U.S. Fish and Wildlife Service

Icicle Creek Instream Flow and Fish Habitat Analysis for the Leavenworth National Fish Hatchery

U.S. Fish and Wildlife Service
Columbia River Fisheries Program Office
Vancouver, WA 98683

On the cover*: The Icicle Creek historical channel at approximately 150 cfs taken in October 2011. This view is about half way between structures 2 and 5 and is typical of the study site. Note the undercut banks with overhanging vegetation which is excellent fish habitat but there is a lack of alluvium higher up along the river banks. Photograph by Joe Skalicky.*

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Final 401 CWA Certification Order No. 7192 for the Leavenworth National Fish Hatchery on Icicle Creek, Chelan County, Washington

Submitted to:

The Section Manager, Water Quality Program, Washington Department of Ecology
Central Regional Office, 15 West Yakima Ave., Suite 200, Yakima, WA 98902

Submitted for:

The U. S. Fish and Wildlife Service, Leavenworth National Fish Hatchery
12790 Fish Hatchery Road Leavenworth, WA 98826

Submitted by:

The U. S. Fish and Wildlife Service, Columbia River Fisheries Program Office
1211 SE Cardinal Court, Suite 100
Vancouver, WA 89683

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Disclaimers

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the U.S. Fish and Wildlife Service.

The mention of trade names or commercial products in this report does not constitute endorsement or recommendation for use by the federal government.

Executive Summary

The purpose of this study was to characterize the relationship between streamflow and fish habitat in the Icicle Creek historical channel, Washington, upstream from the Leavenworth National Fish Hatchery. The creek exhibits a very complex set of fish habitats including many islands, back channels and overhanging banks. Peak stream flow occurs during late spring and low flows occur during late summer and fall. Fish species selected for habitat assessment included: coho, spring/summer Chinook, steelhead/rainbow trout, bull trout, Westslope cutthroat, mountain whitefish Pacific lamprey and suckers.

The method used incorporated output from a two-dimensional hydrodynamic model (River2D) and a unique GIS cell-based habitat modeling approach. The method was approved by the Washington State Department of Ecology. This method is based on the premise that stream dwelling fish prefer a certain range of depths, velocities, substrates and cover types, depending on the species and life stage, and that the availability of these preferred habitat conditions varies with streamflow. Weighted Usable Area (WUA) is the primary product of PHABSIM and the primary results produced for the GIS cell-based habitat modeling approach. Weighted usable area is an index of habitat availability or quantity for the selected species/life stage at each simulated flow. Weighted usable area was calculated for a range of streamflows between 20 and 1500 cfs. Graphs and tables of WUA versus flow are presented for each life stage and species of interest. This technical information can be used by the relevant stakeholders and managers along with other site specific hydrological and biological information as the basis for instream flow recommendations in the Icicle Creek historical channel.

An instream flow and fish habitat analysis cannot by itself determine the instream flow required by a given fish species. The WUA graphs only show whether an increase or decrease in streamflow will increase or decrease the quantity of fish habitat. The study's predicted fish habitat versus streamflow results have to be interpreted by knowledgeable biologists and others to arrive at an instream flow regime that satisfies applicable laws.

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Introduction

On January 7, 2010 the Washington Department of Ecology (Ecology) issued Order number 7192, in the matter of granting a Water Quality Certification to the U.S. Fish and Wildlife Service (USFWS) for the Leavenworth National Fish Hatchery (Leavenworth NFH). The certification requires implementation of an instream flow study to aid in determining the effect of hatchery operations on fish habitat. This report describes the Leavenworth NFH's requirement to evaluate fish habitat with an instream flow study as required in the CWA Certification Order No. 7192. Prior to implementing this study, a detailed study plan was submitted to Ecology for approval. The study plan was approved by Ecology and included input from the Leavenworth NFH, Washington Department of Fish and Wildlife (WDFW), The USFWS Mid-Columbia Fishery Resource Office and Ecology. A companion report submitted to Ecology details fish passage evaluations in Icicle Creek and is not discussed here, but the results of this instream flow study supported components of the passage evaluations.

Project Goal

The overall goal of the Icicle Creek Instream Flow Study is to quantify fish habitat as a function of streamflow in the Icicle Creek historical channel (hereafter referred to as historical channel) for the required fish species lifestages; to determine streamflows required to maintain channel structure, complexity, and physical habitat; and to provide guidance regarding the integration of the target species habitat needs for the Icicle Creek historical channel hydrograph configuration. With the exception of streamflow in cubic feet/second (cfs) and River Mile (RM) all measurement units are metric including calculations of habitat unless otherwise noted.

Objectives

1) Produce species/lifestage specific habitat – flow relationships using a two-dimensional (2D) hydrodynamic model and a GIS cell-based habitat model.

2) Produce spatially explicit maps depicting the distribution of the primary habitat variables for representative stream flows.

3) Produce tabular and graphic results that quantify species/lifestage specific habitat for streamflows from 20 to 1,500 cfs and the corresponding incremental gains or losses over a range of flows.

4) Estimate flushing flows, channel maintenance flows, and channel forming flows for the Icicle Creek historical channel.

5) Integrate species-specific habitat-flow relationships to accommodate the habitat needs for multiple target fish species/lifestages that may occur simultaneously in the Icicle Creek historical channel.

Project Description

The Leavenworth NFH is located in North Central Washington adjacent to Icicle Creek at river mile (RM) 3.0 and is two miles south of Leavenworth, Washington. In the 1930's, the 160 acre Leavenworth NFH was authorized by Congress as mitigation for fish losses associated with the construction and operation of Grand Coulee Dam. Leavenworth NFH withdraws surface water from Icicle Creek at RM 4.5, utilizes it for fish production at the hatchery, and returns it to Icicle Creek at RM 2.8 (Figure 1). The hatchery annually produces 1.2 million juvenile spring Chinook salmon and provides acclimation facilities for coho salmon. These salmon contribute to commercial, sport, and tribal in-river and ocean fisheries alike.

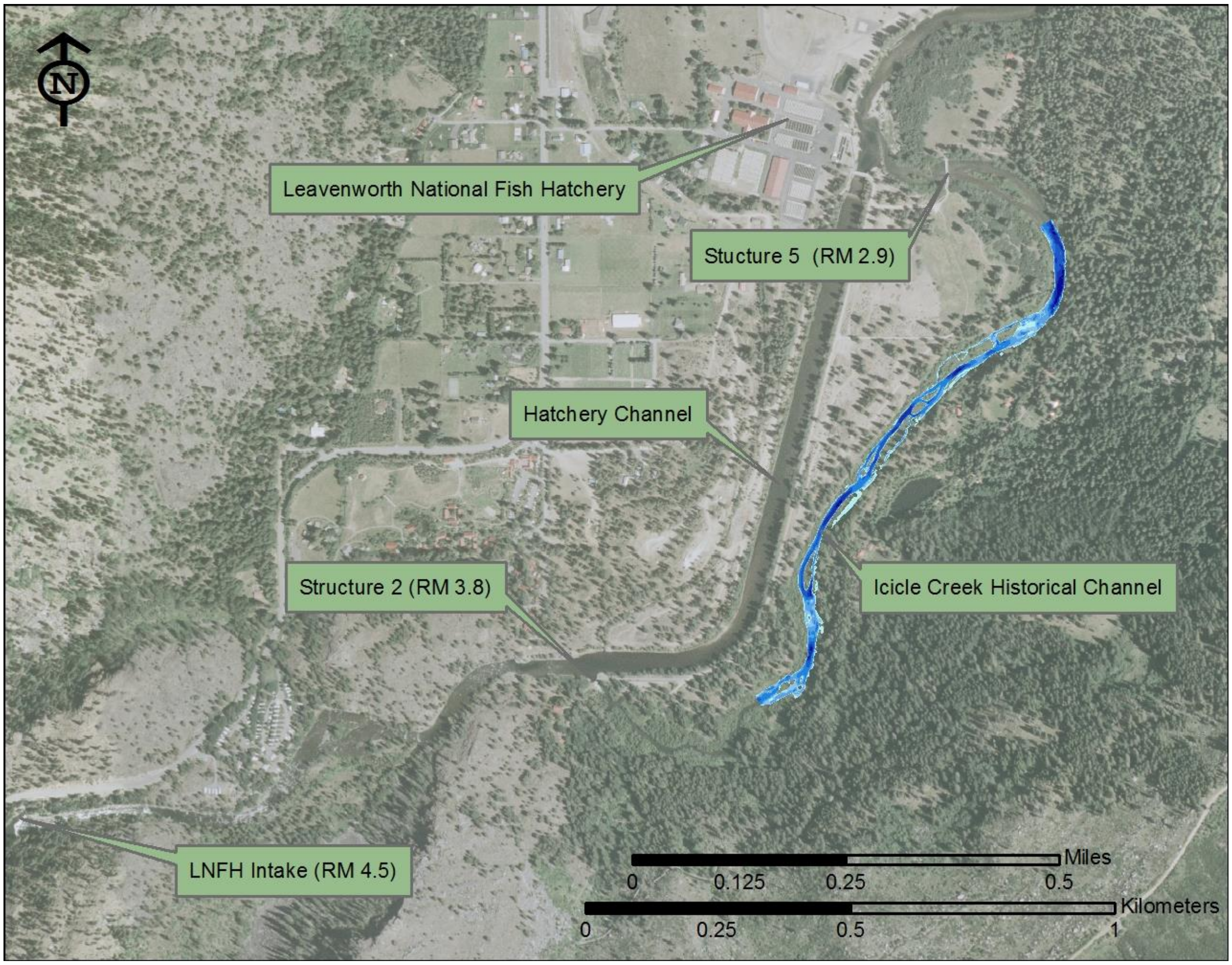

Figure 1. **Project overview depicting the location of Leavenworth NFH, the hatchery intake, the Icicle Creek historical channel, the Icicle Creek hatchery channel, and Structures 2 and 5.**

Instream Flow Study Reach Description

The portion of Icicle Creek to be evaluated with an instream flow study is known as the Icicle Creek historical channel and extends approximately one mile from RM 2.8 to 3.8. Most of the historical channel was modeled with the exception of the lower and upper one quarter miles. The downstream model boundary requires a robust rating curve that is not hydraulically affected by other flow parameters (Icicle Creek – hatchery channel spillway or Wenatchee River backwater), islands, and/or artificial control structures (Structure 5). As such, the boundary is upstream from the confluence of the Icicle Creek – hatchery channel (hereafter referred to as hatchery channel) and Structure 5. The reach to be modeled is depicted in Figure 2 and is the portion highlighted in blue. To address an unexpected funding shortfall in Fiscal Year 2012, the top 400 m (~1/4 mile) of the study site near Structure 2 was omitted from the hydrodynamic model; however estimates of fish habitat are valid for this area since the fundamental channel morphology and hydrodynamics appeared to be similar.

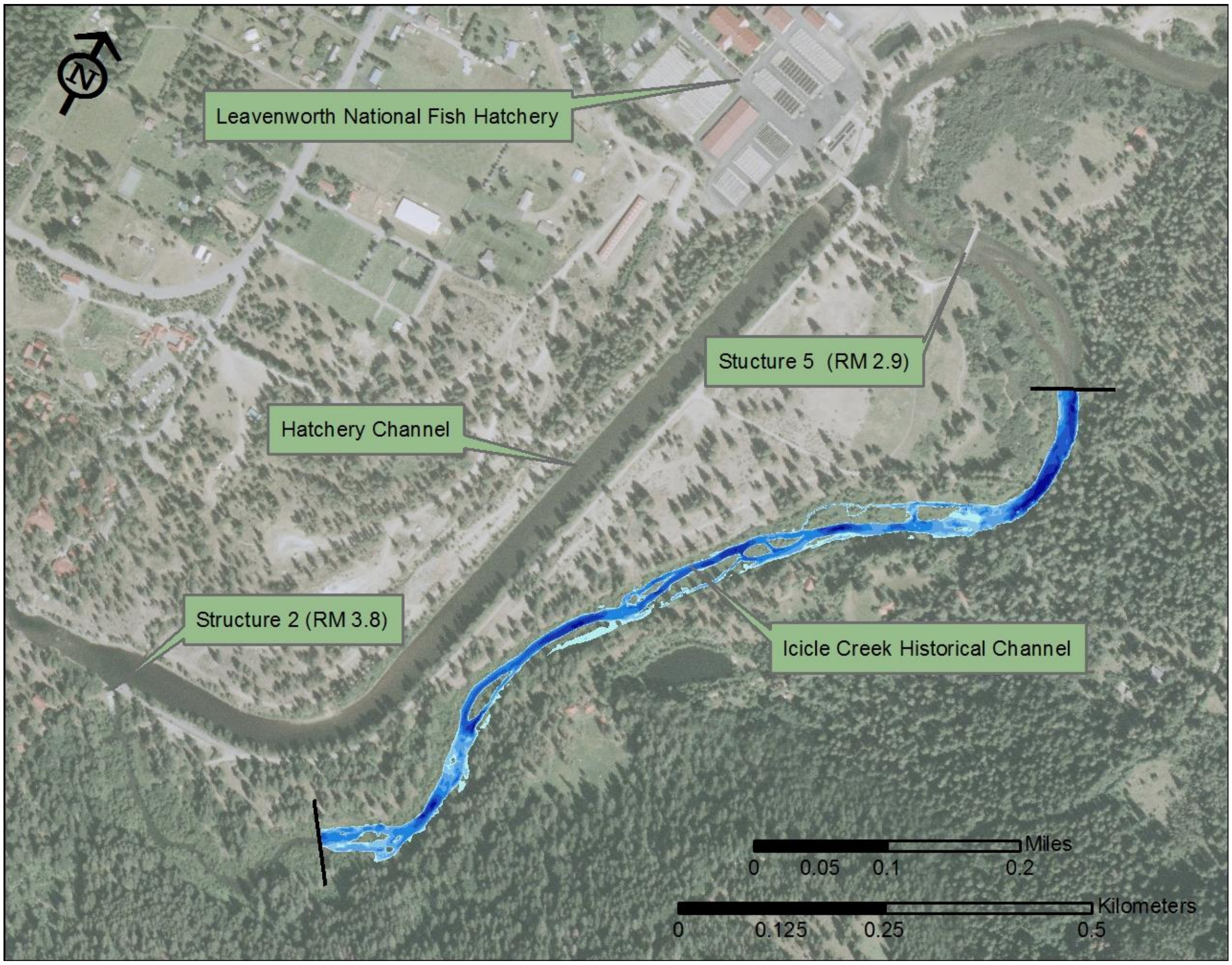

Figure 2. Overview of the instream flow study site. The Icicle Creek historical channel is outlined in blue and the black bars depict the upstream and downstream boundaries of the instream flow study reach.

Leavenworth National Fish Hatchery History

In 1939, a series of small control structures were built in the historical channel to function as an actual instream hatchery and to assist with the capture of migrating anadromous salmon for hatchery broodstock. A separate channel (hatchery channel) was also built adjacent to the Icicle Creek historical channel (Figure 2) to control flows between the two channels for hatchery operations. This regulation of streamflow in addition to Icicle Creek being a very high sediment load stream induced sediment deposition in the historical channel and led to subsequent colonization of the stream channel and banks by riparian plants (Lorang 2005). The historical channel was used for fish production from the 1940's to the late 1970's, and seasonally, as recently as 2005. Some of the small structures have since been removed but two structures remain at the terminal ends of the Icicle Creek historical channel, Structures 2 and 5 (Figure 2). Due to the streamflow limitations through Structure 2, the historical channel has not benefited from the channel forming flows and undercut banks are far more extensive than they otherwise might be (Jim Craig, pers. comm. 2010). Historic and new sedimentation from upstream mass wasting and the sediment deposits from the old control structures are still present. The Icicle Creek historical channel still appears to be in flux.

Hydrology

The Icicle Creek drainage is located on the eastern flanks of the Cascade Mountain Range and the hydrology encompasses an area of 193 square miles. Icicle Creek is a high elevation drainage with 14 glaciers, 102 lakes, and 85 tributaries. The hydrology is primarily driven by snowmelt, and peak flows as measured by the USGS Gage #12458000 (Icicle Creek above Snow Creek near Leavenworth, WA) occur during late spring, while low flows occur during late summer, fall, and winter (Figure 3). Extremes for the period of record range from a minimum of 44 cubic feet per second (cfs) to a maximum of 19,800 cfs, and the mean annual flow is 624 cfs. The USGS gage at RM 5.8 is located above all major points of diversion. Icicle Creek streamflows below the USGS gage are altered by water diversions which reduce downstream flows. The City of Leavenworth and the Icicle-Peshastin Irrigation District divert water above the Snow Lakes trailhead (RM 5.7), and Leavenworth NFH and the Cascade Orchard Irrigation Company divert water below the trailhead (RM 4.5). These irrigation diversions can remove up to 48% and 79% of the mean monthly August and September streamflows, respectively (Mullan *et al.* 1992). To assure adequate water for the Leavenworth NFH, a supplementary water supply (~16,000 acre-feet) was developed in the Snow Lakes Basin (Nada, Upper and Lower Snow Lakes, about seven miles upstream from Leavenworth NFH. Without the water release of approximately 50 cfs from the Snow Lakes Basin, from late July through early October, some downstream reaches of Icicle Creek could potentially go dry in low snow pack years.

