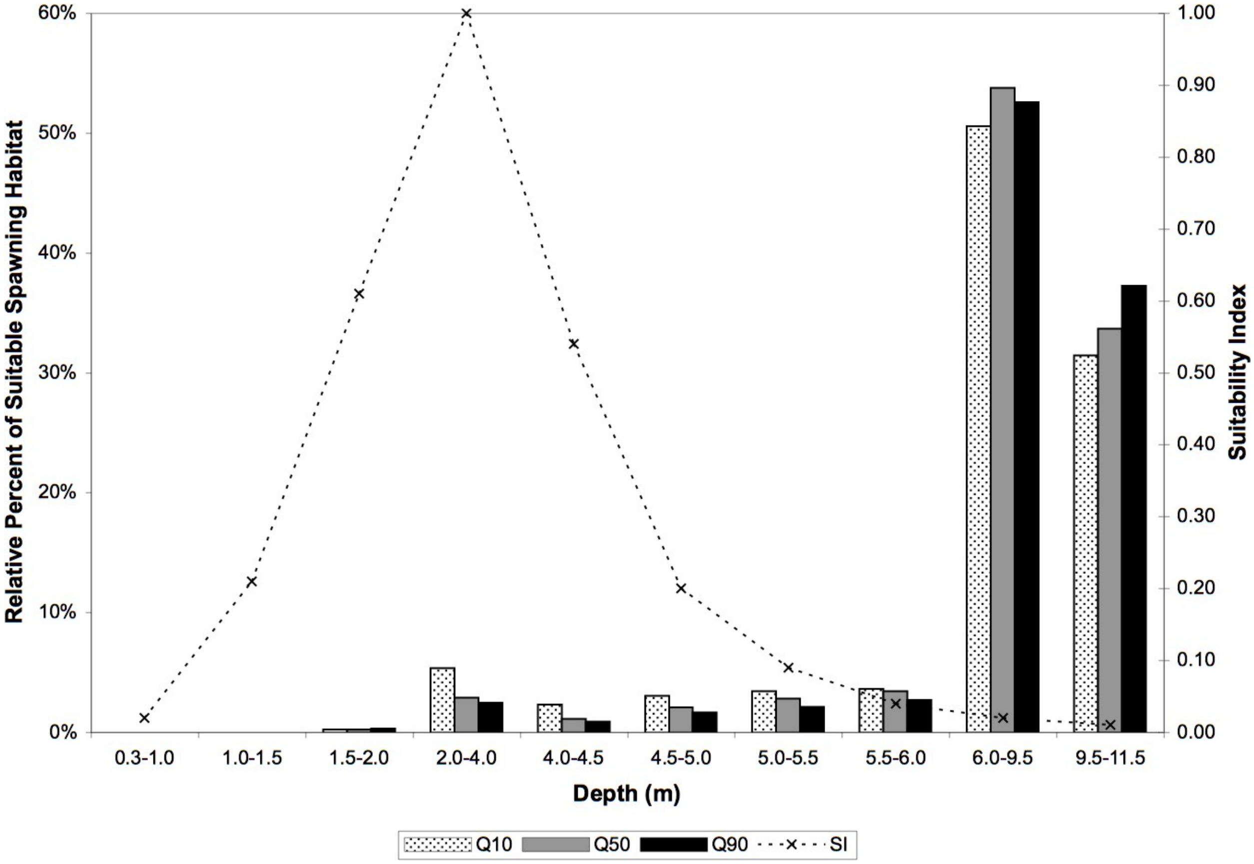

Figure B.15. Depth within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Lower Granite Dam, with the Little Goose Dam Forebay at Normal Pool Elevation, During a Normal Water Year. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

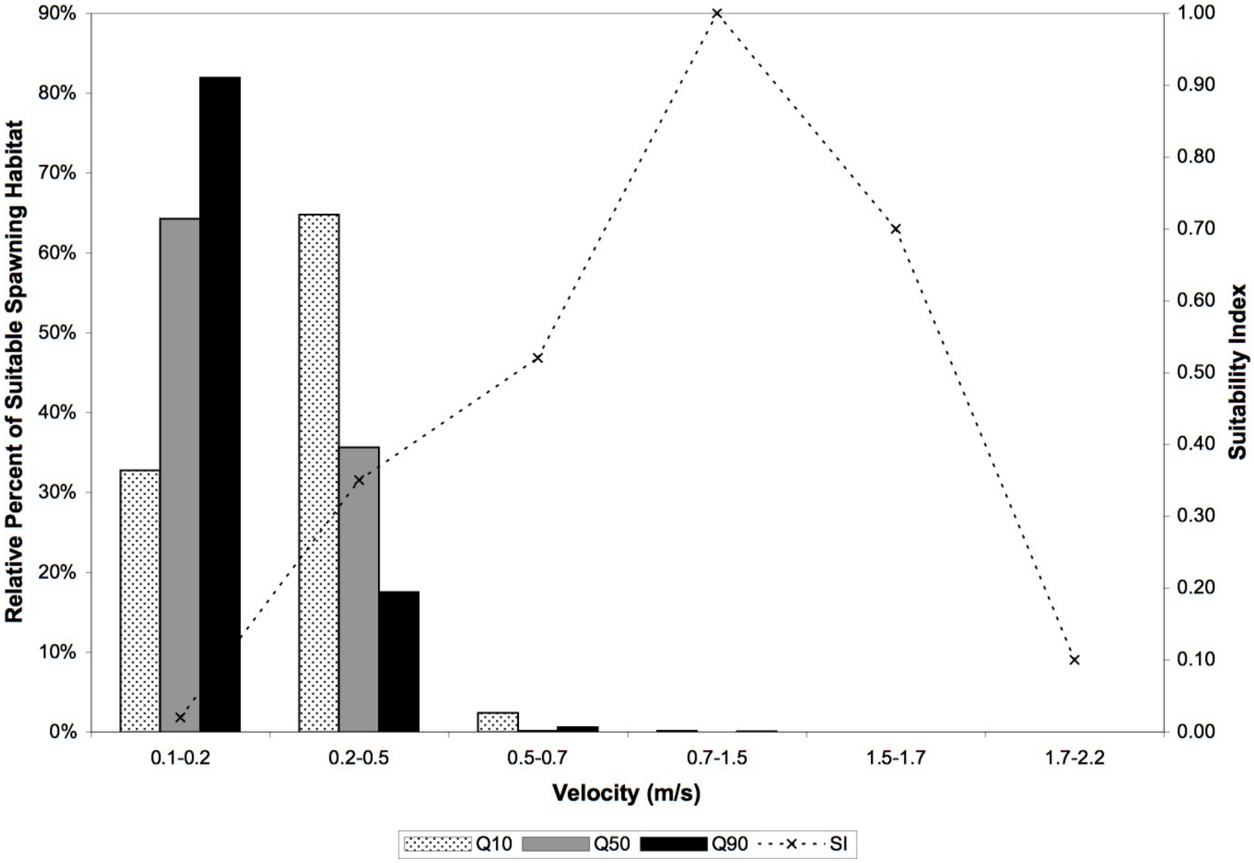

Figure B.16. Velocity within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Lower Granite Dam, with the Little Goose Dam Forebay at Normal Pool Elevation, During a Normal Water Year. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

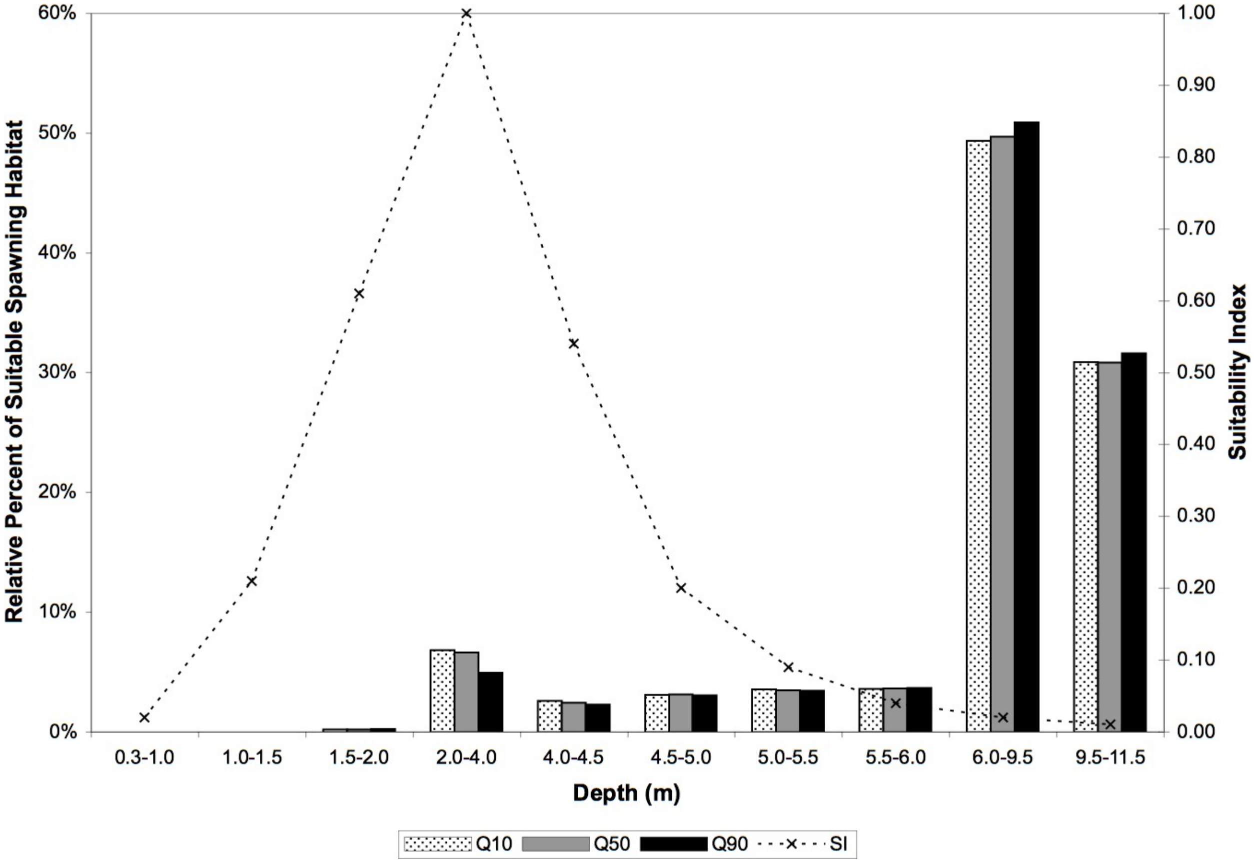

Figure B.17. Depth within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Lower Granite Dam, with the Little Goose Dam Forebay at Normal Pool Elevation, During a Wet Water Year. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

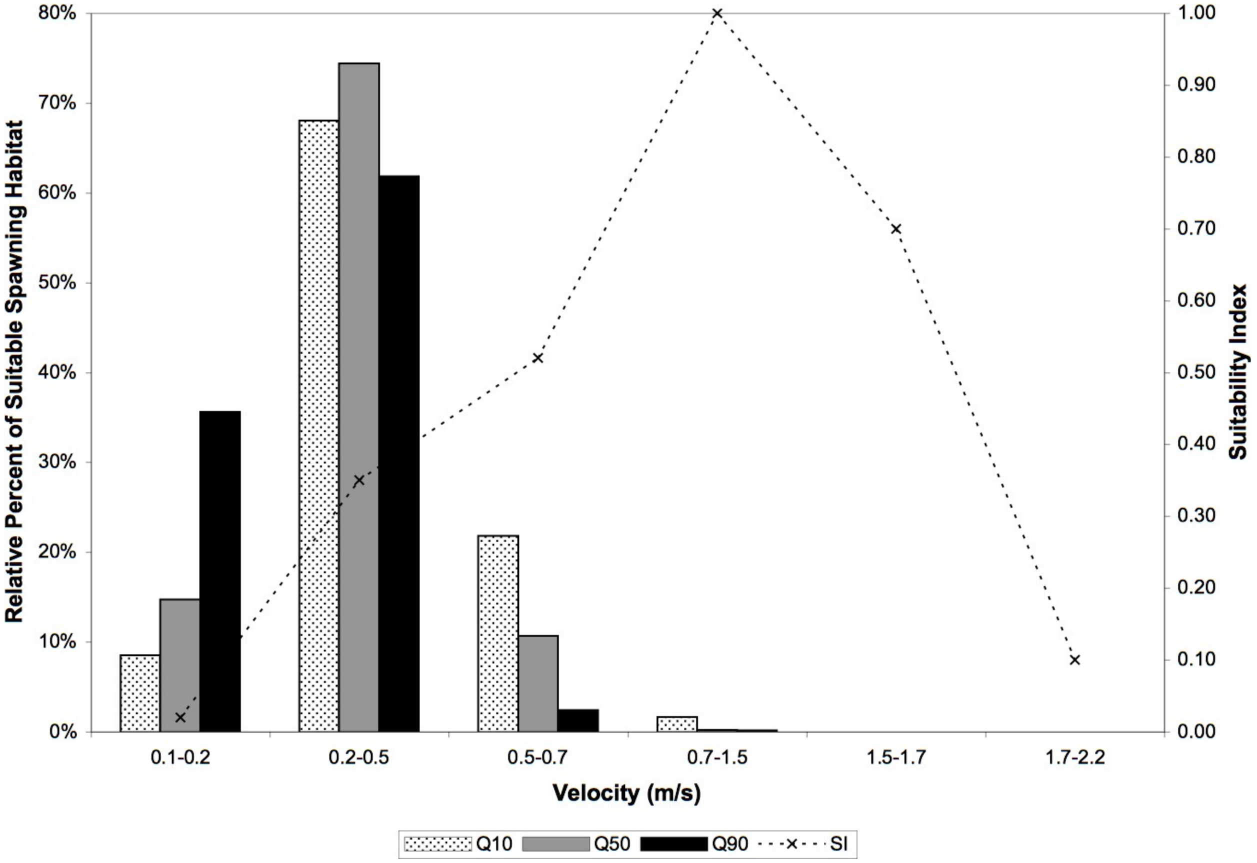

Figure B.18. Velocity within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Lower Granite Dam, with the Little Goose Dam Forebay at Normal Pool Elevation, During a Wet Water Year. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

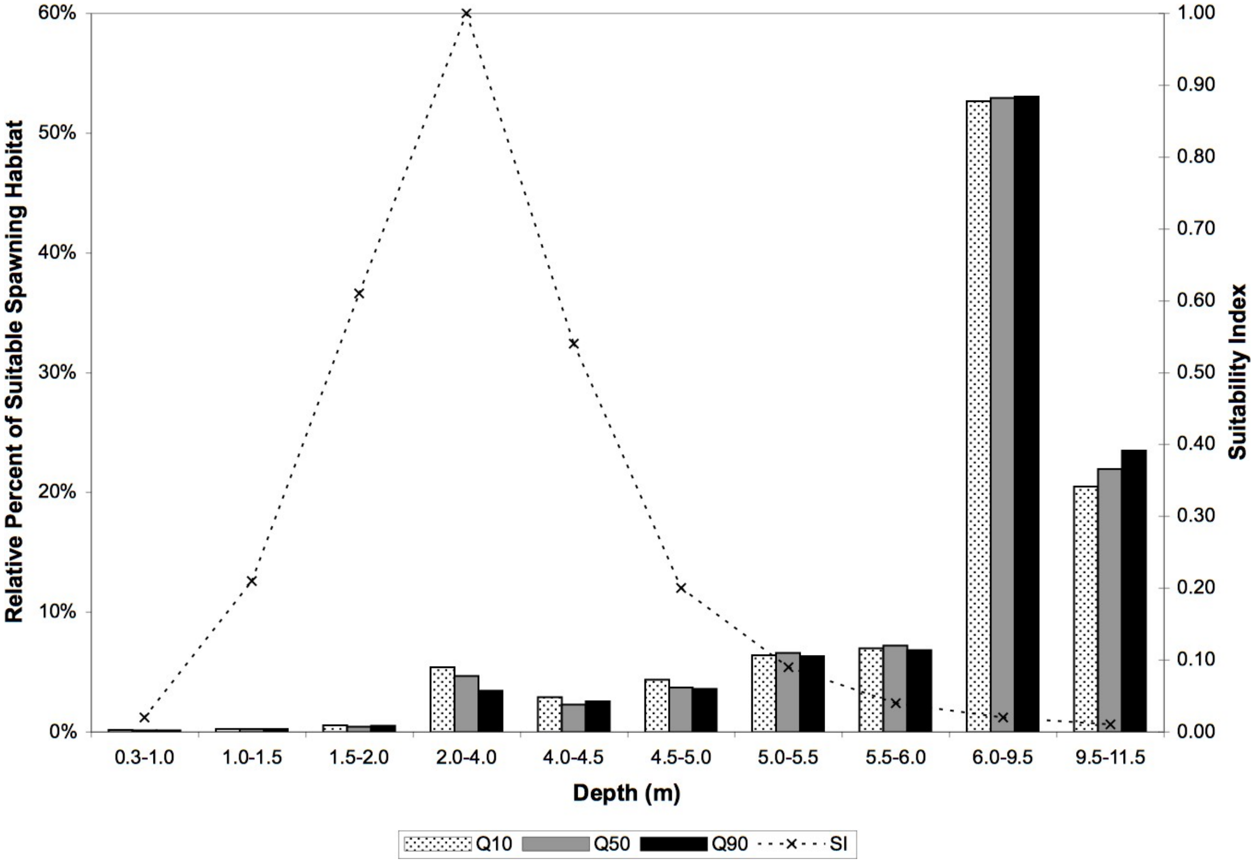

Figure B.19. Depth within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Lower Granite Dam, with the Little Goose Dam Forebay at Minimum Pool Elevation, During a Dry Water Year. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

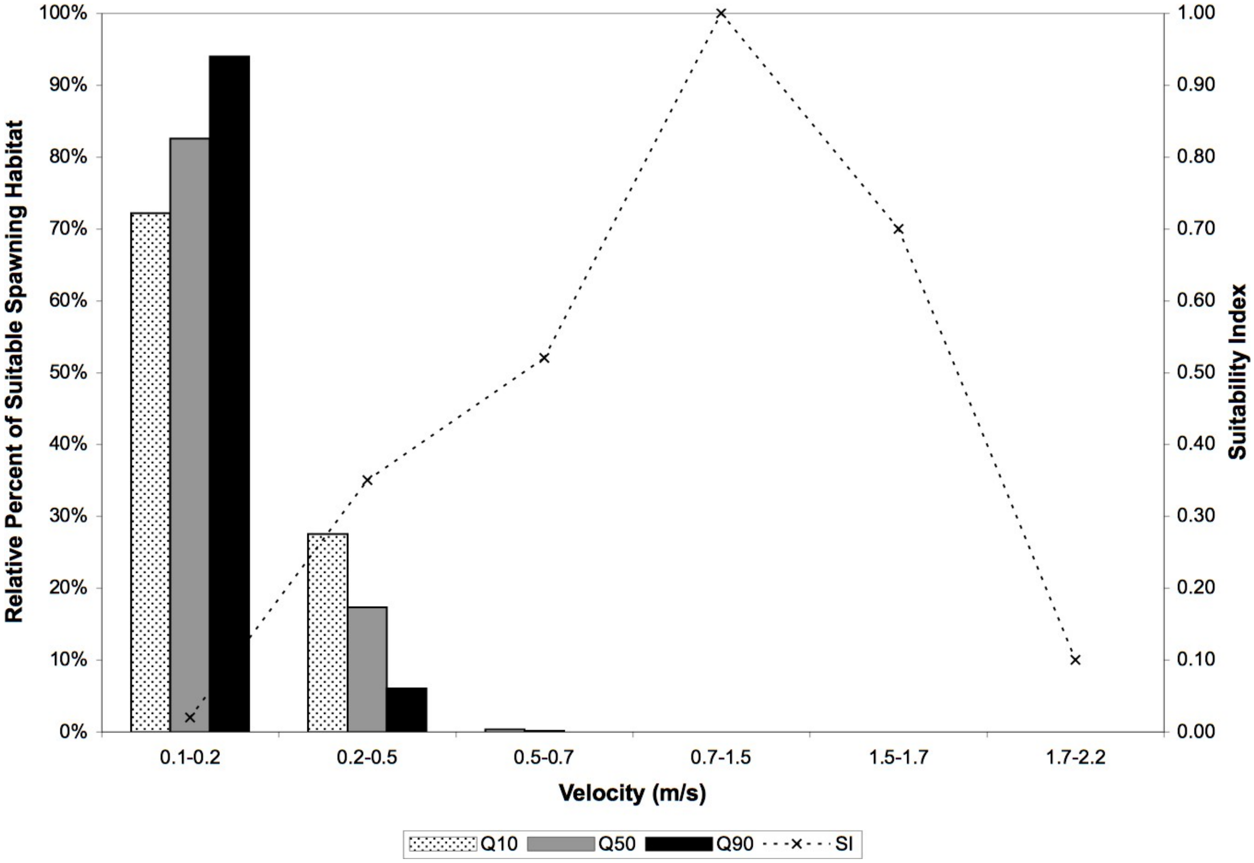

Figure B.20. Velocity within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Lower Granite Dam, with the Little Goose Dam Forebay at Minimum Pool Elevation, During a Dry Water Year. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

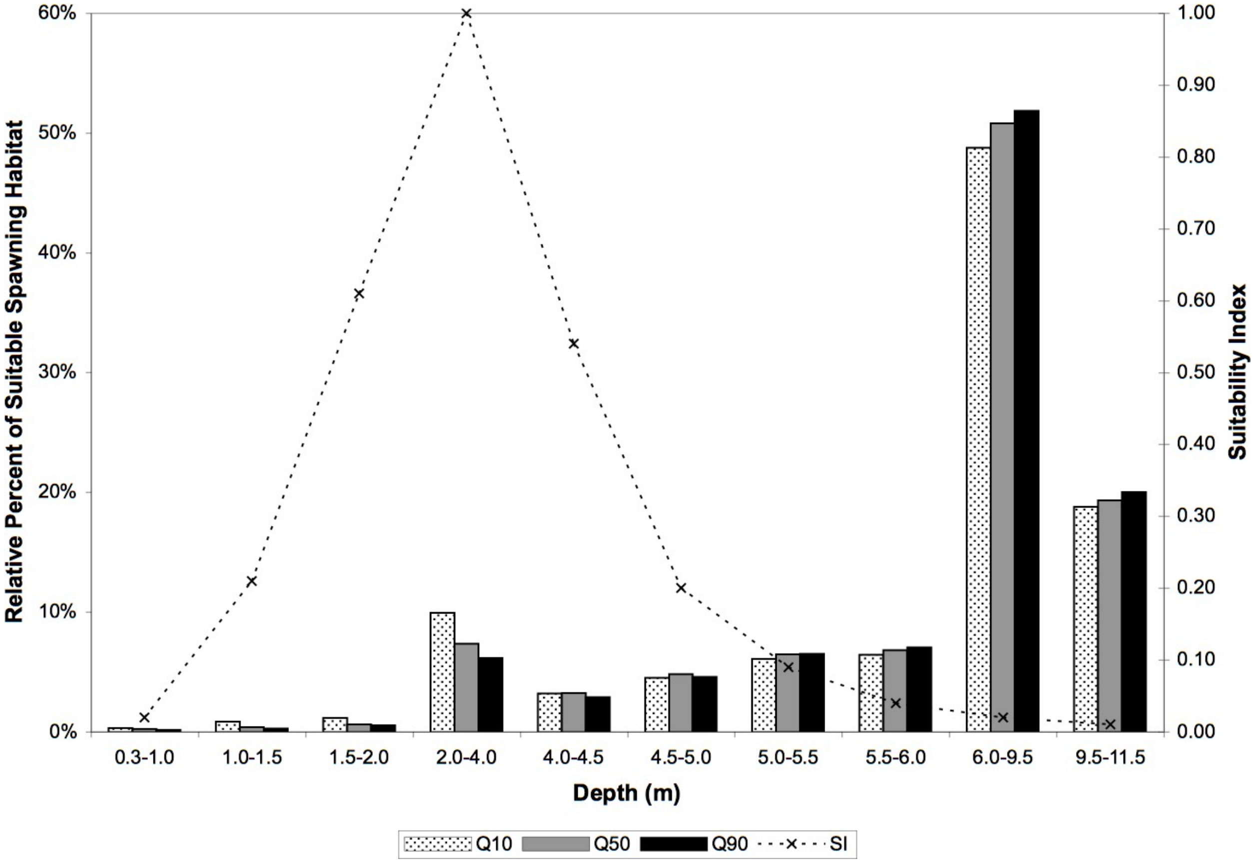

Figure B.21. Depth within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Lower Granite Dam, with the Little Goose Dam Forebay at Minimum Pool Elevation, During a Normal Water Year. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

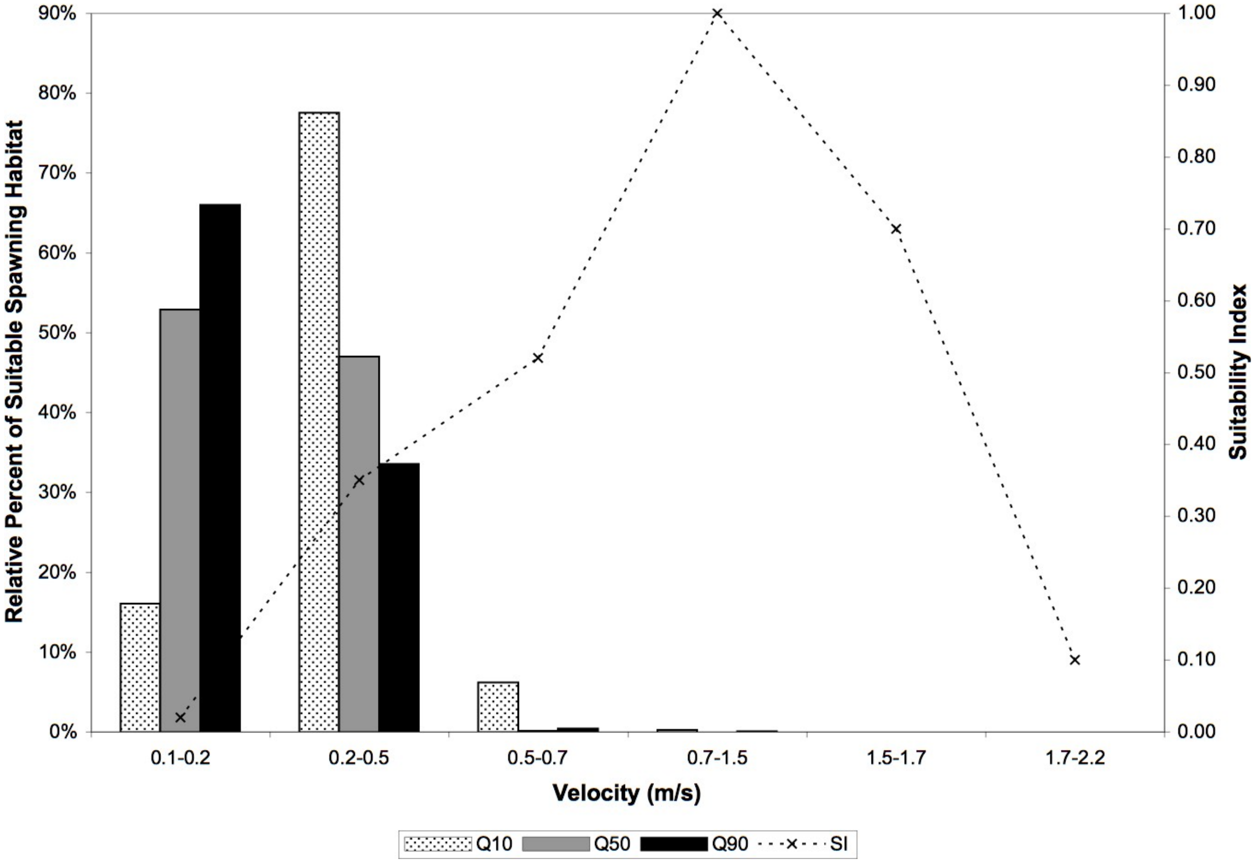

Figure B.22. Velocity within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Lower Granite Dam, with the Little Goose Dam Forebay at Minimum Pool Elevation, During a Normal Water Year. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

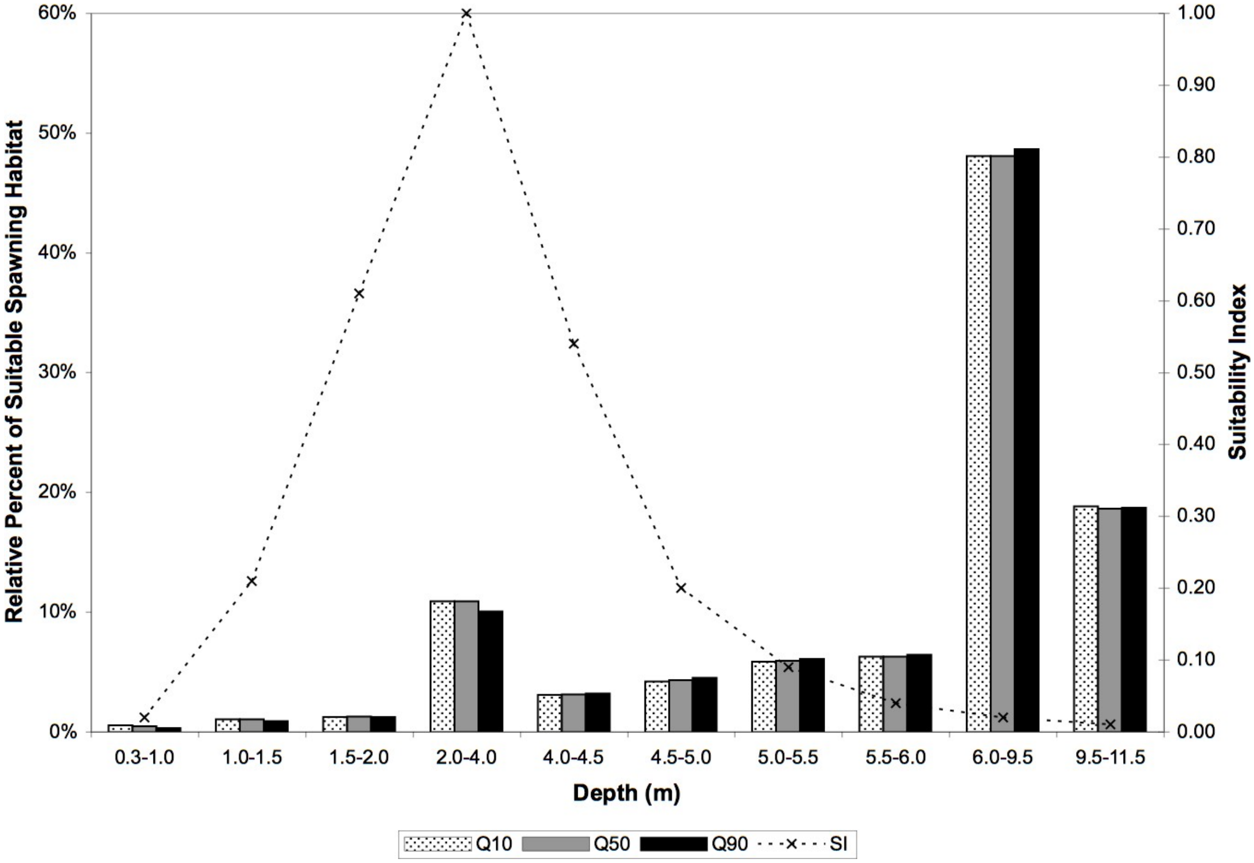

Figure B.23. Depth within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Lower Granite Dam, with the Little Goose Dam Forebay at Minimum Pool Elevation, During a Wet Water Year. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

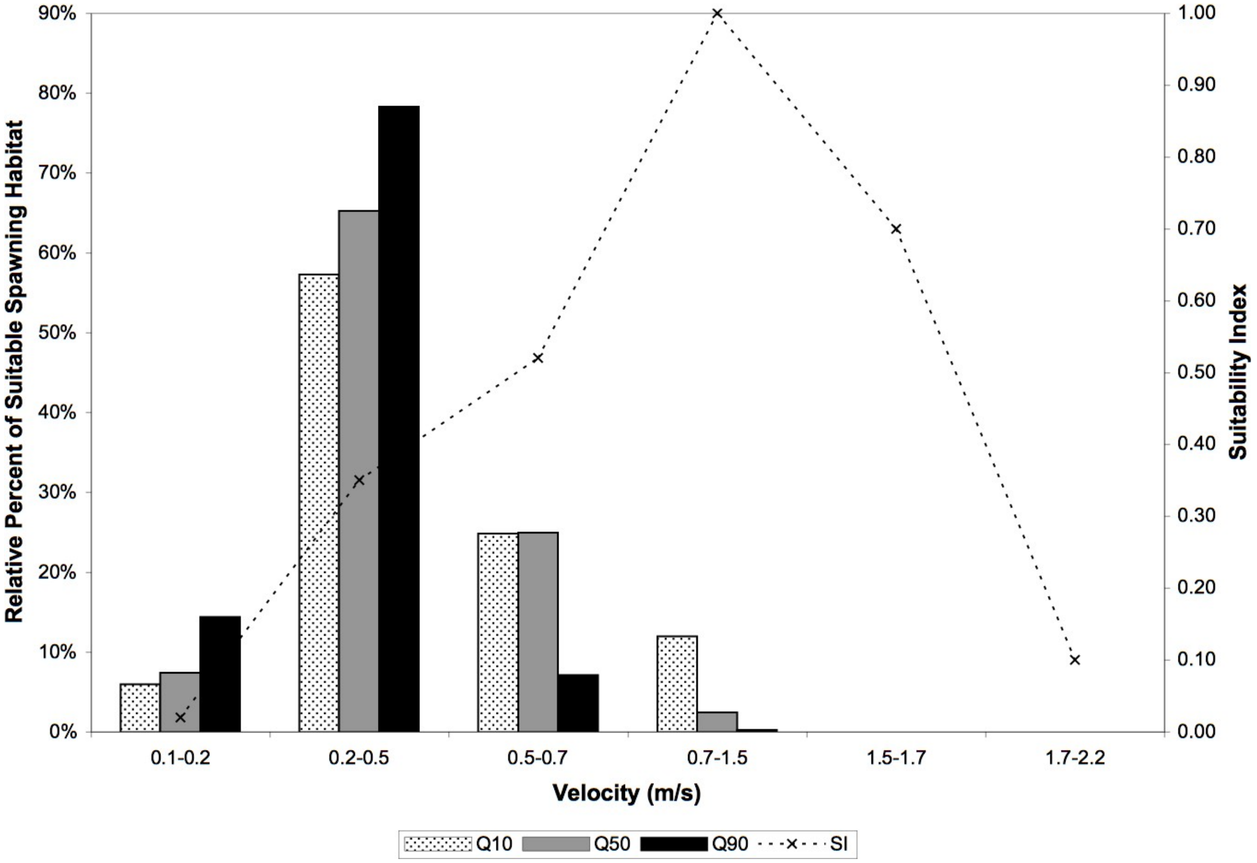

Figure B.24. Velocity within Suitable Fall Chinook Salmon Spawning Habitat Downstream from Lower Granite Dam, with the Little Goose Dam Forebay at Minimum Pool Elevation, During a Wet Water Year. Suitability index values indicate a range of potential habitat from unsuitable (0.0) to high quality (1.0).

