FA-05 SKAGIT RIVER GORGE BYPASS REACH HYDRAULIC AND INSTREAM FLOW MODEL DEVELOPMENT STUDY REPORT

SKAGIT RIVER HYDROELECTRIC PROJECT FERC NO. 553

Seattle City Light

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Updated Study Report

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List of Acronyms and Abbreviations

2-D .....two-dimensional
3-D .....three-dimensional
ADCP.....acoustic Doppler current profiler
ADV.....acoustic Doppler velocimeter
cfs.....cubic feet per second
City Light.....Seattle City Light
DEM.....Digital Elevation Model
Ecology .....Washington State Department of Ecology
ESH.....effective spawning habitat (model)
FERC.....Federal Energy Regulatory Commission
ft .....foot/feet
GIS .....Geographic Information System
GPS .....Global Positioning System
HDR.....HDR Engineering, Inc.
HEC-RAS .....Hydrologic Engineering Center River Analysis System
HSC.....habitat suitability criteria
HSI .....Habitat Suitability Index
IFIM .....Instream Flow Incremental Method
ISR .....Initial Study Report
LiDAR.....Light Detection and Ranging
LP.....licensing participant
LSPIV .....Large Scale Particle Image Velocimetry
PRM.....Project River Mile
Project .....Skagit River Hydroelectric Project
QSI.....Quantum Spatial, Inc.
RP.....recommended preference
RSP .....Revised Study Plan
SZF.....stage of zero flow
UAV.....unmanned aerial vehicle
UHA.....usable habitat area
USACE .....U.S. Army Corps of Engineers

USGS .....U.S. Geological Survey

USR.....Updated Study Report

WDFW.....Washington Department of Fish and Wildlife

WSE .....water surface elevation

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1.0 INTRODUCTION

The FA-05 Skagit River Gorge Bypass Reach Hydraulic and Instream Flow Model Development Study (Bypass Instream Flow Model Development Study) is being conducted in support of the relicensing of the Skagit River Hydroelectric Project (Project), Federal Energy Regulatory Commission (FERC) No. 553, as identified in the Revised Study Plan (RSP) submitted by Seattle City Light (City Light) on April 7, 2021 (City Light 2021). On June 9, 2021, City Light filed a "Notice of Certain Agreements on Study Plans for the Skagit Relicensing" (June 9, 2021 Notice)[1] that detailed additional modifications to the RSP agreed to between City Light and supporting licensing participants (LP) (which include the Swinomish Indian Tribal Community, Upper Skagit Indian Tribe, National Marine Fisheries Service, National Park Service, U.S. Fish and Wildlife Service, Washington State Department of Ecology [Ecology], and Washington Department of Fish and Wildlife [WDFW]). The June 9, 2021 Notice included agreed to modifications to the Bypass Instream Flow Model Development Study.

In its July 16, 2021 Study Plan Determination, FERC approved the Bypass Instream Flow Model Development Study without modification. On March 8, 2022, City Light filed its Initial Study Report (ISR). The Upper Skagit Indian Tribe filed a request for study modification. FERC's August 8, 2022 Determination on Requests for Study Modification did not require any modifications to the Bypass Instream Flow Model Development Study.

This study is complete and a report of the study efforts is being filed with FERC as part of City Light's Updated Study Report (USR).

[1] Referred to by FERC in its July 16, 2021 Study Plan Determination as the "updated RSP."

2.0 STUDY GOALS AND OBJECTIVES

The goal of the Bypass Instream Flow Model Development Study is to develop a flow-habitat evaluation tool for the Gorge bypass reach (defined as the reach between Gorge Dam and Gorge Powerhouse) and to develop hydraulic data necessary to support an evaluation of fish passage at two locations in the Gorge bypass reach.

Specific objectives include:

- Develop and calibrate a numerical hydraulic model (or models) of the Gorge bypass reach.
- Integrate hydraulic model outputs and observed characteristics of substrate and cover with biological (fish species, life stages, periodicities) and physical (depth, velocity) criteria to develop flow-habitat relationships for the Gorge bypass reach.
- Apply the model to provide hydraulic data to support the evaluation of fish passage, particularly at two previously identified potential upstream passage barriers[2] (Envirosphere 1989) within the Gorge bypass reach located approximately 0.6 and 1.3 miles upstream from Gorge Powerhouse.

Once the study is complete (i.e., the model has been developed), the flow-habitat model will be used to support additional discussions regarding hydraulic conditions and aquatic habitat within the Gorge bypass reach, the potential for fish passage at Gorge bypass reach Existing Features and, through integration with results from the FA-02 Instream Flow Model Development Study[3] (City Light 2023a), evaluation of instream flows in the mainstem Skagit River between Gorge Dam and the Sauk River.

In the following sections two distinct models are discussed as part of the Bypass Instream Flow Model Development Study: (1) the hydraulic model of the Gorge bypass reach (referred to as the "Bypass Hydraulic Model"); and (2) the habitat model, which integrates hydraulic model output with habitat data (referred to as the "Bypass Habitat Model").

The June 9, 2021 Notice commitments addressed in the Bypass Instream Flow Model Development Study are summarized below:[4]

- City Light will provide a planned higher flow event (4,000+ cubic feet per second [cfs]) in summer/fall if opportunistic high flow is not available. Data collected during this event will be used in calibration of the Bypass Hydraulic Model and in evaluation of fish passage under the FA-04 Fish Passage Technical Studies Program (FA-04 Fish Passage Study; City Light 2023b). The report for the FA-04 Fish Passage Study will include an assessment of the impacts to fish migration, both beneficial and detrimental, of certain flow regimes (City Light 2023b).

[2] The potential upstream passage barriers are boulder cascades which, following discussion with LPs, are referred to in the study report as "Existing Feature 1" and "Existing Feature 2" (collectively, the "Existing Features").

[3] The FA-02 Instream Flow Model Development Study developed an instream flow model for the mainstem Skagit River from Gorge Powerhouse to the confluence with the Sauk River.

[4] A complete listing of June 9, 2021 Notice commitments related to the Bypass Instream Flow Model Development Study is provided in Section 6.1 of this study report.

- City Light and LPs will be treating Pacific Lamprey (*Entosphenus tridentatus*), Salish Sucker (*Catostomus catostomus*), and Dolly Varden (*Salvelinus malma*) as present in the Gorge bypass reach. City Light and LPs will be selecting species for habitat suitability criteria (HSC) analysis.

3.0 STUDY AREA

The study area extends from Gorge Dam at Project River Mile (PRM) 97.21 downstream to the U.S. Geological Survey (USGS) Skagit River at Newhalem gage (12178000) at PRM 94.19, located approximately 0.5 miles downstream from Gorge Powerhouse (Figure 3.0-1).[5] Reach length is 3.02 miles. The study area is coincident with the extents of the Bypass Habitat and Bypass Hydraulic Models (Table 3.0-1).

Table 3.0-1. Model longitudinal extents.

Model	Lower Extent	Upper Extent	Distance (miles)
Bypass Habitat Model	USGS gage Skagit River at Newhalem, WA (12178000) at PRM 94.19	Gorge Dam at PRM 97.21	3.0
Bypass Hydraulic Model	USGS gage Skagit River at Newhalem, WA (12178000) at PRM 94.19	Gorge Dam at PRM 97.21	3.0

The downstream limit of the hydraulic model, i.e., the USGS Skagit River at Newhalem gage, was selected to allow use of the stage-discharge rating at the gage site as a robust downstream model boundary and to overlap with the FA-02 Upper Skagit Hydraulic Model, which extends from just above Gorge Powerhouse at PRM 94.75 to the USGS gage Skagit River above Miller Creek near Rockport (USGS 12189700) at PRM 64.95, and was developed under the FA-02 Instream Flow Model Development Study (City Light 2023a).

[5] City Light extended the study area to approximately one-half mile downstream from Gorge Powerhouse to the U.S. Geological Survey (USGS) Skagit River at Newhalem gage to provide a robust downstream boundary for instream flow modeling and to facilitate integration with the FA-02 Instream Flow Model Development Study. Further discussion is provided in Section 7.0 of this study report.

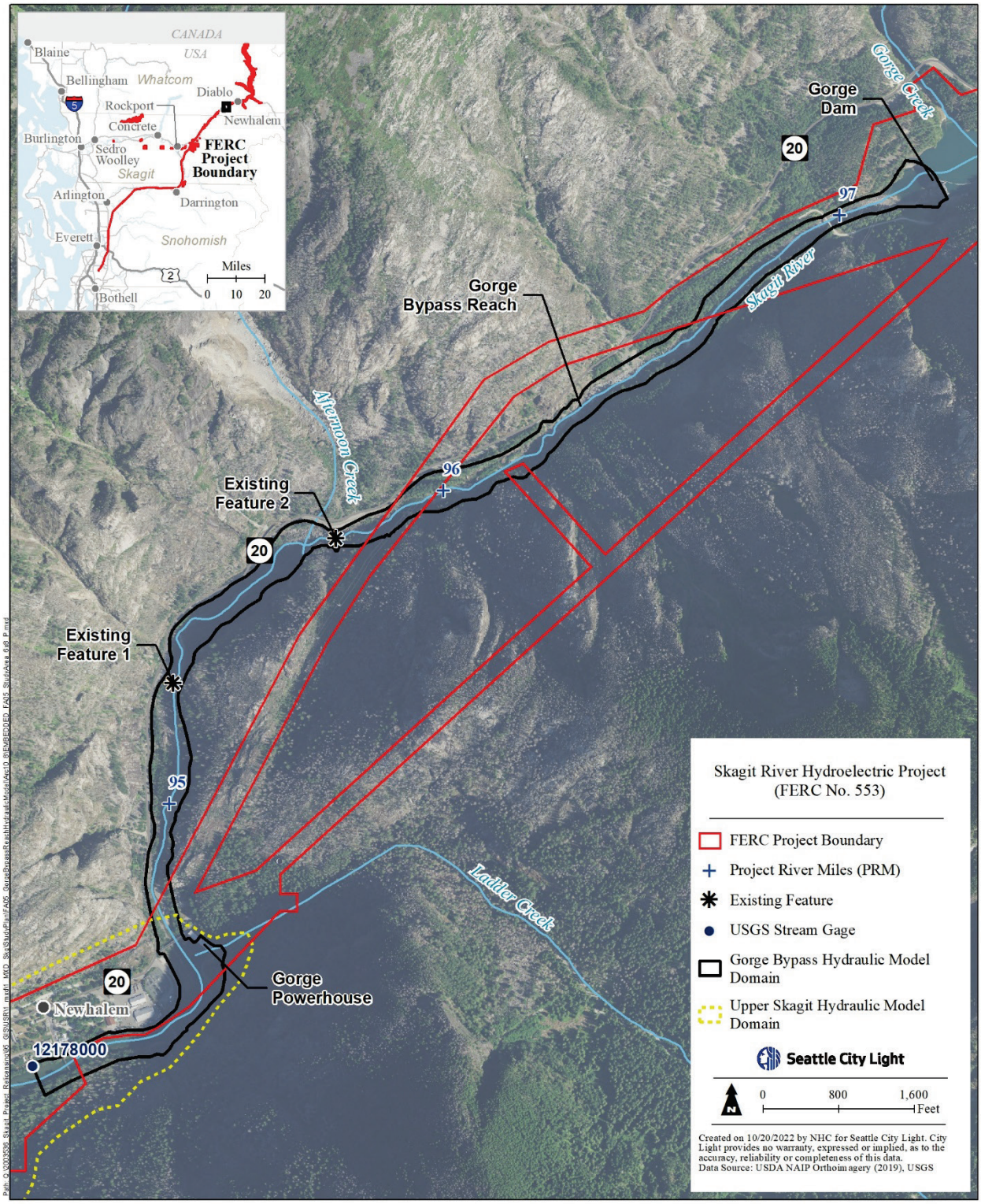

Figure 3.0-1. Overview of study area for the Bypass Instream Flow Model Development Study.

4.0 METHODS

4.1 Overview

Creation of a flow-habitat evaluation tool to analyze instream flows for the Gorge bypass reach required the development of two distinct models: (1) a two-dimensional (2-D) hydraulic model (the Bypass Hydraulic Model) and (2) a habitat model (the Bypass Habitat Model). The Bypass Habitat Model integrates water depth and velocity outputs from the Bypass Hydraulic Model with biological criteria (HSCs) and habitat data to produce flow-habitat relationships for the Gorge bypass reach for fish species and life stages of interest. The Bypass Hydraulic Model also supports fish passage evaluation at Existing Features 1 and 2 as part of the FA-04 Fish Passage Study (Figure 3.0-1).

The principal tasks involved, described in the following sections, comprised:

- Data collection (Section 4.2);
- Bypass Hydraulic Model development (Section 4.3);
- Bypass Hydraulic Model sensitivity testing (Section 4.4);
- Bypass Hydraulic Model calibration (Section 4.5);
- Bypass Habitat Model development (Section 4.6);
- Flow-habitat analysis (Section 4.7);
- Production of hydraulic data in support of fish passage evaluation (Section 4.8);
- Evaluation of the November and December 2021 Large Spills above Newhalem (Section 4.9); and,
- Extensive consultation with LPs throughout the course the study (Section 4.10).

4.2 Data Collection

The primary components required to build a 2-D numerical model for instream flow assessment include topographic and bathymetric data, hydrologic and hydraulic data observations for model calibration/validation, substrate mapping, and cover mapping. The following sections summarize the collection and preparation of this information.

A more detailed discussion of the topographic and bathymetric data and hydrologic and hydraulic data collected and prepared for the Bypass Hydraulic Model is provided in the Bypass Hydraulic Model Calibration Report (Attachment A).

4.2.1 Topographic and Bathymetric Data

Three-dimensional (3-D) terrain mapping was necessary to develop a detailed topographic surface of the river channel and overbank regions for import to the Bypass Hydraulic Model. A combination of topobathymetric Light Detection and Ranging (LiDAR) and standard LiDAR returns covering the Bypass Hydraulic Model domain were acquired including:

- Quantum Spatial topobathymetric LiDAR ("green LiDAR") contracted by City Light; acquired April 25 and 26, 2018 (QSI 2018). Topobathymetric LiDAR includes both topographic (out-of-water) and bathymetric (underwater) terrain as observed during the time of survey; and
- Quantum Spatial topographic LiDAR ("standard" LiDAR) contracted by the USGS; acquired March 2016 – September 2016 (QSI 2017).

The 2018 topobathymetric LiDAR was the primary terrain source for the Bypass Hydraulic Model, while the 2016 LiDAR was used to extend coverage of the channel edge and/or overbank where the 2018 LiDAR did not extend far enough. Additionally, there are four locations where underwater voids (areas of inadequate laser returns) exist in the 2018 LiDAR, either due to turbid water, deep water, aerated water, vegetation cover, and/or a non-reflective channel bottom. These voids were filled with either surveyed bathymetry provided by City Light or by interpolating from LiDAR returns bordering each void and/or professional judgment.

4.2.2 Hydrologic and Hydraulic Data

Development of the Bypass Hydraulic Model required both the collection of discharge and stage records to define operational flows and model boundaries, and field measurements of depth, velocity, and water surface elevation (WSE) within the model domain to calibrate the model. The following sections summarize the collection and processing of hydrologic information and the coinciding field efforts to obtain hydraulic observations during the summer and fall of 2021.

4.2.2.1 Hydrology

The primary hydrologic input to the Gorge bypass reach is flow released from Gorge Dam, while the combined release from Gorge Dam and discharge from Gorge Powerhouse together with stage at the USGS Skagit River at Newhalem gage control conditions at the downstream end. Flow records for Gorge Dam spillway operations were provided by City Light while stage and discharge records for the USGS Skagit River at Newhalem gage were obtained online from the USGS National Water Information System website. Discharges from Gorge Powerhouse were determined by computing the difference between releases from Gorge Dam and corresponding discharges at the USGS Skagit River at Newhalem gage. Tributary inflows between Gorge Dam and the USGS Skagit River at Newhalem gage include Afternoon Creek and Ladder Creek (both ungaged). These tributaries provided negligible inflows during the dry summer conditions when field data were collected.

Controlled spillway releases for model calibration were chosen in consultation with LPs and coordinated with Gorge Dam operators from July 26-29, 2021. Stable daily flows of approximately 1,200, 500, 250, and 50 cfs were targeted for this period (subsequently referred to as "controlled releases"). An unscheduled spillway release with flows exceeding 6,000 cfs occurred in late June/early July 2021, allowing for additional measurements at the Existing Features to extend the range of model calibration in these areas.

4.2.2.2 Hydraulics

Field data collection efforts throughout the Gorge bypass reach to support hydraulic model calibration consisted of (1) water level logger recordings; (2) transect surveys; and (3) unmanned aerial vehicle (UAV) photography and videography.

Water Level Loggers

During Spring 2021, members of the FA-04 Fish Passage Study and FA-05 Bypass Instream Flow Model Development Study teams identified six locations at each Existing Feature that represented nominally stable pools and that connected a longitudinal water surface profile along the entirety of each feature (Figures 4.2-1 and 4.2-2). Onset HOBO U20 water level loggers were installed at these locations in May 2021 to measure water stage at Existing Features 1 and 2 to support hydraulic model calibration and the FA-04 Fish Passage Study (City Light 2023b). Level loggers began recording on May 27, 2021 providing WSE records for the unscheduled spills in late June/early July 2021 and for the controlled releases in late July 2021.

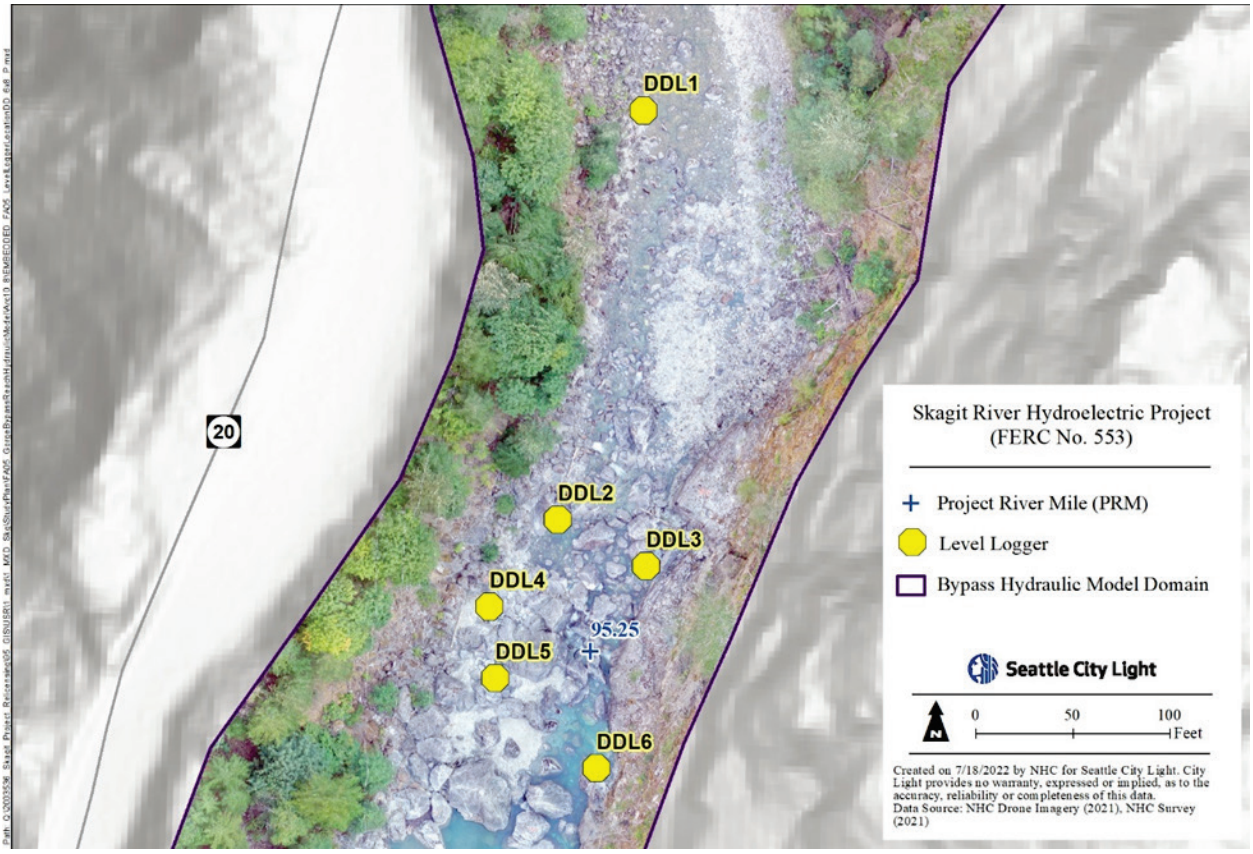

Figure 4.2-1. Level logger locations at Existing Feature 1.

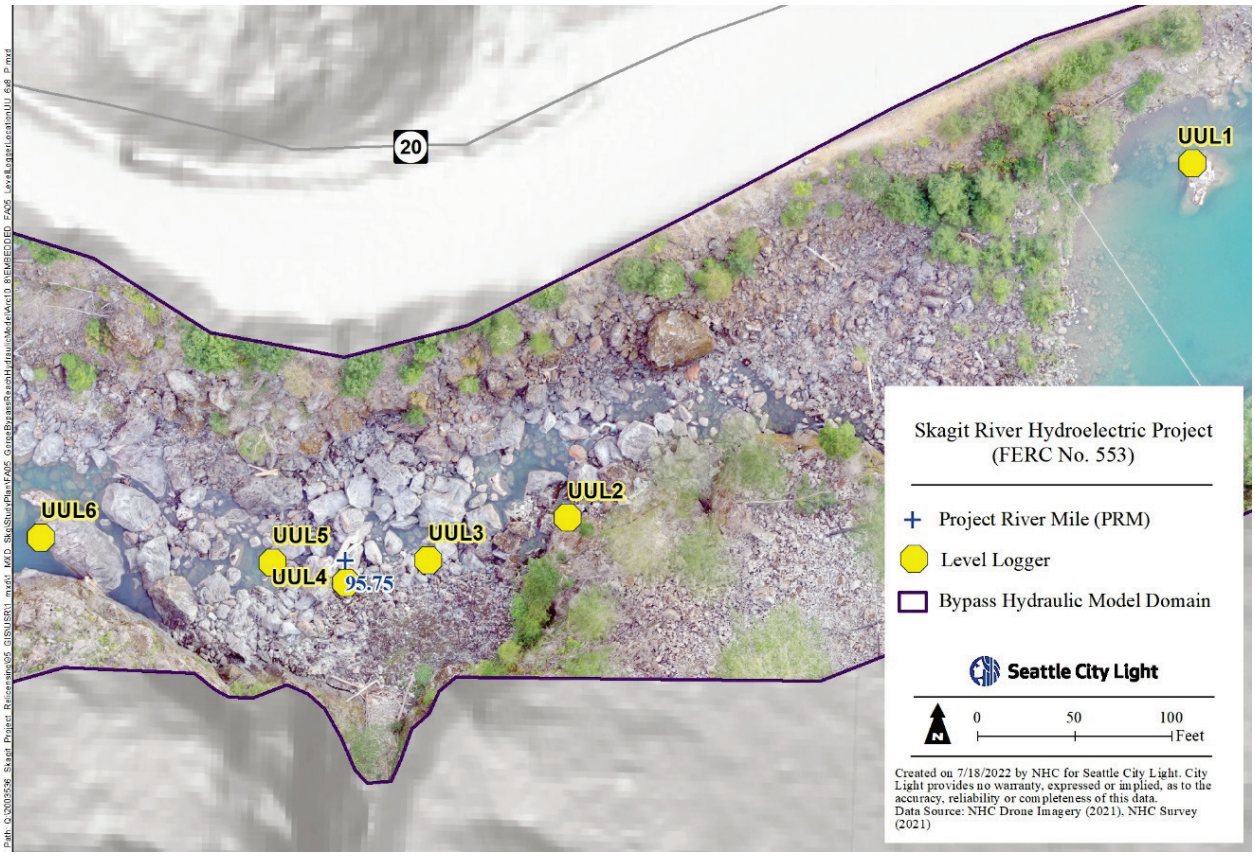

Figure 4.2-2. Level logger locations at Existing Feature 2.

Transect Surveys

Five transect locations were established in consultation with City Light and LPs to measure water depths and velocities during the controlled releases (Figure 4.2-3). The primary objective for selecting the transect locations was to capture hydraulic characteristics from a variety of geomorphic units represented in the Gorge bypass reach. Depth and velocity measurements were acquired at each transect with either an acoustic Doppler current profiler (ADCP) or with an acoustic Doppler velocimeter (ADV) and wading rod depending on water depth. Depth and velocity measurements were also used to compute discharge at each transect via the USGS mid-section method (Turnipseed and Sauer 2010).

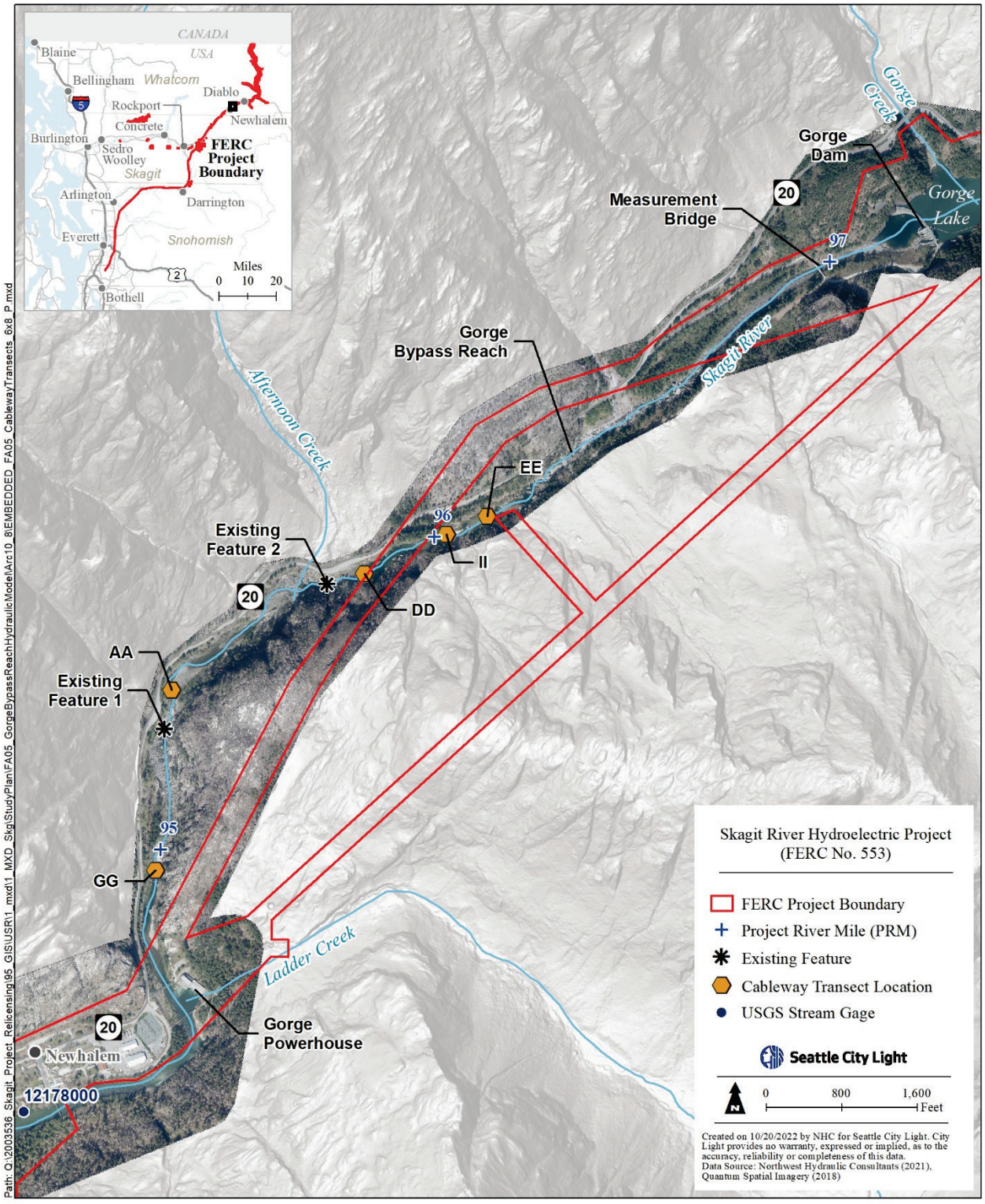

Figure 4.2-3. Hydraulic measurement transect locations.

UAV Photography and Video

Oblique and nadir (downward facing) photographs and video were taken with an UAV throughout the Gorge bypass reach during each of the controlled releases and during base flow conditions on July 30, 2021. Orthomosaic images (Figure 4.2-4) were processed from nadir photos to characterize substrate, vegetative cover, and channel characteristics for delineating hydraulic roughness zones and to define WSEs to inform hydraulic model calibration (Section 4.5.2). These photo series were also made available for use by other relicensing studies. Video recordings were collected with the UAV at Existing Features 1 and 2 to support Large Scale Particle Image Velocimetry (LSPIV) analysis, which is a technique for measuring 2-D surface velocity vectors. Unfortunately, hydraulic conditions (highly turbulent flow) were such that no reliable surface velocity data could be obtained.

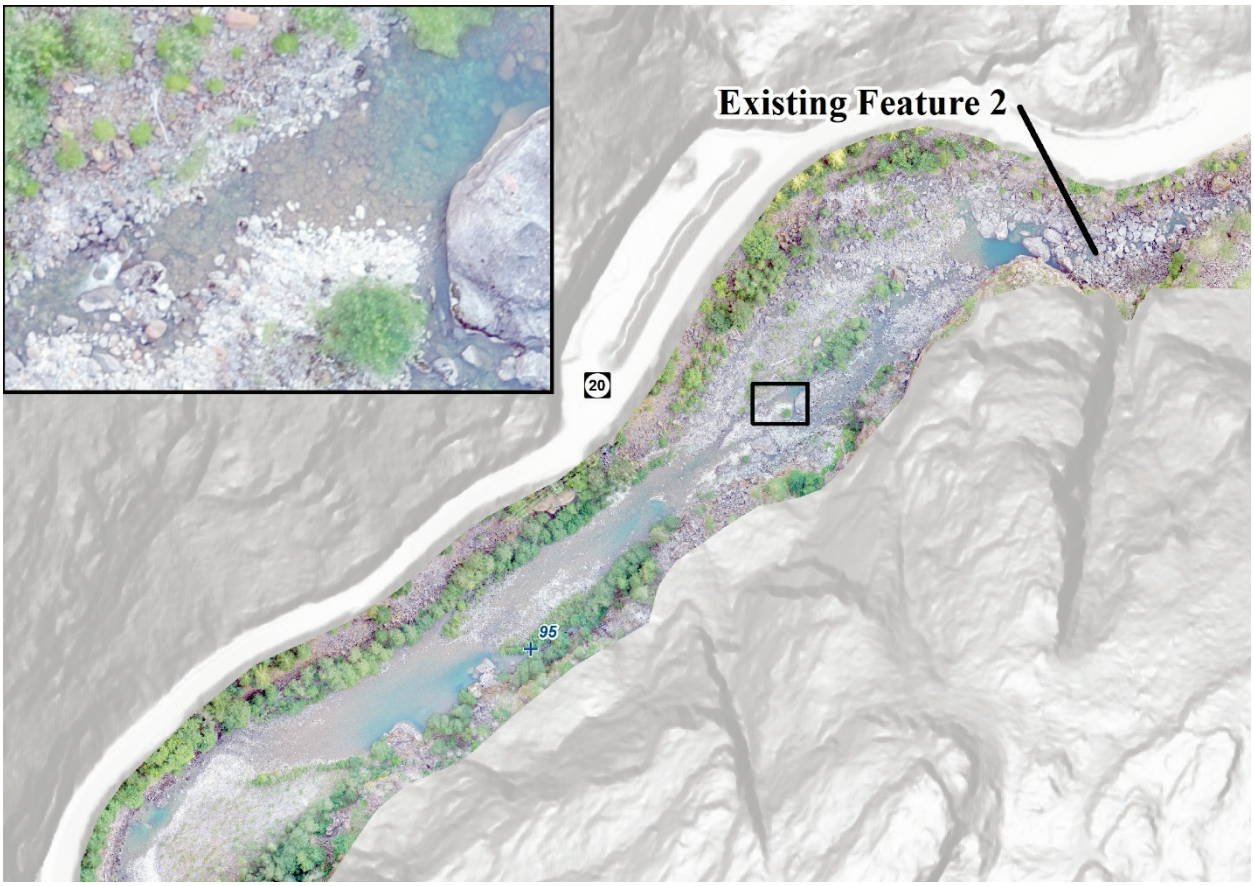

Figure 4.2-4. Processed orthoimagery example from UAV photos of base flow conditions on July 30, 2021.

4.2.3 Substrate and Cover Field Data Collection

Substrate and cover were mapped in the Gorge bypass reach using ground-based visual mapping supplemented by desktop mapping to fill in remaining data gaps after the field effort was completed. The field data collection effort is described below, and subsequent post-processing and desktop mapping is described in Section 4.6.6.

For the 3.02 mile-long study reach, the ground-based visual mapping effort occurred during the first week of August 2021 and consisted of a two-person crew experienced in substrate and cover mapping walking the accessible portions of the Gorge bypass reach and collecting detailed information on substrate/cover types and locations. The field crew mapped approximately 70 percent of the Gorge bypass reach on foot over a 1-week period. Areas not mapped in the field were too difficult to access and/or were in areas prone to landslides and deemed not safe to work in, or nearby.

Substrate and cover types were recorded in the field using handheld iPads equipped with differential Global Positioning System (GPS) and Geographic Information System (GIS) software loaded with base layers of the model area including aerial imagery and digital elevation terrain information. The substrate and cover mapping effort utilized the default methodology and codes provided in Washington State's Instream Flow Study Guidelines (Beecher and Caldwell 2022). Substrate codes used in the field effort used the format "ab.c" where "a" is the component code for dominant particle size (i.e., the type of substrate that covers the greatest area of the cell, and not necessarily the largest particle size in the cell); "b" is the component code for the subdominant particle size; and "c" is the percentage of the cell area covered by the dominant (50 percent or greater) substrate type. For example, the code 46.8 indicates 80 percent medium gravel and 20 percent small cobble. Table 4.2-1 lists codes 1 through 9, which are components of the substrate code, and 0.1 through 0.9, which are the cover codes.

Table 4.2-1. Washington State Instream Flow Study Guidelines substrate and cover codes (Beecher and Caldwell 2022).

Substrate Code	Type of Substrate	Cover Code	Type of Cover
1	Silt, clay, or organic	00.1	Undercut bank
2	Sand	00.2	Overhanging vegetation near or touching water[1]
3	Small Gravel (0.1 - 0.5 inches)	00.3	Rootwad (including partly undercut)
4	Medium Gravel (0.5 - 1.5 inches)	00.4	Log jam/submerged brush pile
5	Large Gravel (1.5 - 3 inches)	00.5	Log(s) parallel to bank
6	Small Cobble (3 - 6 inches)	00.6	Aquatic vegetation
7	Large Cobble (6 - 12 inches)	00.7	Short (<1 ft) terrestrial grass
8	Boulder (>12 inches)	00.8	Tall (>3 ft) dense grass[2]
9	Bedrock	00.9	Vegetation >3 vertical ft above stage of zero flow

1 This includes low tree branches (<3 vertical ft above water surface elevation at stage of zero flow [SZF]) and bushes overhanging the bank-full water's edge.

2 This category refers to stout, almost bushy type grasses such as reed canary grass up to the bank-full water's edge.

4.3 Bypass Hydraulic Model Development

Hydraulic conditions in the Gorge bypass reach were computed using the 2-D capabilities of the U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Center River Analysis System (HEC-RAS) Version 6.1.0 modeling platform (USACE 2021). Key model components of HEC-RAS 2-D are summarized in the sections below, with more detailed descriptions provided in Attachment A.

4.3.1 Topographic Information

The topographic surface used in the Bypass Hydraulic Model consists of a bare earth Digital Elevation Model (DEM) derived from the 2016 and 2018 LiDAR datasets described in Section 4.2.1. The original processing of the 2018 topobathymetric LiDAR produced a ground and bathymetric bottom classified density of 0.52 points/ft^2 (QSI 2018), which was sufficient to generate a 3-ft resolution DEM. To improve characterization of channel features in the hydraulic model, geospatial analysts expanded upon the original point classification to classify additional ground points from the 2018 LiDAR along the channel bottom and bank toe below vegetated areas (Figure 4.3-1). Ground point density in the reclassified areas increased to 2.51 points/ft^2 and a DEM with a 1-ft cell resolution was generated to increase terrain detail in these areas. It is noteworthy that outside the reclassified areas, point density remains 0.52 points/ft^2.

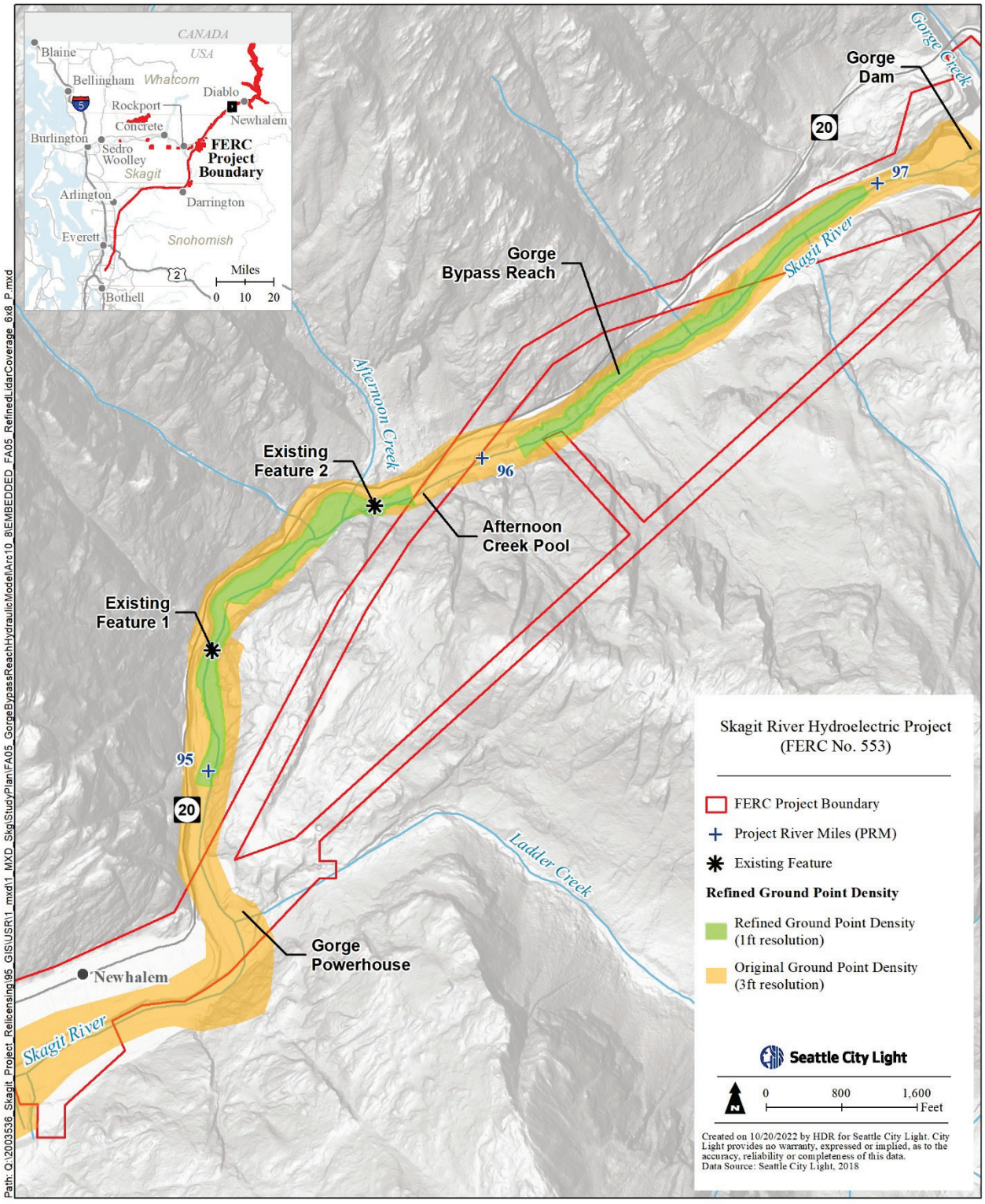

Figure 4.3-1. Refined and original 2018 LiDAR coverage.

4.3.2 Hydraulic Roughness Zones

Hydraulic roughness zones were mapped within the model domain to delineate zones of similar frictional flow resistance associated with unresolved terrain features, substrate, vegetation, and any other sources of flow obstruction not explicitly represented by other components of the model geometry. Each zone was assigned a roughness value, represented by a Manning's n coefficient (Barnes 1967). Roughness zones were separated into channel and bank areas, corresponding to different model mesh cell sizes (described in Section 4.3.4). The zone defined as "channel" corresponds to the refinement region where the mesh has a 1-ft resolution while the zone defined as "bank" includes the upper bank and valley walls where the mesh has a 9-ft resolution. Roughness zone delineations and Manning's n coefficients were evaluated and modified during model calibration (Section 4.5).

4.3.3 Model Boundaries

Model boundaries identify the locations where flow either enters or exits the model. Collection of hydrologic data used to define boundary conditions for the Bypass Hydraulic Model is discussed in Section 4.2.2.1. Inflow boundaries are included at the base of Gorge Dam spillway, at the exit from Gorge Powerhouse turbine Unit 24, at the combined exits from turbine Units 21, 22, and 23, and on Ladder Creek approximately 460 ft upstream from its mouth. Other local tributaries and groundwater inflows are excluded from the Bypass Hydraulic Model due to their negligible influence on hydraulic conditions. The model's downstream boundary is the rating curve from the USGS Skagit River at Newhalem gage (12178000). Bypass Hydraulic Model boundary locations are shown in Figure 4.3-2.

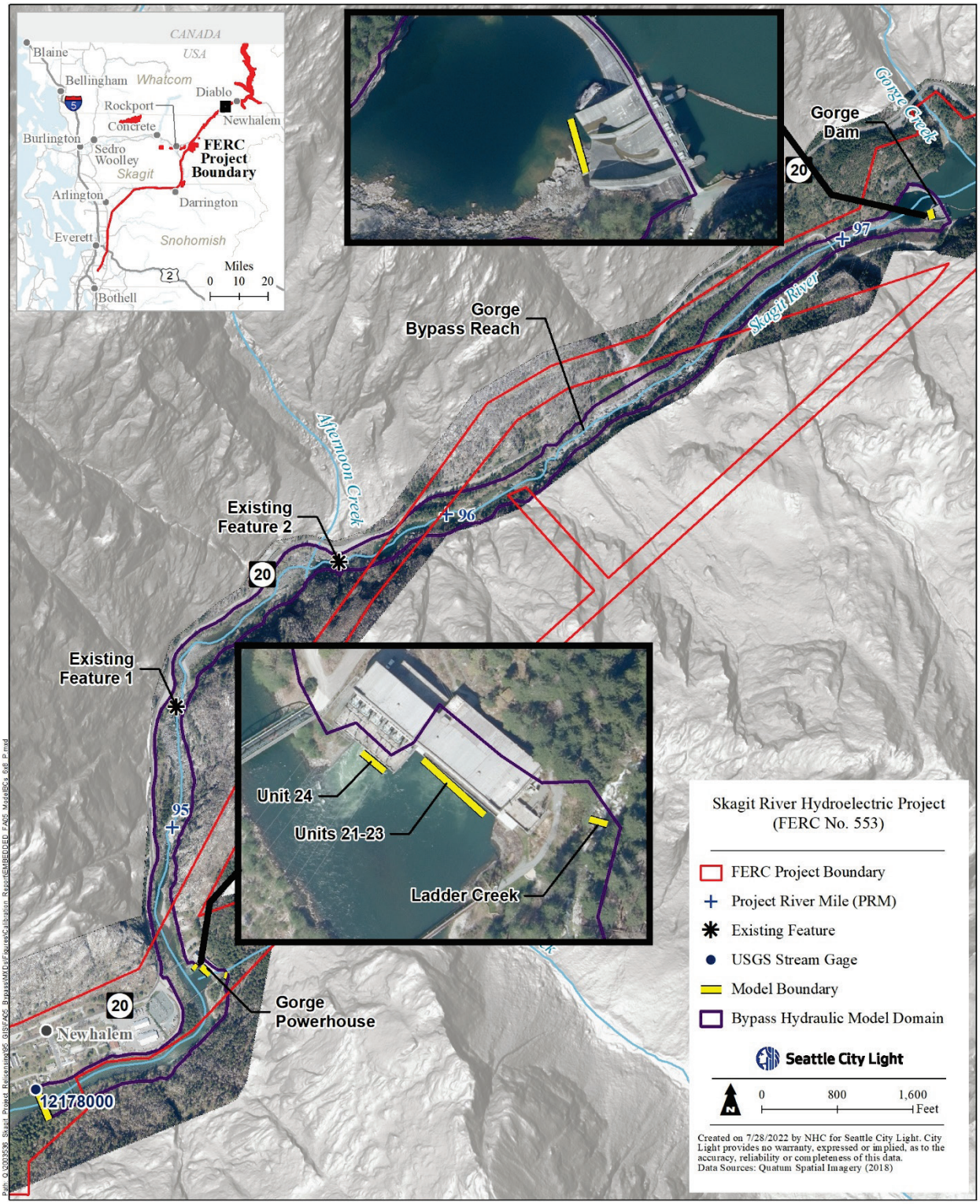

Figure 4.3-2. Bypass Hydraulic Model boundary locations.

4.3.4 Model Mesh

A HEC-RAS 2-D model geometry consists of a mesh of variable size polygons that encode information about the underlying terrain and hydraulic roughness. Mesh characteristics are controlled by the model domain, mesh refinement regions, and breaklines, each of which have associated mesh control parameters. The Bypass Hydraulic Model spans the Skagit River channel from the upstream end of the plunge pool immediately below Gorge Dam to the USGS Skagit River at Newhalem gage (Figure 4.3-3). A mesh refinement region encompasses the Gorge bypass reach channel and bank toe where terrain refinement was performed (Section 4.3.1). One-ft cells were used within the mesh refinement region, while 9-ft cells were used for the balance of the model domain. Cell size selection within the refinement region relied heavily on sensitivity testing described in Section 4.4.1. No hydraulic structures such as bridges were incorporated in the Bypass Hydraulic Model.

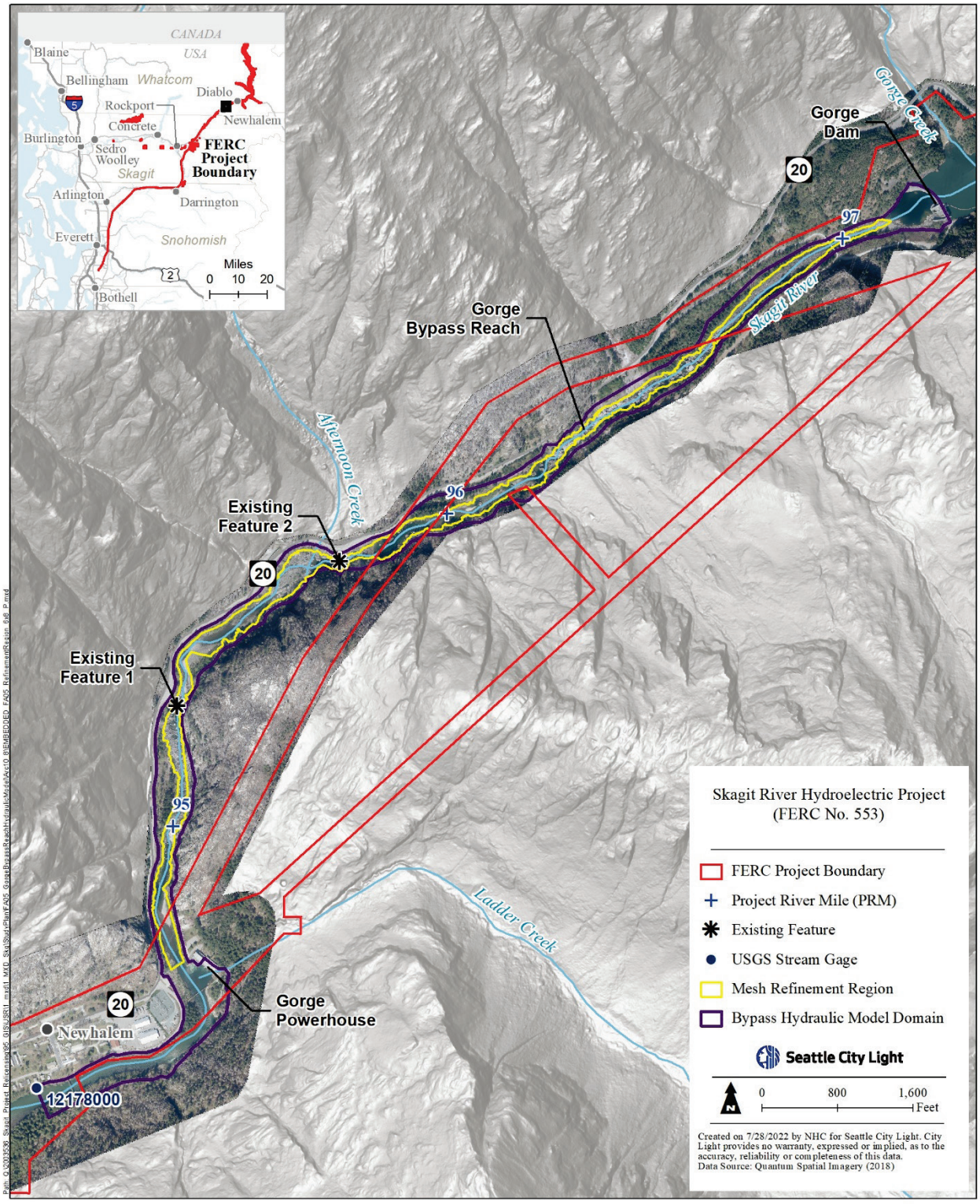

Figure 4.3-3. Bypass Hydraulic Model domain and mesh refinement region.

4.3.5 Run Control Parameters

Options for controlling 2-D model computations in HEC-RAS include specification of the solution equations, initial conditions, solution weighting factor (Theta), solver tolerances and iterations, and the computational time step. The full momentum shallow water equations were selected to capture momentum fluctuations that influence computed water levels and velocities. A dry channel initial condition was used for sensitivity tests and initial base model condition simulations. For subsequent calibration simulations, a "hot-start" initial condition was used where an output file from the preceding calibration simulation was used to reduce the time needed to reach steady-state conditions. Default Theta, tolerances, and solver iteration options were specified for all simulations. Selection of the computational time step is described in Section 4.4.2.

4.4 Sensitivity Testing

The Bypass Hydraulic Model's sensitivity to four parameters was investigated to evaluate their impact on the model solution, computational stability, and runtime efficiency. These investigations informed parameter selection for base model conditions prior to model calibration. The four parameters evaluated were: cell size, simulation timestep, turbulence input, and roughness coefficient. Parameter sensitivities were tested for a simulation of 1,200 cfs release from Gorge Dam. The following sections summarize results of the sensitivity testing, which is further described in Attachment A.

4.4.1 Cell Size

The objective of evaluating sensitivity to mesh cell size is to balance maximizing numerical accuracy while minimizing computation time. Cell size sensitivity testing focused on the Bypass Hydraulic Model refinement region where hydraulic conditions are significantly influenced by longitudinal slope, sub-channel size features, and substrate. One-ft cells were ultimately selected within this region, as this cell size provides the most accurate and detailed characterization of hydraulic conditions that can be achieved given the surface terrain resolution. Using a cell size smaller than 1 ft is unwarranted considering the terrain resolution within the refinement region is also 1 ft.

4.4.2 Time Step

The time step used for Bypass Hydraulic Model computations was evaluated by assessing the Courant condition associated with the mesh to ensure use of an appropriate value. A 0.2-second time step was deemed adequate for achieving good numerical accuracy while also optimizing computational efficiency. For most simulations with a 0.2-second time step and the final mesh configuration, a stable solution is achieved within approximately 20 hours of model runtime.

4.4.3 Turbulence Parameters

Highly turbulent flow is prevalent throughout many sections of the Gorge bypass reach and therefore the impact of increasing turbulence coefficients was tested. HEC-RAS's default turbulence coefficients, representative of moderate mixing intensity, were selected for base (initial) model calibration simulations. However, explicit turbulence parameters were subsequently turned off to improve model stability at calibration flows exceeding 1,200 cfs. Even without turbulence explicitly turned on, the HEC-RAS solution scheme includes numerical diffusion that mimics the effects of turbulence processes.

4.4.4 Hydraulic Roughness

A series of Manning's n coefficients were tested in the channel roughness zones (described in Section 4.3.2) to assess sensitivity under the final mesh configuration and time step. An unvegetated channel zone coefficient of 0.05 achieved computed velocities of similar magnitude to field observations while maintaining model stability given limitations on other input parameters, and therefore was selected for the initial calibration condition. Sensitivity to coefficients as low as 0.02 was evaluated and that assessment is described in Attachment A.

4.5 Bypass Hydraulic Model Calibration

Calibration of a hydraulic model is crucial to establish confidence in the model's ability to simulate hydraulic characteristics reliably and accurately for a range of conditions. Calibration involves the refinement of model parameters within plausible limits to best match simulated results with field observations for one or more hydrologic events. The following sections summarize the calibration methods adopted and performance evaluation of the final calibrated model, with a detailed description provided in Attachment A.

4.5.1 Calibration Process

To calibrate a 2-D hydraulic model, the outputs generated from a unique set of model inputs are compared to observed data, and conclusions are drawn that inform adjustment of the model parameters. The calibration process is iterative until the results are judged to be adequate for the designated purpose and further significant improvements are not possible or warranted. Calibration took place over the course of six months using four cloud computers (for advanced computing power) and an estimated 1,500 hours of simulation time. Calibration focused on adjustment of hydraulic roughness zones and Manning's n coefficients to evaluate model performance for controlled and unscheduled releases (Section 4.2.2.1). Roughness zones and Manning's n coefficients for the calibrated model are presented in Figure 4.5-1.

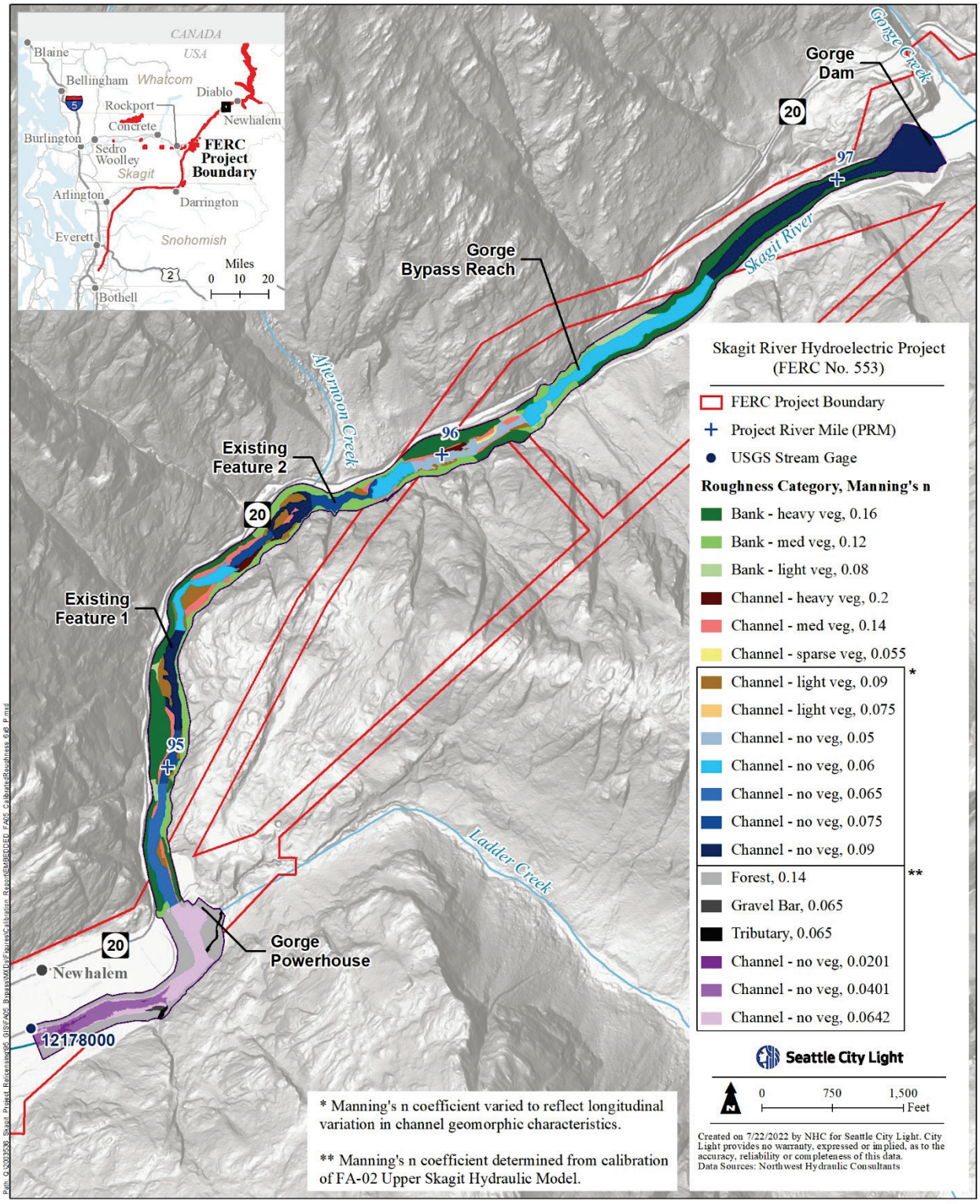

Figure 4.5-1. Roughness parameters for final calibrated model.

4.5.2 Performance Evaluation

The ability of the Bypass Hydraulic Model to accurately compute both depths and velocities, within the constraints of a 2-D depth-averaged model, is critical for assessment of instream flows and fish passage. Therefore, depth and velocity output were primarily used to determine the model's adequacy. WSE output was also included in model performance evaluation since depth is a derivative output from WSE. Calibration efforts first focused on replicating transect and water level logger observations described in Section 4.2.2.2. Adjustments were then made to match observed water surface profiles derived from UAV aerial imagery to the extent that model performance relative to observations from transects and water level loggers was uncompromised. This section summarizes the observed and simulated datasets and performance metrics used to evaluate the final calibrated model.

4.5.2.1 Transect Velocities and Depths

A total of 642 velocity and depth observations from five transects (Section 4.2.2.2) were used to evaluate model performance. Linear regression analysis was used to compare simulated against observed velocities and a spatial evaluation of velocities and depth compared transect observations to computed results. Velocity statistical metrics indicate the model is performing well (Table 4.5-1 and Attachment A). An average coefficient of determination (R^2) of 0.82 across all calibrated flows shows strong model performance for velocity calculation (Pasternack [2011] recommends R^2 of 0.4-0.8 for calibration target). The average slope (0.85) and y-intercept (0.2) of the linear regression analysis also support a good correlation. On average, 71 percent of simulated velocities were within 0.5 ft/s of corresponding observed values, and 90 percent were within 1 ft/s. Mean depth errors (on average 0.2 ft) indicate the model computes WSE accurately at all transects (Table 4.5-1). Spatial evaluation of simulated versus observed depths found that depth calculations track well across each transect with little to no bias across transects or calibration flows (see Attachment A).

Table 4.5-1. Statistical summary of lumped transect velocity and depth evaluation.

Nominal Flow[1] (cfs)	Velocity Statistics					Depth Statistics
	R^2	Slope	y-intercept	% within 0.5 ft/s	% within 1.0 ft/s	Mean Error (ft)
1,200	0.91	0.89	0.27	63	83	0.3
500	0.89	0.87	0.16	69	89	0.1
250	0.80	0.84	0.24	69	92	0.2
50	0.67	079	0.11	83	95	0.1
Avg.	0.82	0.85	0.20	71	90	0.2

1 Actual measured flows provided in Attachment A.

4.5.2.2 Existing Features Water Surface Elevations

WSEs recorded by the 12 water level loggers at Existing Features 1 and 2 (Section 4.2.2.2) were time-averaged over each calibration flow and compared with simulated output to assess model performance. In addition to the controlled releases, simulated WSEs were also compared to mean level logger measurements for nominal flows of 4,800 cfs and 6,200 cfs from the late June/early July 2021 unscheduled spills. This extended evaluation of model performance at Existing Features

1 and 2 was undertaken to support use of the Bypass Hydraulic Model for fish passage assessment under the FA-04 Fish Passage Study (City Light 2023b). Model performance was evaluated at each level logger location by computing the difference in simulated versus observed mean WSE. WSE residuals for the calibrated model are provided in Table 4.5-2 and Table 4.5-3. For the controlled releases, model results at level loggers bounding the Existing Features (i.e., level loggers DDL1, DDL6, UUL1, and UUL6 – see Figure 4.2-1 and Figure 4.2-2) show very good agreement with observations, with residuals less than 0.5 ft. Larger residuals were generally observed within each Existing Feature where the model's inability to simulate flow beneath boulders significantly impacted results (see Attachment A). As expected, residuals related to this limitation decreased with increasing flow magnitude. WSE residuals were mostly within 1 ft for the unscheduled spills.

Table 4.5-2. Summary of WSE residuals at Existing Feature 1.

Nominal Flow[1] (cfs)	WSE Residual (ft)					
	DDL1	DDL2	DDL3	DDL4	DDL5	DDL6
6,200	0.90	0.34	0.94	0.03	0.06	0.18
4,800	0.69	0.64	0.84	0.19	0.53	-0.12
1,200	0.05	0.53	0.09	0.65	0.96	-0.24
500	-0.05	0.65	-0.08	0.87	1.44	-0.21
250	-0.07	0.86	-0.03	1.09	1.76	0.18
50	0.26	1.71	0.14	2.11	3.59	0.37

1 Actual measured flows provided in Attachment A.

Table 4.5-3. Summary of WSE residuals at Existing Feature 2.

Nominal Flow[1] (cfs)	WSE Residual (ft)					
	UUL1	UUL2	UUL3	UUL4	UUL5	UUL6
6,200	0.46	1.80	1.39	0.22	0.60	1.03
4,800	0.29	1.64	0.80	-0.10	0.60	0.63
1,200	0.13	0.66	0.53	-0.03	0.59	0.00
500	0.09	0.68	0.38	0.36	0.21	-0.06
250	0.29	0.94	0.56	0.52	0.46	0.06
50	0.50	1.71	1.66	1.69	1.16	0.24

1 Actual measured flows provided in Attachment A.

4.5.2.3 Water Surface Profiles

Reach-long water surface profiles were developed from UAV imagery (Section 4.2.2.2) for each controlled release. Model performance was evaluated by computing the mean difference between simulated and imagery-derived WSEs within nine channel sub-reaches spanning the available orthomosaic imagery (see Attachment A). Mean differences between simulated and observed WSE by sub-reach are provided in Table 4.5-4 for the final calibrated model. Almost all mean WSE differences were within 0.6 ft and half were within 0.2 ft.

Table 4.5-4. Summary of mean WSE differences from water surface profile evaluation.

Sub-Reach	Mean Water Surface Difference (simulated minus observed; ft)				
	50 cfs[1]	250 cfs[1]	500 cfs[1]	1,200 cfs[1]	Average[2]
1	0.2	0.3	0.2	-0.1	0.1
2	1.2	0.4	0.0	-0.1	0.1
3	0.6	0.1	0.0	-0.2	-0.1
4	0.6	0.4	0.3	0.0	0.2
5	-0.1	-0.1	-0.3	-0.1	-0.2
6	-0.6	-0.2	-0.3	-0.1	-0.2
7	-0.2	0.1	-0.1	-0.4	-0.1
8	-0.2	-0.3	-0.4	0.3	-0.1
9	-0.3	-0.4	-0.6	-0.2	-0.4

1 A total of 3,643; 3,084; 3,992; and 3,935 water's edge points were used to create reach-long water surface profiles for the 1,200; 500; 250; and 50 cfs controlled releases, respectively (Attachment A).
2 Excludes 50 cfs controlled release to omit influence of flow beneath boulders (Attachment A).

4.5.3 Discussion of Calibration Results

Overall, performance evaluation shows the Bypass Hydraulic Model represents hydraulic conditions with sufficient resolution and accuracy to simulate velocities and depths for fish habitat assessment. The model also provides acceptable representation of hydraulics at Existing Features 1 and 2 to be used by the FA-04 Fish Passage Study team for assessment of fish passage (City Light 2023b). However, depth-averaged hydraulic model limitations at these features should be accounted for in any assessment.

4.6 Bypass Habitat Model Development

The Bypass Habitat Model integrates aquatic habitat data with depth and velocity results from the Bypass Hydraulic Model in an Instream Flow Incremental Methodology (IFIM)-type analysis to produce outputs of usable habitat area (UHA) for fish species and life stages of interest. Habitat model development consists of three components: channel structure, hydraulic simulation, and aquatic HSC. Channel structure includes all fixed-channel features that generally do not change with flow, such as channel cross-sectional geometry, substrate composition and distribution, and structural cover. Hydraulic variables are those that change with flow, such as WSE, depth, velocity, wetted perimeter, and channel surface area. HSC are numeric representations of preferred depths, velocities, substrate, and cover for the various life stages of the aquatic species of interest (Bovee et al. 1998).

The hydraulic modeling component, provided by the Bypass Hydraulic Model, simulates water depths and velocities under a range of different flow regimes. The aquatic HSC, commonly referred to as HSC curves, contain information on tolerances or preferences of aquatic organisms with respect to the hydraulic and structural characteristics of the stream. They most often are comprised of depth, velocity, and substrate/cover preferences.

This section discusses the following key aspects of the development of the Bypass Habitat Model:

- Aquatic species and life stages of interest (Section 4.6.1);
- Life stage periodicity (Section 4.6.2);
- Development of HSC (Section 4.6.3);
- The domain or spatial extent of the Bypass Habitat Model (Section 4.6.4);
- Selection of flows for which UHA and flow-habitat relationships were developed (Section 4.6.5); and
- Substrate and cover mapping (Section 4.6.6).

Computation of UHA and flow-habitat relationships is discussed in Section 4.7.

4.6.1 Target Species and Life Stages

City Light, in consultation with LPs, selected target species and life stages to be considered for modeling from a list of species known to be present in the Skagit River mainstem and the Gorge bypass reach. In addition, LPs requested additional species and life stages be added that may not have been collected or observed in the Skagit River mainstem and the Gorge bypass reach but have the potential to be present. A list of target species and life stages considered for instream flow modeling is provided in Table 4.6-1.

Table 4.6-1. Target species and life stages considered for the Upper Skagit (mainstem from Gorge Powerhouse to Sauk River) and the Bypass Instream Flow Models.[1]

Species	Scientific Name	Life Stage			
		Spawning	Adult	Juvenile	Fry
Steelhead	*Oncorhynchus mykiss*	X	X	X	
Chinook Salmon	*Oncorhynchus tshawytscha*	X		X	X
Pink Salmon	*Oncorhynchus gorbuscha*	X			
Chum Salmon	*Oncorhynchus keta*	X			X
Coho Salmon	*Oncorhynchus kisutch*	X		X	X
Sockeye Salmon	*Oncorhynchus nerka*	X			
Rainbow Trout	*Oncorhynchus mykiss*	X	X	X	X
Bull Trout/Dolly Varden	*Salvelinus confluentus/Salvelinus malma*	X		X	X
Sea-Run Bull Trout	*Salvelinus confluentus*	X			
Cutthroat Trout	*Oncorhynchus clarkii*	X	X	X	X
Sea-Run Cutthroat Trout	*Oncorhynchus clarkii*	X			
Mountain Whitefish	*Prosopium williamsoni*	X	X	X	X
Pacific Lamprey	*Entosphenus tridentatus*	X			
Lamprey (generic)	*Lampetra* spp.			X	
Western Brook Lamprey	*Lampetra richardsoni*	X			
Western River Lamprey	*Lampetra ayresii*	X			
White Sturgeon	*Acipenser transmontanus*	X			
Salish Sucker	*Catostomus*	X		X	

1 Some species and/or life stages selected for habitat modeling consideration may not be present in the mainstem Skagit River, but in collaboration with LPs, have been included to evaluate the amount of potential habitat created under various flow regimes. The habitat model results for these species/life stages may or may not be considered in future instream flow management decisions.

4.6.2 Life Stage Periodicity

The period of year when a species or life stage is present in the study area is an important component of habitat modeling where the model results are used to determine the amount of habitat available over a period of time with varying flow conditions (often referred to as time series analysis). The periodicity for each of the target species and life stages (Table 4.6-2) was determined in consultation with the LPs. Periodicity was determined primarily from literature resources and professional input from City Light staff and LPs with Skagit-specific field experience. The periodicity information provided in Table 4.6-2 applies to both the Skagit mainstem and Gorge bypass reach instream flow study areas.

Table 4.6-2. Periodicity for target species and life stages.

Species	Life Stage	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Steelhead	Adult												
	Spawning			Eval	License Required Spawning Period		Eval						
	Juvenile												
Chinook Salmon	Spawning									License Required	Eval		
	Fry	Salmon Fry Protection Period											
	Juvenile												
Pink Salmon	Spawning								Evaluate	License Required			
Chum Salmon	Spawning								Evaluate			License Required	
	Fry	Salmon Fry Protection Period											
Coho Salmon	Spawning												
	Fry	Salmon Fry Protection Period											
	Juvenile												
Sockeye Salmon	Spawning												
Rainbow Trout	Adult												
	Spawning												
	Fry												
	Juvenile												
Bull Trout/Dolly Varden	Spawning												
	Fry												
	Juvenile												
Sea-Run Bull Trout	Spawning												
Cutthroat Trout	Adult												
	Spawning												
	Fry												
	Juvenile												
Sea-run Cutthroat Trout	Spawning												

Species	Life Stage	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mountain Whitefish	Adult												
	Spawning												
	Fry												
	Juvenile												
Pacific Lamprey	Spawning												
Lamprey (generic)	Juvenile												
Western Brook Lamprey	Spawning												
Western River Lamprey	Spawning												
Salish Sucker	Spawning												
Salish Sucker	Juvenile												
White Sturgeon	Spawning												

Note: Evaluate (or Eval) indicates lower Skagit observations and carcass recoveries and/or technical group interest in evaluating effects of extending current license required protection periods.

4.6.3 Habitat Suitability Criteria

Skagit River HSC LP Workshops began in May 2021. After the June and July 2021 Workshops, a recommendation was made to form a smaller technical group of people knowledgeable about HSC and its use in instream flow habitat modeling. In August 2021, the HSC Technical Group was formed and comprised of LPs, City Light, and consultant team members. The HSC Technical Group met a total of 10 times (approximately bi-weekly) from August 2021 through January 2022. The HSC Technical Group's objective was to gather and review available HSC information relevant to the Skagit River and develop a step-wise process to evaluate and ultimately propose recommended HSC curves for each species and life stage being considered for habitat modeling on the Skagit River mainstem and Gorge bypass reach. In addition, the HSC Technical Group evaluated 2021 field validation data collected on the Skagit River as well as additional studies that were subsequently included in WDFW/Ecology's updated Instream Flow Study Guidelines (Beecher and Caldwell 2022).

As a starting point for the HSC curve selection (and in some cases development) process, an HSC library was assembled consisting of curves from City Light's existing effective spawning habitat (ESH) model, Washington State's Instream Flow Study Guidelines (Beecher and Caldwell 2022), curves from other west coast region instream flow studies for rivers comparable in size to the Skagit River, and literature from other relevant studies and research.

HSC curves are often referred to by "type," which indicates the basis of the curves (Bovee 1986). Type 1 curves are based on professional judgment with little or no empirical data. Type 2 curves are based on data from locations where target species are observed or collected. Commonly referred to as utilization (or use) curves, Type 2 curves can be biased by a limited range of hydraulic conditions that were available at the time the target species were observed. Type 3 curves are based on data from locations where target species are observed or collected under a variety of conditions to remove environmental bias. Type 3 curves include measurements of "available" habitat (at the time the discrete observation data were collected), which are used to adjust utilization data to become "preference curves." Type 3 curves tend to be less site-specific than Type 2 curves and can be applied more broadly.

Table 4.6-3 provides a list of species and life stages where habitat results were modeled. They are grouped based on the availability and type of existing HSC curves:

Group A includes species and life stages where HSC curves were available from both the Skagit ESH model and WDFW/Ecology Type 3 curves. With the exception of Chum spawning,[6] field validation studies were conducted in 2021 to collect additional site-specific data (i.e., depth, velocity, substrate, and cover) for Group A species and life stages. These data were used qualitatively to support decisions on HSC curve selection and/or modification. The field validation studies are described in the Habitat Suitability Criteria – 2021 Field Validation Data Summary (HDR Engineering, Inc. [HDR] 2022a; Attachment B to the FA-02 Instream Flow Model Development Study Report [City Light 2023a]).

[6] Due to unseasonably high flows and turbid water conditions during the 2021 late-fall/early-winter period, field validation data collection efforts for Chum spawning were not conducted.

Group B originally consisted of two species and life stages where Skagit-specific Type 2 curves (i.e., based on Skagit River field observation data) and WDFW/Ecology Type 3 curves were available (i.e., Chum spawning and Pink spawning). Early in the HSC evaluation process LPs recommended adding these two species to Group A as there was interest in collecting additional field observation data during the 2021 field validation study efforts. Moving these two species/life stages into Group A effectively eliminated Group B.

Group C includes species and life stages where HSC curves were not available from the ESH model but were available as WDFW/Ecology Type 3 curves. For these species and life stages, the WDFW/Ecology Type 3 curves were used as the default.

Group D HSC curves were not available from the ESH model or WDFW/Ecology. For these species and life stages, available HSC curves from other instream flow studies were used as a surrogate and/or consensus curves were developed in collaboration with LPs by modifying available HSC curves. In some cases, literature was available to support development of HSC consensus curves.

Group E consists of the fry life stage for several salmonids. Type 3 HSC curves were not available from WDFW/Ecology; therefore, individual salmonid fry HSC curves from the ESH model were used for habitat modeling purposes.

Group F surrogate HSC curves were not available, so consensus curves were developed based on literature review.

HSC curves used in the current ESH model are based on a variety of Type 1 and Type 2 data sources. For example, HSC curves for Steelhead, Chinook, Pink, and Chum spawning life stage are based on hundreds of Skagit-specific field observation data from Crumley and Stober (1984) and considered to be Type 2 curves (attempts to locate detailed field observation data from the studies were unsuccessful). Data collected during the 2021 HSC field validation effort for these four species (spawning life stage) were determined to be insufficient to create new Type 3 curves. However, these data (i.e., observations of redds or fish) were reviewed by the HSC Technical Group and were determined to be consistent with the ESH and statewide HSC curves. Other HSC curves used in the ESH model are based on Type 1 and Type 2 curves from other (non-Skagit) data sources and are considered to be a hybrid of Type 1-2 curves. As a result, in most cases, the HSC Technical Group recommended habitat modeling approach was to use the WDFW/Ecology Type 3 HSC curves for Skagit River habitat modeling purposes when available.

When WDFW/Ecology Type 3 curves were unavailable, the HSC Technical Group typically recommended: using (a) curves from other surrogate species with statewide Type 3 curves; (b) Type 2 curves from other studies; or developing (c) consensus curves from available and relevant literature.

Depth, velocity, and substrate/cover HSC curves for each species and life stage listed in Table 4.6-3 are provided in Attachment B.

Table 4.6-3. Skagit River target species and life stages.

Species	Life Stage	HSC Group	HSC Status	WDFW/Ecology Guidelines (Beecher and Caldwell 2022) or other reference	
				Substrate	Cover
Steelhead	Spawning	A	WDFW/Ecology Type 3 curves	Table 4	N/A
	Adult holding	D	WDFW/Ecology Type 3 curves for Rainbow Trout adult rearing	Table 3	Table 3
	Juvenile	A	WDFW/Ecology Type 3 curves	Table 3	Table 3
Chinook Salmon	Spawning	A	WDFW/Ecology Type 3 curves	Table 2	N/A
	Juvenile	A	WDFW/Ecology Type 3 curves	Table 3	Table 3
	Fry	E	ESH Model Type 2 curves	ESH Model	N/A
Pink Salmon	Spawning	A	WDFW/Ecology Type 3 curves	Table 2	N/A
Chum Salmon	Spawning	A	WDFW/Ecology Type 3 curves	Table 2	N/A
	Fry	E	ESH Model Type 2 curves	Fraser River (Rempel et al. 2012)	N/A
Coho Salmon	Spawning	C	WDFW/Ecology Type 3 curves	Table 2	N/A
	Juvenile	D	ESH Model Type 2 curves	Table 3	Table 3
	Fry	E	ESH Model Type 2 curves	ESH Model	N/A
Sockeye Salmon	Spawning	C	WDFW/Ecology Type 3 curves	Table 2	N/A
Rainbow Trout	Spawning	C	WDFW/Ecology Type 3 curves	Table 5	N/A
	Adult rearing			Table 3	Table 3
	Juvenile			Table 3	Table 3
	Fry	E	ESH Model Type 2 curves	ESH Model	N/A
Bull Trout / Dolly Varden	Spawning	C	WDFW/Ecology Type 3 curves	Table 6	N/A
	Juvenile	A	WDFW/Ecology Type 3 curves (updated 2021)	Table 3	Table 3
	Fry	E	ESH Model Type 2 curves	ESH Model	N/A
Sea-Run Bull Trout	Spawning	F	Consensus curves developed	Table 6	N/A

Species	Life Stage	HSC Group	HSC Status	WDFW/Ecology Guidelines (Beecher and Caldwell 2022) or other reference	
				Substrate	Cover
Cutthroat Trout	Spawning	C	WDFW/Ecology Type 3 curves	Table 5	N/A
	Adult	D	WDFW/Ecology Type 3 curves for Cutthroat Trout juvenile	Table 3	Table 3
	Juvenile	C	WDFW/Ecology Type 3 curves (updated 2021)	Table 3	Table 3
	Fry	E	ESH Model Type 2 curves	ESH Model	N/A
Sea-Run Cutthroat Trout	Spawning	D	Consensus curves developed	Table 5	N/A
Mountain Whitefish	Spawning	C	WDFW/Ecology Type 3 curves	Table 7	N/A
	Adult rearing			Table 8	Table 1
	Juvenile			Table 9	Table 1
	Fry	E	ESH Model Type 2 curves	ESH Model	N/A
Pacific Lamprey	Spawning	D	Consensus curves developed	Vadas 2021	N/A
Lamprey (generic)	Juvenile rearing			Vadas 2021	N/A
Western Brook Lamprey	Spawning	F	Consensus curves developed	Vadas 2021	N/A
Western River Lamprey	Spawning			Vadas 2021	N/A
Salish Sucker	Spawning	F	Consensus curves developed	Pearson 2003	N/A
	Juvenile rearing				Pearson 2003
White Sturgeon	Spawning	F	Consensus curves developed	Sacramento River (Gard 1996)	N/A

4.6.4 Bypass Habitat Model Extent

The Bypass Habitat Model extends longitudinally from Gorge Dam at PRM 97.21 to the USGS Skagit River at Newhalem gage (12178000) at PRM 94.19 for a total reach length of approximately 3.0 miles. The lateral extent of the Bypass Habitat Model is defined by the area inundated by a 3,000 cfs release from Gorge Dam and by the 5 percent exceedance flow released from Gorge Powerhouse, these being the maximum flow rates simulated for habitat modeling as discussed in Section 4.6.5. The Bypass Habitat Model domain is shown in Attachment C.

Output from the Bypass Habitat Model can be readily combined with output from the FA-02 Upper Skagit Habitat Model (developed under the FA-02 Instream Flow Model Development Study [City Light 2023a]), which extends from the USGS Skagit River at Newhalem gage to the confluence with the Sauk River, to provide habitat data for the entire 31-mile reach from Gorge Dam to the confluence with the Sauk River.

Where there is a tributary inflow into the Bypass Reach Hydraulic Model at Ladder Creek, the inundated area controlled by mainstem water levels extends upstream of the confluence with the mainstem channel. The tributary mouth of Ladder Creek was included in the Bypass Habitat Model so far as City Light's operations affect the WSE in the tributary channel. Figure 4.6-1 provides a graphic illustrating this concept. The vertical dashed line in the graphic represents the point where the mainstem hydraulics no longer dictate the WSE of the tributary channel, but rather the tributary inflow defines the wetted boundary. In this example, the habitat model domain would exclude wetted tributary area upstream of the dashed line.

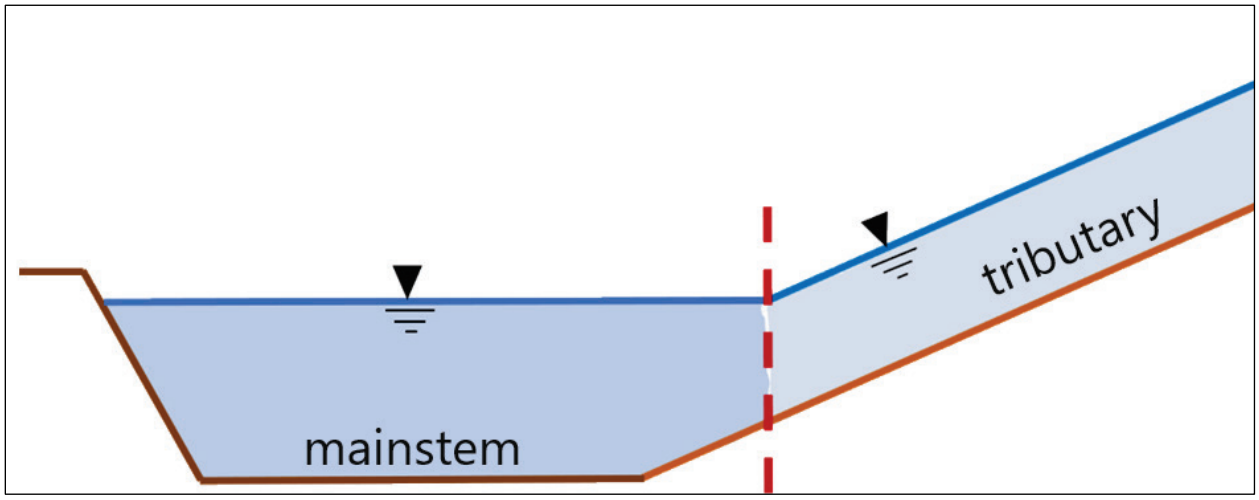

Figure 4.6-1. Extent of area included at Ladder Creek confluence within the Bypass Habitat Model domain.

The combined study areas of the Bypass Habitat Model and the FA-02 Upper Skagit Habitat Model from Gorge Dam to the confluence with the Sauk River were sub-divided into 19 reaches to reduce model processing times, make output file sizes more manageable, and facilitate user review of UHA outputs. Reaches 1-6 are within the domain of the Bypass Habitat Model and reaches 7-19 are within the domain of the FA-02 Upper Skagit Habitat Model. Reach break locations for Bypass Habitat Model reaches 1-4 were set to maintain manageable file sizes given the large number of

inundated cells that were processed as part of the habitat modeling effort. Reach 5 extends from the upstream limit of backwater influence from Gorge Powerhouse operations down to Gorge Powerhouse itself. Reach 6 then extends from Gorge Powerhouse to the USGS Skagit River at Newhalem gage, which forms the downstream boundary of the Bypass Habitat Model and the upstream boundary of the FA-02 Upper Skagit Habitat Model. Reach locations and reach lengths for the six Bypass Habitat Model reaches are summarized in Table 4.6-4. The Bypass Habitat Model reaches are shown, along with the model domain, in Attachment C.

Table 4.6-4. Bypass Habitat Model reaches.[1]

Reach ID	Location	Length (mi)
1	Gorge Dam to geomorphic reach break	0.5
2	Geomorphic reach break to upstream of Afternoon Creek pool	0.6
3	Upstream of Afternoon Creek pool to downstream end of pool	0.3
4	Downstream end of Afternoon Creek pool to upstream limit of Gorge Powerhouse backwater	0.7
5	Upstream limit of Gorge Powerhouse backwater to Gorge Powerhouse	0.4
6	Gorge Powerhouse to USGS Skagit River at Newhalem gage	0.5

1. Bypass Habitat Model reaches are shown in Attachment C.

4.6.5 Selection of Flows for Habitat Modeling

In consultation with LPs, City Light selected 42 combinations of flow (i.e., combinations of release from Gorge Dam and discharge from Gorge Powerhouse) to define flow-habitat relationships for the six habitat reaches in the Bypass Habitat Model. Each set of flows was input to the Bypass Hydraulic Model, with the resulting water depth and velocity outputs providing key inputs to the habitat model. The selection of flows is discussed below by habitat reach. The selected combinations of flow are shown in Table 4.6-5. (Definition of habitat reaches was discussed in Section 4.6.4.)

Habitat Reaches 1-4

Under current Project operations, flows in habitat reaches 1-4 are restricted to occasional spill from Gorge Dam, seepage from Gorge Dam, and inflows from minor tributaries such as Afternoon Creek. Absent spill from the dam, flows are typically less than 10 cfs and may drop to as low as 1 or 2 cfs in late summer.

Of interest is habitat availability under hypothetical future sustained releases from Gorge Dam. A range of Gorge Dam releases from 50 cfs to 1,000 cfs was originally selected for instream flow modeling based on the findings of a previous habitat evaluation (Envirosphere 1989). This range was subsequently expanded in consultation with LPs to cover Gorge Dam releases from 50 cfs to 3,000 cfs. Because of their minor contribution, seepage from the dam and minor tributary inflows to reaches 1-4 were not represented in the Bypass Hydraulic Model.

Habitat Reach 5

Hydraulic conditions in habitat reach 5 are determined by both inflows from the upstream reach 4 and discharge from Gorge Powerhouse at the downstream end of the reach. Reach 5 has a relatively

low gradient such that Gorge Powerhouse discharges impose a backwater control that affects water depth and velocity extending to the upstream boundary of the reach. Investigation of habitat availability in reach 5 thus required selection of a combination of inflow from reach 4 (i.e., release from Gorge Dam) and Gorge Powerhouse discharge, as indicated in Table 4.6-5.

Habitat Reach 6

Hydraulic conditions in habitat reach 6, which extends from Gorge Powerhouse to the USGS Skagit River at Newhalem gage, are determined by the combined release from Gorge Dam and Gorge Powerhouse discharge, plus tributary inflows from Ladder Creek, which enters the Skagit River immediately downstream from Gorge Powerhouse. For simplicity, references to Gorge Powerhouse discharges in the remainder of this section include Ladder Creek flows, which are small relative to Gorge Powerhouse discharges. The Bypass Hydraulic Model assumed a nominal tributary inflow from Ladder Creek of 50 cfs for all simulations. Gorge Powerhouse discharge was assumed to be represented by the observed record of daily discharge from the USGS Skagit River at Newhalem gage. Twelve sets of flows with exceedance probabilities ranging from greater than 99.9 percent to 5 percent were selected for modeling based on analysis of daily discharge data from the Skagit River at Newhalem gage for water years 1988-2020. This is the same set of flows selected for modeling of habitat reach 7 in the FA-02 Upper Skagit Habitat Model and provides for seamless mapping of habitat at the interface between the Bypass Habitat Model and the FA-02 Upper Skagit Habitat Model.

Table 4.6-5. Combinations of Gorge Dam releases and Gorge Powerhouse discharges selected for habitat modeling.

Gorge Powerhouse (cfs)	Gorge Dam (cfs)									
	0	50	100	200	400	600	800	1,000	2,000	3,000
1,400	x	x	x	x	x	x	x	x	x	x
1,600	x									
1,700	x									
2,010	x									
2,500	x									
2,980	x	x	x	x	x	x	x	x		
3,740	x									
4,480	x									
5,057	x	x	x	x	x	x	x	x		
6,000	x									
6,954	x									
7,521	x	x	x	x	x	x	x	x		

4.6.6 Substrate and Cover Mapping

After the substrate and cover field data collection effort was completed in early October 2021 (see Section 4.2.3), the resulting substrate and cover layers (consisting of individual polygons of corresponding substrate and cover codes) were quality controlled by visual inspection of the field data, and post-processed utilizing GIS software tools to rectify overlap between adjacent polygons and to form a continuous layer of substrate and cover information. Post-processed results were then quality controlled again by field team members. Data gaps remaining after post-processing were filled in via a desktop approach, which used a combination of available high resolution aerial imagery, ground-level photographs, digital elevation terrain models, and communications with personnel familiar with areas that were inaccessible during the field data collection effort. Staff with specific expertise and experience with mapping substrate and cover for instream flow modeling purposes were utilized for both the quality control and data gap filling process.

Once the Bypass Habitat Model domain was determined (see Section 4.6.4), a second round of desktop data gap filling was completed to ensure the GIS substrate and cover layers matched the habitat model domain. Areas filled in during this second round of desktop mapping mostly consisted of extending the substrate and cover layers for the main channel stream margins. The resulting substrate and cover mapbooks are provided in Attachment D.

4.7 Flow-Habitat Analysis

4.7.1 Overview

HSC curves and periodicity information in combination with the calibrated Bypass Hydraulic Model allows for detailed analyses of the amount, timing of availability, and location of suitable habitat under a range of discharges for species and life stages of interest. The Bypass Habitat Model integrates habitat data with depth and velocity results from the Bypass Hydraulic Model in an IFIM-type analysis to produce flow-habitat relationships for each of the species and life stages of interest. The flow-habitat analysis was executed using a combination of ArcGIS and Python-scripted modeling processes.

The purpose of the habitat model was to develop a library of UHA curves, i.e., relationships between UHA and flow, for each of the 37 fish species/life stage combinations identified as being of potential interest by City Light in consultation with LPs. These curves were used in the evaluation of alternative flow management scenarios subsequent to this Bypass Instream Flow Model Development Study.

To create the UHA curves for the six reaches within the Bypass Habitat Model, hydraulic model simulations were performed for each of the 42 combinations of flows released from Gorge Dam and discharge from Gorge Powerhouse shown in Table 4.6-5, to produce depth and velocity data for each 1-ft-by-1-ft cell within the Bypass Habitat Model domain. These depth and velocity data, along with substrate and cover data developed from the substrate and cover maps discussed in Section 4.6.6, were used as inputs to the habitat model. Lookup tables of habitat preference value were developed for the full range of depth, velocity, substrate, and cover values based on the HSC for each species/life stage combination. Preference values were calculated for each of the four variables (depth, velocity, substrate, and cover) for each species/life stage combination for each individual model cell.

A composite Habitat Suitability Index (HSI) was determined from the preference values for depth, velocity, substrate, and cover, as described in Section 4.7.4, and the UHA for each species/life stage combination was then computed by multiplying the composite HSI by the area of each model cell. The total UHA for a reach for a specific species/life stage combination is the summation of computed UHAs for all model cells within a specified reach. Figure 4.7-1 provides a visual representation of this modeling procedure. Further details of the computational procedure are provided in the following sections.

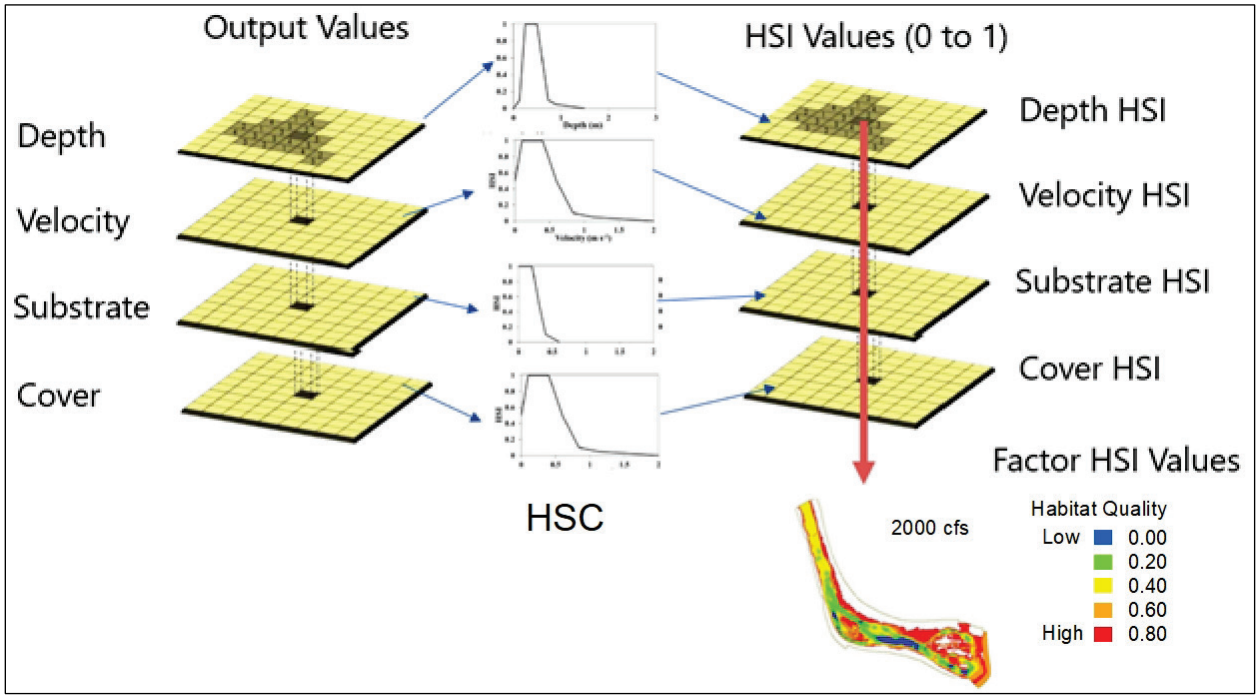

Figure 4.7-1. Habitat modeling UHA calculation procedure.

4.7.2 Depth and Velocity Rasters

The Bypass Hydraulic Model was run for the 42 flow combinations shown in Table 4.6-5 to develop depth and velocity raster outputs (see examples in Figure 4.7-2 and Figure 4.7-3). These simulated depths and velocities were output from the Bypass Hydraulic Model on a cell size of 1 ft by 1 ft, which dictates the resolution of the Bypass Habitat Model outputs. The six reaches in the Bypass Habitat Model contain nearly 2.5 million inundated cells for the largest flow included in the habitat modeling.

The Bypass Hydraulic Model results were used as inputs to the Bypass Habitat Model by creating a point shapefile with one point at the centroid of each cell. The point shapefile was then attributed with the depth and velocity values for each cell utilizing an ArcGIS script. This process was completed for all 42 flow combinations.

Depths less than 0.05 ft were filtered out of the model to create cleaner inundation boundaries and make for more efficient model run times. This limit was chosen because it represents the lowest depth where habitat suitability preference is not zero. Bull Trout/Dolly Varden is the only fish species included in the model that has an assigned preference value for depth as low as 0.05 ft.

Therefore, eliminating depths less than 0.05 ft had no bearing on how the HSC are applied, nor did it affect the UHA results.

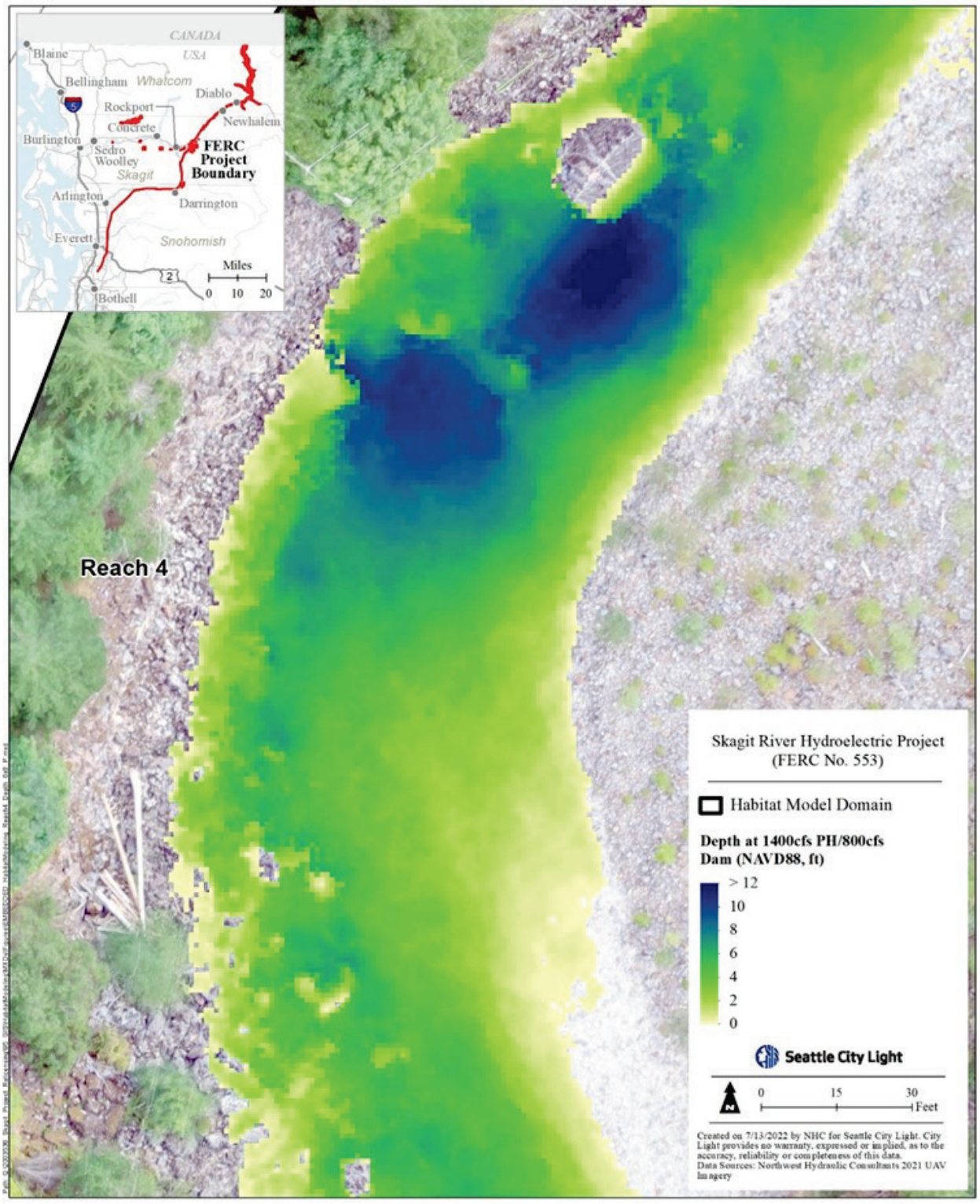

Figure 4.7-2. Depth based on a release of 1,400 cfs from Gorge Powerhouse and 800 cfs from Gorge Dam within Bypass Habitat Model Reach 4.

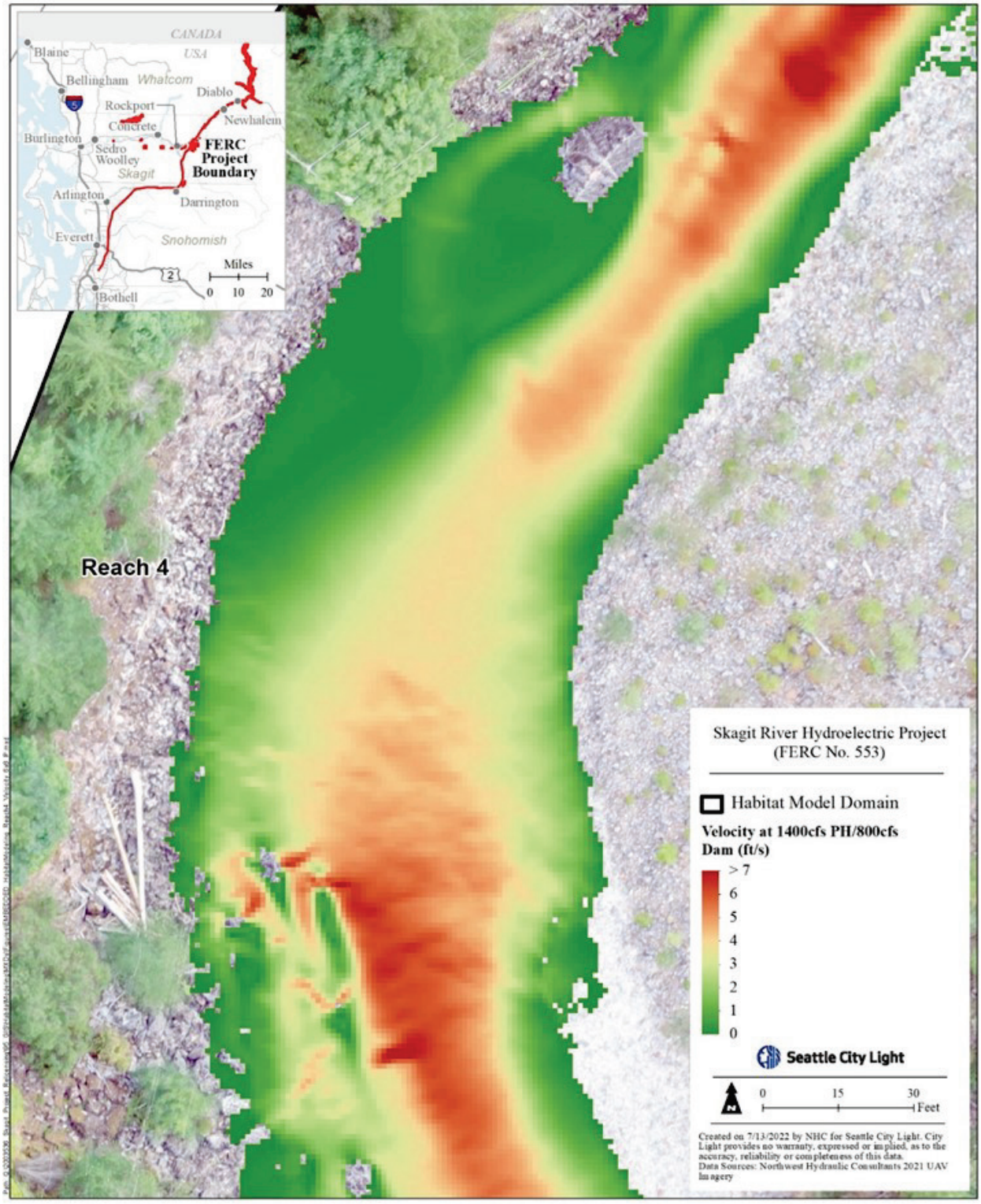

Figure 4.7-3. Velocity based on a release of 1,400 cfs from Gorge Powerhouse and 800 cfs from Gorge Dam within Bypass Habitat Model Reach 4.

4.7.3 Substrate and Cover Rasters

The point shapefiles created and attributed with depth and velocity data were also assigned cover and substrate codes utilizing an ArcGIS script. The cover and substrate polygon shapefiles discussed in Section 4.6.6 (see examples in Figure 4.7-4 and Figure 4.7-5) were converted into raster files as a means of speeding up model processing times. Assigning substrate and cover codes to each point from the rasterized datasets was more efficient than extracting values from larger polygon areas and assigning those to each gridded point. Review was done following this step to ensure that the substrate and cover codes assigned to each point matched those in the overlying substrate and cover mapping shapefiles.

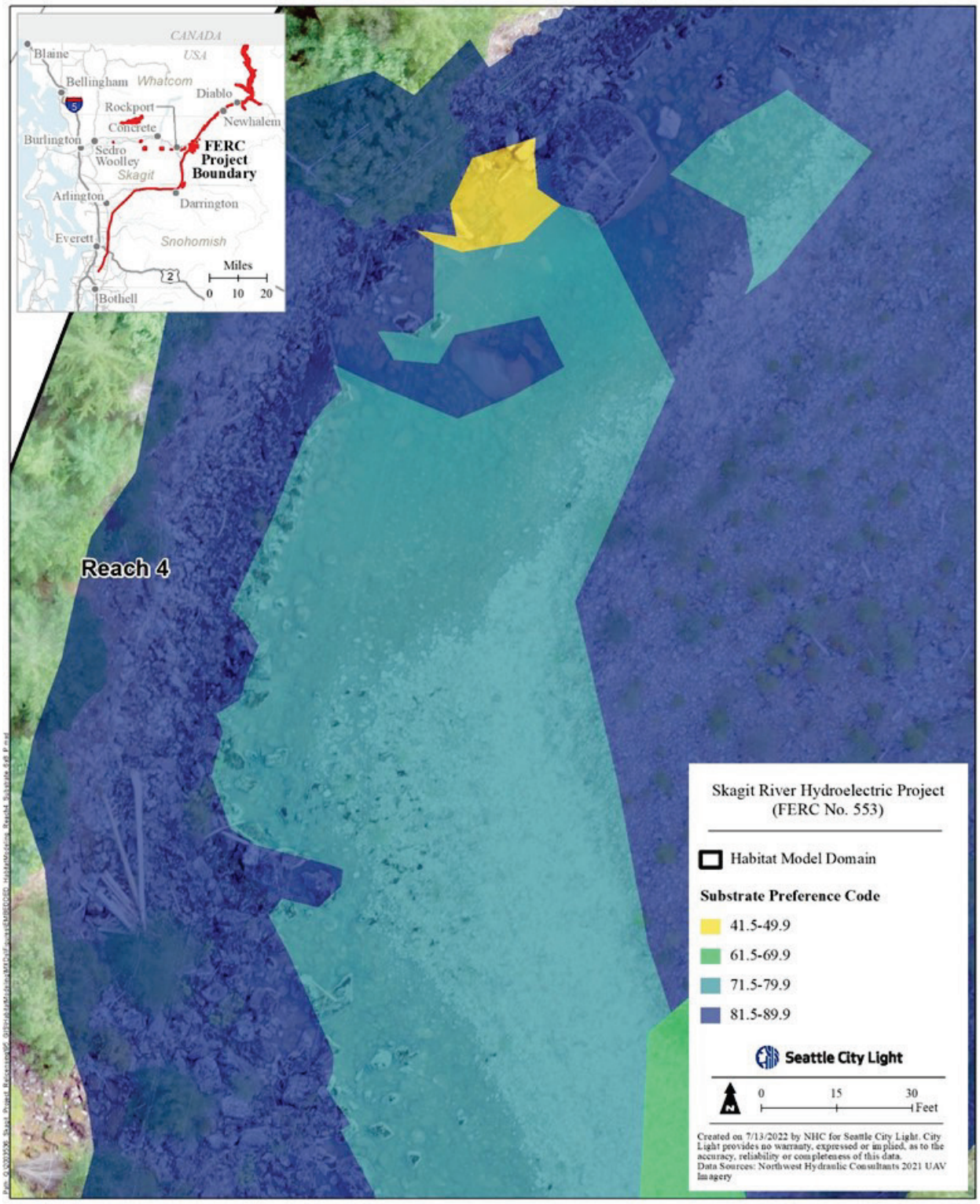

Figure 4.7-4. Substrate mapping within Bypass Habitat Model Reach 4.

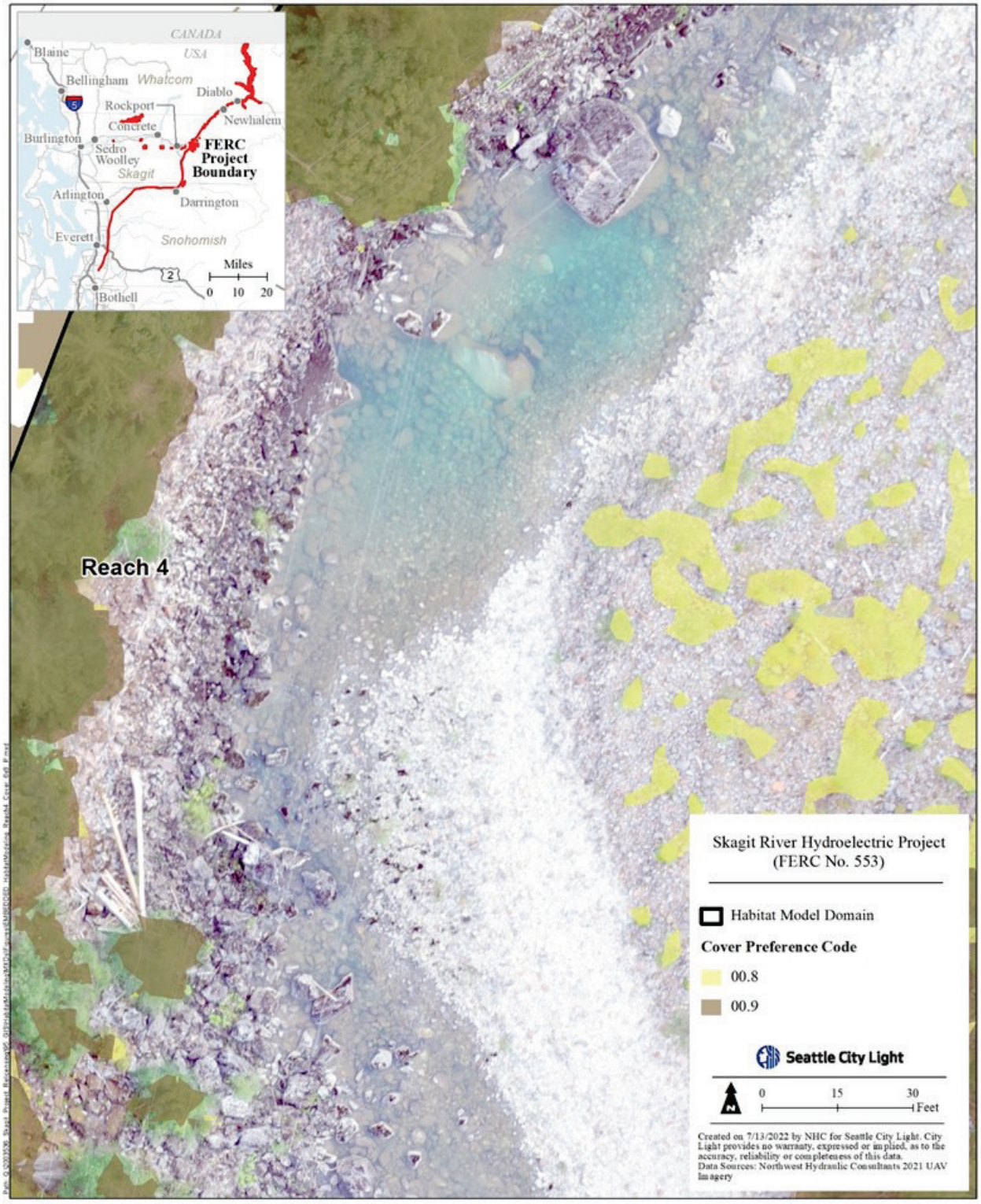

Figure 4.7-5. Cover mapping within Bypass Habitat Model Reach 4.

4.7.4 Computation of Flow-Habitat Relationships

The point shapefiles attributed with values for each of the four input variables of depth, velocity, substrate, and cover were exported to text files and then assigned habitat preference values from the corresponding HSC curves (see Section 4.6.3 and Attachment B). Once preference values were established for each variable, a composite HSI was calculated utilizing the methodology described in the Washington State Instream Flow Study Guidelines (Beecher and Caldwell 2022) applied to each 2-D model cell as follows:

*HSI = (Depth preference) * (Velocity preference) * (Substrate OR Cover preference)*

The determination of whether substrate or cover preference is used in the habitat suitability calculation is based on the Washington State Instream Flow Study Guidelines (Beecher and Caldwell 2022) as summarized in Table 4.7-1. These nuances were built into the modeling Python script and reviewed prior to finalizing the results to ensure the output HSI and UHA values were accurate for each species/life stage combination.

Table 4.7-1. Skagit River HSI Calculation Methodology.

Species	Cover	Substrate[1]	HSI Calculation Description
Salmonids	Steelhead, Chinook, Pink, Chum, Coho, Sockeye, Rainbow Trout, Bull Trout/Dolly Varden, Sea-Run Bull Trout, Cutthroat Trout, Sea-Run Cutthroat Trout, Mountain Whitefish		
Spawning		X	Only substrate is used (i.e., never defaults to cover). Also, dominant substrates of Code 1, 2, or 9 always result in a substrate Recommended Preference (RP) = 0.00
Adult[2]	X	X	Cover OR substrate (whichever is greater); any boulder presence (dominant or subdominant) results in a RP = 1.00 (except for Mountain Whitefish adult[3])
Juvenile[2]	X	X	Cover OR substrate (whichever is greater); any boulder presence (dominant or subdominant) results in a RP = 1.00 (except for Mountain Whitefish juvenile[3])
Fry		X	Only substrate is used (i.e., never defaults to cover)
Non-Salmonids	Pacific Lamprey, Western Brook Lamprey, Western River Lamprey, Salish Sucker, White Sturgeon		
Spawning		X	Only substrate is used (cover HSC is not available)
Juvenile	X	X	Cover OR substrate (whichever is greater); only applies to Salish Sucker juvenile (cover HSC not available for Pacific Lamprey juvenile)

1 Substrate Tables 1-9 provided in the Washington State Instream Flow Study Guidelines (Beecher and Caldwell 2022) were used for salmonid species.

2 Substrate Table 3 (Beecher and Caldwell 2022) was used for both adult and juvenile salmonids. As a result, adults and juveniles have the same rule regarding boulder presence (i.e., any boulder presence, dominant or subdominant, results in a RP = 1.00).

3 Mountain Whitefish adults and juveniles have separate substrate RP values provided in Tables 8 and 9, respectively (Beecher and Caldwell 2022).

HSI values range from zero to one for each model cell within the habitat model domain, with zero representing no habitat value and one representing the maximum habitat value. Rasters of the resulting HSI values were created to provide a spatial representation of habitat suitability within each reach, for each simulated flow combination (i.e., combination of release from Gorge Dam and discharge from Gorge Powerhouse) and for each species/life stage combination. Within the Bypass Habitat Model domain this equated to nearly 3,400 raster files. Figure 4.7-6 presents one of the resultant HSI rasters in reach 4, for a release of 800 cfs from Gorge Dam and 1,400 cfs from Gorge Powerhouse, modeling the habitat suitability for Mountain White Fish adults. (As discussed in Section 4.6-5, releases from Gorge Powerhouse have no influence on conditions in reach 4.)

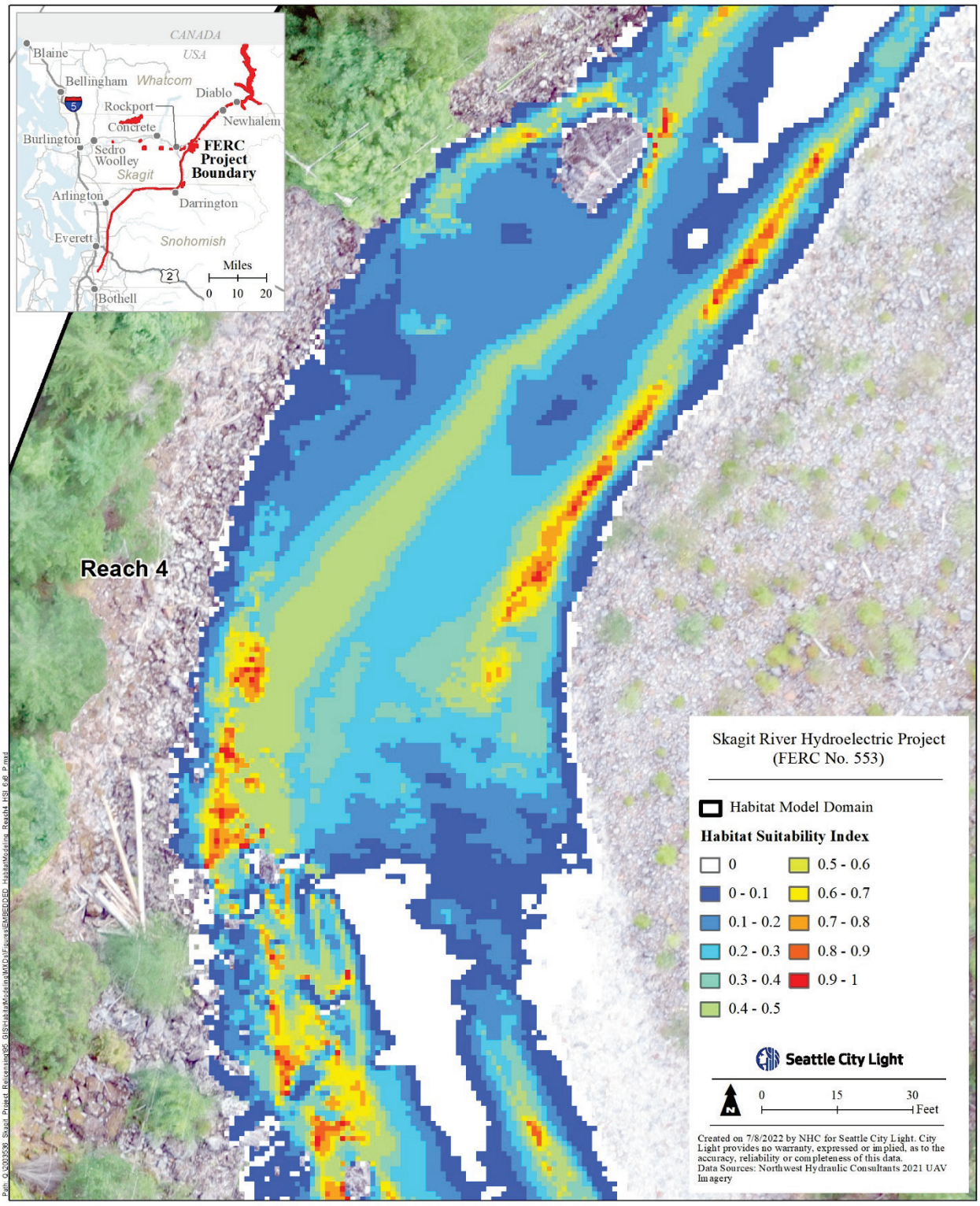

Figure 4.7-6. HSI mapping for Mountain White Fish adults for a release of 1,400 cfs from Gorge Powerhouse and 800 cfs from Gorge Dam flow in Bypass Habitat Model Reach 4.

HSI values for each cell were multiplied by the area of the cell (one square foot within the Bypass Habitat Model domain) to calculate the UHA for that cell. These UHAs were summed to determine the total UHA within each model reach for each species/life stage combination and each simulated flow combination.

The model produced tabular results of UHA by flow for each reach. The tabular results were then used to produce graphical displays of UHA. For reaches 1-4 and reach 6, the graphical displays are conventional 2-D plots of UHA against flow, with flow in reaches 1-4 representing release from Gorge Dam, and flow in reach 6 representing the release from Gorge Dam plus discharge from Gorge Powerhouse and a nominal allowance for tributary inflow from Ladder Creek.

Graphical display of results for reach 5 is more complicated because water depth and velocity (and hence depth and velocity preference) are a function of both the inflow to that reach (i.e., the release from Gorge Dam) and the discharge from Gorge Powerhouse at the downstream end of the reach, which as discussed in Section 4.6.5 imposes a backwater effect. The UHA results for reach 5 are thus displayed as 3-D plots of UHA against release from Gorge Dam and discharge from Gorge Powerhouse in the form of colormap charts.

Each 2-D or 3-D plot provides the relationship between total UHA and flow or combination of flows for a specific habitat model reach and specific species/life stage combination. With six reaches in the Bypass Habitat Model domain and 37 species/life stage combinations, this resulted in a total of 222 individual plots. To facilitate comparison of results, these flow-habitat relationships were grouped into the following six categories for purposes of presentation in this study report:

- Salmonid spawning;
- Salmonid fry;
- Salmonid juveniles;
- Salmonid adults;
- Lamprey and Salish Sucker; and
- White Sturgeon.

Example UHA plots for reach 4 and reach 5 are provided in Figure 4.7-7 and Figure 4.7-8 respectively. The 3-D plot in Figure 4.7-8 shows discrete color-coded UHA results from simulation of each combination of Gorge Dam release and Gorge Powerhouse discharge identified in Table 4.6-5. The key to the species/life stage codes on Figure 4.7-7 and Figure 4.7-8 along with the full set of UHA plots are provided in Attachment E. All Bypass Habitat Model input and output data (including HSI, depth, velocity, substrate, and cover rasters) are available upon request.

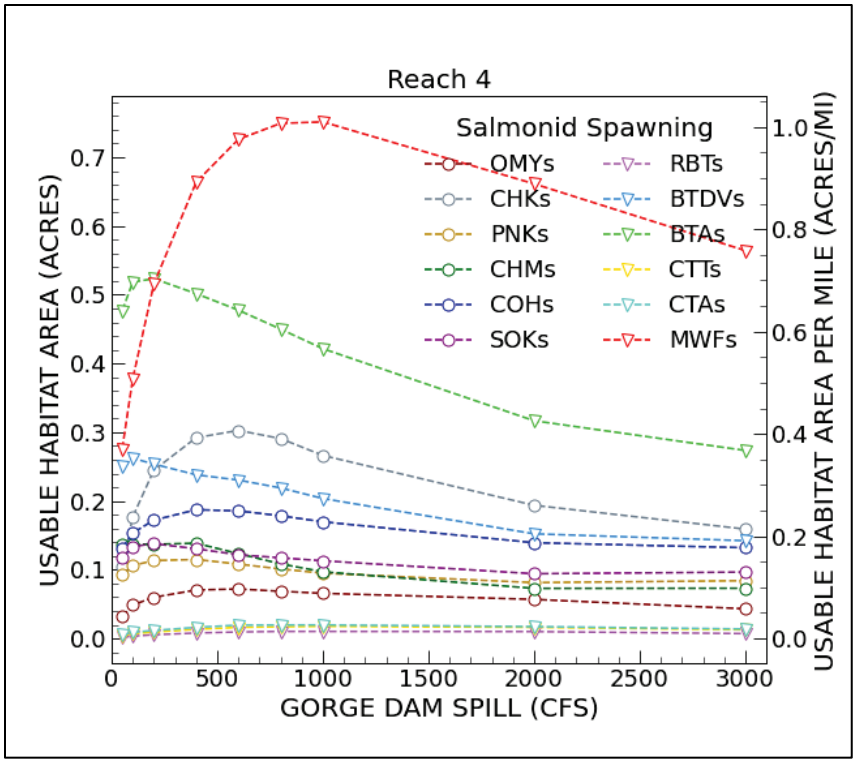

Figure 4.7-7. **Sample UHA plot for salmonid spawning species/life stage in Bypass Habitat Model Reach 4.**

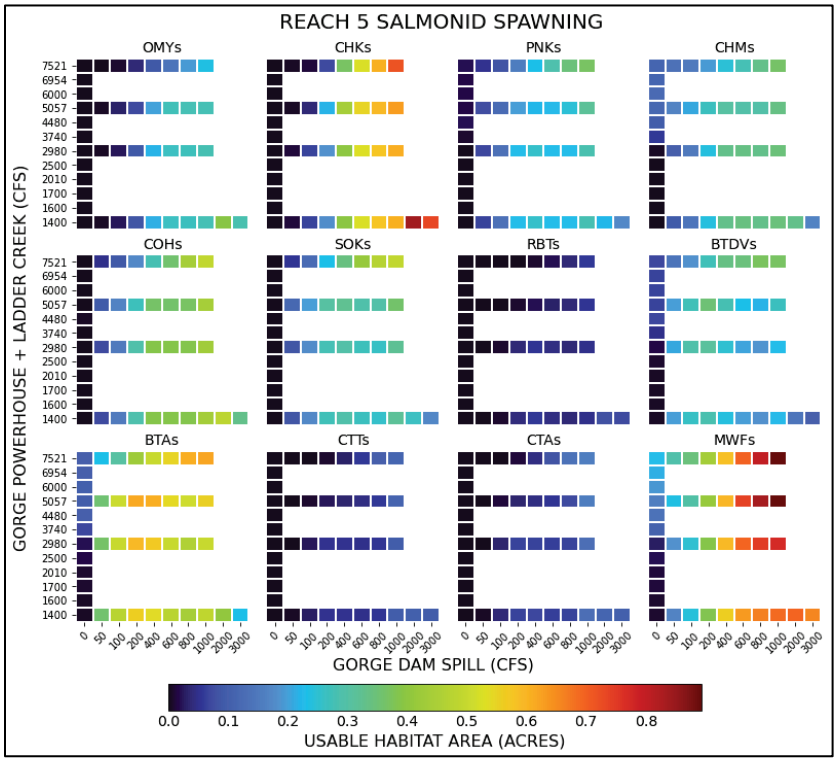

Figure 4.7-8. **Sample UHA plot for salmonid spawning species/life stage in Bypass Habitat Model Reach 5.**

4.8 Hydraulic Data for Fish Passage Analysis

A series of 17 steady-state runs were simulated with the calibrated Bypass Hydraulic Model to generate hydraulic data to support fish passage evaluation at Existing Features 1 and 2. Simulations assumed releases from Gorge Dam ranging from 50 cfs to 4,800 cfs (see Table 4.8-1) determined in consultation with LPs and FA-04 Fish Passage Study team fish passage specialists. A concurrent steady state discharge of 2,000 cfs from Gorge Powerhouse was assumed; however, releases from Gorge Powerhouse have no impact on hydraulic conditions at the Existing Features, which are upstream from reach 5. The fish passage evaluation itself was conducted as part of the FA-04 Fish Passage Study (City Light 2023b). Additional products provided to the FA-04 Fish Passage Study included UAV photos and videos of the Gorge bypass reach, and water level logger records at the Existing Features. The results of the fish passage analysis at Existing Features are presented in the FA-04 Fish Passage Study (City Light 2023b).

Table 4.8-1. Flows simulated to generate hydraulic data in support of fish passage evaluation.[1]

Run No.	Release from Gorge Dam (cfs)
1	50
2	100
3	200
4	400
5	600
6	800
7	1,000
8	1,200
9	1,400
10	1,600
11	1,800
12	2,000
13	2,500
14	3,000
15	3,500
16	4,000
17	4,800

1 All simulations included a constant Gorge Powerhouse discharge of 2,000 cfs.

4.9 Evaluation of the November and December 2021 Large Spills above Newhalem

In November 2021, the Gorge bypass reach experienced high flows due to a significant weather event, with spill from Gorge Dam peaking at approximately 24,000 cfs on November 16, 2021. Localized impacts to channel topography were observed, including mobilization of large boulders within the Existing Features. An evaluation of the November and December 2021 large spills above Newhalem on hydraulic conditions and aquatic habitat within the Gorge bypass reach is provided in Attachment F of this study report.

4.10 Consultation

A total of six consultation workshops were held to apprise LPs of progress on the study and to solicit feedback and input. Of these, four workshops addressed Bypass Hydraulic Model development, and two workshops addressed Bypass Habitat Model development. The two habitat model development workshops were joint meetings with the FA-02 Instream Flow Model Development Study (City Light 2023a) and addressed development of both the Bypass Habitat Model and the FA-02 Upper Skagit Habitat Model. In addition to these six workshops, two smaller technical group meetings were held on January 11, 2022 and January 21, 2022 to discuss calibration of the Bypass Hydraulic model. These smaller technical groups were comprised of staff from WDFW, Ecology, and the consultant team.

The four workshops held to address development of the Bypass Hydraulic Model were as follows:

FA-05 Workshop 1 (May 17, 2021)

The primary purpose of FA-05 Workshop 1 was to discuss and address LP concerns, raised in Workshop 1 of the FA-02 Instream Flow Model Development Study, surrounding the use of numerical hydraulic models for evaluation of fish passage in the Gorge bypass reach (City Light 2023a). The workshop was presented jointly by the Bypass Instream Flow Model Development Study team and the FA-04 Fish Passage Study team. The workshop included:

- Review and discussion of objectives and methodology for fish passage evaluation;
- Discussion of the role of hydraulic modeling in evaluation of fish passage;
- Discussion of concerns raised by LPs regarding the use of the HEC-RAS 2-D model as a fish passage evaluation tool; and
- Discussion of the proposed data collection program to support development of the Bypass Hydraulic Model.

FA-05 Workshop 2

FA-05 Workshop 2 was proposed in the RSP to review and discuss proposed updates to biological and habitat metrics. However, following Workshop 1 of the FA-02 Instream Flow Model Development Study (City Light 2023a), it was decided to hold a separate series of workshops and smaller technical working group meetings to specifically address development of HSCs and periodicity data relevant to both the FA-02 Instream Flow Model Development Study and Bypass Instream Flow Model Development Study areas, thus obviating the need for Workshop 2. A summary of the HSC workshops and HSC and periodicity workgroup meetings is provided in the FA-02 Instream Flow Model Development Study (City Light 2023a).

FA-05 Workshop 3 (August 26, 2021)

FA-05 Workshop 3 provided an update on and discussion of development of the Bypass Hydraulic Model, including:

- Presentation and discussion of the field data collection;
- Review and discussion of the development of the Bypass Hydraulic Model terrain dataset; and

- An overview of the approach to Bypass Hydraulic Model development.

FA-05 Workshop 4 (November 2, 2021)

FA-05 Workshop 4 provided a further study update, including:

- Discussion of uncertainty in the discharge data used for the Bypass Hydraulic Model calibration;
- Update and discussion of Bypass Hydraulic Model development, including the model terrain, geometry, and roughness, and associated model sensitivity tests;
- Presentation and discussion of the approach to Bypass Hydraulic Model calibration and the status of the calibration;
- An update on development of biological and habitat data, including substrate and cover mapping, HSC, and periodicity data; and
- A preview of the planned approach to the integration of Bypass Hydraulic Model outputs and biological/habitat data for instream flow analysis.

FA-05 Workshop 5 (February 1, 2022)

Topics covered in FA-05 Workshop 5 included:

- Review of the field data collection program;
- Presentation and discussion of the final Bypass Hydraulic Model calibration;
- Presentation of flows proposed for use in model simulations to support fish habitat and fish passage analyses;
- An update on substrate and cover mapping, and HSC and periodicity development; and
- Review of the approach to integrating hydraulic model outputs with biological and habitat data.

The agenda, presentation material, and meeting notes for FA-05 Workshops 1, 3, 4, and 5 are provided in Attachments G, H, I, and J respectively.

The two habitat model development workshops are summarized below.

Habitat Model Workshop 1 (April 5, 2022)

Habitat Model Workshop 1 included:

- An overview of the approach to development of the Bypass Habitat Model and Upper Skagit Habitat Model;
- Discussion of habitat model domain and flows used to develop flow-habitat relationships;
- Presentation of sample habitat model outputs; and
- Presentation of an example application of habitat model outputs.

Habitat Model Workshop 2 (July 6, 2022)

Habitat Model Workshop 2 included:

- Review and update of development of habitat models;
- Review of habitat model outputs, including UHA curves and maps;
- Review of example time series analysis application of habitat models; and
- Discussion of integration of the Upper Skagit Habitat Model with other models developed in support of Project relicensing.

The agenda, presentation material, and meeting notes for Habitat Model Workshops 1 and 2 are provided in Attachments K and L, respectively.

Additionally, a series of parallel workshops and smaller technical workgroup meetings was held under the FA-02 Instream Flow Model Development Study (City Light 2023a) with content and discussion relevant to the Bypass Instream Flow Model Development Study. Of particular relevance was the series of workshops and technical workgroup meetings held to address development of HSCs and periodicity data. The resulting preliminary HSC curves and preliminary periodicity table were presented and reviewed during HSC Workshop 5 on February 3, 2022. At HSC Workshop 5, consensus was reached on the majority of the proposed HSC curves (representing 29 species and life stage combinations). Consensus was achieved for the remaining HSC curves (representing 8 species and life stage combinations) via email on February 18, 2022. A summary of those workshops and workgroup meetings is provided in the FA-02 Instream Flow Model Development Study (City Light 2023a).

5.0 RESULTS

The following work products represent the results from the Bypass Instream Flow Model Development Study:

- **Bypass Hydraulic Model** – A 2-D numerical hydraulic model calibrated to depth, velocity and WSE data has been developed for the approximately 3-mile reach of the Skagit River from Gorge Dam to the USGS Skagit River at Newhalem gage. The model encompasses the Gorge bypass reach from Gorge Dam to Gorge Powerhouse and a short stretch of the mainstem Skagit River from Gorge Powerhouse to the USGS Skagit River at Newhalem gage.
- **Bypass Habitat Model** – An aquatic habitat model has been developed for the approximately 3-mile reach of the Skagit River from Gorge Dam to the USGS Skagit River at Newhalem gage. As with the Bypass Hydraulic Model, the Bypass Habitat Model encompasses the Gorge bypass reach from Gorge Dam to Gorge Powerhouse and a short stretch of the mainstem Skagit River from Gorge Powerhouse to the USGS Skagit River at Newhalem gage. The lateral extent of the Bypass Habitat Model is defined by the area inundated by a 3,000 cfs release from Gorge Dam and by the 5 percent exceedance discharge from Gorge Powerhouse. The Bypass Habitat model integrates depth and velocity outputs from the Bypass Hydraulic Model with substrate and cover data and with HSC to produce outputs of UHA for each of 37 combinations of fish species and life stage.
- **Flow-Habitat Relationships** – Outputs of depth and velocity from the Bypass Hydraulic Model were integrated with substrate and cover data and with HSC within the Bypass Habitat Model to produce flow-habitat relationships for each of the 37 species/life stage combinations of interest for the reach of the Skagit River from Gorge Dam to the USGS Skagit River at Newhalem gage.
- **FA-04 Fish Passage Study Support** – The calibrated Bypass Habitat model was run for releases from Gorge Dam ranging from 50 cfs to 4,800 cfs to generate hydraulic data to support the evaluation of fish passage at two boulder cascades, the Existing Features, within the Gorge bypass reach. The evaluation of fish passage was conducted as part of the FA-04 Fish Passage Study (City Light 2023b).

6.0 DISCUSSION AND FINDINGS

This study is complete and has met the goals and objectives stated in Section 2.0 of this study report, namely:

- A 2-D numerical hydraulic model (the Bypass Hydraulic Model) has been developed and calibrated, extending from Gorge Dam to the USGS Skagit River at Newhalem gage, encompassing the Gorge bypass reach.
- Hydraulic model outputs and observed substrate and cover information have been integrated with biological criteria in the form of HSCs (the Bypass Habitat Model) to develop flow-habitat relationships for the reach of the Skagit River from Gorge Dam to the USGS Skagit River at Newhalem gage, encompassing the Gorge bypass reach, for 37 combinations of fish species and life stages.
- The Bypass Hydraulic Model has been applied to provide hydraulic data in support of the evaluation of fish passage at two boulder cascades (referred to as Existing Feature 1 and Existing Feature 2) within the Gorge bypass reach. The evaluation of fish passage was conducted under the FA-04 Fish Passage Study (City Light 2023b).

The Bypass Hydraulic Model and Bypass Habitat Model were developed to support on-going and future evaluation and discussion of hydraulic conditions and aquatic habitat within the Gorge bypass reach for current and potential alternative Project operations.

6.1 Notice of Agreements

The status of June 9, 2021 Notice commitments related to the Bypass Instream Flow Model Development Study is provided in Table 6.1-1.

Table 6.1-1. Status of Bypass Instream Flow Model Development Study modifications identified in the June 9, 2021 Notice.

Study Modifications Identified in the June 9, 2021 Notice: As Written	Status
City Light will provide a planned higher flow event in summer/fall if opportunistic high flow is not available. The study report will assess impacts to fish migration, both beneficial and detrimental, of certain flow regimes.	Complete. A high flow event occurred in late-June/early-July 2021 with a maximum flow of approximately 7,400 cfs. The hydraulic model was calibrated to water level data collected in the Existing Features during this event at sustained flows of about 4,800 cfs and 6,200 cfs. The hydraulic model developed as part of this study was used to support an assessment of fish migration. However, the results of the fish migration assessment will be reported on in the FA-04 Fish Passage Study.
City Light will clarify the study plan to allow for consideration of additional species [pink salmon (*Oncorhynchus gorbuscha*); chum salmon (*O.keta*); sea-run cutthroat (*O. clarkii clarkii*); Pacific lamprey (*Entosphenus tridentatus*)] for passage analysis.	The additional species were added to the list of target species to be considered for passage analysis under the FA-04 Fish Passage Study.

Study Modifications Identified in the June 9, 2021 Notice: As Written	Status
City Light and the LPs will be treating these species [Pacific Lamprey, Salish Sucker; Dolly Varden] as present. City Light and the LPs will be selecting species for HSC analysis.	The HSC Tech Group developed/recommended HSC curves for all three requested species. Details are provided below: a) Pacific lamprey (spawning and juvenile rearing life stages) – HSC curves were developed based on literature review of West Fork Hoquiam River, Chehalis River basin and Trapp Creek, Washington and Nicola/coastal Salmon River, British Columbia (Vadas 2021). b) Salish sucker (spawning and juvenile rearing life stages) – HSC curves were developed based on literature review from several sources in Washington State and western Canada and are largely based on research performed by Pearson et al. (2003). c) Dolly Varden (spawning, juvenile, and fry) – It is WDFW/Ecology's preference to use statewide Type 3 HSC curves when available. As a result, the recommended habitat modeling approach is to use the WDFW/Ecology Type 3 HSC curves for Bull Trout and Dolly Varden spawning and juvenile life stages (Beecher and Caldwell 2022). HSC curves are unavailable from WDFW/Ecology for the fry life stage; therefore, the HSC Technical Group recommended using the Type 2 HSC curves from Crumley and Stober (1984), which rely on data from the Arctic Environmental Information and Data Center.
City Light will address downstream and upstream fish passage at the plunge pool to the extent necessary.	The potential for downstream and upstream fish passage at the plunge pool is being considered as part of FA-04 Fish Passage Study implementation.
Address process flows Study Requests specifically: a) Which flows activate channel forming, channel maintenance, and channel flushing flows and upstream (probably covered) and outmigration of fish, and b) Look at magnitude, duration, frequency, seasonality, and timing (rate of change)	The data and analyses conducted for the GE-04 Skagit River Geomorphology Between Gorge Dam and the Sauk River Study will support identification of flow scenarios to meet these interests, and the available data were discussed at Geomorphology Work Group meetings after the ISR.
City Light and the LPs recognize that there is a need for further dialogue about the use of best professional judgment for decision-making, such as passage flow assessment, and the establishment of objective criteria for evaluating studies as well as implementation of the studies.	Incorporated in the FA-04 Fish Passage Study implementation effort. City Light continued to work with LPs during biweekly Agency Work Sessions in support of this study through January 2023.

7.0 VARIANCES FROM FERC-APPROVED STUDY PLAN AND PROPOSED MODIFICATIONS

As described in the Bypass Instream Flow Model Development Study Interim Report (City Light 2022), several variances were adopted during study implementation as summarized below. These variances were adopted to better meet the study plan objectives by addressing data gaps that became apparent during the study, improving the safety and efficiency of field data collection, and enhancing consultation with LPs:

(1) **Terrain refinement**: The RSP proposed using the topobathymetric surface developed by QSI from the 2018 LiDAR (QSI 2018) directly to represent the Gorge bypass reach hydraulic model terrain. This surface has a 3-ft terrain resolution. During review of the LiDAR data, it became apparent that a finer resolution terrain was needed in several parts of the Bypass Hydraulic Model domain to provide a more realistic representation of actual conditions and to assure model accuracy. Consequently, City Light leveraged additional information in the raw LiDAR data to refine the model terrain to a 1-ft resolution. The process of developing the refined terrain is described in the Upper Skagit River Green LiDAR Classification memorandum (HDR 2022b; Attachment A to the Bypass Hydraulic Model Calibration Report). The Bypass Hydraulic Model Calibration Report is Attachment A to this study report. This refinement is consistent with but beyond the RSP requirements.

(2) **Method for acquiring water surface profile data**: The RSP proposed acquiring WSE profile data, subject to safety considerations, for each of the controlled releases and for base-flow conditions by manually marking profiles and surveying using conventional survey techniques. Following clarification of the conditions under which UAVs could by flown within the study area, it was decided to acquire WSE profiles by UAV. This method was determined to be more efficient and safer than the method originally proposed while providing data of equal or better accuracy than could be achieved practically using conventional survey methods.

(3) **Bypass Hydraulic Model Validation**: The RSP states the model will be validated before evaluating alternative Project flow scenarios, without explicitly stating what or how many observations will be reserved for validation. A proposed validation approach of reserving transect observations from the 250 cfs controlled release was proposed at FA-05 Workshop 4 and subsequently discussed at a small group technical meeting on January 11, 2022 (Section 4.10), and the decision was made to forgo a strict validation. The decision to forgo validation was based on a consensus that calibration to the entire data set was more likely to produce favorable results compared to holding data for validation. The Bypass Hydraulic Model does not rely on transect-specific calibration parameters and, therefore, there is limited benefit in validating model parameters if model performance is adequate for all performance metrics.

(4) **Consultation process**. The RSP proposed a series of five consultation workshops to apprise LPs of progress on the study and to solicit feedback and input. The consultation program was expanded during study implementation to include a total of six workshops and several smaller technical workgroup meetings, as described in Section 4.10.

Additionally, the study area was extended beyond the requirements of the RSP. The RSP goals and objectives called for development of a flow-habitat evaluation tool for the Gorge bypass reach, defined as the reach of the Skagit River between Gorge Dam and Gorge Powerhouse. To provide a robust downstream boundary for hydraulic modeling, the Bypass Hydraulic Model extends from Gorge Dam to the USGS Skagit River at Newhalem gage (12178000), approximately one-half mile downstream from Gorge Powerhouse. To facilitate computation of flow-habitat relationships, the same modeling extents were adopted for habitat modeling by extending the downstream limit of the Bypass Habitat Model from Gorge Powerhouse to the USGS Skagit River at Newhalem gage. Flow-habitat relationships developed under the Bypass Instream Flow Model Development Study thus cover the reach between Gorge Dam and the USGS Skagit River at Newhalem gage. This extent is consistent with but beyond the RSP requirements. A corresponding adjustment was made in the extent of habitat modeling under the FA-02 Instream Flow Model Development Study.

The Bypass Instream Flow Model Development Study is complete in accordance with the approved RSP, study modifications agreed to in the June 9, 2021 Notice (Section 6.1), and the variances described above.

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SKAGIT RIVER GORGE BYPASS REACH HYDRAULIC AND INSTREAM FLOW MODEL DEVELOPMENT STUDY REPORT

ATTACHMENT A

BYPASS HYDRAULIC MODEL CALIBRATION REPORT

FA-05 SKAGIT RIVER GORGE BYPASS REACH HYDRAULIC AND INSTREAM FLOW MODEL DEVELOPMENT STUDY
BYPASS HYDRAULIC MODEL CALIBRATION REPORT

SKAGIT RIVER HYDROELECTRIC PROJECT
FERC NO. 553

Seattle City Light

Prepared by:
Northwest Hydraulic Consultants, Inc. and
HDR Engineering, Inc.

March 2023

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Attachment F	Model Performance Evaluation: Transect Velocities and Depths

List of Acronyms and Abbreviations

2-D .....two-dimensional
ADCP.....acoustic Doppler current profiler
ADV.....acoustic Doppler velocimeter
cfs.....cubic feet per second
City Light.....Seattle City Light
DEM.....Digital Elevation Model
FAA.....Federal Aviation Administration
FERC.....Federal Energy Regulatory Commission
ft .....foot/feet
GIS .....Geographic Information System
GPS .....Global Positioning System
HEC-RAS .....Hydrologic Engineering Center River Analysis System
HDR .....HDR Engineering, Inc.
LiDAR.....Light Detection and Ranging
LP.....licensing participant
LSPIV .....Large Scale Particle Image Velocimetry
NAVD 88.....North American Vertical Datum of 1988
PRM .....Project River Mile
Project .....Skagit River Hydroelectric Project
QSI .....Quantum Spatial, Inc.
RSP .....Revised Study Plan
RTK.....real-time kinematic
SfM .....Structure from Motion
UAV.....unmanned aerial vehicle
USACE .....U.S. Army Corps of Engineers
USGS .....U.S. Geological Survey
WSE .....Water Surface Elevation

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1.0 INTRODUCTION

1.1 Purpose and Background

The FA-05 Skagit River Gorge Bypass Reach Hydraulic and Instream Flow Model Development Study (Bypass Instream Flow Model Development Study) is being conducted in support of the relicensing of the Skagit River Hydroelectric Project (Project), Federal Energy Regulatory Commission (FERC) No. 553, as identified in the Revised Study Plan (RSP) submitted by Seattle City Light (City Light) on April 7, 2021 (City Light 2021). The goal of the Bypass Instream Flow Model Development Study is to develop flow/habitat relationships for select fish species and life stages within the Gorge bypass reach (defined as the reach between Gorge Dam and Gorge Powerhouse). Creation of the flow/habitat relationships involves the development, calibration, and application of a two-dimensional (2-D) hydraulic model. The hydraulic model depth and velocity outputs are integrated with observed characteristics of substrate and cover and biological criteria for select fish species, life stages, and periodicities. The same 2-D hydraulic model (termed the Bypass Hydraulic Model in the Bypass Instream Flow Model Development Study Interim Report (City Light 2022) will also support fish passage evaluation at Existing Features 1 and 2 (Figure 1.2-1) by the FA-04 Fish Passage Technical Studies Program (City Light 2023b). This report describes data collection, development, sensitivity testing, and calibration of the Bypass Hydraulic Model.

1.2 Study Area

The Bypass Hydraulic Model extends from Gorge Dam at about Project River Mile (PRM) 97.21 downstream to the U.S. Geological Survey (USGS) Skagit River at Newhalem gage (USGS gage 12178000) at PRM 94.19, located approximately 0.5 miles downstream from Gorge Powerhouse (Figure 1.2-1). The model domain is 3.02 miles long.

The downstream limit of the hydraulic model at the USGS Skagit River at Newhalem gage, was selected to overlap with the FA-02 Upper Skagit Hydraulic Model (Attachment A to the FA-02 Instream Flow Model Development Study [City Light 2023a]). This model extends from just above Gorge Powerhouse at PRM 94.75 to the USGS Skagit River above Miller Creek gage near Rockport (USGS 12189700) at PRM 64.95 and is being used to develop flow/habitat relationships below Newhalem.

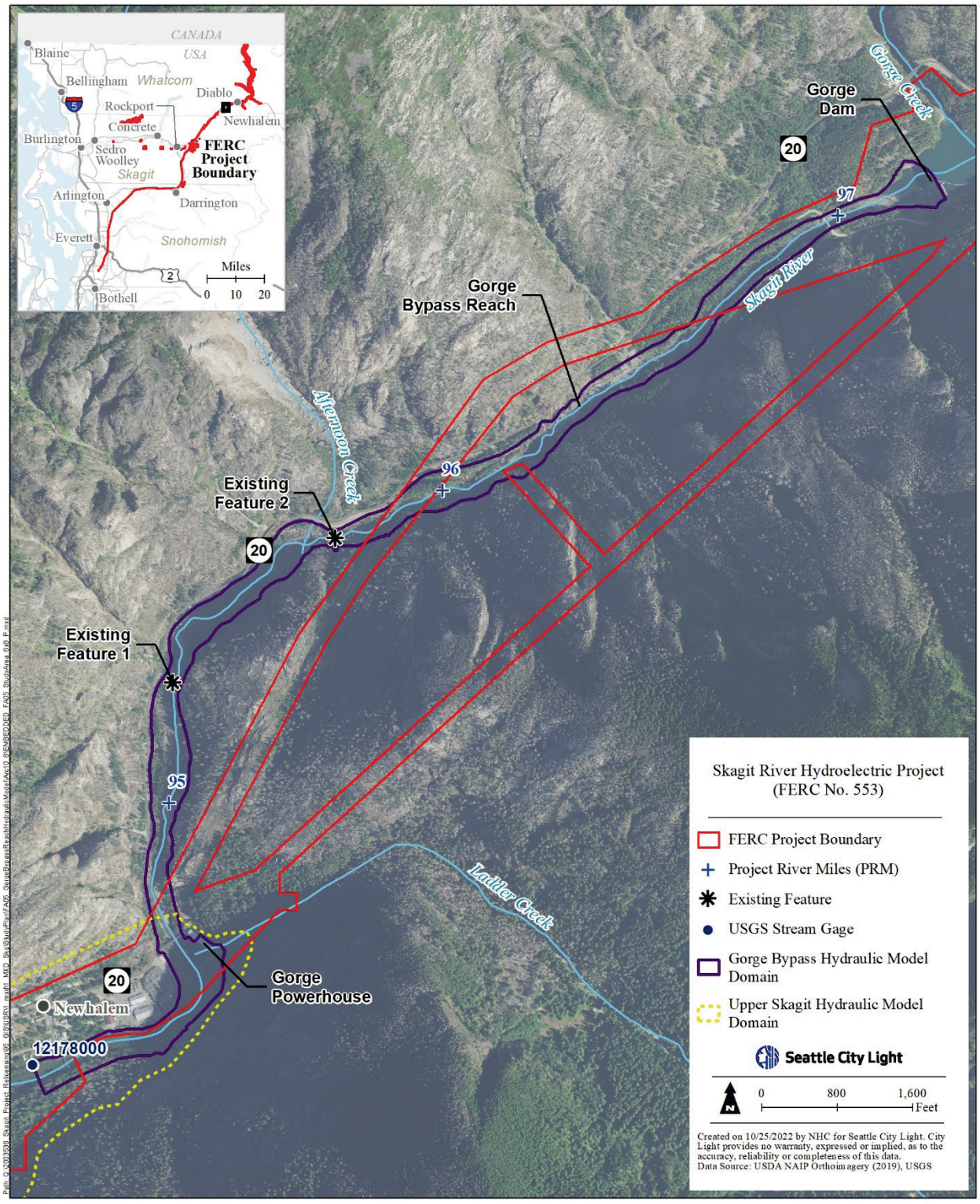


Figure 1.2-1. Bypass Hydraulic Model Study Area.

2.0 DATA COLLECTION

The primary components required to build a 2-D hydraulic model include topographic and bathymetric data to define the river channel and floodplain, hydrologic data to define operational flows, and hydraulic data observations for model calibration. The following sections detail the collection and preparation of this information.

2.1 Topographic and Bathymetric Data

Three-dimensional terrain mapping was necessary to develop a detailed topographic surface of the river channel and overbank regions for import to the Bypass Hydraulic Model. A combination of topobathymetric Light Detection and Ranging (LiDAR) and standard LiDAR returns covering the Bypass Hydraulic Model domain were acquired including:

- Quantum Spatial, Inc. (QSI) topobathymetric LiDAR ("green LiDAR") contracted by City Light; acquired April 25 and 26, 2018 (QSI 2018). Topobathymetric LiDAR includes both topographic (out-of-water) and bathymetric (underwater) terrain as observed during the time of survey; and
- QSI topographic LiDAR ("standard" LiDAR) contracted by the USGS; acquired March 2016 – September 2016 (QSI 2017).

The 2018 topobathymetric LiDAR data have an absolute unvegetated vertical accuracy of 0.182 feet (ft) with 95 percent confidence for topographic points and a vertical accuracy of 0.366 ft with 95 percent confidence for submerged bathymetric points. The 2016 standard LiDAR returns have an absolute unvegetated vertical accuracy of 0.263 ft with 95 percent confidence. Full details of the LiDAR resolution and accuracy assessments can be found in the LiDAR technical data reports (QSI 2017, 2018).

The 2018 topobathymetric LiDAR was the primary terrain source for the Bypass Hydraulic Model as it provided high resolution topography and bathymetry for almost the entire study area. There are, however, several locations where underwater voids (areas of inadequate laser returns) exist, either due to turbid water, deep water, aerated water, vegetation cover, and/or a non-reflective channel bottom. These voids in the bathymetry are located at:

- The plunge pool below Gorge Dam;
- A deep pool approximately 1.4 miles upstream of Gorge Powerhouse, commonly referred to as the Afternoon Creek Pool;
- The Gorge Powerhouse tailrace; and
- A short stretch of deep and fast water between the Gorge Powerhouse and the USGS Skagit River at Newhalem gage.

City Light provided surveyed bathymetry to fill the void in the plunge pool below Gorge Dam. The remaining three void areas were filled by interpolating from LiDAR returns bordering each void, and/or professional judgment, which likely underestimates true depth to an unknown degree. However, each of these void locations represent relatively deep pools under base-flow conditions

where terrain interpolation will not significantly impact hydraulic model results or unduly skew habitat modeling.

Four locations in the 2018 LiDAR were also identified that did not extend far enough to provide complete coverage of the channel edge and/or overbank for modeling high flows (Figure. 2.1-1). In these locations the 2016 LiDAR was used to extend the data coverage as discussed in the Upper Skagit River Green LiDAR Reclassification memorandum, Attachment A (HDR Engineering, Inc. [HDR] 2022). Use of less detailed topographic information in the extended areas is adequate as terrain features in these areas have negligible impact on hydraulic model results and habitat modeling.