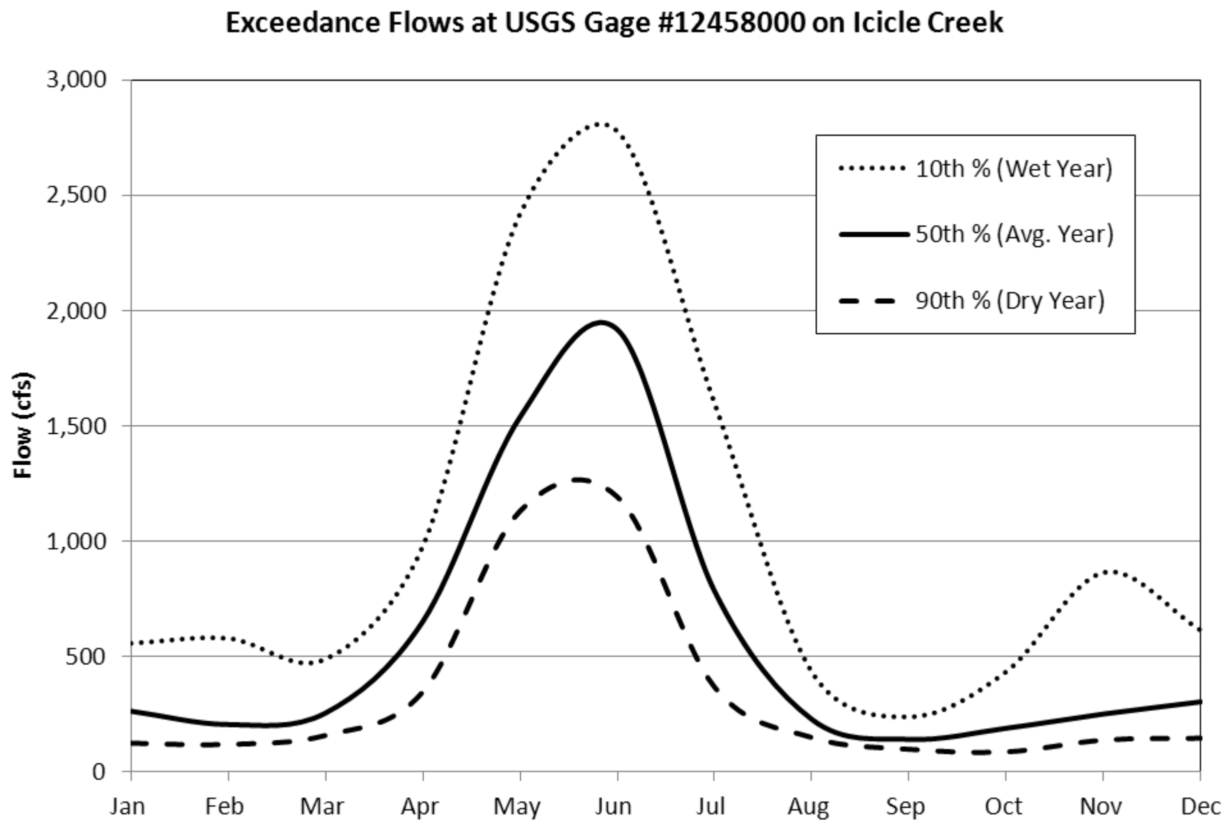

Figure 3. **Exceedance flows as measured at USGS Gage #12458000 on Icicle Creek near Leavenworth, WA for an average, wet, and dry year for the period of record (1936 – 2012). Mean annual flow is 624 cfs.**

Hydrodynamic Modeling

Hydrodynamic Model Introduction and Overview

The use of two-dimensional hydrodynamic models has gained wide use and acceptance in fisheries and instream flow assessments (Tharme 2003, Stewart et al. 2005, Mingelbier et al. 2008, Hatten et al. 2008, Lee et al. 2010, Waddle 2010, Ban et al. 2011). Two-dimensional flow models describe flow dynamics in two horizontal vectors whereas a one-dimensional model describes them in only one. Neither model calculates any difference in vertical conditions thus they are termed "depth-averaged" models.

For the historical channel instream flow assessment, the River2D hydrodynamic model (Ghanem et al. 1996, Steffler and Blackburn 2002) was used to simulate continuous surfaces of hydrologic parameters throughout the study site. The only parameters output from the model were depth and velocity magnitude. River2D is a two dimensional (2D), depth averaged, finite element hydrodynamic model. The model and documentation are available at: http://www.river2d.ualberta.ca/. As with other 2D models, River2D uses three governing equations to solve for three unknowns; depth and mass flux in both the x and y directions. As well, the model has three basic assumptions.

1. *The vertical pressure distribution is hydrostatic. This can potentially limit the accuracy of the model in areas of steep slopes and rapid changes of bed slopes. In general, bed features of horizontal size less than about 10 depths (typically dune formations) will not be modeled accurately.*
2. *The distributions of horizontal velocities over the depth are essentially constant (depth-averaged).*
3. *Wind and Coriolis forces are assumed negligible. These forces are only significant to very large bodies of water, the historical channel not being one of them.*

Fundamental Concepts

Conservation of Mass. Mass conservation is the principal that at any point in the model, inflow of fluid matches outflow. This is evidenced by summing the mass flux in the x and y directions and setting the total mass flux equal to the change in depth over a smaller time increment. As such, if inflow is greater than outflow over a small time frame, the depth increases. If inflow equals outflow, the depth is unchanged, and so on. This approach is used in hydrodynamic models to allow simulation of unsteady flow conditions based on varying inflow and outflow.

Conservation of x- and y-direction momentum. A major contribution of 2D flow models is the ability to represent physical forces acting on the fluid. Changes to the momentum in River2D are represented as a sum of forces. The forces include shear stresses, gravitation force and friction forces. The great advantage of this representation in rivers is evidenced by the representation of divided flow situations (islands) when compared to transect-based models. This is one the reasons we chose River2D in the Icicle Creek historical channel over the PHABSIM method.

Frictional Forces. Friction in River2D is represented by a continuous surface or "skin" which is constructed directly from effective bed roughness height. Effective roughness height is used because it tends to remain constant over a wider flow range than other measures of roughness including Manning's n and it can be approximated from dominant bed material.

The ability of River2D to accurately model supercritical flow and edge wetting is an additional advantage over transect based modeling. In the event that the historical channel study site has any supercritical flows we can be confident that the model will accurately simulate them. River2D uses a Petrov_Galerkin upwinding formulation to solve the flow-field. With this feature, the model can represent situations where upstream flow conditions limit the water surface at a downstream point. This enables the model to accurately simulate hydraulic conditions over sills, steep bars and other conditions that could possibly be present in the historical channel.

The historical channel study site has many side channels that are only wet at specific streamflows. This is a difficult process for numerical models and River2D has a unique and robust method of estimating this. The depth of flow is a dependent variable and is not known in advance when performing a two-dimensional flow simulation. As such, the horizontal range of the water coverage is therefore unknown. Additionally, significant computational difficulties are encountered when the depth is very shallow or it is dry at part of the modeled area. Various methods have been proposed to deal with this "edge wetting" problem. For example, some models simply neglect or drop out partially wet edge elements; others declare edge elements to be porous. The River2D model handles these occurrences by incorporating a simplified ground water model with the surface water model. In these wet/dry areas, the model changes the surface flow equations to groundwater flow equations. This allows a mesh element to have some nodes that are under surface water using the open-channel flow equation of mass conservation and some that are under the land surface using a sub-surface representation for mass conservation. A continuous free surface with positive (above ground) and negative (below ground) depths is calculated. This unique approach allows calculations to carry on without changing or updating the boundary conditions as water levels fluctuate.

Icicle Creek Hydrodynamic Modeling – Methods & Results

Both the Methods and Results for hydrodynamic modeling are presented here for reader continuity and they are precursors to the subsequent habitat assessment.

Hydrodynamic modeling in the Icicle historical channel was comprised of the following steps:

1. ***Develop a digital elevation model (DEM) of the Icicle Creek historical channel study site***
2. ***Collect hydrologic boundary data (paired inflow discharge and outflow WSE's)***
3. ***Collect representative roughness data***
4. ***Construct Computational Meshes***
5. ***Calibrate and Validate the hydrodynamic model***
6. ***Simulate unmeasured flows***

1. Digital Elevation Model Development

Two dimensional hydrodynamic models require a digital elevation model (DEM) of the stream channel to construct computational meshes and simulate streamflows. For the Icicle Creek historical channel instream flow assessment all geographic data including the DEM, were collected in or adjusted to a common projection and coordinate system, *Lambert Conformal Conic and Washing State-plane North*, respectively. In addition, the *Horizontal Datum, North American Datum of 1983 (NAD83)* as well as the *Vertical Datum, North American Vertical Datum of 1988 (NAVD88)* was used.

Preexisting topographic information consisting of LiDAR data collected in 2006 (Watershed Sciences 2006) was initially evaluated for use but found to have too much error. Lidar for the Icicle Creek area was flown during the month of October, 2006 with a reported point density of ≥8 points/meter. The vegetative cover in this area ranges from flat, grassy banks along the creek, to steep, highly vegetated slopes. Surveying with RTK and a total station was conducted during October, 2011. The total station points, accurate within ±5 mm were compared with the Lidar points classified as bare earth. Both sets of points were loaded into a GIS and the Near tool was used to determine the closest Lidar point to each total station point. The first 50 pairs of points, representing the smallest distance (≤25 mm) between a Lidar and a total station point, were compared. The difference in elevation values ranged from 1 mm to 1.7 m. The vegetation cover for each point as well as the location along the creek was noted. There is no consistent variation of elevation values given vegetation or location. Due to the error and inconsistencies, LiDAR data was not used. Collection of new LiDAR data was scheduled but inclimate weather preempted data collection.

Up to four survey grade Real Time Kinematic (RTK) GPS instruments and a single auto-tracking total station were used to collect topographic and bathymetric data in the field (Figure 4). The RTK accuracy is approximately 3 cm. Data was collected along natural stream and channel breaks depicting the topography of the stream channel. Data collection occurred on the weeks of October 18th and November 1st in 2011 and again the week of September 17th 2012. The September date was the first opportunity to collect deep water bathymetry which is only accessible at the lowest of streamflows in the Icicle Creek historical channel. A total of 4,988 georeferenced data points were collected in Icicle Creek historical channel study site (Figure 5).

At each point, X, Y and Z geographic positions were recorded as well measures of substrate and cover.

Figure 4. Survey grade RTK GPS (left) and Total Station used to collect DEM data of the Icicle Creek historical Channel Study Site.

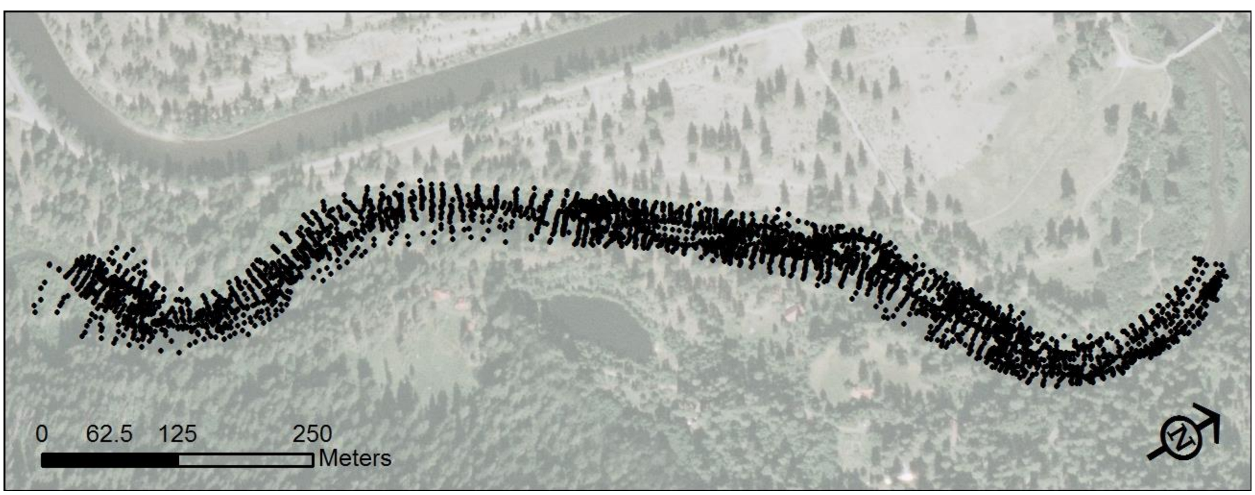

Figure 5. Point data collected in the study site comprised of 4,988 points used to generate a DEM. The hatchery channel with water in it is visible above the historical channel study site.

2. Collect Boundary Data (Paired inflow and outflow WSE's)

Using USGS rating curve standards, staff from the USFWS, Water Resources Division and Leavenworth NFH jointly collected hydrologic data in the historical channel in conjunction with other hydrologic evaluations related to hatchery operations. River2D requires two input boundary conditions for hydrodynamic simulation at a given discharge. These conditions include an inflow discharge at the upstream boundary and the corresponding downstream water surface elevation. Standard practice is to develop a rating curve so that all flow conditions between the lowest and highest flow can be simulated with the required data pairs (streamflow and water surface elevation). Table 1 depicts the relationship derived between streamflow at the upstream boundary and water surface elevation at the downstream boundary. In addition, the relationship between streamflow and the upstream boundary was derived to initiate each model run.

Table 1. – Relationship between streamflow and water surface elevations used for hydrodynamic modeling in the Icicle Creek historical Channel.

Discharge		Water Surface Elevations (m)	
cfs	cms	Downstream Boundary	Upstream Boundary
20	0.566	340.331	342.475
30	0.850	340.361	342.492
40	1.133	340.385	342.509
50	1.416	340.406	342.526
60	1.699	340.425	342.543
70	1.982	340.443	342.559
80	2.265	340.461	342.576
90	2.549	340.477	342.592
100	2.832	340.493	342.608
120	3.398	340.525	342.640
140	3.964	340.553	342.671
160	4.531	340.579	342.702
180	5.097	340.606	342.732
200	5.663	340.631	342.762
250	7.079	340.690	342.833
300	8.495	340.746	342.901
350	9.911	340.798	342.965
400	11.327	340.848	343.026
450	12.743	340.895	343.083
500	14.158	340.942	343.136
550	15.574	340.986	343.186
600	16.990	341.030	343.232
650	18.406	341.070	343.274
700	19.822	341.112	343.313
750	21.238	341.151	343.349
800	22.653	341.190	343.380
850	24.069	341.228	343.408

900	25.485	341.265	343.433
950	26.901	341.302	343.454
1000	28.317	341.339	343.471
1050	29.733	341.372	343.485
1100	31.148	341.410	343.495
1150	32.564	341.442	343.501
1200	33.980	341.476	343.504
1250	35.396	341.509	343.503
1300	36.812	341.540	343.499
1350	38.228	341.573	343.491
1400	39.644	341.602	343.479
1450	41.059	341.637	343.464
1500	42.475	341.668	343.445

3. Collect Representative Roughness Data

Frictional bed forces within a moving body of water have a direct effect on the fluids moving past them. Large boulders will slow water down more than small pebbles due their greater height into the water column (roughness height). River2D requires a skin or layer of roughness heights to accurately estimate hydrodynamic conditions. Measurements of substrate size and their associated roughness heights were used to characterize roughness throughout the model domain. Substrate was mapped among classes matching WDFW's generic substrate codes (WDFW and WDOE, April 1, UPDATED 2013 publication). The field effort occurred in conjunction with the topographic and bathymetric mapping. In total 4,988 data points describing roughness (substrate size) were collected and mapped in the GIS. A Euclidian allocation algorithm was used in the GIS to interpolate substrate values in-between point collected in the field. Interpolation provided a continuous surface of substrate values (Figure 6). The average particle size for each dominate substrate class mapped was size was used to generate the roughness values. In addition, codes values for vegetation were also used to infer roughness values where required (Figure 7).

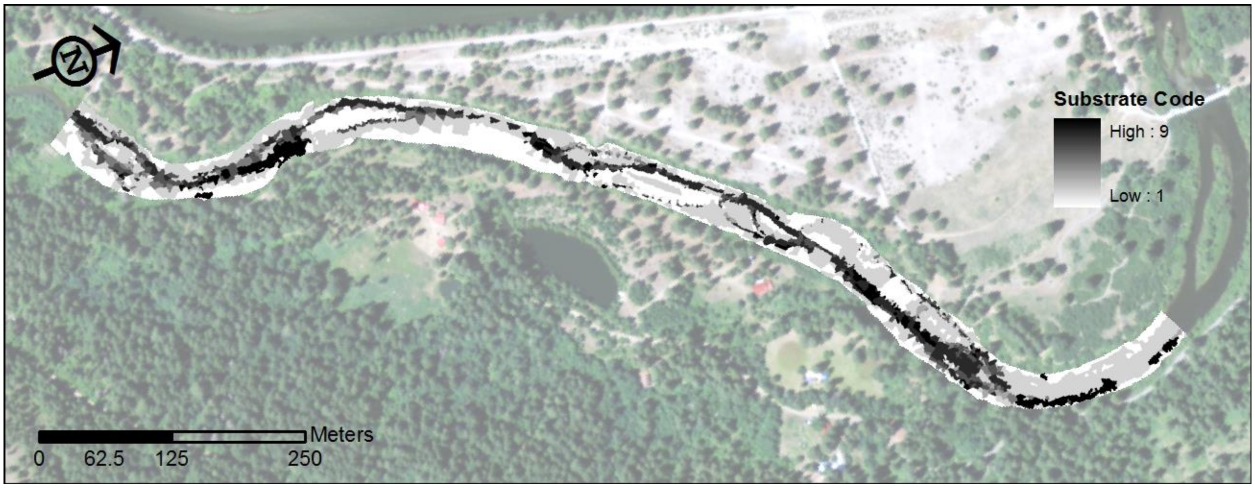

Figure 6. Continuous surface of substrate values interpolated from point data collected in the field using the Euclidean allocation algorithm.

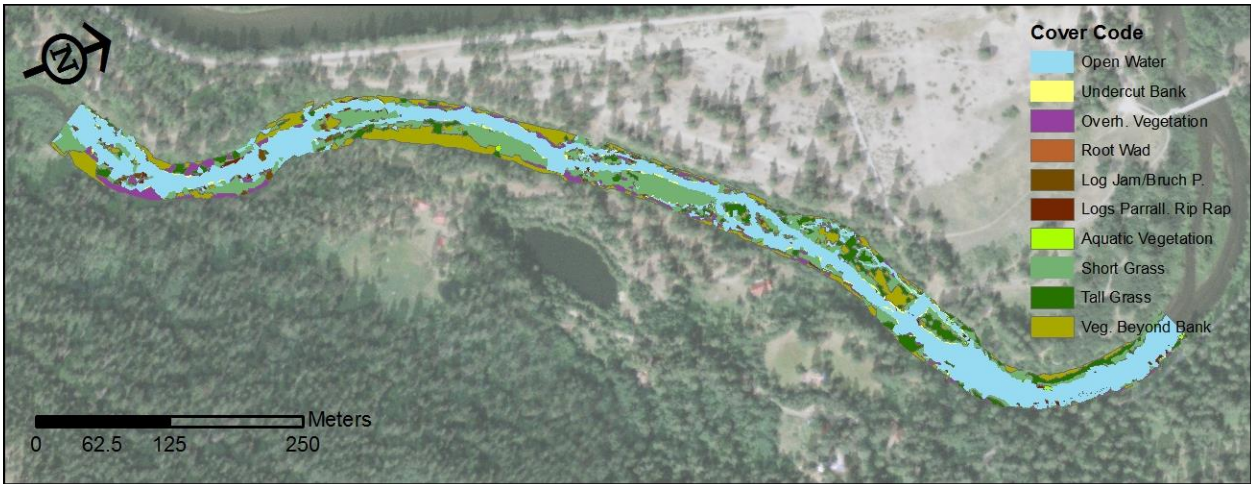

Figure 7. Continuous surface of cover values interpolated from point data collected in the field using the Euclidean allocation algorithm.