Appendix C

Maps of Depth and Velocity within Suitable Fall Chinook Salmon Spawning Habitat

Appendix C

Maps of Depth and Velocity within Suitable Fall Chinook Salmon Spawning Habitat

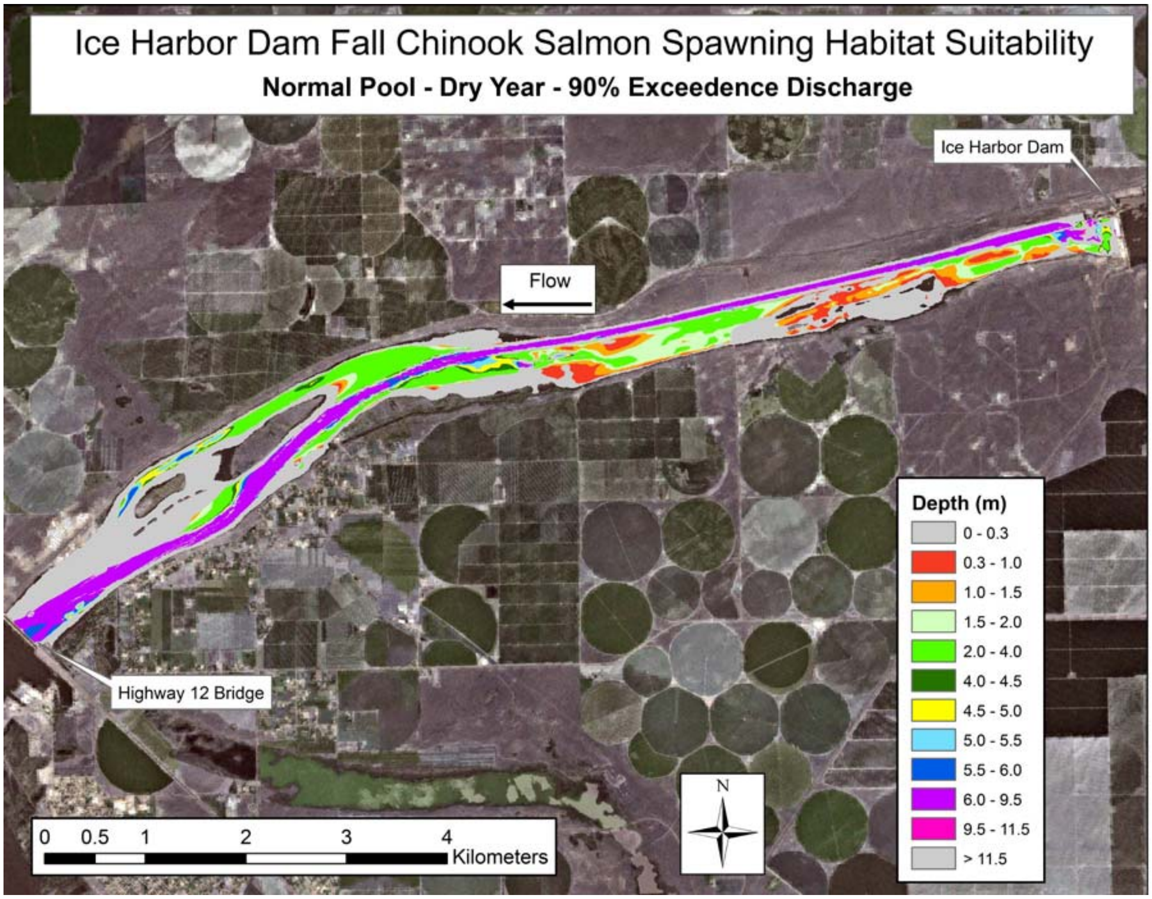

Figure C.1. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 90% Exceedence Discharge (12.6 kcfs) During a Dry Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

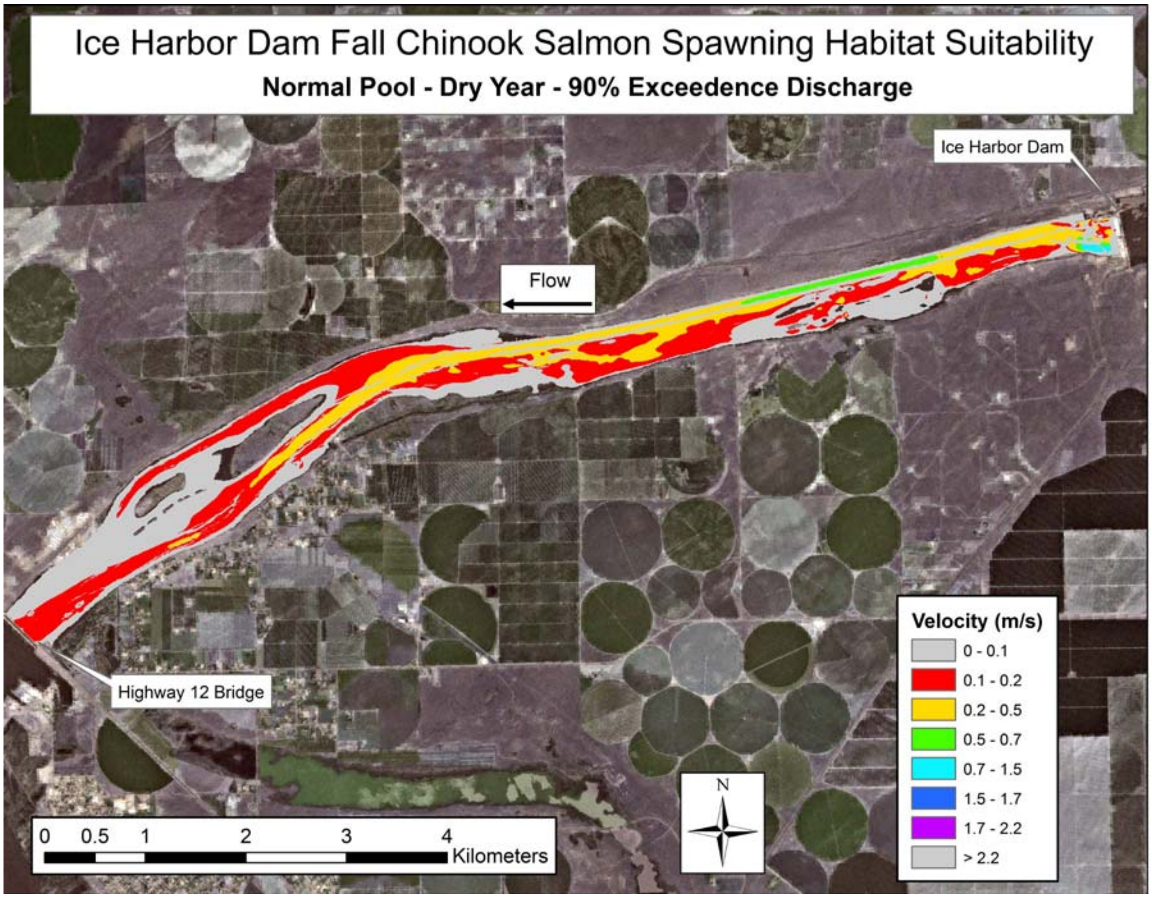

Figure C.2. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 90% Exceedence Discharge (12.6 kcfs) During a Dry Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

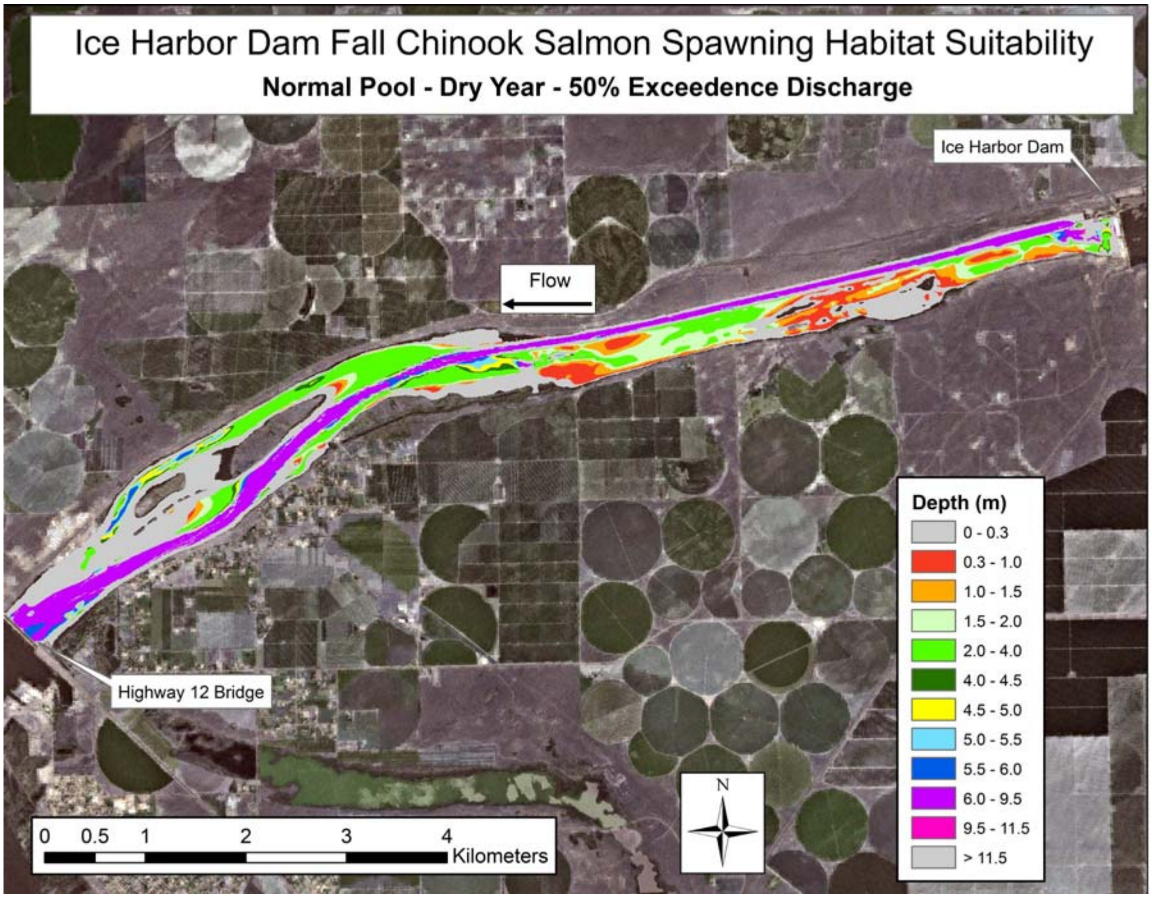

Figure C.3. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 50% Exceedence Discharge (15.3 kcfs) During a Dry Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

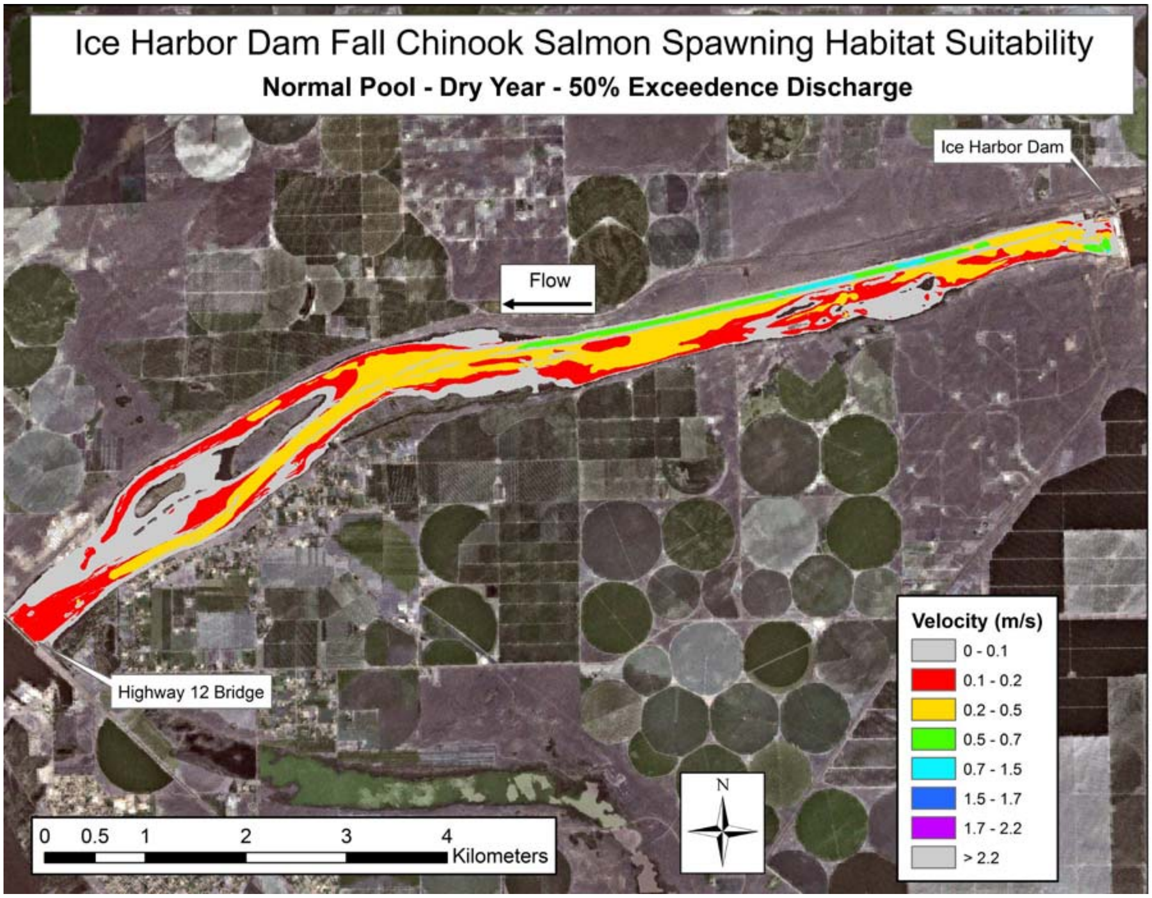

Figure C.4. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 50% Exceedence Discharge (15.3 kcfs) During a Dry Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

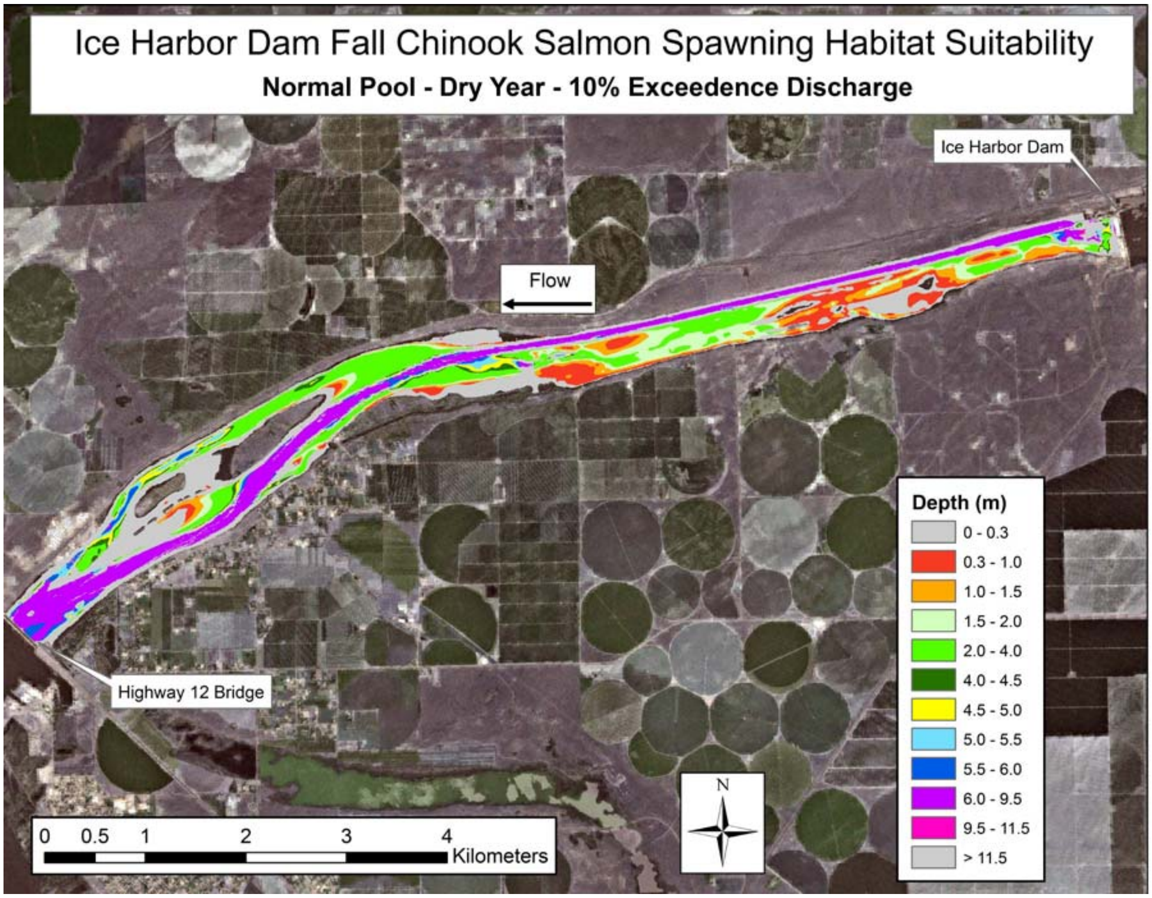

Figure C.5. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 10% Exceedence Discharge (18.2 kcfs) During a Dry Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

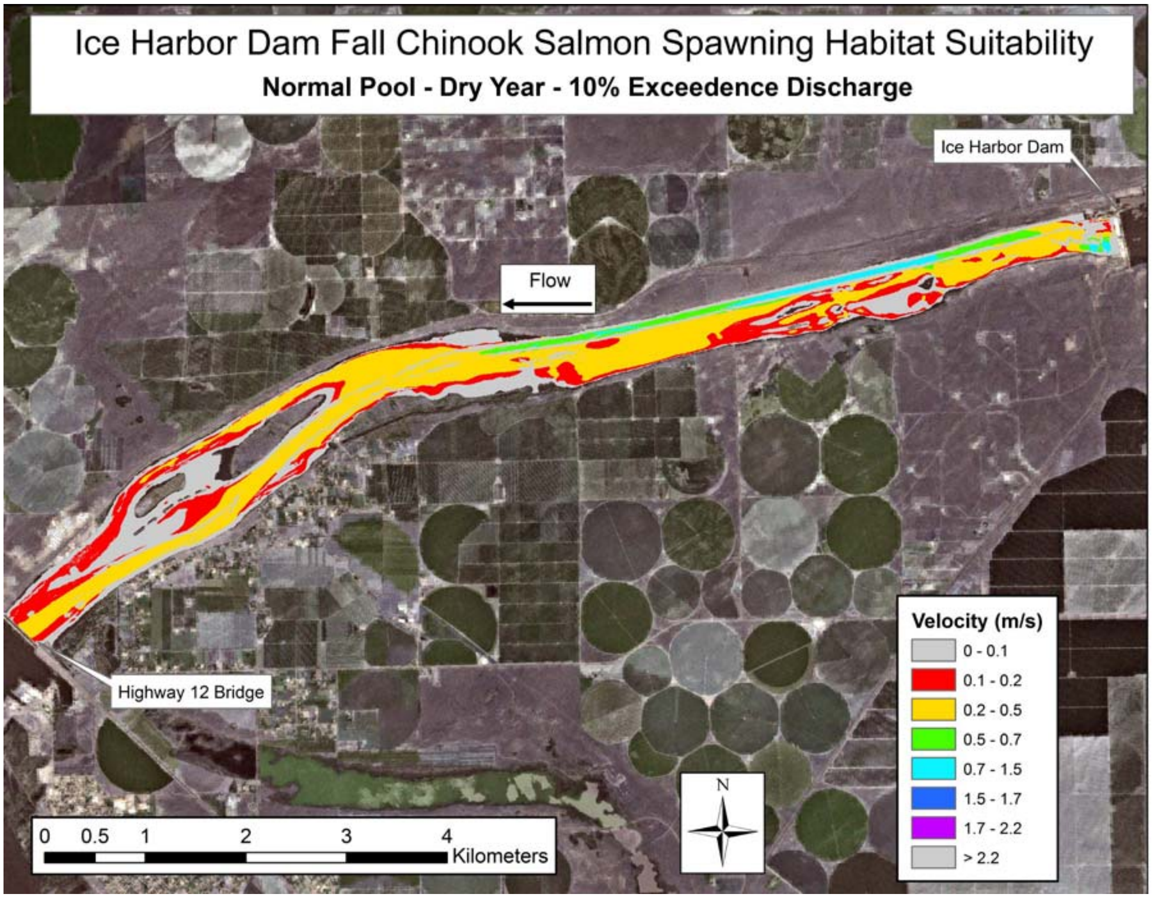

Figure C.6. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 10% Exceedence Discharge (18.2 kcfs) During a Dry Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

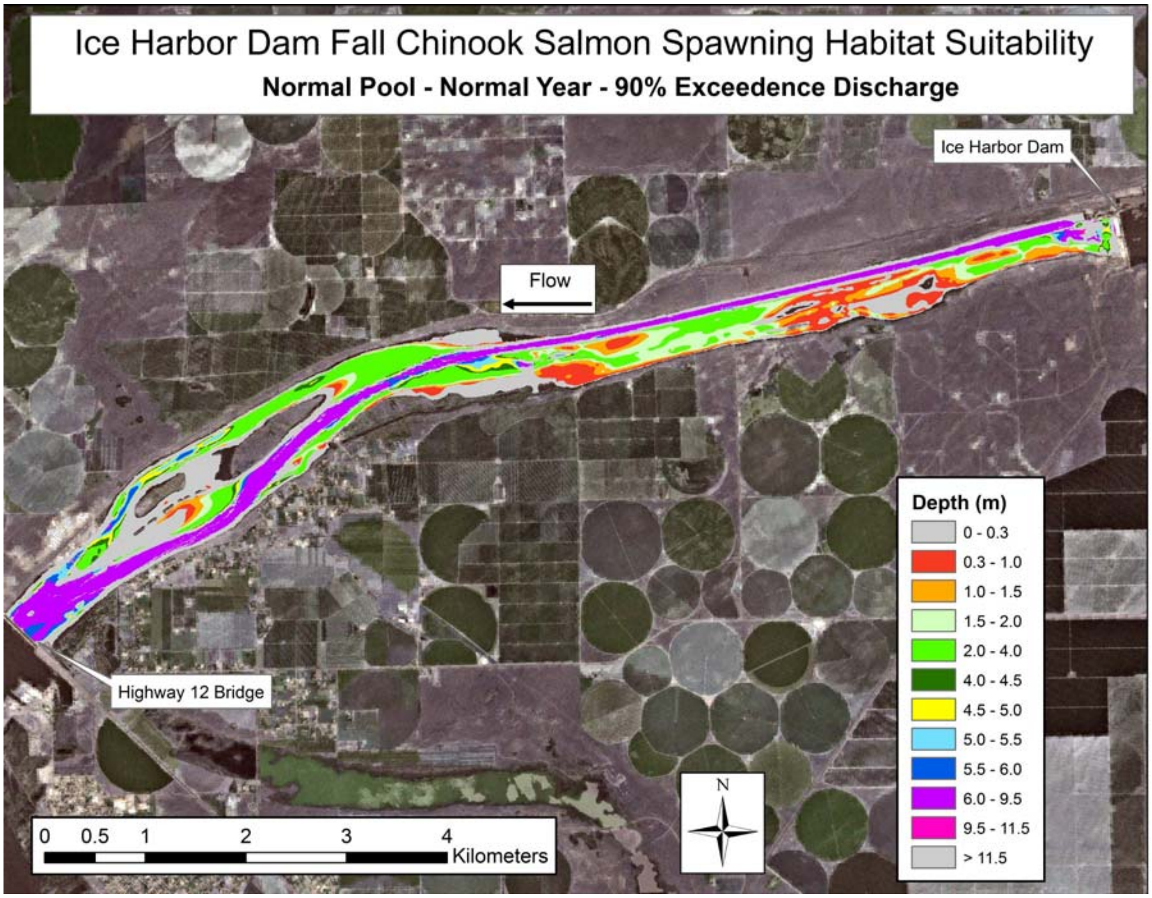

Figure C.7. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 90% Exceedence Discharge (19.1 kcfs) During a Normal Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

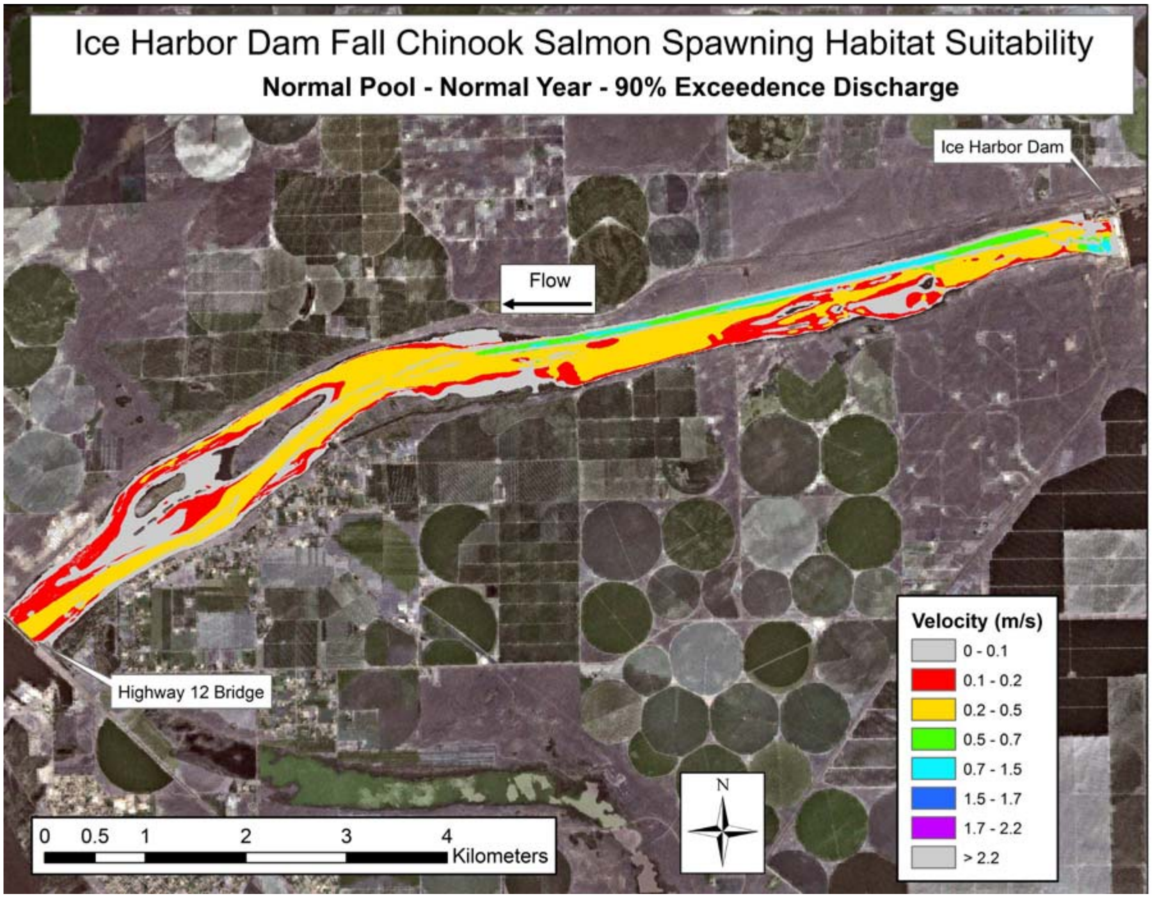

Figure C.8. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 90% Exceedence Discharge (19.1 kcfs) During a Normal Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

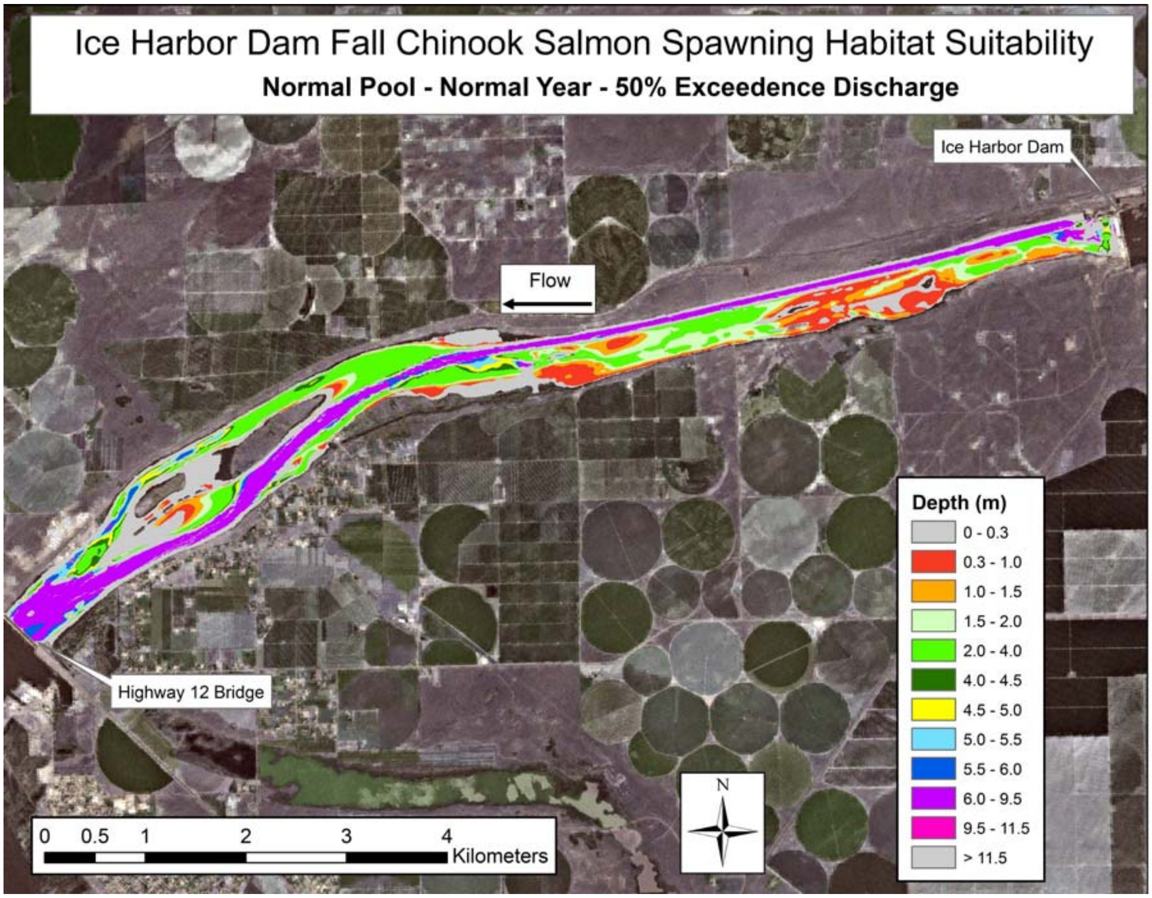

Figure C.9. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 50% Exceedence Discharge (21.7 kcfs) During a Normal Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

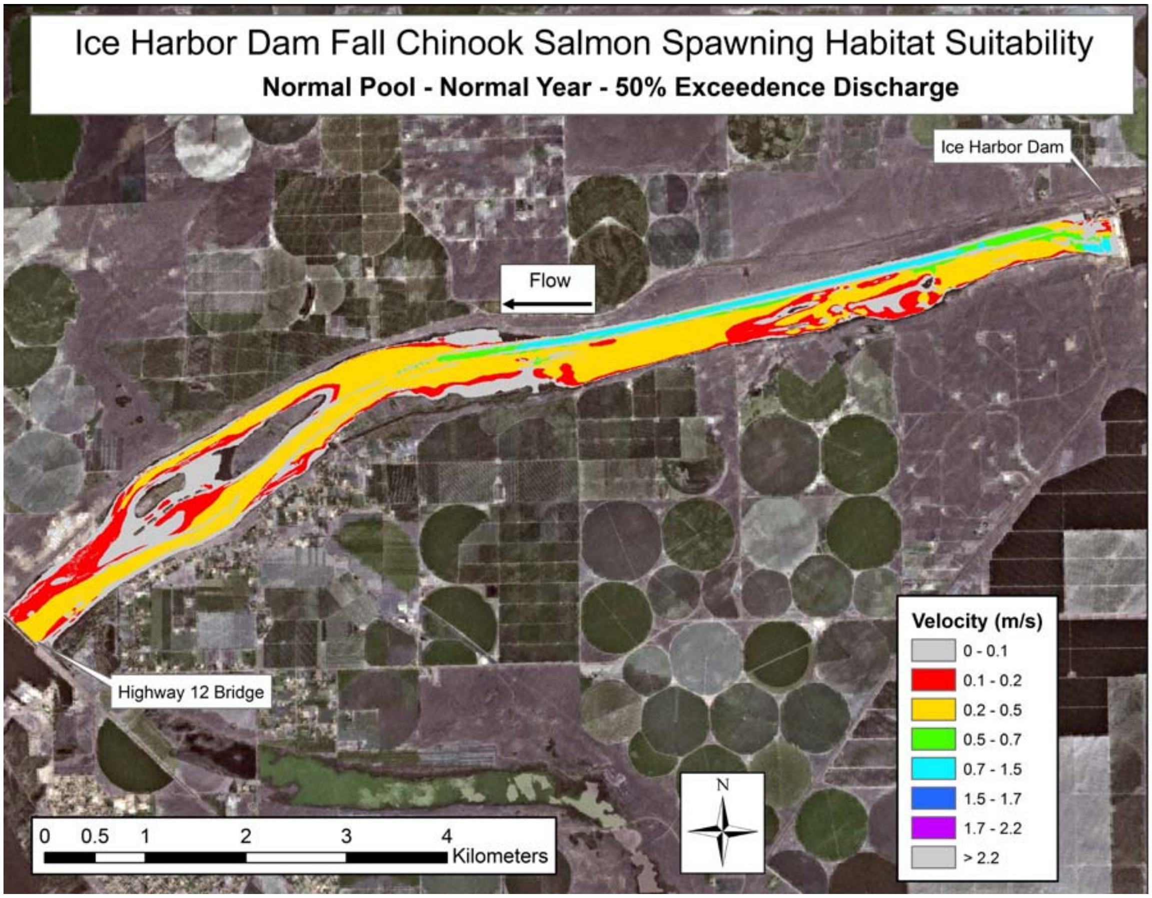

Figure C.10. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 50% Exceedence Discharge (21.7 kcfs) During a Normal Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