A vertical elevation discrepancy was observed between the 2018 LiDAR, 2016 LiDAR, and field survey observations during calibration of the FA-02 Upper Skagit Hydraulic Model (Attachment A to the FA-02 Instream Flow Model Development Study [City Light 2023a]). Complete documentation of the terrain discrepancy and resolution are documented in the Attachment B, Skagit LiDAR Vertical Adjustment, and Attachment C, Skagit Bathymetric LiDAR Evaluation (HDR 2020). In summary, the 2018 LiDAR was shifted 0.37 ft vertically up, bringing the dataset vertically in line with the 2016 LiDAR, which was corroborated by field survey.

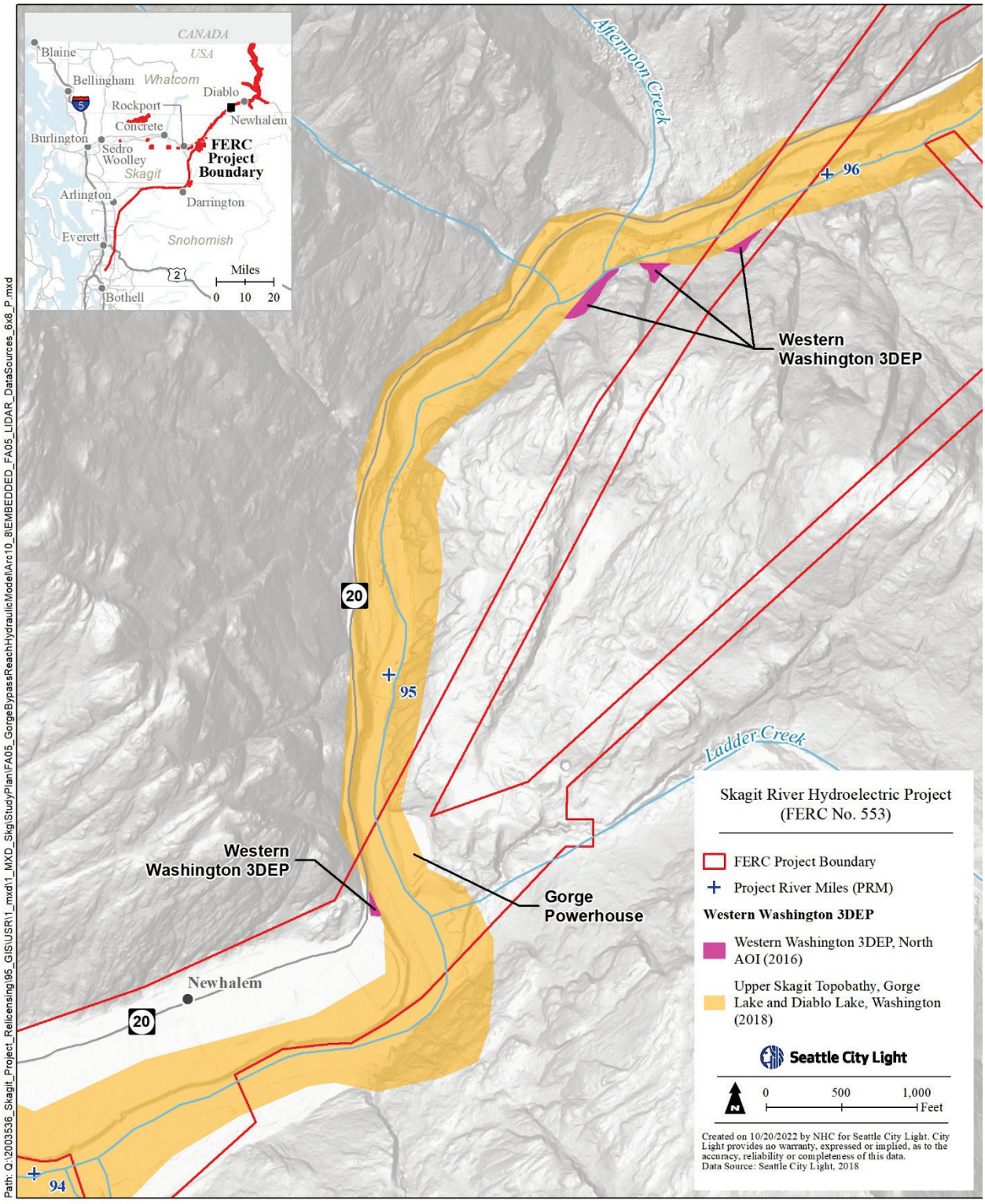


Figure 2.1-1. LiDAR sources used to create terrain surface.

2.2 Hydrologic and Hydraulic Data

Development of the Bypass Hydraulic Model required both the collection of discharge and stage records to define operational flows and model boundaries, and field measurements of depth, velocity, water surface elevation (WSE) and flow within the model domain to calibrate the model. Collection of this information for the Gorge bypass reach was conducted during the summer and fall of 2021. Controlled spillway releases for model calibration were chosen in consultation with licensing participants (LP) and coordinated with Gorge Dam operators from July 26-29, 2021, for an intensive field data collection effort. Stable daily flows of approximately 1,200, 500, 250, and 50 cubic feet per second (cfs) were targeted for this period (subsequently referred to as "controlled releases"). An unscheduled spillway release with flows exceeding 6,000 cfs occurred in late-June/early-July 2021, allowing for additional measurements at the Existing Features to extend the range of model calibration in these areas (subsequently referred to as "unscheduled spills"). The following sections describe the collection and processing of hydrologic information and the coinciding field efforts to obtain hydraulic observations.

2.2.1 Hydrology

Hydrologic data collection for the Gorge bypass reach included acquisition of operational records of releases (spill) at Gorge Dam, stage and discharge records for the USGS Skagit River at Newhalem gage, and field measurements of stage and discharge. The primary hydrologic input to the Gorge bypass reach is flow released from Gorge Dam, while discharge from Gorge Powerhouse and stage at the USGS Skagit River at Newhalem gage control conditions at the downstream end. Flow records for Gorge Dam spillway operations were provided by City Light while stage and discharge records for the USGS gage were obtained online from the USGS National Water Information System website. Discharges from Gorge Powerhouse were determined by computing the difference between releases from Gorge Dam and corresponding discharges at the USGS Skagit River at Newhalem gage.

Controlled releases from Gorge Dam were made by operating one spillway gate for nominal releases of 1,200, 500, and 250 cfs, and by operating the Gorge Dam log chute for a nominal release of 50 cfs. Releases of 1,200, 500, and 250 cfs required very small gate openings (for example, of the order of 3 inches for a 500 cfs release) determined using the established spillway gate ratings. The actual release is sensitive to uncertainty in the precise opening of the spillway gate at small gate openings. Similarly, release via the log chute is sensitive to fluctuations in reservoir levels. Therefore, discharge was measured at five cableway transects, selected in consultation with LPs, and at the bridge immediately below Gorge Dam to determine the actual flow during each controlled release for input to the Bypass Hydraulic Model during model calibration. Discharge measurement methods for the controlled releases are documented in the Gorge Bypass Reach Data Collection for Hydraulic Model Calibration memorandum, Attachment D (NHC 2022a), and evaluation of associated uncertainty with these measurements is discussed in the Gorge Bypass Reach Discharge Measurement Uncertainty Analysis memorandum, Attachment E (NHC 2022b).

Tributary inflows between Gorge Dam and the USGS Skagit River at Newhalem gage include Afternoon Creek and Ladder Creek (both ungaged). These tributaries provided negligible inflow during dry summer conditions when field data was collected. To estimate the contribution of these tributaries and groundwater inputs, discharge measurements were made at base flow conditions

(no spill from Gorge Dam) on July 30, 2021. An average flow of 4 cfs was measured at the measurement transects, likely generated by a combination of minor tributary inflows, groundwater inputs, and seepage from Gorge Dam.

2.2.2 Hydraulics

Field data collection efforts throughout the Gorge bypass reach to support model calibration consisted of (1) water level logger recordings; (2) transect surveys; and (3) unmanned aerial vehicle (UAV) photography and videography. This section summarizes the planning, application, and observations made with these technologies, while a more detailed discussion is provided in Attachment D.

2.2.2.1 Water level loggers

Onset HOBO U20 water level loggers were installed in May 2021 to measure water stage at Existing Features 1 and 2 to support hydraulic model calibration and the FA-04 Fish Passage Technical Studies Program (City Light 2023b). During Spring 2021, members of the Fish Passage Study and Bypass Instream Flow Model Development study teams visited Existing Features 1 and 2 at base-flow conditions and during a spillway release of approximately 1,200 cfs to identify installation locations that represented nominally stable pools and that connected a longitudinal water surface profile along the entirety of each feature. To achieve these objectives, six locations were identified at each feature (Figures 2.2-1 and 2.2-2). Level loggers began recording on May 27, 2021 at 10 minute intervals through July 2021, at which point the recording interval was changed to 5 minute. Figures 2.2-3 and 2.2-4 show processed WSE records for the unscheduled spills in late June/early July and the corresponding discharges are shown in Figure 2.2-5. Figures 2.2-6 and 2.2-7 show processed WSE records for the controlled releases in late July.

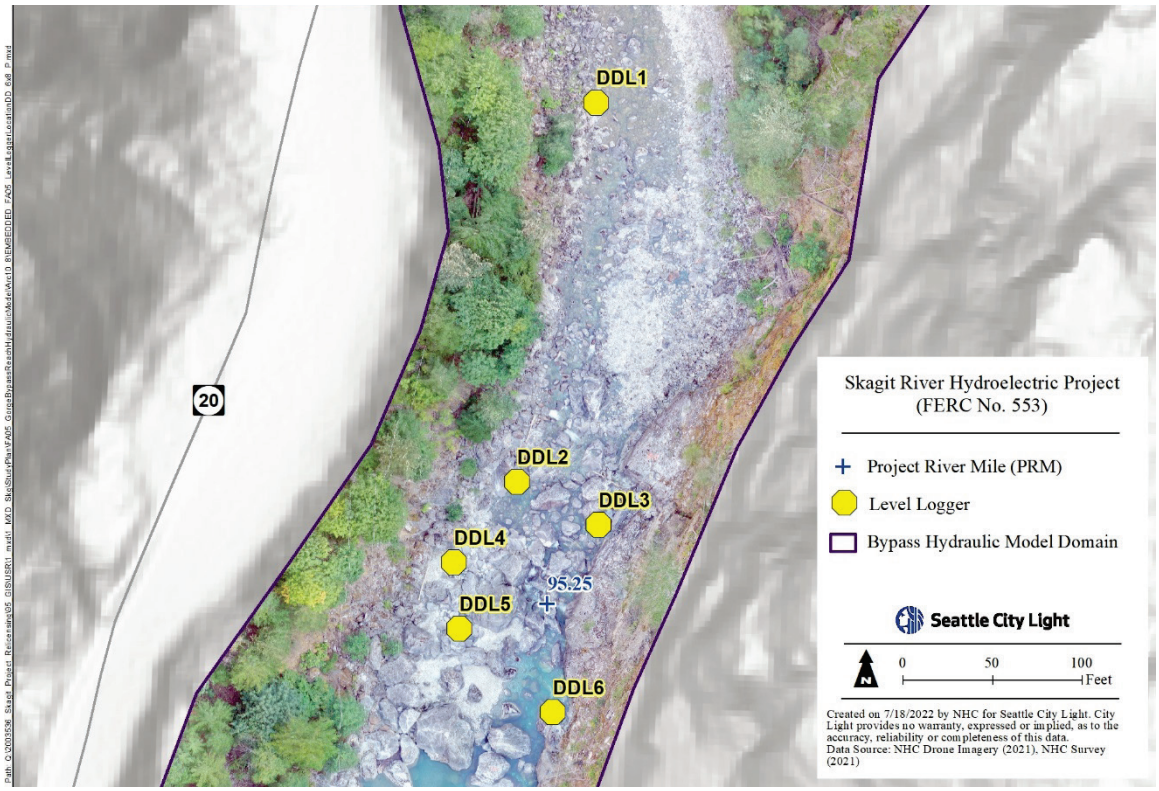


Figure 2.2-1. Level logger locations at Existing Feature 1.

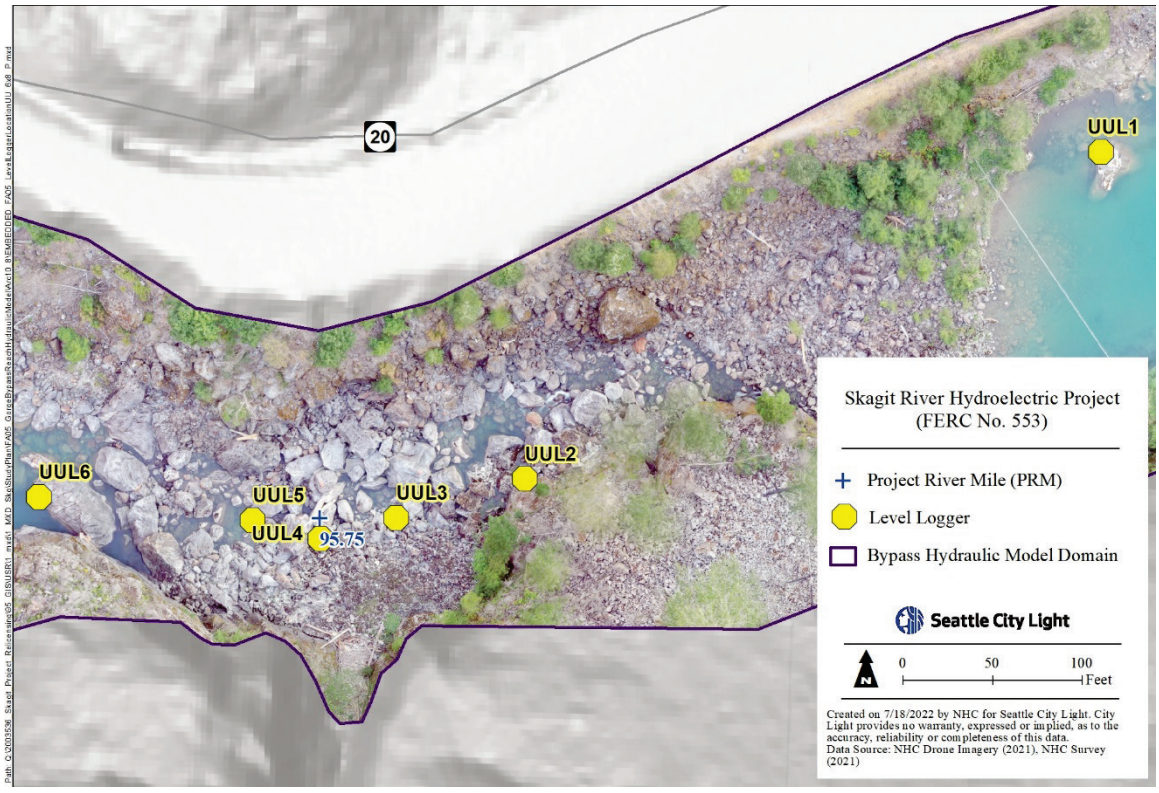


Figure 2.2-2. Level logger locations at Existing Feature 2.

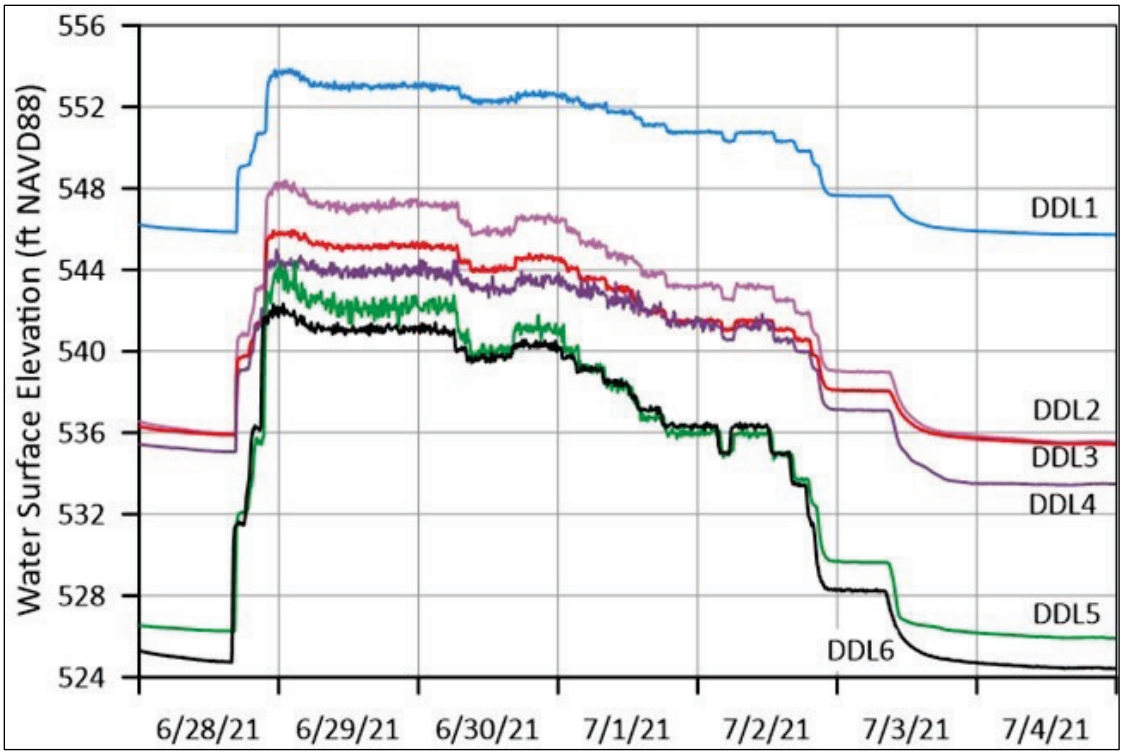


Figure 2.2-3. Level logger records at Existing Feature 1 for June 28, 2021 – July 4, 2021 unscheduled spills.

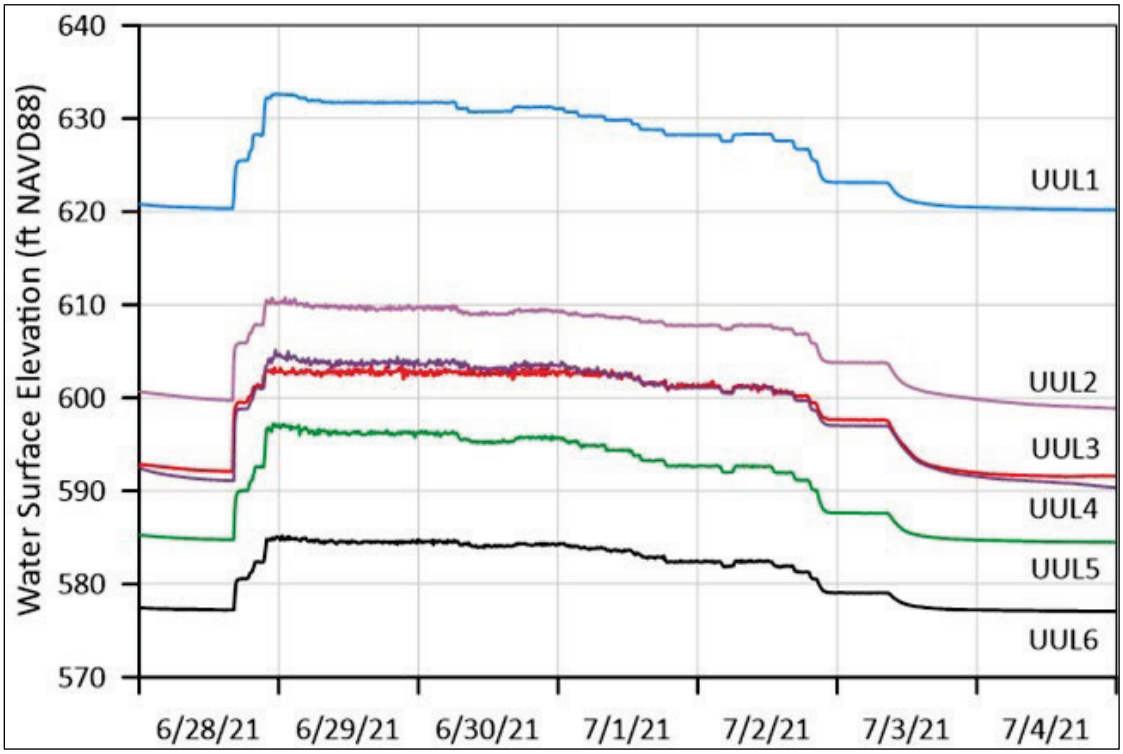


Figure 2.2-4. Level logger records at Existing Feature 2 for June 28, 2021 – July 4, 2021 unscheduled spills.

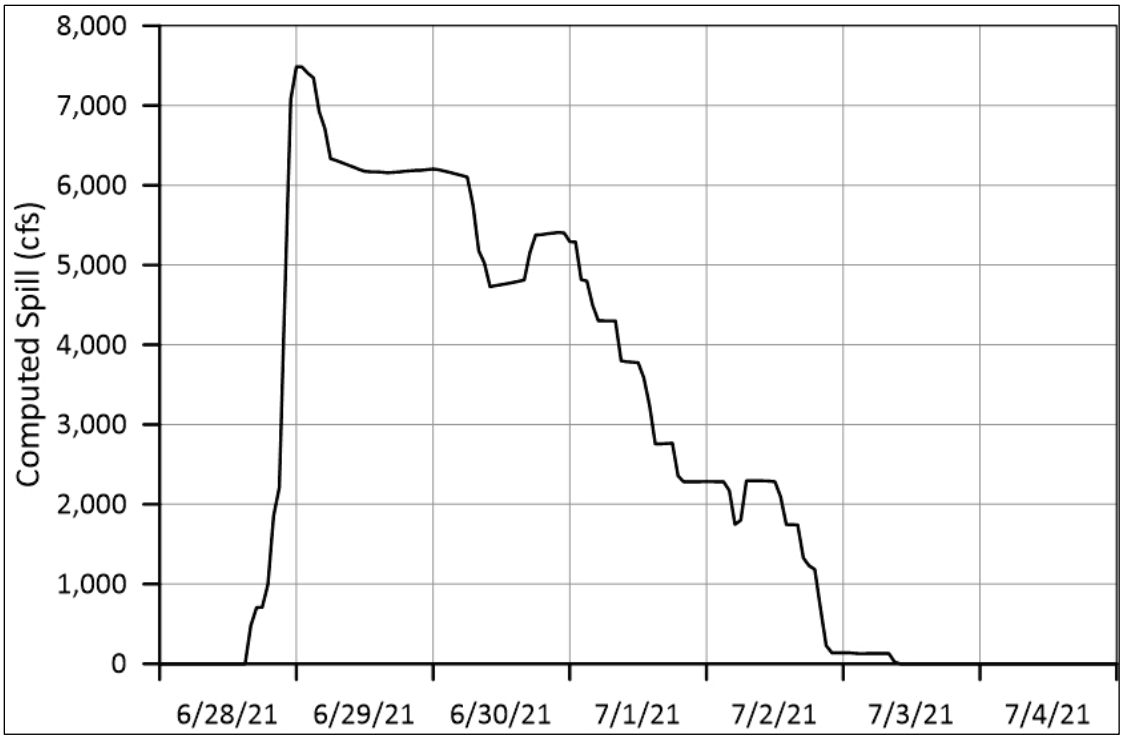


Figure 2.2-5. Gorge Dam unscheduled spill for June 28, 2021 – July 4, 2021.

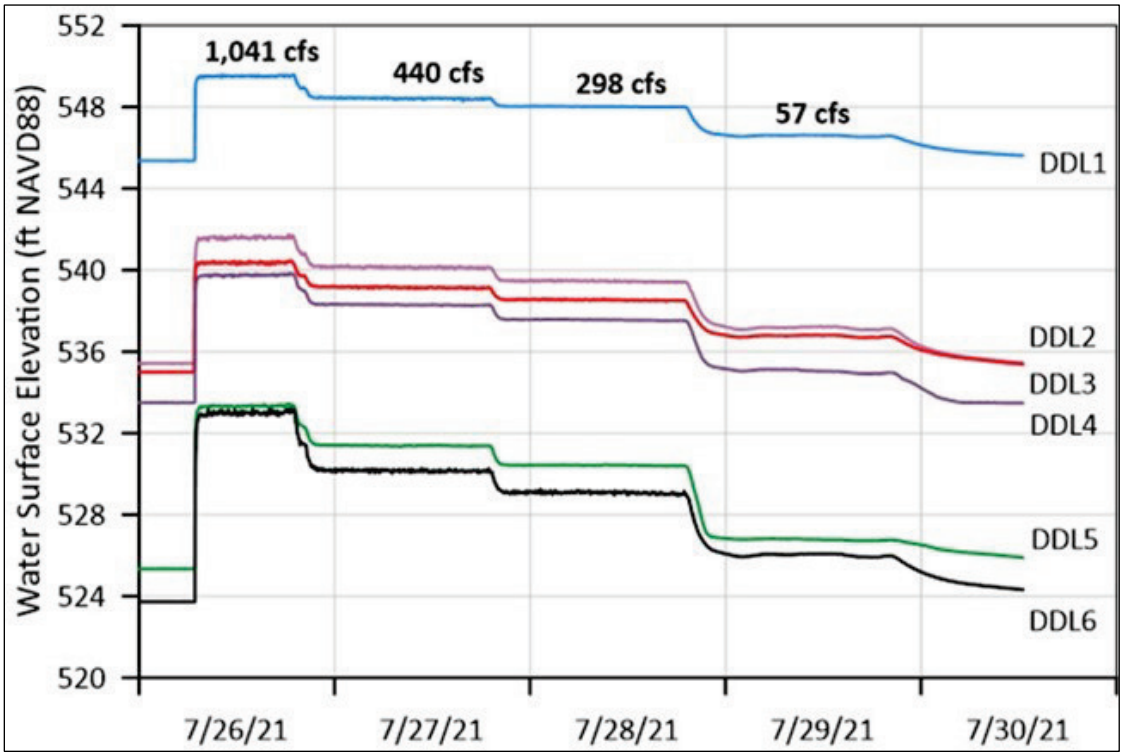


Figure 2.2-6. Level logger records at Existing Feature 1 for July 26-29, 2021 controlled releases. Flow values correspond to average flow measured below Afternoon Creek (see Attachment E).

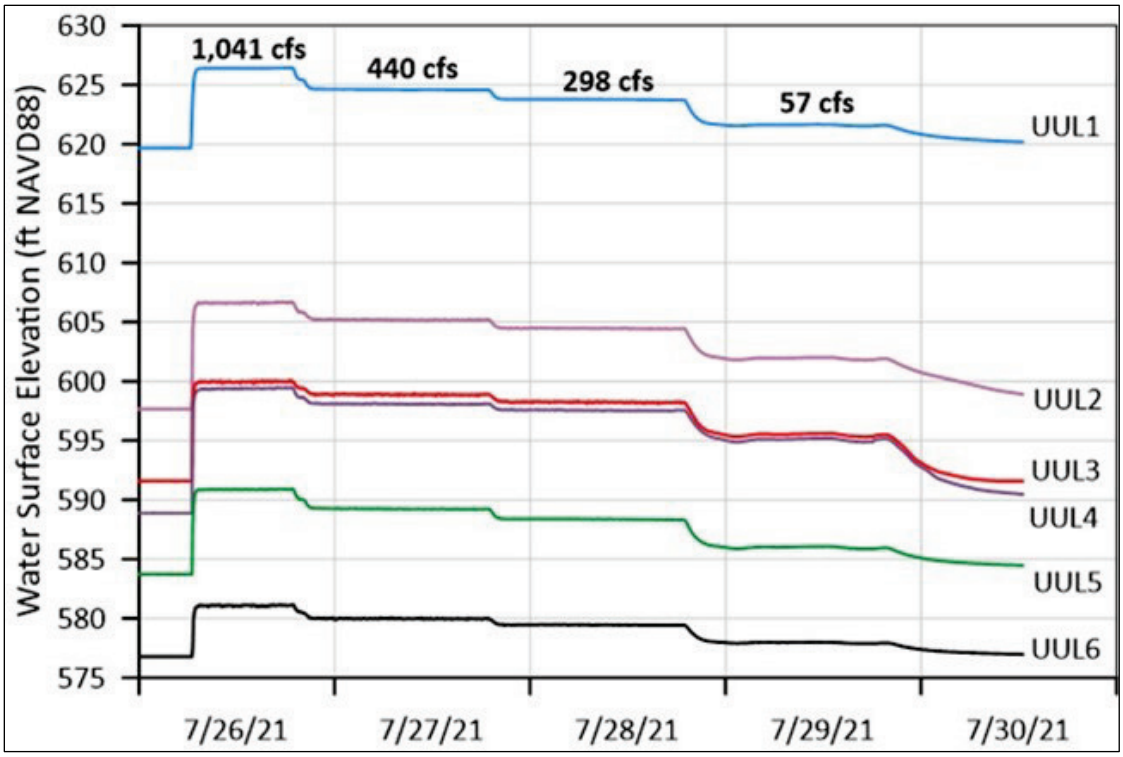


Figure 2.2-7. Level logger records at Existing Feature 2 for July 26-29, 2021 controlled releases. Flow values correspond to average flow measured below Afternoon Creek (see Attachment E).

2.2.2.2 Transect Surveys

Five transect locations were established in consultation with City Light and LPs to measure depths and velocities during the controlled releases of 1,200, 500, 250, and 50 cfs (Figure 2.2-8). The primary objective for selecting the transect locations was to capture hydraulic characteristics from a variety of geomorphic units represented in the Gorge bypass reach. At each transect, a bank-operated cableway was installed to deploy a raft-mounted acoustic Doppler current profiler (ADCP). When transect depths were shallower than the ADCP's operational range, velocity and depth measurements were acquired with an acoustic Doppler velocimeter (ADV) and wading rod, respectively. Velocities were measured throughout the water column at each measurement station along the cableway, with measurement recordings over a 40 second duration to average out turbulence fluctuations. Vertical velocity profiles were then post-processed to compute a depth-averaged velocity. Depth and velocity measurements were also used to compute discharge at each transect via the USGS mid-section method (Turnipseed and Sauer 2010).

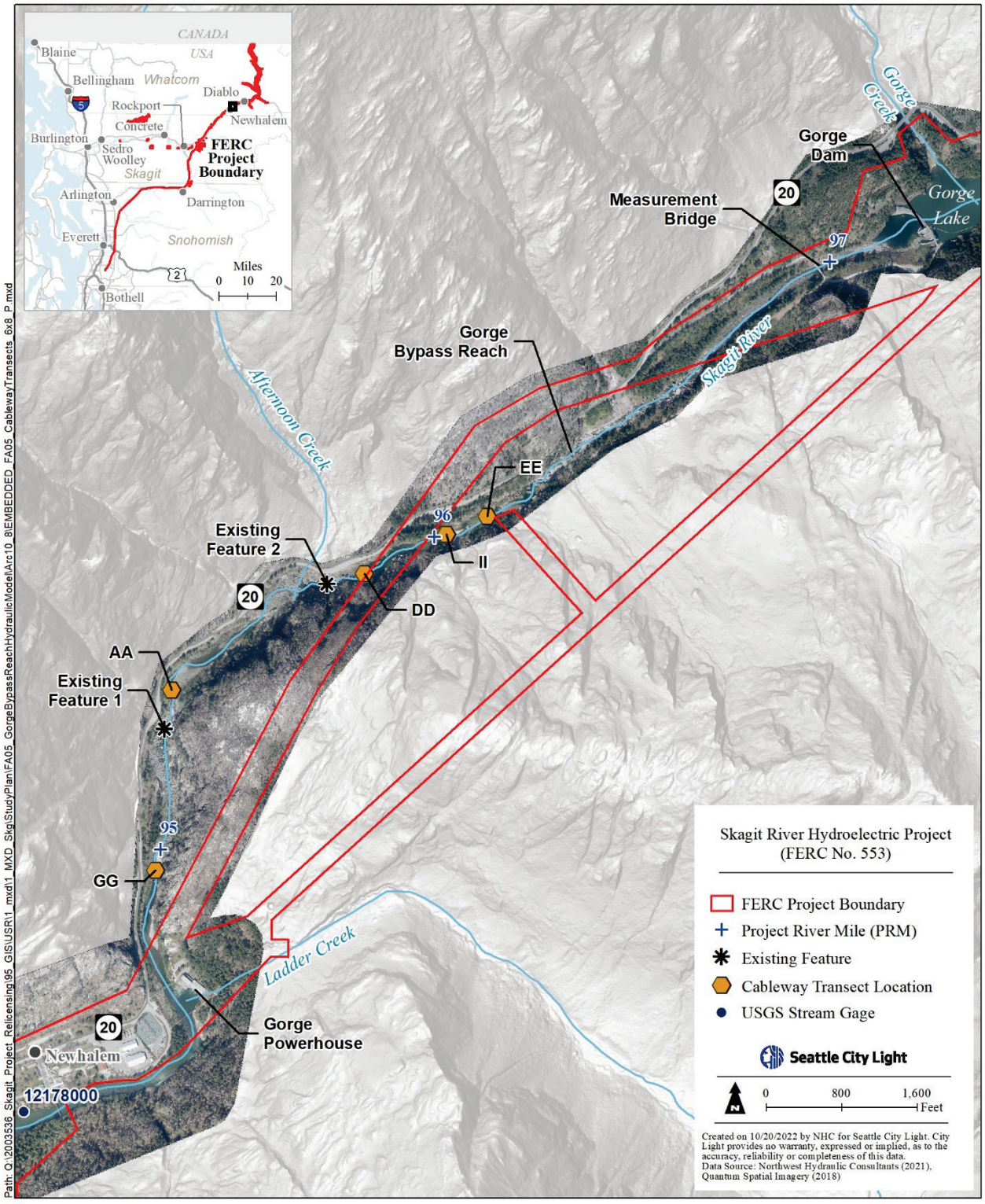


Figure 2.2-8. Hydraulic measurement transect locations.

Real-time kinematic (RTK) Global Positioning System (GPS) signal was not available to georeference measurement stations at the transects. Instead, each cableway anchor point was surveyed with a total station, and field personnel recorded the distance to each depth and velocity measurement from the right bank anchor point. This allowed measurements to be georeferenced in a Geographic Information System (GIS) by plotting measurement stations along each surveyed transect line. The ADCP raft drifted downstream of the cableway line some amount during each deployment. The downstream offset from the cableway line was assessed with photos and video taken of the ADCP deployment at each transect. Figure 2.2-9 provides an example of post-processed transect measurements.

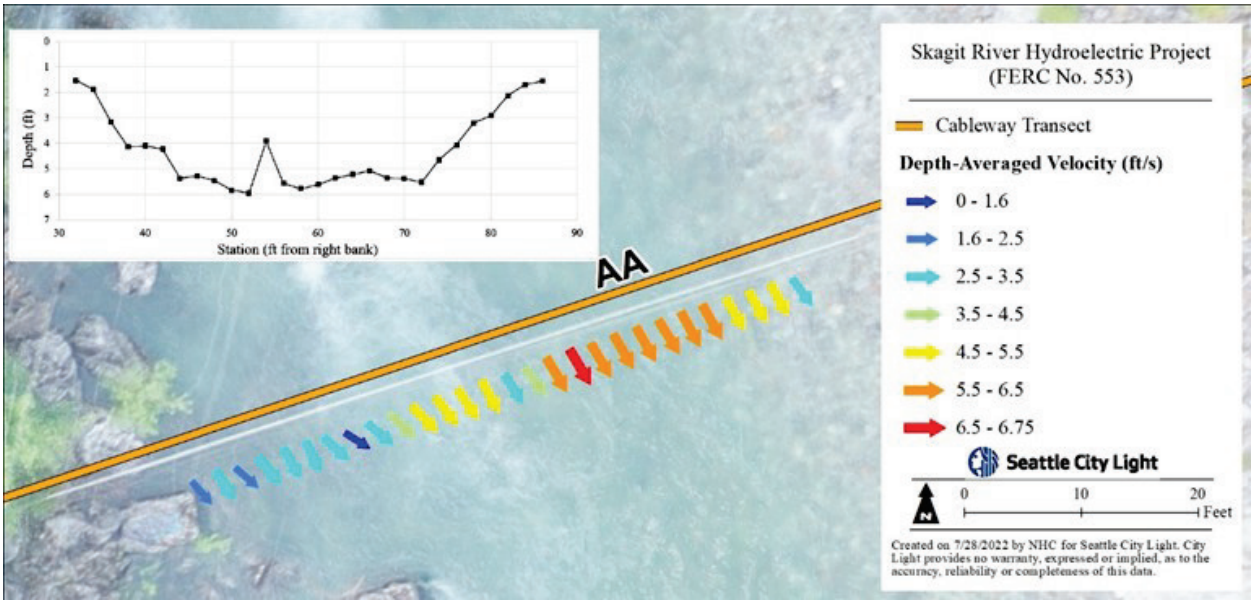


Figure 2.2-9. ADCP measurements at Transect AA for 1,200 cfs controlled flow release.

2.2.2.3 UAV Photography

Oblique and nadir (downward facing) photographs and video were taken with an UAV throughout the Gorge bypass reach during each of the controlled releases and during base flow conditions on July 30, 2021. Surveyed control points were marked throughout the Gorge bypass reach with temporary high visibility chalk prior to UAV deployment for georeferencing the photography. Nadir photos were captured where both Federal Aviation Administration (FAA) compliance and safe drone operation could be achieved (Figure 2.2-10). These photos were processed using Structure from Motion (SfM) software to produce orthomosaic images (Figure 2.2-11) that were used to characterize substrate, vegetative cover, and channel characteristics for delineating hydraulic roughness zones and to define WSEs and inundation extents to compare with hydraulic model results (Section 5.2.3 of this report). These photo series were also made available for use by other relicensing studies.

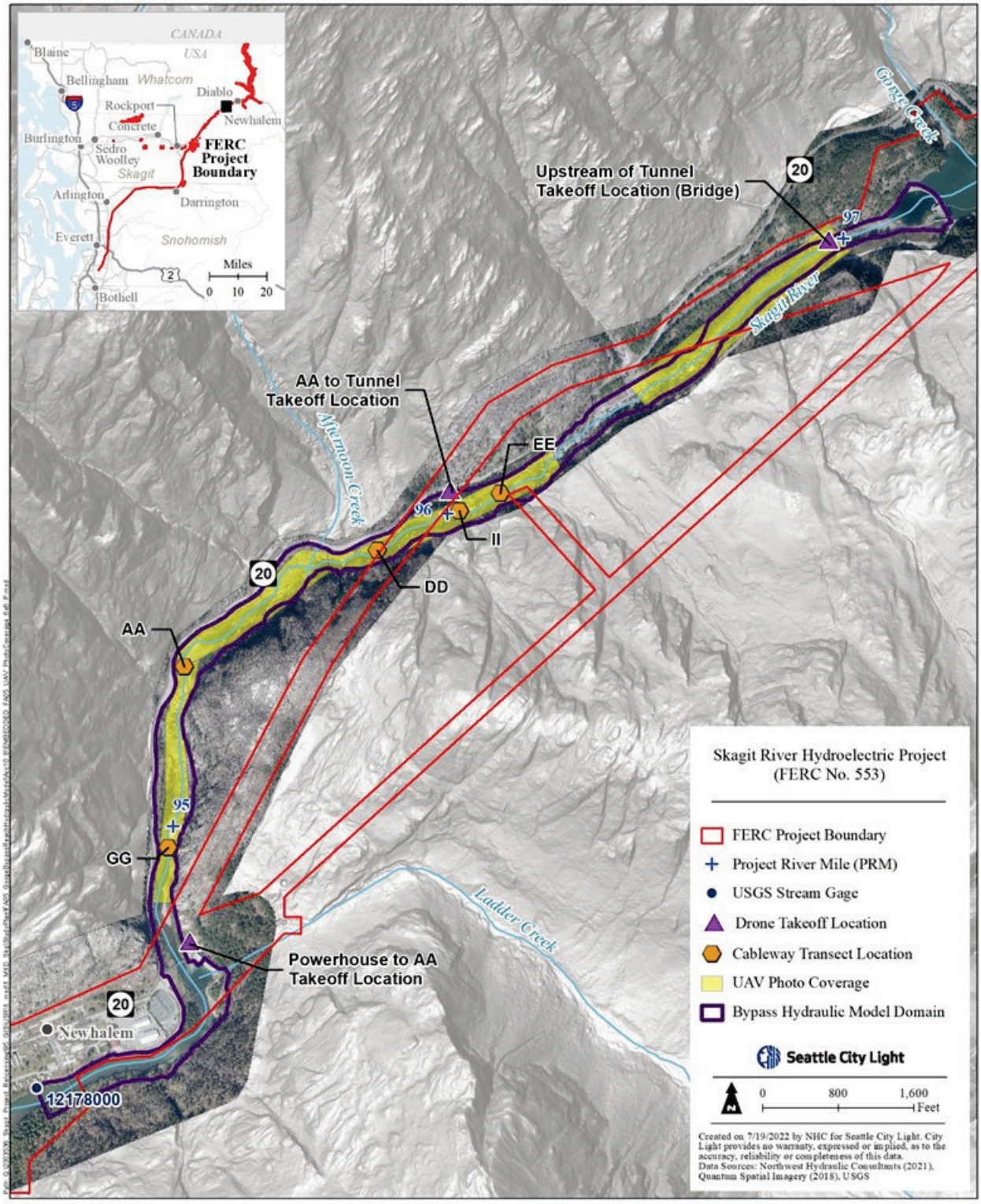


Figure 2.2-10. UAV nadir photo coverage.

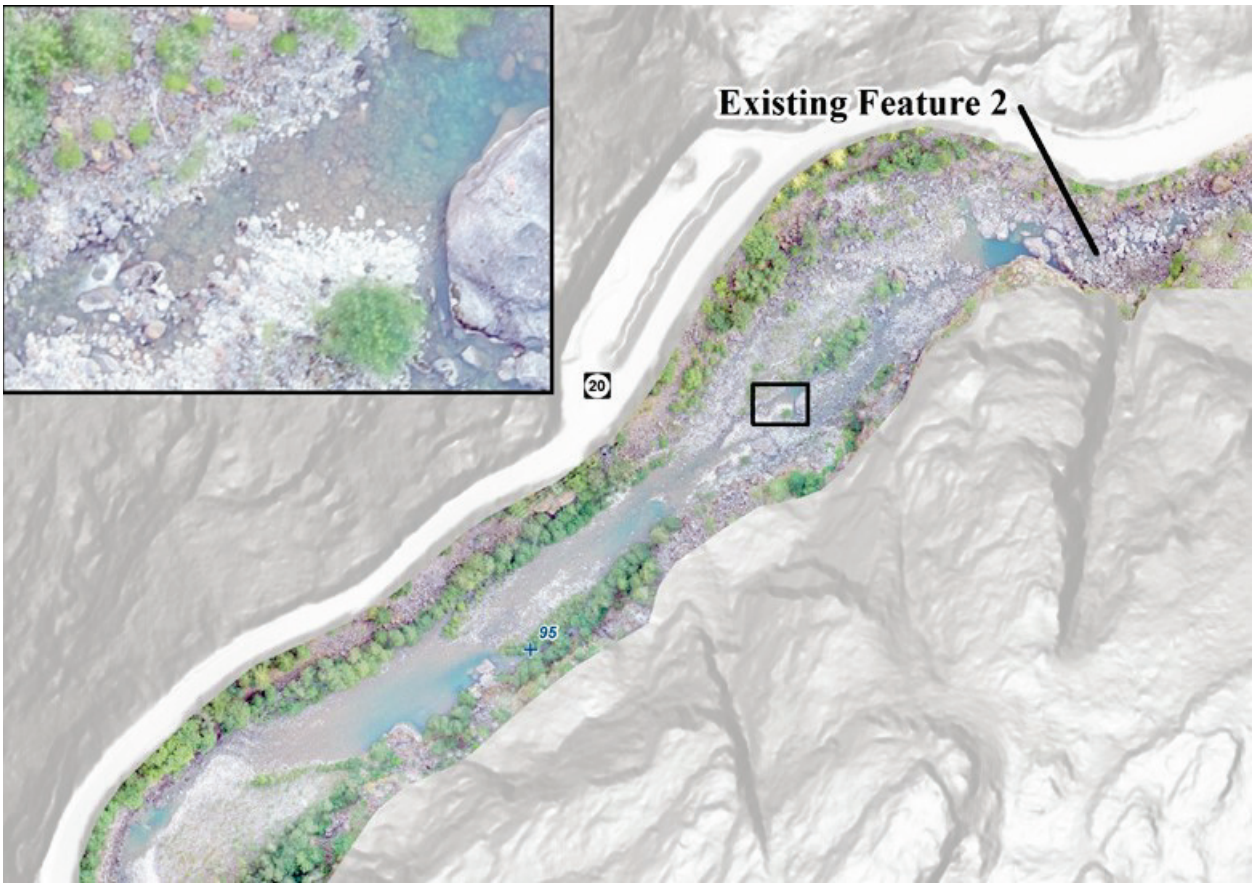


Figure 2.2-11. Processed orthoimagery example from UAV photos of base flow conditions on July 30, 2021.

2.2.2.4 UAV Video

Video recordings were collected with the UAV at Existing Features 1 and 2 to support Large Scale Particle Image Velocimetry (LSPIV) analysis, which is a technique for measuring 2-D surface velocity vectors. Field data collection and analysis for LSPIV are described in Attachment D. Unfortunately, hydraulic conditions (highly turbulent flow) were such that no reliable surface velocity data was obtained.

3.0 HYDRAULIC MODEL DEVELOPMENT

Hydraulic conditions in the Gorge bypass reach were computed using the 2-D capabilities of the U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Center River Analysis System (HEC-RAS) Version 6.1.0 modeling platform (USACE 2021a). HEC-RAS 2-D solves the 2-D shallow water equations using an implicit finite volume algorithm and returns depth-averaged hydraulic properties such as depth, velocity, and shear stress. The following factors, identified in the RSP, were considered in selecting the model platform:

(1) Efficiency of model development;

(2) Model resolution required to meet study objectives;

(3) Speed of model execution;

(4) Integration with other model platforms (for example, Project operations models);

(5) Availability of model support and model maintenance;

(6) Availability of visualization tools and software features for analysis, synthesis and display of model output;

(7) Efficiency with which metrics of interest for Project flow management can be generated from model output;

(8) Acceptance by the engineering community and both governmental and non-governmental institutions; and

(9) Size of user community (which relates to the pool of expertise available for model updates and application).

The following key model components of HEC-RAS 2-D are explained in the sections below.

(1) A high-resolution Digital Elevation Model (DEM) of the hydraulic model domain (referred to as a Terrain in HEC-RAS);

(2) Spatial bed roughness mapping that characterizes zones of similar hydraulic roughness;

(3) Upstream, downstream, and interior hydraulic boundary conditions;

(4) A model mesh consisting of variable polygon cells where each cell incorporates both the underlying terrain and bed roughness (this mesh is what the model performs its calculations on); and

(5) Run control parameters such as the computational time step needed to initialize and simulate a scenario in a stable, accurate manner.

3.1 Topographic Information

A critical element to a hydraulic model is accurate topographic information, as the resolution and accuracy of the terrain is linked to the detail and accuracy of model results. A good terrain captures sufficient elevation changes, channel shape, and obstructions to allow accurate modeling of WSEs, inundation extents, and flow patterns at the desired model output scale.

The Bypass Hydraulic Model terrain for the Gorge bypass reach consists of a bare earth DEM derived from the 2016 and 2018 LiDAR datasets described in Section 2.1 of this report. The original processing of the 2018 topobathymetric LiDAR returns by QSI produced a ground and bathymetric bottom classified density of 0.52 points/ft^2 (QSI 2018), which was sufficient to generate a 3 ft resolution DEM. Note that the 2018 LiDAR used in the surface terrain included the resolution of the vertical elevation discrepancy described in Attachment B. Geospatial analysts expanded upon QSI's original point classification to classify additional ground points from the 2018 LiDAR and develop a higher resolution DEM as summarized below and detailed in Attachment A.

The Gorge bypass reach terrain is characterized by steep slopes and large riverbed material that strongly influence flow dynamics. To improve characterization of these features in the model, ground point density was increased along the channel bottom and bank toe below vegetated areas extending from the bridge immediately below Gorge Dam to the upstream end of Afternoon Creek pool, and from the downstream end of Afternoon Creek pool to the upstream end of the Gorge Powerhouse tailrace (Figure 3.1-1). Point density was not increased in areas classified as bathymetric bottom by QSI as these areas are typically inundated from groundwater and tributary inflows and have little influence on hydraulic conditions. Ground point density in the reclassified areas increased to 2.51 points/ft^2 and a DEM with a 1 ft cell resolution was generated to preserve detail in these areas. Note that outside the reclassified areas, point density remains 0.52 points/ft^2.

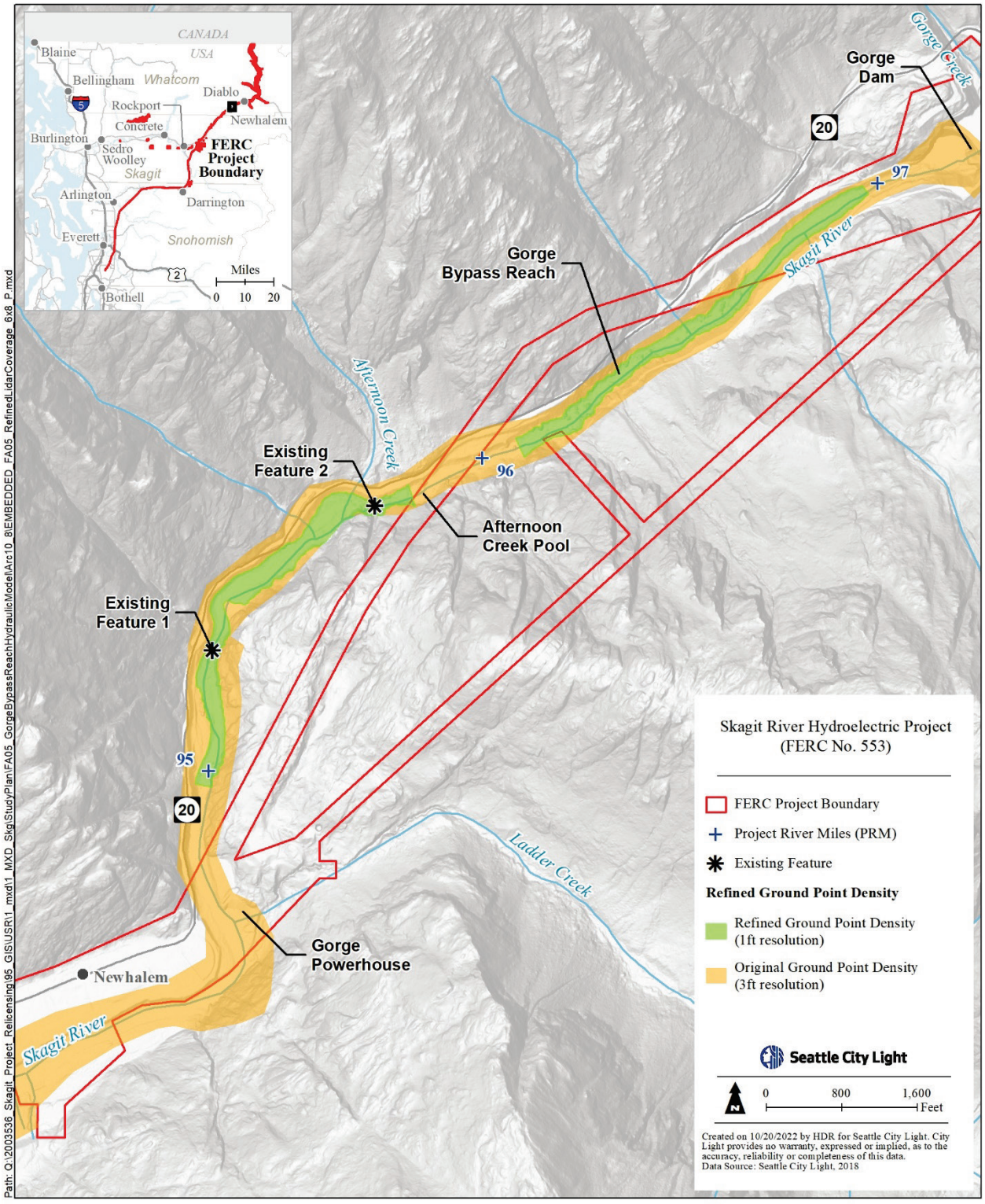


Figure 3.1-1. Refined and original 2018 LiDAR coverage.

3.2 Hydraulic Roughness Zones

Hydraulic roughness zones were mapped within the model domain to delineate zones of similar frictional flow resistance associated with unresolved terrain features, substrate, vegetation, and any other sources of flow obstruction not explicitly represented by other components of the model geometry. Each zone was assigned a roughness value, represented by a Manning's n coefficient (Barnes 1967). Manning's n coefficients are not solely linked to surface roughness but are also linked to scale, terrain resolution, and mesh cell size. Representation of surface features coarsens as cell size increases, requiring more of the flow resistance imposed by terrain features to be accounted for with the roughness coefficient. Section 3.4 describes how the model mesh is comprised of areas with 1 ft and 9 ft cell resolution. To accommodate this, roughness zones were separated into channel and bank areas, corresponding to different mesh cell sizes. The area defined as "channel" corresponds to the refinement region where the mesh has a 1 ft resolution while the area defined as "bank" includes the upper bank and valley walls where the mesh has a 9 ft resolution. Within the channel and bank areas, roughness zones were further subdivided based on observed vegetation density from UAV-based orthoimagery. Figure 3.2-1 shows roughness zone delineations for the base model condition that were evaluated and modified as part of model calibration (Section 5.0 of this report).

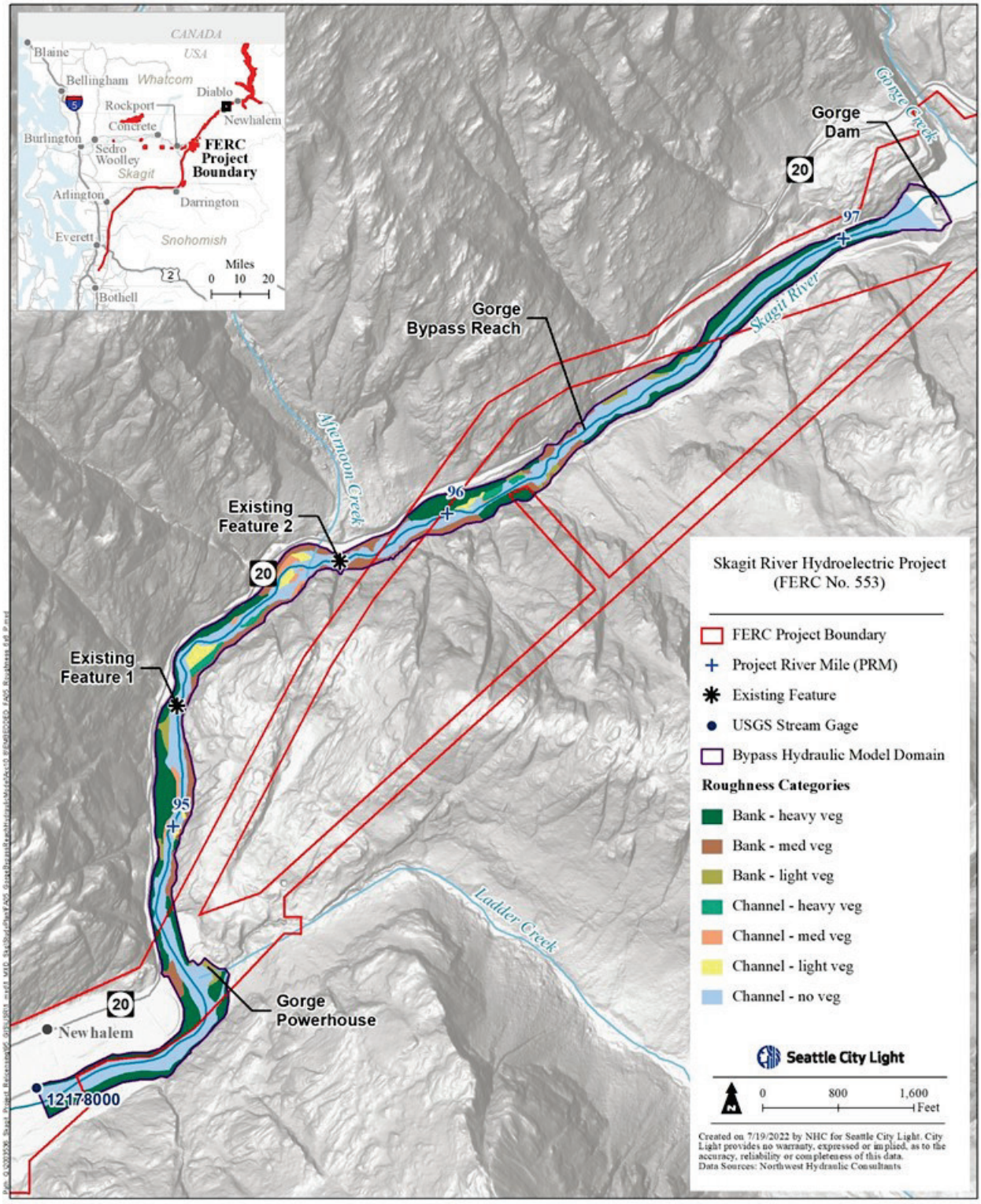


Figure 3.2-1. Roughness zone delineations.

3.3 Model Boundaries

Model boundaries identify the locations flow either enters or exits the model. Collection of hydrologic data used to define boundary conditions for the Bypass Hydraulic Model was discussed in Section 2.2.1 of this report. Inflow boundaries are included at the base of Gorge Dam spillway, at the exit from Gorge Powerhouse turbine Unit 24, at the combined exit from turbine Units 21, 22, and 23, and on Ladder Creek approximately 460 ft upstream from its mouth. Inflows from Gorge Powerhouse are allocated between turbine Unit 24 and Units 21-23 following typical powerhouse operations with respect to each turbine's flow capacity. Other local tributaries and groundwater inflows are excluded from the Bypass Hydraulic Model due to their negligible influence on hydraulic conditions. The model's downstream boundary is the rating curve from the USGS Skagit River at Newhalem gage.

The Bypass Hydraulic Model was run using steady-state conditions, i.e., input for each simulation consists of a constant discharge at inflow locations that corresponds to a constant stage determined from the gage rating curve at the downstream boundary. Calibration simulations include releases from Gorge Dam of approximately 4,800 cfs and 6,200 cfs (from the late-June 2021 unscheduled spill) and the four controlled releases that occurred July 26-29, 2021. Bypass Hydraulic Model boundary locations are shown in Figure 3.3-1 and calibration event simulation data is provided in Table 3.3-1.

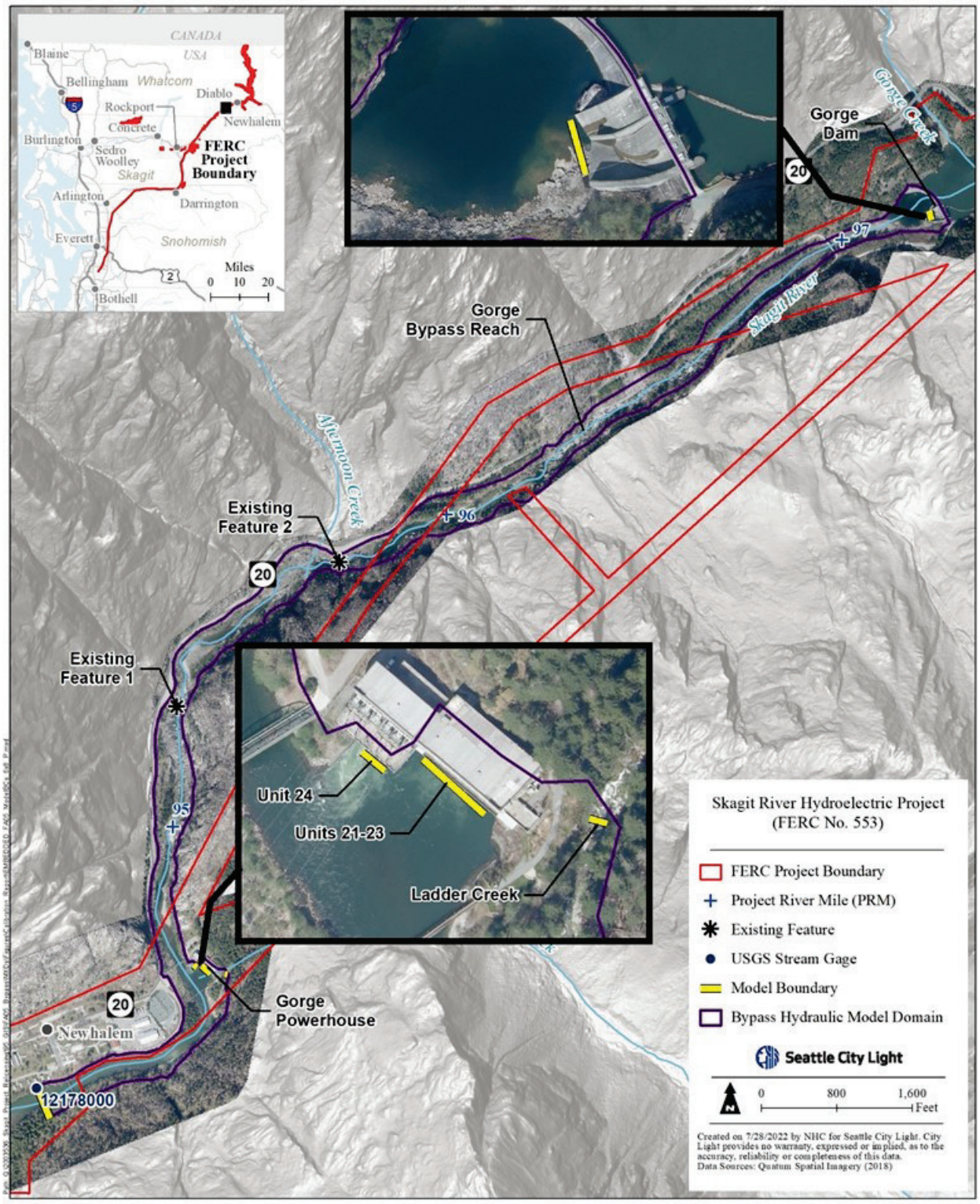


Figure 3.3-1. Bypass Hydraulic Model boundary locations.

Table 3.3-1. Bypass Hydraulic Model boundary conditions.

Nominal Gorge Dam Release (cfs)	Actual (measured) Gorge Dam Release (cfs)	Gorge Powerhouse + Tributary Discharge[1] (cfs)	Downstream Stage (ft NAVD 88[2])
6,200	6,175	5,537	492.99
4,800	4,770	6,430	492.78
1,200	1,113/1,041[3]	2,998	489.87
500	500/440[3]	2,736	489.33
250	322/298[3]	2,686	489.18
50	57	2,962	489.19

1 USGS Skagit River at Newhalem minus Gorge Dam release downstream of Afternoon Creek pool.[3]
2 NAVD 88 = North American Vertical Datum of 1988.
3 Flows upstream/downstream of Afternoon Creek pool (Attachment E).

3.4 Model Mesh

A HEC-RAS 2-D model geometry consists of a mesh of variable size polygons that encode information about the underlying terrain and hydraulic roughness. Mesh characteristics are controlled by the model domain, mesh refinement regions, and breaklines, each of which have associated mesh control parameters. No hydraulic structures such as bridges were incorporated in the Bypass Hydraulic Model.

The Bypass Hydraulic Model spans the Skagit River channel from the upstream end of the plunge pool immediately below Gorge Dam to the USGS Skagit River at Newhalem gage (Figure 3.4-1). Preliminary model simulations informed delineation of the domain to ensure the range of evaluated flows were contained within the domain. A mesh refinement region encompasses the Gorge bypass reach channel and bank toe where terrain refinement was performed (Section 3.1 of this report). One ft cells were used within the mesh refinement region, while 9 ft cells were used for the balance of the model domain. Cell size selection within the refinement region relied heavily on sensitivity testing described in Section 4.1 of this report. 9 ft cells were utilized outside the refinement region because: (1) larger cells in these areas reduce the model's total cell count, decreasing simulation runtimes; and (2) areas outside of the refinement region include the upper bank/valley walls of the Gorge and deep pools/backwater areas where higher mesh resolution has negligible impact on hydraulic conditions. Cell sizes along the border of the refinement region smoothly transition from 1 ft to 9 ft cells, improving numerical stability between these regions. A sample mesh configuration is shown in Figure 3.4-2.

3.4.1 Model Resolution at Gorge Dam and Powerhouse

The Gorge Dam inflow boundary is located at the base of the spillway adjacent to the lower level outlet gates. Powerhouse inflow boundaries are located in front of the Unit 24 and Units 21-23 draft tubes where the nearby riverbed surface is interpolated across an underwater void, described in Section 2.1 of this report. The Bypass Hydraulic Model simulates depths and velocities in the adjacent reaches to these boundaries with sufficient accuracy for the aquatic habitat assessment. However, the model does not include the dam's actual spillway and outlet gates or the Powerhouse's draft tube exits and is not sufficient to evaluate detailed hydraulic conditions at these structures.

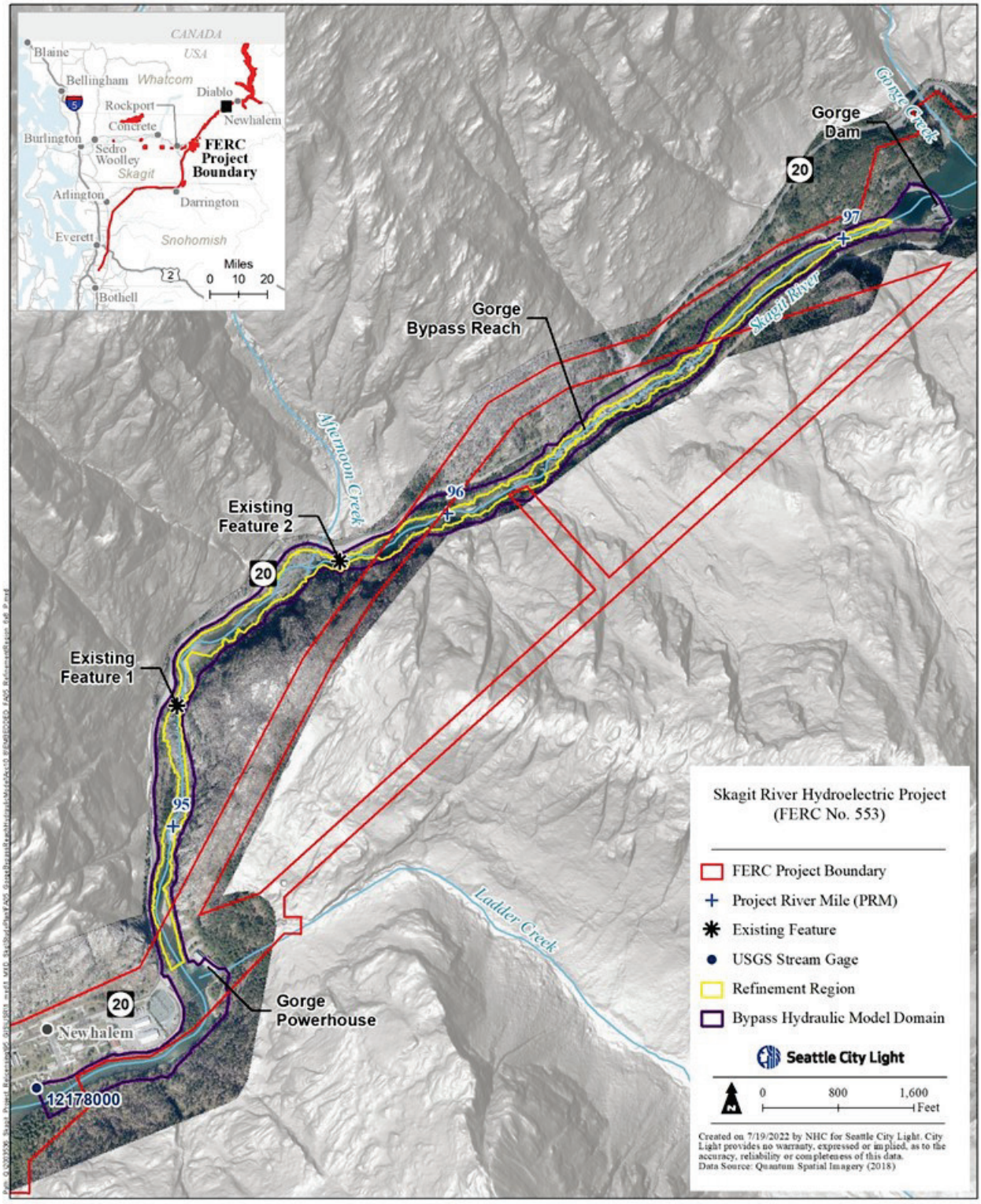


Figure 3.4-1. Bypass Hydraulic Model domain and mesh refinement region.

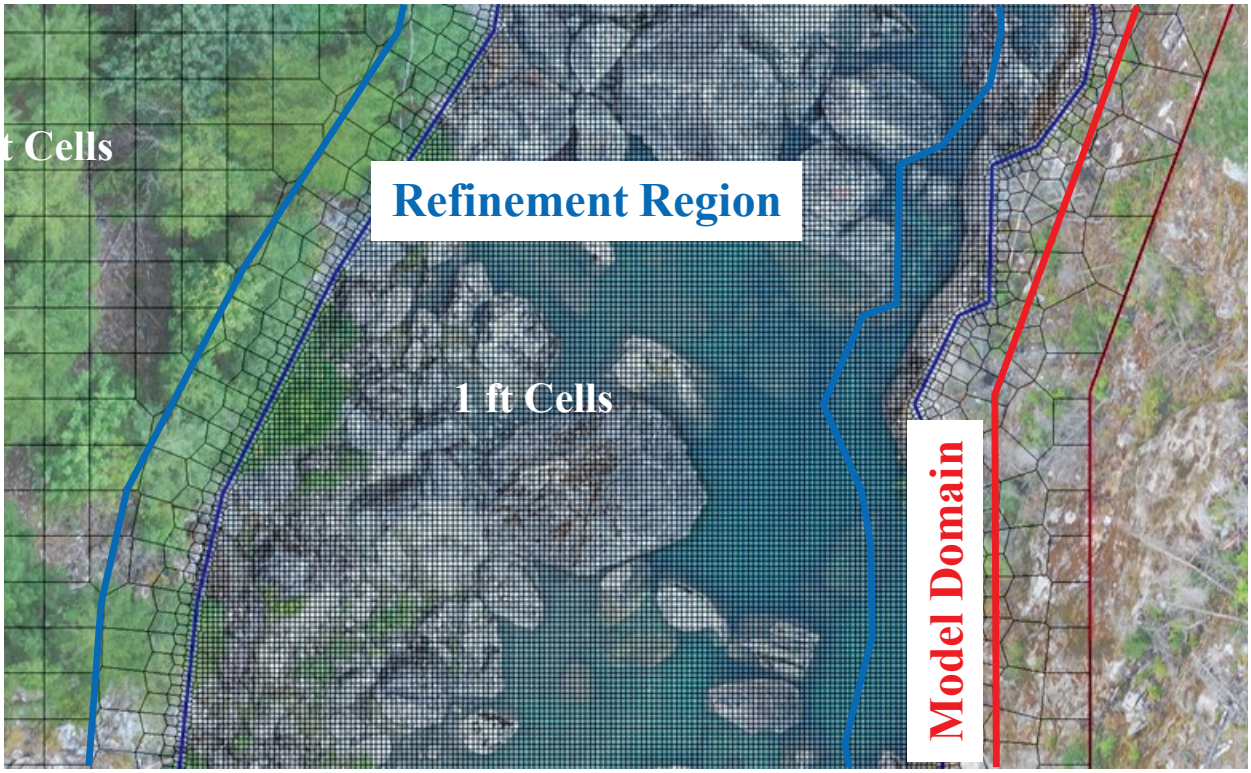


Figure 3.4-2. Sample mesh configuration showing refinement region (1 ft cells) and bank/valley walls (9 ft cells).

3.5 Run Control Parameters

Options for controlling 2-D model computations in HEC-RAS include specification of the solution equation set, initial conditions, solution weighting factor (Theta), solver tolerances and iterations, and the computational time step. The full momentum shallow water equations were selected to capture momentum fluctuations that influence computed water levels and velocities. A dry channel initial condition was used for sensitivity tests and initial base model condition simulations. For subsequent calibration simulations, a "hot-start" initial condition was used where an output file from the preceding calibration simulation was used to reduce the time needed to reach steady-state conditions. Default Theta, tolerances, and solver iteration options were specified for all simulations (Table 3.5-1). Selection of the computational time step is described in Section 4.2 of this report.

Table 3.5-1. Selected run control parameters for the Bypass Hydraulic Model.

Theta	Water Surface Tolerance (ft)	Volume Tolerance (ft)	Maximum Solver Iterations
1.0	0.01	0.01	40

4.0 SENSITIVITY TESTING

The Bypass Hydraulic Model's sensitivity to four parameters was investigated to evaluate their impact on the model solution, computational stability, and runtime efficiency. These investigations informed parameter selection for base model conditions prior to model calibration. The four parameters evaluated were: cell size, simulation timestep, turbulence input, and roughness coefficient. Parameter sensitivities were tested for a simulation of 1,200 cfs release from Gorge Dam.

4.1 Cell Size

The objective of evaluating sensitivity to mesh cell size is to balance maximizing numerical accuracy while minimizing computation time. In general, smaller cells incorporate more terrain detail, yielding more detailed and accurate results. However, less terrain detail is added with each incremental decrease in cell size. At some point, further mesh resolution no longer provides a significant impact on model results. Also, model results are less sensitive to cell size as channel slope and vertical variability in surface topography decrease. As cell size decreases, the total number of cells increases and the time step must decrease, leading to increased computation time.

Cell size sensitivity testing focused on areas in the Bypass Hydraulic Model refinement region where hydraulic conditions are significantly influenced by longitudinal slope, sub-channel size features, and substrate. Nominally square computation cells were evaluated at 9, 6, 3, 2, and 1 ft sizes. The terrain resolution within the refinement region is 1 ft (Attachment A). Therefore, 1 ft mesh cells were the smallest size tested, as the use of smaller cells would not provide additional terrain detail. Figure 4.1-1 depicts the scale of 9, 3, and 1 ft mesh cells relative to typical streambed composition at Existing Feature 1, illustrating the detail with which each mesh configuration represents the underlying channel.

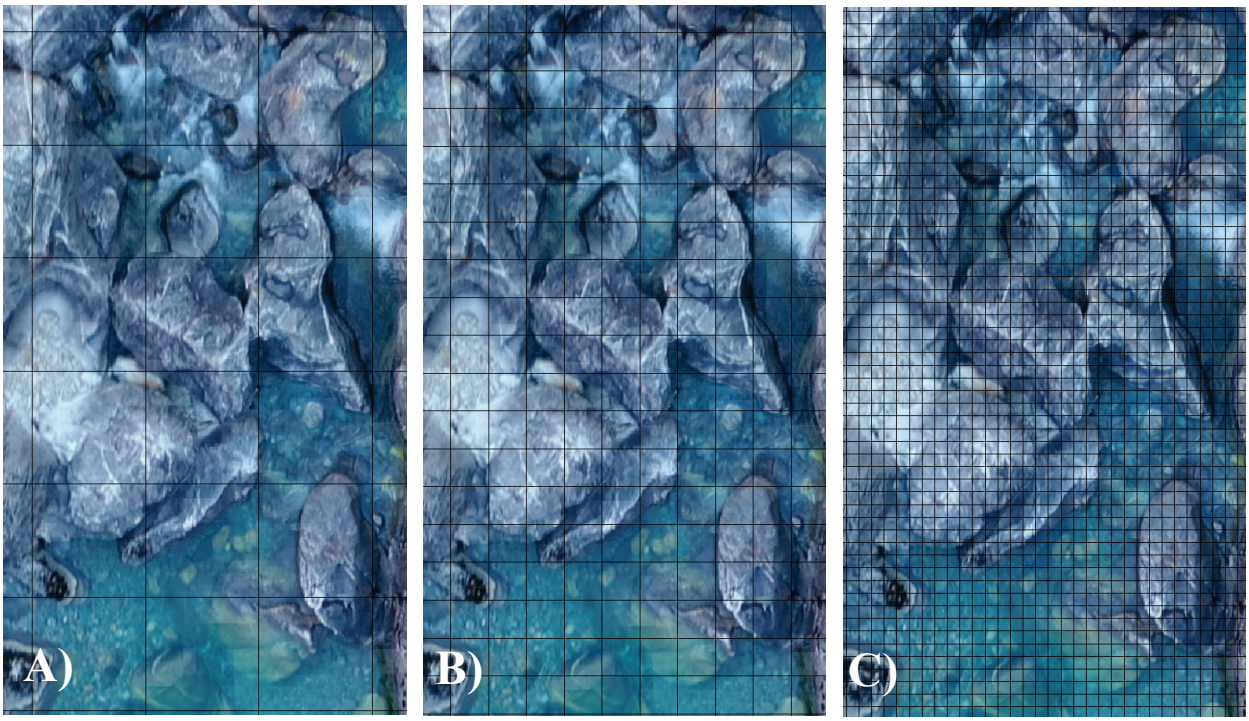


Figure 4.1-1. A) 9 ft; B) 3 ft; and C) 1 ft mesh cells overlaying aerial image of Existing Feature 1.

Figure 4.1-2 illustrates how decreasing cell size in the refinement region results in correspondingly deeper water. There is a general converging trend in water depth as cell size incrementally decreases from 9 to 1 ft, though results do not yet completely stabilize between cell sizes of 2 and 1 ft. Using a cell size smaller than 1 ft is unwarranted considering the terrain resolution limit described above. Figure 4.1-2 also shows the corresponding increase in computation time as mesh size decreases.

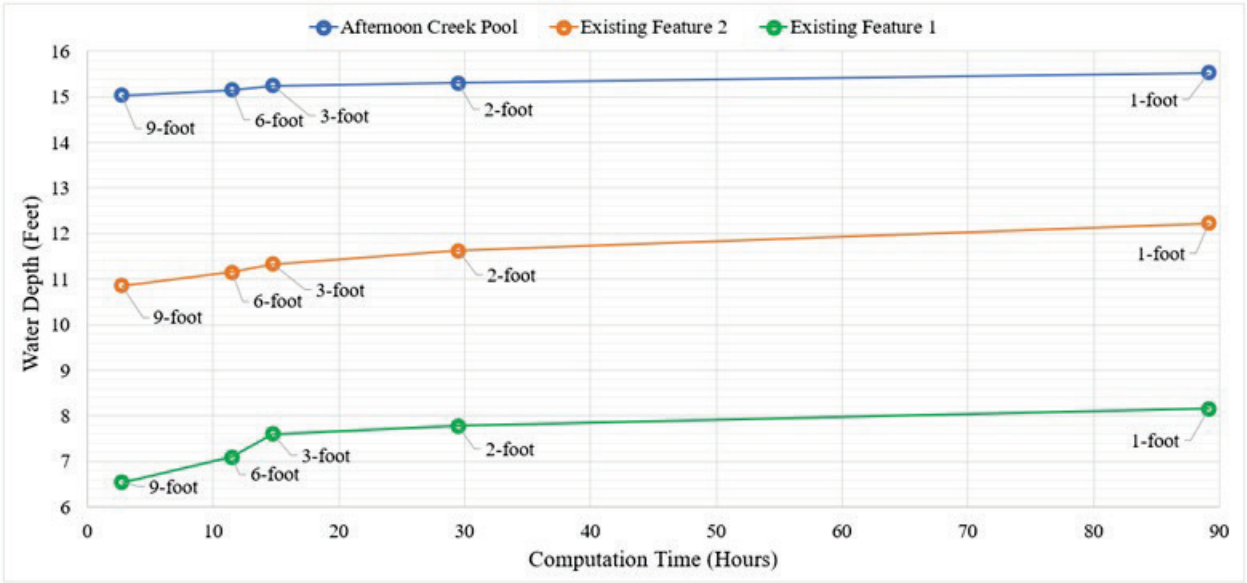


Figure 4.1-2. Computed water depth vs. computation time at three different locations.

The improvement of using 1 ft cells as opposed to 2 ft cells is more clearly illustrated when spatially observing the difference in computed water surface and velocity. Figure 4.1-3 and Figure 4.1-4 illustrate the difference in WSE and velocity output from 1 ft and 2 ft meshes. Differences are greatest along sections with steep channel slopes and large boulders where resolution of channel topography in the 1 ft mesh significantly improves the detail of velocity output versus the 2 ft mesh (Figure 4.1-5).

Despite requiring significantly longer computation times than other tested cell sizes (four times that of the 2 ft mesh) 1 ft cells were selected within the Bypass Hydraulic Model refinement region. This cell size provides the most accurate and detailed characterization of hydraulic conditions that can be achieved given the surface terrain resolution.

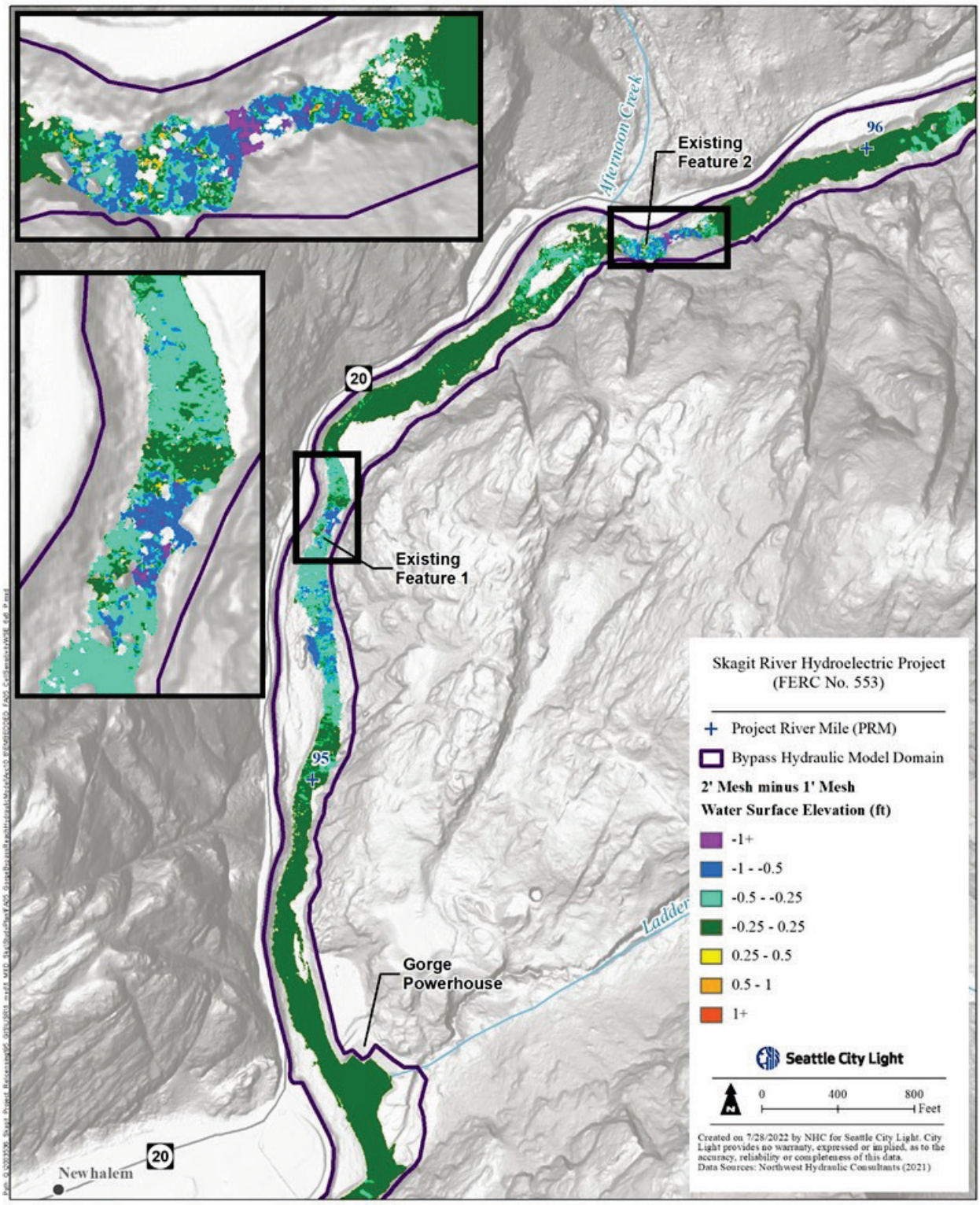


Figure 4.1-3. Difference in water surface elevation from 2 ft and 1 ft computational meshes.

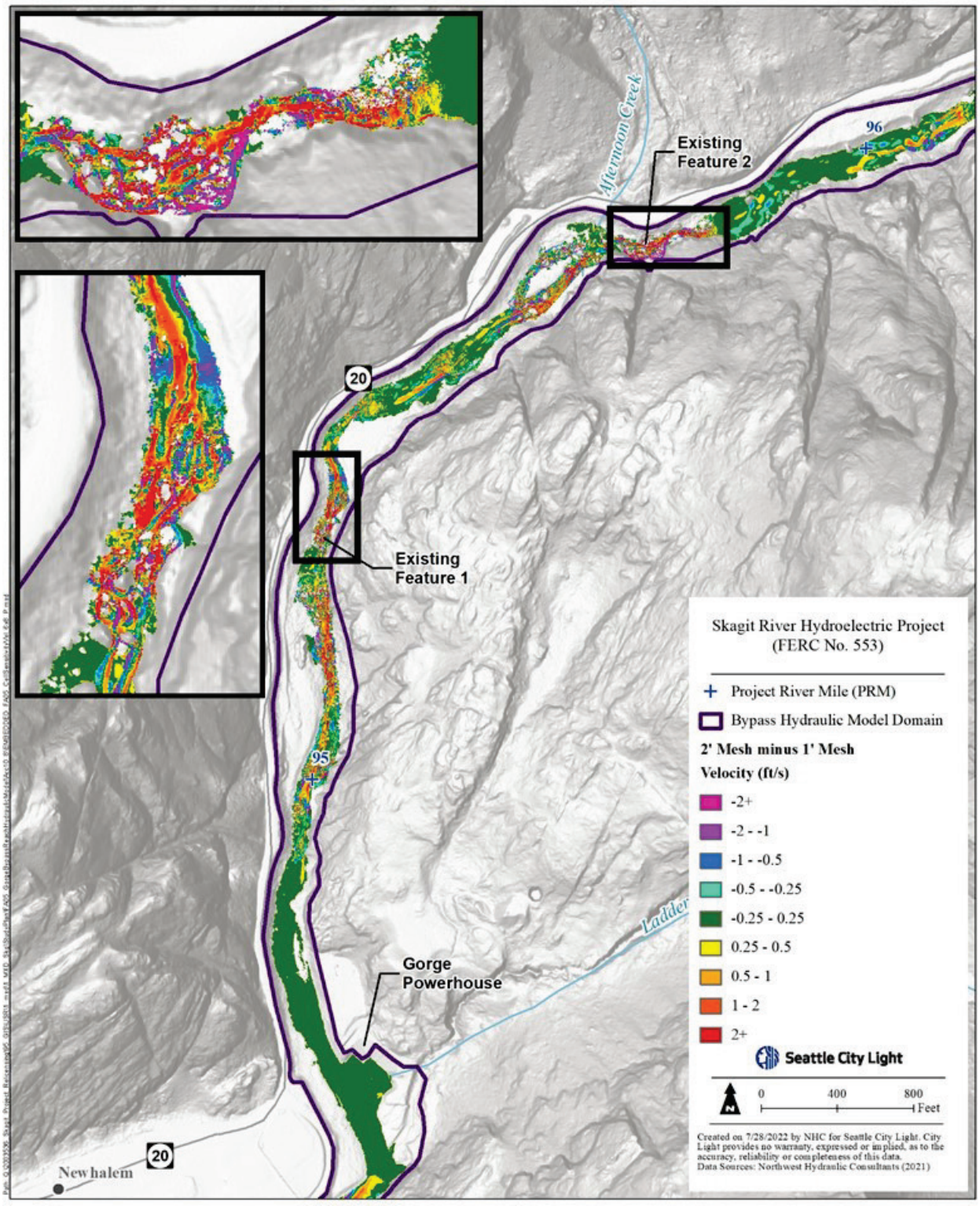


Figure 4.1-4. Difference in velocity output from 2 ft and 1 ft computational meshes.

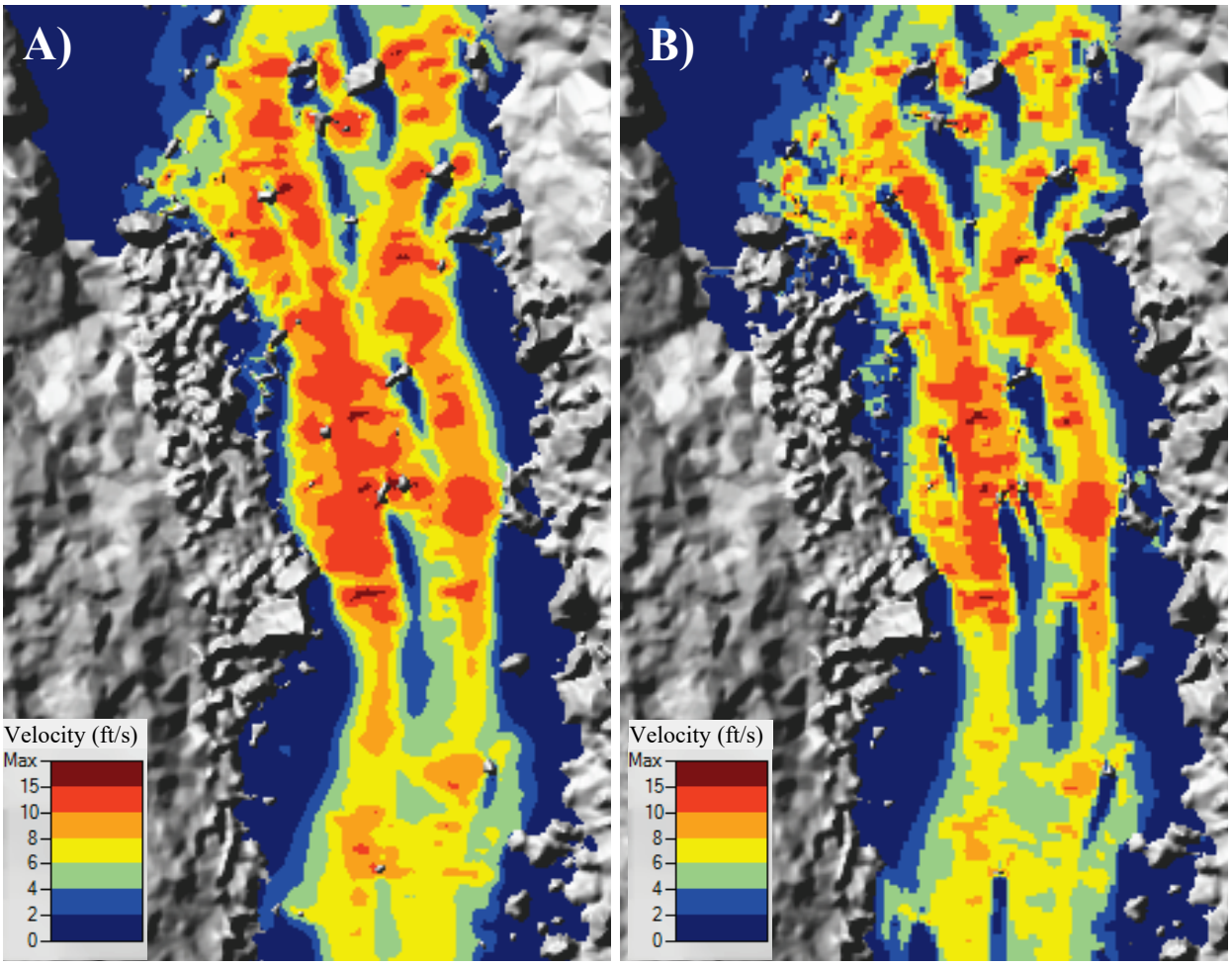


Figure 4.1-5. Computed velocities with A) 2 ft and B) 1 ft mesh cells.

4.2 Time Step

The time step used for Bypass Hydraulic Model computations was evaluated to ensure use of an appropriate value. Selection of an adequate time step is typically evaluated by assessing the Courant condition associated with the mesh, where the Courant number is a function of cell size and water velocity moving through the cell. For the solution scheme employed, the HEC-RAS user's manual recommends Courant numbers not exceed a value of 3 to achieve stable and accurate results (USACE 2021b). Testing showed a 0.3 second time step was the maximum that could be used to avoid numerical instabilities large enough to cause simulation failure; however, Courant numbers exceeded 3 in multiple locations using a 0.3 second time step. Use of a 0.1 second time step achieved a Courant number less than 3 in all mesh cells. A 0.2 second time step achieved a Courant number less than 3 throughout most of the model except where hydraulic conditions consist of cascading flow over extremely large boulders and steep drops in channel elevation (Figure 4.2-1). Note that cascading flow is exceedingly turbulent and three-dimensional in nature and two-dimensional models use depth-averaged computations and therefore provide a limited representation of these complex conditions. Therefore, a 0.2 second time step was deemed adequate for achieving good numerical accuracy while significantly improving computational efficiency over a 0.1 second time step, reducing runtimes nearly by half. For most simulations with

a 0.2 second time step and the final mesh configuration, a stable solution is achieved within approximately 20 hours of model runtime.

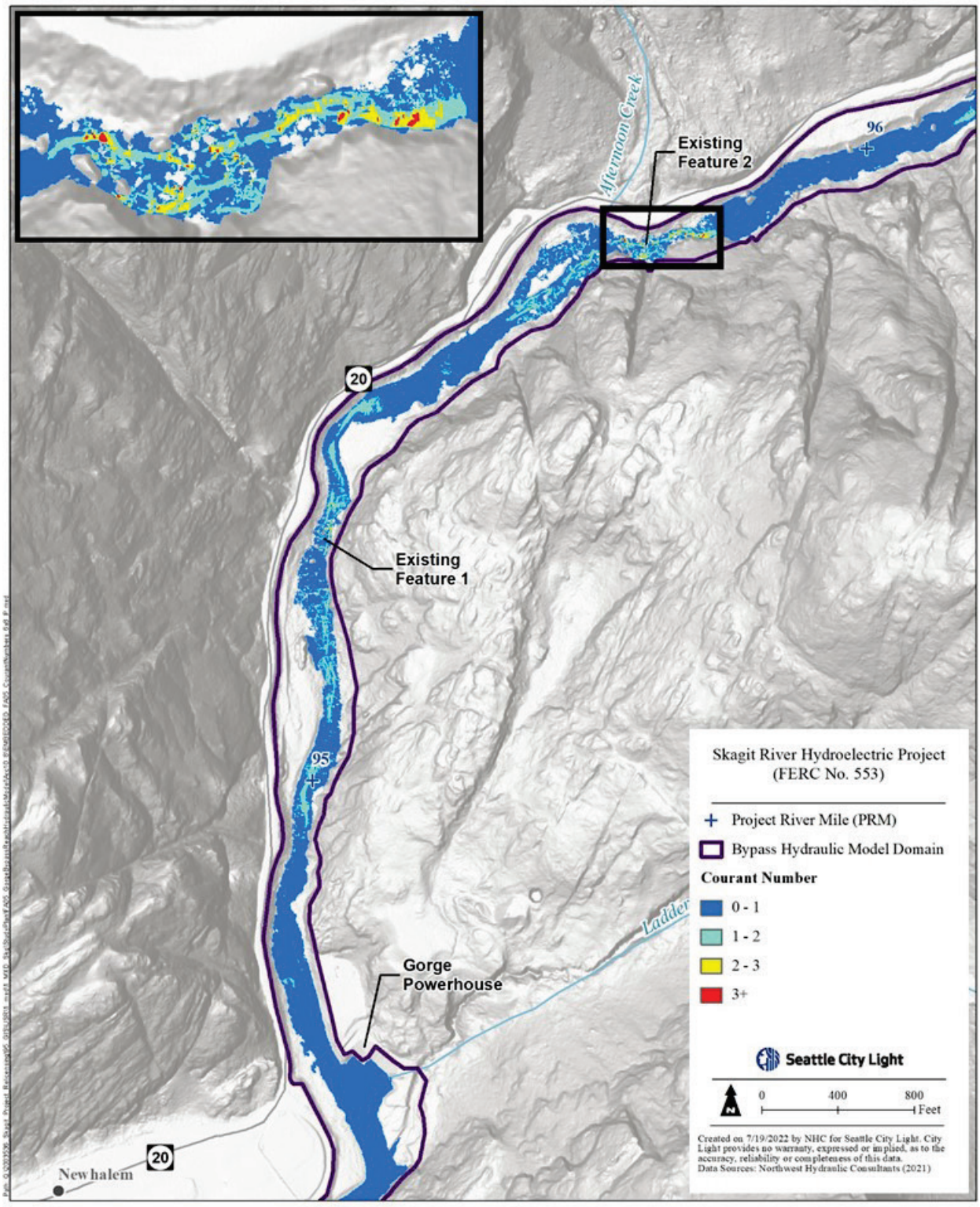


Figure 4.2-1. Example Courant Numbers for a 1 ft cell size and a 0.2 second timestep.

4.3 Turbulence Parameters

HEC-RAS offers the ability to include increasing effects of turbulence in the flow field. Highly turbulent flow is prominent throughout many sections of the Gorge bypass reach and therefore the impact of increasing turbulence coefficients was tested. HEC-RAS provides a range of turbulence coefficients and their qualitative expected mixing intensity (USACE 2021b). Sensitivity testing analyzed the relative impact of using no explicit turbulence input versus the maximum turbulence coefficients that were numerically stable. It should be noted even without turbulence explicitly turned on, the HEC-RAS solution scheme includes numerical diffusion that mimics the effects of turbulence processes. It was observed that as turbulence input is decreased in the Bypass Hydraulic Model, flow patterns develop stronger, more pronounced eddies, and flow paths become narrower and stronger (Figure 4.3-1). HEC-RAS's default turbulence coefficients, representative of moderate mixing intensity, were selected for the base model condition. However, explicit turbulence parameters were subsequently turned off to improve model stability at calibration flows exceeding 1,200 cfs (see Section 5.1). Table 4.3-1 provides the range of turbulence coefficient values tested and selected values for the base and calibrated Bypass Hydraulic Model.

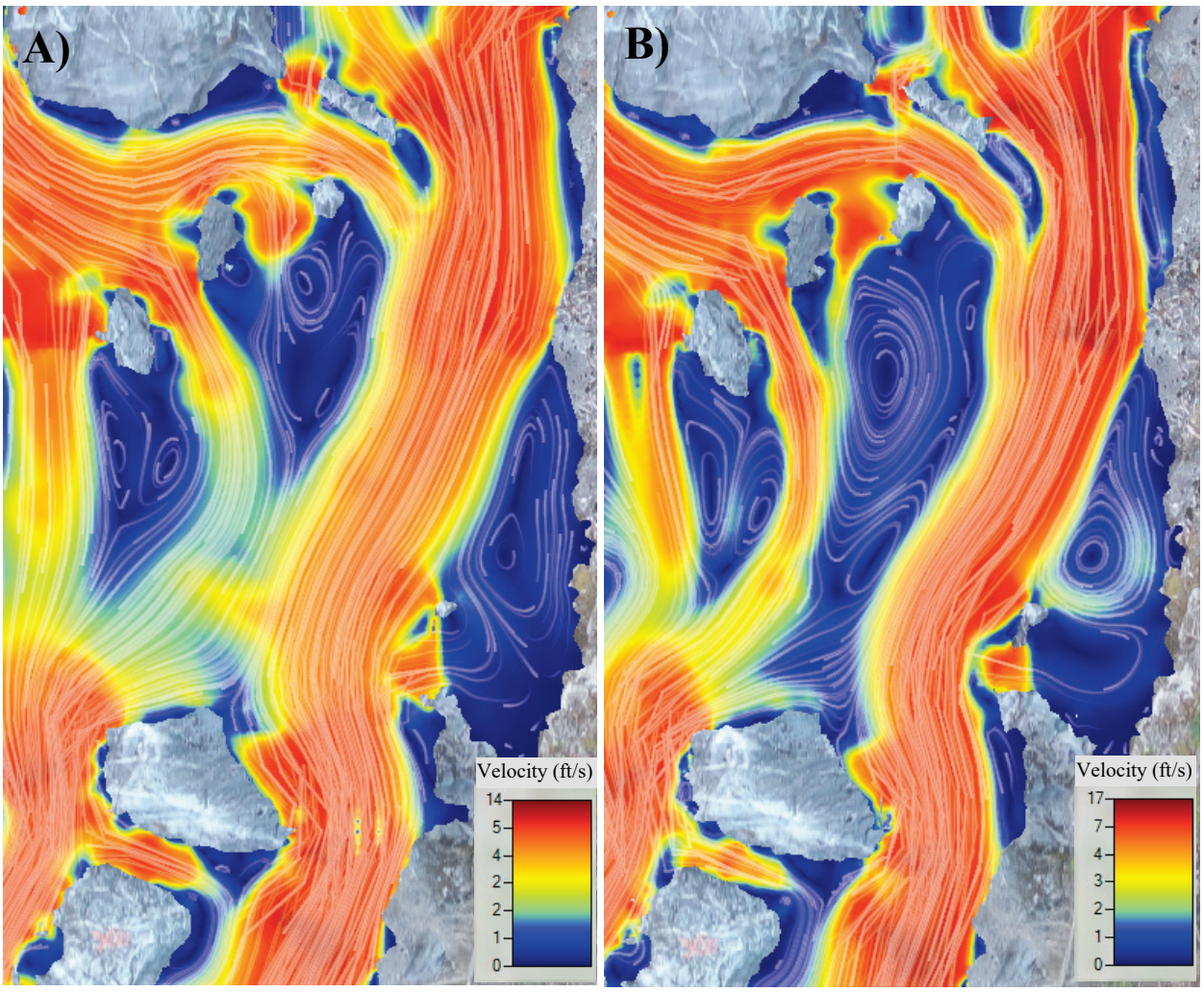


Figure 4.3-1. Computed velocities and flow patterns using A) maximum allowable turbulence parameters and B) no explicit turbulence input.

Table 4.3-1. Turbulence sensitivity test parameters.

Turbulence Coefficient	Parameter Values		
	Low[1]	Moderate[2]	Maximum[3]
Longitudinal	0	0.3	0.65
Transverse	0	0.1	0.2
Smagorinsky	0	0.05	0.1

1 Explicit turbulence input omitted – selected for calibrated model condition.
2 Selected values for base model condition.
3 Maximum values constrained by requirements for model stability at 1,200 cfs.

4.4 Hydraulic Roughness

The majority of water for the range of expected model simulations is confined to the "channel" hydraulic roughness zones. A series of Manning's n coefficients were tested in the channel roughness zones (described in Section 3.2 of this report) to assess sensitivity given base conditions cell size and time step. Table 4.4-1 provides the Manning's n coefficients used for each sensitivity test. Unvegetated channel coefficients of 0.02 and 0.03 caused numerical instability. Even when a stable parameter set was applied, the magnitude of computed velocities was generally much higher than field observations (Figure 4.4-1). An unvegetated channel coefficient of 0.05 achieved computed velocities of similar magnitude to field observations without requiring strict limitations to other input parameters, and therefore was selected for the base condition.

Table 4.4-1. Channel roughness sensitivity tests for the Bypass Hydraulic Model.

Hydraulic Roughness Zone	Manning's n Coefficient		
	Test 1	Test 2	Test 3
Channel - Unvegetated	0.02	0.03	0.05
Channel – Light Vegetation	0.03	0.03	0.08
Channel – Medium Vegetation	0.04	0.04	0.12
Channel – Heavy Vegetation	0.05	0.05	0.16

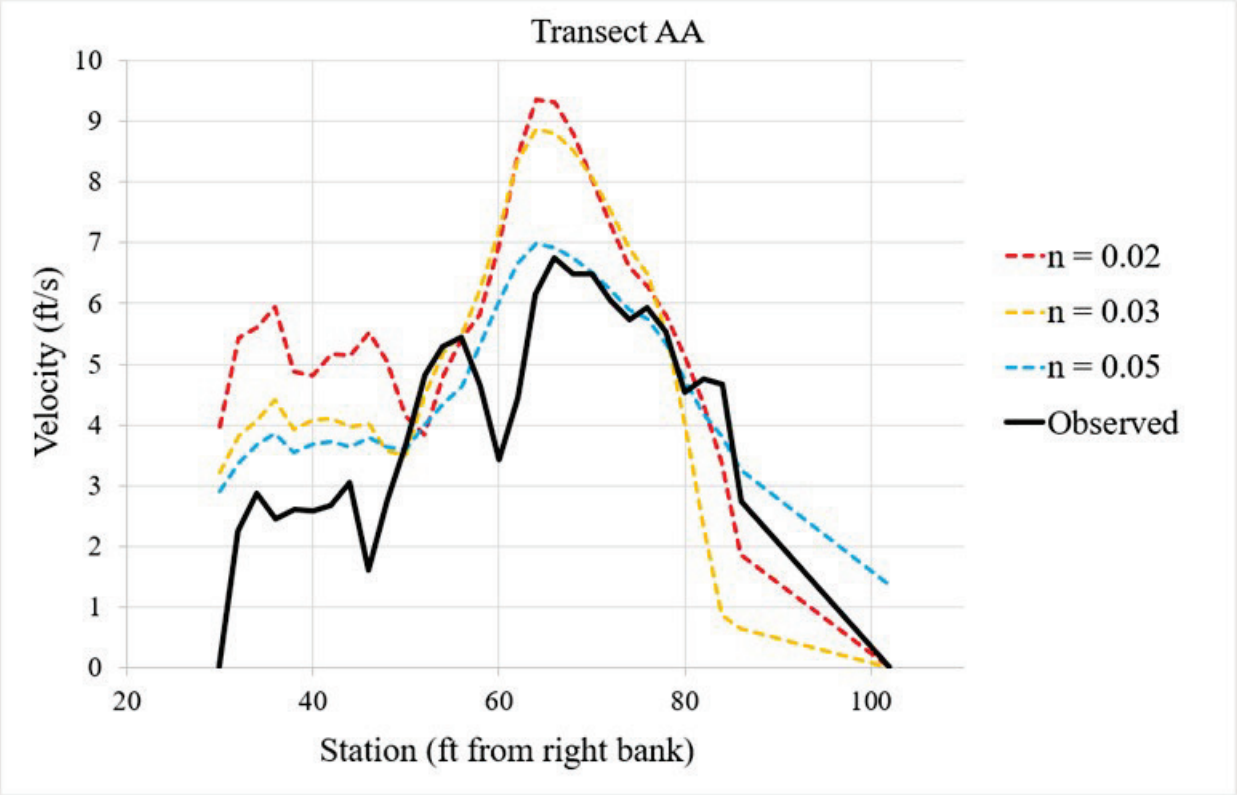


Figure 4.4-1. Computed versus observed velocities at Transect AA for varied Manning's n coefficients at 1,200 cfs.

5.0 MODEL CALIBRATION

Calibration of a hydraulic model is crucial to establish confidence in the model's ability to simulate hydraulic characteristics reliably and accurately for a range of conditions. Calibration involves the refinement of model parameters within plausible limits to best match simulated results with field observations for one or more hydrologic events. The following sections describe the calibration methods adopted and performance evaluation of the final calibrated condition.

5.1 Calibration Process

To calibrate a 2-D hydraulic model, the outputs generated from a particular set of model inputs are compared to observed data, and conclusions are drawn that inform manipulation of the model inputs. The calibration process is iterative until the results are judged to be adequate for the designated purpose and further significant improvements are not possible or warranted. A flow chart of this process as employed for calibration of the Bypass Hydraulic Model is detailed in Figure 5.1-1.

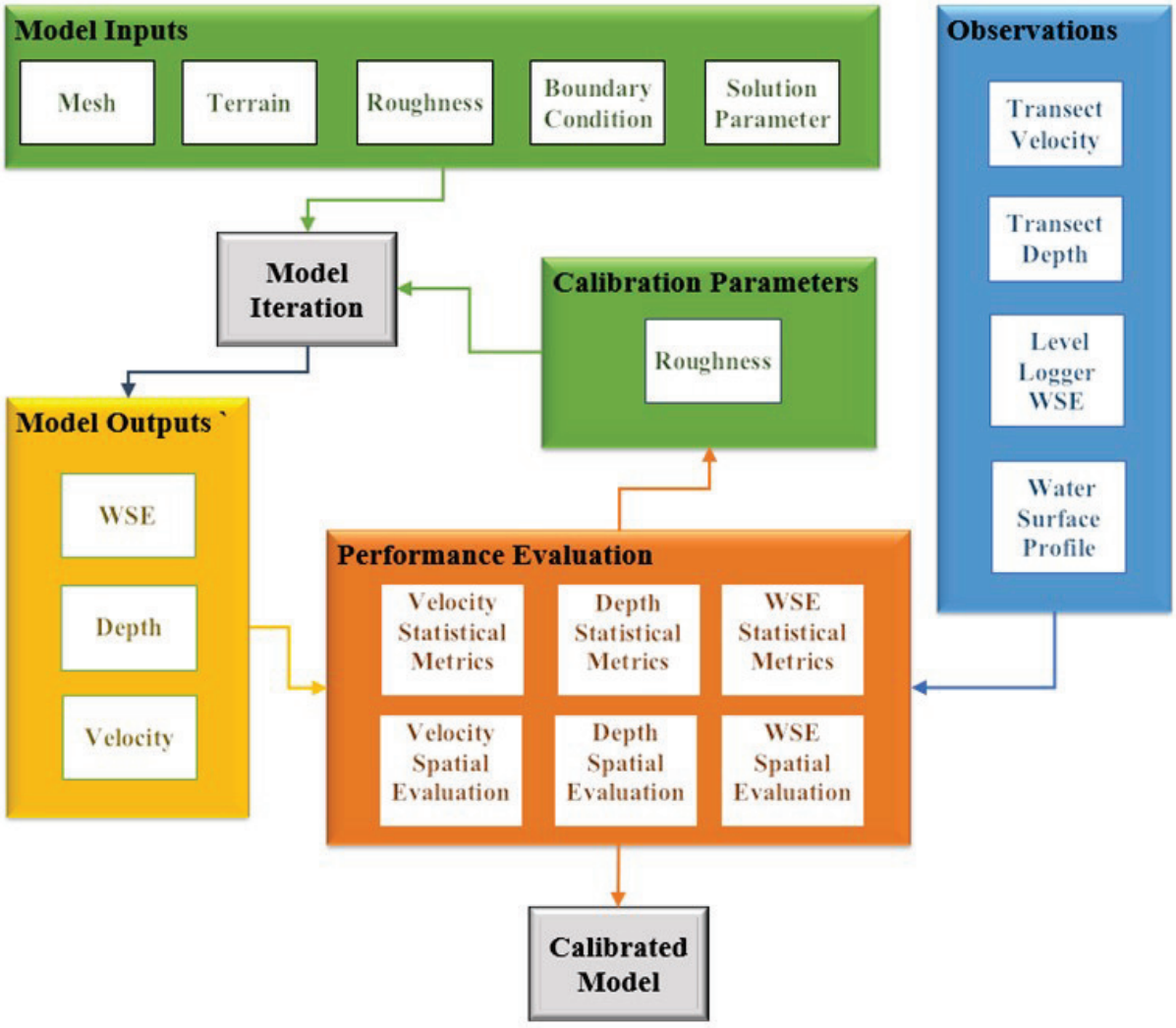


Figure 5.1-1. Process flow chart of the model calibration procedure.

Model inputs such as the terrain and boundaries were considered static after sensitivity testing and outside of the calibration process (Sections 3.1 and 3.3 of this report). Dynamic parameters such as the model solution algorithm were fixed at the start of model development (Section 3.5 of this report). Other dynamic parameters including mesh resolution, time step, and turbulence coefficients were determined prior to calibration through sensitivity testing to optimize model stability, efficiency, and precision (Section 4.0 of this report). During initial calibration simulations, it was observed that explicit turbulence coefficients determined from sensitivity testing caused unreasonable instabilities for flows exceeding 1,200 cfs. Explicit turbulence input was therefore omitted from subsequent calibration iterations, significantly improving model stability and efficiency for flows exceeding 1,200 cfs while contributing little difference to model calibration relative to use of base turbulence parameters.

Calibration took place over the course of six months using four cloud computers (for advanced computing power) and an estimated 1,500 hours of simulation time. Calibration focused on adjustment of hydraulic roughness zones and Manning's n coefficients to evaluate model performance for controlled and unscheduled releases (Section 2.2.1 of this report). Roughness zones and Manning's n coefficients for the calibrated model condition are presented in Figure 5.1-2. Adjustments to achieve the final calibrated condition included:

- Longitudinally varying Manning's n coefficients along the unvegetated channel bed to account for hydraulic losses due to geomorphic characteristics.
- Revising the delineation and Manning's n coefficient of vegetated channel regions to further resolve hydraulic losses due to variability in vegetation density and height.
- Between PRM 94.75 and the model's downstream boundary, roughness parameterization and mesh configuration were modified to match the FA-02 Upper Skagit Hydraulic Model, which was calibrated in this region to observations from the USGS Skagit River at Newhalem gage (Attachment A to the FA-02 Instream Flow Model Development Study [City Light 2023a]).

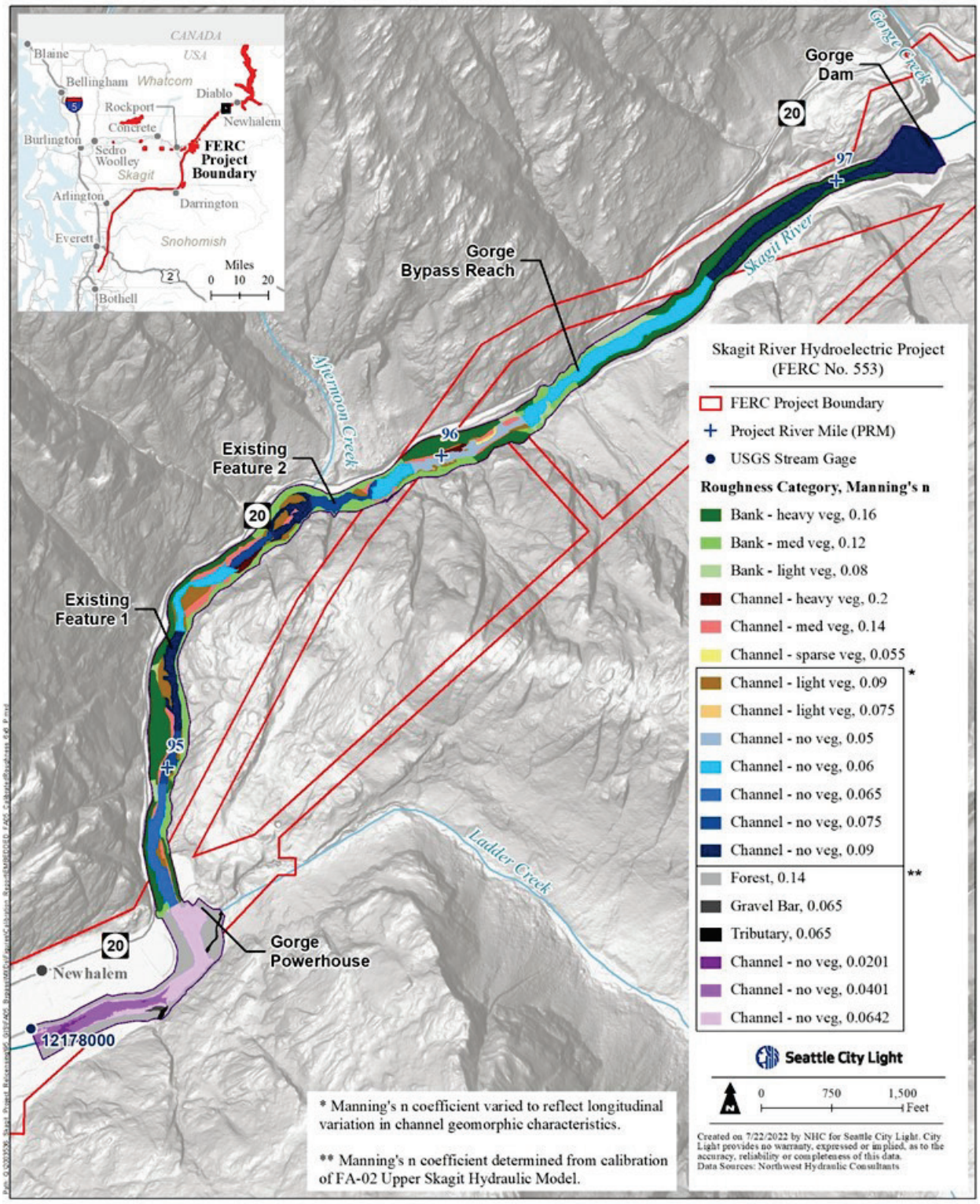


Figure 5.1-2. Roughness parameters for final calibrated model.

5.2 Performance Evaluation

The ability of the Bypass Hydraulic Model to accurately compute both depths and velocities, within the constraints of a 2-D depth-averaged model, is critical for assessment of instream flows and fish passage. Therefore, depth and velocity output were primarily used to determine the model's adequacy. WSE output was also included in model performance evaluation since depth is a derivative output from WSE. Selection and evaluation of model performance indicators for these outputs was primarily adapted from Pasternack (2011). Evaluation of model performance was divided into two groups: statistical evaluation and spatial evaluation. Statistical evaluation includes computation of mean error and regression analysis metrics of slope, y-intercept, coefficient of determination (R^2). Spatial evaluation includes qualitatively and quantitatively comparing simulated versus observed values in longitudinal and cross-sectional profiles to identify spatial trends and biases in model performance. The term "residual" indicates the difference between simulated minus observed values.

To account for differing observation accuracy and ability to inform model performance, calibration metrics from observed datasets were prioritized as follows:

(1) Transect velocity and depth metrics were given the highest priority. Field observations were highly accurate and informed model performance across a wide range of geomorphic and hydraulic conditions.

(2) WSEs at Existing Features 1 and 2 were assigned second priority for model performance optimization. While level logger measurements were very accurate, they only provide insight to model performance within and around the Existing Features.

(3) Having more uncertainty in observed values than transect and level logger measurements, water surface profiles from SfM software were assigned lowest priority. However, these datasets were instrumental to evaluating model performance in areas where transect and level logger observations were absent.

Calibration efforts first focused on replicating transect and level logger observations. Then adjustments were made to match observed water surface profiles to the extent that model performance relative to transects and level loggers was not compromised.

The following sections describe the observed and simulated datasets used to evaluate the model and the performance metrics and only the final calibrated model results are presented herein.

5.2.1 Transect Velocities and Depths

Velocity and depth observations from five Gorge bypass reach transects (Section 2.2.2.2 of this report) were used to evaluate model performance across a variety of geomorphic units, each with unique hydraulic characteristics. Table 5.2-1 provides brief descriptions of reach characteristics at each transect and Table 5.2-2 summarizes the number of depth and velocity observations collected.

Table 5.2-1. Transect descriptions.

Transect ID	Project River Mile	Geomorphic Description	Hydraulic Characteristics
EE	96.12	Riffle	Uniformly distributed shallow, high velocity flow
II	96.02	Glide	Primary flow path concentrated along channel left; low velocities through vegetation along channel right
DD	95.84	Pool	Very deep, nearly stagnant flow
AA	95.33	Run	Wide velocity range with flow splits around boulders
GG	94.95	Riffle-Pool Transition	Primary flow path concentrated along channel left; low velocities and reverse flow along channel right

Table 5.2-2. Transect observations.

Nominal Flow (cfs)	Depth/Velocity Observations					
	Transect EE	Transect II	Transect DD	Transect AA	Transect GG	All Transects
1,200	37	32	25	27	20	141
500	27	30	36	34	41	168
250	22	38	30	33	44	167
50	29	33	37	31	36	166

Transect observations provided a wide, well-distributed range of velocities and depths to evaluate model performance. Linear regression analysis was used to compare simulated with observed velocities by individual transect and with observations from all transects for each controlled release flow. Statistical metrics including coefficient of determination (R^2), slope, and y-intercept were evaluated. The percent of velocities matching within 0.5 ft/s and 1.0 ft/s of observed values were also quantified. Mean error between simulated and observed output was used to evaluate depths at each transect. A perfect match between simulated and observed depths along a transect is not expected because of limitations in the model terrain surface. However, near zero mean error indicates the simulated water level is equivalent to the observed condition.

Spatial evaluation of velocity and depth compared transect observations to computed results for the corresponding flow. Observed and simulated values were both plotted along a cross-section profile to identify lateral trends and localized differences related to transect features.

Detailed comparisons of velocities and depths for the final calibrated condition are found in the Model Performance Evaluation: Transect Velocities and Depths, Attachment F. Velocity statistical metrics indicate that the model is performing well (Table 5.2-3 and Figure 5.2-1). An average R^2 of 0.82 across all calibrated flows shows strong model performance for velocity prediction (Pasternack [2011] recommends R^2 of 0.4-0.8 for calibration target). The average slope (0.85) and y-intercept (0.2) indicate a good match, with a slight tendency to overestimate low velocities and underestimate high velocities. On average, 71 percent of simulated velocities were within 0.5 ft/s of corresponding observed values and 90 percent were within 1 ft/s. Simulated and observed cross-channel velocity variations were similar in all transects at all flows. Much of the remaining velocity difference is associated with local variations around channel substrate not fully captured by the

model as explained in Figures 5.2-2 and 5.2-3, possibly due to surface terrain limitations. The ADCP drift below each cableway was estimated from recorded video and photos for extracting simulated results, which may have also contributed to some of the difference between simulated and observed velocities (Figure 5.2-2). Negative values in regression and cross-section plots (Figure 5.2-1 and Attachment F) indicate velocities with a primary upstream direction (from eddies or flow recirculation). Mean depth errors (on average 0.2 ft) indicate that the model does a good job computing WSE at all transects (Table 5.2-3). Spatial evaluation of simulated versus observed depths found that depth calculations track well across each transect with little to no bias across transects or calibration flows (Attachment F).

Table 5.2-3. Statistical summary of lumped transect velocity evaluation.

Nominal Flow[1] (cfs)	Velocity Statistics					Depth Statistics
	R^2	Slope	y-intercept	% within 0.5 ft/s	% within 1.0 ft/s	Mean Error (ft)
1,200	0.91	0.89	0.27	63	83	0.3
500	0.89	0.87	0.16	69	89	0.1
250	0.80	0.84	0.24	69	92	0.2
50	0.67	079	0.11	83	95	0.1
Avg.	0.82	0.85	0.20	71	90	0.2

1 Actual measured flows provided in Table 3.3-1.

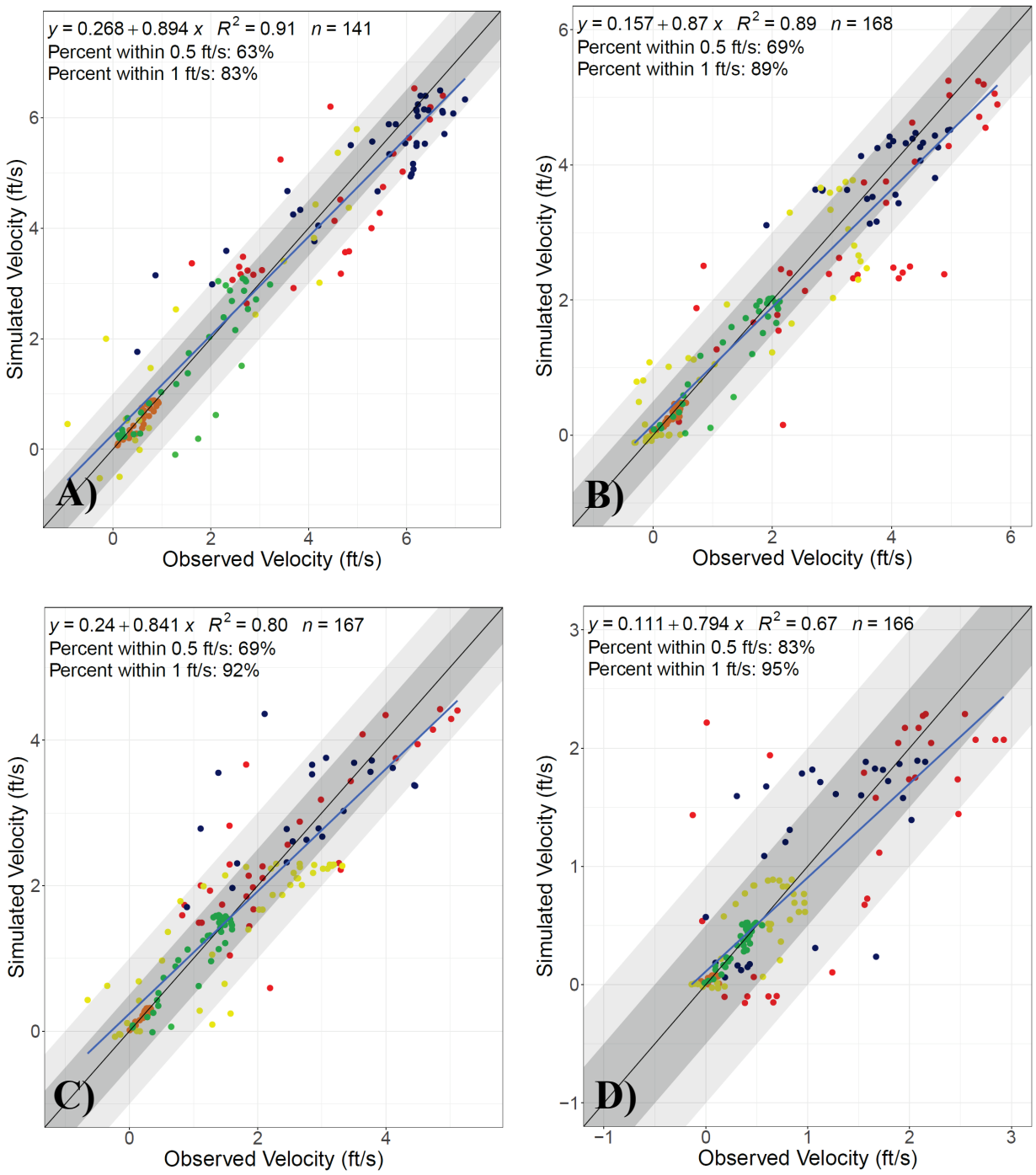


Figure 5.2-1. Statistical summary of transect velocity evaluation for A) 1,200, B) 500, C) 250, and D) 50 cfs nominal flows.

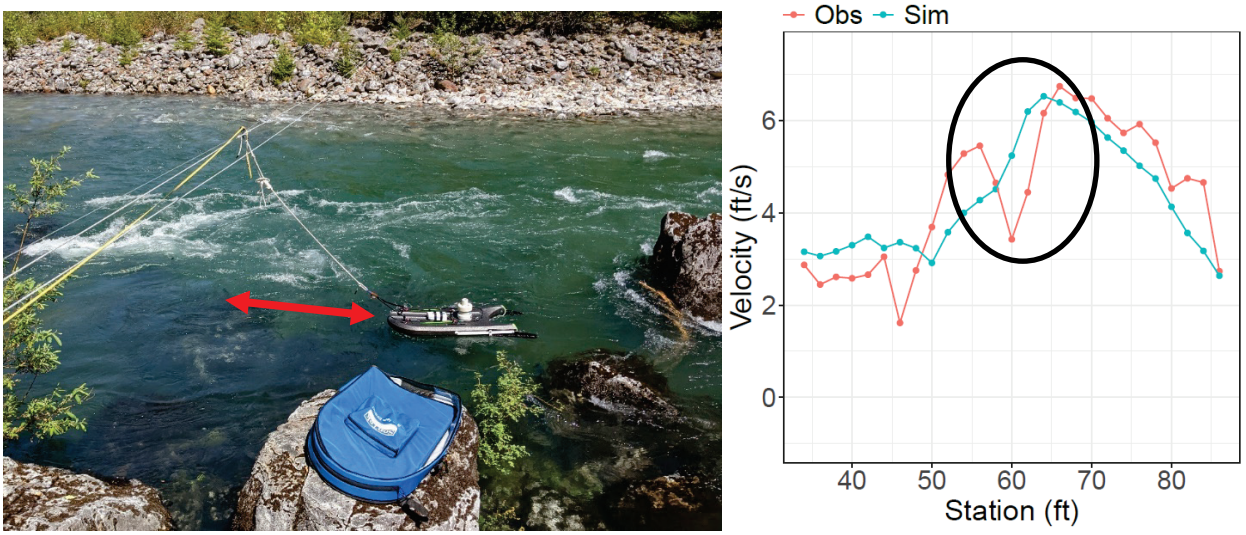


Figure 5.2-2. **(Left) Observed flow split around submerged boulder in middle of channel and ADCP drift below transect line (red arrow) at Transect AA; (Right) Observed versus simulated velocities reflecting missing effect of flow split in model simulation (circled in black).**

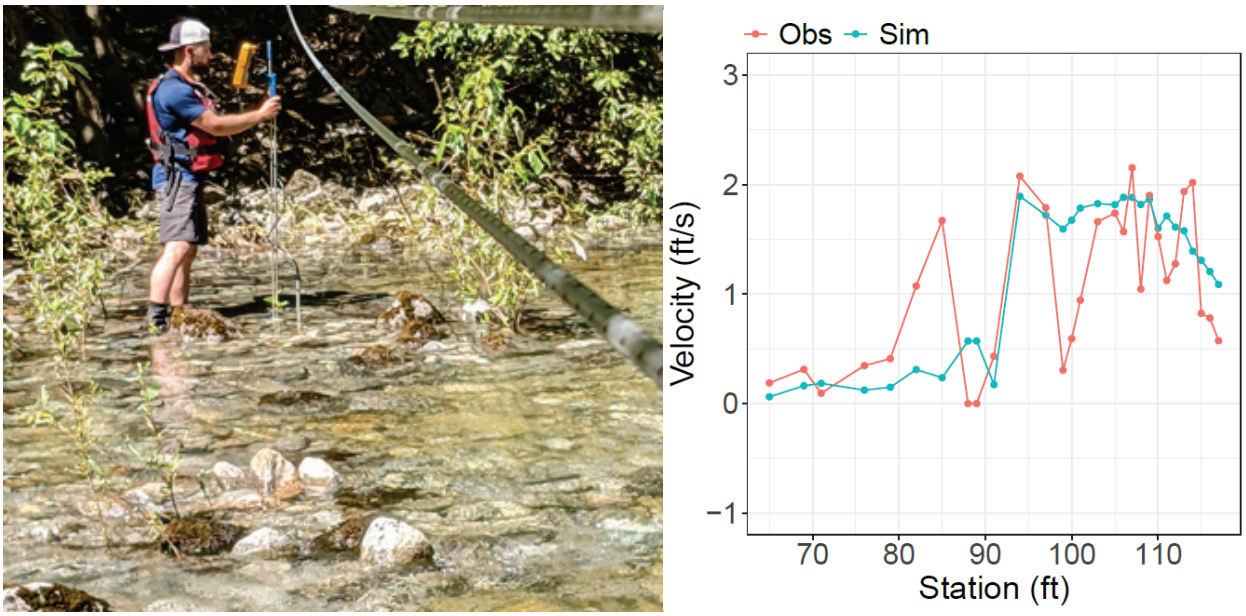
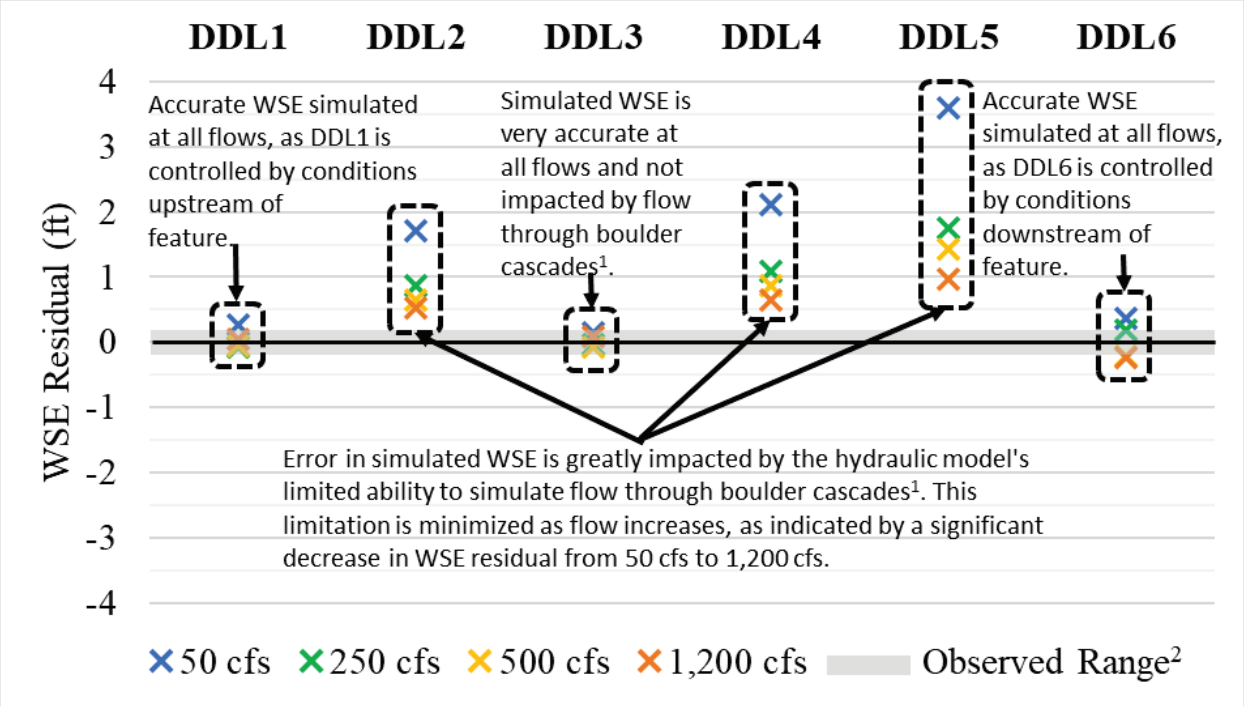


Figure 5.2-3. **(Left) Observed flow conditions at Transect EE showing flow around channel substrate typically protruding less than 8 inches above grade; (Right) Observed versus simulated velocities reflecting model inability to represent local velocity variation around channel substrate, likely due to surface terrain limitations.**

5.2.2 Existing Features Water Surface Elevations

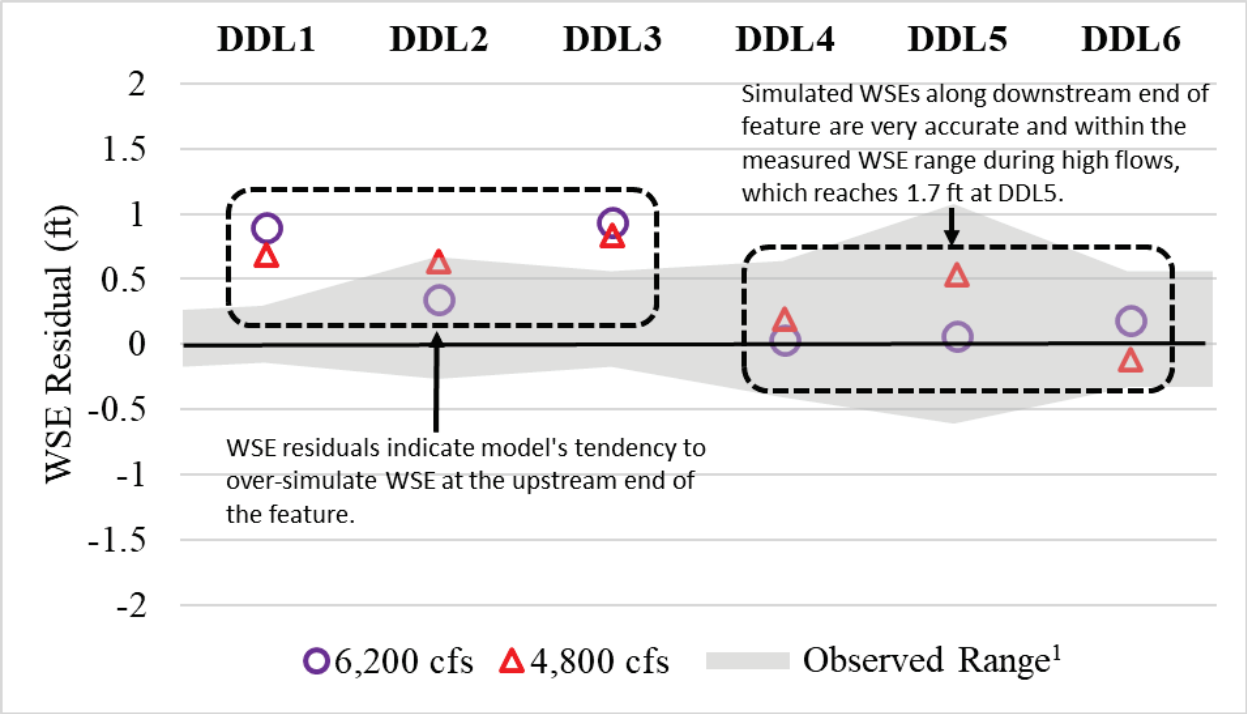
WSEs recorded by the 12 level loggers at Existing Features 1 and 2 (Section 2.2.2.1 of this report) were time-averaged over each calibration flow and compared with simulated output to assess model performance. In addition to the controlled releases, simulated WSEs were also compared to mean level logger measurements for nominal flows of 4,800 cfs and 6,200 cfs from the late June/early July unscheduled spills. This extended evaluation of model performance at Existing Features 1 and 2 was undertaken to support use of the model for fish passage assessment under the FA-04 Fish Passage Technical Studies Program (City Light 2023b).

Model performance was evaluated at each level logger by computing the difference in simulated versus observed mean WSE. Residuals were plotted along a longitudinal profile at each Existing Feature to identify trends in model performance both spatially and across the range of calibration flows. Residual WSEs at each level logger were used to adjust channel roughness along both Existing Features and in the adjacent channel reaches. Figures 5.2-4 through 5.2-7 present a longitudinal evaluation of the calibrated results, while residuals are documented in Table 5.2-4 and Table 5.2-5. Range in observed WSE at each level logger was also computed for each calibration flow to characterize confidence in observed mean WSEs and is included in the aforementioned figures and tables.



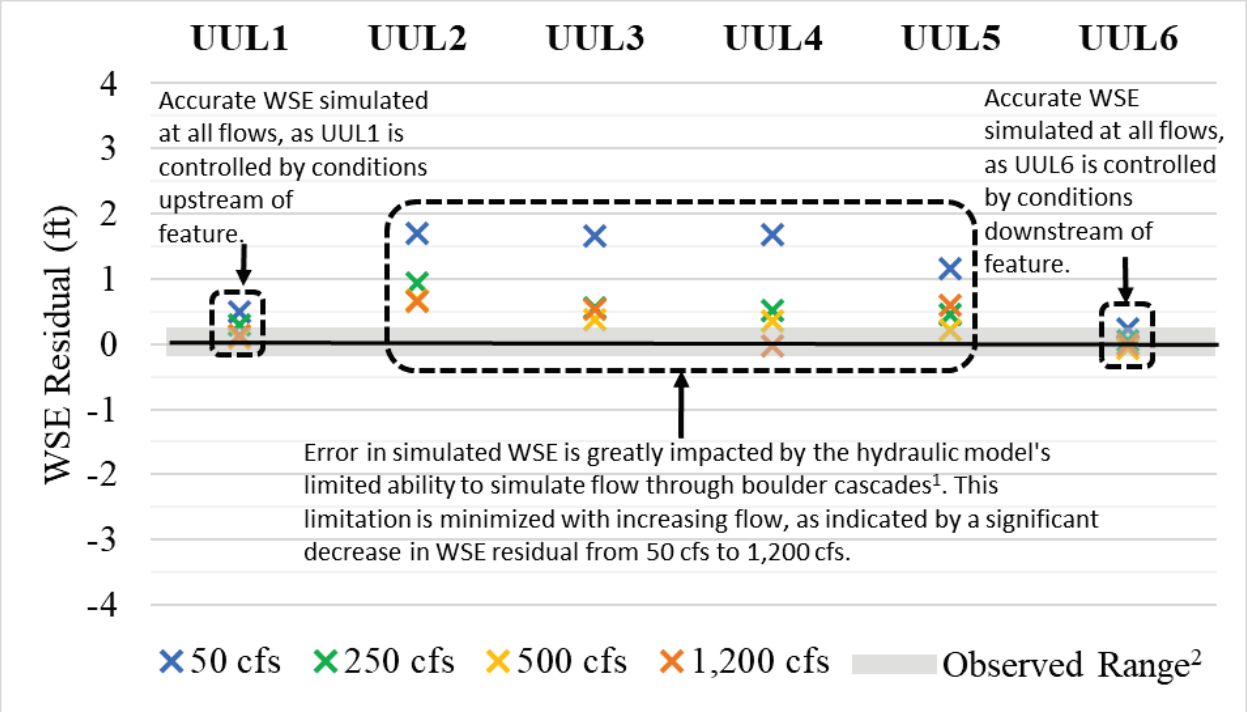
1 See Section 5.2.2.1 of this report.
2 Range of measured WSE generally within 0.2 ft at all level loggers.

Figure 5.2-4. WSE residuals at Existing Feature 1 for controlled releases.



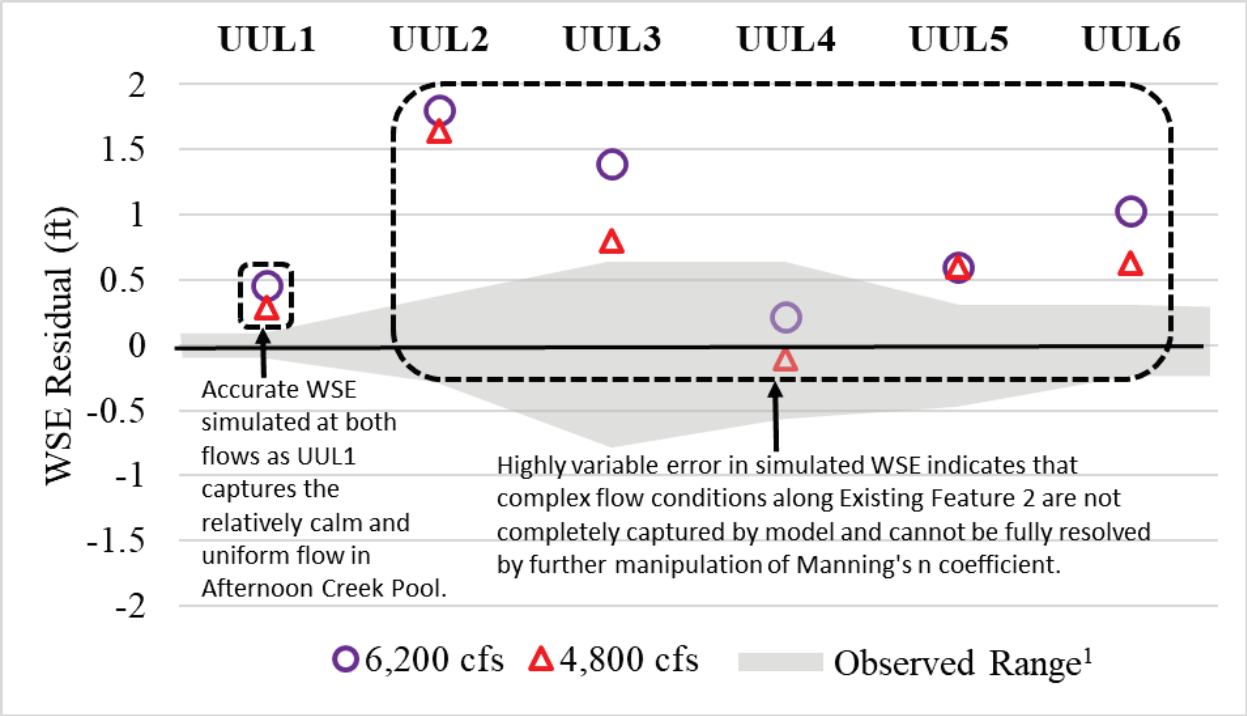
1 Range of measured WSE varies from 0.4 ft to 1.7 ft.

Figure 5.2-5. WSE residuals at Existing Feature 1 for unscheduled spills.



1 See Section 5.2.2.1 of this report.
2 Range of measured WSE generally within 0.2 ft at all level loggers.

Figure 5.2-6. WSE residuals at Existing Feature 2 for controlled releases.



1 Range of measured WSE varies from 0.2 ft to 1.4 ft.

Figure 5.2-7. WSE residuals at Existing Feature 2 for unscheduled spills.

Table 5.2-4. Summary of WSE performance at Existing Feature 1.

Flow[1] (cfs)	DDL1		DDL2		DDL3		DDL4		DDL5		DDL6	
	Residual (ft)[2]	Range (ft)[3]	Residual (ft)[2]	Range (ft)[3]	Residual (ft)[2]	Range (ft)[3]	Residual (ft)[2]	Range (ft)[3]	Residual (ft)[2]	Range (ft)[3]	Residual (ft)[2]	Range (ft)[3]
6,200	0.90	0.4	0.34	0.7	0.94	0.4	0.03	0.8	0.06	1.6	0.18	0.6
4,800	0.69	0.4	0.64	0.9	0.84	0.7	0.19	1.1	0.53	1.7	-0.12	0.9
1,200	0.05	0.1	0.53	0.3	0.09	0.2	0.65	0.2	0.96	0.2	-0.24	0.4
500	-0.05	0.2	0.65	0.2	-0.08	0.1	0.87	0.1	1.44	0.1	-0.21	0.2
250	-0.07	0.0	0.86	0.1	-0.03	0.1	1.09	0.1	1.76	0.1	0.18	0.3
50	0.26	0.1	1.71	0.2	0.14	0.1	2.11	0.2	3.59	0.1	0.37	0.2

1 Nominal flow values. Actual measured flows provided in Table 3.3-1.
2 Simulated WSE residual relative to observed.
3 Range in WSE recorded by level logger.

Table 5.2-5. Summary of WSE performance at Existing Feature 2.

Flow[1] (cfs)	UUL1		UUL2		UUL3		UUL4		UUL5		UUL6	
	Residual (ft)[2]	Range (ft)[3]	Residual (ft)[2]	Range (ft)[3]	Residual (ft)[2]	Range (ft)[3]	Residual (ft)[2]	Range (ft)[3]	Residual (ft)[2]	Range (ft)[3]	Residual (ft)[2]	Range (ft)[3]
6,200	0.46	0.2	1.80	0.7	1.39	1.4	0.22	1.2	0.60	0.8	1.03	0.3
4,800	0.29	0.6	1.64	0.6	0.80	1.1	-0.10	1.0	0.60	0.6	0.63	0.5
1,200	0.13	0.1	0.66	0.2	0.53	0.3	-0.03	0.1	0.59	0.1	0.00	0.2
500	0.09	0.0	0.68	0.2	0.38	0.3	0.36	0.1	0.21	0.1	-0.06	0.2
250	0.29	0.1	0.94	0.1	0.56	0.3	0.52	0.1	0.46	0.1	0.06	0.1
50	0.50	0.1	1.71	0.2	1.66	0.3	1.69	0.6	1.16	0.2	0.24	0.1

1 Nominal flow values. Actual measured flows provided in Table 3.3-1.
2 Simulated WSE residual relative to observed.
3 Range in WSE recorded by level logger.

Model results at level loggers bounding the Existing Features (DDL1, DDL6, UUL1, and UUL6) show very good agreement with observations for the controlled releases, with residuals less than 0.5 ft. Larger residuals were generally observed within each Existing Feature where the model's inability to simulate flow beneath boulders significantly impacts results (see Section 5.2.2.1 of this report). As expected, residuals related to this limitation are greatest at the 50 cfs controlled release flow, ranging from 1 to 4 ft. Between 250 and 1,200 cfs, the influence of flow beneath boulders diminishes and residuals are generally 1 ft or less. As flows exceed 1,200 cfs, WSE residuals are more variable throughout the features, with the largest residuals occurring along the upstream half of Existing Feature 1 and along the entirety of Existing Feature 2 downstream of Afternoon Creek Pool. Range in measured WSE is also greater at these flows, illustrating the increasingly chaotic and complex hydraulic conditions which cannot be fully captured within the framework of a depth-averaged hydraulic model. WSE residuals are mostly within 0.5 to 1 ft at these flows, though residuals on the order of 1 to 2 ft are found at UUL2 and UUL3 placing lower confidence in model results within the vicinity of these level loggers.

5.2.2.1 Flow Through Boulder Cascades

The ability to accurately simulate WSEs through the Existing Features is limited by the ability of the 2-D model to represent the hydraulic complexity of these features. The model surface terrain accounts for elevations and features that can be viewed from directly overhead. However, the boulder cascades comprising Existing Features 1 and 2 provide a multitude of flow paths beneath the boulders (examples shown in Figure 5.2-8) which cannot be represented within the surface terrain or model mesh. Water that in reality flows beneath boulders is forced to flow over boulders within the 2-D model, artificially increasing upstream WSEs. Such errors are more pronounced at lower flows when a larger percentage of the total flow is conveyed by these flow paths, but gradually loses significance as total flow increases and the boulders become submerged. For model performance evaluation, this meant higher priority was placed in matching observed WSEs at level loggers located upstream and downstream of each feature (DDL1, DDL6, UUL1, and UUL6) which were minimally affected in comparison to level loggers located within the boulder cascades.



Figure 5.2-8. Example flow paths beneath boulders at Existing Feature 1.

5.2.3 Water Surface Profiles

Reach-long water surface profiles were developed from UAV imagery (Section 2.2.2.3 of this report) for each controlled release. Points were marked along the water's edge in GIS software and elevations assigned from the surface terrain to each point. Figure 5.2-9 provides an example of water's edge points. A total of 3,643, 3,084, 3,992, and 3,935 water's edge points were used to create reach-long water surface profiles for the 1,200, 500, 250, and 50 cfs controlled releases, respectively.

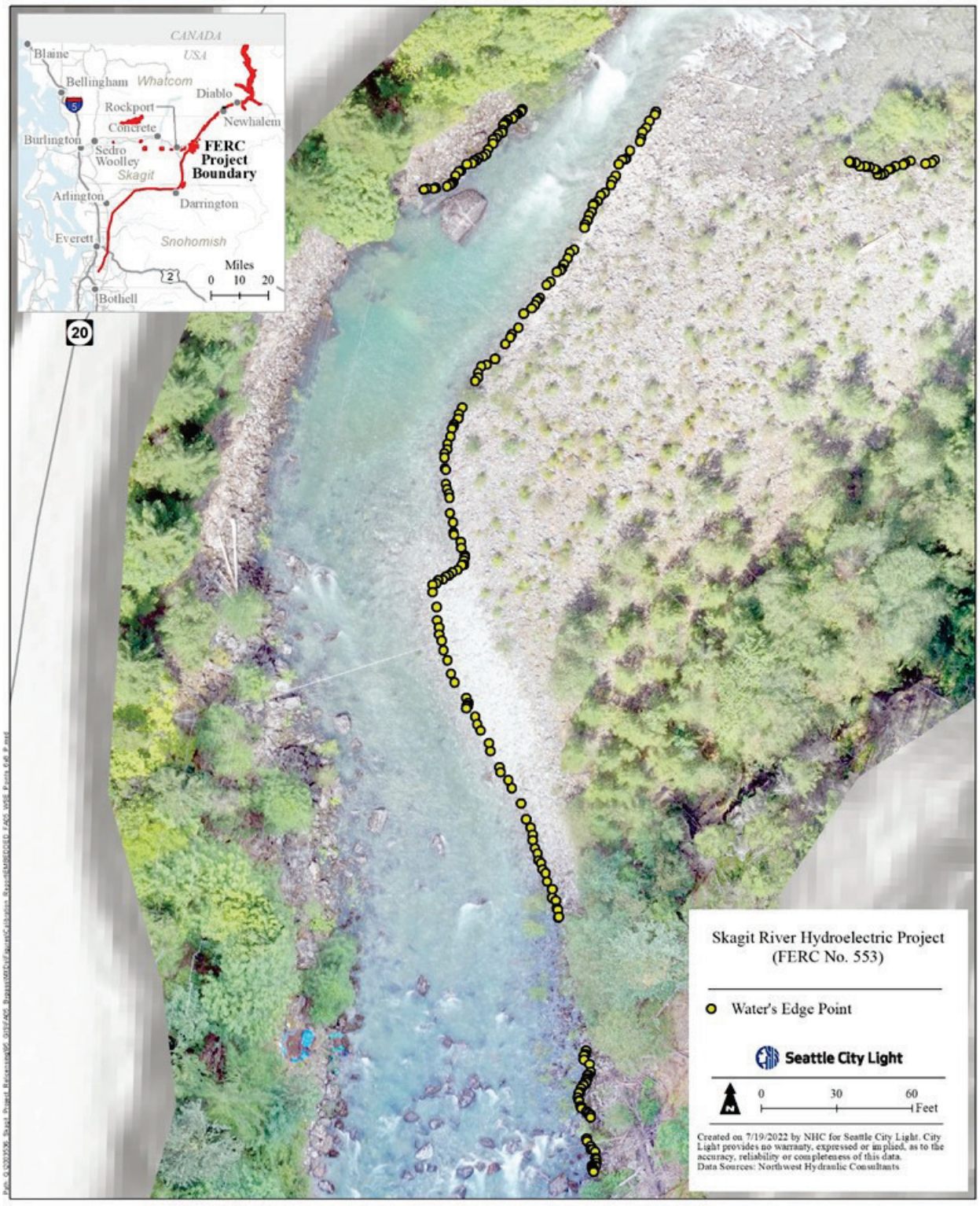


Figure 5.2-4. Example of water's edge points for 500 cfs controlled release.