4. Computational Mesh Construction

The computational mesh, with its intersecting nodes is the numerical framework for which all the hydrodynamic computations both occur and are produced. In 2D hydrodynamic modeling, there is a trade-off between the density of nodes in the computational mesh, the required accuracy to represent the study site, and the time required to arrive at a solution for a single discharge. Generally, to obtain the best fit to the main channel and other significant or complex habitat areas, the mesh density will vary among locations and channel configurations (Figure 8). It is desirable to have a minimum of 8 to 10 nodes across channels carrying significant amounts of water to ensure the model can adequately convey flow downstream without calculating too much of the flow at any one node. The upstream and downstream model boundaries usually need to be subdivided into 20 or more nodes to again, ensure that no node carries too much of the computational burden. Some sites in the historical channel have numerous side channels or large boulders and it was necessary to increase the mesh/node density to capture and adequately represent the natural complexity.

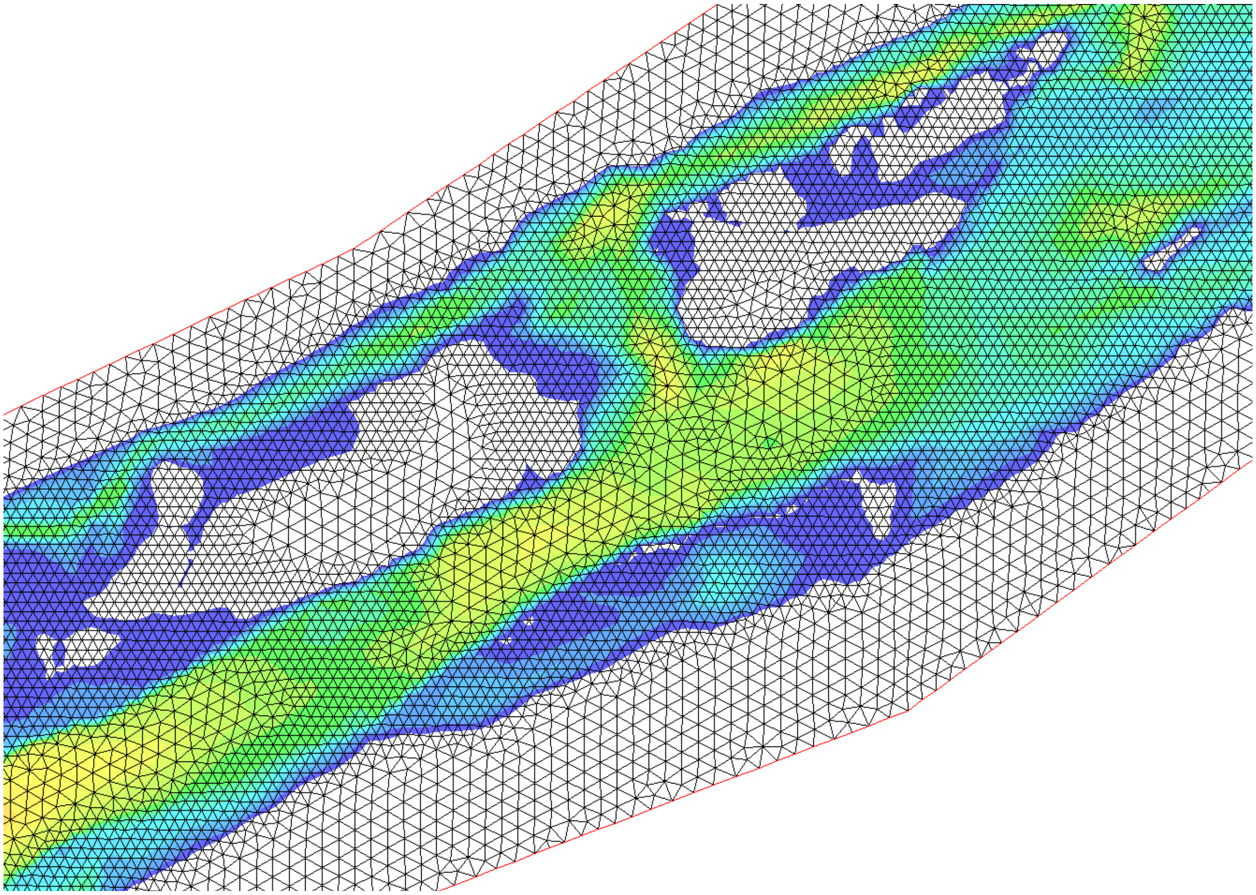

Figure 8. **Computational mesh from River2D depicting varying node densities across the stream channel. This section is Icicle Creek is in the lower third of the study site. The intersections of the mesh elements (triangles) define the computation domain and are called nodes.**

Three unique and distinct meshes were constructed for the low, medium and high flows, respectively. Figure 8 above depicts the mesh that was constructed for the medium flows. All three meshes were built with a dual mesh density composed of 1.0 and 2.0 meter spacing. However, areas with complex bathymetry had densities as fine as 0.125 m. A 2.0 m node spacing was only used for dry areas. The number of computational nodes ranged from 41,847 to 75,819 and elements from 82,382 to 149,168.

5. Model Calibration and Validation

When compared to the real world all models contain some amount of error. In hydrodynamic modeling, this error can arise from assumptions built into the model itself, but predominantly, errors arise from misrepresentations of the stream channel (DEM). Most error results from an under-representation of the stream bathymetry, bed interpolation related errors, and/or actual errors in bathymetry measurement. Additional "false" error can arise if changes in the stream channel occur between mapping of the stream channel and collection of model validation data. In 2D hydrodynamic modeling, the general calibration process consists of calibrating the model to three separate and bounding conditions; a low, average, and high flow condition. This is done by comparing and validating empirical field measurements of water surface elevation, velocity, and depth to the corresponding modeled calibration flows. In practice, calibration to a longitudinal profile of water surface elevations (upstream to downstream) is the most accurate method (Terry Waddle, USGS – Fort Collins, personal communication). Fundamentally, if water surface elevations are accurate then so will the depths and the resulting water velocity magnitudes as well. For the depth and velocity comparisons, data was collected along 4 cross sections, perpendicular to streamflow (Figure 9). When collecting field data it is imperative that the calibration data is collected at a steady stream flow throughout the study site.

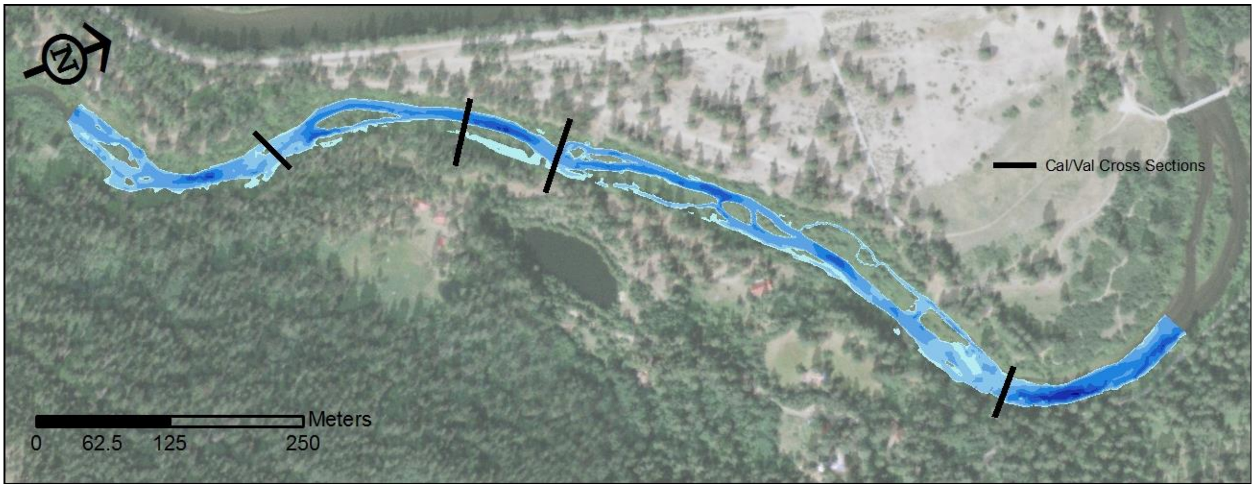

Figure 9. Location of cross sections used to collect observations of depth and velocity at a low, medium and high flow.

Like many other models, roughness values are used to adjust the model output to more closely match observed conditions. In practice this is a balancing act given that an adjustment of water surface elevation will have a direct effect on velocities and depth. For the historical channel, we ran each of the three calibration flows to steady state convergence and then incrementally adjusted roughness values for each specific calibration flow to bound the error between observed and simulated water surface profiles (Figure 10, Figure 11 and Figure 12).

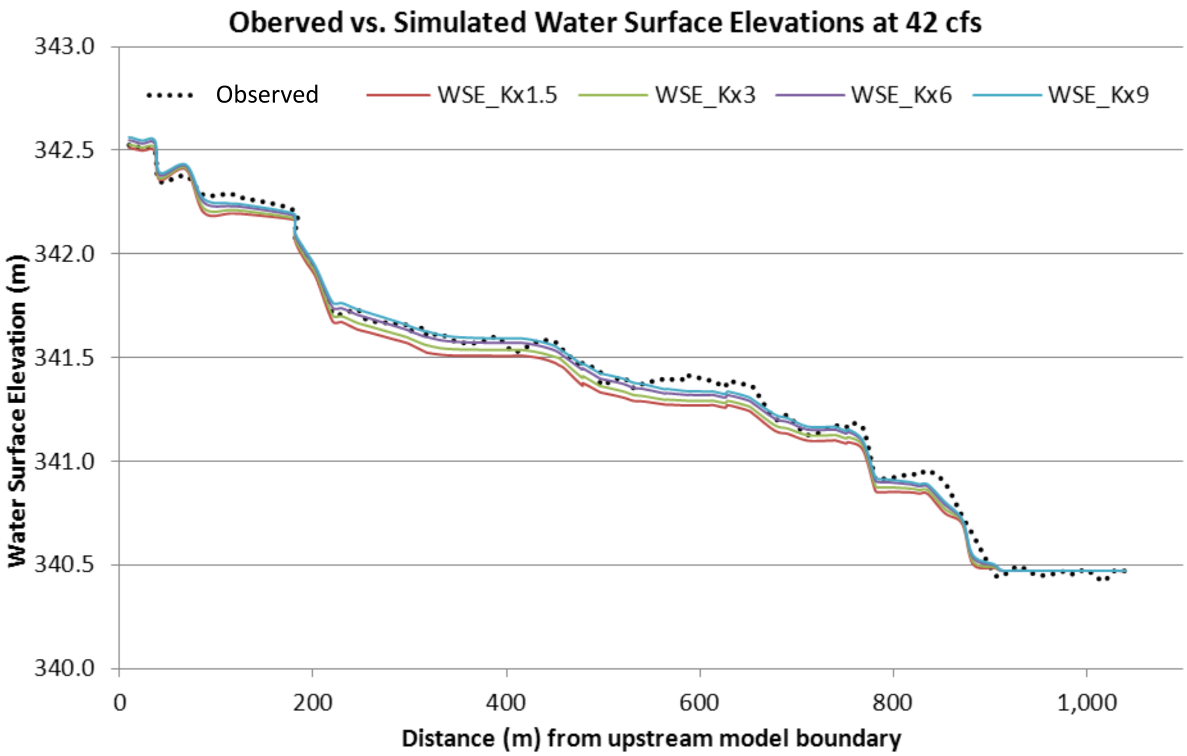

Figure 10. Observed vs. Simulated water surface elevations at 42 cfs (low calibration flow) for four potential roughness calibration flows. WSE_Kx6 represented the best overall fit and balance upstream to downstream.

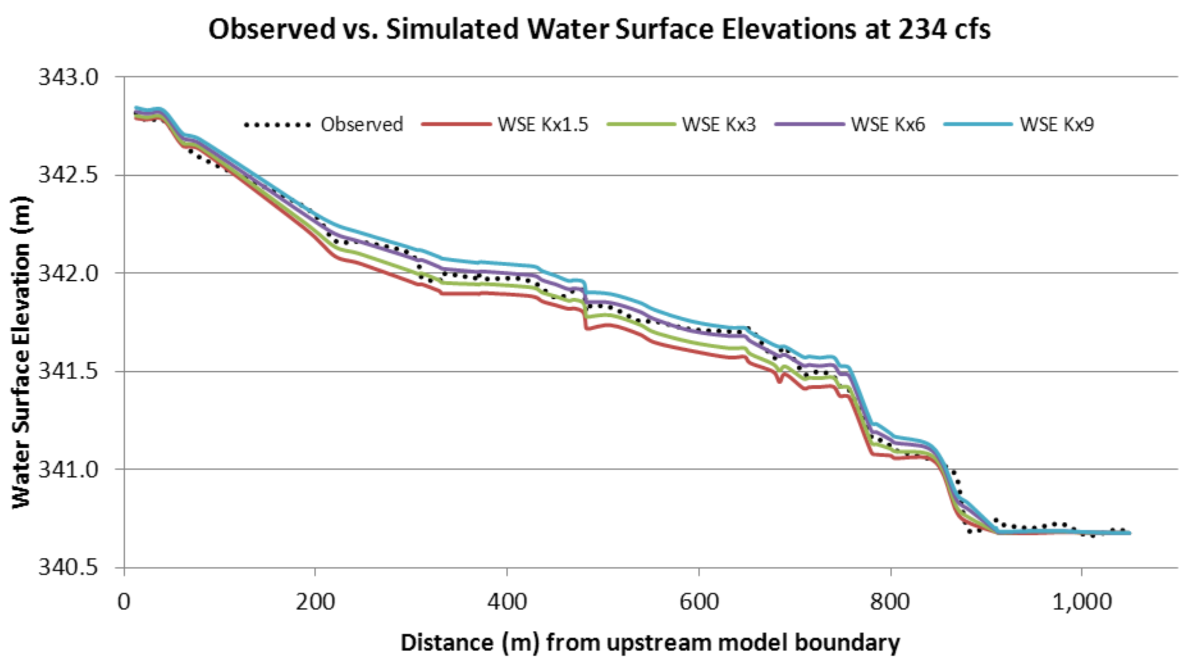

Figure 11. Observed vs. Simulated water surface elevations at 234 cfs (medium calibration flow) for four potential roughness calibration flows. WSE_Kx6 represented the best overall fit and balance upstream to downstream.

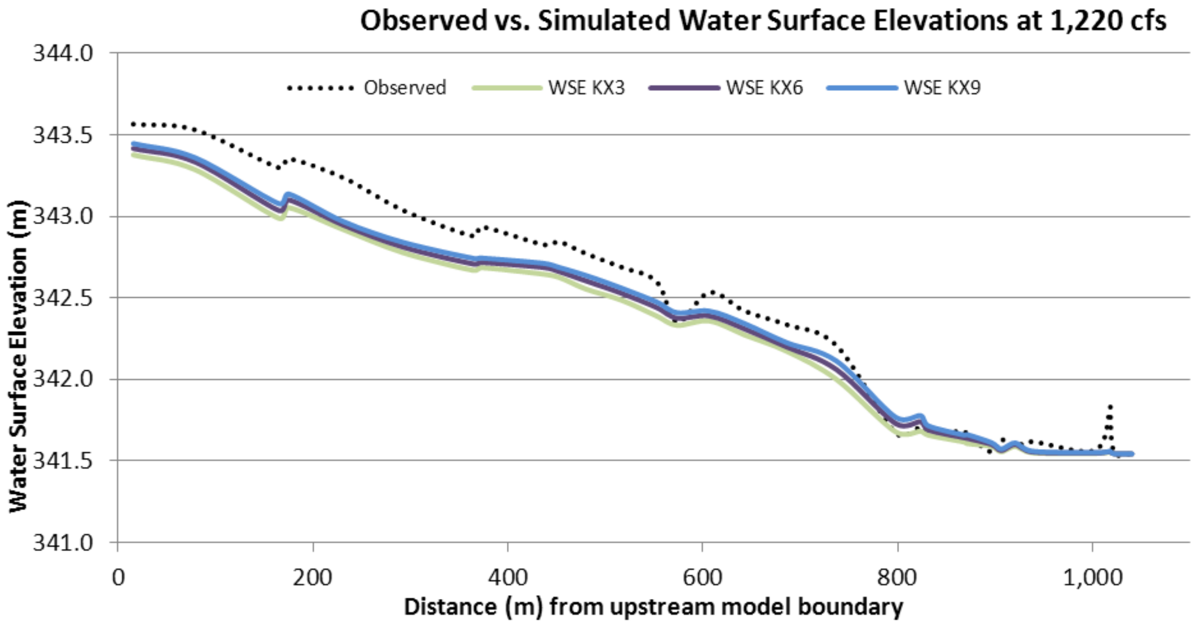

Figure 12. Observed vs. Simulated water surface elevations at 1,220 cfs (high calibration flow) for three potential roughness calibration flows. WSE_Kx9 represented the best overall fit and balance upstream to downstream.