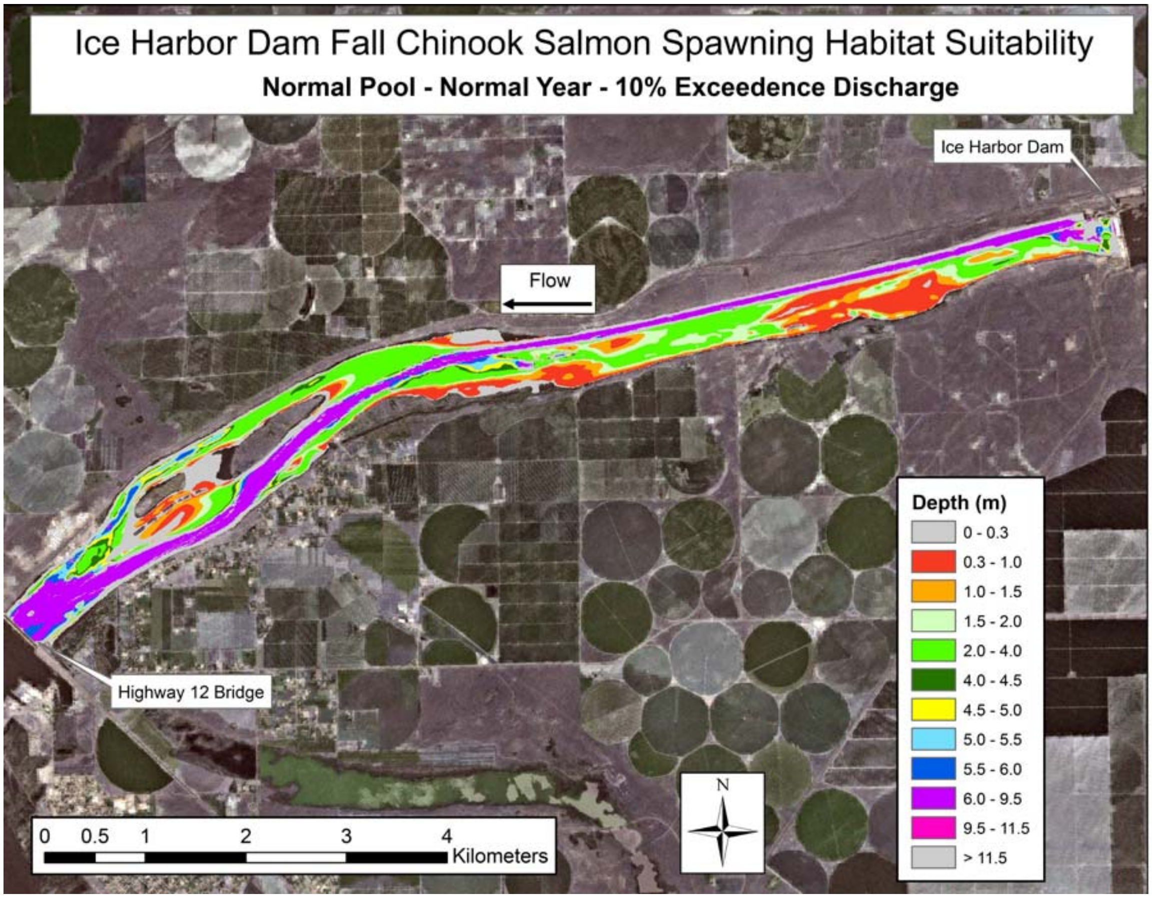

Figure C.11. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 10% Exceedence Discharge (34.5 kcfs) During a Normal Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

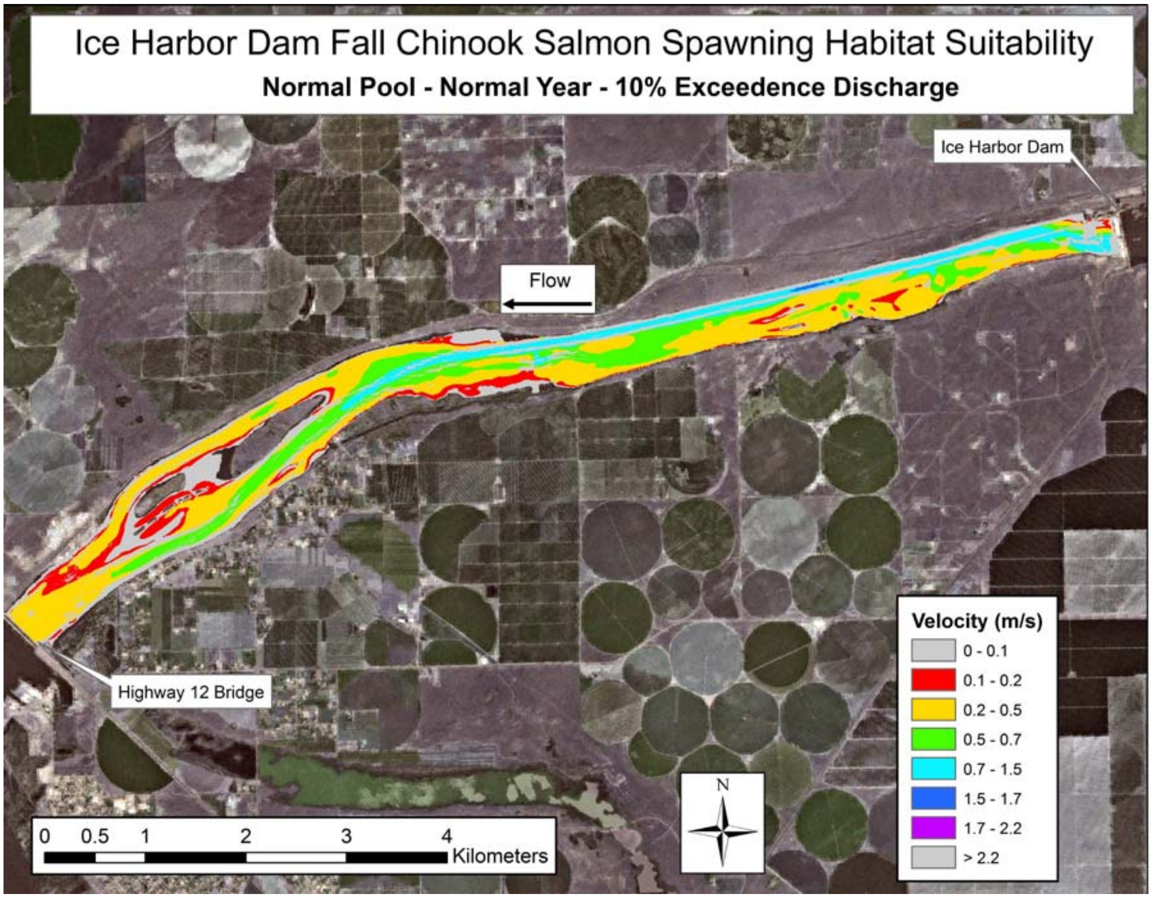

Figure C.12. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 10% Exceedence Discharge (34.5 kcfs) During a Normal Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

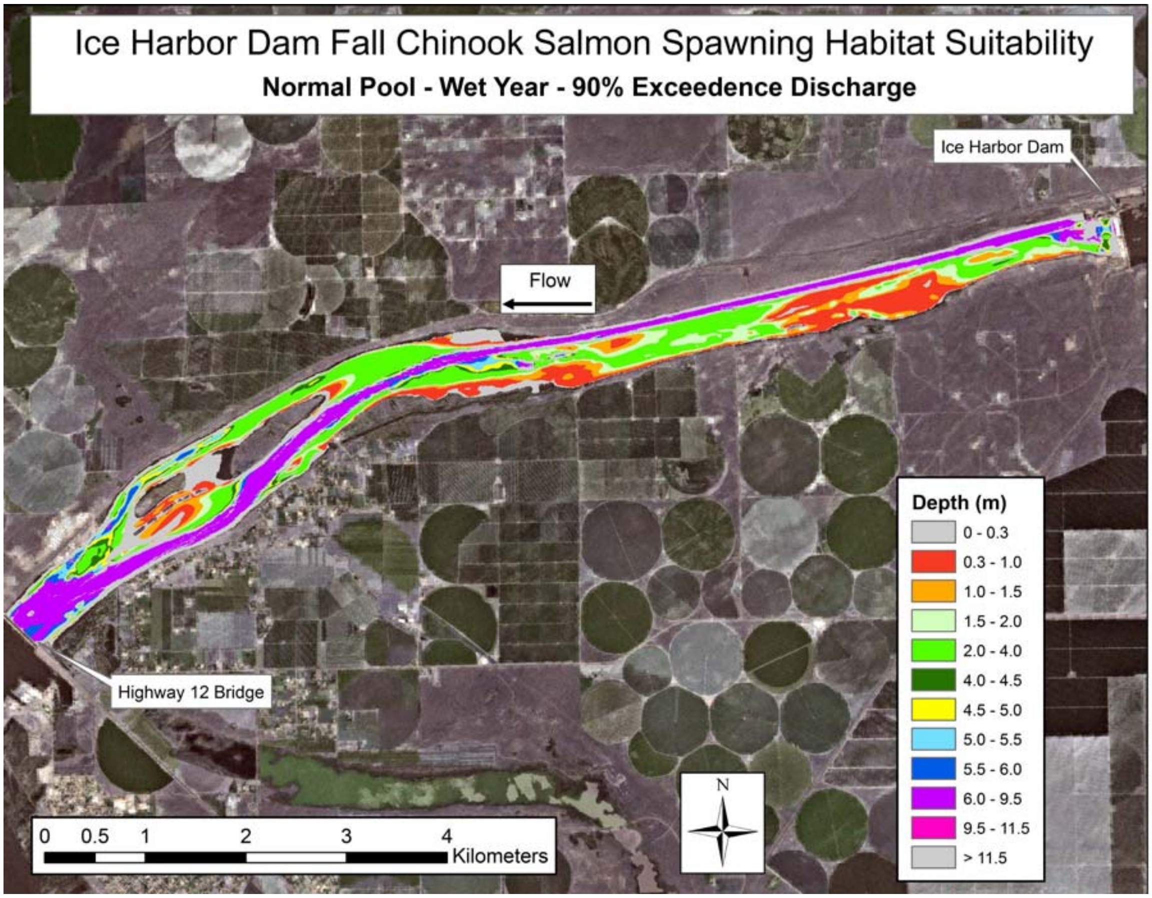

Figure C.13. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 90% Exceedence Discharge (34.5 kcfs) During a Wet Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

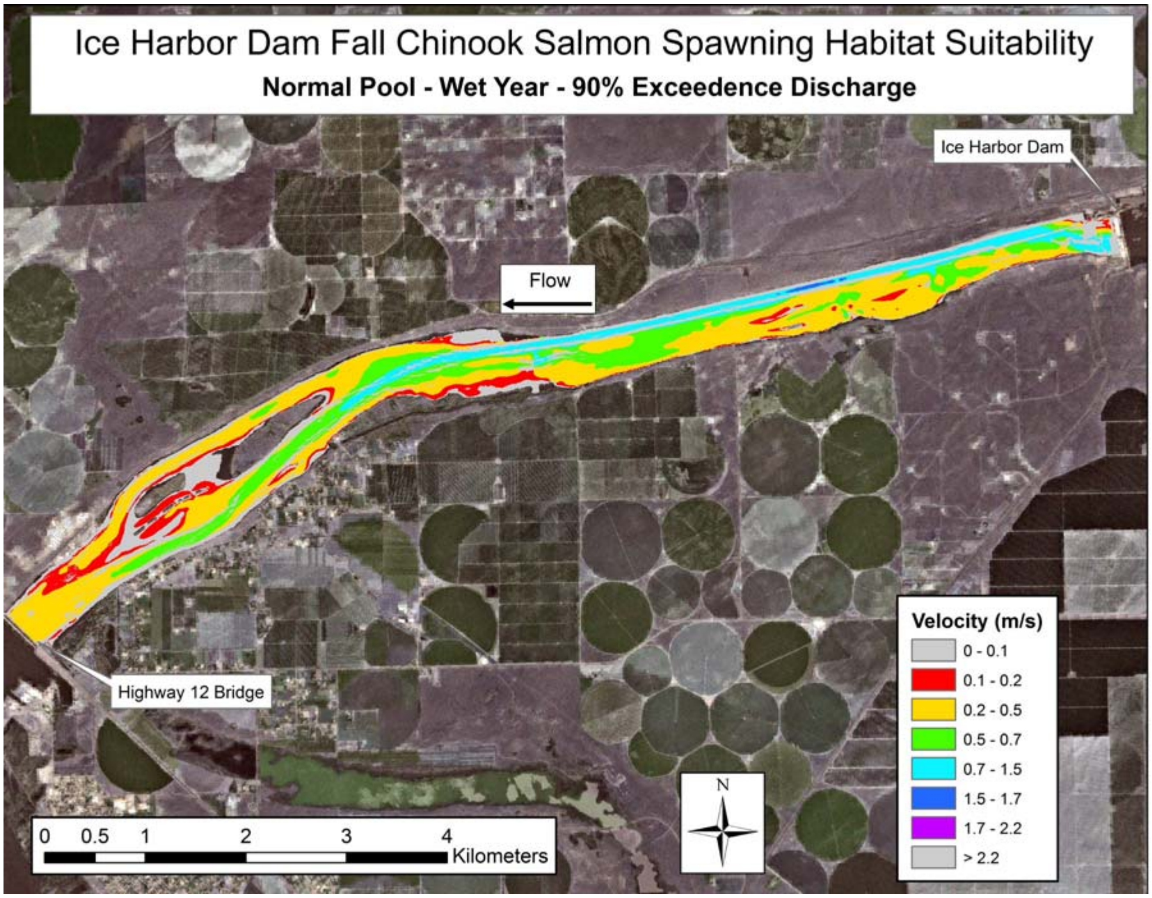

Figure C.14. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 90% Exceedence Discharge (34.5 kcfs) During a Wet Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

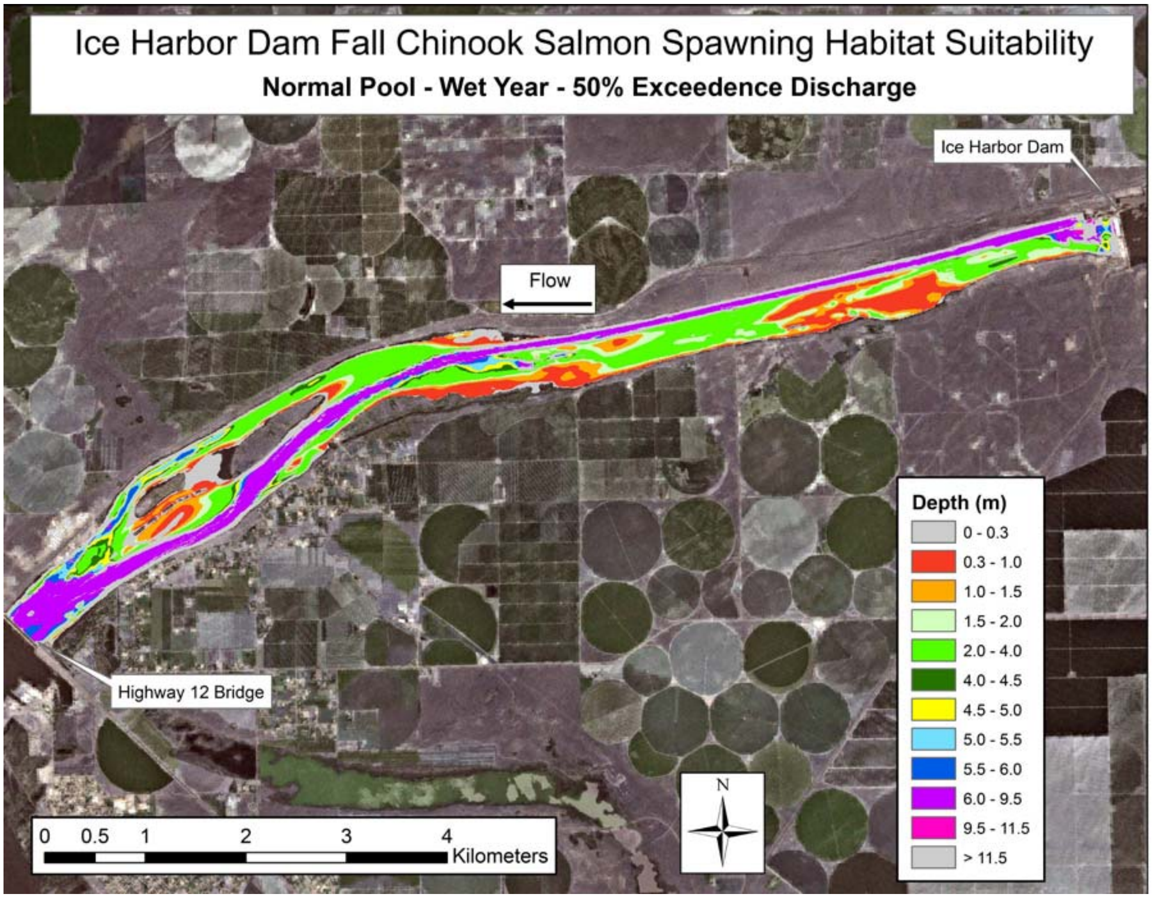

Figure C.15. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 50% Exceedence Discharge (44.0 kcfs) During a Wet Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

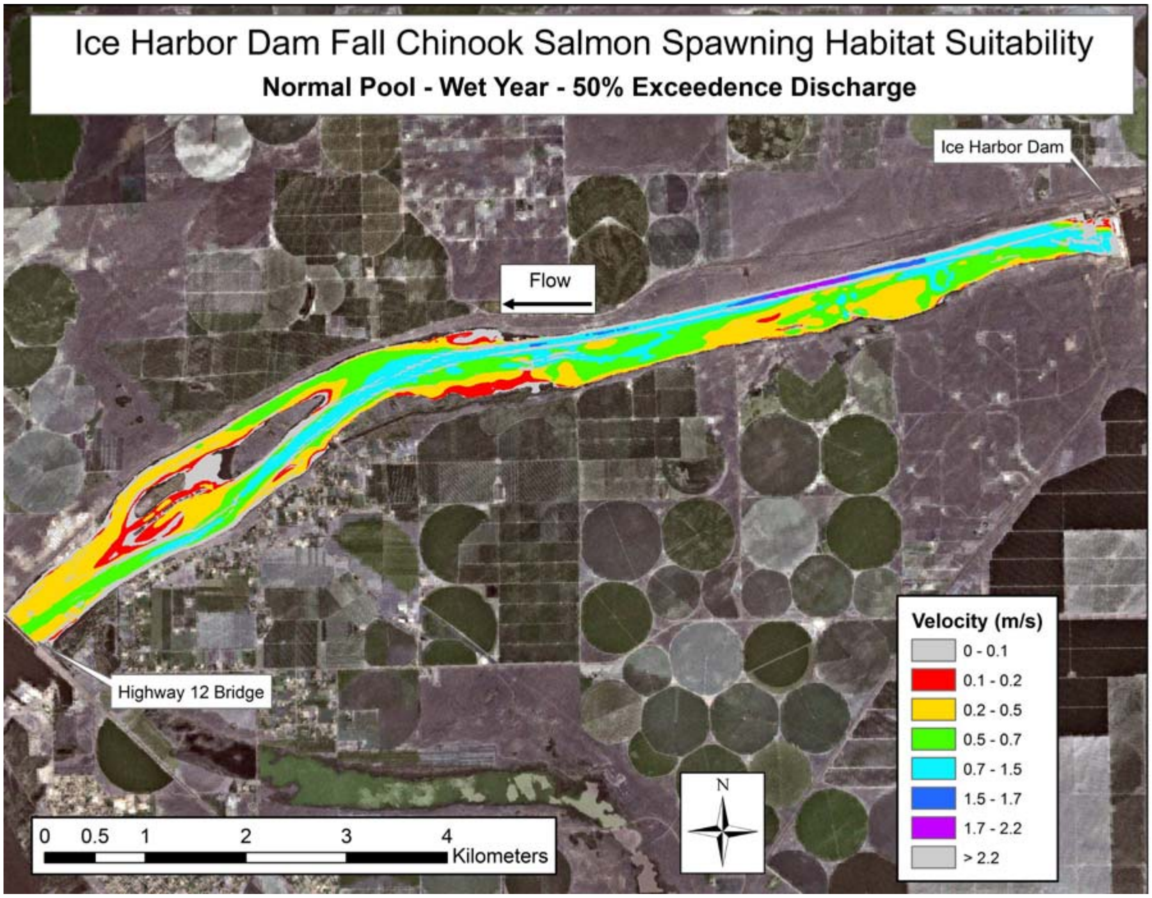

Figure C.16. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 50% Exceedence Discharge (44.0 kcfs) During a Wet Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

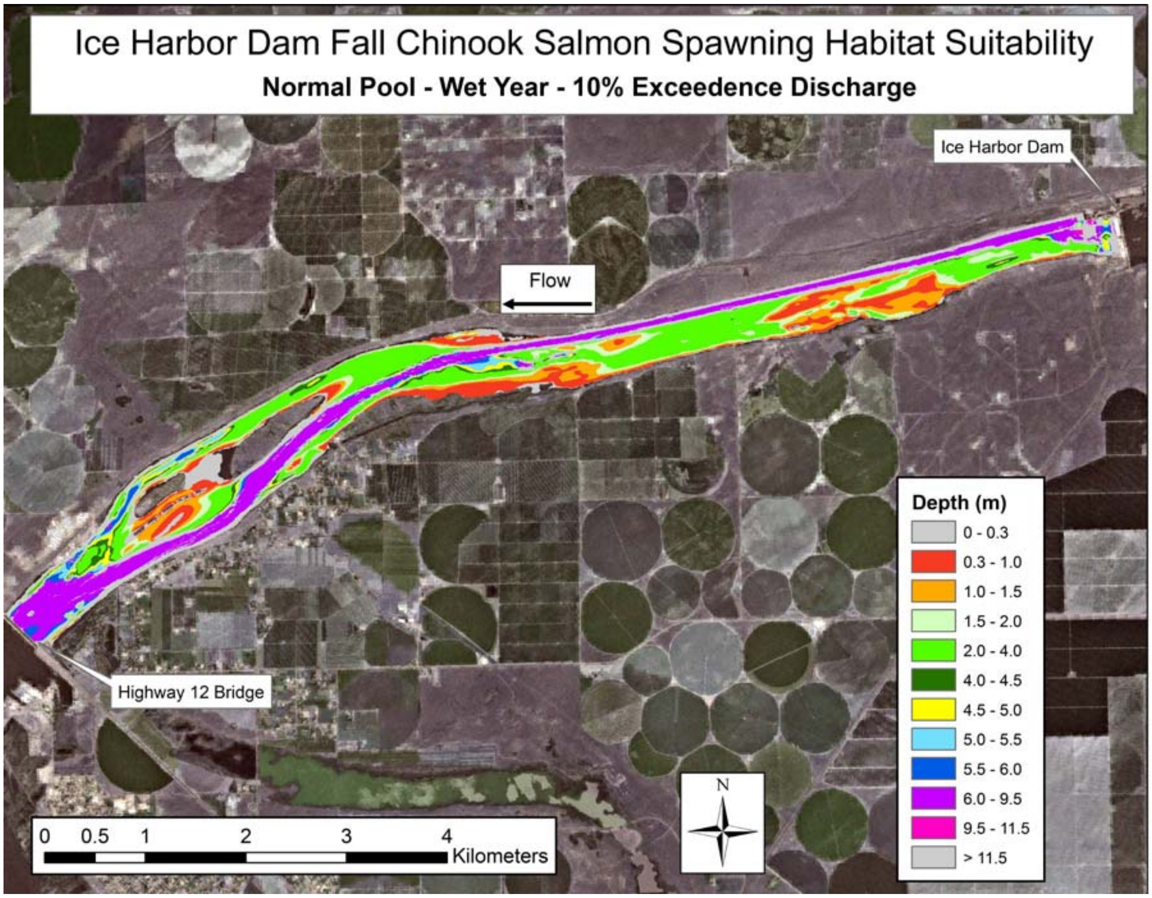

Figure C.17. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 10% Exceedence Discharge (52.0 kcfs) During a Wet Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

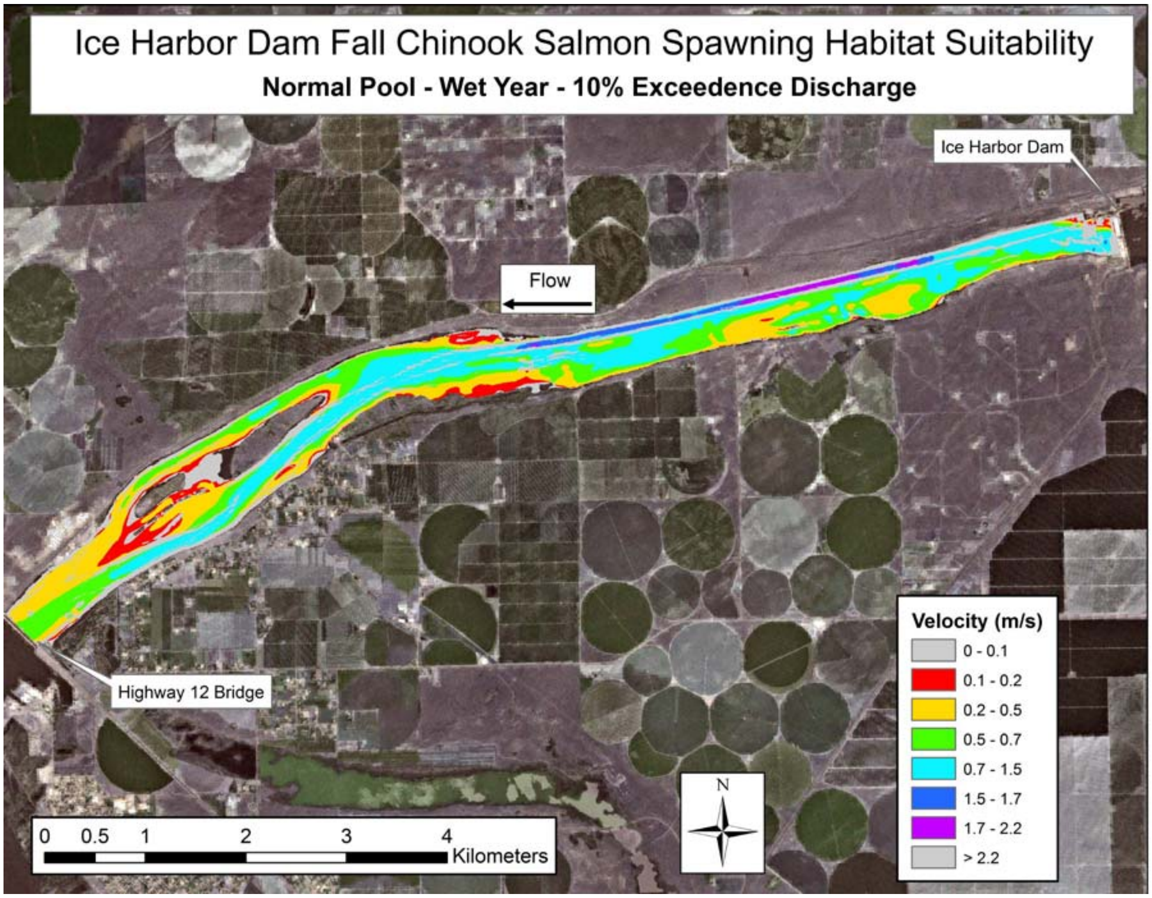

Figure C.18. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 10% Exceedence Discharge (52.0 kcfs) During a Wet Water Year, with the McNary Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

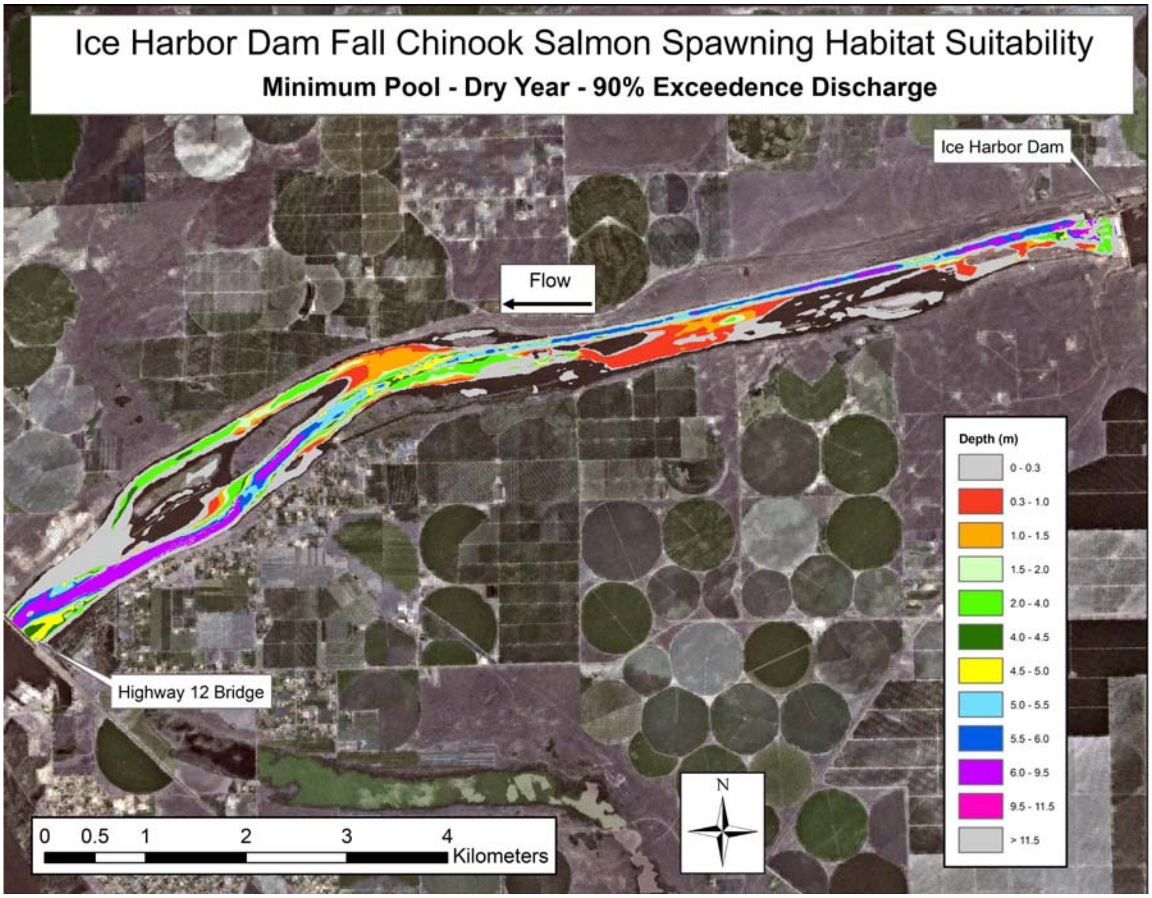

Figure C.19. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 90% Exceedence Discharge (12.6 kcfs) During a Dry Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

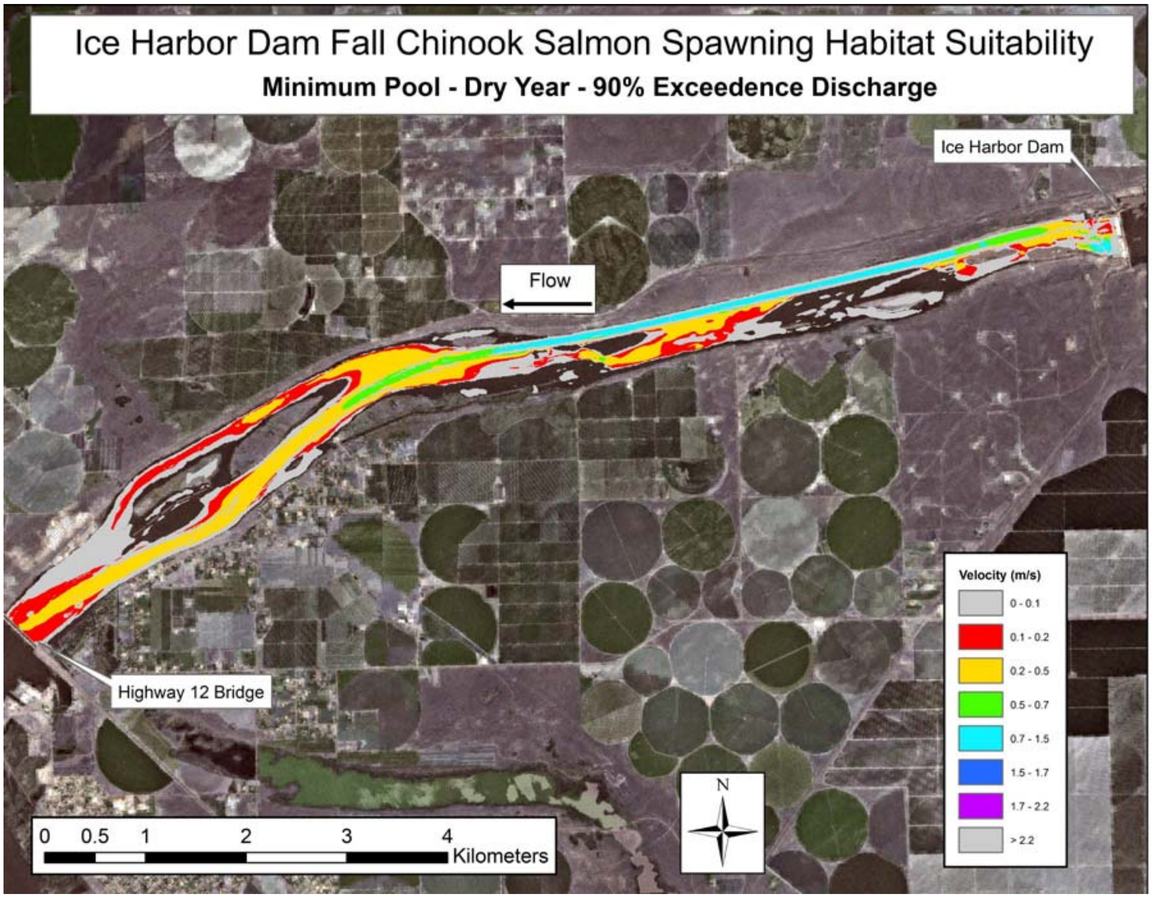

Figure C.20. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 90% Exceedence Discharge (12.6 kcfs) During a Dry Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

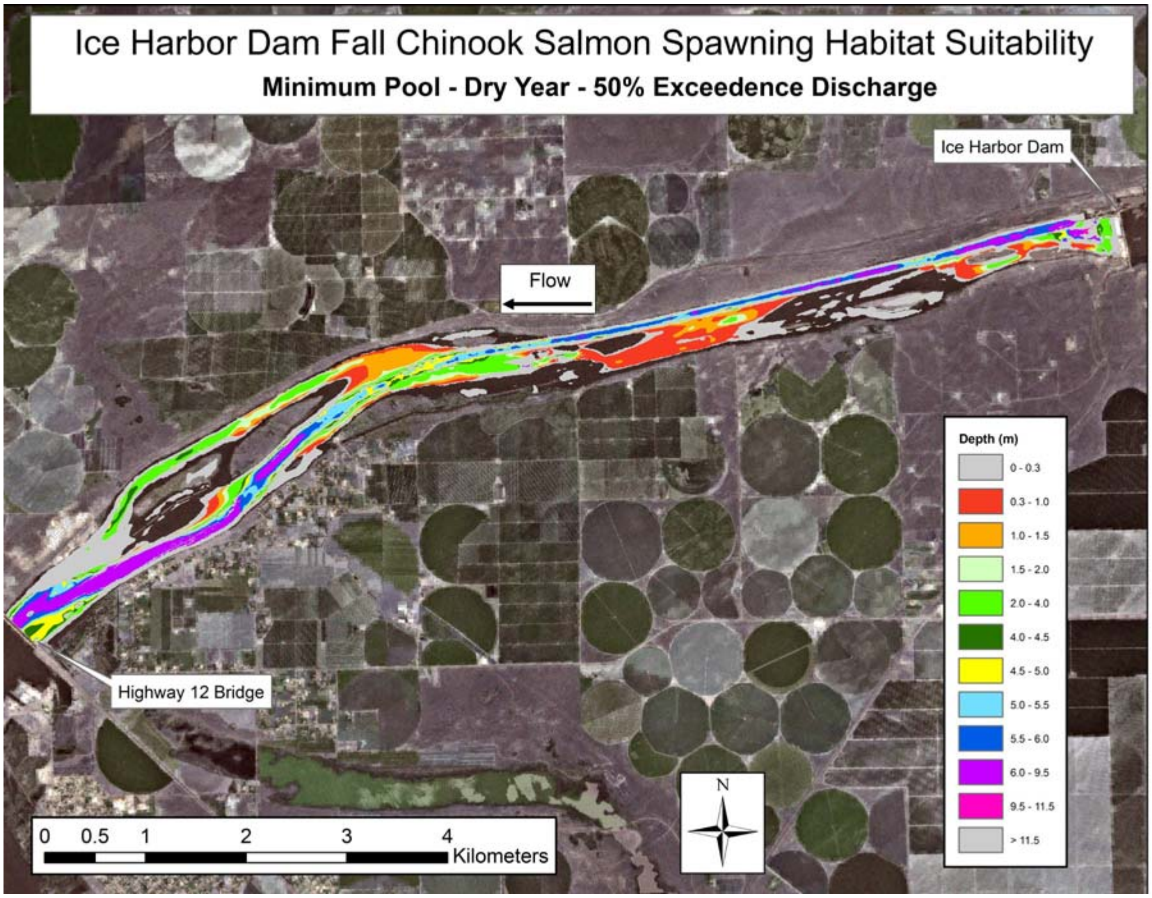

Figure C.21. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 50% Exceedence Discharge (15.3 kcfs) During a Dry Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