Elevations assigned to water's edge points were subject to multiple sources of error. Surface elevations could have changed from the time the LiDAR was flown in 2018 to the controlled releases in July 2021. Georeferencing of the UAV imagery is inexact, as some distortion of the image relative to real-world coordinates will always exist even after post-processing with surveyed control points. For orthomosaic images of the Gorge bypass reach, these distortions generally resulted in positional errors of less than 0.2 ft, though some areas could be shifted by as much as 0.5 ft. Such inaccuracies would lead to water's edge points intersecting the 2018 surface terrain at incorrect locations and propagate further error in the water surface estimate derived from the terrain. Additionally, some degree of inaccuracy can be expected from extracting elevations from the model terrain even in the absence of geomorphic and georeferencing based errors. While the model surface is high resolution (Section 3.1 of this report), areas between measured LiDAR points are an approximation of the real terrain and cannot provide WSEs with the same accuracy achieved from field survey. The following methods were employed for reach-long water surface profile development and evaluation to minimize the influence of these error sources:

(1) Water's edge points were only marked where the water's edge was clearly visible in the imagery;

(2) Higher priority was given to marking water's edge points along channel banks and features with flat slopes where vertical errors due to horizontal position uncertainty are minimized;

(3) Clusters of water's edge points within localized areas were averaged to assign a single elevation for the water surface profile. This was done to reduce random error in the individual points. Figure 5.2-10 provides an example of a processed water surface profile relative to the water's edge point clusters used for profile development; and

(4) Model performance was evaluated by computing the mean difference between simulated and cluster-averaged WSEs within nine channel sub-reaches spanning the extents of available orthomosaic imagery (Figure 5.2-11). Sub-reaches were delineated at geomorphic reach breaks to determine how geomorphic characteristics influence hydraulic roughness. Brief descriptions of each sub-reach are provided in Table 5.2-8.

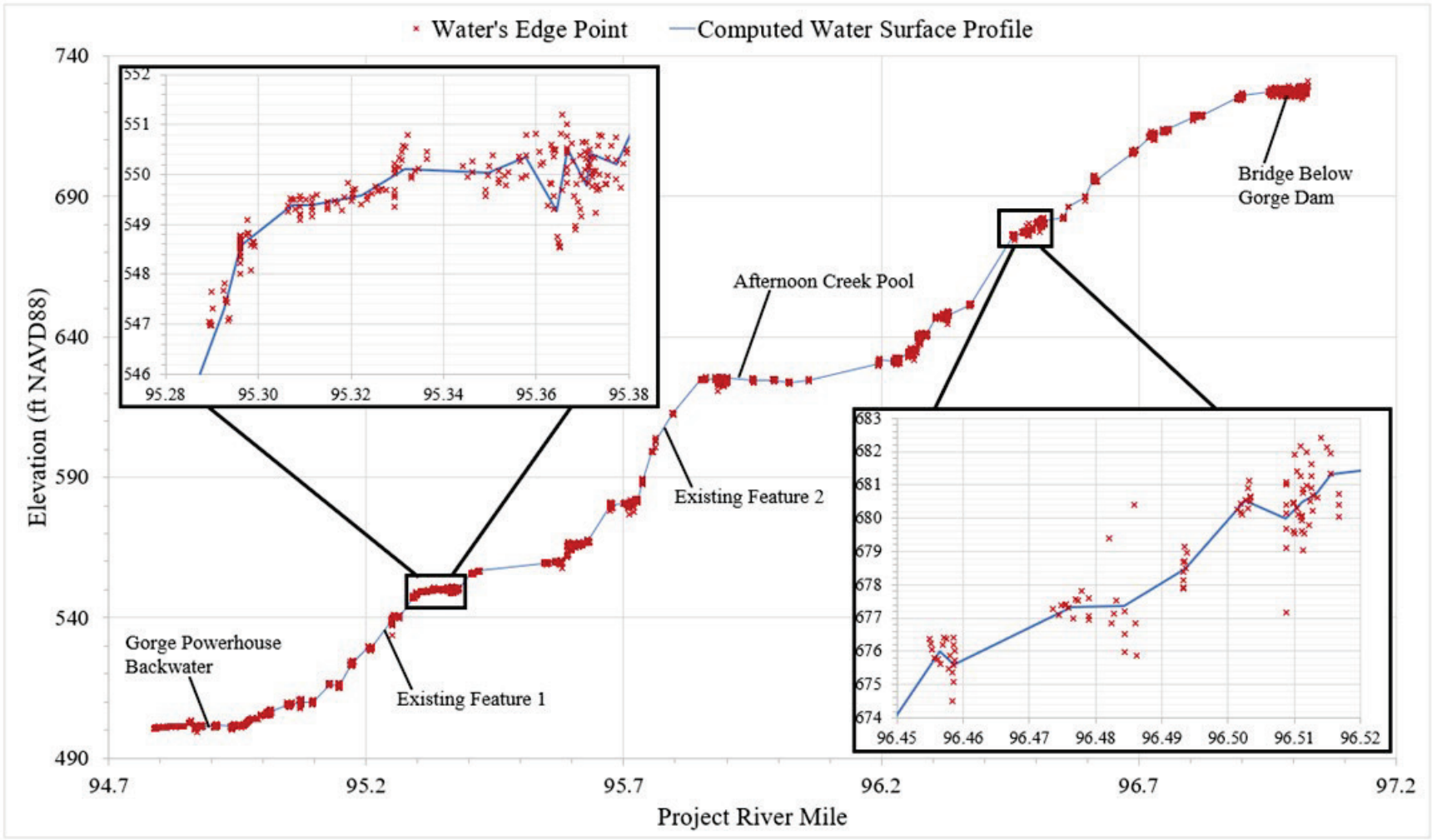


Figure 5.2-5. Profile of water's edge points and computed water surface profile for 500 cfs controlled release.

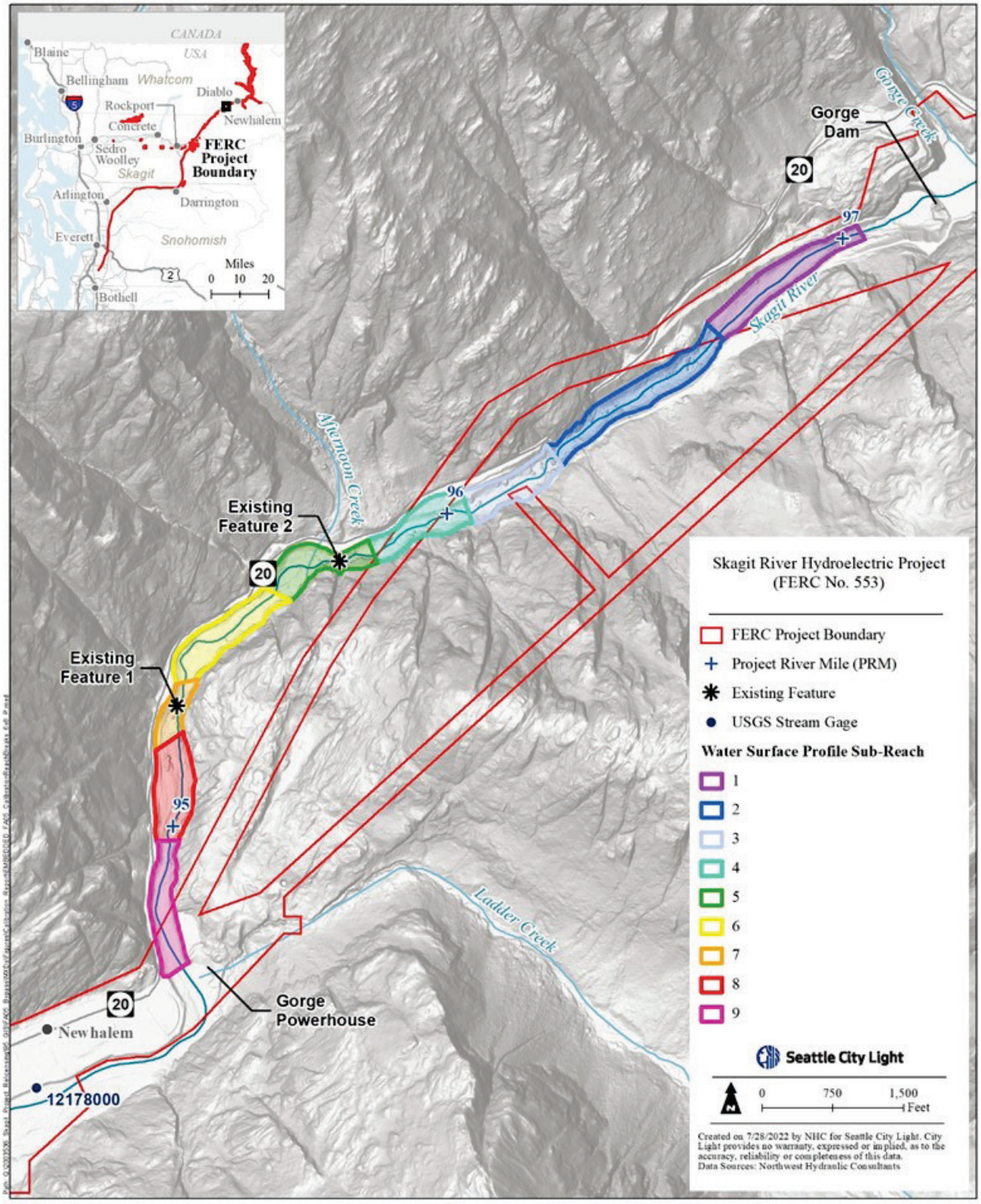


Figure 5.2-6. Sub-reaches for water surface profile performance evaluation.

Table 5.2.8. Water surface profile sub-reach descriptions.

Sub-Reach ID	Sub-Reach Description
1	Riffle
2	Cascades
3	Pool-Riffle Sequence
4	Afternoon Creek Pool
5	Existing Feature 2 and Downstream Cascades
6	Pool-Riffle Sequence
7	Existing Feature 1 and Downstream Pool
8	Rapids
9	Powerhouse Backwater Zone

Mean differences between simulated and observed WSE by sub-reach are provided in Table 5.2-9 for the final calibrated model. Almost all mean WSE differences were within 0.6 ft and half were within 0.2 ft. The only exception occurs at Sub-reach 2 for the 50 cfs controlled release. Sub-reach 2 consists of multiple cascades that allow for flow beneath boulders as was described in Section 5.2.2.1 of this report. At 50 cfs, a significant portion of the total flow is conveyed beneath some of these boulder cascades (see Figure 5.2-12), but model limitations force all flow over the boulder cascades, artificially increasing water levels.

Table 5.2-9. Summary of mean WSE differences from water surface profile evaluation.

	Mean Water Surface Difference (simulated minus observed, ft)				
Sub-Reach	50 cfs[1]	250 cfs[1]	500 cfs[1]	1,200 cfs[1]	Average[2]
1	0.2	0.3	0.2	-0.1	0.1
2	1.2	0.4	0.0	-0.1	0.1
3	0.6	0.1	0.0	-0.2	-0.1
4	0.6	0.4	0.3	0.0	0.2
5	-0.1	-0.1	-0.3	-0.1	-0.2
6	-0.6	-0.2	-0.3	-0.1	-0.2
7	-0.2	0.1	-0.1	-0.4	-0.1
8	-0.2	-0.3	-0.4	0.3	-0.1
9	-0.3	-0.4	-0.6	-0.2	-0.4

1 A total of 3,643, 3,084, 3,992, and 3,935 water's edge points were used to create reach-long water surface profiles for the 1,200, 500, 250, and 50 cfs controlled releases, respectively.
2 Excludes 50 cfs controlled release to omit influence of flow beneath boulders.



Figure 5.2-7. Water conveyed beneath boulder cascade (circled in black) in Sub-reach 2 for 50 cfs controlled release. Model limitations force all flow over the boulders, artificially increasing water levels.

5.3 Discussion of Calibration Results

The following comments on the calibrated model are provided:

- Statistical evaluation of transect velocities and depths show the model performs very well relative to recommended metrics (Pasternack 2011).
- Spatial comparison between observed and simulated values at transects does not indicate that remaining velocity and depth differences warrant further resolve by adjusting model roughness.
- Simulated and observed WSEs agree very well at Existing Feature locations not subject to limitations from a depth-averaged hydraulic model and the surface terrain.
- Mean differences between computed and observed water surface profiles are within expected values and indicate that hydraulic conditions are replicated well throughout the entire Gorge bypass reach.

Overall, performance evaluation shows the Bypass Hydraulic Model represents hydraulic conditions with sufficient resolution and accuracy to simulate velocities and depths for fish habitat assessment. The model also provides acceptable representation of hydraulics at Existing Features 1 and 2 to be used by the FA-04 study team for assessment of fish passage (City Light 2023b) while recognizing the limitations of depth-averaged hydraulic models at these features.

6.0 SUMMARY

The Bypass Hydraulic Model is a detailed depth-averaged hydraulic model of the Gorge bypass reach, extending from Gorge Dam to the USGS Skagit River at Newhalem gage below Gorge Powerhouse. To support model development and calibration, a significant data collection effort was undertaken to procure a high-resolution surface terrain, hydrologic inputs, and a large, well-distributed range of hydraulic observations. The model was developed with HEC-RAS 2-D to ensure optimal accuracy, efficiency, and functionality for meeting study objectives. Sensitivity testing was performed to determine optimal parameters for mesh resolution, computational time step, and turbulence coefficients. Model calibration focused on adjusting roughness parameters to match simulated velocities, depths, and WSEs with observed data from six steady flows ranging from 50 to 6,800 cfs. Statistical and spatial evaluation of model performance shows that the Bypass Hydraulic Model performs very well relative to established metrics, confidence in observed data, and inherent model limitations. The model is well-suited to characterize velocities and depths for assessment of fish habitat in support of the Bypass Instream Flow Model Development Study and as a tool to inform fish passage at Existing Features 1 and 2 for the FA-04 Fish Passage Study (2023b).

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SKAGIT RIVER GORGE BYPASS REACH HYDRAULIC AND INSTREAM FLOW MODEL DEVELOPMENT STUDY
BYPASS HYDRAULIC MODEL CALIBRATION REPORT

ATTACHMENT A

UPPER SKAGIT RIVER GREEN LIDAR RECLASSIFICATION MEMORANDUM

Memo

Date:	March 2022
Project:	Skagit River Project FERC Relicensing
To:	Chris Long, Northwest Hydraulic Consultants (NHC)
From:	Kira Lofgren, HDR Inc. (HDR)
Subject:	Upper Skagit River Green LiDAR Classification

1.0 INTRODUCTION

HDR aided NHC in assessing and modifying Light Detection and Ranging (LiDAR) data collected for Seattle City Light (City Light) to support improved hydraulic modeling of the Gorge bypass reach. HDR's intent is to better characterize the Skagit River basin by refining the LiDAR point classification with the intent to improve point density and develop a more detailed ArcGIS terrain. The final product is a high-resolution bare earth digital elevation model (DEM) of the Gorge bypass reach including detailed topographic features in the riverbed.

1.1 LiDAR Data Utilized

Quantum Spatial (QSI) was contracted by City Light to collect topobathymetric LiDAR data and digital imagery in the spring of 2018 for three sites located in the Skagit River corridor: Upper Skagit River, Gorge Lake, and Diablo Lake (QSI 2018). This data collection utilized bathymetric LiDAR (sometimes referred to as Green LiDAR) which provides some penetration into the water column, resulting in combination of bathymetric and topographic dataset. Table 1 provides dataset details specific to this effort.

1.2 LiDAR Assessment

HDR performed an initial assessment of the products delivered to City Light focusing on LiDAR accuracy, density, and classification. LAS files and derivative LiDAR products were reviewed using ESRI ArcPro. A more thorough visual review of the LAS files was performed using Terrasolid's TerraScan Module. HDR also reviewed QSI's Topobathymetric LiDAR and Orthoimagery Technical Data Report (QSI 2018).

QSI followed LAS ASPRS standards including classification of bathymetric bottom, water surface, and water column (Table 2). QSI's workflow for identifying water points consisted of both manual and automated techniques including bathymetric refraction. A combination of bathymetric bottom and ground returns were used to produce the bare earth DEM. The ground and bathymetric bottom classified density of LiDAR data for the Upper Skagit, Gorge Lake and Diablo Lake project was 0.52 points/ft^2 (5.56 points/m^2).

Table 1. Characteristics of LiDAR dataset.

Project Name and Dates	Bathymetric	Total Acres (US)	Data Resolution and Quality	Original Spatial Reference	Acquisition Dates	Notes
Upper Skagit, Gorge Lake and Diablo Lake, Washington	Y	4,894	Cell Size: 3 ft raster DEM provided by QSI	Projection: Washington State Plane North Horizontal Datum: NAD83 (2011) Vertical Datum: NAVD 88 (GEOID12B) Units: US Survey Feet	4/25/2018 to 4/26/2018	QSI processing report provides analysis of final datasets including LiDAR accuracy and density.

Table 2. American Society for Photogrammetry and Remote Sensing (ASPRS) LAS classification standards applied to the Upper Skagit, Gorge Lake, and Diablo Lake dataset.

Classification Number	Classification Name	Classification Description
1	Default/Unclassified	Laser returns that are not included in the ground class, composed of vegetation and anthropogenic features
2	Ground	Laser returns that are determined to be ground, using automated and manual cleaning algorithms
40	Bathymetric Bottom	Refracted Riegl sensor returns that fall within the water's edge breakline which characterize the submerged topography.
41	Water Surface	Green laser returns that are determined to be water surface points using automated and manual cleaning algorithms.
45	Water Column	Refracted Riegl sensor returns that are determined to be water, using automated and manual cleaning algorithms.

HDR recommended improving upon QSI's already classified ground points. All returns in a point cloud are unclassified to start. Typically, a set of automated processes are used to classify points as ground. These methods do not capture all available ground points. Manually classifying additional ground points in a focused corridor along the river will increase point density and spacing in areas important to improving resolution and accuracy of hydraulic model results. To ensure a reprocessing effort covered an adequate extent for the hydraulic model, NHC identified these extents from analysis of preliminary hydraulic model results and provided HDR with a delineated boundary within which to perform the point reclassification analysis. The reclassification extent includes the channel bottom and, at a minimum, the bank toe below vegetated area. These extents are displayed on Figure 1. Areas delineated as bathymetric bottom would be left as is. Increased ground-point density in the riverbed will allow for the development of a bare earth DEM with one-foot terrain resolution along the riverbed in areas that weren't previously identified as bathymetric bottom to support detailed hydraulic analyses for instream flow and fish passage in the Gorge bypass reach. A sample area was processed and reviewed by NHC and HDR before proceeding with reprocessing.

1.3 LiDAR Data Processing

LiDAR processing broadly utilized three workflows; these are:

(1) Point Cloud Classification – This workflow uses tools specific to Terrasolid products to identify and assign points from default to ground class.

(2) Terrain Surface Creation – This workflow creates ESRI terrain datasets.

(3) Raster DEM Creation – Generating derivative GIS products from the ESRI terrain dataset.

1.3.1 Point Cloud Classification

Ground classification routines do not delineate riverbed topography well. Most automated ground classification methods will pick up small changes in topography but not drastic elevation changes such as boulders. Therefore, HDR manually classified additional default points to ground using the following steps:

- LiDAR points were associated with RGB values using ArcGIS Pro Colorize LAS.
- Areas with bathymetric bottom returns that should not be modified were delineated as polygons. LAS points in these polygons were coded with a unique class to ensure points were not classified as ground. ArcGIS Pro tool Change LAS Class Codes was used to change class from default to an unreserved temporary class (65).
- Default returns were manually classified as ground points using a suite of classification tools available in TerraScan. Terrasolid's TerraScan module is run through OpenRoads Designer which can be formatted for multiple data views allowing the analyst to see both top down and profile views to aid in classification. Figure 2 is an example of the cross-section view.
- Boulders were revisited to ensure ample points were classified as ground.

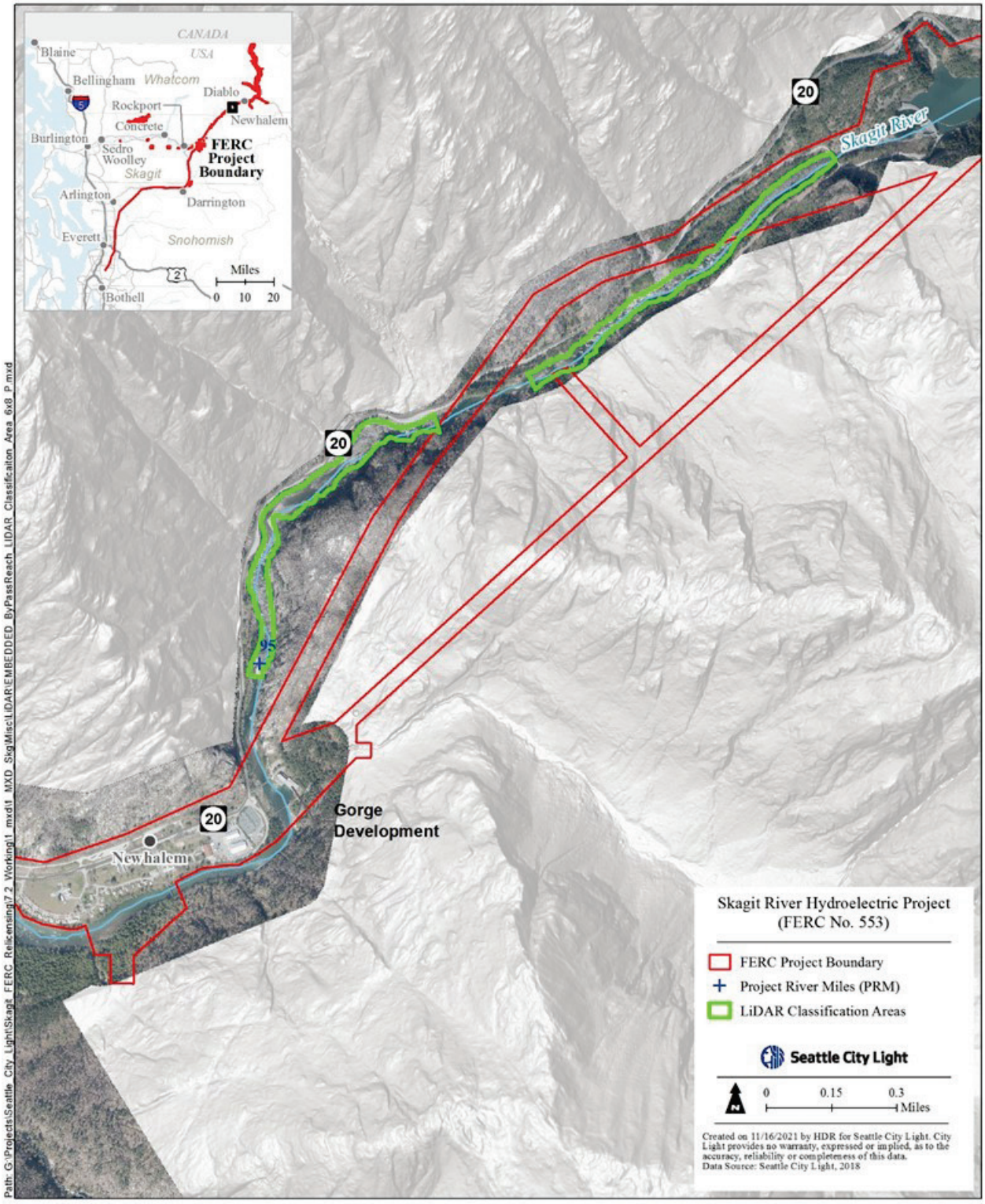


Figure 1. Project footprint and LiDAR classification areas.

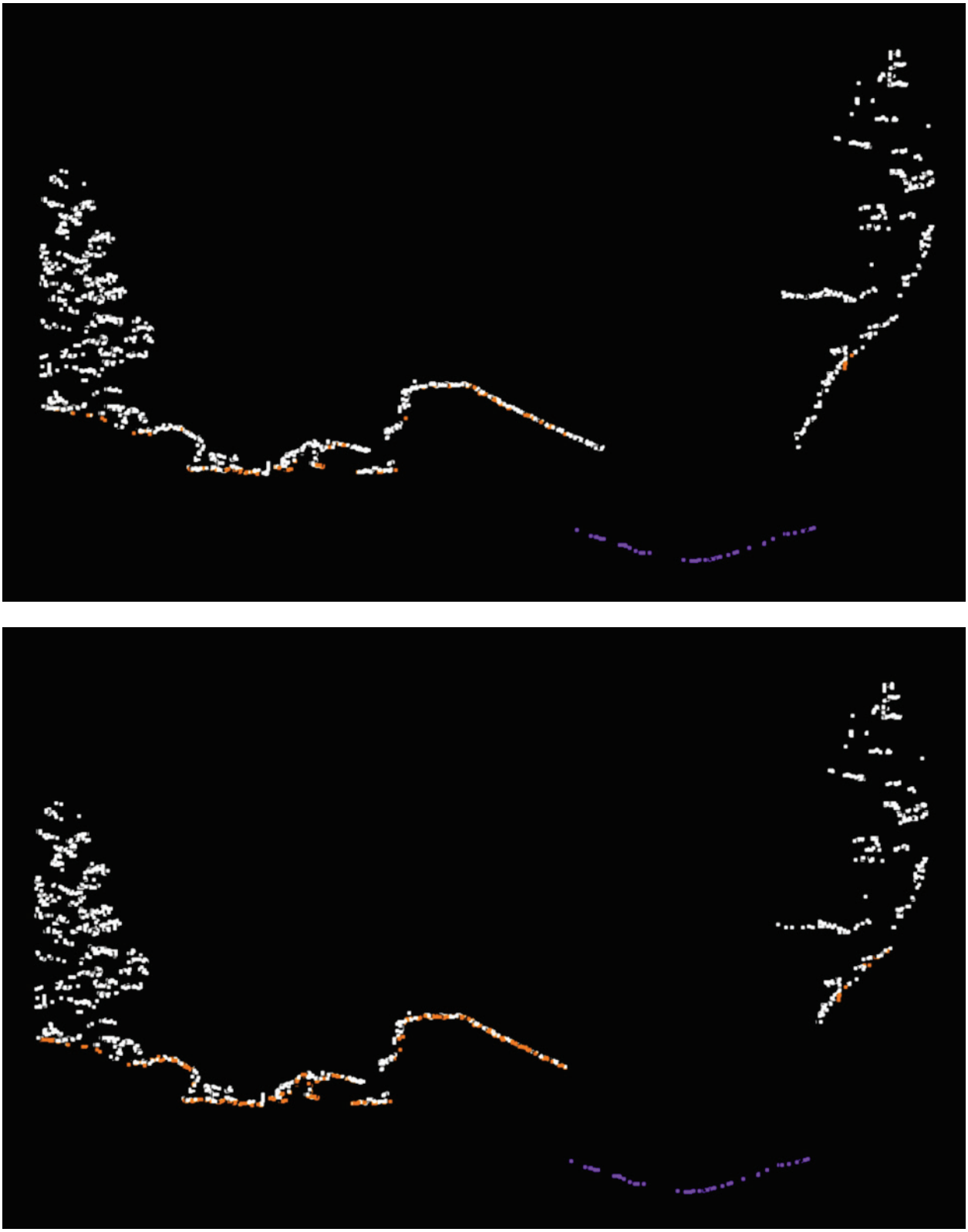


Figure 2. **Cross sections showing default (white), ground (orange) and bathymetric bottom (purple) points before (upper) and after (lower) manual ground classification.**

1.3.2 Terrain Surface Creation

NHC identified areas where the 2018 bathymetric LiDAR survey extent did not cover enough area to accommodate the hydraulic model. The United States Geological Survey's (USGS) Western Washington 3DEP – North AOI (2016) LiDAR dataset (QSI 2017) was utilized to expand coverage where needed. LiDAR data extents and sources are displayed on Figure 3.

LAS files were utilized to produce an ESRI terrain triangulated surface. Digital elevation models (DEMs) were produced from bare earth ground surfaces consisting of only classified ground and bathymetric bottom returns (LAS class 2 and 40). The ESRI terrain was created using the following steps:

- A file Geodatabase was created containing a feature dataset (FDS) set to the FIPS 2926 project coordinate system;
- The 2018 LAS data was filtered by ground and bathymetric bottom returns and converted to ESRI multipoint format in the FDS. The 2016 LAS data was filtered by ground returns and converted to ESRI multipoint format in the FDS;
- Data boundary polygons were loaded into the FDS. Water's edge break lines were provided by QSI but were not granular enough to include in the terrain;
- The blank terrain was created in the FDS;
- Z-tolerance pyramids were created in the terrain. This set requirements for reduced resolution versions of the terrain that can be useful for larger footprint modeling. For instance, watershed-level models frequently use reduced resolution terrains. The Z-tolerance setting was used to control the degree of any potential elevation offsets in the reduced resolution terrains;
- All Feature Classes in the FDS were added to the terrain;
- The terrain was built; and,
- Terrain was reviewed visually for general consistency and through summary statistics for anomalous values.

The terrain datasets provide a flexible environment that can be updated in the future if City Light has a need to integrate newly acquired survey data.

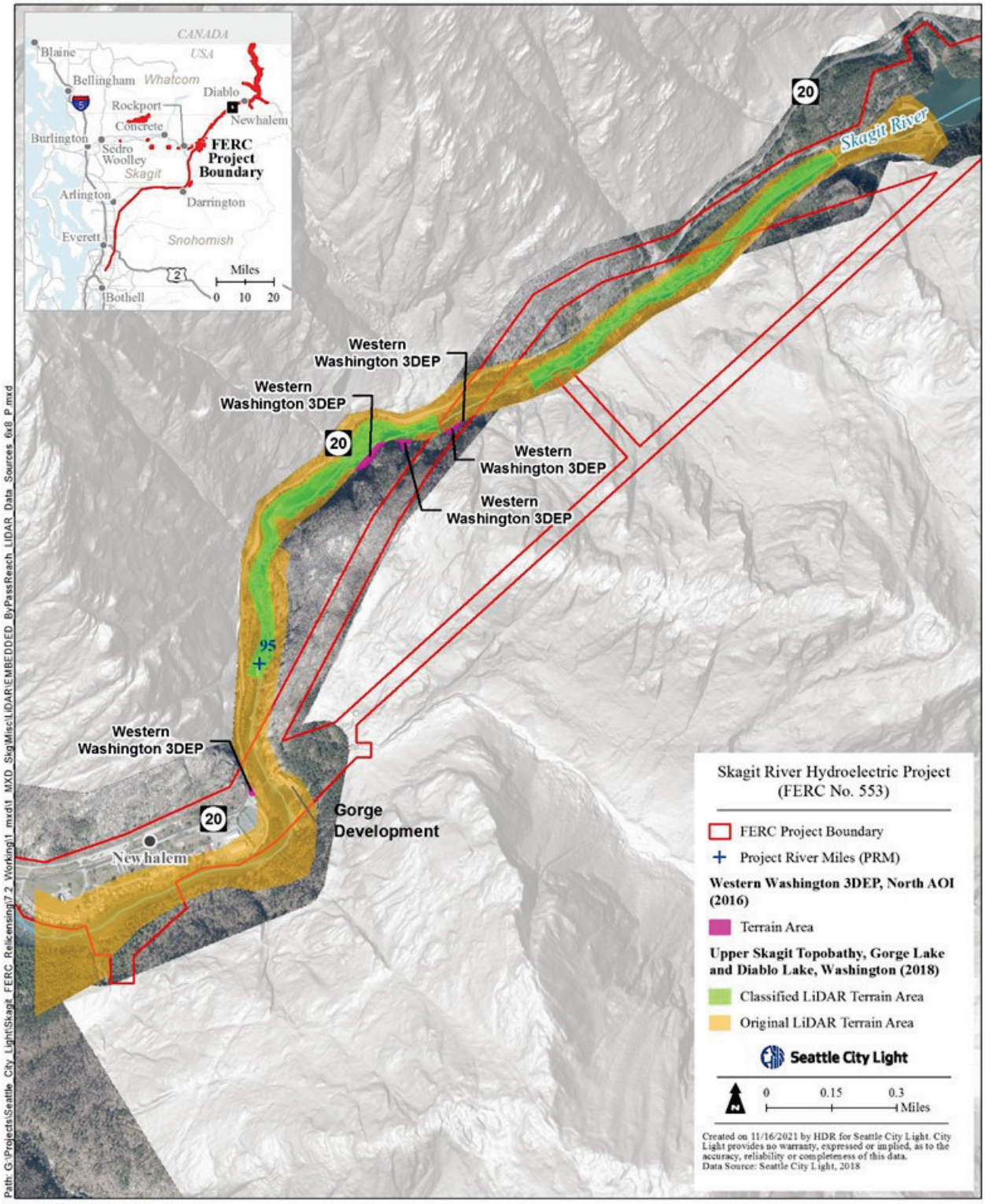


Figure 3. Bare Earth DEM LiDAR data sources.

1.3.3 Raster DEM Creation

Bare earth DEMs were generated utilizing the classified ground and bathymetric bottom LAS data terrain. HDR used the ArcGIS Pro Tool, Terrain to Raster generating a DEM with a 1-foot raster cell resolution. Raster cell resolution was selected to preserve detail in higher ground point density. The higher ground point density supports a raster resolution down to 1 foot in areas of particular relevance for improving the accuracy of hydraulic modeling, but the majority of the dataset does not support a resolution smaller than 3 feet.

The Hillshade dataset is a visualization of the Bare Earth DEM. This visualization uses the ESRI Spatial Analyst hillshade tool utilizing default settings. This provides an easily-interpreted surface for LiDAR data visualization. Figure 4 displays a comparison of the DEM with a 3-foot raster cell resolution provided by QSI as part of the LiDAR deliverables package and the HDR DEM with a 1-foot raster cell resolution.

1.3.4 Modified LiDAR Review

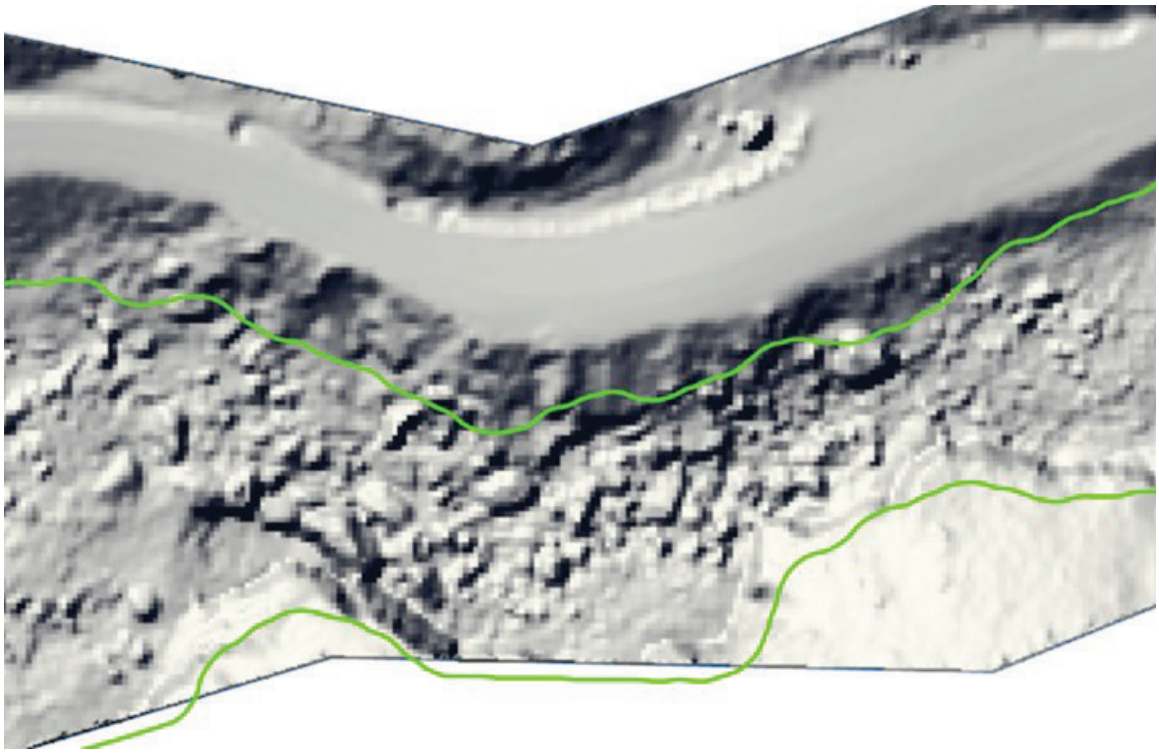
In areas where we focused our efforts, the ground and bathymetric bottom classified density of LiDAR data is 27 points/m^2; a large increase compared to QSI's reported density of 5.56 points/m^2. A standard deviation of 19.65 in the updated dataset reflects the large variance between the densities in comparison to areas covered by riverbed and water. Steep slopes and standing water areas have a low point density. Rocky riverbeds and areas with boulders have a higher density, see Figure 5.

1.3.5 Coordinate System

LAS files were transformed to City Light's preferred coordinate system using ESRI ArcPro LiDAR Tools. No vertical datum shift was required. All LiDAR datasets and derivative products are in:

Projection: Washington State Plane North
Horizontal Datum: NAD83 (HARN)
Vertical Datum: NAVD88 (GEOID12B)
Units: US Survey Feet

Original QSI-produced DEM with a 3-foot raster cell resolution.



HDR-produced DEM with 1-foot raster cell resolution.

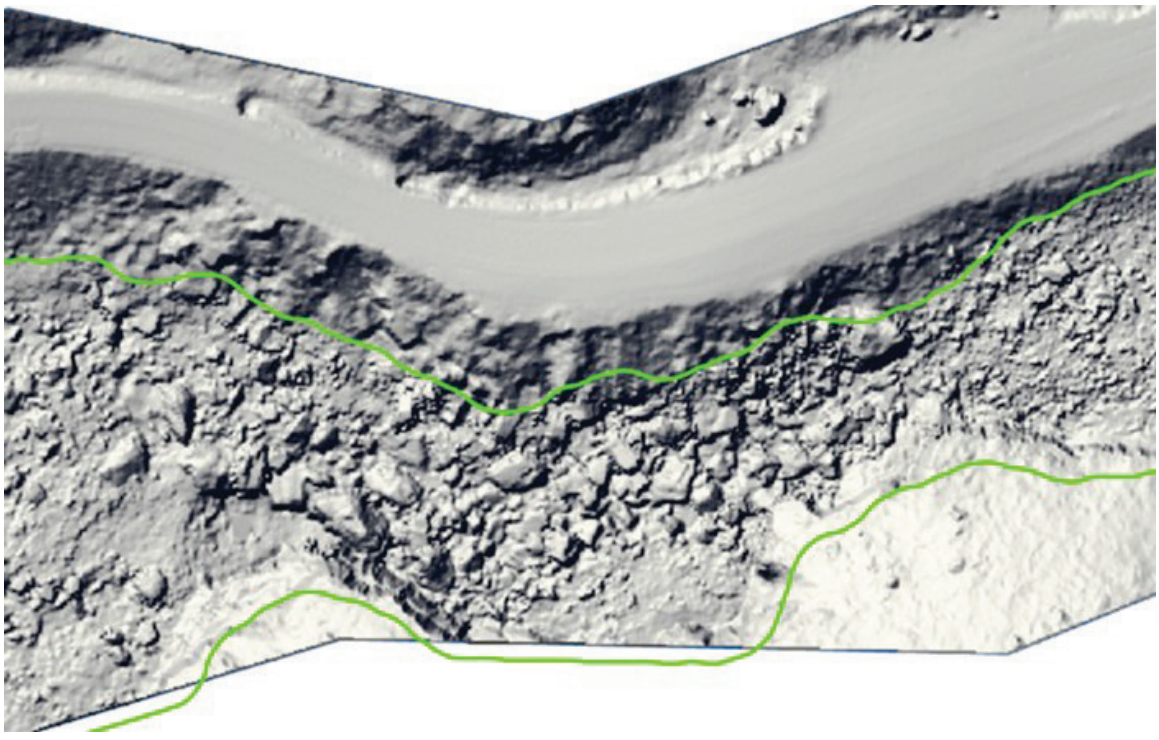


Figure 4. **Bare earth DEM hillshade comparison. Green line indicates boundary of additional ground point classification.**

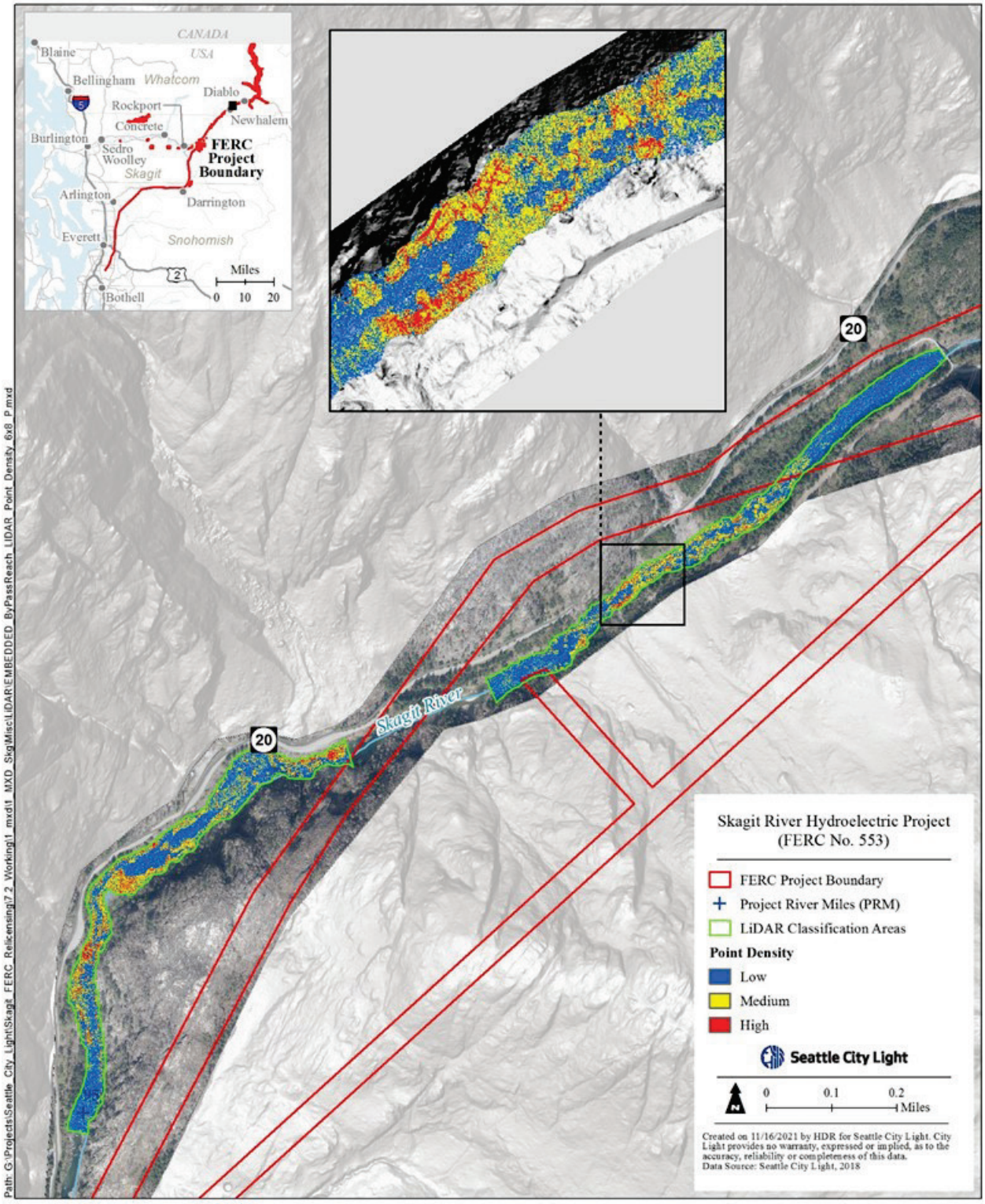


Figure 5. LiDAR point density.

1.3.6 Additional Resources

- APSRS LAS specifications:
    - https://www.asprs.org/a/society/committees/standards/LAS_1_4_r13.pdf
- ESRI Terrain datasets.
    - https://pro.arcgis.com/en/pro-app/help/data/terrain-dataset/terrain-dataset-in-arcgis-pro.htm

1.4 Conclusions

HDR assessed and modified LiDAR data contracted by City Light to support improved hydraulic modeling of the Gorge bypass reach. HDR better characterized the Gorge bypass reach riverbed by refining the LiDAR point classification, thereby improving point density and developing a more detailed terrain. The final product is a high-resolution bare earth DEM of the Gorge bypass reach including detailed topographic features in the riverbed. Note that while the reclassified data more accurately reflects terrain conditions in the riverbed, this did not follow a standard processing workflow and should not be used outside the context of this specific hydraulic modeling effort.

2.0 REFERENCES

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SKAGIT RIVER GORGE BYPASS REACH HYDRAULIC AND INSTREAM FLOW MODEL DEVELOPMENT STUDY
BYPASS HYDRAULIC MODEL CALIBRATION REPORT

ATTACHMENT B

SKAGIT LIDAR VERTICAL ADJUSTMENT

Memo

Date:	March 2023
Project:	Skagit River Project FERC Relicensing
To:	Chris Long, Northwest Hydraulic Consultants (NHC)
From:	Thomas Prescott, HDR Engineering, Inc. (HDR)
Subject:	Skagit LiDAR Vertical Adjustment

1.0 INTRODUCTION

HDR Engineering, Inc. (HDR) aided Northwest Hydraulic Consultants (NHC) with their use of Light Detection and Ranging (LiDAR) data to support hydraulic modeling of the Skagit River for Seattle City Light (City Light). HDR staff have over 15 years of experience collecting and processing aerial LiDAR data and often provide guidance to clients and contractors regarding the use of airborne LiDAR.

Vertical misalignments between three of the LiDAR datasets used to create the hydraulic model were observed and are discussed in a previous tech memo "Skagit Bathymetric LiDAR Evaluation" (HDR 2020). Small (1 to 2 inch) positional differences between LiDAR datasets are not uncommon and often can be attributed to differences in the survey control used to position the data.

This memo documents a series of steps that were performed to align/normalize the elevations of the three LiDAR datasets used to create the hydraulic model.

1.1 Software

The following programs were used for data analysis and processing.

- Bentley MicroStation: A computer aided drafting program designed for generating engineering drawings.
- TerraSolid TerraScan: Runs as a MicroStation plug-in and is an industry standard program for LiDAR point cloud classification and data accuracy assessment.
- ESRI ArcGIS: A geographic information system used for working with maps and other geospatial data.
- Blue Marble Graphics Global Mapper: A geographic information system used for working with maps and other geospatial data, most commonly used for coordinate transformations and reprojections of geospatial data.

1.2 LiDAR Datasets

Two of the datasets used in the study were collected with bathymetric (green) LiDAR technology that allows for some penetration of the water column. The third was collected under the U.S. Geological Survey (USGS) 3DEP (3D Elevation Program) program utilizing traditional infrared LiDAR. The datasets are:

- "Skagit Topobathy, Washington" (herein referred to as Barnaby Slough), topobathymetric green LiDAR, 2017
- "Upper Skagit, Gorge Lake and Diablo Lake, Washington," topobathymetric green LiDAR, 2018
- "Western Washington 3DEP," traditional infrared LiDAR, 2017

The Upper Skagit, Gorge Lake, and Diablo Lake LiDAR dataset occupies the northern reaches of the Skagit River. Barnaby Slough is further down river and overlaps the southern section of the Upper Skagit, Gorge Lake, and Diablo Lake dataset. The Western Washington 3DEP – North area of interest (AOI) data is the largest of the three. It covers a significant portion of Western Washington and overlaps the two other datasets (see Figure 1).

The Upper Skagit, Gorge Lake, and Diablo Lake and Barnaby Slough LiDAR collections were flown and processed by Quantum Spatial Inc. (QSI) for City Light. The Western Washington 3DEP LiDAR data were collected by a consortium of data vendors all working under QSI.

All three datasets were transformed in Global Mapper to share the same Coordinate Reference Frame, Washington State Plane North, North American Datum of 1983 High Accuracy Reference Network (NAD83 [HARN]), North American Vertical Datum of 1988 (NAVD 88) via Geoid 12B, U.S. Survey feet (ft).

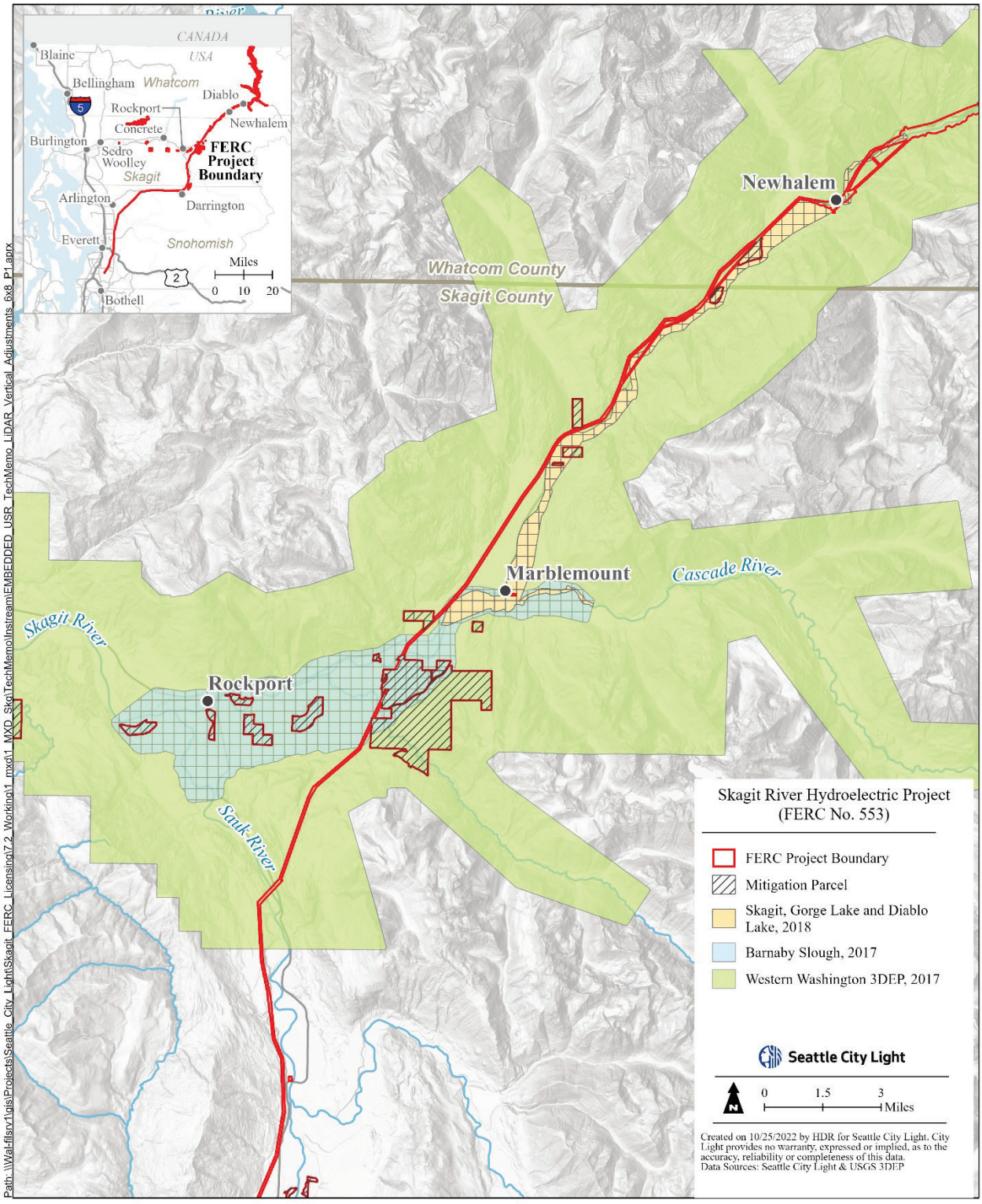


Figure 1. LiDAR dataset locations used in the vertical alignment.

2.0 DATA ANALYSIS

LiDAR point cloud data were analyzed and adjusted in TerraScan, an industry standard software used for working with LiDAR that runs as a Bentley MicroStation plug-in. Datasets were loaded for simultaneous analysis and viewed in cross section to assess overlap. Offsets between datasets were measured using the measure distance tool in MicroStation and recorded in a spreadsheet. Measurements were scaled off flat planar targets (i.e., roads and rooftops).

Flat paved surfaces are regularly used by LiDAR vendors to assess Non-Vegetated Vertical Accuracy (NVA). Systematic biases in the LiDAR apparatus caused by environmental variables such as air pressure, manifest in the dataset as being up or down relative to quality control (QC) points. Vendors calculate the average offset of LiDAR relative to QC points and perform a linear vertical adjustment of the LiDAR point cloud, known as a "Dz" adjustment. A similar approach was utilized here with the Western Washington LiDAR used as the reference, because the Western Washington data completely overlaps the other two datasets, and because an exceptionally large ground survey was performed by QSI to verify the data.

The town of Newhalem resides in the center of the Upper Skagit, Gorge Lake, and Diablo Lake data and was the focus of several measurements for comparison with the Western Washington data. The town of Rockport resides near the center of the Barnaby Slough data and was the location of several measurements for comparison with the Western Washington data. The two towns were chosen because of the relative abundance of paved roads and rooftops. Measurements were scaled in a few other areas, including the small town of Marblemount, to help ensure measurements were spatially distributed throughout the data.

For comparison of the Western Washington 3DEP data with the Barnaby Slough data, 22 measurements were collected to determine the average vertical offset between the two datasets (Appendix A). The 2017 Barnaby Slough data measured 0.1256 ft lower relative to the 2017 Western Washington data with a root-mean-square error (RMSE) of 0.1515 ft.

Table 1 and Figure 2 contain the comparison results. Note, the negative average value indicates the Barnaby Slough data is lower relative to the Western Washington 3DEP data.

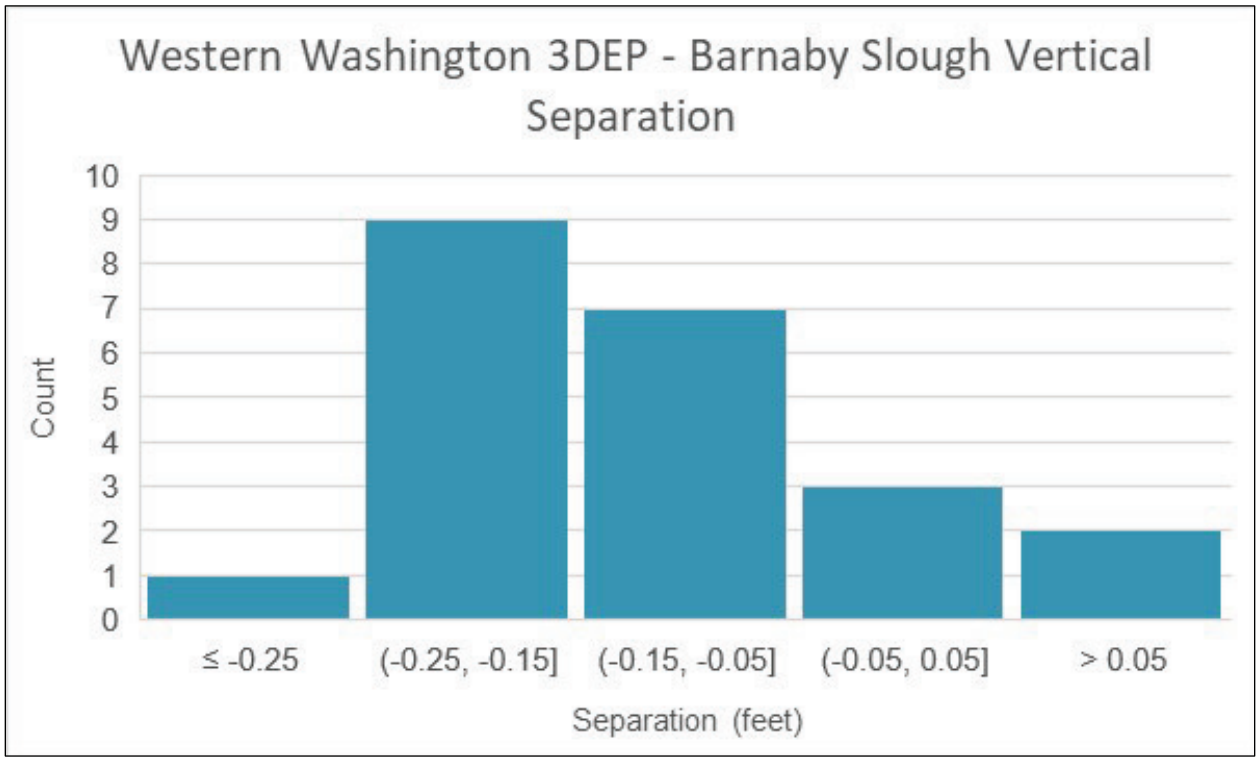
Table 1. Western Washington 3DEP vertical separation – Barnaby Slough.

Western Washington 3DEP Vertical Separation – Barnaby Slough[1]	
Average Dz (ft)	-0.1256
RMSE (ft)	0.1515
Min Dz (ft)	-0.2515
Max Dz (ft)	+0.0729

1 Measurements obtained by subtracting Barnaby Slough LiDAR elevation values from the Western Washington 3DEP LiDAR elevation values at select locations.

For comparison of the Upper Skagit, Gorge Lake, and Diablo Lake LiDAR data with the Western Washington LiDAR data, 21 measurements were collected to determine the average vertical offset between the two datasets (Appendix B). Upper Skagit, Gorge Lake, and Diablo Lake data measured 0.372 ft lower relative to the Western Washington data with an RMSE of 0.378.

Table 2 and Figure 3 contain results from the comparison. Note the negative average value indicates the Upper Skagit, Gorge Lake, and Diablo Lake data are lower relative to the Western Washington 3DEP data.



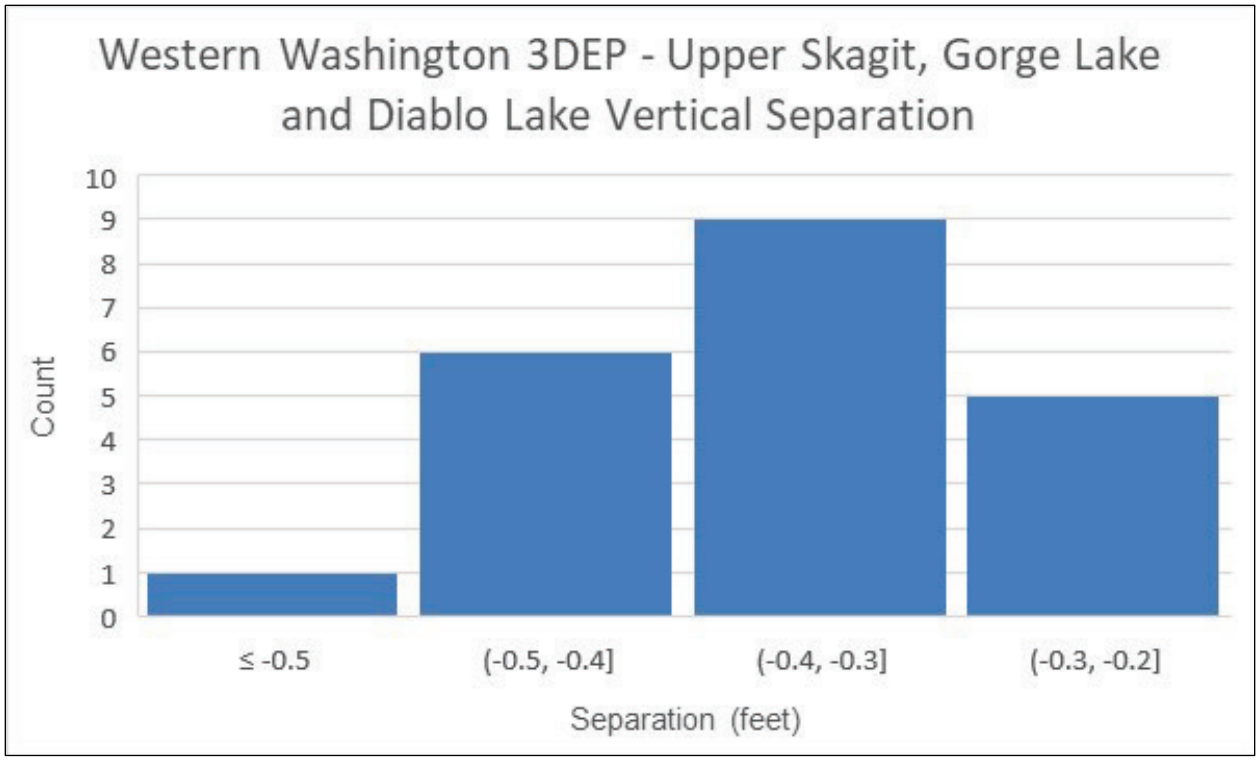
Source: Frequency distribution obtained by subtracting elevation values of the Barnaby Slough LiDAR from the Western Washington 3DEP LiDAR at select locations.

Figure 2. Barnaby Slough and Western Washington 3DEP LiDAR frequency distribution histogram.

Table 2. Western Washington 3DEP – Upper Skagit, Gorge Lake and Diablo Lake.

Western Washington 3DEP – Upper Skagit, Gorge Lake and Diablo Lake[1]	
Average DZ (ft)	-0.3720
RMSE (ft)	0.3786
Min Dz (ft)	-0.5091
Max Dz (ft)	+0.2728

1 Measurements obtained by subtracting Upper Skagit, Gorge Lake and Diablo Lake elevation values from Western Washington elevation values at select locations.



Source: Frequency distribution obtained by subtracting elevation values of the Barnaby Slough LiDAR from the Western Washington 3DEP LiDAR at select locations.

Figure 3. Upper Skagit, Gorge Lake and Diablo Lake and Western Washington 3DEP LiDAR frequency distribution histogram.

More than 400 survey points were also collected by NHC to support their hydraulic modeling efforts and were compared by HDR to the Upper Skagit, Gorge Lake, and Diablo Lake LiDAR data. The survey points were not intended to support NVA analysis. The survey points NHC collected fit the description of Vegetated Vertical Accuracy (VVA) QC points. VVA points are used in less-than-ideal areas to characterize accuracy, (i.e., vegetated, sloped, rocky areas). Though not all the points collected occur within the LiDAR AOI, more than 250 survey points overlapped the 2018 Upper Skagit, Gorge Lake, and Diablo Lake LiDAR point cloud.

The survey points referenced the Washington State Reference Network (WSRN). The WSRN is a high accuracy real-time Global Positioning System (GPS) network used to reduce errors in GPS surveys. Both the survey points and the LiDAR were compared to each other in NAD83 (2011) NAVD 88, before the LiDAR data were converted to NAD83(HARN).

The Upper Skagit, Gorge Lake, and Diablo Lake LiDAR measured -0.293 ft lower than the survey points with an RMSE value of 0.684 ft (Appendix C).

VVA points are generally not used to vertically adjust LiDAR because they are collected in less ideal ground conditions (i.e., rocky slopes, vegetation); however, the large quantity of points collected by NHC and magnitude of average offset (-0.293 ft) suggests the presence of a negative bias in the 2018 LiDAR.

NVA and VVA are both discussed in American Society for Photogrammetry and Remote Sensing (ASPRS) Positional Accuracy Standards.

Under HDR advisement, NHC and HDR decided to hold the Western Washington 3DEP LiDAR as control and adjust the other two datasets to it. This was decided in part because it (Western Washington 3DEP data) is the largest of the three datasets, but also because it already lined up well (vertically) with the 2017 Barnaby Slough data and because the Upper Skagit, Gorge Lake and Diablo Lake data was already proven to be low relative to survey. Furthermore, an exceptionally large ground campaign was performed by QSI to help process and verify the Western Washington 3DEP LiDAR involving over 100 survey monuments, 14,675 supplemental ground control points, and 182 quality assurance points (QSI 2017b). The scale of this effort increases confidence in the accuracy of the Western Washington dataset.

The previously noted measurements collected over flat surfaces between the LiDAR point clouds were used as the basis to vertically adjust the Barnaby Slough and Upper Skagit, Gorge Lake and Diablo Lake, LiDAR datasets. A summary of adjustments is provided in Table 3. Survey points collected by NHC were not factored into the adjustment values. No additional survey points were available for this effort.

Table 3. Summary of vertical adjustments.

Project Name	Bathymetric	Total Acres	Resolution and Quality	Acquisition Dates	Dz Adjustment
Western Washington 3DEP – North AOI	No	1,984,774	0.5 meters	03/17/2016 – 06/06/2017	0
Barnaby Slough	Yes	11,650	0.5 meters	04/21/2017	+0.12 ft
Upper Skagit, Gorge Lake and Diablo Lake	Yes	4,894	0.5 meters	04/25/2018 to 04/26/2018	+0.37 ft

3.0 DATA PROCESSING

LiDAR processing involved the following three main steps:

(1) Dz adjustment – This step uses tools specific to TerraScan to vertically adjust the LiDAR point clouds.

(2) Terrain Surface Creation – This step creates ESRI terrain datasets.

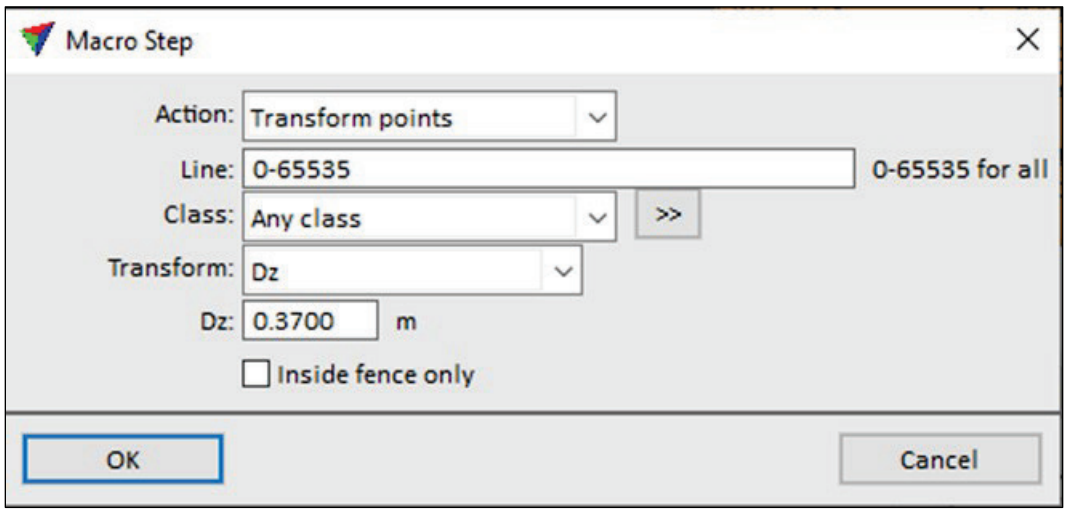
(3) Raster digital elevation model (DEM) Creation – Generating derivative GIS products from the ESRI terrain dataset.

3.1 DZ Adjustments

The original point cloud data were adjusted, and new terrain models created from the adjusted data, as it is best practice to go back to the source data rather than adjust raster DEMs.

A project was created in TerraScan to facilitate batch processing of large volumes of LiDAR with minimal steps and minimize the risk of human error that may occur through repetitive interaction with the data.

Next, a macro was created in TerraScan with the Data Transformation option selected as the action. Dz adjustment was selected as the transformation method (Figure 4). For the Upper Skagit, Gorge Lake, and Diablo Lake data a value of 0.37 ft was entered. The macro was then applied to the entire dataset. The same transformation method was used for the Barnaby Slough data with a value of 0.12 ft.



Note: the "m" to signify meters in this figure, is the default unit always represented in the TerraScan graphical user interface. The units are US Survey Feet as defined in the dgn seed file and the LiDAR point cloud data.

Figure 4. Macro used to adjust data in TerraScan.

The adjusted data were compared in cross section to the Western Washington data, again over paved roads, to ensure the macro worked as expected (Figure 5 and Figure 6). The data were saved with modified file names to avoid confusion with any non-vertically adjusted data.

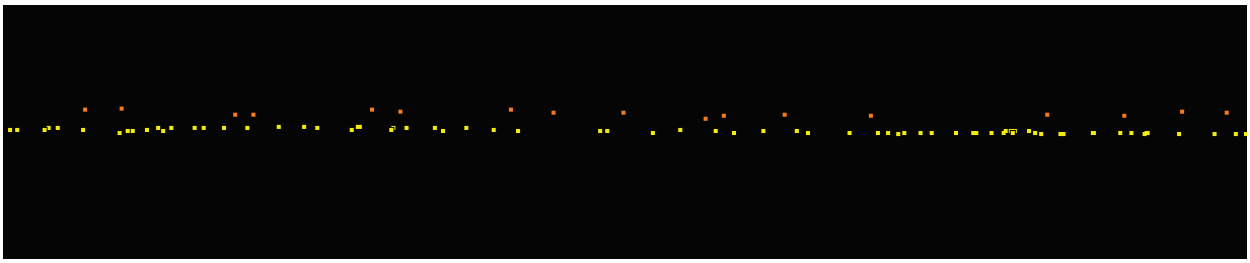


Figure 5. **Cross section of Upper Skagit, Gorge Lake, and Diablo Lake (yellow), and the Western Washington 3DEP Data (brown), before the adjustment.**

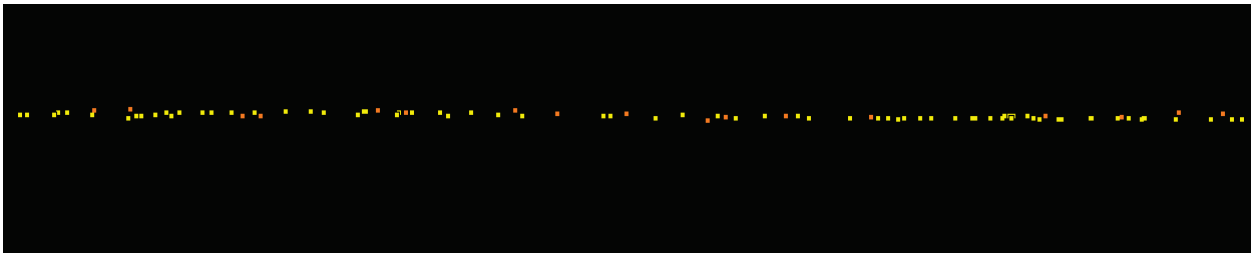


Figure 6. **Cross section of the Upper Skagit, Gorge Lake, and Diablo Lake (yellow) and Western Washington 3DEP (brown), after the adjustment.**

3.2 Terrain Creation

An ESRI terrain triangulated surface was created from LAS files. DEMs were produced from bare earth ground surfaces consisting of only classified ground and bathymetric bottom returns (LAS class 2 and 40). The ESRI terrain was created using the following steps:

- A file Geodatabase was created containing a Feature Dataset (FDS) set to the FIPS 2926 project coordinate system.
- LAS data was filtered by ground and bathymetric bottom returns and converted to ESRI multipoint format in the FDS.
- Data boundary polygons were loaded into the FDS to mask the terrain extent.
- The blank terrain was created in the FDS.
- Z-tolerance pyramids were created in the terrain. This set requirements for reduced resolution versions of the terrain that can be useful for larger footprint modeling. For instance, watershed level models frequently use reduced resolution terrains. The Z-tolerance setting was used to control the degree of any potential elevation offsets in the reduced resolution terrains.
- All Feature Classes in the FDS were added to the terrain.
- The terrain was built.
- Terrain was reviewed visually for general consistency and through summary statistics for anomalous values.

The terrain datasets provide a flexible environment that can be updated in the future if City Light needs to integrate newly acquired survey data.

3.3 Raster DEM Creation

Bare earth DEMs were generated using the classified ground and bathymetric bottom LAS data terrain. HDR used the ArcGIS Pro Tool, Terrain to Raster generating a DEM with a 3-ft raster cell resolution. Raster cell resolution matched the cell resolution of DEMs provided by QSI in the original data deliverables.

3.4 Missing Data

NHC discovered an anomalous area in the Upper Skagit, Gorge Lake, and Diablo Lake data that appeared a little different than the raster DEM originally provided by the vendor. Upon further review, it was determined some of the LiDAR points were missing in tile 92 of LiDAR point cloud data provided by City Light.

HDR created a subset of points from the original DEM and added them to the terrain using the following steps:

- The Raster to Points tool in ArcGIS was used to extract a subset of points from tile 92 of the original raster DEM.
- The points were loaded into Global Mapper and converted from NAD83 (2011) to NAD83 (HARN).
- The points were loaded into TerraScan and a +0.37-ft Dz shift applied to the points.
- The points were added as a new feature class to the terrain FDS.
- The terrain was recreated.
- A new Raster DEM was created from the terrain.

4.0 SUMMARY

HDR analyzed and vertically adjusted the Barnaby Slough and Upper Skagit, Gorge Lake, and Diablo Lake, LiDAR datasets to line up with the Western Washington 3DEP LiDAR. A new set of terrain models and raster DEMs was created from the adjusted point cloud data and provided to NHC for use in the hydraulic models.

5.0 REFERENCES

American Society for Photogrammetry and Remote Sensing (ASPRS). 2014. Positional Accuracy Standards for Digital Geospatial Data. Edition 1. Version 1. November 2014. [Online] URL: https://www.asprs.org/wp-content/uploads/2015/01/ASPRS_Positional_Accuracy_Standards_Edition1_Version100_November2014.pdf.

HDR Engineering, Inc. 2020. Skagit Bathymetric LiDAR Evaluation. January 2020.

Quantum Spatial, Inc. (QSI). 2017a. Skagit Topobathy, Washington Topobathymetric LiDAR Technical Report. Report prepared for the Skagit River System Cooperative. July 21, 2017.

_____. 2017b. Western Washington 3DEP LiDAR technical data report. Report prepared for USGS. September 29, 2017.

_____. 2018. Upper Skagit, Gorge Lake & Diablo Lake, Washington. Topobathymetric LiDAR & orthoimagery technical data report. Report prepared for Seattle City Light. August 17, 2018.

SKAGIT LIDAR VERTICAL ADJUSTMENT

APPENDIX A

BARNABY SLOUGH AVERAGE VERTICAL OFFSET

Measurements to determine the offset between the 2017 Skagit Topobathy Barnaby Slough and 2017 Western Washington 3DEP LiDAR datasets.

Western Washington –(minus) Barnaby Slough Data				
Measurement	**Z Difference**	**Difference Squared**	**X**	**Y**
1	-0.1399	0.01957201	1458624.58	538479.19
2	0.0729	0.00531441	1458648.59	538373.29
3	-0.2091	0.04372281	1458739.78	538359.75
4	-0.2451	0.06007401	1459838.04	537826.59
5	-0.0675	0.00455625	1460366.16	537750.11
6	-0.1402	0.01965604	1454938.84	542965.14
7	-0.1517	0.02301289	1454969.27	542448.54
8	-0.1676	0.02808976	1455387.05	542452.78
9	-0.1541	0.02374681	1456254.83	541969.2
10	-0.137	0.018769	1456020.3	542868.42
11	-0.1131	0.01279161	1454695.64	542190.88
12	0.0536	0.00287296	1454651.24	542262.66
13	-0.1388	0.01926544	1455788.18	542874.95
14	-0.0277	0.00076729	1458712.07	535660.13
15	-0.0315	0.00099225	1459030.67	535651.75
16	-0.1639	0.02686321	1459356.45	535646.87
17	-0.0478	0.00228484	1488351.86	552872.81
18	-0.1661	0.02758921	1488354.94	552869.35
19	-0.1453	0.02111209	1487005.45	553318.6
20	-0.153	0.023409	1486537.49	552428.2
21	-0.2515	0.06325225	1487062.45	553452.7
22	-0.2393	0.05726449	1486544.36	552714.3
Average	-0.125622727	0.022953574		
RMSE		0.15150437		

SKAGIT LIDAR VERTICAL ADJUSTMENT

APPENDIX B

UPPER SKAGIT, GORGE LAKE, AND DIABLO LAKE AVERAGE VERTICAL OFFSET

Measurements to determine the offset between the 2018 Upper Skagit, Gorge Lake, and Diablo Lake and 2017 Western Washington LiDAR datasets.

Western Washington –(minus) Upper Skagit, Gorge Lake and Diablo Lake				
Measurement	**Z Difference**	**Difference Squared**	**X**	**Y**
1	-0.397	0.157609	1541338.96	610695.18
2	-0.39	0.1521	1541351.49	610667.02
3	-0.4477	0.20043529	1539194.83	609923.14
4	-0.287	0.082369	1540153	610324.43
5	-0.358	0.128164	1540084.59	610296.89
6	-0.3403	0.11580409	1541359.71	610585.17
7	-0.5091	0.25918281	1541752.19	610800.26
8	-0.4625	0.21390625	1539555.23	610037.44
9	-0.4615	0.21298225	153910212	609953.38
10	-0.3555	0.12638025	1539485.8	610123.14
11	-0.4607	0.21224449	1539746.25	610138.12
12	-0.4163	0.17330569	1537864.63	610540.9
13	-0.4495	0.20205025	1543587.03	615946.72
14	-0.344	0.118336	1544868.68	616611.43
15	-0.3247	0.10543009	1487288.99	553995.57
16	-0.2832	0.08020224	1487846.25	553823.61
17	-0.2987	0.08922169	1487659.54	555196.51
18	-0.281	0.078961	1487913.24	553450.59
19	-0.357	0.127449	1487825.98	553830.32
20	-0.3156	0.09960336	1488224.82	553994.77
21	-0.2728	0.07441984	1495799.36	559976.76
Average	-0.372004762	0.14334079		
RMSE		0.378603737		

SKAGIT LIDAR VERTICAL ADJUSTMENT

APPENDIX C

CONTROL REPORT

Control report generated in TerraScan by comparing survey points collected by NHC with the 2018 Upper Skagit, Gorge Lake, and Diablo Lake LiDAR datasets.

Number	Easting	Northing	Known Z	LaserZ	Dz
1	1466715.662	544873.268	236.214	outside	*
2	1466715.667	544873.263	236.235	outside	*
3	1466715.638	544873.256	236.235	outside	*
1003	1478161.196	541972.212	298.035	outside	*
1004	1478154.750	541969.206	297.968	outside	*
1005	1478147.797	541965.390	297.902	outside	*
1006	1478144.769	541963.294	297.933	outside	*
1007	1478138.412	541959.848	298.185	outside	*
1008	1478131.382	541956.042	298.670	outside	*
1009	1478127.424	541954.075	298.469	outside	*
1011	1478133.581	541957.531	297.755	outside	*
1012	1478141.027	541961.570	298.347	outside	*
1013	1478146.365	541965.143	298.509	outside	*
1014	1478152.158	541967.636	298.432	outside	*
1015	1478155.015	541969.238	298.000	outside	*
1016	1478159.414	541971.199	298.165	outside	*
1017	1478163.230	541973.666	297.930	outside	*
1018	1478169.505	541976.804	299.344	outside	*
1019	1478172.154	541978.289	299.669	outside	*
1020	1478172.606	541978.458	299.513	outside	*
1021	1466828.789	545045.537	239.250	outside	*
1022	1466823.398	545047.832	237.578	outside	*
1023	1466818.354	545048.494	237.771	outside	*
1024	1466813.641	545050.289	237.592	outside	*
1025	1466808.625	545051.326	237.444	outside	*
1026	1466803.877	545052.606	237.662	outside	*
1027	1466799.234	545054.156	238.363	outside	*
1028	1466795.693	545057.427	239.028	outside	*
1030	1466686.049	545057.762	250.214	outside	*
1031	1466690.613	545065.459	244.933	outside	*
1032	1466688.083	545063.589	244.597	outside	*
1033	1466686.599	545061.651	244.069	outside	*
1036	1466687.202	545060.078	246.267	outside	*
1037	1466685.847	545058.892	246.497	outside	*
1038	1466685.908	545058.850	246.570	outside	*
1043	1451739.963	541760.669	212.044	outside	*
1044	1451736.637	541752.139	212.127	outside	*
1045	1451732.617	541743.426	212.530	outside	*
1046	1451728.824	541733.564	212.308	outside	*

Number	Easting	Northing	Known Z	LaserZ	Dz
1047	1451725.915	541724.226	212.611	outside	*
1048	1451722.959	541714.652	212.865	outside	*
1049	1451720.210	541704.959	212.939	outside	*
1050	1451717.255	541695.255	212.878	outside	*
1051	1451713.940	541685.928	213.220	outside	*
1052	1451710.818	541676.342	213.409	outside	*
1053	1451707.310	541667.116	213.158	outside	*
1054	1451704.363	541657.653	213.149	outside	*
1055	1451700.394	541648.600	213.174	outside	*
1056	1451696.819	541639.150	213.221	outside	*
1057	1451693.939	541629.364	213.512	outside	*
1058	1451690.761	541620.025	213.671	outside	*
1059	1451687.988	541610.595	213.645	outside	*
1060	1451685.648	541600.853	213.049	outside	*
1061	1451683.378	541591.329	212.222	outside	*
1062	1451681.889	541581.342	211.653	outside	*
1063	1451680.482	541571.573	213.259	outside	*
1064	1451679.415	541565.672	214.260	outside	*
1065	1457501.410	543662.885	221.332	outside	*
1066	1457501.475	543658.172	220.822	outside	*
1067	1457502.099	543653.334	219.953	outside	*
1068	1457502.243	543648.793	219.305	outside	*
1069	1457503.649	543645.114	218.949	outside	*
1070	1467008.736	545012.010	239.177	outside	*
1071	1467021.495	545017.399	239.114	outside	*
1072	1467033.167	545022.745	239.195	outside	*
1073	1467046.854	545028.060	239.132	outside	*
1074	1467061.997	545034.974	239.194	outside	*
1075	1467077.324	545040.679	239.298	outside	*
1076	1467099.067	545049.716	239.145	outside	*
1077	1467123.012	545062.397	239.217	outside	*
1078	1467144.185	545073.251	239.228	outside	*
1079	1467165.605	545083.557	239.124	outside	*
1080	1467185.469	545090.685	239.097	outside	*
1081	1467206.077	545098.376	239.097	outside	*
1082	1467220.842	545104.824	239.197	outside	*
1083	1467235.177	545118.166	239.166	outside	*
1084	1466989.657	545005.906	238.973	outside	*
1085	1466972.004	545000.353	239.074	outside	*
1086	1466950.797	544999.380	239.118	outside	*
1087	1466928.523	544999.280	239.032	outside	*
1088	1466914.990	545003.218	239.006	outside	*

Number	Easting	Northing	Known Z	LaserZ	Dz
1089	1466899.720	545009.792	239.081	outside	*
1090	1466881.542	545008.372	238.945	outside	*
1091	1495862.163	559946.704	313.291	slope	*
1092	1495863.493	559948.791	313.195	slope	*
1093	1495867.013	559936.850	313.041	outside	*
1094	1502282.710	576158.998	341.036	340.950	-0.086
1095	1502282.721	576159.012	341.039	340.950	-0.089
1096	1502273.343	576161.119	340.491	340.350	-0.141
1097	1502263.714	576163.988	340.401	340.240	-0.161
1098	1502254.868	576167.945	339.834	339.820	-0.014
1099	1502245.915	576171.356	339.251	339.130	-0.121
1100	1502435.625	576261.645	342.834	342.830	-0.004
1101	1502487.170	576279.253	340.912	340.640	-0.272
1102	1502491.951	576278.856	340.480	340.510	+0.030
1103	1504153.647	578963.756	347.970	342.380	-5.590
1105	1512638.652	584116.172	368.018	slope	*
1106	1529469.434	604109.015	450.450	slope	*
1107	1526449.232	600706.100	424.817	424.490	-0.327
1108	1526445.425	600708.105	424.832	425.320	+0.488
1109	1526445.177	600708.671	424.905	slope	*
1110	1526444.992	600708.703	426.215	slope	*
1111	1526452.791	600701.736	424.417	424.260	-0.157
1112	1526456.339	600698.265	424.638	424.620	-0.018
1113	1526460.347	600695.022	424.848	424.800	-0.048
1114	1526464.183	600691.509	425.021	424.870	-0.151
1115	1526467.670	600688.003	424.823	424.850	+0.027
1116	1526471.846	600685.099	424.917	424.820	-0.097
1117	1526475.612	600682.188	424.865	424.780	-0.085
1118	1526479.243	600678.815	424.653	424.740	+0.087
1119	1526483.429	600675.585	424.558	424.650	+0.092
1120	1526485.014	600674.371	424.562	424.480	-0.082
1121	1526480.997	600675.907	423.564	424.590	+1.026
1144	1527057.586	601119.729	427.261	427.120	-0.141
1145	1527053.049	601128.723	427.045	426.880	-0.165
1146	1527048.437	601137.849	426.966	426.680	-0.286
1148	1527036.426	601153.946	426.550	426.020	-0.530
1149	1527031.035	601162.447	426.313	425.870	-0.443
1150	1527024.970	601170.155	426.575	426.300	-0.275
1151	1527019.689	601178.195	426.906	426.430	-0.476
1152	1527015.012	601186.510	427.051	426.530	-0.521
1153	1527011.513	601194.798	427.123	426.550	-0.573
1155	1527003.836	601212.491	427.984	427.510	-0.474

Number	Easting	Northing	Known Z	LaserZ	Dz
1157	1527306.829	601433.444	429.212	429.730	+0.518
1160	1527305.813	601686.162	429.397	429.440	+0.043
1161	1527310.633	601685.858	429.734	429.740	+0.006
1162	1527315.657	601686.652	429.939	429.760	-0.179
1163	1527320.876	601685.796	429.816	429.830	+0.014
1164	1527325.761	601685.889	429.281	429.530	+0.249
1165	1527331.170	601686.597	429.221	429.350	+0.129
1166	1527335.614	601686.223	428.989	429.060	+0.071
1167	1527340.661	601686.905	429.430	429.350	-0.080
1168	1527345.703	601686.690	429.894	429.790	-0.104
1169	1527350.357	601686.584	430.241	430.270	+0.029
1170	1527355.689	601686.870	430.413	430.420	+0.007
1171	1527360.321	601686.872	430.529	430.560	+0.031
1172	1527365.608	601687.022	430.358	430.290	-0.068
1173	1527370.481	601687.320	429.745	430.010	+0.265
1174	1527375.714	601687.343	429.870	429.790	-0.080
1175	1527380.828	601687.577	430.279	429.800	-0.479
1176	1527384.485	601687.702	429.861	430.290	+0.429
1177	1527385.311	601687.345	432.366	430.540	-1.826
1179	1527291.706	601685.972	429.126	429.120	-0.006
1180	1527287.228	601686.961	431.445	430.830	-0.615
1181	1527290.717	601685.711	429.177	429.330	+0.153
1182	1527295.812	601686.055	428.931	428.880	-0.051
1183	1527300.578	601686.362	428.899	428.950	+0.051
1184	1527289.434	601651.737	430.352	434.350	+3.998
1185	1531897.358	606729.189	453.208	452.800	-0.408
1186	1531897.521	606729.145	453.172	452.800	-0.372
1187	1531905.671	606714.902	452.864	452.380	-0.484
1188	1531908.910	606710.855	452.364	452.490	+0.126
1189	1531915.046	606703.027	452.106	452.160	+0.054
1190	1531922.497	606695.658	451.684	451.720	+0.036
1191	1531928.561	606687.659	451.169	451.270	+0.101
1192	1531933.015	606681.145	451.109	450.910	-0.199
1193	1526501.937	601498.052	432.666	432.660	-0.006
1194	1526501.934	601498.062	432.644	432.660	+0.016
1195	1526501.876	601498.041	432.665	432.670	+0.005
1196	1526501.938	601498.022	432.664	432.660	-0.004
4	1537885.672	610081.282	475.077	474.830	-0.247
165	1500154.047	570065.430	337.197	outside	*
166	1500153.959	570065.336	337.389	outside	*
167	1500153.952	570065.494	337.170	outside	*
171	1502655.099	578195.856	366.251	outside	*

Number	Easting	Northing	Known Z	LaserZ	Dz
172	1502495.956	576285.035	340.194	340.430	+0.236
173	1502499.172	576283.372	339.864	339.630	-0.234
174	1502501.536	576283.401	338.692	339.030	+0.338
175	1502504.504	576282.824	337.962	338.300	+0.338
176	1502506.990	576281.159	338.121	338.080	-0.041
177	1502510.071	576280.621	337.845	337.930	+0.085
178	1502512.816	576280.003	337.931	337.790	-0.141
179	1502515.591	576279.099	338.045	337.970	-0.075
180	1502518.634	576278.509	338.123	338.090	-0.033
181	1502521.324	576277.601	338.104	338.170	+0.066
185	1502524.456	576412.882	340.866	341.310	+0.444
186	1502530.217	576412.559	340.614	340.810	+0.196
187	1502534.453	576412.918	340.318	340.900	+0.582
188	1502538.477	576413.298	339.433	340.580	+1.147
189	1502538.492	576421.750	340.145	340.840	+0.695
190	1502541.626	576420.953	339.715	340.760	+1.045
191	1502544.009	576419.359	339.570	340.360	+0.790
192	1502534.102	576422.166	340.704	340.970	+0.266
193	1502528.184	576423.106	340.885	341.030	+0.145
194	1502522.389	576424.377	341.286	341.390	+0.104
195	1502520.635	576442.839	341.580	341.620	+0.040
196	1502527.212	576443.086	341.614	341.490	-0.124
197	1502532.853	576441.820	341.198	341.410	+0.212
198	1502540.077	576442.030	340.713	341.310	+0.597
199	1502546.638	576443.586	340.662	340.920	+0.258
200	1502552.390	576444.840	340.753	341.180	+0.427
201	1502556.385	576450.532	341.308	341.410	+0.102
202	1502559.165	576457.712	341.109	341.380	+0.271
203	1502563.657	576463.562	340.679	341.620	+0.941
204	1502558.586	576464.985	341.307	341.020	-0.287
205	1502551.987	576466.050	341.162	341.200	+0.038
206	1502544.885	576466.832	341.778	341.680	-0.098
207	1502535.806	576466.837	341.746	341.710	-0.036
208	1502526.366	576466.870	341.709	341.670	-0.039
209	1502517.843	576470.167	341.814	341.650	-0.164
210	1502521.986	576495.858	341.929	342.100	+0.171
211	1502531.719	576496.020	342.023	341.940	-0.083
212	1502542.846	576495.904	341.742	341.720	-0.022
213	1502552.132	576494.685	341.430	341.400	-0.030
214	1502560.064	576493.865	341.128	341.070	-0.058
215	1502569.326	576492.594	342.126	341.820	-0.306
216	1502576.639	576490.886	341.653	341.480	-0.173

Number	Easting	Northing	Known Z	LaserZ	Dz
217	1502582.436	576490.296	340.949	340.800	-0.149
218	1502593.596	576509.658	341.073	340.250	-0.823
219	1502584.982	576515.318	341.456	341.370	-0.086
220	1502578.780	576516.259	341.663	341.470	-0.193
221	1502570.094	576518.095	341.763	341.650	-0.113
222	1502561.278	576518.955	341.508	341.580	+0.072
223	1502551.200	576520.529	342.197	342.050	-0.147
224	1502541.269	576522.581	341.820	341.930	+0.110
225	1502529.861	576523.890	341.798	341.950	+0.152
226	1502516.740	576527.649	341.723	341.850	+0.127
227	1502504.681	576533.075	341.285	341.300	+0.015
228	1502494.123	576537.463	340.953	341.020	+0.067
229	1502565.050	576464.043	341.143	341.700	+0.557
230	1502559.016	576456.961	341.087	341.440	+0.353
231	1502556.098	576450.857	341.335	341.370	+0.035
232	1502551.471	576444.894	340.866	341.100	+0.234
233	1502547.979	576439.149	340.759	340.960	+0.201
237	1526526.657	600784.532	424.712	425.140	+0.428
238	1526530.492	600781.599	424.591	424.560	-0.031
239	1526535.002	600779.073	424.701	424.290	-0.411
240	1526544.041	600773.782	425.993	424.040	-1.953
241	1526552.505	600769.358	424.410	424.130	-0.280
242	1526561.002	600764.628	424.936	424.200	-0.736
243	1526569.826	600759.562	424.245	423.760	-0.485
244	1526578.744	600754.865	424.199	423.660	-0.539
245	1526587.370	600750.139	424.201	423.640	-0.561
246	1526595.905	600745.215	424.338	423.910	-0.428
247	1526600.483	600743.243	424.253	424.050	-0.203
248	1526603.354	600739.232	424.373	424.020	-0.353
250	1526525.137	600788.609	426.188	425.620	-0.568
251	1526527.169	600792.287	426.177	425.690	-0.487
252	1526544.414	600814.440	425.999	425.610	-0.389
253	1526567.351	600836.590	426.155	425.650	-0.505
254	1526582.556	600853.041	426.187	425.520	-0.667
255	1526607.918	600886.037	426.042	425.560	-0.482
256	1526641.093	600928.488	426.345	425.850	-0.495
257	1526668.909	600960.203	426.155	425.840	-0.315
258	1526723.767	601344.197	430.320	430.050	-0.270
259	1526717.478	601359.542	430.474	430.190	-0.284
260	1526705.175	601366.660	430.487	430.140	-0.347
261	1526689.824	601372.120	429.968	429.660	-0.308
262	1526674.506	601376.679	429.330	429.120	-0.210

Number	Easting	Northing	Known Z	LaserZ	Dz
263	1526656.421	601373.582	428.919	428.670	-0.249
264	1526643.309	601364.512	428.378	428.230	-0.148
265	1526636.193	601350.783	428.506	428.240	-0.266
266	1526627.763	601336.361	428.333	428.380	+0.047
267	1526621.413	601322.841	428.492	428.460	-0.032
268	1526613.185	601310.150	428.477	428.310	-0.167
269	1526609.676	601297.258	428.604	slope	*
270	1526603.743	601290.441	428.462	slope	*
271	1492727.854	557878.650	317.697	outside	*
272	1478175.812	541980.075	300.531	outside	*
273	1478171.261	541977.762	299.438	outside	*
274	1478164.630	541980.031	297.870	outside	*
275	1478161.025	541976.914	297.769	outside	*
276	1478155.242	541972.942	298.091	outside	*
277	1478151.345	541971.563	297.372	outside	*
278	1478147.446	541967.428	298.089	outside	*
279	1478142.770	541964.386	298.121	outside	*
280	1478139.989	541963.411	297.742	outside	*
281	1478135.235	541961.988	298.369	outside	*
282	1478130.448	541959.399	298.631	outside	*
284	1478125.585	541952.999	298.846	outside	*
285	1478124.425	541952.009	299.735	outside	*
286	1451740.353	541721.918	212.787	outside	*
287	1451739.473	541716.978	212.775	outside	*
288	1451737.750	541713.051	212.768	outside	*
289	1451735.975	541708.164	212.769	outside	*
290	1451734.999	541703.335	212.774	outside	*
291	1451733.992	541698.156	212.836	outside	*
292	1451732.619	541693.776	213.084	outside	*
293	1451731.468	541688.785	213.000	outside	*
294	1451730.639	541684.124	213.168	outside	*
295	1451730.000	541679.203	213.087	outside	*
296	1451729.217	541674.370	213.103	outside	*
297	1451726.635	541669.687	213.209	outside	*
298	1451725.062	541665.085	213.160	outside	*
299	1451723.196	541660.532	213.114	outside	*
300	1451721.868	541656.038	213.102	outside	*
301	1451720.726	541651.050	213.168	outside	*
302	1451719.500	541646.357	213.086	outside	*
303	1451717.448	541641.084	213.176	outside	*
304	1451715.640	541636.645	213.112	outside	*
305	1451714.062	541632.353	213.295	outside	*

Number	Easting	Northing	Known Z	LaserZ	Dz
306	1451712.725	541627.682	213.337	outside	*
307	1451711.367	541622.681	213.381	outside	*
308	1451710.537	541617.742	213.476	outside	*
309	1451709.416	541612.777	213.678	outside	*
310	1451707.735	541608.042	213.675	outside	*
311	1451706.900	541603.017	213.444	outside	*
312	1451705.513	541598.533	213.237	outside	*
313	1451703.738	541593.811	213.089	outside	*
314	1451702.031	541589.000	212.637	outside	*
315	1451700.699	541584.284	212.269	outside	*
316	1451699.560	541579.726	211.728	outside	*
317	1451698.978	541574.816	211.454	outside	*
318	1451697.474	541569.632	211.576	outside	*
319	1451694.491	541560.258	212.853	outside	*
320	1451694.660	541550.985	214.103	outside	*
321	1457502.589	543660.992	220.646	outside	*
322	1457503.440	543656.044	220.032	outside	*
323	1457503.828	543651.203	219.595	outside	*
324	1457505.291	543646.194	219.259	outside	*
325	1457506.373	543641.032	218.896	outside	*
326	1457507.016	543636.221	218.526	outside	*
327	1457509.079	543631.125	218.569	outside	*
328	1457508.071	543627.614	218.517	outside	*
329	1467035.623	545021.507	238.261	outside	*
330	1467032.815	545014.710	237.689	outside	*
331	1467034.672	545010.133	237.514	outside	*
332	1467037.907	545001.101	236.734	outside	*
333	1467041.869	544992.267	236.224	outside	*
334	1467045.224	544983.308	235.853	outside	*
335	1467049.913	544974.813	236.120	outside	*
336	1466831.711	545053.859	239.467	outside	*
337	1466827.878	545046.141	238.911	outside	*
344	1466810.595	545054.431	237.878	outside	*
346	1466804.677	545055.885	237.479	outside	*
347	1466801.890	545057.251	237.916	outside	*
348	1466799.679	545057.938	238.690	outside	*
349	1466797.485	545058.409	240.533	outside	*
1	1529469.483	604108.941	450.819	slope	*
2	1531501.426	606523.518	451.065	450.840	-0.225
3	1531503.478	606518.962	450.561	450.390	-0.171
4	1531506.034	606515.185	450.357	449.880	-0.477
5	1531509.368	606511.476	450.100	449.750	-0.350

Number	Easting	Northing	Known Z	LaserZ	Dz
6	1531512.049	606507.508	450.120	449.540	-0.580
7	1531514.105	606503.226	449.606	449.210	-0.396
8	1531516.280	606499.111	449.505	448.910	-0.594
9	1531519.614	606493.505	449.202	448.590	-0.612
10	1531522.287	606489.877	449.054	448.560	-0.494
11	1531524.954	606484.169	448.993	448.330	-0.663
12	1531528.645	606480.346	449.115	448.480	-0.635
13	1531529.915	606474.243	449.230	448.660	-0.570
14	1531531.936	606470.368	449.392	448.590	-0.802
15	1531533.657	606464.453	449.266	448.750	-0.516
16	1531536.898	606460.377	449.267	448.580	-0.687
17	1531541.403	606455.934	449.283	448.460	-0.822
18	1531538.779	606454.686	449.046	448.430	-0.616
19	1531542.188	606450.082	449.048	448.320	-0.728
21	1531548.142	606442.997	448.695	448.030	-0.664
22	1531552.298	606433.537	448.285	447.880	-0.405
23	1531551.864	606433.380	448.276	447.890	-0.386
24	1531558.060	606424.423	447.881	447.700	-0.181
25	1531563.512	606418.690	448.063	447.630	-0.433
26	1531568.259	606412.851	448.041	447.650	-0.391
27	1531572.155	606408.869	448.348	447.650	-0.698
28	1531575.735	606402.617	448.593	448.000	-0.593
29	1531579.262	606396.650	448.660	448.070	-0.590
30	1531580.897	606393.729	449.226	448.090	-1.136
31	1531583.939	606389.669	448.532	448.580	+0.048
33	1531592.178	606380.930	449.218	448.820	-0.398
35	1531658.920	606795.939	450.557	450.230	-0.327
36	1531679.771	606802.644	450.677	450.390	-0.287
37	1531698.337	606807.888	450.458	450.390	-0.068
38	1531718.019	606814.862	450.665	450.370	-0.295
39	1531733.618	606822.186	450.567	450.260	-0.307
40	1531753.702	606828.707	450.550	450.210	-0.340
41	1531772.980	606834.757	450.649	450.360	-0.289
42	1531790.859	606836.143	450.641	450.630	-0.011
43	1531810.332	606841.422	450.451	450.410	-0.041
44	1531826.949	606845.158	450.577	450.500	-0.077
45	1531844.155	606851.091	450.697	450.520	-0.177
46	1531862.589	606858.153	450.669	450.540	-0.129
47	1531880.447	606859.816	450.354	450.540	+0.186
48	1531954.051	606750.394	453.130	452.890	-0.240
49	1531937.516	606740.196	453.138	452.920	-0.218
50	1531921.963	606729.390	452.925	452.740	-0.185

Number	Easting	Northing	Known Z	LaserZ	Dz
51	1531904.031	606717.511	452.705	452.310	-0.395
52	1531886.973	606711.382	452.692	452.360	-0.332
53	1531871.154	606703.272	452.721	452.230	-0.491
54	1531849.797	606691.716	452.530	452.460	-0.070
55	1531834.807	606679.926	452.317	452.290	-0.027
67	1536097.935	610814.826	477.304	476.790	-0.514
68	1536098.026	610814.977	477.301	476.800	-0.501
70	1536103.467	610814.837	477.313	476.630	-0.683
71	1536108.164	610813.873	477.750	477.520	-0.230
72	1536114.062	610814.252	479.348	479.200	-0.148
74	1535213.204	610839.294	491.193	outside	*
75	1535213.212	610839.279	491.181	outside	*
76	1535213.026	610839.454	491.216	outside	*
77	1502654.254	578198.209	366.051	outside	*
83	1512733.754	589094.386	372.743	372.640	-0.103
86	1504084.602	578966.567	343.556	340.820	-2.736
34	1500152.340	570069.780	332.460	outside	*
58	1529469.410	604109.010	450.550	slope	*
6	1467002.289	544995.583	237.315	outside	*
7	1467006.055	544990.090	236.709	outside	*
8	1467008.245	544984.532	236.205	outside	*
9	1467010.610	544979.924	236.005	outside	*
10	1467012.195	544976.043	235.806	outside	*
11	1467014.402	544970.326	235.811	outside	*
12	1467016.781	544965.010	235.757	outside	*
13	1466810.084	545018.105	238.434	outside	*
14	1466813.130	545020.990	237.781	outside	*
15	1466817.483	545022.499	237.379	outside	*
16	1466820.896	545023.780	237.039	outside	*
17	1466825.159	545025.644	237.212	outside	*
18	1466827.383	545027.044	237.419	outside	*
19	1466832.029	545029.575	238.013	outside	*
20	1466835.799	545030.391	238.262	outside	*
100	1481208.687	551091.149	306.600	outside	*
101	1500154.105	570065.423	337.308	outside	*
102	1502654.993	578195.838	366.616	outside	*
103	1507771.857	579533.135	349.468	348.590	-0.878
105	1507778.416	579524.766	349.699	348.710	-0.989
106	1507784.504	579517.671	349.508	348.960	-0.548
107	1507789.185	579508.910	349.782	348.980	-0.802
108	1507796.912	579501.324	349.524	348.440	-1.084
109	1507803.384	579494.218	349.540	348.550	-0.990

Number	Easting	Northing	Known Z	LaserZ	Dz
110	1507808.621	579485.511	350.588	348.520	-2.068
111	1507813.802	579477.086	349.458	348.540	-0.918
112	1507820.233	579469.772	349.298	348.480	-0.818
113	1507827.493	579462.822	348.974	348.430	-0.544
114	1507834.549	579455.778	348.903	348.350	-0.553
115	1507842.412	579449.541	349.011	348.230	-0.781
116	1507849.255	579445.386	348.944	348.370	-0.574
117	1507856.894	579439.747	349.011	348.290	-0.721
118	1507863.755	579434.937	349.063	348.360	-0.703
119	1507871.874	579427.575	349.013	348.420	-0.593
120	1507878.161	579420.741	349.191	348.490	-0.701
121	1507885.359	579413.961	349.538	348.680	-0.858
122	1507893.350	579406.803	349.241	348.640	-0.601
123	1507900.682	579399.697	349.393	348.860	-0.533
124	1507907.615	579392.773	349.655	348.960	-0.695
125	1507915.044	579385.042	349.557	349.170	-0.387
126	1507922.396	579378.487	350.043	349.310	-0.733
127	1507928.562	579372.184	349.676	349.280	-0.396
128	1507935.779	579365.257	349.847	349.240	-0.607
129	1507942.382	579358.042	349.979	349.400	-0.579
130	1507949.023	579351.251	349.586	349.270	-0.316
131	1507956.045	579344.570	349.610	349.140	-0.470
132	1507963.078	579337.580	349.725	348.890	-0.835
133	1507968.790	579330.184	349.417	348.960	-0.457
134	1507975.636	579322.485	349.231	349.020	-0.211
135	1507982.920	579315.070	349.262	348.940	-0.322
136	1507990.729	579308.353	349.061	348.490	-0.571
137	1507997.584	579300.937	349.166	348.640	-0.526
138	1508004.163	579294.038	349.236	348.060	-1.176
139	1508009.533	579285.752	348.976	348.270	-0.706
140	1508015.537	579278.442	348.705	348.460	-0.245
141	1505034.551	578882.513	346.543	345.690	-0.853
142	1505035.828	578875.498	345.791	344.960	-0.831
143	1505035.315	578870.755	345.088	344.210	-0.878
144	1505034.323	578866.247	345.294	344.280	-1.014
145	1505033.722	578861.357	345.125	344.510	-0.615
146	1505032.815	578856.330	345.226	344.520	-0.706
147	1505032.029	578851.907	345.681	344.700	-0.981
148	1505031.328	578846.996	345.506	344.760	-0.746
149	1505030.424	578842.343	345.981	344.790	-1.191
150	1505029.325	578837.471	345.557	344.760	-0.797
151	1505028.168	578832.621	345.571	344.780	-0.791

Number	Easting	Northing	Known Z	LaserZ	Dz
152	1505027.468	578828.061	345.363	344.700	-0.663
153	1505026.060	578822.753	345.631	344.810	-0.821
154	1505026.478	578822.508	345.532	344.800	-0.732
155	1505023.983	578818.388	345.630	344.750	-0.880
156	1505023.166	578813.830	345.838	344.730	-1.108
157	1505021.769	578808.886	345.506	344.750	-0.756
158	1505021.165	578804.113	345.432	344.640	-0.792
159	1505019.917	578799.056	345.632	344.550	-1.082
160	1505018.478	578794.193	345.383	344.490	-0.893
161	1505018.142	578789.734	345.313	344.390	-0.923
162	1505015.324	578784.402	345.108	344.260	-0.848
163	1502655.008	578195.962	366.204	outside	*

Summary Statistics	
Average DZ	-0.293
Minimum DZ	-5.590
Maximum DZ	+3.998
Average Magnitude	0.438
Root Mean Square	0.684
Std Deviation	0.619

SKAGIT RIVER GORGE BYPASS REACH HYDRAULIC AND INSTREAM FLOW MODEL DEVELOPMENT STUDY
BYPASS HYDRAULIC MODEL CALIBRATION REPORT

ATTACHMENT C

SKAGIT BATHYMETRIC LIDAR EVALUATION

Memo

Date: Monday, January 20, 2020

Note: Figure 1 map updated on April 7, 2022. Typo in Figure 2 caption fixed. No other changes made to Memo.

Project: Skagit River Project FERC Relicensing

To: Seattle City Light

From: HDR

Subject: Skagit LiDAR Bathymetric Evaluation

1.0 INTRODUCTION

This document contains a brief examination and comparison of three overlapping Light Detection and Ranging (LiDAR) datasets collected in the proximity of the Skagit River Basin in Washington State. Two of these datasets were collected with bathymetric (green) LiDAR technology that allows for some penetration of the water column. The third was collected under the U.S. Geological Survey (USGS) 3DEP (3D Elevation Program) program utilizing traditional infrared LiDAR frequencies that are absorbed by water. Figure 1 shows the location of these datasets.

1.1 Datasets

- Skagit Topobathy, Washington (Barnaby Slough), Topobathymetric LiDAR, 2017
- Upper Skagit, Gorge Lake & Diablo Lake, Washington, Topobathymetric LiDAR & Orthoimagery, 2018
- Western Washington 3DEP LiDAR, 2017

1.2 Spatial Reference Frame

Table 1. Spatial reference details.

	Barnaby	Sky Gorge	3DEP
Projection	Washington SP North	Washington SP North	Washington SP South
Datum	NAD83, 2011	NAD83, 2011	NAD83 (CORS96), Labeled HARN*
Geoid	12B	12B	03
Units	US survey feet	US survey feet	US survey feet

1 QSI referenced the Western Washington 3DEP LiDAR to NAD83(CORS96) and labeled it NAD83(HARN). HDR learned about this through discussions with QSI staff.

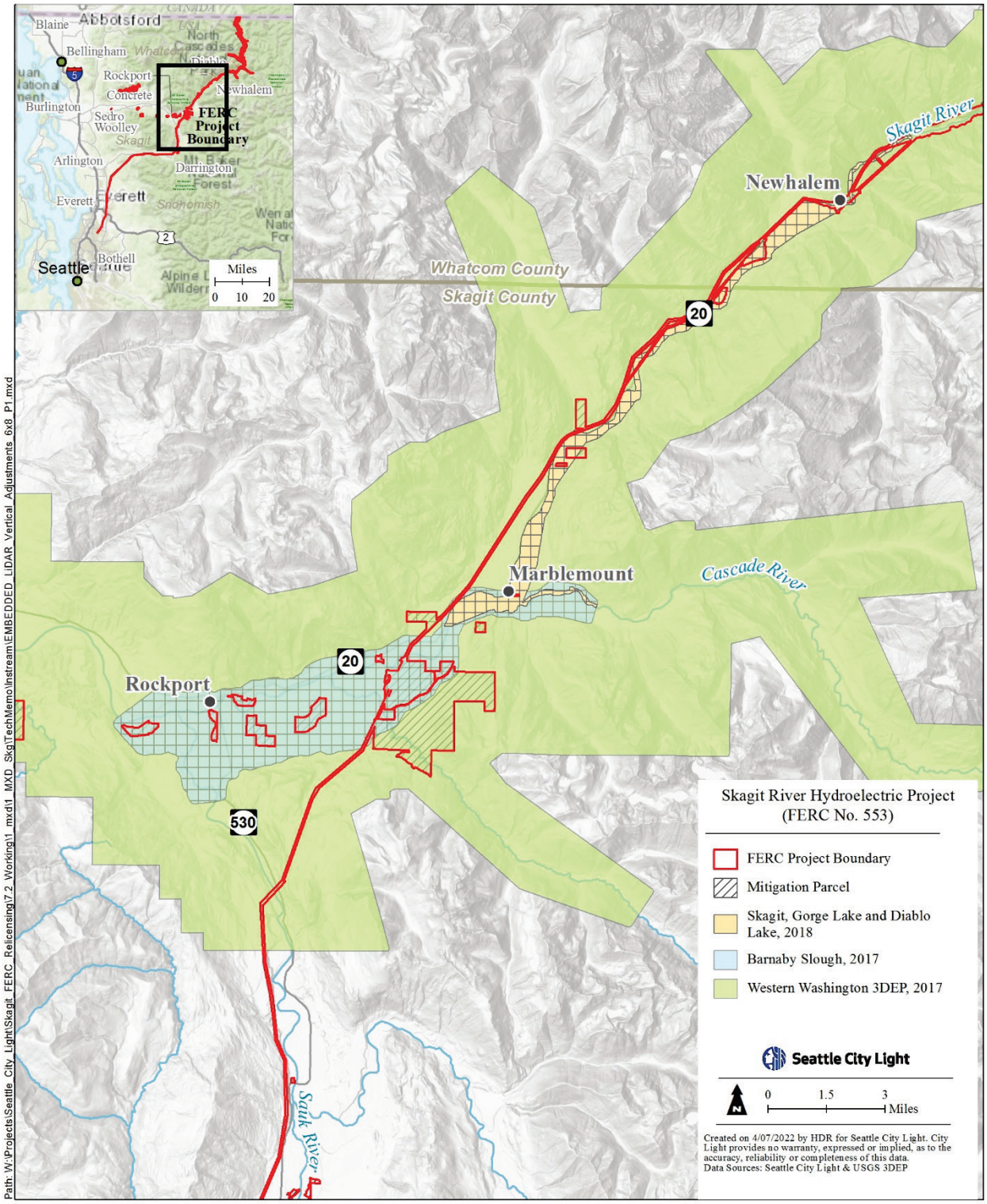


Figure 1. Location of the three datasets used in bathymetric LiDAR comparison.

2.0 CROSS-SECTION ANALYSIS

Cross sections of ground returns from all three datasets were compared over flat open areas to determine overall differences in elevation.

Barnaby slough is approximately 0.35 (4.2 inches) feet above the Sky Gorge dataset in overlapping flat and open areas (Figure 2).

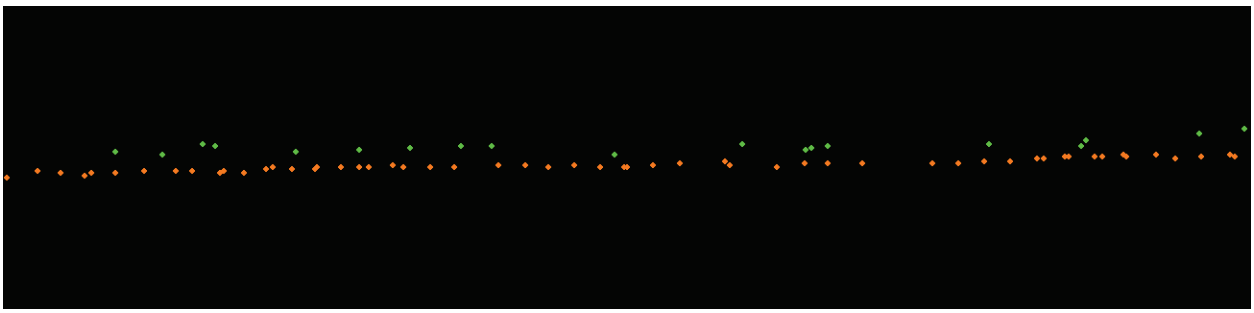


Figure 2. One-foot cross section of Barnaby (green) and Sky Gorge (brown).

Integrating the 3DEP data into the analysis showed that dataset to be approximately 0.3 feet (3.6 inches) above the Barnaby dataset and 0.65 feet (7.8 inches) above the Sky Gorge dataset. However, the 3DEP dataset is in the Geoid 03 Vertical Datum, while the other two datasets are in the Geoid 12B Vertical Datum.

As a test, HDR transformed several control points in the vicinity of the overlap between the three datasets. Table 2 details the resulting offset calculations. Applying the median offset calculation adjustment of -0.15 feet (approximately -1.8 inches), HDR derived an estimate for the 3DEP dataset of approximately 0.15 feet (1.8 inches) above the Barnaby dataset and 0.5 feet (6 Inches) above the Sky Gorge dataset, once all the datasets have been converted to the Geoid 12B Vertical Datum.

Table 2. Comparison of survey control points.

Point ID	Latitude	Longitude	Geoid03 Elevation (US Survey foot)	Geoid12B Elevation (US Survey foot)	Elevation Comparison (US Survey foot)
1	48 30’ 54.19052”	-121 27’ 44.72248”	299.93	299.781	0.149
2	48 30’ 54.16309”	-121 28’ 01.25136”	306.3	306.148	0.152
3	48 28’ 18.10120”	-121 37’ 31.89180”	238.78	238.694	0.086
4	48 29’ 05.29765”	-121 31’ 19.48905”	265.81	265.657	0.153

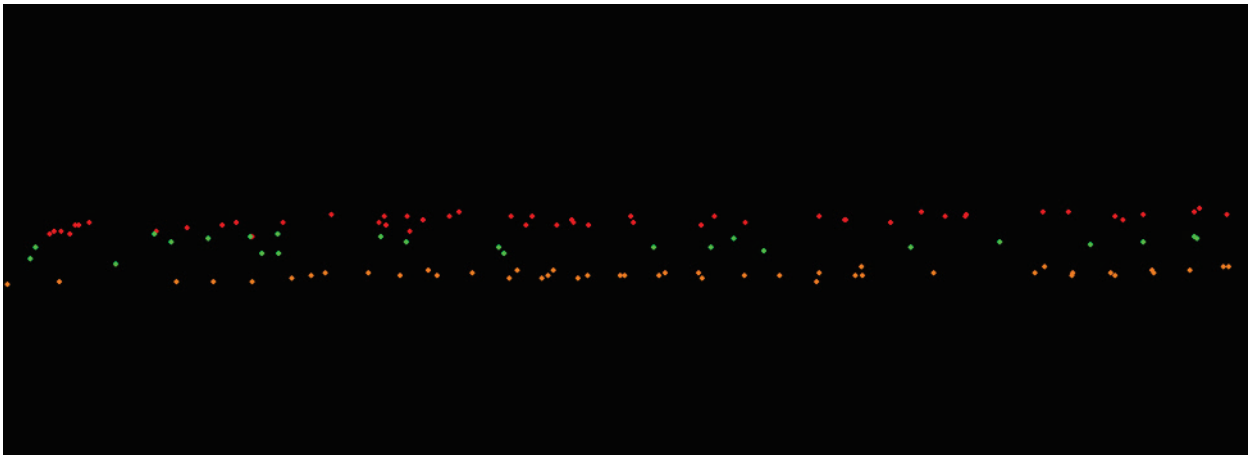


Figure 3. **One-foot cross section of Barnaby (green), Sky Gorge (brown), and 3DEP (red), before Geoid adjustment.**

2.1 IMU Misalignment

IMU Misalignment was assessed by drawing cross sections over properly oriented targets in each of the three datasets (one dataset at a time). Targets should be hard surfaces with well-defined topographic characteristics, most commonly roofs and roads. It appears that all IMU calibration biases are solved for in the roll, pitch, and heading. This indicates good spatial agreement between flight lines.

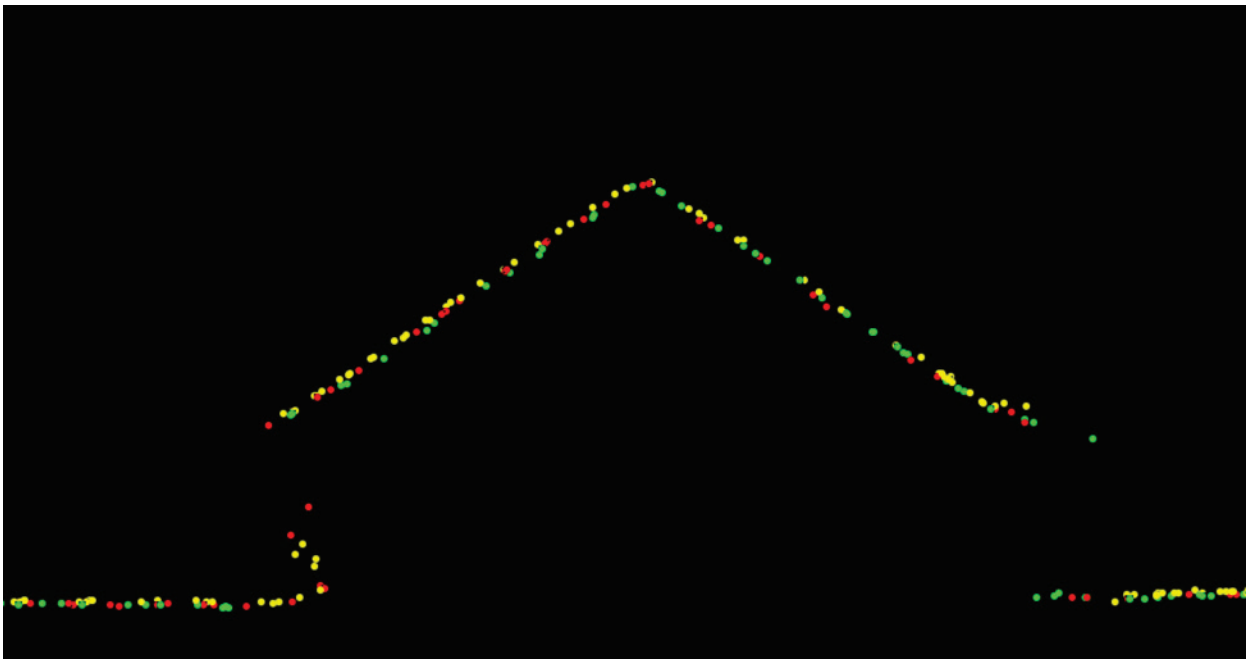


Figure 4. **One-foot cross section of a pitched roof in one single dataset. Data are color coded by flight line. Biases in pitch and heading alignment will show as multiple offset peaks in the roof line.**

2.2 Point Density

Point density was tested in both open and vegetated areas to provide an assessment of pulse density under different vegetative conditions. The overall point density was tested for the ground classified returns in a relatively flat open area where ground point density is expected to be highest, and in forested areas where ground point density is expected to be lowest. Results are expressed as Nominal Pulse Density (NPD) and defined in USGS LiDAR base specification version 1.2.

Figures 5 and 6 show cross sections of LiDAR ground returns in open and forested areas that were utilized for this assessment. Non ground returns are shown as white and are not counted in the assessment.



Figure 5. **One-foot cross section of a relatively flat and open area in an area where all three datasets overlap.**

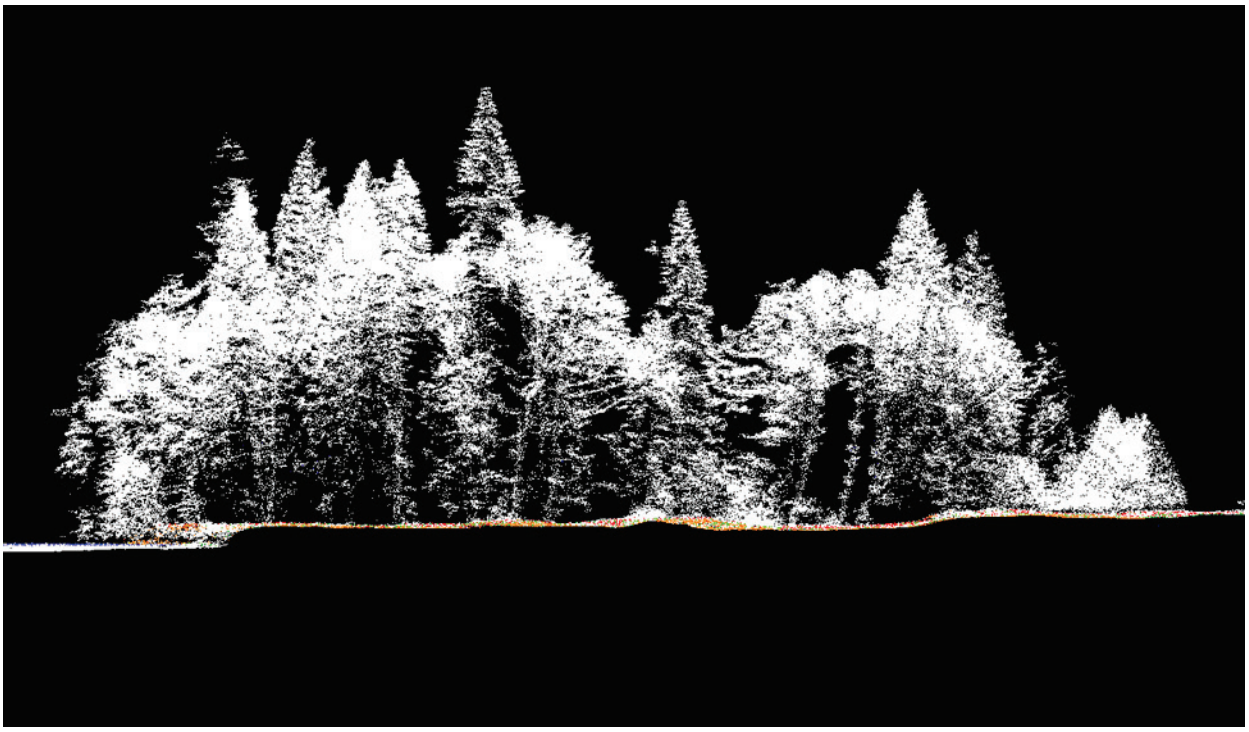


Figure 6. Ten-foot cross section of a forested area used for testing ground point density.

2.3 NPD in open areas

- Sky Gorge 10.65 points per square meter
- Barnaby 3.23 points per square meter
- 3DEP 9.04 points per square meter

2.4 NPD in vegetated areas

- Sky Gorge 5.43 points per square meter
- Barnaby 2.33 points per square meter
- 3DEP 2.32 points per square meter

2.5 Scan Pattern

Scan pattern was evaluated as a proximate indicator of proper symmetry in the datasets. Typical scan patterns for LiDAR data are herringbone, where the laser sweeps side to side, and circular. The data were checked for cross track and down track symmetry.

Artifacts of the scan pattern are clearly visible in the Sky Gorge dataset in areas with high ground point density. This looks like long arcuate streaks in the point data. This may be caused by poor flight planning or a function of the sensor itself. The artifacts did result in a noticeable asymmetry of the laser returns. Though not quantified for this investigation, the effects are visible in a top-down view (Figures 7 through 9).

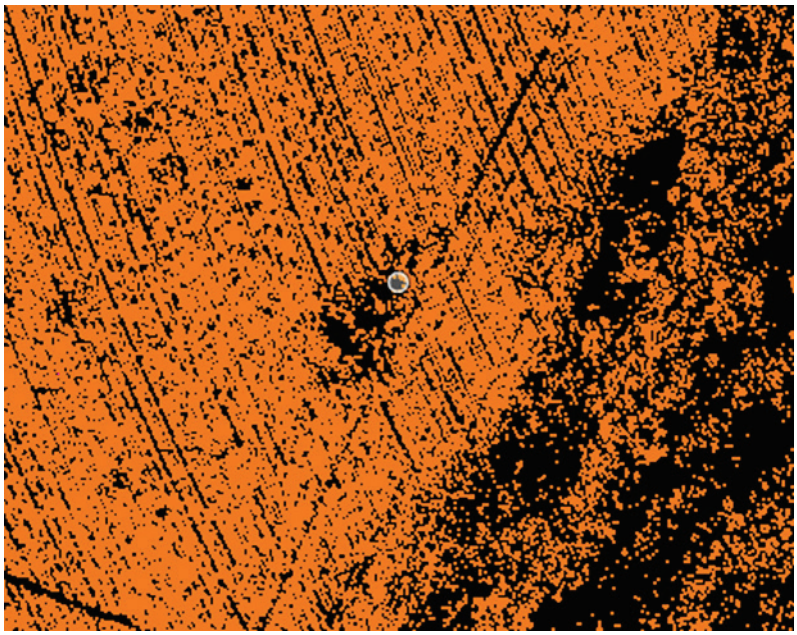


Figure 7. **Top-down view of Sky Gorge LiDAR. The circular scan pattern is clearly visible (left side of image).**

Barnaby and the 3DEP data appear symmetrical by visual analysis.

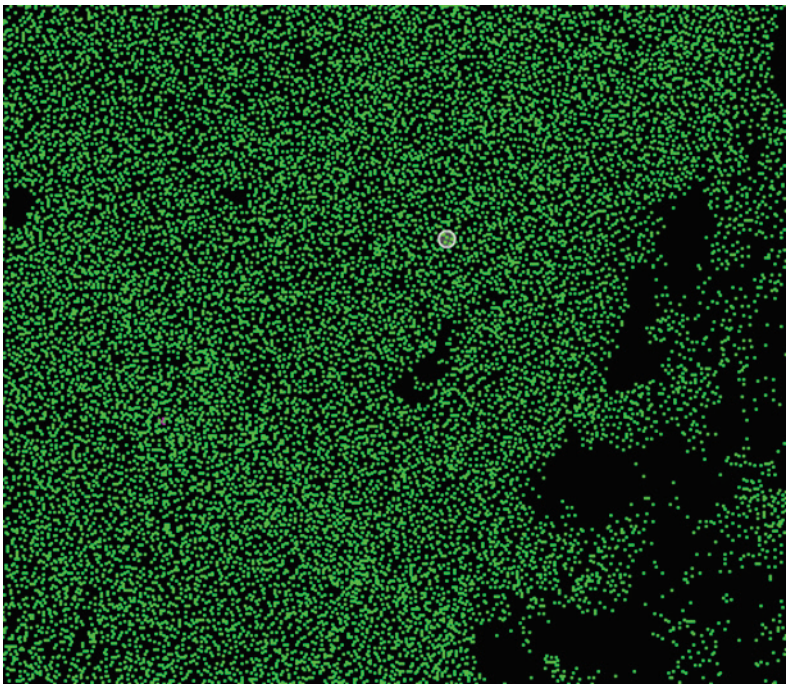


Figure 8. **Top-down view of the Barnaby LiDAR. The scan pattern is not clearly visible.**

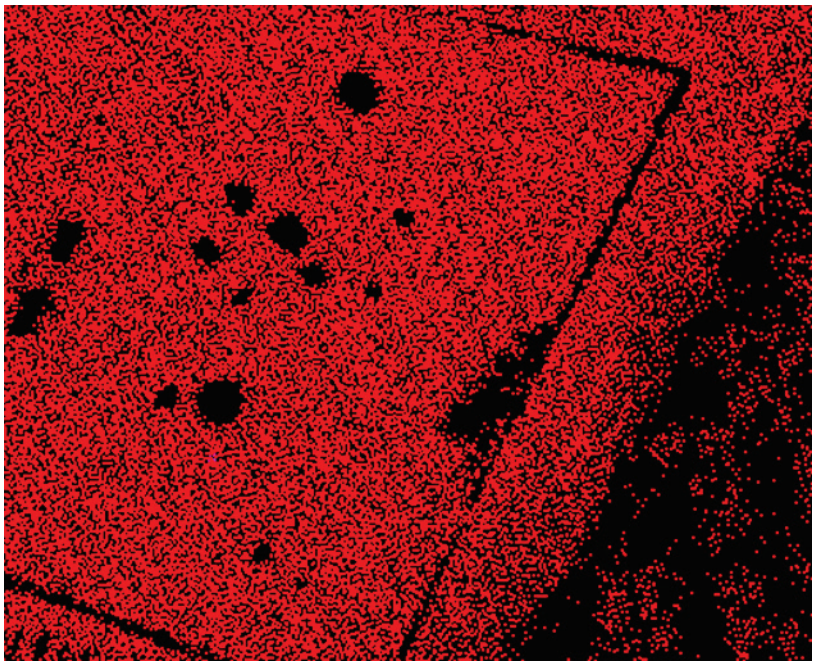


Figure 9. Top-down view of the 3DEP LiDAR data. The scan pattern is not visible.

2.6 River Edge Detection

Definition of the river channel is an important function of LiDAR data, especially green LiDAR data. Due to the typical dense vegetation, bank edge detection can be a challenge. All three datasets share an overall common delineation of the riverbank in the ground class; however, the 3DEP data appears to exhibit a slightly lower point density in riparian areas making it less detailed. The ground class of the Barnaby data appears to map the water's edge to a slightly lower elevation than the other two datasets, though this is subjective in some areas. Some differences in elevation and XY location may be accounted for temporal differences in the data collection.

3.0 SUMMARY

Each dataset contains unique characteristics such as scan pattern, point density, and vegetation penetration. Selecting one that is better than another will rely in part on the application of the data to meet a projects objective. Asymmetry of the Sky Gorge data is unfortunate, but relatively more ground points under vegetation is positive and the data appears to be within industry standards. The Barnaby data has lower point density, but it appears to have slightly better river edge detection in some areas. The fact that all three datasets are vertically offset may need to be addressed depending on the accuracy requirements of any analysis performed on the data.

SKAGIT RIVER GORGE BYPASS REACH HYDRAULIC AND INSTREAM FLOW MODEL DEVELOPMENT STUDY
BYPASS HYDRAULIC MODEL CALIBRATION REPORT

ATTACHMENT D

GORGE BYPASS REACH DATA COLLECTION FOR HYDRAULIC MODEL CALIBRATION MEMORANDUM

nhc
northwest hydraulic consultants

12787 Gateway Drive South | Seattle, WA 98168 | 206.241.6000 |

MEMORANDUM

To: **Project File** Date: March 2022

NHC Ref. No. 2003536

From: Chris Long, PE – NHC

Re: Gorge Bypass Reach Data Collection for Hydraulic Model Calibration

Note: Figure 1 map symbology updated on October 20, 2022. Figure 2 map symbology updated on July 19, 2022. No other changes made to Memo.

1 INTRODUCTION

Northwest Hydraulic Consultants (NHC) collected hydraulic data of the Skagit River between Gorge Dam and Gorge Powerhouse during the period May-July 2021, with some data collection ongoing, for use in calibrating and validating a new hydraulic model. This hydraulic model will be used for assessing instream flows and evaluating fish passage among other tasks related to the relicensing of Seattle City Light's (City Light's) Skagit River Hydroelectric Project. Several field efforts occurred prior to controlled flow releases from Gorge Dam during the week of July 26, 2021, at which point a large fieldwork effort commenced to observe hydraulic characteristics at discharges ranging from 50 to 1,200 cfs. This memorandum describes the methods employed and summarizes the data collected.

2 METHODOLOGY

Three categories of data were collected during the controlled releases at the end of July: depth and velocity measurements at established transects, drone imagery flights, and water levels recorded by level logger sensors. In addition to the July 26-29, 2021, controlled releases, level logger sensors have been continuously recording water levels since May 2021. The following sections describe the methods employed to collect the hydraulic information.

2.1 Transect Measurements

Five measurement transects were established in the Gorge bypass reach to record depths and velocities during the July 26-29, 2021, controlled releases from Gorge Dam (Figure 1). Transect locations were selected in consultation with City Light and licensing participants to capture hydraulic characteristics from a variety of geomorphic units. The Gorge bypass reach is not boat accessible and could not be waded at the transect locations for most of the controlled release flows. Therefore, temporary bank-operated cableways were installed at each transect to deploy a raft-mounted SonTek M9 Acoustic Doppler Current Profiler (ADCP) (Figure 2).

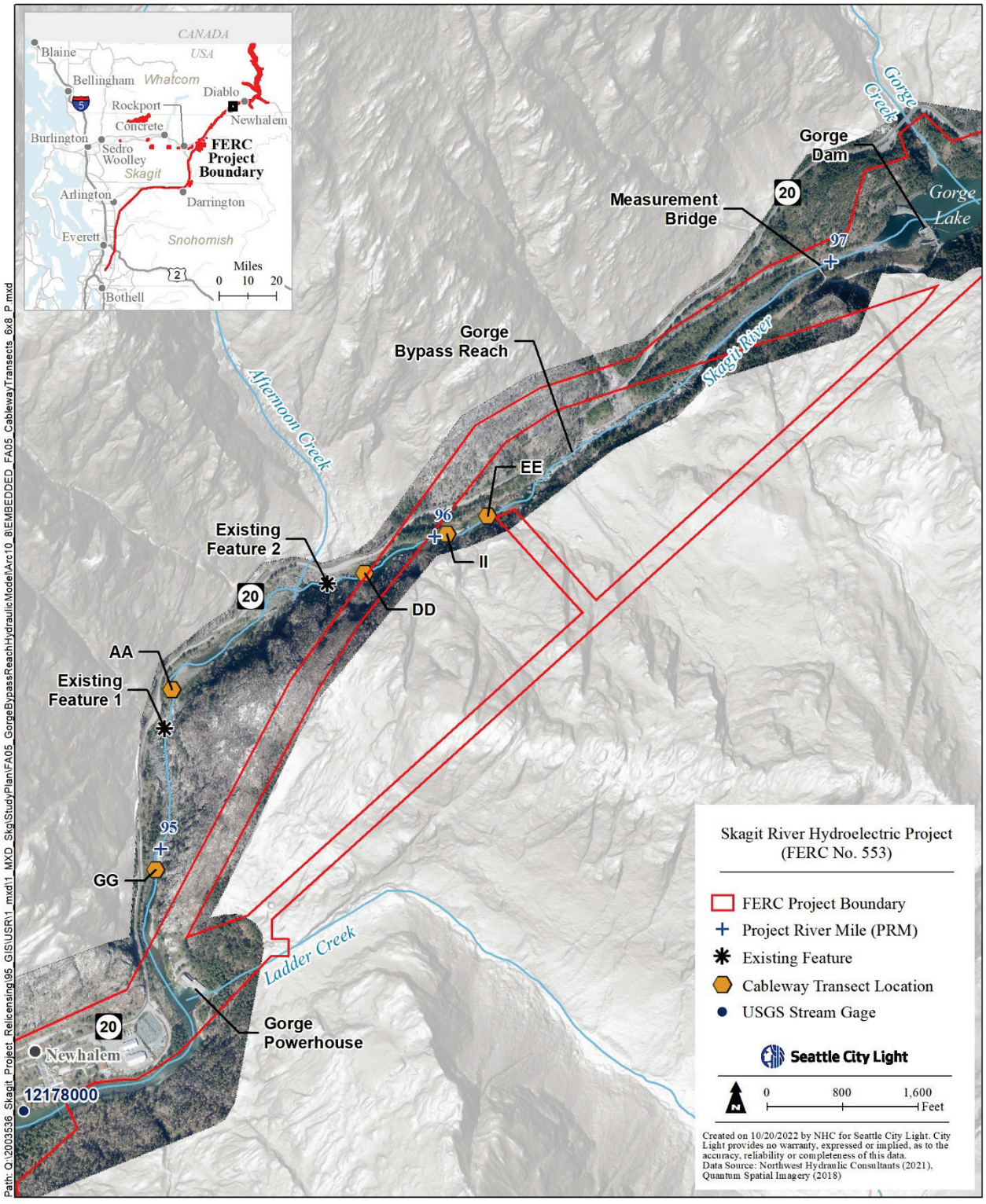


Figure 1. Temporary cableway locations.



Figure 1. Cableway deployment of ADCP at Transect AA on July 26, 2021.

Depth and velocity measurements were recorded at 20-50 stationary positions along each transect, the count depending on wetted channel width. Measurement stations were selected to 1) locate the ADCP where the instrument could be safely operated and perform accurate measurements; and 2) capture less than 5 percent of the total flow between measurement stations. Acoustic signals transmitted by the ADCP record the vertical velocity profile through the water column which is converted to depth-averaged velocity. Velocities were recorded at each station for 40 seconds to average out turbulence fluctuations. Depth and velocity measurements were used to compute discharge at each transect using the USGS mid-section method (Turnipseed and Sauer, 2010). Measurements were collected and processed during the survey with SonTek's RiverSurveyor Stationary LIVE software.

The ADCP's deployment configuration limited instrument operation to depths greater than approximately one foot. When depths along significant portions of a transect were shallower than the ADCP's operable range, field personnel measured depths with a wading rod and velocities with a SonTek FlowTracker2 Acoustic Doppler Velocimeter (ADV) (Figure 3). Wading depths and velocities were recorded and processed with the FlowTracker2's dedicated handheld processor.



Figure 2. ADV operation at Transect EE on July 29, 2021.

High precision RTK GPS is not available throughout much of the Gorge bypass reach, including at all five transects. To geolocate the transects and associated hydraulic measurements, the cableway anchor points were surveyed with a total station relative to nearby National Geodetic Survey (NGS) monuments. A tagline was run along each cableway to record the measurement station distance from the right bank anchor point. Measurement locations were then georeferenced in ArcMap by plotting each measurement station along the surveyed transect (Figure 4). Wherever flow velocities exceeded more than approximately one ft/sec, the ADCP raft drifted downstream of the transect. Photos and video taken of the ADCP deployment at each transect were used to determine any downstream offset relative to the cableway.

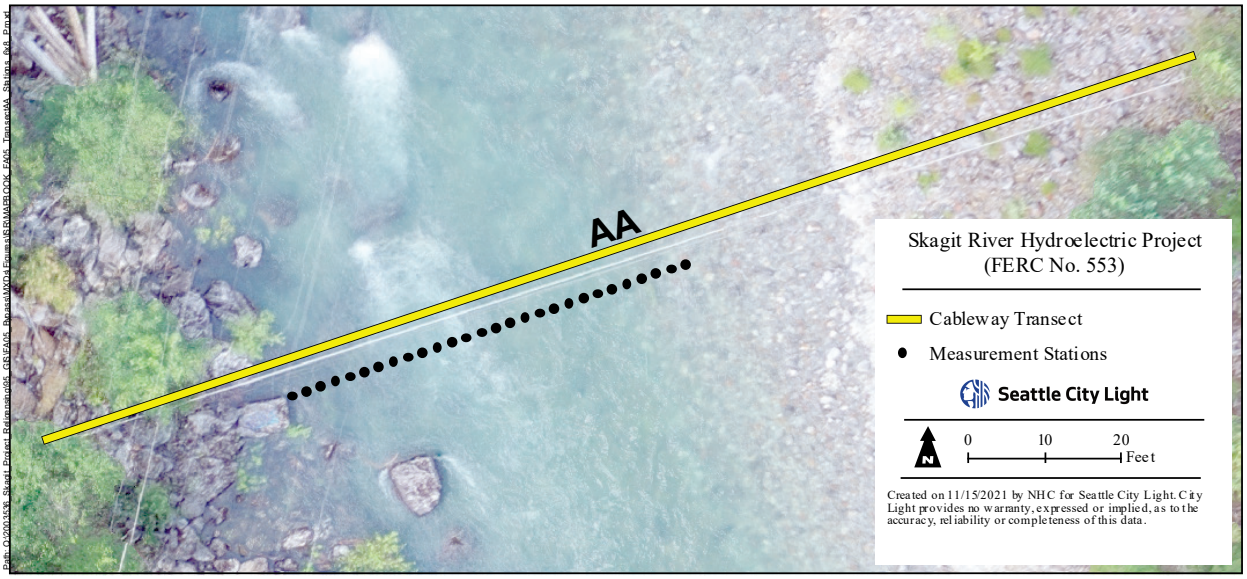


Figure 3. Measurement stations at Transect AA recorded during 1,200 cfs targeted spill. Stations are offset from cableway to account for ADCP drift.

2.2 UAV Imagery

Oblique and nadir (downward facing) photographs and videos were taken with a drone, or unmanned aerial vehicle (UAV), throughout the Gorge bypass reach during the week of the controlled releases. The still photographs were collected to visually document conditions at each controlled release and under baseflow conditions, and for processing through Structure from Motion (SfM), a photogrammetric method to create a three-dimensional model from two-dimensional photographs. Drone-based videos were recorded to support Large Scale Particle Image Velocimetry (LSPIV) analysis, which is a technique for measuring two-dimensional (2D) surface velocity vectors (magnitude and direction).

2.2.1 Structure from Motion

Structure from Motion (SfM) is a photogrammetric imaging technique for estimating three-dimensional structures (models) from two-dimensional image sequences. The primary inputs for the SfM processing completed in the Gorge bypass reach were overlapping nadir photographs. These photos were taken with a drone at altitude during the controlled releases, primarily to develop orthomosaic images for use during hydraulic model calibration; however, they have also been made available to support other Skagit relicensing studies for a variety of applications, including for example, substrate and cover mapping.

UAV Still Photo Collection

Prior to the controlled releases, UAV reconnaissance missions of the Gorge bypass reach were conducted to determine safe flight elevations and flight times to ensure the drone would both avoid obstacles and have sufficient battery life for pre-planned missions. Four pre-planned flight paths were required to achieve the desired coverage of the Gorge bypass reach while complying with FAA safety guidelines and operation restrictions. Note that drone operations were not conducted for approximately

300 feet adjacent the SR 20 tunnel due to the limited field of view and the inability to maintain visual line-of-sight. See Figure 5 for a map of these flight boundaries. The UAV flew a pre-determined gridded path at an altitude of 300 feet above takeoff, as determined in the initial reconnaissance. The drone was programmed to capture photos with 85 percent frontal and side overlap for each flight path (Figure 6), considering the terrain complexity and application in SfM. In consultation with City Light, all drone missions launched and landed within the FERC-designated Project Boundary also shown on Figure 5. The drone was a DJI Mavic2 Pro quadcopter, equipped with a 20-megapixle camera, 4K 10-bit HDR video quality, and a polarizing lens. Prior to dispatching the UAV, 50 surveyed ground control points were marked with high-visibility, temporary chalk that would be easily distinguishable in the photos taken during the controlled releases. The survey points were established utilizing a combination total station survey and RTK GPS where possible, and they were used to georeference the UAV imagery during SfM processing.

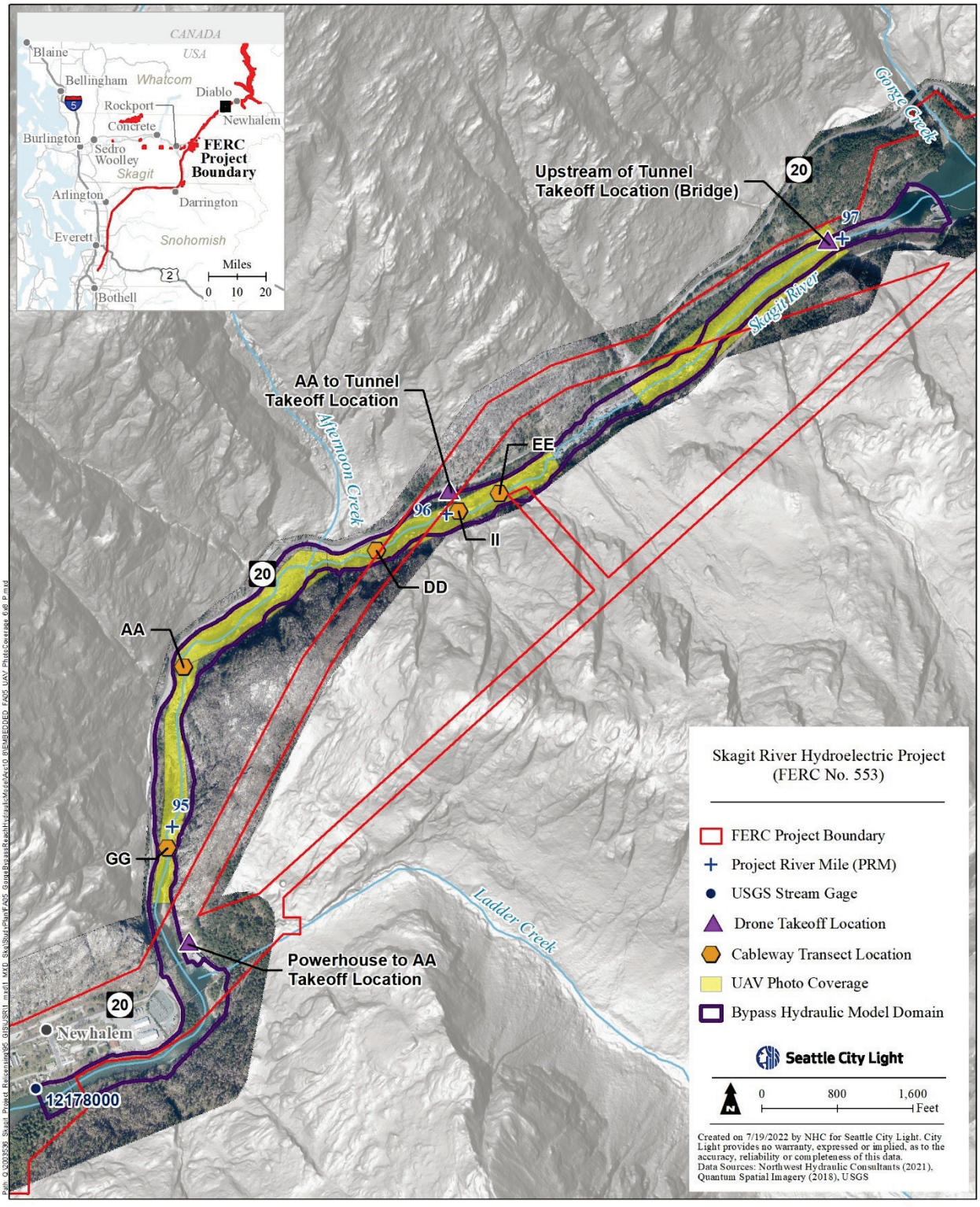


Figure 5. UAV pre-programmed flight plans.

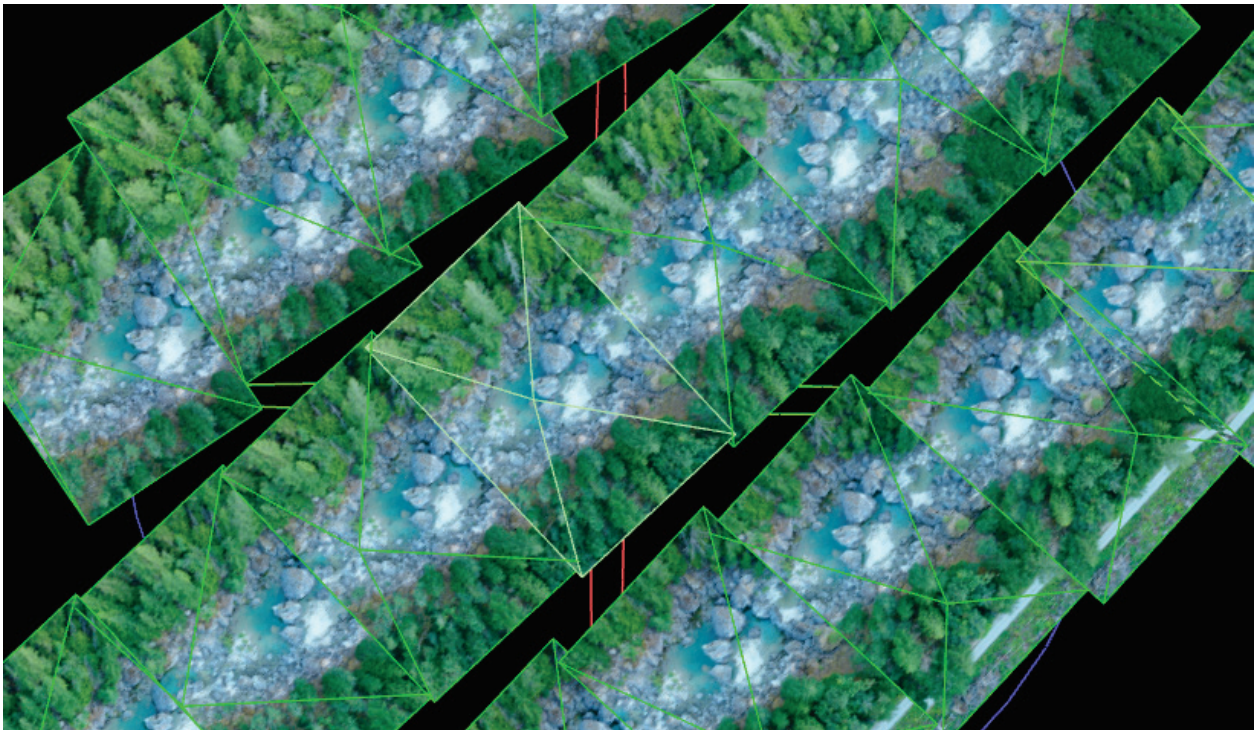


Figure 6. Overlapping nadir photographs of Existing Feature 1 (July 30, 2021).