Observed vs. simulated velocities and depths were also compared for further validation to determine if additional adjustment of roughness values was warranted (Table 2). If additional adjustment was warranted, we further adjusted roughness values to accomplish the best fit for matching both simulated water surface elevations and velocities to the empirical data. Observations of water surface elevations were collected at 42, 234 and 1,220 cfs with 80, 57 and 30 data points respectively. The number of data points collected was based on observed water surface elevation variability in the field, GPS availability and site access. Site access was limited at the 1,220 cfs. Survey grade RTK GPS instruments were used to collect water surface elevations and an Acoustic Doppler Current Profiler (ADCP) as well as a held meter was used to collect the velocity profiles perpendicular to the flow. Depth and velocity observations were collected along four cross sections spaced throughout the reach for each of the low, medium and high calibration flows. After each calibration flow was adjusted to the best fit, production modeling was conducted and model error for simulated depths and velocities relative to measured (observed) depths and velocities was assessed and reported as the mean absolute error MAE (Table 2). As well, Table 2 depicts the roughness adjustment factors used for all of the production modeling. Each adjustment factor i.e. kx6 denotes the multiplication factor used to adjust the substrate size. In this example it’s a multiplier of 6.

Table 2. Comparison between measured and simulated water surface elevation, velocity and depth at each of the low, medium and high calibration flows. Values in bold are those with the least mean absolute error and the highlighted rows represent the roughness calibration factor used to simulate or model the unmeasured flows.

Mean Absolute Error (m) - **Water Surface Elevation**

Roughness	Low Flow	Medium Flow	High Flow
kx1.5	0.066	0.072	
kx3	0.048	0.040	0.140
kx6	0.033	**0.036**	0.105
kx9	**0.030**	0.062	**0.103**

Mean Absolute Error (m) - **Velocity**

Roughness	Low Flow	Medium Flow	High Flow
kx1.5	0.130	0.225	*
kx3	0.106	0.200	*
kx6	**0.090**	**0.196**	*
kx9	0.105	0.203	*

Mean Absolute Error (m) - **Depth**

Roughness	Low Flow	Medium Flow	High Flow
kx1.5	0.108	0.099	*
kx3	0.093	0.069	*
kx6	0.080	**0.044**	*
kx9	**0.073**	0.048	*

* Fines and a moving bed precluded the processing and spatial orientation of ADCP data collected at the high flows for velocity and depth.

6. Simulation of Unmeasured Flows

Once the model has been calibrated to the best fit, simulation of unmeasured flows can ensue. This is simply done by adjusting the boundary conditions (discharge and water surface elevation) of the nearest calibration flow to that of the unmodeled flow and running the model to solution. This process was repeated until all unmeasured flows have been simulated. Streamflows from 20 to 1,500 cfs were successfully simulated (Table 3) as well the resulting depths and velocity magnitudes for subsequent habitat modeling. Table 3 also depicts which roughness values were used for the production runs based on the calibration process. Figure 13 and Figure 14 depict water velocity magnitudes and depths at 20, 300 and 1,000 cfs at the same velocity scales.

Table 3. Streamflows and the associate roughness calibration adjustment factors used for production in the Icicle Creek historical channel downstream of Structure 2. Roughness calibration factors are italicized.

Streamflows (cfs) and the Associated Roughness Calibration Adjustment Factors							
20	*Kx6*	140	*Kx6*	550	*Kx6*	1,050	*Kx6*
30	*Kx6*	160	*Kx6*	600	*Kx6*	1,100	*Kx6*
40	*Kx6*	180	*Kx6*	650	*Kx6*	1,150	*Kx6*
50	*Kx6*	200	*Kx6*	700	*Kx6*	1,200	*Kx6*
60	*Kx6*	250	*Kx6*	750	*Kx6*	1,250	*Kx6*
70	*Kx6*	300	*Kx6*	800	*Kx9*	1,300	*Kx9*
80	*Kx6*	350	*Kx6*	850	*Kx9*	1,350	*Kx9*
90	*Kx6*	400	*Kx6*	900	*Kx9*	1,400	*Kx9*
100	*Kx6*	450	*Kx6*	950	*Kx9*	1,450	*Kx9*
120	*Kx6*	500	*Kx6*	1,000	*Kx9*	1,500	*Kx9*

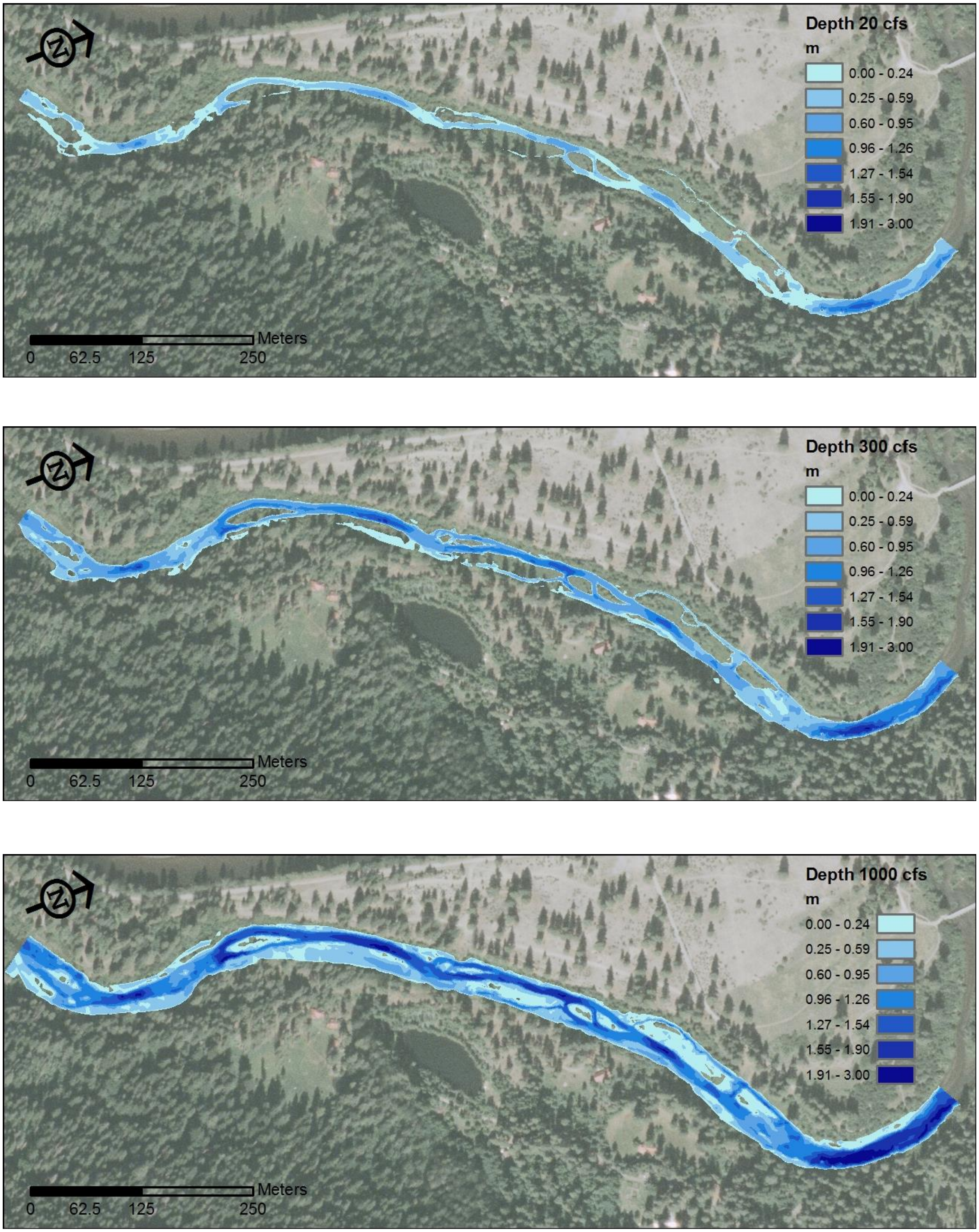

Figure 13. Comparison of modeled depths at 20, 300 and 1,000 cfs, respectively.

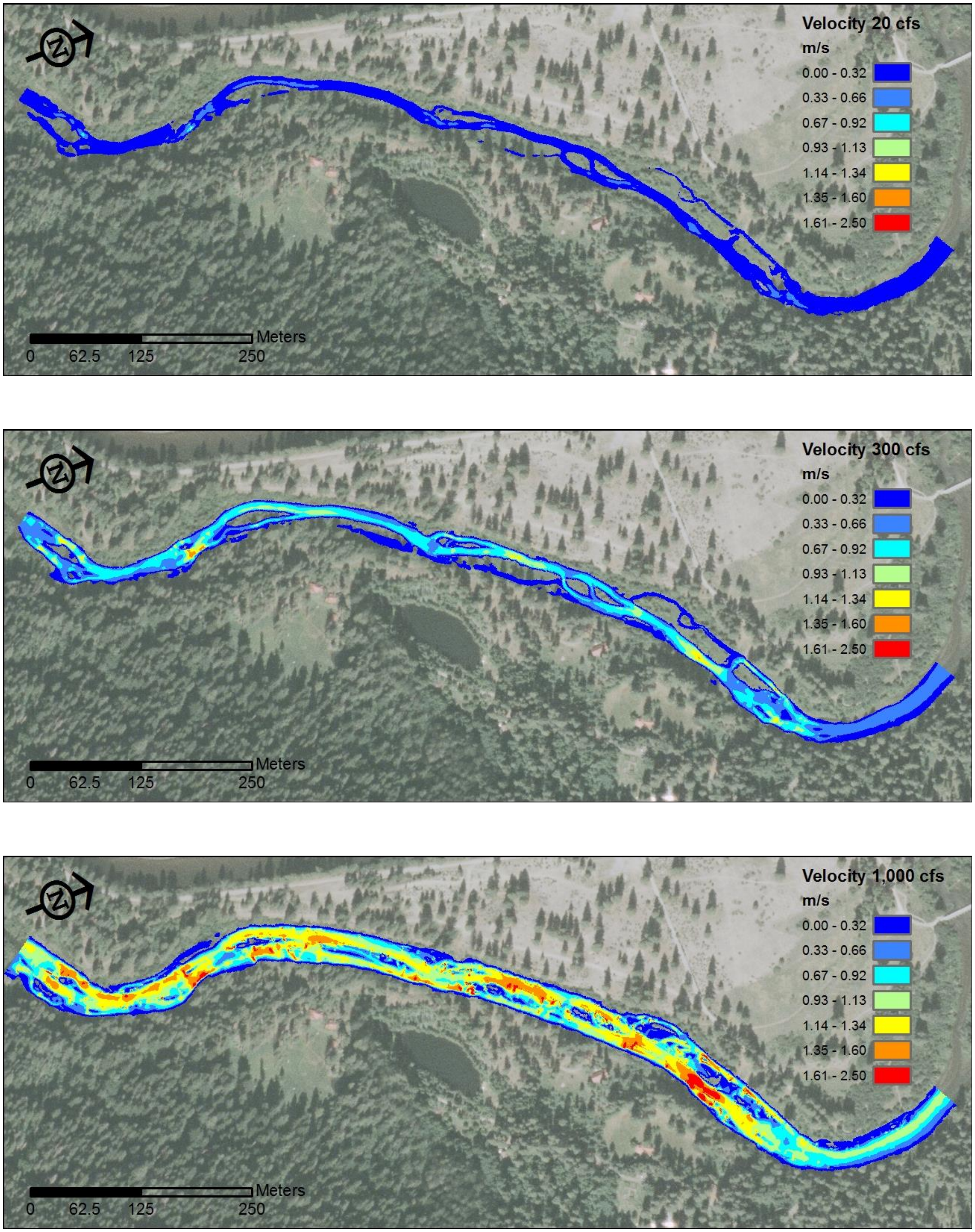

Figure 14. Comparison of modeled velocity magnitudes at 20, 300 and 1,000 cfs, respectively.

Habitat Modeling Methods

Integration of the results of hydrodynamic modeling and physical parameter distribution (substrate and cover) with habitat preference or suitability criteria for the fish species/lifestages of interest was required to develop the relationship between streamflow and the amount, quality, and distribution of physical habitat.

Icicle Creek Fish Species/Lifestages and Periodicity

Fish species/lifestages that were evaluated for the historical channel instream flow study have been discussed by staff from the Leavenworth NFH, MCFRO and CRFPO, WDFW, and WDOE. Table 4 lists the species/lifestages evaluated. The various lifestages for each species may occur in the historical channel during specific time periods. These time periods (Table 4) were the focal point for physical conditions and habitat estimates for each species/lifestage.

Table 4. Fish species/lifestages and periodicity for habitat assessment in the Icicle Creek historical channel.

Species	Life-Stage	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bull Trout	Adult-rearing	■	■	■	■	■	■	■	■	■	■	■	■
	Juvenile rearing	■	■	■	■	■	■	■	■	■	■	■	■
Steelhead / Rainbow	Adult spawning				■	■	■						
	Juvenile rearing	■	■	■	■	■	■	■	■	■	■	■	■
Coho	Adult spawning									■	■	■	■
Summer Chinook	Adult spawning									■	■		
	Juvenile rearing	■	■	■	■	■	■	■	■	■	■	■	■
Spring Chinook	Adult spawning							■	■	■			
	Juvenile rearing	■	■	■	■	■	■	■	■	■	■	■	■
Mountain Whitefish	Adult spawning							■	■	■			
	Adult rearing	■	■	■	■	■	■	■	■	■	■	■	■
	Juvenile rearing	■	■	■	■	■	■	■	■	■	■	■	■
Largescale & Bridgelip Suckers	Adult spawning							■	■	■			
	Adult rearing	■	■	■	■	■	■	■	■	■	■	■	■
	Juvenile rearing	■	■	■	■	■	■	■	■	■	■	■	■

Westslope Cutthroat	Adult spawning												
	rearing												
Pacific Lamprey	Adult spawning												

Habitat Suitability Criteria

Habitat suitability criteria (HSC) that define the suitability (on a scale of 0 to 1) of physical and hydraulic factors such as water depth and velocity, substrate, cover and slope can be developed in many forms ranging from frequency distributions of habitat use for each parameter, to complex models using combinations of parameters to predict the probability of habitat use. The WDFW and WDOE have compiled habitat preference curves for a wide range of species and lifestages in the publication, Washington State Instream Flow Study Guidelines (WDFW and WDOE, April 1, UPDATED 2013 publication) that consist of observations of fish use relative to parameter availability. This approach more accurately describes selection of specific conditions, or preference for those conditions compared to simple frequency analysis of field observations (habitat utilization curves). By accounting for both habitat use and habitat availability, the resulting curves tend to be much less site-specific than utilization curves (Bovee 1986, Bovee and Zuboy *eds*. 1988).

The State of Washington's most recent fish preference curves HSC for the historical channel habitat assessment were used for the cell based habitat assessment. The criteria used were from the 2013 Guidelines. The curve sets identified by the State do not include curves for Pacific lamprey or suckers. As such curves used in other instream flow studies were reviewed and used for lamprey and suckers. For largescale and bridgelip suckers Murdoch et al. (2005) indicated that suckers use the same habitat as rainbow trout and no differences were found in the water depth and water velocity used by rainbow trout and bridgelip sucker for spawning. For lamprey criteria from a flow study in the Yuba River, Yuba County Water Agency (2012) were used. These criteria also compared well with data collected by Stone (2006) in Cedar Creek in Southwest Washington State. For whitefish there are no substrate criteria listed in the States publication so substrate curves from a flow study in the Spokane River were used (EES Consulting. 2007).

Physical Parameters

Characterization of the component physical parameters and their spatial distribution is the primary task leading to an evaluation of habitat suitability. While some physical parameters remain fixed in space, others vary with streamflow. Depth and velocity are the primary variable parameters. Other parameters include substrate and cover. Depth and velocity were produced from River2D and substrate and cover were mapped in the field with survey grade RTK GPS. Dominant, sub-dominant and % dominant substrates are consistent with WDFW's preference curves (Table 5). All of these parameters were exported into ArcGIS for subsequent habitat assessment and quantification as individual habitat grids using cell based modeling and map algebra. The cell size of each final habitat grid was one square meter.

Substrate and Cover

We modeled new raster data layers with the Euclidean allocation process in our GIS using the 4,988 vector-based substrate/cover data points. Each raster is a continuous cell-based model of the data for each of the four criteria used. The Euclidean algorithm records the identity of the closest source point for each cell in the new raster. A distance is then calculated from the source point to the center of each of the surrounding cells without values. The algorithm proceeds as follows. For each cell, the distance is calculated to each source cell by calculating the hypotenuse with the x-max and y-max as the other two legs of the triangle. This calculation derives the true Euclidean, not cell, distance. The shortest distance to a source is determined and the value is assigned to the cell location on the output grid. That is to say, the cells were assigned characteristics of the nearest point with empirical data. At the end of the process, a continuous and complete surface is produced. This process was completed for each of the substrate coding systems (rearing and spawning), for cover codes, and for the percent fines layer, resulting in four separate grids.

Table 5. Generic cover and substrate codes with preference values.

Substrate Code	Description	Size (inch)	Spawning				Rearing		Holding
			salmon	steelhead	resident trout	bull trout	fry	juv.	adult
1	silt, clay, or organic		0.00	0.00	0.00	0.00	0.10	0.10	0.10
2	sand		0.00	0.00	0.00	0.00	0.10	0.10	0.10
3	sm gravel	0.1 - 0.5	0.30	0.50	0.80	1.00	0.10	0.10	0.10
4	med gravel	0.5 - 1.5	1.00	1.00	1.00	1.00	1.00	0.30	0.30
5	lrg gravel	1.5 - 3.0	1.00	1.00	0.80	1.00	1.00	0.30	0.30
6	sm cobble	3.0 - 6.0	1.00	1.00	0.50	0.70	1.00	0.50	0.30
7	lrg cobble	6.0 - 12.0	0.50	0.30	0.00	0.70	1.00	0.70	0.30
8	boulder	>12.0	0.00	0.00	0.00	0.00	1.00	1.00	1.00
9	bedrock	NA	0.00	0.00	0.00	0.00	0.10	0.30	0.30

Cover Code	Description (Note: Cover codes are not used for spawning)	Rearing		Holding
		fry	juv	adult
00.1	undercut bank	1.00	1.00	1.00
00.2	overhanging vegetation	1.00	1.00	1.00
00.3	root wad (including partly undercut)	1.00	1.00	1.00
00.4	log jam/submerged brush pile	1.00	1.00	1.00
00.5	log(s) parallel to bank/Rip-rap	0.30	0.80	0.80
00.6	aquatic vegetation	1.00	0.80	0.80
00.7	short (<1') terrestrial grass	0.40	0.10	0.10
00.8	tall (>3') dense grass	0.70	0.70	0.10
00.9	vegetation beyond the bank-full waters edge	0.20	0.20	0.20

GIS Cell-Based Habitat Modeling

GIS cell based modeling was used to compute WUA for all species and lifestages. The River2D hydrodynamic model was used to simulate continuous cell-based surfaces of depth and velocity for a range of streamflows from 20 to 1500 cfs. One River2D output file (CDG file) was produced for each flow for a total of 40 raw output files in standard ASCII text format. Ten cfs increments were modeled for flows from 20-100 cfs, 20 cfs increments were modeled for flows from 100-200 cfs, and 50 cfs increments were modeled for flows from 200-1500 cfs. ArcGIS was used to process the River2D modeled output files as well as rasters of substrate size and cover type to quantify fish habitat for each species and lifestage. A raster or grid is much like a checker board that has equal sized cells arranged in rows and columns (Figure 15). A cell size of one meter by one meter was used for this analysis. To process the many files required to quantify habitat, scripts were written to automate the process.