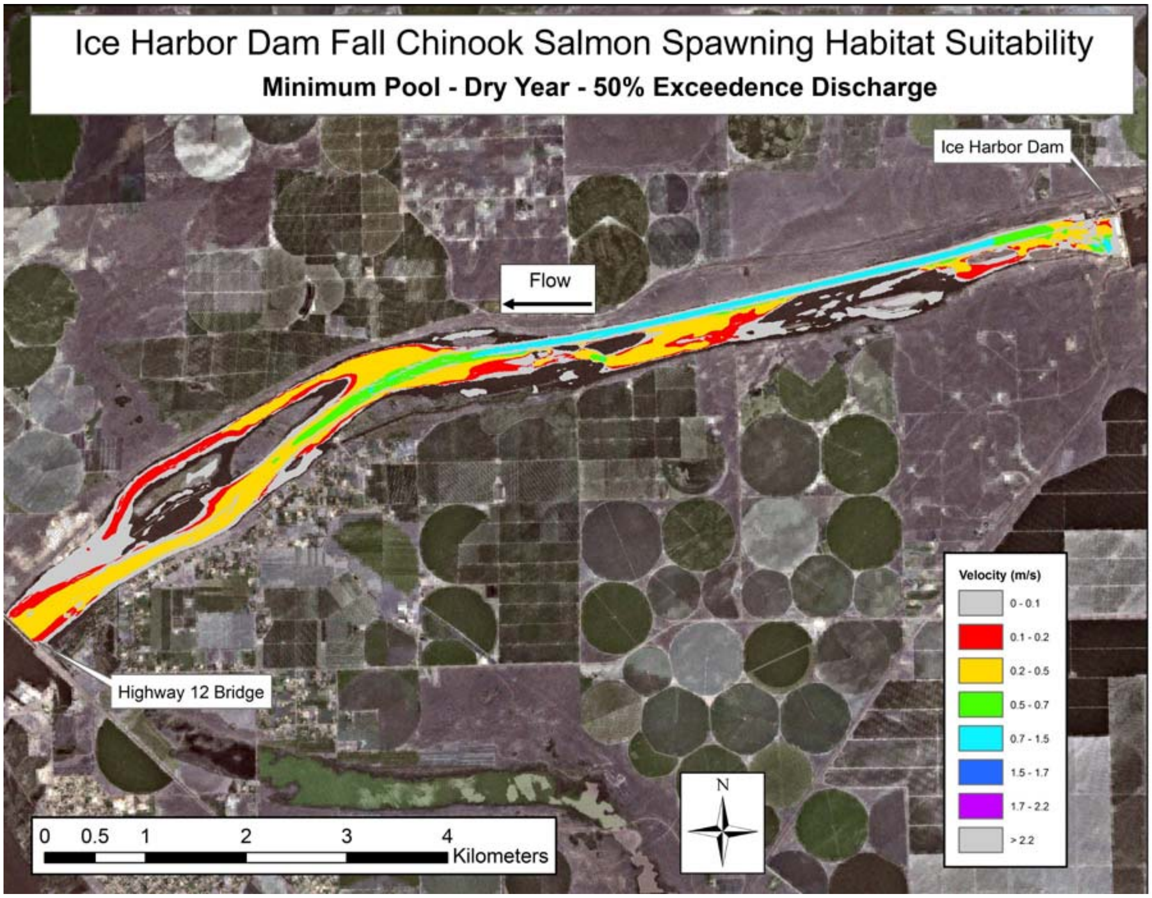

Figure C.22. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 50% Exceedence Discharge (15.3 kcfs) During a Dry Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

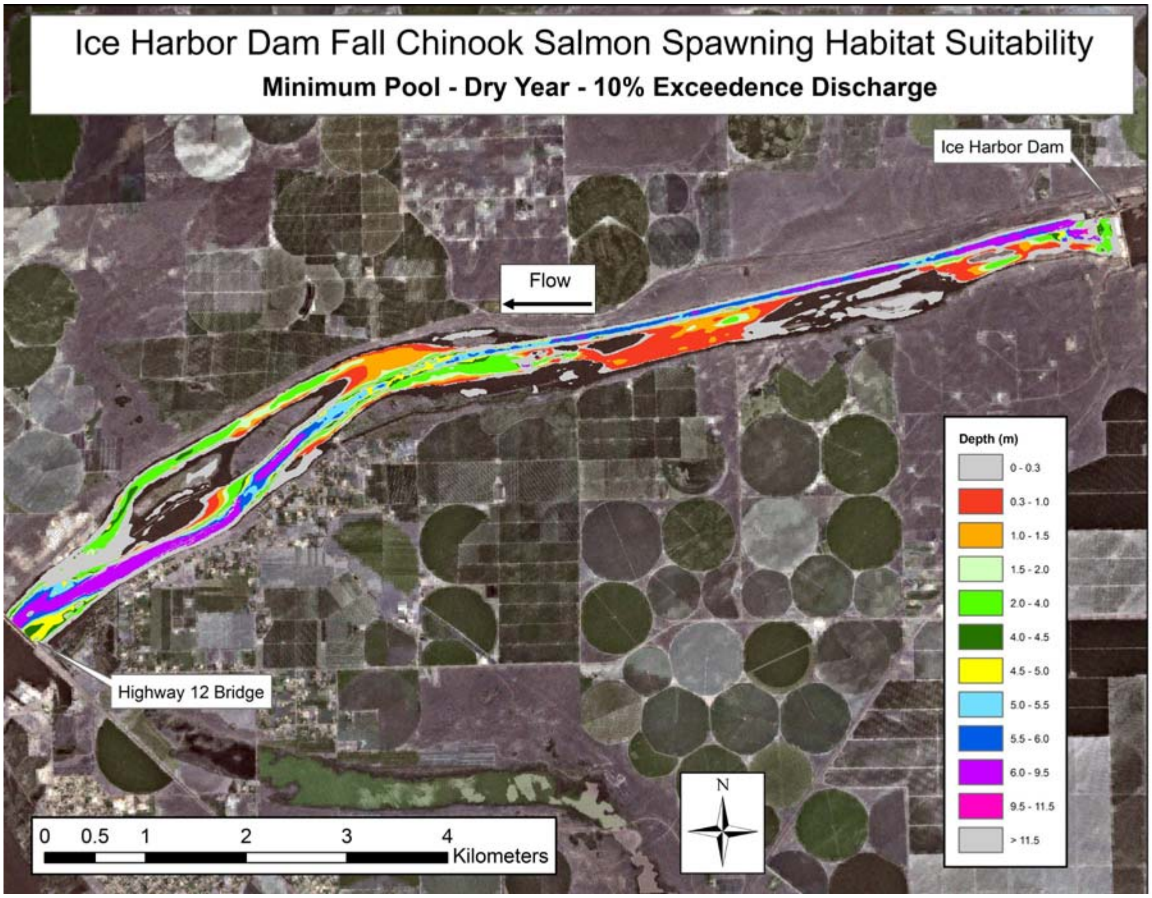

Figure C.23. Depth within fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 10% Exceedence Discharge (18.2 kcfs) During a Dry Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

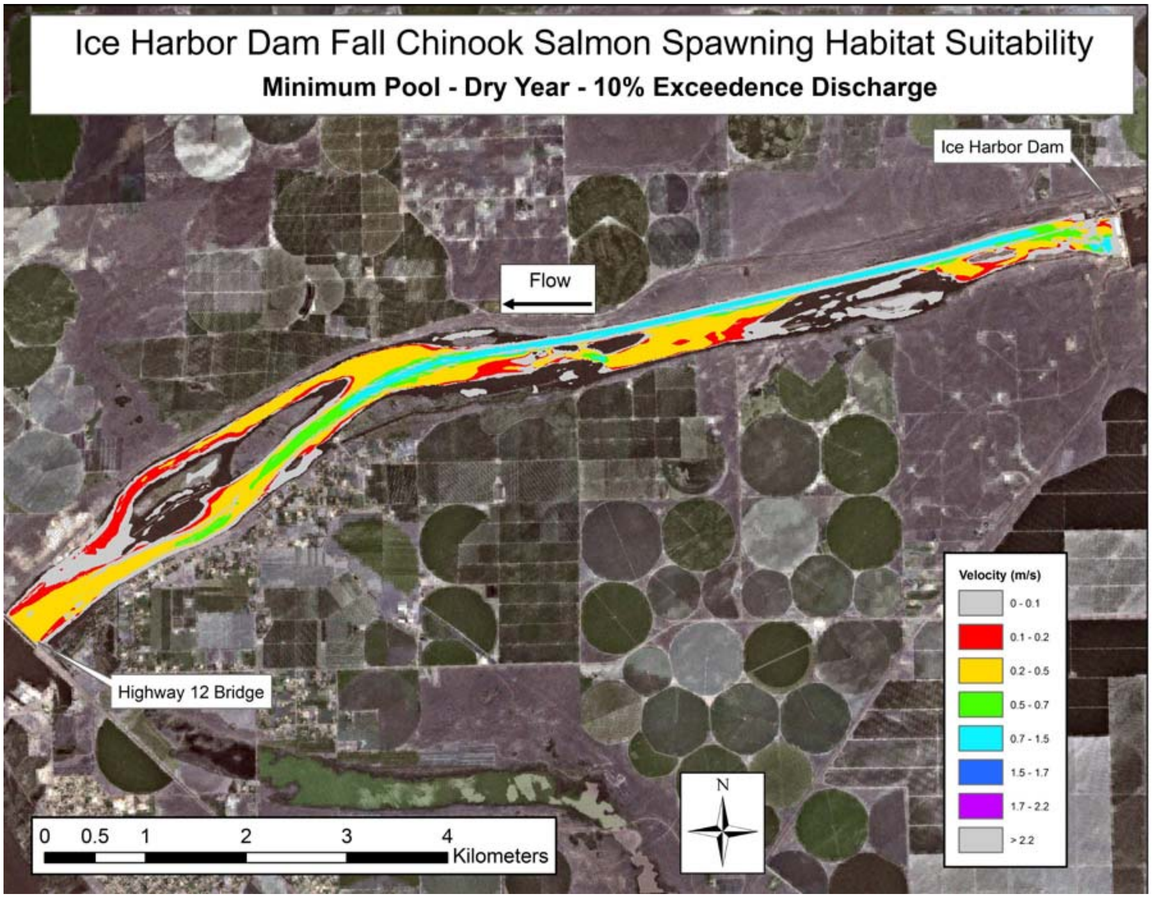

Figure C.24. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 10% Exceedence Discharge (18.2 kcfs) During a Dry Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

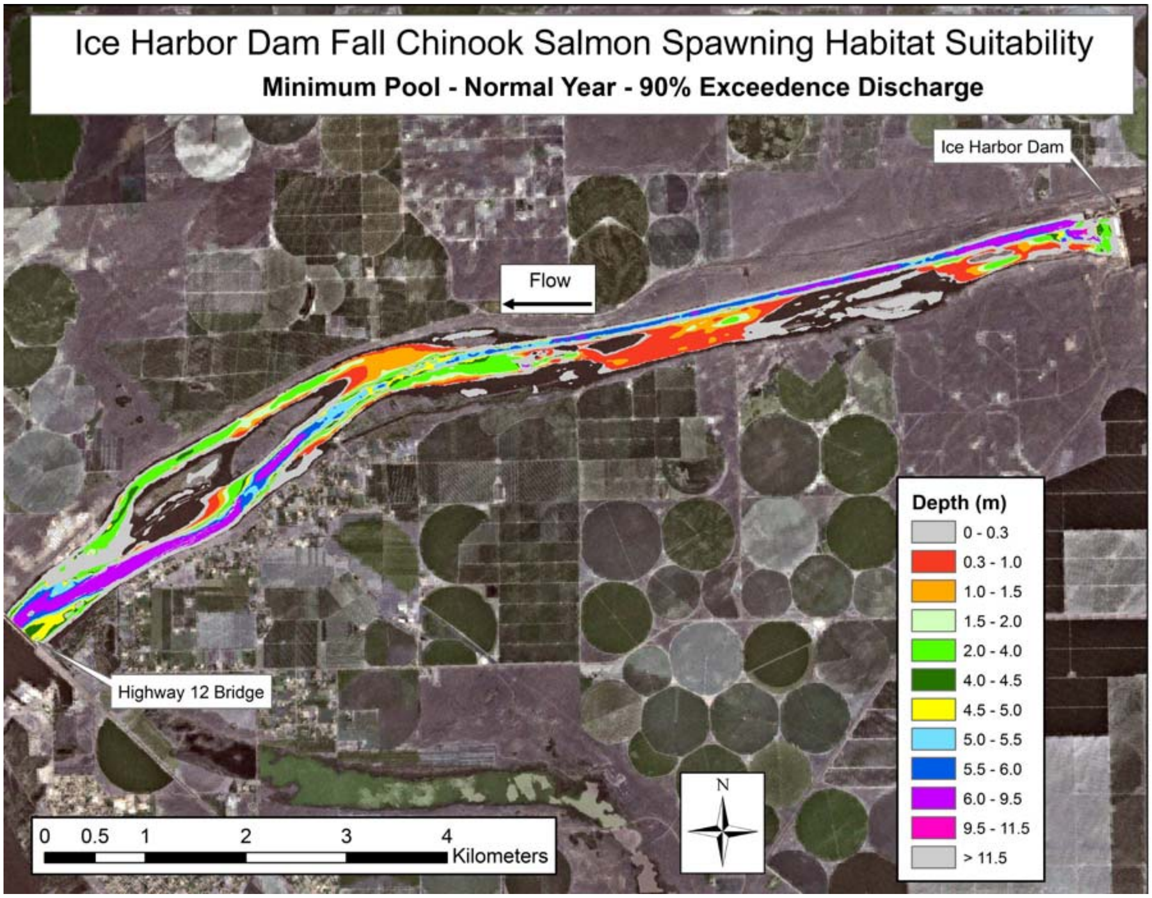

Figure C.25. Depth within fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 90% Exceedence Discharge (19.1 kcfs) During a Normal Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

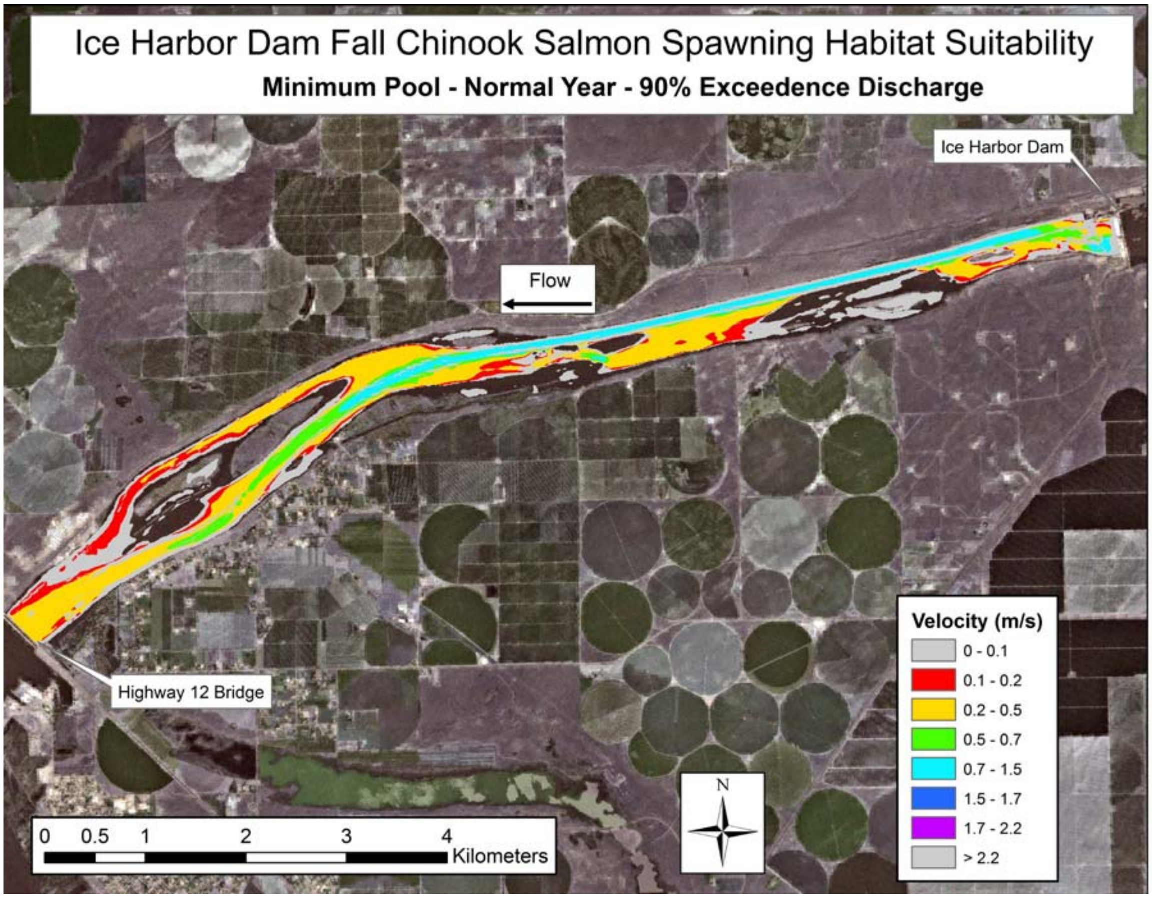

Figure C.26. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 90% Exceedence Discharge (19.1 kcfs) During a Normal Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

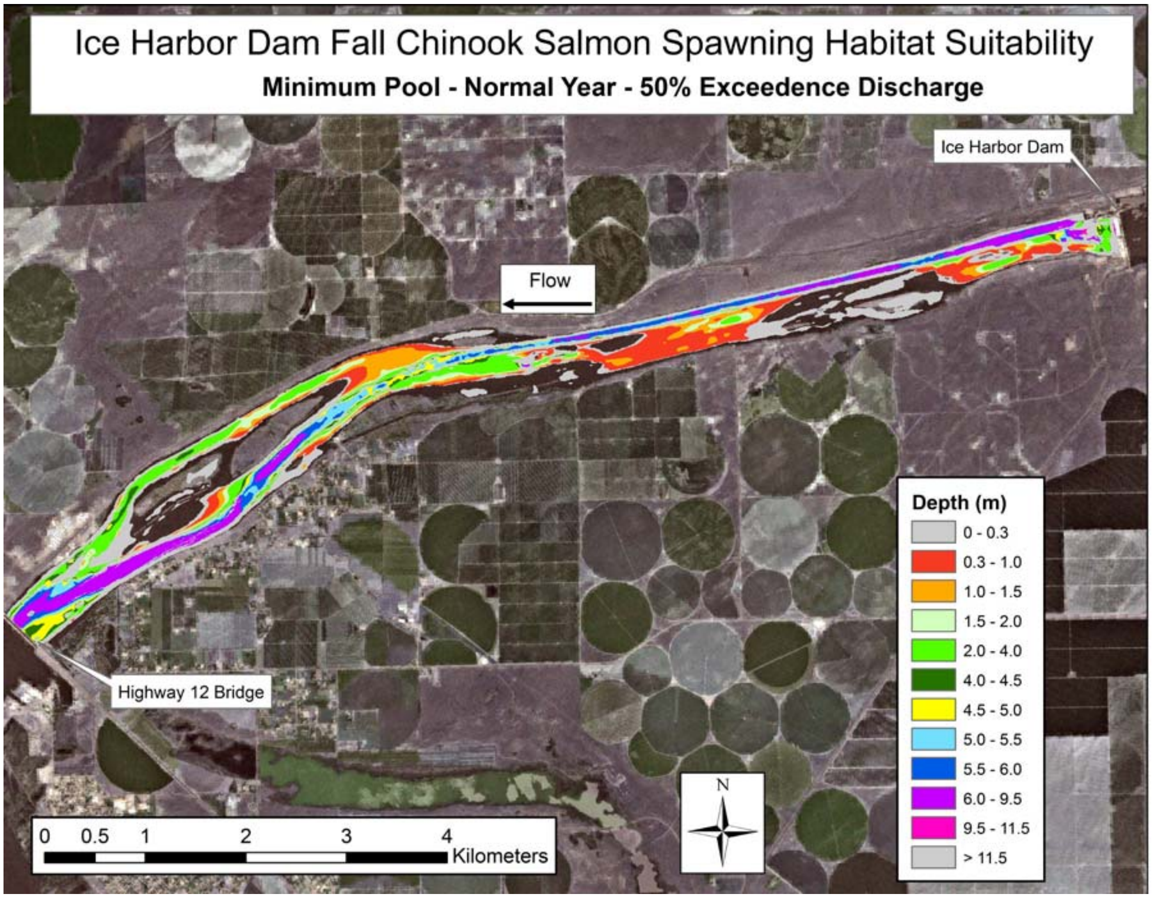

Figure C.27. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 50% Exceedence Discharge (21.7 kcfs) During a Normal Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

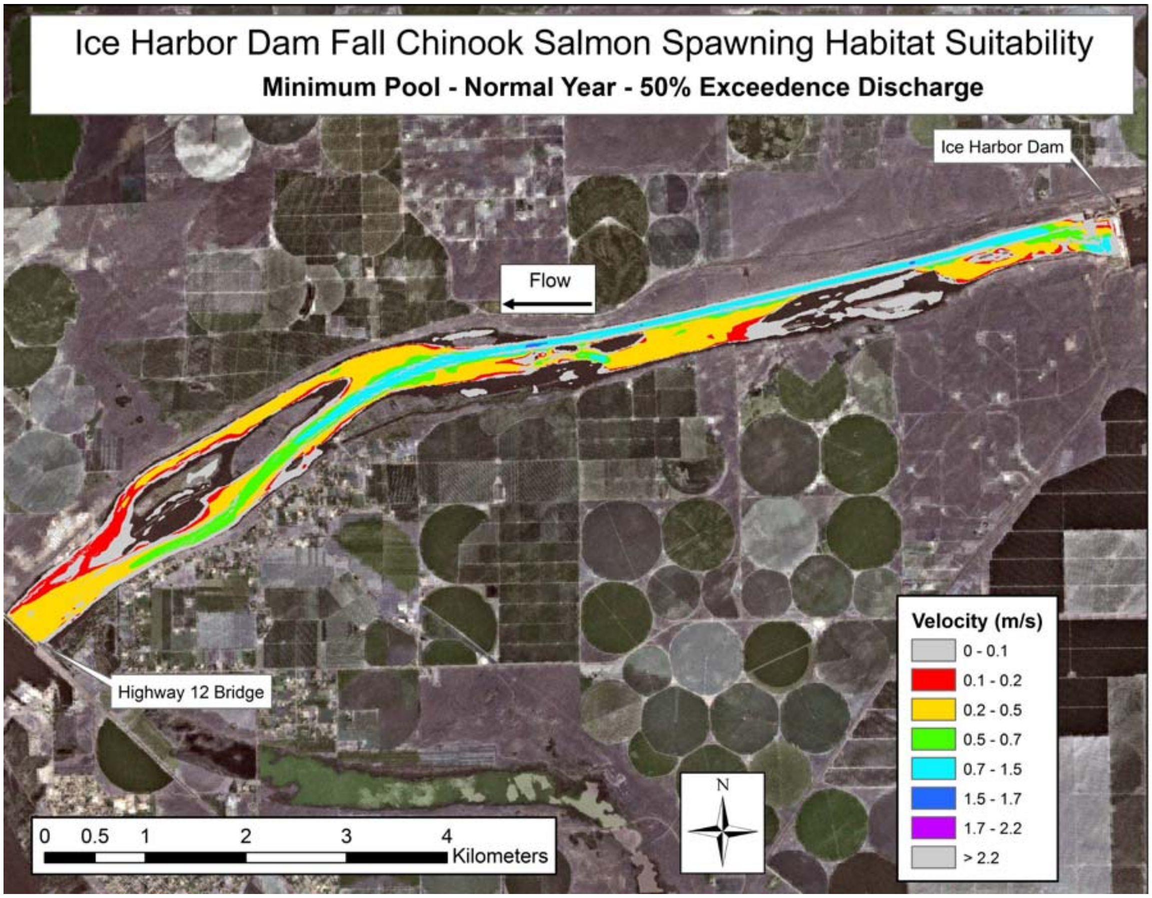

Figure C.28. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 50% Exceedence Discharge (21.7 kcfs) During a Normal Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

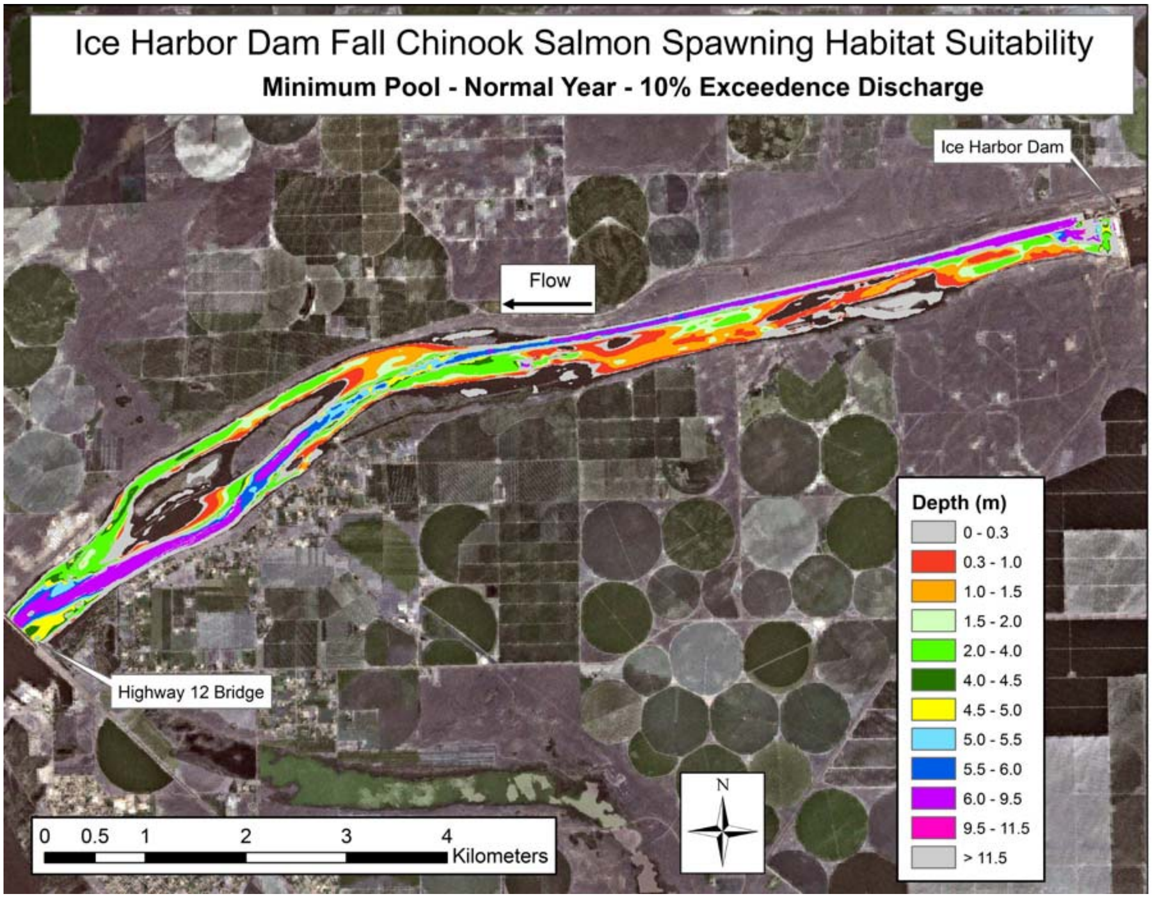

Figure C.29. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 10% Exceedence Discharge (34.5 kcfs) During a Normal Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

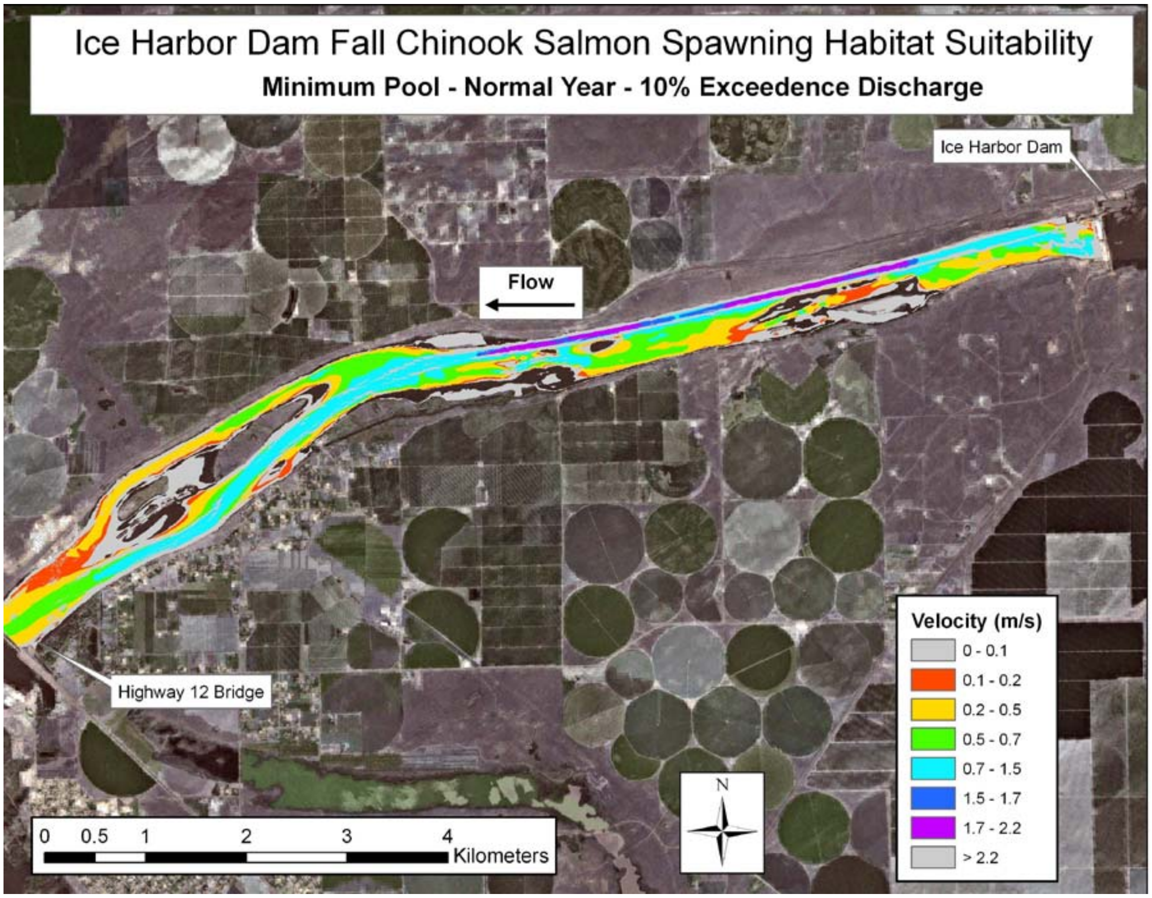

Figure C.30. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 10% Exceedence Discharge (34.5 kcfs) During a Normal Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

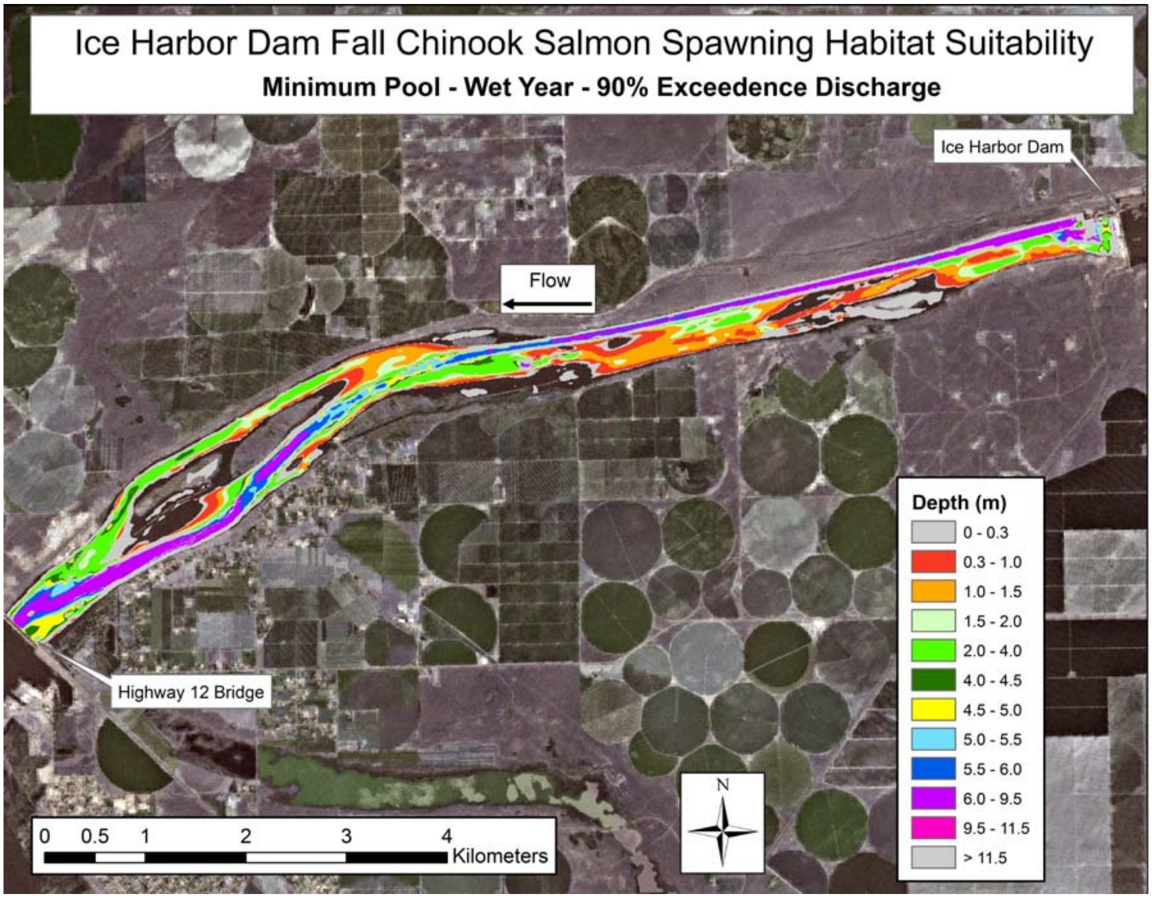

Figure C.31. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 90% Exceedence Discharge (34.5 kcfs) During a Wet Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