UAV Still Photo Processing (Structure from Motion)

Approximately 850 UAV-based nadir photos were taken each day of the controlled release week, for a total of almost 4,300 photos covering all four flight paths. The daily photographs were processed through Pix4Dmapper Version 4.3.33, typically applying Standard 3D map settings. Prioritization was given to the photos taken on July 30, 2021, corresponding to no spill from Gorge Dam. These photos supported substrate mapping field efforts and captured the most ground control points. Photos from the remaining days were processed in order from the highest discharge (July 26, 2021) to lowest (July 29, 2021) to support calibration of the hydraulic model.

2.2.2 Large Scale Particle Image Velocimetry

Large Scale Particle Image Velocimetry (LSPIV) analysis was another field method applied for measuring two-dimensional (2D) surface flow velocity vectors (velocity, magnitude, and direction). These measured velocities will be utilized as a verification of the hydraulic model as well as to provide another perspective of fish passage potential for the FA-04 Fish Passage Technical Studies Program (Fish Passage Study, City Light 2022). In summary, the LSPIV method measures the surface flow velocities by video recording the movement of tracer particles seeded onto the flow surface and analyzing the tracer movement in successive video frames (Dermisis and Papanicolaou 2005, Muste et al. 2008). The LSPIV methodology is comprised of two phases, namely: 1) field data collection and 2) field data processing, which are presented in the following Sections.

LSPIV Field Data Collection

The collected field data for the LSPIV method was comprised of video footage recording the movement of tracer particles seeded into the flow. Wood chips were selected as the preferred tracer for these measurements as they closely follow the flow streamlines, offer strong contrast relative to the turbulent white-water surface, and are an ecofriendly, naturally biodegradable material. Approximately 81 cubic feet of wood chips were utilized for the entire LSPIV measurement campaign, which included measurements at Existing Features 1 and 2 during the four controlled releases from July 26-29, 2021. Both Existing Features, shown on Figure 1, are large boulder cascades and were targeted for LSPIV to support fish passage evaluation objectives as part of the FA-04 Fish Passage Study. The wood chips were transported by field personnel to staging areas adjacent to the river channel at the upstream end of both Existing Features (Figure 7). The chips were manually introduced to the flow during each drone video recording. Between eight and ten cubic feet of wood chips were utilized for the 1,200 cfs flow and progressively smaller amounts were used for the smaller discharges.



Figure 7. Staging of wood chips used for flow seeding.

Nadir video footage at Existing Features 1 and 2 were captured with a DJI Mavic 2 Pro drone, which recorded video at 4K resolution, producing 3840 x 2160-pixel video frames at a rate of 30 frames per second. To maximize the velocity vector resolution, the UAV was positioned at the lowest possible altitude (approximately 175 feet) above the water surface, such that the width of the camera field of view (FOV) was marginally larger than the wetted perimeter of the reach. At this altitude, the lengths of the Existing Features were larger than the length of the UAV camera FOV, requiring two sequential FOVs to be captured at each feature (Figure 8). These sequential FOVs were overlapped by about 50 percent to 80 percent to facilitate the juxtaposition of the velocity fields from LSPIV analysis in each FOV. Four

ground control points from the still photos taken by the drone were identified in each FOV to determine the scale (i.e., the pixel to physical length ratio) and to juxtapose velocity fields from overlapping FOVs. The duration of captured video footage varied from about five minutes for the 1,200 cfs discharge to about three minutes at the 50 cfs discharge.

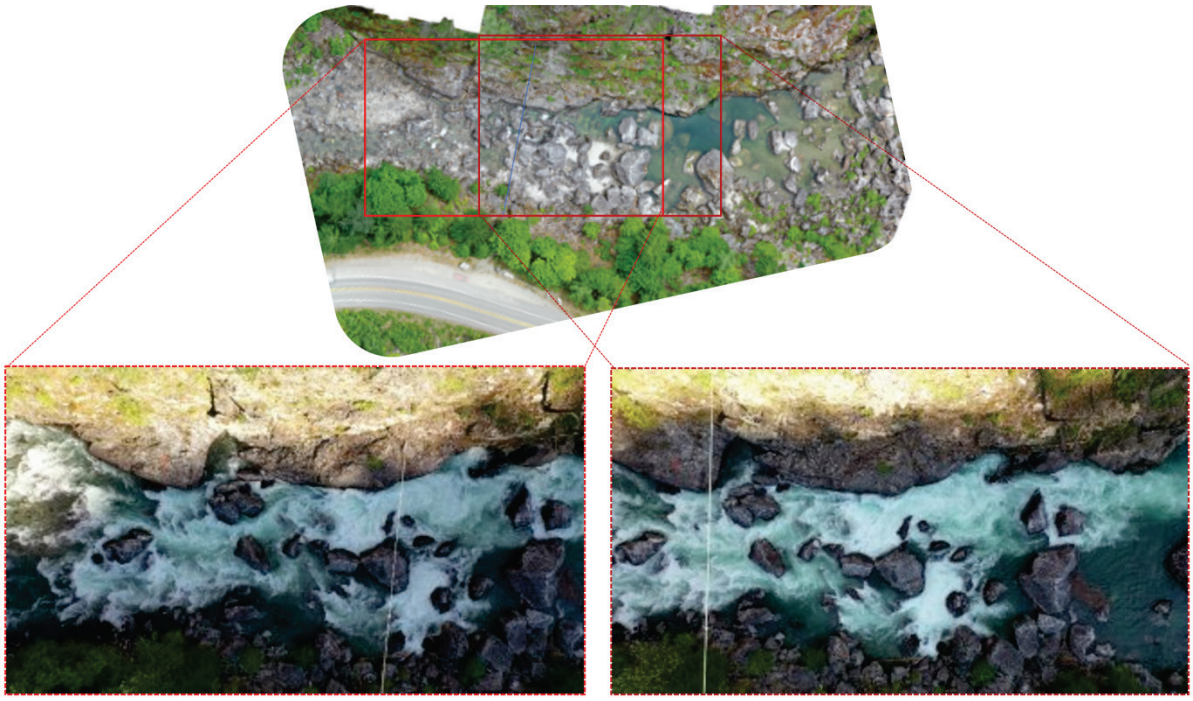


Figure 4. Example of sequential still Fields of View (FOVs) recorded at Existing Feature 1 during the 1,200 cfs spill (July 26, 2021).

LSPIV Field Data Processing

The videos filmed each day at each Existing Feature, including both sequential FOVs captured at each feature, were carefully inspected, and one-minute-long segments from each FOV were isolated and cropped utilizing OpenShot Video Editor software. The one-minute clips provide sufficiently accurate mean (time-averaged) velocity while minimizing processing time and associated file sizes (Dermisis and Papanicolaou 2005; Muste et al. 2008). LSPIV analysis was performed utilizing RIVeR Version 2.5 software (Patalano et al. 2017). Each 1-minute video clip was imported into RIVeR and separated into 1,800 individual 3840 by 2160-pixel frames (60 second clip captured at 30-fps). The frames were then converted to grayscale to reduce file size and processing times. Dry areas within each frame, such as protruding boulders and riverbanks, were excluded from the analysis by masking these areas within a PIVlab routine (Thielicke and Stamhuis 2014a, 2014b, 2014c) built into RIVeR (Figure 9).

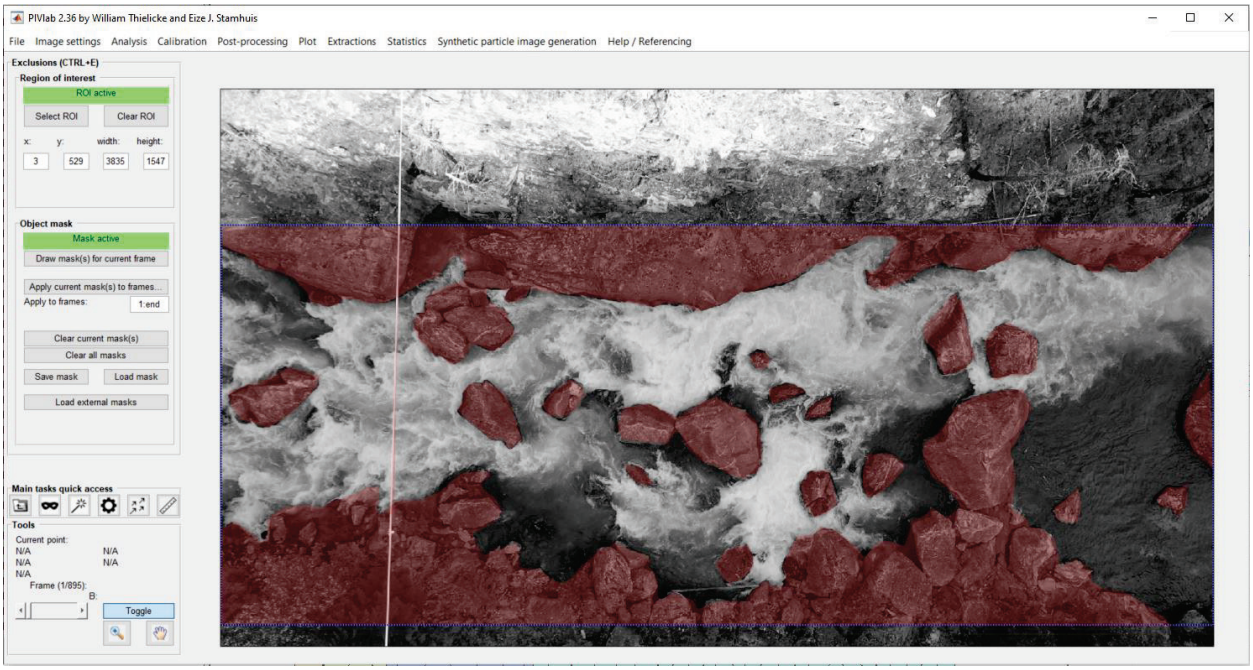


Figure 5. Example of masked areas in the PIVlab environment.

2D velocity vectors (in pixels per second) were estimated by PIVlab using standard PIV methods (Raffel et al. 1998, Muste et al. 2008, Thielicke and Stamhuis 2014c). PIVlab considers a pair of successive image frames, the first of which is discretized into windows of a specified dimension. These windows are displaced by a given amount in the second image frame. The software then estimates the average displacement from the original window on the first image frame to the displaced window on the second, thus calculating a 2D velocity vector. The 2D velocity vector fields were averaged to estimate the mean 2D velocity vector field (time-averaged across 60 seconds) with an approximately 1.1-foot resolution. Processed velocity fields, still in pixels per second, were imported into RIVeR and georeferenced with respect to the ground control points in each FOV (Figure 10). The instantaneous and mean 2D velocity vectors were then rectified by RIVeR and converted to physical space units expressed in feet per second.

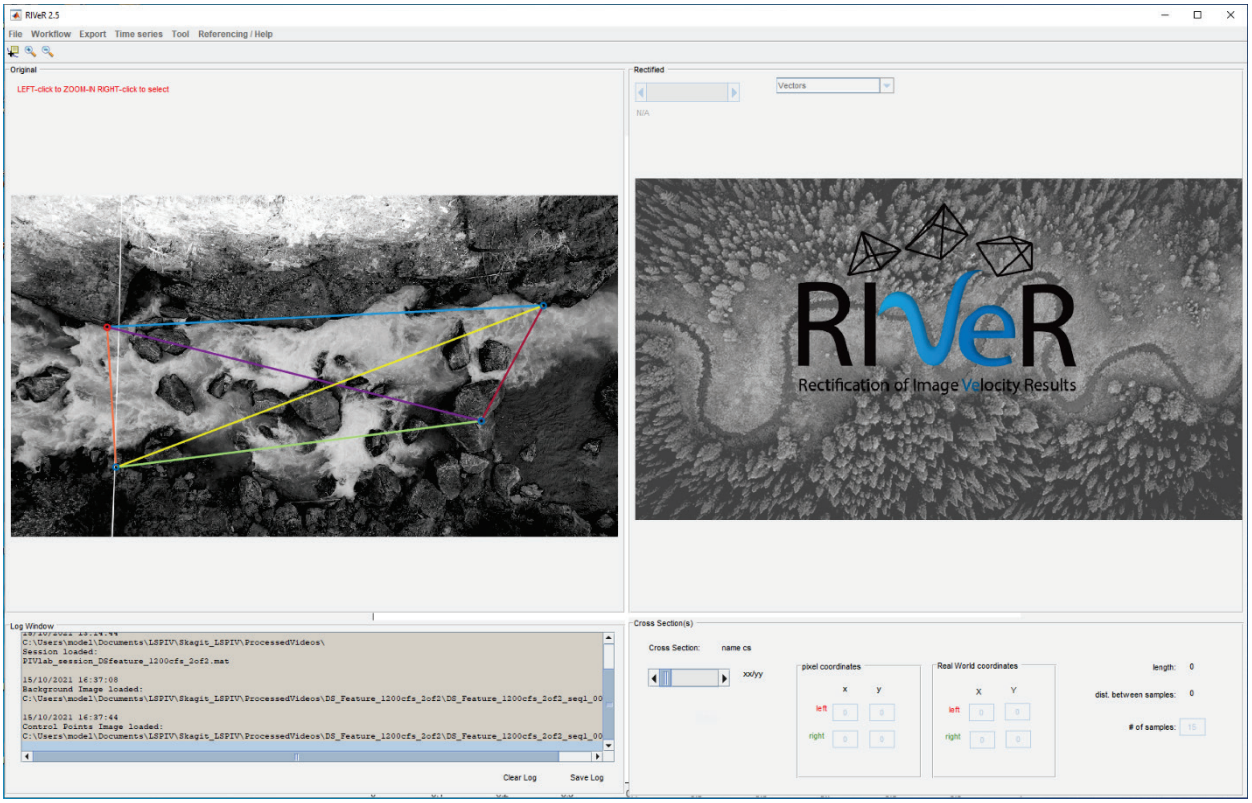


Figure 6. Specification of ground control points for scaling the 2D velocity vector fields.

2.3 Water Level Logger Data

NHC installed 12 water level loggers at Existing Features 1 and 2 in May 2021 to measure water stage for calibration and validation of the hydraulic model and to support the fish passage assessment as part of the FA-04 Fish Passage Study. Members of both the Fish Passage Study and FA-05 Skagit River Gorge Bypass Reach Hydraulic and Instream Flow Model Development Study (Bypass Instream Flow Model Development) teams visited Existing Features 1 and 2 in spring 2021 to assess site conditions at base flow (no Gorge Dam spill) and at approximately 1,200 cfs. From these visits, the teams determined six locations at each Existing Feature to install water level loggers (Figure 11 and Figure 12). The loggers are numbered DDL1 through DDL6 at the downstream Existing Feature 1, and UUL1 through UUL6 at the upstream Existing Feature 2. The selected locations provide water levels that 1) represent nominally stable pools at each Existing Feature and 2) span the entire length of each Existing Feature, providing a comprehensive, longitudinal water surface profile.

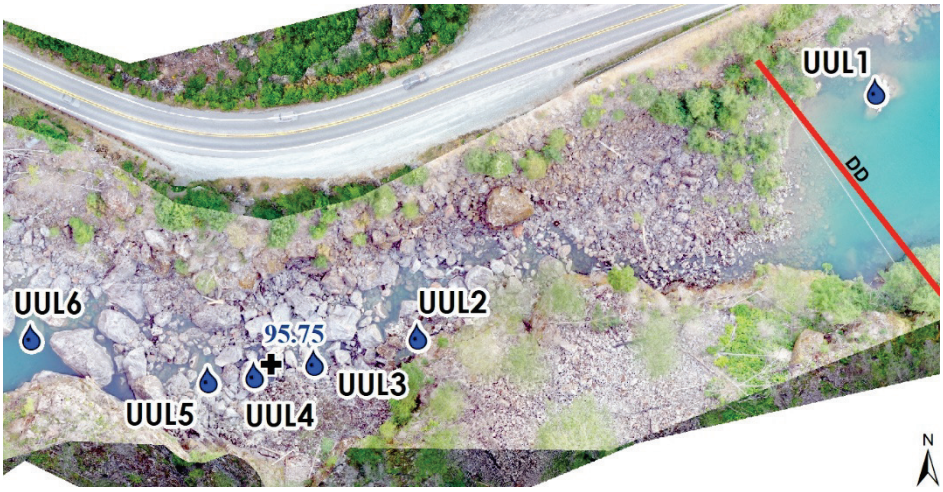


Figure 7. Water level logger locations at Existing Feature 2.

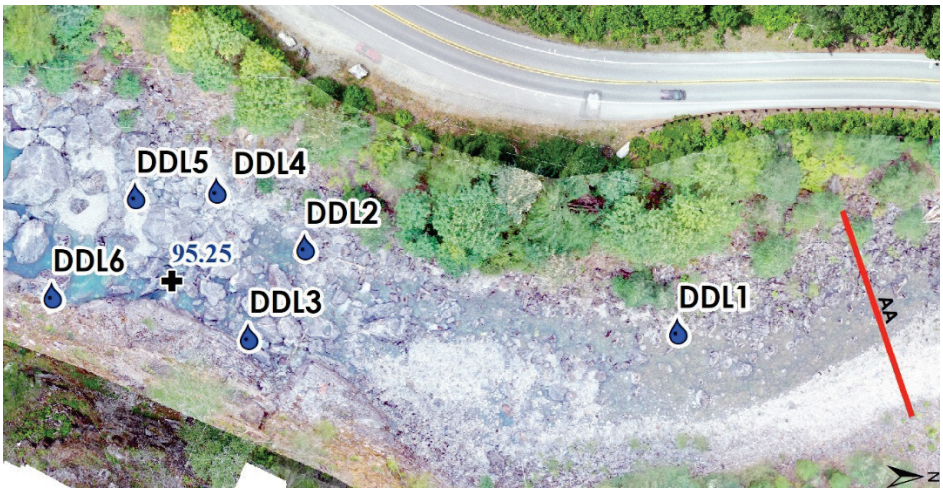


Figure 8. Water level logger locations at Existing Feature 1

Onset HOBO U20 water level loggers were deployed with pressure transducers that can record depths up to 30 feet, with a resolution of .007 feet of water and accuracy within 0.09 psi (maximum error). The loggers record instantaneous pressure and temperature values at a pre-configured interval. To compensate for barometric pressure, one additional U20 level logger was mounted in a vented PVC housing and staged above high-water levels at both Existing Features.

Secure installations in the Gorge bypass reach required careful consideration of channel hydraulics in this high energy environment. Stilling wells were fabricated from 1.5-inch diameter stainless steel conduit to house the pressure transducers and ensure protection against transported cobbles and boulders. The stilling well construction includes an aluminum flat bar to hold the pressure transducer inside, a stopper bolt at the bottom of the tube to stabilize the logger and bar, and a vented cap to equalize pressure. Two metal brackets and anchor bolts were used to secure the pipes against boulders at each install location (Figure 13). Permits to mount the stilling wells were first secured from the National Park Service (NPS) by HDR and SCL.



Figure 9 Mounted stilling well at Existing Feature 2.

Water levels have been collected since May 27, 2021, and they are downloaded approximately monthly. The data were initially captured at ten-minute intervals from May 27, 2021, through July 25, 2021, at which time the interval was decreased to five-minute, primarily for consistency with the recording interval at the USGS Skagit River at Newhalem stream gage (USGS #12178000). Monthly data collection was continued through November 2021. At the November download, due to memory capacity limitations the recording interval was increased to 15-minute to allow the loggers to operate for longer periods between downloads during the winter months without loss of data.

Additional measurements were made during each logger download to independently verify the recorded water levels for quality control. The distance from a surveyed reference bolt to the water surface was measured, as shown in Figure 14, to calculate water surface elevation. This water surface elevation was compared to the value determined from the transducer data to check for any drift. Each stilling well contains one reference bolt, either associated with one of the two metal brackets or installed separately on a boulder face nearby. Reference bolt elevations were established by carrying control point elevations set along SR 20 into the Gorge bypass reach with a total station. All resulting water surface elevations reference the North American Vertical Datum of 1988 (NAVD 88) datum. Manual depth measurements were also taken from the stopper bolt at the bottom of the stilling wells for quality control.



Figure 10. Distance to water reading from separate reference bolt at logger DDL3.

3 SUMMARY OF DATA COLLECTED

3.1 Transect Data

Measurements were made at all five transects for targeted flows of 1,200, 500, 250, and 50 cfs during the July 26-29, 2021, controlled releases. Table 1-Table 4 below summarize the depths, velocities, and discharges measured and the instrumentation used at each transect for the controlled releases. Additional discharge measurements were made at the bridge immediately below Gorge Dam, which are also documented in the tables below. Analysis of depth and velocity measurements with RiverSurveyor Stationary LIVE (ADCP) and FlowTracker2 (ADV) software at the five cableway transects shows high quality data was collected with the ADCP and ADV. The number of measurements at each transect provides a complete and detailed representation of hydraulic characteristics across the transect for each controlled release. Measured velocities ranging from near zero to over seven feet/second and depths from near zero to 16 feet were observed. In sum, 644 velocity/depth measurements (587 by ADCP and 57 by ADV) were made to calibrate/validate the hydraulic model. Careful analysis of the computed discharge at each transect reveals an apparent loss of water at Afternoon Creek pool, located immediately upstream of Transect DD (Figure 1). This apparent loss and a detailed discussion of the uncertainty associated with transect discharge measurements is provided in the Gorge Bypass Reach Discharge Measurement Uncertainty Analysis memorandum (NHC 2022, as attached to the FA-05 Bypass Instream Flow Model Development Study Hydraulic Model Calibration Report [Attachment E]).

Table 1. 1,200 cfs Targeted Spill Transect Measurement Summary

Transect	Depth-Averaged Velocity (ft/s)			Depth (ft)			Discharge (cfs)	Instrument
	Avg	Min	Max	Avg	Min	Max		
Bridge	n/a	n/a	n/a	n/a	n/a	n/a	1165	ADCP
EE	5.36	0.50	7.20	2.4	0.7	3.6	1145	ADCP/ADV
II	1.63	0.11	3.21	6.3	1.9	8.7	1082	ADCP
DD	0.59	0.10	0.93	10.7	2.8	16.0	1045	ADCP
AA	4.30	1.62	6.75	4.3	1.5	6.0	1096	ADCP
GG	1.85	0.93	4.99	7.2	1.9	9.2	1038	ADCP

Table 2. 500 cfs Targeted Spill Transect Measurement Summary

Transect	Depth-Averaged Velocity (ft/s)			Depth (ft)			Discharge (cfs)	Instrument
	Avg	Min	Max	Avg	Min	Max		
Bridge	n/a	n/a	n/a	n/a	n/a	n/a	494	ADCP
EE	3.93	1.90	4.98	2.0	1.5	2.9	491	ADCP
II	1.31	0.01	2.12	5.0	2.2	6.8	514	ADCP
DD	0.31	0.02	0.55	9.5	2.9	14.2	442	ADCP
AA	3.53	0.43	5.77	3.4	1.1	4.3	535	ADCP
GG	1.29	0.31	3.58	6.8	2.4	8.1	438	ADCP

Table 3. 250 cfs Targeted Spill Transect Measurement Summary

Transect	Depth-Averaged Velocity (ft/s)			Depth (ft)			Discharge (cfs)	Instrument
	Avg	Min	Max	Avg	Min	Max		
Bridge	n/a	n/a	n/a	n/a	n/a	n/a	319	ADCP
EE	2.78	0.90	4.46	1.7	0.6	2.7	316	ADV
II	1.08	0.05	1.60	4.6	1.6	6.0	331	ADCP
DD	0.24	0.00	0.34	9.6	2.1	13.4	297	ADCP
AA	2.55	0.82	5.12	3.2	1.5	4.0	306	ADCP
GG	1.67	0.65	3.32	6.3	2.7	7.1	298	ADCP

Table 4. 50 cfs Targeted Spill Transect Measurement Summary

Transect	Depth-Averaged Velocity (ft/s)			Depth (ft)			Discharge (cfs)	Instrument
	Avg	Min	Max	Avg	Min	Max		
Bridge	n/a	n/a	n/a	n/a	n/a	n/a	60	ADCP
EE	1.05	0.00	2.15	1.1	0.0	1.9	56	ADV
II	0.32	0.01	0.55	2.8	0.9	3.9	57	ADCP
DD	0.07	0.05	0.13	8.2	1.5	11.2	58	ADCP
AA	1.47	0.13	2.93	1.9	1.3	2.3	68	ADCP
GG	0.48	0.14	0.97	4.5	1.5	5.4	54	ADCP

3.2 UAV Imagery

The 955 drone-based photos taken on July 30, 2021, of the Gorge bypass reach under base-flow or no-spill conditions were processed in PIX4Dmapper to create a digital model and subsequent orthomosaic images that offer a single high-resolution image of the reaches identified in Figure 5. Figure 15 shows some of the composite orthomosaic image created from the UAV flights between Transect AA and Existing Feature 2, where the UAV-based image has a resolution of 2.4 cm/pixel and the underlying USDA NAIP 2019 ortho image is one meter/pixel. Similar processing was also accomplished for photos taken July 26-29, 2021. Once complete, the following information could be extracted from the orthomosaic imagery for calibration and validation of the hydraulic model and to support other Skagit relicensing studies: 1) characterization of substrate, vegetative cover, and channel characteristics for defining roughness parameters; 2) a water surface elevation profile of the entire reach for each controlled release; and 3) mapping of water surface extents to compare with model output.

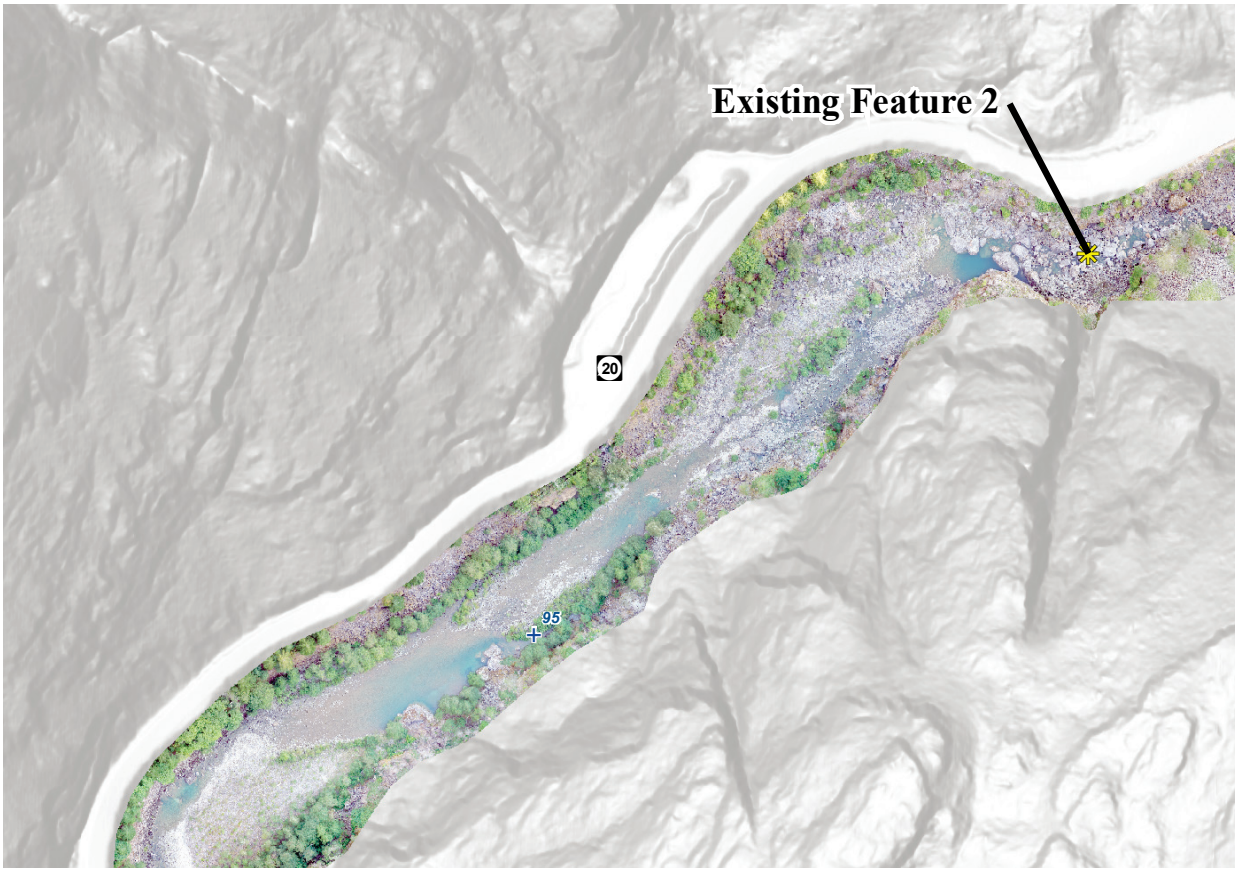


Figure 11. Composite orthomosaic image from July 30, 2021, UAV flights.

3.3 LSPIV

The main outcome of the LSPIV analysis were ~1,800 instantaneous 2D velocity vector fields, containing the streamwise and transverse velocity components within the camera FOV for the one-minute duration of the analyzed video footage

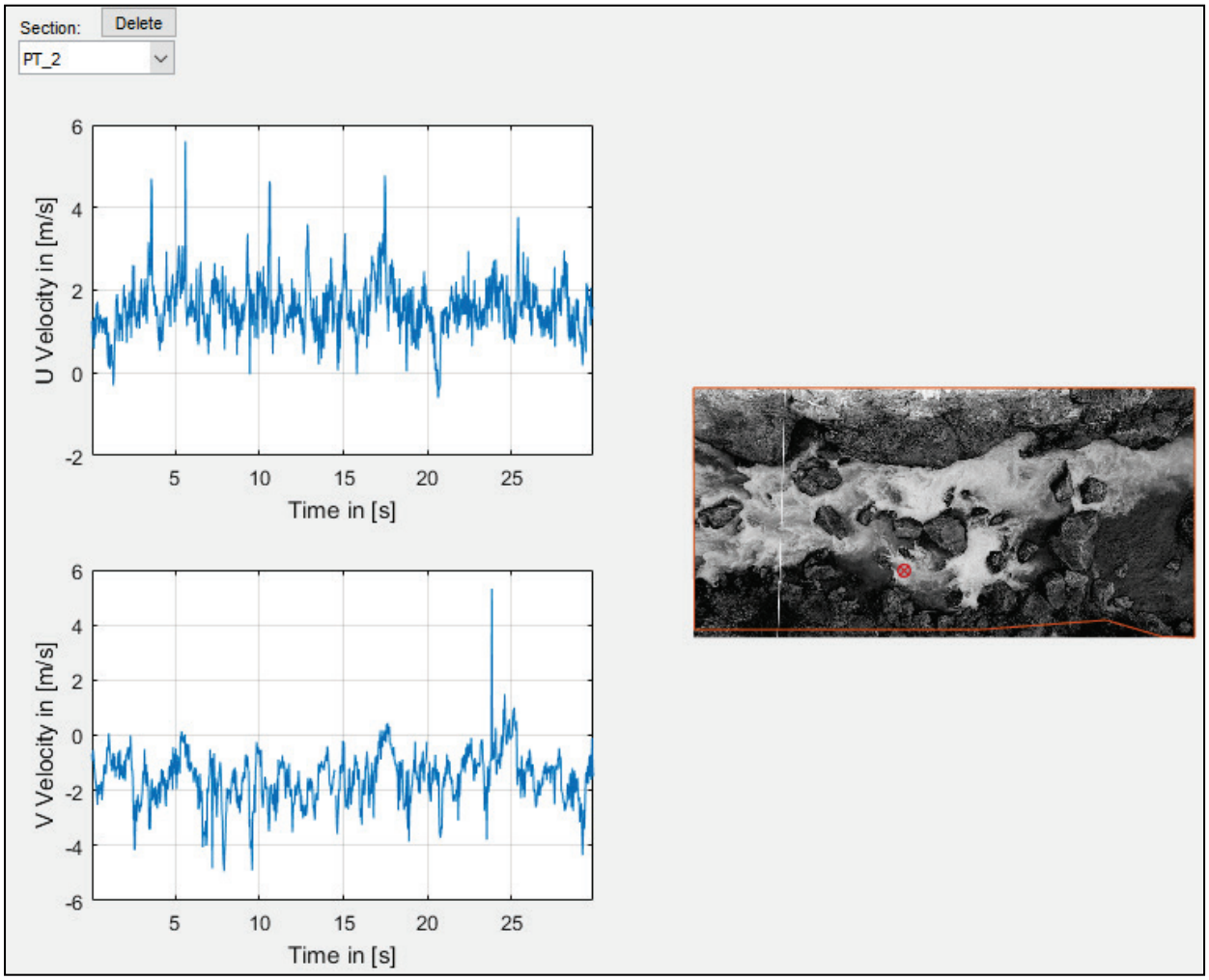


Figure 12. Instantaneous streamwise and transverse velocities at a point in the flow field calculated from the LSPIV method.

The 2D velocity vector fields were averaged to provide the mean (time-averaged) 2D velocity vector field within the camera FOV (Figure 17). The calculated vector field was also used to provide the flow streamlines to facilitate visualization of flow patterns through the measurement domain (Figure 18). Once processed, the mean 2D velocity fields corresponding to the upstream and downstream FOVs for each feature were juxtaposed to produce a combined mean 2D velocity field over the entire extent of Existing Features 1 and 2. A total of eight combined mean 2D velocity fields were produced to support

validation of the hydraulic model and evaluation of fish passage under the FA-04 Fish Passage Study, one for each of the four controlled release events at Existing Features 1 and 2.

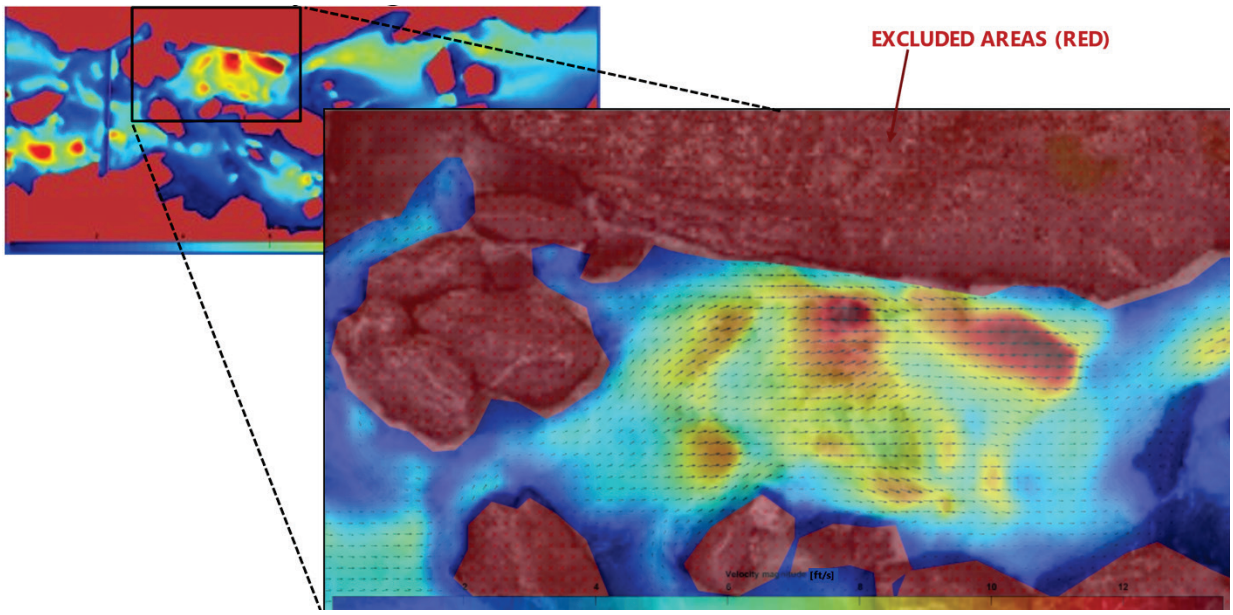


Figure 13. Mean 2D velocity vector field (direction and magnitude) calculated from the LSPIV analysis.

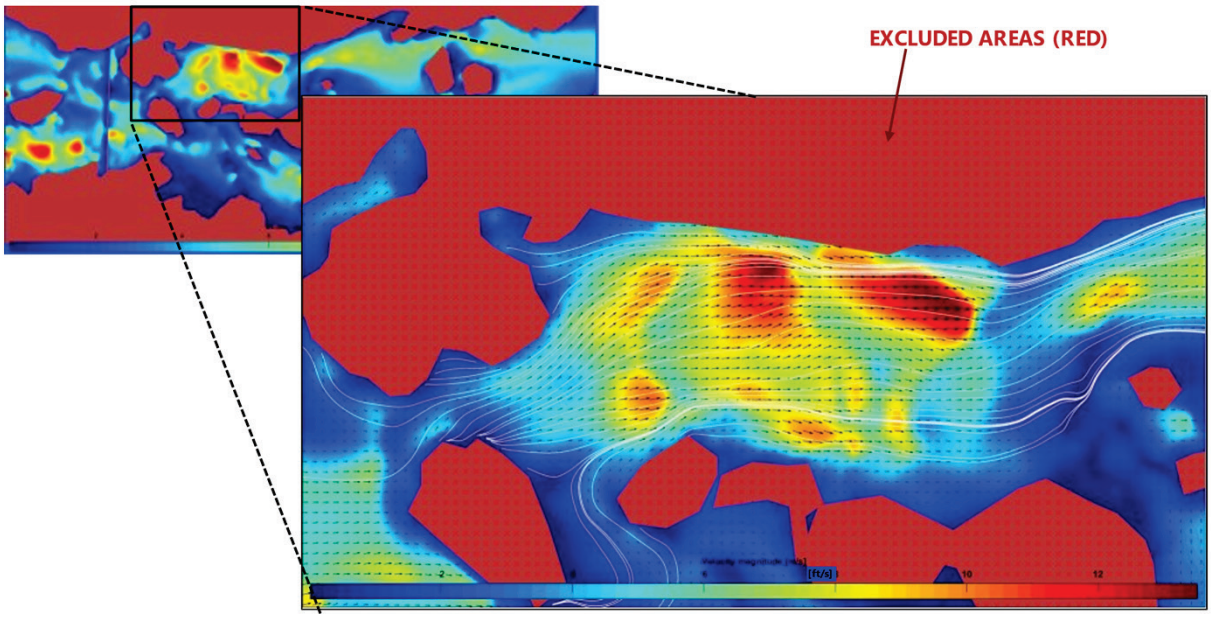


Figure 14. Flow streamlines calculated from the LSPIV analysis.

3.4 Water Level Logger Data

Water stage data have been recorded at Existing Features 1 and 2 since May 2021 for calibration and validation of the hydraulic model and to support the fish passage assessment under the FA-04 Fish Passage Study. The level logger recordings were downloaded monthly through November 2021 and were post-processed for quality control. Note that the Gorge bypass reach is dry (base-flow conditions) most of the time and that water-level data for those periods have no value for hydraulic model calibration.

To date, the most informative observations for model calibration are those collected during the controlled releases (July 26-29, 2021) and during an unscheduled spill from June 28 to July 3, 2021. The unscheduled spill was associated with an historic heat dome over western Washington which resulted in high snowmelt runoff requiring spill at Gorge Dam. Figure 19 and Figure 20 show the recorded water levels at Existing Features 1 and 2, respectively, during the controlled releases from July 26-29, 2021. Average flowrates determined from NHC's field observations and applied during model calibration, as reported in the Gorge Bypass Reach Discharge Measurement Uncertainty Analysis memorandum (as attached to the FA-05 Bypass Instream Flow Model Development Study Hydraulic Model Calibration Report [Attachment E]) are displayed on the figures to provide context relating stage and discharge.

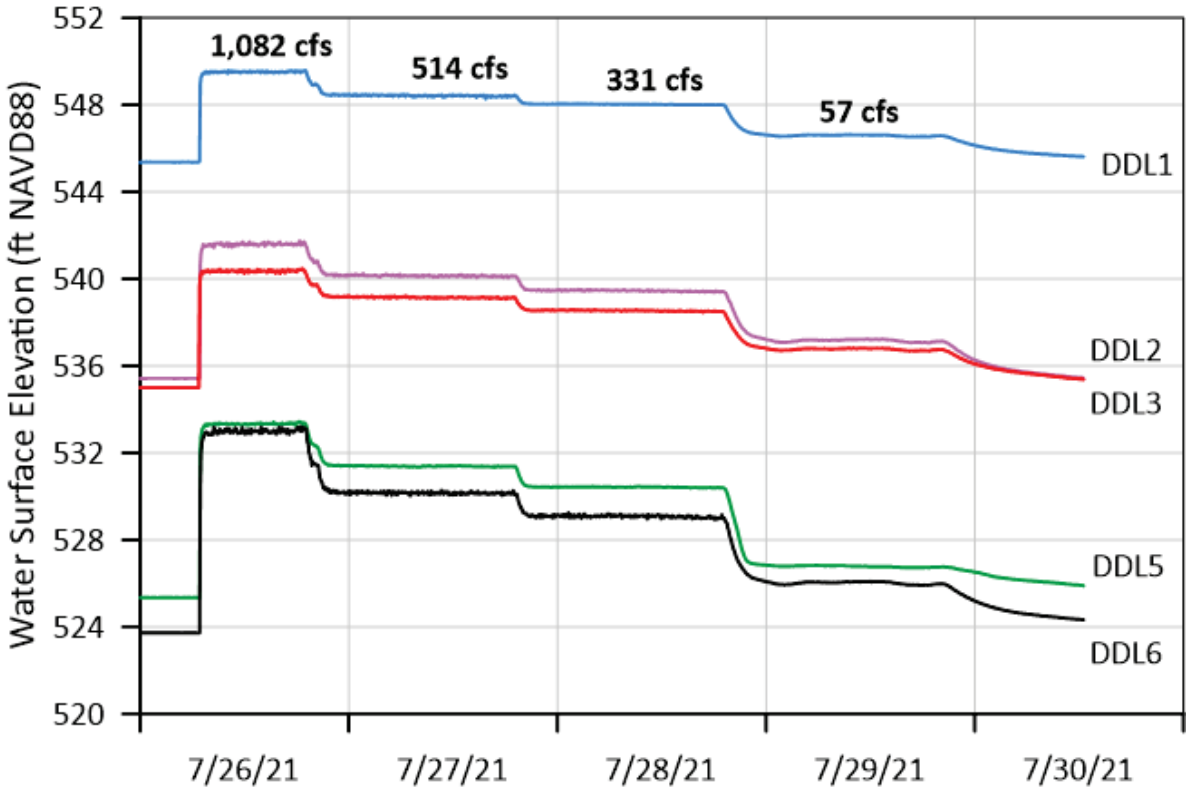


Figure 15. Recorded water levels at Existing Feature 1 during controlled releases from July 26-29, 2021.

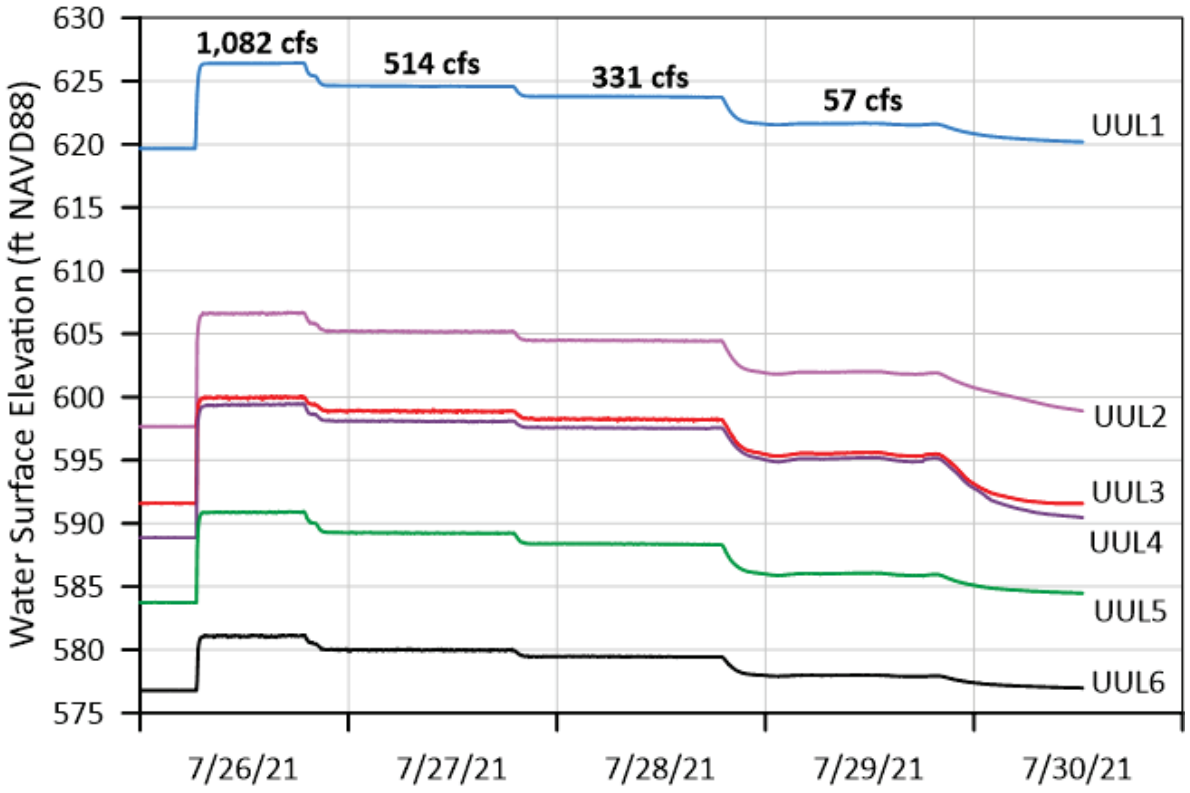


Figure 16. Recorded water levels at Existing Feature 2 during controlled releases from July 26-29, 2021.

Recorded water levels at Existing Features 1 and 2 resulting from spill associated with rapid snowmelt during the extreme heat in late June 2021 are shown in Figure 21 in addition to a graphic of the computed spill. The computed spill is determined with the Gorge Dam Spill Calculator which is a spreadsheet calculation of theoretical spill, given reservoir level and gate opening.

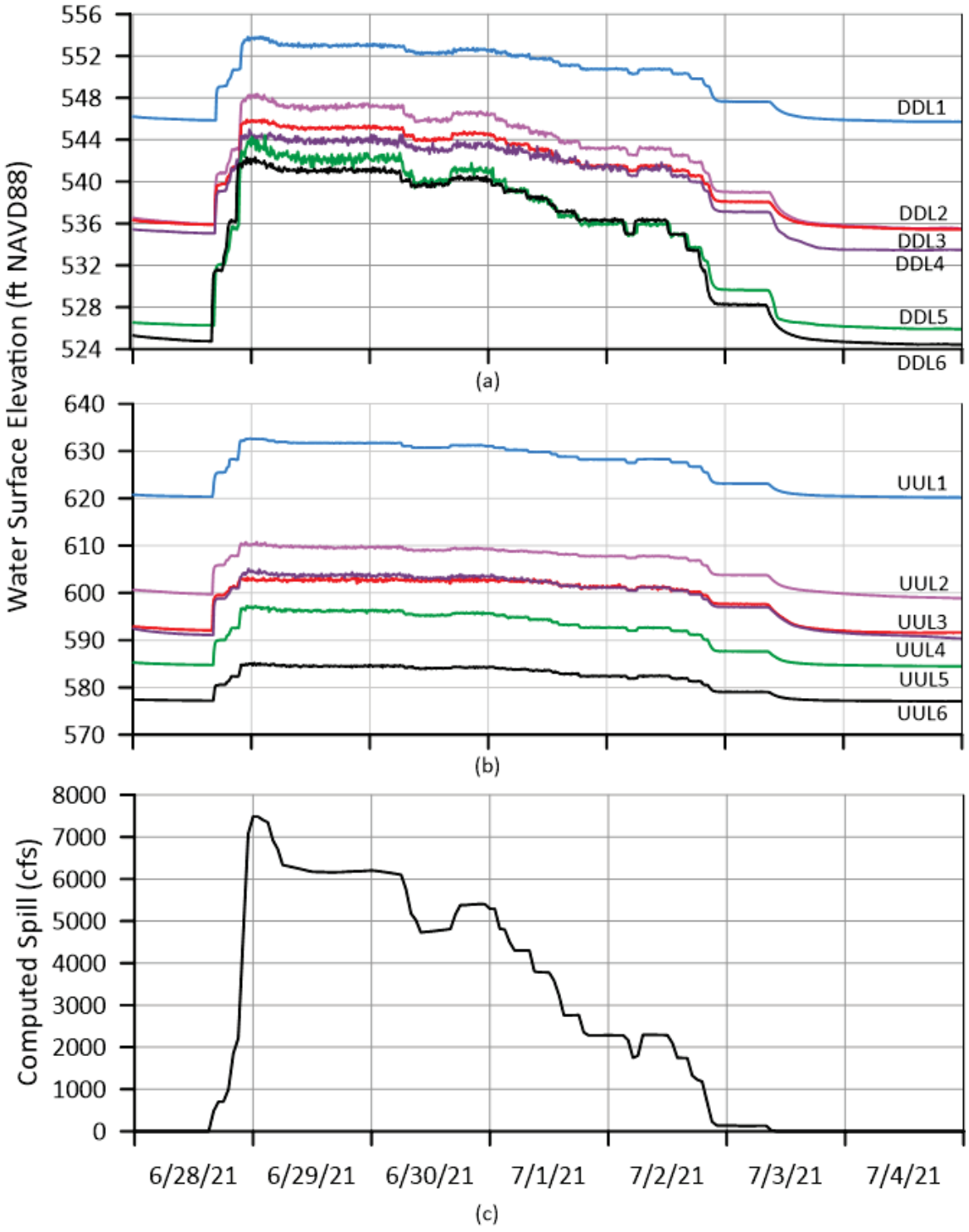


Figure 17. (a) (b) Recorded water levels at Existing Feature 1 and Existing Feature 2 during the unscheduled spill from 28 June to 3 July. (c) Computed spill during the unscheduled release.

4 CONCLUSIONS

Field measurements were conducted of the Skagit River in the Gorge bypass reach for calibrating a new hydraulic model and for use in other relicensing studies. Hydraulic characteristics were measured at nominal controlled releases of 1,200, 500, 250, and 50 cfs from Gorge Dam during the week of July 26, 2021. Three categories of data were collected: measurements at established transects, drone-based still photos and videos, and data recorded by water level loggers placed at each of the Existing Features.

Depth and velocity measurements were made using an ADCP and ADV at five established transects and the bridge immediately below Gorge Dam. Analysis of the measurements shows high quality data was collected with excellent coverage along each transect. Measured velocities ranged from near zero at channel margins to over seven feet/sec, and depths up to 16 feet were observed. In sum, 644 velocity/depth measurements (587 by ADCP and 57 by ADV) were made to calibrate/validate the hydraulic model. A discussion of measurement uncertainty and an apparent loss of flow at Afternoon Creek Pool is discussed in Gorge Bypass Reach Discharge Measurement Uncertainty Analysis Technical Memorandum (as attached to the FA-05 Bypass Instream Flow Model Development Study Hydraulic Model Calibration Report [Attachment E]).

Nearly 4,300 nadir photographs were taken of the Gorge bypass reach between Gorge Dam and Gorge Powerhouse from a drone at altitude. Overlapping photographs from each day were processed through Structure from Motion (SfM) software to produce a 3D model (point cloud) and ultimately a composite orthomosaic of the observed conditions each day. These 3D models and orthomosaics are available to support hydraulic model calibration/validation and to assist other Skagit Project relicensing studies. Video footage at Existing Features 1 and 2 were also recorded at each controlled spill in late July and have been processed in large scale particle image velocimetry software. Resultant velocity vector maps and digital streamlines are available to ground truth the hydraulic model and to support the FA-04 Fish Passage Study.

Twelve water level loggers were installed at Existing Features 1 and 2 in May 2021, and they have been recording water stage since that date. Notably, stages were recorded for an unplanned spill in late June, where a maximum discharge of ~7,400 cfs was achieved, as well as for the planned controlled releases in late July 2021. Plots of the observed stages track well with spill records, and quality control measurements taken during monthly data downloads reveal little drift and therefore high reliability of records. These records are available to calibrate/validate the hydraulic model.

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SKAGIT RIVER GORGE BYPASS REACH HYDRAULIC AND INSTREAM FLOW MODEL DEVELOPMENT STUDY
BYPASS HYDRAULIC MODEL CALIBRATION REPORT

ATTACHMENT E

GORGE BYPASS REACH DISCHARGE MEASUREMENT UNCERTAINTY ANALYSIS MEMORANDUM

nhc
northwest hydraulic consultants

12787 Gateway Drive South | Seattle, WA 98168 | 206.241.6000 |

MEMORANDUM

To: **Project File**

Date: March 2022

NHC Ref. No. 2003536

From: Donnie Jones, EIT – NHC
Chris Long, PE – NHC

Re: Gorge Bypass Reach Discharge Measurement Uncertainty Analysis

Note: Figure 1 map symbology updated on October 20, 2022. No other changes made to Memo.

1 INTRODUCTION

Northwest Hydraulic Consultants (NHC) collected hydraulic data of the Skagit River between Gorge Dam and Gorge Powerhouse, otherwise known as the Gorge bypass reach, from July 26-29, 2021, for use in calibrating and validating a new hydraulic model as part of the FA-05 Skagit River Gorge Bypass Reach Hydraulic and Instream Flow Model Development Study (Bypass Instream Flow Model Development Study). This hydraulic model is being developed to support the Federal Energy Regulatory Commission (FERC) relicensing of the Skagit River Hydroelectric Project (Project) and will be used for assessing instream flows and evaluating fish passage conditions among other FERC relicensing tasks. As requested by licensing participants (LPs) during the FA-05 Study Workshop 3 on August 26, 2021, this memorandum documents NHC's evaluation of uncertainty for measured discharges and subsequent selection of inflows for the hydraulic model representative of discharge in the Gorge bypass reach during the July 26-29, 2021, controlled releases.

2 CONTROLLED RELEASE FLOW MEASUREMENTS

Four controlled flows were released from Gorge Dam from July 26-29, 2021, to allow for field data collection to support hydraulic model calibration. During each controlled release, NHC collected discharge measurements at the bridge immediately below Gorge Dam and at five cableway transects (Figure 1). Flow magnitudes of 1,200, 500, 250, and 50 cfs were targeted for the release events on four consecutive days. To release flows of 1,200, 500, and 250 cfs into the bypass reach, one spillway gate on Gorge Dam was raised according to the Project's spillway discharge calculator. At the targeted flow range, this required the 50-foot-tall spillway gate be opened by mere inches. For the targeted release of 50 cfs, both spillway gates were closed, and the log chute was opened to pass flow from Gorge Lake into the Gorge bypass reach. Maintaining a steady flow through the spillway gate and log chute required operators to maintain a constant reservoir elevation throughout each spill event. Sensitivity of the flow releases to fluctuation in reservoir levels and uncertainty in the precise opening of the spillway gate at small gate openings required physical measurements be made to verify the actual discharge released.

Detailed discussion of how discharge measurements were made at the bridge and cableway transects is provided in the Gorge Bypass Reach Data Collection for Hydraulic Model Calibration memorandum (NHC 2022, as attached to the FA-05 Bypass Instream Flow Model Development Study Hydraulic Model Calibration Report [Attachment D]). The following sections detail how uncertainty was assessed for each discharge measurement and what discharge values were selected to represent the controlled spill events in the hydraulic model.

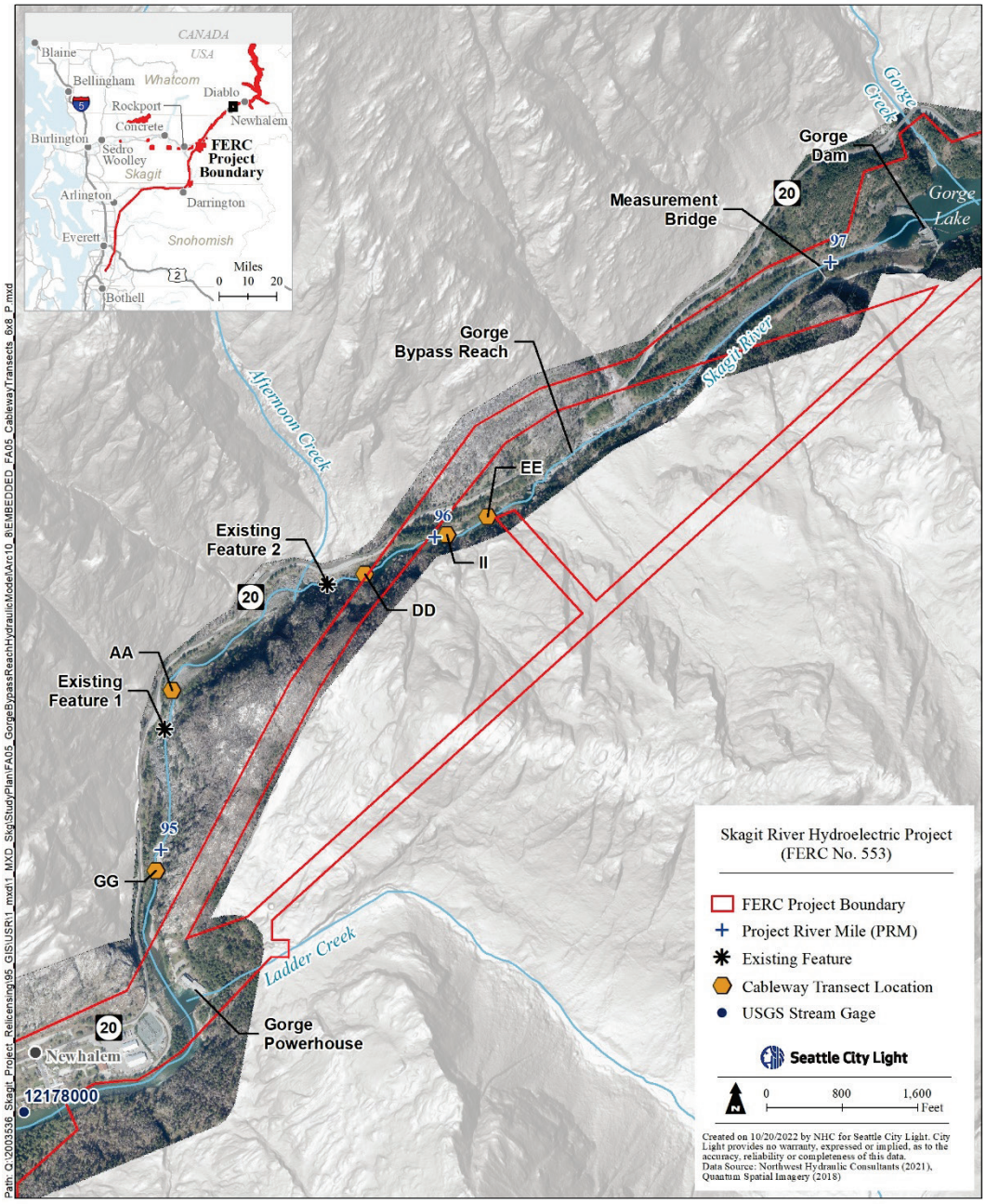

Figure 1. Bridge and cableway transect measurement locations for hydraulic model calibration.

3 MEASUREMENT UNCERTAINTY

The five cableway transect locations were selected in consultation with LPs, primarily Washington State Department of Ecology (Ecology) and Washington Department of Fish and Wildlife (WDFW) after NHC completed an initial reconnaissance of the Gorge bypass reach. The transect locations were selected considering factors such as access, safety, and equipment logistics; however, as the focus of the hydraulic model is assessing instream flows, it was of primary importance to LPs to represent a variety of geomorphic units. Since the transects would be used primarily to calibrate the hydraulic model to observed velocities and depths, selecting locations based on characteristics of an ideal discharge measurement were of lesser importance. Note that an ideal transect for measuring discharge is 1) located along a longitudinally uniform channel, 2) has an even and smooth distribution of velocity, and 3) has a smooth and firm channel bed for measurement of cross-sectional area (Turnipseed and Sauer, 2010). None of the five cableway transects strictly meets these criteria. During each discharge measurement, field staff evaluated both the characteristics of the measurement section and the performance of the data collection process to make a qualitative assessment of confidence in the computed discharge. The following characteristics were found to impact discharge measurement quality at the cableway transects and at the bridge below Gorge Dam:

- Large material and bed features causing abrupt changes in channel elevation relative to flow depth (Bridge; Transects EE and AA);
- Non-uniform channel conditions upstream and/or downstream of measurement cross-section (Transects EE, II, and AA);
- Uneven distribution and rapid changes of velocity along cross-section (Bridge; Transects EE, II, AA, and GG);
- Significant lateral and vertical velocity components (Transects EE and AA);
- Turbulence fluctuations similar in magnitude to time-averaged velocity (Transect DD); and
- Recirculation creating reverse flow (Transect GG).

The preceding field observations were qualitatively assessed to determine the measurement locations that provided the most reliable discharge measurements. Based on the overall poor quality of site conditions at Transect AA, this transect was not used in the discharge assessment. The bridge below Gorge Dam, Transect II, and Transect DD were observed to provide the most reliable discharge measurement conditions, while conditions at Transects EE and GG were deemed acceptable to aid in verification of flows. Note that all velocity and depth measurements are being used to calibrate the hydraulic model; this assessment was focused only on quantifying uncertainty in the computed discharge.

All but one discharge measurement taken at all locations across all four days was made using the USGS mid-section method (Turnipseed and Sauer 2010). The only exception to this was a moving-vessel ADCP measurement (Mueller et al. 2013) at the bridge immediately below Gorge Dam during the 1,200 cfs targeted spill. Unfortunately, the bridge did not provide appropriate conditions to consistently repeat transects during moving-vessel operation. Therefore, this discharge measurement was excluded from

this quantitative uncertainty analysis and the mid-section method was used at the bridge for subsequent measurements.

4 UNCERTAINTY QUANTIFICATION

A quantitative assessment of uncertainty for each discharge measurement is provided in Table 1-4. While not used for assessing discharge in the Gorge bypass reach, data from Transect AA is included in these tables for completeness. To quantify total uncertainty, the following individual components were assessed:

- Uncertainty due to 1) changes in depth and velocity between each stationary measurement along a transect and 2) the extent of extrapolated depth and velocity data not directly measured over the entire transect;
- Uncertainty owing to the angle of primary flow direction differing from the cableway angle (not applicable for waded discharge measurements); and
- Uncertainty in estimating the distance to far edge of water from the last measured station. This component is only applicable for cableway measurements made when the channel could not be waded. (The “far edge of water” is on the left bank of the Gorge bypass reach looking downstream and is generally not accessible except under baseflow conditions).

Table 1. 1,200 cfs Targeted Spill Measurement Uncertainty

Transect	Measured Flow (cfs)	Uncertainty (%)				Error Bounds (cfs)	
		Measurement	Flow Angle	Far Edge	Total	Minimum	Maximum
Bridge	1165	14.8	N/A	N/A	14.8	993	1338
EE	1145	3.0	1.2	0.2	4.4	1095	1196
II	1082	2.5	0.4	2.1	5.0	1028	1136
DD	1045	1.9	0.1	1.1	3.1	1013	1077
AA	1096	2.9	0.3	1.9	5.1	1040	1152
GG	1038	6.3	1.5	1.1	8.9	946	1130

Table 2. 500 cfs Targeted Spill Measurement Uncertainty

Transect	Measured Flow (cfs)	Uncertainty (%)				Error Bounds (cfs)	
		Measurement	Flow Angle	Far Edge	Total	Minimum	Maximum
Bridge	494	3.7	1.5	N/A	5.2	469	523
EE	491	3.0	2.3	2.5	7.8	452	529
II	514	2.4	2.1	1.9	6.4	481	547
DD	442	2.3	2.1	0.1	4.5	422	462
AA	535	3.8	0.5	2.5	6.8	499	572
GG	438	2.1	1.6	0.4	4.1	420	455

Table 3. 250 cfs Targeted Spill Measurement Uncertainty

Transect	Measured Flow (cfs)	Uncertainty (%)				Error Bounds (cfs)	
		Measurement	Flow Angle	Far Edge	Total	Minimum	Maximum
Bridge	319	4.5	0.5	N/A	5.0	303	343
EE	316	5.0	N/A	N/A	5.0	300	331
II	331	2.4	0.3	1.4	4.1	318	345
DD	297	2.3	1.7	0.2	4.2	285	310
AA	306	3.2	0.4	3.3	6.9	285	327
GG	298	3.9	0.9	1.9	6.7	279	318

Table 4. 50 cfs Targeted Spill Measurement Uncertainty

Transect	Measured Flow (cfs)	Uncertainty (%)				Error Bounds (cfs)	
		Measurement	Flow Angle	Far Edge	Total	Minimum	Maximum
Bridge	60	4.7	1.7	N/A	6.4	56	63
EE	56	8.1	N/A	N/A	8.1	51	60
II	57	3.7	2.7	0.7	7.1	53	61
DD	58	5.6	0.6	1.1	7.3	54	62
AA	68	7.5	1.4	15.3	24.2	52	85
GG	54	5.9	8.0	2.0	15.9	46	63

The computed discharge from each processed measurement along with error bounds based on computed uncertainty are charted in Figure 2-5.

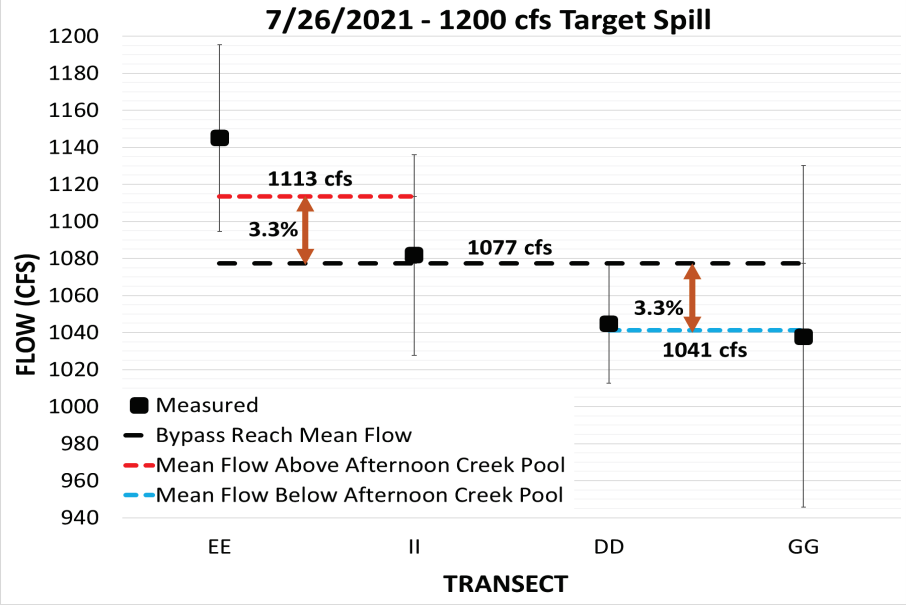

Figure 2. Measured transect flows and computed mean flows during July 26, 2021, controlled spill. Vertical lines indicate error bounds determined from uncertainty analyses.

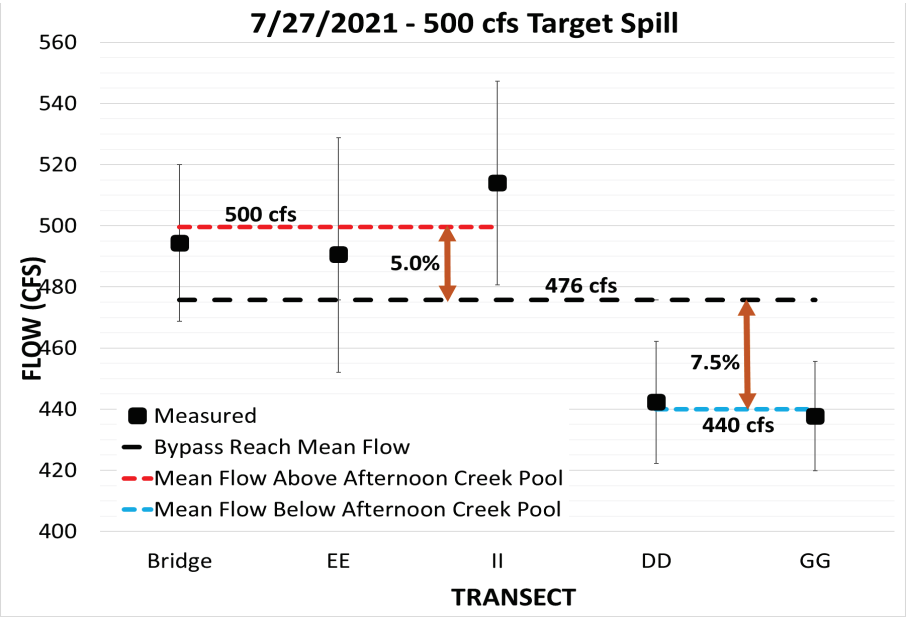

Figure 3. Measured transect flows and computed mean flows during July 27, 2021, controlled spill. Vertical lines indicate error bounds determined from uncertainty analyses.

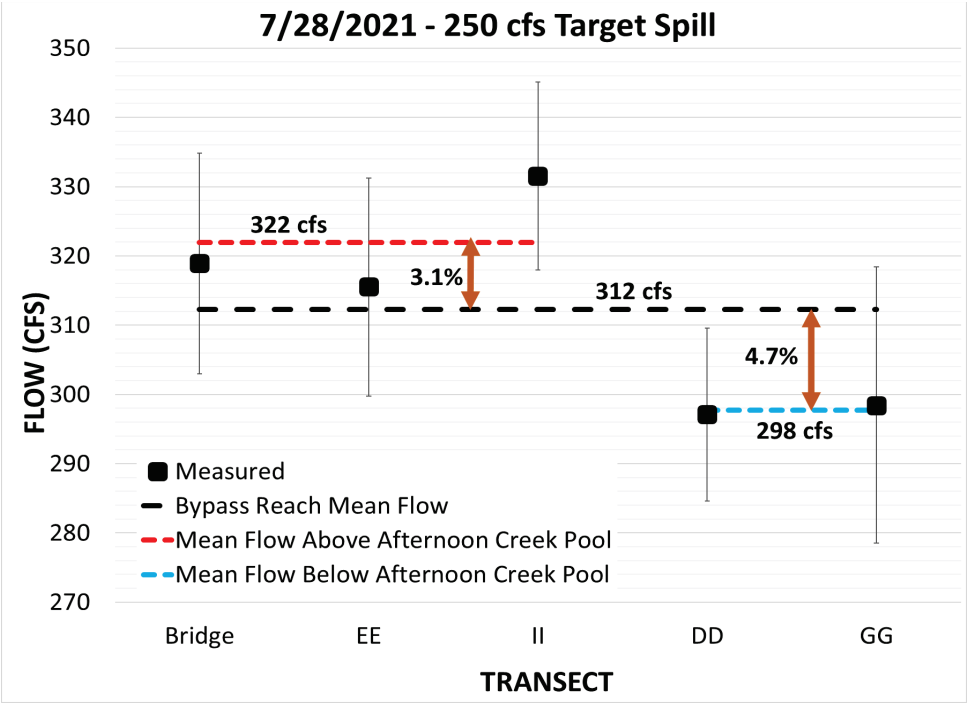

Figure 4. Measured transect flows and computed mean flows during July 28, 2021, controlled spill. Vertical lines indicate error bounds determined from uncertainty analyses.

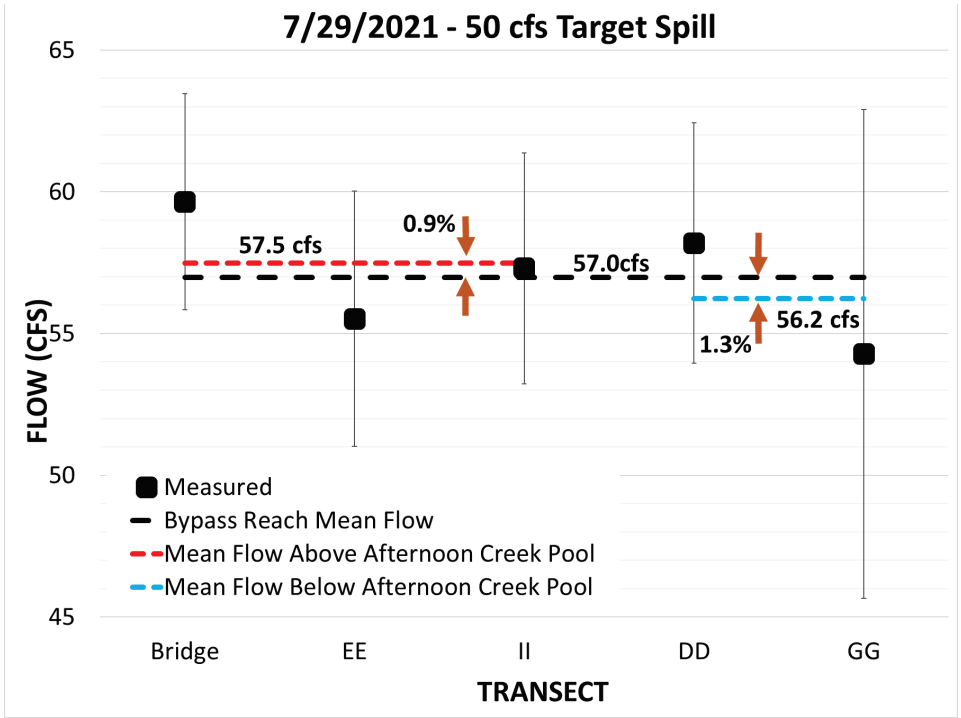

Figure 5. Measured transect flows and computed mean flows during July 29, 2021, controlled spill. Vertical lines indicate error bounds determined from uncertainty analyses.

5 POTENTIAL FLOW LOSS

A significant trend is discernable from the plots in Figure 2-5 where measured flows decrease between Transects II and DD. This was noted at FA-05 Workshop 3 and prompted LPs to request this memorandum. The reach between these transects is characterized by a low gradient (0.7%) and encompasses the largest standing pool in the Gorge bypass reach (Afternoon Creek Pool) which forms behind landslide material otherwise known as Existing Feature 2 (see Figure 1). The decrease in flow within this section amounts to 6.6%, 12.5%, and 7.8% of the mean reach flow for the 1,200 cfs, 500 cfs, and 250 cfs targeted spills, respectively. It is unlikely this trend is solely attributable to a coincidence of random measurement error since it is observed across multiple releases over multiple days. Additionally, the observed mean flow between transects upstream of Afternoon Creek Pool (Bridge, EE and II) falls outside or at the extreme end of the error bounds for measured flows below the pool (DD and GG) and vice versa. During the 50 cfs targeted spill this trend is much less discernable, constituting a 2.2% decrease relative to the mean reach flow.

Within the Gorge bypass reach, large amounts of coarse material are distributed throughout the channel bottom, giving opportunity for water to percolate through. This coarse material includes gravel fill found 200-300 feet deep beneath Gorge Dam; significant deposits of cobble and boulder gravels introduced by landslides, glacial outburst flood deposits, debris flows, small tributary debris cones; and fill from human activities (J. Riedel, personal communication, September 28, 2021; Riedel et al. 2020; Riedel et al. 2006; Riedel 2017). These large material deposits throughout the Gorge bypass reach may provide significant groundwater storage as well as pathways allowing water to flow subsurface. A “mass-movement terrace” (Riedel et al. 2020) and material from the 2004 Afternoon Creek landslide have created large deposits for such groundwater paths to exist near the Afternoon Creek Pool. It’s also important to note that prior to the controlled releases, western Washington experienced a historic “heat dome” in late June with temperatures well over 100 degrees Fahrenheit for a week, and the Gorge bypass reach did not see flow exceeding more than a few cubic feet per second during the month of July. With such extremely dry antecedent conditions, it is possible that significant groundwater storage was available prior to the controlled releases and that this storage was recharged over the course of the week until full, as indicated by the lack of flow loss on July 29, 2021. Further investigation of flow loss is beyond the scope of this study. However, knowledge of the geology of the reach and confidence bounds in the discharge measurements provides a plausible explanation for the apparent loss in observed flow.

6 MODEL CALIBRATION FLOWS

Apparent flow loss at Afternoon Creek Pool during the 1,200, 500, and 250 cfs targeted spills will be accounted for in calibration of the hydraulic model by simulating a mean discharge for measurements made upstream (Bridge, Transects EE and II) and downstream (Transects DD and GG) of the feature. Observed data will be compared to model output from the mean flow corresponding to the location where the observed data were measured. Since discharge measurements during the 50 cfs targeted spill did not indicate discernable flow fluctuations relative to random error, a mean flow was computed from all measurements along the reach for input to the hydraulic model. The following table provides the inflows selected to represent the controlled release events in the hydraulic model.

Table 5. Mean Flows for Hydraulic Model Calibration

Calibration Simulation	U/S Mean Flow (cfs)*	D/S Mean Flow (cfs)**
July 26, 2021	1113	1041
July 27, 2021	500	440
July 28, 2021	322	298
July 29, 2021	57***	57***

* Mean flow measured upstream of Afternoon Creek Pool (Gorge Dam Bridge, Transects EE and II)
** Mean flow measured downstream of Afternoon Creek Pool (Transects DD and GG)
*** Mean of all discharge measurements

7 REFERENCES

Mueller, D.S., C.R. Wagner, M.S. Rehmel, K.A. Oberg, and Francois Rainville, 2013. Measuring discharge with acoustic Doppler current profilers from a moving boat. (Version 2.0, No. 3-A22). U.S. Geological Survey. December 2013. 95 p. https://dx.doi.org/10.3133/tm3A22

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Riedel, J.L. 2017. Deglaciation of the North Cascade Range from the last glacial maximum to the Holocene. Cuadernos de Investigación Geográfica 4: 467-496.

Riedel, J.L, R.A Haugerud, and J.J. Clague. 2007. Geomorphology of a Cordilleran ice sheet drainage network through breached divides in the North Cascades Mountains of Washington and British Columbia. Geomorphology 91: 1-18.

Riedel, J., S. Sarrantonio, K. Ladig, and M. Larrabee. 2020. Skagit River Geomorphology Inventory Report: Part I – Gorge Dam to Sauk River. Report to Seattle City Light. U.S. National Park Service.

Turnipseed, D.P., and V.B. Sauer. 2010. Discharge measurements at gaging stations. (No. 3-8) U.S. Geological Survey. 87 p. (Also available at https://pubs.usgs.gov/tm/tm3-a8/)

SKAGIT RIVER GORGE BYPASS REACH HYDRAULIC AND INSTREAM FLOW MODEL DEVELOPMENT STUDY
BYPASS HYDRAULIC MODEL CALIBRATION REPORT

ATTACHMENT F

MODEL PERFORMANCE EVALUATION: TRANSECT VELOCITIES AND DEPTHS

Memo

Date:	March 2023
Project:	Skagit River Project FERC Relicensing
To:	Project File, NHC
From:	Donnie Jones, NHC Chris Long, NHC
Subject:	Model Performance Evaluation – Transect Velocities and Depths

1.0 INTRODUCTION

In support of the FA-05 Instream Flow Model Development Study for the Skagit Hydroelectric Project FERC Relicensing, statistical analysis of model performance was completed by comparing simulated data of the final calibrated instream flow hydraulic model against observed data collected during controlled releases in the Gorge bypass reach from July 26-29, 2021 (NHC 2022).

2.0 MODEL PERFORMANCE METRICS

Model performance metrics are documented for the final calibrated model in Section 5.2 of the Bypass Hydraulic Model Calibration Report. The parameters analyzed include depth and velocity at transects. For linear regression plots, the y-Intercept, R^2, and slope of linear regression line, and number of points compared are tabulated. For each calibration discharge event, transect comparisons are shown discretized by individual transect. Model performance metrics included are listed below:

Page

1,200 cfs Controlled Release Individual Transects 2
500 cfs Controlled Release Individual Transects 7
250 cfs Controlled Release Individual Transects 12
50 cfs Controlled Release Individual Transects 17

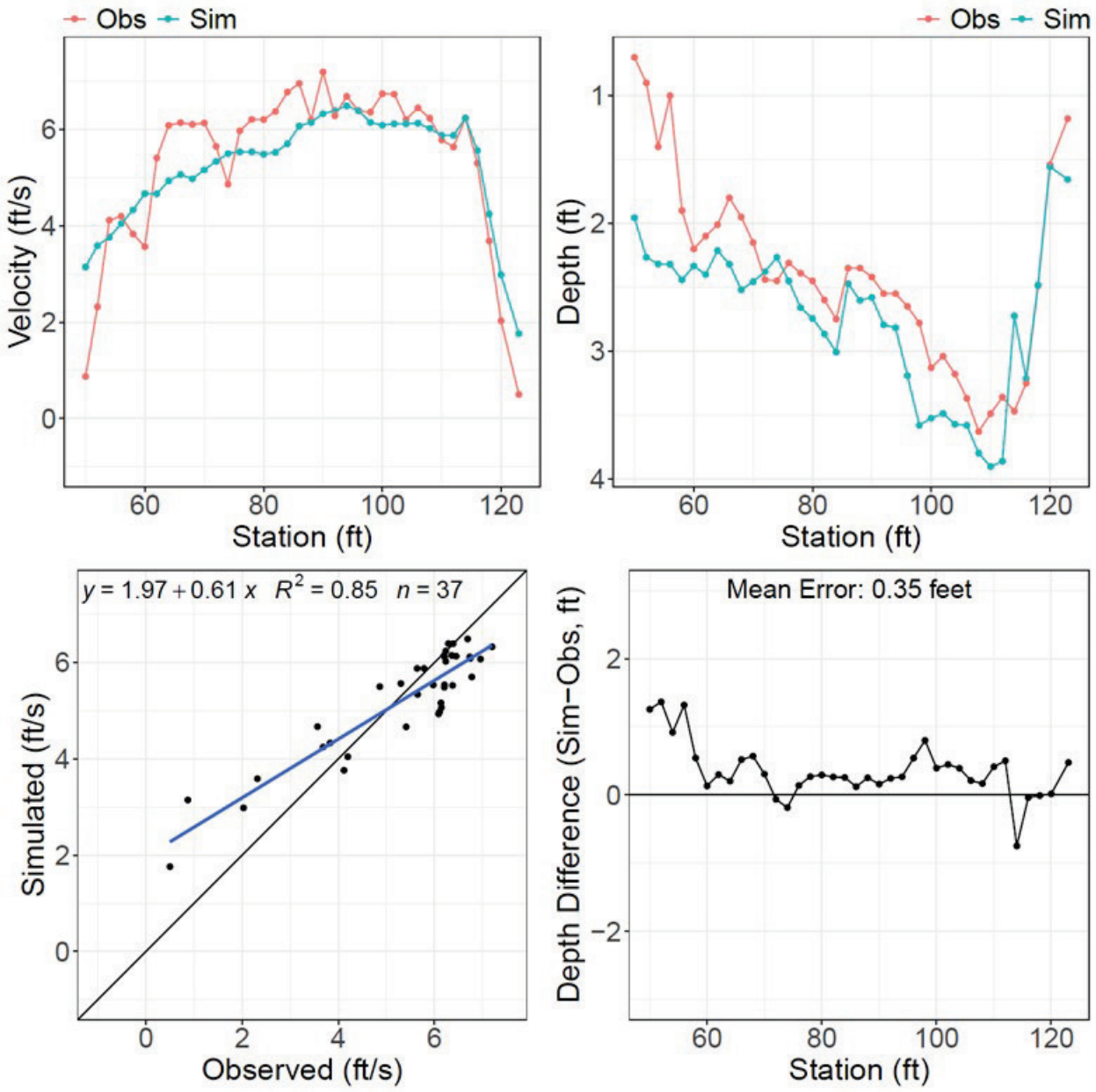


Figure F-1. Calibration results at Transect EE for 1,200 cfs controlled release.

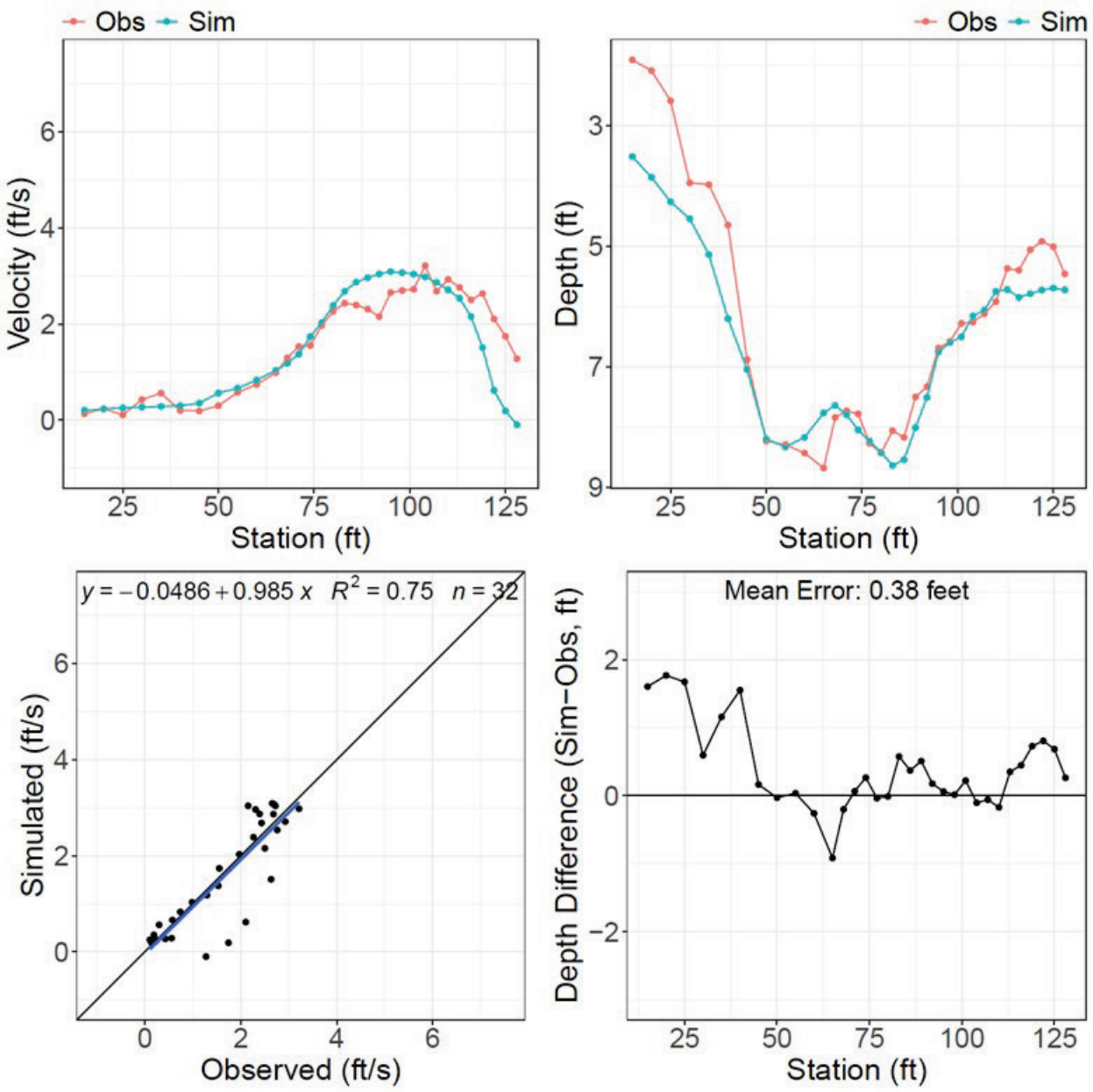


Figure F-2. Calibration results at Transect II for 1,200 cfs controlled release.

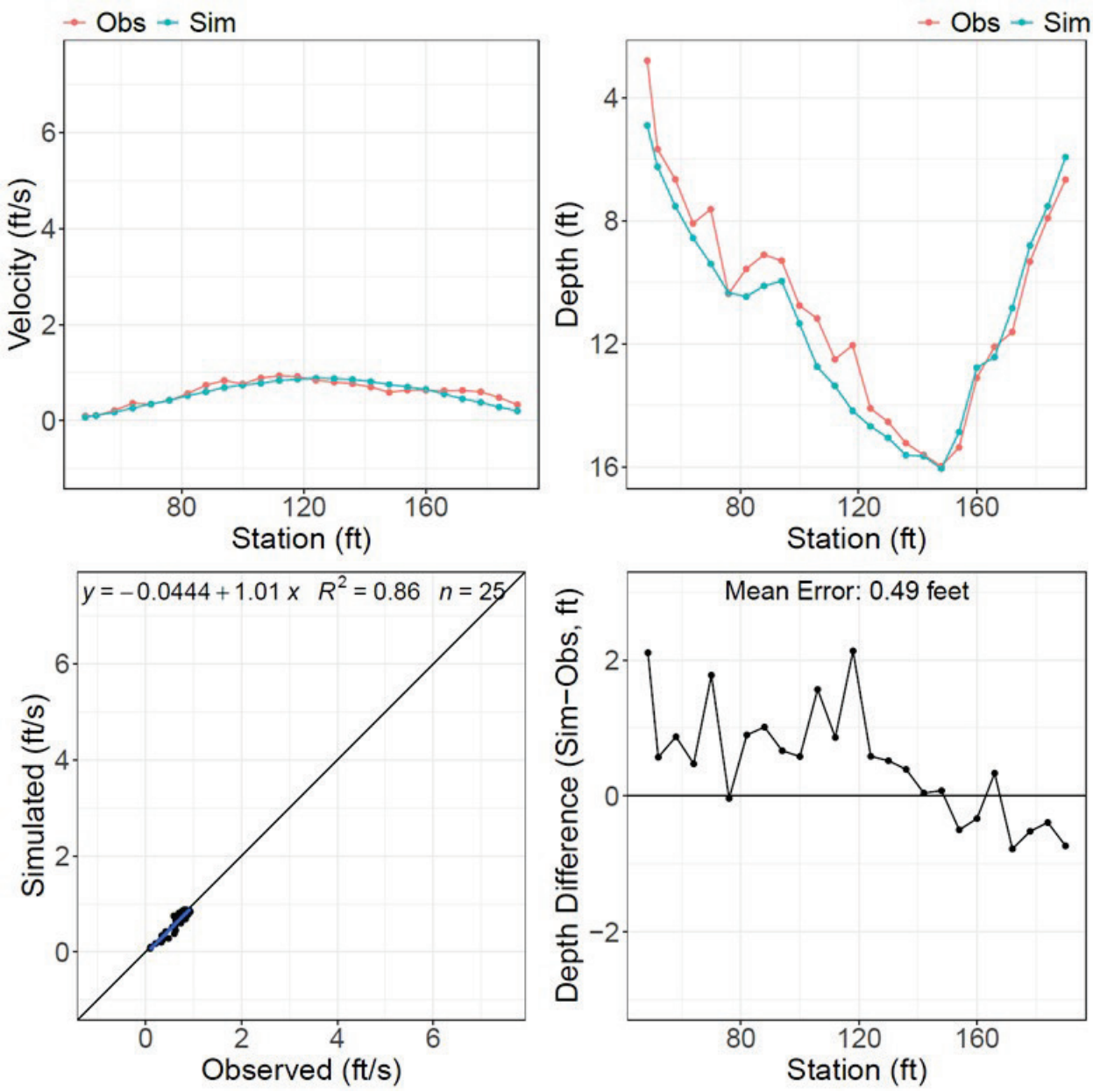


Figure F-3. Calibration results at Transect DD for 1,200 cfs controlled release.

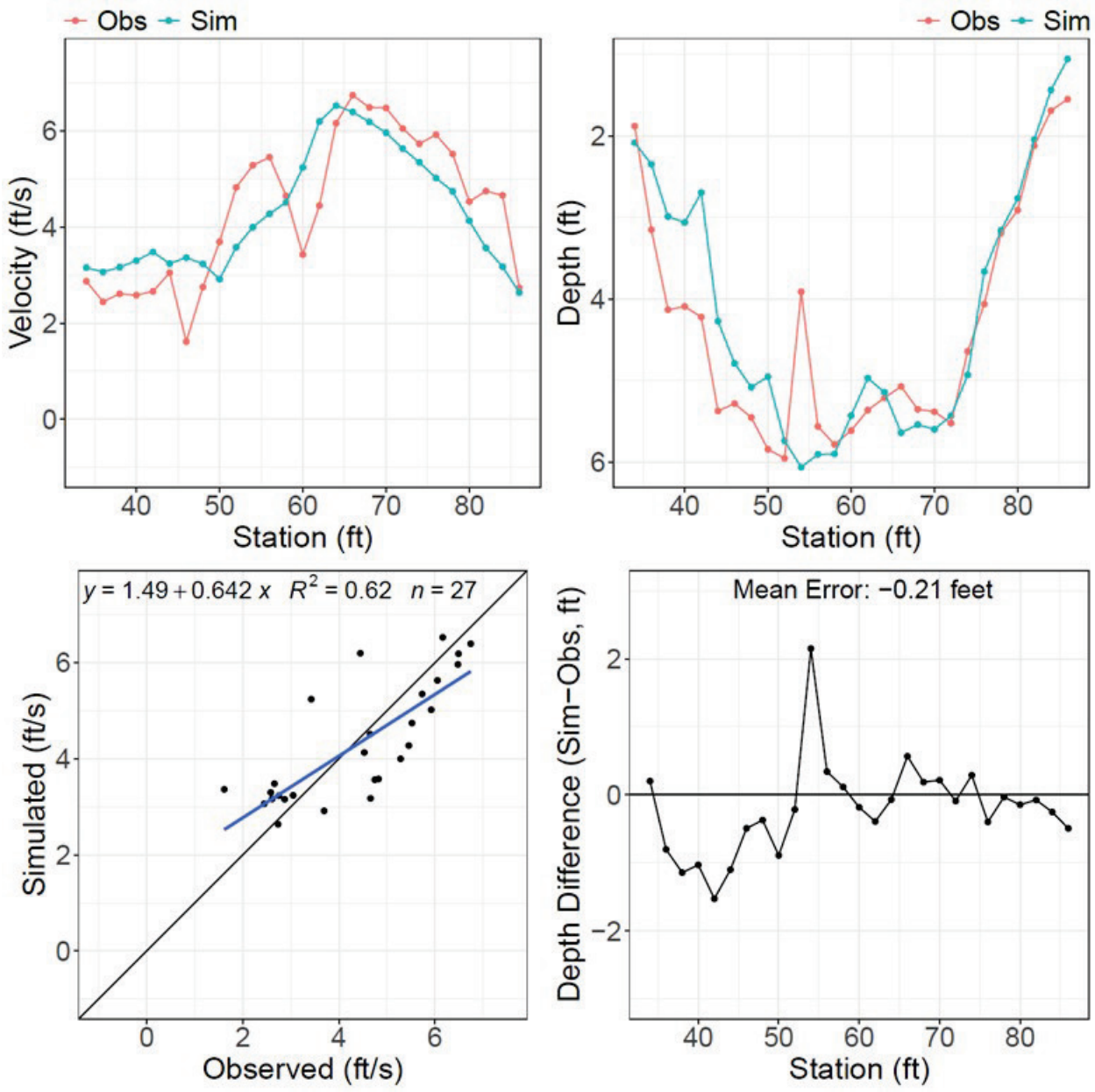


Figure F-4. Calibration results at Transect AA for 1,200 cfs controlled release.

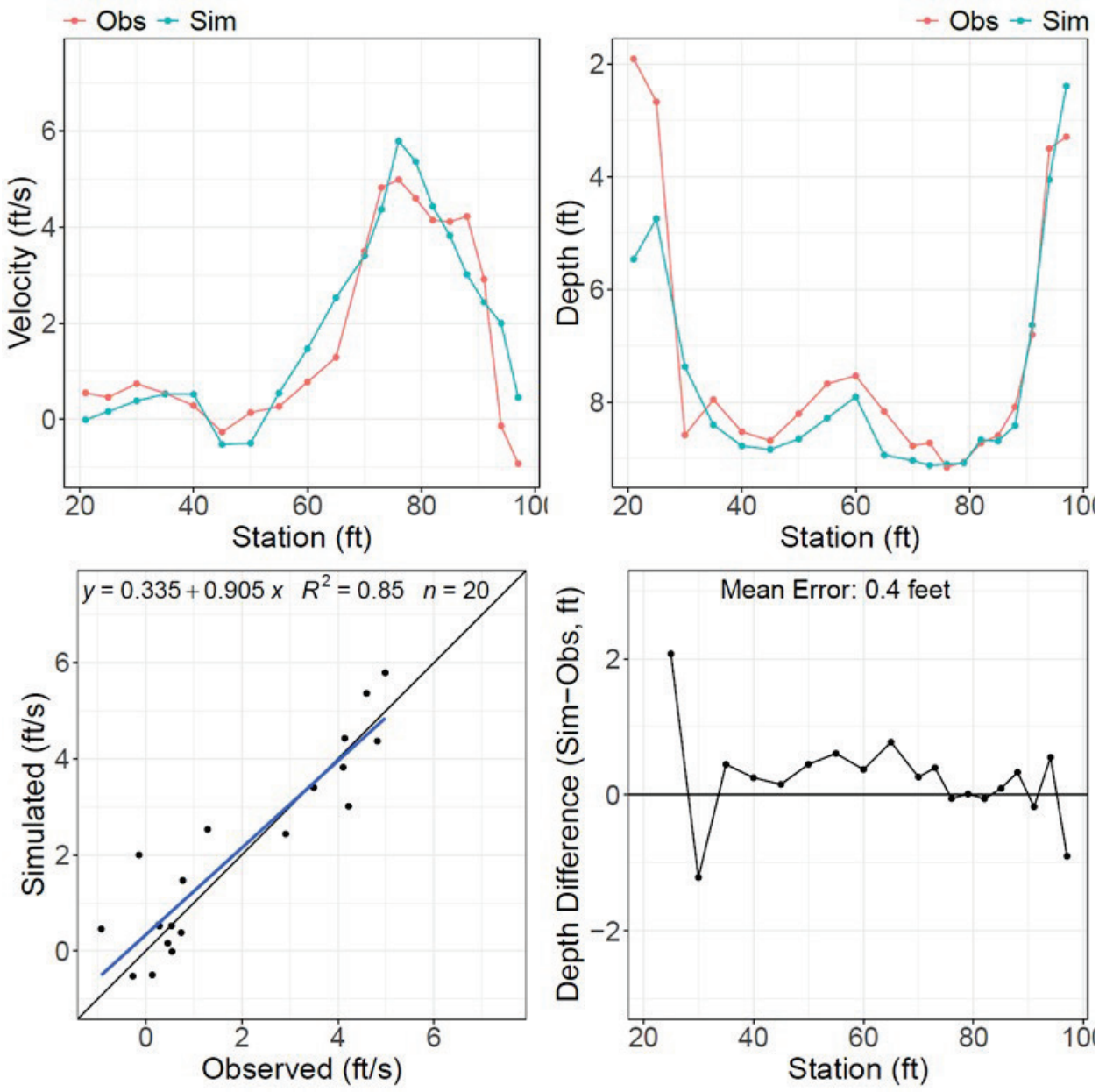


Figure F-5. Calibration results at Transect GG for 1,200 cfs controlled release.

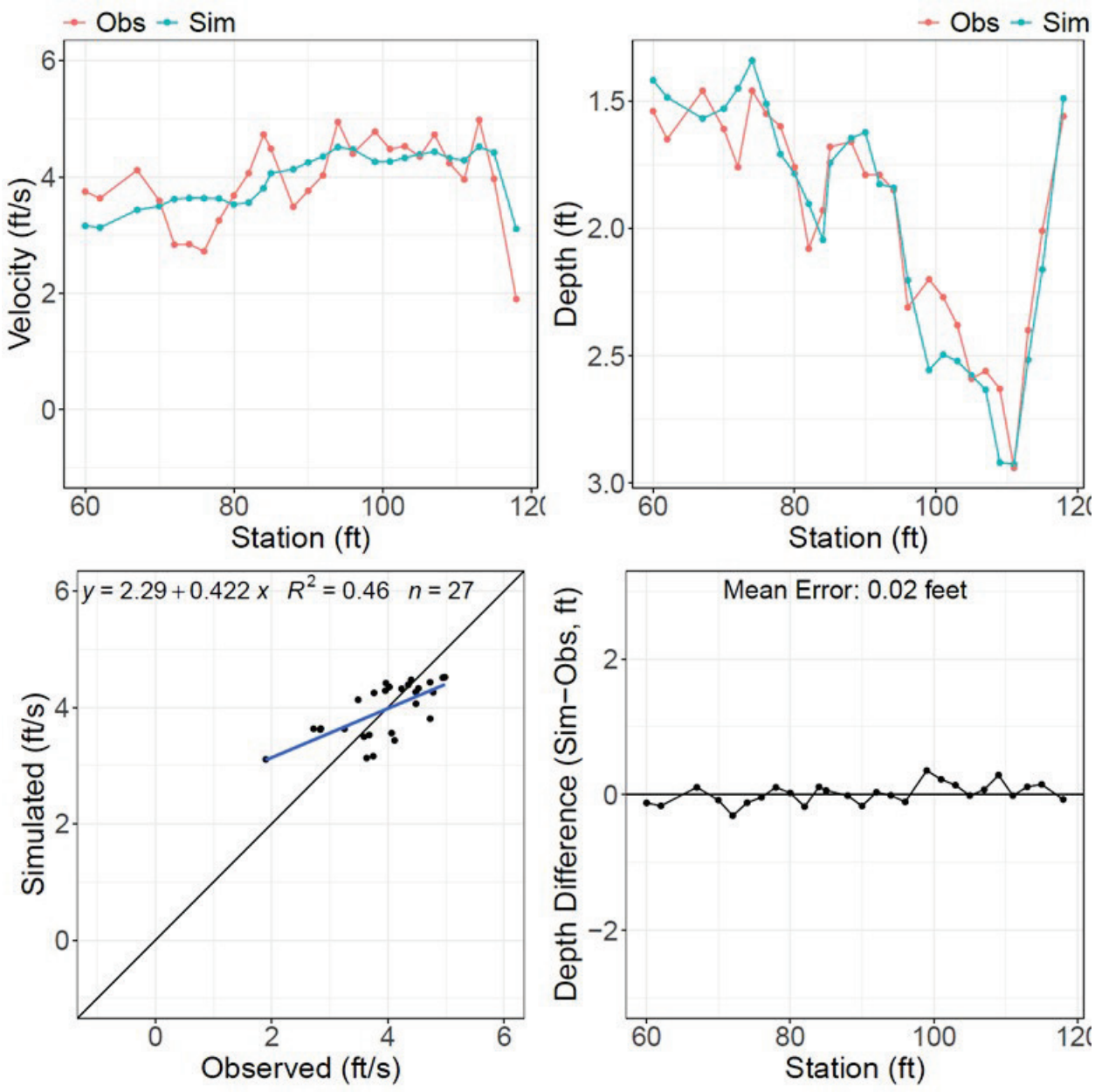


Figure F-6. Calibration results at Transect EE for 500 cfs controlled release.

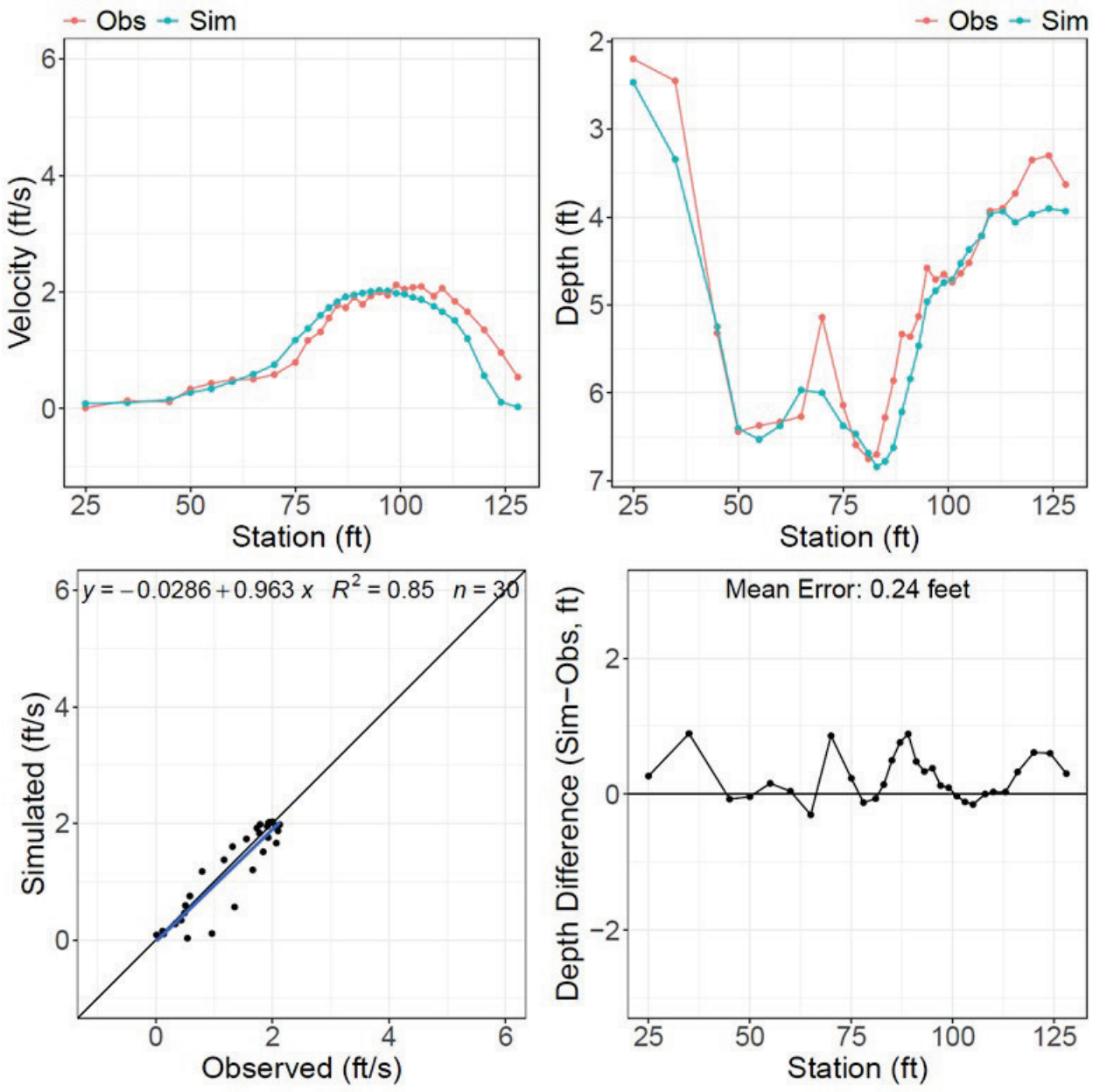


Figure F-7. **Calibration results at Transect II for 500 cfs controlled release.**

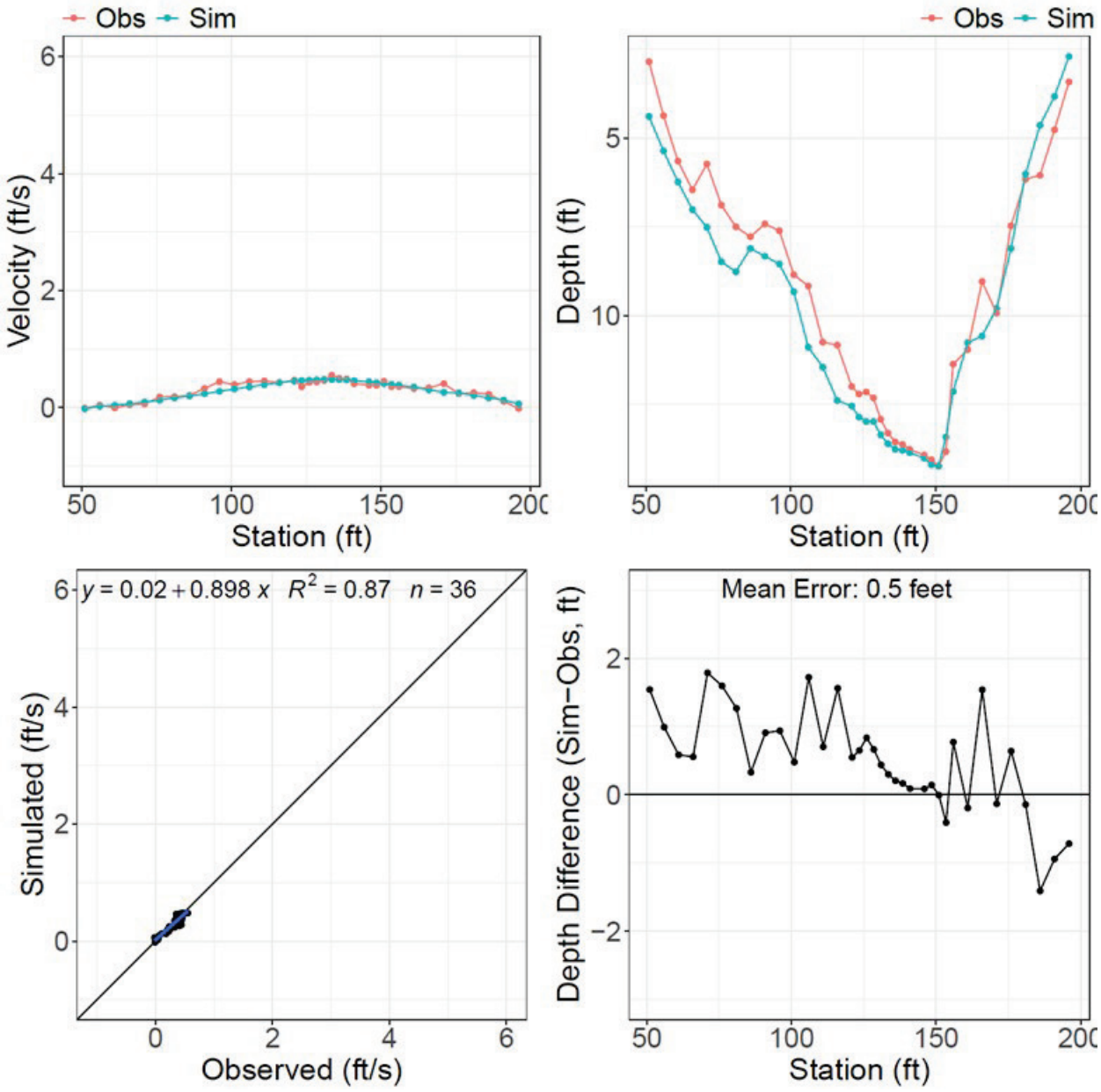


Figure F-8. Calibration results at Transect DD for 500 cfs controlled release.

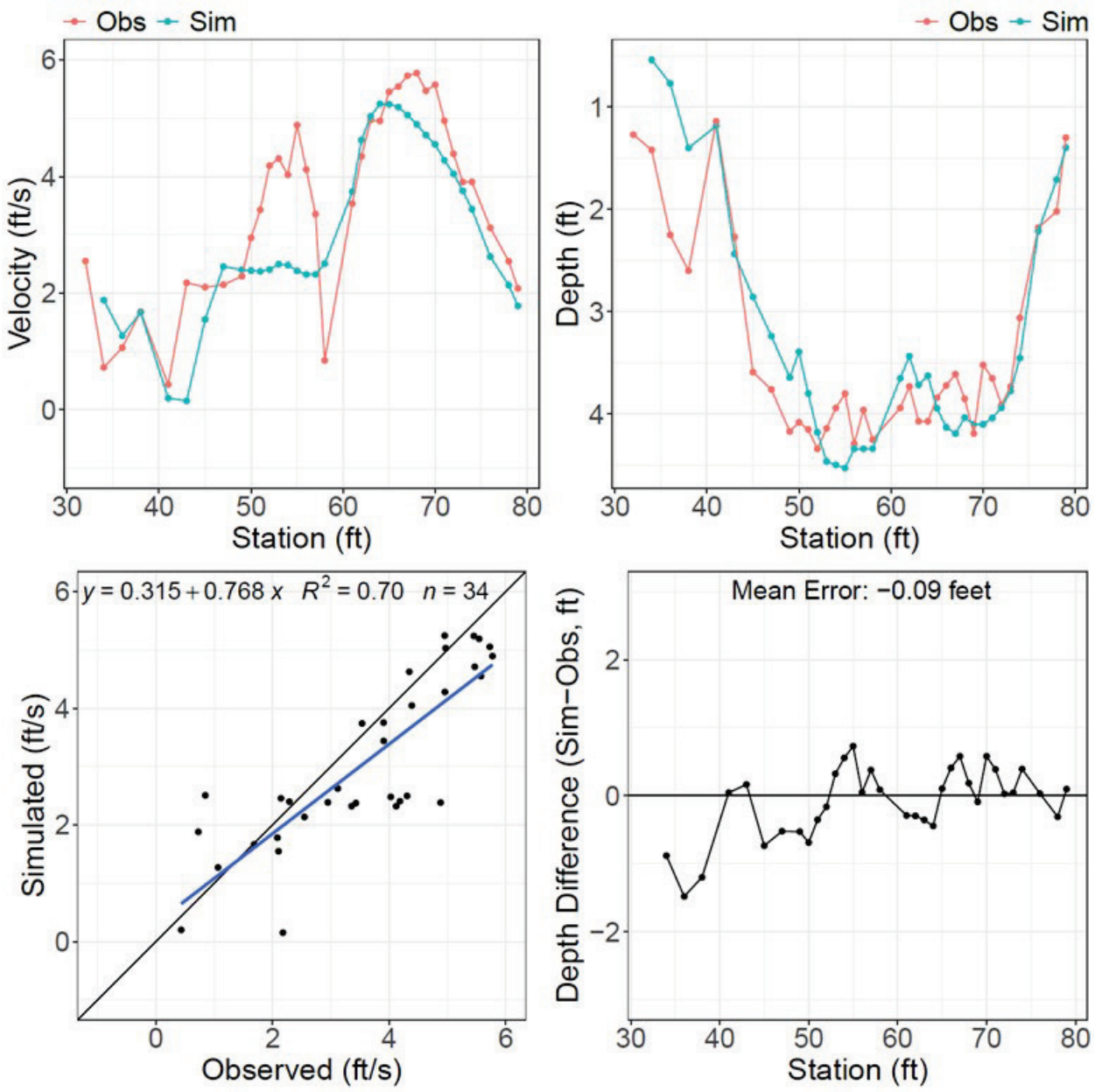


Figure F-9. Calibration results at Transect AA for 500 cfs controlled release.

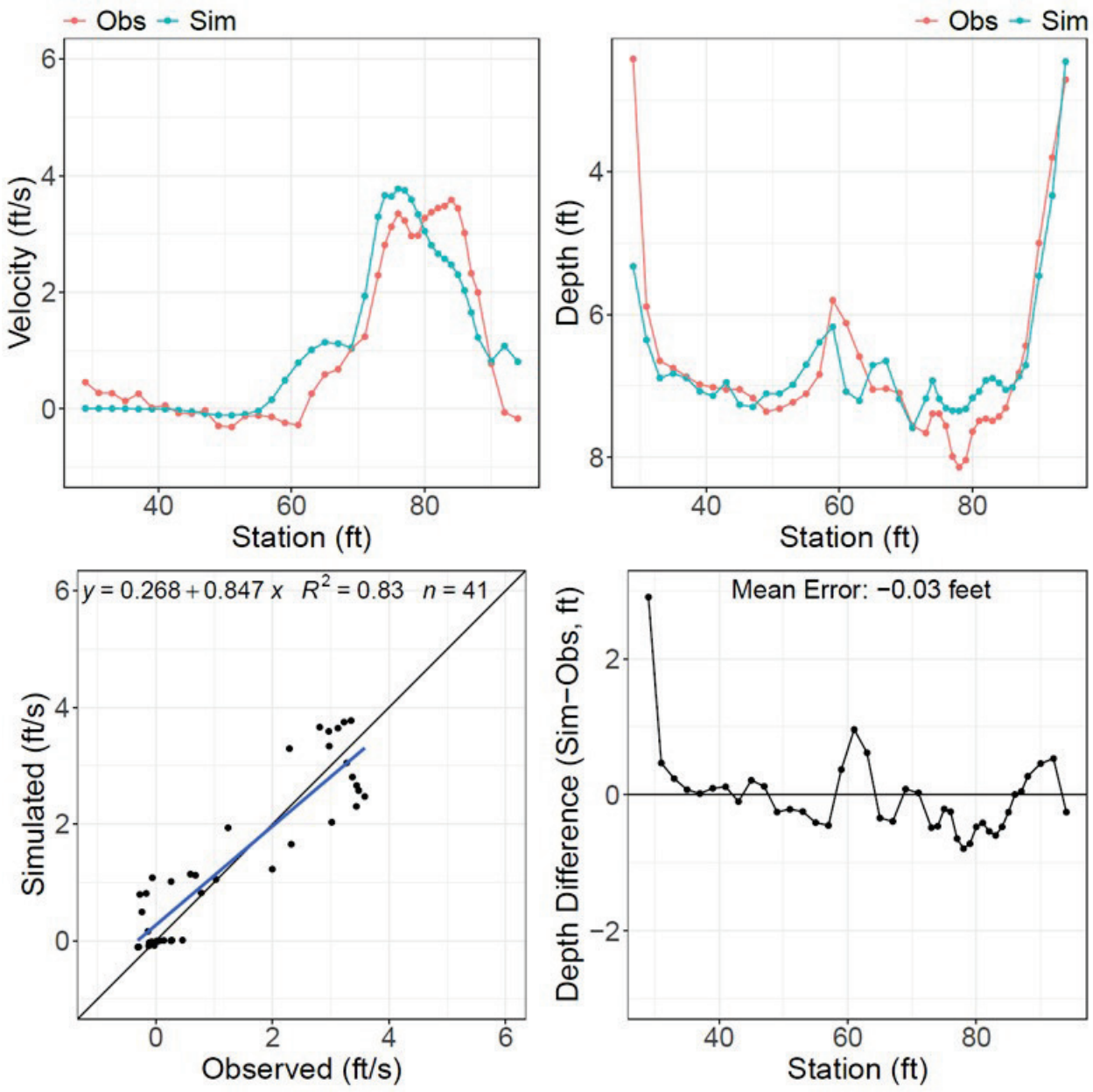


Figure F-10. Calibration results at Transect GG for 500 cfs controlled release.

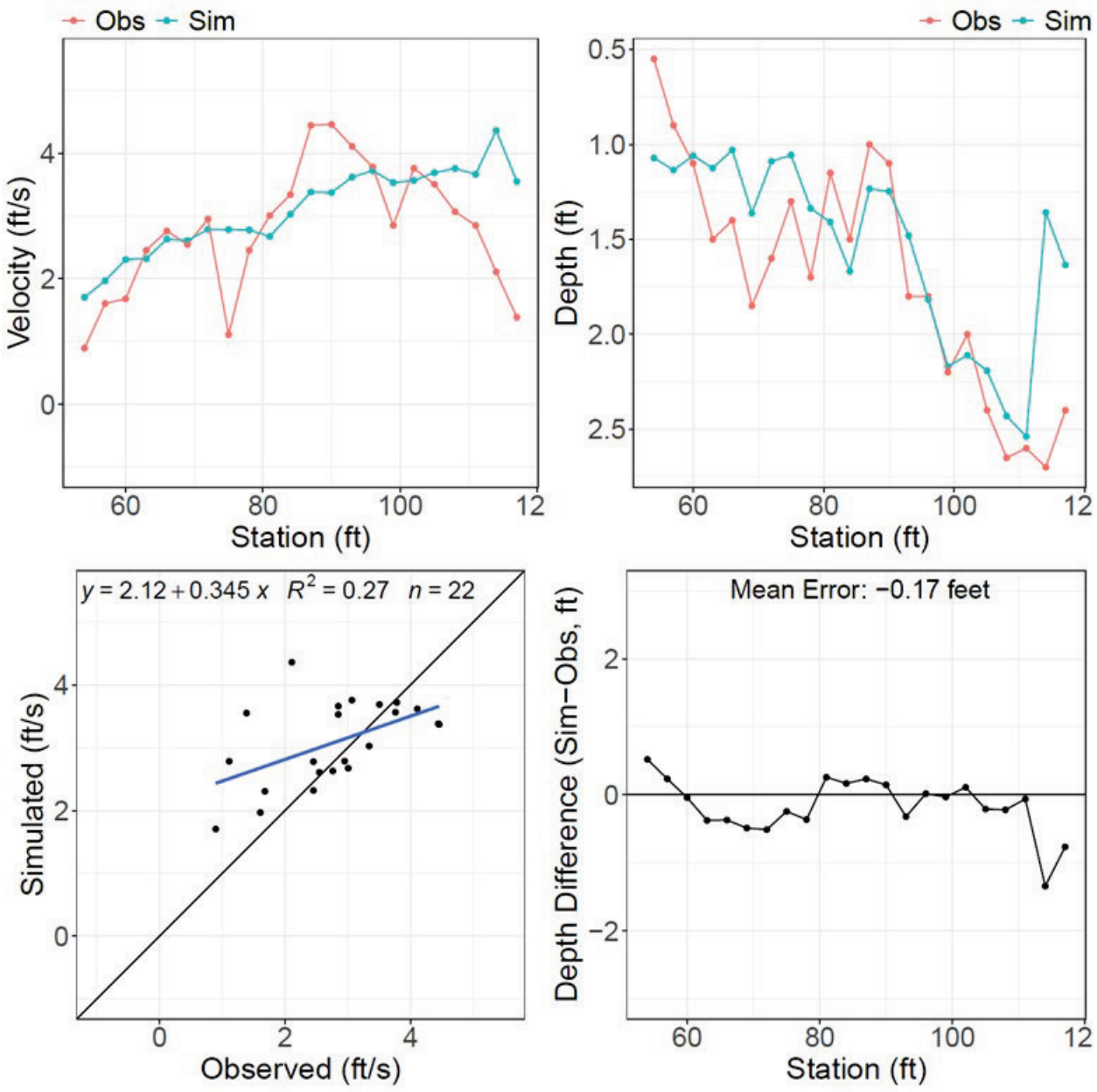


Figure F-11. Calibration results at Transect EE for 250 cfs controlled release.

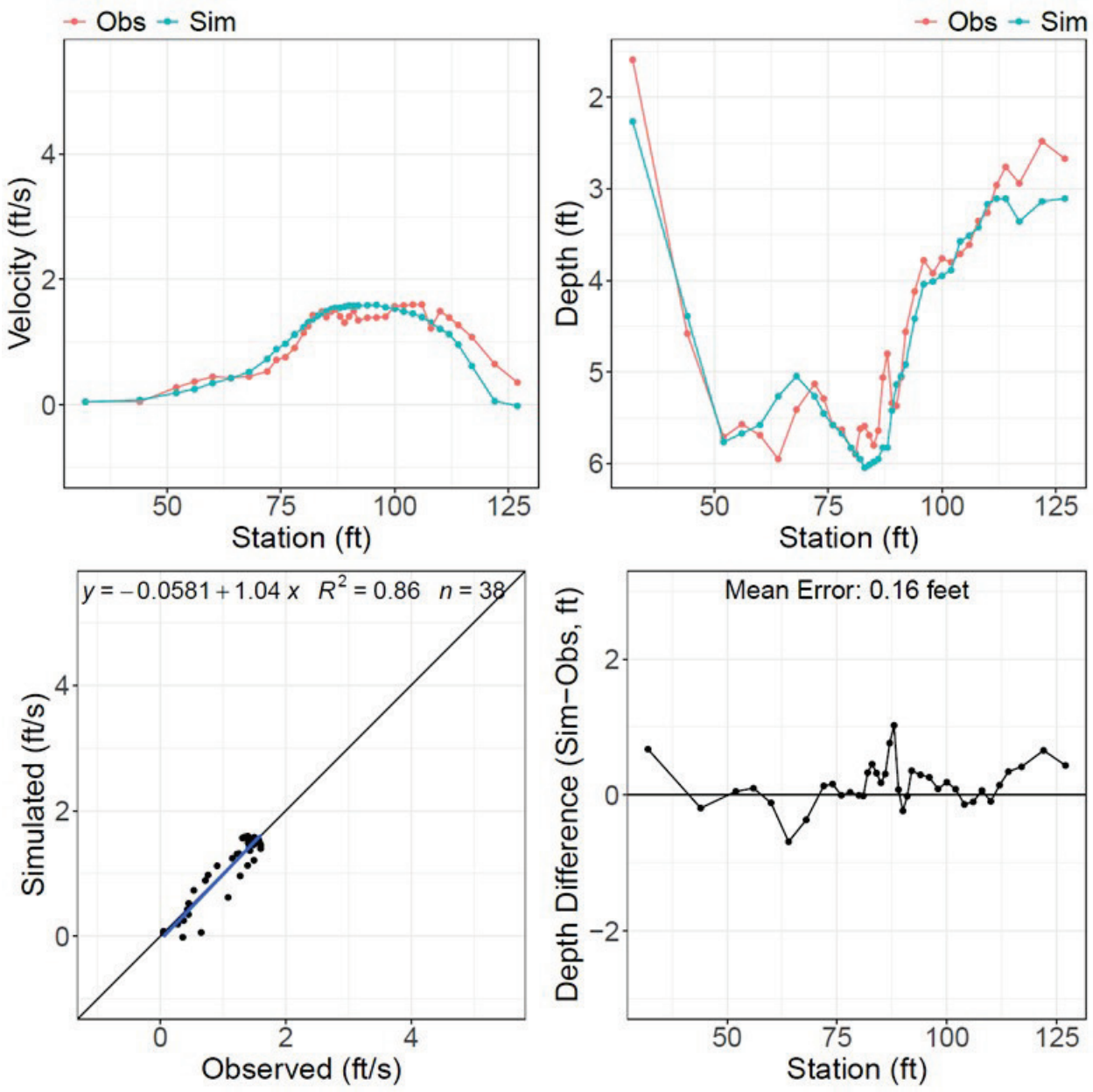


Figure F-12. Calibration results at Transect II for 250 cfs controlled release.

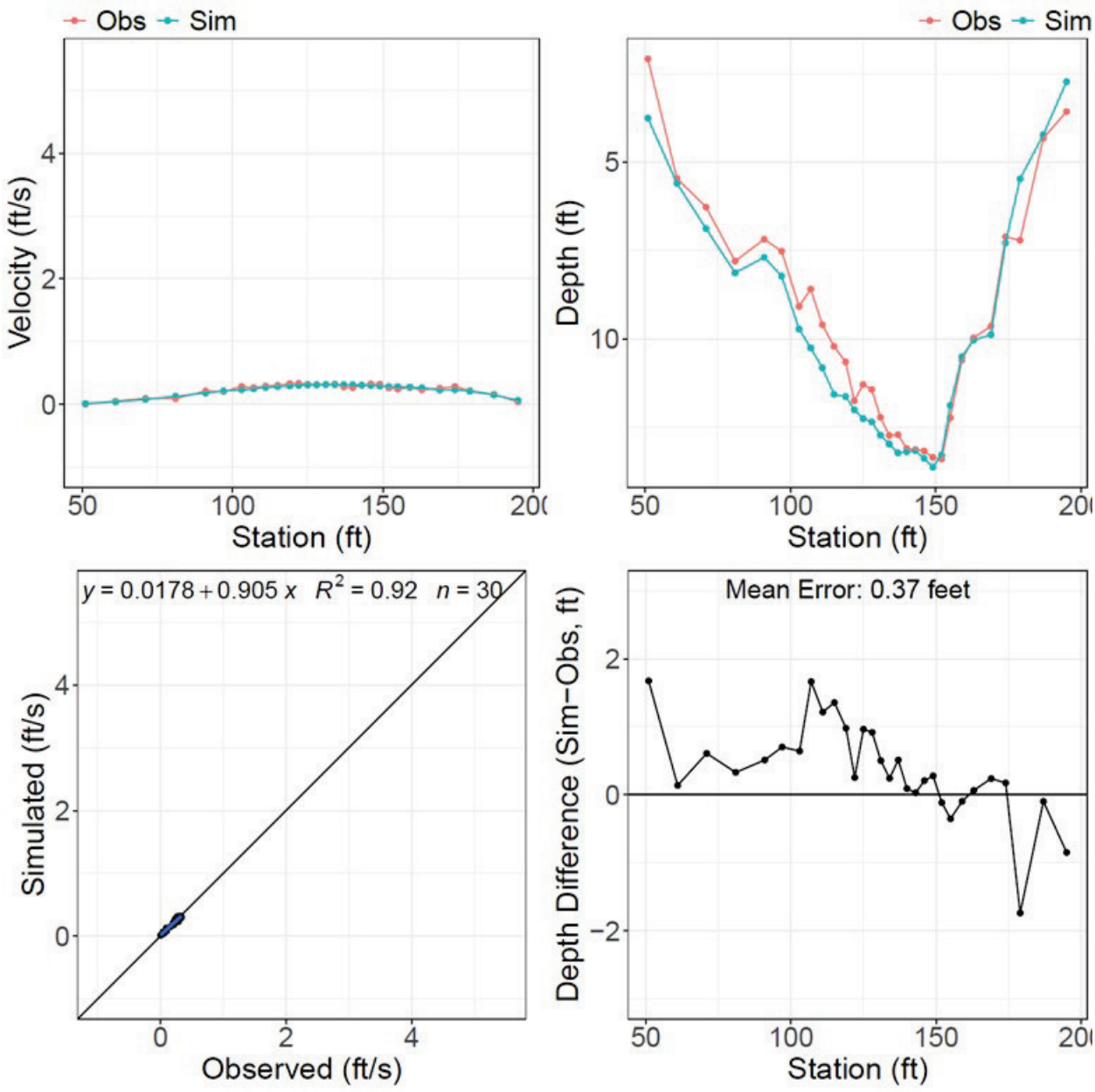


Figure F-13. Calibration results at Transect DD for 250 cfs controlled release.

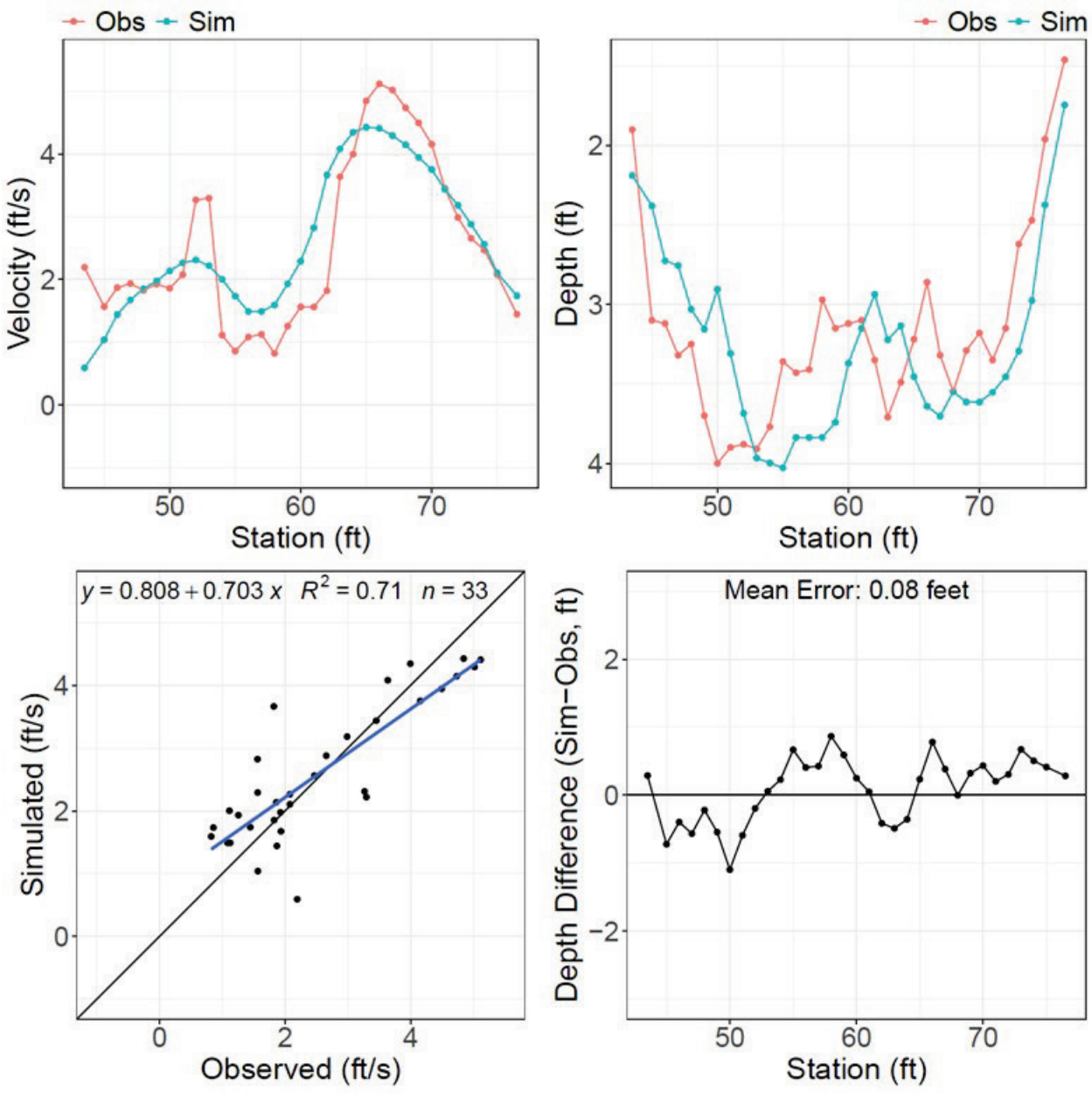


Figure F-14. Calibration results at Transect AA for 250 cfs controlled release.

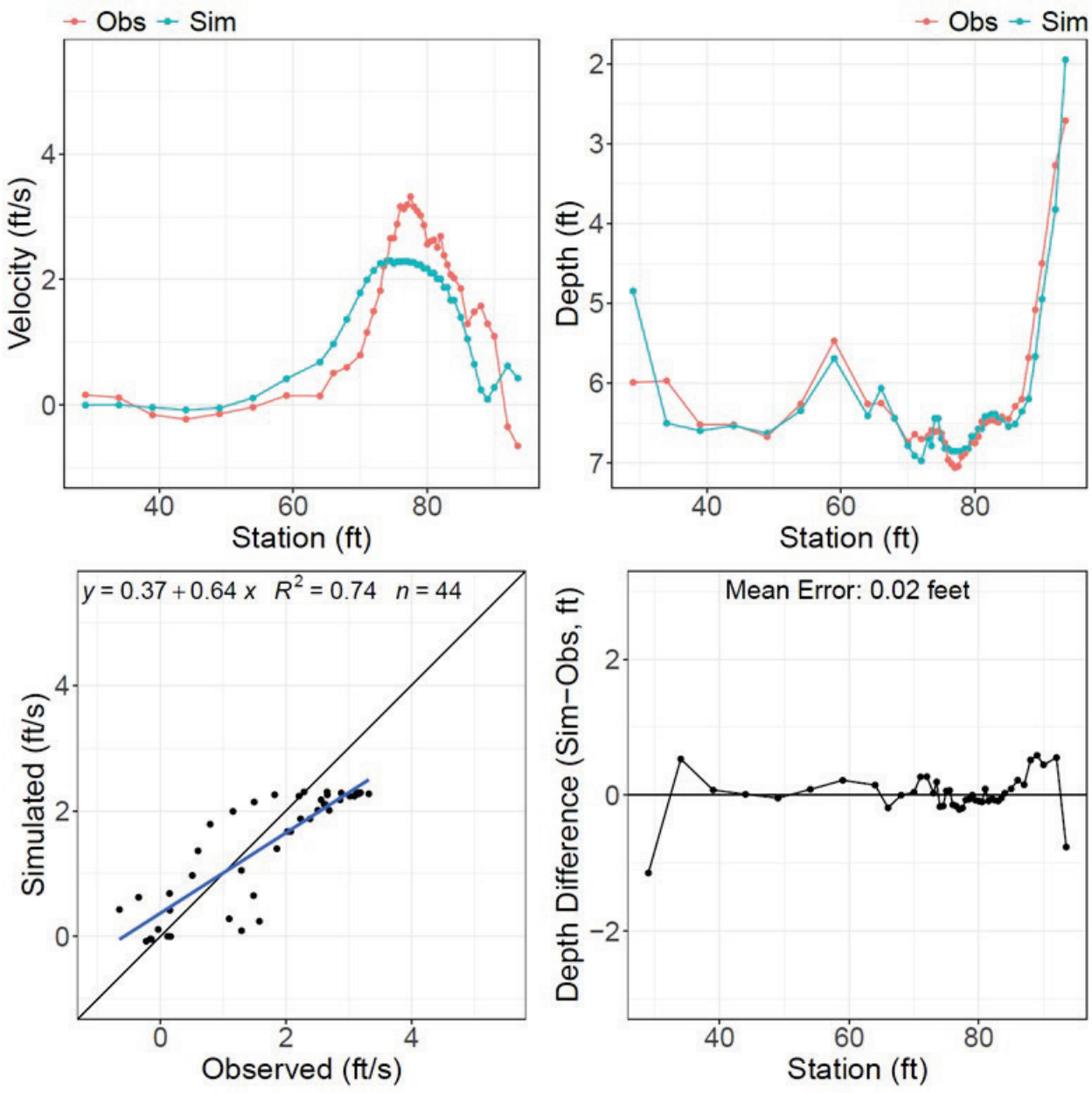


Figure F-15. Calibration results at Transect GG for 250 cfs controlled release.

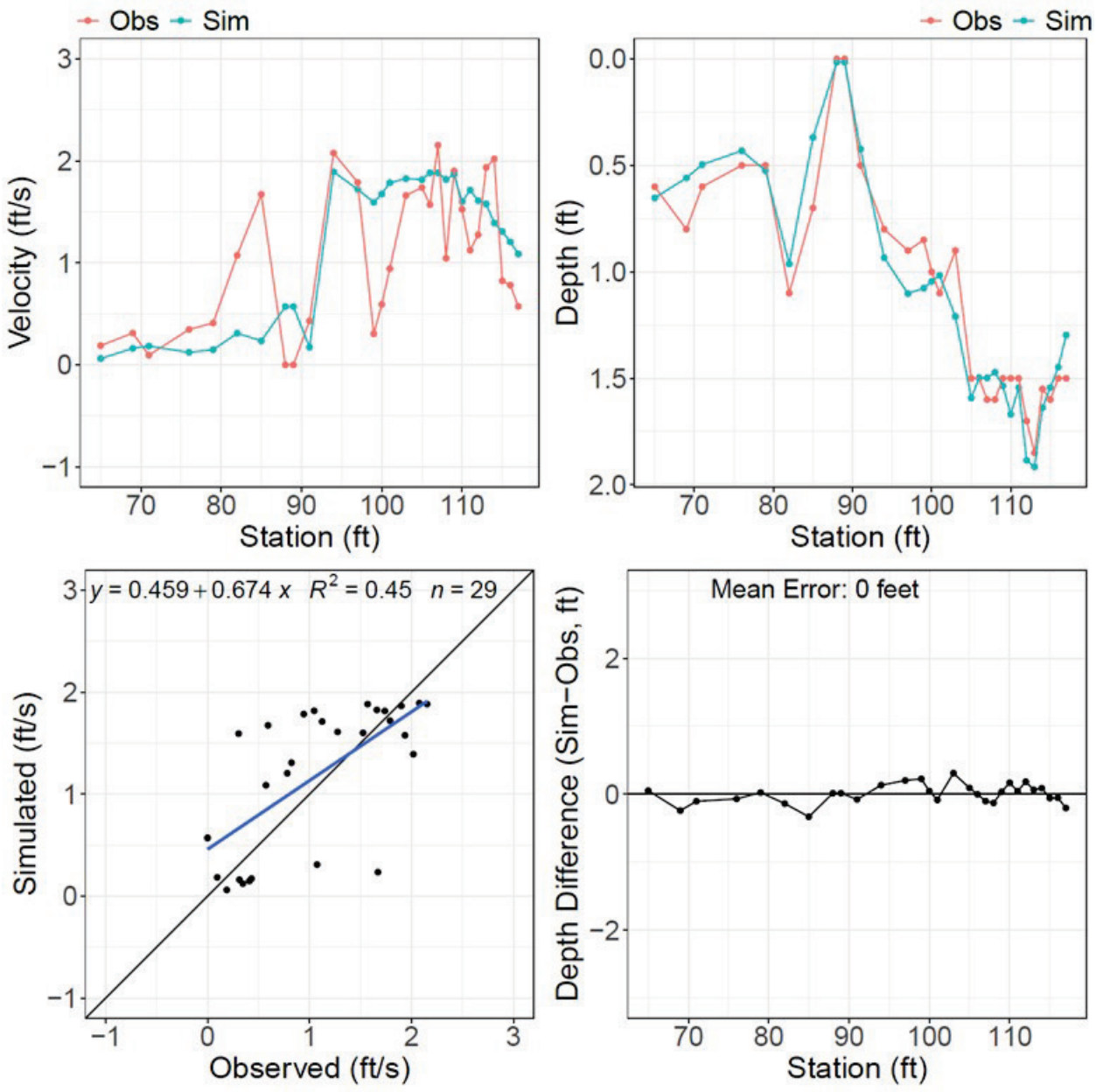


Figure F-16. Calibration results at Transect EE for 50 cfs controlled release.

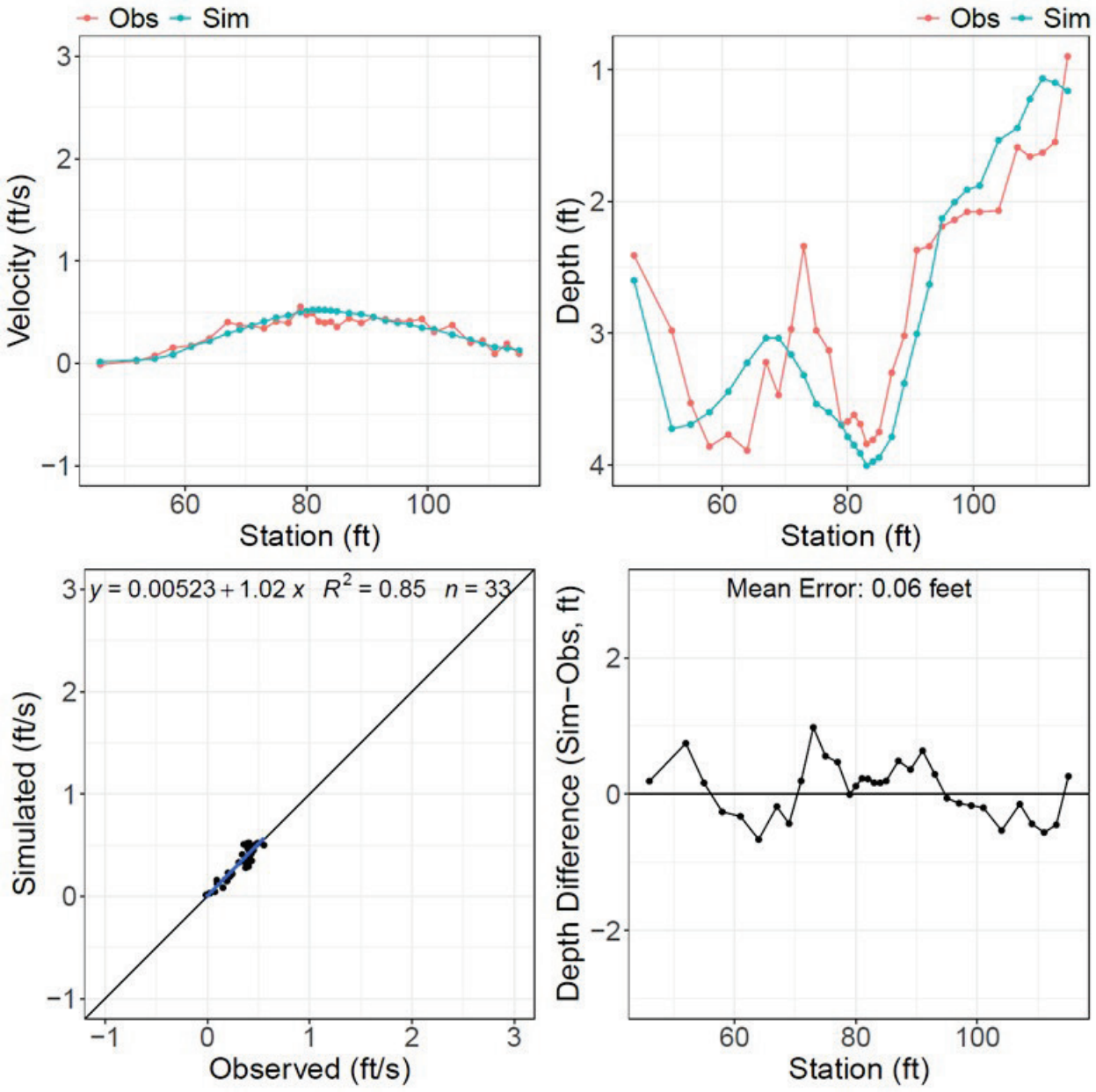


Figure F-17. Calibration results at Transect II for 50 cfs controlled release.

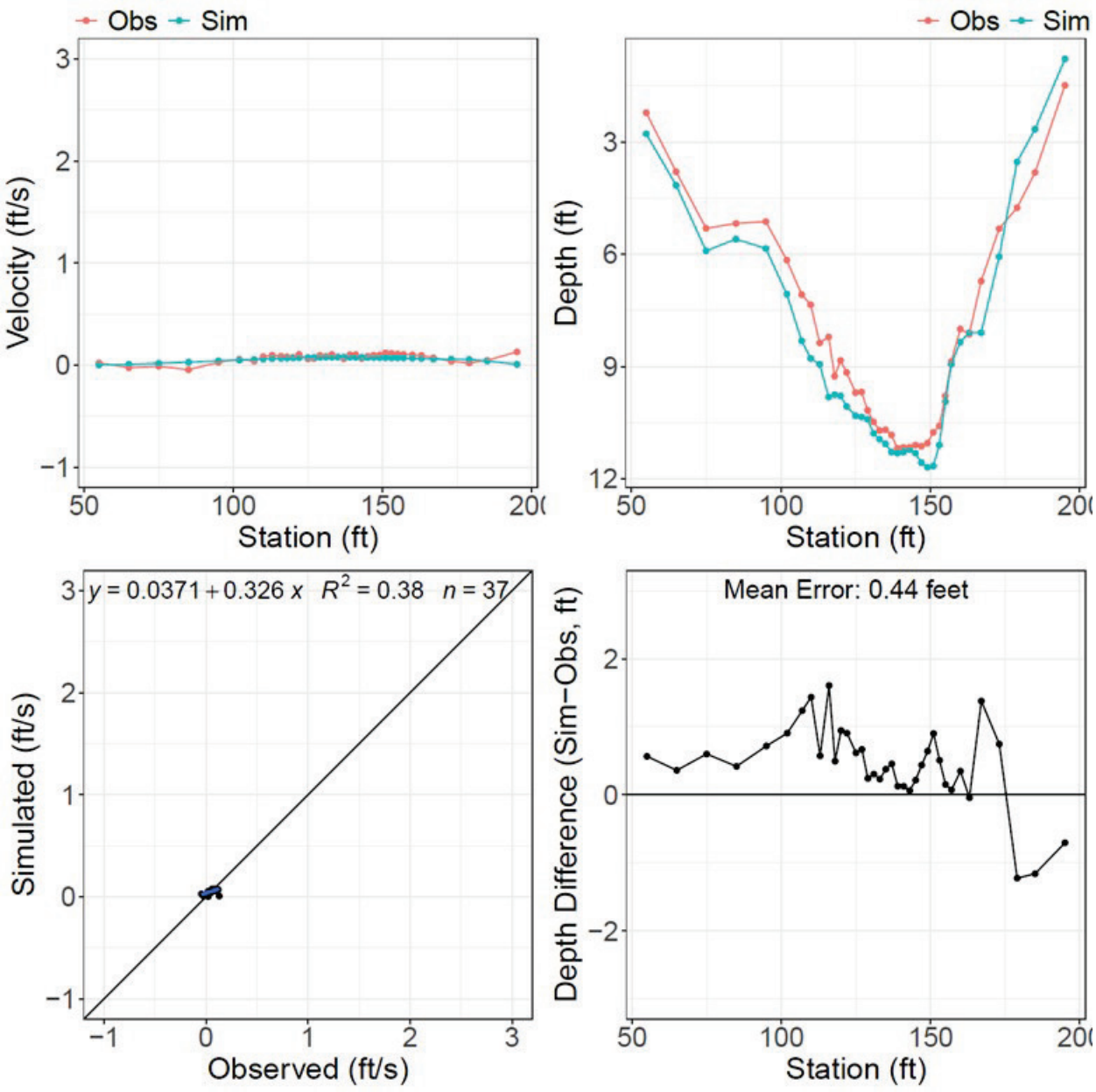


Figure F-18. Calibration results at Transect DD for 50 cfs controlled release.

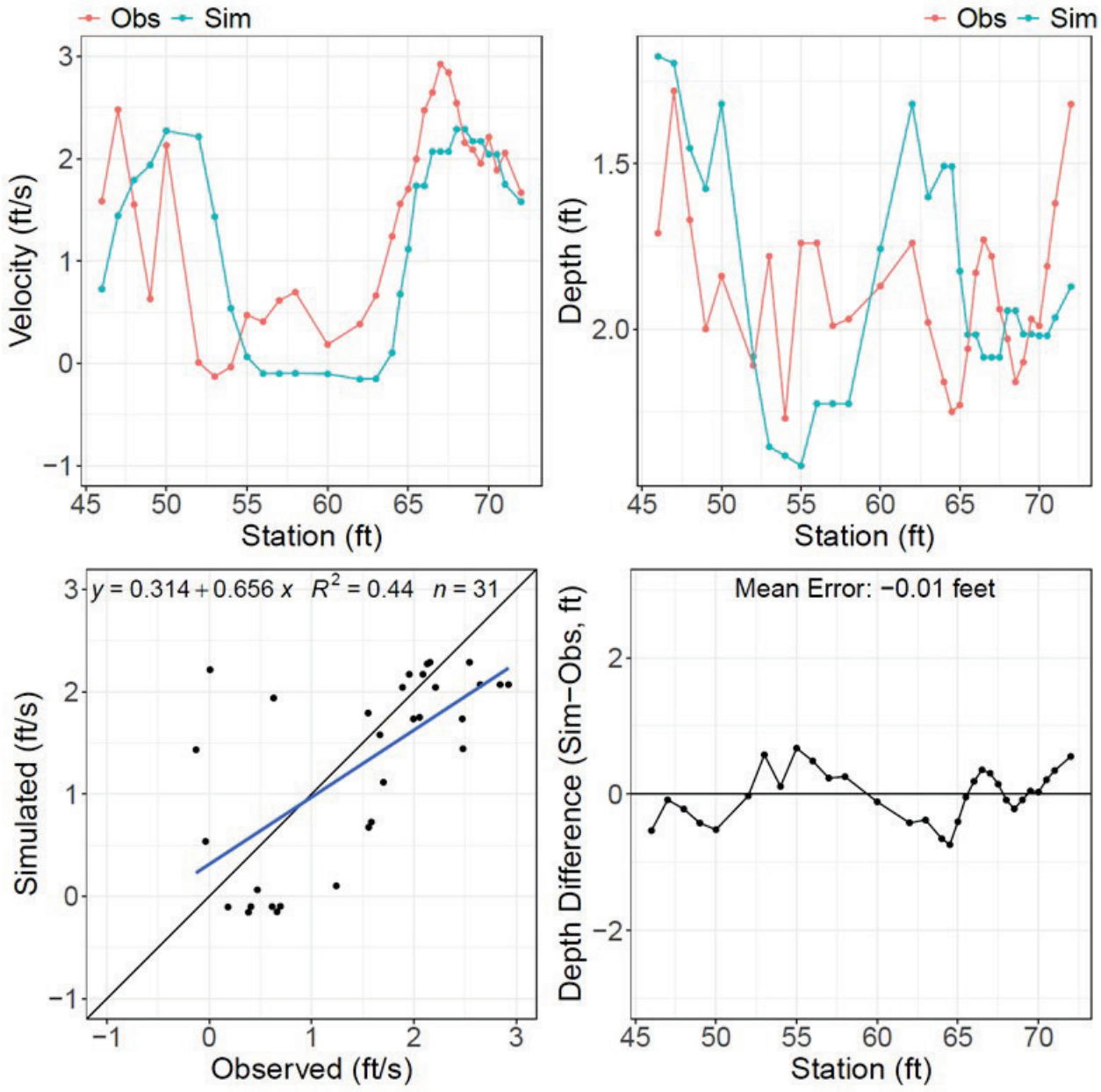


Figure F-19. Calibration results at Transect AA for 50 cfs controlled release.