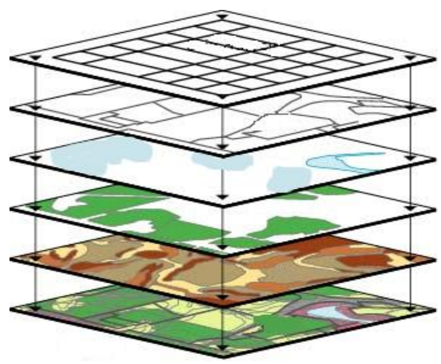

Figure 15. Example of how a GIS cell-based model might look where each layer represents a different habitat variable (depth, velocity and substrate) used to calculate fish habitat.

The cell based modeling process can be viewed as having two steps. The first step is processing the depth and velocity data which is done once for each flow (Figure 16). The second step integrates the habitat preference criteria with the depth, velocity, substrate, and cover data to produce a combined suitability index (CSI) for each cell, species, life stage, and streamflow. The first step required creating a custom script to import the River2D output into an ArcGIS point shapefile which is the basic format used by ArcGIS. For each point in the shapefile there is a database record that contains the depth and velocity values at that location. A TIN (triangulated irregular network) was created for depth and another for velocity, so that a continuous surface can be created for each habitat metric. This facilitates interpolation between neighboring points. Next, each TIN was converted to a raster so it could be combined with the substrate and cover rasters during the second step of the habitat modeling process.

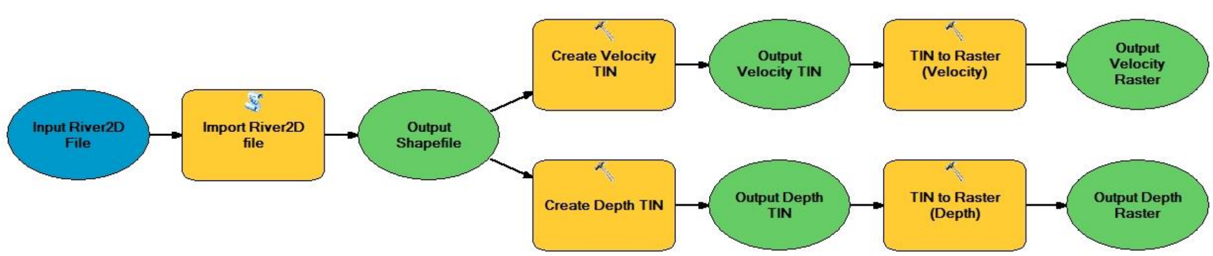

Figure 16. Flow diagram depicted the first step in converting the raw River2d output files.

The second step of the process involves using referenced depth and velocity preference files to convert each raster value into the corresponding preference for depth and velocity for each species and life stage (Figure 17). The preference rasters resulted in values from 0 to 1 with 1 being the most preferred. The same was done for substrate and cover data resulting in a value between 0 and 1. Substrate was used for spawning life stages and cover was used for rearing life stages. In places where cover was absent, substrate characteristics were substituted. After the preference rasters were created for depth, velocity, substrate, and/or cover, all three rasters were multiplied together to create a combined suitability index (CSI) raster with values ranging from 0 to 1 with 1 being the most suitable habitat. The CSI grids were created for each species and life stage for each flow. After all the grids were created, another script was written to summarize the results for each species, life stage, and streamflow. The summary statistics include total weighted usable area (WUA), total usable area (UA), and high quality UA which was defined as a CSI score >= 0.6 For this report we only report on WUA and in an Appendix B high quality UA. Appendix B lists both the wetted area by streamflow and the amount of high quality UA for both the spawning and rearing lifestages, Appendix B1 and B2, respectively.

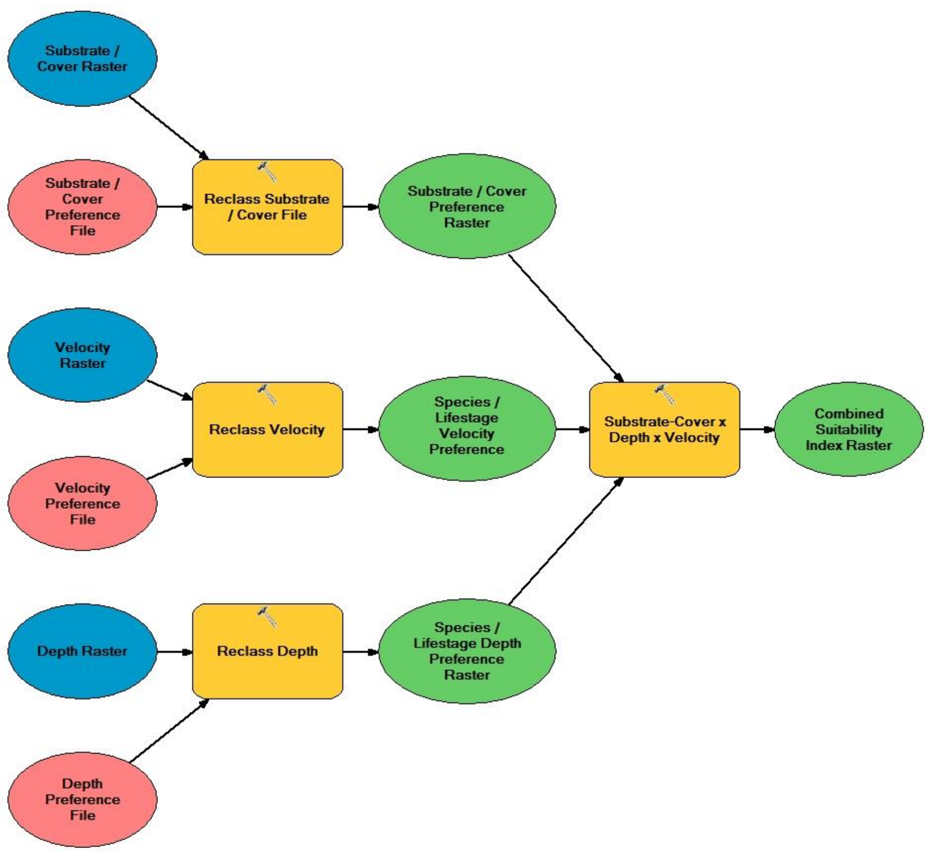

Figure 17. Flow diagram depicted the second step of the process which involves using depth and velocity preference files to convert each raster value into the corresponding preference for depth and velocity for each species and life stage.

Channel Maintenance Flows

Channel maintenance flows are comprised of higher streamflows that generally occur at a lower frequency in a natural, unaltered hydrograph, but are important for maintaining the geomorphology and physical channel structure and form which supports the ecological function of the stream network. These lower frequency, higher magnitude flows maintain the basic physical characteristics that comprise physical habitat for the biological community. They provide functions important for stream habitat such as channel flushing, sediment transport, wood recruitment, and maintenance of riparian and floodplain habitat (Wald 2009). Instream flow recommendations for high flows should include high flow pulses and flushing flows for in-channel functions, channel maintenance flows for in-channel and riparian functions, and channel forming flows for side-channel and floodplain functions (Wald 2009).

Channel maintenance flows are typically derived using either of two basic methods. Analysis of empirical streamflow data from gaging stations can provide statistics such as mean annual discharge and streamflow frequency, duration, and recurrence interval. These statistics have been used in a number of different methodologies for developing channel maintenance flows (e.g. Tennant 1975, Wesche and Rechard 1980, Orsborn 1982, Rosgen 1982). The second basic method is based on the relationship between hydraulic forces and the physical characteristics of the stream channel and existing substrate, or sediment. It consists of determining the force (velocities and streamflow) required to mobilize and entrain various sediment sizes.

For streams in the State of Washington, Wald (2009) recommends three different levels of streamflow for maintaining channel function and floodplain processes, creating and maintaining physical habitat, and facilitating fish migration and flushing fines from the stream channel for maintenance of spawning and rearing habitat. His recommendations include the following specific guidance (Wald 2009):

<u>Flushing flows</u>

Flushing flows to improve gravel quality for spawning and incubation habitat provide the greatest benefit when they occur at the beginning of spawning seasons. Flushing flows in the fall remove organic matter and fines that accumulate during the summer. Flushing flows in the spring provide migration flows while they reduce the amount of fines in spawning gravels. The author recommends preserving or providing the mean annual discharge as a flushing flow for 6 to 12 hours duration during specified seasons and at intervals of at least 2 per year if not provided naturally.

<u>Channel maintenance flows</u>

Channel maintenance flows for activating geomorphic processes are greater in magnitude and duration than flows necessary for initiation of bedload movement. The author recommends preserving or providing the 2-year frequency peak flow or 200% of mean annual discharge for at least 24 hours duration at specified seasons as a channel maintenance flow at intervals of 2 years if not provided naturally. Release rates should be controlled according to specified ramping rates (Hunter 1992).

Channel forming flows

The author recommends preserving or providing the 10-year frequency peak flow for at least 24 hours duration at specified seasons as a channel forming flow at intervals of 10 years if not provided naturally. Release rates should be controlled according to specified ramping rates (Hunter 1992).

For the assessment of channel maintenance flows, Wald's (2009) guidelines were used for developing the Icicle Creek historical channel: channel flushing, channel maintenance and channel forming flows in the historical channel. *Flushing, channel maintenance, and channel forming flow* recommendations were developed from analysis of the hydrograph at the USGS Gage #12458000, Icicle Creek above Snow Creek near Leavenworth, Washington. This included an assessment accounting for the portion of streamflows that are diverted away from Icicle Creek proper at upstream locations, hence the difference.

Habitat Assessment Results

Physical Parameters

Substrate and Cover

We used point substrate and cover data collected in the field to model continuous raster surfaces for the study site (Figure 18) and (Figure 19). Point vector data were converted in the GIS to grids (rasters) with a 1.0 m cell size. We used a Euclidean allocation process to assign values to the cells. We collected a total of 4,988 data points for Icicle Creek. Points were collected along shorelines up to bankfull where accessible and in-river. At every point, dominant substrate, subdominant substrate, percent fines, and cover data were recorded.

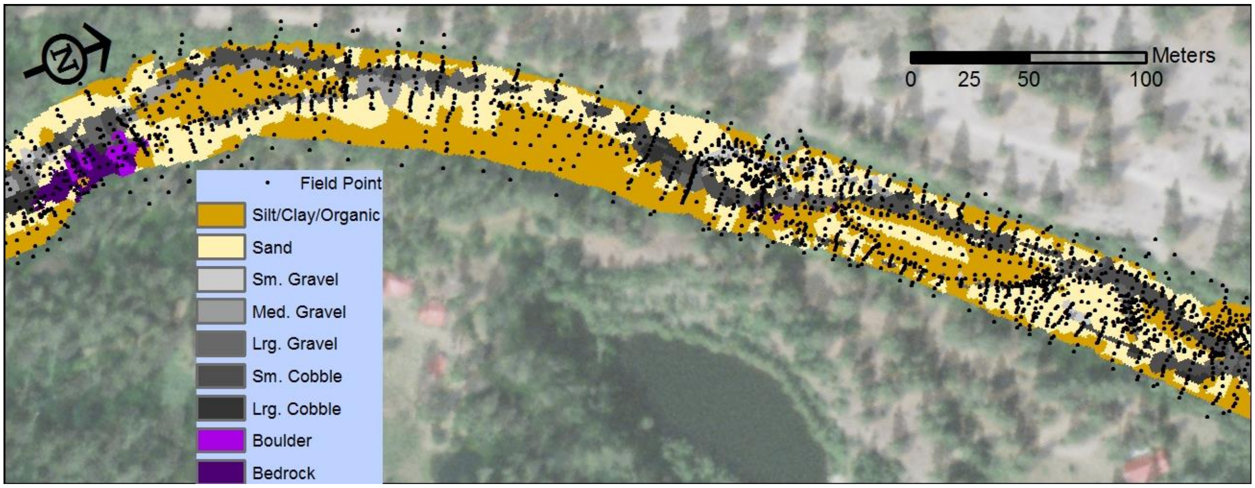

Figure 18. Results of Euclidean allocation process (interpolation) for substrate.

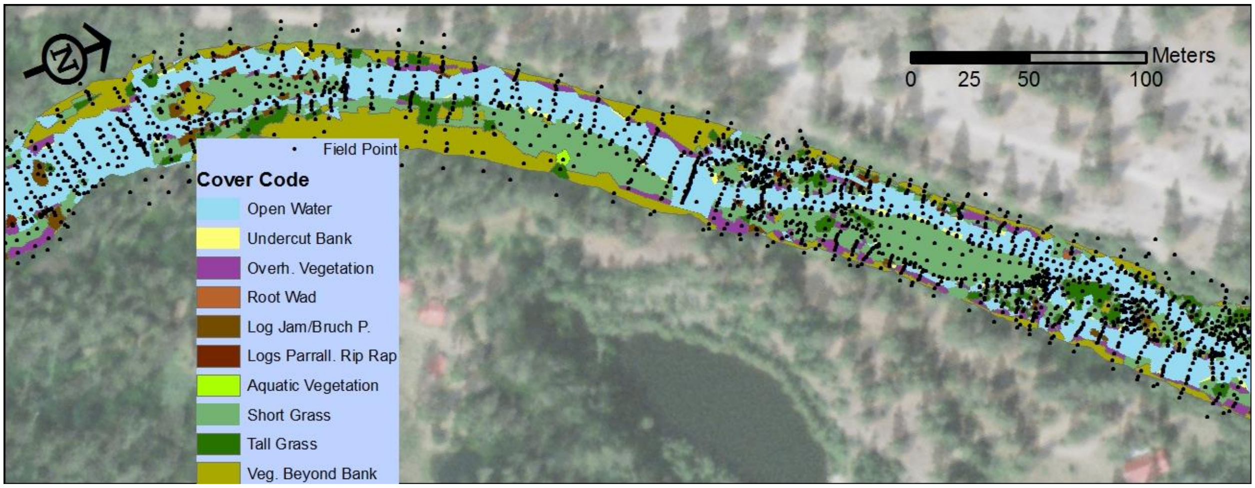

Figure 19. Results of Euclidean allocation process (interpolation) for cover.

As shown in Table 6 and Table 7 the dominant substrates were primarily the smaller size classes (fines to small gravels). The largest portion of cover was open water with no cover, followed by short grass that was very common along shorelines and on islands. Combined, fines including Sand, Silt/Clay/Organic comprised 70.4 % by area of the mapped within the stream channel. Substrates comprised of gravel and cobble accounted for 26.2 percent by area of the mapped stream channel.

Table 6. Dominant substrate distribution by total area

Code	Class	Area (Sq. Meters)	Percent
1	Silt/Clay/Organic	15,106	31.9%
2	Sand	18,236	38.5%
3	Small Gravel	5,309	11.2%
4	Medium Gravel	3,128	6.6%
5	Large Gravel	1,836	3.9%
6	Small Cobble	692	1.5%
7	Large Cobble	1,449	3.1%
8	Boulder	1,170	2.5%
9	Bedrock	453	1.0%
	Total:	47,379	

Table 7. Cover distribution by total area.

Code	Class	Area (Sq. Meters)	Percent
0	Open Water	21,471	45.3%
0.1	Undercut Bank	586	1.2%
0.2	Overhanging Vegetation	2,765	5.8%
0.3	Root Wad	54	0.1%
0.4	Log Jam/Submerged Brush Pile	522	1.1%
0.5	Logs Parallel to Bank/Rip-rap	729	1.5%
0.6	Aquatic Vegetation	190	0.4%
0.7	Short Grass	9,924	21.0%
0.8	Tall Grass	4,233	8.9%
0.9	Vegetation Beyond Bankfull	6,907	14.6%
	Total:	47,380	

Weighted Usable Area (WUA) Estimates

With the use of cell based modeling in a GIS, estimates of spawning Weighted Usable Area (WUA) were made for nine species of fish for the Icicle Creek historical channel (Figure 20). Estimates of rearing WUA were made for 9 species for the relevant life stages (Figure 21) using 1,800 GIS generated grids. The WUA output from the GIS is expressed as flow per 1,000 feet (305 m) of lineal stream, for each species and life stage of concern and is an index of available habitat. WUA calculated for the Icicle Creek historical channel incorporates the hydraulic variables of depth, velocity, substrate and cover with the specific habitat needs of species/lifestage to illustrate how the habitat for each species varies with stream flow. A graphical example of what the actual calculated habitat looks like is depicted for both spawning and rearing steelhead habitats at 20, 300 and 1000 cfs in Figure 22 and Figure 23, respectively.