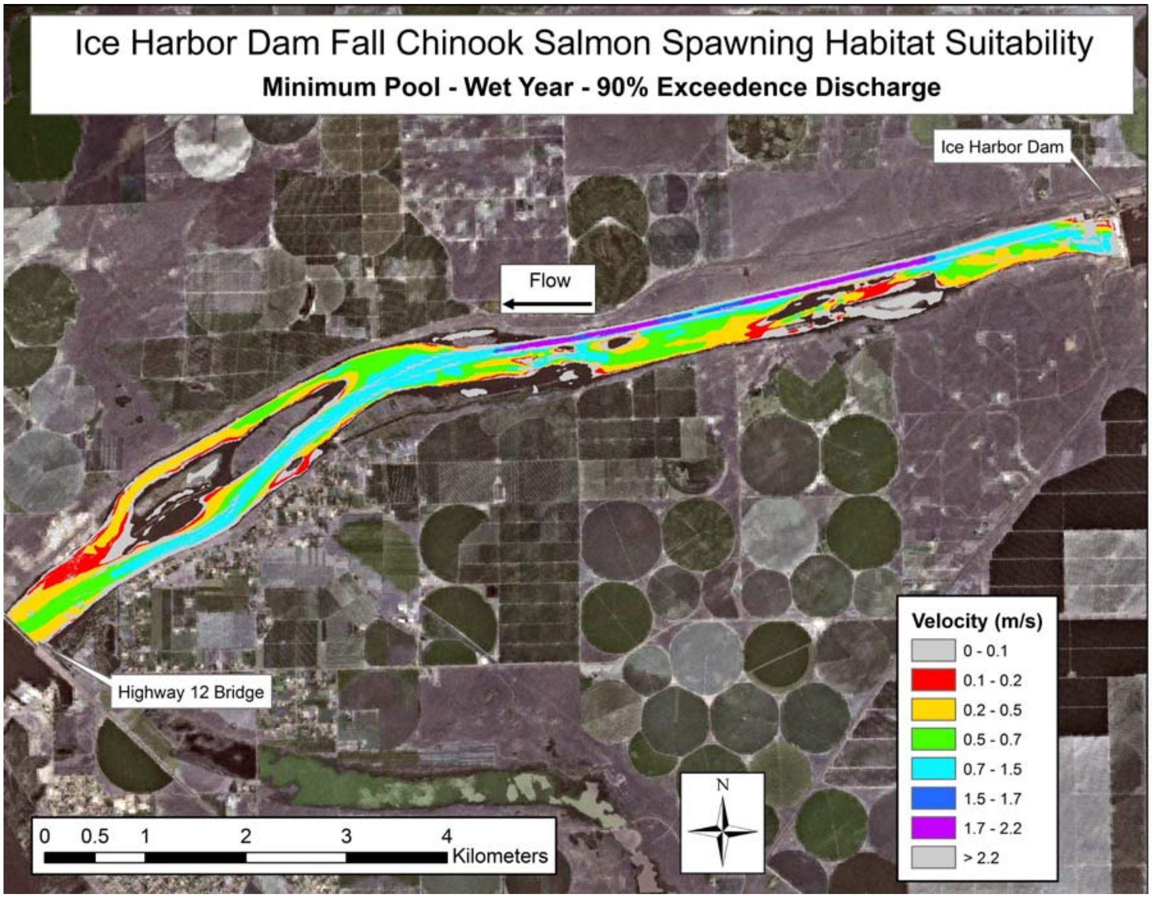

Figure C.32. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 90% Exceedence Discharge (34.5 kcfs) During a Wet Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

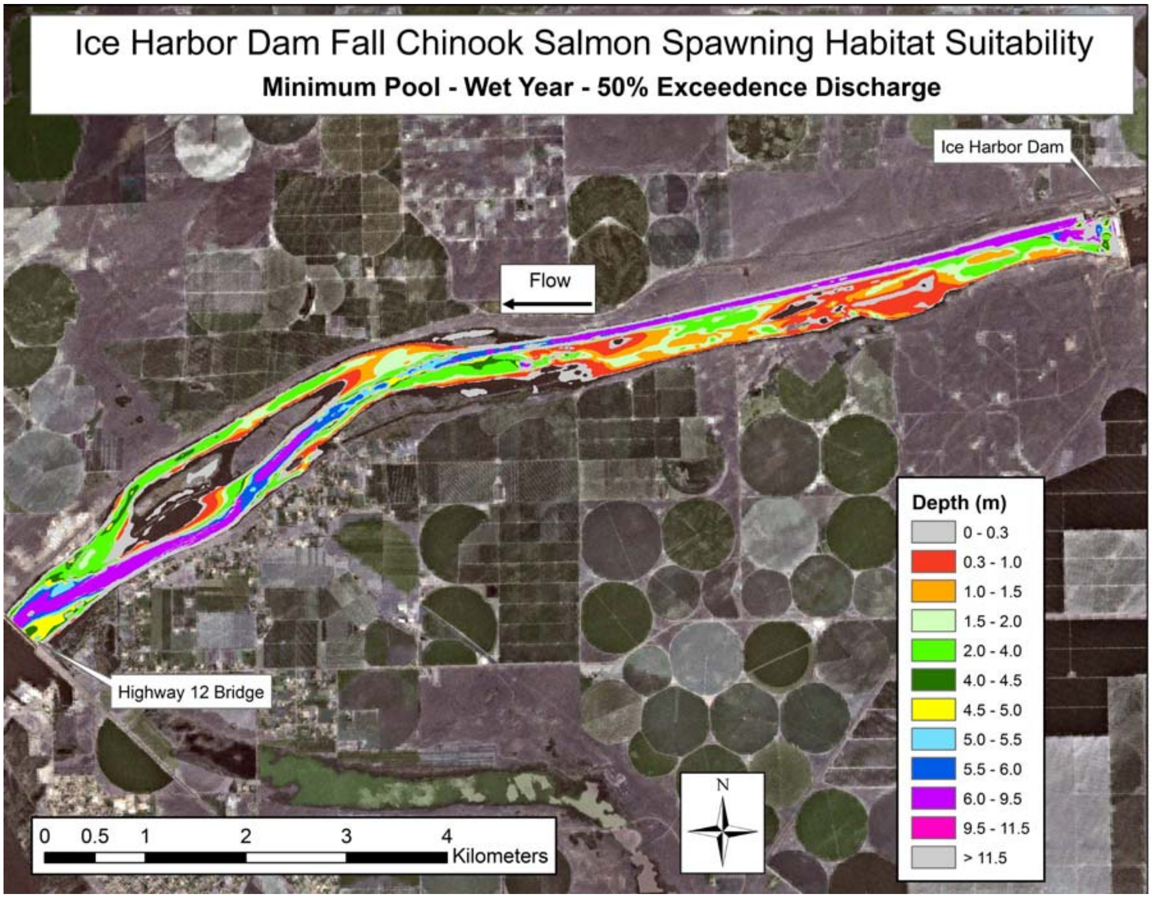

Figure C.33. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 50% Exceedence Discharge (44.0 kcfs) During a Wet Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

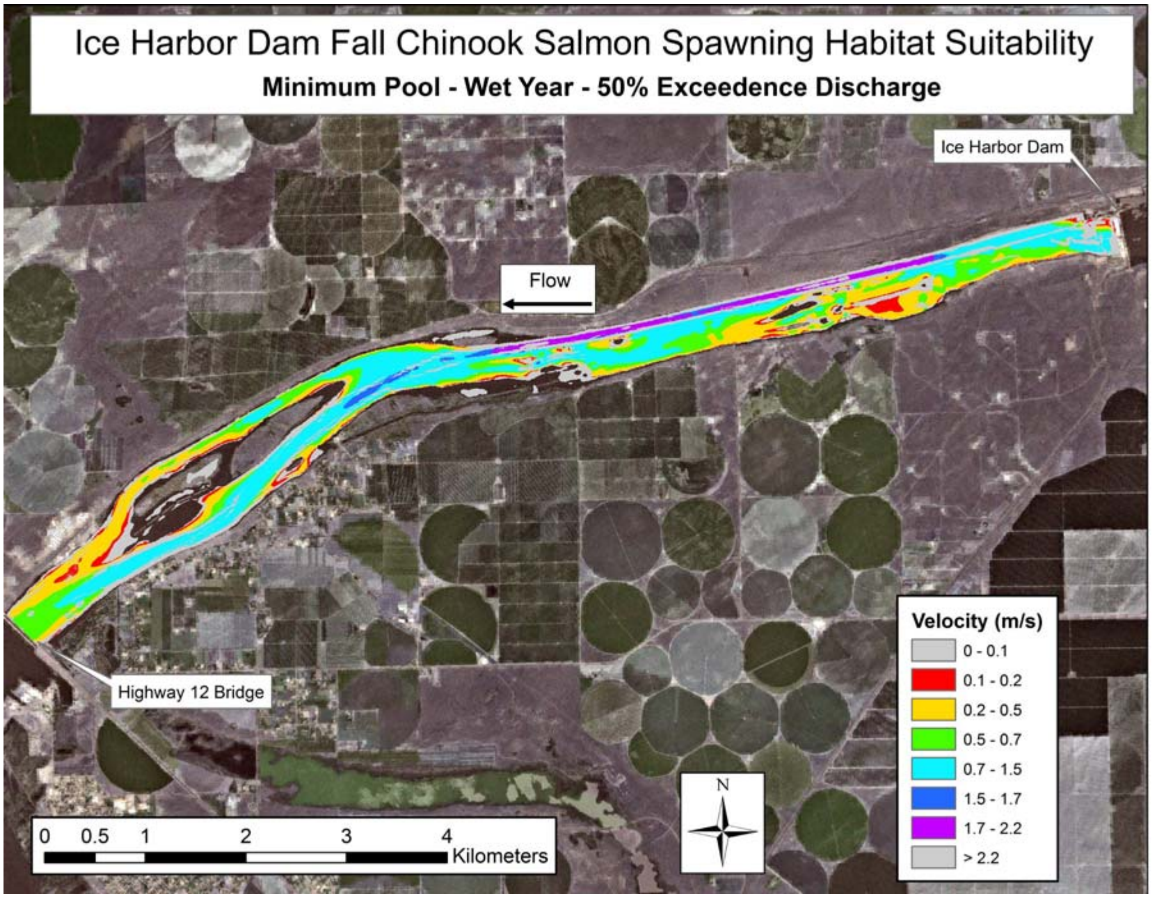

Figure C.34. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 50% Exceedence Discharge (44.0 kcfs) During a Wet Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

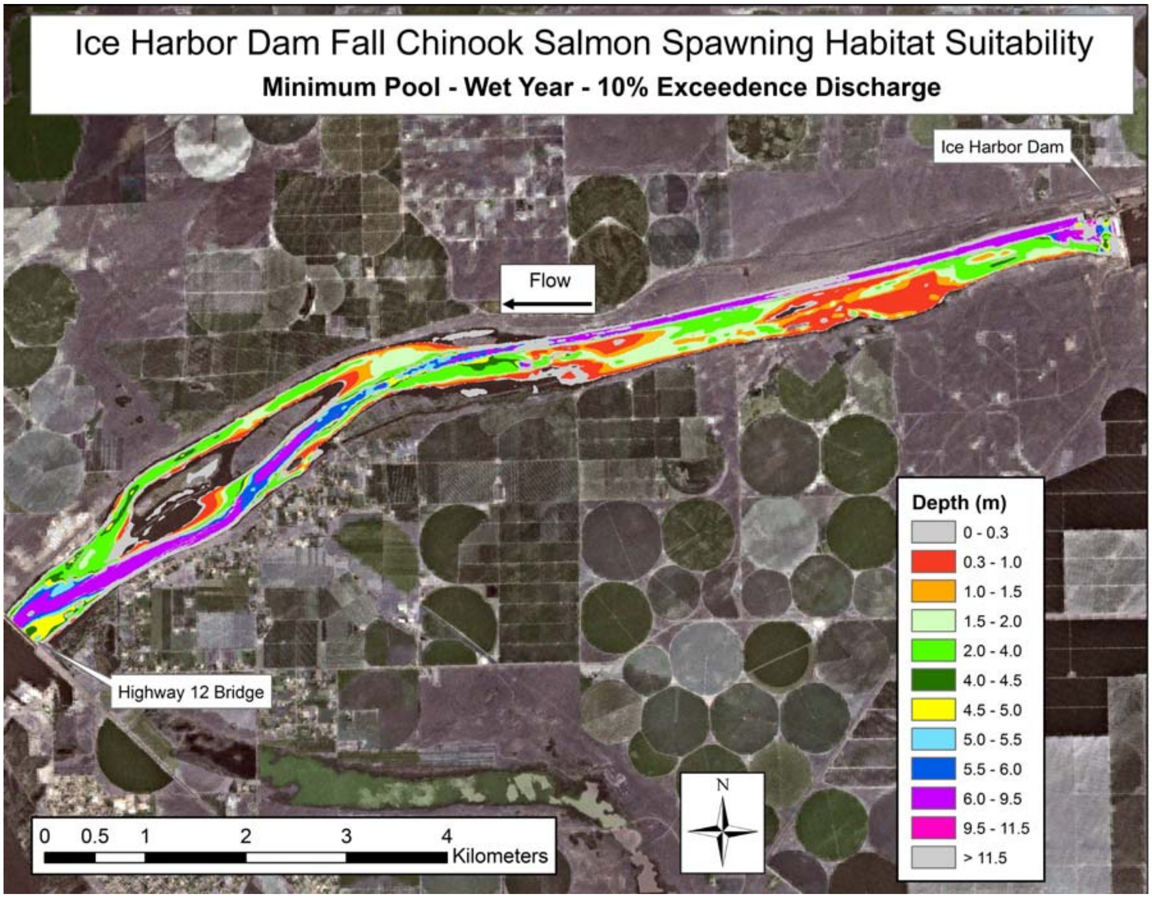

Figure C.35. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 10% Exceedence Discharge (52.0 kcfs) During a Wet Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

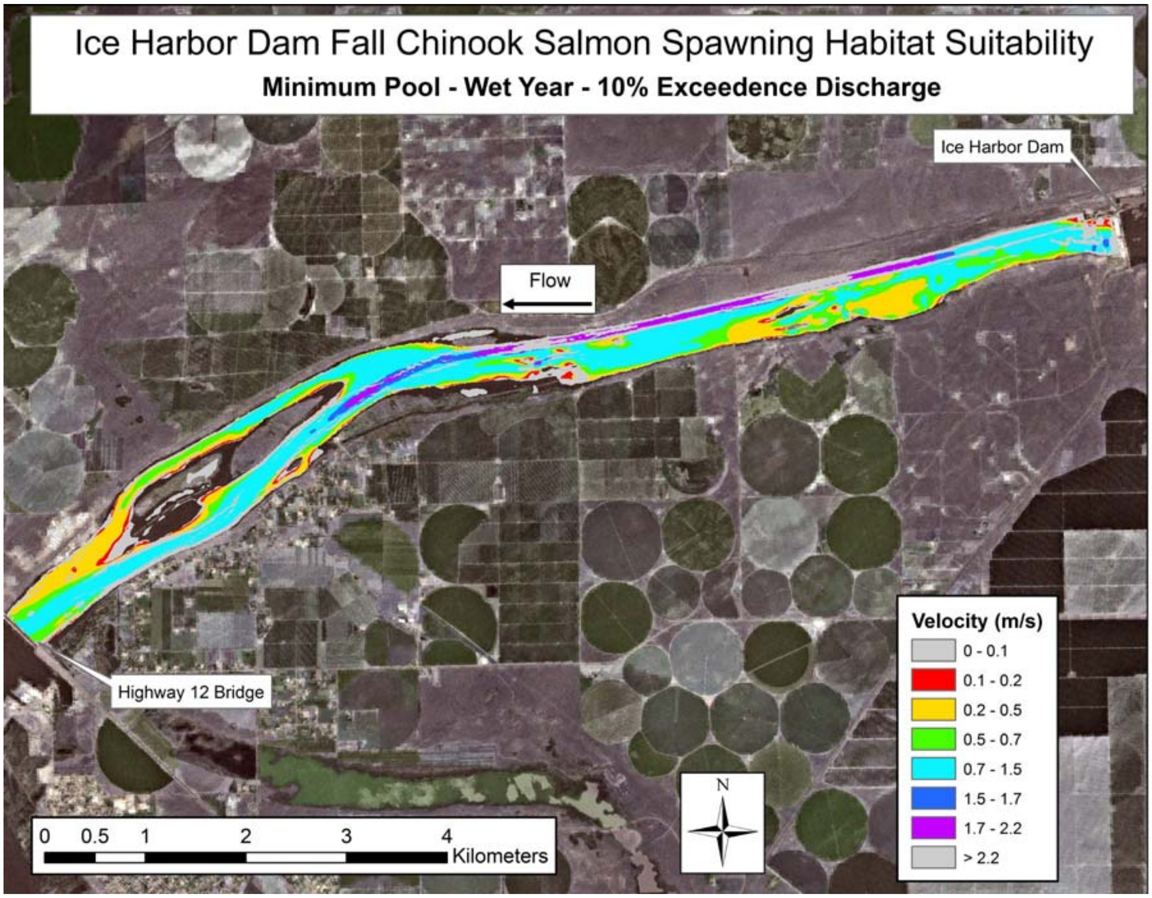

Figure C.36. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Ice Harbor Dam, Based on a 10% Exceedence Discharge (52.0 kcfs) During a Wet Water Year, with the McNary Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

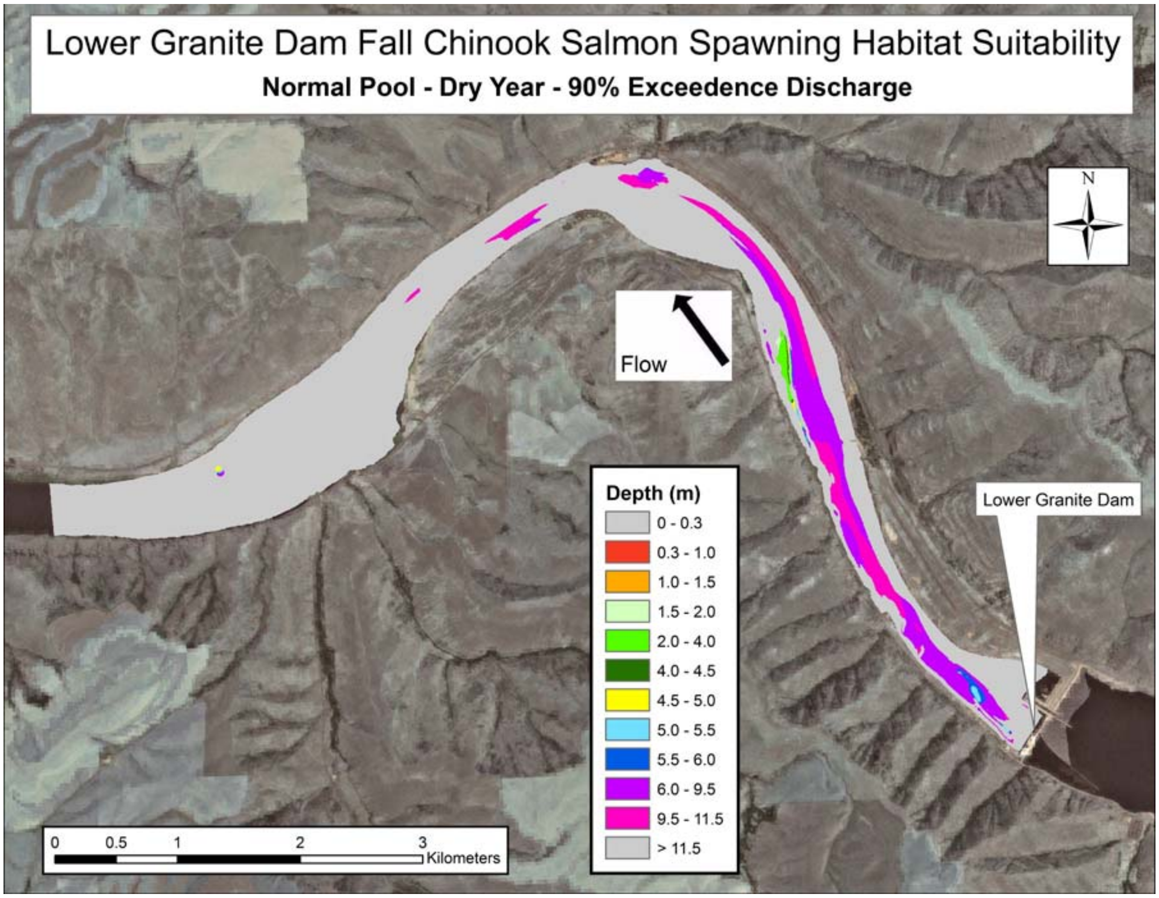

Figure C.37. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 90% Exceedence Discharge (12.6 kcfs) During a Dry Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

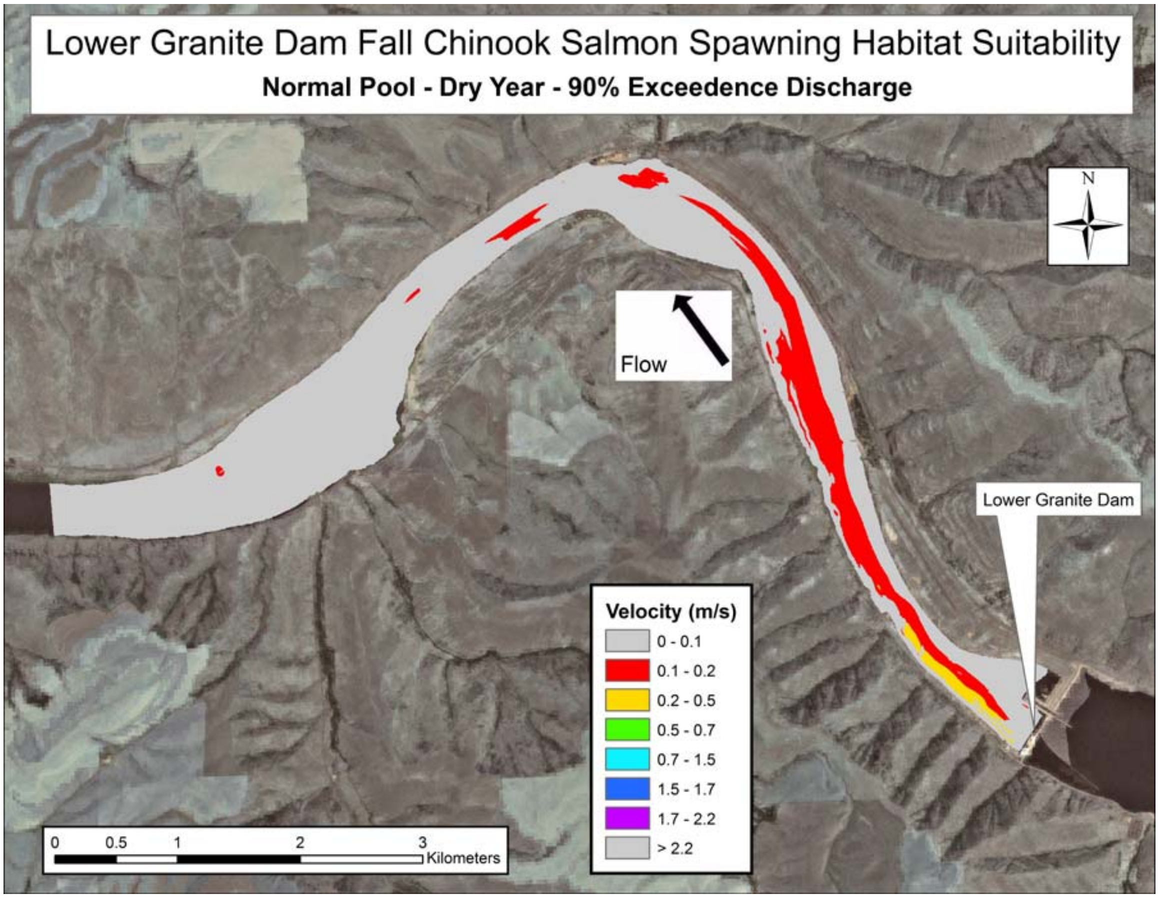

Figure C.38. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 90% Exceedence Discharge (12.6 kcfs) During a Dry Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

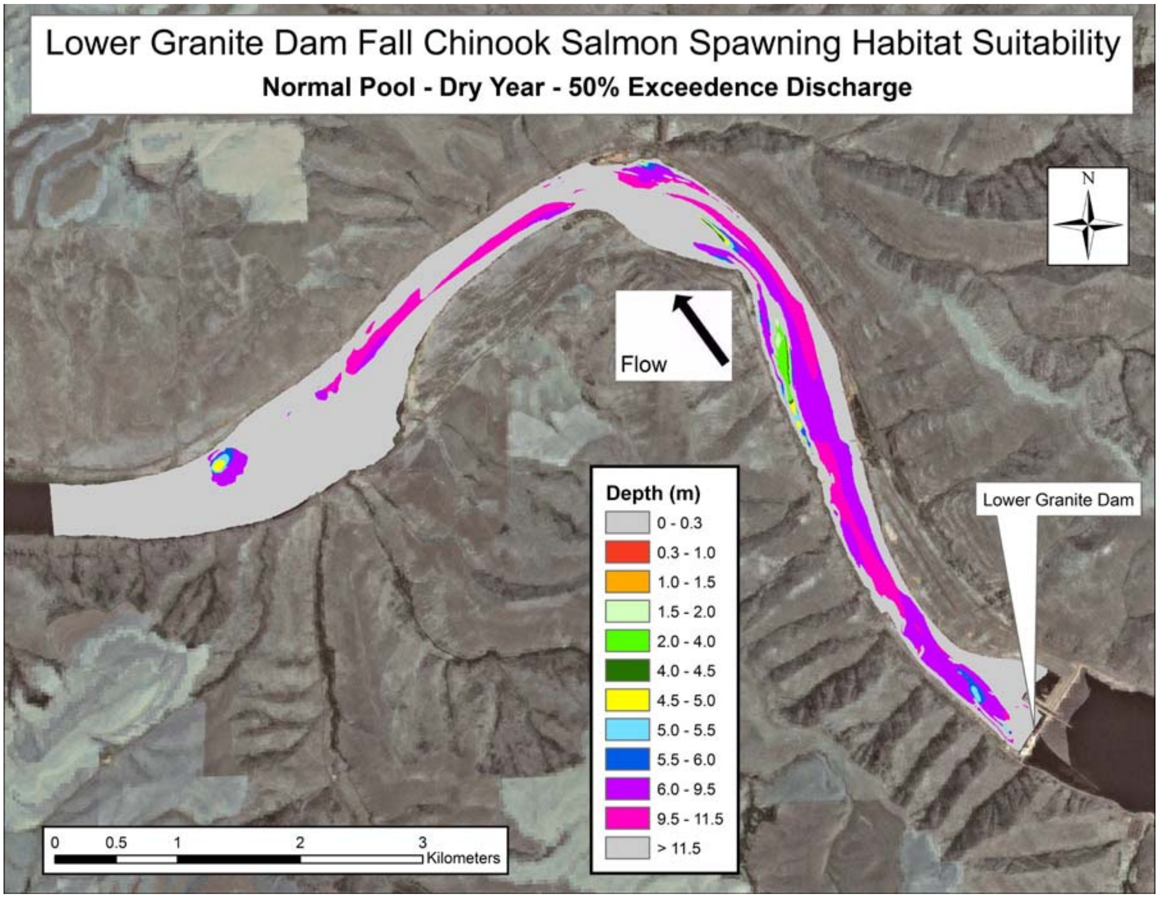

Figure C.39. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 50% Exceedence Discharge (15.3 kcfs) During a Dry Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

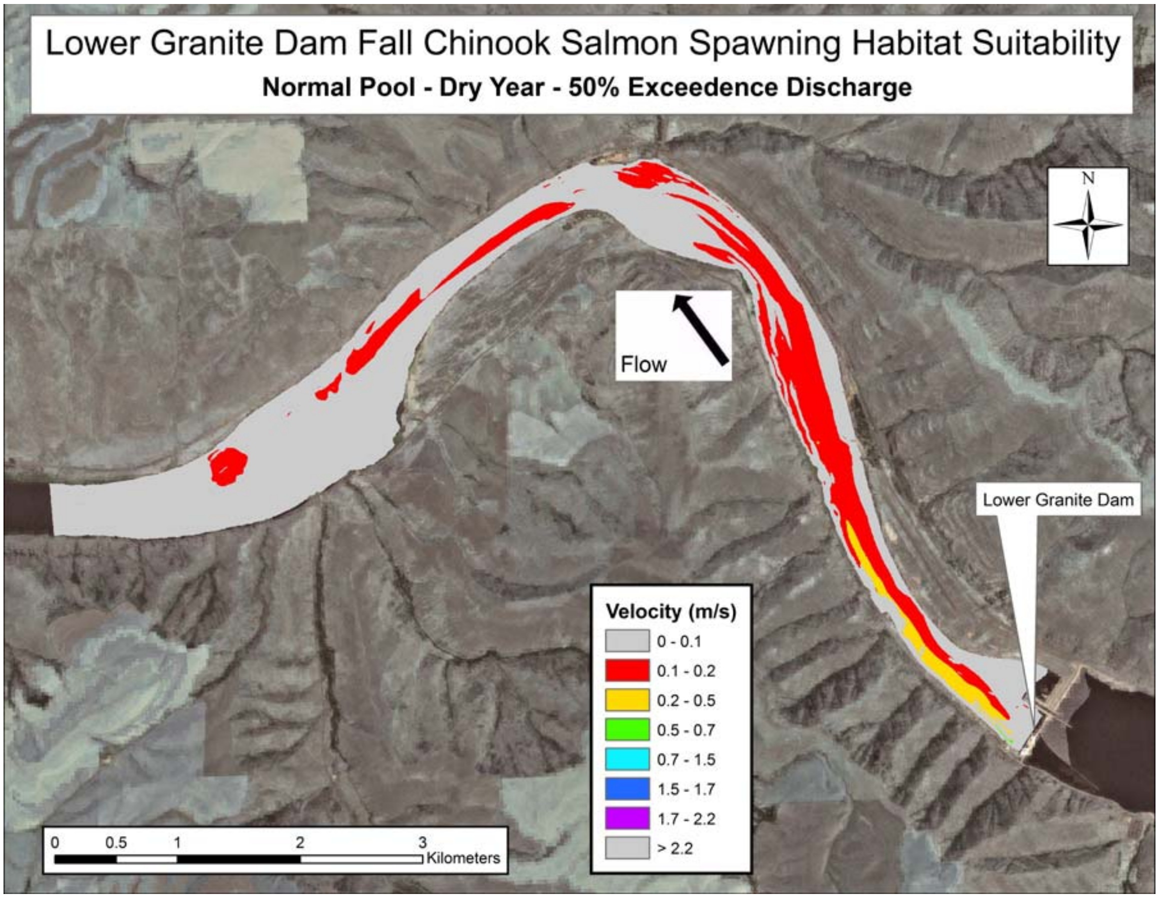

Figure C.40. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 50% Exceedence Discharge (15.3 kcfs) During a Dry Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

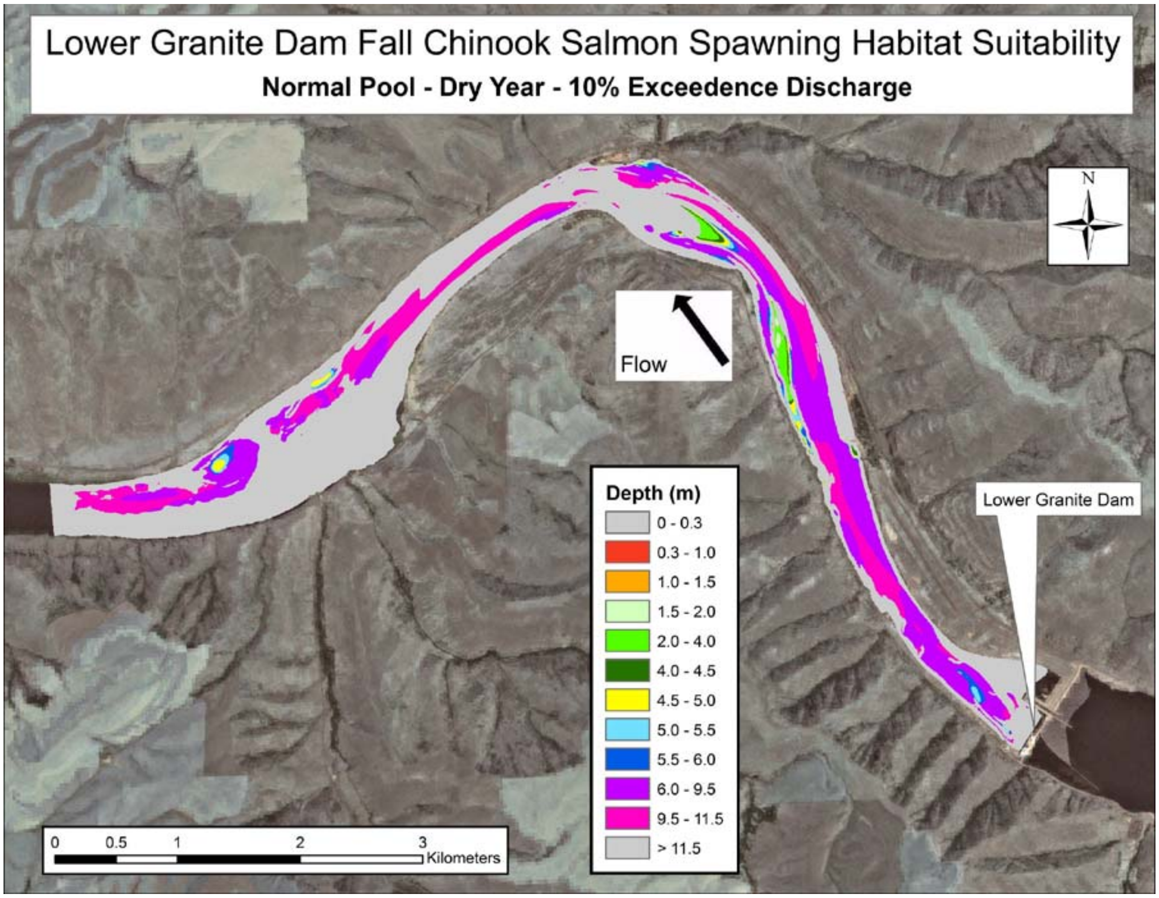

Figure C.41. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 10% Exceedence Discharge (18.2 kcfs) During a Dry Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