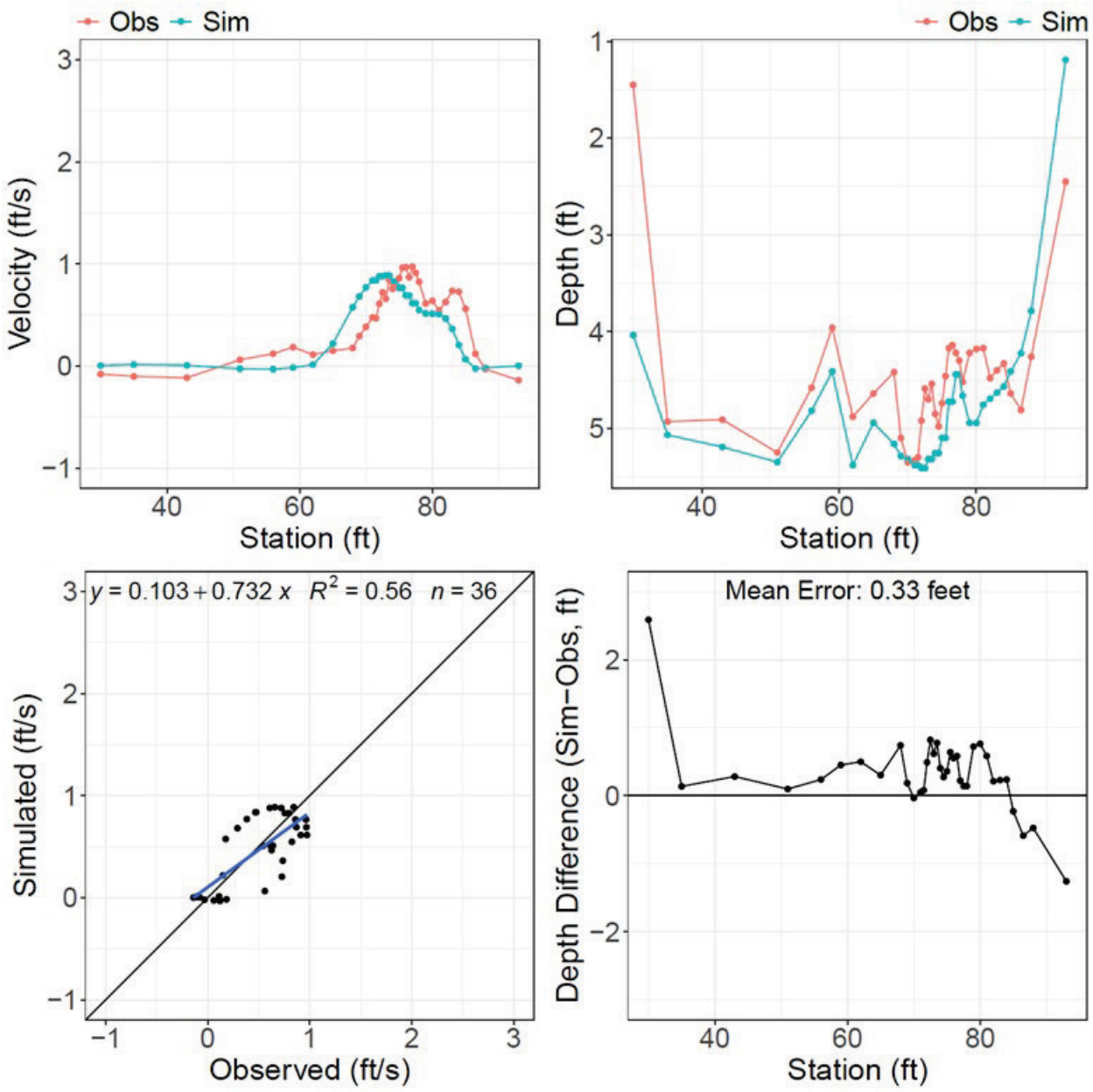


Figure F-20. Calibration results at Transect GG for 50 cfs controlled release.

3.0 REFERENCES

Northwest Hydraulic Consultants (NHC), 2022. Gorge Bypass Reach Data Collection for Hydraulic Model Calibration. Technical Memorandum. March 2022.

SKAGIT RIVER GORGE BYPASS REACH HYDRAULIC AND INSTREAM FLOW MODEL DEVELOPMENT STUDY REPORT

ATTACHMENT B

HABITAT SUITABILITY CRITERIA CURVES

Skagit River Habitat Suitability Criteria

HSC Technical Group

Skagit River Habitat Suitability Criteria (HSC) Licensing Participant (LP) Workshops began in May 2021. After the June and July 2021 Workshops, a recommendation was made to form a smaller technical group of people knowledgeable about HSC and its use in instream flow habitat modeling. In August 2021, the HSC Technical Group was formed and comprised of LPs, Seattle City Light, and Consultant Team members. The HSC Technical Group met a total of 10 times (approximately bi-weekly) from August 2021 through January 2022. The HSC Technical Group's objective was to gather and review available HSC information relevant to the Skagit River and develop a step-wise process to evaluate and ultimately propose recommended HSC curves for each species and life stage being considered for habitat modeling on the Skagit mainstem and bypass reach. In addition, the HSC Technical Group evaluated 2021 field validation data collected on the Skagit River (see below) as well as additional studies that were included in updated WDFW/Ecology Type 3 HSC curves for Bull Trout juveniles and Cutthroat Trout juveniles.

HSC Background

As a starting point for the HSC curve selection (and in some cases development) process, an HSC library was assembled consisting of curves from City Light's existing effective spawning habitat (ESH) model, Washington State's Instream Flow Study Guidelines (Beecher and Caldwell 2022), curves from other west coast region instream flow studies for rivers comparable in size to the Skagit River, and literature from other relevant studies and research.

HSC curves are often referred to by "type," which indicates the basis of the curves (Bovee 1986). Type 1 curves are based on general life history and professional judgement with little or no empirical data. Type 2 curves are based on data from locations where target species are observed or collected. Commonly referred to as utilization (or use) curves, Type 2 curves can be biased by a limited range of hydraulic conditions that were available at the time the target species were observed. Type 3 curves are based on data from locations where target species are observed or collected under a variety of conditions to remove environmental bias. Type 3 curves include measurements of "available" habitat (at the time the discrete observation data were collected) which are used to adjust utilization data to become "preference curves". Type 3 curves tend to be less site-specific than Type 2 curves and can be applied more broadly.

The HSC List tab provides a list of species and life stages to be considered for modeling. They are grouped based on the availability and type of existing HSC curves as described below.

HSC Groups

Group A includes species and life stages where HSC curves are available from both the Skagit ESH model and WDFW/Ecology Type 3 curves. With the exception of Chum Salmon spawning, field validation studies were conducted in 2021 to collect additional site-specific data (i.e., depth, velocity, substrate, and cover) for Group A species and life stages. These data were used qualitatively to support decisions on HSC curve selection and/or modification.

Group B originally consisted of two species and life stages where both Skagit-specific Type 2 curves (i.e., based on Skagit River field observation data) and WDFW/Ecology Type 3 curves were available (i.e., Chum spawning and Pink spawning). Early in the HSC evaluation process the larger LP team recommended adding these two species to Group A as there was interest in collecting additional field observation data during the 2021 field validation study efforts. Moving these two species/life stages into Group A effectively eliminated Group B.

Group C includes species and life stages where HSC curves are not available from the ESH model but are available as WDFW/Ecology Type 3 curves. The Type 3 curves will be used as a default unless field validation studies conducted for Group A provide information that a modification of the WDFW/Ecology Type 3 curves is warranted to better represent site-specific observations on the Skagit River.

Group D HSC curves are not available from either the ESH model, or WDFW/Ecology. For these species and life stages, available HSC curves from other instream flow studies were used as a surrogate and/or consensus curves were developed in collaboration with LPs by modifying available HSC curves. In some cases, literature was available to support development of HSC consensus curves.

Group E consists of the fry life stage for several species. Instead of modeling individual fry species, consensus curves were developed for generic salmonid fry.

Group F surrogate HSC curves were not available, so consensus curves were developed based on literature review.

2021 Field Validation Studies

During the first HSC Workshop on May 12, 2021, LPs discussed and ultimately recommended collecting field validation data (i.e., observations of fish and/or redds) on the Skagit River to support the HSC evaluation and selection process. Target species and number of observations during the 2021 study period were: spawning life stage [Steelhead (19), Chinook (31), Pink (31), and Chum (NA)] and juvenile life stage [Steelhead (116), Chinook (41), and Bull Trout (4)]. Note due to unseasonably high flows and turbid water conditions during the late-fall/early-winter period, field validation data collection efforts for Chum spawning were not conducted.

HSC Evaluation Process

Based on WDFW/Ecology policy, the statewide Type 3 curves are preferred unless:

a) Enough site-specific, Type 3 data can be found or collected to develop new HSC curves, or
b) Enough site-specific Type 3 data can be collected in the field to use as a rationale for adjusting the statewide Type 3 curves, or
c) Type 3 curves from another source can be found and determined to be equal to, or more representative than, the statewide Type 3 curves.

HSC curves used in the current ESH model are based on a variety of Type 1 and Type 2 data sources. For example, HSC curves for Steelhead, Chinook, Pink, and Chum spawning life stage are based on hundreds of Skagit-specific field observation data from Crumley and Stober 1984, and considered to be Type 2 curves (attempts to locate detailed field observation data from the studies were unsuccessful). Data collected during the 2021 HSC field validation effort for these four species (spawning life stage) were determined to be insufficient to create new Type 3 curves. However, these data (i.e., observations of redds or fish) were reviewed by the HSC Technical Group and were determined to be consistent with the ESH and statewide HSC curves. Other HSC curves used in the ESH model are based on Type 1 and Type 2 curves from other (non-Skagit) data sources and are considered to be a hybrid of Type 1-2 curves. As a result, in most cases, the recommended habitat modeling approach is to use the WDFW/Ecology Type 3 HSC curves for Skagit River habitat modeling purposes when available.

When WDFW/Ecology Type 3 curves were not available, the HSC Technical Group typically recommended a) curves from other surrogate species with statewide Type 3 curves, b) Type 2 curves from other studies, or c) developed consensus curves from available and relevant literature.

Skagit River Habitat Suitability Criteria (HSC) Summary					
				WDFW/Ecology Guidelines (Beecher and Caldwell 2022) or other reference	
Species	**Life Stage**	**HSC Group**	**HSC Status**	**Substrate**	**Cover**
Steelhead	spawning	A	WDFW/Ecology Type 3 curves	Table 4	N/A
	adult holding	D	WDFW/Ecology Type 3 curves for RBT adult/rearing	Table 3	Table 3
	juvenile	A	WDFW/Ecology Type 3 curves	Table 3	Table 3
Chinook Salmon	spawning	A	WDFW/Ecology Type 3 curves	Table 2	N/A
	juvenile			Table 3	Table 3
	fry	E	ESH Model Type 2 curves	ESH Model	N/A
Pink Salmon	spawning	A	WDFW/Ecology Type 3 curves	Table 2	N/A
Chum Salmon	spawning	A	WDFW/Ecology Type 3 curves	Table 2	N/A
	fry	E	Fraser River Type 2 curves	Fraser River (Rempel et al. 2012)	N/A
Coho Salmon	spawning	C	WDFW/Ecology Type 3 curves	Table 2	N/A
	juvenile	D	ESH Model Type 2 curves	Table 3	Table 3
	fry	E	ESH Model Type 2 curves	ESH Model	N/A
Sockeye Salmon	spawning	C	WDFW/Ecology Type 3 curves	Table 2	N/A
Rainbow Trout	spawning	C	WDFW/Ecology Type 3 curves	Table 5	N/A
	adult rearing			Table 3	Table 3
	juvenile			Table 3	Table 3
	fry	E	ESH Model Type 2 curves	ESH Model	N/A
Bull Trout/ Dolly Varden	spawning	C	WDFW/Ecology Type 3 curves	Table 6	N/A
	juvenile	A		Table 3	Table 3
	fry	E	ESH Model Type 2 curves	ESH Model	N/A
Sea-Run Bull Trout	spawning	F	Proposed consensus curves developed	Table 6	N/A
Cutthroat Trout	spawning	C	WDFW/Ecology Type 3 curves	Table 5	N/A
	adult	D	Use WDFW/Ecology Type 3 curve for Cutthroat juvenile	Table 3	Table 3
	juvenile	C	WDFW/Ecology Type 3 curves	Table 3	Table 3
	fry	E	ESH Model Type 2 curves	ESH Model	N/A
Sea-Run Cutthroat Trout	spawning	D	Proposed consensus curves developed	Table 5	N/A
Mountain Whitefish	spawning	C	WDFW/Ecology Type 3 curves	Table 7	N/A
	adult rearing			Table 8	Table 1
	juvenile			Table 9	Table 1
	fry	E	ESH Model Type 2 curves	ESH Model	N/A
Pacific Lamprey	spawning	D	Proposed consensus curves developed	Vadas 2021	N/A
	juvenile rearing				

Skagit River Habitat Suitability Criteria (HSC) Summary					
				WDFW/Ecology Guidelines (Beecher and Caldwell 2022) or other reference	
Species	**Life Stage**	**HSC Group**	**HSC Status**	**Substrate**	**Cover**
Western Brook Lamprey	spawning	F	Proposed consensus curves developed	Vadas 2021	N/A
Western River Lamprey	spawning	F	Proposed consensus curves developed	Vadas 2021	N/A
Salish Sucker	spawning	F	Proposed consensus curves developed	Pearson 2003	N/A
	juvenile rearing				Pearson 2003
White Sturgeon	spawning	F	Proposed consensus curves developed	Sacramento River (Gard 1996)	N/A

Steelhead

Spawning (Group A)

Steelhead spawning HSC curves from several sources were evaluated including WDFW/Ecology (Type 3; 108 redds), the ESH model (Skagit River-specific Type 2; 305 redds), and the Trinity River (Type 2). It is WDFW/Ecology's preference to use the statewide Type 3 HSC curves when available unless additional site-specific field observation data is collected on the Skagit River in sufficient numbers to revisit, and possibly revise, the statewide curves. The statewide curves are based on analysis from 6 studies and 108 redds [Rock Creek (WRIA 31), Cedar (2 studies) and Sultan rivers and Chelan Fish Channel (2 studies)] (Beecher and Caldwell 2022). Field validation studies conducted on the Skagit River during 2021 resulted in an additional 19 redd observations. These data were reviewed by the HSC Technical Group and were determined to be consistent with the ESH and statewide HSC curves (i.e., observation data points were generally captured within the defined area under the HSC depth and velocity curves). As a result, the recommended habitat modeling approach is to use the WDFW/Ecology Type 3 HSC curves.

Adult Holding (Group D)

WDFW/Ecology HSC curves for Steelhead adult holding are not available and the ESH model HSC curves are not based on Skagit-specific field observation data (hybrid Type 1-2). As a result, the WDFW/Ecology Type 3 HSC curves for resident Rainbow Trout adult rearing are proposed to represent Steelhead adult. The Rainbow Trout adult rearing curves are based on analysis from 15 studies totaling 638 fish observations [mostly streams west of the Cascades, but includes Yakima River, upper Mill Creek (WRIA 32), and Douglas Creek (WRIA 44)] (Beecher and Caldwell 2022).

Juvenile (Group A)

Steelhead juvenile HSC curves from several sources were evaluated including WDFW/Ecology (Type 3; 1,954 fish observations), the ESH model (hybrid Type 1-2), and the Trinity River (Type 2). It is WDFW/Ecology's preference to use the statewide Type 3 HSC curves when available unless additional site-specific field observation data is collected on the Skagit River in sufficient numbers to revisit, and possibly revise, the statewide curves. The statewide curves are based on analysis from 32 studies and 1,954 fish observations (from multiple Washington streams of differing sizes and stream types) (Beecher and Caldwell 2022). Field validation studies conducted on the Skagit River during 2021 resulted in an additional 116 fish observations. These data were reviewed by the HSC Technical Group and were determined to be consistent with the ESH and statewide HSC curves (i.e., observation data points were generally captured within the defined area under the HSC depth and velocity curves). As a result, the recommended habitat modeling approach is to use the WDFW/Ecology Type 3 HSC curves.

Additional Notes

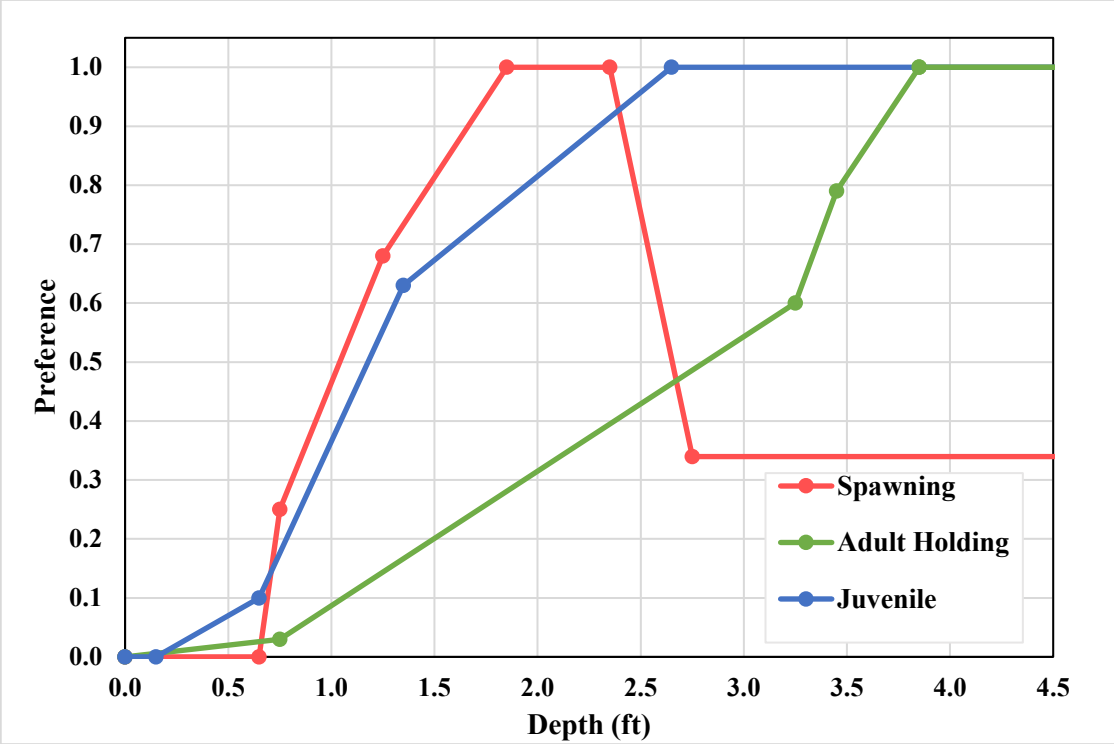
There is no clear biological evidence that depth becomes a limiting factor for adult and juvenile Steelhead. Therefore, the HSC Technical Group recommended that once depth reaches 3.85 ft (1.0 preference) for adult and 2.65 ft (1.0 preference) for juvenile, it be considered "non-limiting" in the HSC depth curves.

References

WDFW/Ecology: spawning, adult, and juvenile (Beecher and Caldwell 2022)
ESH model: spawning (Crumley and Stober 1984); adult (Bovee 1978); juvenile (Crumley and Stober 1984; Bovee 1978)
Trinity River: spawning, adult, and juvenile (Hampton et al. 1997)
Fraser River: juvenile (Rempel et al. 2012)
Klamath River: juvenile (Hardy and Addley 2001)
McKenzie River: juvenile (Hardin-Davis 1990)

Steelhead

Depth Preference Curves

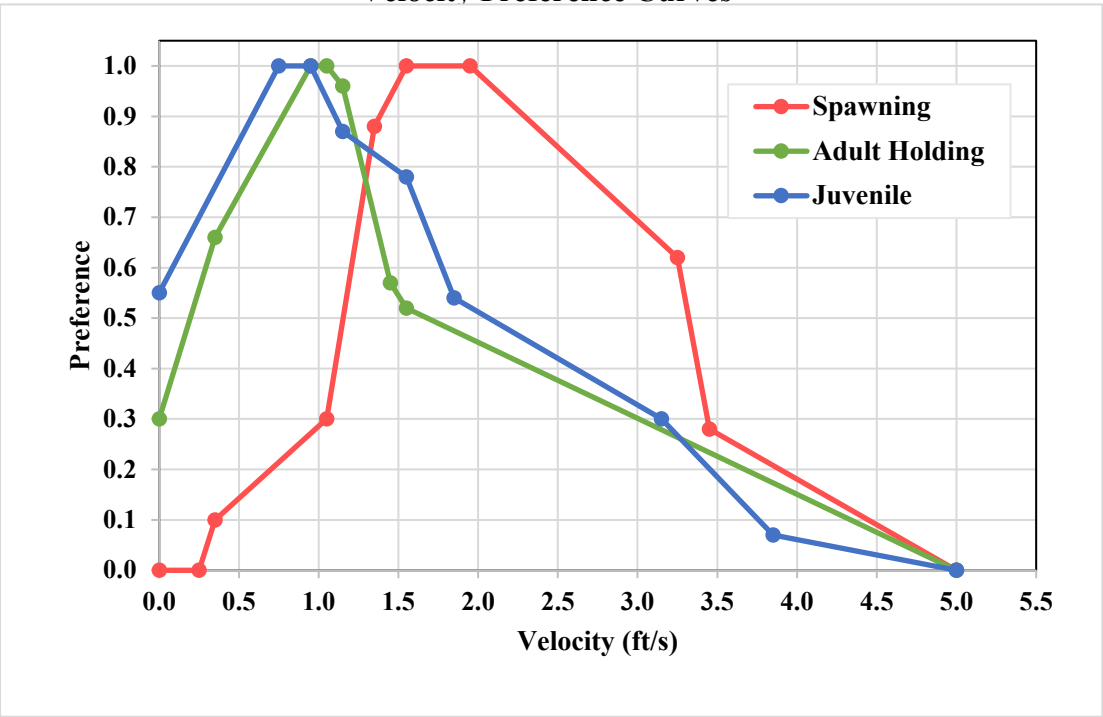


Spawning	
Depth (ft)	Preference
0.00	0.00
0.65	0.00
0.75	0.25
1.25	0.68
1.85	1.00
2.35	1.00
2.75	0.34
99.00	0.34

Adult Holding	
Depth (ft)	Preference
0.00	0.00
0.75	0.03
3.25	0.60
3.45	0.79
3.85	1.00
99.00	1.00

Juvenile	
Depth (ft)	Preference
0.00	0.00
0.15	0.00
0.65	0.10
1.35	0.63
2.65	1.00
99.00	1.00

Steelhead



Spawning	
Velocity (ft/s)	Preference
0.00	0.00
0.25	0.00
0.35	0.10
1.05	0.30
1.35	0.88
1.55	1.00
1.95	1.00
3.25	0.62
3.45	0.28
5.00	0.00

Adult Holding	
Velocity (ft/s)	Preference
0.00	0.30
0.35	0.66
0.95	1.00
1.05	1.00
1.15	0.96
1.45	0.57
1.55	0.52
5.00	0.00

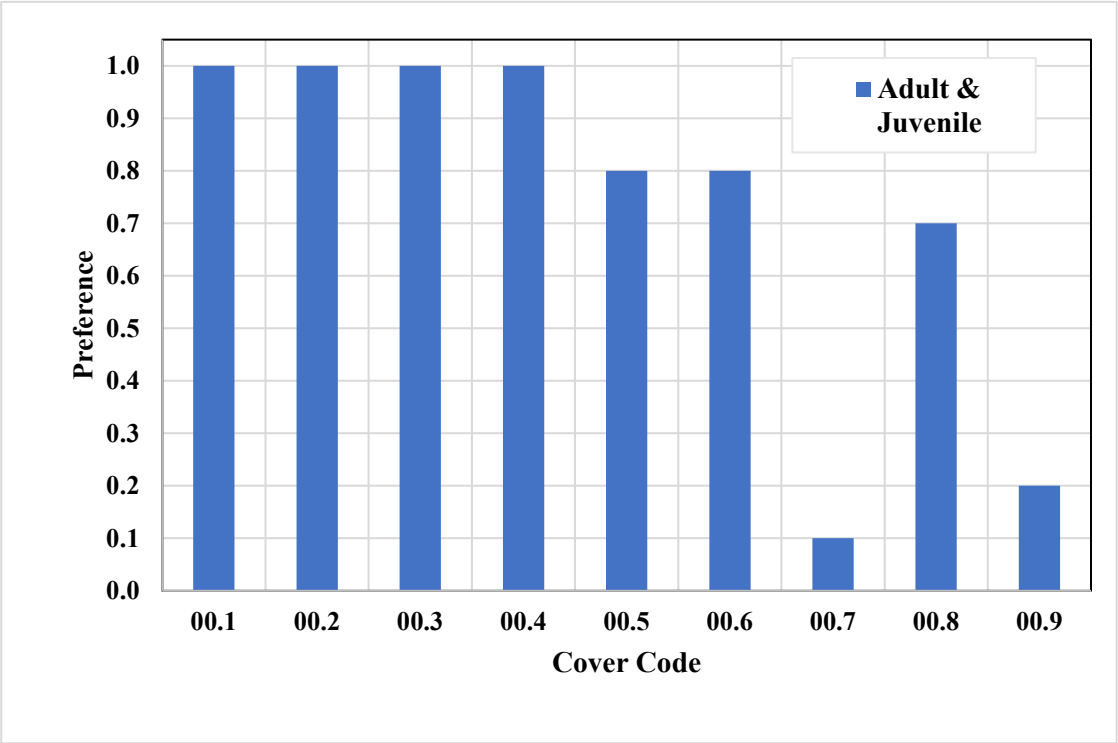
Juvenile	
Velocity (ft/s)	Preference
0.00	0.55
0.75	1.00
0.95	1.00
1.15	0.87
1.55	0.78
1.85	0.54
3.15	0.30
3.85	0.07
5.00	0.00

Steelhead

Substrate Preference Criteria

For Steelhead Spawning Substrate Preference, use Table 4 (Beecher and Caldwell 2022)
For Steelhead Juvenile and Resident Adult Substrate and Cover Preference, use Table 3 (Beecher and Caldwell 2022)

Steelhead
Cover Preference



Code	Type of Cover Note: cover codes are not used for spawning life stage	Adult & Juvenile Preference
00.1	Undercut bank	1.00
00.2	Overhanging vegetation near or touching water	1.00
00.3	Rootwad (including parly undercut)	1.00
00.4	Log jam/submerged brush pile	1.00
00.5	Log(s) parallel to bank	0.80
00.6	Aquatic vegetation	0.80
00.7	Short (<1 ft) terrestrial grass	0.10
00.8	Tall (>3 ft) dense grass	0.70
00.9	Vegetation >3 vertical ft above SZF	0.20

Source: Table 3, Beecher and Caldwell 2022

Chinook Salmon

Spawning (Group A)

Chinook spawning HSC curves from several sources were evaluated including WDFW/Ecology (Type 3; 440 redds), the ESH model (Skagit River-specific Type 2; 436 redds), and the Klamath and Trinity rivers (both Type 2). Two sets of WDFW/Ecology Type 3 curves are available; one is recommended for large rivers (examples include the Skagit and Snohomish rivers) and the other is recommended for the Columbia and Snake rivers (Beecher and Caldwell 2022). It is WDFW/Ecology's preference to use the statewide Type 3 HSC curves when available unless additional site-specific field observation data is collected on the Skagit River in sufficient numbers to revisit, and possibly revise, the statewide curves for large rivers. Field validation studies conducted on the Skagit River during 2021 resulted in an additional 31 redd observations. These data were reviewed by the HSC Technical Group and were determined to be consistent with both the ESH and statewide HSC curves (i.e., observation data points were generally captured within the defined area under the HSC depth and velocity curves). As a result, the recommended HSC curves for use in the habitat modeling are the large river WDFW/Ecology Type 3 HSC curves.

Juvenile (Group A)

Chinook juvenile HSC curves from several sources were evaluated including WDFW/Ecology (Type 3; 5,615 fish) and the Klamath and Trinity rivers (both Type 2). No curves were available from the ESH model. It is WDFW/Ecology's preference to use the statewide Type 3 HSC curves when available unless additional site-specific field observation data is collected on the Skagit River in sufficient numbers to revisit, and possibly revise, the statewide curves. The statewide curves are based on analysis from 9 studies totaling 5,615 fish observations (Dungeness, Chiwawa, Mad & Similkameen, and Tucannon rivers and Kendall Creek (Beecher and Caldwell 2022). Kendall Creek was a utilization study with 5,055 fish observations (Beecher and Caldwell 2022). Field validation studies conducted on the Skagit River during 2021 resulted in an additional 41 fish observations. These data were reviewed by the HSC Technical Group and were determined to be consistent with the statewide HSC curves (i.e., observation data points were generally captured within the defined area under the HSC depth and velocity curves). As a result, the recommended habitat modeling approach is to use the WDFW/Ecology Type 3 HSC curves.

Fry (Group E)

Type 3 HSC curves are not available from WDFW/Ecology as the salmonid fry life stage is not commonly modeled in instream flow studies. However, habitat results for the fry life stage are of interest on the Skagit River in evaluating the relationship between flow and available habitat along the stream margins/shoreline areas as well as off-channel habitats that may be activated during higher flow events. As a result, the HSC Technical Group recommended using existing Type 2 fry curves when available. For Chinook fry, the HSC Technical Group reviewed existing Type 2 curves used in the ESH model (FRI and WDF) as well as the Trinity River. The velocity curves used in the ESH model are based velocity HSC for Rainbow Trout juvenile which are likely too high for Chinook fry. Therefore, the HSC Technical Group recommended using the Type 2 depth and velocity fry curves from the Trinity River study. Habitat cover preference information was not available from literature, so this physical attribute will be removed from the habitat modeling process (i.e., habitat model results will be based on depth, velocity, and substrate preferences).

Additional Notes

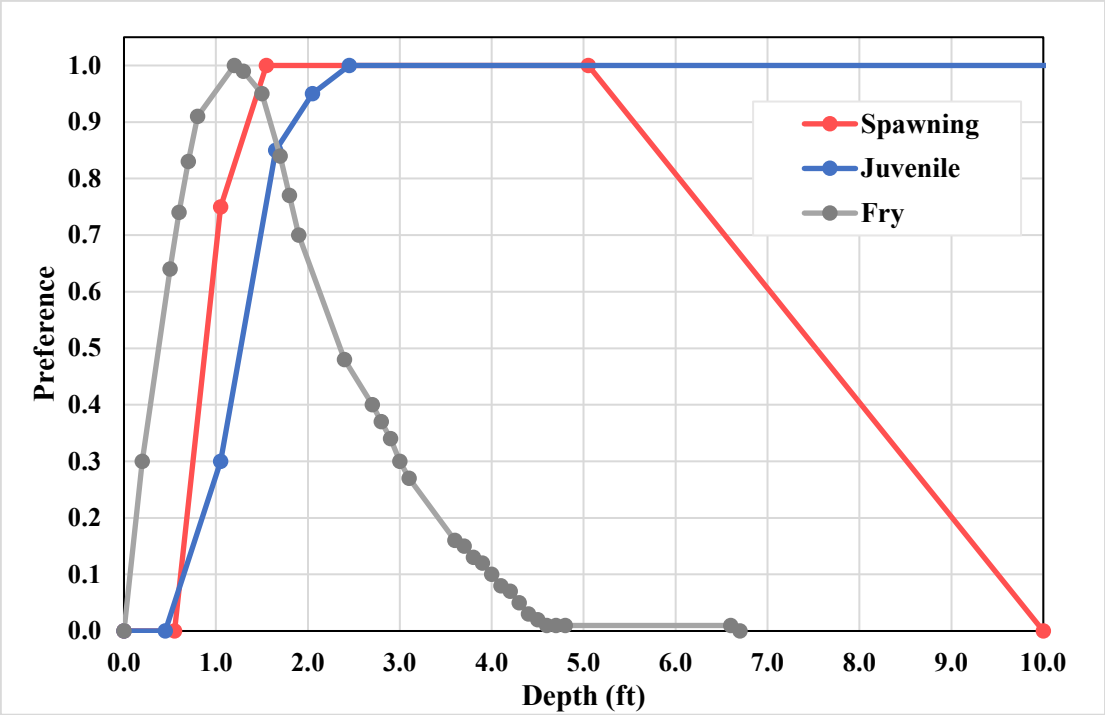
There is no clear biological evidence that depth becomes a limiting factor for juvenile Chinook salmon. Therefore, the HSC Technical Group recommended that once depth reaches 2.45 ft (1.0 preference), it be considered "non-limiting" in the HSC depth curve.

References

WDFW/Ecology: spawning and juvenile (Beecher and Caldwell 2022)
ESH model: spawning and fry (Crumley and Stober 1984; FRI and WDF)
Trinity River: spawning, juvenile, and fry (Hampton et al. 1997)
Klamath River: spawning and juvenile (Hardin et al. 2005; Hardy and Addley 2001)
Fraser River: juvenile (Rempel et al. 2012)

Chinook Salmon

Depth Preference Curves



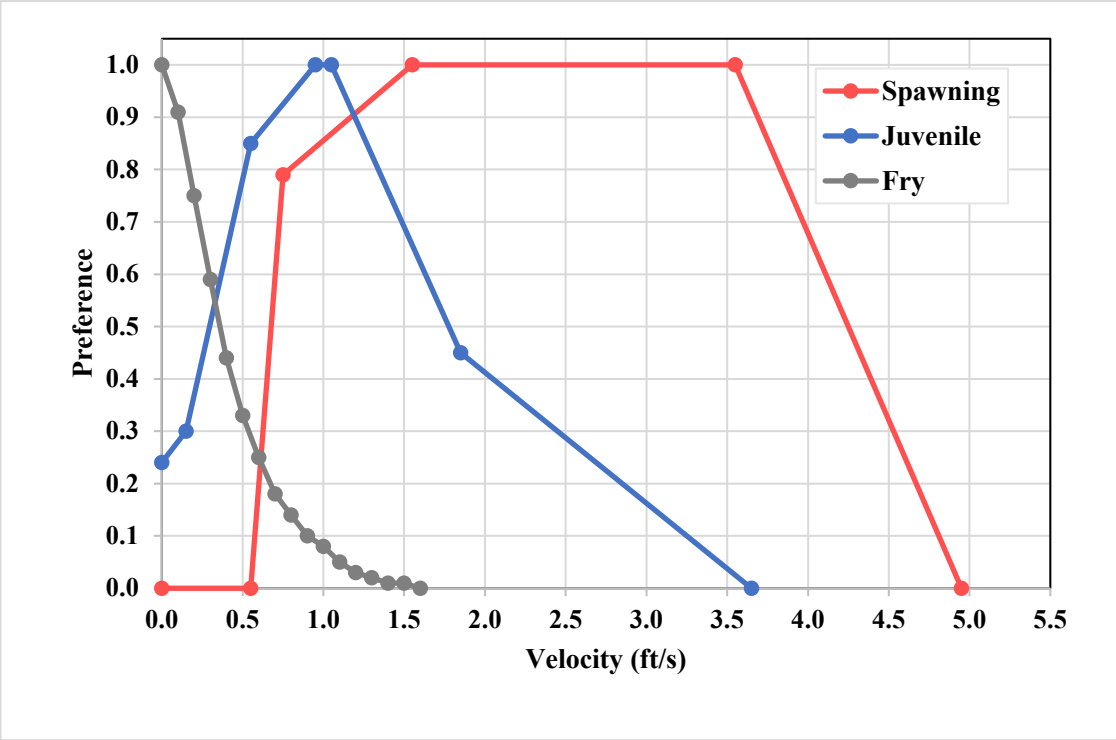
Spawning	
Depth (ft)	Preference
0.00	0.00
0.55	0.00
1.05	0.75
1.55	1.00
5.05	1.00
10.00	0.00

Juvenile	
Depth (ft)	Preference
0.00	0.00
0.45	0.00
1.05	0.30
1.65	0.85
2.05	0.95
2.45	1.00
99.00	1.00

Fry	
Depth (ft)	Preference
0.00	0.00
0.20	0.30
0.50	0.64
0.60	0.74
0.70	0.83
0.80	0.91
1.20	1.00
1.30	0.99
1.50	0.95
1.70	0.84
1.80	0.77
1.90	0.70
2.40	0.48
2.70	0.40
2.80	0.37
2.90	0.34
3.00	0.30
3.10	0.27
3.60	0.16
3.70	0.15
3.80	0.13
3.90	0.12
4.00	0.10
4.10	0.08
4.20	0.07
4.30	0.05
4.40	0.03
4.50	0.02
4.60	0.01
4.70	0.01
4.80	0.01
6.60	0.01
6.70	0.00

Chinook Salmon

Velocity Preference Curves



Fry	
Velocity (ft/s)	Preference
0.00	1.00
0.10	0.91
0.20	0.75
0.30	0.59
0.40	0.44
0.50	0.33
0.60	0.25
0.70	0.18
0.80	0.14
0.90	0.10
1.00	0.08
1.10	0.05
1.20	0.03
1.30	0.02
1.40	0.01
1.50	0.01
1.60	0.00

Spawning	
Velocity (ft/s)	Preference
0.00	0.00
0.55	0.00
0.75	0.79
1.55	1.00
3.55	1.00
4.95	0.00

Juvenile	
Velocity (ft/s)	Preference
0.00	0.24
0.15	0.30
0.55	0.85
0.95	1.00
1.05	1.00
1.85	0.45
3.65	0.00

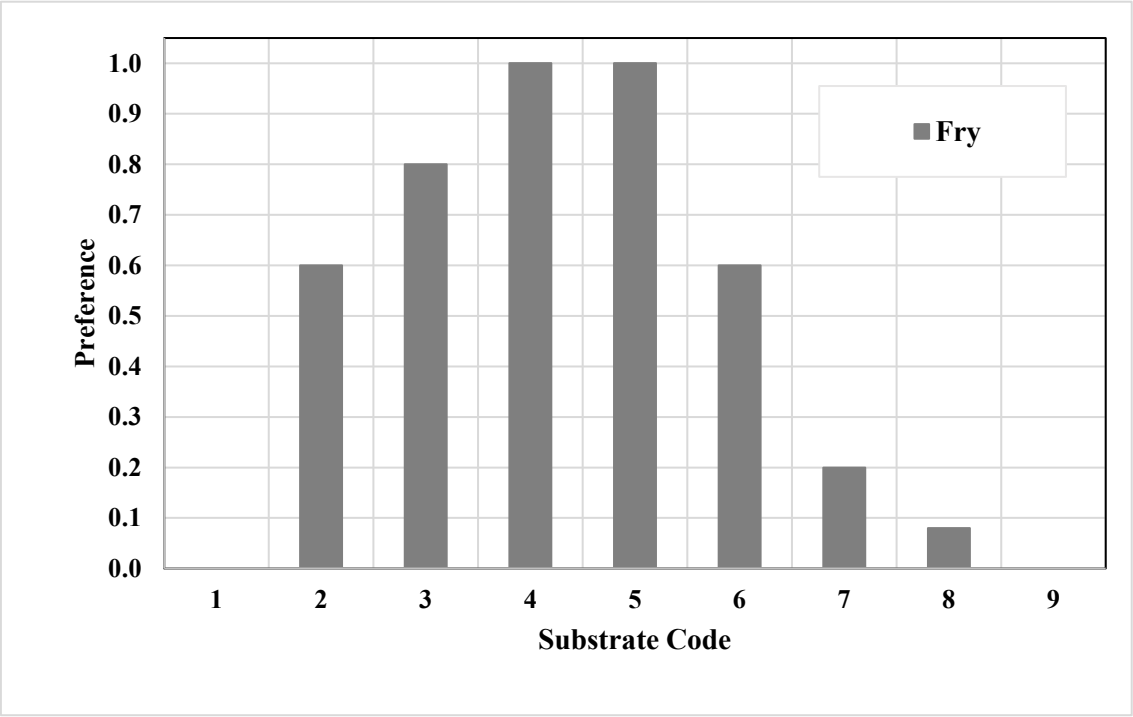
Chinook Salmon

Substrate Preference Criteria

For Chinook Salmon Spawning Substrate Preference, use Table 2 (Beecher and Caldwell 2022)
For Chinook Salmon Juvenile Substrate and Cover Preference, use Table 3 (Beecher and Caldwell 2022)
For Chinook Salmon Fry Substrate Preference, use data from the ESH Model

Chinook Salmon

Substrate Preference

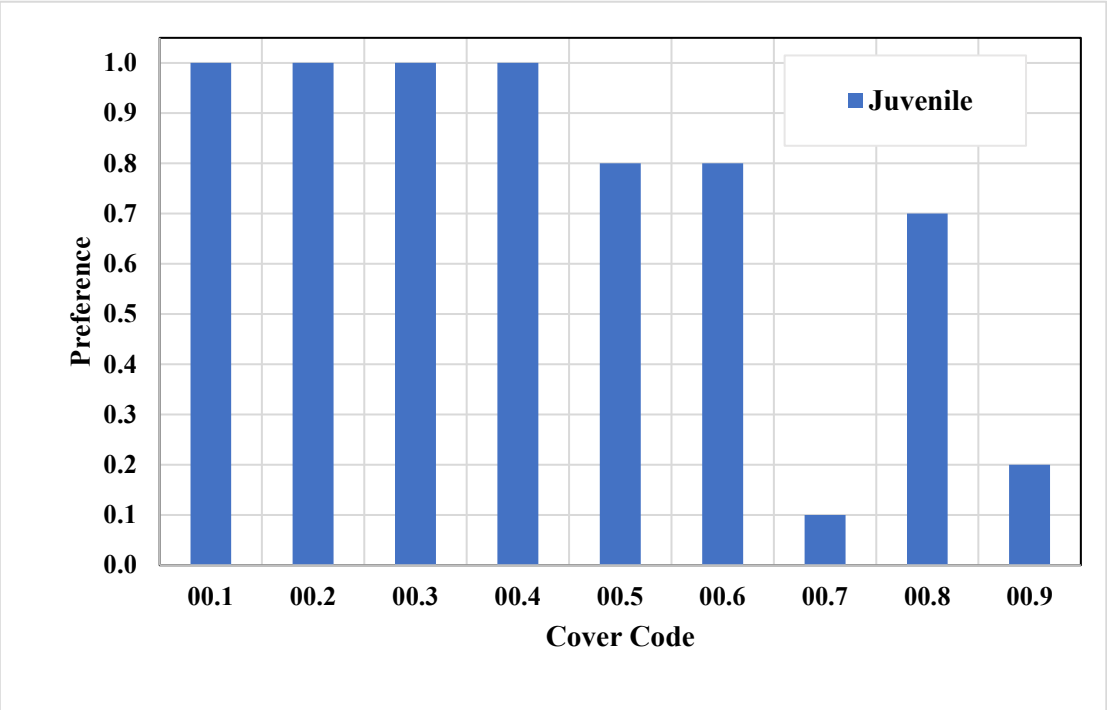


Sustrate Code	Substrate Type	Fry Preference
1	Silt, Clay, or Organic	0.00
2	Sand	0.60
3	Small Gravel (0.1-0.5")	0.80
4	Med Gravel (0.5-1.5")	1.00
5	Large Gravel (1.5-3.0")	1.00
6	Small Cobble (3.0-6.0")	0.60
7	Large Cobble (6.0-12")	0.20
8	Boulder (>12")	0.08
9	Bedrock	0.00

Source: ESH Model

Chinook Salmon

Cover Preference



Code	Type of Cover Note: cover codes are not used for spawning life	Juvenile Preference
00.1	Undercut bank	1.00
00.2	Overhanging vegetation near or touching water	1.00
00.3	Rootwad (including parly undercut)	1.00
00.4	Log jam/submerged brush pile	1.00
00.5	Log(s) parallel to bank	0.80
00.6	Aquatic vegetation	0.80
00.7	Short (<1 ft) terrestrial grass	0.10
00.8	Tall (>3 ft) dense grass	0.70
00.9	Vegetation >3 vertical ft above SZF	0.20

Source: Table 3, Beecher and Caldwell 2022

Pink Salmon

Spawning (Group A)

Pink spawning HSC curves from WDFW/Ecology (Type 3; 104 redds) and the ESH model (Skagit River-specific Type 2; 347 redds) were evaluated by the HSC Technical Group. It is WDFW/Ecology's preference to use the statewide Type 3 HSC curves when available unless additional site-specific field observation data is collected on the Skagit River in sufficient numbers to revisit, and possibly revise, the statewide curves. Field validation studies conducted on the Skagit River during 2021 resulted in an additional 31 redd observations. These data were reviewed by the HSC Technical Group and were determined to be consistent with both the ESH and statewide HSC curves (i.e., observation data points were generally captured within the defined area under the HSC depth and velocity curves). The statewide curves are based on data from 6 studies and 104 redds [Squire Creek/North Fork Stillaguamish, Dosewallips (3 studies), and Duckabush (2 studies) rivers] (Beecher and Caldwell 2022). As a result, the recommended habitat modeling approach is to use the WDFW/Ecology Type 3 HSC curves.

Additional Notes

There is no clear biological evidence that depth becomes a limiting factor for spawning Pink salmon. Therefore, the HSC Technical Group recommended that once depth reaches 1.35 ft (0.30 preference), it be considered "non-limiting" in the HSC depth curve.

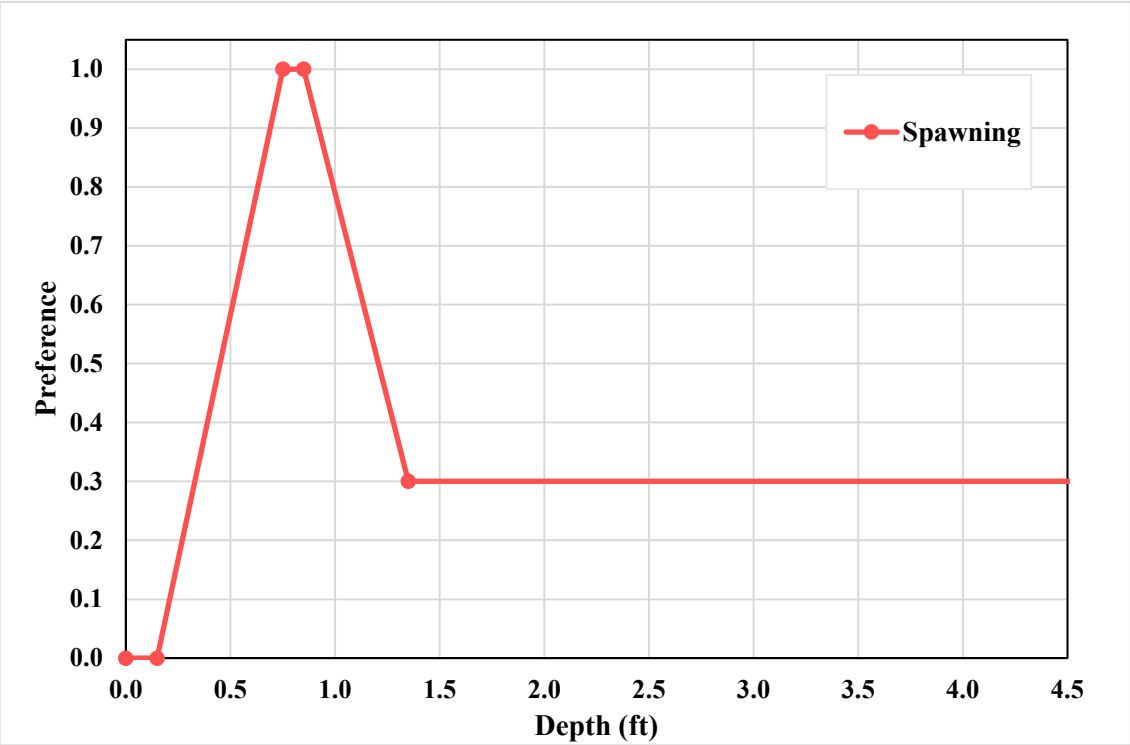
Pink salmon is an "ocean-type" rearing species, therefore, juvenile HSC curves are not recommended for habitat modeling in the Skagit River. However, the HSC Technical Group has developed a set of "generic salmonid fry" HSC curves based on an evaluation of HSC currently used in the ESH model for several salmonid species (see Fry tab in this spreadsheet). The generic salmonid fry HSC curves will be used to evaluate potential fry habitat along stream margins and side-channel areas.

References

WDFW/Ecology: spawning (Beecher and Caldwell 2022)
ESH model: spawning (Crumley and Stober 1984)

Pink Salmon

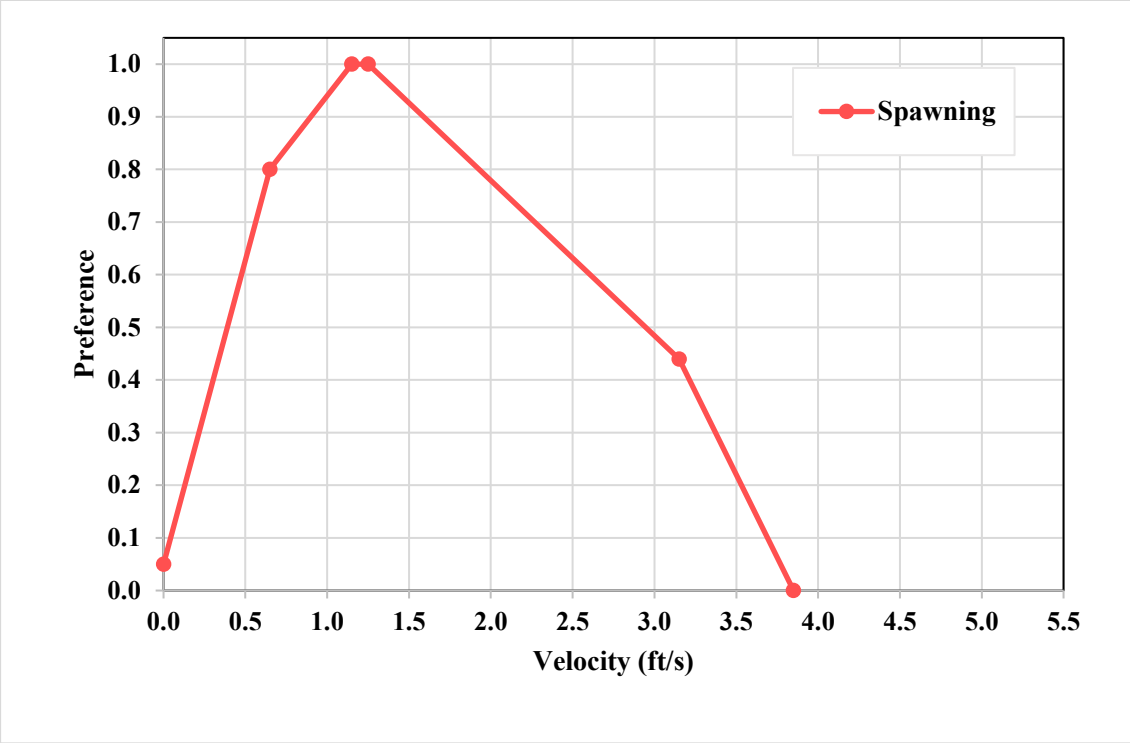
Depth Preference Curves



Spawning	
Depth (ft)	Preference
0.00	0.00
0.15	0.00
0.75	1.00
0.85	1.00
1.35	0.30
99.00	0.30

Pink Salmon

Velocity Preference Curves



Spawning	
Velocity (ft/s)	Preference
0.00	0.05
0.65	0.80
1.15	1.00
1.25	1.00
3.15	0.44
3.85	0.00

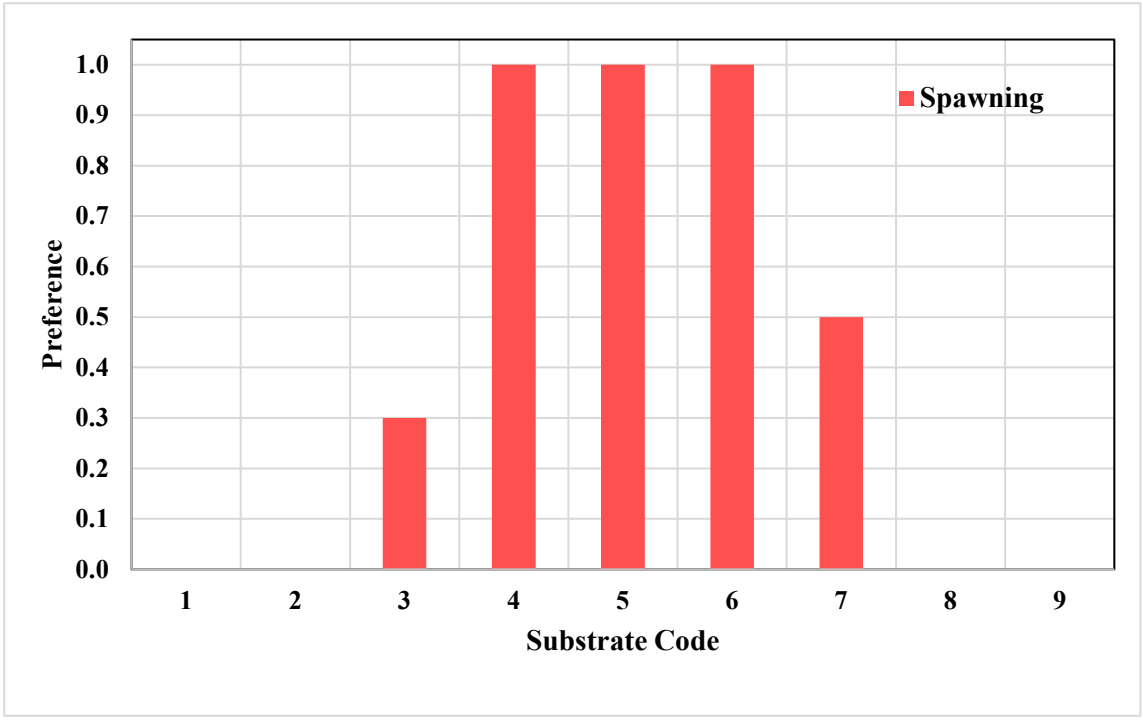
Pink Salmon

Substrate Preference Criteria

For Pink Salmon Spawning Substrate Preference, use Table 2 (Beecher and Caldwell 2022)

Pink Salmon

Calculated Substrate Preference



Sustrate Code	Substrate Type	Spawning Preference
1	Silt, Clay, or Organic	0.0
2	Sand	0.0
3	Small Gravel (0.1-0.5")	0.3
4	Med Gravel (0.5-1.5")	1.0
5	Large Gravel (1.5-3.0")	1.0
6	Small Cobble (3.0-6.0")	1.0
7	Large Cobble (6.0-12")	0.5
8	Boulder (>12")	0.0
9	Bedrock	0.0

Source: Table 12, Beecher and Caldwell 2022

Chum Salmon

Spawning (Group A)

Chum spawning HSC curves from WDFW/Ecology (Type 3; 225 redds) and the ESH model (Skagit River-specific Type 2; 251 redds) were evaluated by the HSC Technical Group. It is WDFW/Ecology's preference to use the statewide Type 3 HSC curves when available unless additional site-specific field observation data is collected on the Skagit River in sufficient numbers to revisit, and possibly revise, the statewide curves. The statewide curves are based on data from 16 studies and 225 redds [Hill Creek, Kennedy Creek (3 studies), Duckabush (9 studies) and Dosewallips rivers (3 studies)] (Beecher and Caldwell 2022). As a result, the recommended habitat modeling approach is to use the WDFW/Ecology Type 3 HSC curves.

Fry (Group E)

Type 3 curves are not available from WDFW/Ecology or the ESH model for Chum fry. As a result, the proposed HSC curves are based on information from a juvenile fish habitat survey on the Lower Fraser River (Rempel et al. 2012). The authors noted that the HSC curves are consistent with the Type 2 curves proposed by Hale et al. (1985). Habitat cover preference information was not available from literature, so this physical attribute will be removed from the habitat modeling process (i.e., habitat model results will be based on depth, velocity, and substrate preferences).

Additional Notes

The 2021 HSC field validation study included spawning Chum as a target species. However, due to unseasonably high flows on the Skagit River (and poor visibility conditions due to turbidity) during Chum spawning window (i.e., late-fall/early-winter), field observations were not possible.

There is no clear biological evidence that depth becomes a limiting factor for the fry and spawning life stages. Therefore, the HSC Technical Group recommended that once depth reaches 1.31 ft (1.0 preference) for fry and 2.65 ft (0.17 preference) for spawning, it be considered "non-limiting" in the HSC depth curves.

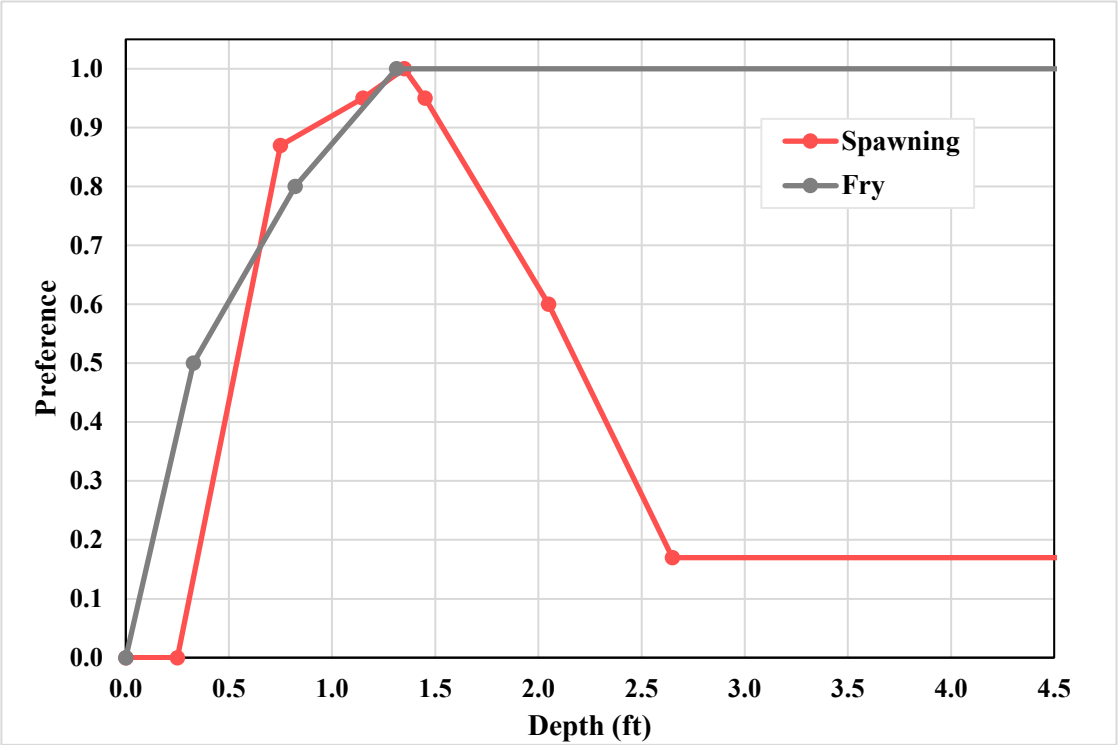
Chum salmon is an "ocean-type" rearing species, therefore, juvenile HSC curves are not recommended for habitat modeling in the Skagit River. However, the HSC Technical Group has developed a set of "generic salmonid fry" HSC curves based on an evaluation of HSC currently used in the ESH model for several salmonid species (see Fry tab in this spreadsheet). The generic salmonid fry HSC curves will be used to evaluate potential fry habitat along stream margins and side-channel areas.

References

WDFW/Ecology: spawning (Beecher and Caldwell 2022)
ESH model: spawning (Crumley and Stober 1984)
Fraser River: spawning and fry (Rempel et al. 2012)

Chum Salmon

Depth Preference Curves

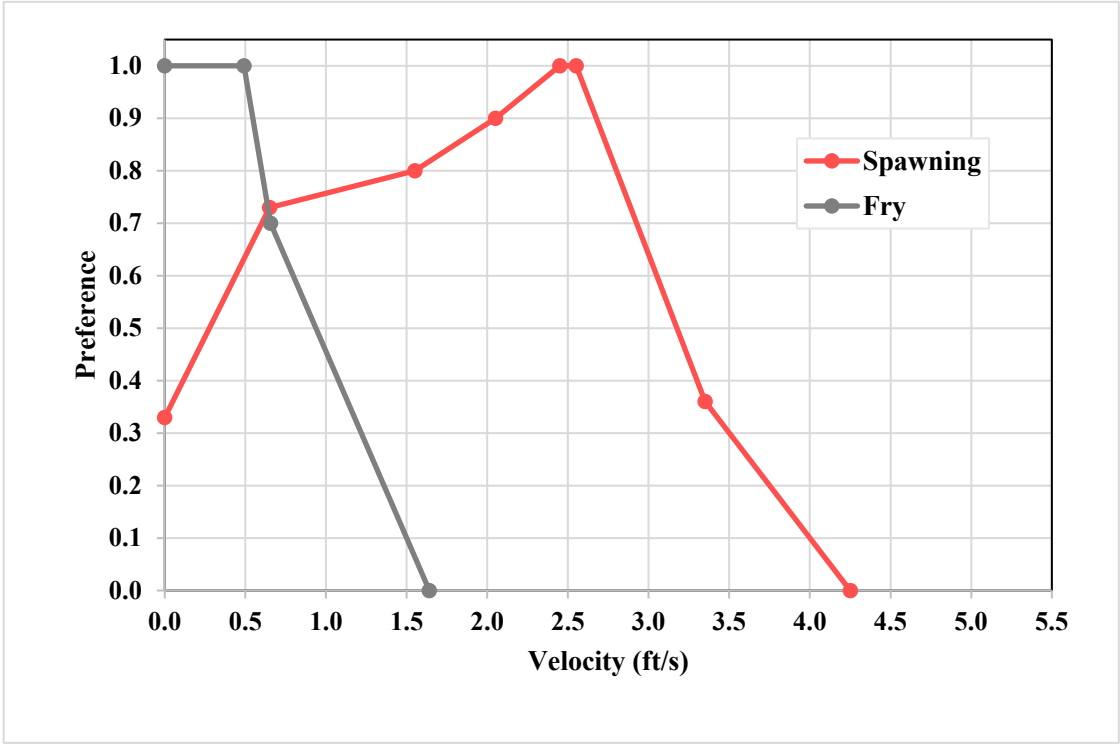


Spawning	
Depth (ft)	Preference
0.00	0.00
0.25	0.00
0.75	0.87
1.15	0.95
1.35	1.00
1.45	0.95
2.05	0.60
2.65	0.17
99.00	0.17

Fry	
Depth (ft)	Preference
0.00	0.00
0.33	0.50
0.82	0.80
1.31	1.00
99.00	1.00

Chum Salmon

Velocity Preference Curves



Spawning	
Velocity (ft/s)	Preference
0.00	0.33
0.65	0.73
1.55	0.80
2.05	0.90
2.45	1.00
2.55	1.00
3.35	0.36
4.25	0.00

Fry	
Velocity (ft/s)	Preference
0.00	1.00
0.49	1.00
0.66	0.70
1.64	0.00

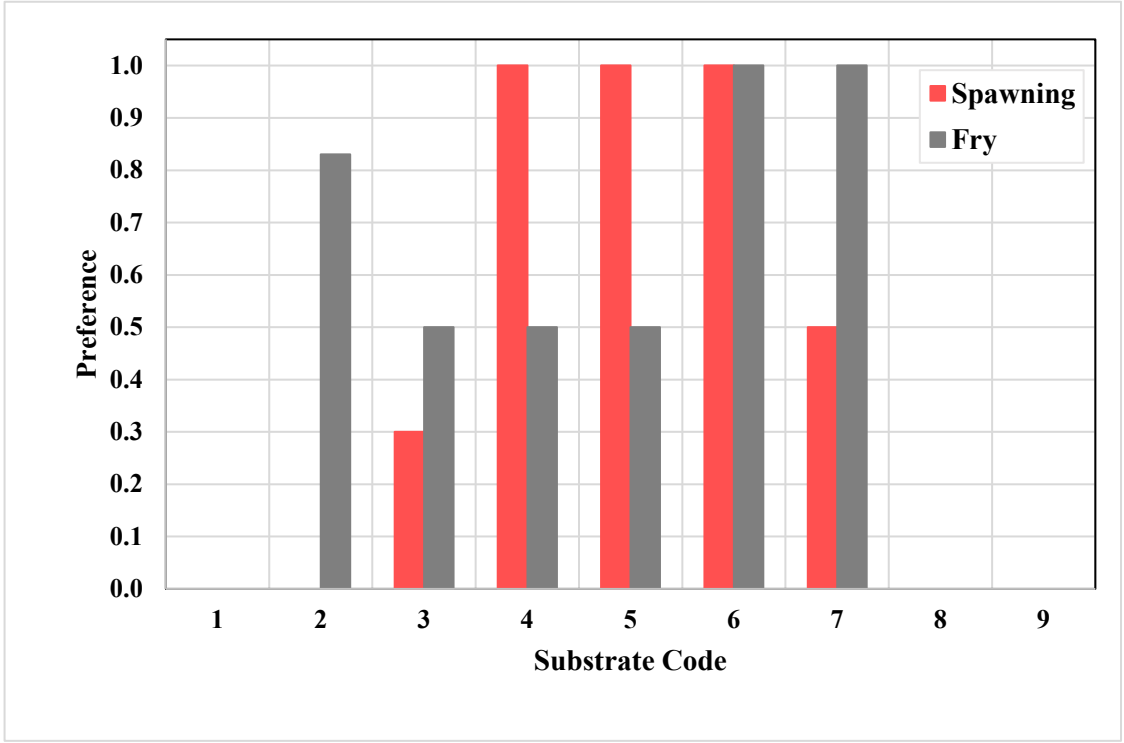
Chum Salmon

Substrate Preference Criteria

For Chum Salmon Spawning Substrate Preference, use Table 2 (Beecher and Caldwell 2022)
For Chum Salmon Fry Substrate Preference, use Rempel et al. 2012

Chum Salmon

Substrate Preference



Sustrate Code	Substrate Type	Spawning Preference	Fry Preference
1	Silt, Clay, or Organic	0.0	0.0
2	Sand	0.0	0.8
3	Small Gravel (0.1-0.5")	0.3	0.5
4	Med Gravel (0.5-1.5")	1.0	0.5
5	Large Gravel (1.5-3.0")	1.0	0.5
6	Small Cobble (3.0-6.0")	1.0	1.0
7	Large Cobble (6.0-12")	0.5	1.0
8	Boulder (>12")	0.0	0.0
9	Bedrock	0.0	0.0

Source: Spawning (Table 10, Beecher and Caldwell 2022); Fry (Rempel et al. 20

Coho Salmon

Spawning (Group C)

Coho spawning HSC curves from several sources were evaluated including WDFW/Ecology (Type 3; 66 redds), the ESH model (hybrid Type 1-2), and the Trinity River (Type 2). It is WDFW/Ecology's preference to use statewide Type 3 HSC curves when available unless additional site-specific field observation is collected on the Skagit River in sufficient numbers to revisit, and potentially revise, the statewide curves. The statewide HSC curves are based on data from 5 studies and 66 redds (Fletcher Canyon and Irely creeks, and Humptulips and Dewatto rivers). As a result, the proposed habitat modeling approach is to use the existing WDFW/Ecology Type 3 HSC curves.

Juvenile (Group D)

The WDFW/Ecology Instream Flow Study Guidelines are periodically updated with best available data. Versions of the WDFW/Ecology Instream Flow Study Guidelines prior to 2013 provided default Coho juvenile depth and velocity HSC curves developed in earlier studies (Beecher et al. 2002). Subsequent research has shown that the stream flow relating to peak Coho rearing habitat did not resemble the stream flow relating to increased Coho salmon production (Beecher et al. 2010). Based on this, WDFW/Ecology removed the statewide Coho juvenile HSC curves from subsequent versions (Beecher et al. 2013; Beecher and Caldwell 2022).

HSC curves from the ESH model (Type 2) and the Trinity River (Type 2) were evaluated by the HSC Technical Group. While the ESH curves are not based on Skagit-specific field observation data, the HSC Technical Group recommended their use primarily because there is a history of using these curves for Skagit River habitat modeling purposes.

Fry (Group E)

Type 3 HSC curves are not available from WDFW/Ecology as the salmonid fry life stage is not commonly modeled in instream flow studies. However, habitat results for the fry life stage are of interest on the Skagit River in evaluating the relationship between flow and available habitat along the stream margins/shoreline areas as well as off-channel habitats that may be activated during higher flow events. As a result, the HSC Technical Group recommended using existing Type 2 fry curves when available. For Coho fry, the HSC Technical Group reviewed existing Type 2 curves used in the ESH model (Crumley and Stober 1984) as well as the Trinity River with a recommendation to use the ESH model curves for habitat modeling purposes. Habitat cover preference information was not available from literature, so this physical attribute will be removed from the habitat modeling process (i.e., habitat model results will be based on depth, velocity, and substrate preferences).

Additional Notes

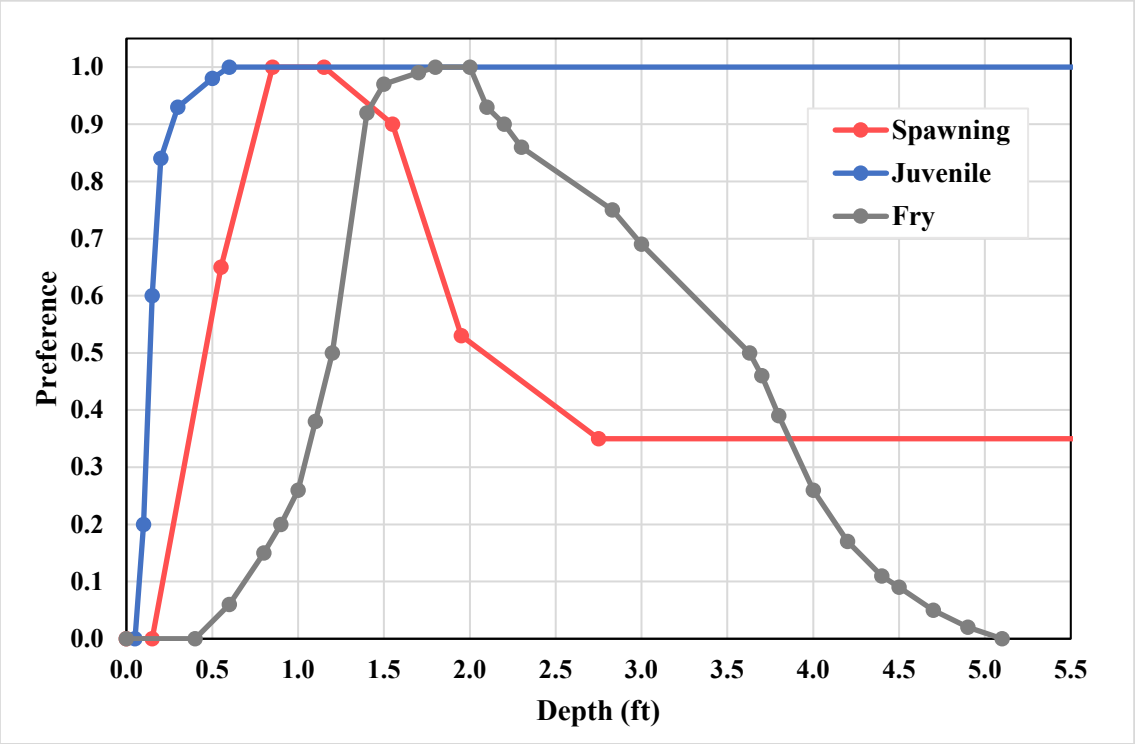
There is no clear biological evidence that depth becomes a limiting factor for spawning and juvenile Coho salmon. Therefore, the HSC Technical Group recommended that once depth reaches 2.75 ft (0.35 preference) for spawning and 2.0 ft (1.0 preference) for juvenile, it be considered "non-limiting" in the HSC depth curves.

References

WDFW/Ecology: spawning (Beecher and Caldwell 2022)
ESH model: spawning, juvenile, and fry (Wampler 1980; Bovee 1978; Crumley and Stober 1984)
Trinity River: spawning, juvenile, and fry (Hampton et al. 1997)

Coho Salmon

Depth Preference Curves



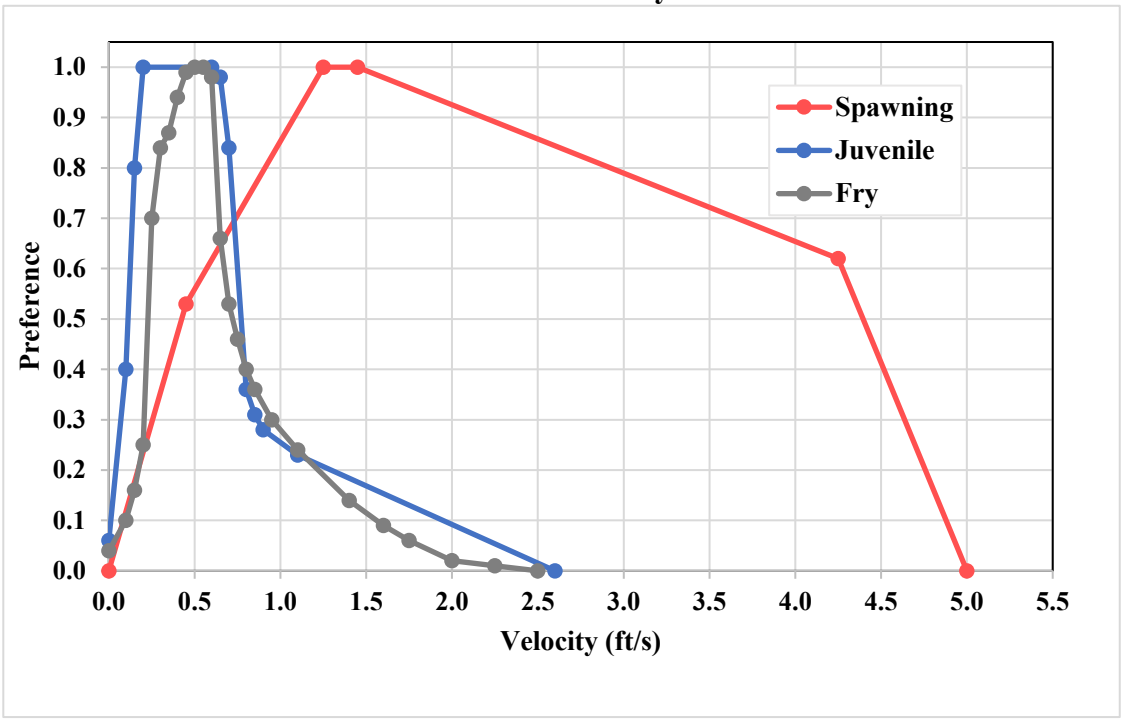
Spawning	
Depth (ft)	Preference
0.00	0.00
0.15	0.00
0.55	0.65
0.85	1.00
1.15	1.00
1.55	0.90
1.95	0.53
2.75	0.35
99.00	0.35

Juvenile	
Depth (ft)	Preference
0.05	0.00
0.10	0.20
0.15	0.60
0.20	0.84
0.30	0.93
0.50	0.98
0.60	1.00
99.00	1.00

Fry	
Depth (ft)	Preference
0.00	0.00
0.40	0.00
0.60	0.06
0.80	0.15
0.90	0.20
1.00	0.26
1.10	0.38
1.20	0.50
1.40	0.92
1.50	0.97
1.70	0.99
1.80	1.00
2.00	1.00
2.10	0.93
2.20	0.90
2.30	0.86
2.83	0.75
3.00	0.69
3.63	0.50
3.70	0.46
3.80	0.39
4.00	0.26
4.20	0.17
4.40	0.11
4.50	0.09
4.70	0.05
4.90	0.02
5.10	0.00

Coho Salmon

Velocity Preference Curves



Spawning	
Velocity (ft/s)	Preference
0.00	0.00
0.45	0.53
1.25	1.00
1.45	1.00
4.25	0.62
5.00	0.00

Juvenile	
Velocity	Preference
0.00	0.06
0.10	0.40
0.15	0.80
0.20	1.00
0.60	1.00
0.65	0.98
0.70	0.84
0.80	0.36
0.85	0.31
0.90	0.28
1.10	0.23
2.60	0.00

Fry	
Velocity (ft/s)	Preference
0.00	0.04
0.10	0.10
0.15	0.16
0.20	0.25
0.25	0.70
0.30	0.84
0.35	0.87
0.40	0.94
0.45	0.99
0.50	1.00
0.55	1.00
0.60	0.98
0.65	0.66
0.70	0.53
0.75	0.46
0.80	0.40
0.85	0.36
0.95	0.30
1.10	0.24
1.40	0.14
1.60	0.09
1.75	0.06
2.00	0.02
2.25	0.01
2.50	0.00

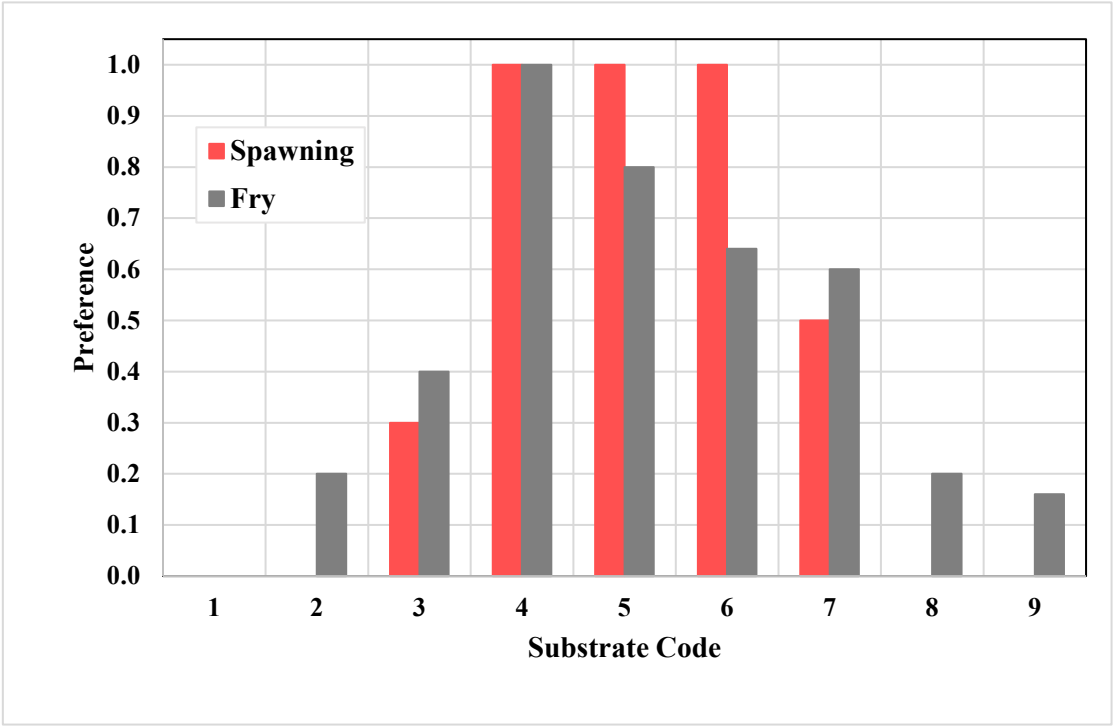
Coho Salmon

Substrate Preference Criteria

For Coho Salmon Spawning Substrate Preference, use Table 2 (Beecher and Caldwell 2022)
For Coho Salmon Juvenile Substrate and Cover Preference, use Table 3 (Beecher and Caldwell 2022)
For Coho Salmon Fry Substrate Preference, use data from the ESH Model

Coho Salmon

Substrate Preference

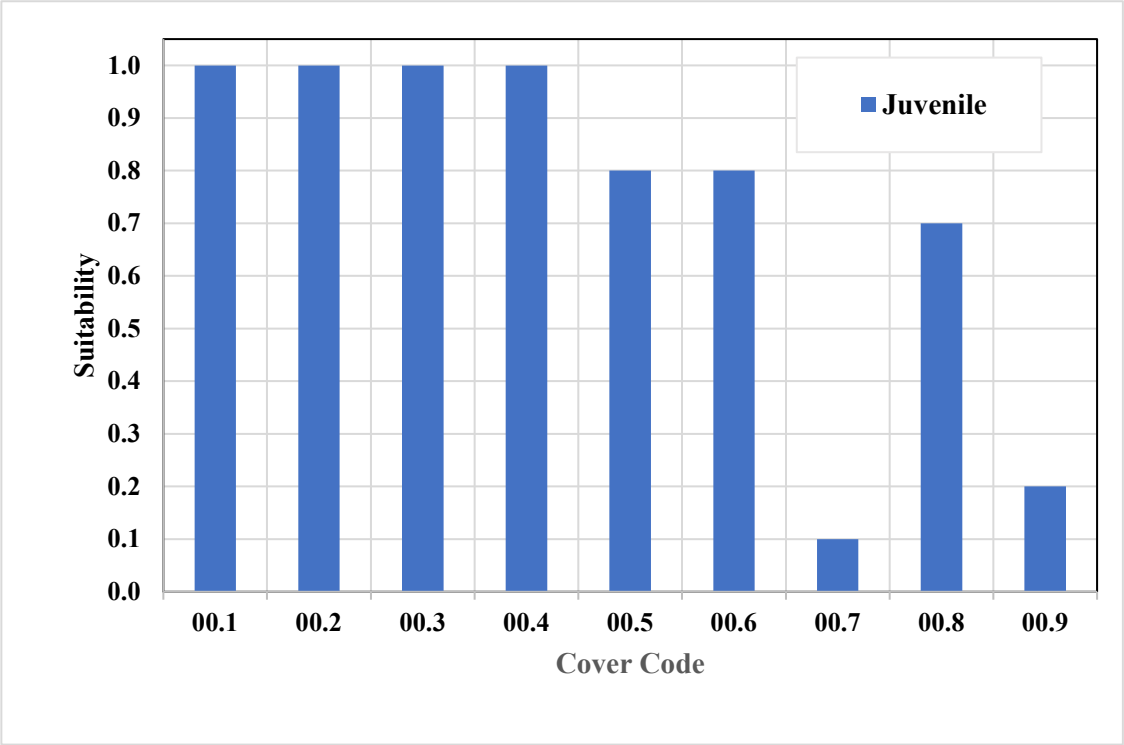


Sustrate Code	Substrate Type	Spawning Preference	Fry Preference
1	Silt, Clay, or Organic	0.0	0.00
2	Sand	0.0	0.20
3	Small Gravel (0.1-0.5")	0.3	0.40
4	Med Gravel (0.5-1.5")	1.0	1.00
5	Large Gravel (1.5-3.0")	1.0	0.80
6	Small Cobble (3.0-6.0")	1.0	0.64
7	Large Cobble (6.0-12")	0.5	0.60
8	Boulder (>12")	0.0	0.20
9	Bedrock	0.0	0.16

Source: Spawning (Table 11, Beecher and Caldwell 2022); Fry (ESH Model)

Coho Salmon

Cover Preference



Code	Type of Cover Note: Cover Codes are not used for Spawning life stage	Juvenile Preference
00.1	Undercut bank	1.00
00.2	Overhanging vegetation near or touching water	1.00
00.3	Rootwad (including parly undercut)	1.00
00.4	Log jam/submerged brush pile	1.00
00.5	Log(s) parallel to bank	0.80
00.6	Aquatic vegetation	0.80
00.7	Short (<1 ft) terrestrial grass	0.10
00.8	Tall (>3 ft) dense grass	0.70
00.9	Vegetation >3 vertical ft above SZF	0.20

Source: Table 3, Beecher and Caldwell 2022

Sockeye Salmon

Spawning (Group C)

For Sockeye spawning, only Type 3 HSC curves from WDFW/Ecology were evaluated by the HSC Technical Group as ESH curves are not available. It is WDFW/Ecology's preference to use the statewide Type 3 HSC curves when available unless additional site-specific field observation data is collected on the Skagit River in sufficient numbers to revisit, and possibly revise, the statewide curves. The statewide curves are based on data from 4 studies and 1,053 redds [Cedar River (3 studies) and Big Creek (Quinault basin)] (Beecher and Caldwell 2022). As a result, the recommended habitat modeling approach is to use the WDFW/Ecology Type 3 HSC

Additional Notes

There is no clear biological evidence that depth becomes a limiting factor for spawning Sockeye salmon. Therefore, the HSC Technical Group recommended that once depth reaches 1.55 ft (0.45 preference), it be considered "non-limiting" in the HSC depth curve.

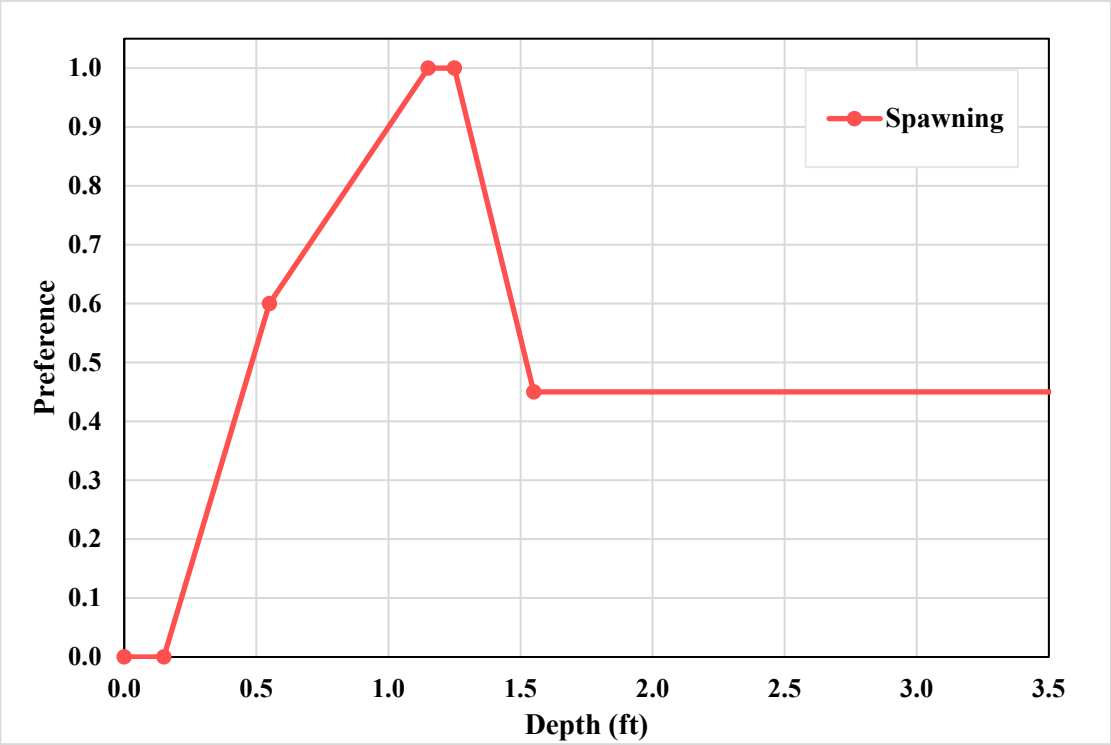
Sockeye salmon is an "ocean-type" rearing species, therefore, juvenile HSC curves are not recommended for habitat modeling in the Skagit River. However, the HSC Technical Group has developed a set of "generic salmonid fry" HSC curves based on an evaluation of HSC currently used in the ESH model for several salmonid species (see Fry tab in this spreadsheet). The generic salmonid fry HSC curves will be used to evaluate potential fry habitat along stream margins and side-channel areas.

References

WDFW/Ecology: spawning (Beecher and Caldwell 2022)
Fraser River: spawning (Rempel et al. 2012)

Sockeye Salmon

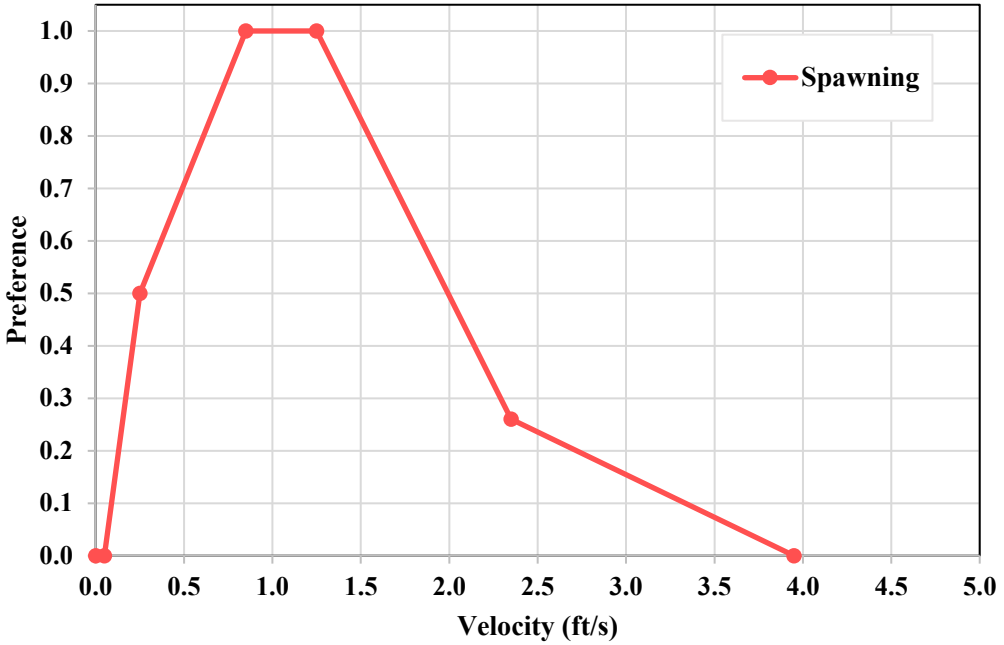
Depth Preference Curves



Spawning	
Depth (ft)	Preference
0.00	0.00
0.15	0.00
0.55	0.60
1.15	1.00
1.25	1.00
1.55	0.45
99.00	0.45

Sockeye Salmon

Velocity Preference Curves



Spawning	
Velocity (ft/s)	Preference
0.00	0.00
0.05	0.00
0.25	0.50
0.85	1.00
1.25	1.00
2.35	0.26
3.95	0.00

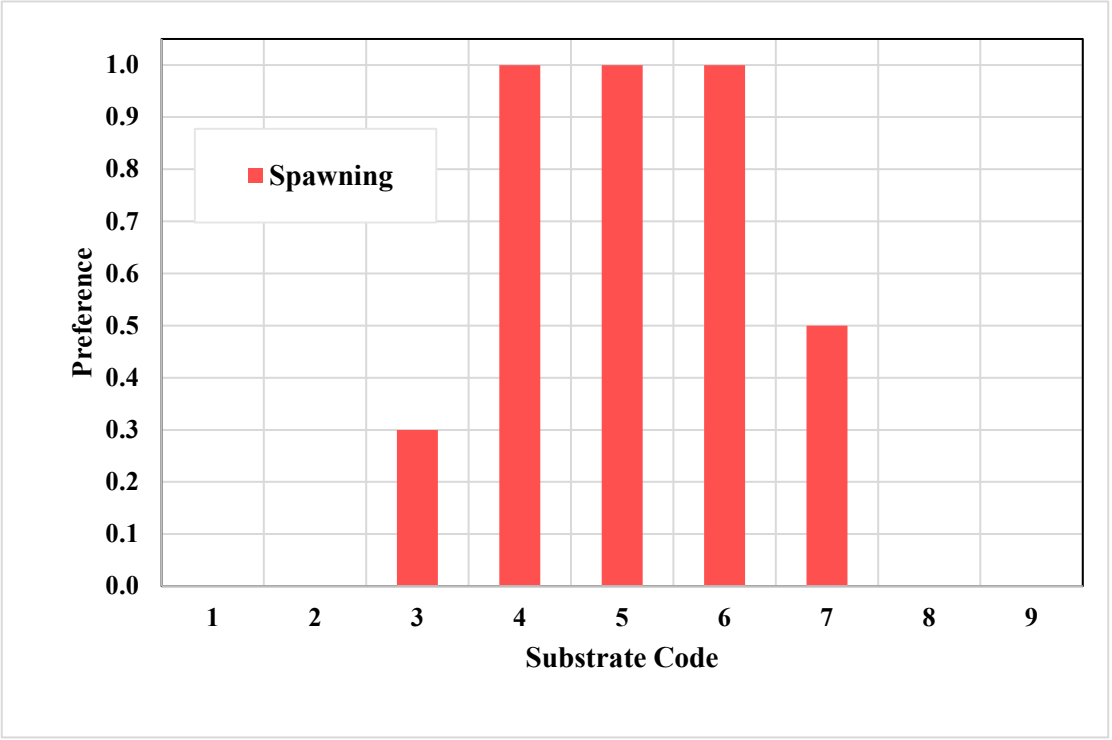
Sockeye Salmon

Substrate Preference Criteria

For Sockeye Salmon Spawning Substrate Preference, use Table 2 (Beecher and Caldwell 2022)

Sockeye Salmon

Calculated Substrate Preference



Sustrate Code	Substrate Type	Spawning Preference
1	Silt, Clay, or Organic	0.0
2	Sand	0.0
3	Small Gravel (0.1-0.5")	0.3
4	Med Gravel (0.5-1.5")	1.0
5	Large Gravel (1.5-3.0")	1.0
6	Small Cobble (3.0-6.0")	1.0
7	Large Cobble (6.0-12")	0.5
8	Boulder (>12")	0.0
9	Bedrock	0.0

Source: Table 13, Beecher and Caldwell 2022

Rainbow Trout

General Approach

For Rainbow Trout spawning, adult rearing, and juvenile life stages, HSC curves from WDFW/Ecology (Type 3), the ESH model (hybrid Type 1-2), and the Fraser River (Type 2, juvenile only) were evaluated by the HSC Technical Group. It is WDFW/Ecology's preference to use the statewide Type 3 HSC curves when available unless additional site-specific field observation data is collected on the Skagit River in sufficient numbers to revisit, and possibly revise, the statewide curves. As a result, the recommended habitat modeling approach is to use the WDFW/Ecology Type 3 HSC curves for all three Rainbow Trout life stages. Information specific to each life stage is provided below.

Spawning (Group C)

The WDFW/Ecology Type 3 HSC curves for Rainbow Trout spawning are based on analysis from 2 studies and 27 redds (from the upper Lake and Muller creeks) (Beecher and Caldwell 2022).

Adult Rearing (Group C)

The WDFW/Ecology Type 3 HSC curves for Rainbow Trout adult rearing are based on analysis from 15 studies and 638 fish observations [mostly streams west of the Cascades, but includes Yakima River, upper Mill Creek (WRIA 32), and Douglas Creek (WRIA 44)] (Beecher and Caldwell 2022).

Juvenile (Group C)

The WDFW/Ecology Type 3 HSC curves are based on analysis from 32 studies and 1,954 fish observations (from multiple Washington streams of differing sizes and stream types) (Beecher and Caldwell 2022).

Fry (Group E)

Type 3 HSC curves are not available from WDFW/Ecology as the salmonid fry life stage is not commonly modeled in instream flow studies. However, habitat results for the fry life stage are of interest on the Skagit River in evaluating the relationship between flow and available habitat along the stream margins/shoreline areas as well as off-channel habitats that may be activated during higher flow events. As a result, the HSC Technical Group recommended using existing Type 2 fry curves when available. For Rainbow Trout fry, the HSC Technical Group reviewed existing Type 2 curves used in the ESH model (Bovee 1978) as well as the Fraser River with a recommendation to use the ESH model curves for habitat modeling purposes. Habitat cover preference information was not available from literature, so this physical attribute will be removed from the habitat modeling process (i.e., habitat model results will be based on depth, velocity, and substrate preferences).

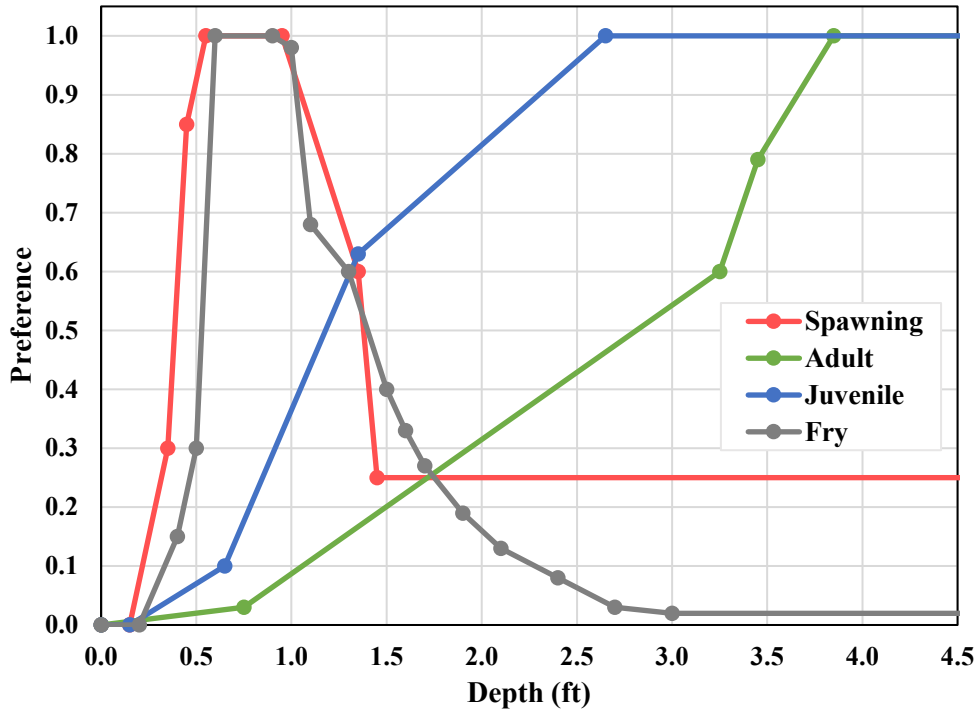
Additional Notes

There is no clear biological evidence that depth becomes a limiting factor for spawning, adult, and juvenile Rainbow Trout. Therefore, the HSC Technical Group recommended that once depth reaches 1.45 ft for spawning (0.25 preference), 3.85 ft (1.0 preference) for adult, and 2.65 ft (1.0 preference) for juvenile, it be considered "non-limiting" in the HSC depth curves.

References

WDFW/Ecology: spawning, adult rearing, and juvenile (Beecher and Caldwell 2022)
ESH model: spawning and fry (Bovee 1978); adult and juvenile (Bovee 1978; Crumley and Stober 1984)
Fraser River: juvenile and fry (Rempel et al. 2012)
Klamath River: spawning, adult, and juvenile (Allen DATE)
McKenzie River: spawning, adult, and juvenile (Hardin-Davis 1990)

Rainbow Trout
Depth Preference Curves



Spawning	
Depth (ft)	Preference
0.00	0.00
0.15	0.00
0.35	0.30
0.45	0.85
0.55	1.00
0.95	1.00
1.35	0.60
1.45	0.25
99.00	0.25

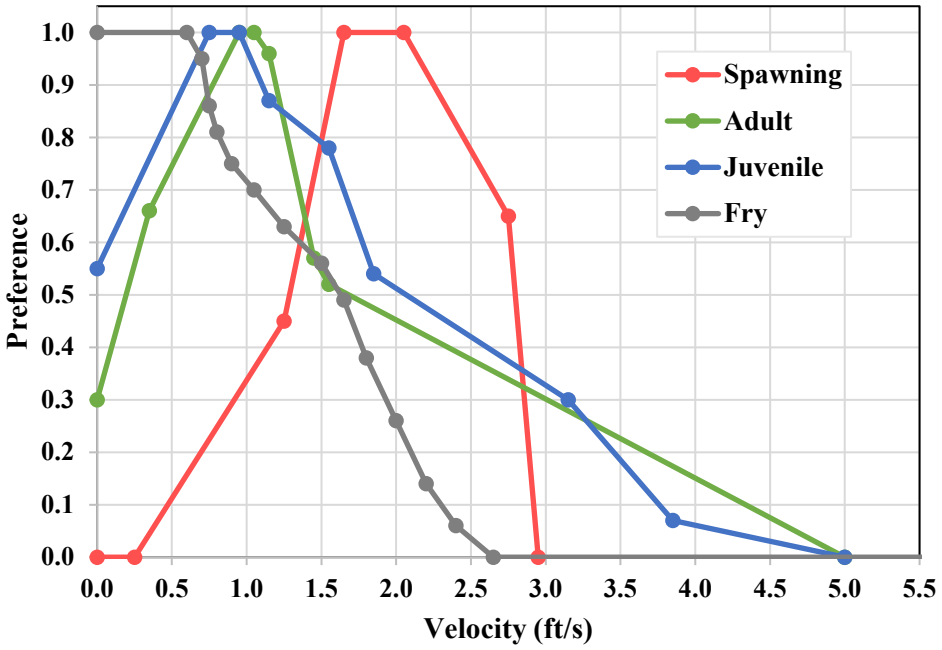
Adult	
Depth (ft)	Preference
0.00	0.00
0.75	0.03
3.25	0.60
3.45	0.79
3.85	1.00
99.00	1.00

Juvenile	
Depth (ft)	Preference
0.00	0.00
0.15	0.00
0.65	0.10
1.35	0.63
2.65	1.00
99.00	1.00

Fry	
Depth (ft)	Preference
0.00	0.00
0.20	0.00
0.40	0.15
0.50	0.30
0.60	1.00
0.90	1.00
1.00	0.98
1.10	0.68
1.30	0.60
1.50	0.40
1.60	0.33
1.70	0.27
1.90	0.19
2.10	0.13
2.40	0.08
2.70	0.03
3.00	0.02
5.00	0.02
6.00	0.02
100.00	0.02

Rainbow Trout

Velocity Preference Curves



Fry	
Velocity (ft/s)	Preference
0.00	1.00
0.60	1.00
0.70	0.95
0.75	0.86
0.80	0.81
0.90	0.75
1.05	0.70
1.25	0.63
1.50	0.56
1.65	0.49
1.80	0.38
2.00	0.26
2.20	0.14
2.40	0.06
2.65	0.00
100.00	0.00

Spawning	
Velocity (ft/s)	Preference
0.00	0.00
0.25	0.00
1.25	0.45
1.65	1.00
2.05	1.00
2.75	0.65
2.95	0.00

Adult	
Velocity (ft/s)	Preference
0.00	0.30
0.35	0.66
0.95	1.00
1.05	1.00
1.15	0.96
1.45	0.57
1.55	0.52
5.00	0.00

Juvenile	
Velocity (ft/s)	Preference
0.00	0.55
0.75	1.00
0.95	1.00
1.15	0.87
1.55	0.78
1.85	0.54
3.15	0.30
3.85	0.07
5.00	0.00

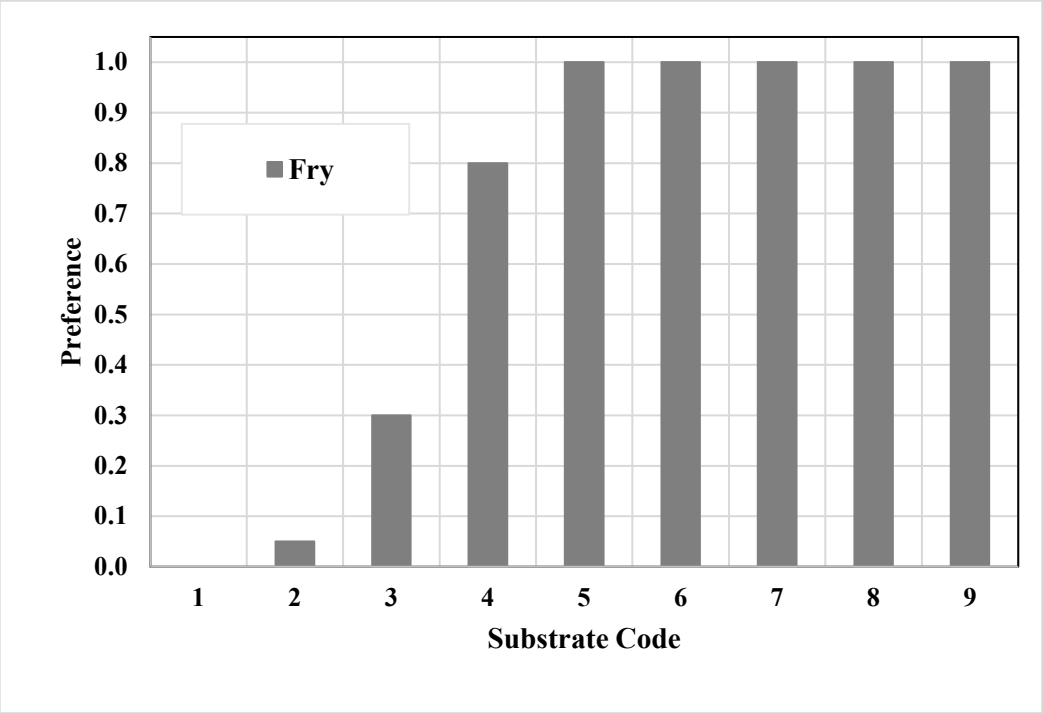
Rainbow Trout

Substrate Preference Criteria

For Rainbow Trout Spawning Substrate Preference, use Table 5 (Beecher and Caldwell 2022)
For Rainbow Trout Adult Rearing and Juvenile Substrate and Cover Preference, use Table 3 (Beecher and Caldwell 2022)
For Rainbow Trout Fry Substrate Preference, use data from the ESH Model

Rainbow Trout

Substrate Preference

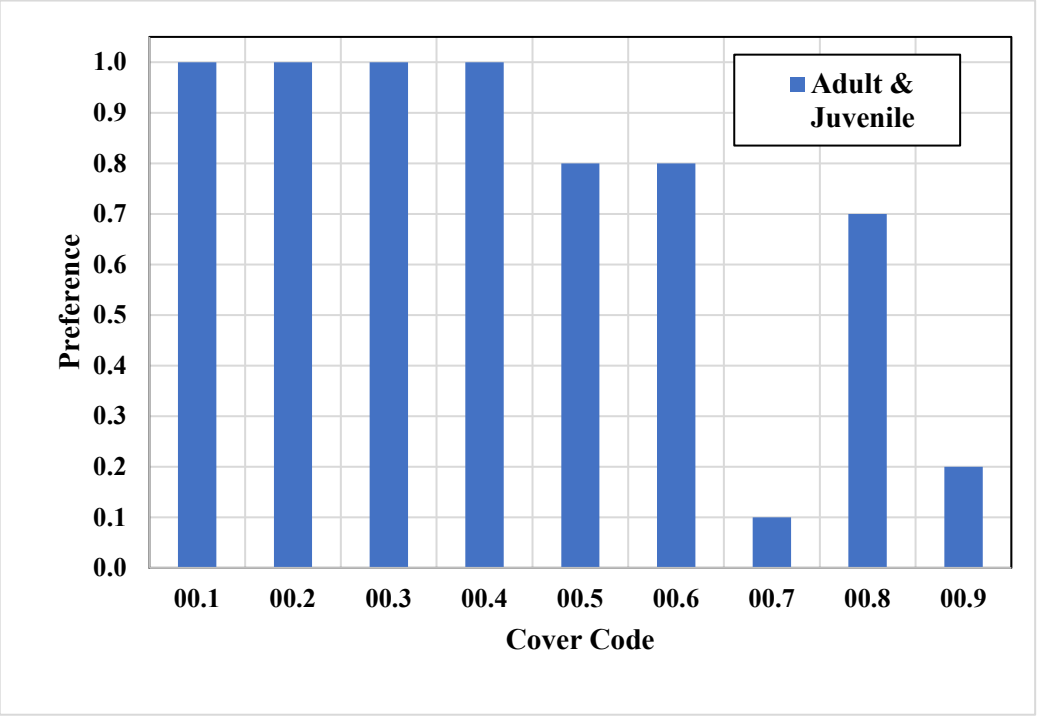


Sustrate Code	Substrate Type	Fry Preference
1	Silt, Clay, or Organic	0.00
2	Sand	0.05
3	Small Gravel (0.1-0.5")	0.30
4	Med Gravel (0.5-1.5")	0.80
5	Large Gravel (1.5-3.0")	1.00
6	Small Cobble (3.0-6.0")	1.00
7	Large Cobble (6.0-12")	1.00
8	Boulder (>12")	1.00
9	Bedrock	1.00

Source: ESH Model

Rainbow Trout

Cover Preference Criteria



Code	Type of Cover Note: Cover Codes are not used for Spawning life stage	Adult & Juvenile Preference
00.1	Undercut bank	1.00
00.2	Overhanging vegetation near or touching water	1.00
00.3	Rootwad (including parly undercut)	1.00
00.4	Log jam/submerged brush pile	1.00
00.5	Log(s) parallel to bank	0.80
00.6	Aquatic vegetation	0.80
00.7	Short (<1 ft) terrestrial grass	0.10
00.8	Tall (>3 ft) dense grass	0.70
00.9	Vegetation >3 vertical ft above SZF	0.20

Source: Table 3, Beecher and Caldwell 2022

Bull Trout and Dolly Varden

General Approach

For Bull Trout and Dolly Varden spawning and juvenile life stages, HSC curves from WDFW/Ecology (Type 3) and the ESH model (hybrid Type 1-2) were evaluated by the HSC Technical Group. It is WDFW/Ecology's preference to use the statewide Type 3 HSC curves when available unless additional site-specific field observation data is collected on the Skagit River in sufficient numbers to revisit, and possibly revise, the statewide curves. As a result, the recommended habitat modeling approach is to use the WDFW/Ecology Type 3 HSC curves for Bull Trout and Dolly Varden spawning and juvenile life stages. Information specific to each life stage is provided below.

Spawning (Group C)

The WDFW/Ecology Type 3 HSC curves for Bull Trout and Dolly Varden spawning are based on analysis from 8 studies and 122 redds [WRIA 7, WRIA 38, WRIA 45 95), and WRIA 46] (Beecher and Caldwell 2022).

Juvenile (Group A)

The WDFW/Ecology Type 3 HSC curves for Bull Trout and Dolly Varden spawning provided in Beecher and Caldwell 2022 were updated in December 2021 and are now based on analysis from 11 studies totaling 127 fish observations [from the Mad, Chiwawa (2 studies), Dungeness, Tucannon, and Kachess rivers; Rock, Early Winters, Phelps, Troublesome, and Box Canyon creeks] (Beecher and Caldwell 2022, Granger 2021). The WDFW/Ecology Instream Flow Guidelines are in the process of being updated and the revised Bull Trout and Dolly Varden juvenile HSC curves will be included in the updated 2022 report. Field validation studies conducted on the Skagit River during 2021 resulted in an additional 4 fish observations (not included in the 2021 update to the HSC curves). Data from these 4 fish observations was reviewed by the HSC Technical Group and were determined to be consistent with both the ESH model and statewide HSC curves (i.e., observation data points were generally captured within the defined area under the HSC depth and velocity curves).

Fry (Group E)

Type 3 HSC curves are not available from WDFW/Ecology as the salmonid fry life stage is not commonly modeled in instream flow studies. However, habitat results for the fry life stage are of interest on the Skagit River in evaluating the relationship between flow and available habitat along the stream margins/shoreline areas as well as off-channel habitats that may be activated during higher flow events. As a result, the HSC Technical Group recommended using existing Type 2 fry curves when available. For Bull Trout and Dolly Varden fry, the HSC Technical Group recommended using the existing Type 2 curves from the ESH model which are based on data from the Arctic Environmental Information and Data Center (1981). Habitat cover preference information was not available from literature, so this physical attribute will be removed from the habitat modeling process (i.e., habitat model results will be based on depth, velocity, and substrate preferences).

Additional Notes

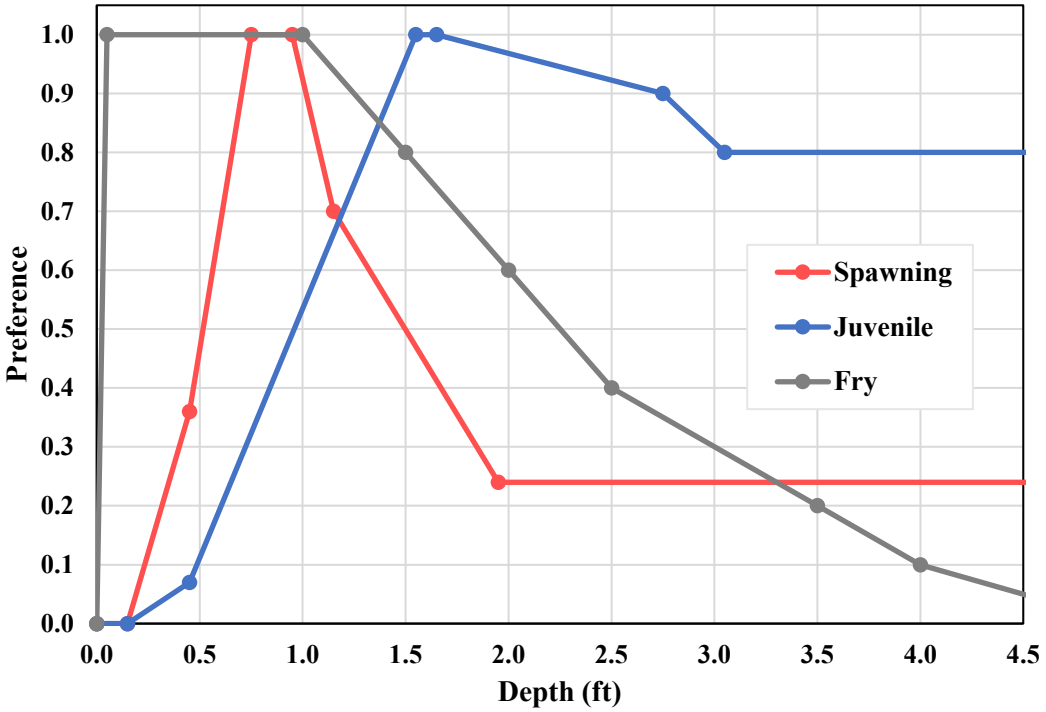
There is no clear biological evidence that depth becomes a limiting factor for spawning and juvenile Bull Trout and Dolly Varden. Therefore, the HSC Technical Group recommended that once depth reaches 1.95 ft (0.24 preference) for spawning and 3.05 ft (0.80 preference) for juvenile, it be considered "non-limiting" in the HSC depth curves.

References

WDFW/Ecology: spawning (Beecher and Caldwell 2022); juvenile (Granger 2021 provisional data)
ESH model: spawning and juvenile (Crumley and Stober 1984); fry (AEIDC 1981)

Bull Trout and Dolly Varden

Depth Preference Curves



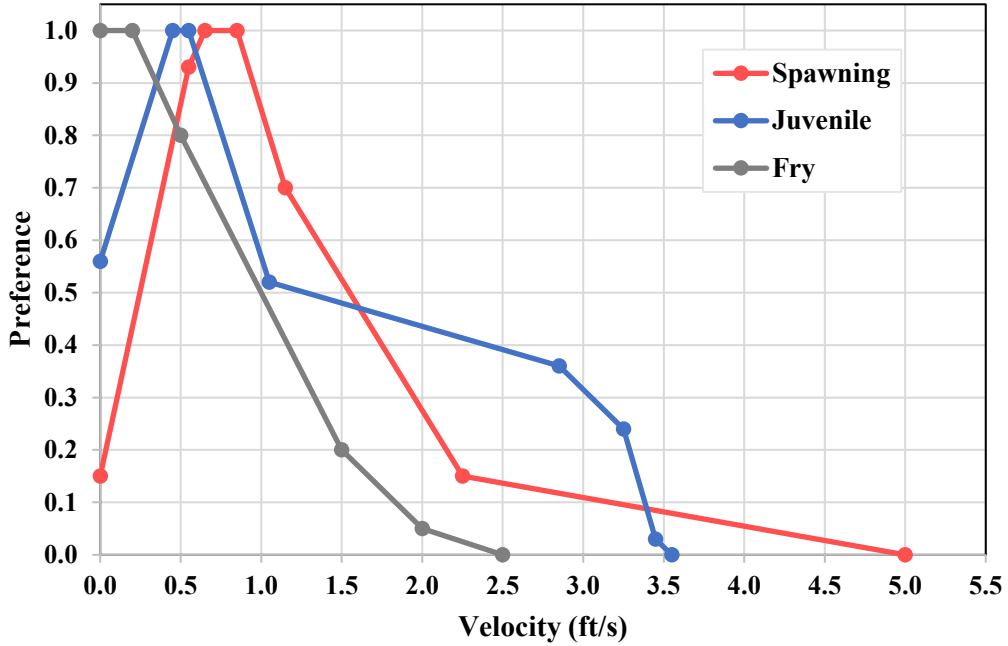
Spawning	
Depth (ft)	Preference
0.00	0.00
0.15	0.00
0.45	0.36
0.75	1.00
0.95	1.00
1.15	0.70
1.95	0.24
99.00	0.24

Juvenile	
Depth (ft)	Preference
0.00	0.00
0.15	0.00
0.45	0.07
1.55	1.00
1.65	1.00
2.75	0.90
3.05	0.80
99.00	0.80

Fry	
Depth (ft)	Preference
0.00	0.00
0.05	1.00
1.00	1.00
1.50	0.80
2.00	0.60
2.50	0.40
3.50	0.20
4.00	0.10
5.00	0.00
100.00	0.00

Bull Trout and Dolly Varden

Velocity Preference Curves



Spawning	
Velocity (ft/s)	Preference
0.00	0.15
0.55	0.93
0.65	1.00
0.85	1.00
1.15	0.70
2.25	0.15
5.00	0.00

Juvenile	
Velocity (ft/s)	Preference
0.00	0.56
0.45	1.00
0.55	1.00
1.05	0.52
2.85	0.36
3.25	0.24
3.45	0.03
3.55	0.00

Fry	
Velocity (ft/s)	Preference
0.00	1.00
0.20	1.00
0.50	0.80
1.50	0.20
2.00	0.05
2.50	0.00

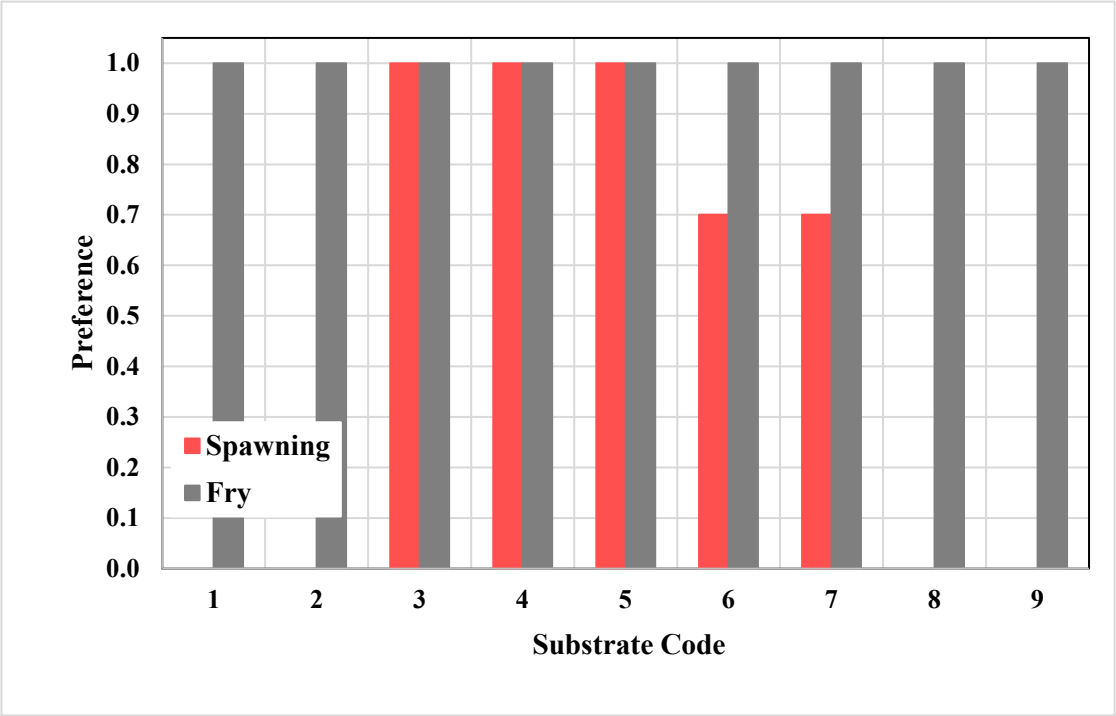
Bull Trout and Dolly Varden

Substrate Preference Criteria

For Bull Trout and Dolly Varden Spawning Substrate Preference, use Table 6 (Beecher and Caldwell 2022)
For Bull Trout and Dolly Varden Juvenile Substrate and Cover Preference, use Table 3 (Beecher and Caldwell 2022)
For Bull Trout and Dolly Varden Fry Substrate Preference, use data from the ESH Model

Bull Trout and Dolly Varden

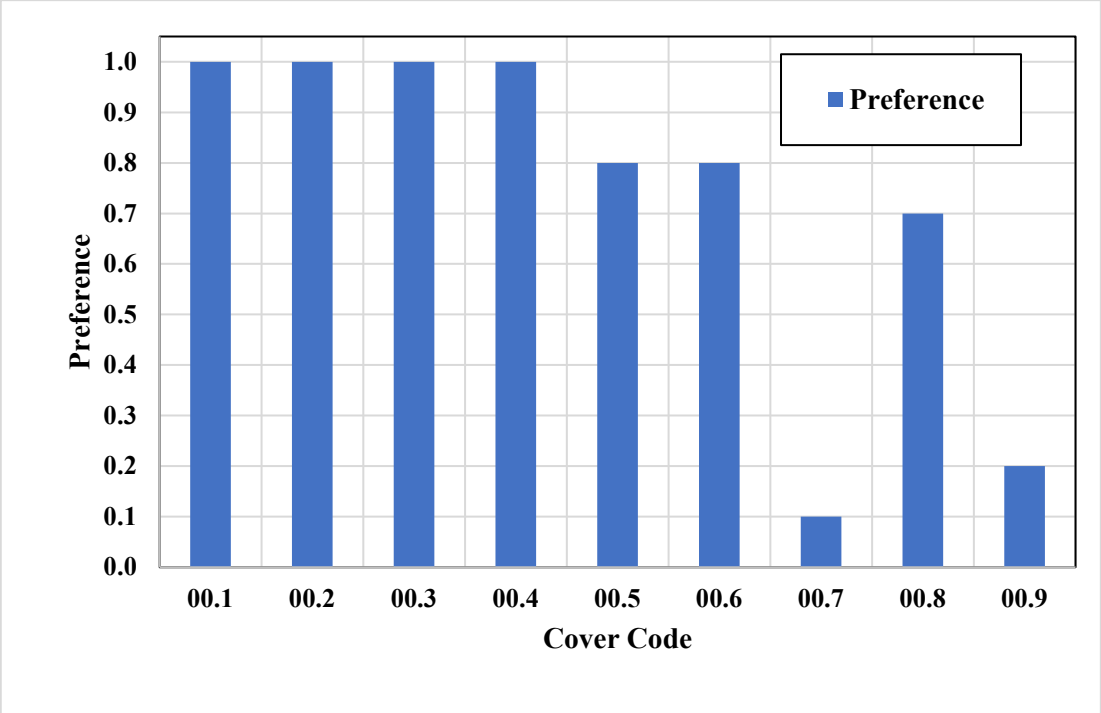
Substrate Preference



Sustrate Code	Substrate Type	Spawning Preference	Fry Preference
1	Silt, Clay, or Organic	0.00	1.00
2	Sand	0.00	1.00
3	Small Gravel (0.1-0.5")	1.00	1.00
4	Med Gravel (0.5-1.5")	1.00	1.00
5	Large Gravel (1.5-3.0")	1.00	1.00
6	Small Cobble (3.0-6.0")	0.70	1.00
7	Large Cobble (6.0-12")	0.70	1.00
8	Boulder (>12")	0.00	1.00
9	Bedrock	0.00	1.00

Source: Spawning (Table 14, Beecher and Caldwell 2022); Fry (ESH Model)

Bull Trout and Dolly Varden



Code	Type of Cover Note: Cover Codes are not used for Spawning life stage	Juvenile Preference
00.1	Undercut bank	1.00
00.2	Overhanging vegetation near or touching water	1.00
00.3	Rootwad (including parly undercut)	1.00
00.4	Log jam/submerged brush pile	1.00
00.5	Log(s) parallel to bank	0.80
00.6	Aquatic vegetation	0.80
00.7	Short (<1 ft) terrestrial grass	0.10
00.8	Tall (>3 ft) dense grass	0.70
00.9	Vegetation >3 vertical ft above SZF	0.20

Source: Table 3, Beecher and Caldwell 2022

Sea-Run Bull Trout

Spawning (Group F)

WDFW/Ecology Type 3 HSC curves are not available and Sea-Run Bull Trout spawning HSC curves are not included in the ESH model. The HSC Technical Group reviewed HSC curves from other studies and developed proposed consensus curves using that information. The other available studies included the Cedar, Yakima, and Wenatchee Rivers in Washington State; the Chowade River, Kemess Creek, and Duncan River in British Columbia; and Smith-Dorrien Creek in Alberta. The general approach was to envelop the depth and velocity HSC curves from the other studies.

Additional Notes

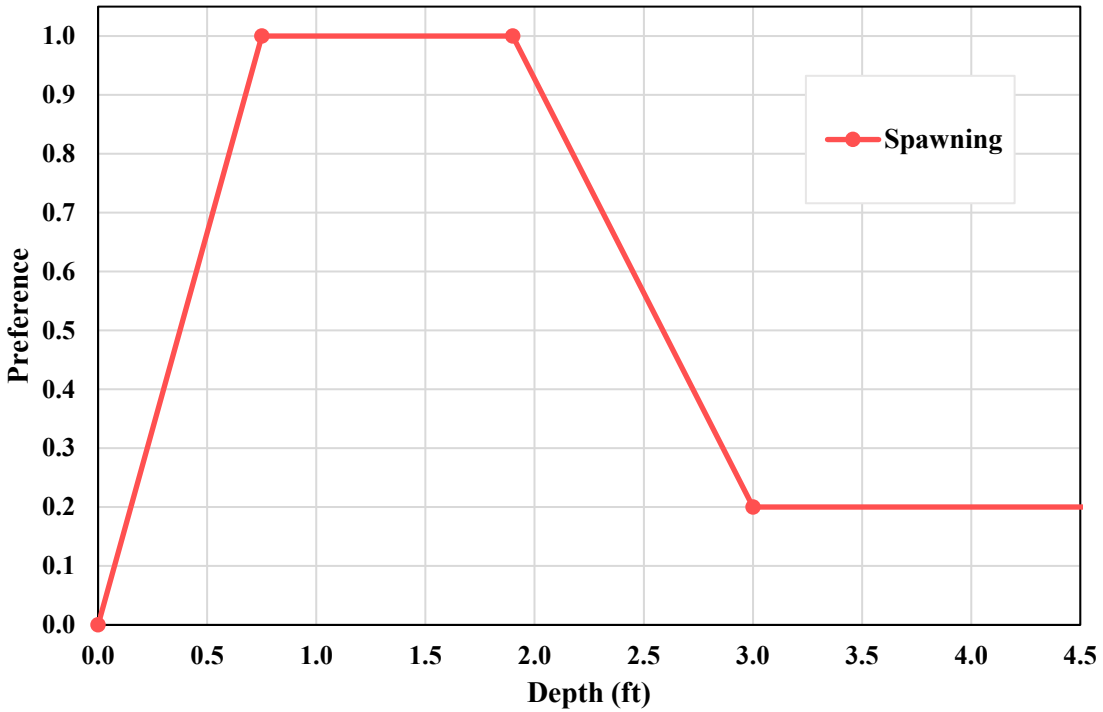
There is no clear biological evidence that depth becomes a limiting factor for spawning Sea-run Bull Trout. Therefore, the HSC Technical Group recommended that once depth reaches 3.0 ft (0.20 preference), it be considered "non-limiting" in the HSC depth curve.

References

Cedar River (Reiser et al. 1997)
Yakima and Wenatchee rivers (Sexauer 1994)
Chowade, British Columbia (Baxter 1995)
Kemess Creek, British Columbia (Bustard and Royea 1995)
Duncan River, British Columbia (O'Brien 1996)
Smith-Dorrien Creek, Alberta (Stelfox and Egan 1995)

Sea-Run Bull Trout

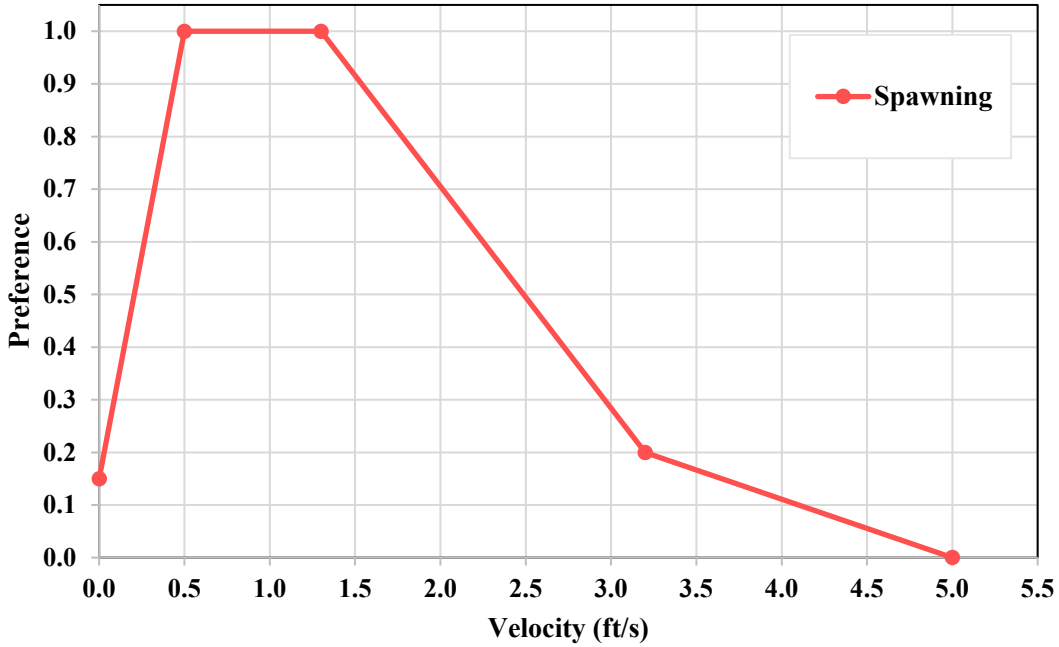
Depth Preference Curves



Spawning	
Depth (ft)	Preference
0.00	0.00
0.75	1.00
1.90	1.00
3.00	0.20
99.00	0.20

Sea-Run Bull Trout

Velocity Preference Curves



Spawning	
Velocity (ft/s)	Preference
0.00	0.15
0.50	1.00
1.30	1.00
3.20	0.20
5.00	0.00

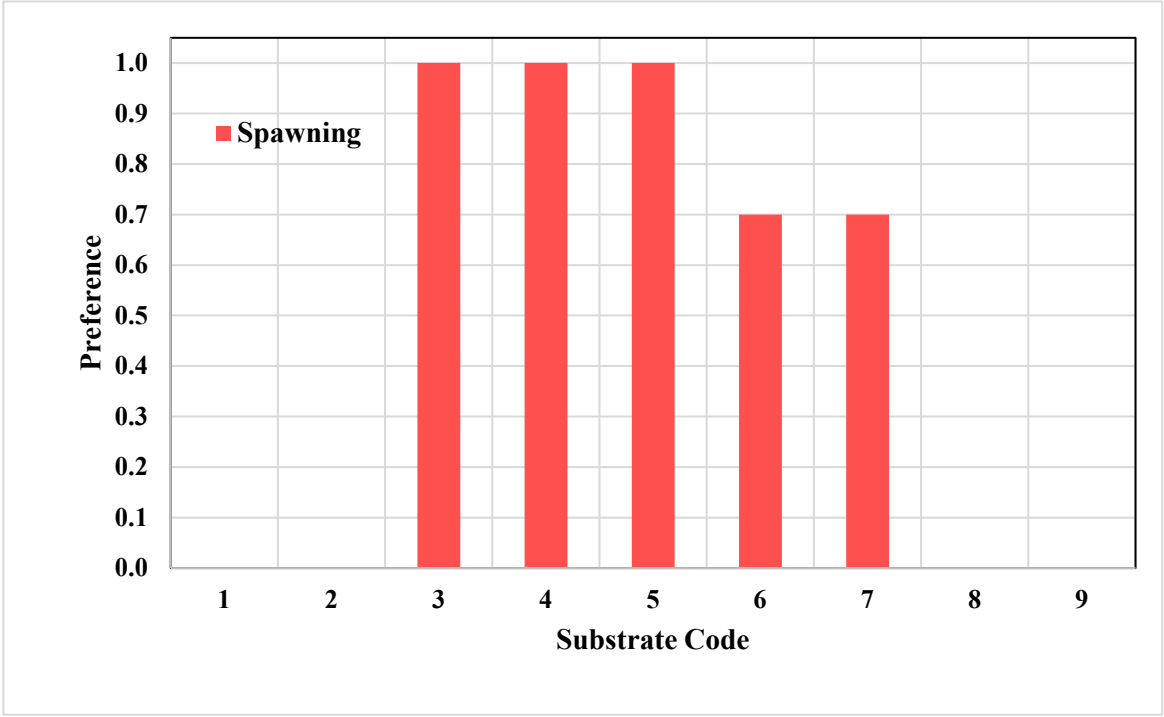
Sea-Run Bull Trout

Substrate Preference Criteria

For Sea-Run Bull Trout Spawning Substrate Preference, use Table 6 (Beecher and Caldwell 2022)

Sea-Run Bull Trout

Calculated Substrate Preference



Sustrate Code	Substrate Type	Spawning Preference
1	Silt, Clay, or Organic	0.0
2	Sand	0.0
3	Small Gravel (0.1-0.5")	1.0
4	Med Gravel (0.5-1.5")	1.0
5	Large Gravel (1.5-3.0")	1.0
6	Small Cobble (3.0-6.0"	0.7
7	Large Cobble (6.0-12")	0.7
8	Boulder (>12")	0.0
9	Bedrock	0.0

Source: Table 14, Beecher and Caldwell 2022

Cutthroat Trout

General Approach

For Cutthroat Trout spawning and juvenile life stages, HSC curves from WDFW/Ecology (Type 3) and the ESH model (hybrid Type 1-2) were evaluated by the HSC Technical Group. It is WDFW/Ecology's preference to use the statewide Type 3 HSC curves when available unless additional site-specific field observation data is collected on the Skagit River in sufficient numbers to revisit, and possibly revise, the statewide curves. As a result, the recommended habitat modeling approach is to use the WDFW/Ecology Type 3 HSC curves for Cutthroat Trout life stages. Information specific to each life stage is provided below.

Spawning (Group C)

The WDFW/Ecology Type 3 HSC curves for Cutthroat Trout spawning are based on analysis from 7 studies and 123 redds [from the Irely (4 studies) and Skookum (3 studies) creeks] (Beecher and Caldwell 2022).

Adult (Group D)

WDFW/Ecology Type 3 HSC curves are not available for the Cutthroat Trout adult life stage and the ESH model curves are Type 2. Therefore, the HSC Technical Group recommended using the WDFW/Ecology Type 3 HSC curves for Cutthroat Trout juvenile (see below) to also represent the adult life stage.

Juvenile (Group C)

The WDFW/Ecology Type 3 HSC curves for Cutthroat Trout juvenile provided in Beecher and Caldwell 2022 were updated in 2021 and are now based on analysis from 11 studies and 518 fish observations [from the Ohanapecosh and Kachess rivers; Warm, Grade, Martin, Olson, Perry (2 studies), Skookum, Box Canyon, and Mineral creeks] (Beecher and Caldwell 2022, Granger 2021). The WDFW/Ecology Instream Flow Guidelines are in the process of being updated and the revised Cutthroat Trout juvenile HSC curves will be included in the updated 2022 report.

Fry (Group E)

Type 3 HSC curves are not available from WDFW/Ecology as the salmonid fry life stage is not commonly modeled in instream flow studies. However, habitat results for the fry life stage are of interest on the Skagit River in evaluating the relationship between flow and available habitat along the stream margins/shoreline areas as well as off-channel habitats that may be activated during higher flow events. As a result, the HSC Technical Group recommended using existing Type 2 fry curves when available. For Cutthroat Trout fry, the HSC Technical Group recommended using the existing Type 2 curves from the ESH model (Bovee 1978). Habitat cover preference information was not available from literature, so this physical attribute will be removed from the habitat modeling process (i.e., habitat model results will be based on depth, velocity, and substrate preferences).

Additional Notes

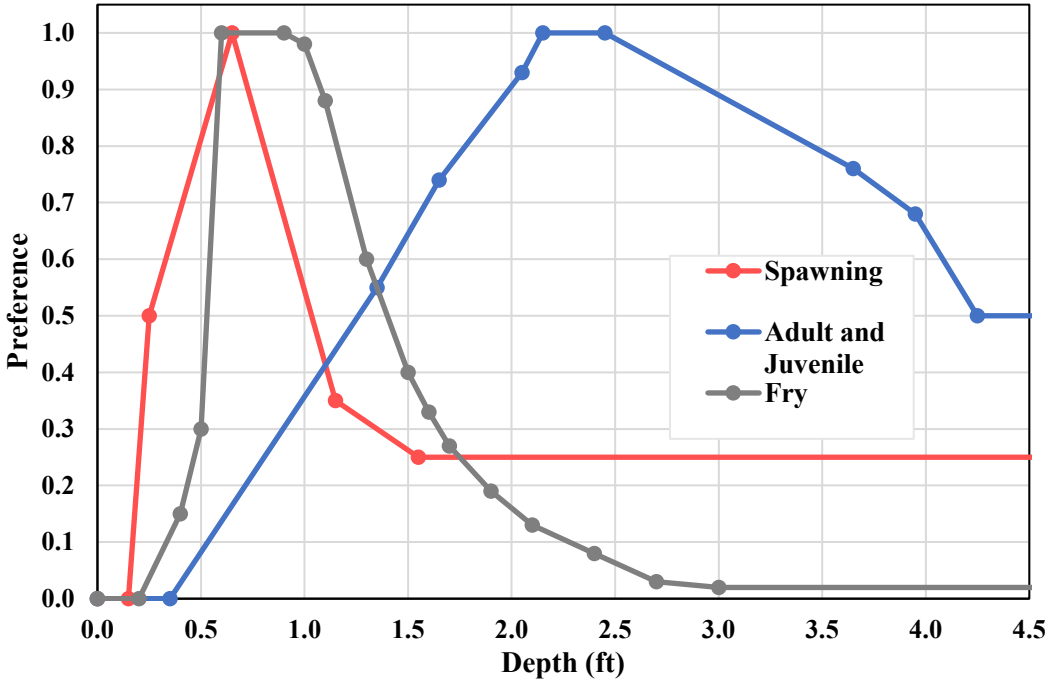
There is no clear biological evidence that depth becomes a limiting factor for spawning, adult, and juvenile Cutthroat Trout. Therefore, the HSC Technical Group recommended that once depth reaches 1.55 ft (0.25 preference) for spawning and 4.25 ft (0.50 preference) for adult and juvenile, it be considered "non-limiting" in the HSC depth curve.

References

WDFW/Ecology: spawning and adult (Beecher and Caldwell 2022); juvenile (Granger 2021 provisional data)
ESH model: spawning, adult, juvenile, and fry (Bovee 1978; Crumley and Stober 1984)
Additional sources of information:
Hickman and Raleigh 1982; Katopodis and Gervais 2016; Skookum Creek (Losee et al. 2016)

Cutthroat Trout

Depth Preference Curves



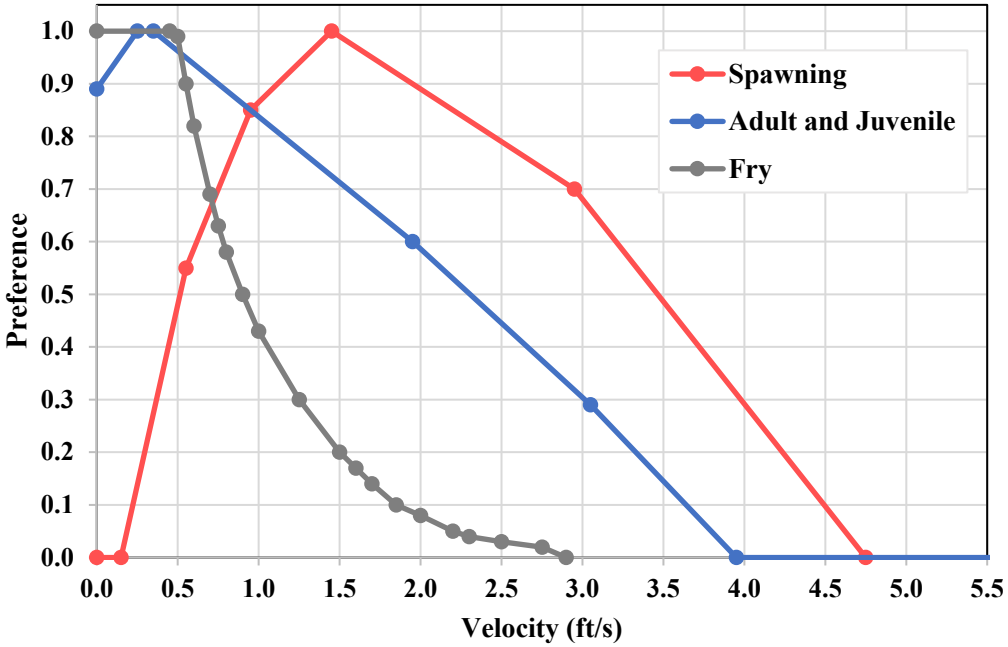
Spawning	
Depth (ft)	Preference
0.00	0.00
0.15	0.00
0.25	0.50
0.65	1.00
1.15	0.35
1.55	0.25
99.00	0.25

Adult and Juvenile	
Depth (ft)	Preference
0.00	0.00
0.35	0.00
1.35	0.55
1.65	0.74
2.05	0.93
2.15	1.00
2.45	1.00
3.65	0.76
3.95	0.68
4.25	0.50
99.00	0.50

Fry	
Depth (ft)	Preference
0.00	0.00
0.20	0.00
0.40	0.15
0.50	0.30
0.60	1.00
0.90	1.00
1.00	0.98
1.10	0.88
1.30	0.60
1.50	0.40
1.60	0.33
1.70	0.27
1.90	0.19
2.10	0.13
2.40	0.08
2.70	0.03
3.00	0.02
5.00	0.02
6.00	0.02
100.00	0.02

Cutthroat Trout

Velocity Preference Curves



Spawning	
Velocity (ft/s)	Preference
0.00	0.00
0.15	0.00
0.55	0.55
0.95	0.85
1.45	1.00
2.95	0.70
4.75	0.00

Adult and Juvenile	
Velocity (ft/s)	Preference
0.00	0.89
0.25	1.00
0.35	1.00
1.95	0.60
3.05	0.29
3.95	0.00
99.00	0.00

Fry	
Velocity (ft/s)	Preference
0.00	1.00
0.45	1.00
0.50	0.99
0.55	0.90
0.60	0.82
0.70	0.69
0.75	0.63
0.80	0.58
0.90	0.50
1.00	0.43
1.25	0.30
1.50	0.20
1.60	0.17
1.70	0.14
1.85	0.10
2.00	0.08
2.20	0.05
2.30	0.04
2.50	0.03
2.75	0.02
2.90	0.00

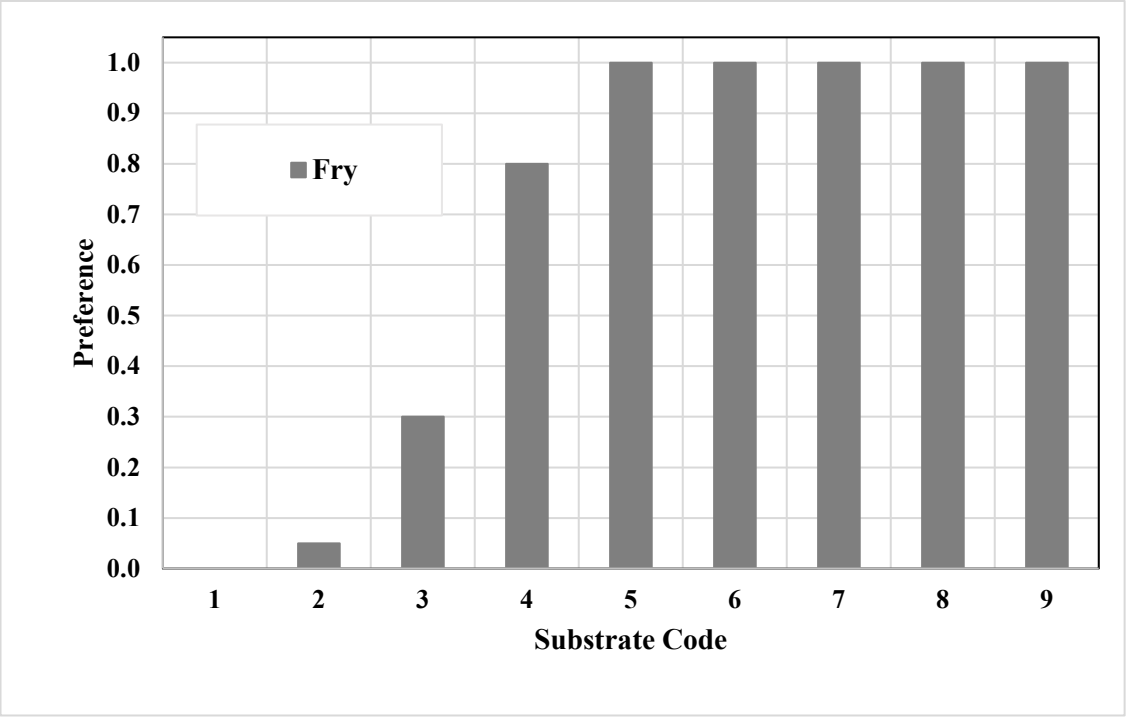
Cutthroat Trout

Substrate Preference Criteria

For Cutthroat Trout Spawning Substrate Preference, use Table 5 (Beecher and Caldwell 2022)
For Cutthroat Trout Adult and Juvenile Substrate and Cover Preference, use Table 3 (Beecher and Caldwell 2022)
For Cutthroat Trout Fry Substrate Preference, use data from the ESH Model

Cutthroat Trout

Substrate Preference

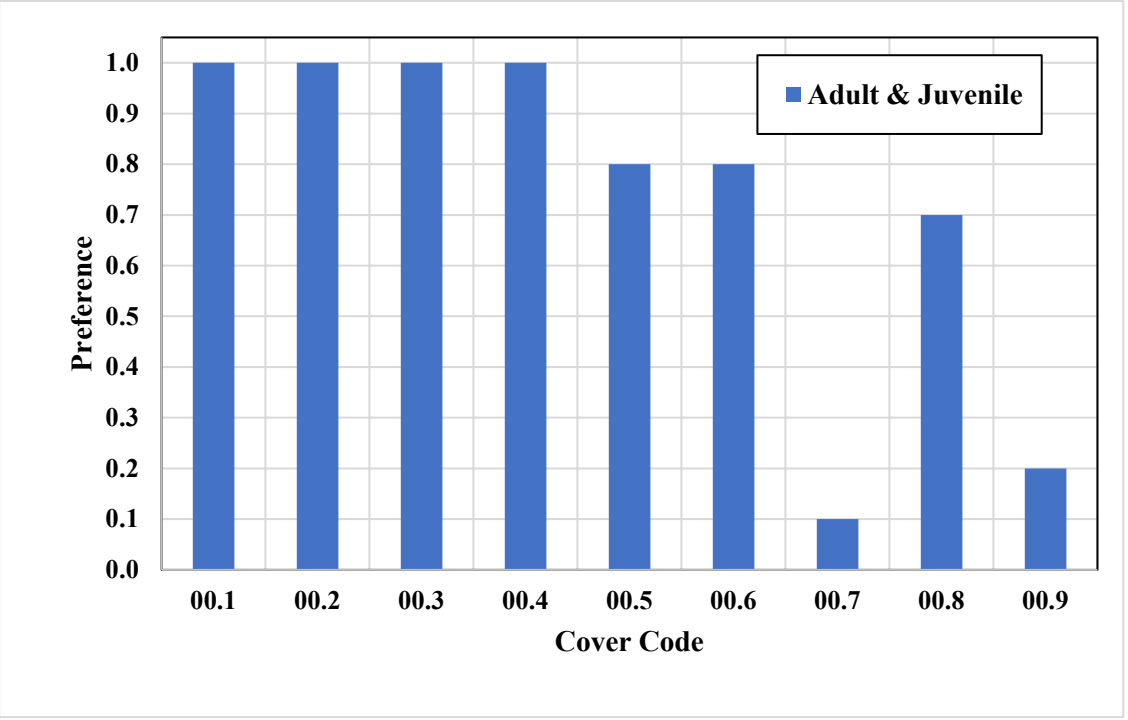


Sustrate Code	Substrate Type	Fry Preference
1	Silt, Clay, or Organic	0.00
2	Sand	0.05
3	Small Gravel (0.1-0.5")	0.30
4	Med Gravel (0.5-1.5")	0.80
5	Large Gravel (1.5-3.0")	1.00
6	Small Cobble (3.0-6.0")	1.00
7	Large Cobble (6.0-12")	1.00
8	Boulder (>12")	1.00
9	Bedrock	1.00

Source: ESH Model

Cutthroat Trout

Cover Preference



Code	Type of Cover Note: Cover Codes are not used for Spawning life stage	Adult & Juvenile Preference
00.1	Undercut bank	1.00
00.2	Overhanging vegetation near or touching water	1.00
00.3	Rootwad (including parly undercut)	1.00
00.4	Log jam/submerged brush pile	1.00
00.5	Log(s) parallel to bank	0.80
00.6	Aquatic vegetation	0.80
00.7	Short (<1 ft) terrestrial grass	0.10
00.8	Tall (>3 ft) dense grass	0.70
00.9	Vegetation >3 vertical ft above SZF	0.20

Source: Table 3, Beecher and Caldwell 2022

Sea-Run Cutthroat Trout

Spawning (Group D)

For Sea-run Cutthroat Trout, HSC curves from several sources were evaluated by the HSC Technical Group including WDFW/Ecology curves for Cutthroat Trout spawning (Type 3; 66 redds), curves used in the ESH model (hybrid Type 1-2), and Skookum Creek, WA (Losee et al. 2016). While it is WDFW/Ecology's preference to use statewide Type 3 HSC curves when available, for Sea-run Cutthroat Trout, the HSC Technical Group developed proposed consensus curves that basically envelop the WDFW/Ecology Type 3 curve for Cutthroat Trout spawning, but with a little widening of the peak preference range for both the depth and velocity HSC curves.