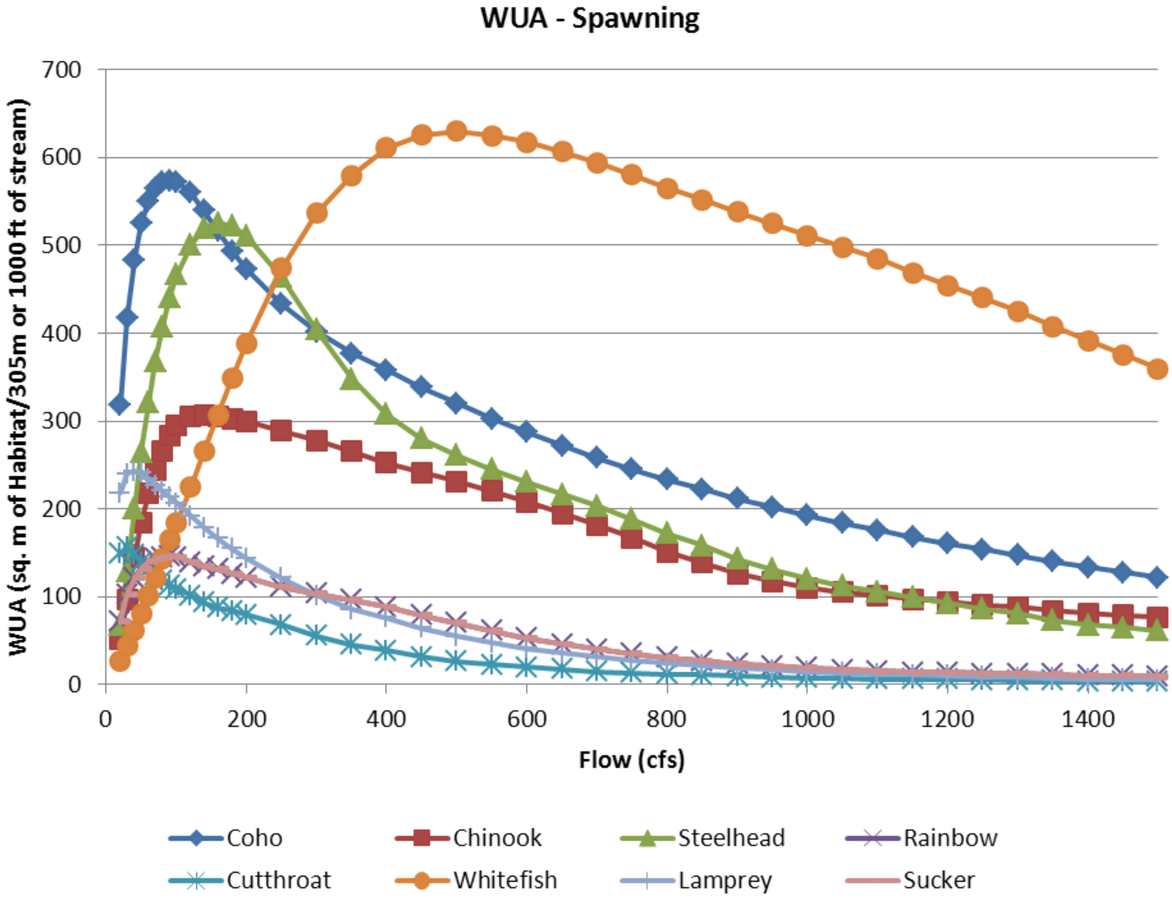

Figure 20. Estimates of spawning WUA for 9 species of fish in the Icicle Creek historical channel. Chinook criteria for both the spring and summer races are identical.

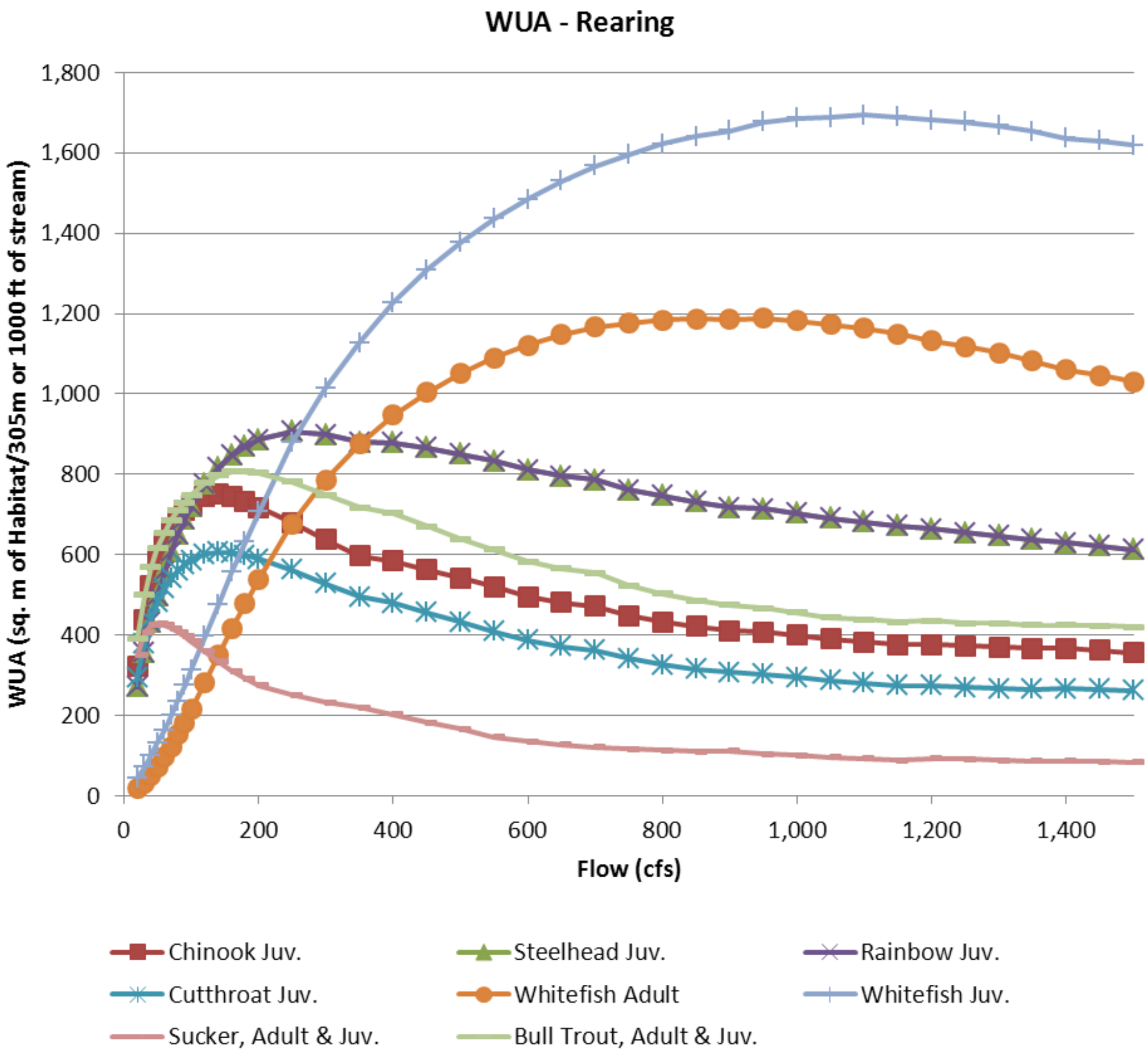

Figure 21. Estimates of rearing WUA for 9 species of fish in the Icicle Creek historical channel. Chinook criteria for both the spring and summer races are identical.

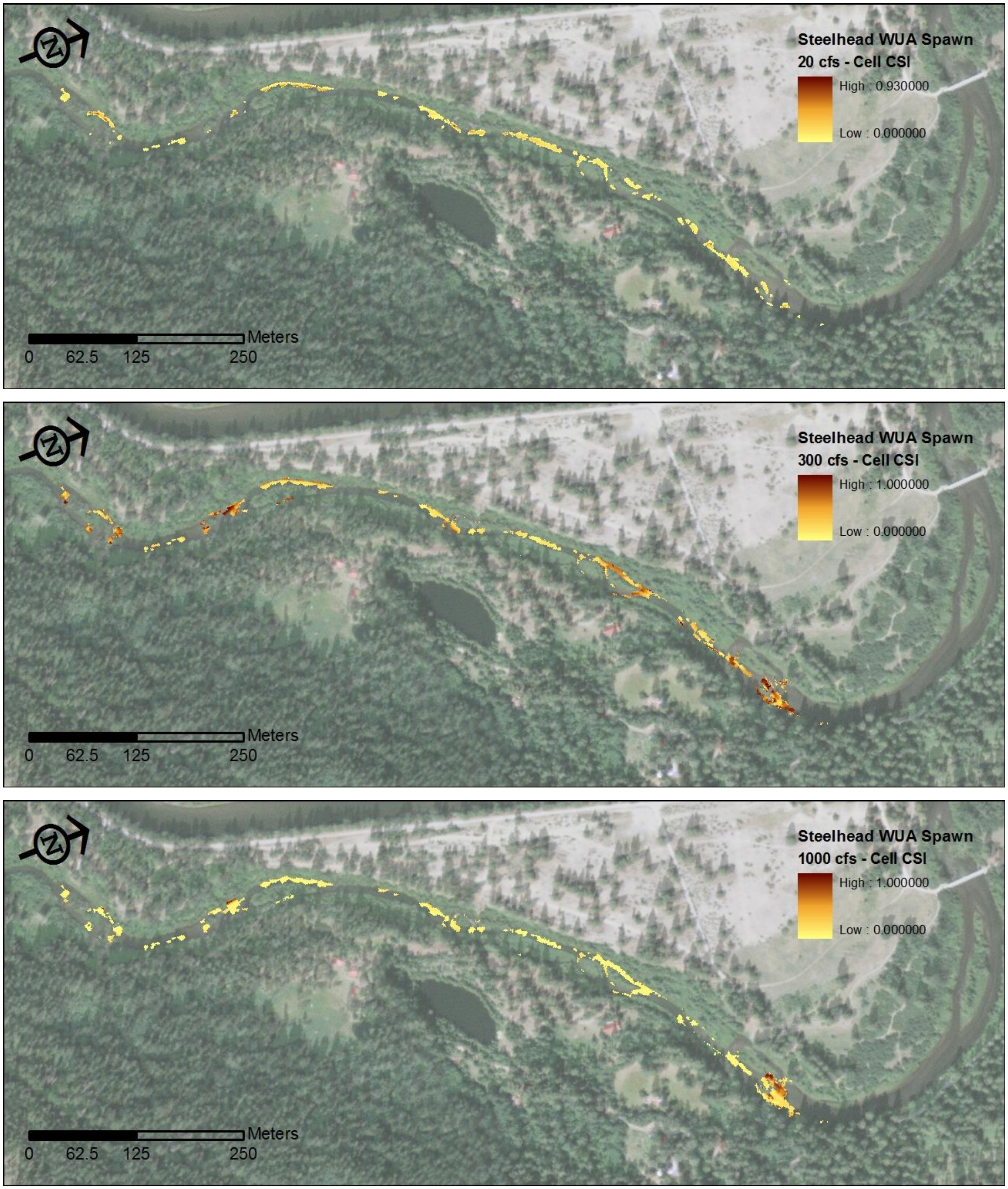

Figure 22. Plotted steelhead spawning habitat individual cell CSI values for 20, 300 and 1,000 cfs.

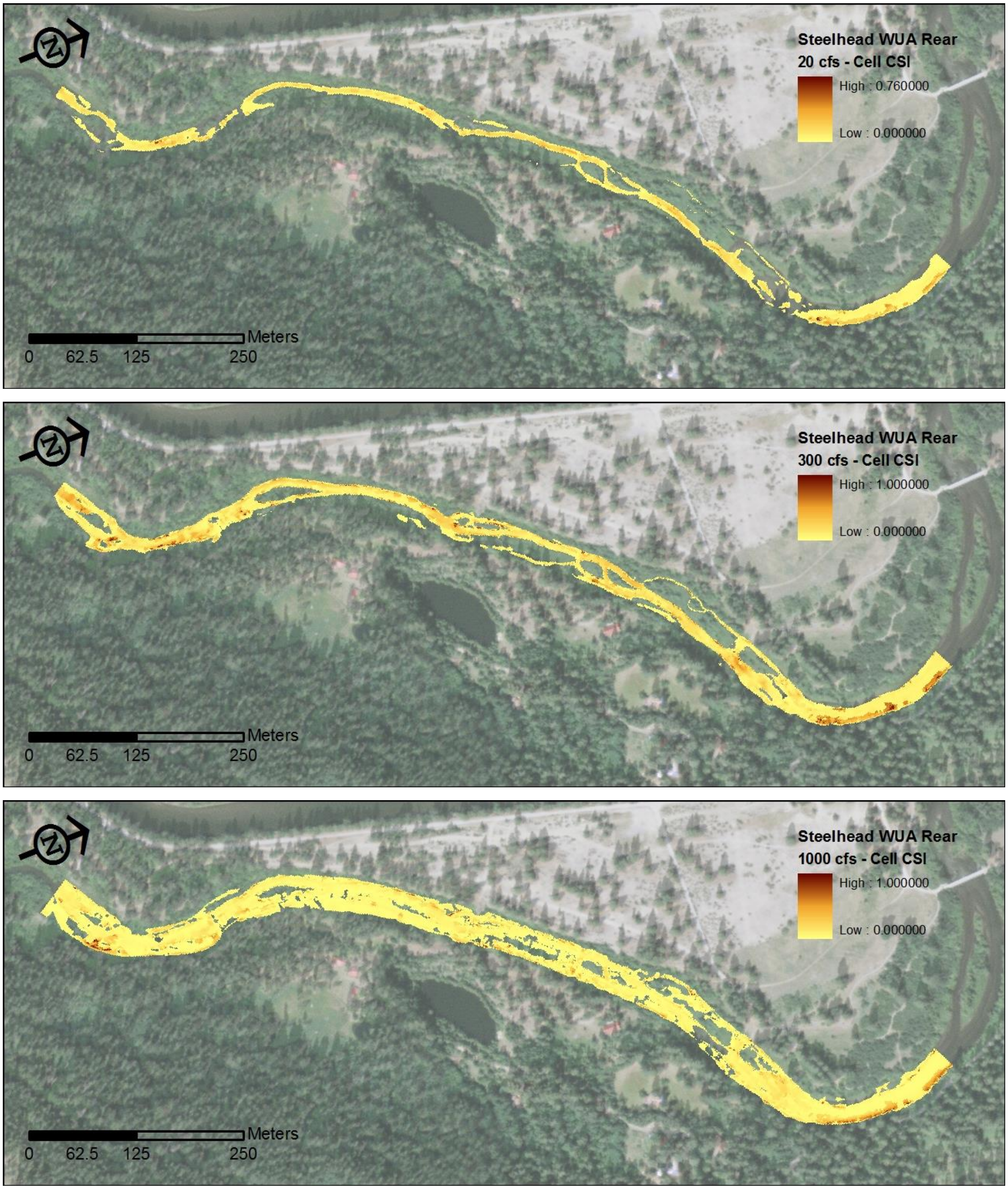

Figure 23. Plotted juvenile steelhead rearing habitat, individual cell CSI values for 20, 300 and 1,000 cfs.

Table 10 and Table 11 depict Icicle Creek historical channel flow vs. spawning WUA per 1,000 feet (305 m) of lineal stream channel and by percent of peak for each specific species, respectively. The blue bars are for visual reference relating flow to habitat availability. Two columns of flow are listed including the modeled flow running through Structure 2 into the Icicle Creek historical channel and the corresponding USGS flow. This is presented for management purposed but should be viewed with some caution. For example, if the streamflow out Snow and Nada Lake is actively managed (opened) or if Structure 2 is closed the relationship may change. The relationship is based on data collected between 10/05/2010 - 11/30/2012 at Structure 2 and the USGS 12458000. Three separate relationships were developed and are presented in Table 8.

Table 8. Data Range, R Squared and equation for the relationship between USGS Gage 12458000 and Structure 2.

Range	USGS Range	r^2	Equation
1	88-950	[r=0.944169]	y = 0.26799 * (x + 12.8967)^ 1.174500
2	950-3600	[r=0.976185]	y = 32.4955 * (x - 231.914)^ 0.497566
3	3600-5810	[r=0.947703]	y = 1623.88 * (x - 3220.6)^ 0.0265487

Individual Time Range: 10/05/2010 00:00 - 11/30/2012 18:19

Regression line x: USGS 1245800/ Icicle Cr. above Snow Cr nr Leavenworth WA

Regression line y: historical channel at Structure 2

Table 9 Relationship between streamflow at the USGS Gage 12458000 at RM 5.8 and Icicle Creek historical channel Structure 2 at RM 3.8. Both tables below use the same relationship. Data for the relationship collected: 10/05/2010 - 11/30/2012. R^2 for flows (88-959 cfs) = 0.944 and from (950-3600 cfs) = 0.976.

S2	USGS
20	na
30	na
40	na
50	na
60	88
70	101
80	115
90	129
100	142
120	168
140	193
160	218
180	243
200	266
250	325
300	382
350	437
400	491
450	544
500	596
550	648
600	699
650	749
700	799
750	848
800	896
850	944
900	1,024
950	1,115
1,000	1,215
1,050	1,315
1,100	1,425
1,150	1,525
1,200	1,640
1,250	1,760
1,300	1,890
1,350	2,020
1,400	2,150
1,450	2,300
1,500	2,440

S2	USGS
69	100
145	200
229	300
317	400
408	500
503	600
601	700
701	800
804	900
886	1,000
942	1,100
994	1,200
1,040	1,300
1,090	1,400
1,140	1,500
1,180	1,600
1,220	1,700
1,260	1,800
1,300	1,900
1,340	2,000
1,380	2,100
1,420	2,200
1,450	2,300
1,490	2,400
1,520	2,500

Table 10. Spawning adult WUA per 1,000 feet (305 m) of lineal stream channel.