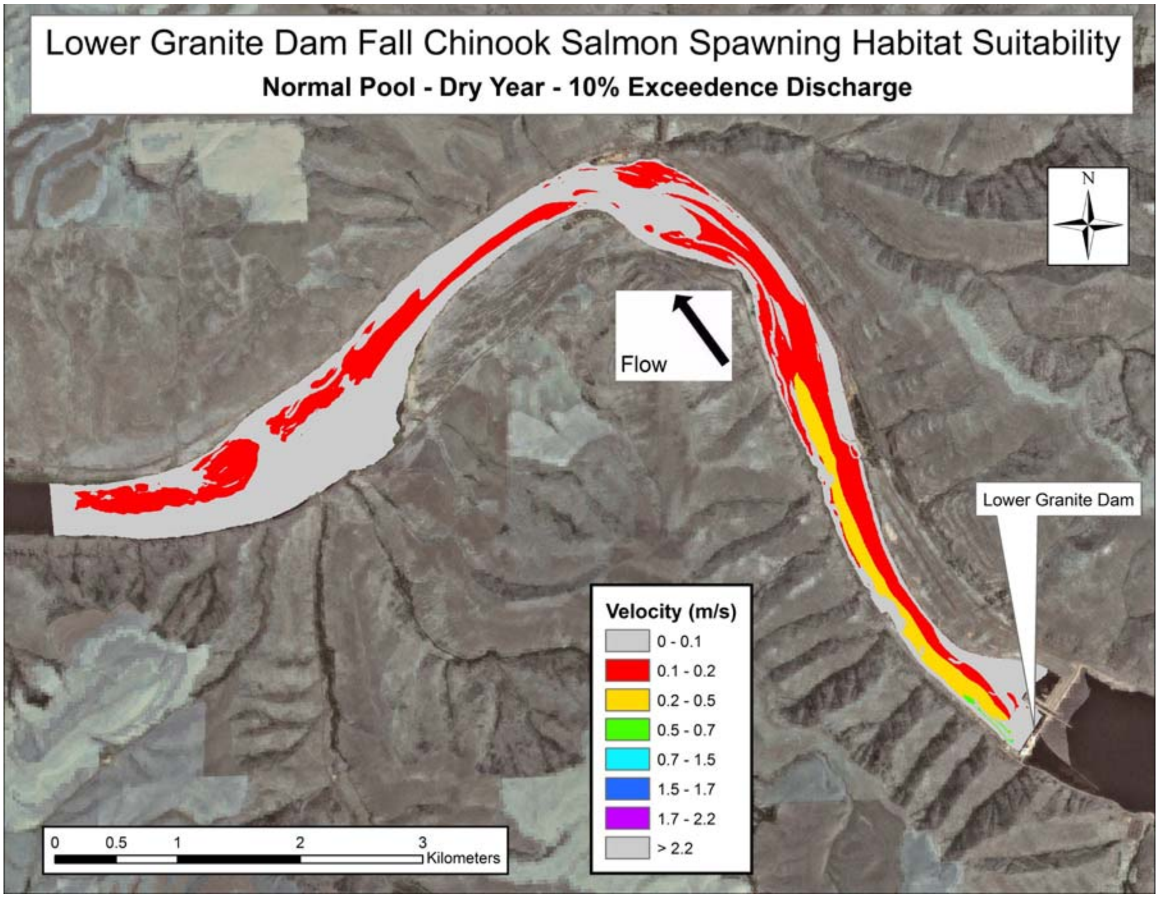

Figure C.42. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 10% Exceedence Discharge (18.2 kcfs) During a Dry Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

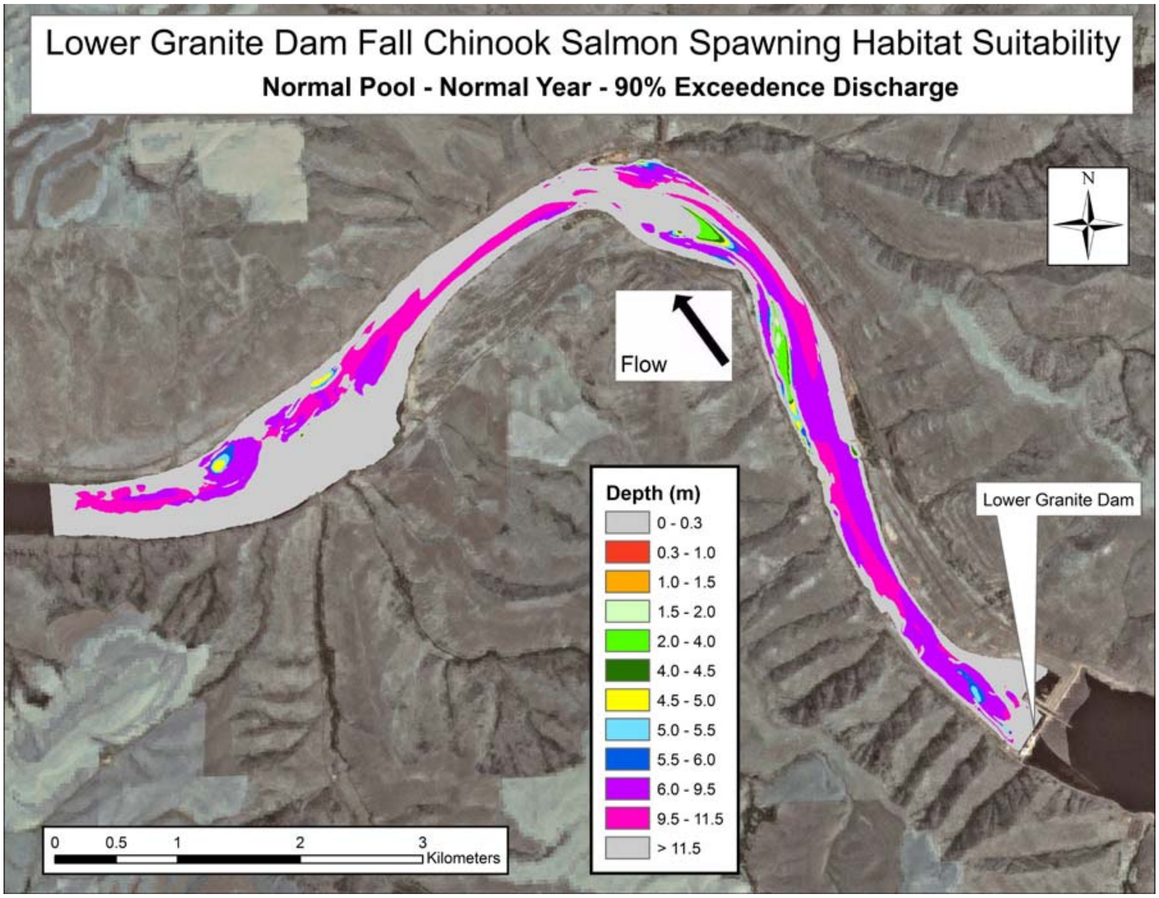

Figure C.43. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 90% Exceedence Discharge (19.1 kcfs) During a Normal Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

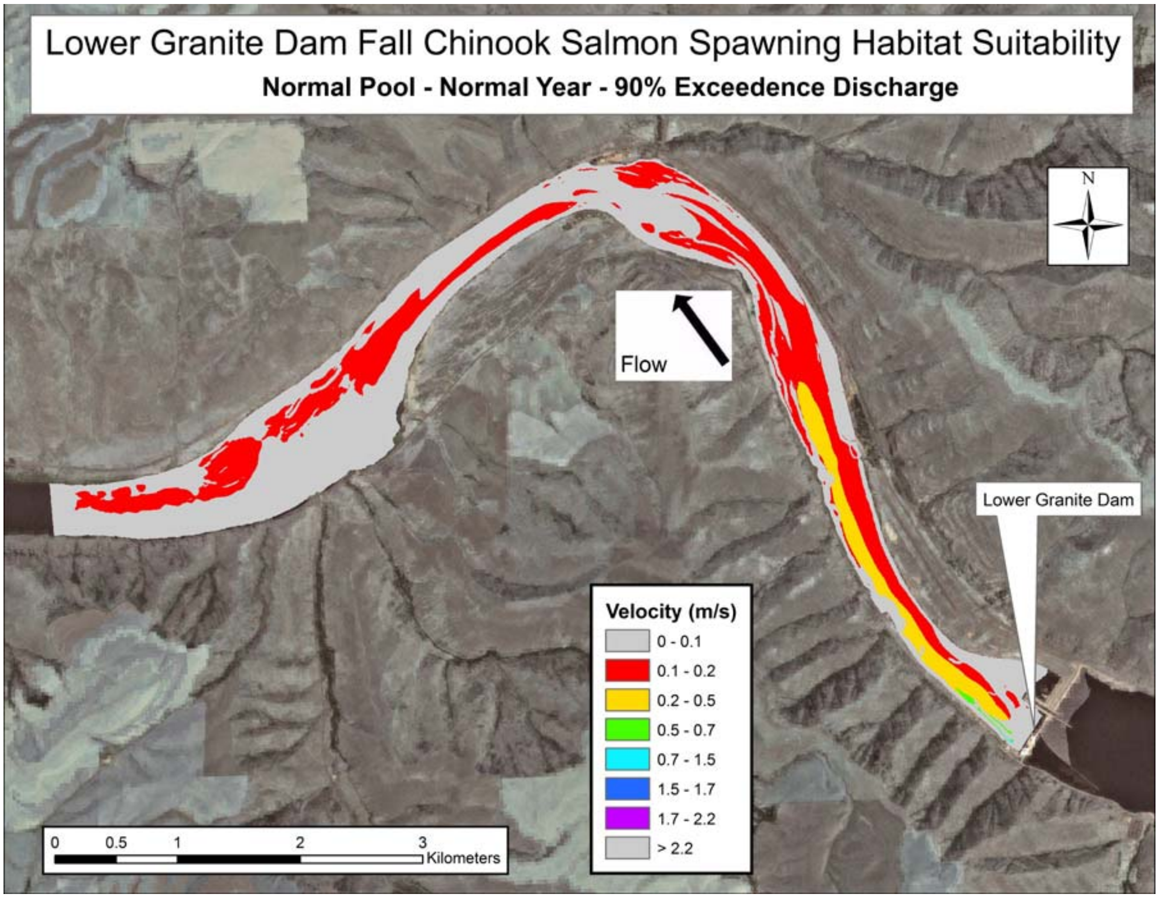

Figure C.44. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 90% Exceedence Discharge (19.1 kcfs) During a Normal Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

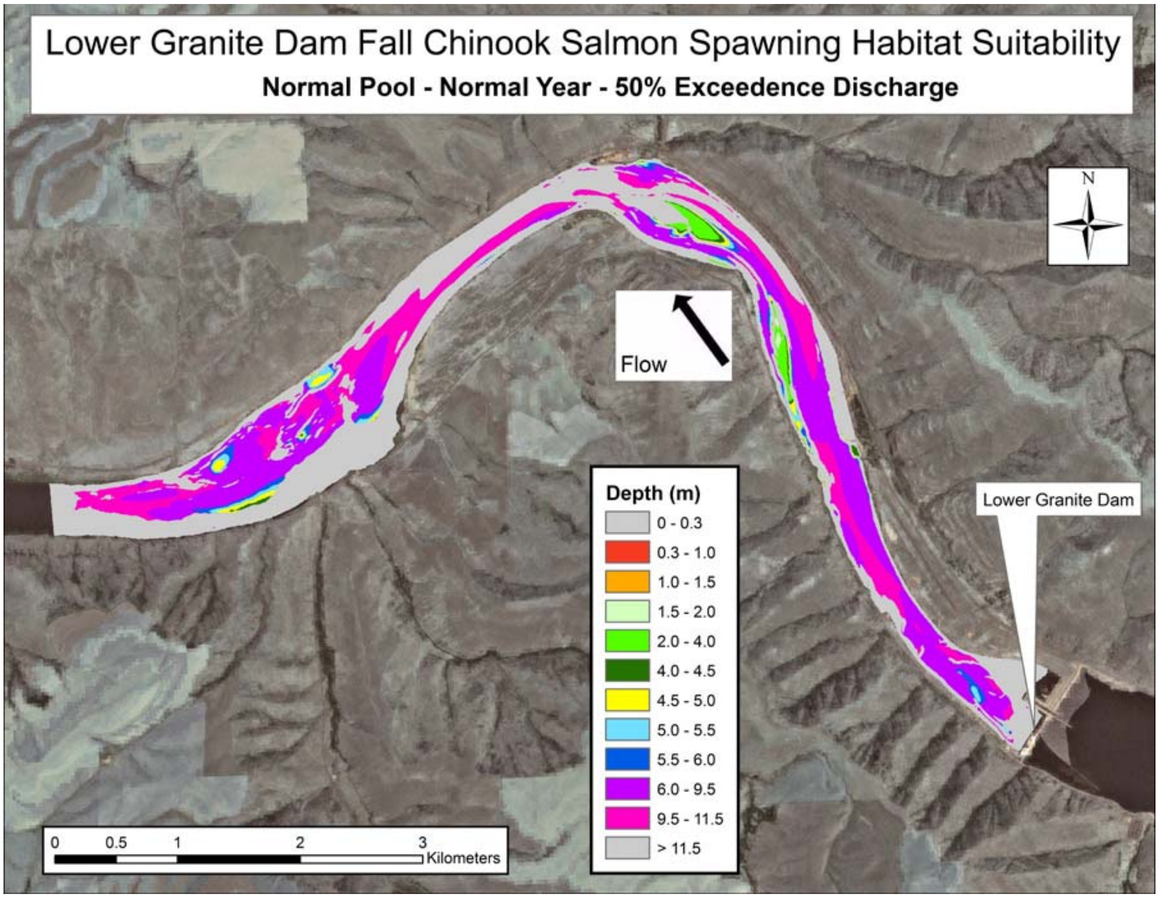

Figure C.45. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 50% Exceedence Discharge (21.7 kcfs) During a Normal Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

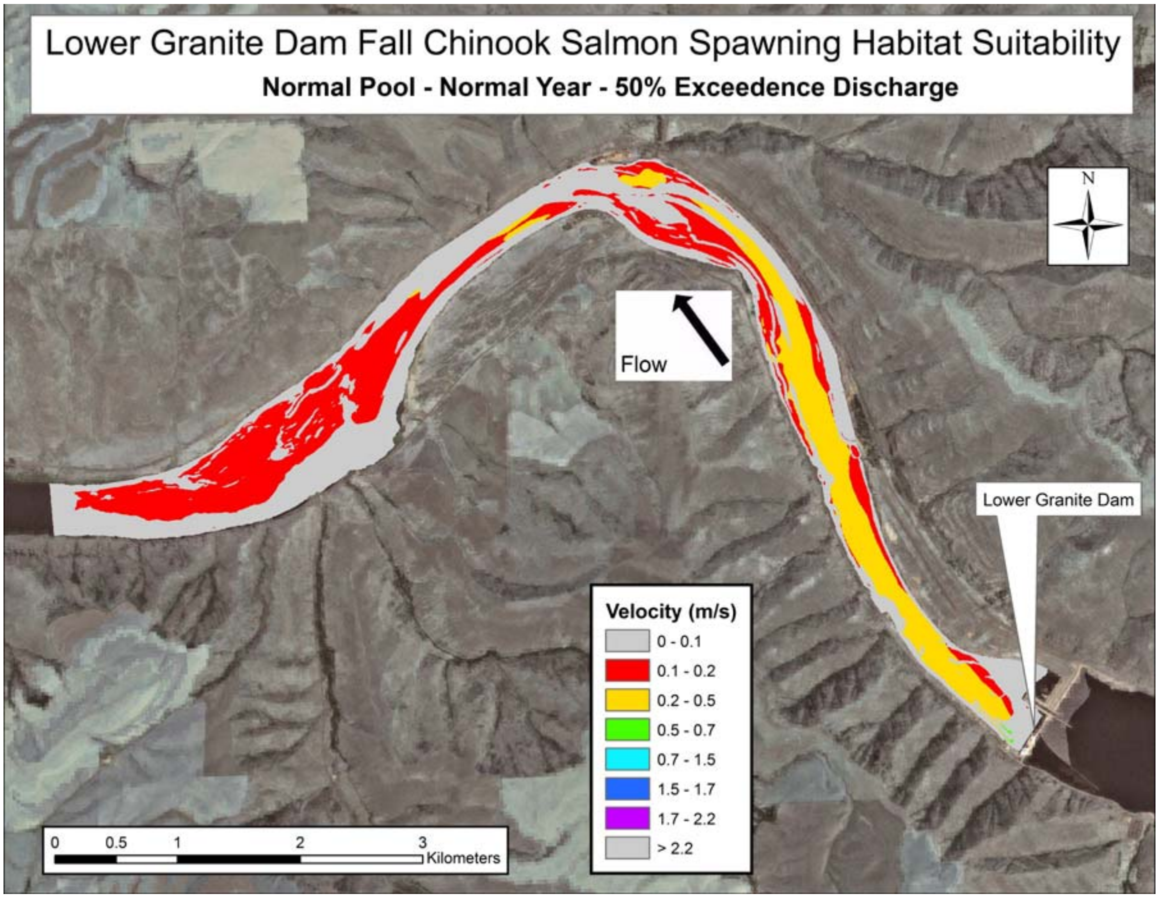

Figure C.46. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 50% Exceedence Discharge (21.7 kcfs) During a Normal Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

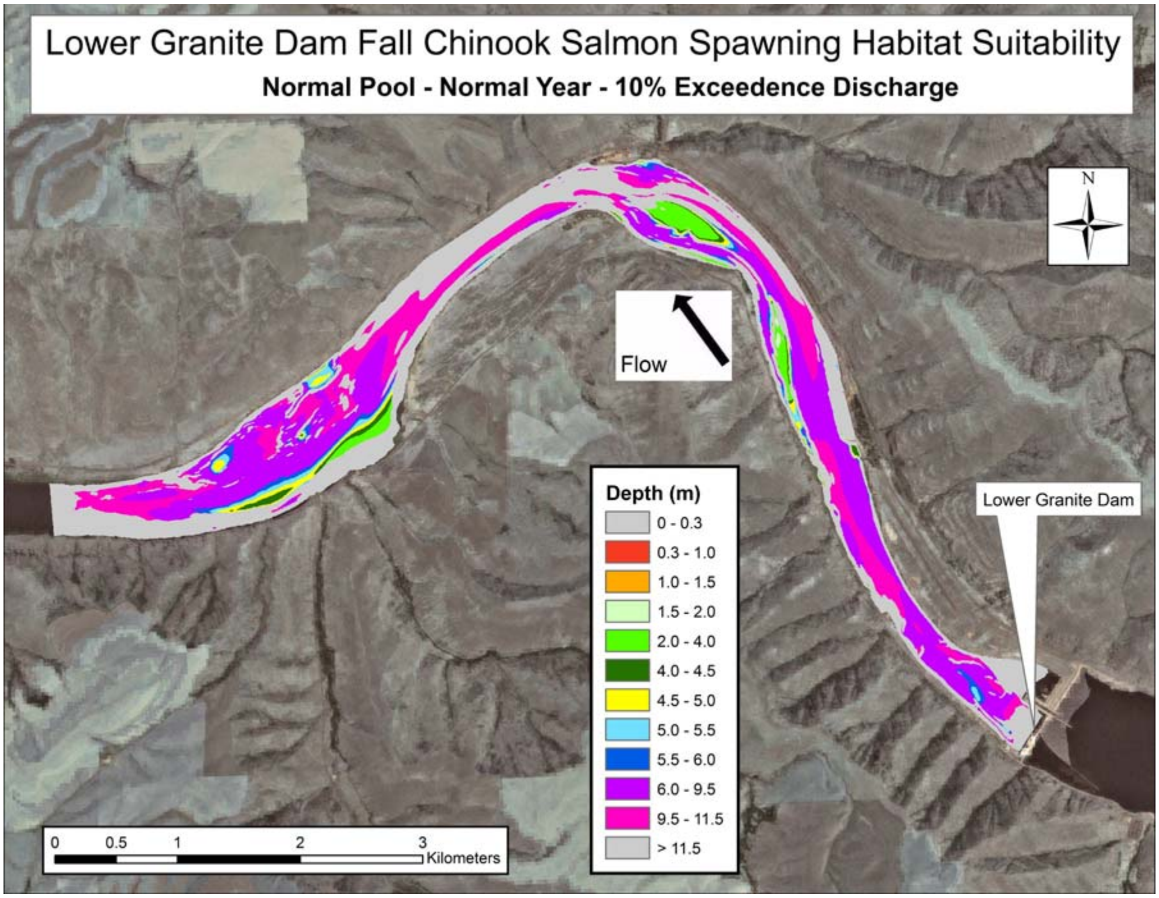

Figure C.47. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 10% Exceedence Discharge (34.5 kcfs) During a Normal Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

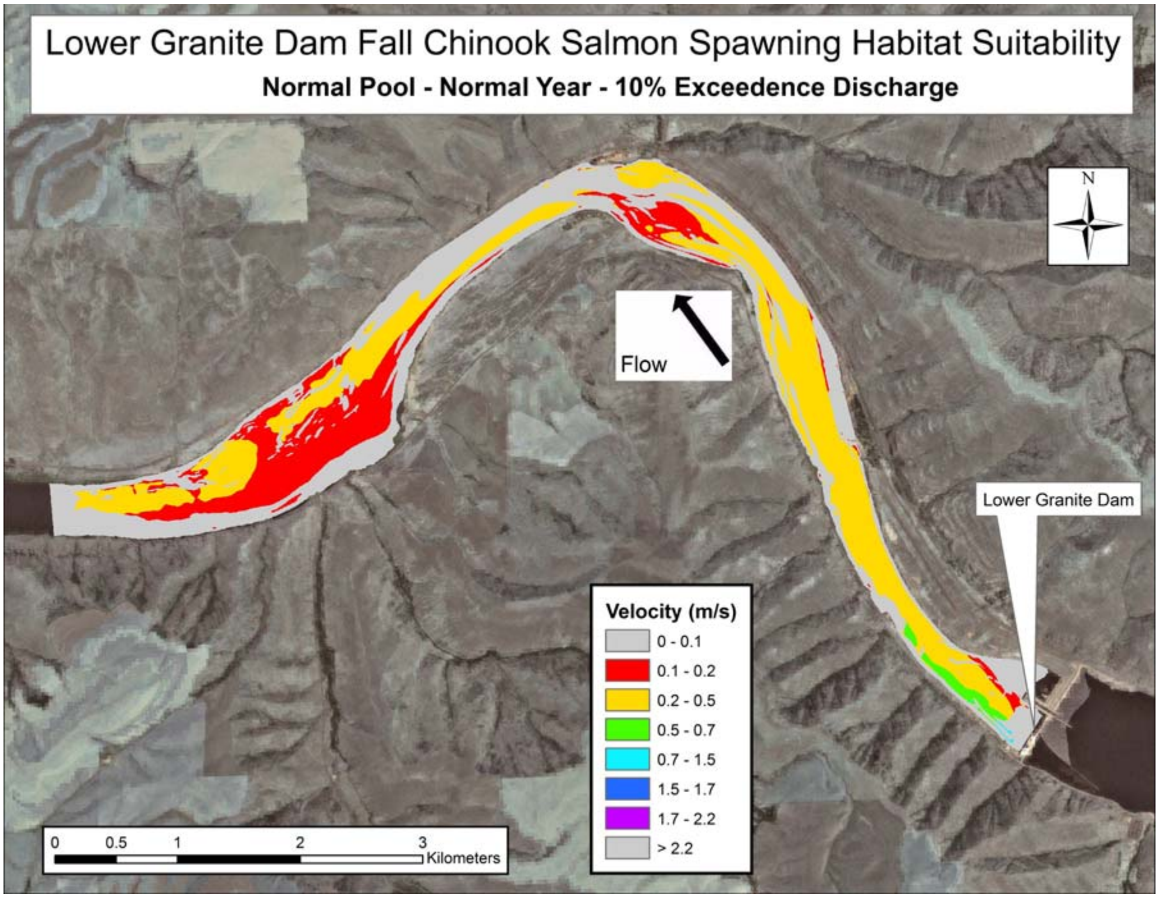

Figure C.48. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 10% Exceedence Discharge (34.5 kcfs) During a Normal Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

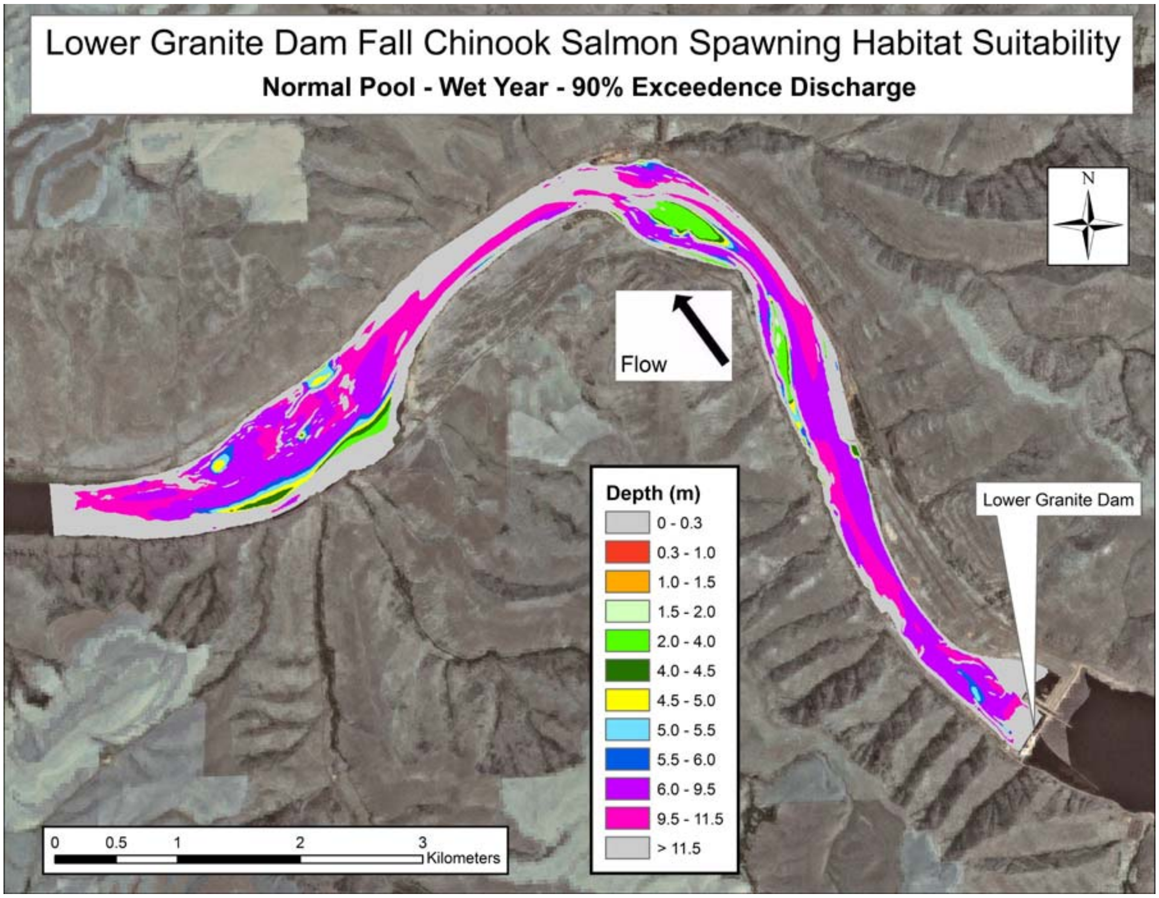

Figure C.49. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 90% Exceedence Discharge (34.5 kcfs) During a Wet Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

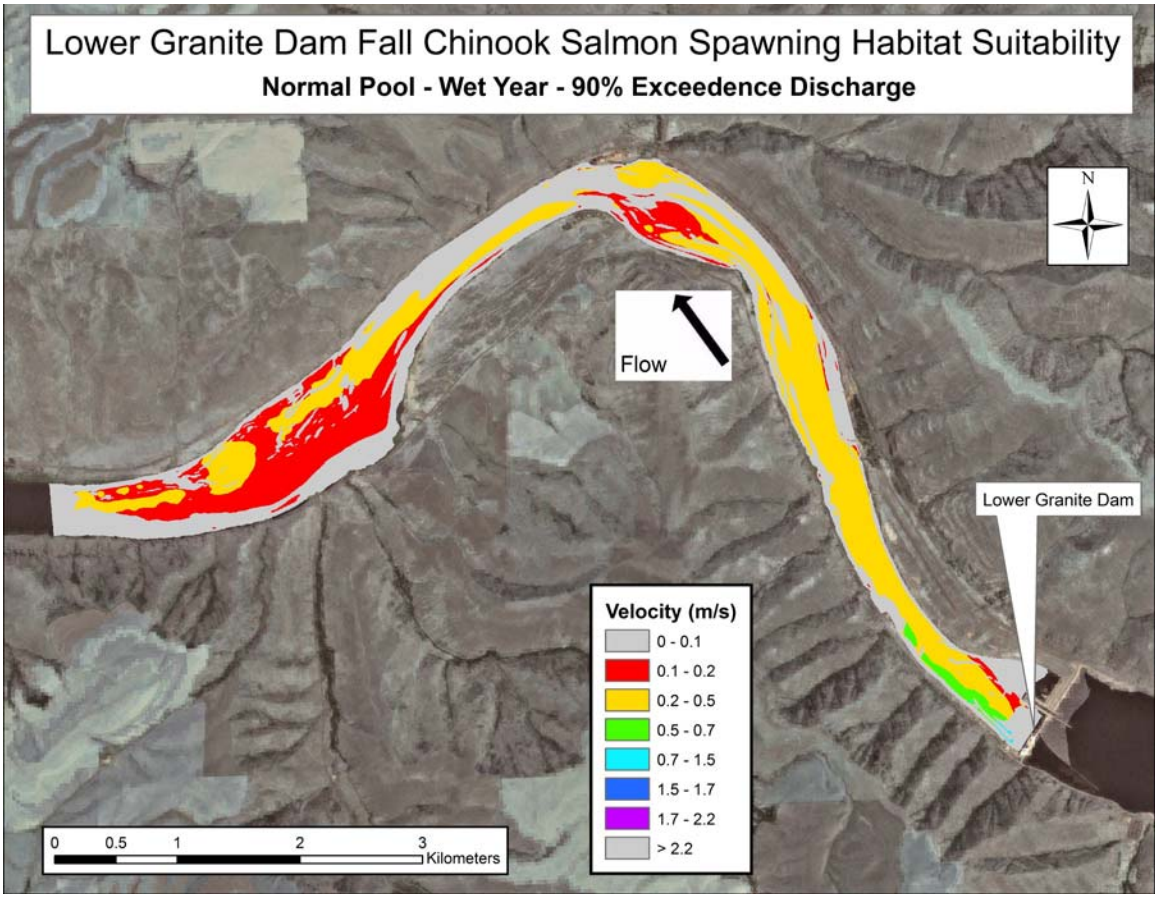

Figure C.50. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 90% Exceedence Discharge (34.5 kcfs) During a Wet Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

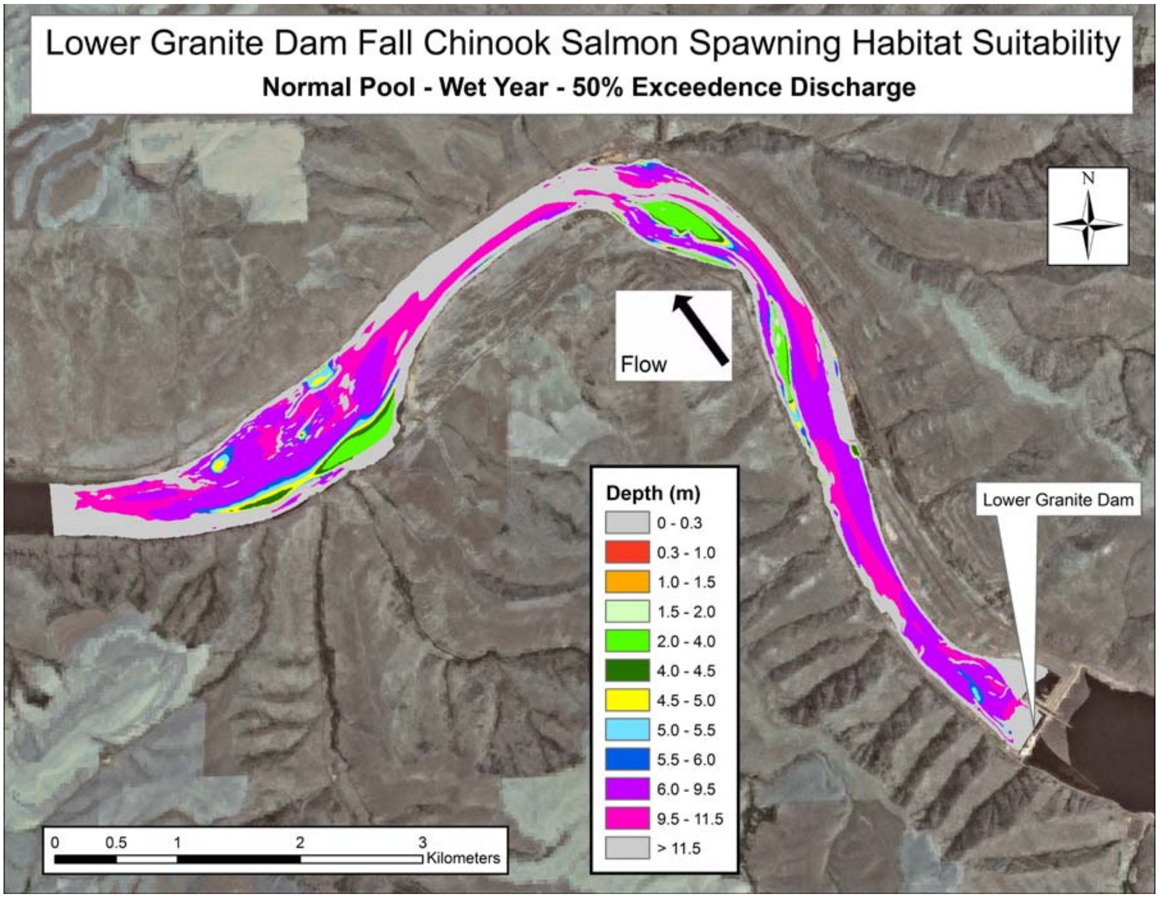

Figure C.51. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 50% Exceedence Discharge (44.0 kcfs) During a Wet Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