Additional Notes

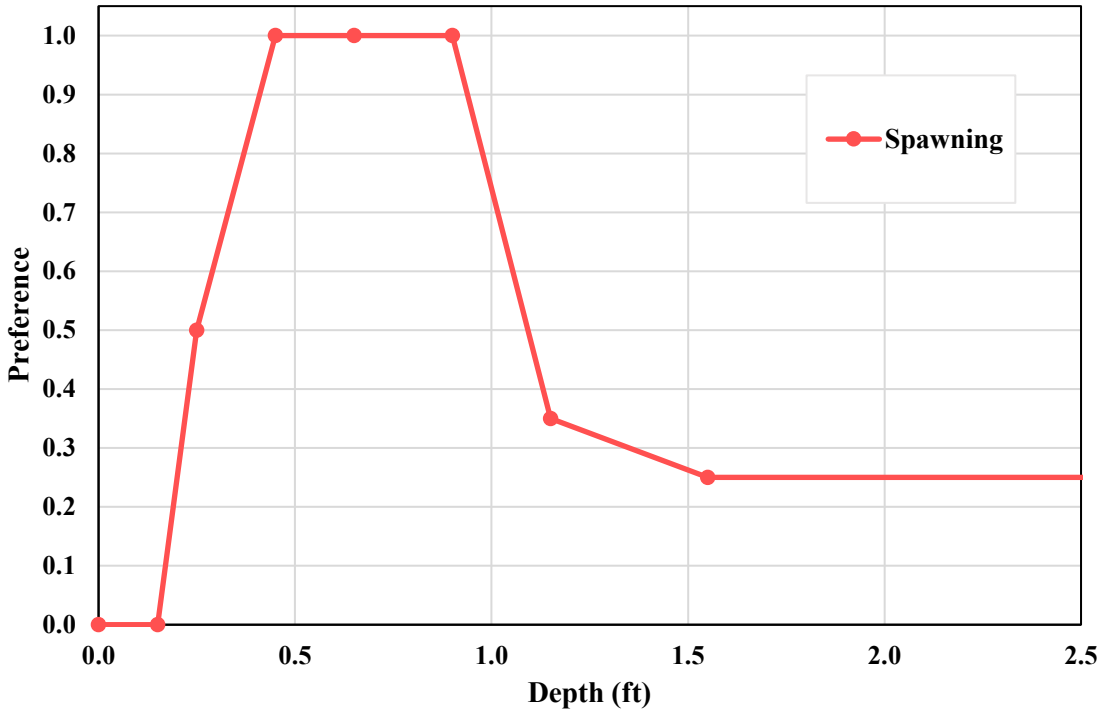
There is no clear biological evidence that depth becomes a limiting factor for spawning Sea-run Cutthroat Trout. Therefore, the HSC Technical Group recommended that once depth reaches 1.55 ft (0.25 preference), it be considered "non-limiting" in the HSC depth curve.

References

WDFW/Ecology: spawning (Beecher and Caldwell 2022)
ESH model: spawning (Crumley and Stober 1984)
Additional sources of information:
Skookum Creek (Losee et al. 2016)
(Hickman and Raleigh 1982)
(Katopodis and Gervais 2016)

Sea-Run Cutthroat Trout

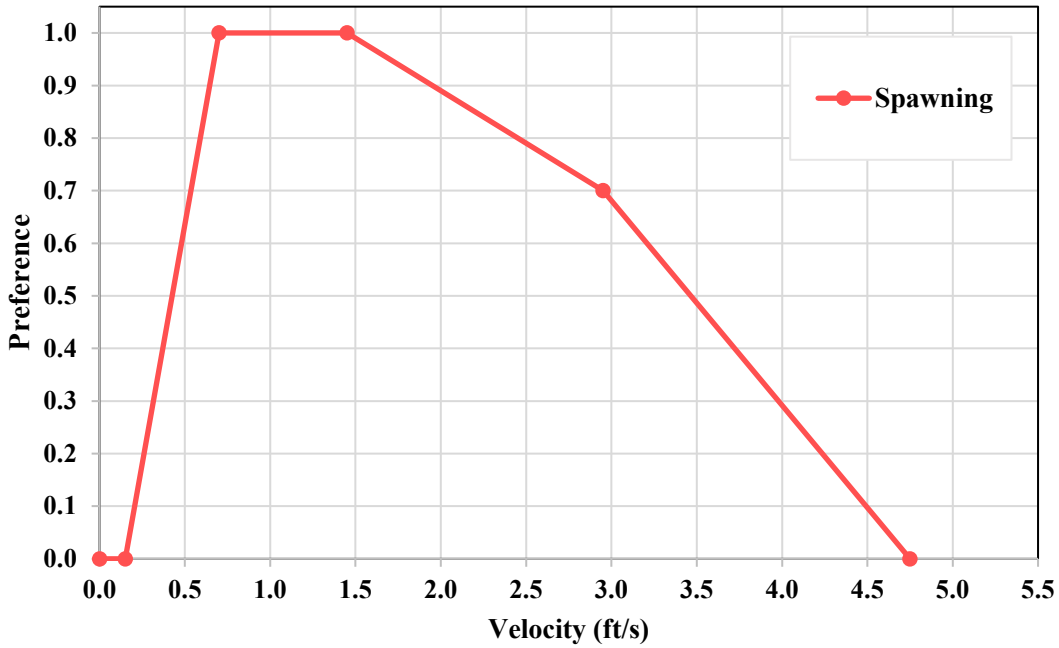
Depth Preference Curves



Spawning	
Depth (ft)	Preference
0.00	0.00
0.15	0.00
0.25	0.50
0.45	1.00
0.65	1.00
0.90	1.00
1.15	0.35
1.55	0.25
99	0.25

Sea-Run Cutthroat Trout

Velocity Preference Curves



Spawning	
Velocity (ft/s)	Preference
0.00	0.00
0.15	0.00
0.70	1.00
1.45	1.00
2.95	0.70
4.75	0.00

Substrate Preference Criteria

For Sea-Run Cutthorat Trout Spawning Substrate Preference, use Table 5 (Beecher and Caldwell 2022)

Mountain Whitefish

General Approach

For Mountain Whitefish spawning, adult, and juvenile life stages, HSC curves from WDFW/Ecology (Type 3), the ESH model (hybrid Type 1-2), and the Fraser River (Type 2, juvenile only) were evaluated by the HSC Technical Group. It is WDFW/Ecology's preference to use the statewide Type 3 HSC curves when available unless additional site-specific field observation data is collected on the Skagit River in sufficient numbers to revisit, and possibly revise, the statewide curves. As a result, the recommended habitat modeling approach is to use the WDFW/Ecology Type 3 HSC curves for all three Mountain Whitefish life stages. Information specific to each life stage is provided below.

Spawning (Group C)

The WDFW/Ecology Type 3 HSC curves for Mountain Whitefish spawning are based on a composite of 8 Canadian studies totaling 3,789 fish observations [from the Oldman, Bow, Sheep, Kananaskis, Red Deer (2), and Highwood rivers] (Beecher and Caldwell 2022).

Adult Rearing (Group C)

The WDFW/Ecology Type 3 HSC curves for Mountain Whitefish adult rearing are based on a composite of 8 Canadian studies totaling 1,616 fish observations [from the Oldman, Bow, Sheep, Kananaskis, Red Deer (2 studies), Highwood, and Fraser rivers] (Beecher and Caldwell 2022).

Juvenile (Group C)

The WDFW/Ecology Type 3 HSC curves for Mountain Whitefish juvenile are based on a composite of 6 Canadian studies totaling 2,306 fish observations (from the Oldman, Bow, Kananaskis, Red Deer, Highwood, and Fraser rivers) (Beecher and Caldwell 2022).

Fry (Group E)

Type 3 HSC curves are not available from WDFW/Ecology as the salmonid fry life stage is not commonly modeled in instream flow studies. However, habitat results for the fry life stage are of interest on the Skagit River in evaluating the relationship between flow and available habitat along the stream margins/shoreline areas as well as off-channel habitats that may be activated during higher flow events. As a result, the HSC Technical Group recommended using existing Type 2 fry curves when available. For Mountain Whitefish fry, the HSC Technical Group reviewed existing Type 2 curves used in the ESH model (Bovee 1978) as well as the Fraser River with a recommendation to use the ESH model curves for habitat modeling purposes. Habitat cover preference information was not available from literature, so this physical attribute will be removed from the habitat modeling process (i.e., habitat model results will be based on depth, velocity, and substrate preferences).

Additional Notes

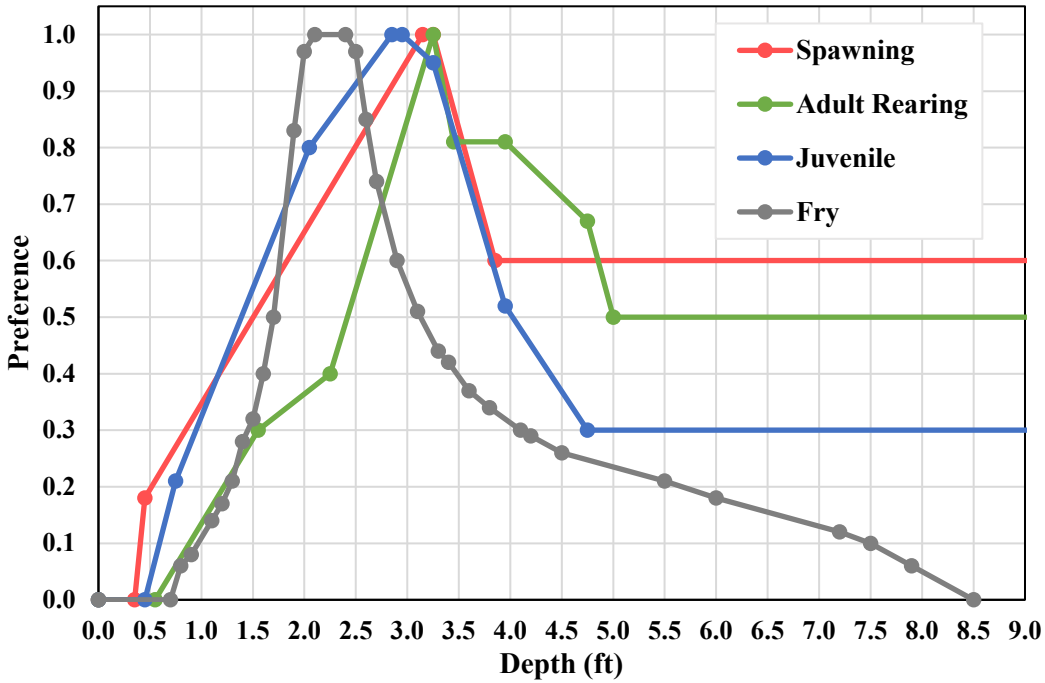
There is no clear biological evidence that depth becomes a limiting factor for spawning, adult rearing, and juvenile Mountain Whitefish. Therefore, the HSC Technical Group recommended that once depth reaches 3.85 ft for spawning (0.60 preference), 5.0 ft (0.50 preference) for adult rearing, and 4.75 ft (0.30 preference) for juvenile, it be considered "non-limiting" in the HSC depth curves.

References

WDFW/Ecology: spawning, adult rearing, and juvenile (Beecher and Caldwell 2022)
ESH model: spawning and fry (Bovee 1978); adult and juvenile (Bovee 1978; Crumley and Stober 1984)
Fraser River: juvenile and fry (Rempel et al. 2012)

Mountain Whitefish

Depth Preference Curves



Spawning	
Depth (ft)	Preference
0.00	0.00
0.35	0.00
0.45	0.18
3.15	1.00
3.25	1.00
3.85	0.60
99.00	0.60

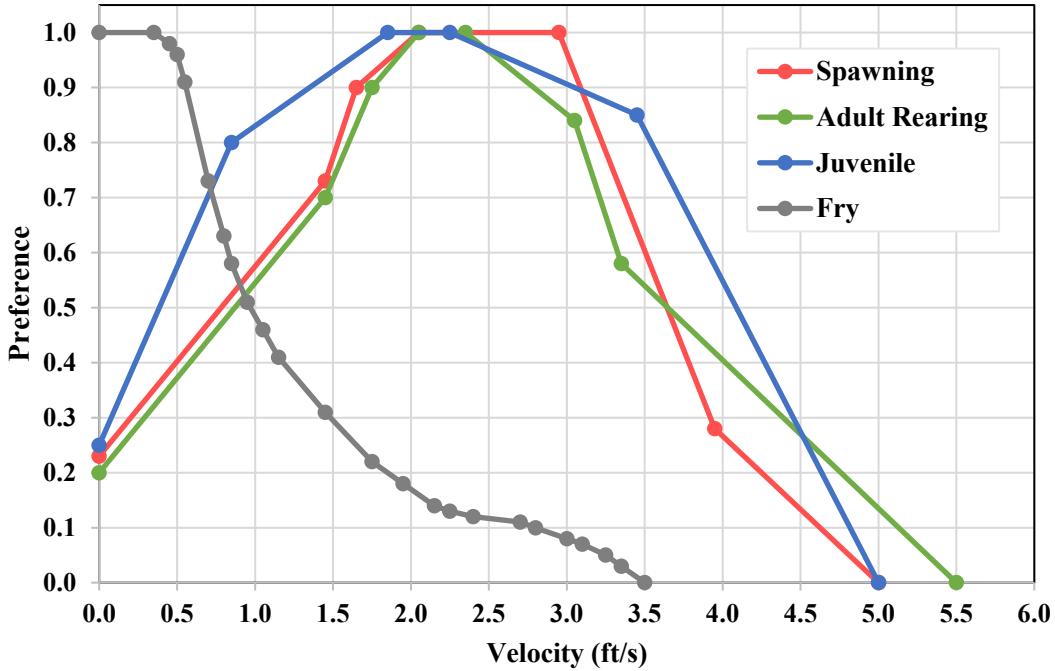
Adult Rearing	
Depth (ft)	Preference
0.00	0.00
0.55	0.00
1.55	0.30
2.25	0.40
3.25	1.00
3.45	0.81
3.95	0.81
4.75	0.67
5.00	0.50
99.00	0.50

Juvenile	
Depth (ft)	Preference
0.00	0.00
0.45	0.00
0.75	0.21
2.05	0.80
2.85	1.00
2.95	1.00
3.25	0.95
3.95	0.52
4.75	0.30
99.00	0.30

Fry	
Depth (ft)	Preference
0.00	0.00
0.70	0.00
0.80	0.06
0.90	0.08
1.10	0.14
1.20	0.17
1.30	0.21
1.40	0.28
1.50	0.32
1.60	0.40
1.70	0.50
1.90	0.83
2.00	0.97
2.10	1.00
2.40	1.00
2.50	0.97
2.60	0.85
2.70	0.74
2.90	0.60
3.10	0.51
3.30	0.44
3.40	0.42
3.60	0.37
3.80	0.34
4.10	0.30
4.20	0.29
4.50	0.26
5.50	0.21
6.00	0.18
7.20	0.12
7.50	0.10
7.90	0.06
8.50	0.00

Mountain Whitefish

Velocity Preference Curves



Spawning	
Velocity (ft/s)	Preference
0.00	0.23
1.45	0.73
1.65	0.90
2.05	1.00
2.95	1.00
3.95	0.28
5.00	0.00

Adult Rearing	
Velocity (ft/s)	Preference
0.00	0.20
1.45	0.70
1.75	0.90
2.05	1.00
2.35	1.00
3.05	0.84
3.35	0.58
5.50	0.00

Juvenile	
Velocity (ft/s)	Preference
0.00	0.25
0.85	0.80
1.85	1.00
2.25	1.00
3.45	0.85
5.00	0.00

Fry	
Velocity (ft/s)	Preference
0.00	1.00
0.35	1.00
0.45	0.98
0.50	0.96
0.55	0.91
0.70	0.73
0.80	0.63
0.85	0.58
0.95	0.51
1.05	0.46
1.15	0.41
1.45	0.31
1.75	0.22
1.95	0.18
2.15	0.14
2.25	0.13
2.40	0.12
2.70	0.11
2.80	0.10
3.00	0.08
3.10	0.07
3.25	0.05
3.35	0.03
3.50	0.00

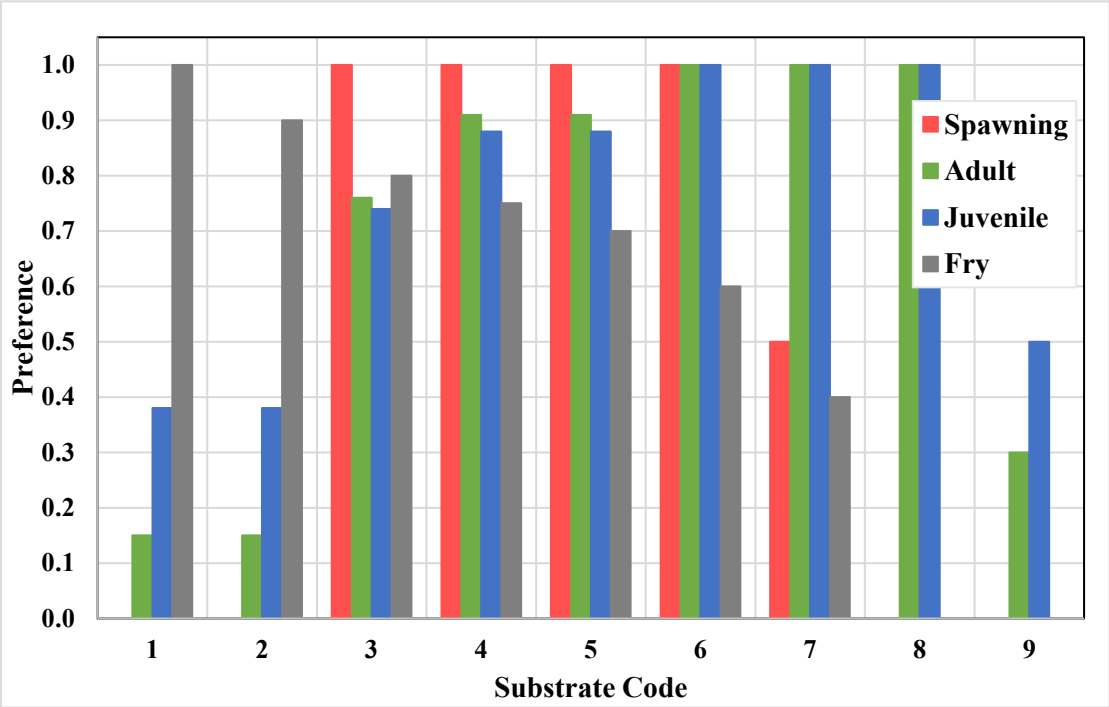
Mountain Whitefish

Substrate Preference Criteria

For Mountain Whitefish Spawning Substrate Preference, use Table 7 (Beecher and Caldwell 2022)
For Mountain Whitefish Adult Rearing Substrate Preference, use Table 8 (Beecher and Caldwell 2022)
For Mountain Whitefish Juvenile Substrate Preference, use Table 9 (Beecher and Caldwell 2022)
For Mountain Whitefish Fry Substrate Preference, use data from the ESH Model

Mountain Whitefish

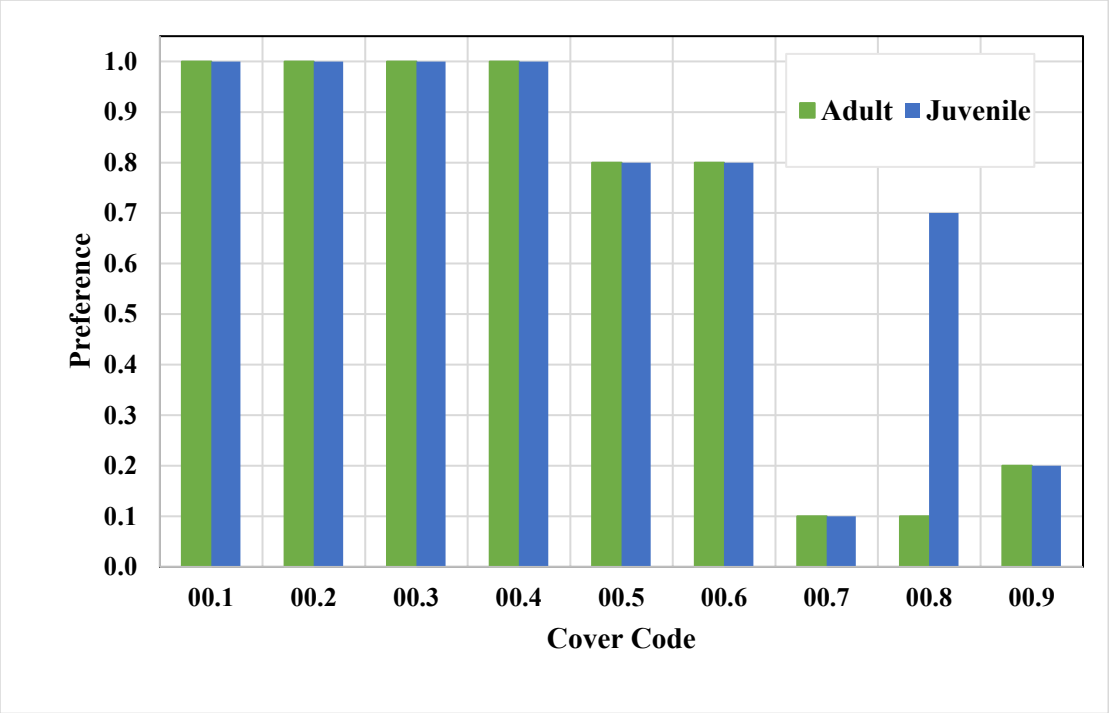
Substrate Preference



Sustrate Code	Substrate Type	Spawning	Adult	Juvenile	Fry
1	Silt, Clay, or Organic	0.00	0.15	0.38	1.00
2	Sand	0.00	0.15	0.38	0.90
3	Small Gravel (0.1-0.5")	1.00	0.76	0.74	0.80
4	Med Gravel (0.5-1.5")	1.00	0.91	0.88	0.75
5	Large Gravel (1.5-3.0")	1.00	0.91	0.88	0.70
6	Small Cobble (3.0-6.0")	1.00	1.00	1.00	0.60
7	Large Cobble (6.0-12")	0.50	1.00	1.00	0.40
8	Boulder (>12")	0.00	1.00	1.00	0.00
9	Bedrock	0.00	0.30	0.50	0.00
Source: Beecher and Caldwell 2022		Table 15	Table 16	Table 17	ESH Model

Mountain Whitefish

Cover Preference



Code	Type of Cover Note: Cover Codes are not used for Spawning life stage	Adult Preference	Juvenile Preference
00.1	Undercut bank	1.00	1.00
00.2	Overhanging vegetation near or touching water	1.00	1.00
00.3	Rootwad (including parly undercut)	1.00	1.00
00.4	Log jam/submerged brush pile	1.00	1.00
00.5	Log(s) parallel to bank	0.80	0.80
00.6	Aquatic vegetation	0.80	0.80
00.7	Short (<1 ft) terrestrial grass	0.10	0.10
00.8	Tall (>3 ft) dense grass	0.10	0.70
00.9	Vegetation >3 vertical ft above SZF	0.20	0.20

Source: Table 1, Beecher and Caldwell 2022

Pacific Lamprey

Spawning (Group D)

WDFW/Ecology HSC curves are not available and Pacific Lamprey HSC curves are not included in the ESH model. The HSC Technical Group reviewed HSC curves from other studies and developed proposed consensus curves using that information. The proposed consensus curves envelop depth and velocity preferences from studies on the Lower Merced and Chehalis Rivers and Vadas 2021 literature with a recommended extension of suboptimal preference (i.e., preference = 0.5) depth to 7 ft made by Ralph Lampman (a lamprey research biologist at Yakama Nation Fisheries in Prosser, WA).

Juvenile Rearing (Group D)

WDFW/Ecology HSC curves are not available and Pacific Lamprey HSC curves are not included in the ESH model. The HSC Technical Group reviewed HSC curves from other studies and developed proposed consensus curves using that information. The proposed consensus curves envelop depth and velocity preferences from studies on the Chehalis River (Winkowksi and Kendall 2018) and Vadas 2021 literature. Note due to uncertainty about maximum depth and velocity preferences, both HSC curves have been extended to infinity at a preference of 0.1.

Additional Notes

There is no clear biological evidence that depth becomes a limiting factor for spawning and juvenile rearing Pacific Lamprey. Therefore, the HSC Technical Group recommended that once depth reaches 9.0 ft for spawning (0.10 preference) and 5.0 ft (0.10 preference) for juvenile rearing, it be considered "non-limiting" in the HSC depth curves.

Habitat cover preference information for Pacific Lamprey was not available from literature, so this physical attribute will be removed from the habitat modeling process (i.e., habitat model results will be based on depth, velocity, and substrate preferences).

References

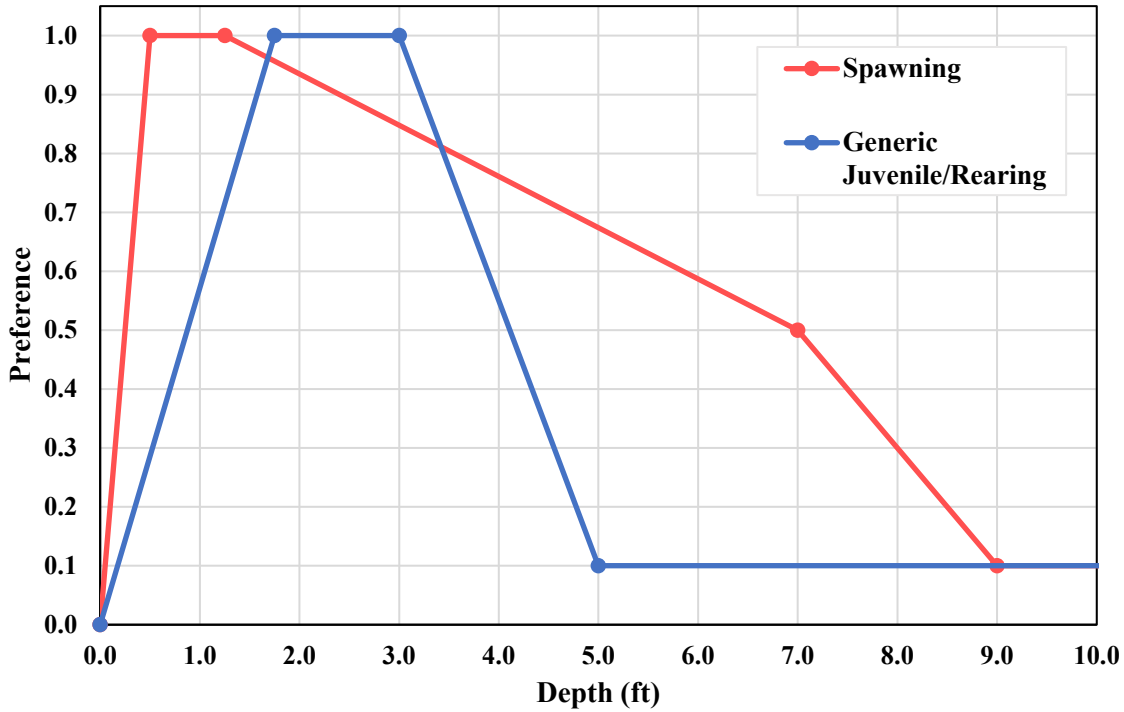
West-coast lamprey species based on literature review of West Fork Hoquiam River, Chehalis River basin and Trapp Creek, Washington and Nichola/coastal Salmon River, British Columbia (Vadas 2000, 2013, and 2021)

Chehalis River, Washington (Winkowski and Kendall 2018)

Additional data source:
Smith River, Oregon (Gunckel et al. 2006)

Pacific Lamprey

Depth Preference Curves

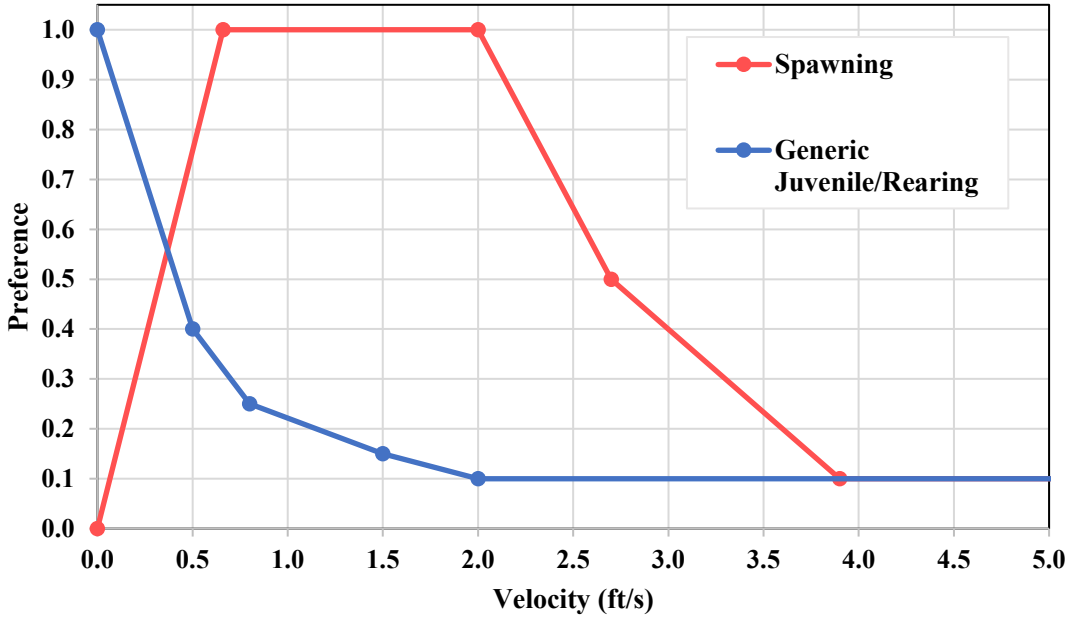


Spawning	
Depth (ft)	Preference
0.00	0.00
0.50	1.00
1.25	1.00
7.00	0.50
9.00	0.10
99.00	0.10

Generic	
Depth (ft)	Preference
0.00	0.00
1.75	1.00
3.00	1.00
5.00	0.10
99.00	0.10

Pacific Lamprey

Velocity Preference Curves

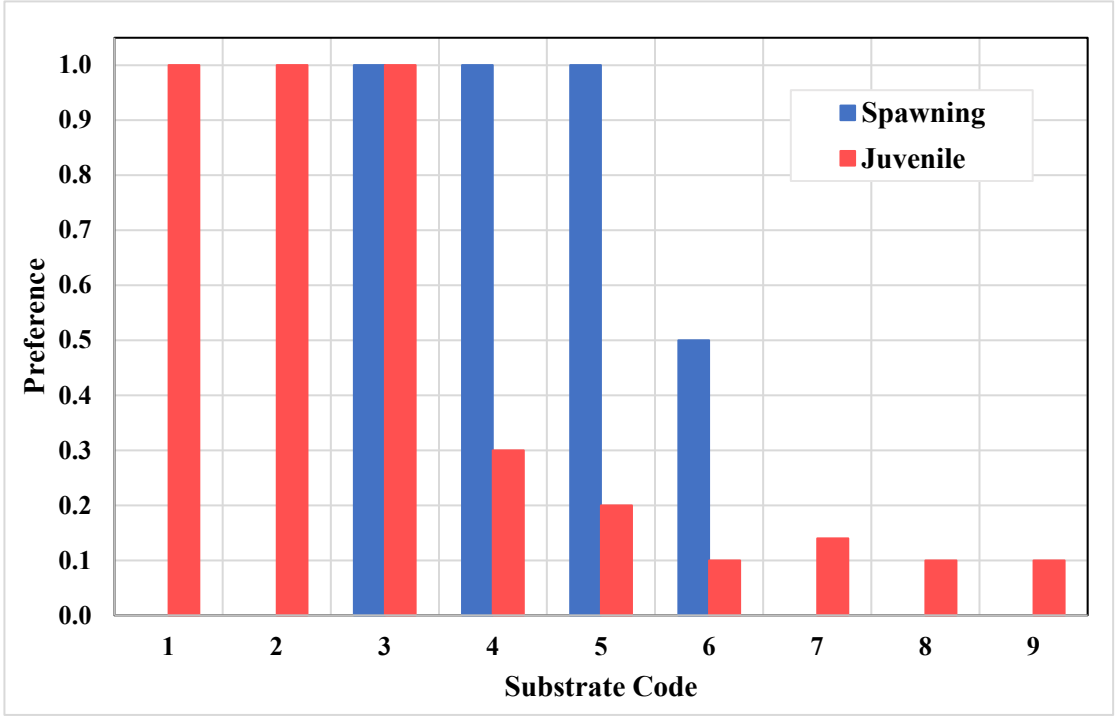


Spawning	
Velocity (ft/s)	Preference
0.00	0.00
0.66	1.00
2.00	1.00
2.70	0.50
3.90	0.10
99.00	0.10

Generic	
Velocity (ft/s)	Preference
0.00	1.00
0.50	0.40
0.80	0.25
1.50	0.15
2.00	0.10
99.00	0.10

Pacific Lamprey

Substrate Preference



Sustrate Code	Substrate Type	Spawning Preference	Juvenile Preference
1	Silt, Clay, or Organic	0.0	1.0
2	Sand	0.0	1.0
3	Small Gravel (0.1-0.5")	1.0	1.0
4	Med Gravel (0.5-1.5")	1.0	0.3
5	Large Gravel (1.5-3.0")	1.0	0.2
6	Small Cobble (3.0-6.0")	0.5	0.1
7	Large Cobble (6.0-12")	0.0	0.1
8	Boulder (>12")	0.0	0.1
9	Bedrock	0.0	0.1

Source: Vadas 2021

Western Brook & Western River Lamprey

Western Brook Lamprey Spawning (Group F)

WDFW/Ecology HSC curves are not available and Western Brook Lamprey HSC curves are not included in the ESH model. The HSC Technical Group reviewed HSC curves from other studies and developed proposed consensus curves using that information. The proposed consensus curve is based on research and literature review by Vadas (2000, 2013, and 2021) which includes data from the West Fork Hoquiam River, WA; Nichola/coastal Salmon River, BC; Trapp Creek, WA, and Chehalis River basin, WA.

Western River Lamprey Spawning (Group F)

WDFW/Ecology HSC curves are not available and Western River Lamprey HSC curves are not included in the ESH model. The HSC Technical Group reviewed HSC curves from other studies and developed proposed consensus curves using that information. The proposed consensus curve is based on Vadas 2021 which includes data from the West Fork Hoquiam River, WA; Nichola/coastal Salmon River, BC; Trapp Creek, WA, and Chehalis River basin, WA.

Additional Notes

There is no clear biological evidence that depth becomes a limiting factor for spawning Western Brook Lamprey and Western River Lamprey. Therefore, the HSC Technical Group recommended that once depth reaches 1.40 ft for Western Brooke Lamprey (0.10 preference) and 1.80 ft (0.10 preference) for Western River Lamprey, it be considered "non-limiting" in the HSC depth curves.

Habitat cover preference information for Western Brook Lamprey and Western River Lamprey was not available from literature, so this physical attribute will be removed from the habitat modeling process (i.e., habitat model results will be based on depth, velocity, and substrate preferences).

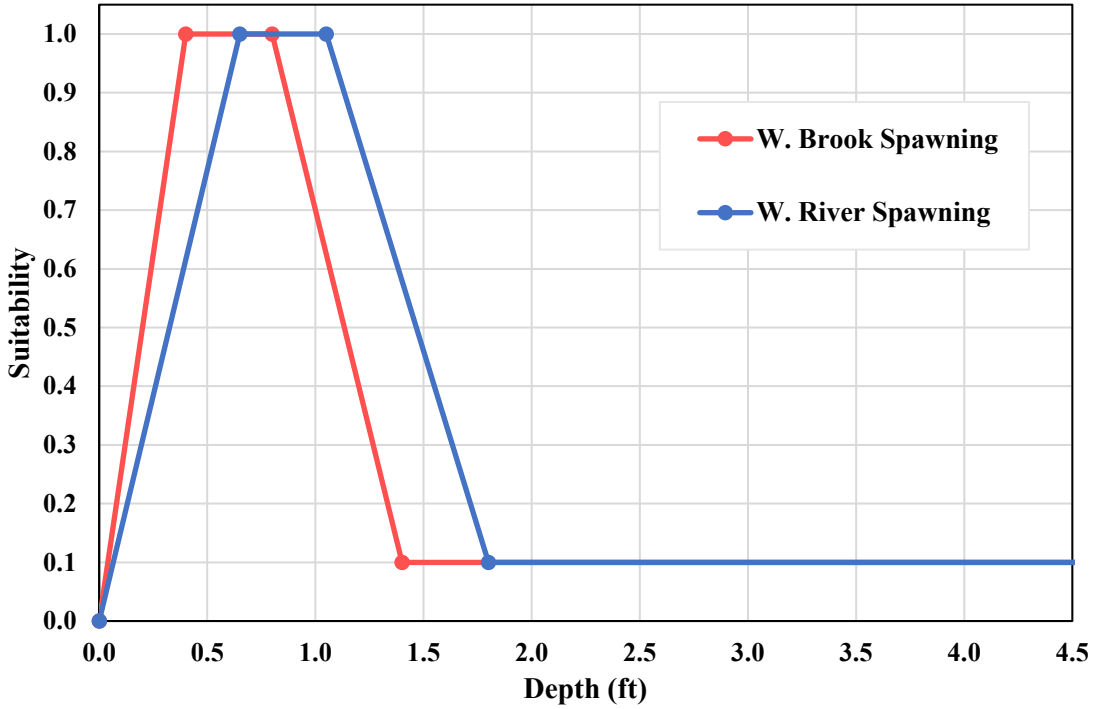
References

West-coast lamprey species based on literature review of West Fork Hoquiam River, Chehalis River basin and Trapp Creek, Washington and Nichola/coastal Salmon River, British Columbia (Vadas 2000, 2013, and 2021)

Additional data source:
(Gunckel et al. 2006)

Western Brook & Western River Lamprey

Depth Preference Curves

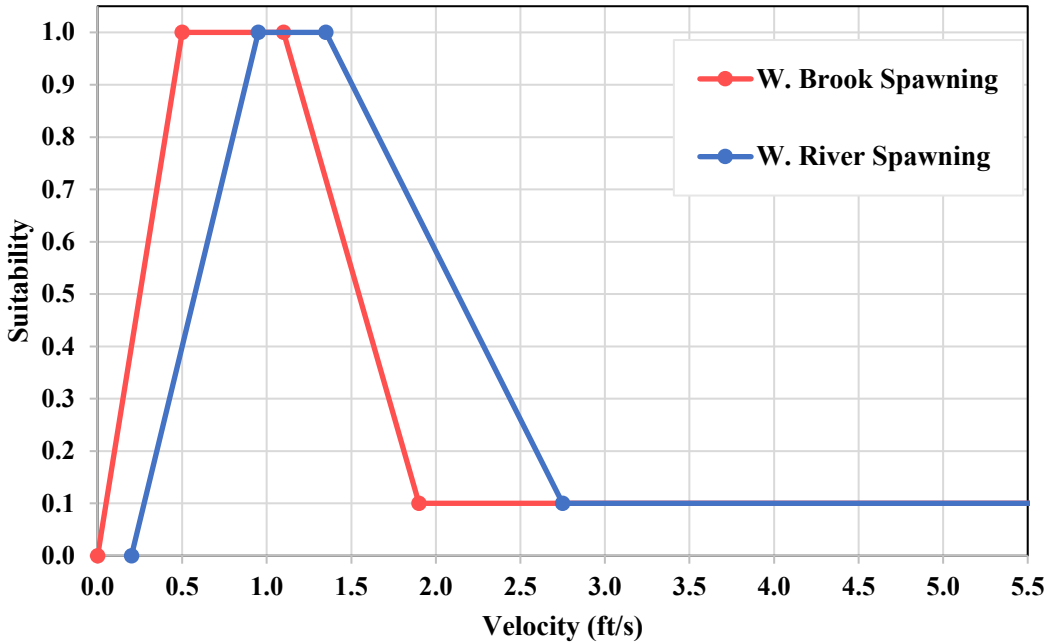


W. Brook Spawning	
Depth (ft)	Preference
0.00	0.00
0.40	1.00
0.80	1.00
1.40	0.10
99.00	0.10

W. River Spawning	
Depth (ft)	Preference
0.00	0.00
0.65	1.00
1.05	1.00
1.80	0.10
99.00	0.10

Western Brook & Western River Lamprey

Velocity Preference Curves

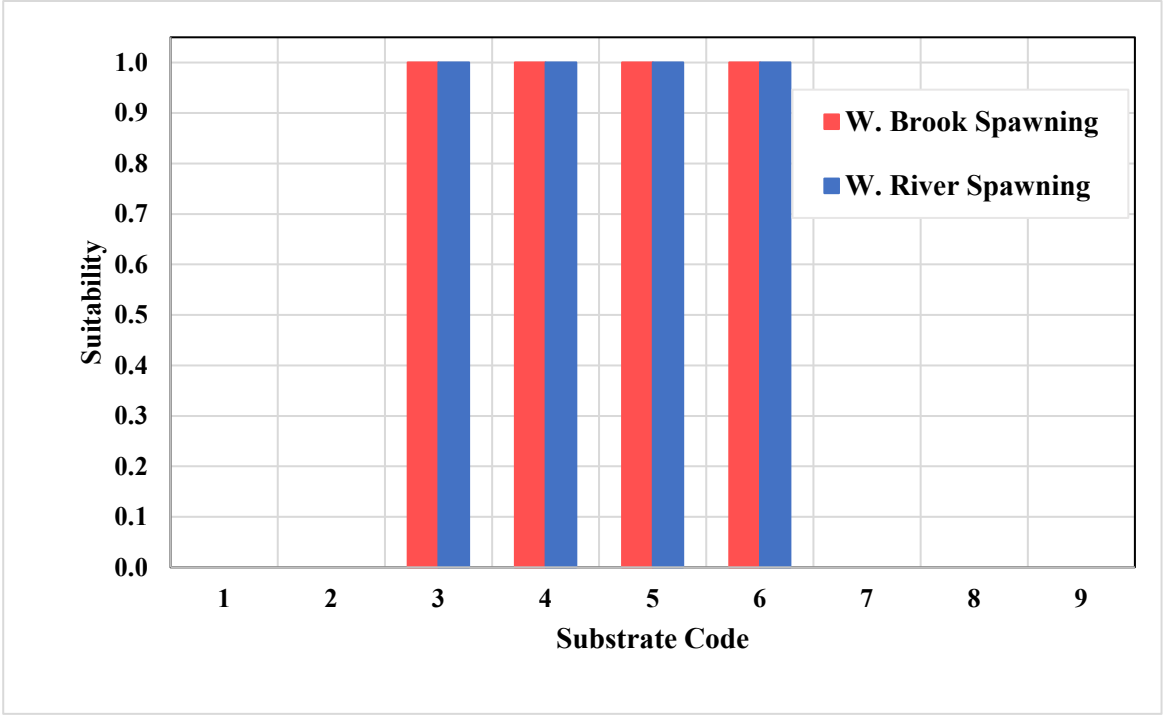


W. Brook Spawning	
Velocity (ft/s)	Preference
0.00	0.00
0.50	1.00
1.10	1.00
1.90	0.10
99.00	0.10

W. River Spawning	
Velocity (ft/s)	Preference
0.20	0.00
0.95	1.00
1.35	1.00
2.75	0.10
99.00	0.10

Western Brook & Western River Lamprey

Substrate Preference Criteria



Sustrate Code	Substrate Type	W. Brook Preference	W. River Preference
1	Silt, Clay, or Organic	0.0	0.0
2	Sand	0.0	0.0
3	Small Gravel (0.1-0.5")	1.0	1.0
4	Med Gravel (0.5-1.5")	1.0	1.0
5	Large Gravel (1.5-3.0")	1.0	1.0
6	Small Cobble (3.0-6.0")	1.0	1.0
7	Large Cobble (6.0-12")	0.0	0.0
8	Boulder (>12")	0.0	0.0
9	Bedrock	0.0	0.0

Source: Vadas 2021

Salish Sucker

Spawning (Group F)

WDFW/Ecology HSC curves are not available and Salish Sucker spawning HSC curves are not included in the ESH model. The HSC Technical Group reviewed literature and HSC data from several sources in Washington State and western Canada (see references cited below). The proposed consensus curves are largely based on research performed by Pearson et al. (2000 and 2003) with a slightly broader peak depth preference that extends an additional 0.5 ft from 2.0 ft to 2.5 ft and a slightly broader peak velocity preference that extends an additional 0.35 ft/s from 1.65 ft/s to 2.0 ft/s.

Juvenile Rearing (Group F)

WDFW/Ecology HSC curves are not available and Salish Sucker juvenile rearing HSC curves are not included in the ESH model. The HSC Technical Group reviewed literature and HSC data from several sources in Washington State and western Canada (see references cited below). The proposed consensus curves are largely based on research performed by Pearson et al. (2000 and 2003) with a slightly broader peak depth preference range and slightly extended sub-optimal velocity preference range.

Additional Notes

There is no clear biological evidence that depth becomes a limiting factor for juvenile rearing Salish Sucker. Therefore, the HSC Technical Group recommended that once depth reaches 3.0 ft (0.50 preference) for juvenile rearing, it be considered "non-limiting" in the HSC depth curves.

Habitat cover preference information for Salish Sucker spawning life stage was not available from literature, so this physical attribute will be removed from the habitat modeling process (i.e., habitat model results will be based on depth, velocity, and substrate preferences).

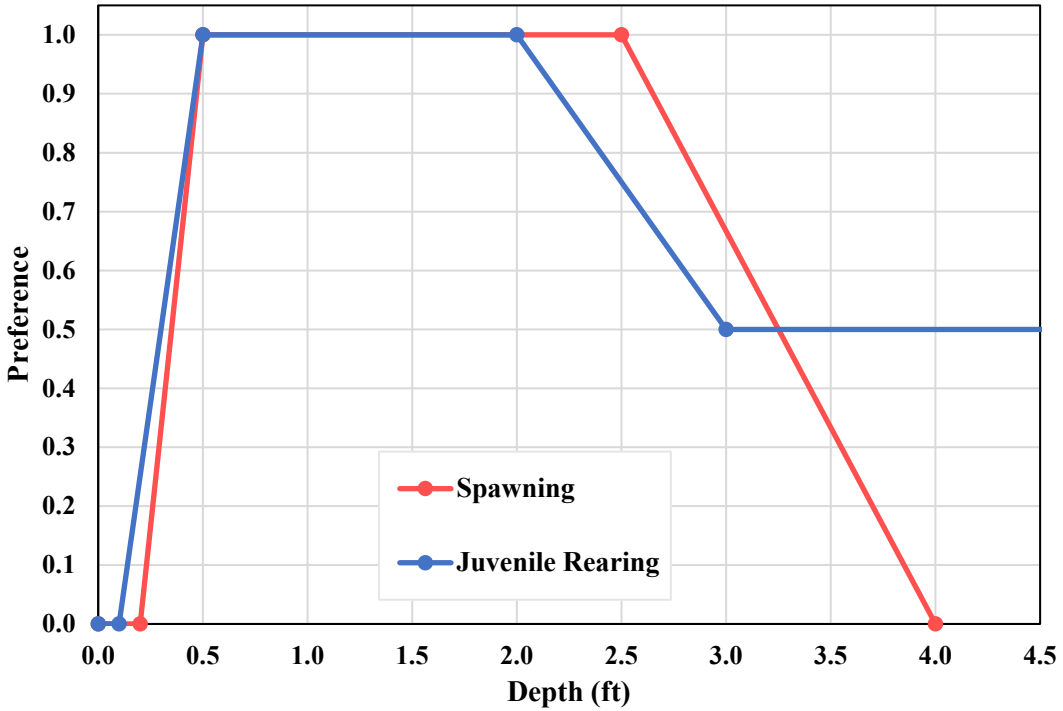
References

Consensus HSC curves: (Pearson et al. 2000 and 2003)

Additional sources of information:
COSEWIC 2012
McPhail 1986
Washington Department of Fish and Wildlife 2015

Salish Sucker

Depth Preference Curves

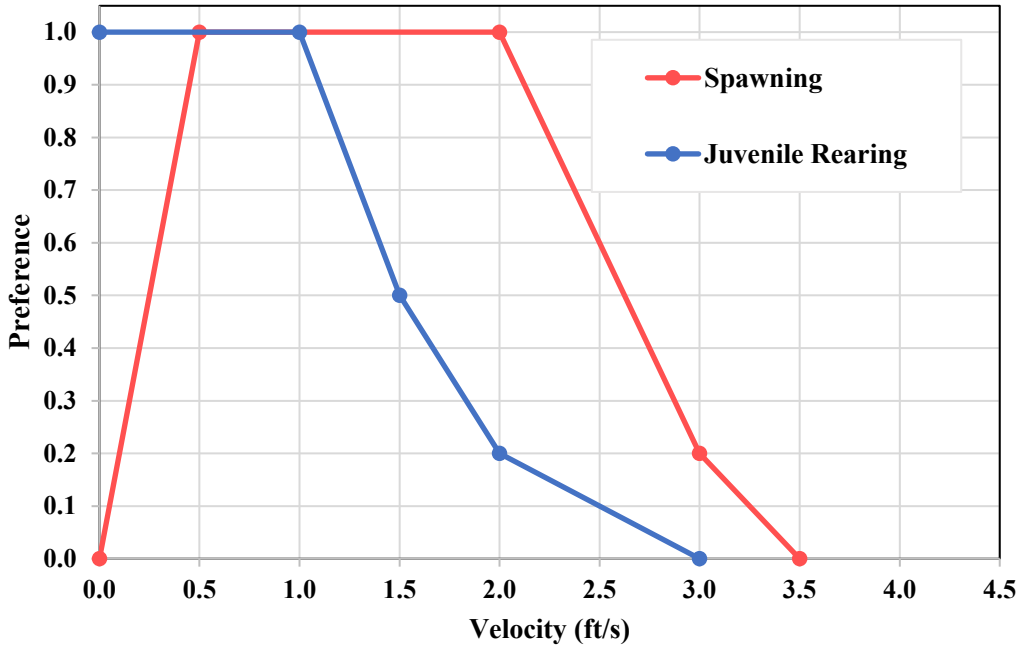


Spawning	
Depth (ft)	Preference
0.00	0.00
0.20	0.00
0.50	1.00
2.50	1.00
4.00	0.00

Juvenile Rearing	
Depth (ft)	Preference
0.00	0.00
0.10	0.00
0.50	1.00
2.00	1.00
3.00	0.50
99.00	0.50

Salish Sucker

Velocity Preference Curves

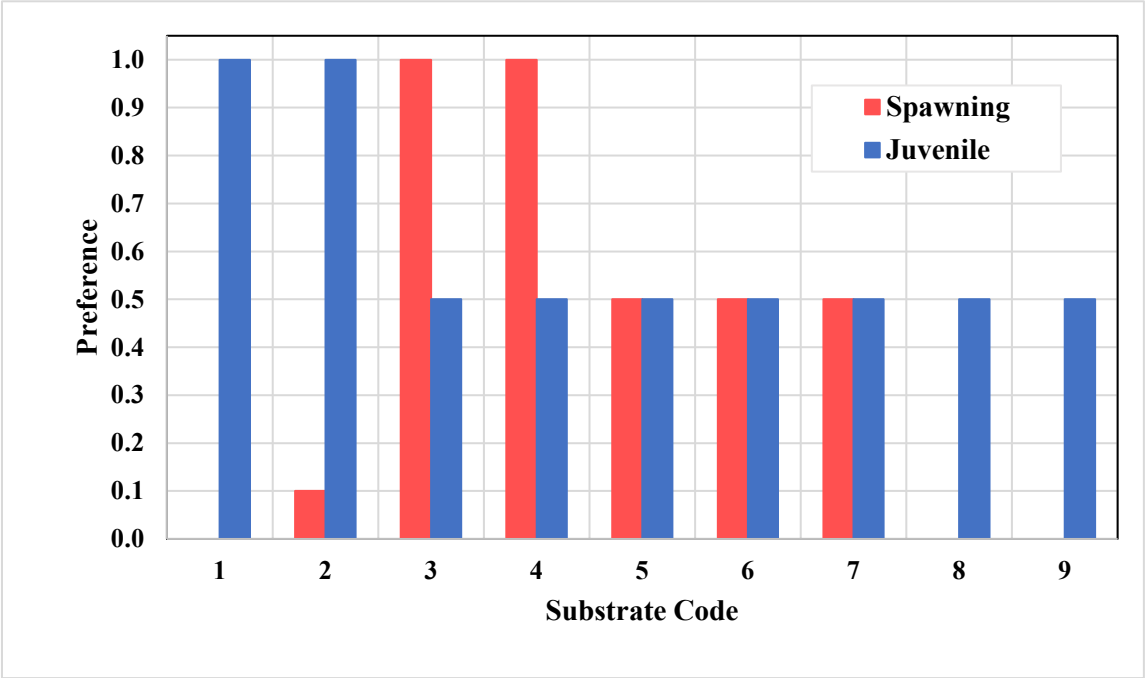


Spawning	
Velocity (ft/s)	Preference
0.00	0.00
0.50	1.00
2.00	1.00
3.00	0.20
3.50	0.00

Juvenile Rearing	
Velocity (ft/s)	Preference
0.00	1.00
1.00	1.00
1.50	0.50
2.00	0.20
3.00	0.00

Salish Sucker

Substrate Preference

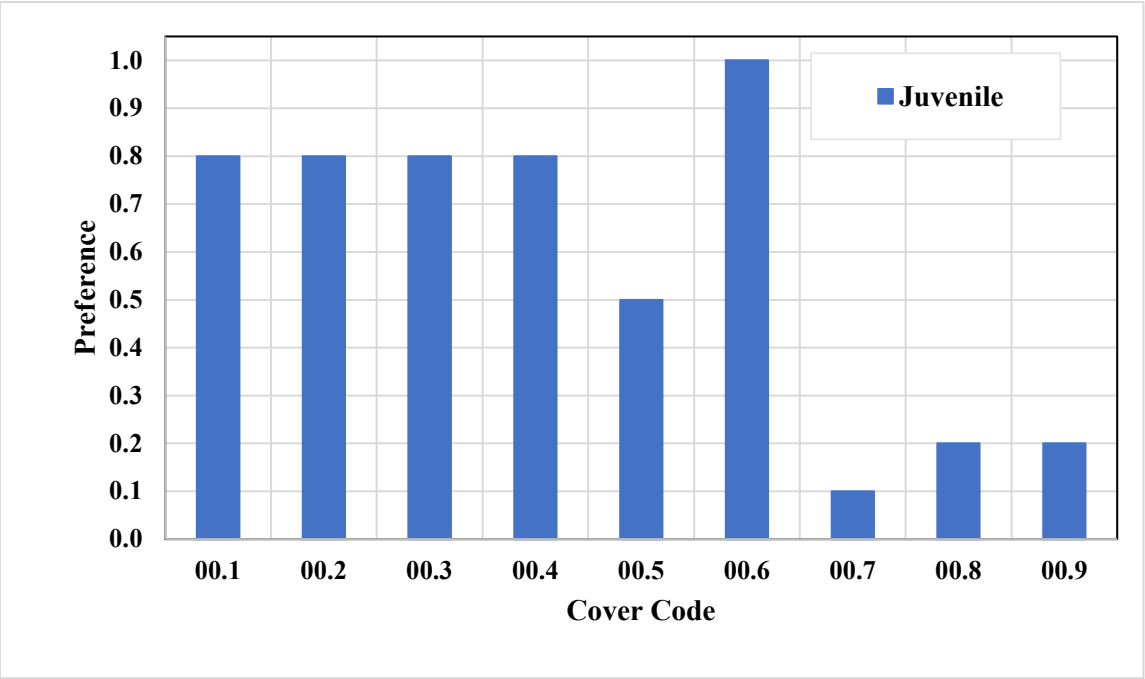


Sustrate Code	Substrate Type	Spawning Preference	Juvenile Preference
1	Silt, Clay, or Organic	0.0	1.0
2	Sand	0.1	1.0
3	Small Gravel (0.1-0.5")	1.0	0.5
4	Med Gravel (0.5-1.5")	1.0	0.5
5	Large Gravel (1.5-3.0")	0.5	0.5
6	Small Cobble (3.0-6.0")	0.5	0.5
7	Large Cobble (6.0-12")	0.5	0.5
8	Boulder (>12")	0.0	0.5
9	Bedrock	0.0	0.5

Source: Pearson et al. 2003

Salish Sucker

Cover Preference



Code	Type of Cover Note: Cover Codes are not used for Spawning	Juvenile Preference
00.1	Undercut bank	0.80
00.2	Overhanging vegetation near or touching	0.80
00.3	Rootwad (including parly undercut)	0.80
00.4	Log jam/submerged brush pile	0.80
00.5	Log(s) parallel to bank	0.50
00.6	Aquatic vegetation	1.00
00.7	Short (<1 ft) terrestrial grass	0.10
00.8	Tall (>3 ft) dense grass	0.20
00.9	Vegetation >3 vertical ft above SZF	0.20

Source: Pearson et al. 2003

White Sturgeon

Spawning (Group F)

WDFW/Ecology HSC curves are not available and White Sturgeon HSC curves are not included in the ESH model. The HSC Technical Group reviewed HSC curves from studies on the Columbia River, WA and Sacramento River, CA. The HSC Technical Group considered the Sacramento River curves to be more representative of the Skagit River as these two rivers are more comparable in size compared to the Columbia River which is much larger; albeit, both sets of HSC curves are similar. As a result, the Sacramento River HSC curves are recommended for habitat modeling.

Additional Notes

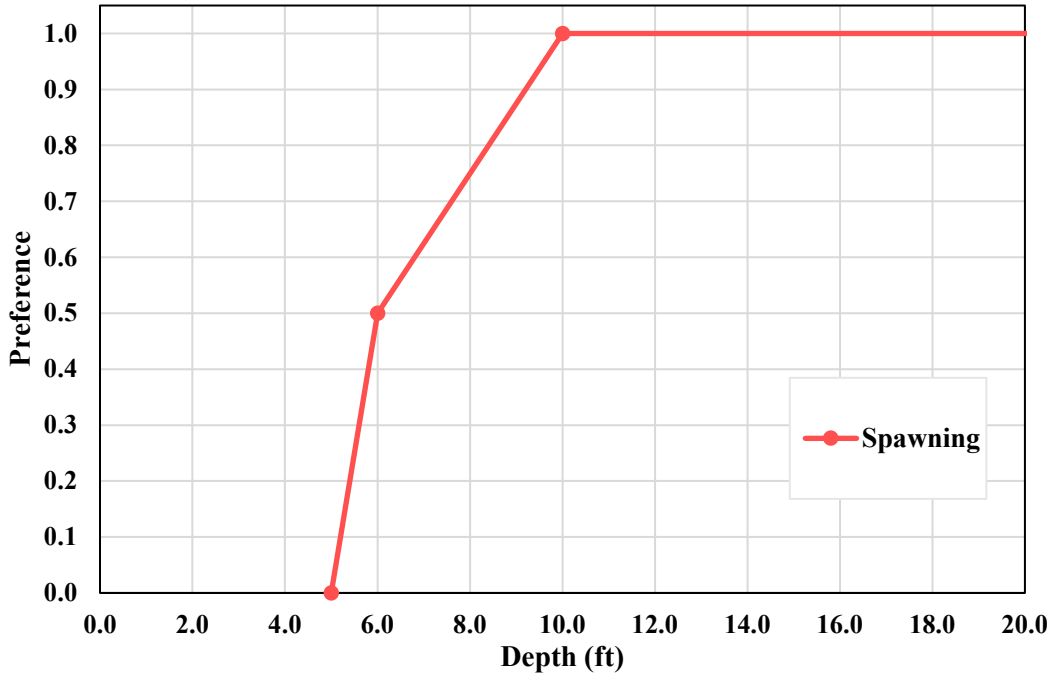
There is no clear biological evidence that depth becomes a limiting factor for spawning White Sturgeon. Therefore, the Sacramento River HSC depth curve is considered to be "non-limiting" once depth reaches 10.0 ft (1.0 preference).

References

Sacramento River: spawning (Gard 1996)

White Sturgeon

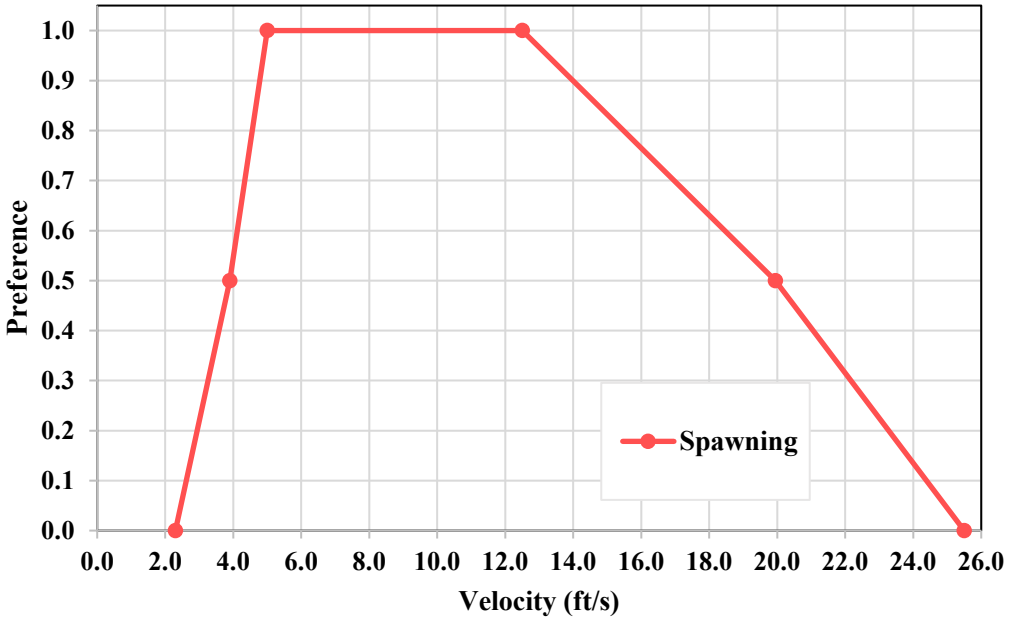
Depth Preference Curves



Spawning	
Depth (ft)	Preference
5.00	0.00
6.00	0.50
10.00	1.00
99.00	1.00

White Sturgeon

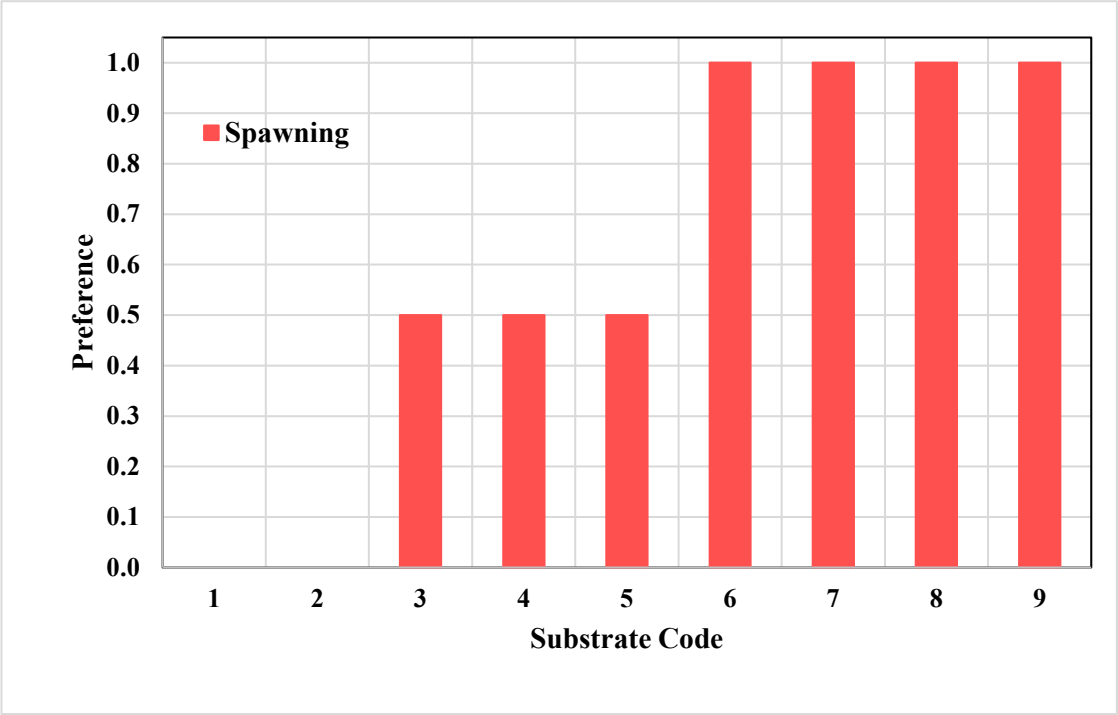
Velocity Preference Curves



Spawning	
Velocity (ft/s)	Preference
2.30	0.00
3.90	0.50
5.00	1.00
12.50	1.00
19.95	0.50
25.50	0.00

White Sturgeon

Substrate Preference Criteria



Sustrate Code	Substrate Type	Spawning Preference
1	Silt, Clay, or Organic	0.0
2	Sand	0.0
3	Small Gravel (0.1-0.5")	0.5
4	Med Gravel (0.5-1.5")	0.5
5	Large Gravel (1.5-3.0")	0.5
6	Small Cobble (3.0-6.0")	1.0
7	Large Cobble (6.0-12")	1.0
8	Boulder (>12")	1.0
9	Bedrock	1.0

Source: Gard 1996

REFERENCE LIST used for Skagit River HSC review and development

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Additional sources relied upon by Crumley and Stober:

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12 FRI Fisheries Research Institute, University of Washington. Data only (no

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14 WDF Washington State Department of Fisheries. 1982. Puget Sound salmon spawning ground data report. Water resource inventory areas 1 - 19 for escapement years 1978 - 1981. Progress Report 175. 574 pp.

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TABLE 1. Generic Cover/Substrate Codes and Preference Value1 (Beecher and Caldwell 2022)

Code	Type of Cover Note: Cover Codes are not used for Spawning	Salmon & Trout Rearing	Whitefish Rearing	
		Juvenile & Resident Adult	Juvenile	Adult
00.1	Undercut bank	1.00	1.00	1.00
00.2	Overhanging vegetation near or touching water2	1.00	1.00	1.00
00.3	Rootwad (including parly 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	0.80	0.80	0.80
00.6	Aquatic vegetation	0.80	0.80	0.80
00.7	Short (<1 ft) terrestrial grass	0.10	0.10	0.10
00.8	Tall (>3 ft) dense grass[3]	0.70	0.70	0.10
00.9	Vegetation >3 vertical ft above SZF	0.20	0.20	0.20

Code	Type of Substrate	Spawning					Salmon & Trout Rearing	Whitefish Rearing	
		Salmon	Steelhead[4]	Resident Trout	Native Char[5]	Whitefish	Juvenile & Resident Adult	Juvenile	Adult
1	Silt, clay, or organic	0.00	0.00	0.00	0.00	0.00	0.10	0.38	0.15
2	Sand	0.00	0.00	0.00	0.00	0.00	0.10	0.38	0.15
3	Sm Gravel (0.1 - 0.5")	0.30	0.50	0.80	1.00	1.00	0.10	0.74	0.76
4	Med Gravel (0.5 - 1.5")	1.00	1.00	1.00	1.00	1.00	0.30	0.88	0.91
5	Lrg Gravel (1.5 - 3")	1.00	1.00	0.80	1.00	1.00	0.30	0.88	0.91
6	Sm Cobble (3 - 6")	1.00	1.00	0.50	0.70	1.00	0.50	1.00	1.00
7	Lrg Cobble (6 - 12")	0.50	0.30	0.00	0.70	0.50	0.70	1.00	1.00
8	Boulder (>12")	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
9	Bedrock	0.00	0.00	0.00	0.00	0.00	0.30	0.50	0.30

Notes:

1. This table reflects average values for the listed species. Site specific preferences would supersede this table.
2. This includes low tree branches (<3 vertical ft. above water surface elevation at stage of zero flow (SZF)) and bushes overhanging the bank-full water's edge.
3. This category refers to stout, almost bushy type grasses such as reed canary grass up to the bank-full water's edge.
4. This category includes intermountain and coastal cutthroat (*Oncorhynchus clarki*).
5. This category includes Bull Trout (*Salvelinus confluentus*) and Dolly Varden (*S. malma*).

TABLE 2. Generic Salmon Spawning Substrate Preference[1]

Code (ab.c)	Preference value a	Preference value b	Recommended Preference
00.0	Cover codes are not factors for spawning habitat		
00.1			
00.2			
00.3			
00.4			
00.5			
00.6			
00.7			
00.8			
00.9			
11.9[2]	0.00	0.00	0.00
13.9	0.00	0.30	0.00*
17.9	0.00	0.30	0.00*
18.5	0.00	0.00	0.00
21.5	0.00	0.00	0.00
23.9	0.00	0.30	0.00*
27.9	0.00	0.50	0.00*
28.5	0.00	0.00	0.00
29.9	0.00	0.00	0.00
31.5	0.30	0.00	0.00*
31.7	0.30	0.00	0.00*
31.8	0.30	0.00	0.24
31.9	0.30	0.00	0.27
32.5	0.30	0.00	0.00*
32.7	0.30	0.00	0.00*
32.8	0.30	0.00	0.24
32.9	0.30	0.00	0.27
33.9	0.30	0.30	0.30
34.5	0.30	1.00	0.65
34.9	0.30	1.00	0.37
35.5	0.30	1.00	0.65
35.9	0.30	1.00	0.37
36.5	0.30	1.00	0.65
36.9	0.30	1.00	0.37
37.5	0.30	0.50	0.40
37.9	0.30	0.50	0.32
38.5	0.30	0.00	0.15
38.9	0.30	0.00	0.27
39.5	0.30	0.00	0.00*
39.9	0.30	0.00	0.00*
41.5	1.00	0.00	0.00*
41.7	1.00	0.00	0.00*
41.8	1.00	0.00	0.80
41.9	1.00	0.00	0.90
42.5	1.00	0.00	0.00*
42.7	1.00	0.00	0.00*
42.8	1.00	0.00	0.80
42.9	1.00	0.00	0.90
43.5	1.00	0.30	0.65
43.9	1.00	0.30	0.93
44.9	1.00	1.00	1.00
46.9	1.00	1.00	1.00
47.5	1.00	0.50	0.75
47.9	1.00	0.50	0.95
48.5	1.00	0.00	0.5
48.9	1.00	0.00	0.9
49.5	1.00	0.00	0.00*
49.9	1.00	0.00	0.00*
51.5	1.00	0.00	0.00*
51.7	1.00	0.00	0.00*
51.8	1.00	0.00	0.80
51.9	1.00	0.00	0.90
52.5	1.00	0.00	0.00*
52.7	1.00	0.00	0.00*
52.8	1.00	0.00	0.80
52.9	1.00	0.00	0.90
53.5	1.00	0.30	0.65
53.9	1.00	0.30	0.93
54.5	1.00	1.00	1.00
56.9	1.00	1.00	1.00
57.5	1.00	0.50	0.75
57.9	1.00	0.50	0.95
58.5	1.00	0.00	0.5
58.9	1.00	0.00	0.9
59.5	1.00	0.00	0.00*
59.9	1.00	0.00	0.00*

[1] Assume straight line between codes. Values are derived from RP equation (see pg. 23).

[2] Substrate code section begins at 11.9. This is an example of a redundant code (see pg 24).

* Asterisk indicated deviation from the RP formula.

Table 2 Continued

Code (ab.c)	Preference value a	Preference value b	Recommended Preference
61.5	1.00	0.00	0.00*
61.7	1.00	0.00	0.00*
61.8	1.00	0.00	0.80
61.9	1.00	0.00	0.90
62.5	1.00	0.00	0.00*
62.7	1.00	0.00	0.00*
62.8	1.00	0.00	0.80
62.9	1.00	0.00	0.90
63.5	1.00	0.30	0.65
63.9	1.00	0.30	0.93
64.5	1.00	1.00	1.00
66.9	1.00	1.00	1.00
67.5	1.00	0.50	0.75
67.9	1.00	0.50	0.95
68.5	1.00	0.00	0.50
68.9	1.00	0.00	0.90
69.5	1.00	0.00	0.00*
71.7	0.50	0.00	0.00*
71.8	0.50	0.00	0.40
71.9	0.50	0.00	0.45
72.5	0.50	0.00	0.00*
72.7	0.50	0.00	0.00*
72.8	0.50	0.00	0.40
72.9	0.50	0.00	0.45
73.5	0.50	0.30	0.40
73.9	0.50	0.30	0.48
74.5	0.50	1.00	0.75
74.9	0.50	1.00	0.55
75.5	0.50	1.00	0.75
75.9	0.50	1.00	0.55
76.5	0.50	1.00	0.75
76.9	0.50	1.00	0.55
77.9	0.50	0.50	0.50
78.5	0.50	0.00	0.25
78.9	0.50	0.00	0.45
79.5	0.50	0.00	0.00*
79.9	0.50	0.00	0.00*
81.5	0.00	0.00	0.00
82.9	0.00	0.00	0.00
83.5	0.00	0.30	0.00*
87.9	0.00	0.50	0.00*
88.9	0.00	0.00	0.00
92.9	0.00	0.00	0.00
93.5	0.00	0.30	0.00*
97.9	0.00	0.50	0.00*
98.5	0.00	0.00	0.00
99.9	0.00	0.00	0.00

TABLE 3. Generic Juvenile & Resident Adult Salmon and Trout Cover/Substrate Preference[1]

Code (ab.c)	Preference value a	Preference value b	Recommended Preference
00.1	a & b values are not used to determine cover preference		1.00
00.2			1.00
00.3			1.00
00.4			1.00
00.5			0.80
00.6			0.80
00.7			0.10
00.8			0.70
00.9			0.20
11.9[2]	0.10	0.10	0.10
13.9	0.10	0.10	0.10
14.5	0.10	0.30	0.20
14.9	0.10	0.30	0.12
15.5	0.10	0.30	0.20
15.9	0.10	0.30	0.12
16.5	0.10	0.50	0.30
16.9	0.10	0.50	0.14
17.5	0.10	0.70	0.40
17.9	0.10	0.70	0.16
18.5	0.10	1.00	1.00*
18.9	0.10	1.00	1.00*
19.5	0.10	0.30	0.20
19.9	0.10	0.30	0.12
21.5	0.10	0.10	0.10
23.9	0.10	0.10	0.10
24.5	0.10	0.30	0.20
24.9	0.10	0.30	0.12
25.5	0.10	0.30	0.20
25.9	0.10	0.30	0.12
26.5	0.10	0.50	0.30
26.9	0.10	0.50	0.14
27.5	0.10	0.70	0.40
27.9	0.10	0.70	0.16
28.5	0.10	1.00	1.00*
28.9	0.10	1.00	1.00*
29.5	0.10	0.30	0.20
29.9	0.10	0.30	0.12
31.5	0.10	0.10	0.10
33.9	0.10	0.10	0.10
34.5	0.10	0.30	0.20
34.9	0.10	0.30	0.12
35.5	0.10	0.30	0.20
35.9	0.10	0.30	0.12
36.5	0.10	0.50	0.30
36.9	0.10	0.50	0.14
37.5	0.10	0.70	0.40
37.9	0.10	0.70	0.16
38.5	0.10	1.00	1.00*
38.9	0.10	1.00	1.00*
39.5	0.10	0.30	0.20
39.9	0.10	0.30	0.12
41.5	0.30	0.10	0.20
41.9	0.30	0.10	0.28
42.5	0.30	0.10	0.20
42.9	0.30	0.10	0.28
43.5	0.30	0.10	0.20
43.9	0.30	0.10	0.28
44.9	0.30	0.30	0.30
45.9	0.30	0.30	0.30
46.5	0.30	0.50	0.40
46.9	0.30	0.50	0.32
47.5	0.30	0.70	0.50
47.9	0.30	0.70	0.34
48.5	0.30	1.00	1.00*
48.9	0.30	1.00	1.00*
49.5	0.30	0.30	0.30
49.9	0.30	0.30	0.30
51.5	0.30	0.10	0.20
51.9	0.30	0.10	0.28
52.5	0.30	0.10	0.20
52.9	0.30	0.10	0.28
53.5	0.30	0.10	0.20
53.9	0.30	0.10	0.28
54.5	0.30	0.30	0.30
55.9	0.30	0.30	0.30
56.5	0.30	0.50	0.40
56.9	0.30	0.50	0.32
57.5	0.30	0.70	0.50
57.9	0.30	0.70	0.34

[1] Assume straight line between codes. Values are derived from RP equation (see pg 23).

[2] Substrate code section begins at 11.9. This is an example of a redundant code (see pg 24).

* Asterisk indicated deviation from the RP formula.

Table 3 Continued

Code (ab.c)	Preference value a	Preference value b	Recommended Preference
58.5	0.30	1.00	1.00*
58.9	0.30	1.00	1.00*
59.5	0.30	0.30	0.30
59.9	0.30	0.30	0.30
61.5	0.50	0.10	0.30
61.9	0.50	0.10	0.46
62.5	0.50	0.10	0.30
62.9	0.50	0.10	0.46
63.5	0.50	0.10	0.30
63.9	0.50	0.10	0.46
64.5	0.50	0.30	0.40
64.9	0.50	0.30	0.48
65.5	0.50	0.30	0.40
65.9	0.50	0.30	0.48
66.9	0.50	0.50	0.50
67.5	0.50	0.70	0.60
67.9	0.50	0.70	0.52
68.5	0.50	1.00	1.00*
68.9	0.50	1.00	1.00*
69.5	0.50	0.30	0.40
69.9	0.50	0.30	0.48
71.5	0.70	0.10	0.40
71.9	0.70	0.10	0.64
72.5	0.70	0.10	0.40
72.9	0.70	0.10	0.64
73.5	0.70	0.10	0.40
73.9	0.70	0.10	0.64
74.5	0.70	0.30	0.50
74.9	0.70	0.30	0.66
75.5	0.70	0.30	0.50
75.9	0.70	0.30	0.66
76.5	0.70	0.50	0.60
76.9	0.70	0.50	0.68
77.9	0.70	0.70	0.70
78.5	0.70	1.00	1.00*
78.9	0.70	1.00	1.00*
79.5	0.70	0.30	0.50
79.9	0.70	0.30	0.66
81.5	1.00	0.10	1.00*
87.9	1.00	0.70	1.00*
88.9	1.00	1.00	1.00
89.5	1.00	0.30	1.00*
89.9	1.00	0.30	1.00*
91.5	0.30	0.10	0.20
91.9	0.30	0.10	0.28
92.5	0.30	0.10	0.20
92.9	0.30	0.10	0.28
93.5	0.30	0.10	0.20
93.9	0.30	0.10	0.28
94.5	0.30	0.30	0.30
95.9	0.30	0.30	0.30
96.5	0.30	0.50	0.40
96.9	0.30	0.50	0.32
97.5	0.30	0.70	0.50
97.9	0.30	0.70	0.34
98.5	0.30	1.00	1.00*
98.9	0.30	1.00	1.00*
99.9	0.30	0.30	0.30

TABLE 4. Steelhead (Oncorhynchus mykiss) Spawning Substrate Preference[1]

Code (ab.c)	Preference value a	Preference value b	Recommended Preference
00.0	Cover codes are not factors for spawning habitat		
00.1			
00.2			
00.3			
00.4			
00.5			
00.6			
00.7			
00.8			
00.9			
11.9[2]	0.00	0.00	0.00
13.9	0.00	0.50	0.00*
14.5	0.00	1.00	0.00*
16.9	0.00	1.00	0.00*
17.5	0.00	0.30	0.00*
17.9	0.00	0.30	0.00*
18.5	0.00	0.00	0.00
21.5	0.00	0.00	0.00
23.9	0.00	0.50	0.00*
27.9	0.00	0.30	0.00*
28.5	0.00	0.00	0.00
29.9	0.00	0.00	0.00
31.5	0.50	0.00	0.00*
31.7	0.50	0.00	0.00*
31.8	0.50	0.00	0.40
31.9	0.50	0.00	0.45
32.5	0.50	0.00	0.00*
32.7	0.50	0.00	0.00*
32.8	0.50	0.00	0.40
32.9	0.50	0.00	0.45
33.9	0.50	0.50	0.50
34.5	0.50	1.00	0.75
34.9	0.50	1.00	0.55
35.5	0.50	1.00	0.75
35.9	0.50	1.00	0.55
36.5	0.50	1.00	0.75
36.9	0.50	1.00	0.55
37.5	0.50	0.30	0.40
37.9	0.50	0.30	0.48
38.5	0.50	0.00	0.00*
38.9	0.50	0.00	0.00*
39.5	0.50	0.00	0.00*
39.9	0.50	0.00	0.00*
41.5	1.00	0.00	0.00*
41.7	1.00	0.00	0.00*
41.8	1.00	0.00	0.80
41.9	1.00	0.00	0.90
42.5	1.00	0.00	0.00*
42.7	1.00	0.00	0.00*
42.8	1.00	0.00	0.80
42.9	1.00	0.00	0.90
43.5	1.00	0.50	0.75
43.9	1.00	0.50	0.95
44.9	1.00	1.00	1.00
46.9	1.00	1.00	1.00
47.5	1.00	0.30	0.65
47.9	1.00	0.30	0.93
48.5	1.00	0.00	0.00*
48.9	1.00	0.00	0.00*
49.5	1.00	0.00	0.00*
49.9	1.00	0.00	0.00*
51.5	1.00	0.00	0.00*
51.7	1.00	0.00	0.00*
51.8	1.00	0.00	0.80
51.9	1.00	0.00	0.90
52.5	1.00	0.00	0.00*
52.7	1.00	0.00	0.00*
52.8	1.00	0.00	0.80
52.9	1.00	0.00	0.90
53.5	1.00	0.50	0.75
53.9	1.00	0.50	0.95
54.5	1.00	1.00	1.00
56.9	1.00	1.00	1.00
57.5	1.00	0.30	0.65
57.9	1.00	0.30	0.93

[1] Assume straight line between codes. Values are derived from RP equation (see pg 23).

[2] Substrate code section begins at 11.9. This is an example of a redundant code (see pg 24).
* Asterisk indicated deviation from the RP formula.

Table 4 Continued

Code (ab.c)	Preference value a	Preference value b	Recommended Preference
58.5	1.00	0.00	0.00*
58.9	1.00	0.00	0.00*
59.5	1.00	0.00	0.00*
59.9	1.00	0.00	0.00*
61.5	1.00	0.00	0.00*
61.7	1.00	0.00	0.00*
61.8	1.00	0.00	0.80
61.9	1.00	0.00	0.90
62.5	1.00	0.00	0.00*
62.7	1.00	0.00	0.00*
62.8	1.00	0.00	0.80
62.9	1.00	0.00	0.90
63.5	1.00	0.50	0.75
63.9	1.00	0.50	0.95
64.5	1.00	1.00	1.00
66.9	1.00	1.00	1.00
67.5	1.00	0.30	0.65
67.9	1.00	0.30	0.93
68.5	1.00	0.00	0.00*
68.9	1.00	0.00	0.00*
69.5	1.00	0.00	0.00*
69.9	1.00	0.00	0.00*
71.5	0.30	0.00	0.00*
71.7	0.30	0.00	0.00*
71.8	0.30	0.00	0.24
71.9	0.30	0.00	0.27
72.5	0.30	0.00	0.00*
72.7	0.30	0.00	0.00*
72.8	0.30	0.00	0.24
72.9	0.30	0.00	0.27
73.5	0.30	0.50	0.40
73.9	0.30	0.50	0.32
74.5	0.30	1.00	0.65
74.9	0.30	1.00	0.37
75.5	0.30	1.00	0.65
75.9	0.30	1.00	0.37
76.5	0.30	1.00	0.65
76.9	0.30	1.00	0.37
77.9	0.30	0.30	0.30
78.5	0.30	0.00	0.00*
78.9	0.30	0.00	0.00*
79.5	0.30	0.00	0.00*
79.9	0.30	0.00	0.00*
81.5	0.00	0.00	0.00*
82.9	0.00	0.00	0.00*
83.5	0.00	0.50	0.00*
83.9	0.00	0.50	0.00*
84.5	0.00	1.00	0.00*
86.9	0.00	1.00	0.00*
87.5	0.00	0.30	0.00*
87.9	0.00	0.30	0.00*
88.5	0.00	0.00	0.00
92.9	0.00	0.00	0.00
93.5	0.00	0.50	0.00*
93.9	0.00	0.50	0.00*
94.5	0.00	1.00	0.00*
96.9	0.00	1.00	0.00*
97.5	0.00	0.30	0.00*
97.9	0.00	0.30	0.00*
98.5	0.00	0.00	0.00
99.9	0.00	0.00	0.00

TABLE 5. Generic Trout Spawning Substrate Preference[1]

Code (ab.c)	Preference value a	Preference value b	Recommended Preference
00.1	Cover codes are not factors for spawning habitat		
00.2			
00.3			
00.4			
00.5			
00.6			
00.7			
00.8			
00.9			
11.9[2]	0.00	0.00	0.00
13.9	0.00	0.80	0.00*
14.5	0.00	1.00	0.00*
14.9	0.00	1.00	0.00*
15.5	0.00	0.80	0.00*
15.9	0.00	0.80	0.00*
16.5	0.00	0.50	0.00*
16.9	0.00	0.50	0.00*
17.5	0.00	0.00	0.00
21.5	0.00	0.00	0.00
23.9	0.00	0.80	0.00*
24.5	0.00	1.00	0.00*
24.9	0.00	1.00	0.00*
25.5	0.00	0.80	0.00*
25.9	0.00	0.80	0.00*
26.5	0.00	0.50	0.00*
26.9	0.00	0.50	0.00*
27.5	0.00	0.00	0.00
29.9	0.00	0.00	0.00
31.5	0.80	0.00	0.00*
31.7	0.80	0.00	0.00*
31.8	0.80	0.00	0.64
31.9	0.80	0.00	0.72
32.5	0.80	0.00	0.00*
32.7	0.80	0.00	0.00*
32.8	0.80	0.00	0.64
32.9	0.80	0.00	0.72
33.9	0.80	0.80	0.80
34.5	0.80	1.00	0.90
34.9	0.80	1.00	0.82
35.5	0.80	0.80	0.80
35.9	0.80	0.80	0.80
36.5	0.80	0.50	0.65
36.9	0.80	0.50	0.77
37.5	0.80	0.00	0.00*
37.9	0.80	0.00	0.00*
38.5	0.80	0.00	0.00*
38.9	0.80	0.00	0.00*
39.5	0.80	0.00	0.00*
39.9	0.80	0.00	0.00*
41.5	1.00	0.00	0.00*
41.7	1.00	0.00	0.00*
41.8	1.00	0.00	0.80
41.9	1.00	0.00	0.90
42.5	1.00	0.00	0.00*
42.7	1.00	0.00	0.00*
42.8	1.00	0.00	0.80
42.9	1.00	0.00	0.90
43.5	1.00	0.80	0.90
43.9	1.00	0.80	0.98
44.9	1.00	1.00	1.00
45.5	1.00	0.80	0.90
45.9	1.00	0.80	0.98
46.5	1.00	0.50	0.75
46.9	1.00	0.50	0.95
47.5	1.00	0.00	0.00*
47.9	1.00	0.00	0.00*
48.5	1.00	0.00	0.00*
48.9	1.00	0.00	0.00*
49.5	1.00	0.00	0.00*
49.9	1.00	0.00	0.00*
51.5	0.80	0.00	0.00*
51.7	0.80	0.00	0.00*
51.8	0.80	0.00	0.64
51.9	0.80	0.00	0.72
52.5	0.80	0.00	0.00*
52.7	0.80	0.00	0.00*
52.8	0.80	0.00	0.64
52.9	0.80	0.00	0.72
53.5	0.80	0.80	0.80
53.9	0.80	0.80	0.80

[1] Assume straight line between codes. Values are derived from RP equation (see pg 23).

[2] Substrate code section begins at 11.9. This is an example of a redundant code (see pg 24).

* Asterisk indicated deviation from the RP formula.

TABLE 5 Continued

Code (ab.c)	Preference value a	Preference value b	Recommended Preference
54.5	0.80	1.00	0.90
54.9	0.80	1.00	0.82
55.9	0.80	0.80	0.80
56.5	0.80	0.50	0.65
56.9	0.80	0.50	0.77
57.5	0.80	0.00	0.00*
57.9	0.80	0.00	0.00*
58.5	0.80	0.00	0.00*
58.9	0.80	0.00	0.00*
59.5	0.80	0.00	0.00*
59.9	0.80	0.00	0.00*
61.5	0.50	0.00	0.00*
61.7	0.50	0.00	0.00*
61.8	0.50	0.00	0.40
61.9	0.50	0.00	0.45
62.5	0.50	0.00	0.00*
62.7	0.50	0.00	0.00*
62.8	0.50	0.00	0.40
62.9	0.50	0.00	0.45
63.5	0.50	0.80	0.65
63.9	0.50	0.80	0.53
64.5	0.50	1.00	0.75
64.9	0.50	1.00	0.55
65.5	0.50	0.80	0.65
65.9	0.50	0.80	0.53
66.9	0.50	0.50	0.50
67.5	0.50	0.00	0.00*
67.9	0.50	0.00	0.00*
68.5	0.50	0.00	0.00*
68.9	0.50	0.00	0.00*
69.5	0.50	0.00	0.00*
69.9	0.50	0.00	0.00*
71.5	0.00	0.00	0.00
72.9	0.00	0.00	0.00
73.5	0.00	0.80	0.00*
73.9	0.00	0.80	0.00*
74.5	0.00	1.00	0.00*
74.9	0.00	1.00	0.00*
75.5	0.00	0.80	0.00*
75.9	0.00	0.80	0.00*
76.5	0.00	0.50	0.00*
76.9	0.00	0.50	0.00*
77.9	0.00	0.00	0.00
82.9	0.00	0.00	0.00
83.5	0.00	0.80	0.00*
83.9	0.00	0.80	0.00*
84.5	0.00	1.00	0.00*
84.9	0.00	1.00	0.00*
85.5	0.00	0.80	0.00*
85.9	0.00	0.80	0.00*
86.5	0.00	0.50	0.00*
86.9	0.00	0.50	0.00*
87.5	0.00	0.00	0.00
92.9	0.00	0.00	0.00
93.5	0.00	0.80	0.00*
93.9	0.00	0.80	0.00*
94.5	0.00	1.00	0.00*
94.9	0.00	1.00	0.00*
95.5	0.00	0.80	0.00*
95.9	0.00	0.80	0.00*
96.5	0.00	0.50	0.00*
96.9	0.00	0.50	0.00*
97.5	0.00	0.00	0.00
99.9	0.00	0.00	0.00

TABLE 6. Bull Trout (Salvelinus confluentus) and Dolly Varden (S. malma) Spawning Substrate Preference[1]

Code (ab.c)	Preference value a	Preference value b	Recommended Preference
00.1	Cover codes are not factors for spawning habitat		
00.2			
00.3			
00.4			
00.5			
00.6			
00.7			
00.8			
00.9			
11.9[2]	0.00	0.00	0.00
31.7	1.00	0.00	0.00*
31.8	1.00	0.00	0.80
31.9	1.00	0.00	0.90
32.5	1.00	0.00	0.00*
32.7	1.00	0.00	0.00*
32.8	1.00	0.00	0.80
32.9	1.00	0.00	0.90
33.9	1.00	1.00	1.00
35.9	1.00	1.00	1.00
36.5	1.00	0.70	0.85
36.9	1.00	0.70	0.97
37.5	1.00	0.70	0.85
37.9	1.00	0.70	0.97
38.5	1.00	0.00	0.50
38.9	1.00	0.00	0.90
39.5	1.00	0.00	0.00*
41.7	1.00	0.00	0.00*
41.8	1.00	0.00	0.80
41.9	1.00	0.00	0.90
42.5	1.00	0.00	0.00*
42.7	1.00	0.00	0.00*
42.8	1.00	0.00	0.80
42.9	1.00	0.00	0.90
43.5	1.00	1.00	1.00
45.9	1.00	1.00	1.00
46.5	1.00	0.70	0.85
46.9	1.00	0.70	0.97
47.5	1.00	0.70	0.85
47.9	1.00	0.70	0.97
48.5	1.00	0.00	0.50
48.9	1.00	0.00	0.90
49.5	1.00	0.00	0.00*
51.7	1.00	0.00	0.00*
51.8	1.00	0.00	0.80
51.9	1.00	0.00	0.90
52.5	1.00	0.00	0.00*
52.7	1.00	0.00	0.00*
52.8	1.00	0.00	0.80
52.9	1.00	0.00	0.90
53.5	1.00	1.00	1.00
55.9	1.00	1.00	1.00
56.5	1.00	0.70	0.85
56.9	1.00	0.70	0.97
57.5	1.00	0.70	0.85
57.9	1.00	0.70	0.97
58.5	1.00	0.70	0.85
58.9	1.00	0.70	0.97
59.5	1.00	0.00	0.00*
61.7	0.70	0.00	0.00*
61.8	0.70	0.00	0.56
61.9	0.70	0.00	0.63
62.5	0.70	0.00	0.00*
62.7	0.70	0.00	0.00*
62.8	0.70	0.00	0.56
62.9	0.70	0.00	0.63
63.5	0.70	1.00	0.85
63.9	0.70	1.00	0.73
64.5	0.70	1.00	0.85
64.9	0.70	1.00	0.73
65.5	0.70	1.00	0.85
65.9	0.70	1.00	0.73
66.9	0.70	0.70	0.70
67.9	0.70	0.70	0.70
68.5	0.70	0.00	0.35
68.9	0.70	0.00	0.63
69.5	0.70	0.00	0.00*

[1] Assume straight line between codes. Values are derived from RP equation (see pg 23).

[2] Substrate code section begins at 11.9. This is an example of a redundant code (see pg 20).

* Asterisk indicated deviation form RP formula.

Table 6 Continued

Code (ab.c)	Preference value a	Preference value b	Recommended Preference
71.7	0.70	0.00	0.00*
71.8	0.70	0.00	0.56
71.9	0.70	0.00	0.63
72.5	0.70	0.00	0.00*
72.7	0.70	0.00	0.00*
72.8	0.70	0.00	0.56
72.9	0.70	0.00	0.63
73.5	0.70	1.00	0.85
73.9	0.70	1.00	0.73
74.5	0.70	1.00	0.85
74.9	0.70	1.00	0.73
75.5	0.70	1.00	0.85
75.9	0.70	1.00	0.73
76.5	0.70	0.70	0.70
76.9	0.70	0.70	0.70
77.9	0.70	0.70	0.70
78.5	0.70	0.00	0.35
78.9	0.70	0.00	0.63
79.5	0.70	0.00	0.00*
82.9	0.00	0.00	0.00*
83.5	0.00	1.00	0.50
83.9	0.00	1.00	0.10
84.5	0.00	1.00	0.50
84.9	0.00	1.00	0.10
85.5	0.00	1.00	0.50
85.9	0.00	1.00	0.10
86.5	0.00	0.70	0.35
86.9	0.00	0.70	0.07
87.5	0.00	0.70	0.35
87.9	0.00	0.70	0.07
88.9	0.00	0.00	0.00
93.5	0.00	0.00	0.00*
97.9	0.00	1.00	0.00*
99.9	0.00	0.00	0.00

TABLE 7. Mountain Whitefish (*Prosopium williamsoni*) Spawning Substrate Preference[1]

Code (ab.c)	Preference value a	Preference value b	Recommended Preference
00.1	Cover codes are not factors for spawning habitat		
00.2			
00.3			
00.4			
00.5			
00.6			
00.7			
00.8			
00.9			
11.9[2]	0.0	0.0	0.0
21.9	0.00	0.00	0.00
31.5	1.00	0.00	0.50
31.9	1.00	0.00	0.90
32.5	1.00	0.00	0.50
32.9	1.00	0.00	0.90
33.9	1.00	1.00	1.00
36.9	1.00	1.00	1.00
37.5	1.00	0.50	0.75
37.9	1.00	0.50	0.95
38.5	1.00	0.00	0.50
38.9	1.00	0.00	0.90
39.5	1.00	0.00	0.50
39.9	1.00	0.00	0.90
41.5	1.00	0.00	0.50
41.9	1.00	0.00	0.90
42.5	1.00	0.00	0.50
42.9	1.00	0.00	0.90
43.5	1.00	1.00	1.00
46.9	1.00	1.00	1.00
47.5	1.00	0.50	0.75
47.9	1.00	0.50	0.95
48.5	1.00	0.00	0.50
48.9	1.00	0.00	0.90
49.5	1.00	0.00	0.50
49.9	1.00	0.00	0.90
51.5	1.00	0.00	0.50
51.9	1.00	0.00	0.90
52.5	1.00	0.00	0.50
52.9	1.00	0.00	0.90
53.5	1.00	1.00	1.00
56.9	1.00	1.00	1.00
57.5	1.00	0.50	0.75
57.9	1.00	0.50	0.95
58.5	1.00	0.00	0.50
58.9	1.00	0.00	0.90
59.5	1.00	0.00	0.50
59.9	1.00	0.00	0.90
61.5	1.00	0.00	0.50
61.9	1.00	0.00	0.90
62.5	1.00	0.00	0.50
62.9	1.00	0.00	0.90
63.5	1.00	1.00	1.00
66.9	1.00	1.00	1.00
67.5	1.00	0.50	0.75
67.9	1.00	0.50	0.95
68.5	1.00	0.00	0.50
68.9	1.00	0.00	0.90
69.5	1.00	0.00	0.50
69.9	1.00	0.00	0.90
71.5	0.50	0.00	0.25
71.9	0.50	0.00	0.45
72.5	0.50	0.00	0.25
72.9	0.50	0.00	0.45
73.5	0.50	1.00	0.75
73.9	0.50	1.00	0.55
74.5	0.50	1.00	0.75
74.9	0.50	1.00	0.55
75.5	0.50	1.00	0.75
75.9	0.50	1.00	0.55
76.5	0.50	1.00	0.75
76.9	0.50	1.00	0.55
77.9	0.50	0.50	0.50
78.5	0.50	0.00	0.25
78.9	0.50	0.00	0.45
79.5	0.50	0.00	0.25
79.9	0.50	0.00	0.45

[1] Assume straight line between codes. Values are derived from RP equation (see pg 23).

[2] Substrate code section begins at 11.9. This is an example of a redundant code (see pg 24).
* Asterisk indicated deviation from the RP formula.

Table 7 Continued

Code (ab.c)	Preference value a	Preference value b	Recommended Preference
81.5	0.00	0.00	0.00
82.9	0.00	0.00	0.00
83.5	0.00	1.00	0.50
83.9	0.00	1.00	0.10
84.5	0.00	1.00	0.50
84.9	0.00	1.00	0.10
85.5	0.00	1.00	0.50
85.9	0.00	1.00	0.10
86.5	0.00	1.00	0.50
86.9	0.00	1.00	0.10
87.5	0.00	1.00	0.50
87.9	0.00	1.00	0.10
88.9	0.00	0.00	0.00
92.9	0.00	0.00	0.00
93.5	0.00	1.00	0.50
93.9	0.00	1.00	0.10
94.5	0.00	1.00	0.50
94.9	0.00	1.00	0.10
95.5	0.00	1.00	0.50
95.9	0.00	1.00	0.10
96.5	0.00	1.00	0.50
96.9	0.00	1.00	0.10
97.5	0.00	1.00	0.50
97.9	0.00	1.00	0.10
98.5	0.00	0.00	0.00
99.9	0.00	0.00	0.00

TABLE 8. Mountain Whitefish Adult Rearing Cover/Substrate Preference [1]

Code (ab.c)	Preference value a	Preference value b	Recommended Preference
00.1	a & b values are not used to determine cover preference		1.0
00.2			1.0
00.3			1.0
00.4			1.0
00.5			0.8
00.6			0.8
00.7			0.1
00.8			0.1
00.9			0.2
11.9[2]	0.15	0.15	0.15
12.9	0.15	0.15	0.15
13.5	0.15	0.76	0.46
13.9	0.15	0.76	0.21
14.5	0.15	0.91	0.53
14.9	0.15	0.91	0.23
15.5	0.15	0.91	0.53
15.9	0.15	0.91	0.23
16.5	0.15	1.0	0.58
16.9	0.15	1.0	0.24
17.5	0.15	1.0	0.58
17.9	0.15	1.0	0.24
18.5	0.15	1.0	0.58
18.9	0.15	1.0	0.24
19.5	0.15	0.30	0.23
19.9	0.15	0.30	0.17
21.5	0.15	0.15	0.15
22.9	0.15	0.15	0.15
23.5	0.15	0.76	0.46
23.9	0.15	0.76	0.21
24.5	0.15	0.91	0.53
24.9	0.15	0.91	0.23
25.5	0.15	0.91	0.53
25.9	0.15	0.91	0.23
26.5	0.15	1.00	0.58
26.9	0.15	1.00	0.24
27.5	0.15	1.00	0.58
27.9	0.15	1.00	0.24
28.5	0.15	1.00	0.58
28.9	0.15	1.00	0.24
29.5	0.15	0.30	0.23
29.9	0.15	0.30	0.17
31.5	0.76	0.15	0.46
31.9	0.76	0.15	0.70
32.5	0.76	0.15	0.46
32.9	0.76	0.15	0.70
33.9	0.76	0.76	0.76
34.5	0.76	0.91	0.84
34.9	0.76	0.91	0.78
35.5	0.76	0.91	0.84
35.9	0.76	0.91	0.78
36.5	0.76	1.0	0.88
36.9	0.76	1.0	0.78
37.5	0.76	1.0	0.88
37.9	0.76	1.0	0.78
38.5	0.76	1.0	0.88
38.9	0.76	1.0	0.78
39.5	0.76	0.30	0.53
39.9	0.76	0.30	0.71
41.5	0.91	0.15	0.53
41.9	0.91	0.15	0.83
42.5	0.91	0.15	0.53
42.9	0.91	0.15	0.83
43.5	0.91	0.76	0.84
43.9	0.91	0.76	0.90
44.9	0.91	0.91	0.91
45.9	0.91	0.91	0.91
46.5	0.91	1.0	0.96
46.9	0.91	1.0	0.92
47.5	0.91	1.0	0.96
47.9	0.91	1.0	0.92
48.5	0.91	1.0	0.96
48.9	0.91	1.0	0.92
49.5	0.91	0.30	0.61
49.9	0.91	0.30	0.85
51.5	0.91	0.15	0.53
51.9	0.91	0.15	0.83
52.5	0.91	0.15	0.53
52.9	0.91	0.15	0.83
53.5	0.91	0.76	0.84
53.9	0.91	0.76	0.90
54.5	0.91	0.91	0.91
55.9	0.91	0.91	0.91
56.5	0.91	1.0	0.96
56.9	0.91	1.0	0.92

[1] Assume straight line between codes. Values are derived from RP equation (see pg 23).

[2] Substrate code section begins at 11.9. This is an example of a redundant code (see pg 24).
* Asterisk indicated deviation from the RP formula.

Table 8 Continued

Code (ab.c)	Preference value a	Preference value b	Recommended Preference
57.5	0.91	1.0	0.96
57.9	0.91	1.0	0.92
58.5	0.91	1.0	0.96
58.9	0.91	1.0	0.92
59.5	0.91	0.30	0.61
59.9	0.91	0.30	0.85
61.5	1.0	0.15	0.58
61.9	1.0	0.15	0.92
62.5	1.0	0.15	0.58
62.9	1.0	0.15	0.92
63.5	1.0	0.76	0.88
63.9	1.0	0.76	0.98
64.5	1.0	0.91	0.96
64.9	1.0	0.91	0.99
65.5	1.0	0.91	0.96
65.9	1.0	0.91	0.99
66.9	1.0	1.0	1.00
68.9	1.0	1.0	1.00
69.5	1.0	0.30	0.65
69.9	1.0	0.30	0.93
71.5	1.0	0.15	0.58
71.9	1.0	0.15	0.92
72.5	1.0	0.15	0.58
72.9	1.0	0.15	0.92
73.5	1.0	0.76	0.88
73.9	1.0	0.76	0.98
74.5	1.0	0.91	0.96
74.9	1.0	0.91	0.99
75.5	1.0	0.91	0.96
75.9	1.0	0.91	0.99
76.5	1.0	1.0	1.00
78.9	1.0	1.0	1.00
79.5	1.0	0.30	0.65
79.9	1.0	0.30	0.93
81.5	1.0	0.15	0.58
81.9	1.0	0.15	0.92
82.5	1.0	0.15	0.58
82.9	1.0	0.15	0.92
83.5	1.0	0.76	0.88
83.9	1.0	0.76	0.98
84.5	1.0	0.91	0.96
84.9	1.0	0.91	0.99
85.5	1.0	0.91	0.96
85.9	1.0	0.91	0.99
86.5	1.0	1.0	1.00
88.9	1.0	1.0	1.00
89.5	1.0	0.30	0.65
89.9	1.0	0.30	0.93
91.5	0.30	0.15	0.23
91.9	0.30	0.15	0.29
92.5	0.30	0.15	0.23
92.9	0.30	0.15	0.29
93.5	0.30	0.76	0.53
93.9	0.30	0.76	0.35
94.5	0.30	0.91	0.61
94.9	0.30	0.91	0.36
95.5	0.30	0.91	0.61
95.9	0.30	0.91	0.36
96.5	0.30	1.0	0.65
96.9	0.30	1.0	0.37
97.5	0.30	1.0	0.65
97.9	0.30	1.0	0.37
98.5	0.30	1.0	0.65
98.9	0.30	1.0	0.37
99.9	0.30	0.30	0.30

TABLE 9. Mountain Whitefish Juvenile Rearing Cover/Substrate Preference [1]

Code (ab.c)	Preference value a	Preference value b	Recommended Preference
00.1	a & b values are not used to determine cover preference		1.00
00.2			1.00
00.3			1.00
00.4			1.00
00.5			0.80
00.6			0.80
00.7			0.10
00.8			0.70
00.9			0.20
11.9[2]	0.38	0.38	0.38
12.9	0.38	0.38	0.38
13.5	0.38	0.74	0.56
13.9	0.38	0.74	0.42
14.5	0.38	0.88	0.63
14.9	0.38	0.88	0.43
15.5	0.38	0.88	0.63
15.9	0.38	0.88	0.43
16.5	0.38	1.0	0.69
16.9	0.38	1.0	0.44
17.5	0.38	1.0	0.69
17.9	0.38	1.0	0.44
18.5	0.38	1.0	0.69
18.9	0.38	1.0	0.44
19.5	0.38	0.50	0.44
19.9	0.38	0.50	0.39
21.5	0.38	0.38	0.38
22.9	0.38	0.38	0.38
23.5	0.38	0.74	0.56
23.9	0.38	0.74	0.42
24.5	0.38	0.88	0.63
24.9	0.38	0.88	0.43
25.5	0.38	0.88	0.63
25.9	0.38	0.88	0.43
26.5	0.38	1.0	0.69
26.9	0.38	1.0	0.44
27.5	0.38	1.0	0.69
27.9	0.38	1.0	0.44
28.5	0.38	1.0	0.69
28.9	0.38	1.0	0.44
29.5	0.38	0.50	0.44
29.9	0.38	0.50	0.39
31.5	0.74	0.38	0.56
31.9	0.74	0.38	0.70
32.5	0.74	0.38	0.56
32.9	0.74	0.38	0.70
33.9	0.74	0.74	0.74
34.5	0.74	0.88	0.81
34.9	0.74	0.88	0.75
35.5	0.74	0.88	0.81
35.9	0.74	0.88	0.75
36.5	0.74	1.0	0.87
36.9	0.74	1.0	0.77
37.5	0.74	1.0	0.87
37.9	0.74	1.0	0.77
38.5	0.74	1.0	0.87
38.9	0.74	1.0	0.77
39.5	0.74	0.50	0.62
39.9	0.74	0.50	0.72
41.5	0.88	0.38	0.63
41.9	0.88	0.38	0.83
42.5	0.88	0.38	0.63
42.9	0.88	0.38	0.83
43.5	0.88	0.74	0.81
43.9	0.88	0.74	0.87
44.9	0.88	0.88	0.88
45.9	0.88	0.88	0.88
46.5	0.88	1.0	0.94
46.9	0.88	1.0	0.89
47.5	0.88	1.0	0.94
47.9	0.88	1.0	0.89
48.5	0.88	1.0	0.94
48.9	0.88	1.0	0.89
49.5	0.88	0.50	0.69
49.9	0.88	0.50	0.84
51.5	0.88	0.38	0.63
51.9	0.88	0.38	0.83
52.5	0.88	0.38	0.63
52.9	0.88	0.38	0.83
53.5	0.88	0.74	0.81
53.9	0.88	0.74	0.87
54.5	0.88	0.88	0.88
55.9	0.88	0.88	0.88
56.5	0.88	1.0	0.94
56.9	0.88	1.0	0.89

[1] Assume straight line between codes. Values are derived from RP equation (see pg 23).

[2] Substrate code section begins at 11.9. This is an example of a redundant code (see pg 24).
* Asterisk indicated deviation from the RP formula.

Table 9 Continued

Code (ab.c)	Preference value a	Preference value b	Recommended Preference
57.5	0.88	1.0	0.94
57.9	0.88	1.0	0.89
58.5	0.88	1.0	0.94
58.9	0.88	1.0	0.89
59.5	0.88	0.50	0.69
59.9	0.88	0.50	0.84
61.5	1.0	0.38	0.69
61.9	1.0	0.38	0.94
62.5	1.0	0.38	0.69
62.9	1.0	0.38	0.94
63.5	1.0	0.74	0.87
63.9	1.0	0.74	0.97
64.5	1.0	0.88	0.94
64.9	1.0	0.88	0.99
65.5	1.0	0.88	0.94
65.9	1.0	0.88	0.99
66.9	1.0	1.0	1.00
68.9	1.0	1.0	1.00
69.5	1.0	0.50	0.75
69.9	1.0	0.50	0.95
71.5	1.0	0.38	0.69
71.9	1.0	0.38	0.94
72.5	1.0	0.38	0.69
72.9	1.0	0.38	0.94
73.5	1.0	0.74	0.87
73.9	1.0	0.74	0.97
74.5	1.0	0.88	0.94
74.9	1.0	0.88	0.99
75.5	1.0	0.88	0.94
75.9	1.0	0.88	0.99
76.5	1.0	1.0	1.00
78.9	1.0	1.0	1.00
79.5	1.0	0.5	0.75
79.9	1.0	0.5	0.95
81.5	1.0	0.38	0.69
81.9	1.0	0.38	0.94
82.5	1.0	0.38	0.69
82.9	1.0	0.38	0.94
83.5	1.0	0.74	0.87
83.9	1.0	0.74	0.97
84.5	1.0	0.88	0.94
84.9	1.0	0.88	0.99
85.5	1.0	0.88	0.94
85.9	1.0	0.88	0.99
86.5	1.0	1.0	1.00
88.9	1.0	1.0	1.00
89.5	1.0	0.5	0.75
89.9	1.0	0.5	0.95
91.5	0.50	0.38	0.44
91.9	0.50	0.38	0.49
92.5	0.50	0.38	0.44
92.9	0.50	0.38	0.49
93.5	0.50	0.74	0.62
93.9	0.50	0.74	0.52
94.5	0.50	0.88	0.69
94.9	0.50	0.88	0.54
95.5	0.50	0.88	0.69
95.9	0.50	0.88	0.54
96.5	0.50	1.0	0.75
96.9	0.50	1.0	0.55
97.5	0.50	1.0	0.75
97.9	0.50	1.0	0.55
98.5	0.50	1.0	0.75
98.9	0.50	1.0	0.55
99.9	0.50	0.5	0.50

SKAGIT RIVER GORGE BYPASS REACH HYDRAULIC AND INSTREAM FLOW MODEL DEVELOPMENT STUDY REPORT

ATTACHMENT C

BYPASS HABITAT MODEL DOMAIN

FA-05 HABITAT MODEL DOMAIN & REACH BREAKS PANEL 1

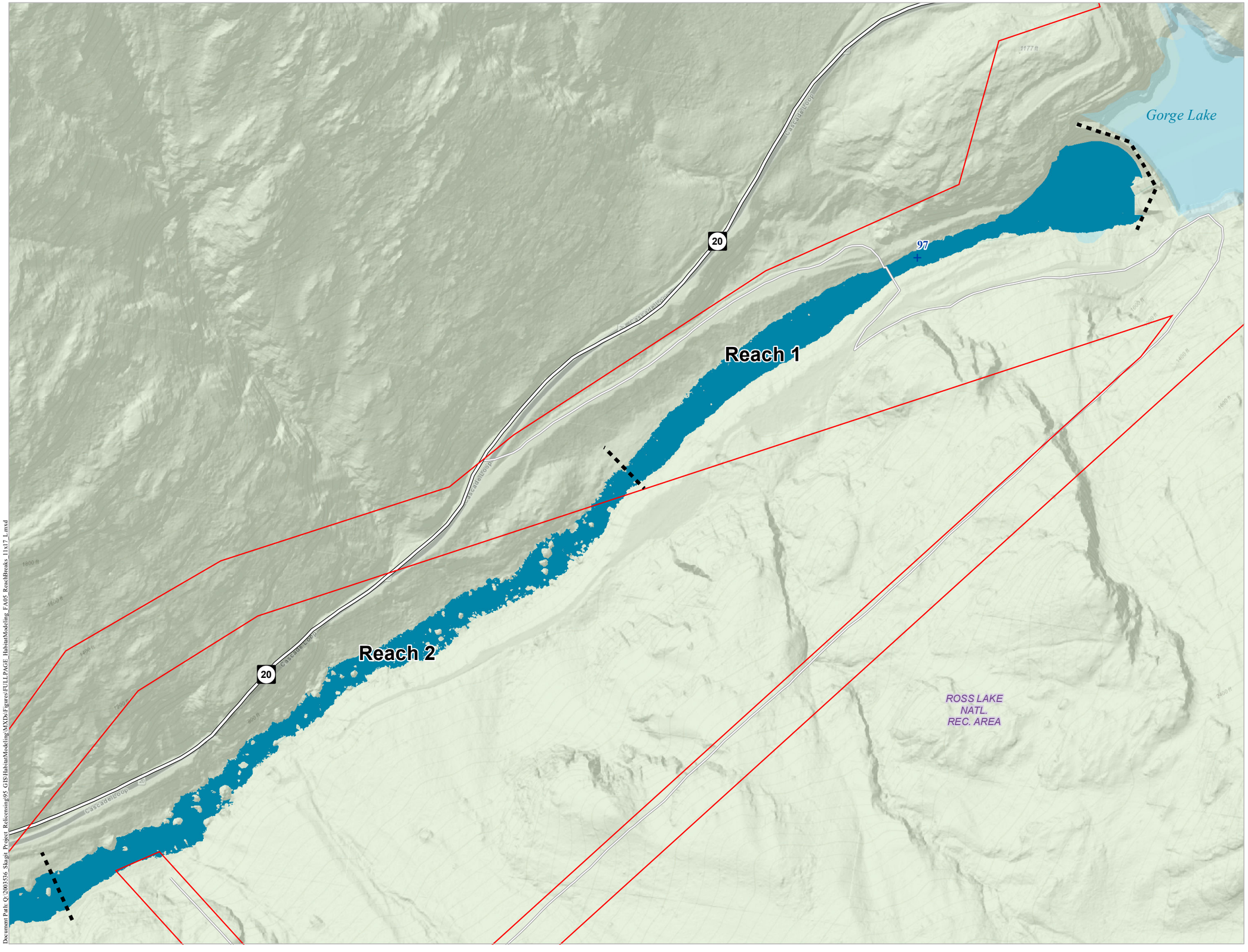
- FERC Project Boundary
- Project River Mile (PRM)
- National Park / National Recreation Area Boundary
- Habitat Reach Boundary

Inundation within Habitat Model Domain

- Reaches 1-5: 3000 cfs Spill from Gorge Dam
  Reaches 5-6: 5% Probability Exceedance from Gorge PH

Inundation outside of Habitat Model Domain

- 5% Probability Exceedence from Gorge PH



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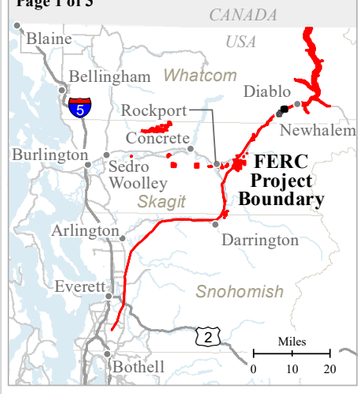
Page 1 of 3



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FA-05 HABITAT MODEL DOMAIN & REACH BREAKS PANEL 2

- FERC Project Boundary
- Project River Mile (PRM)
- National Park / National Recreation Area Boundary
- Habitat Reach Boundary

Inundation within Habitat Model Domain

- Reaches 1-5: 3000 cfs Spill from Gorge Dam
  Reaches 5-6: 5% Probability Exceedance from Gorge PH

Inundation outside of Habitat Model Domain

- 5% Probability Exceedence from Gorge PH

Reach 3

Reach 4

Reach 5

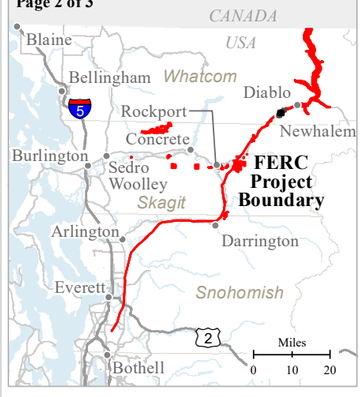
96

95

20

ROSS LAKE NATL. REC. AREA

0 200 400 Feet



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FA-05 HABITAT MODEL DOMAIN & REACH BREAKS PANEL 3

- FERC Project Boundary
- \+ Project River Mile (PRM)
- National Park / National Recreation Area Boundary
- Habitat Reach Boundary

Inundation within Habitat Model Domain

- Reaches 1-5: 3000 cfs Spill from Gorge Dam
  Reaches 5-6: 5% Probability Exceedance from Gorge PH

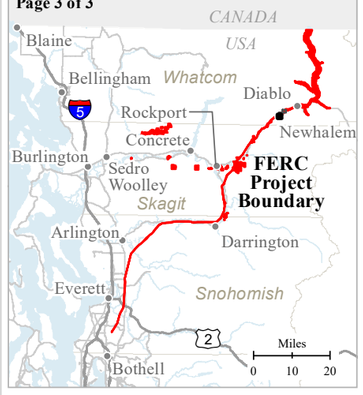
Inundation outside of Habitat Model Domain

- 5% Probability Exceedence from Gorge PH

N

0 200 400 Feet

Page 3 of 3



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SKAGIT RIVER GORGE BYPASS REACH HYDRAULIC AND INSTREAM FLOW MODEL DEVELOPMENT STUDY REPORT

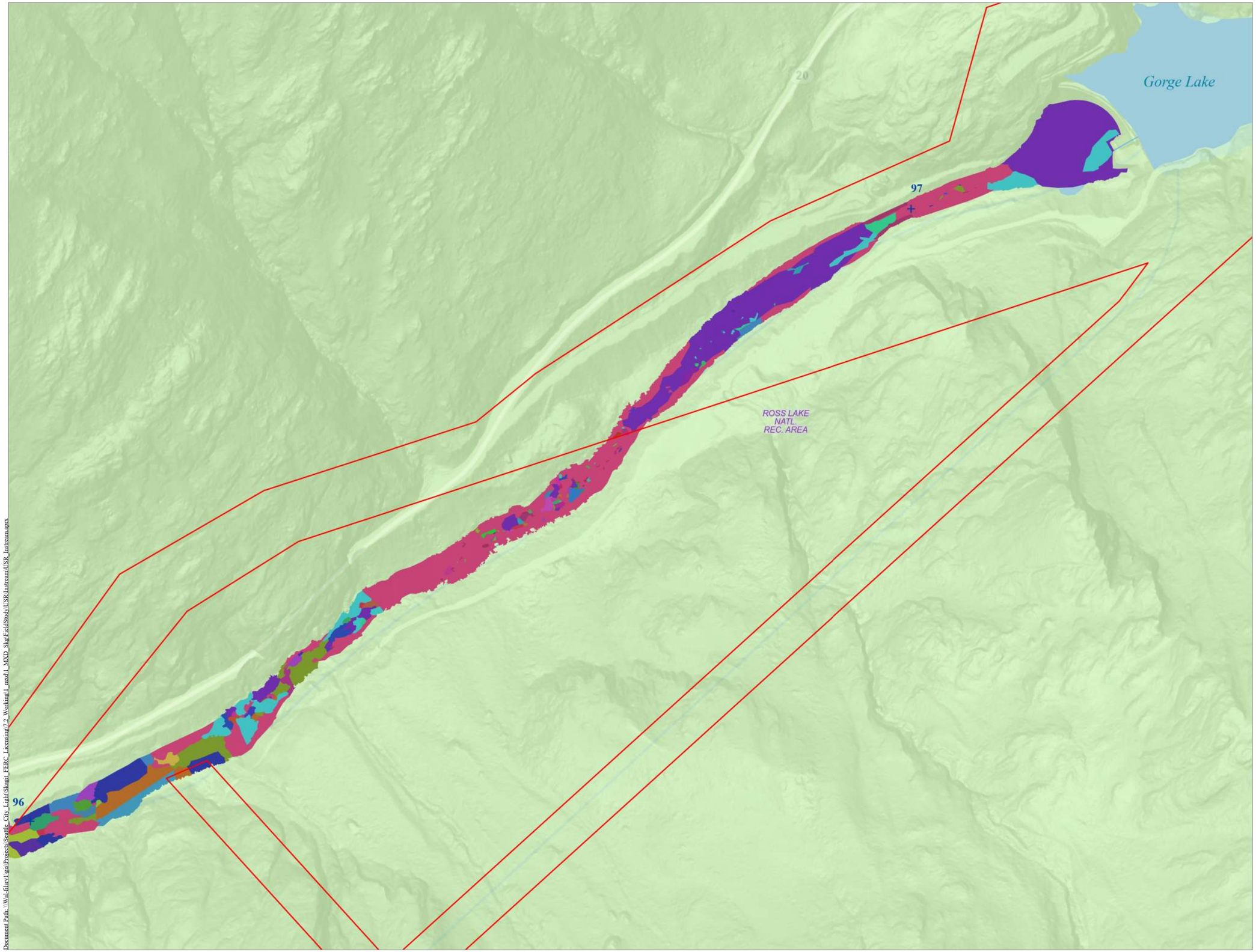
ATTACHMENT D

SUBSTRATE AND COVER MAPBOOKS

The following substrate and cover maps show substrate and cover codes for the Gorge bypass reach per Washington State's Instream Flow Study Guidelines (Beecher and Caldwell 2022). Details on the coding system are provided in Section 4.2.3 of the preceding report text.

With respect to substrate codes, the guidelines stipulate use of dominant and subdominant substrate combinations that result in numerous possible substrate codes. The polygon visual attributes in the following substrate maps and the corresponding legend were selected to highlight the detail resulting from mapping efforts, while also condensing results to a point that is reasonable for an informed review of a large 2-D instream flow study area.

FA-05 BYPASS INSTREAM FLOW MODEL DEVELOPMENT STUDY – SUBSTRATE



FERC Project Boundary

Project River Miles (PRM)

Substrate

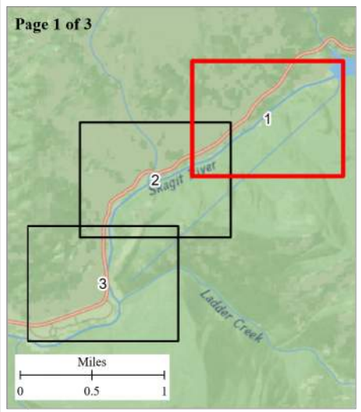
23.5	48.5	67.6	85.8
24.6	48.6	67.7	85.9
28.5	48.7	67.8	86.6
28.8	53.6	68.7	86.8
32.6	53.7	68.8	86.9
32.8	54.5	76.5	87.6
34.6	54.7	76.7	87.7
34.7	54.8	78.7	87.8
34.8	56.6	78.8	87.9
34.9	56.7	82.5	88.5
35.7	56.8	83.5	89.6
35.9	57.7	83.6	89.7
38.7	58.6	83.7	89.8
38.8	58.8	83.9	97.9
45.5	59.8	84.6	98.6
45.6	62.5	84.7	98.8
45.7	65.5	84.9	98.9
45.8	65.6	85.5	99.5
46.6	65.7	85.6	
47.7	65.8	85.7	

Land Ownership

National Park / National Recreation Area Boundary

N

0 250 500 Feet



Seattle City Light

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ROSS LAKE NATL. REC. AREA

96

FA-05 BYPASS INSTREAM FLOW MODEL DEVELOPMENT STUDY – SUBSTRATE

FERC Project Boundary

Project River Miles (PRM)

Substrate

12.5	47.7	75.5	86.5
18.5	48.6	76.5	86.6
23.5	54.5	76.6	86.7
23.8	56.6	76.7	86.8
28.5	56.7	76.8	86.9
28.6	56.8	76.9	87.5
28.8	57.5	78.6	87.6
32.9	57.8	78.7	87.7
34.6	58.7	78.8	87.8
34.7	62.5	78.9	87.9
34.8	65.5	82.5	88.5
34.9	65.6	82.7	89.6
36.9	65.8	83.5	89.7
38.7	67.6	83.7	89.8
38.9	67.7	83.8	95.8
43.5	67.8	83.9	98.6
43.6	67.9	84.6	98.8
45.5	68.6	84.7	98.9
45.7	68.7	85.5	99.5
45.8	68.8	85.7	
47.6	68.9	85.8	
	74.8	85.9	

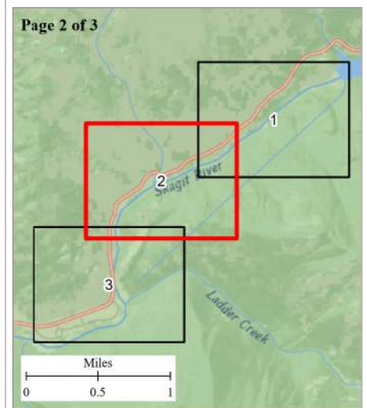
Land Ownership

National Park / National Recreation Area Boundary

N

0 250 500 Feet

Page 2 of 3



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FA-05 BYPASS INSTREAM FLOW MODEL DEVELOPMENT STUDY – SUBSTRATE

FERC Project Boundary

Project River Miles (PRM)

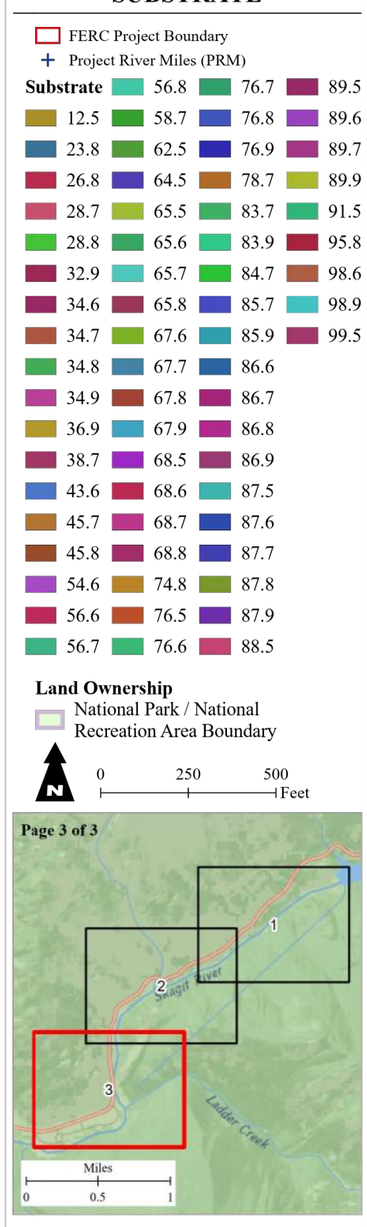
Substrate			
12.5	23.8	26.8	28.7
28.8	32.9	34.6	34.7
34.8	34.9	36.9	38.7
43.6	45.7	45.8	54.6
56.6	56.7	56.8	58.7
62.5	64.5	65.5	65.6
65.7	65.8	67.6	67.7
67.8	67.9	68.5	68.6
68.7	68.8	74.8	76.5
76.6	76.7	76.8	76.9
78.7	83.7	83.9	84.7
85.7	85.9	86.6	86.7
86.8	86.9	87.5	87.6
87.7	87.8	87.9	88.5
89.5	89.6	89.7	89.9
91.5	95.8	98.6	98.9
99.5			

Land Ownership

National Park / National Recreation Area Boundary

N

0 250 500 Feet



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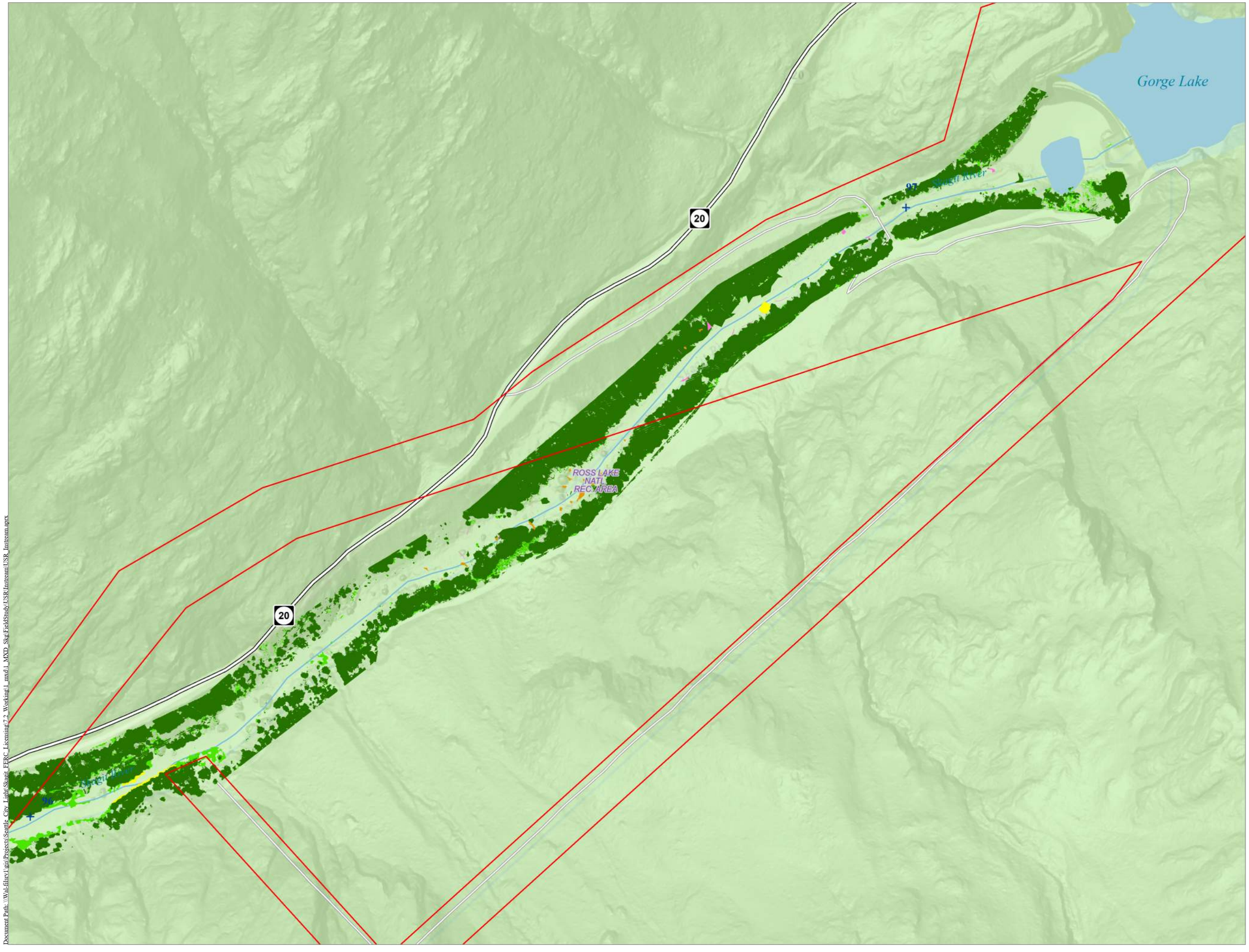
FA-05 BYPASS INSTREAM FLOW MODEL DEVELOPMENT STUDY – COVER



Cover Code

- 00.2
- 00.3
- 00.4
- 00.5
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- 00.9

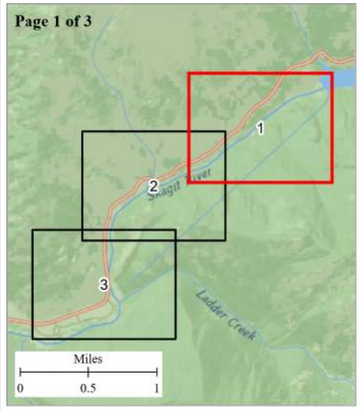
Land Ownership

- National Park / National Recreation Area Boundary

- FERC Project Boundary
- \+ Project River Miles (PRM)

N

0 250 500 Feet



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FA-05 BYPASS INSTREAM FLOW MODEL DEVELOPMENT STUDY – COVER

FERC Project Boundary

Project River Miles (PRM)

Cover Code

- 00.2
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- 00.9

Land Ownership

National Park / National Recreation Area Boundary

N

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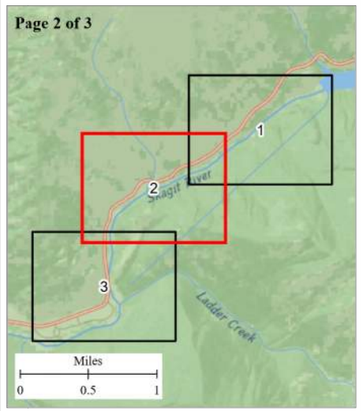

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FA-05 BYPASS INSTREAM FLOW MODEL DEVELOPMENT STUDY – COVER

FERC Project Boundary

\+ Project River Miles (PRM)

Cover Code

- 00.2
- 00.3
- 00.4
- 00.5
- 00.8
- 00.9

Land Ownership

National Park / National Recreation Area Boundary

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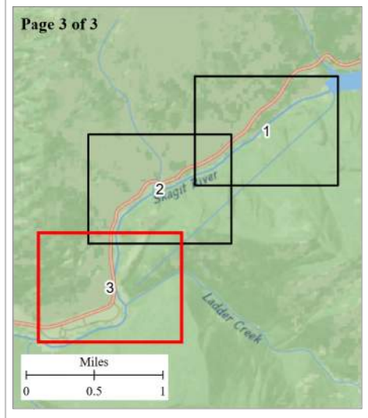

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SKAGIT RIVER GORGE BYPASS REACH HYDRAULIC AND INSTREAM FLOW MODEL DEVELOPMENT STUDY REPORT

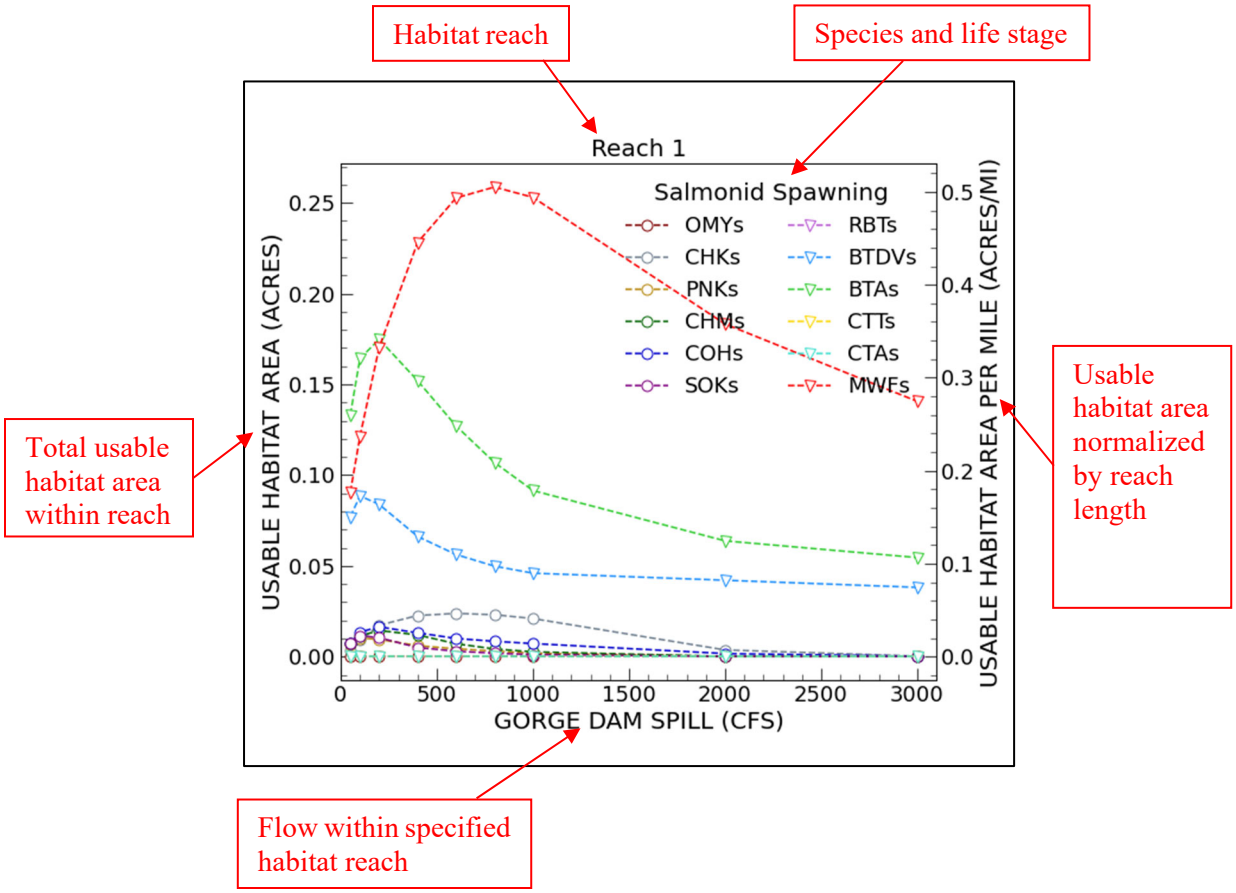
ATTACHMENT E

USABLE HABITAT AREA CURVES

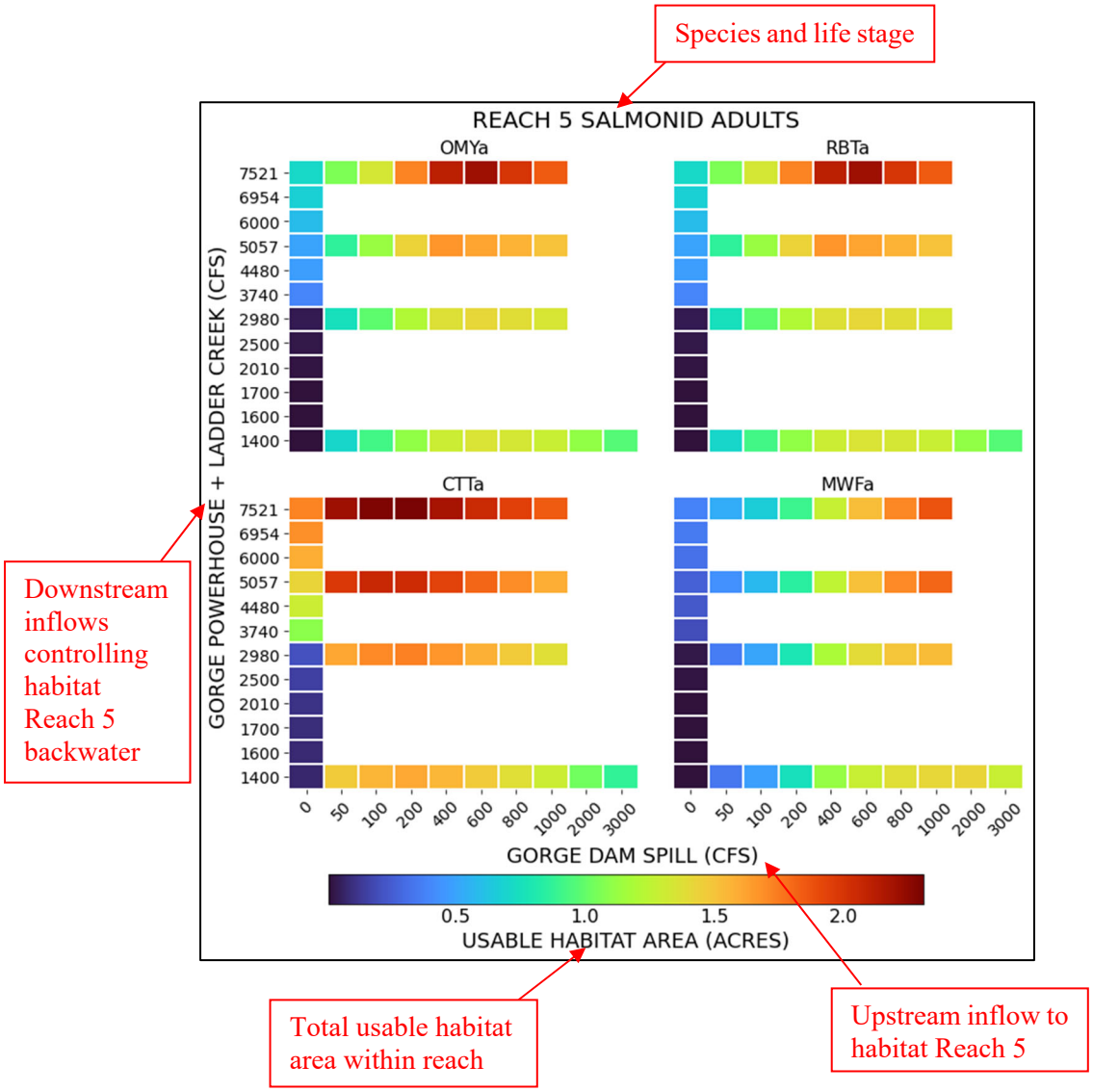
Usable Habitat Area Curves - Key

Species	Life Stage	Abbreviation
Steelhead	Spawning	OMYs
Steelhead	Adult	OMYa
Steelhead	Juvenile	OMYj
Chinook Salmon	Spawning	CHKs
Chinook Salmon	Juvenile	CHKj
Chinook Salmon	Fry	CHKf
Pink Salmon	Spawning	PNKs
Chum Salmon	Spawning	CHMs
Chum Salmon	Fry	CHMf
Coho Salmon	Spawning	COHs
Coho Salmon	Juvenile	COHj
Coho Salmon	Fry	COHf
Sockeye Salmon	Spawning	SOKs
Rainbow Trout	Spawning	RBTs
Rainbow Trout	Adult	RBTa
Rainbow Trout	Juvenile	RBTj
Rainbow Trout	Fry	RBTf
Bull Trout/Dolly Varden	Spawning	BTDVs
Bull Trout/Dolly Varden	Juvenile	BTDVj
Bull Trout/Dolly Varden	Fry	BTDVf
Sea-Run Bull Trout	Spawning	BTAs
Cutthroat Trout	Spawning	CTTs
Cutthroat Trout	Adult	CTTa
Cutthroat Trout	Juvenile	CTTj
Cutthroat Trout	Fry	CTTf
Sea-Run Cutthroat Trout	Spawning	CTAs
Mountain Whitefish	Spawning	MWFs
Mountain Whitefish	Adult	MWFa
Mountain Whitefish	Juvenile	MWFj
Mountain Whitefish	Fry	MWFf
Pacific Lamprey	Spawning	PALs
Lamprey (generic)	Juvenile	LAMj
Western Brook Lamprey	Spawning	WBLs
Western River Lamprey	Spawning	WRLs
White Sturgeon	Spawning	WSTs
Salish Sucker	Spawning	SASs
Salish Sucker	Juvenile	SASj