Flows (cfs)		Adult Spawning							
USGS	Structure 2	Coho	Chinook	Steelhead	Rainbow	Cutthroat	Whitefish	Lamprey	Sucker
na	20	319	51	68	72	149	27	218	72
na	30	417	97	130	103	156	44	240	103
na	40	483	144	200	121	148	62	243	121
na	50	525	184	265	133	139	80	241	133
88	60	550	217	321	140	130	101	234	140
101	70	564	243	368	143	124	122	227	143
115	80	572	265	408	145	119	144	220	145
129	90	574	283	440	146	113	165	213	146
142	100	572	294	466	145	109	185	206	145
168	120	560	305	500	139	101	224	192	139
193	140	539	307	520	135	94	265	179	135
218	160	516	305	525	131	88	307	166	131
243	180	493	303	522	126	84	348	155	126
266	200	473	300	511	122	79	388	144	122
325	250	433	289	463	111	68	474	121	111
382	300	402	278	404	104	56	536	102	104
437	350	377	265	348	96	46	579	86	96
491	400	358	253	308	88	39	611	76	88
544	450	338	242	280	79	32	625	65	79
596	500	320	231	261	70	26	629	55	70
648	550	303	220	245	62	23	625	48	62
699	600	287	208	231	53	20	617	41	53
749	650	272	195	217	46	18	606	36	46
799	700	259	182	203	40	15	594	32	40
848	750	245	167	189	35	13	580	28	35
896	800	233	151	172	31	12	564	24	31
944	850	223	138	158	28	11	552	22	28
1,024	900	212	126	143	24	10	538	20	24
1,115	950	202	118	131	22	9	525	17	22
1,215	1,000	192	111	121	19	7	511	15	19
1,315	1,050	184	105	112	17	7	498	13	17
1,425	1,100	176	101	106	16	6	485	12	16
1,525	1,150	168	97	99	14	6	469	11	14
1,640	1,200	161	94	93	14	6	454	10	14
1,760	1,250	154	90	86	13	5	440	9	13
1,890	1,300	148	88	81	13	5	425	9	13
2,020	1,350	140	84	73	12	4	407	7	12
2,150	1,400	134	81	68	11	4	391	6	11
2,300	1,450	128	79	65	11	4	375	6	11
2,440	1,500	122	77	62	10	3	359	5	10

Table 11. Spawning adult WUA as percent of peak.

Flows (cfs)		Adult Spawning							
USGS	Structure 2	Coho	Chinook	Steelhead	Rainbow	Cutthroat	Whitefish	Lamprey	Sucker
na	20	56%	17%	13%	49%	95%	4%	90%	49%
na	30	73%	32%	25%	70%	100%	7%	99%	70%
na	40	84%	47%	38%	83%	95%	10%	100%	83%
na	50	91%	60%	50%	91%	89%	13%	99%	91%
88	60	96%	71%	61%	96%	83%	16%	96%	96%
101	70	98%	79%	70%	98%	79%	19%	93%	98%
115	80	100%	87%	78%	99%	76%	23%	91%	99%
129	90	100%	92%	84%	100%	73%	26%	88%	100%
142	100	100%	96%	89%	99%	70%	29%	85%	99%
168	120	98%	100%	95%	95%	65%	36%	79%	95%
193	140	94%	100%	99%	92%	60%	42%	74%	92%
218	160	90%	100%	100%	90%	56%	49%	68%	90%
243	180	86%	99%	99%	86%	54%	55%	64%	86%
266	200	82%	98%	97%	83%	51%	62%	59%	83%
325	250	76%	94%	88%	76%	44%	75%	50%	76%
382	300	70%	91%	77%	71%	36%	85%	42%	71%
437	350	66%	87%	66%	66%	29%	92%	35%	66%
491	400	62%	82%	59%	60%	25%	97%	31%	60%
544	450	59%	79%	53%	54%	20%	99%	27%	54%
596	500	56%	75%	50%	48%	17%	100%	23%	48%
648	550	53%	72%	47%	42%	15%	99%	20%	42%
699	600	50%	68%	44%	36%	13%	98%	17%	36%
749	650	47%	64%	41%	32%	11%	96%	15%	32%
799	700	45%	59%	39%	28%	10%	94%	13%	28%
848	750	43%	54%	36%	24%	9%	92%	11%	24%
896	800	41%	49%	33%	21%	8%	90%	10%	21%
944	850	39%	45%	30%	19%	7%	88%	9%	19%
1,024	900	37%	41%	27%	16%	6%	85%	8%	16%
1,115	950	35%	38%	25%	15%	5%	83%	7%	15%
1,215	1,000	34%	36%	23%	13%	5%	81%	6%	13%
1,315	1,050	32%	34%	21%	12%	4%	79%	5%	12%
1,425	1,100	31%	33%	20%	11%	4%	77%	5%	11%
1,525	1,150	29%	32%	19%	10%	4%	74%	4%	10%
1,640	1,200	28%	31%	18%	10%	4%	72%	4%	10%
1,760	1,250	27%	29%	16%	9%	3%	70%	4%	9%
1,890	1,300	26%	29%	15%	9%	3%	68%	4%	9%
2,020	1,350	24%	27%	14%	8%	3%	65%	3%	8%
2,150	1,400	23%	26%	13%	7%	3%	62%	3%	7%
2,300	1,450	22%	26%	12%	7%	2%	60%	2%	7%
2,440	1,500	21%	25%	12%	7%	2%	57%	2%	7%

Table 12 and Table 13 depict the Icicle Creek historical channel flow vs. rearing WUA tables for WUA per 1,000 feet (305 m) of lineal stream channel and by percent of peak species specific habitat, respectively. The blue bars are for visual reference relating flow to habitat availability.

Table 12. Rearing WUA per 1,000 feet (305 m) of lineal stream channel.

Flows (cfs) USGS	Flows (cfs) Structure 2	Chinook Juvenile	Steelhead Juvenile	Rainbow Juvenile	Cutthroat Juvenile	Whitefish Juvenile	Whitefish Adult	Sucker Adult & Juv.	Bull Trout Adult & Juv.
na	20	323	271	271	295	17	45	349	390
na	30	438	358	358	380	32	72	406	499
na	40	523	433	433	438	51	100	425	569
na	50	584	498	498	481	72	131	428	617
88	60	631	556	556	515	96	164	425	655
101	70	666	606	606	540	123	199	417	686
115	80	691	649	649	560	152	236	407	710
129	90	710	687	687	574	183	274	396	730
142	100	726	720	720	586	215	314	384	749
168	120	745	774	774	601	283	396	359	778
193	140	751	816	816	607	350	477	334	797
218	160	745	847	847	604	416	556	310	806
243	180	733	870	870	598	478	632	292	807
266	200	718	887	887	590	538	706	275	803
325	250	680	906	906	562	677	879	251	782
382	300	637	898	898	528	786	1,015	231	749
437	350	597	880	880	494	875	1,127	220	718
491	400	585	879	879	480	948	1,228	202	703
544	450	563	866	866	456	1,004	1,309	183	670
596	500	542	850	850	432	1,050	1,376	167	640
648	550	520	833	833	410	1,090	1,435	147	612
699	600	495	811	811	387	1,122	1,485	135	583
749	650	480	795	795	372	1,147	1,529	127	565
799	700	472	786	786	362	1,166	1,567	121	554
848	750	449	762	762	341	1,177	1,595	116	523
896	800	433	747	747	327	1,184	1,622	113	502
944	850	421	731	731	316	1,187	1,641	109	485
1,024	900	411	718	718	307	1,185	1,654	111	474
1,115	950	408	714	714	303	1,188	1,677	104	467
1,215	1,000	400	702	702	295	1,182	1,686	101	456
1,315	1,050	390	690	690	286	1,172	1,687	96	444
1,425	1,100	383	681	681	280	1,164	1,694	92	439
1,525	1,150	376	671	671	274	1,149	1,689	88	433
1,640	1,200	376	665	665	274	1,132	1,681	92	435
1,760	1,250	373	655	655	269	1,118	1,678	91	430
1,890	1,300	370	647	647	267	1,102	1,668	88	429
2,020	1,350	367	637	637	266	1,082	1,653	87	424
2,150	1,400	366	629	629	266	1,061	1,636	87	425
2,300	1,450	362	622	622	264	1,046	1,629	85	423
2,440	1,500	356	613	613	262	1,031	1,620	83	420

Table 13. Rearing WUA as percent of peak.

Flows (cfs) USGS	Structure 2	Chinook Juvenile	Steelhead Juvenile	Rainbow Juvenile	Cutthroat Juvenile	Whitefish Juvenile	Whitefish Adult	Sucker Adult & Juv.	Bull Trout Adult & Juv.
na	20	43%	30%	30%	49%	1%	3%	82%	48%
na	30	58%	39%	39%	63%	3%	4%	95%	62%
na	40	70%	48%	48%	72%	4%	6%	99%	71%
na	50	78%	55%	55%	79%	6%	8%	100%	76%
88	60	84%	61%	61%	85%	8%	10%	99%	81%
101	70	89%	67%	67%	89%	10%	12%	97%	85%
115	80	92%	72%	72%	92%	13%	14%	95%	88%
129	90	95%	76%	76%	95%	15%	16%	92%	91%
142	100	97%	79%	79%	97%	18%	19%	90%	93%
168	120	99%	85%	85%	99%	24%	23%	84%	96%
193	140	100%	90%	90%	100%	29%	28%	78%	99%
218	160	99%	93%	93%	100%	35%	33%	72%	100%
243	180	98%	96%	96%	99%	40%	37%	68%	100%
266	200	96%	98%	98%	97%	45%	42%	64%	100%
325	250	91%	100%	100%	93%	57%	52%	59%	97%
382	300	85%	99%	99%	87%	66%	60%	54%	93%
437	350	80%	97%	97%	81%	74%	67%	51%	89%
491	400	78%	97%	97%	79%	80%	73%	47%	87%
544	450	75%	96%	96%	75%	85%	77%	43%	83%
596	500	72%	94%	94%	71%	88%	81%	39%	79%
648	550	69%	92%	92%	68%	92%	85%	34%	76%
699	600	66%	89%	89%	64%	94%	88%	32%	72%
749	650	64%	88%	88%	61%	97%	90%	30%	70%
799	700	63%	87%	87%	60%	98%	93%	28%	69%
848	750	60%	84%	84%	56%	99%	94%	27%	65%
896	800	58%	82%	82%	54%	100%	96%	26%	62%
944	850	56%	81%	81%	52%	100%	97%	26%	60%
1,024	900	55%	79%	79%	51%	100%	98%	26%	59%
1,115	950	54%	79%	79%	50%	100%	99%	24%	58%
1,215	1,000	53%	78%	78%	49%	100%	100%	24%	57%
1,315	1,050	52%	76%	76%	47%	99%	100%	22%	55%
1,425	1,100	51%	75%	75%	46%	98%	100%	21%	54%
1,525	1,150	50%	74%	74%	45%	97%	100%	21%	54%
1,640	1,200	50%	73%	73%	45%	95%	99%	22%	54%
1,760	1,250	50%	72%	72%	44%	94%	99%	21%	53%
1,890	1,300	49%	71%	71%	44%	93%	98%	21%	53%
2,020	1,350	49%	70%	70%	44%	91%	98%	20%	53%
2,150	1,400	49%	69%	69%	44%	89%	97%	20%	53%
2,300	1,450	48%	69%	69%	44%	88%	96%	20%	52%
2,440	1,500	47%	68%	68%	43%	87%	96%	19%	52%

Integration of Species-Specific Habitat-Flow Relationships

To integrate species specific habitat flow relationships in order to accommodate the habitat needs for multiple target fish species and lifestages that may occur simultaneously in the Icicle Creek historical channel, tables depicting the spawners and habitat needs by month were produced (Appendix A). Additionally the 90 to 10% exceedance flows are highlighted. These are the flows that occur for the specific spawning month. With this data managers can easily see who may be spawning in what month, how much habitat is available throughout all flows and how much habitat is typically available for the specific month. The exact exceedance flows are listed at the bottom of each table. Both the Icicle Creek historical channel flows and the USGS flows are listed for reference as well.

Channel Maintenance Flows.

Using Wald's (2009) guidelines for developing the Icicle Creek historical channel: channel flushing, channel maintenance and channel forming flows, the results of the assessment are presented in Table 14. *Flushing, channel maintenance, and channel forming flow* recommendations were developed from analysis of the hydrograph at the USGS Gage #12458000, Icicle Creek above Snow Creek near Leavenworth, Washington. This assessment inherently accounts for the average apportion of flows that are diverted away from the historical channel at upstream locations, hence the different between the two. See Table 8 for additional data regarding the relations between the USGS and Icicle Creek historical channel streamflows. From the relationship it appears that the maximum amount of water that can flow through Structure 2 is just over 2,000 cfs. As such the channel forming flow of 7,930 cfs listed in Table 14 cannot occur in the historical channel.

Table 14. Recommended Channel: Flushing, Maintenance and Forming flows (cfs) and the associated USGS gage flows that would facilitate the recommended flows in the historical channel.

	Icicle Creek Historical Channel (Structure 2) Flow (cfs)	Supporting USGS 12458000 Gage Flow (cfs)
Flushing	624	720
Maintenance	1,248	1,760
Forming	7,930	NA

Discussion

WUA is only an index and it should not be confused with the actual physical area within a stream (Payne 2003). It can only be an index because the estimated "area" is multiplied by the unit-less habitat suitability attributes. As well, the units of WUA are not standard or transferable because they are derived from a range of habitat suitability criteria and selectable combinations of variables (Mathur el al. 1985). The WUA graphs only show whether an increase or decrease in streamflow will increase or decrease the quantity of fish habitat. The study's predicted fish habitat versus streamflow results have to be interpreted by knowledgeable biologists and others to arrive at an instream flow regime that satisfies applicable laws.

The hydrodynamic modeling was rather straightforward but the complexity of the site did required extra effort and attention to detail. An iterative process of running the River2D model, reviewing computational issues and then refining the bed and mesh files to provide higher computational resolution in problem areas was often employed and required considerably more time and attention to detail than a "typical" 2D modeling effort.

Model calibration and validation to water surface elevation was generally near the error of our survey grade GPS of 3.0 cm. We observed 3.3 and 3.6 cm of error at the low and medium calibration flows. Higher error was observed at the highest calibration flow of 1,220 cfs but we feel that layers of fines that were deposited between bathymetric data collection and calibration data collected are the primary cause. Most of the fines observed in the field were deposited at higher riverbank elevations (Figure 24) and undoubtedly had an effect on the comparison of measured vs. observed water surface elevation. These fines were not present on our initial field visits. As such we chose not to adjust the roughness values to unrealistic values. When we collected low flow depth and velocities along 4 cross sections in September of 2012 Structure 2 was closed and water was water was observed seeping from the hatchery channel to the lower elevation historical channel. The net result was an increase in stream flow due to the accretion of seepage. As a result, we used an average stream flow (42 cfs) for the low flow work while in reality the flow was lower at the top and higher in the bottom. This likely resulted in additional error. The lack of empirical depths and velocities due to entrained fines and moving bed in the ADCP files also limits the confidence in our high flow calibration but again considering the deposition of fines we are satisfied with the results.

Overall we believe the model has done an excellent job and most of the "error" is due to the observed deposition fines between the collection of model bathymetry and the collection of model calibration data. As such, we are not concerned with the error levels in observed vs. simulated depths and velocities for which they were only collected at 4 cross sections. Additional changes to the stream bathymetry were also observed on our final field trip. Some banks and sloughed in and even some small islands had completely disappeared. There is little doubt that Icicle Creek historical channel is a state of geomorphic change.

Using GIS cell-based modeling and scripts to compute WUA was also the best approach. With this technique we were able to incorporate precisely mapped field features including complex cover habitat running longitudinally up islands including undercut banks and overhanging vegetation which would have been difficult to capture with cross sections unless a very large number of cross sections was used. As well, we could easily produce other variants of usable habitat such as the high quality estimates of usable area (UA) produced in Appendix B.

Perhaps the biggest surprise was the apparent reduction in available spawning habitat based on the large amounts of new fines deposited throughout the study site (Figure 24). Staff observed and documented large deposits of fine and coarse sand between the start of the field effort in October of 2011 and the end of field work in September 2012. It is likely to conclude that the amount of predicted WUA for spawning will increase as these fines decrease. However, the overall proportion of habitat may remain similar across streamflows. Depositional events from upstream mass wasting events have likely occurred in the basin since time immemorial. The frequency and proportion of which that have historical deposited in the historical channel is not known.

Figure 24. Coarse and fine sand deposits in the Icicle Creek historical channel.

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Appendix A

Appendix A1 – WUA Percent of Peak, for April Spawners

Flows (cfs)		April Spawners			
USGS	Structure 2	Steelhead	Rainbow	Cutthroat	Lamprey
na	20	13%	49%	95%	90%
na	30	25%	70%	100%	99%
na	40	38%	83%	95%	100%
na	50	50%	91%	89%	99%
88	60	61%	96%	83%	96%
101	70	70%	98%	79%	93%
115	80	78%	99%	76%	91%
129	90	84%	100%	73%	88%
142	100	89%	99%	70%	85%
168	120	95%	95%	65%	79%
193	140	99%	92%	60%	74%
218	160	100%	90%	56%	68%
243	180	99%	86%	54%	64%
266	200	97%	83%	51%	59%
325	250	88%	76%	44%	50%
382	300	77%	71%	36%	42%
437	350	66%	66%	29%	35%
491	400	59%	60%	25%	31%
544	450	53%	54%	20%	27%
596	500	50%	48%	17%	23%
648	550	47%	42%	15%	20%
699	600	44%	36%	13%	17%
749	650	41%	32%	11%	15%
799	700	39%	28%	10%	13%
848	750	36%	24%	9%	11%
896	800	33%	21%	8%	10%
944	850	30%	19%	7%	9%
1,024	900	27%	16%	6%	8%
1,115	950	25%	15%	5%	7%
1,215	1,000	23%	13%	5%	6%
1,315	1,050	21%	12%	4%	5%
1,425	1,100	20%	11%	4%	5%
1,525	1,150	19%	10%	4%	4%
1,640	1,200	18%	10%	4%	4%
1,760	1,250	16%	9%	3%	4%
1,890	1,300	15%	9%	3%	4%
2,020	1,350	14%	8%	3%	3%
2,150	1,400	13%	7%	3%	3%
2,300	1,450	12%	7%	2%	2%
2,440	1,500	12%	7%	2%	2%

April Exceedance flows at Structure 2 (90-10%) 270 to 873 cfs and are highlighted in the shaded area.