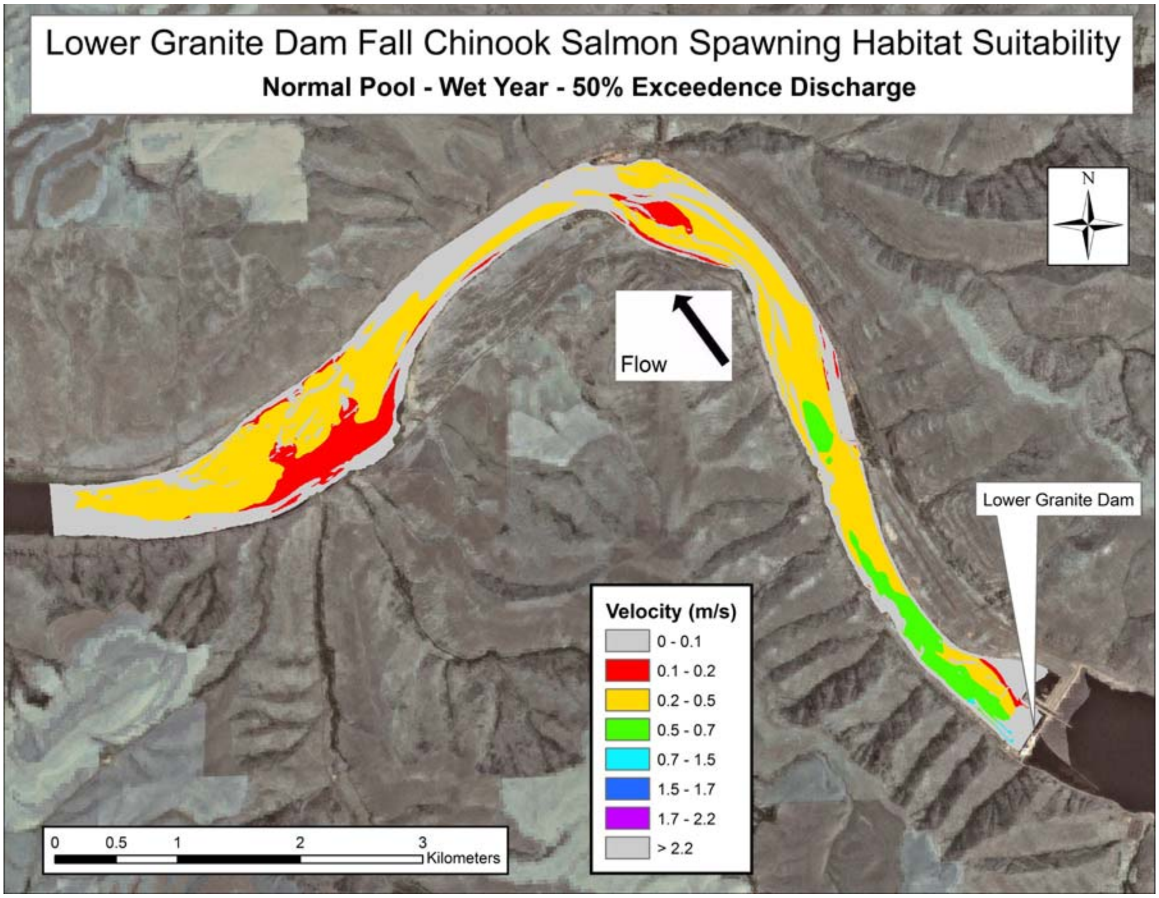

Figure C.52. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 50% Exceedence Discharge (44.0 kcfs) During a Wet Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

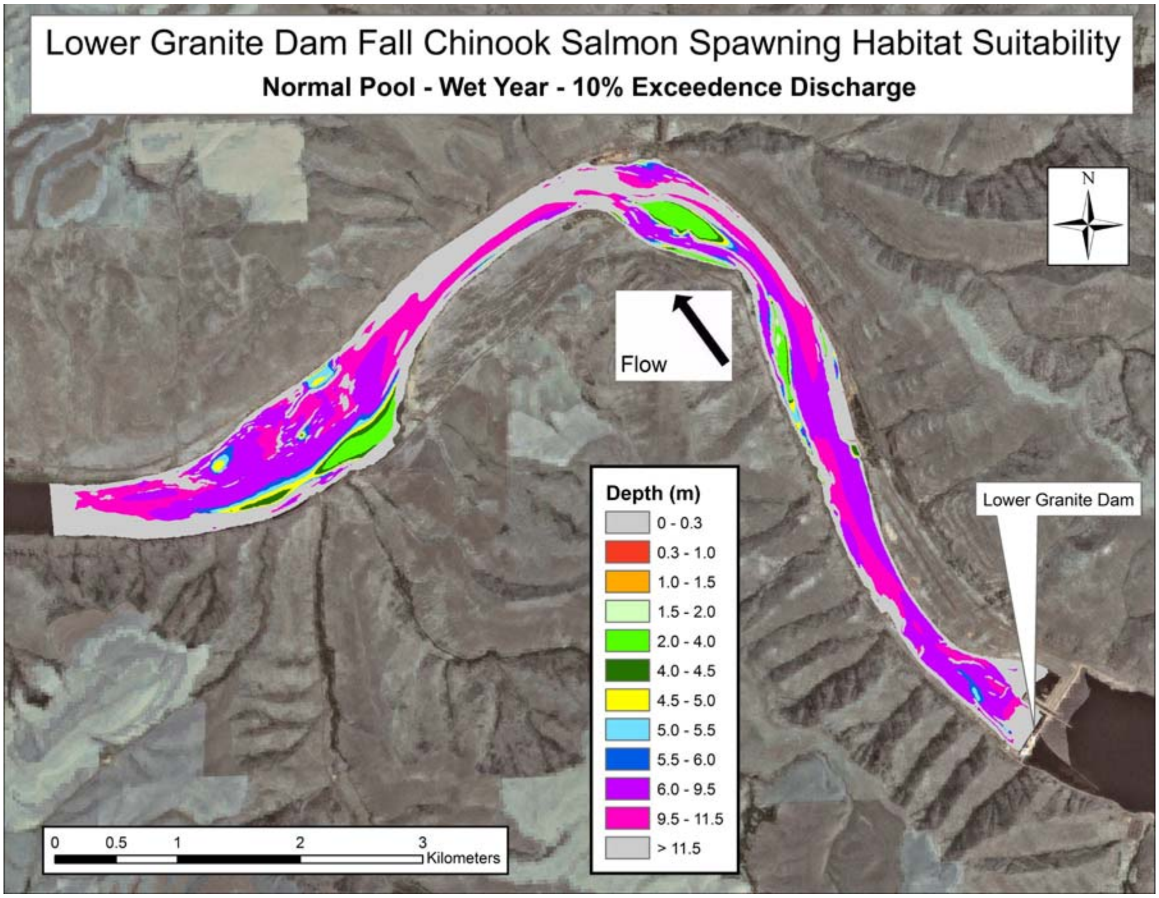

Figure C.53. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 10% Exceedence Discharge (52.0 kcfs) During a Wet Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

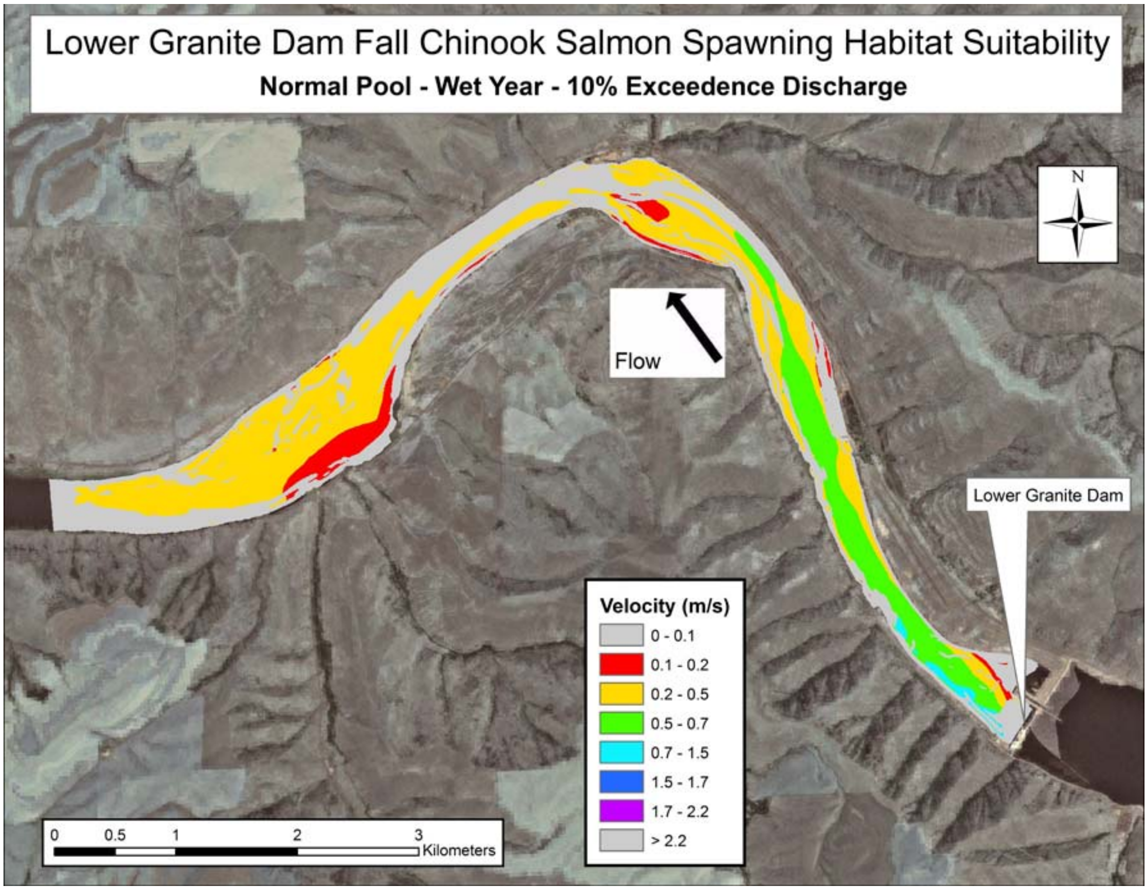

Figure C.54. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 10% Exceedence Discharge (52.0 kcfs) During a Wet Water Year, with the Little Goose Dam Forebay at Normal Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

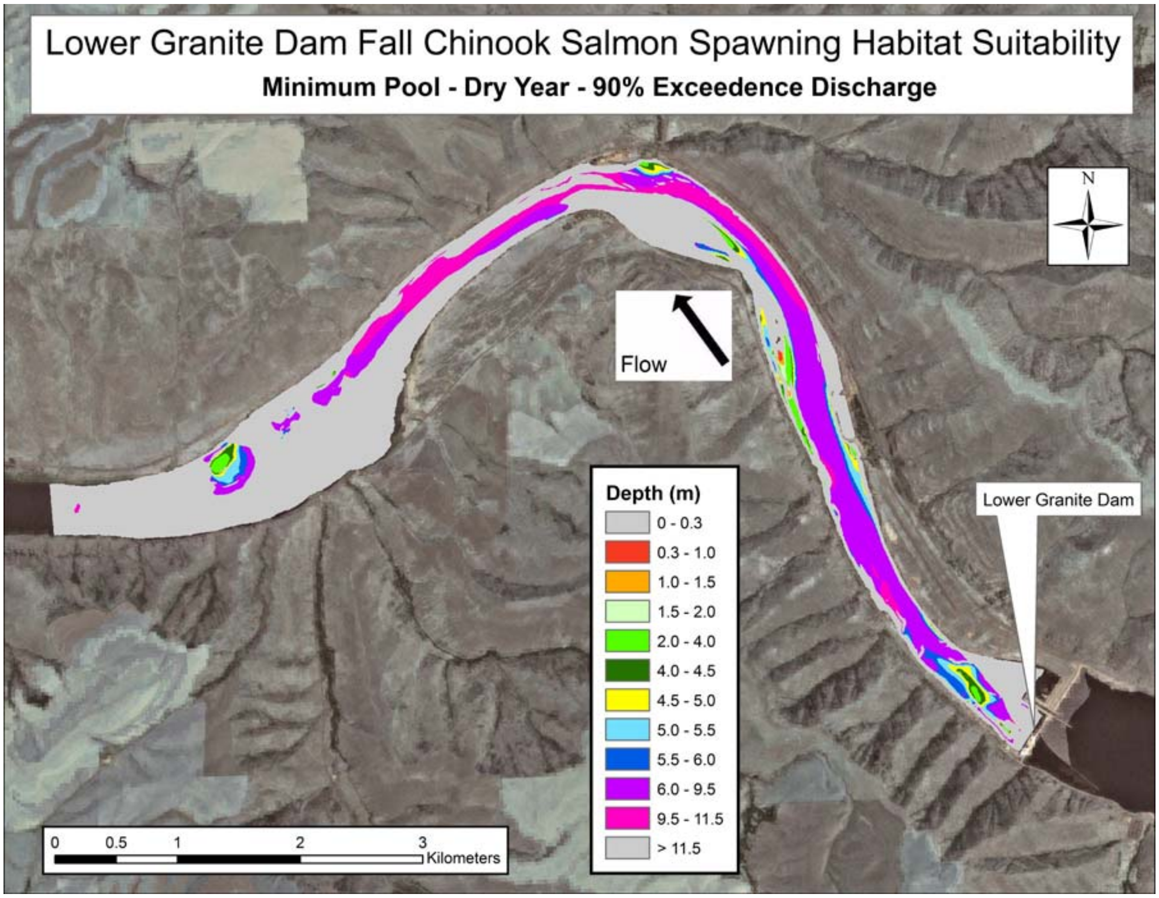

Figure C.55. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 90% Exceedence Discharge (12.6 kcfs) During a Dry Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

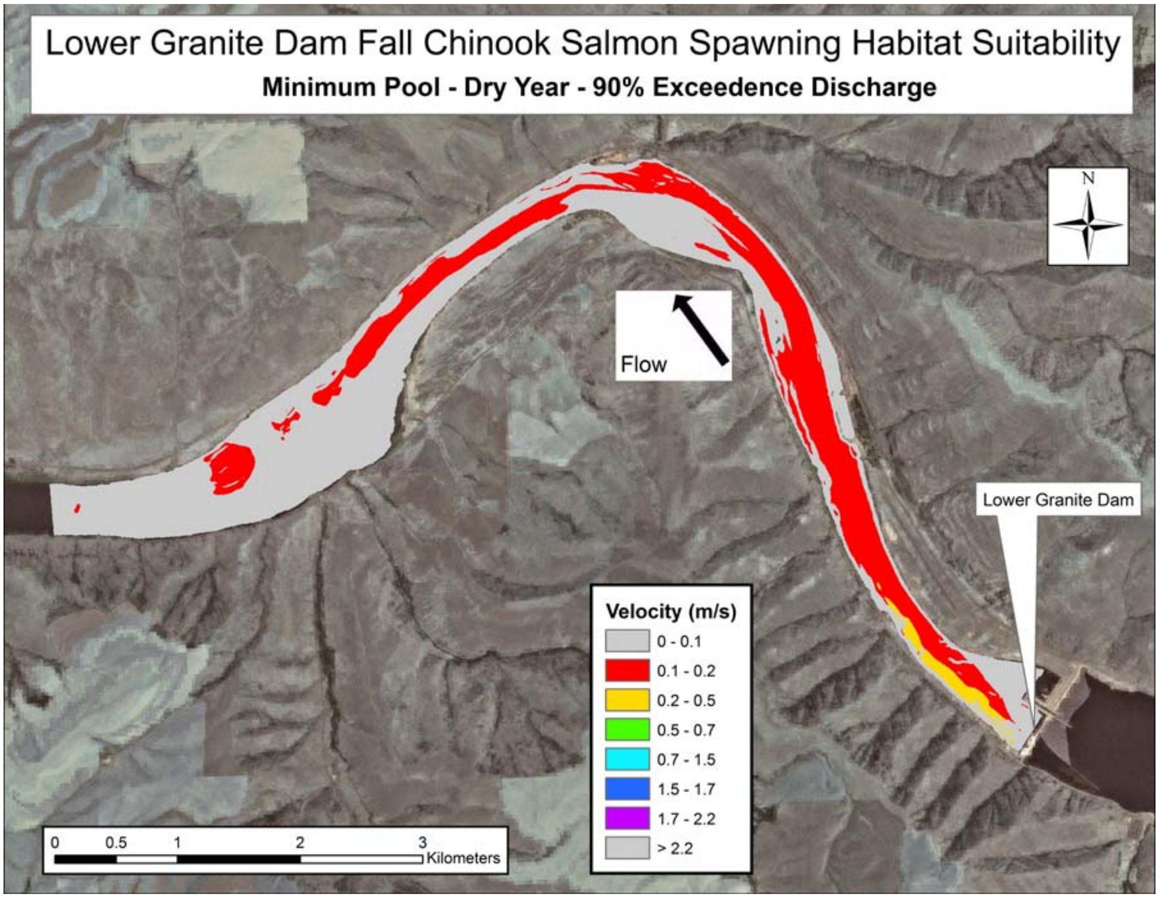

Figure C.56. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 90% Exceedence Discharge (12.6 kcfs) During a Dry Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

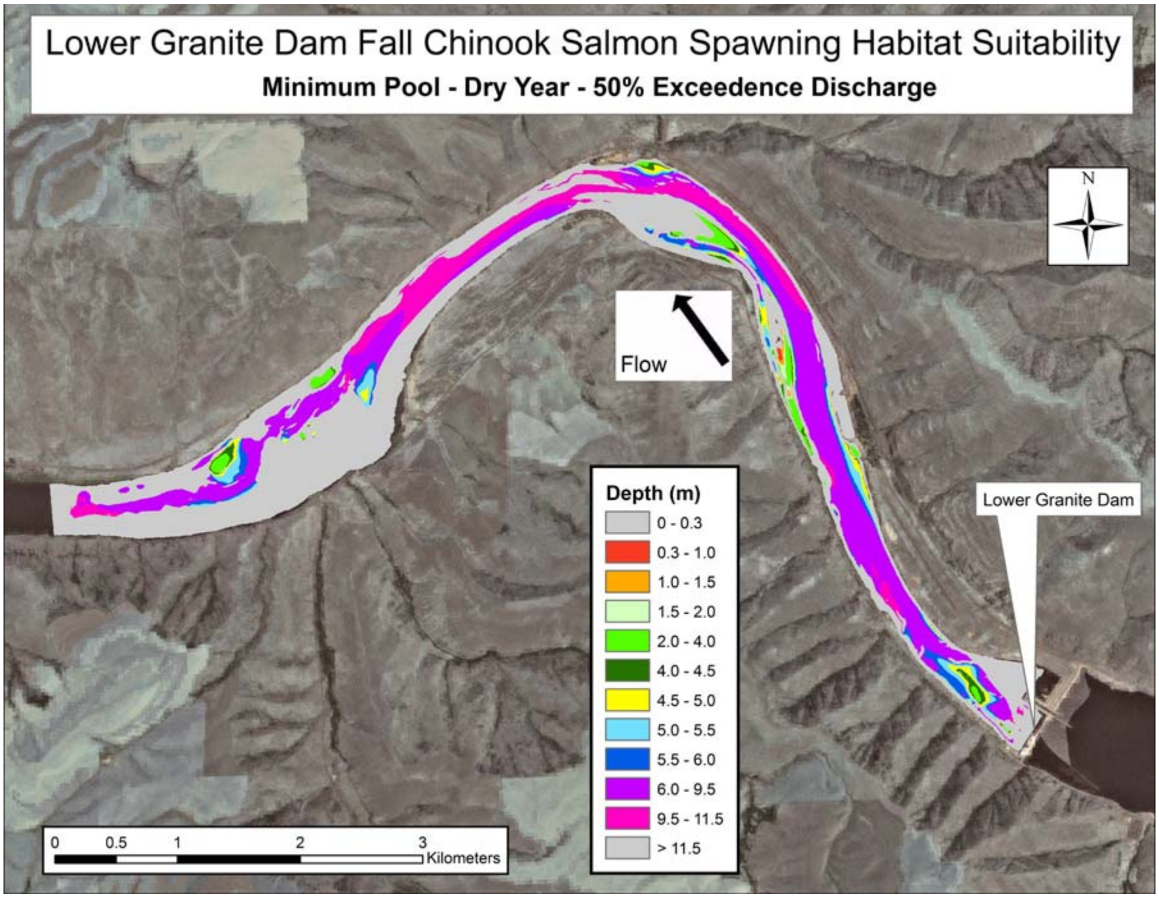

Figure C.57. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 50% Exceedence Discharge (15.3 kcfs) During a Dry Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

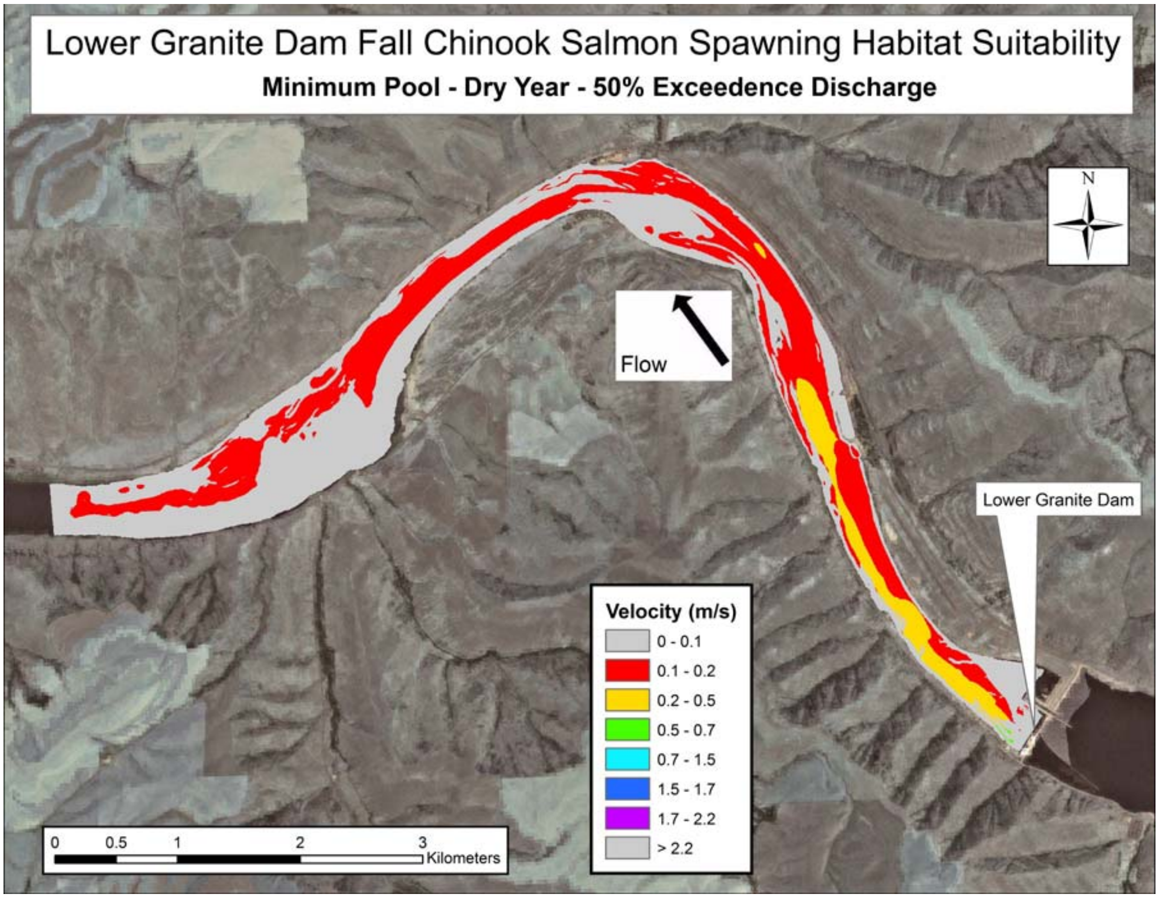

Figure C.58. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 50% Exceedence Discharge (15.3 kcfs) During a Dry Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

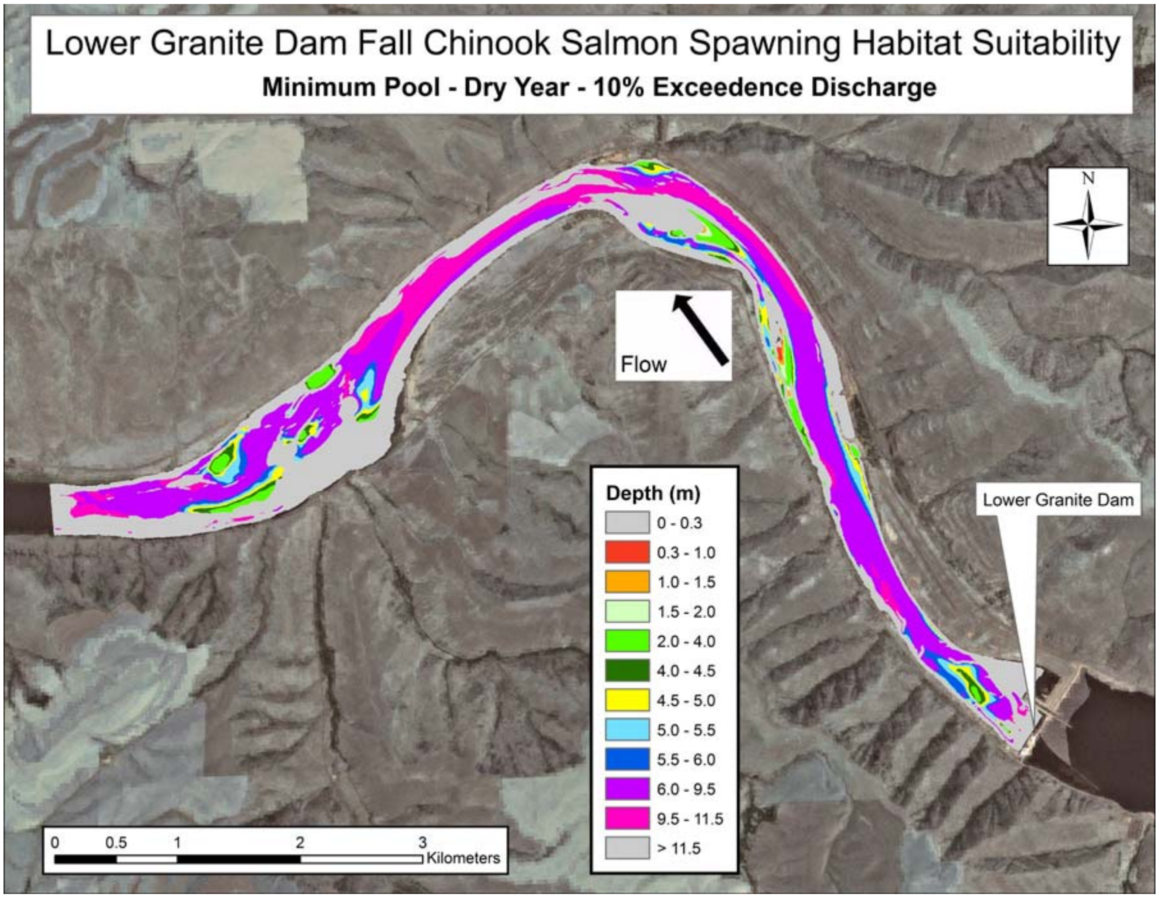

Figure C.59. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 10% Exceedence Discharge (18.2 kcfs) During a Dry Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

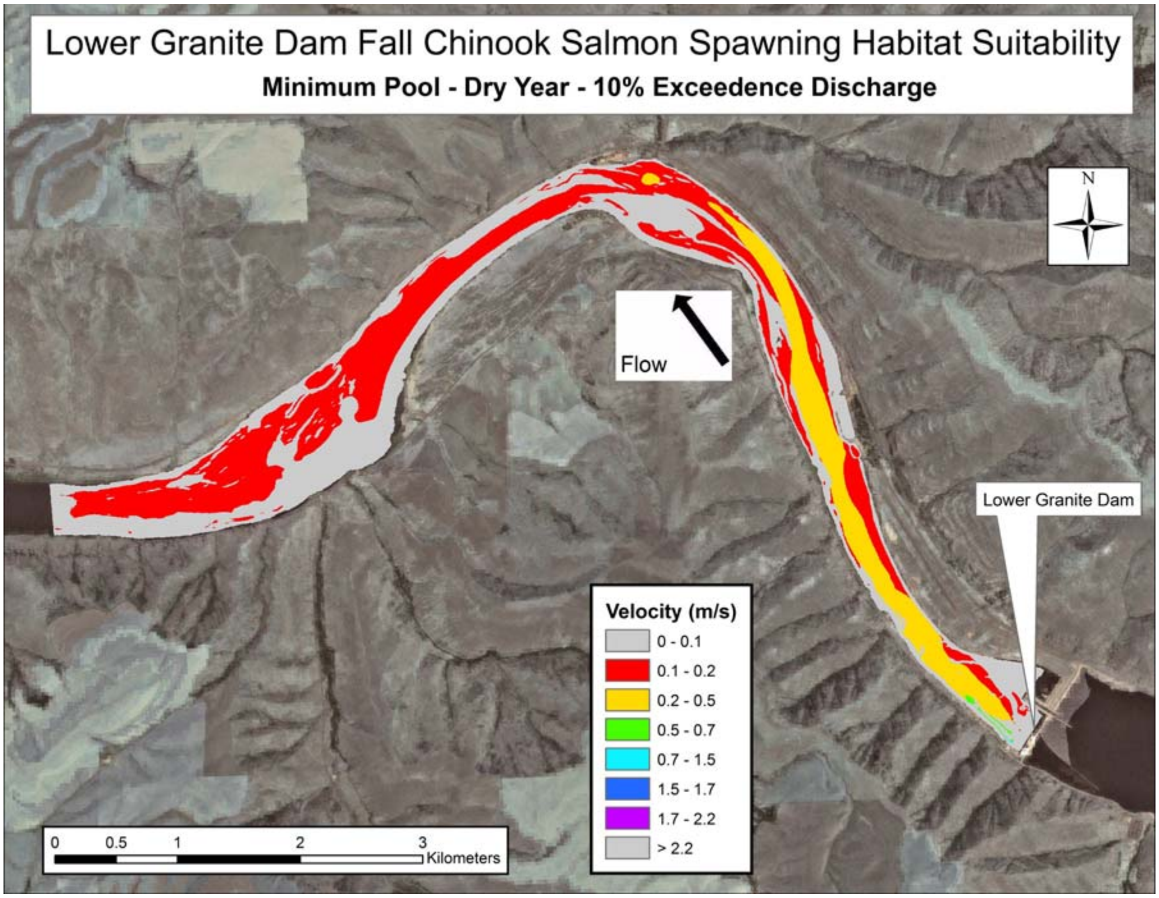

Figure C.60. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 10% Exceedence Discharge (18.2 kcfs) During a Dry Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

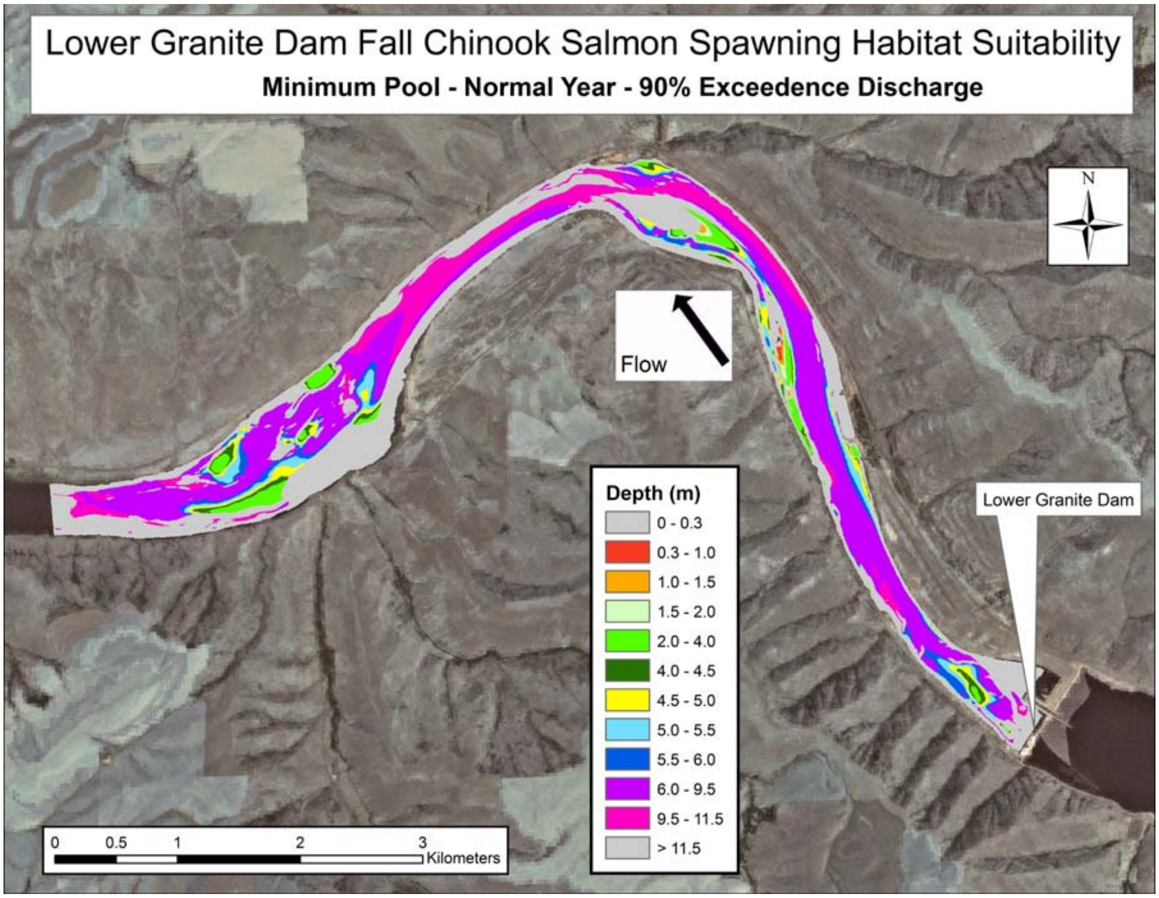

Figure C.61. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 90% Exceedence Discharge (19.1 kcfs) During a Normal Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

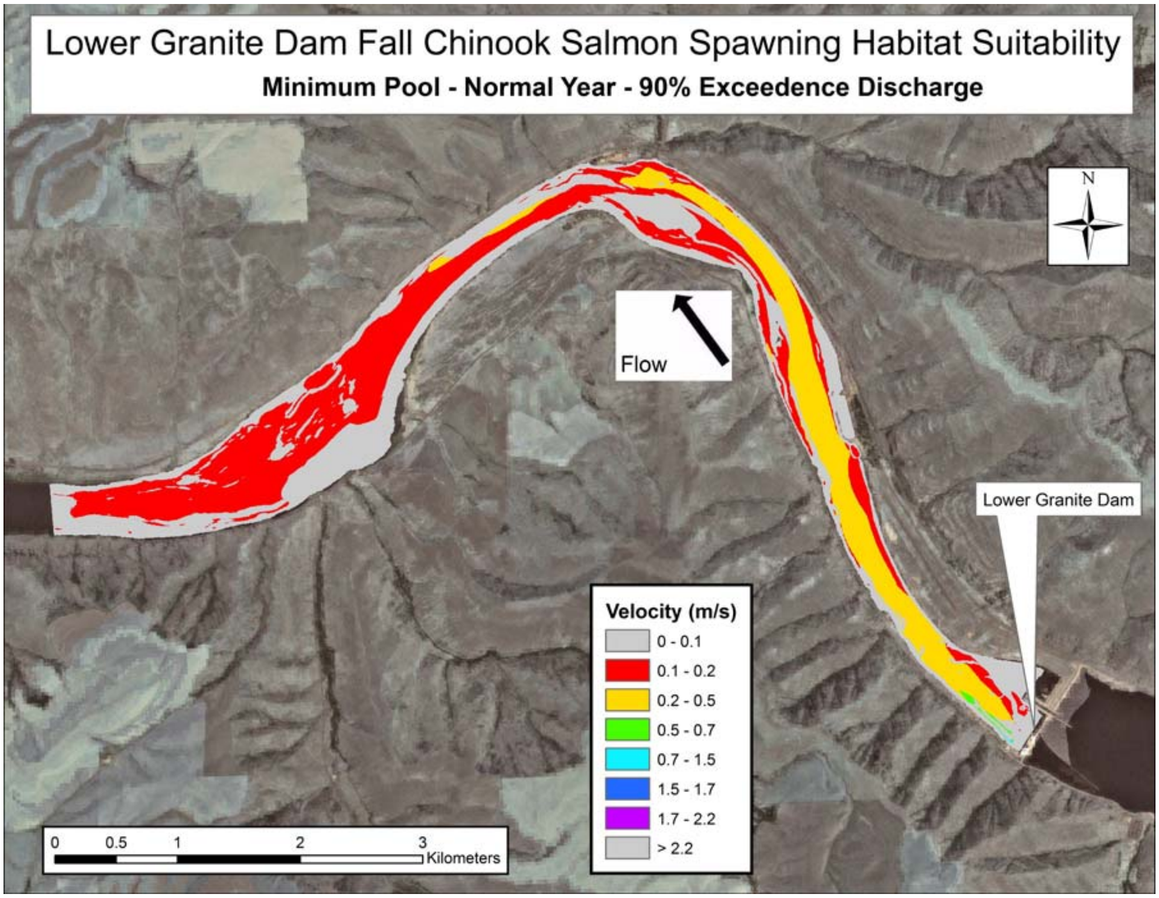

Figure C.62. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 90% Exceedence Discharge (19.1 kcfs) During a Normal Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