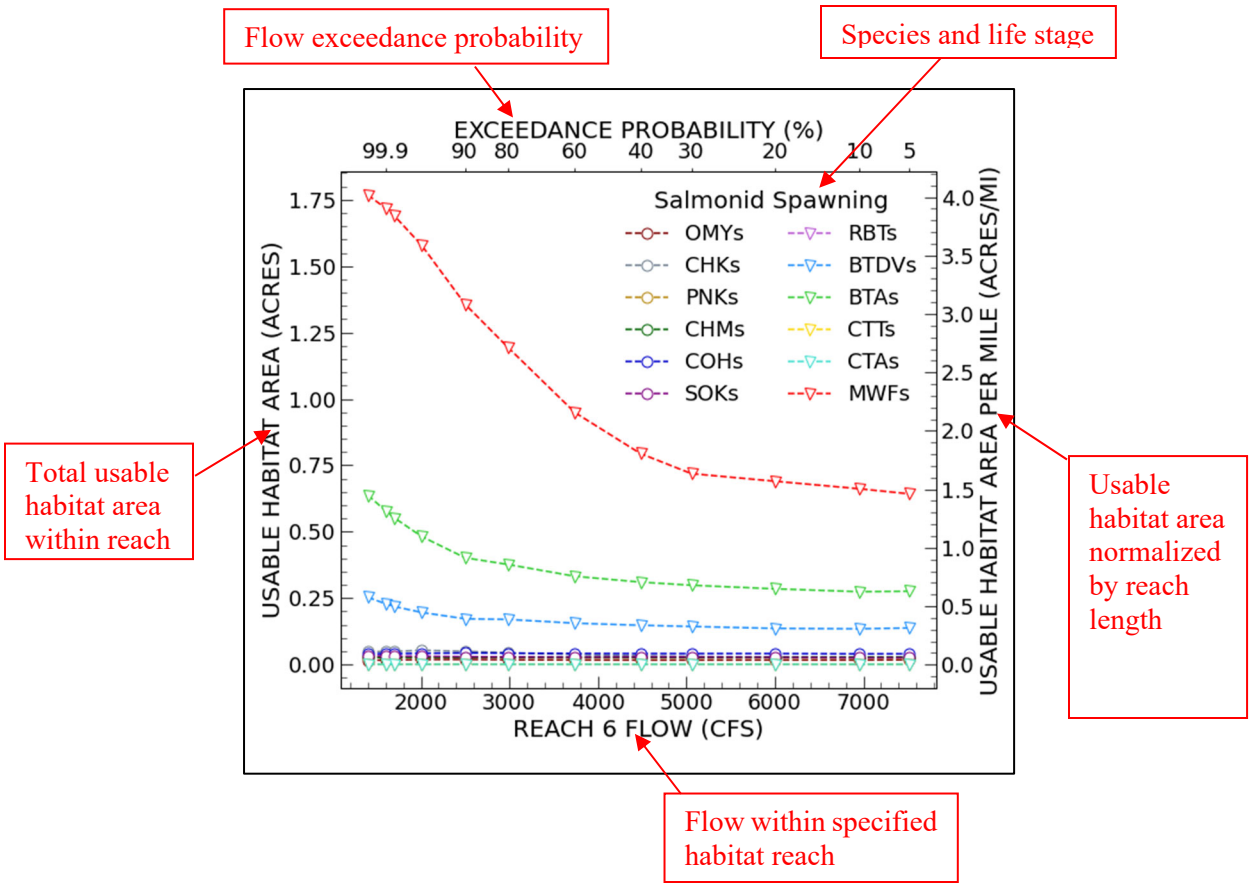
Usable Habitat Area Curves - Key



Usable Habitat Area Curves - Key



Usable Habitat Area Curves - Key



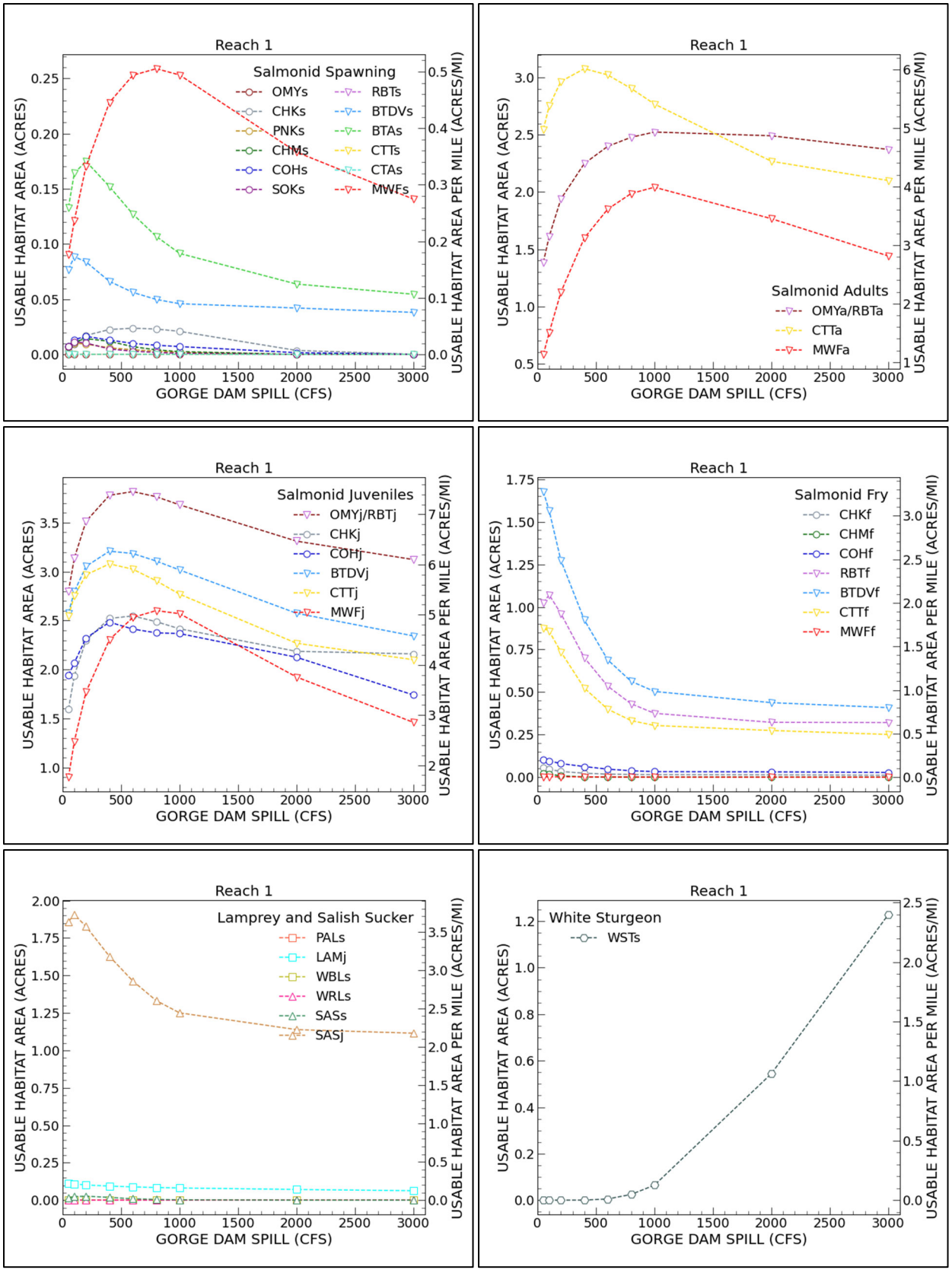


Figure 1. Gorge Bypass Reach 1 Usable Habitat Area Curves

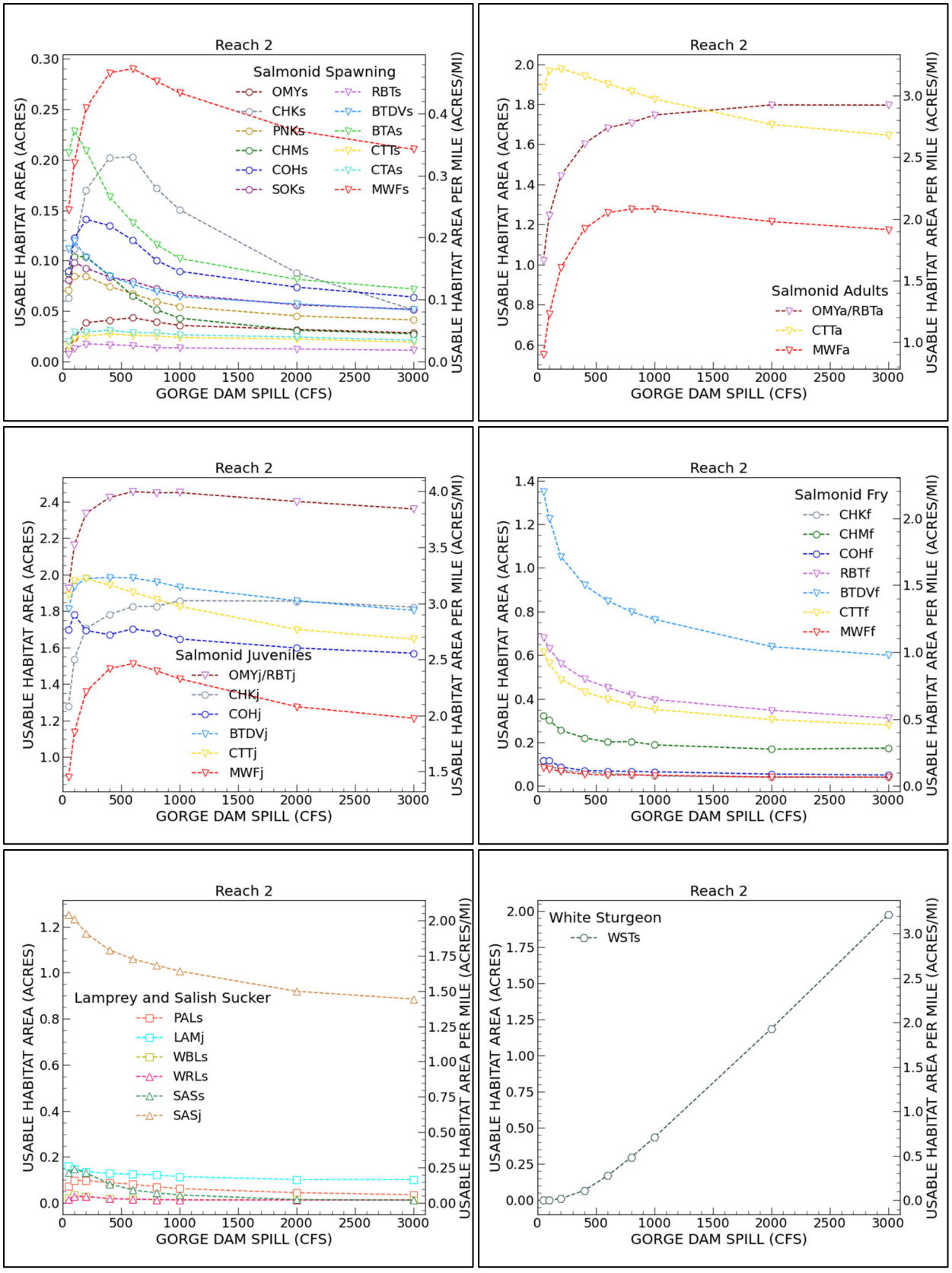


Figure 2. Gorge Bypass Reach 2 Usable Habitat Area Curves

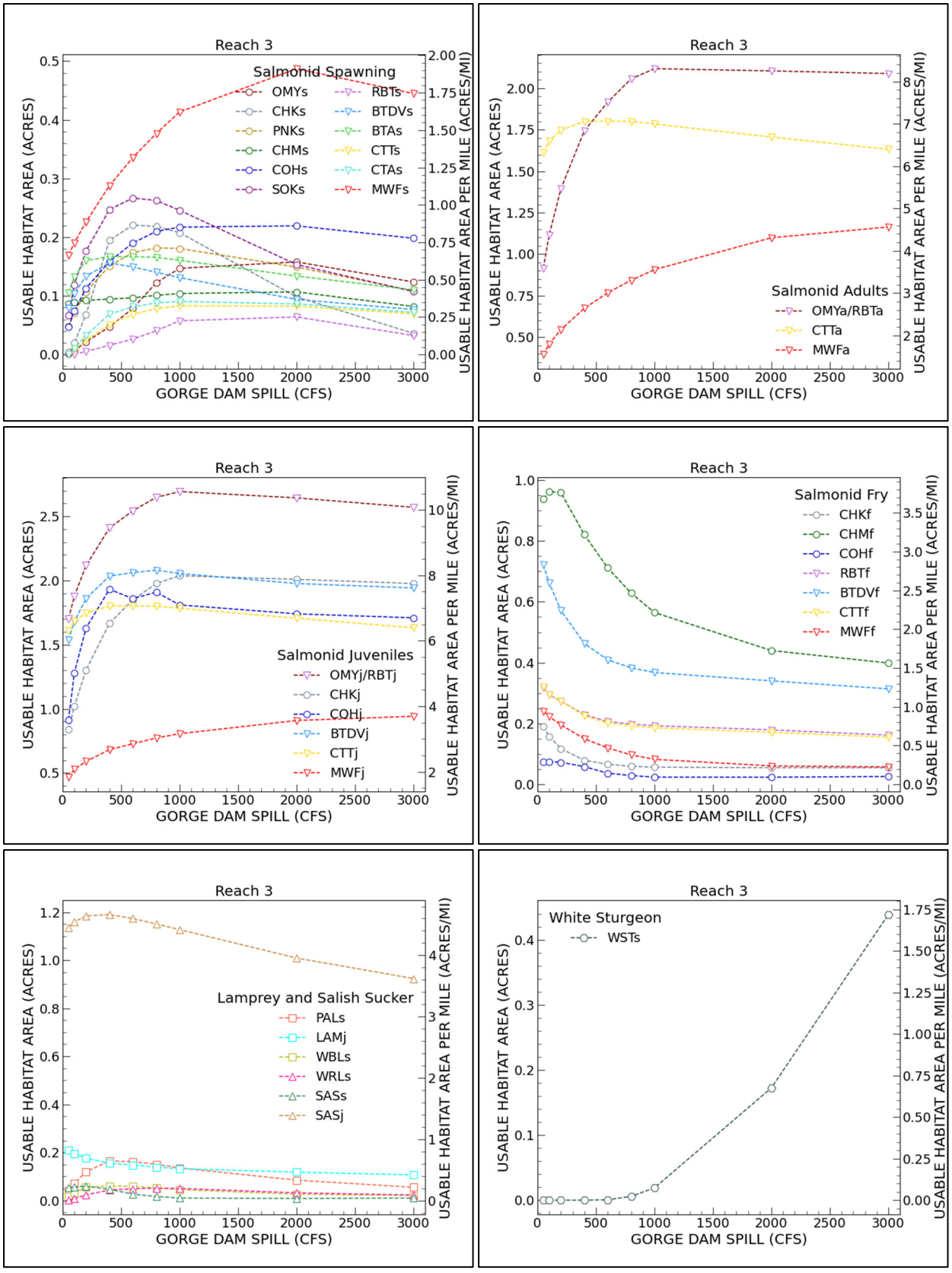


Figure 3. Gorge Bypass Reach 3 Usable Habitat Area Curves

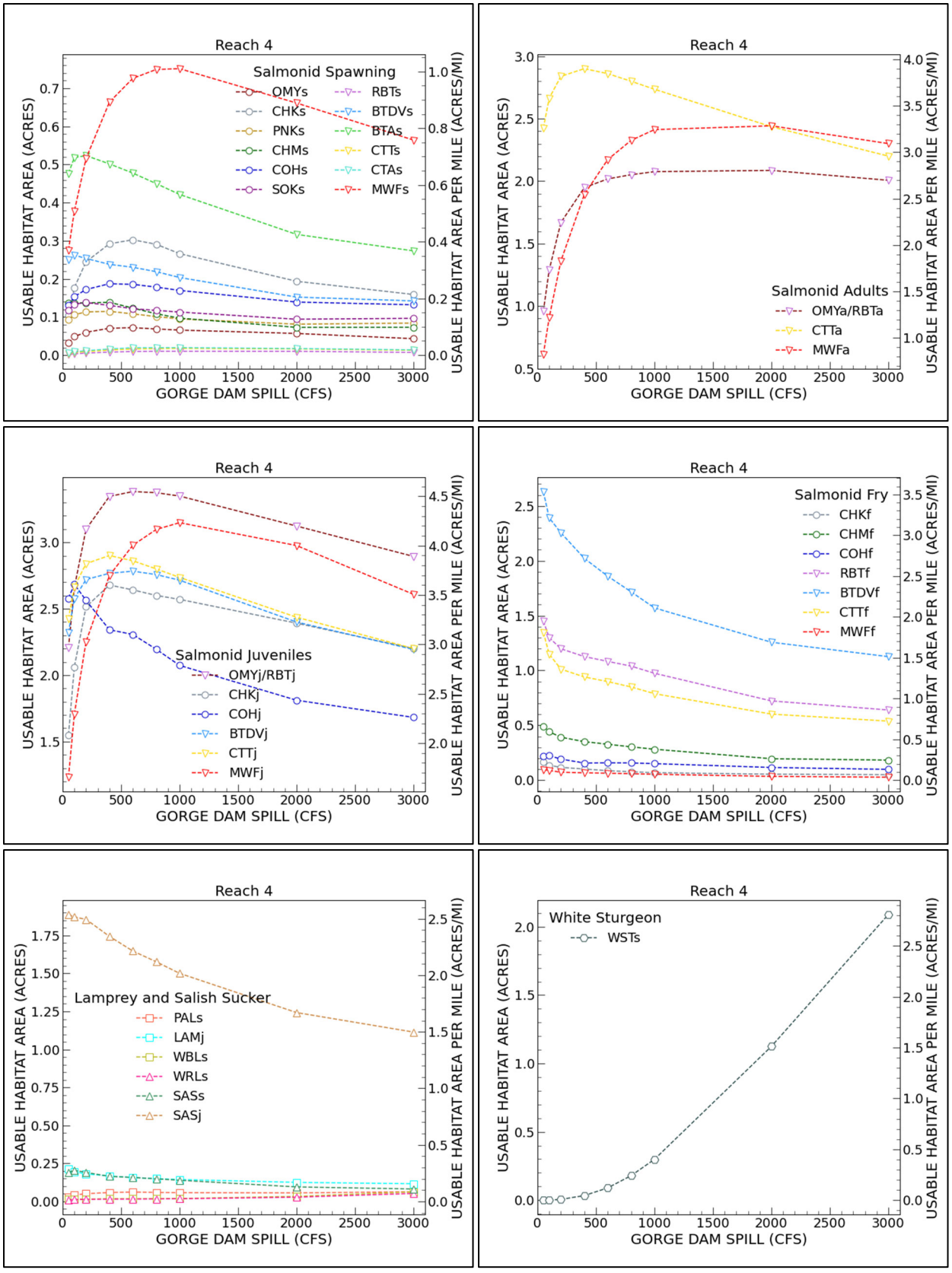


Figure 4. Gorge Bypass Reach 4 Usable Habitat Area Curves

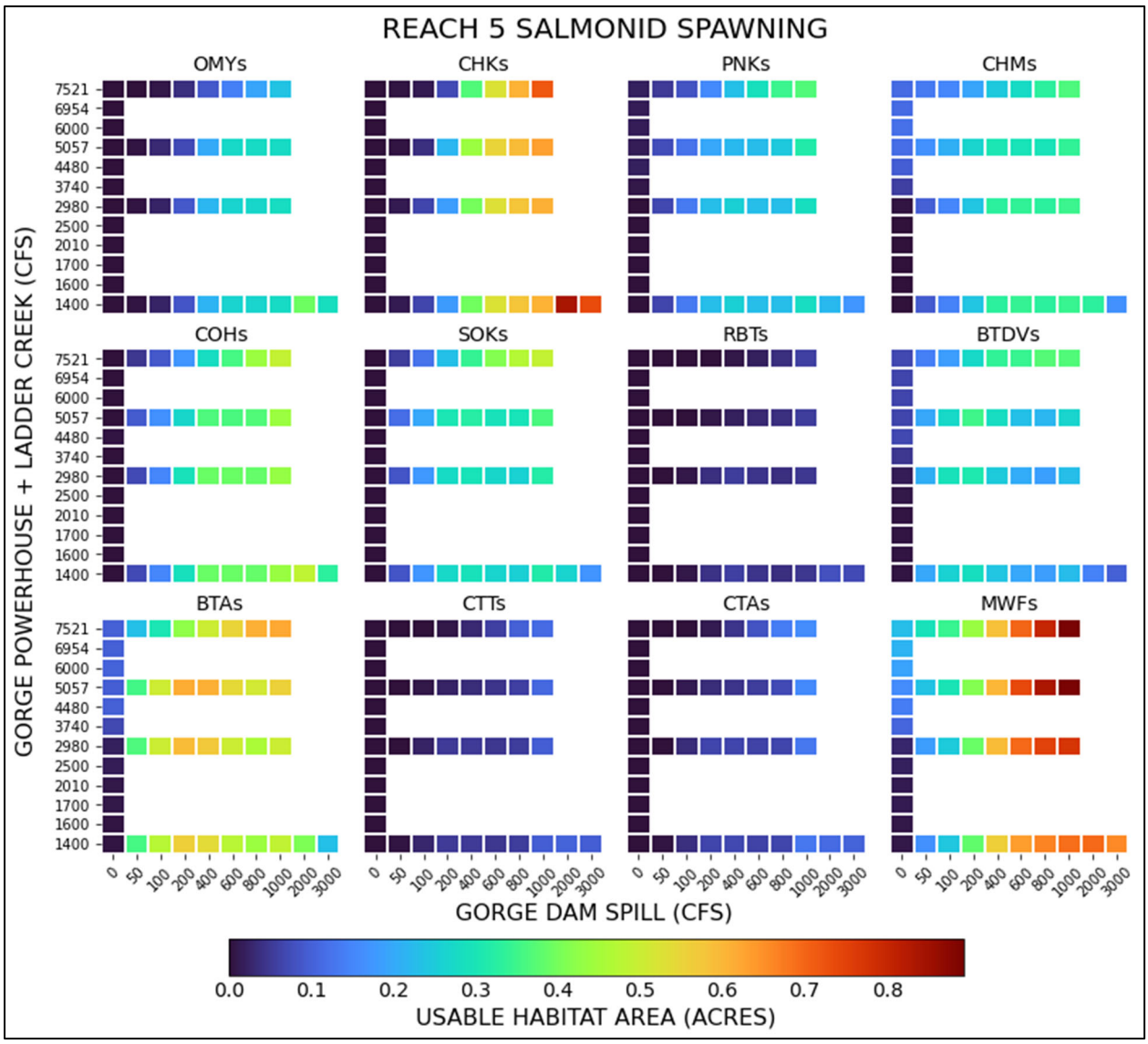


Figure 5a. **Gorge Bypass Reach 5 Usable Habitat Area Curves**

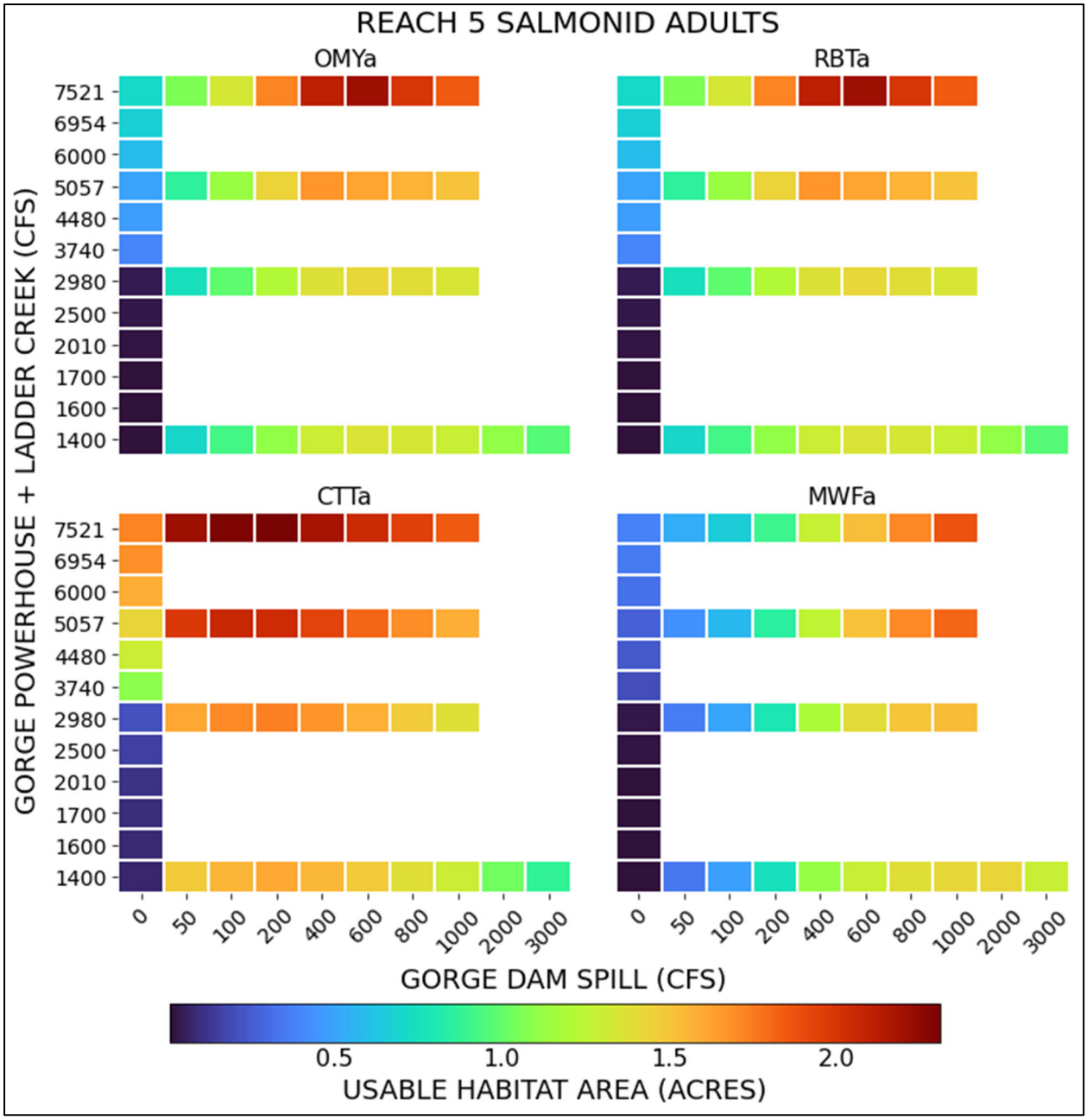


Figure 5b. **Gorge Bypass Reach 5 Usable Habitat Area Curves**

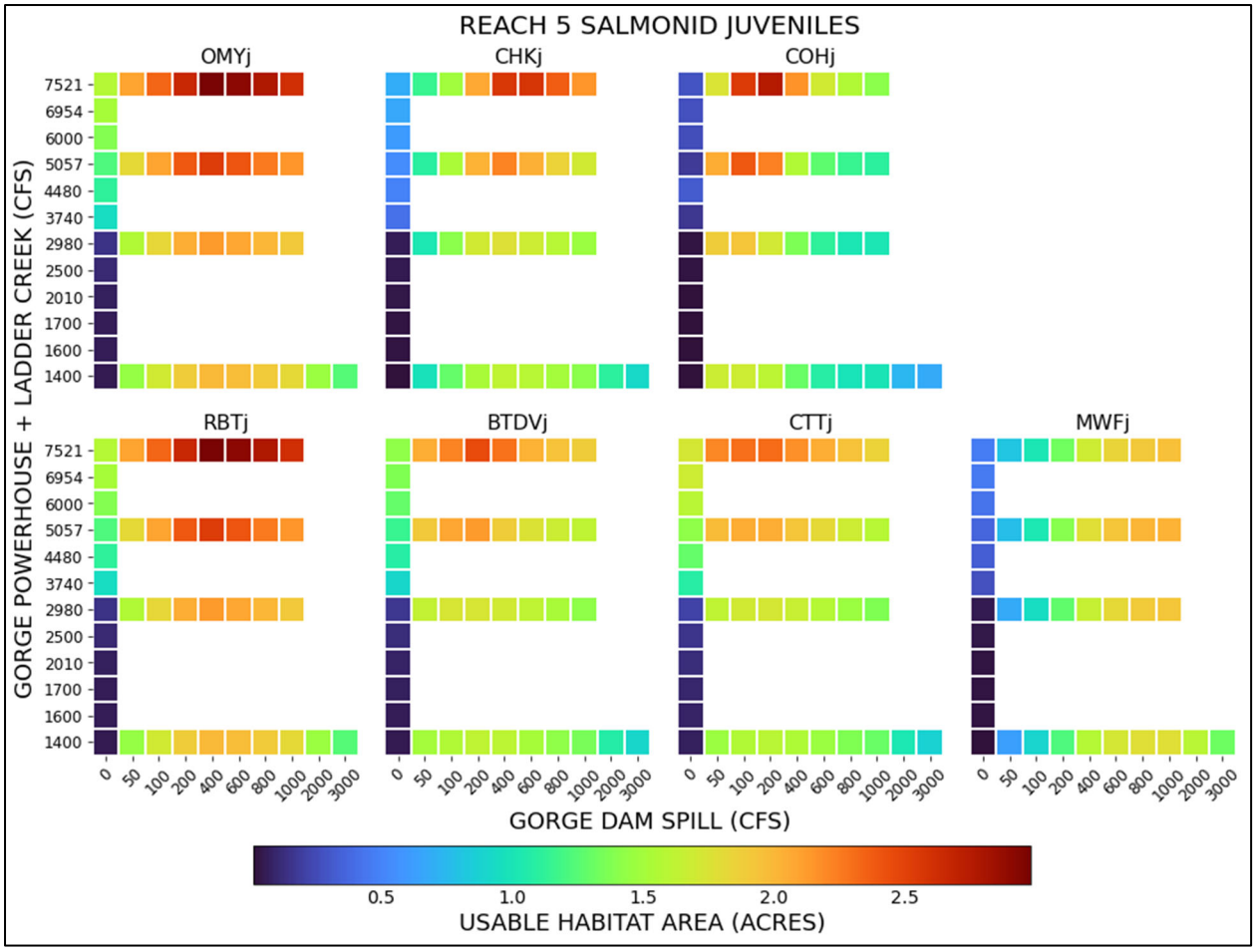


Figure 5c. Gorge Bypass Reach 5 Usable Habitat Area Curves

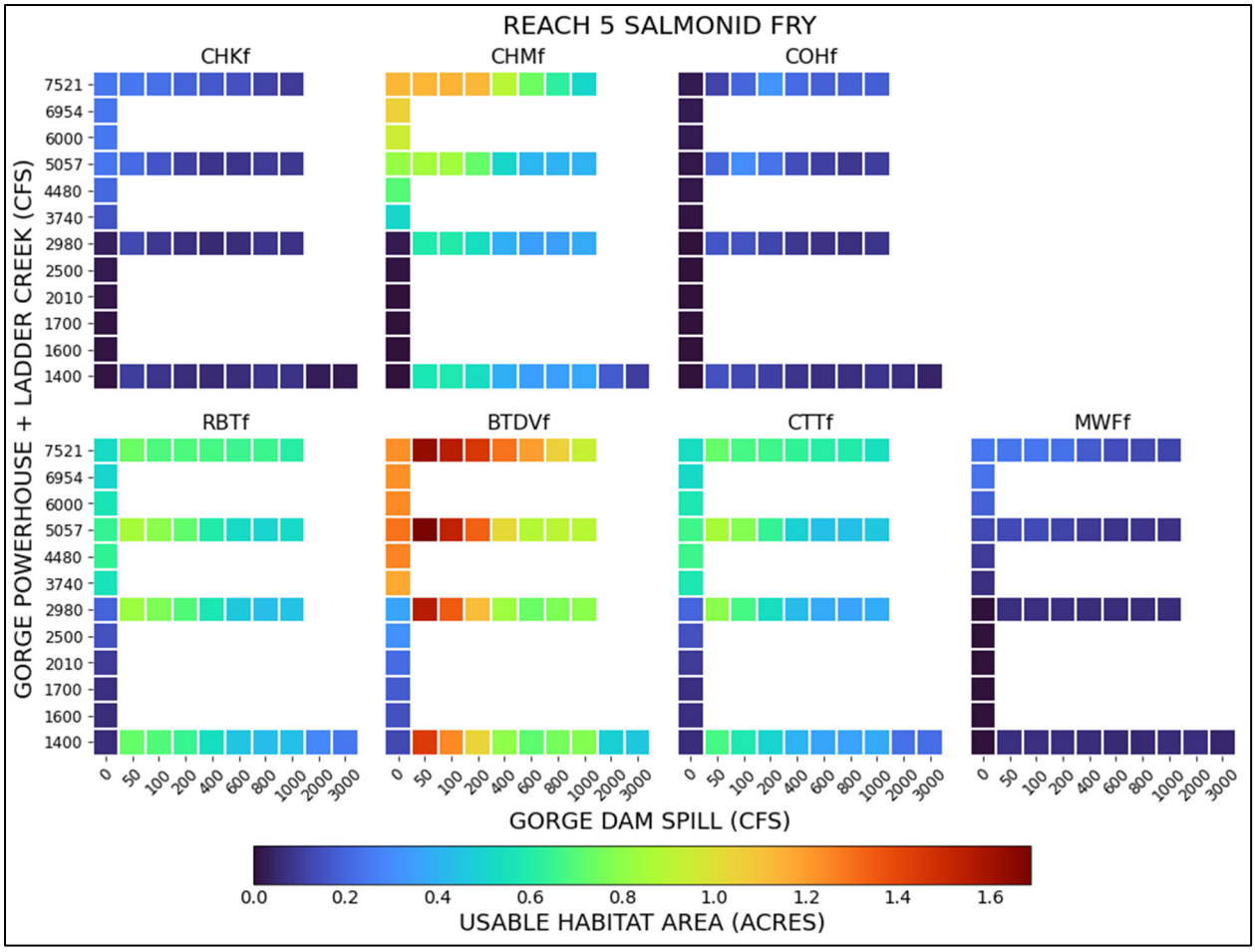


Figure 5d. **Gorge Bypass Reach 5 Usable Habitat Area Curves**

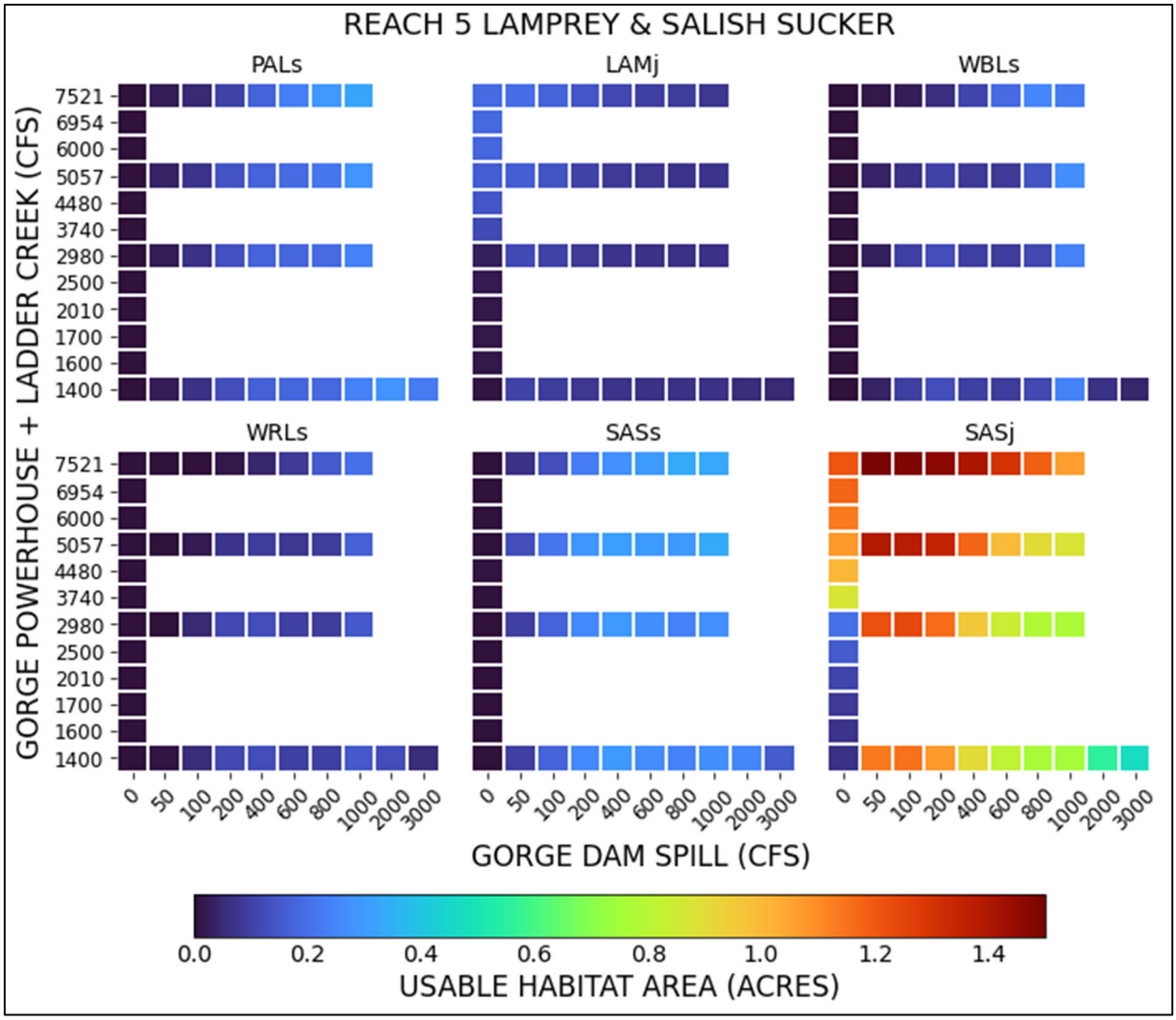


Figure 5e. **Gorge Bypass Reach 5 Usable Habitat Area Curves**

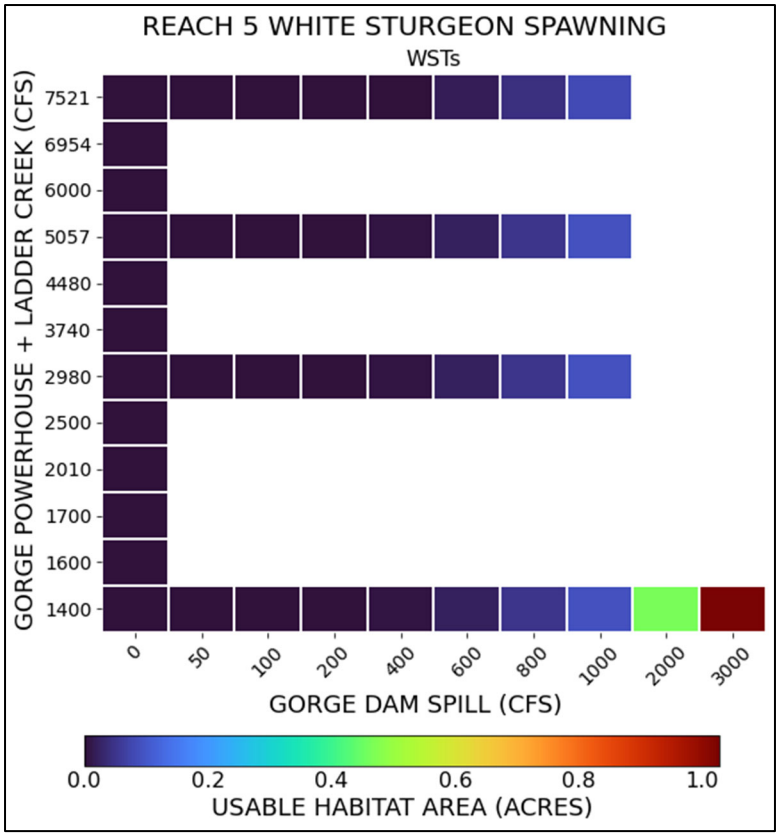


Figure 5f. Gorge Bypass Reach 5 Usable Habitat Area Curves

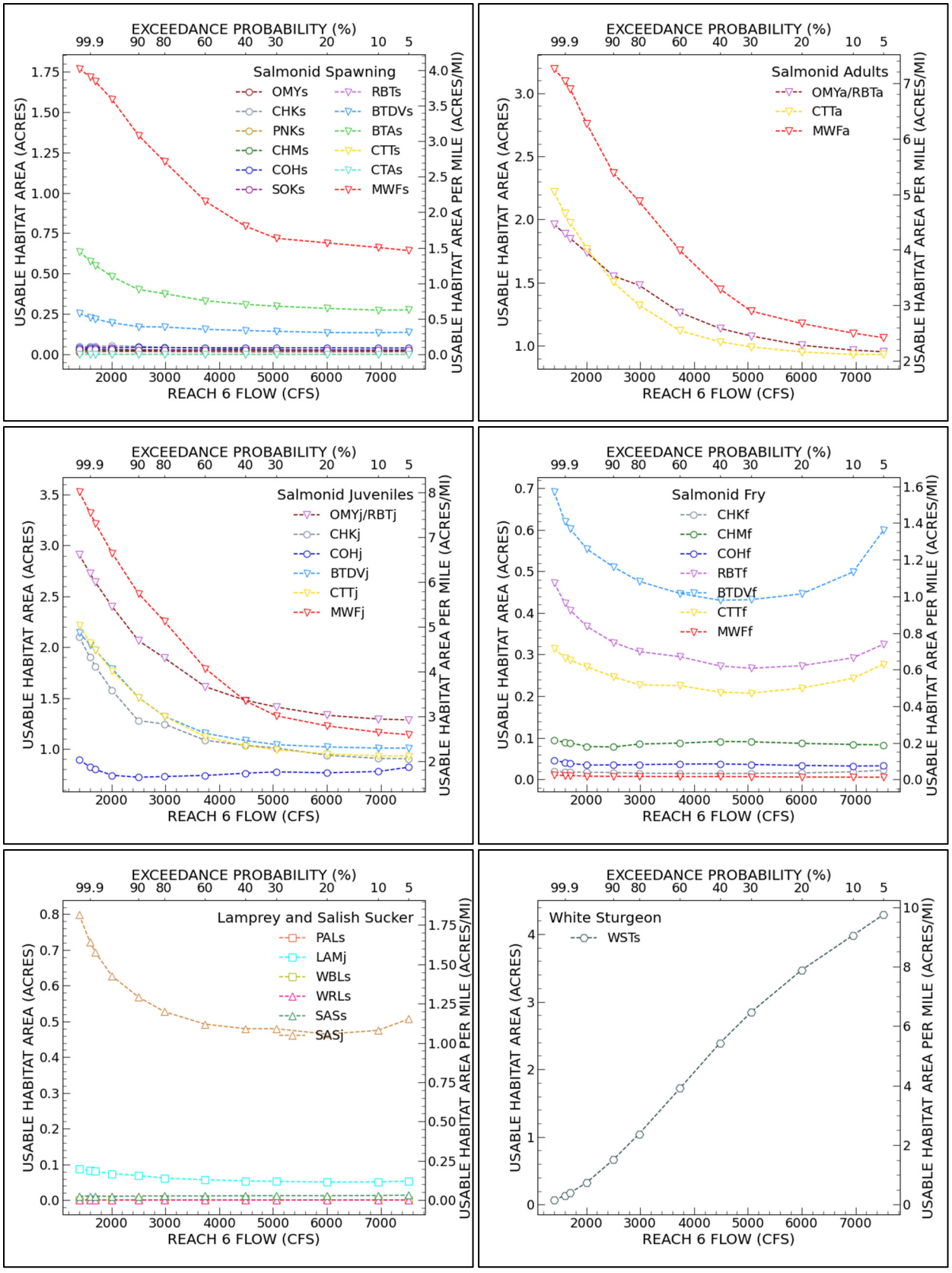


Figure 6. Gorge Bypass Reach 6 Usable Habitat Area Curves

SKAGIT RIVER GORGE BYPASS REACH HYDRAULIC AND INSTREAM FLOW MODEL DEVELOPMENT STUDY REPORT

ATTACHMENT F

EVALUATION OF THE NOVEMBER AND DECEMBER 2021 LARGE SPILLS ABOVE NEWHALEM

12787 Gateway Drive South | Seattle, WA 98168 | 206.241.6000 | www.nhcweb.com

nhc
northwest hydraulic consultants

MEMORANDUM

To: **Seattle City Light**

Date: March 2023

NHC Ref. No. 2003536

From: Chris Long, PE – NHC
Malcolm Leytham, PE – NHC
Theo Malone, PE – HDR Engineering, Inc.
Mike Garello, PE – HDR Engineering, Inc.
Ty Ziegler, PE – HDR Engineering, Inc.

Re: Evaluation of the November and December 2021 Large Spills above Newhalem

1.0 INTRODUCTION

Seattle City Light (City Light) owns and operates the Skagit Hydroelectric Project (Project). As part of the Federal Energy Regulatory Commission (FERC) relicensing, City Light is conducting the FA-05 Skagit River Gorge Bypass Reach Hydraulic and Instream Flow Model Development Study (Bypass Instream Flow Model Development Study) and FA-04 Fish Passage Technical Studies Program (FA-04 Fish Passage Study, City Light 2023a) studies to develop an updated flow-habitat evaluation tool and assess fish passage in the Gorge bypass reach of the Skagit River. Advance field work for both studies began in March 2021 with detailed hydraulic modeling complete by March 2022 to maintain compliance with the FERC's relicensing schedule. In November 2021 a series of floods caused by a "Pineapple Express"[1] resulted in extreme flows throughout parts of British Columbia and Washington State, including the Skagit basin. The Skagit River at Marblemount peaked at 63,400 cfs, second only to 64,800 cfs observed in 2003. The three City Light owned dams on the Skagit River controlled significant runoff, however stored water was eventually released sending near record flows through the Gorge bypass reach and downstream (Figure 1).

Limited impacts of the large spill within the Gorge bypass reach were first observed by the consultant team on December 21, 2021 while downloading recorded stages from 12 level loggers located in Existing Features 1 and 2. Four stilling tubes housing the instruments were completely missing and never recovered, two were damaged beyond repair but the instruments recovered, and one was discovered with the instrument still inside but as yet has not been extracted. Evidence of large boulder movement

[1] A type of atmospheric river characterized by concentrated corridors of warm water vapor transported across the Pacific coast of North America, resulting in heavy precipitation and generally a cause of high surface runoff events.

was evident throughout the Existing Features from displaced and/or missing stilling tubes to damaged anchor bolts. Using qualitative and quantitative methods, this memorandum assesses the potential effects to the aquatic habitat relationships and fish passage conclusions drawn from the Bypass Instream Flow Model Development Study and FA-04 Fish Passage Study, respectively.

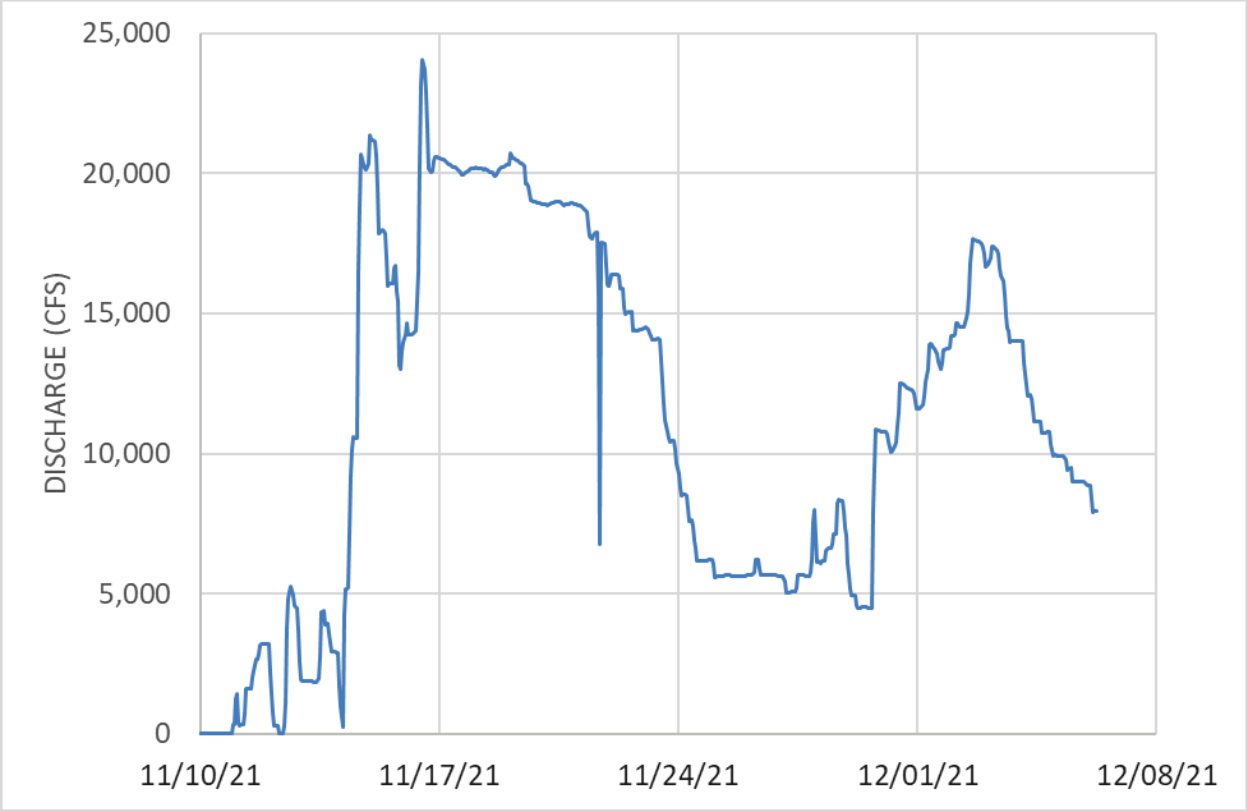


Figure 1. Gorge Dam spill from City Light records.

2.0 STUDY AREA

The study area of this desktop assessment coincides with the limits of the Bypass Hydraulic Model. The evaluation spans from Gorge Dam plunge pool at about Project River Mile (PRM) 97.15 downstream to the U.S. Geological Survey (USGS) Skagit River at Newhalem gage (USGS gage 12178000), approximately 0.5 miles downstream from Gorge Powerhouse at PRM 94.25 (Figure 2). Reach length is approximately 2.9 miles. This span encompasses Existing Features 1 and 2 which are the focus of the fish passage assessment objective under the FA-04 Fish Passage Study (City Light 2023a).

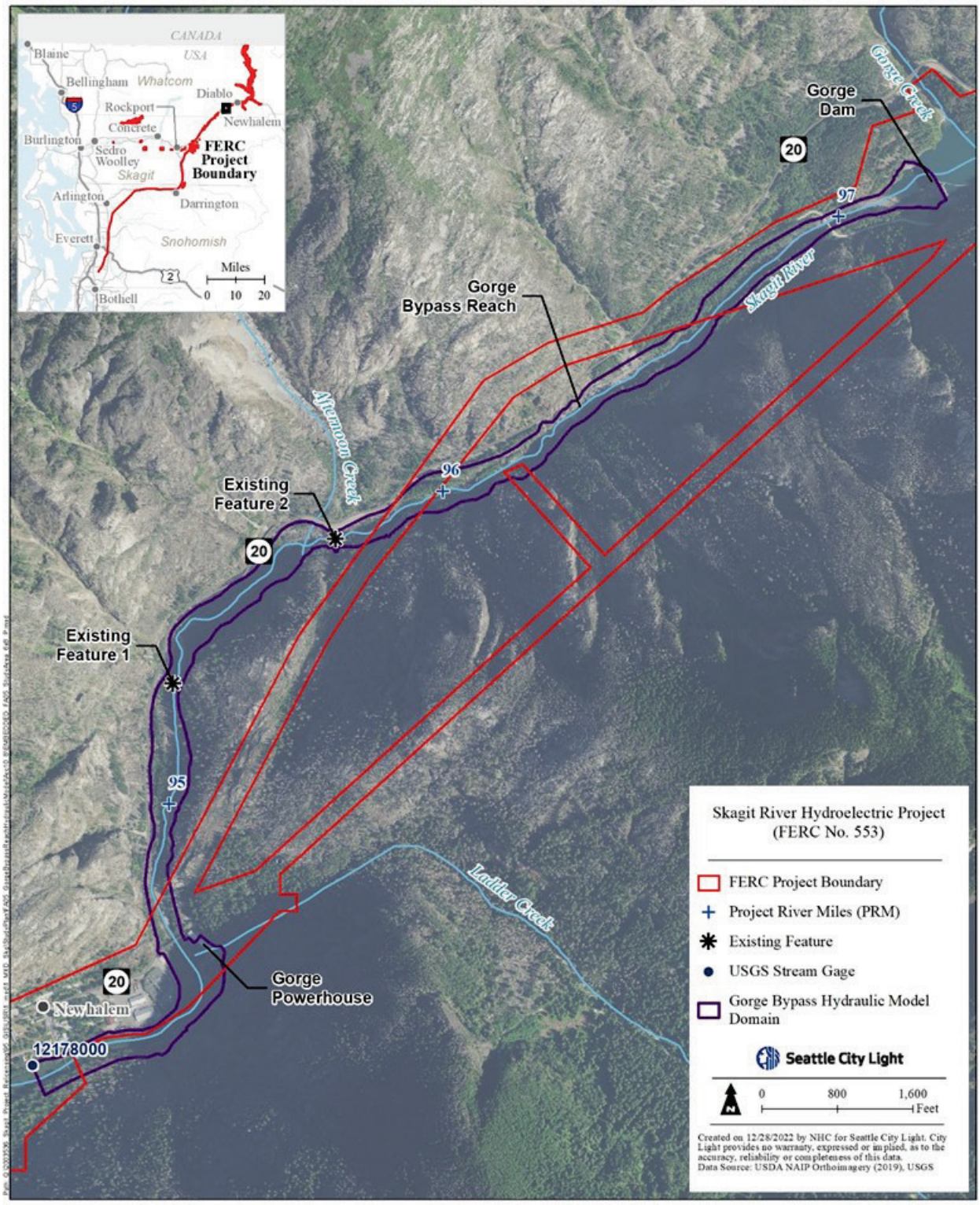


Figure 2. Overview of study area.

3.0 GOALS AND OBJECTIVES

The goal of this assessment is to evaluate the potential effects of the large spills through the Gorge bypass reach that occurred in November and December 2021 on the aquatic habitat evaluation developed under the Bypass Instream Flow Model Development Study and the fish passage assessment completed under the FA-04 Fish Passage Study (City Light 2023a). The specific objectives include:

- Reviewing the Bypass Instream Flow Model Development Study usable habitat area (UHA) versus flow curves (pre-flood) and qualitatively assessing likely impacts to habitat in select reaches;
- Looking for changes to hydraulic controls in Existing Features 1 and 2 by plotting pre- and post-flood 2021 water surface elevation (WSE) vs discharge pairs at select level loggers; and
- Visually identifying boulders that moved within the Existing Features and qualitatively assessing anticipated impact on upstream fish passage.

4.0 METHODS AND RESULTS

The following sections describe the methods used to assess the potential effects of the late 2021 large spills and summarize the results on instream flow-habitat relationships and upstream fish passage.

4.1 Habitat Modeling

For habitat modeling purposes, five habitat reaches (Reaches 1 – 5) were established in the Gorge bypass reach extending from Gorge Dam downstream to the Gorge Powerhouse. Preliminary analysis of UHA in the Gorge bypass reach is shown in Figure 3 below.

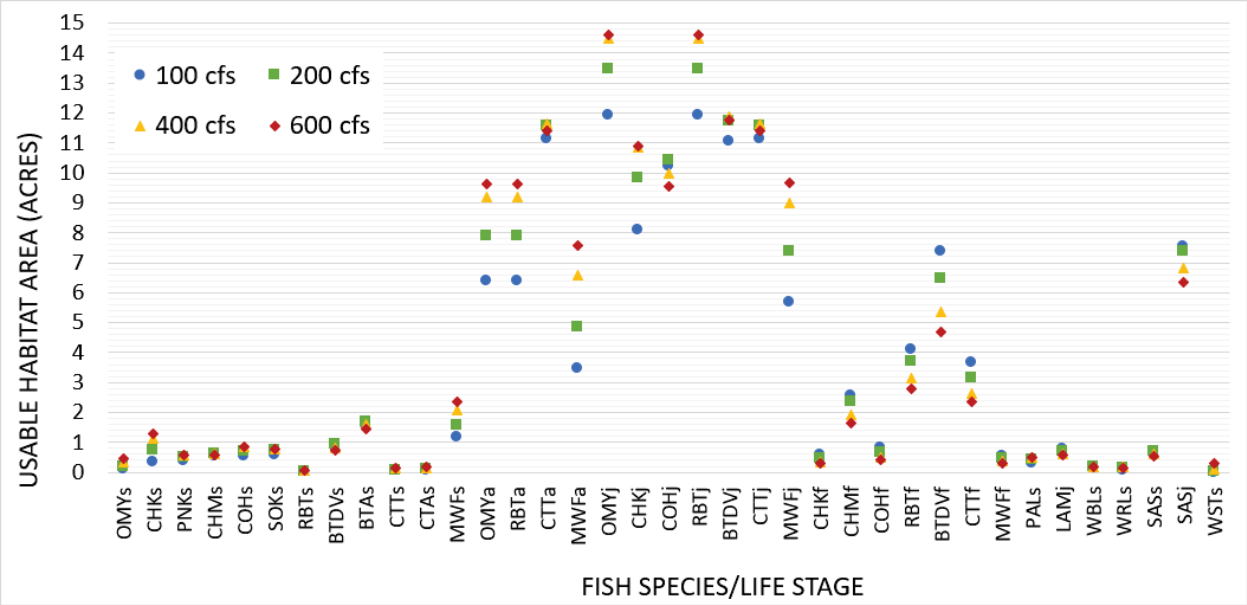


Figure 3. Usable Habitat Area in the Gorge bypass reach (Reaches 1 – 5 combined).

While these results are based on substrate and cover mapping prior to the November 2021 flood event, it is notable that under a range of flow conditions (100 CFS, 200 CFS, 400 CFS, 600 CFS), useable habitat does not vary significantly in the Gorge bypass reach. In particular, very little salmonid spawning habitat is available in the 100-600 CFS flow range (i.e., generally less than 2 acres). Available fry habitat is marginally better at less than 4 acres (with the exception of Bull Trout/Dolly Varden fry at 5 – 8 acres). Most of the available habitat in the Gorge bypass reach in the 100-600 CFS flow range supports adult and juvenile salmonids ranging from 3-15 acres depending on species and life stage.

The amount of available habitat in the Gorge bypass reach (albeit relatively low compared to the Upper Skagit River reach below Gorge Powerhouse) is fairly evenly distributed as shown by the individual UHA curves (by species, life stage, and Reach) provided in Appendix A for habitat Reaches 1 – 4. Evaluating potential effects on available habitat in Reaches 1 – 4 is the focus of this analysis because this portion of the Gorge bypass reach is relatively steep and narrow with larger substrate sizes (i.e., small and large boulders and cobbles) which can become dislodged and move downstream during flood events like those

experienced during November 2021. Reach 5 is located just upstream from the Gorge Powerhouse, has a lower gradient (compared to Reaches 1 – 4), and is affected by backwater from Gorge Powerhouse operations. As a result, the potential for habitat-related impacts to Reach 5 stemming from flood events is likely less than the upstream habitat reaches.

Substrate preference values for salmonids is provided in Appendix B (Beecher and Caldwell 2022). Preference values range from "0.00" indicating zero preference (i.e., no available habitat) to "1.00" indicating preferred substrate type. Spawning salmonids generally prefer substrate sizes ranging from small gravels to large cobbles with a maximum preference (i.e., 1.00) for medium and large gravels and small cobble. Substrate sizes in the Gorge bypass reach are generally larger than salmonid spawners prefer which is in part why very little available habitat is present in the Gorge bypass reach for this life stage. Adult, juvenile, and fry salmonids prefer larger substrate types (small and large cobbles and boulder) and as a result have relatively more available habitat in the Gorge bypass reach.

While large flood events such as those experienced during November 2021 may result in dislodgement and movement of larger substrates, the overall effect on habitat suitability would be minimal. These larger substrates are preferred by adult, juvenile, and fry life stages because they provide velocity shelters in steep gradient streams (like the Gorge bypass reach) as well as instream cover for smaller fish. While the location of the habitat may change based on substrate movement, the amount and suitability of habitat that is provided by that substrate would only change marginally, if at all. And considering the UHA curves represent the flow-habitat relationship for an entire reach, the effect of a localized shift in habitat location within the reach would have little to no effect on the UHA curves for a given habitat reach within the Gorge bypass reach.

4.2 Existing Features Level Loggers

Twelve automatic water level recorders (hereinafter level loggers) were installed at Existing Features 1 and 2 in May 2021, with six level loggers at each Existing Feature. The level loggers recorded water stage for use in calibration of the Bypass Hydraulic Model and to support fish passage assessment as part of the FA-04 Fish Passage Study.

The level loggers were numbered DDL1 through DDL6 at the downstream Existing Feature 1, and UUL1 through UUL6 at the upstream Existing Feature 2. The selected logger locations, shown in Figure 4 and Figure 5 for Existing Feature 1 and Existing Feature 2 respectively, provide water levels that (1) represent nominally stable pools at each Existing Feature and (2) span the entire length of each Existing Feature, providing a comprehensive, longitudinal water surface profile.

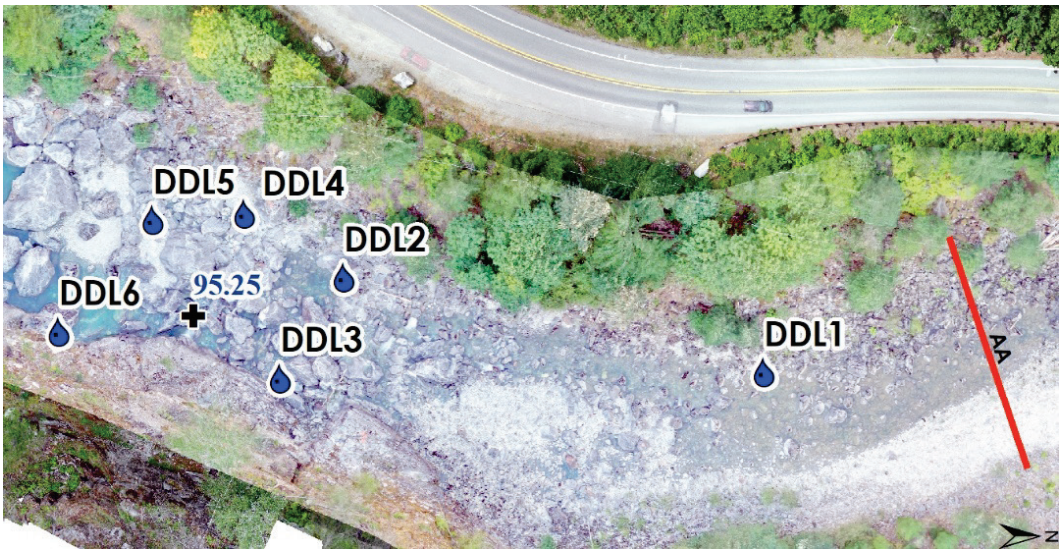


Figure 4. Water level logger locations at Existing Feature 1.

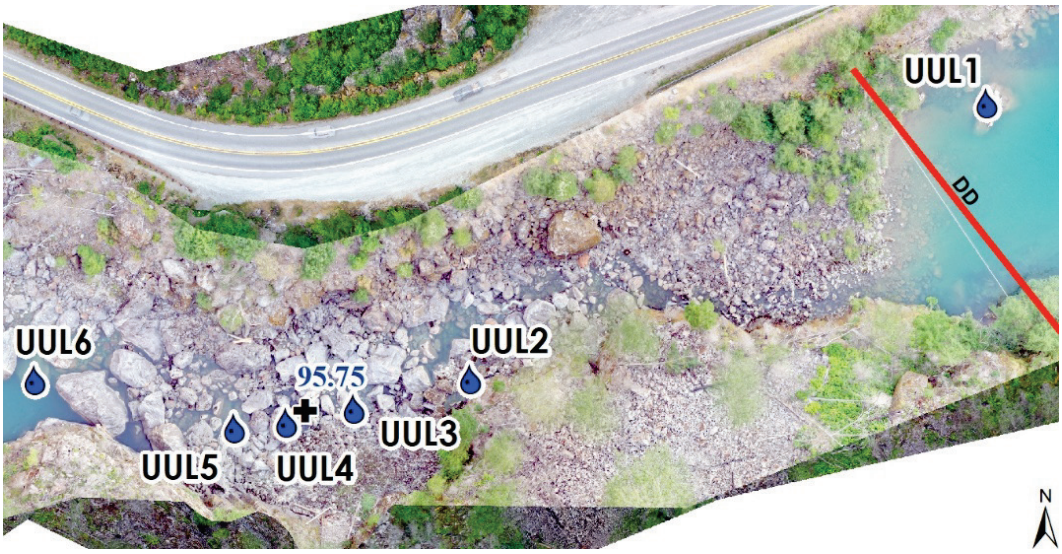


Figure 5. Water level logger locations at Existing Feature 2.

Water levels have been collected by the level loggers since May 27, 2021. The stages were initially captured at ten-minute intervals from May 27, 2021 through July 25, 2021, at which time the interval was decreased to five-minute, primarily for consistency with the recording interval at the USGS Skagit River at Newhalem stream gage (USGS 12178000). Data were downloaded and processed approximately monthly through December 2021. At the December 2021 download, the recording interval was increased to 15-minute to allow the loggers to operate for longer periods between downloads without loss of data.

Further details of the level loggers and their deployment are provided in the Gorge Bypass Reach Data Collection for Hydraulic Model Calibration Memorandum (NHC 2022; Attachment D to the Bypass Hydraulic Model Calibration Report [Attachment A to the Bypass Instream Flow Model Development Study]).

The November 2021 flood event resulted in significant damage to the network of level loggers, with 7 of original twelve level loggers being either destroyed or damaged to the extent that they were no longer usable. Of the five level loggers which survived the flood (DDL1, DDL2, and DDL3 at Existing Feature 1, and UUL1 and UUL6 at Existing Feature 2), three (DDL1, DDL2 and UUL6) sustained little or no damage and continue to operate, and the remaining two (DDL3 and UUL1) sustained minor damage but also continue to operate.

To assess the impact of the November 2021 flood event on hydraulic conditions in the Existing Features, a comparison was made between pre- and post-flood WSE-discharge relationships for the five level loggers which survived the flood.

Pre-flood WSE and discharge data were selected for two periods:

- June 28 – July 3, 2021. This was a period of sustained spill from Gorge Dam during the early summer 2021 snowmelt freshet, providing data over a relatively wide range of discharges from roughly 120 cfs to 7,500 cfs.
- July 26 – 29, 2021. This was the period of controlled releases from Gorge Dam during which detailed measurements were made of discharge and other hydraulic parameters necessary for calibration of the Bypass Hydraulic Model. WSEs and discharge were measured for four controlled releases ranging from nominally 50 cfs to 1,200 cfs. The data collection program during the period of controlled releases is described in the Gorge Bypass Reach Data Collection for Hydraulic Model Calibration Memorandum (NHC 2022; Attachment D to the Bypass Hydraulic Model Calibration Report [Attachment A to the Bypass Instream Flow Model Development Study]).

Post-flood WSE and discharge data were also selected for two periods:

- April 8 – 10, 2022. This was a period of small spills from Gorge Dam with discharges ranging from roughly 150 cfs to 700 cfs. This period was included in the analysis to provide for a lower range of flows than was available during other post-flood spills.
- June 29 – July 9, 2022. This was a period of sustained spill from Gorge Dam during the early summer 2022 snowmelt freshet, providing data over a range of discharges from roughly 250 cfs to 6,700 cfs.

With the exception of data for the period of controlled releases (July 26 – 29, 2021), discharge data were taken from Gorge Dam spill records provided by City Light. The spill data are instantaneous values reported at an hourly interval and computed by City Light from Gorge Lake water levels and the Gorge Dam spillway gate opening. Gorge Dam has two 50-foot-high by 47-foot-wide fixed wheel spillway gates. For small spills, the magnitude of spill is sensitive to the precise spillway gate opening. For example, at a typical reservoir operating level, spill of 240 cfs requires that one spillway gate be opened by only 1.5 inches; a 0.25-inch variation in that gate opening translates into a 20 percent variation in spill. Small spill values are therefore of uncertain accuracy.

To approximately account for the travel time between Gorge Dam and the Existing Features, the WSE data from the level loggers were shifted 30 minutes relative to the hourly spill data. In reviewing concurrent spill and WSE observations it was noted that it typically takes over an hour for WSEs to stabilize following

an abrupt change in spill. The spill data were therefore also filtered to remove values for the hour after an abrupt increase or decrease in spill.

For the period of controlled releases (July 26 -29, 2021), discharge data were taken directly from the field measurements in lieu of spill records.

Plots of WSE against concurrent discharge (WSE-discharge pairs) are provided for Existing Feature 1 (level loggers DDL1, DDL2 and DDL3) in Figure 6, and for Existing Feature 2 (level loggers UUL1 and UUL6) in Figure 7.

Examination of Figure 6 and Figure 7 shows no discernable shift between pre- and post-flood WSE-discharge relationships for level loggers DDL1, DDL2, UUL1 and UUL6. For DDL3 (bottom panel Figure 6), post-flood WSEs appear to trend up to 0.5 feet lower than pre-flood WSEs for discharges in the range 700 cfs to 3,000 cfs. There is also an indication of a similar shift for discharges less than 200 cfs. However, as noted earlier, the accuracy of the discharge data (i.e., the reported spill from Gorge Dam) is uncertain at these low rates; the apparent shift may in part be related to that uncertainty.

The possible shift in the WSE-discharge relationship at logger DDL3 is considered insignificant relative to other sources of uncertainty affecting hydraulic model performance and evaluation of fish passage within the Existing Features.

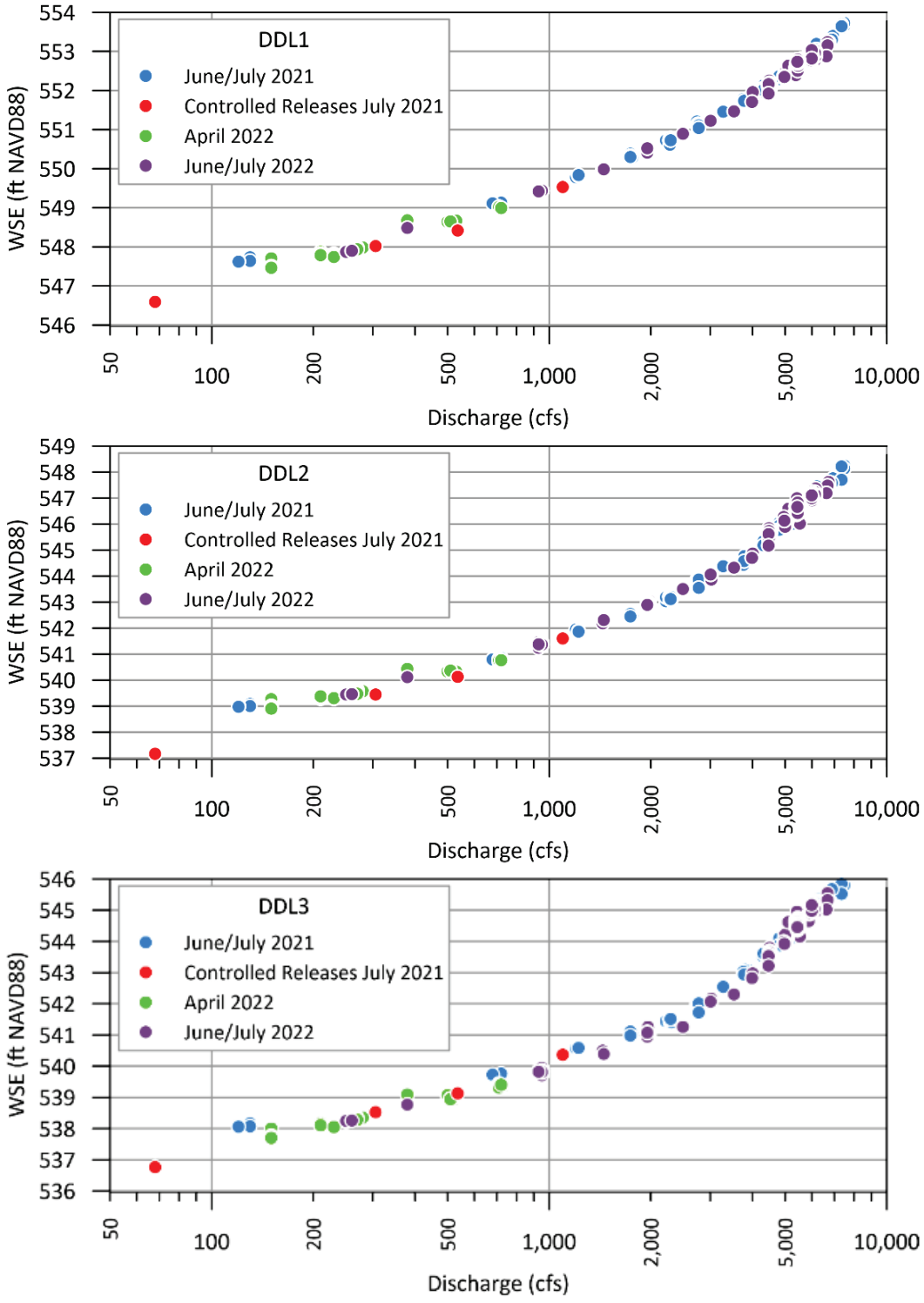


Figure 6. **WSE-discharge pairs from Existing Feature 1, level loggers DDL1 (top), DDL2 (middle), and DDL3 (bottom).**

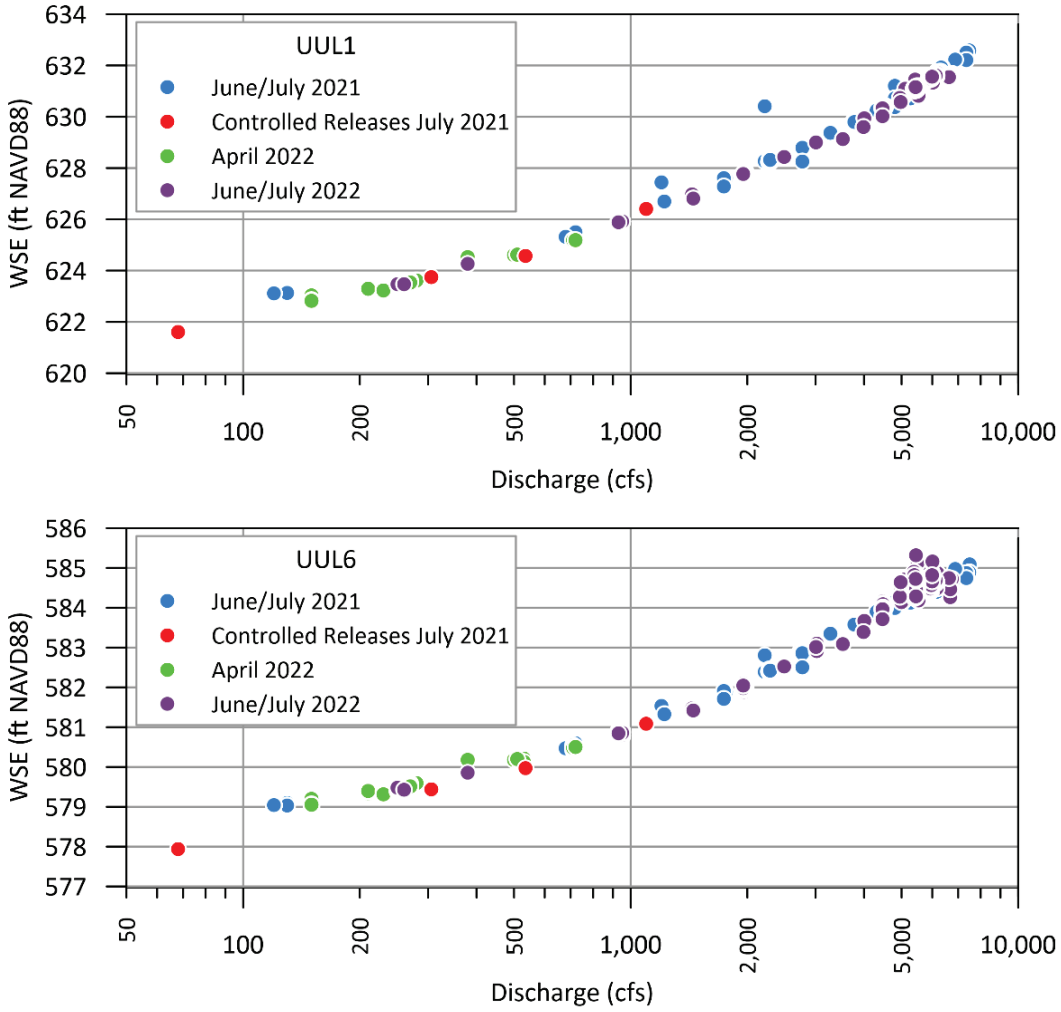


Figure 7. **WSE-discharge pairs from Existing Feature 2, level loggers UUL1 (top) and UUL6 (bottom).**

4.3 Fish Passage

4.3.1 Substrate Change Analyses

The following sections provide descriptions of analyses performed to estimate the location and magnitude of significant changes in substrate within the Existing Features. These analyses use aerial photography and LiDAR surface data to identify potential locations of significant change.

Surface Comparison

LiDAR datasets from 2018 and 2022 were available for the Gorge bypass reach. The 2018 LiDAR data for the Gorge bypass reach was collected by Quantum Spatial, Inc. (QSI) on April 26, 2018 (QSI 2018). The 2022 LiDAR data was collected by NV5 on April 29, 2022 and processed as part of the GE-04 Geomorphology Study (City Light 2023b). After processing the 2022 LiDAR data, it was determined that

72 percent of the bathymetric coverage in the Gorge bypass reach consisted of voids as compared to 12 percent for the 2018 dataset (Table 1). Thus, the 2022 LiDAR data was not sufficient for use in technical analyses. Table 1 provides a comparison summary of the 2018 and 2022 LiDAR datasets.

Table 1. 2018 and 2022 LiDAR data comparison summary for the Gorge bypass reach.

Dataset	Date Collected	Bathymetric Coverage (acres)	Covered		Void		Average Spill through Gorge bypass reach (cfs)
			(acres)	(percent)	(acres)	(percent)	
2018 Gorge bypass reach LiDAR	4/26/2018	24.7	21.8	88	2.9	12	0
2022 Gorge bypass reach LiDAR	4/29/2022	46.0	13.0	28	33.0	72	2,186

The observed differences in the 2018 and 2022 LiDAR datasets can be explained by Project spill operations occurring through the Gorge bypass reach on April 29, 2022 during the time of data collection. The presence of turbid/turbulent water in the Gorge bypass reach during this period when data collection occurred, significantly limited LiDAR ground returns and thus provided areas where ground terrain data was not collected. The Project was not spilling through the Gorge bypass reach during the 2018 data collection period. The lack of water and exposed ground features resulted in more extensive LiDAR ground returns and better collection of ground terrain data.

To add additional detail to the 2022 LiDAR surface, elevation data was generated from stereo photos to help characterize the ground in the Gorge bypass reach. Stereo photos were taken using a Vexcel Eagle M3 camera and the data was processed using automatic triangulation software to generate an unclassified elevation point cloud from the photos. The photos were collected when the water surface elevation was about 6 feet lower than when the LiDAR was collected, thus, more of the river bottom was exposed. Preliminary results were initially promising and indicated that the post-processing efforts of the point cloud data were able to add significant detail to the 2022 model of the river channel in the Gorge bypass reach, with limitations in shaded areas and areas with deeper water (greater than 10 feet in depth). However, upon further review and comparison with the 2018 imagery, 2018 LiDAR, and 2022 imagery, the DEM difference raster showing the elevation differences between the 2018 LiDAR and the 2022 reprocessed elevation data exhibited patterns of geomorphic change that were not consistent with the visual interpretation of aerial imagery for the two periods i.e., there were various locations throughout the Gorge bypass reach that seemed biased towards predicting degradation or aggradation which were not supported through visual comparison of the imagery. Figure 8 and Figure 9 depict the comparison of the 2018 imagery, 2018 LiDAR, 2022 imagery, and 2018-2022 DEM difference raster for the reaches of the Gorge bypass reach that encompass Existing Features 1 and 2, respectively.

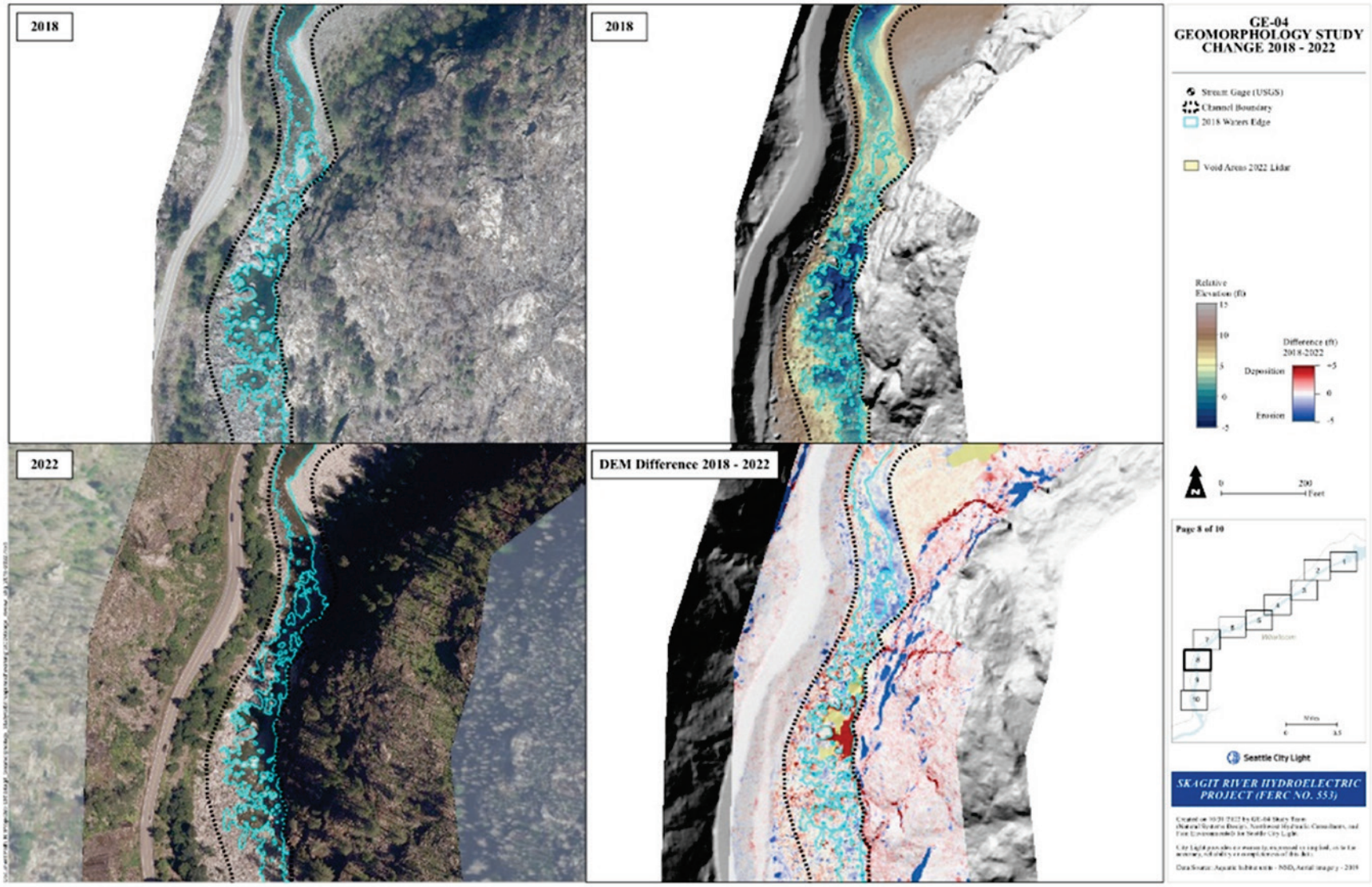


Figure 8. **Comparison of 2018 imagery, 2018 LiDAR, 2022 imagery and 2018-2022 DEM difference raster for reach containing Existing Feature 1 (GE-04 Study Team 2022).**

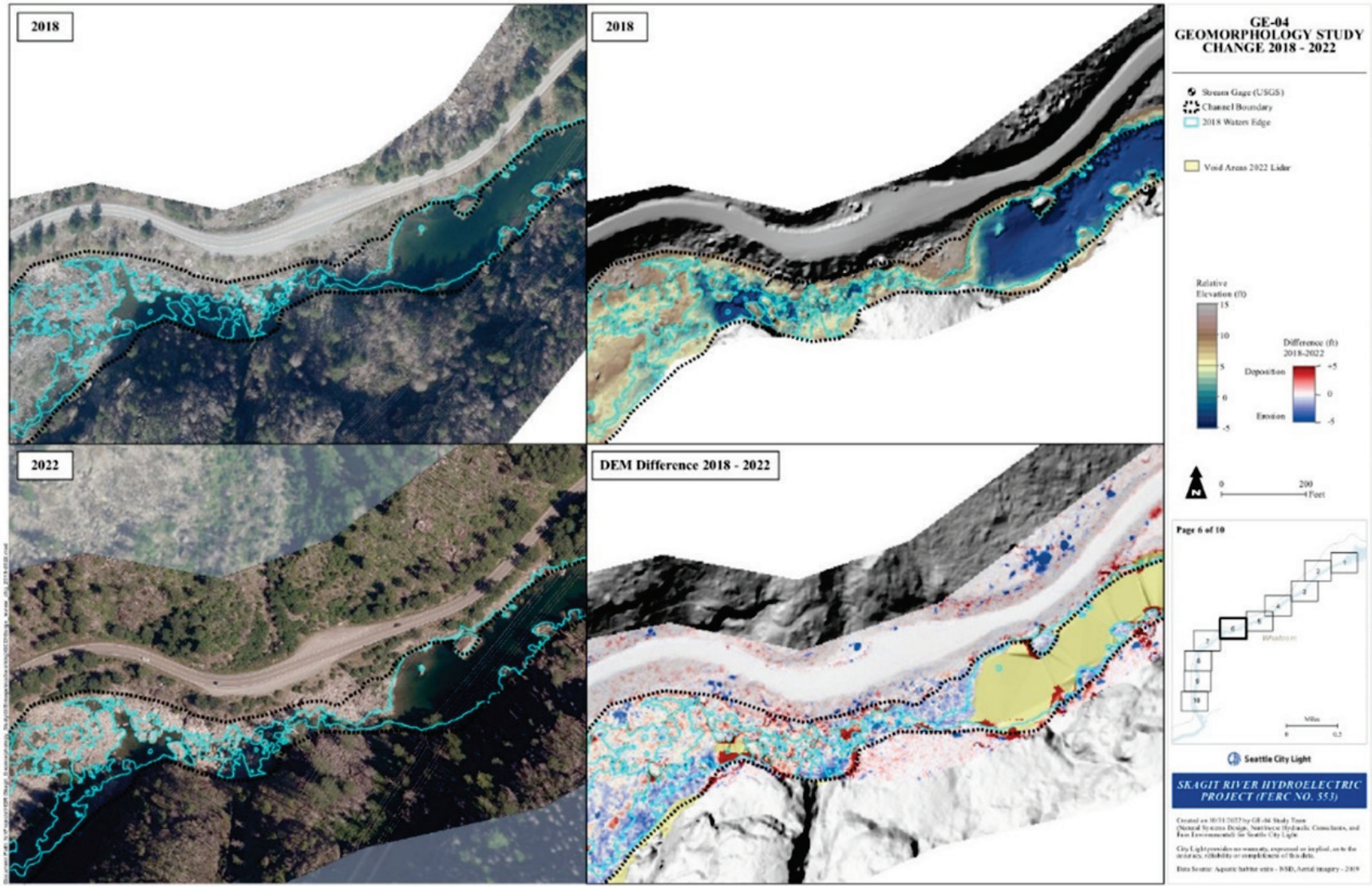


Figure 9. **Comparison of 2018 imagery, 2018 LiDAR, 2022 imagery and 2018-2022 DEM difference raster for reach containing Existing Feature 2 (GE-04 Geomorphology Study; City Light 2023b).**

Due to these inconsistencies in observed geomorphic change between the imagery and reprocessed elevation results, it was recommended by the study team for the GE-04 Skagit River Geomorphology Between Gorge Dam and the Sauk River Study (GE-04 Geomorphology Study; City Light 2023b) that the reprocessed 2022 elevation data for the Gorge bypass reach not be used to conduct analyses. Thus, for the purposes of evaluating impacts of the November 2021 flood event in the Gorge bypass reach, a GIS visual comparison tools and gradation analyses, were utilized to explore substrate changes at the Existing Features within the Gorge bypass reach. These methods are discussed in the subsequent sections below.

GIS Visual Comparison

Visual analysis and comparison tools in ArcMap version 10.7.1 were used to identify potential locations of significant change in substrate. The *Swipe* tool allows the user to compare two aerial images side by side by overlaying one image on top of the other and using a slider to reveal more or less of either image. This is useful for comparing changes in the aerial images over time or for identifying features in one image that are not present in the other. Figure 10 provides an example of the *Swipe* tool in use. The *Adjust Transparency* tool allows the user to change the transparency of an image, making it easier to see through to the other image and compare the two more clearly. Figure 11 provides an example of the *Adjust Transparency* tool. The *Flicker Layer* tool rapidly oscillates between two images, making it easy to detect changes, especially in satellite or aerial images taken at different times of the same location.



Figure 10. Example of the *Swipe* tool in use comparing the 2021 drone image (left) and 2022 aerial image (right).



Figure 31. Example of the *Adjust Transparency* tool in use comparing 2021 drone image (50 percent transparency) and 2022 aerial image (base).

The visual comparison identified a total of 10 potential changes in substrate within the Existing Features. Two major limitations to this analysis were the lack of resolution and shadows present in the 2022 aerial images. Low resolution and light in the 2022 aerial images prevented the identification of boulder movement in the majority of Existing Feature 1 and portions of Existing Feature 2. The resolution difference can be seen in Figure 10 and the shadows are shown in Figure 12 and Figure 13. Given the difficulty with developing consistent comparisons using the above tools, an additional image analysis method was performed to estimate changes in substrate within the Existing Features and is described in the following section.

Gradation Comparison

The Rock/Sediment Gradation Analysis tool in Hydraulic Toolbox, Version 5.1.1.0 (Federal Highway Administration [FHWA] 2021) estimates the gradation of the surface layer of visible substrate using a digital gradation analysis tool. This tool approximates the sizes of rocks in a scaled image and calculates a gradation for the visible substrate. This process is only an estimation and has several limitations including, but not limited to, the resolution of the input image; the presence of water and other materials; and the distribution of light, refraction, and shadows. Figure 11 illustrates the steps for creating ellipses representing the surface layer.

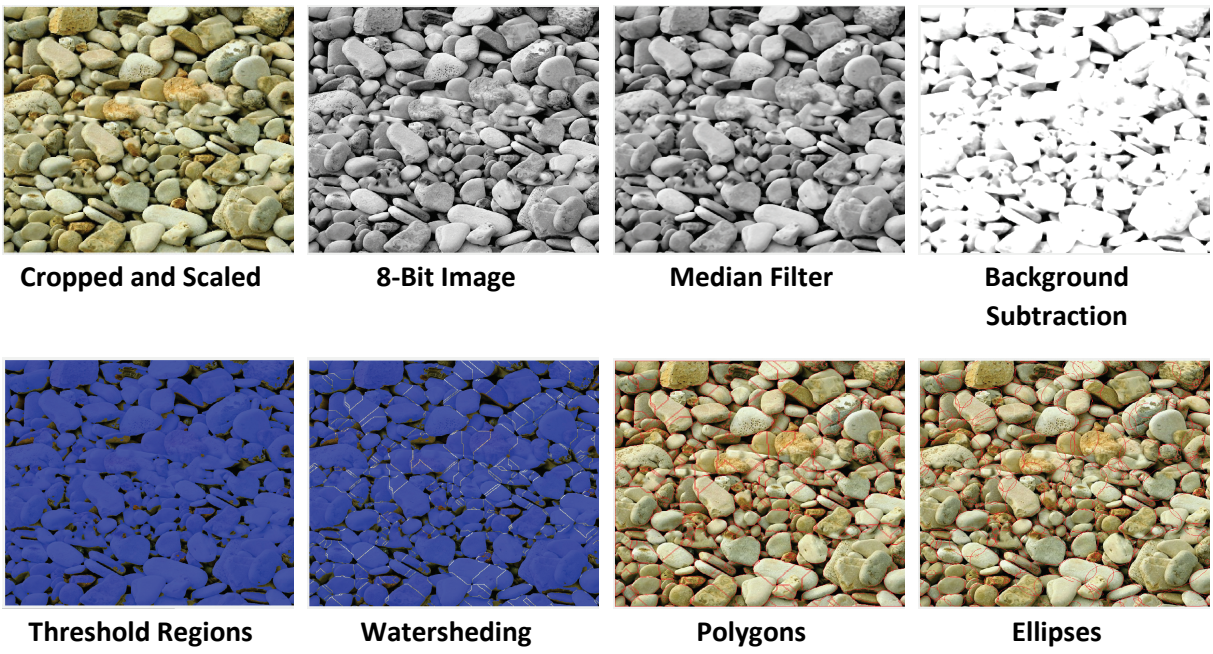


Figure 4. Steps for the Rock/Sediment Gradation Analysis tool in Hydraulic Toolbox (FHWA 2021).

The digital gradation analysis tool was applied to 2021 drone imagery and 2022 aerial imagery for each existing feature. Existing Feature 1 was split into two zones and Existing Feature 2 was split into three zones for the purposes of this analysis. Each zone covers a main channel area within the existing feature. Figure 12 and Figure 13 show the zone locations for Existing Feature 1 and Existing Feature 2, respectively. Only the areas inside each rectangle were analyzed to standardize the output.

The visual and graphical results of this analysis are provided in Figure 14 through Figure 23. The visual results show shadows present in the 2022 aerial image in Existing Feature 1 and to a lesser extent, in Existing Feature 2. These shadows obscure detail in the Existing Features and reduce the ability of the digital gradation analysis tool to discern differences. The 2022 aerial images are also lower resolution than the 2021 drone images, further reducing the accuracy of this analysis. In general, the graphical results show a larger gradation in 2022 than in 2021. This is likely due to the lower resolution of the photos and shadowed areas present. In some instances, water present in the 2021 drone images is interpreted by the digital gradation analysis tool as large boulders.

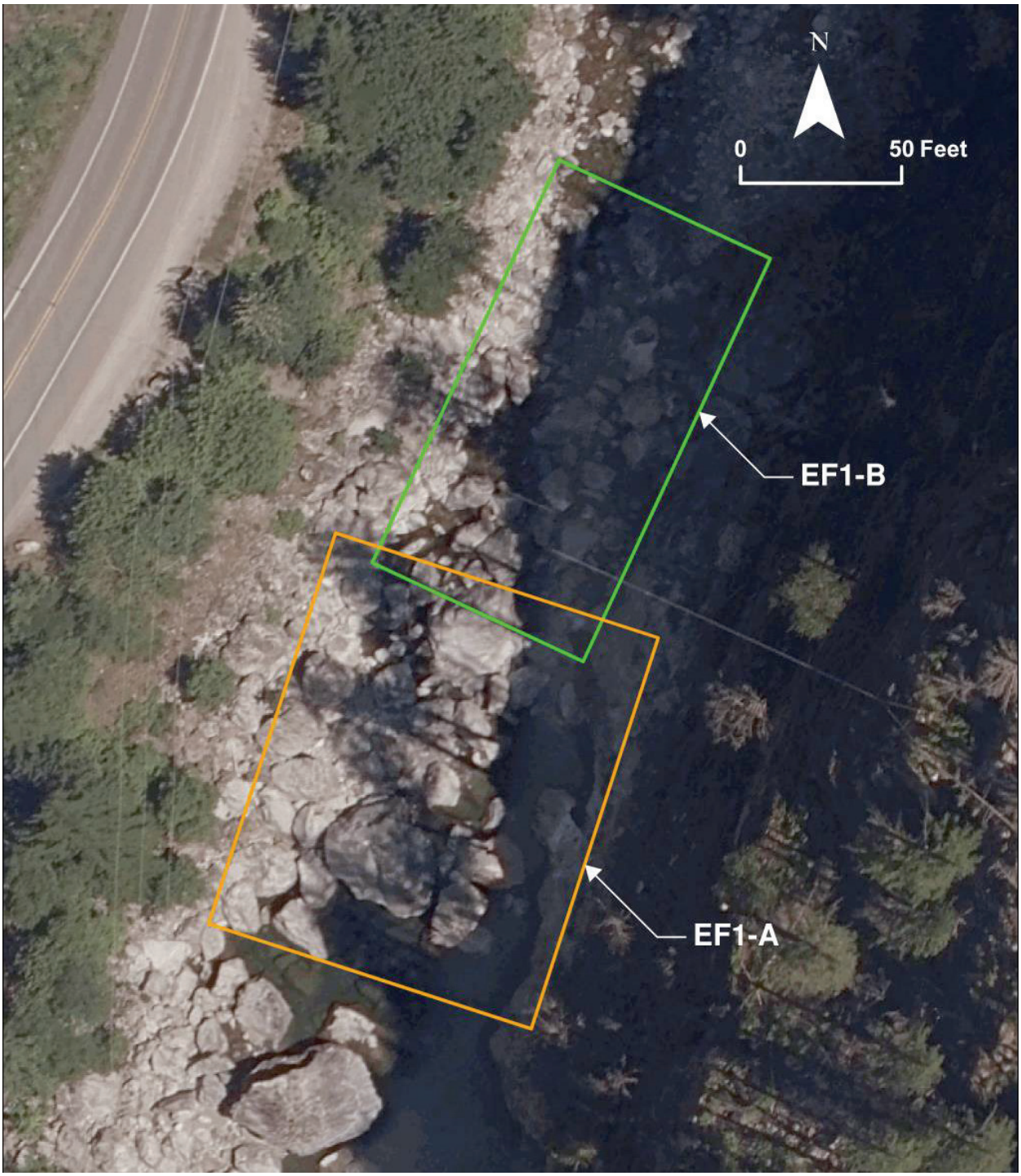


Figure 5. **Existing Feature 1 zones EF1-A and EF1-B used in digital gradation analysis with 2022 aerial image shown.**

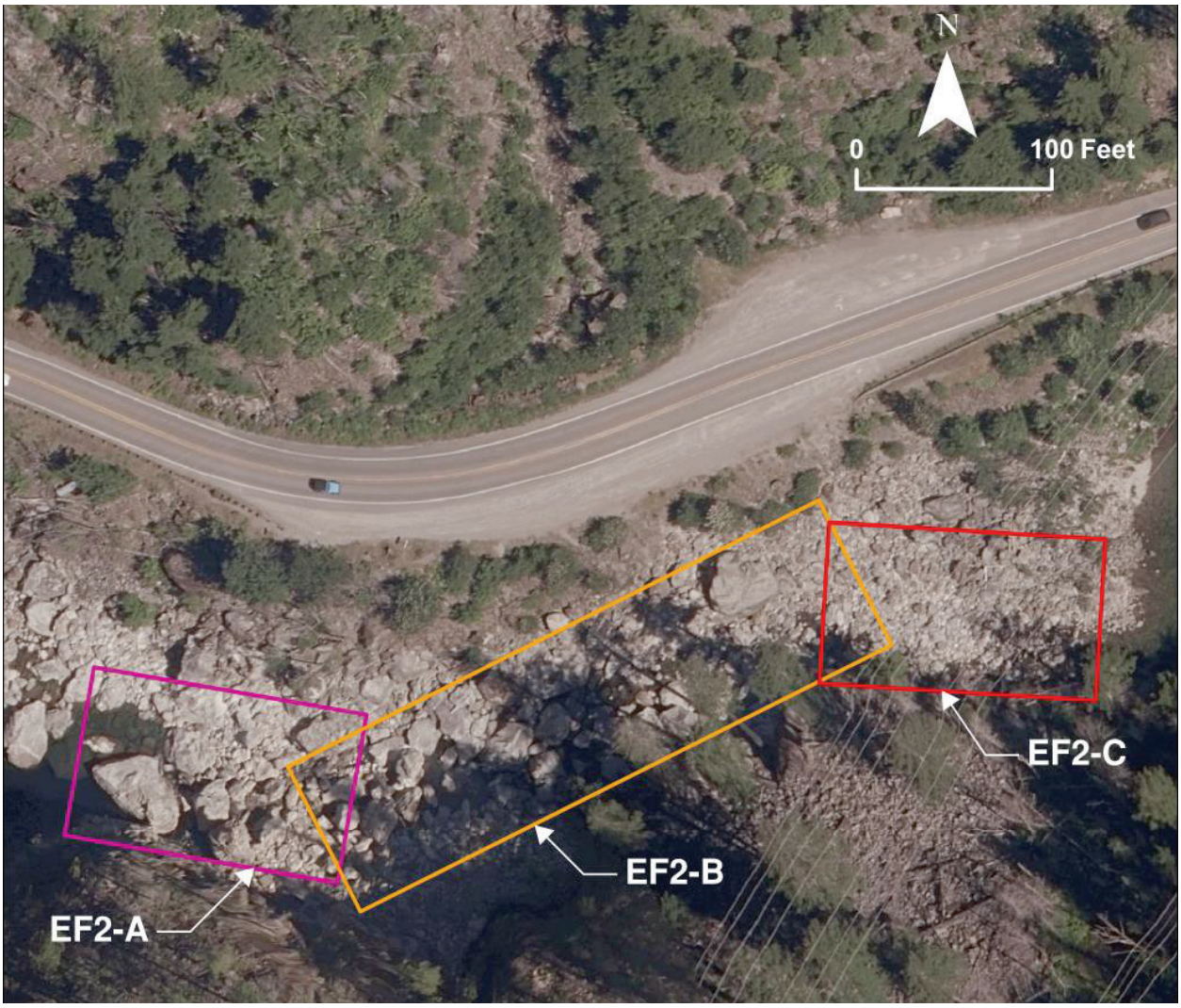


Figure 6. **Existing Feature 2 zones EF2-A, EF2-B, and EF2-C used in digital gradation analysis with 2022 aerial image shown.**

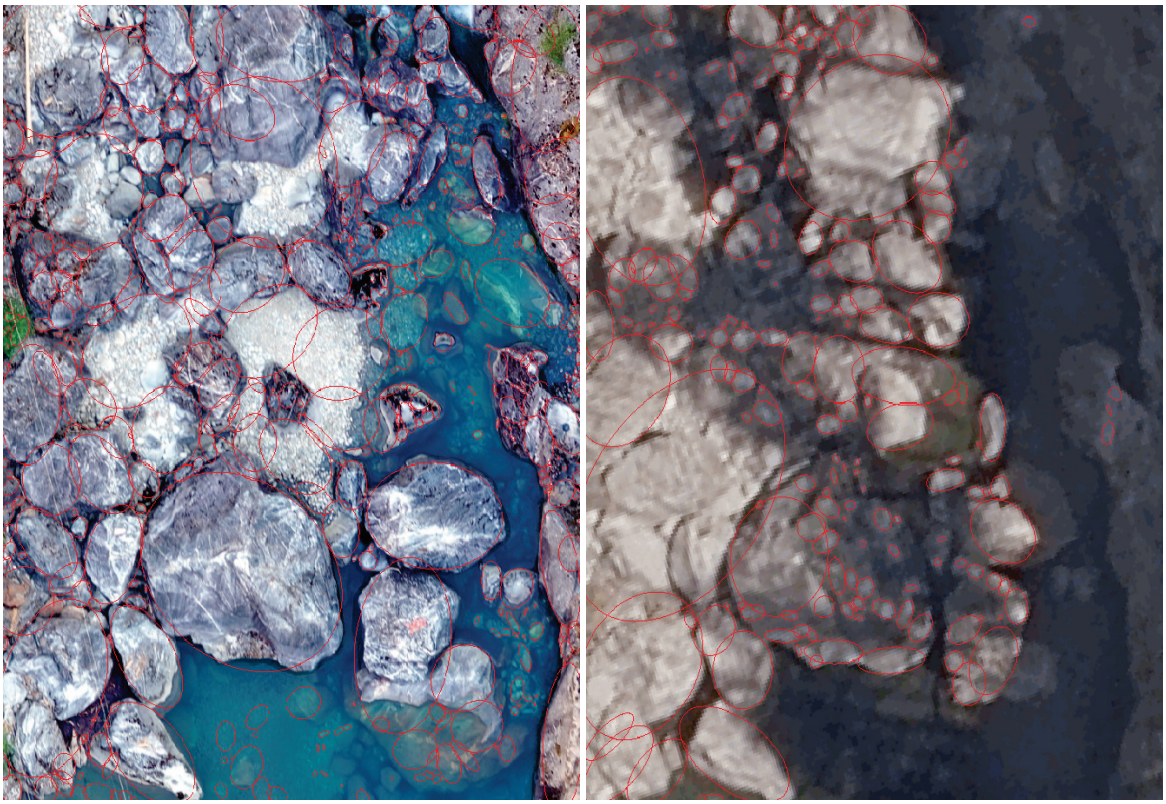


Figure 7. **Comparing visual digital gradation analysis results of 2021 drone image (left) and 2022 aerial image (right) for zone EF1-A.**

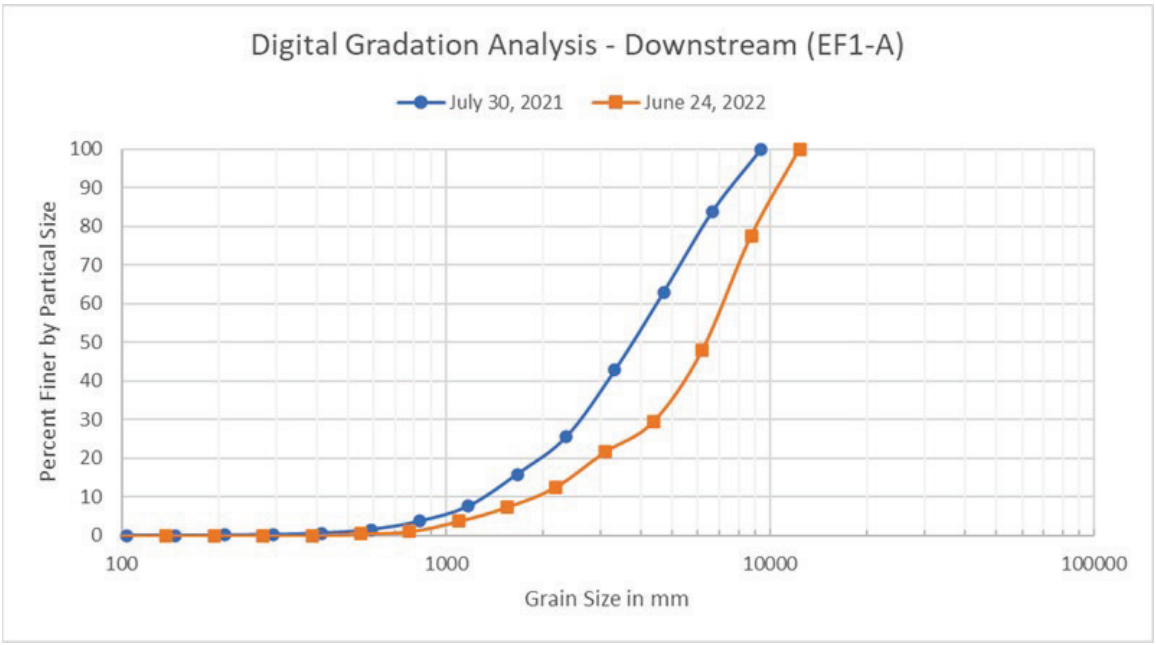


Figure 8. **Graphical digital gradation analysis results of zone EF1-A.**

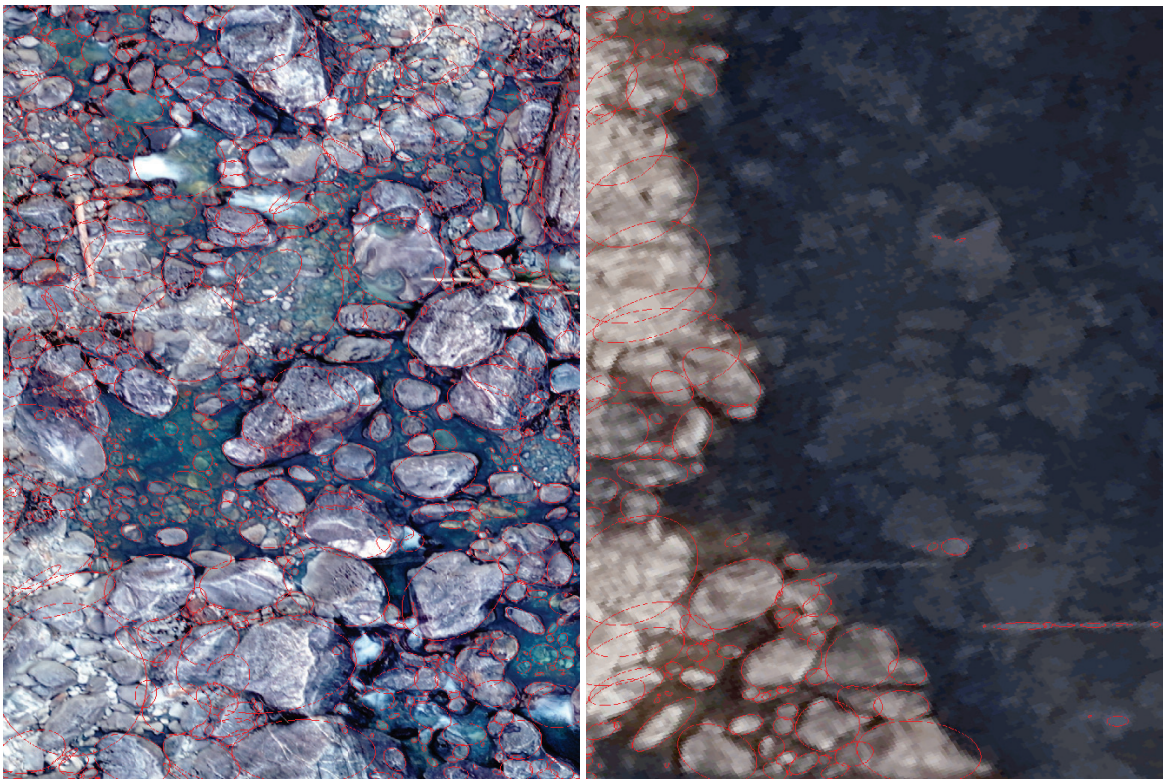


Figure 9. **Visual digital gradation analysis results of 2021 drone image (left) and 2022 aerial image (right) for zone EF1-B.**

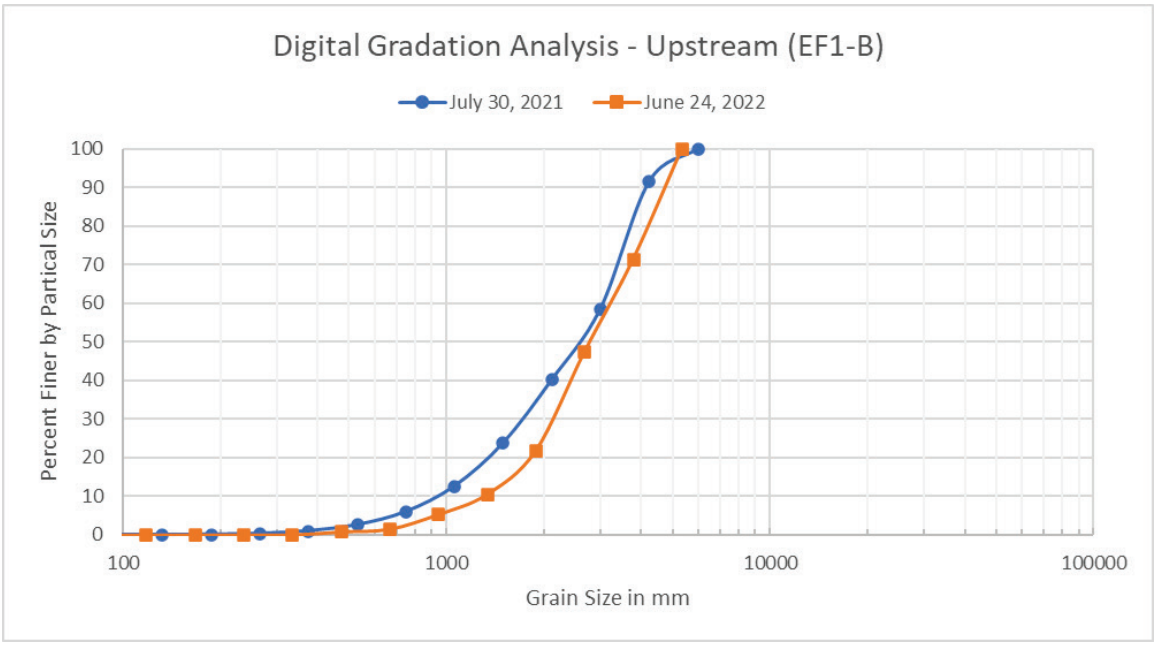


Figure 10. **Graphical digital gradation analysis results of 2021 drone image and 2022 aerial image for zone EF1-B.**



Figure 11. **Visual digital gradation analysis results of 2021 drone image (left) and 2022 aerial image (right) for zone EF2-A.**

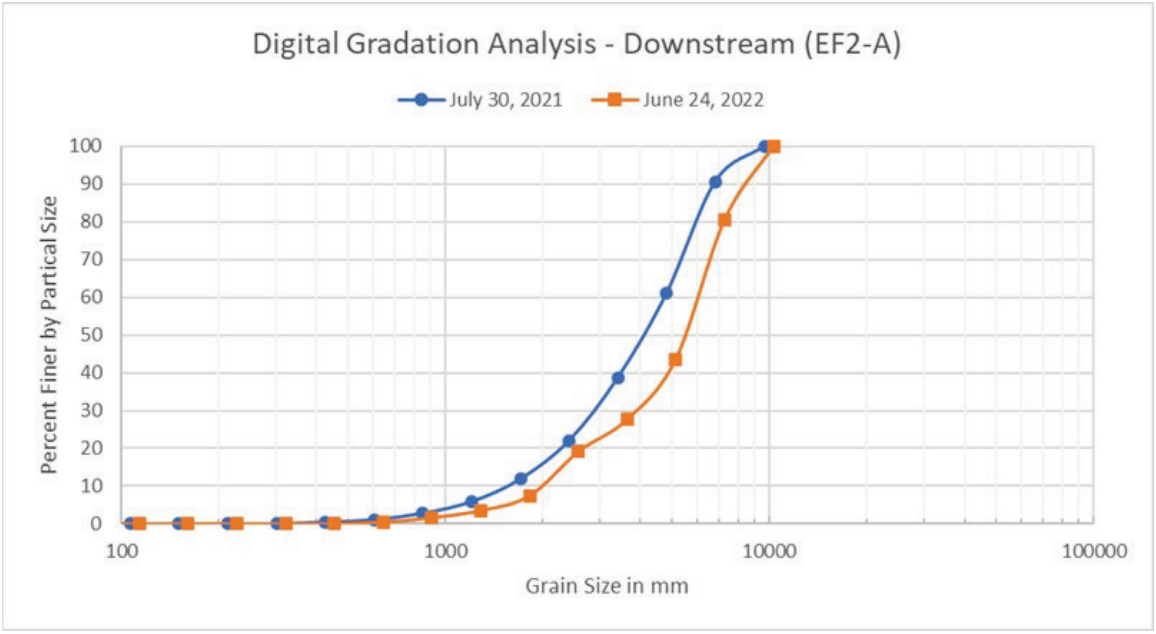


Figure 12. **Graphical digital gradation analysis results of 2021 drone image and 2022 aerial image for zone EF2-A.**



Figure 13. **Visual digital gradation analysis results of 2021 drone image (left) and 2022 aerial image (right) for zone EF2-B.**

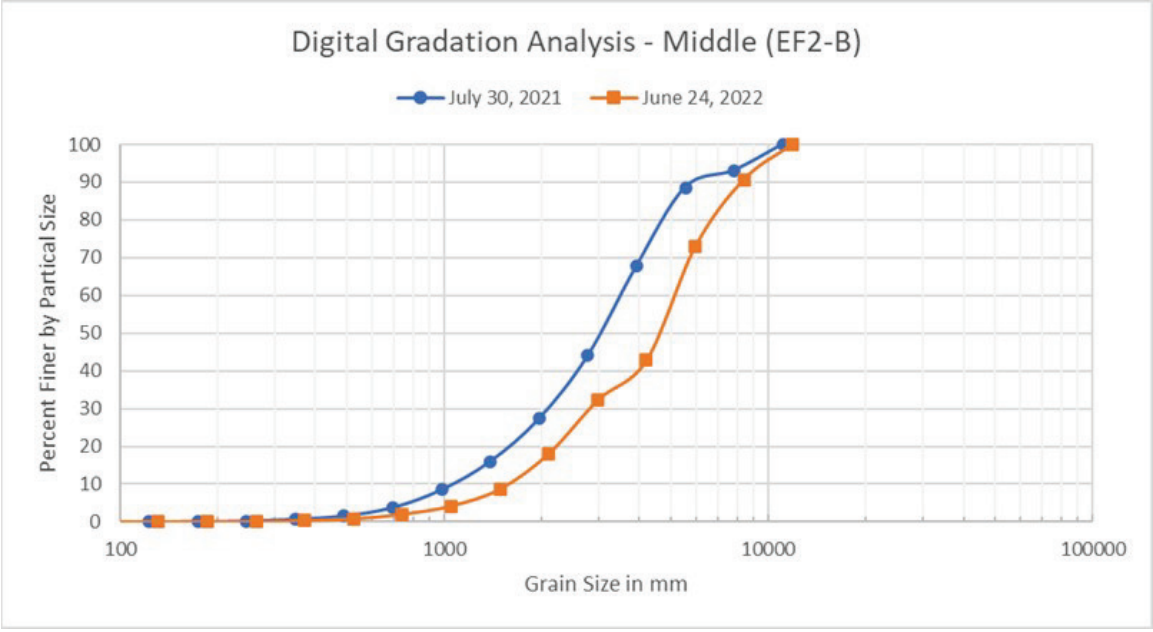


Figure 14. **Graphical digital gradation analysis results of 2021 drone image and 2022 aerial image for zone EF2-B.**

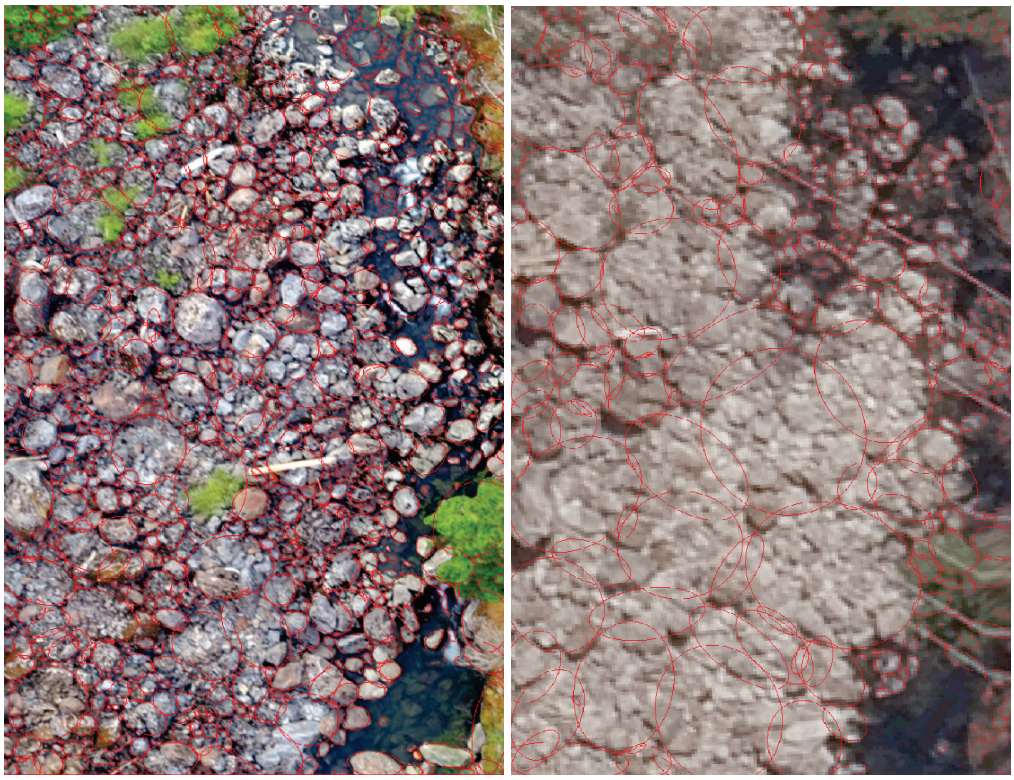


Figure 15. **Visual digital gradation analysis results of 2021 drone image (left) and 2022 aerial image (right) for zone EF2-C.**

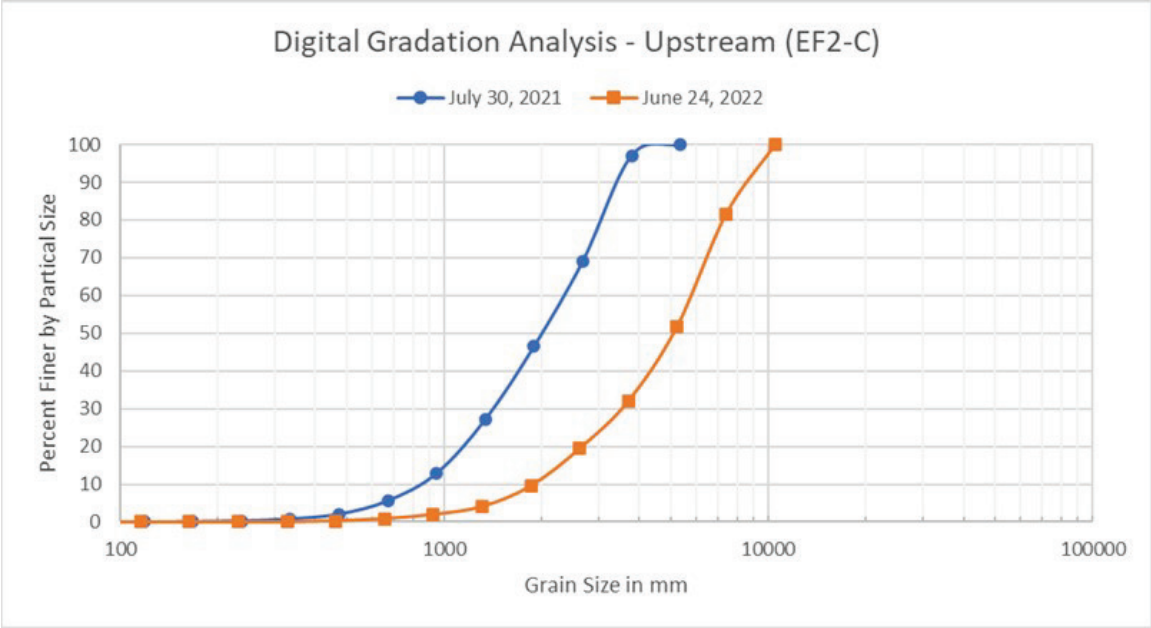


Figure 16. **Graphical digital gradation analysis results of 2021 drone image and 2022 aerial image for zone EF2-C.**

4.3.2 Potential Substrate Changes

Existing Feature 1

Figure 24 provides the results of the surface comparison and GIS visual comparison analyses described above for Existing Feature 1. The two potential substrate changes identified are shown overlaying elevation differences between the 2018 LiDAR data and the 2022 LiDAR data. While the surface comparison results show deposition and erosion throughout Existing Feature 1, areas of substrate change could not be confirmed by the visual analysis due to shadows present in the 2022 aerial images. The downstream potential substrate change appears to be a large, roughly 30-foot diameter, boulder that has shifted multiple feet between the 2021 and 2022 aerial images; however, the resolution of the 2022 aerial image and surface comparison results are too coarse to determine if this is a significant change.

The upstream potential substrate change initially appeared to be several newly deposited smaller boulders; however, upon closer inspection of the 2021 aerial image, the surface comparison results, and a photo taken of this area on June 22, 2021 (Figure 25), it appears small gravel was transported out of the reach uncovering the boulders. Transport of small gravel is expected to occur on a regular basis as the Existing Features experience large flows.

The two potential changes identified in Existing Feature 1 are not considered significant enough to impact fish passage analysis results and are therefore not included in subsequent analyses.

Existing Feature 2

Figure 26 provides the results of the surface comparison and GIS visual comparison analyses for Existing Feature 2. The eight potential substrate changes identified are shown overlaying elevation differences between the 2018 LiDAR data and the 2022 LiDAR data. Similar to Existing Feature 1, areas of substrate change could not be confirmed by the visual analysis due to shadows present in the 2022 aerial images; however, multiple potential substrate change locations identified through visual comparison coincide with areas of apparent erosion or deposition.

While some potential substrate change locations do not coincide with areas of apparent erosion or deposition, they were not excluded from subsequent analyses due to the lack of reliability of the surface comparison. The potential substrate changes in Existing Feature 2 are compared to fish passage pathways in the following section.

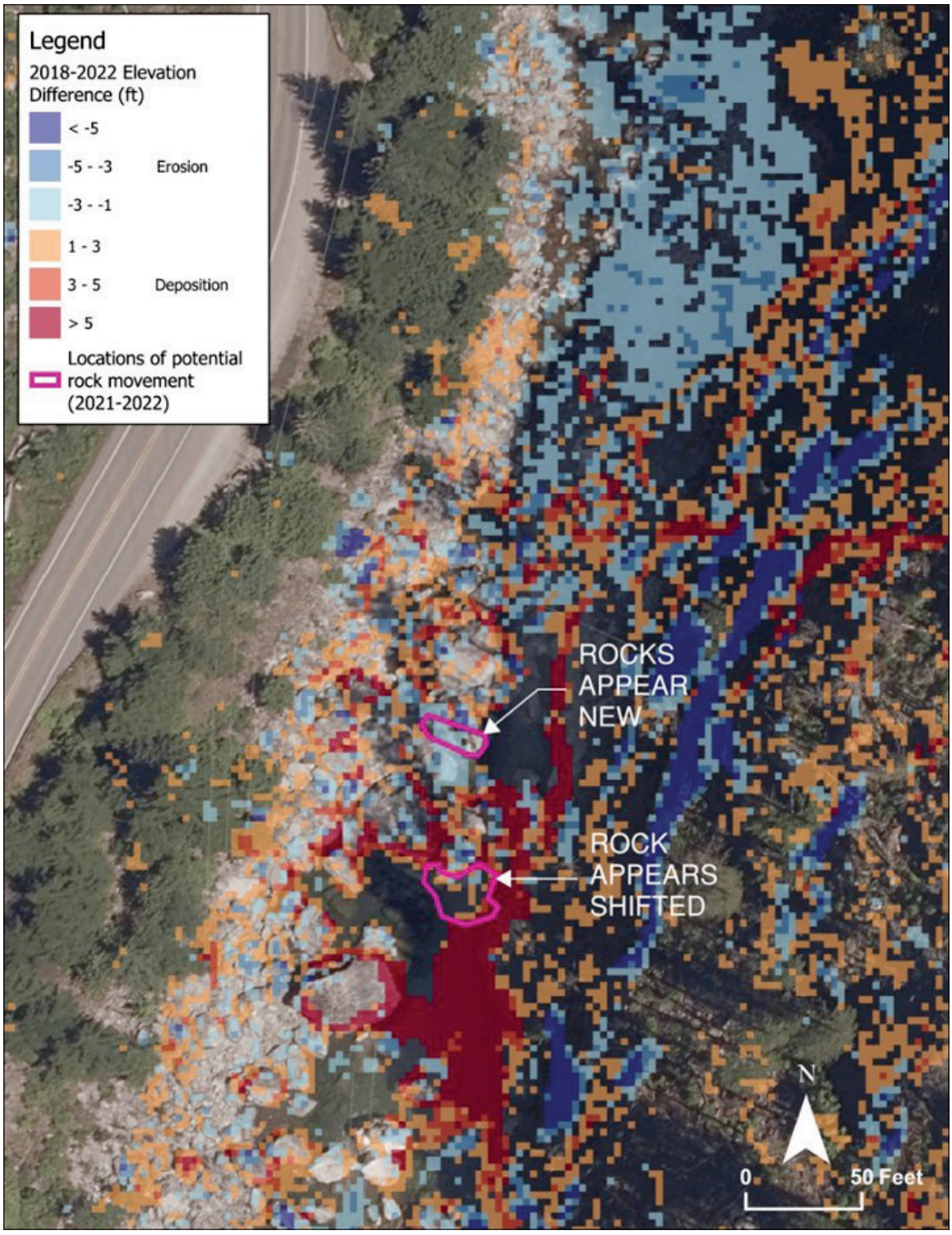


Figure 17. **Locations of potential rock movement overlaying comparison between 2018 LiDAR and 2022 LiDAR data in Existing Feature 1.**



Figure 18. Photo of small gravel in Existing Feature 1, taken June 22, 2021.

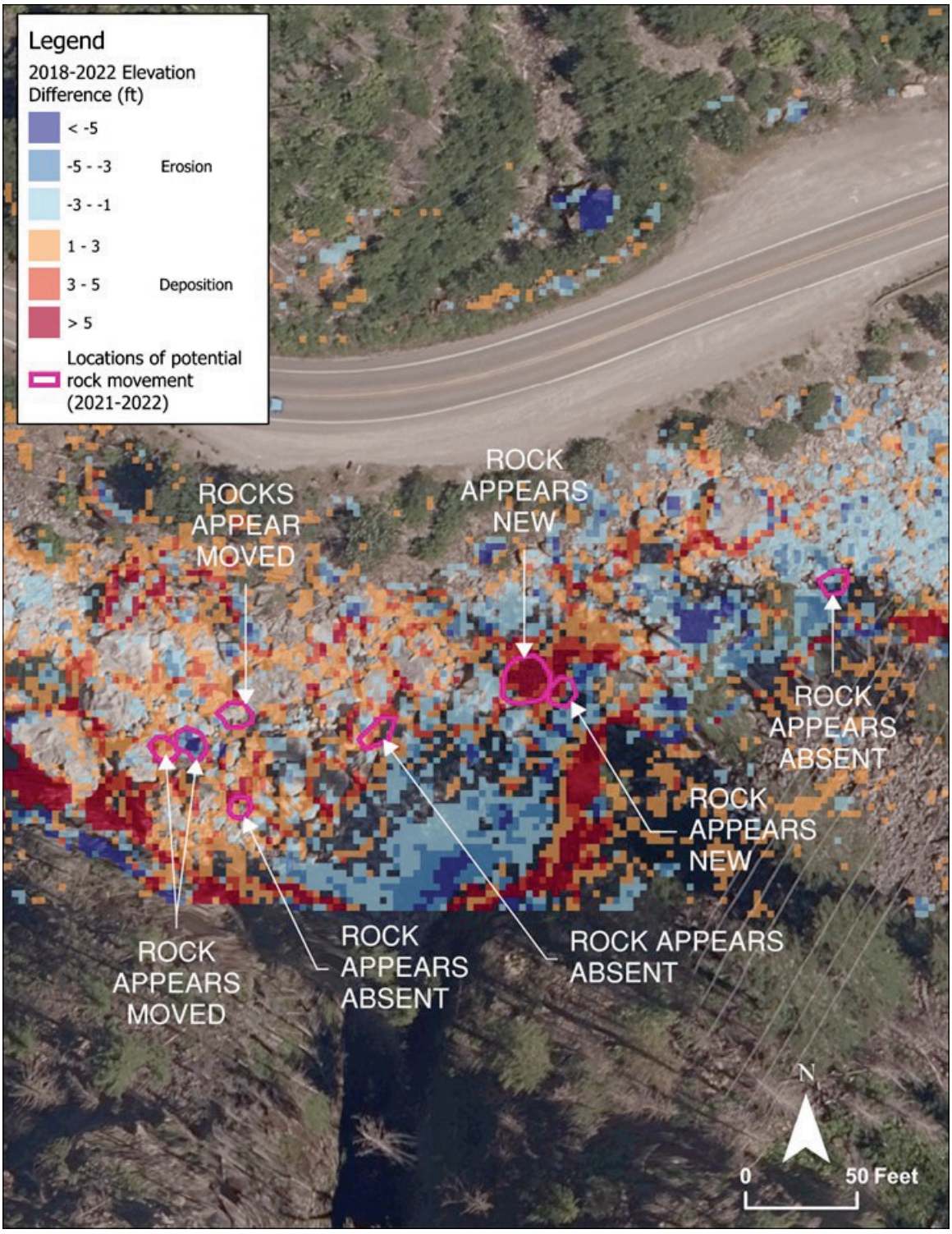


Figure 19. **Locations of potential rock movement overlaying comparison between 2018 LiDAR and 2022 LiDAR data in Existing Feature 2.**

4.4 Fish Passage Pathways

Fish passage pathways within each existing feature were identified based on results for each discharge from the Bypass Hydraulic Model (Attachment A to the Bypass Instream Flow Model Development Study). A depth of 1 foot was considered to be the minimum depth through which an adult fish can swim for this assessment. Then, hydraulic pathways were delineated by following velocity jets and identifying contiguous flow paths greater than 1 foot in depth using the velocity results for the range of flows evaluated. Once the hydraulic pathways were determined, velocity, water surface, and flow depth results were extracted from the hydrodynamic simulations. These Bypass Hydraulic Model results were used in conjunction with aerial photos and time-lapse photos to assess whether each hydraulic pathway was passable. A full description of fish passage pathways and analyses are presented in the Fish Passage Assessment of Existing Features in the Gorge Bypass Reach Report (Bypass Fish Passage Assessment; Attachment J to the FA-04 Fish Passage Study [City Light 2023a]).

Results from Section 4.3.1 of this report were overlaid with the fish passage pathways described above. A total of six potential boulder movement locations intersect with example fish passage pathways delineated in the Bypass Fish Passage Assessment (Attachment J to the FA-04 Fish Passage Study [City Light 2023a]). Figure 27, Figure 28, and Figure 29 show the pathways for flows up to 2,000 cfs with locations of potential boulder movement overlaid. The intersection of bolder movement and a fish passage pathway does not necessarily change the possibility of that pathway, or the possibility of the feature itself, for the range of species and flows assessed. Section 4.5 of this report discusses the examination of passage pathways for individual species at specific flow events and provides possible changes to the fish passage analysis within Existing Feature 2.

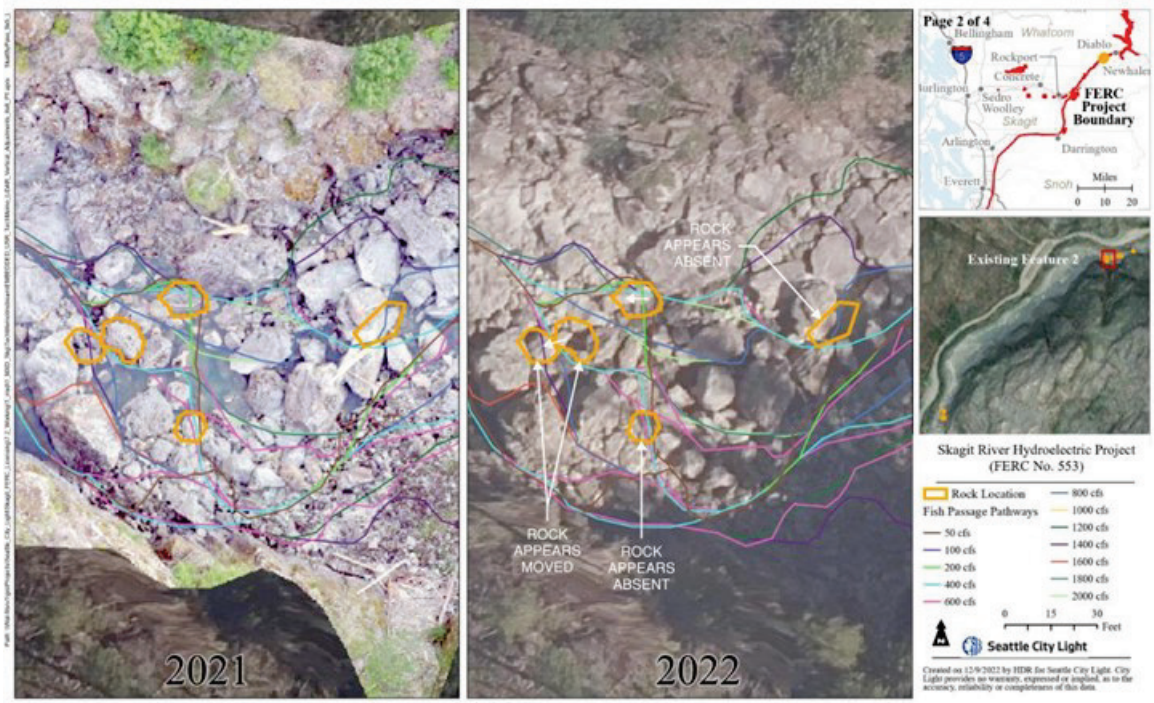


Figure 20. **Potential rock movement in the downstream reach of Existing Feature 2 based on substrate change analyses.**



Figure 21. **Potential rock movement in the middle reach of Existing Feature 2 based on substrate change analyses.**



Figure 22. Potential rock movement in the upstream reach of Existing Feature 2 based on substrate change analyses.

4.5 Fish Passage Analysis

Potential changes in fish passage through Existing Feature 2 were evaluated using results from analyses discussed in Section 4.3.1 and pathways presented in Section 4.4 of this report. Aerial images were reviewed to identify locations where large substrate (boulders) had moved into or out of the fish passage pathways delineated as part of the Bypass Fish Passage Assessment (Attachment J to the FA-04 Fish Passage Study [City Light 2023a]). Due to heavy shadows obscuring substrate in the 2022 imagery and relatively insignificant potential substrate changes identified for Existing Feature 1, potential changes in passage were only evaluated for Existing Feature 2.

A qualitative assessment of potential impacts of the identified substrate changes on fish passage was performed using the following procedure:

1. Fish passage pathways that intersected with potential substrate changes were identified.
2. The identified pathways were initially evaluated for potential impacts to passage at the feature scale, i.e., determine if the ability for a fish to ascend the feature changed as a whole. This portion of the assessment corresponds to large colored cells in Table 2.
3. The identified pathways were then evaluated for potential changes at the subreach scale. Refer to the Bypass Fish Passage Assessment (Attachment J to the FA-04 Fish Passage Study [City Light 2023a]) for descriptions of the subreaches. This step was primarily included to assess whether passable fish passage conditions, anticipated for species that may require a more complex

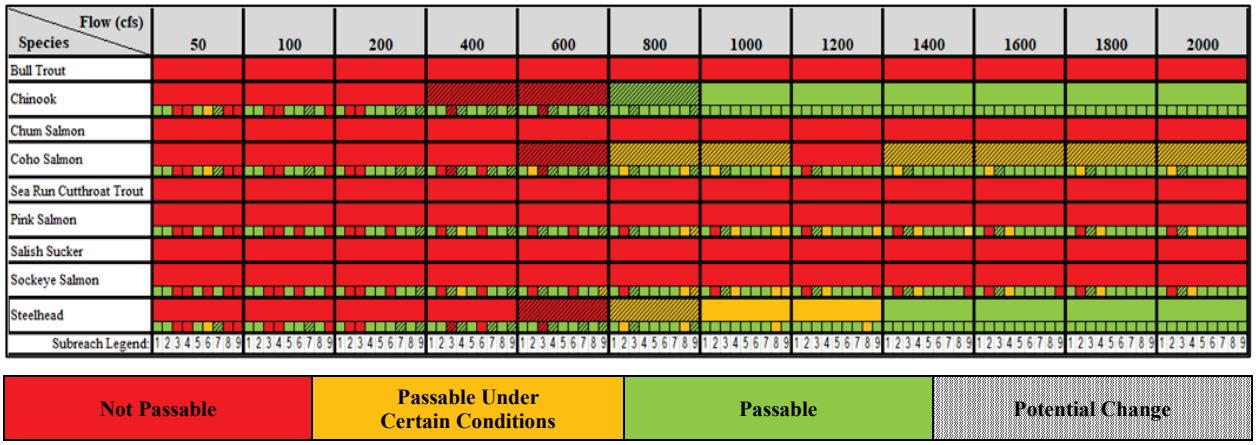
combination of different flows to ascend Existing Feature 2 (e.g., Coho Salmon, Pink Salmon, and Sockeye Salmon), may change under the new substrate conditions. This portion of the assessment corresponds to the small colored cells in Table 2 of this report.

The following categories were used to describe potential changes in passage where apparent boulder movement intersected with a passable or potentially passable fish passage pathway:

1. **No change in passage:** Additional pathways with no conflicting potential boulder movement are available for fish to navigate the feature.
2. **Potential change in hydraulics:** The available pathways are not obstructed by an apparently new boulder, but require that fish navigate around the boulder through a narrow corridor for which hydraulics may be impacted by the presence of the boulder.
3. **Potential change in passage:** All available pathways intersect with an apparently new or absent boulder and it is unclear if fish can swim around feature, potentially resulting in one of the following scenarios:
    a. Passage my require a leap where a leap wasn't previously required for passage.
    b. The height of an existing leap (waterfall/cascade) may increase.
    c. The height of an existing leap (waterfall/cascade) may decrease.

Category 2 and 3 were both considered to be potential impacts to passage, and are not differentiated in Table 2, for simplicity. Exhibits provided in Appendix C illustrate the qualitative assessment and specify locations where passage may be directly impacted by substrate changes as opposed to locations where passage may indirectly impacted by changes in hydraulics resulting from new or absent boulders.

Table 2. Results from the Fish Passage Assessment of Existing Feature 2 in the Bypass Fish Passage Assessment showing potential changes based on visual analysis.



Results of the qualitative assessment indicate that passage for the species that are likely able to ascend Feature 2 at constant flows (Chinook Salmon and steelhead) were generally unimpacted by large substrate changes. These two species were estimated to have stronger swimming abilities, allowing them take advantage of alternative swimming paths that become available at larger flows. One exception is 800 cfs, where the available pathways would require the fish to swim through narrow corridors where hydraulics may be impacted by the presence of new large boulders. In Subreach 4, the absence of a previously existing boulder may reduce the height of a leap barrier and potentially allow Chinook Salmon and steelhead to pass at lower flows than initially estimated (400 to 600 cfs); however, the impacts to leaping conditions are unquantifiable using the data that is currently available.

For species that may require a non-continuous flow hydrograph between subreaches to achieve passage through Feature 2 (Coho Salmon, Pink Salmon, Sockeye Salmon), the ability to ascend through the entire feature was not impacted. In other words, none of the substrate changes would allow these species to ascend Feature 2 at a constant flow. However, passage through specific subreaches within Feature 2 was impacted. Passage through Subreach 3 was consistently impacted for these species, generally requiring fish to swim directly through large boulders for flows up to 1,000 cfs.

The presence of these new boulders may increase the required leap height beyond the estimated abilities for these species. Additionally, hydraulics through the narrow corridor that must be used to circumvent the large boulders within Subreach 3 may be impacted for flows greater than 1,000 cfs. Hydraulics in the narrow corridors that must be used to circumvent the large boulders in Subreaches 7 and 9 may also be impacted for flows greater than 800 cfs. Potential velocity increases through these corridors may limit passage to species with stronger estimated swimming abilities.

As with Chinook Salmon and steelhead, the absence of a previously existing boulder in Subreach 4 may reduce the height of a leap barrier and potentially allow Coho Salmon to pass continuously through Subreaches 3 and 4 at 600 cfs. This specific substrate change does not impact Pink Salmon or Sockeye Salmon, as velocities at the flows when this pathway become available were estimated to be too high for these species to negotiate.

Substrate changes did not improve passage conditions for species for which Feature 2 was determined to be not passable under any flow conditions (Bull Trout/Dolly Varden, Chum Salmon, Sea-run Cutthroat Trout, Salish Sucker).

5.0 CONCLUSIONS

4.6 Habitat Modeling

Very little habitat exists in the Gorge bypass reach for salmonids at flows ranging from 100-600 CFS when compared to the Upper Skagit River (from Gorge Powerhouse to the Sauk River confluence). This is in part due to the relatively high gradient in the Gorge bypass reach which result in depths and velocities that are outside the preference range for most salmonid species and life stages. In addition, the relatively large substrate sizes that dominate the Gorge bypass reach (i.e., small and large cobbles and boulders) are generally preferred by the adult, juvenile, and fry life stages as they provide velocity shelters and instream cover.

While large flood events such as those experienced during November 2021 may result in dislodgement and movement of larger substrates, the overall effect on habitat suitability would be minimal. While the location of the habitat may change based on substrate movement, the amount and suitability of habitat that is provided by that substrate would only change marginally, if at all. And considering the UHA curves represent the flow-habitat relationship for an entire reach, the effect of a localized shift in habitat location within the reach would have little to no effect on the UHA curves for a given habitat reach within the Gorge bypass reach.

4.7 Existing Features Level Loggers

To assess the impact of the November 2021 flood event on hydraulic conditions in the Existing Features, a comparison was made between pre- and post-flood WSE-discharge data from the five level loggers which survived the flood. These were level loggers DDL1, DDL2 and DDL3 at Existing Feature 1, and UUL1 and UUL6 at Existing Feature 2.

No discernable shift was found between pre- and post-flood WSE-discharge relationships for level loggers DDL1, DDL2, UUL1 and UUL6. For level logger DDL3, post-flood WSEs appear to trend up to 0.5 feet lower than pre-flood WSEs for discharges in the range 700 cfs to 3,000 cfs. There is also an indication of a similar shift at discharges less than 200 cfs. This possible shift is considered insignificant relative to other sources of uncertainty affecting hydraulic model performance and evaluation of fish passage within the Existing Features.

4.8 Fish Passage

The potential impact to fish passage of the large spills in late 2021 was evaluated using comparisons of available LiDAR data and aerial imagery. Upon early inspection, it was determined that the LiDAR datasets from 2018 and 2022 were not comparable due to large gaps in terrain data caused by spill from Gorge Dam during the 2021 data collection efforts. GIS visual comparison tools and gradation analyses were then used to explore substrate changes at the Existing Features within the Gorge bypass reach. The results of these visual comparisons found that several minor changes in boulder and substrate position could be identified. These changes and their potential impact were then inspected further by overlaying potential

fish passage pathways (previously delineated in the Bypass Fish Passage Assessment (Attachment J to the FA-04 Fish Passage Study [City Light 2023a]) upon each substrate change identified in Existing Feature 1 and 2.

Conclusions resulting from this assessment indicate that fish passage pathways may have been altered to some limited extent, but there is no quantifiable evidence suggesting that previous conclusions made in the Bypass Fish Passage Assessment should be altered. Although, it is evident that some ranges of flow for specific fish passage pathways may be different, many of those changes in flow magnitude are within the inherent variability of the hydraulic model results and do not suggest a departure from previous findings. Continuous ranges of flow still exist to provide passage opportunities for Chinook Salmon, steelhead, and Lamprey. Non-continuous, more complex ranges of flow are anticipated to provide passage opportunities for Coho Salmon, Pink Salmon, and Sockeye Salmon. Existing Feature 1 and Existing Feature 2 remain a barrier to other target species such as Bull Trout, Dolly Varden, Chum Salmon, Sea-run Cutthroat Trout, and Salish Sucker. Further, such changes in physical condition (some improving passage and some diminishing passage) should be expected within the Gorge bypass reach over time as future spill operations and natural landslide processes occur.

6.0 REFERENCES

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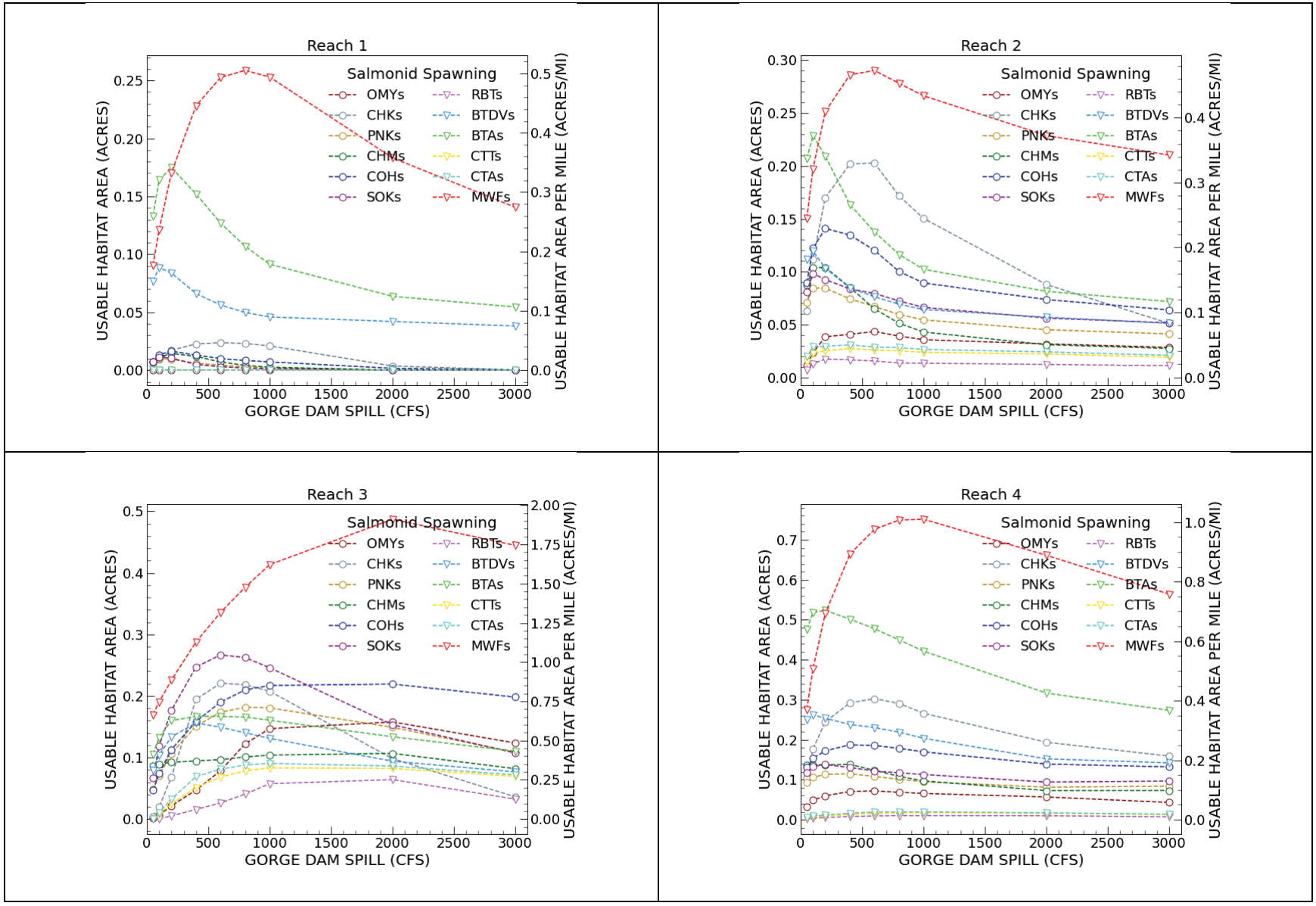
_____. 2023b. GE-04 Skagit River Geomorphology Between Gorge Dam and the Sauk River Study Report for the Skagit River Hydroelectric Project, FERC Project No. 553. Prepared by Natural Systems Design, Inc., Northwest Hydraulic Consultants, Inc. and Fain Environmental LLC. March 2023.