Appendix A2 – WUA Percent of Peak, for May Spawners

Flows (cfs)		May Spawners			
USGS	Structure 2	Steelhead	Rainbow	Cutthroat	Lamprey
na	20	13%	49%	95%	90%
na	30	25%	70%	100%	99%
na	40	38%	83%	95%	100%
na	50	50%	91%	89%	99%
88	60	61%	96%	83%	96%
101	70	70%	98%	79%	93%
115	80	78%	99%	76%	91%
129	90	84%	100%	73%	88%
142	100	89%	99%	70%	85%
168	120	95%	95%	65%	79%
193	140	99%	92%	60%	74%
218	160	100%	90%	56%	68%
243	180	99%	86%	54%	64%
266	200	97%	83%	51%	59%
325	250	88%	76%	44%	50%
382	300	77%	71%	36%	42%
437	350	66%	66%	29%	35%
491	400	59%	60%	25%	31%
544	450	53%	54%	20%	27%
596	500	50%	48%	17%	23%
648	550	47%	42%	15%	20%
699	600	44%	36%	13%	17%
749	650	41%	32%	11%	15%
799	700	39%	28%	10%	13%
848	750	36%	24%	9%	11%
896	800	33%	21%	8%	10%
944	850	30%	19%	7%	9%
1,024	900	27%	16%	6%	8%
1,115	950	25%	15%	5%	7%
1,215	1,000	23%	13%	5%	6%
1,315	1,050	21%	12%	4%	5%
1,425	1,100	20%	11%	4%	5%
1,525	1,150	19%	10%	4%	4%
1,640	1,200	18%	10%	4%	4%
1,760	1,250	16%	9%	3%	4%
1,890	1,300	15%	9%	3%	4%
2,020	1,350	14%	8%	3%	3%
2,150	1,400	13%	7%	3%	3%
2,300	1,450	12%	7%	2%	2%
2,440	1,500	12%	7%	2%	2%

May exceedance flows at Structure 2 (90-10%) 959 to 1490 cfs and are highlighted in the shaded area.

Appendix A3 – WUA Percent of Peak, for June Spawners

Flows (cfs)		June Spawners			
USGS	Structure 2	Steelhead	Rainbow	Cutthroat	Lamprey
na	20	13%	49%	95%	90%
na	30	25%	70%	100%	99%
na	40	38%	83%	95%	100%
na	50	50%	91%	89%	99%
88	60	61%	96%	83%	96%
101	70	70%	98%	79%	93%
115	80	78%	99%	76%	91%
129	90	84%	100%	73%	88%
142	100	89%	99%	70%	85%
168	120	95%	95%	65%	79%
193	140	99%	92%	60%	74%
218	160	100%	90%	56%	68%
243	180	99%	86%	54%	64%
266	200	97%	83%	51%	59%
325	250	88%	76%	44%	50%
382	300	77%	71%	36%	42%
437	350	66%	66%	29%	35%
491	400	59%	60%	25%	31%
544	450	53%	54%	20%	27%
596	500	50%	48%	17%	23%
648	550	47%	42%	15%	20%
699	600	44%	36%	13%	17%
749	650	41%	32%	11%	15%
799	700	39%	28%	10%	13%
848	750	36%	24%	9%	11%
896	800	33%	21%	8%	10%
944	850	30%	19%	7%	9%
1,024	900	27%	16%	6%	8%
1,115	950	25%	15%	5%	7%
1,215	1,000	23%	13%	5%	6%
1,315	1,050	21%	12%	4%	5%
1,425	1,100	20%	11%	4%	5%
1,525	1,150	19%	10%	4%	4%
1,640	1,200	18%	10%	4%	4%
1,760	1,250	16%	9%	3%	4%
1,890	1,300	15%	9%	3%	4%
2,020	1,350	14%	8%	3%	3%
2,150	1,400	13%	7%	3%	3%
2,300	1,450	12%	7%	2%	2%
2,440	1,500	12%	7%	2%	2%

June Exceedance flows at Structure 2 (90-10%) 994 to 1610 cfs and are highlighted in the shaded area.

Appendix A4 – WUA Percent of Peak, for July Spawners

Flows (cfs)		July Spawners		
USGS	Structure 2	Spring Chinook	Whitefish	Sucker
na	20	17%	4%	49%
na	30	32%	7%	70%
na	40	47%	10%	83%
na	50	60%	13%	91%
88	60	71%	16%	96%
101	70	79%	19%	98%
115	80	87%	23%	99%
129	90	92%	26%	100%
142	100	96%	29%	99%
168	120	100%	36%	95%
193	140	100%	42%	92%
218	160	100%	49%	90%
243	180	99%	55%	86%
266	200	98%	62%	83%
325	250	94%	75%	76%
382	300	91%	85%	71%
437	350	87%	92%	66%
491	400	82%	97%	60%
544	450	79%	99%	54%
596	500	75%	100%	48%
648	550	72%	99%	42%
699	600	68%	98%	36%
749	650	64%	96%	32%
799	700	59%	94%	28%
848	750	54%	92%	24%
896	800	49%	90%	21%
944	850	45%	88%	19%
1,024	900	41%	85%	16%
1,115	950	38%	83%	15%
1,215	1,000	36%	81%	13%
1,315	1,050	34%	79%	12%
1,425	1,100	33%	77%	11%
1,525	1,150	32%	74%	10%
1,640	1,200	31%	72%	10%
1,760	1,250	29%	70%	9%
1,890	1,300	29%	68%	9%
2,020	1,350	27%	65%	8%
2,150	1,400	26%	62%	7%
2,300	1,450	26%	60%	7%
2,440	1,500	25%	57%	7%

July Exceedance flows at Structure 2 (90-10%) 288 to 1118 cfs and are highlighted in the shaded area.

Appendix A5 – WUA Percent of Peak, for August Spawners

Flows (cfs)		August Spawners		
USGS	**Structure 2**	**Spring Chinook**	**Whitefish**	**Sucker**
na	20	17%	4%	49%
na	30	32%	7%	70%
na	40	47%	10%	83%
na	50	60%	13%	91%
88	60	71%	16%	96%
101	70	79%	19%	98%
115	80	87%	23%	99%
129	90	92%	26%	100%
142	100	96%	29%	99%
168	120	100%	36%	95%
193	140	100%	42%	92%
218	160	100%	49%	90%
243	180	99%	55%	86%
266	200	98%	62%	83%
325	250	94%	75%	76%
382	300	91%	85%	71%
437	350	87%	92%	66%
491	400	82%	97%	60%
544	450	79%	99%	54%
596	500	75%	100%	48%
648	550	72%	99%	42%
699	600	68%	98%	36%
749	650	64%	96%	32%
799	700	59%	94%	28%
848	750	54%	92%	24%
896	800	49%	90%	21%
944	850	45%	88%	19%
1,024	900	41%	85%	16%
1,115	950	38%	83%	15%
1,215	1,000	36%	81%	13%
1,315	1,050	34%	79%	12%
1,425	1,100	33%	77%	11%
1,525	1,150	32%	74%	10%
1,640	1,200	31%	72%	10%
1,760	1,250	29%	70%	9%
1,890	1,300	29%	68%	9%
2,020	1,350	27%	65%	8%
2,150	1,400	26%	62%	7%
2,300	1,450	26%	60%	7%
2,440	1,500	25%	57%	7%

August Exceedance flows at Structure 2 (90-10%) 106 to 346 cfs and are highlighted in the shaded area.

Appendix A6 – WUA Percent of Peak, for September Spawners

Flows (cfs)		September Spawners				
USGS	Structure 2	Coho	Spring Chinook	Whitefish	Sucker	Summer Chinook
na	20	56%	17%	4%	49%	17%
na	30	73%	32%	7%	70%	32%
na	40	84%	47%	10%	83%	47%
na	50	91%	60%	13%	91%	60%
88	60	96%	71%	16%	96%	71%
101	70	98%	79%	19%	98%	79%
115	80	100%	87%	23%	99%	87%
129	90	100%	92%	26%	100%	92%
142	100	100%	96%	29%	99%	96%
168	120	98%	100%	36%	95%	100%
193	140	94%	100%	42%	92%	100%
218	160	90%	100%	49%	90%	100%
243	180	86%	99%	55%	86%	99%
266	200	82%	98%	62%	83%	98%
325	250	76%	94%	75%	76%	94%
382	300	70%	91%	85%	71%	91%
437	350	66%	87%	92%	66%	87%
491	400	62%	82%	97%	60%	82%
544	450	59%	79%	99%	54%	79%
596	500	56%	75%	100%	48%	75%
648	550	53%	72%	99%	42%	72%
699	600	50%	68%	98%	36%	68%
749	650	47%	64%	96%	32%	64%
799	700	45%	59%	94%	28%	59%
848	750	43%	54%	92%	24%	54%
896	800	41%	49%	90%	21%	49%
944	850	39%	45%	88%	19%	45%
1,024	900	37%	41%	85%	16%	41%
1,115	950	35%	38%	83%	15%	38%
1,215	1,000	34%	36%	81%	13%	36%
1,315	1,050	32%	34%	79%	12%	34%
1,425	1,100	31%	33%	77%	11%	33%
1,525	1,150	29%	32%	74%	10%	32%
1,640	1,200	28%	31%	72%	10%	31%
1,760	1,250	27%	29%	70%	9%	29%
1,890	1,300	26%	29%	68%	9%	29%
2,020	1,350	24%	27%	65%	8%	27%
2,150	1,400	23%	26%	62%	7%	26%
2,300	1,450	22%	26%	60%	7%	26%
2,440	1,500	21%	25%	57%	7%	25%

September Exceedance flows at Structure 2 (90-10%) 68 to 177 cfs and are highlighted in the shaded area.

Appendix A7 – WUA Percent of Peak, for October Spawners

Flows (cfs)		October Spawners	
USGS	Structure 2	Coho	Summer Chinook
na	20	56%	17%
na	30	73%	32%
na	40	84%	47%
na	50	91%	60%
88	60	96%	71%
101	70	98%	79%
115	80	100%	87%
129	90	100%	92%
142	100	100%	96%
168	120	98%	100%
193	140	94%	100%
218	160	90%	100%
243	180	86%	99%
266	200	82%	98%
325	250	76%	94%
382	300	70%	91%
437	350	66%	87%
491	400	62%	82%
544	450	59%	79%
596	500	56%	75%
648	550	53%	72%
699	600	50%	68%
749	650	47%	64%
799	700	45%	59%
848	750	43%	54%
896	800	41%	49%
944	850	39%	45%
1,024	900	37%	41%
1,115	950	35%	38%
1,215	1,000	34%	36%
1,315	1,050	32%	34%
1,425	1,100	31%	33%
1,525	1,150	29%	32%
1,640	1,200	28%	31%
1,760	1,250	27%	29%
1,890	1,300	26%	29%
2,020	1,350	24%	27%
2,150	1,400	23%	26%
2,300	1,450	22%	26%
2,440	1,500	21%	25%

October Exceedance flows at Structure 2 (90-10%) 59 to 348 cfs and are highlighted in the shaded area.

Appendix A8 – WUA Percent of Peak, for November and December Spawners

Flows (cfs)		November Spawners
USGS	Structure 2	Coho
na	20	56%
na	30	73%
na	40	84%
na	50	91%
88	60	96%
101	70	98%
115	80	100%
129	90	100%
142	100	100%
168	120	98%
193	140	94%
218	160	90%
243	180	86%
266	200	82%
325	250	76%
382	300	70%
437	350	66%
491	400	62%
544	450	59%
596	500	56%
648	550	53%
699	600	50%
749	650	47%
799	700	45%
848	750	43%
896	800	41%
944	850	39%
1,024	900	37%
1,115	950	35%
1,215	1,000	34%
1,315	1,050	32%
1,425	1,100	31%
1,525	1,150	29%
1,640	1,200	28%
1,760	1,250	27%
1,890	1,300	26%
2,020	1,350	24%
2,150	1,400	23%
2,300	1,450	22%
2,440	1,500	21%

Flows (cfs)		December Spawners
USGS	Structure 2	Coho
na	20	56%
na	30	73%
na	40	84%
na	50	91%
88	60	96%
101	70	98%
115	80	100%
129	90	100%
142	100	100%
168	120	98%
193	140	94%
218	160	90%
243	180	86%
266	200	82%
325	250	76%
382	300	70%
437	350	66%
491	400	62%
544	450	59%
596	500	56%
648	550	53%
699	600	50%
749	650	47%
799	700	45%
848	750	43%
896	800	41%
944	850	39%
1,024	900	37%
1,115	950	35%
1,215	1,000	34%
1,315	1,050	32%
1,425	1,100	31%
1,525	1,150	29%
1,640	1,200	28%
1,760	1,250	27%
1,890	1,300	26%
2,020	1,350	24%
2,150	1,400	23%
2,300	1,450	22%
2,440	1,500	21%

November Exceedance flows at Structure 2 (90-10%) 98 to 768 cfs and are highlighted in the shaded area.

December Exceedance flows at Structure 2 (90-10%) 103 to 517 cfs and are highlighted in the shaded area.

Appendix B

Appendix B1 Usable Spawning Area

Flows (cfs)		Wetted	Usable Spawning Area m^2 (CSI >= 0.6)								
USGS	Structure 2	Area m^2	Coho	Chinook	Steelhead	Rainbow	Cutthroat	Whitefish	Lamprey	Sucker
na	20	17,419	620	11	44	27	122	0	185	27
na	30	18,221	1,063	54	214	65	128	0	146	65
na	40	18,837	1,422	136	448	105	83	0	115	105
na	50	19,362	1,680	194	696	112	66	0	97	112
88	60	19,787	1,837	271	922	113	52	0	105	113
101	70	20,160	1,869	362	1,124	121	57	16	96	121
115	80	20,475	1,870	428	1,307	117	42	41	87	117
129	90	20,751	1,826	515	1,476	125	35	74	75	125
142	100	21,032	1,774	546	1,603	141	39	98	75	141
168	120	21,553	1,658	549	1,765	141	44	189	67	141
193	140	22,021	1,449	495	1,824	106	34	336	56	106
218	160	22,451	1,254	437	1,845	114	36	491	48	114
243	180	22,924	1,066	387	1,834	99	31	652	34	99
266	200	23,441	922	368	1,723	81	41	822	34	81
325	250	24,611	732	334	1,415	77	26	1,260	24	77
382	300	25,813	653	276	1,048	68	21	1,617	18	68
437	350	27,295	577	215	790	84	14	1,909	14	84
491	400	29,087	547	193	667	67	12	2,150	11	67
544	450	30,787	485	200	587	51	11	2,206	11	51
596	500	32,357	449	238	523	37	3	2,165	8	37
648	550	33,938	418	235	493	33	8	2,097	13	33
699	600	35,482	384	226	475	32	10	2,034	8	32
749	650	36,854	344	202	447	21	5	1,980	7	21
799	700	38,238	305	175	447	17	4	1,862	9	17
848	750	39,365	267	144	423	14	4	1,696	7	14
896	800	40,658	215	103	359	15	4	1,573	6	15
944	850	41,598	161	73	322	18	2	1,433	2	18
1,024	900	42,531	113	42	290	18	2	1,216	4	18
1,115	950	43,449	86	25	244	15	0	1,065	4	15
1,215	1,000	44,210	66	25	205	13	0	1,002	3	13
1,315	1,050	44,811	54	26	184	10	0	954	2	10
1,425	1,100	45,315	41	21	168	5	0	948	1	5
1,525	1,150	45,690	39	18	148	1	0	923	0	1
1,640	1,200	46,025	36	16	132	0	0	891	0	0
1,760	1,250	46,307	27	13	101	0	0	862	0	0
1,890	1,300	46,552	23	8	76	0	0	838	0	0
2,020	1,350	46,799	22	8	36	1	0	802	0	1
2,150	1,400	47,012	19	8	31	0	0	734	0	0
2,300	1,450	47,275	16	9	29	0	0	675	0	0
2,440	1,500	47,484	17	12	30	0	0	608	0	0

Appendix B2 Usable Rearing Area

Flows (cfs)		Wetted	Usable Rearing Area M^2 (CSI >= 0.6)							
			Chinook	Steelhead	Rainbow	Cutthroat	Whitefish	Whitefish	Sucker	Bulltrout
USGS	Structure 2	Area m^2	Juvenile	Juvenile	Juvenile	Juvenile	Juvenile	Adult	Adult & Juv.	Adult & Juv.
na	20	17,419	45	10	10	64	0	0	142	100
na	30	18,221	110	36	36	116	0	0	271	180
na	40	18,837	161	64	64	150	0	0	360	246
na	50	19,362	203	96	96	178	0	0	409	258
88	60	19,787	236	138	138	187	0	1	480	280
101	70	20,160	273	170	170	219	1	2	532	301
115	80	20,475	308	195	195	229	2	11	576	308
129	90	20,751	352	216	216	242	5	16	598	326
142	100	21,032	392	249	249	249	15	34	607	328
168	120	21,553	458	332	332	241	38	70	609	339
193	140	22,021	528	393	393	259	62	108	623	354
218	160	22,451	594	414	414	257	81	149	608	381
243	180	22,924	657	440	440	255	113	218	597	385
266	200	23,441	678	484	484	273	147	299	564	367
325	250	24,611	714	532	532	287	257	456	506	360
382	300	25,813	724	540	540	276	378	615	432	325
437	350	27,295	686	569	569	252	466	775	400	315
491	400	29,087	647	608	608	286	528	963	354	367
544	450	30,787	612	633	633	288	594	1,099	296	345
596	500	32,357	566	631	631	262	656	1,259	253	304
648	550	33,938	514	626	626	228	747	1,458	214	260
699	600	35,482	461	576	576	188	804	1,604	188	239
749	650	36,854	409	513	513	174	871	1,729	184	235
799	700	38,238	379	483	483	166	898	1,816	159	229
848	750	39,365	339	452	452	156	915	1,903	163	216
896	800	40,658	330	426	426	144	928	1,993	154	191
944	850	41,598	304	397	397	148	938	2,085	147	205
1,024	900	42,531	299	372	372	148	928	2,133	150	208
1,115	950	43,449	317	385	385	139	921	2,208	115	195
1,215	1,000	44,210	305	366	366	135	896	2,281	105	195
1,315	1,050	44,811	287	341	341	127	917	2,298	101	185
1,425	1,100	45,315	252	341	341	124	930	2,322	75	169
1,525	1,150	45,690	239	327	327	110	930	2,363	69	152
1,640	1,200	46,025	205	310	310	107	896	2,365	68	171
1,760	1,250	46,307	208	279	279	102	896	2,392	70	179
1,890	1,300	46,552	212	270	270	96	863	2,416	62	198
2,020	1,350	46,799	221	245	245	116	840	2,416	64	197
2,150	1,400	47,012	238	235	235	119	827	2,425	61	199
2,300	1,450	47,275	245	231	231	117	827	2,446	56	201
2,440	1,500	47,484	249	238	238	131	800	2,451	60	189

U.S. Fish and Wildlife Service
Columbia River Fisheries Program Office
1211 SE Cardinal Court, Suite 100
Vancouver, WA 98683

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