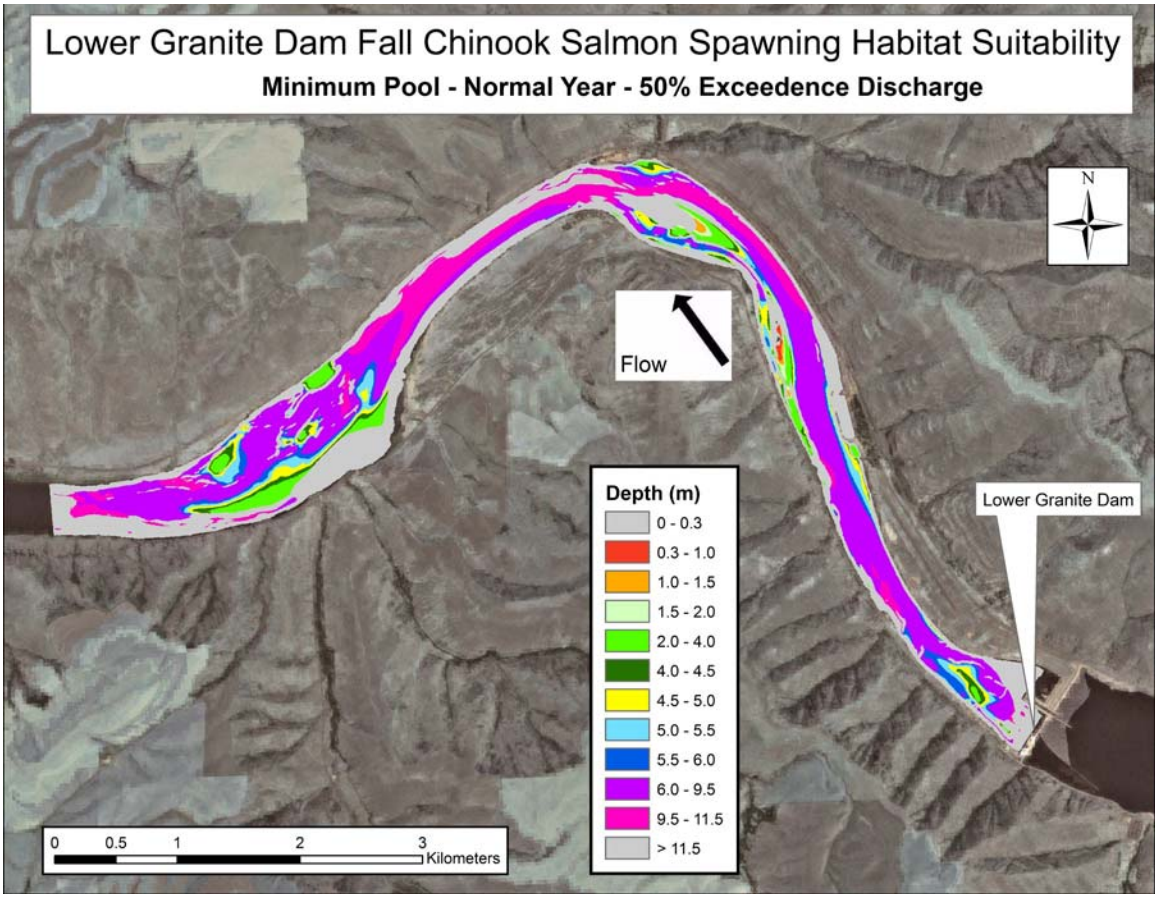

Figure C.63. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 50% Exceedence Discharge (21.7 kcfs) During a Normal Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

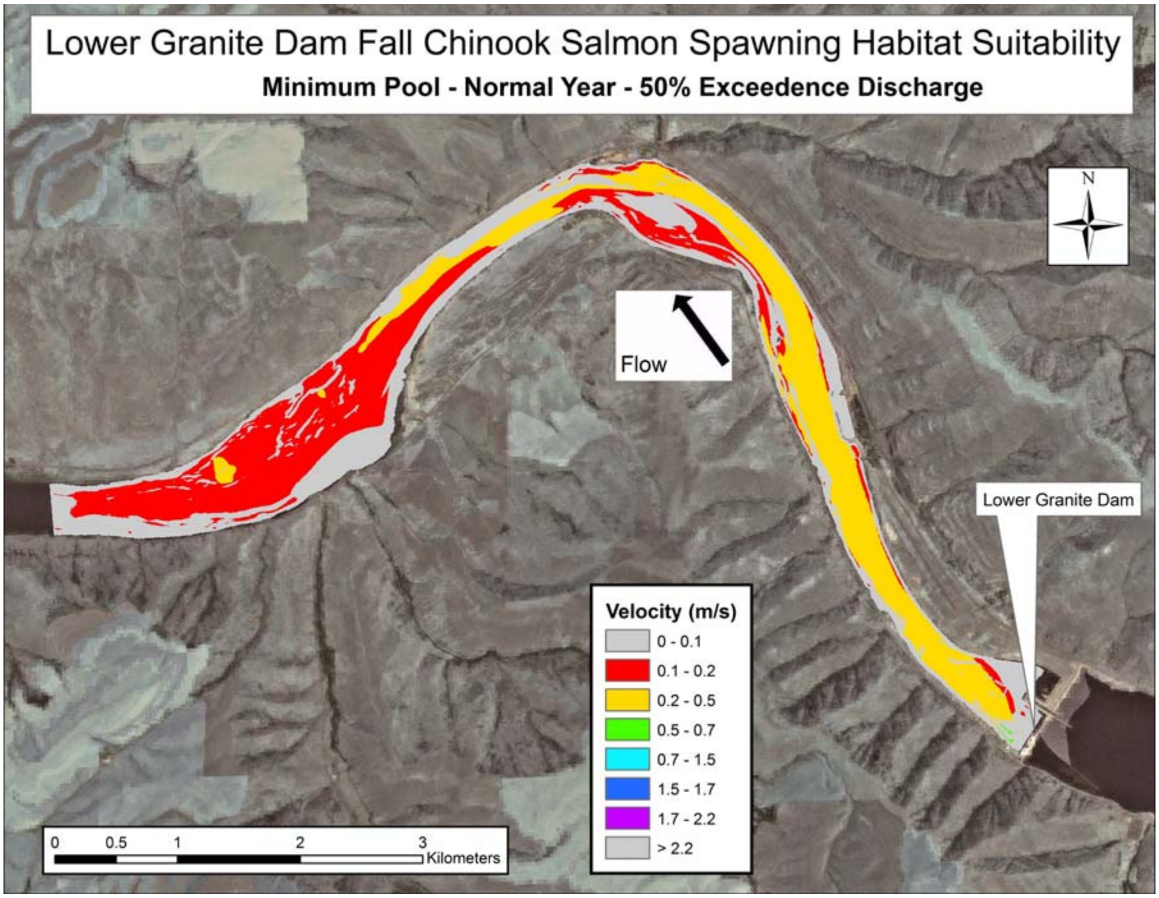

Figure C.64. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 50% Exceedence Discharge (21.7 kcfs) During a Normal Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

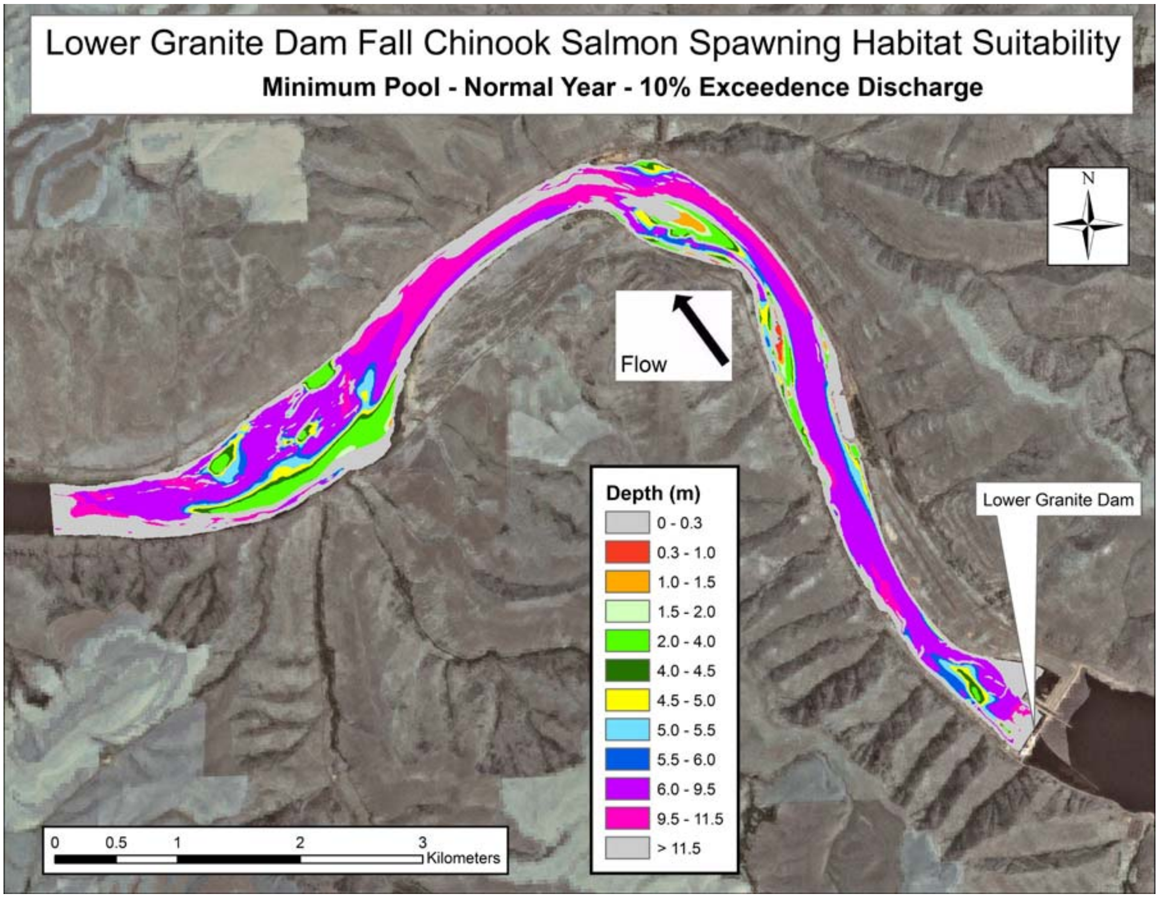

Figure C.65. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 10% Exceedence Discharge (34.5 kcfs) During a Normal Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

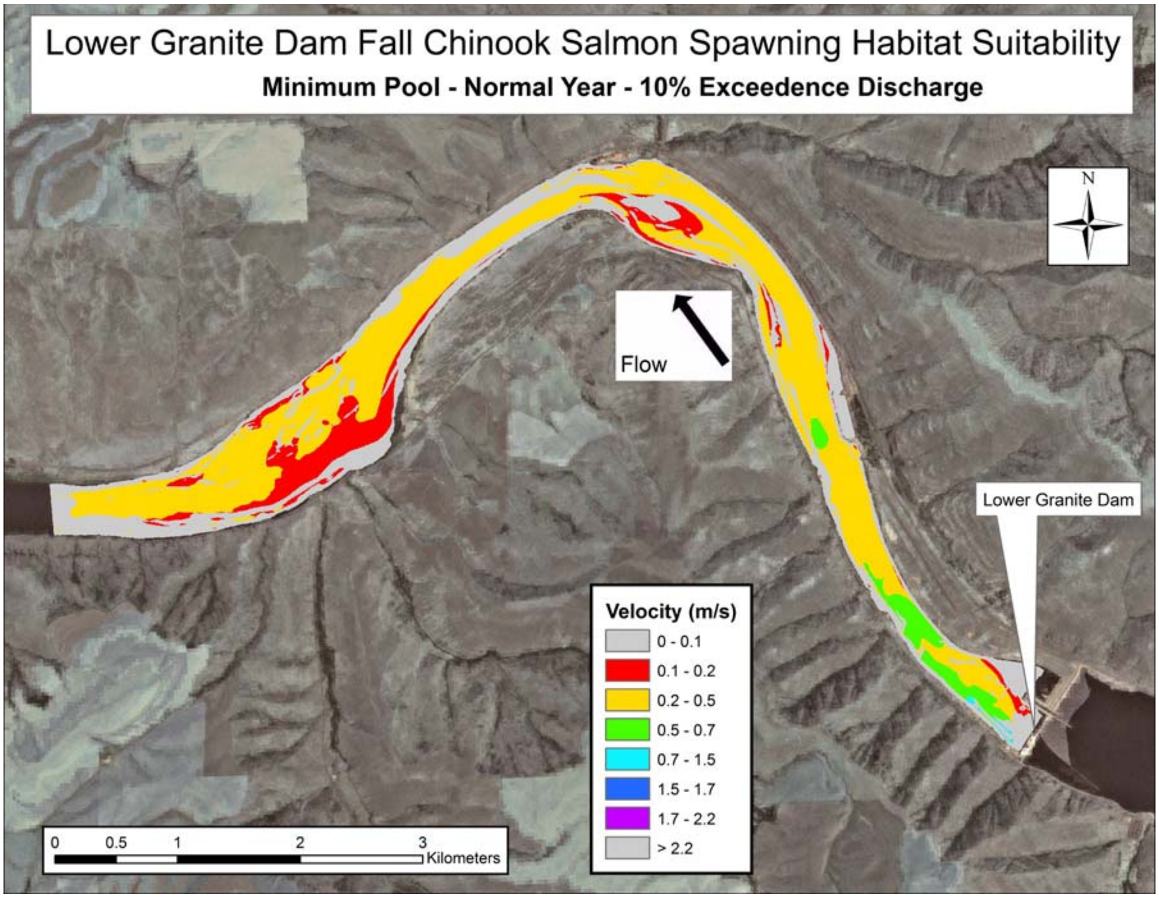

Figure C.66. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 10% Exceedence Discharge (34.5 kcfs) During a Normal Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

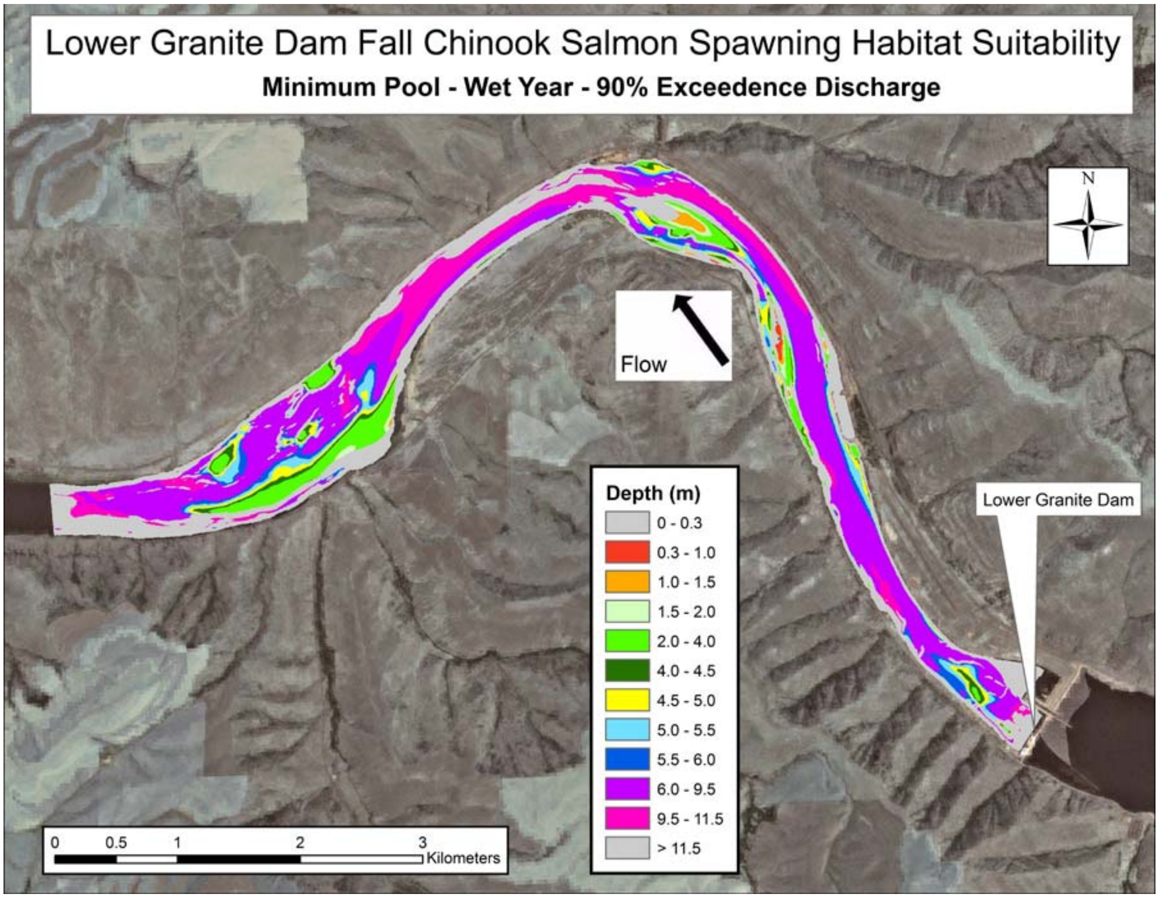

Figure C.67. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 90% Exceedence Discharge (34.5 kcfs) During a Wet Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

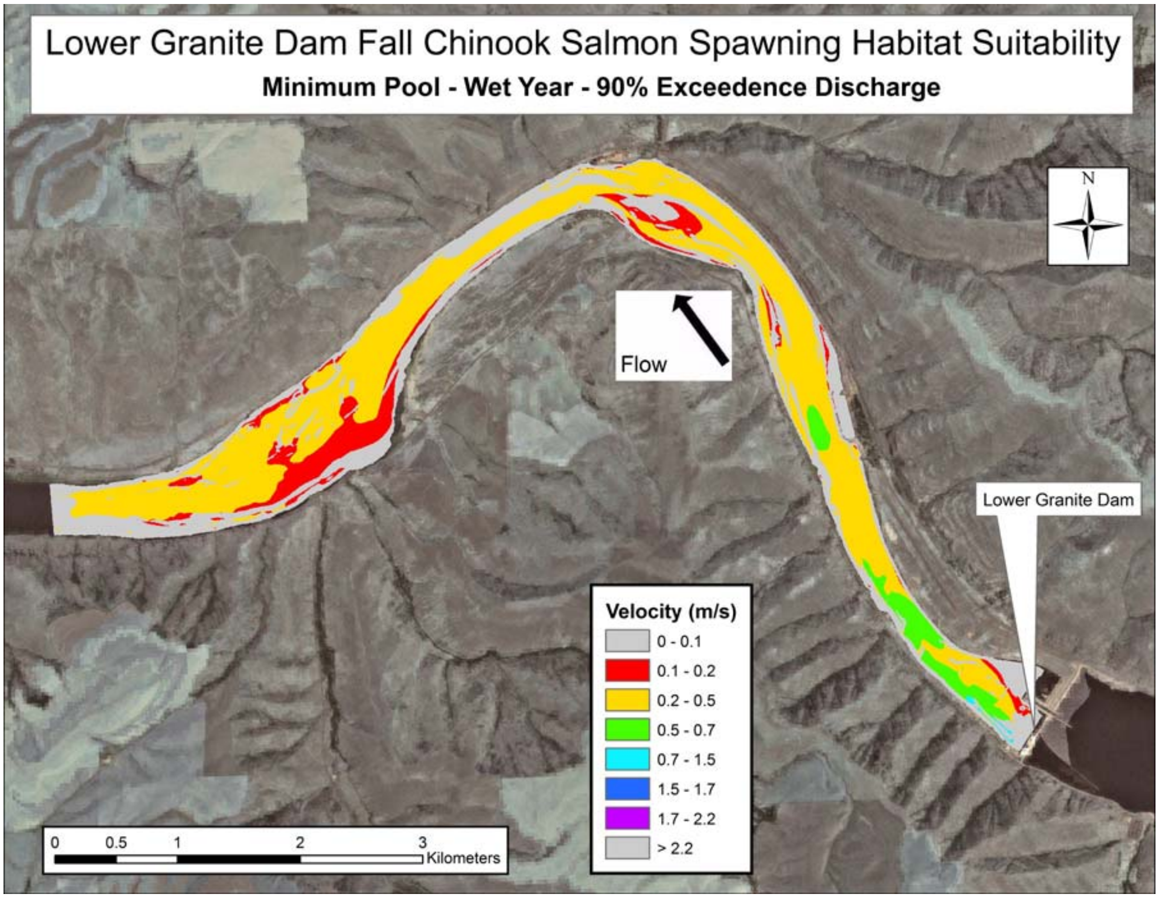

Figure C.68. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 90% Exceedence Discharge (34.5 kcfs) During a Wet Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

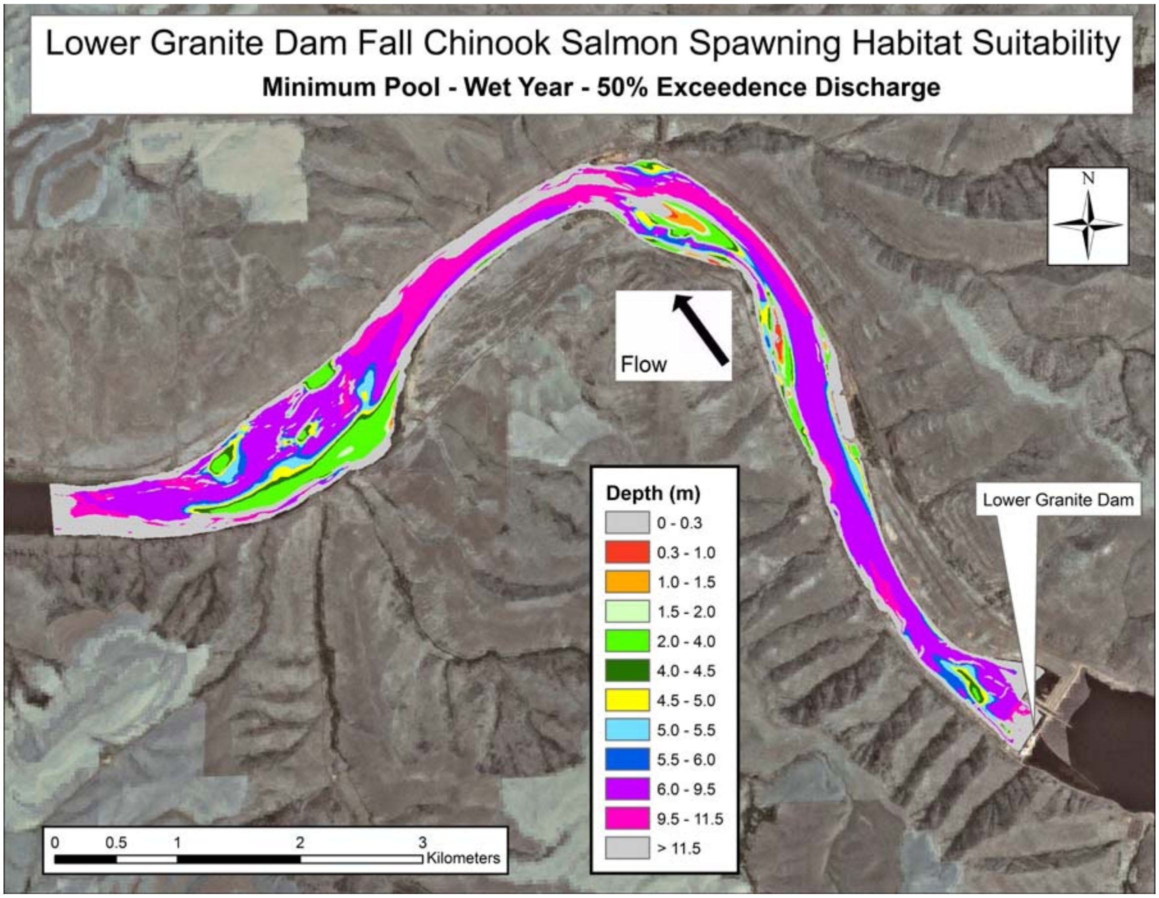

Figure C.69. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 50% Exceedence Discharge (44.0 kcfs) During a Wet Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

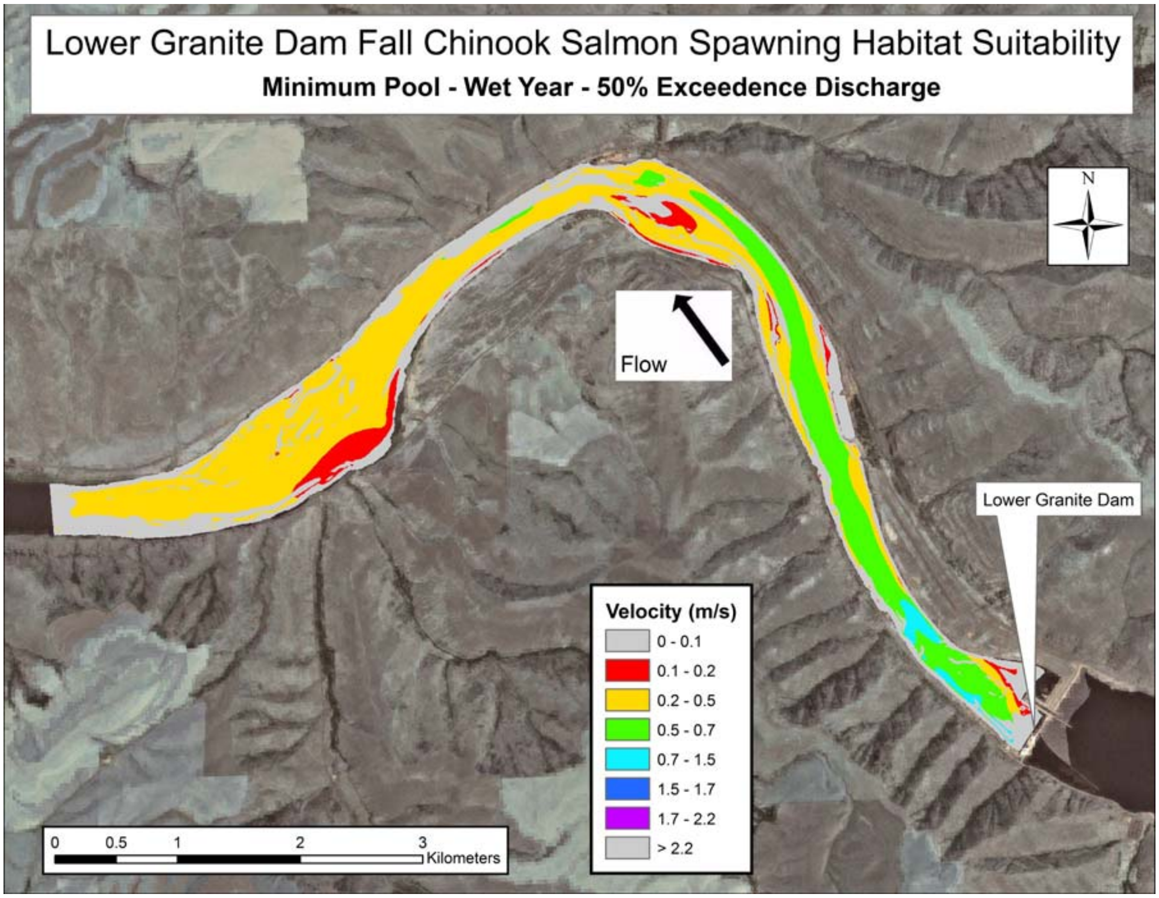

Figure C.70. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 50% Exceedence Discharge (44.0 kcfs) During a Wet Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

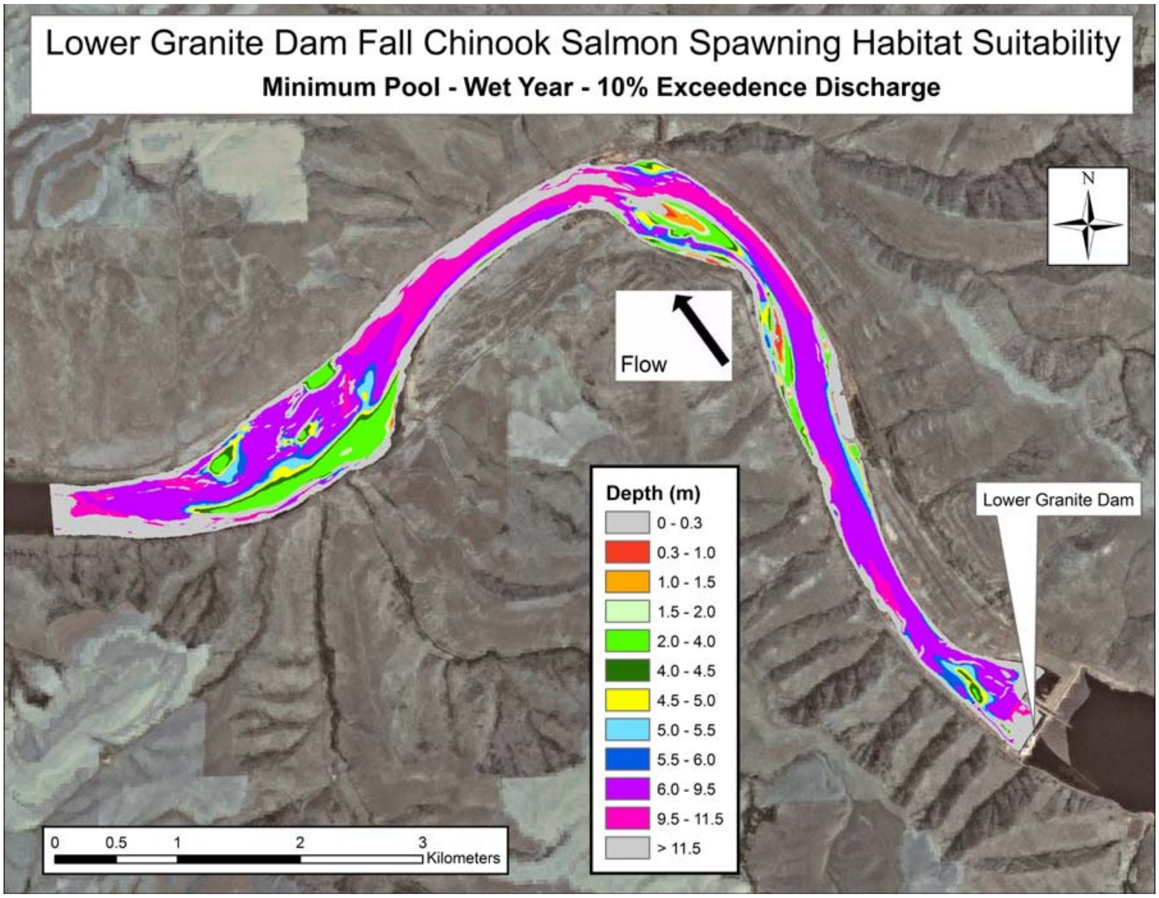

Figure C.71. Depth within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 10% Exceedence Discharge (52.0 kcfs) During a Wet Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.

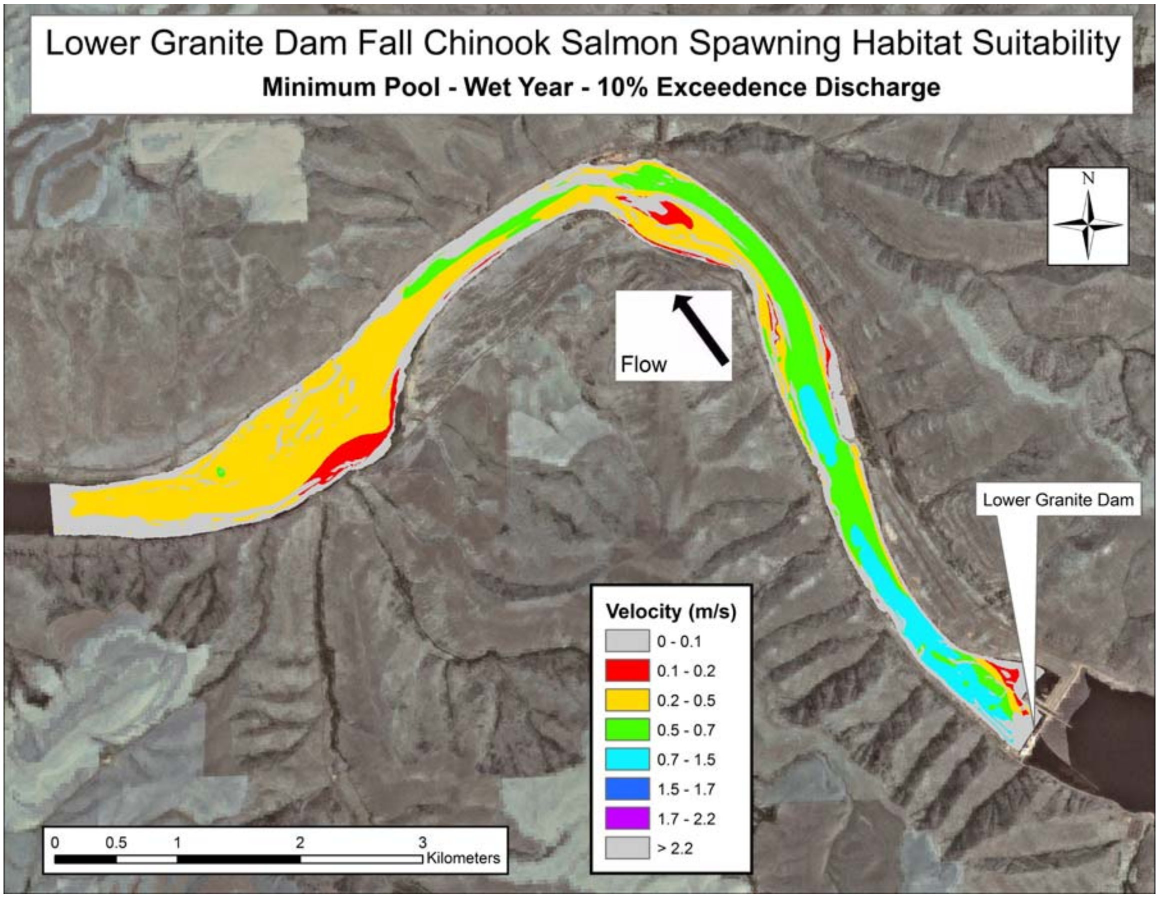

Figure C.72. Velocity within Fall Chinook Salmon Spawning Habitat Suitability Downstream from Lower Granite Dam, Based on a 10% Exceedence Discharge (52.0 kcfs) During a Wet Water Year, with the Little Goose Dam Forebay at Minimum Pool Elevation. Gray values are outside the fall Chinook salmon spawning habitat criteria.