APPENDIX A

SKAGIT RIVER GORGE BYPASS REACH
USABLE HABITAT AREA FIGURES

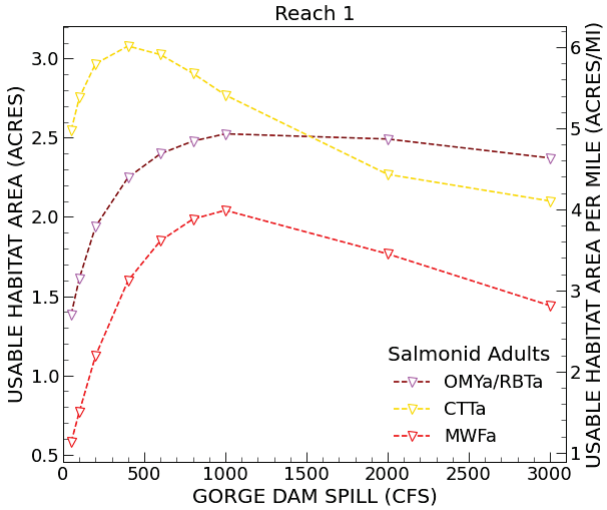
SALMONID SPAWNING LIFE STAGE

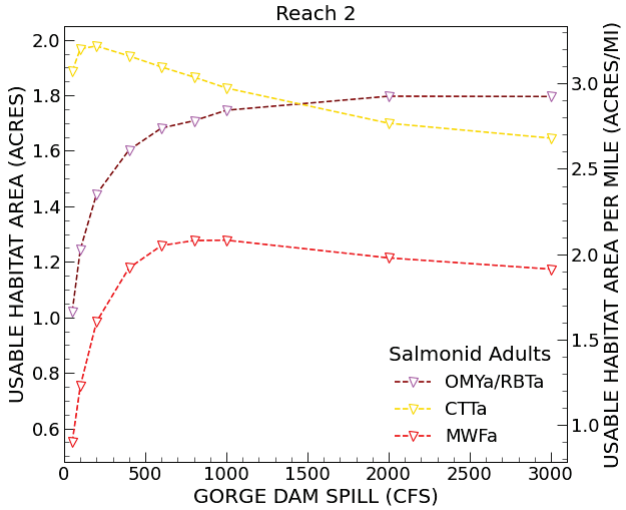

Reach 1
Salmonid Spawning
OMYs
CHKs
PNKs
CHMs
COHs
SOKs
RBTs
BTDVs
BTAs
CTTs
CTAs
MWFs
USABLE HABITAT AREA (ACRES)
USABLE HABITAT AREA PER MILE (ACRES/MI)
GORGE DAM SPILL (CFS)
Reach 2
Salmonid Spawning
USABLE HABITAT AREA (ACRES)
USABLE HABITAT AREA PER MILE (ACRES/MI)
GORGE DAM SPILL (CFS)
Reach 3
Salmonid Spawning
USABLE HABITAT AREA (ACRES)
USABLE HABITAT AREA PER MILE (ACRES/MI)
GORGE DAM SPILL (CFS)
Reach 4
Salmonid Spawning
USABLE HABITAT AREA (ACRES)
USABLE HABITAT AREA PER MILE (ACRES/MI)
GORGE DAM SPILL (CFS)

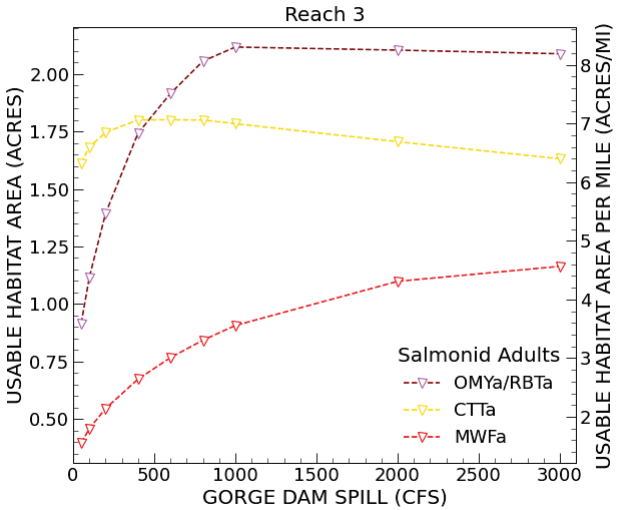
APPENDIX A

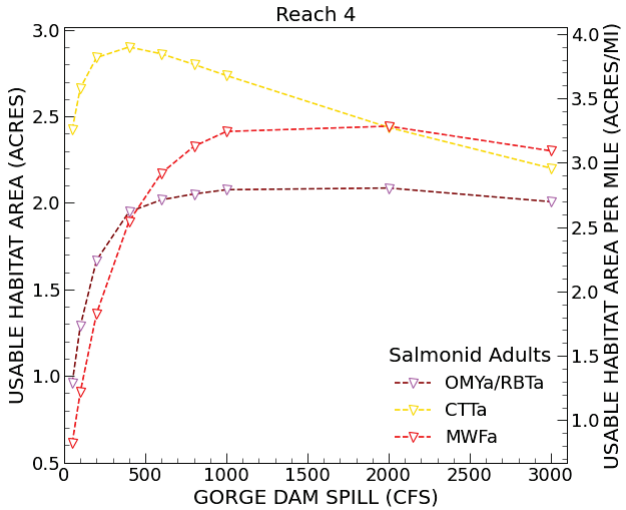
SKAGIT RIVER GORGE BYPASS REACH
USABLE HABITAT AREA FIGURES

SALMONID ADULT LIFE STAGE


Reach 1
USABLE HABITAT AREA (ACRES)
USABLE HABITAT AREA PER MILE (ACRES/MI)
GORGE DAM SPILL (CFS)
Salmonid Adults
OMYa/RBTa
CTTa
MWFa


Reach 2
USABLE HABITAT AREA (ACRES)
USABLE HABITAT AREA PER MILE (ACRES/MI)
GORGE DAM SPILL (CFS)
Salmonid Adults
OMYa/RBTa
CTTa
MWFa

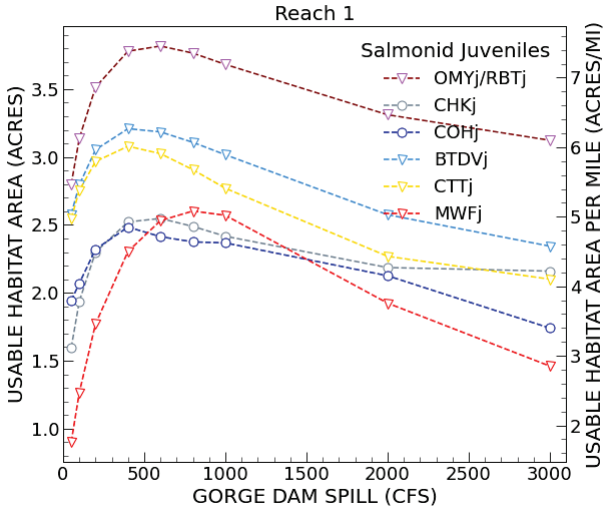

Reach 3
USABLE HABITAT AREA (ACRES)
USABLE HABITAT AREA PER MILE (ACRES/MI)
GORGE DAM SPILL (CFS)
Salmonid Adults
OMYa/RBTa
CTTa
MWFa

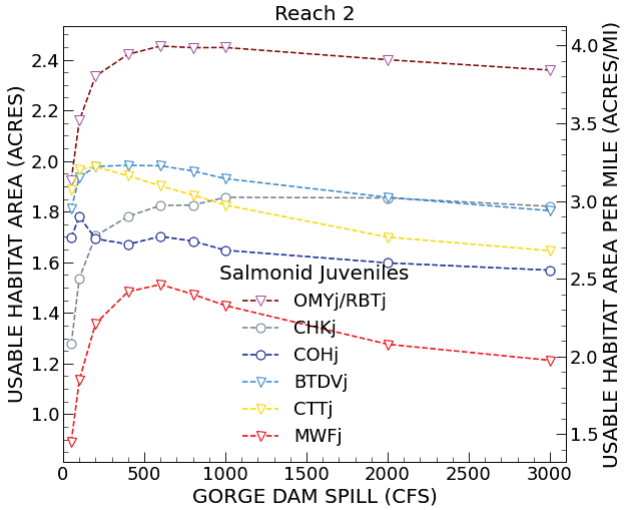

Reach 4
USABLE HABITAT AREA (ACRES)
USABLE HABITAT AREA PER MILE (ACRES/MI)
GORGE DAM SPILL (CFS)
Salmonid Adults
OMYa/RBTa
CTTa
MWFa

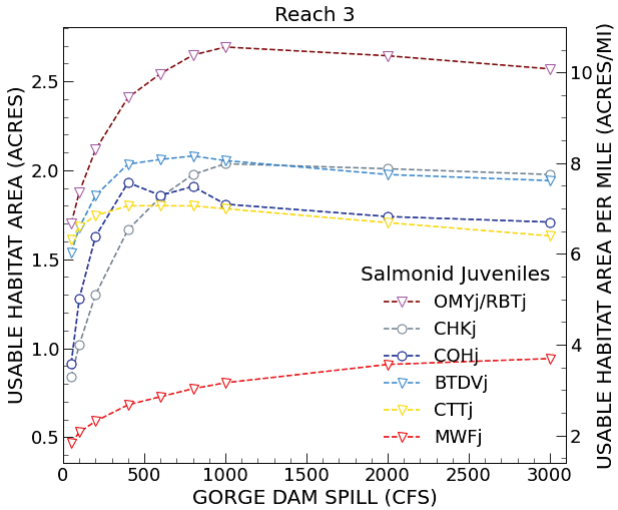
APPENDIX A

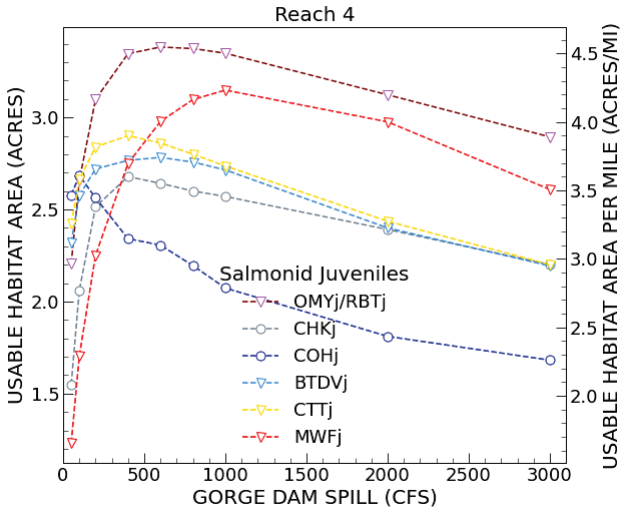
SKAGIT RIVER GORGE BYPASS REACH
USABLE HABITAT AREA FIGURES

SALMONID JUVENILE LIFE STAGE


Reach 1
Salmonid Juveniles
OMYj/RBTj
CHKj
COHj
BTDVj
CTTj
MWFj
USABLE HABITAT AREA (ACRES)
USABLE HABITAT AREA PER MILE (ACRES/MI)
GORGE DAM SPILL (CFS)


Reach 2
Salmonid Juveniles
OMYj/RBTj
CHKj
COHj
BTDVj
CTTj
MWFj
USABLE HABITAT AREA (ACRES)
USABLE HABITAT AREA PER MILE (ACRES/MI)
GORGE DAM SPILL (CFS)

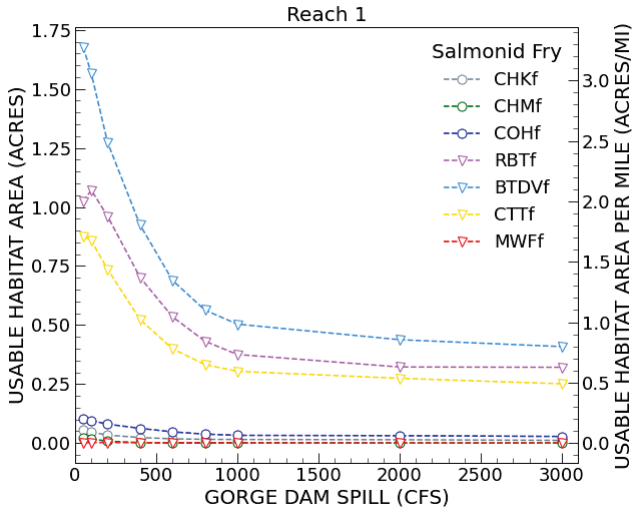

Reach 3
Salmonid Juveniles
OMYj/RBTj
CHKj
COHj
BTDVj
CTTj
MWFj
USABLE HABITAT AREA (ACRES)
USABLE HABITAT AREA PER MILE (ACRES/MI)
GORGE DAM SPILL (CFS)

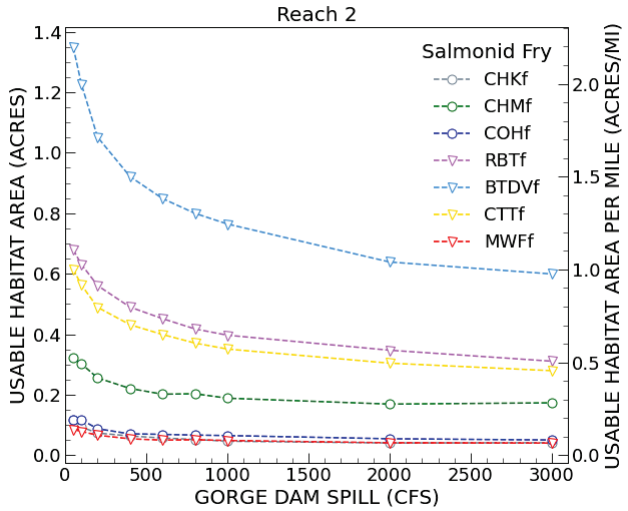

Reach 4
Salmonid Juveniles
OMYj/RBTj
CHKj
COHj
BTDVj
CTTj
MWFj
USABLE HABITAT AREA (ACRES)
USABLE HABITAT AREA PER MILE (ACRES/MI)
GORGE DAM SPILL (CFS)

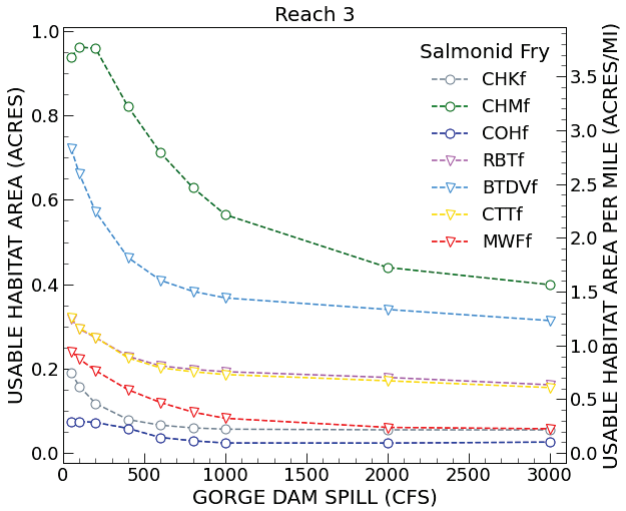
APPENDIX A

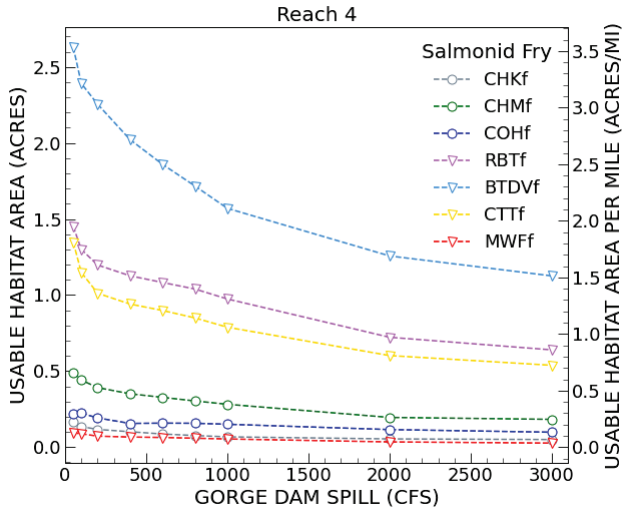
SKAGIT RIVER GORGE BYPASS REACH
USABLE HABITAT AREA FIGURES

SALMONID FRY LIFE STAGE


Reach 1
Salmonid Fry
CHKf
CHMf
COHf
RBTf
BTDVf
CTTf
MWFf
USABLE HABITAT AREA (ACRES)
USABLE HABITAT AREA PER MILE (ACRES/MI)
GORGE DAM SPILL (CFS)


Reach 2
Salmonid Fry
CHKf
CHMf
COHf
RBTf
BTDVf
CTTf
MWFf
USABLE HABITAT AREA (ACRES)
USABLE HABITAT AREA PER MILE (ACRES/MI)
GORGE DAM SPILL (CFS)


Reach 3
Salmonid Fry
CHKf
CHMf
COHf
RBTf
BTDVf
CTTf
MWFf
USABLE HABITAT AREA (ACRES)
USABLE HABITAT AREA PER MILE (ACRES/MI)
GORGE DAM SPILL (CFS)


Reach 4
Salmonid Fry
CHKf
CHMf
COHf
RBTf
BTDVf
CTTf
MWFf
USABLE HABITAT AREA (ACRES)
USABLE HABITAT AREA PER MILE (ACRES/MI)
GORGE DAM SPILL (CFS)

APPENDIX B

SALMONID SUBSTRATE PREFERENCE VALUES (BEECHER AND CALDWELL 2022)

Code	Type of Substrate	Spawning					Salmon & Trout Rearing	Whitefish Rearing	
		Salmon	Steelhead	Resident Trout	Native Char	Whitefish	Juvenile & Resident Adult	Juvenile	Adult
1	Silt, clay, or organic	0.00	0.00	0.00	0.00	0.00	0.10	0.38	0.15
2	Sand	0.00	0.00	0.00	0.00	0.00	0.10	0.38	0.15
3	Sm Gravel (0.1 - 0.5")	0.30	0.50	0.80	1.00	1.00	0.10	0.74	0.76
4	Med Gravel (0.5 - 1.5")	1.00	1.00	1.00	1.00	1.00	0.30	0.88	0.91
5	Lrg Gravel (1.5 - 3")	1.00	1.00	0.80	1.00	1.00	0.30	0.88	0.91
6	Sm Cobble (3 - 6")	1.00	1.00	0.50	0.70	1.00	0.50	1.00	1.00
7	Lrg Cobble (6 - 12")	0.50	0.30	0.00	0.70	0.50	0.70	1.00	1.00
8	Boulder (>12")	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
9	Bedrock	0.00	0.00	0.00	0.00	0.00	0.30	0.50	0.30

APPENDIX C

FISH PASSAGE ASSESSMENT FIGURES

Chinook_Salmon, 50cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

Hydraulics potentially impacted

No existing passage

No existing passage

1 2 3 4 5 6 7 8 9

3.5 2 2.5 2 4 3.2 1.6 0.5 1.1 3.8 2 4.4 3.3 2 1.6 1.9 1.4 2.4

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.40

3.40 - 7.70

7.70 - 11.90

11.90 - 17.10

17.10 - 27.30

> 27.30

Large substrate change boundary

Chinook_Salmon, 100cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

Hydraulics potentially impacted

No existing passage

No existing passage

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.40

3.40 - 7.70

7.70 - 11.90

11.90 - 17.10

17.10 - 27.30

> 27.30

Large substrate change boundary

Chinook_Salmon, 200cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

Hydraulics potentially impacted

Hydraulics potentially impacted

No existing passage

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.40

3.40 - 7.70

7.70 - 11.90

11.90 - 17.10

17.10 - 27.30

> 27.30

Large substrate change boundary

Chinook_Salmon, 400cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

Hydraulics potentially impacted

No existing passage (leap height may be decreased)

Hydraulics potentially impacted

Hydraulics potentially impacted

No existing passage

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.40

3.40 - 7.70

7.70 - 11.90

11.90 - 17.10

17.10 - 27.30

> 27.30

Large substrate change boundary

Chinook_Salmon, 600cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

Hydraulics potentially impacted

No existing passage (leap height may be decreased)

Hydraulics potentially impacted

Hydraulics potentially impacted

Hydraulics potentially impacted

No existing passage

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.40

3.40 - 7.70

7.70 - 11.90

11.90 - 17.10

17.10 - 27.30

> 27.30

Large substrate change boundary

Chinook_Salmon, 800cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

No existing passage (leap height may be decreased)

Hydraulics potentially impacted

Hydraulics potentially impacted

Hydraulics potentially impacted

Passage impacted

Passage impacted

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.40

3.40 - 7.70

7.70 - 11.90

11.90 - 17.10

17.10 - 27.30

> 27.30

Large substrate change boundary

Chinook_Salmon, 1000cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway not impacted by large substrate changes

1 Subreach number

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.40

3.40 - 7.70

7.70 - 11.90

11.90 - 17.10

17.10 - 27.30

> 27.30

Large substrate change boundary

Chinook_Salmon, 1200cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway not impacted by large substrate changes

1 Subreach number

1 2 3 4 5 6 7 8 9

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.40

3.40 - 7.70

7.70 - 11.90

11.90 - 17.10

17.10 - 27.30

> 27.30

Large substrate change boundary

Chinook_Salmon, 1400cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway not impacted by large substrate changes

1 Subreach number

1 2 3 4 5 6 7 8 9

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.40

3.40 - 7.70

7.70 - 11.90

11.90 - 17.10

17.10 - 27.30

> 27.30

Large substrate change boundary

Chinook_Salmon, 1600cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway not impacted by large substrate changes

1 Subreach number

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.40

3.40 - 7.70

7.70 - 11.90

11.90 - 17.10

17.10 - 27.30

> 27.30

Large substrate change boundary

Chinook_Salmon, 1800cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway not impacted by large substrate changes

1 Subreach number

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.40

3.40 - 7.70

7.70 - 11.90

11.90 - 17.10

17.10 - 27.30

> 27.30

Large substrate change boundary

Chinook_Salmon, 2000cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway not impacted by large substrate changes

1 Subreach number

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.40

3.40 - 7.70

7.70 - 11.90

11.90 - 17.10

17.10 - 27.30

> 27.30

Large substrate change boundary

Coho_Salmon, 50cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

Hydraulics potentially impacted

No existing passage

No existing passage

1 2 3 4 5 6 7 8 9

3.5 2 2.5 2 4 3.2 1.6 0.5 1.1 3.8 2 4.4 3.3 2 1.6 1.9 1.4 2.4

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.40

3.40 - 6.60

6.60 - 9.80

9.80 - 13.10

13.10 - 19.70

> 19.70

Large substrate change boundary

Coho_Salmon, 100cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

Hydraulics potentially impacted

No existing passage

No existing passage

1 2 3 4 5 6 7 8 9

4.1 1.6 2 3.4 3.4 1.7 2 0.9 3.6 2 4.4 1.9 2.2 1.6 1.1 1.3 2.4

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.40

3.40 - 6.60

6.60 - 9.80

9.80 - 13.10

13.10 - 19.70

> 19.70

Large substrate change boundary

Coho_Salmon, 200cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

Hydraulics potentially impacted

Hydraulics potentially impacted

No existing passage

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.40

3.40 - 6.60

6.60 - 9.80

9.80 - 13.10

13.10 - 19.70

> 19.70

Large substrate change boundary

Coho_Salmon, 400cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

No existing passage

Hydraulics potentially impacted

No existing passage (leap height may be decreased)

Hydraulics potentially impacted

Hydraulics potentially impacted

No existing passage

No existing passage

1 2 3 4 5 6 7 8 9

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.40

3.40 - 6.60

6.60 - 9.80

9.80 - 13.10

13.10 - 19.70

> 19.70

Large substrate change boundary

Coho_Salmon, 600cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

Hydraulics potentially impacted

No existing passage (leap height may be decreased)

Hydraulics potentially impacted

No existing passage

Hydraulics potentially impacted

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.40

3.40 - 6.60

6.60 - 9.80

9.80 - 13.10

13.10 - 19.70

> 19.70

Large substrate change boundary

Coho_Salmon, 800cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

Hydraulics potentially impacted

No existing passage (leap height may be decreased)

Hydraulics potentially impacted

Passage Impacted

Passage Impacted

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.40

3.40 - 6.60

6.60 - 9.80

9.80 - 13.10

13.10 - 19.70

> 19.70

Large substrate change boundary

Coho_Salmon, 1000cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

Hydraulics potentially impacted

No existing passage (leap height may be decreased)

Passage Impacted

Passage Impacted

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.40

3.40 - 6.60

6.60 - 9.80

9.80 - 13.10

13.10 - 19.70

> 19.70

Large substrate change boundary

Coho_Salmon, 1200cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

No existing passage

No existing passage (leap height may be decreased)

Hydraulics potentially impacted

Passage Impacted

Hydraulics potentially impacted

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.40

3.40 - 6.60

6.60 - 9.80

9.80 - 13.10

13.10 - 19.70

> 19.70

Large substrate change boundary

Coho_Salmon, 1400cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

Hydraulics potentially impacted

No existing passage (leap height may be decreased)

Hydraulics potentially impacted

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.40

3.40 - 6.60

6.60 - 9.80

9.80 - 13.10

13.10 - 19.70

> 19.70

Large substrate change boundary

Coho_Salmon, 1600cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

Hydraulics potentially impacted

No existing passage (leap height may be decreased)

Hydraulics potentially impacted

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.40

3.40 - 6.60

6.60 - 9.80

9.80 - 13.10

13.10 - 19.70

> 19.70

Large substrate change boundary

Coho_Salmon, 1800cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

Hydraulics potentially impacted

No existing passage (leap height may be decreased)

Hydraulics potentially impacted

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.40

3.40 - 6.60

6.60 - 9.80

9.80 - 13.10

13.10 - 19.70

> 19.70

Large substrate change boundary

Coho_Salmon, 2000cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

Hydraulics potentially impacted

No existing passage (leap height may be decreased)

Hydraulics potentially impacted

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.40

3.40 - 6.60

6.60 - 9.80

9.80 - 13.10

13.10 - 19.70

> 19.70

Large substrate change boundary

Pink_Salmon, 50cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

No existing passage

No existing passage

No existing passage

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 2.90

2.90 - 6.00

6.00 - 9.10

9.10 - 12.10

12.10 - 18.20

> 18.20

Large substrate change boundary

Pink_Salmon, 100cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

No existing passage

No existing passage

No existing passage

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 2.90

2.90 - 6.00

6.00 - 9.10

9.10 - 12.10

12.10 - 18.20

> 18.20

Large substrate change boundary

Pink_Salmon, 200cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

1

2

3

4

5

6

7

8

9

Hydraulics potentially impacted

No existing passage

Hydraulics potentially impacted

No existing passage

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 2.90

2.90 - 6.00

6.00 - 9.10

9.10 - 12.10

12.10 - 18.20

> 18.20

Large substrate change boundary

Pink_Salmon, 400cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

No existing passage

Hydraulics potentially impacted

No existing passage

Hydraulics potentially impacted

Passage impacted

Passage impacted

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 2.90

2.90 - 6.00

6.00 - 9.10

9.10 - 12.10

12.10 - 18.20

> 18.20

Large substrate change boundary

Pink_Salmon, 600cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

No existing passage

Hydraulics potentially impacted

No existing passage

Hydraulics potentially impacted

Passage impacted

1 2 3 4 5 6 7 8 9

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 2.90

2.90 - 6.00

6.00 - 9.10

9.10 - 12.10

12.10 - 18.20

> 18.20

Large substrate change boundary

Pink_Salmon, 800cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

No existing passage

Hydraulics potentially impacted

Hydraulics potentially impacted

Passage impacted

Passage impacted

1 2 3 4 5 6 7 8 9

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 2.90

2.90 - 6.00

6.00 - 9.10

9.10 - 12.10

12.10 - 18.20

> 18.20

Large substrate change boundary

Pink_Salmon, 1000cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

No existing passage

Hydraulics potentially impacted

Passage impacted

Passage impacted

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 2.90

2.90 - 6.00

6.00 - 9.10

9.10 - 12.10

12.10 - 18.20

> 18.20

Large substrate change boundary

Pink_Salmon, 1200cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

No existing passage

Hydraulics potentially impacted

Passage impacted

Hydraulics potentially impacted

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 2.90

2.90 - 6.00

6.00 - 9.10

9.10 - 12.10

12.10 - 18.20

> 18.20

Large substrate change boundary

Pink_Salmon, 1400cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

No existing passage

Hydraulics potentially impacted

Hydraulics potentially impacted

1 2 3 4 5 6 7 8 9

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 2.90

2.90 - 6.00

6.00 - 9.10

9.10 - 12.10

12.10 - 18.20

> 18.20

Large substrate change boundary

Pink_Salmon, 1600cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

No existing passage

Hydraulics potentially impacted

Hydraulics potentially impacted

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 2.90

2.90 - 6.00

6.00 - 9.10

9.10 - 12.10

12.10 - 18.20

> 18.20

Large substrate change boundary

Pink_Salmon, 1800cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

No existing passage

Hydraulics potentially impacted

Hydraulics potentially impacted

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 2.90

2.90 - 6.00

6.00 - 9.10

9.10 - 12.10

12.10 - 18.20

> 18.20

Large substrate change boundary

Pink_Salmon, 2000cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

No existing passage

Hydraulics potentially impacted

Hydraulics potentially impacted

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 2.90

2.90 - 6.00

6.00 - 9.10

9.10 - 12.10

12.10 - 18.20

> 18.20

Large substrate change boundary

Sockeye_Salmon, 50cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

No existing passage

No existing passage

No existing passage

1 2 3 4 5 6 7 8 9

3.5 2 2.5 2 4 3.2 1.6 0.5 1.1 3.8 2 4.4 3.3 2 1.6 1.9 1.4 2.4

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.10

3.10 - 6.00

6.00 - 8.90

8.90 - 11.90

11.90 - 17.90

> 17.90

Large substrate change boundary

Sockeye_Salmon, 100cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

1 2 3 4 5 6 7 8 9

No existing passage

No existing passage

No existing passage

4.1 1.6 0.9 3.6 2 4.4 2 3.4 3.4 1.7 1.9 2.2 1.6 1.1 1.3 2.4

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.10

3.10 - 6.00

6.00 - 8.90

8.90 - 11.90

11.90 - 17.90

> 17.90

Large substrate change boundary

Sockeye_Salmon, 200cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

Hydraulics potentially impacted

Hydraulics potentially impacted

No existing passage

No existing passage

1 2 3 4 5 6 7 8 9

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.10

3.10 - 6.00

6.00 - 8.90

8.90 - 11.90

11.90 - 17.90

> 17.90

Large substrate change boundary

Sockeye_Salmon, 400cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

1

2

3

4

5

6

7

8

9

No existing passage

No existing passage

Hydraulics potentially impacted

Hydraulics potentially impacted

Passage impacted

Passage impacted

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.10

3.10 - 6.00

6.00 - 8.90

8.90 - 11.90

11.90 - 17.90

> 17.90

Large substrate change boundary

Sockeye_Salmon, 600cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

No existing passage

Hydraulics potentially impacted

No existing passage

Hydraulics potentially impacted

Hydraulics potentially impacted

Passage impacted

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.10

3.10 - 6.00

6.00 - 8.90

8.90 - 11.90

11.90 - 17.90

> 17.90

Large substrate change boundary

Sockeye_Salmon, 800cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

No existing passage

Hydraulics potentially impacted

Hydraulics potentially impacted

Passage impacted

Passage impacted

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.10

3.10 - 6.00

6.00 - 8.90

8.90 - 11.90

11.90 - 17.90

> 17.90

Large substrate change boundary

Sockeye_Salmon, 1000cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

No existing passage

Hydraulics potentially impacted

Passage impacted

Passage impacted

1 2 3 4 5 6 7 8 9

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.10

3.10 - 6.00

6.00 - 8.90

8.90 - 11.90

11.90 - 17.90

> 17.90

Large substrate change boundary

Sockeye_Salmon, 1200cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

No existing passage

Hydraulics potentially impacted

Passage impacted

Hydraulics potentially impacted

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.10

3.10 - 6.00

6.00 - 8.90

8.90 - 11.90

11.90 - 17.90

> 17.90

Large substrate change boundary

Sockeye_Salmon, 1400cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

No existing passage

Hydraulics potentially impacted

Hydraulics potentially impacted

1 2 3 4 5 6 7 8 9

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.10

3.10 - 6.00

6.00 - 8.90

8.90 - 11.90

11.90 - 17.90

> 17.90

Large substrate change boundary

Sockeye_Salmon, 1600cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

No existing passage

Hydraulics potentially impacted

Hydraulics potentially impacted

1 2 3 4 5 6 7 8 9

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.10

3.10 - 6.00

6.00 - 8.90

8.90 - 11.90

11.90 - 17.90

> 17.90

Large substrate change boundary

Sockeye_Salmon, 1800cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

No existing passage

Hydraulics potentially impacted

Hydraulics potentially impacted

1 2 3 4 5 6 7 8 9

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.10

3.10 - 6.00

6.00 - 8.90

8.90 - 11.90

11.90 - 17.90

> 17.90

Large substrate change boundary

Sockeye_Salmon, 2000cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

No existing passage

Hydraulics potentially impacted

Hydraulics potentially impacted

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.10

3.10 - 6.00

6.00 - 8.90

8.90 - 11.90

11.90 - 17.90

> 17.90

Large substrate change boundary

Steelhead_Trout, 50cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

Hydraulics potentially impacted

No existing passage

No existing passage

1 2 3 4 5 6 7 8 9

3.5 2 2.4 3.2 1.6 0.5 2.5 1.1 3.8 2 4.4 3.3 2 1.6 1.9 1.4 2.4

N

0 12.5 25 50 Feet

- Leap Not Passable
- Leap Passable
- Velocities Passable
- Velocities Not Passable
- May Be Passable Under Certain Conditions

Velocity (ft/s)

- < 3.10
- 3.10 - 6.70
- 6.70 - 10.40
- 10.40 - 14.60
- 14.60 - 23.00
- > 23.00
- Large substrate change boundary

Steelhead_Trout, 100cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

Hydraulics potentially impacted

No existing passage

No existing passage

1 2 3 4 5 6 7 8 9

4.1 1.6 2 3.4 3.4 1.7 2 0.9 3.6 2 4.4 1.9 2.2 1.6 1.1 1.3 2.4

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.10

3.10 - 6.70

6.70 - 10.40

10.40 - 14.60

14.60 - 23.00

> 23.00

Large substrate change boundary

Steelhead_Trout, 200cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

Hydraulics potentially impacted

Hydraulics potentially impacted

No existing passage

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.10

3.10 - 6.70

6.70 - 10.40

10.40 - 14.60

14.60 - 23.00

> 23.00

Large substrate change boundary

Steelhead_Trout, 400cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

Hydraulics potentially impacted

No existing passage (leap height may be decreased)

Hydraulics potentially impacted

Hydraulics potentially impacted

No existing passage

No existing passage

1 2 3 4 5 6 7 8 9

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.10

3.10 - 6.70

6.70 - 10.40

10.40 - 14.60

14.60 - 23.00

> 23.00

Large substrate change boundary

Steelhead_Trout, 600cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

Hydraulics potentially impacted

No existing passage (leap height may be decreased)

Hydraulics potentially impacted

Hydraulics potentially impacted

No existing passage

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.10

3.10 - 6.70

6.70 - 10.40

10.40 - 14.60

14.60 - 23.00

> 23.00

Large substrate change boundary

Steelhead_Trout, 800cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway impacted by large substrate changes

1 Subreach number

Hydraulics potentially impacted

No existing passage (leap height may be decreased)

Hydraulics potentially impacted

Passage Impacted

Passage Impacted

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.10

3.10 - 6.70

6.70 - 10.40

10.40 - 14.60

14.60 - 23.00

> 23.00

Large substrate change boundary

Steelhead_Trout, 1000cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway not impacted by large substrate changes

1 Subreach number

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.10

3.10 - 6.70

6.70 - 10.40

10.40 - 14.60

14.60 - 23.00

> 23.00

Large substrate change boundary

Steelhead_Trout, 1200cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway not impacted by large substrate changes

1 Subreach number

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.10

3.10 - 6.70

6.70 - 10.40

10.40 - 14.60

14.60 - 23.00

> 23.00

Large substrate change boundary

Steelhead_Trout, 1400cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway not impacted by large substrate changes

1 Subreach number

N

0 12.5 25 50 Feet

- Leap Not Passable
- Leap Passable
- Velocities Passable
- Velocities Not Passable
- May Be Passable Under Certain Conditions

Velocity (ft/s)

- < 3.10
- 3.10 - 6.70
- 6.70 - 10.40
- 10.40 - 14.60
- 14.60 - 23.00
- > 23.00
- Large substrate change boundary

Steelhead_Trout, 1600cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway not impacted by large substrate changes

1 Subreach number

1 2 3 4 5 6 7 8 9

1.8 3 2.2 1.2 2.2 2.5 3.2 2.7 2.1 4.1 1.6 2 4.9 4 4.8 2.2 2.8 2.4 3.4 2 5 1.6 1.4 4.1 2.1

N

0 12.5 25 50 Feet

- Leap Not Passable
- Leap Passable
- Velocities Passable
- Velocities Not Passable
- May Be Passable Under Certain Conditions

Velocity (ft/s)

- < 3.10
- 3.10 - 6.70
- 6.70 - 10.40
- 10.40 - 14.60
- 14.60 - 23.00
- > 23.00
- Large substrate change boundary

Steelhead_Trout, 1800cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway not impacted by large substrate changes

1 Subreach number

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.10

3.10 - 6.70

6.70 - 10.40

10.40 - 14.60

14.60 - 23.00

> 23.00

Large substrate change boundary

Steelhead_Trout, 2000cfs

GORGE BYPASS REACH | UPPER SKAGIT RIVER

EXISTING FEATURE 2

Passable or potentially passable pathway not impacted by large substrate changes

1 Subreach number

N

0 12.5 25 50 Feet

Leap Not Passable

Leap Passable

Velocities Passable

Velocities Not Passable

May Be Passable Under Certain Conditions

Velocity (ft/s)

< 3.10

3.10 - 6.70

6.70 - 10.40

10.40 - 14.60

14.60 - 23.00

> 23.00

Large substrate change boundary

SKAGIT RIVER GORGE BYPASS REACH HYDRAULIC AND INSTREAM FLOW MODEL DEVELOPMENT STUDY REPORT

ATTACHMENT G

FA-05 WORKSHOP 1 MATERIALS

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MEETING AGENDA

Skagit Hydroelectric Project Relicensing Meeting

Fish Passage Evaluations and Modeling in the Bypass Reach – Technical Meeting

May 17, 2021, 1:00 PM to 5:00 PM

Webex Meeting: https://meethdr.webex.com/meethdr/j.php?MTID=md626437a9c68be9a255308c98bc5bce8

Conference Call: 1-408-418-9388 (Meeting ID: 187 136 5797)

MEETING OBJECTIVES

- **Fish Passage Evaluation Objectives** – Provide an overview of study objectives, expectations, possible outcomes, and limitations.
- **Fish Passage Evaluation Methods** – Discuss in more detail the approach and strategies to evaluating fish passage in the Bypass Reach.
- **Hydraulic Modeling** – Discuss the role of modeling in the overall fish passage evaluation methodology and provide examples of how hydraulic models have been used at other projects to gain insight on the ability of fish to ascend various hydraulic features.
- **Use of HEC-RAS 2D** – Address concerns regarding use of HEC-RAS 2D as a fish passage evaluation tool.
- **LP Discussion on Study Design**

AGENDA

1:00 – 1:10 p.m. (10 min)	**Introductions** – *Joy Juelson (Triangle Facilitator)* ▪ Roll Call Introduction
1:10 – 1:20 (10 min)	**Meeting Objectives and Agenda Overview –** *Joy Juelson (Triangle Facilitator) and Mike Garello (HDR)* ▪ Review Meeting Objectives and Agenda
1:20 – 1:40 (20 min)	**Evaluation of Fish Passage in the Bypass Reach** – *Mike Garello (HDR)* ▪ Overview of study objectives ▪ Influence of results on related studies ▪ Limitations of fish passage evaluation
1:40 – 2:05 (25 min)	**Observable Discharges** – *Malcolm Leytham (NHC)* ▪ Discussion of releases selected for instream-flow and fish passage evaluation ▪ Opportunity for data collection at higher flows
2:05 – 2:10 (5 min)	**Break**
2:10 – 2:55 (45 min)	**Fish Passage Evaluation Methods and Tools** – *Mike Garello (HDR) and Chris Long (NHC)* ▪ Process overview of fish passage evaluation methodology ▪ Biological and ecohydraulic metrics used in fish passage evaluations ▪ Strategies for site inspection and visual observation ▪ Collection of flow magnitude, depth, elevation, and velocity data ▪ Example Fish Passage Evaluation Projects o Summary of project examples illustrating the wide range of numerical strategies used in fish passage evaluations

2:55 – 3:55 (60 min)	**Use of Hydraulic Model to Support Fish Passage Interpretations** – *Mike Garello (HDR) and Chris Long (NHC)* ▪ The role of modeling in the proposed study ▪ Selection and perceived efficacy of different modeling platforms ▪ How HEC-RAS 2D will be used in the fish passage evaluation strategy
3:55 – 4:00 (5 min)	**Break**
4:00 – 4:40 (40 min)	**LP Discussion on Study Design** - *Facilitator and Meeting Participants*
4:40 – 5:00 (20 min)	**Schedule, Action Items, Next Steps** – *Facilitator and Meeting Participants* ▪ Study schedule review ▪ Review meeting action items ▪ Next steps
5:00	**Meeting Adjourned**



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SKAGIT RIVER INSTREAM FLOW STUDY
FISH PASSAGE EVALUATIONS AND MODELING IN BYPASS REACH

May 17, 2021

INTRODUCTIONS

- Role call and introduction of meeting attendees

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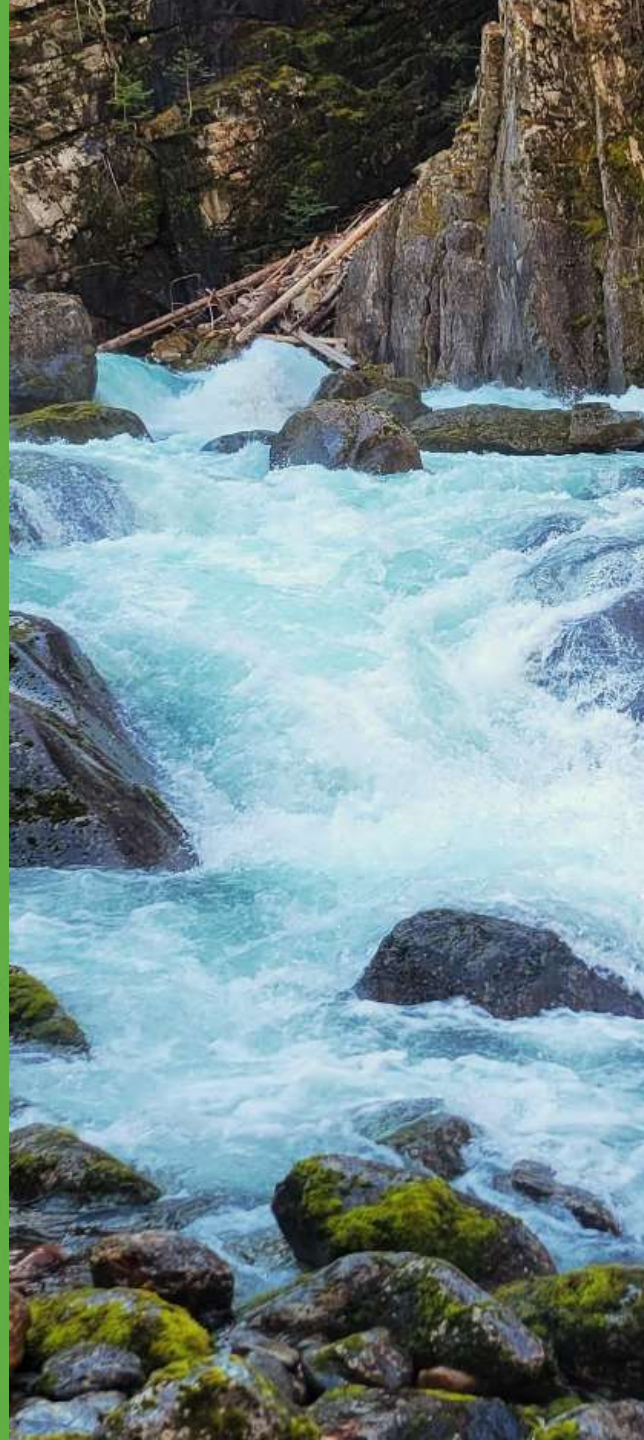
MEETING OBJECTIVES AND AGENDA OVERVIEW



MEETING OBJECTIVES AND AGENDA OVERVIEW

Meeting Objectives

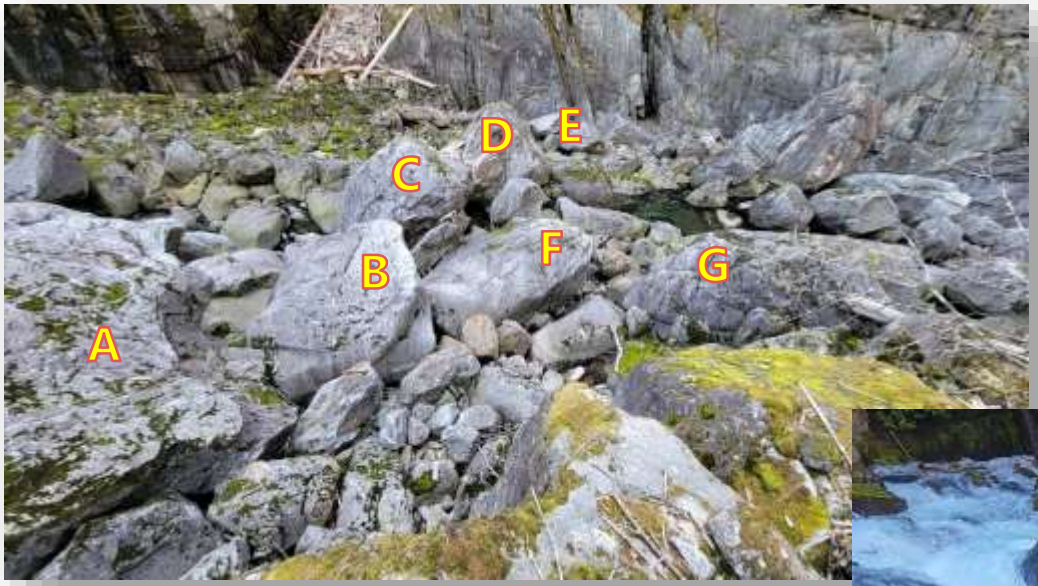
- Review fish passage evaluation objectives
- Discuss fish passage evaluation methods
- Discuss the role of hydraulic modeling in fish passage evaluations
- Address the strategy using HEC-RAS 2D
- LP concurrence with study design

MEETING OBJECTIVES AND AGENDA OVERVIEW

Agenda Overview

- Evaluation of fish passage in the Bypass Reach
- Observable discharges
- Fish Passage evaluation methods and tools
- Use of hydraulic models and HEC-RAS 2D
- LP concurrence with study design

MEETING OBJECTIVES AND AGENDA OVERVIEW



Base flow ~5 to 10 cfs



~1,200 cfs

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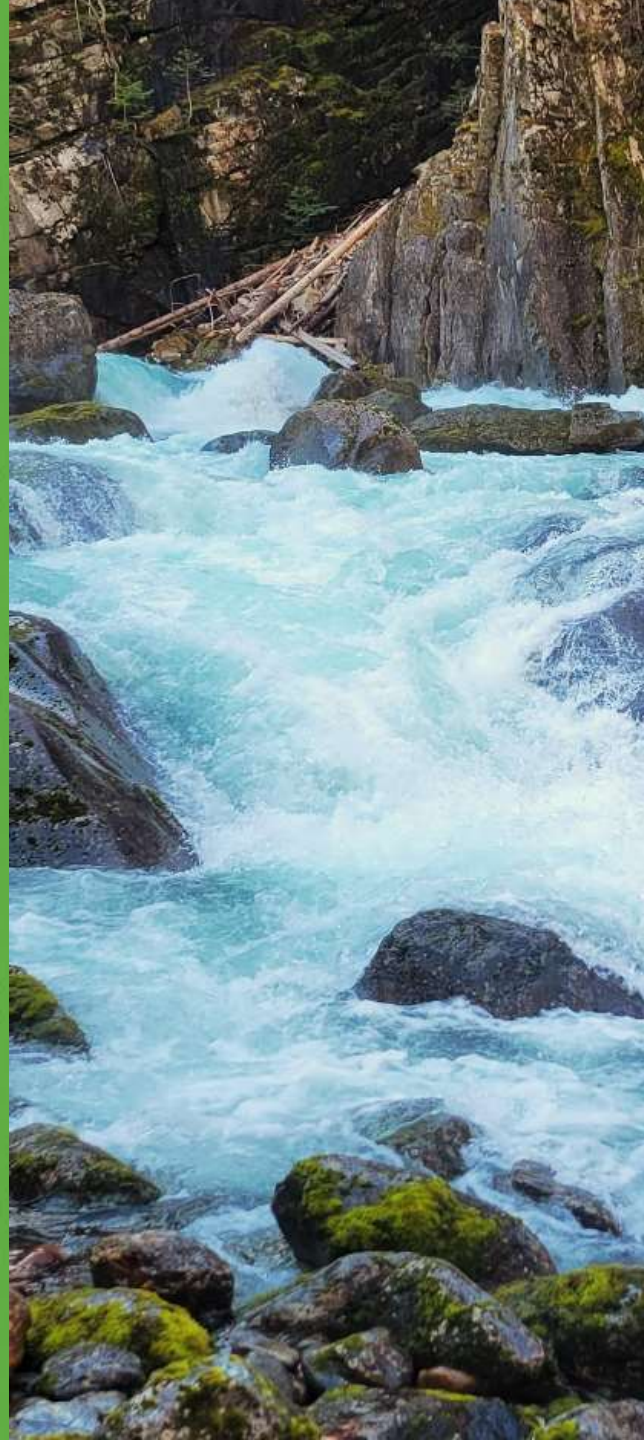
FISH PASSAGE EVALUATION IN THE BYPASS REACH



EVALUATION OF FISH PASSAGE IN THE BYPASS REACH

Key Objectives

- Gain a more detailed understanding of current feature geometry
- Characterize hydraulic pathways that potentially accommodate fish passage
- Better understand conditions that impede and promote fish passage for species considered
- Continuity among features
- Inform related, concurrent studies

EVALUATION OF FISH PASSAGE IN THE BYPASS REACH

Influence on related studies

- Fish Passage Facility Alternatives Study
  - Abundance and rate of passage influences facility type, size, and complexity
  - Potential siting of fish passage facilities to be studied in alternatives assessment
- Habitat and Production Potential
  - Conditions required for passage
  - Use and access of habitat in the bypass reach

EVALUATION OF FISH PASSAGE IN THE BYPASS REACH

Study limitations

- Factors that cause inherent variability
  - Prediction of fish behavior and ability
  - Unique site-specific conditions influence input and output – site complexity
- Level of certainty (qualitative vs. quantitative)
- All methods subject to professional judgement, experience, and interpretation

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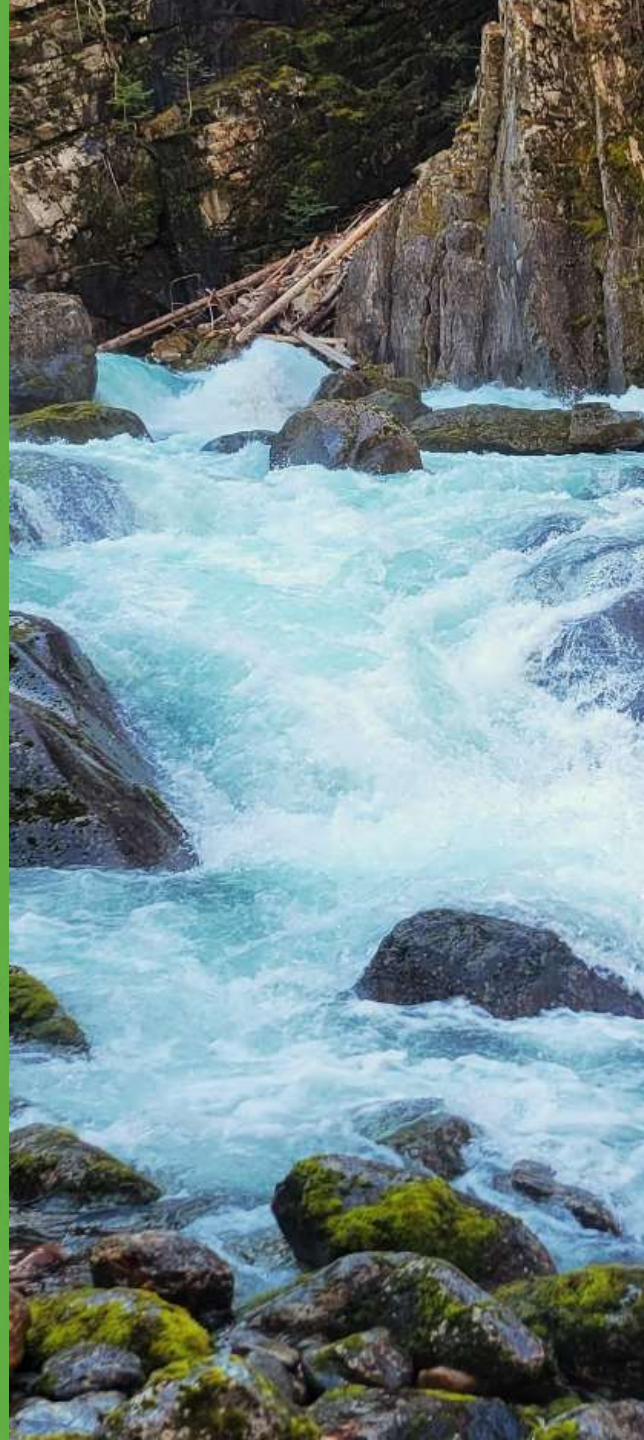
OBSERVABLE DISCHARGES



OBSERVABLE DISCHARGES

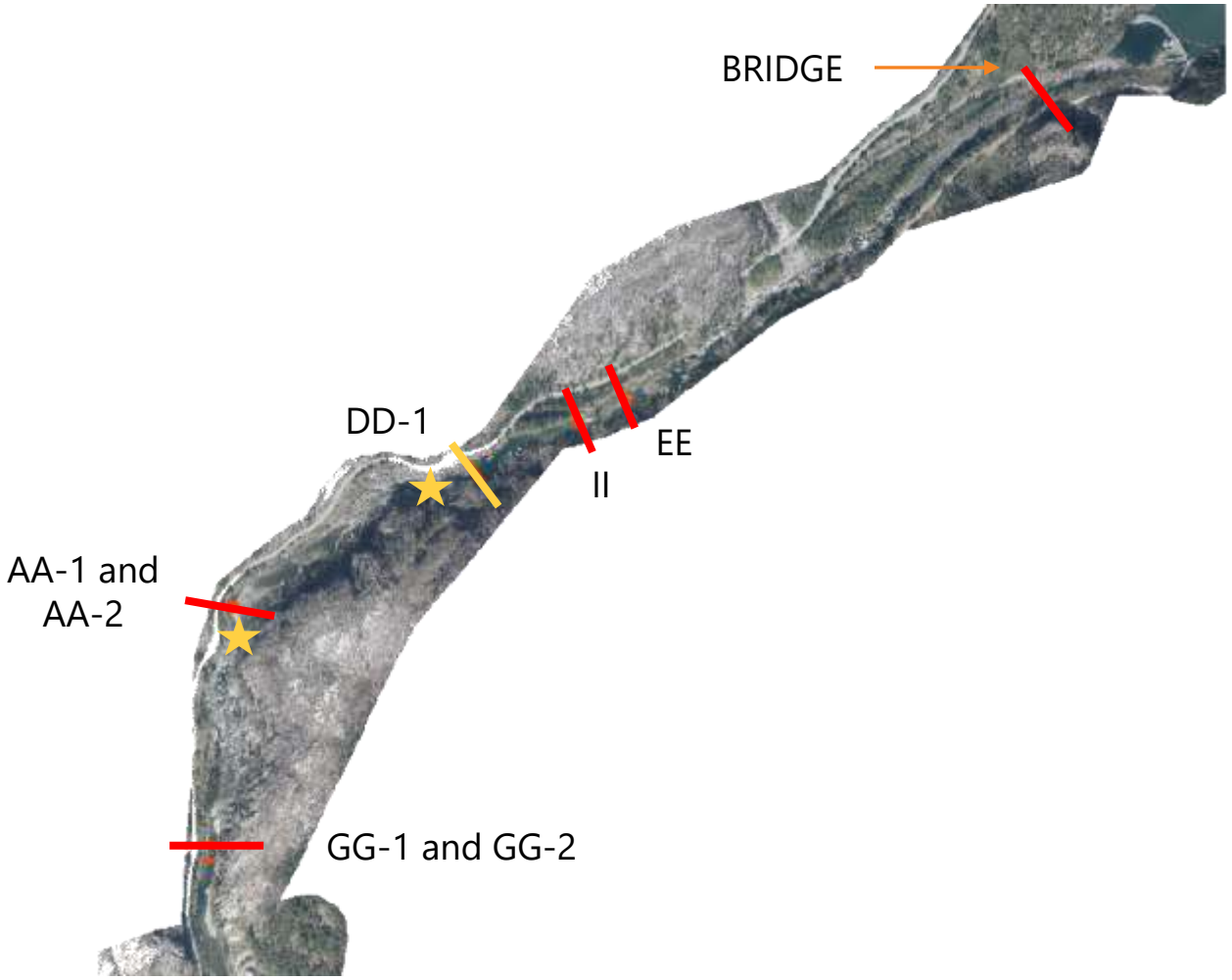
- Releases selected for instream-flow and fish passage evaluation
- Opportunity for data collection at higher flows

PROPOSED DATA COLLECTION

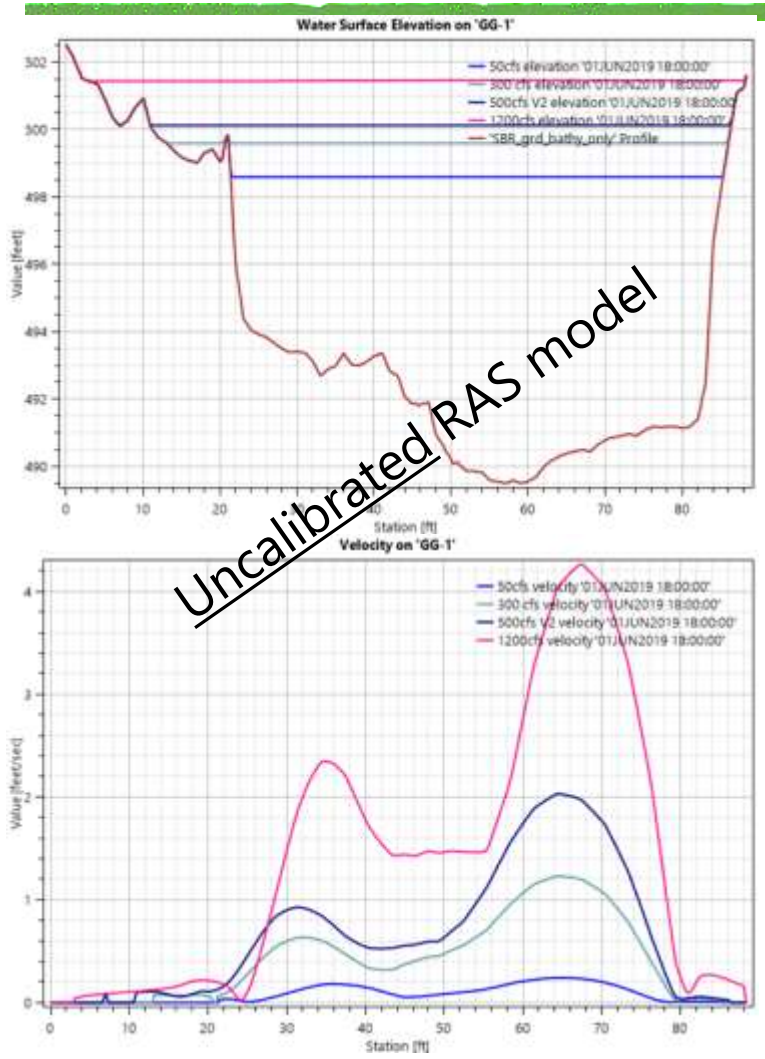
- Water surface elevation profiles for baseflow (no release from Gorge Dam) and controlled releases of 50 cfs, ~300 cfs, 500 cfs and 1,200 cfs.
- Detailed monitoring (depth, velocity, discharge) at 5 transects under baseflow and controlled releases.
- 12 continuous water level recorders provide data to refine model in passage barrier sections and support fish passage evaluation – for both controlled releases and unscheduled spill in monitoring period.
- Time lapse cameras.
- Drone imagery for controlled releases (subject to drone use authorization)

TRANSECTS

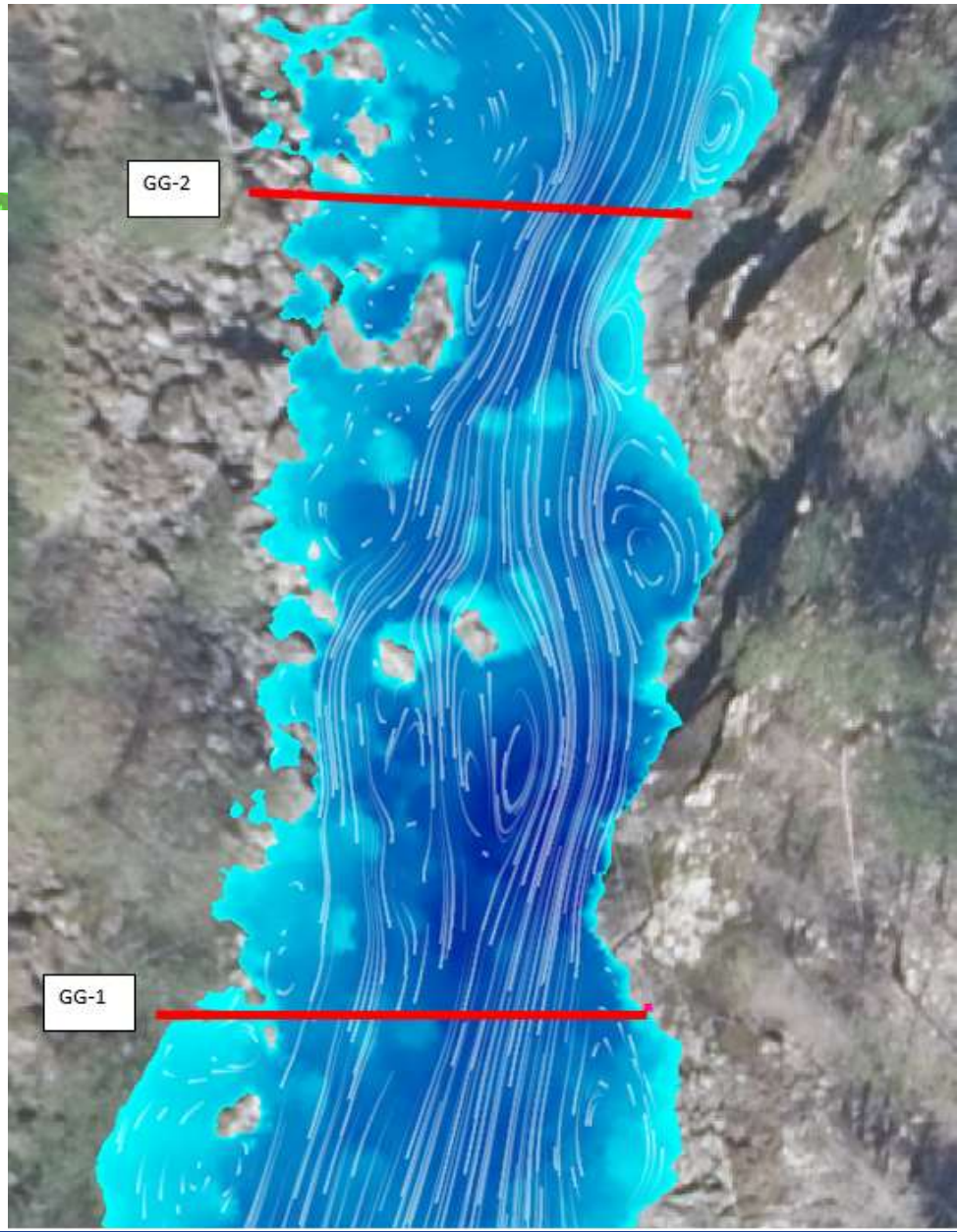
- GG-1
- **GG-2**
- **AA-1**
- AA-2
- DD
- **II**
- **EE**
- **BRIDGE**



TRANSECT GG-1



Uncalibrated RAS model



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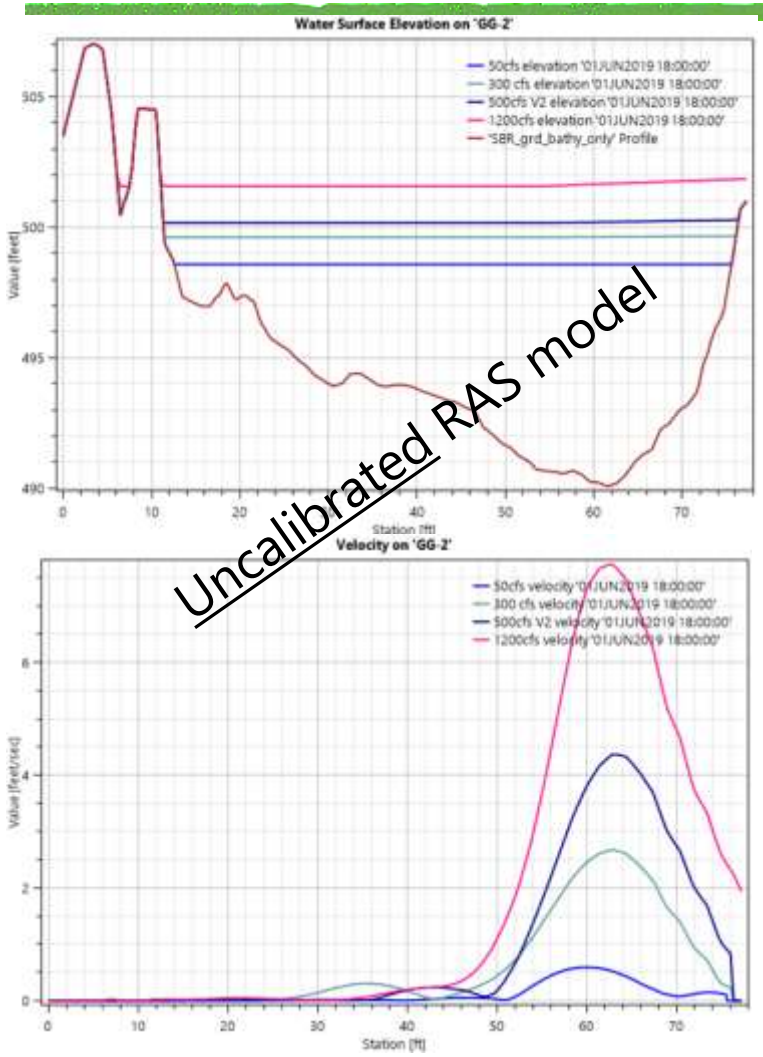
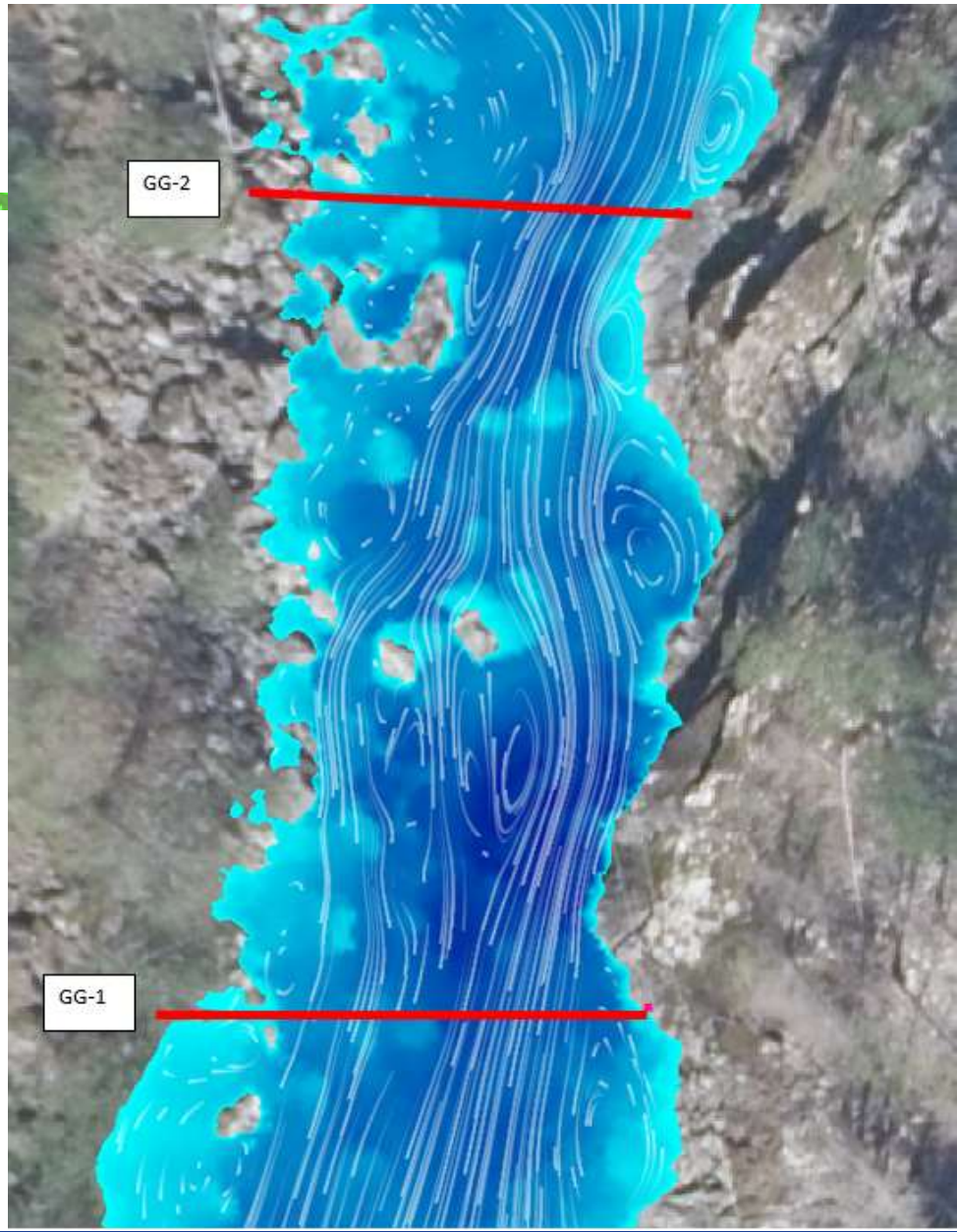


Uncalibrated RAS model



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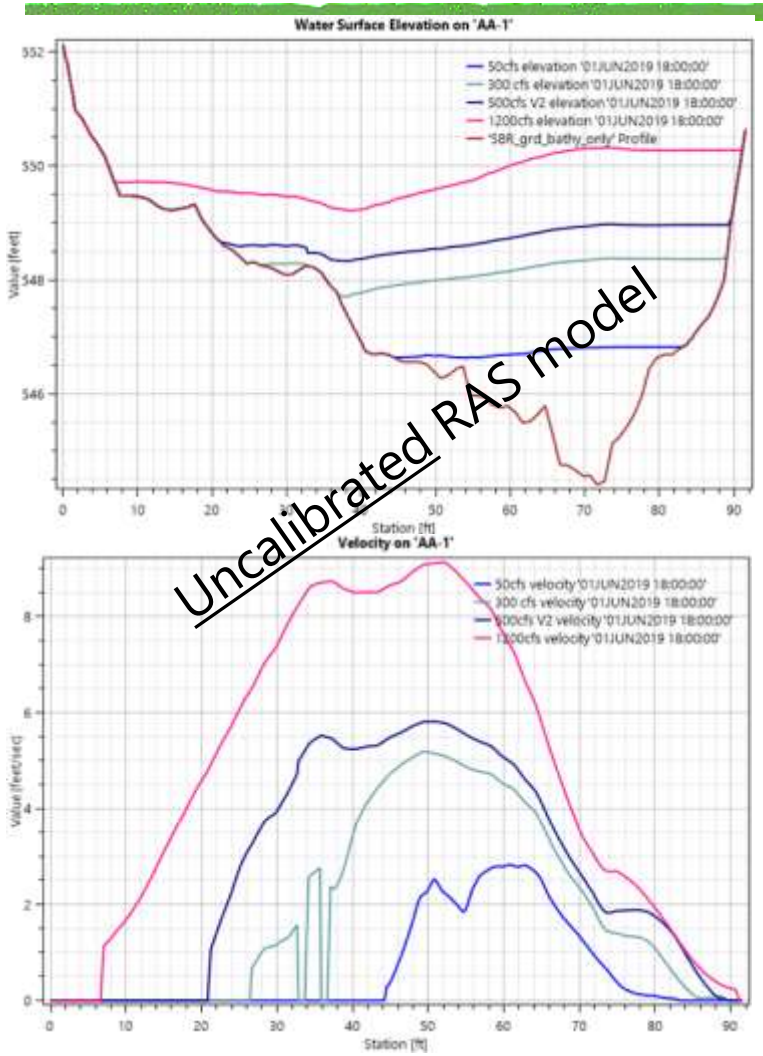
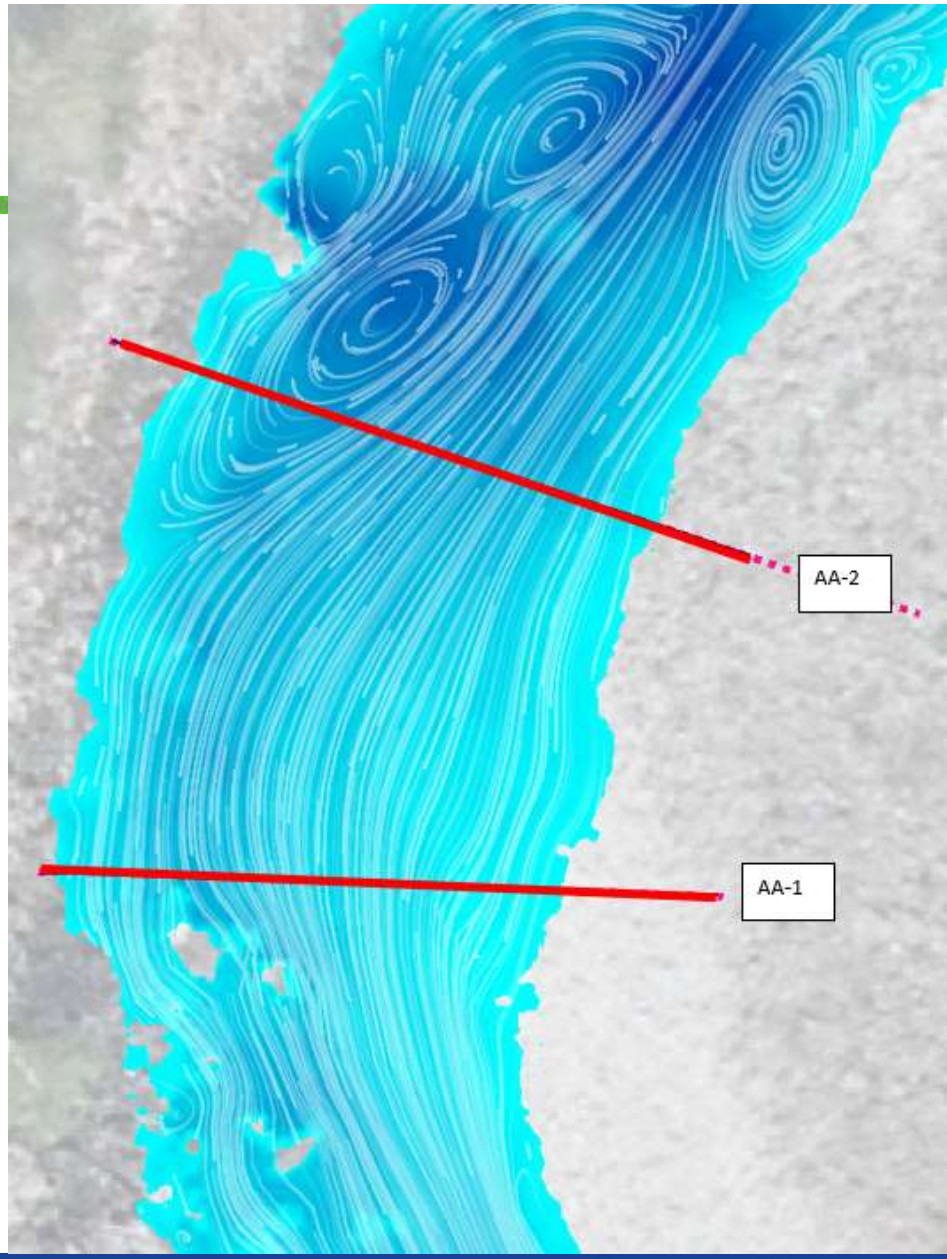
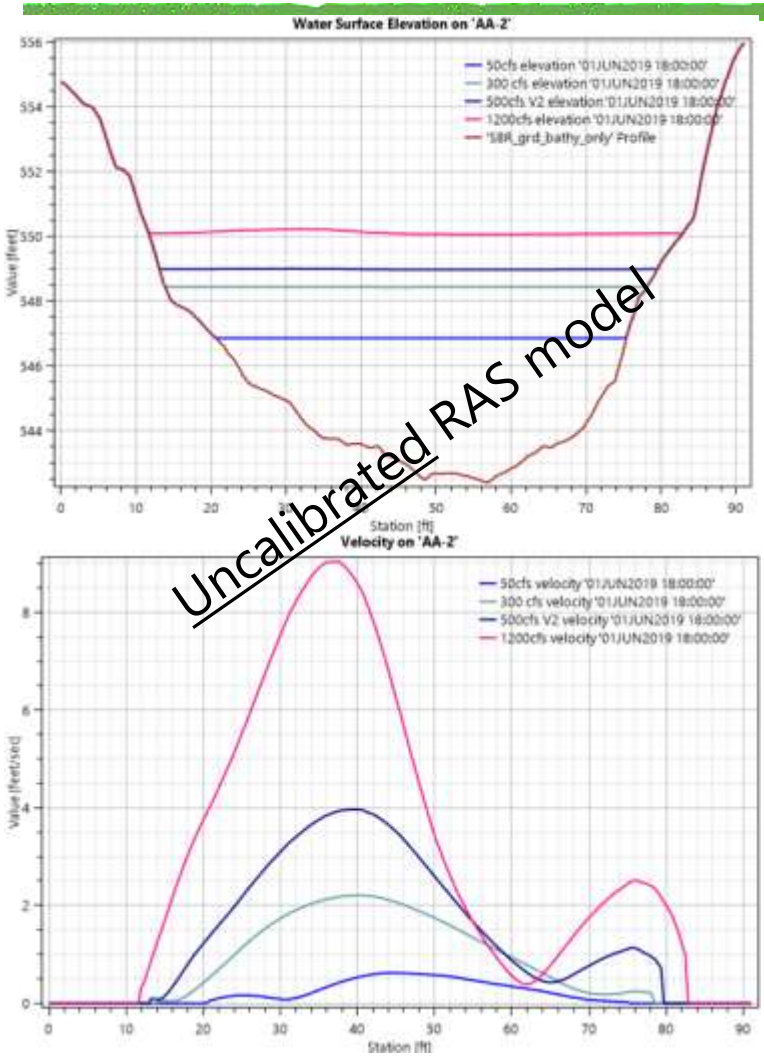


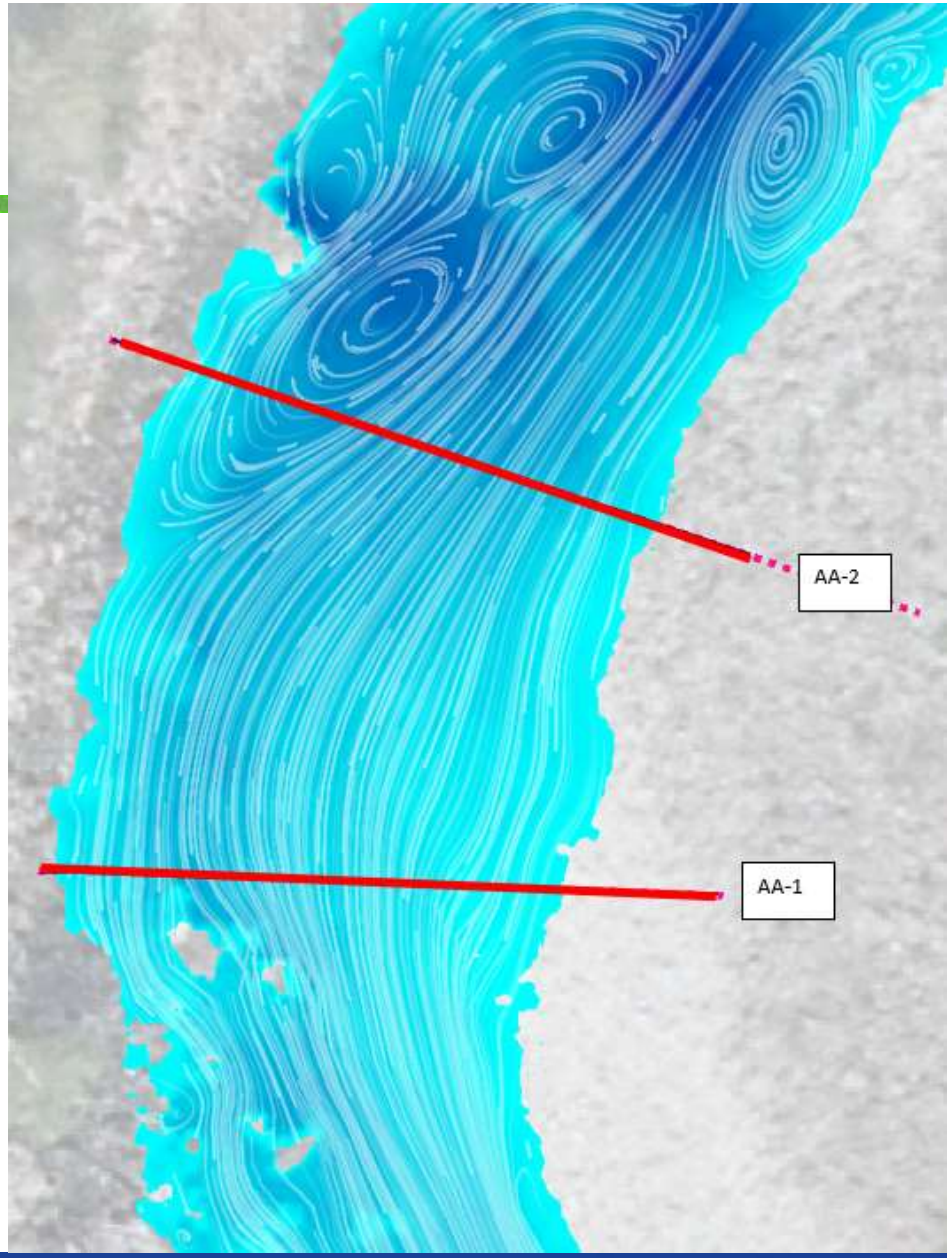
Uncalibrated RAS model



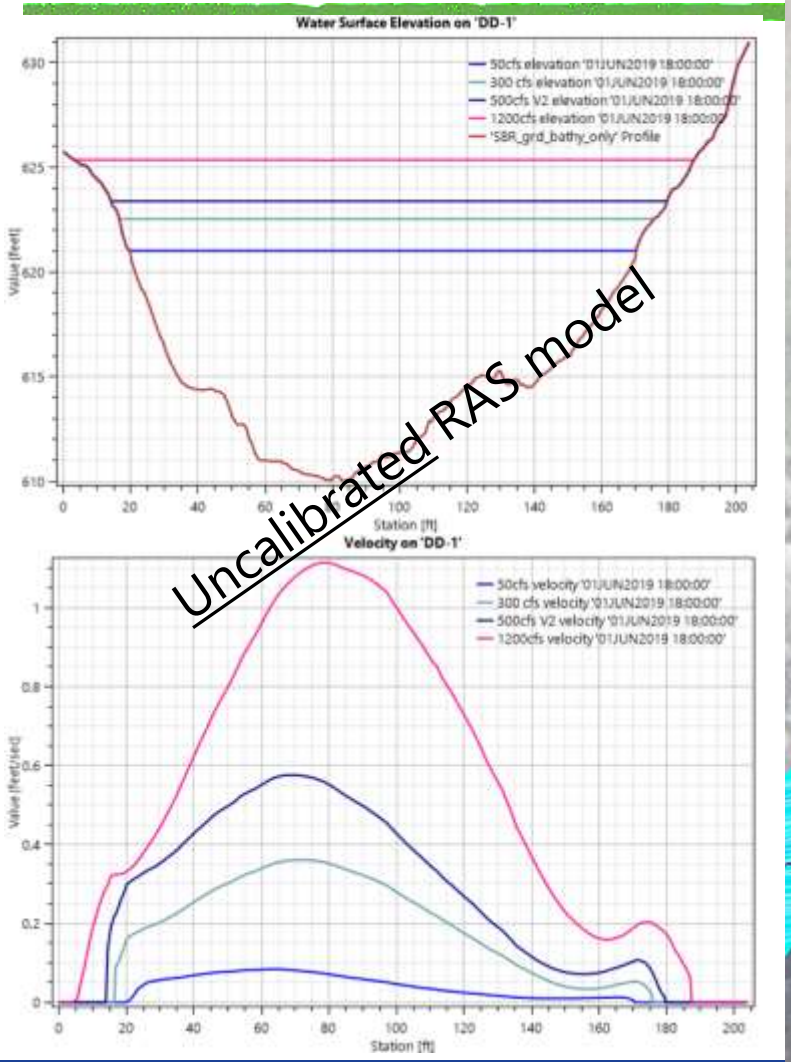
TRANSECT AA-2



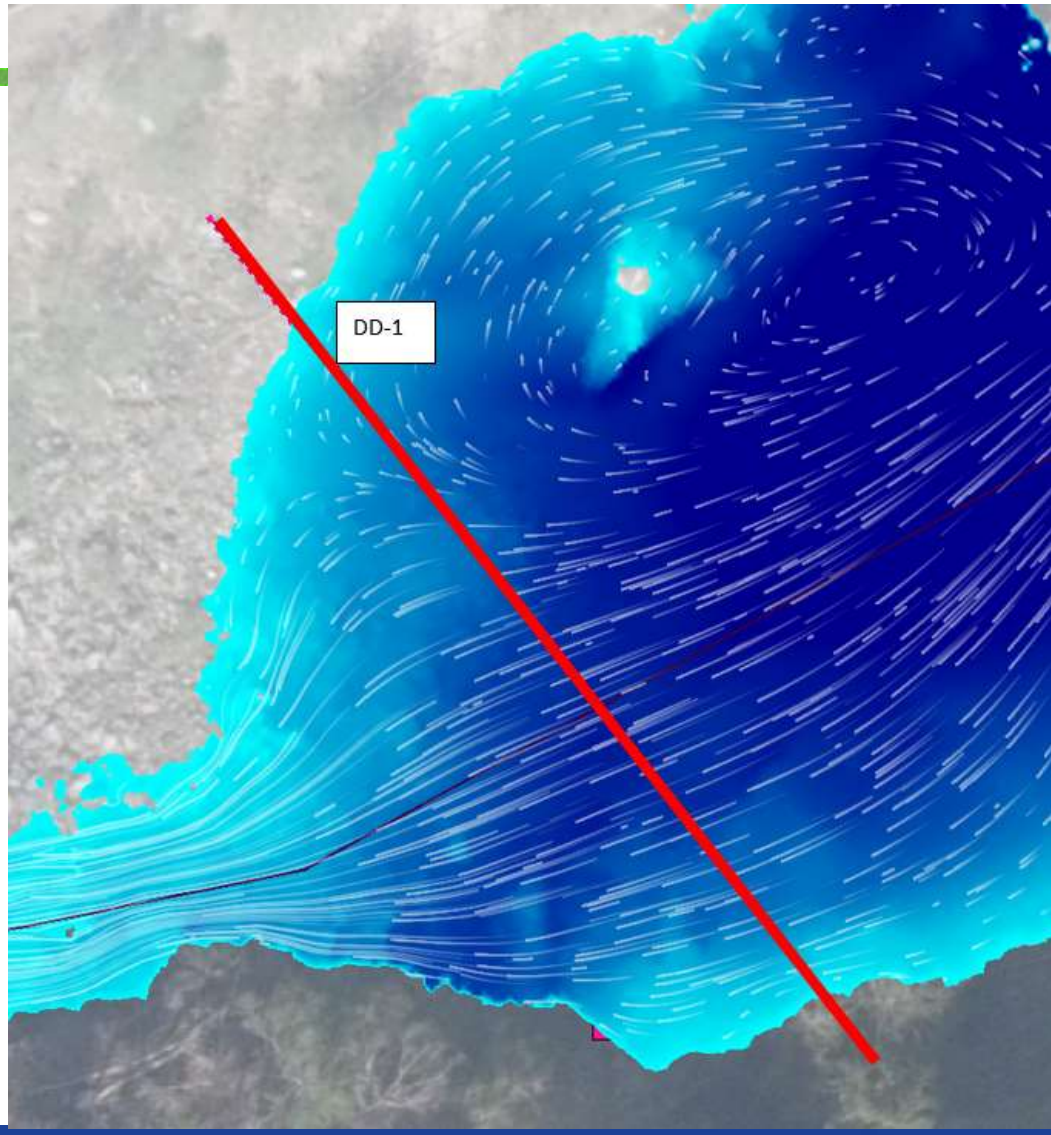
Uncalibrated RAS model



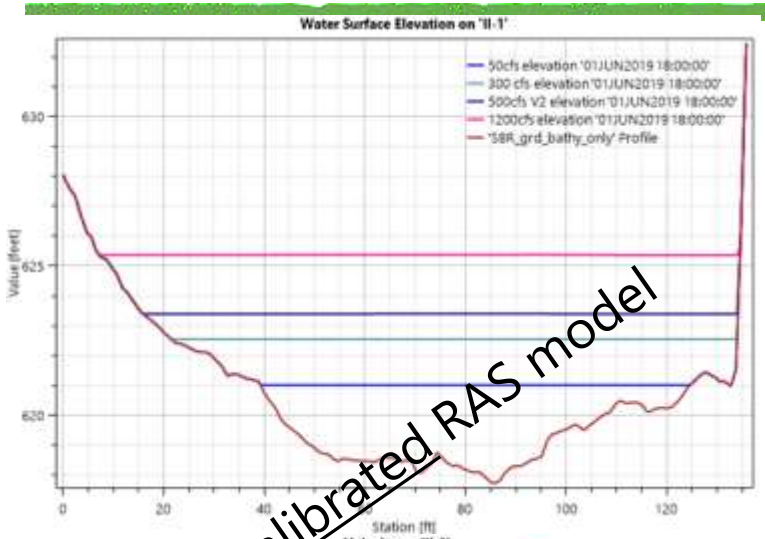
TRANSECT DD



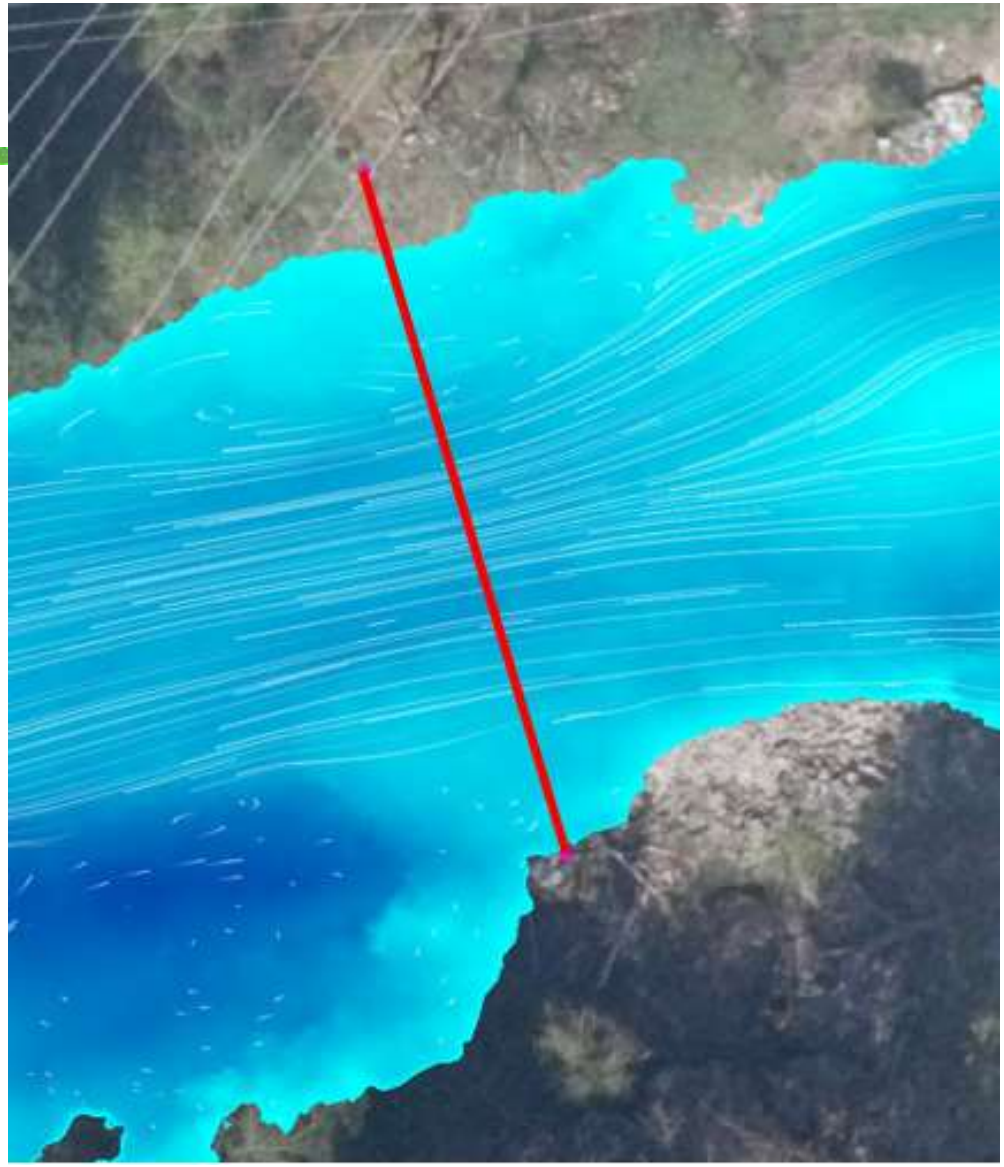
Uncalibrated RAS model



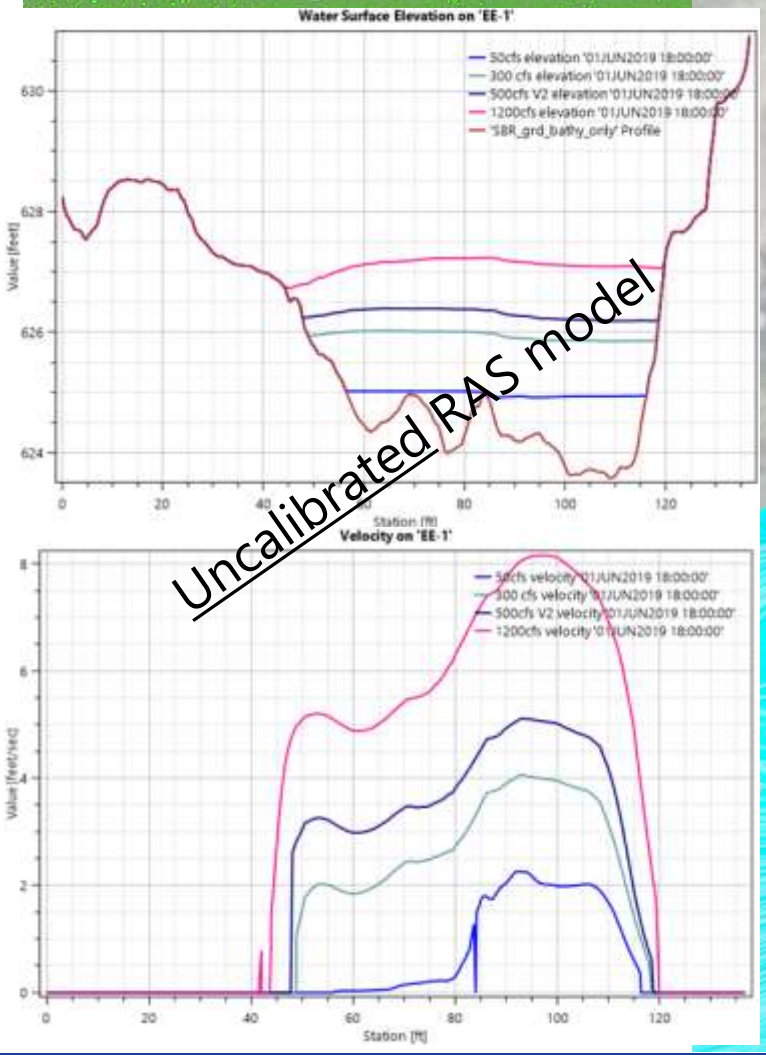
TRANSECT II



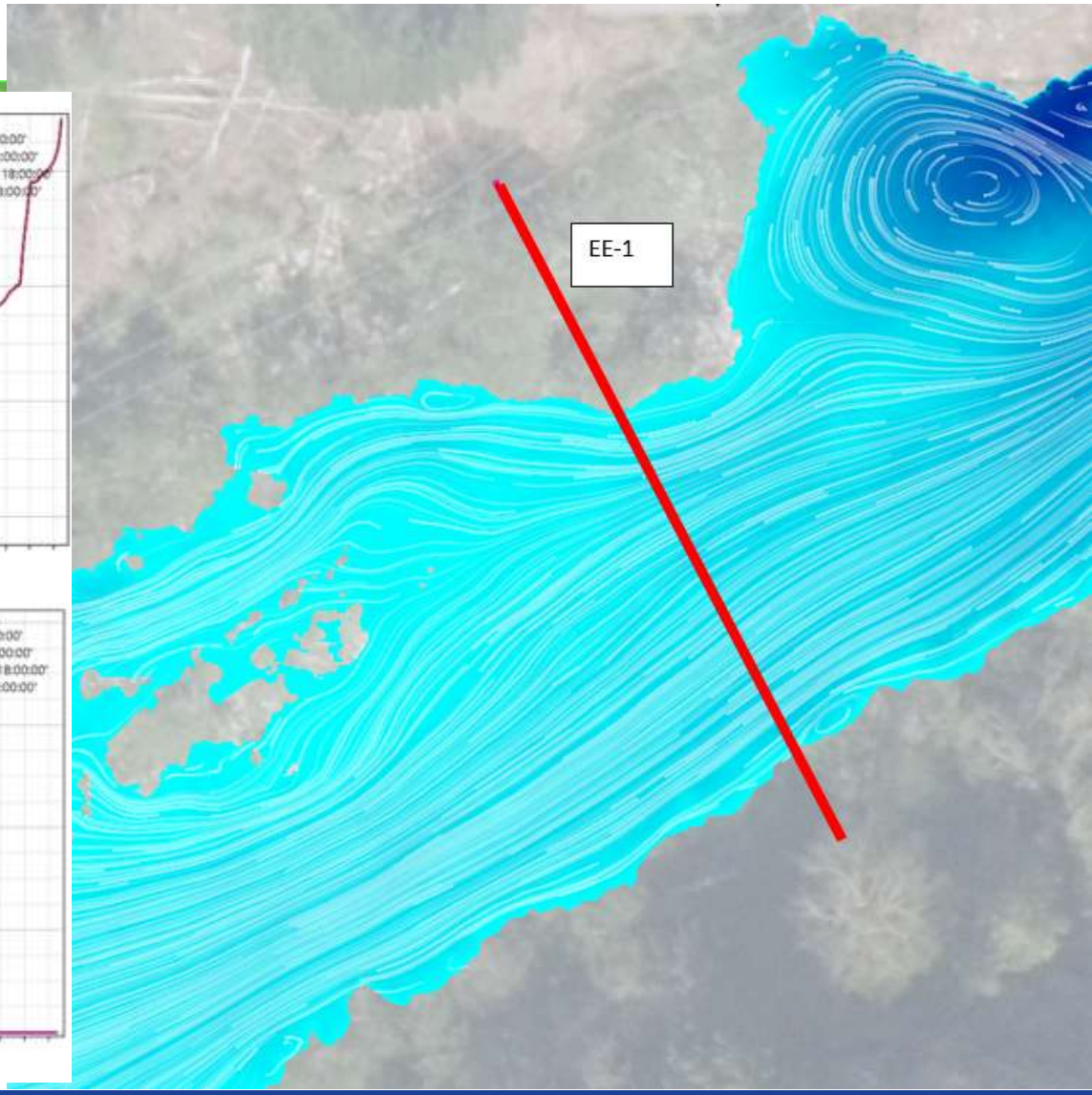
Uncalibrated RAS model



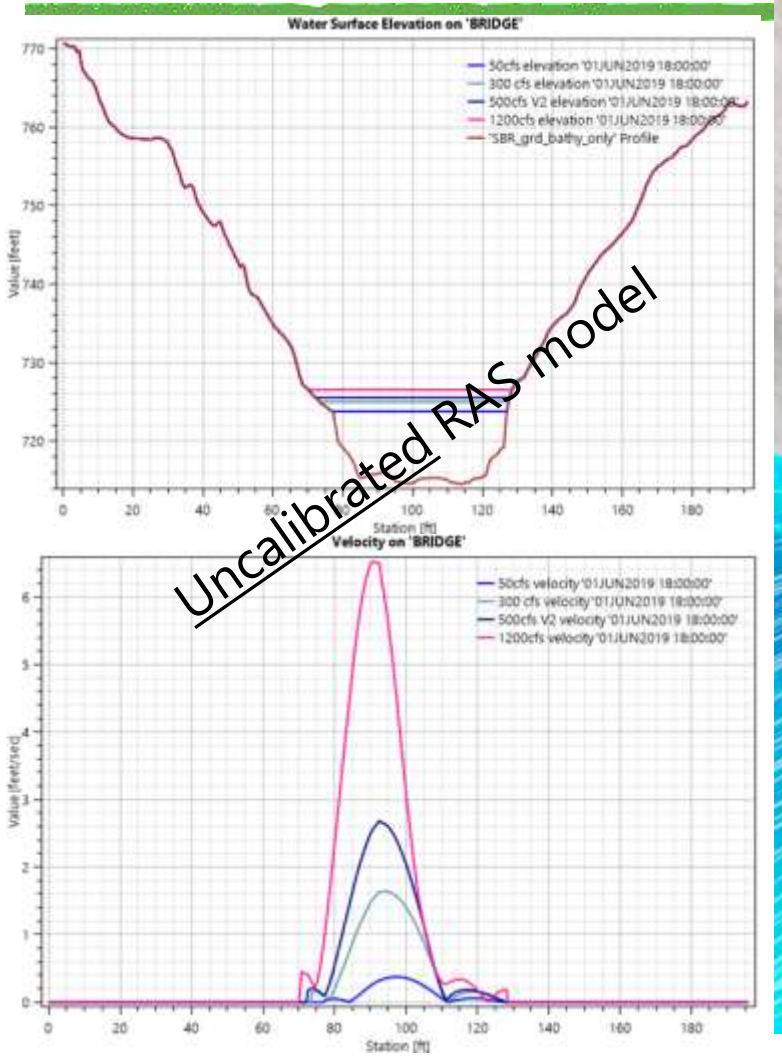
TRANSECT EE



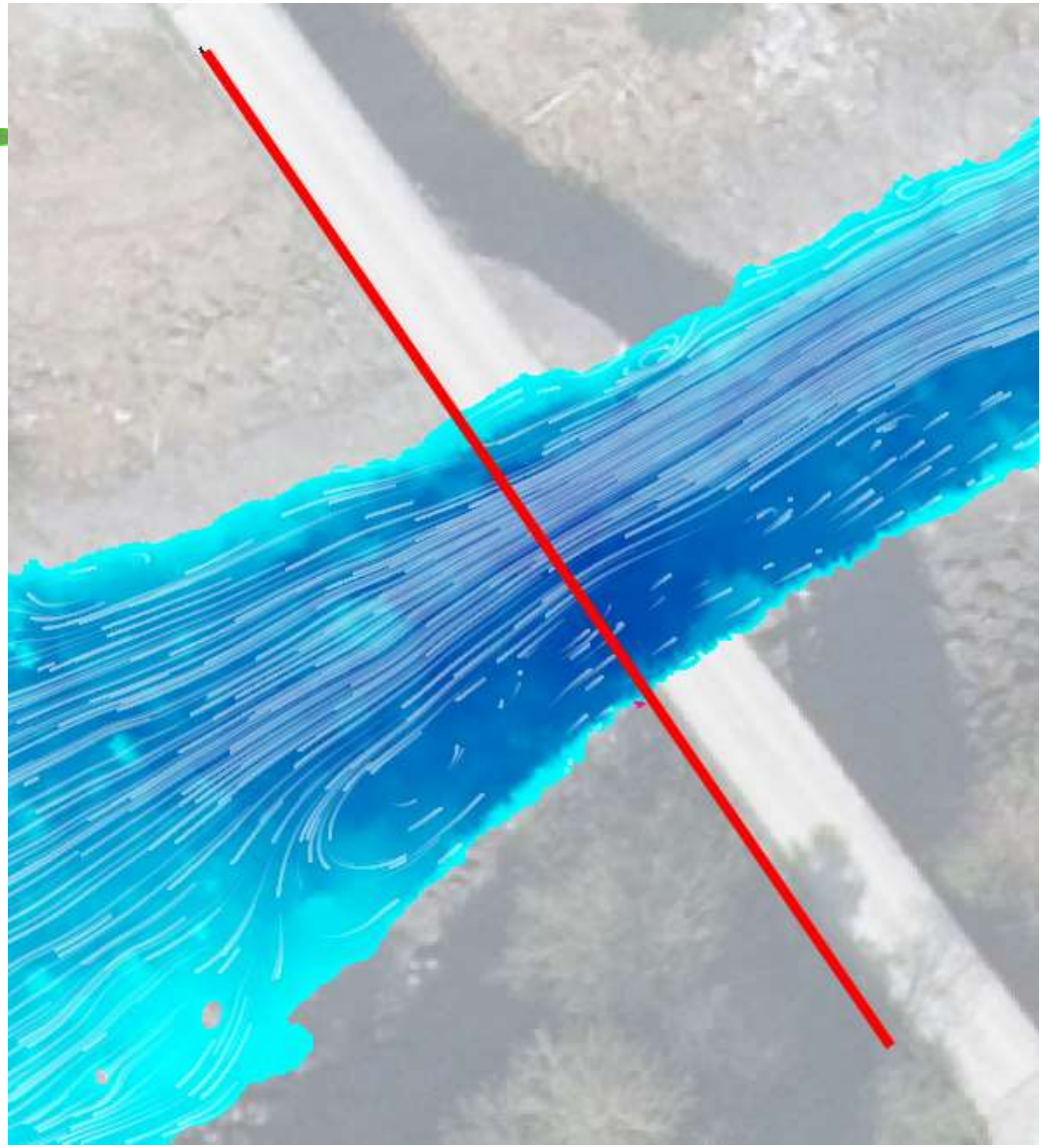
Uncalibrated RAS model



TRANSECT BRIDGE



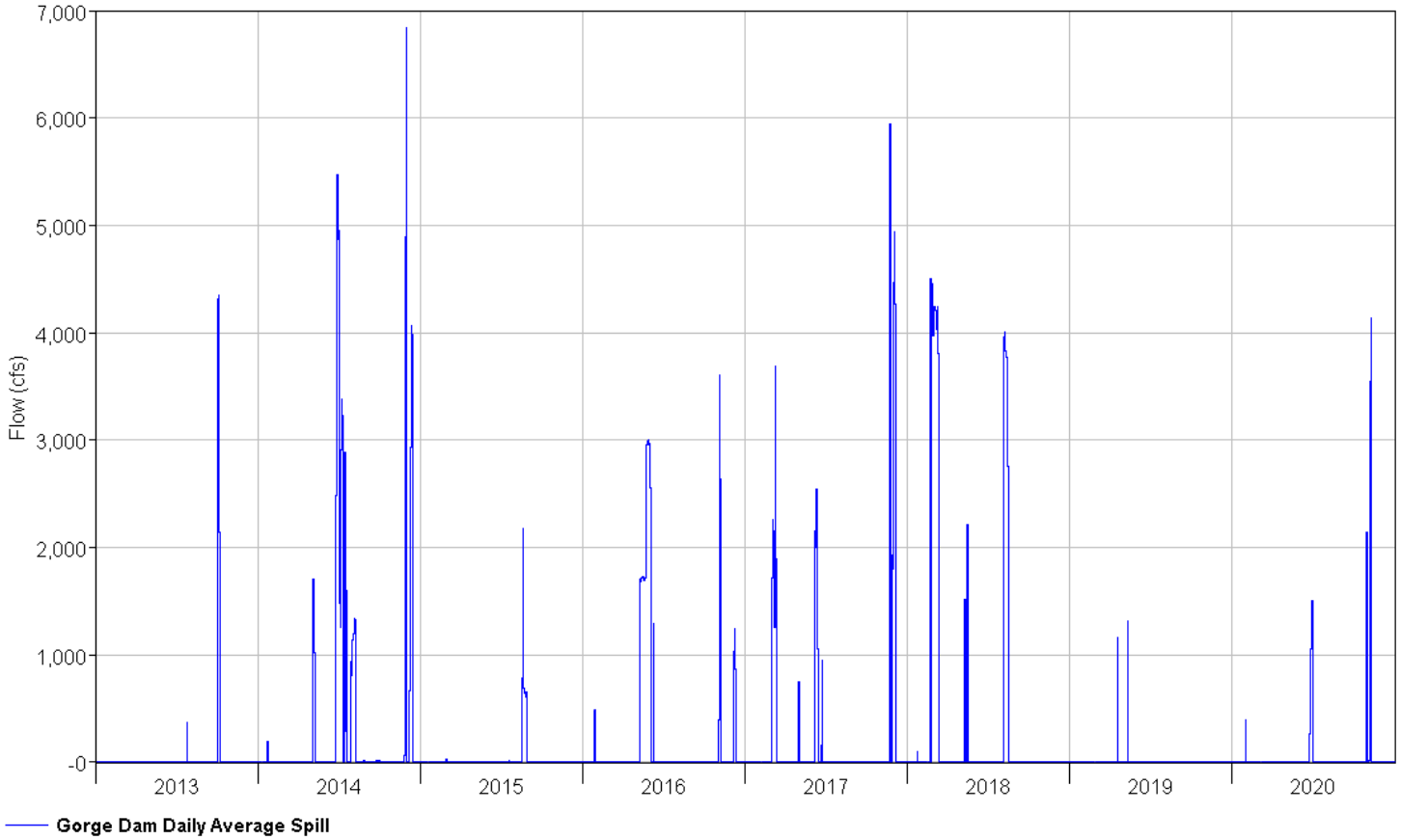
Uncalibrated RAS model



OBSERVABLE DISCHARGES

- Opportunistic Spill - opportunity for data collection at higher flows
  - Flows up to 5000+ cfs observed in records for spring/early summer freshet; 10,000+ cfs in fall/early winter storms.
  - Level loggers and time lapse cameras will be collecting data throughout this period
  - Duration variable dependent upon spill occurrence

OBSERVABLE DISCHARGES



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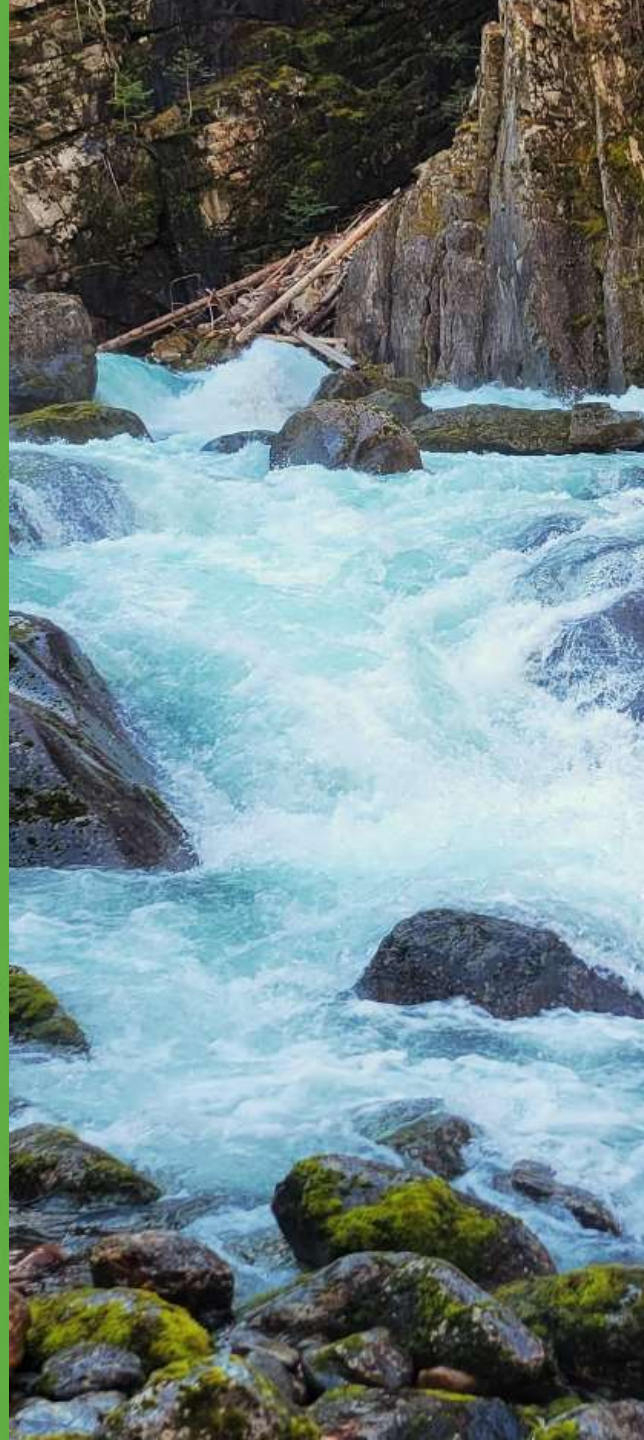
BREAK



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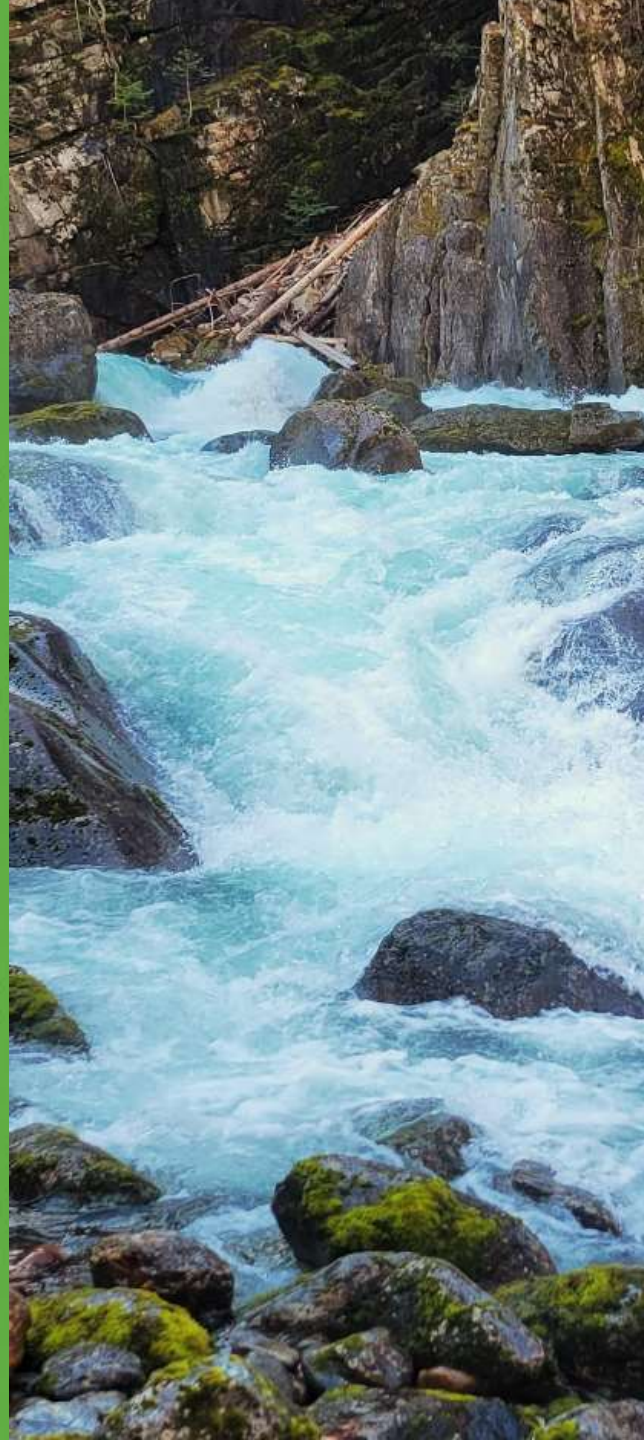
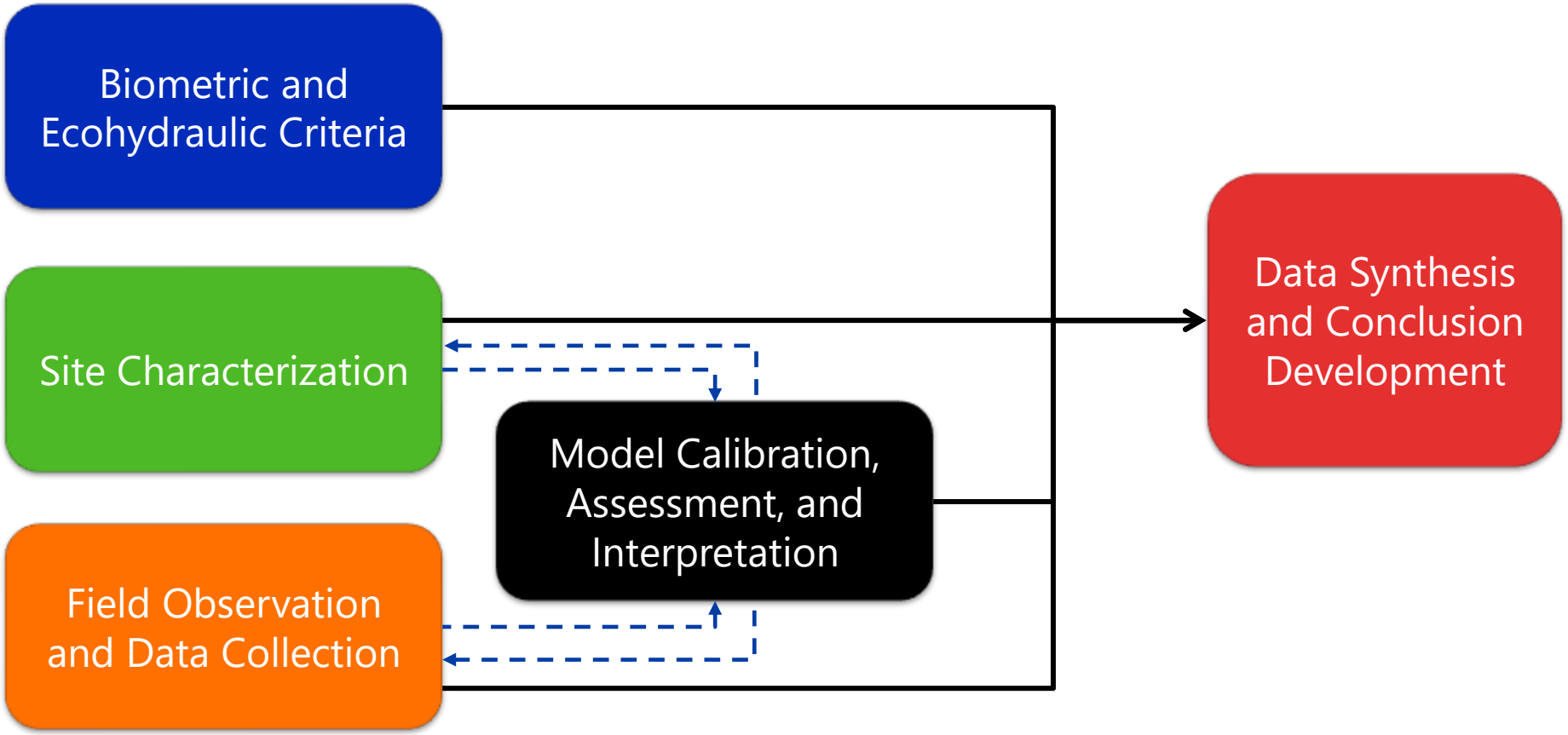
FISH PASSAGE EVALUATION METHODS AND TOOLS



FISH PASSAGE METHODS AND TOOLS



FISH PASSAGE METHODS AND TOOLS

Biometric and Ecohydraulic Criteria

- Fish species and characteristics
- Swimming capability
- Leaping capability

Field Observation and Data Collection

- Video Documentation
- Photo Documentation
- Flow Measurement
- Water depth and elevation data
- Velocity

Data Synthesis and Conclusion Development

Site Characterization

- Topography
  Aerial photography
- Site Inspection
- Site Characterization

Model Calibration and Assessment

- Hydraulic pathways
- Hydraulic trends and variability assessment
- Water surface profile assessment
- Water velocity assessment

FISH PASSAGE METHODS AND TOOLS

- Biological characteristics of species considered
  - Range of size by species
  - Condition upon arrival
  - Swimming capability
  - Leaping capability
- Availability and variance in information available influences basis of biometric or ecohydraulic comparisons

BIOLOGICAL AND ECOHYDRAULIC METRICS

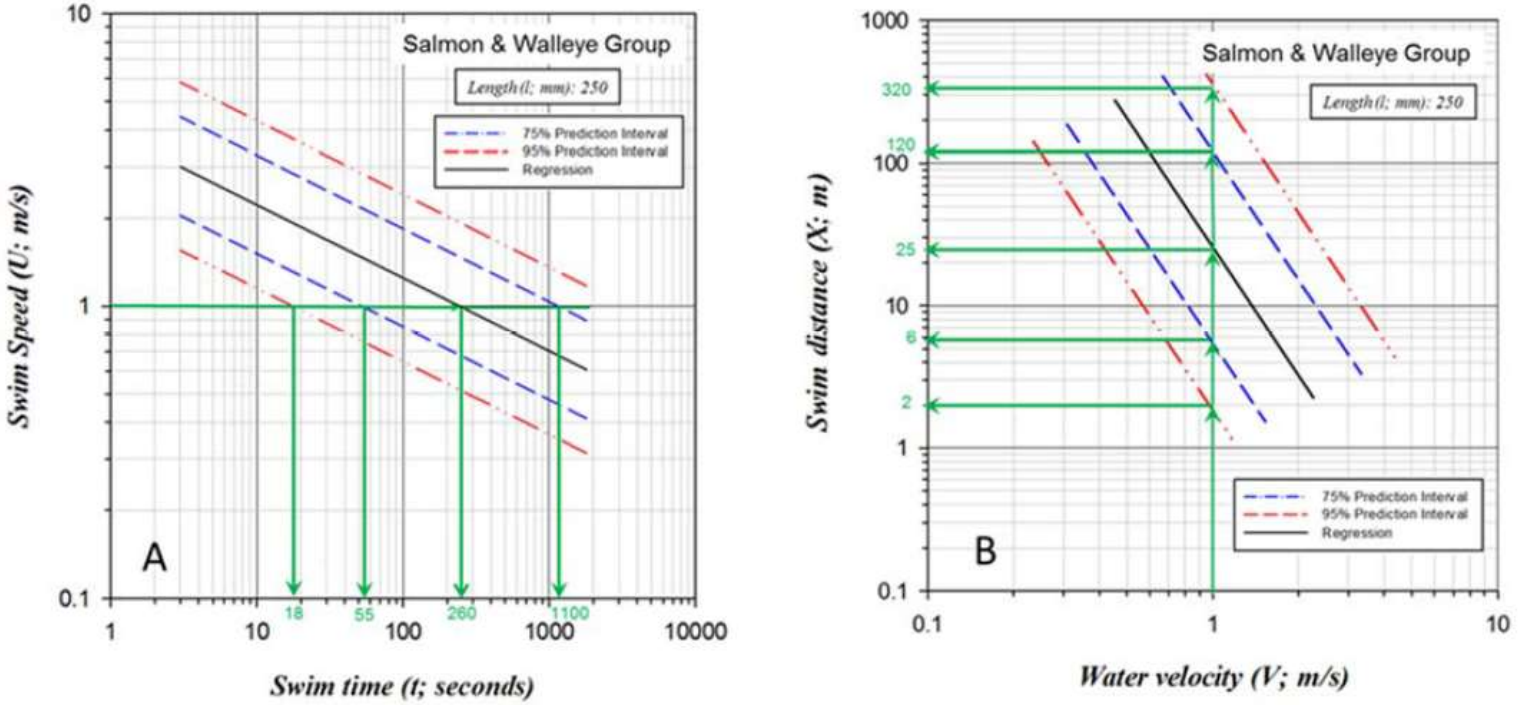
- Example biological and ecohydraulic metrics
  - Hunter and Mayor (1986) - Swimming ability and time to exhaustion calculated based upon regression curves using historical flume data
    - Calculated "sustained," "prolonged," and "burst" swim speeds and durations were used to assess those situations where steep gradients create high velocity, turbulent conditions through chutes or cascades.
    - The combination of calculated swimming and leaping capabilities was used to identify whether or not a hydraulic feature (high velocity or leap condition) is passable.

FISH PASSAGE METHODS AND TOOLS

- Example biological and ecohydraulic metrics
  - Powers and Orsborn (1985)
    - Leaping ability calculated based upon species, size, and condition upon arrival

BIOLOGICAL AND ECOHYDRAULIC METRICS

- Example biological and ecohydraulic metrics
  - Katopodis and Gervais (2016) – swimming fatigue curves



Example of swim endurance and distance estimates for Salmon and Walleye groups for fish length of 250 mm, in Figure A endurance times corresponding to a swimming speed of 1 m/s are shown and in Figure B swim distances corresponding a water velocity of 1 m/s are shown.

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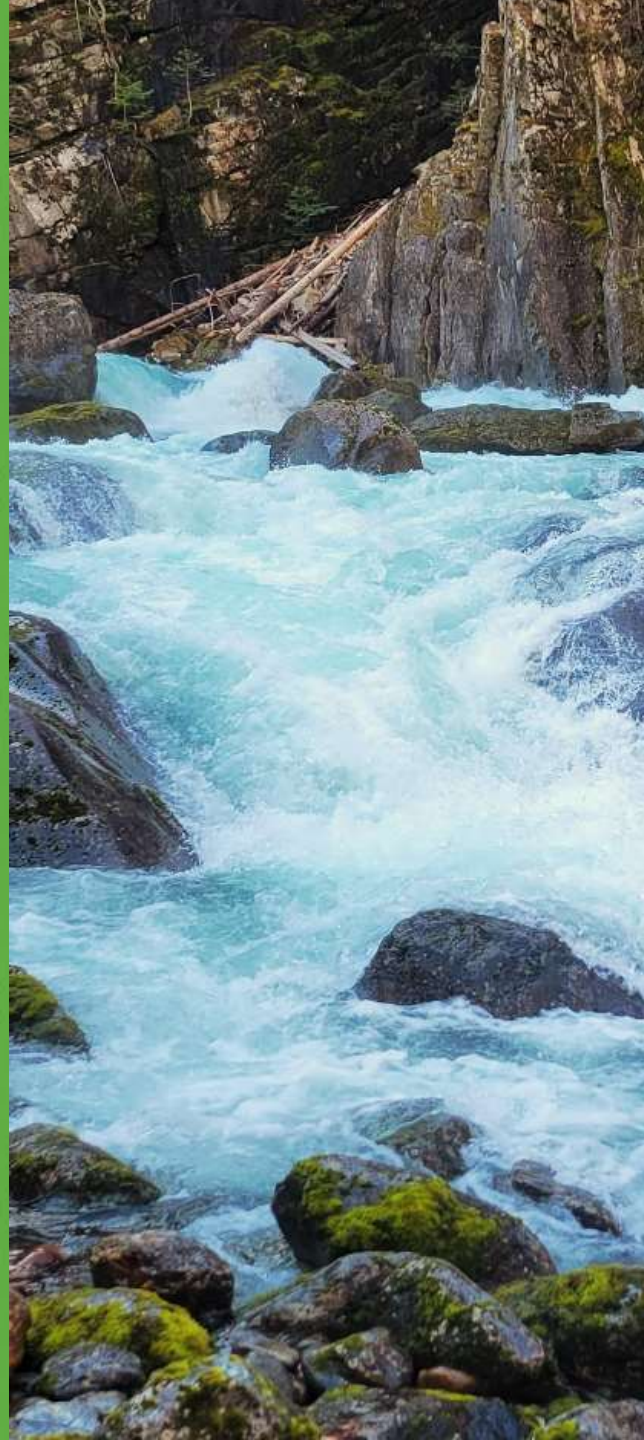
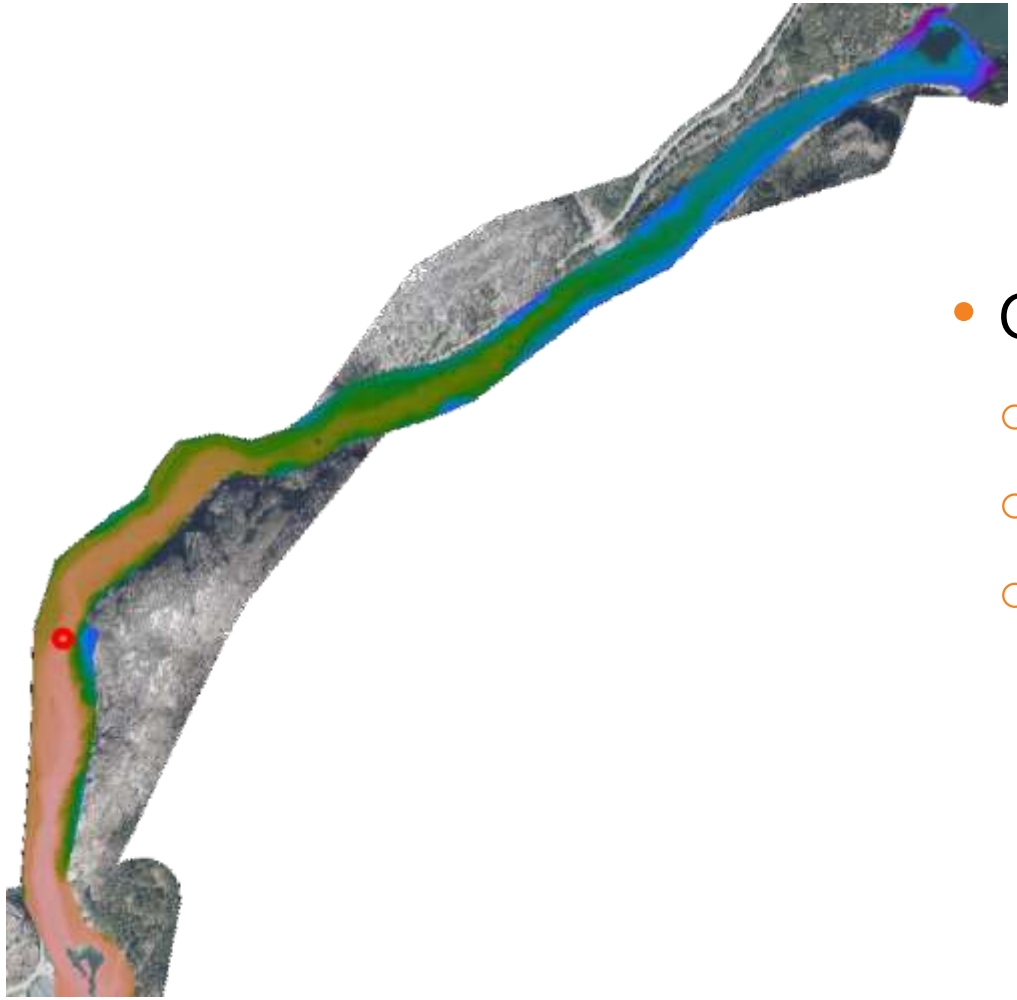
SITE INSPECTION, SURVEYING, AND VISUAL OBSERVATION



FISH PASSAGE METHODS AND TOOLS

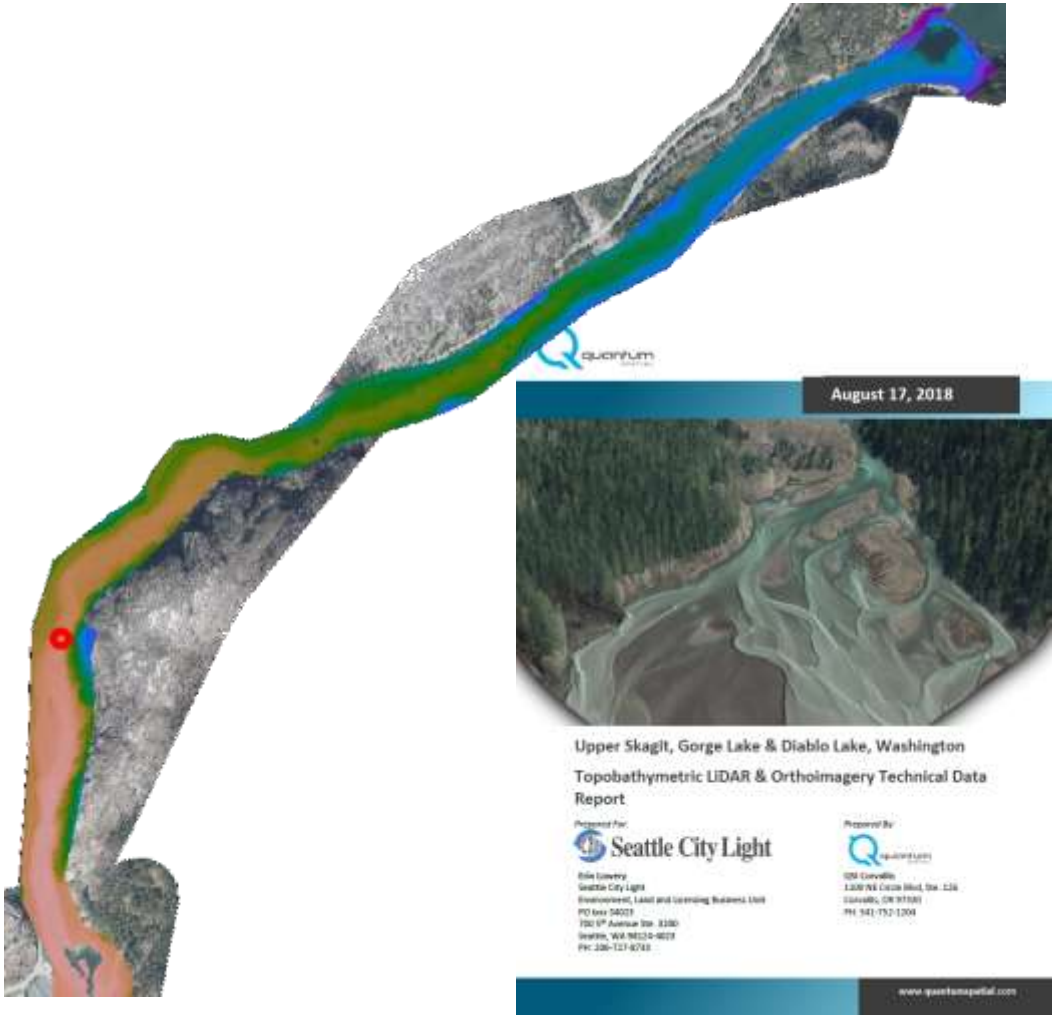
- Site inspection and visual observation
  - Feature Topography - LiDAR
  - Site Inspection
  - Photo and video documentation

FEATURE TOPOGRAPHY



- Quantum Spatial 2018
  - “green” LiDAR
  - water penetrating
  - 3 voids
    - Gorge Dam plunge pool
    - Gorge Powerhouse pool
    - 20’x50’x25+’ deep hole

FEATURE TOPOGRAPHY



- 3′ Topo Raster
- 6″ Imagery
- NVA = 0.201′
  - 95% confidence
- Bathymetric VA = 0.366′
  - 95% confidence

FEATURE TOPOGRAPHY

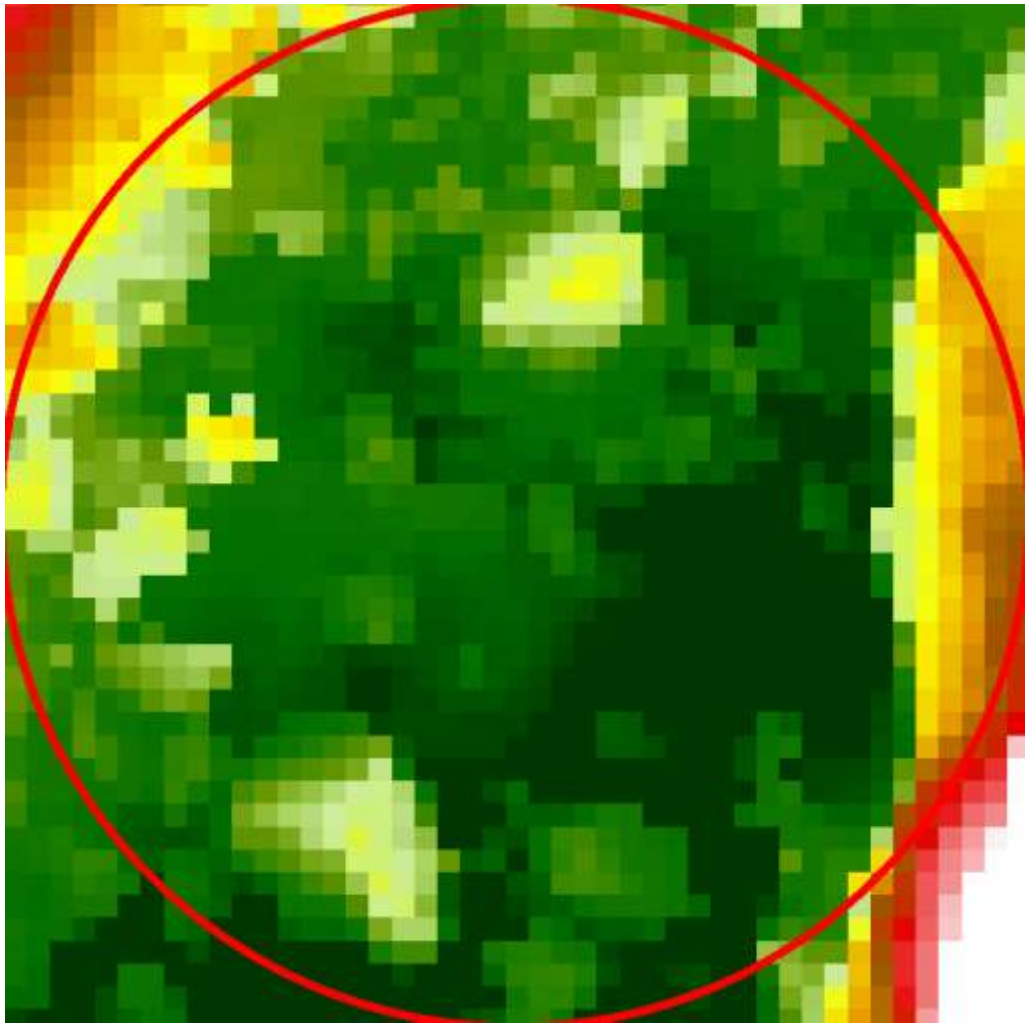


FEATURE TOPOGRAPHY



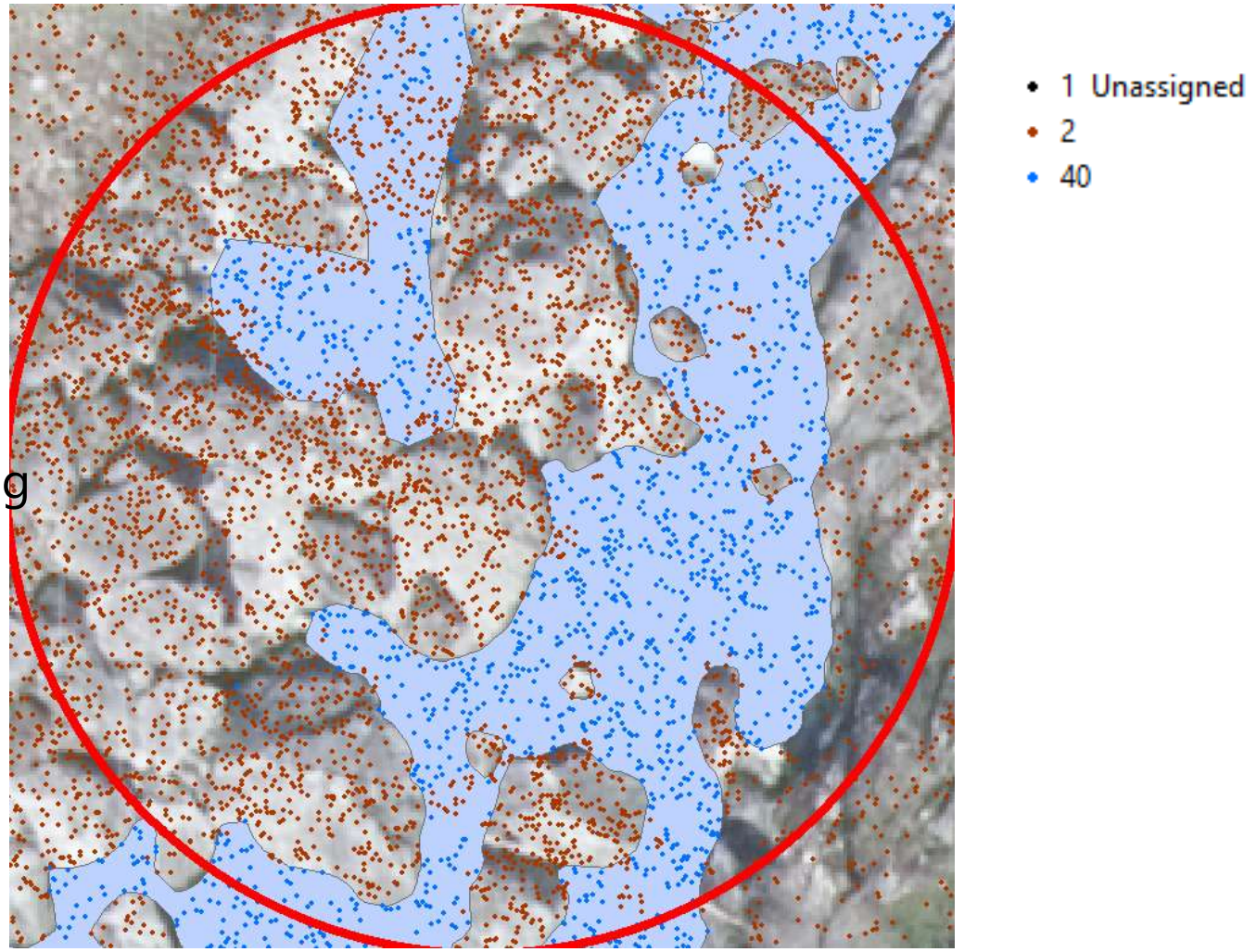
FEATURE TOPOGRAPHY

- 3′ raster



TOPOGRAPHY

- Avg density
  - 6 pulses/m^2
- Pulse spacing
  - 0.41 m
- 2 X pulse spacing
  - 2.7 feet



FEATURE TOPOGRAPHY

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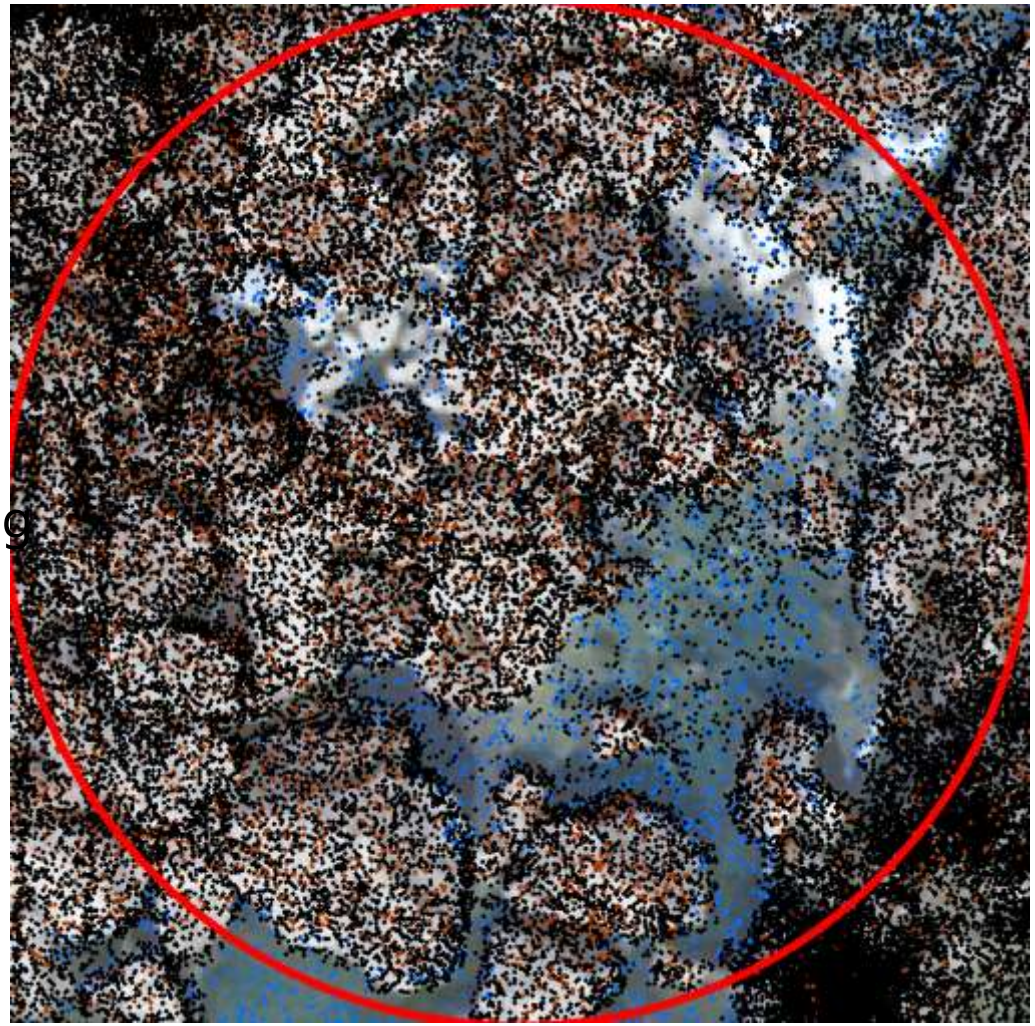
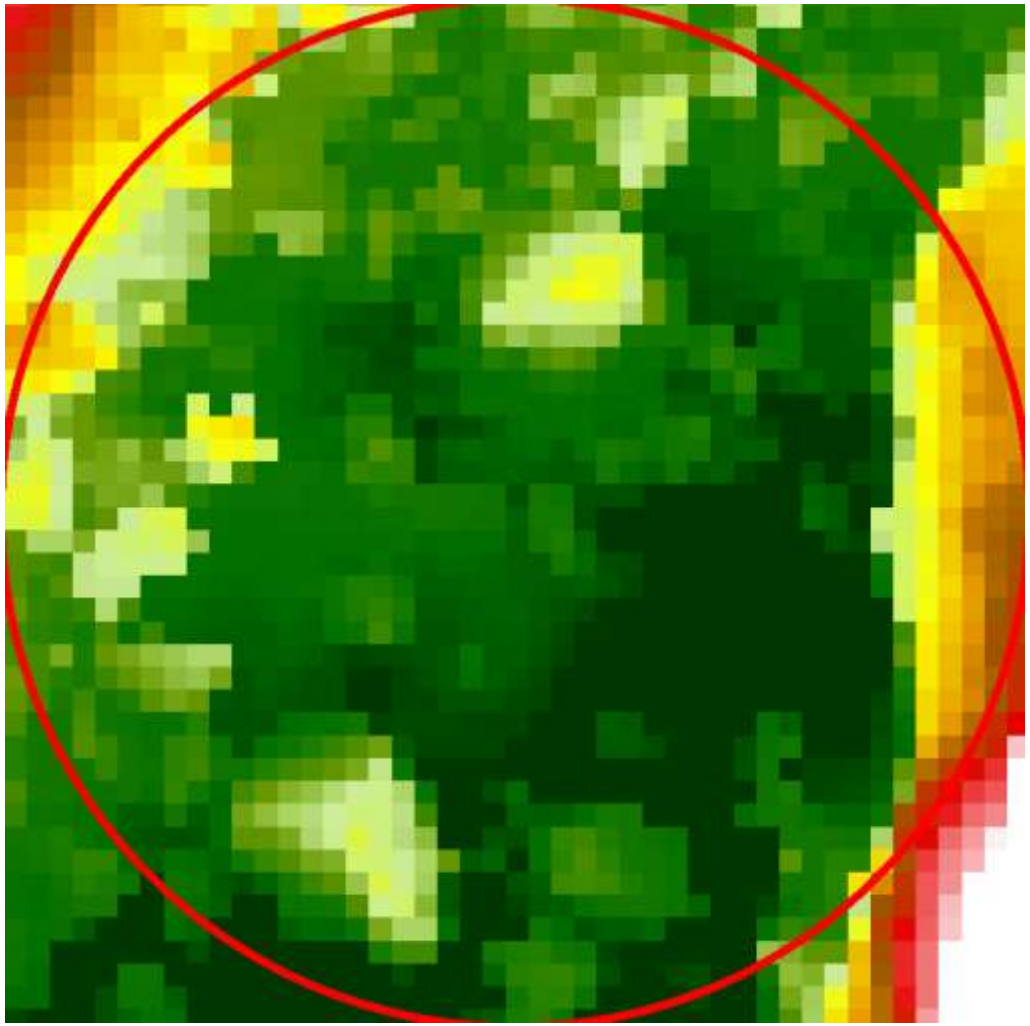


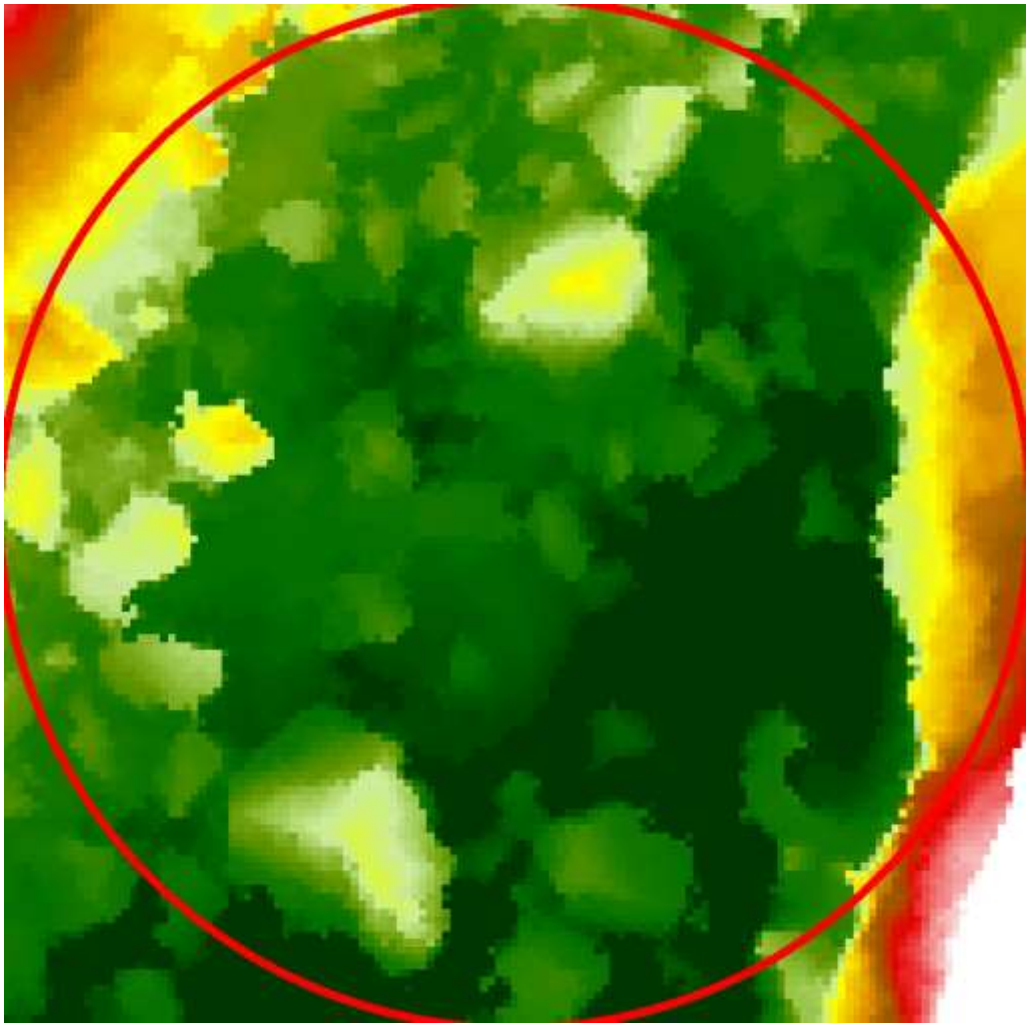
FEATURE TOPOGRAPHY

- 3′ raster

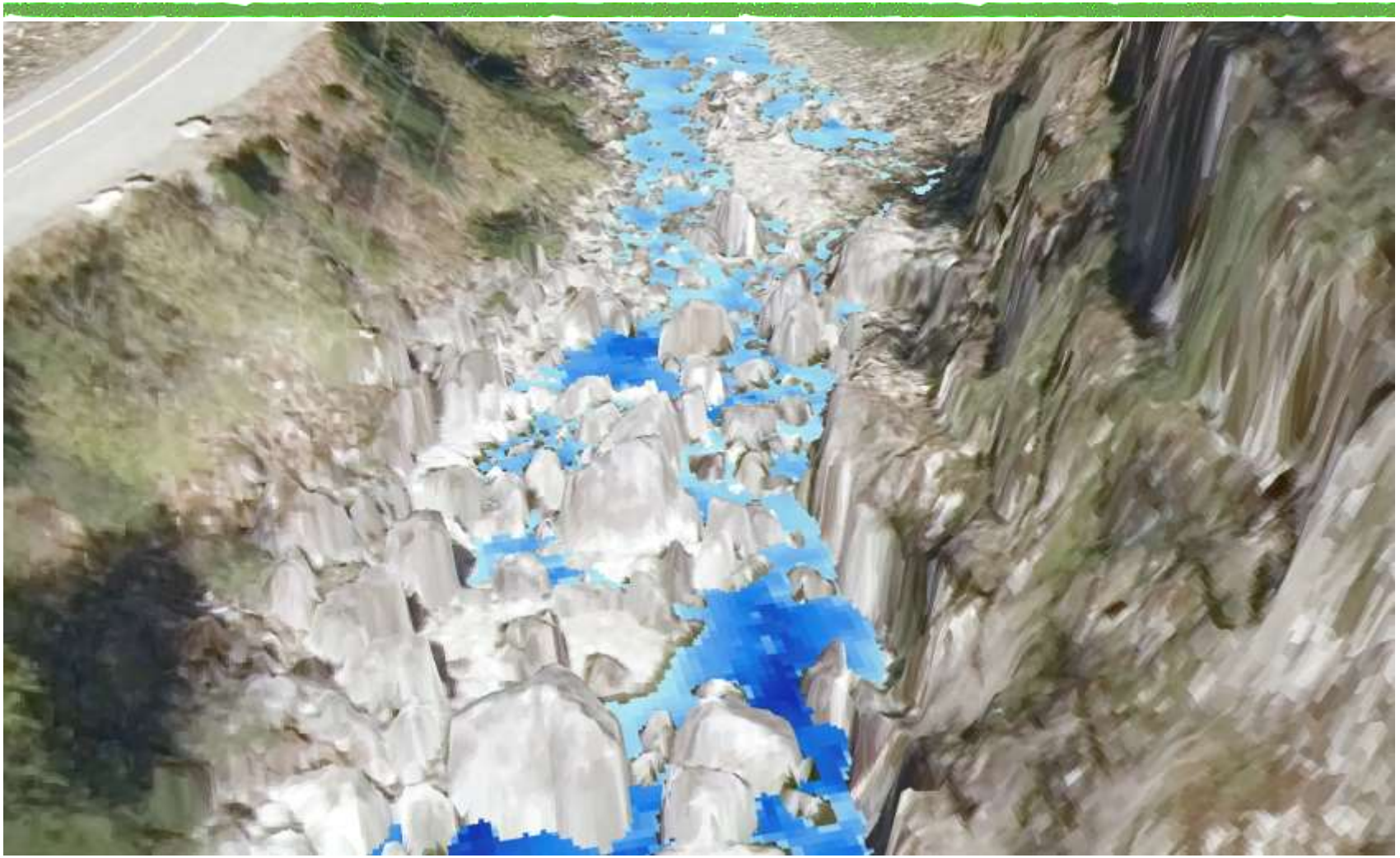


FEATURE TOPOGRAPHY

- 1′ raster



FEATURE TOPOGRAPHY



FEATURE TOPOGRAPHY





SITE INSPECTION AND VISUAL OBSERVATION

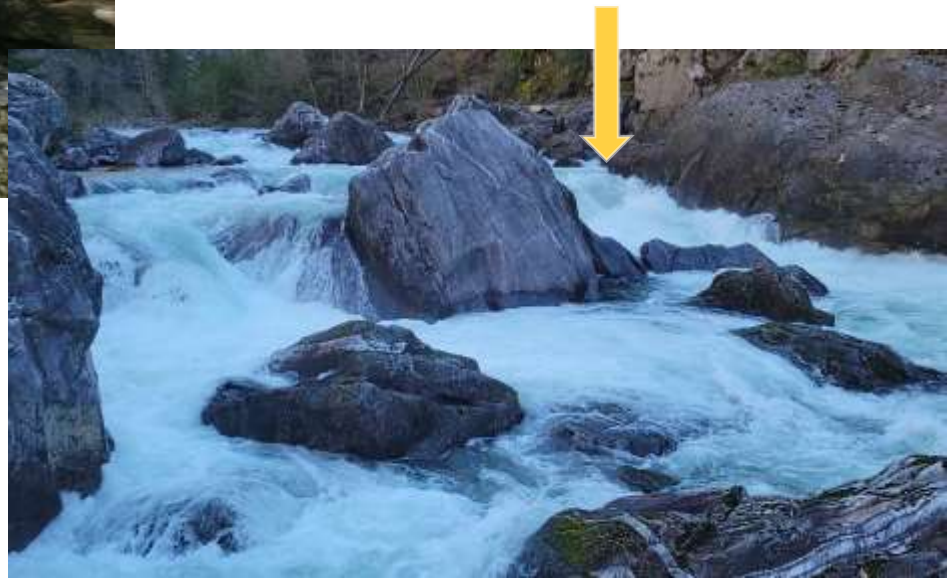
- Minimum observation at range of flows from ~5 to 1,200 cfs
- Anticipated opportunity to capture images and video up to 5,000 cfs
- Time lapse photography at two locations established prior to controlled release period

SITE INSPECTION AND VISUAL OBSERVATION

Feature 1



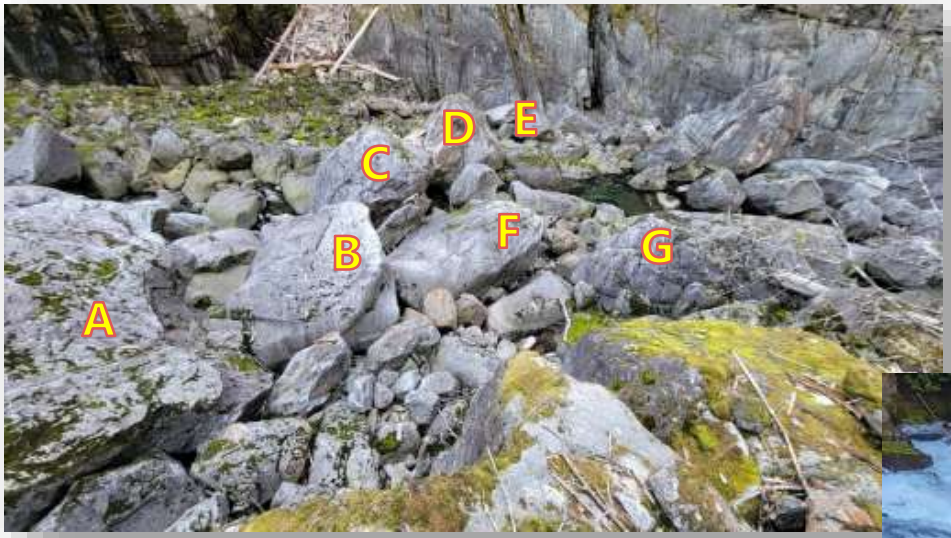
Base flow ~5 to 10 cfs



~1,200 cfs

SITE INSPECTION AND VISUAL OBSERVATION

Feature 2



Base flow ~5 to 10 cfs



~1,200 cfs

SITE INSPECTION AND VISUAL OBSERVATION

Feature complexity







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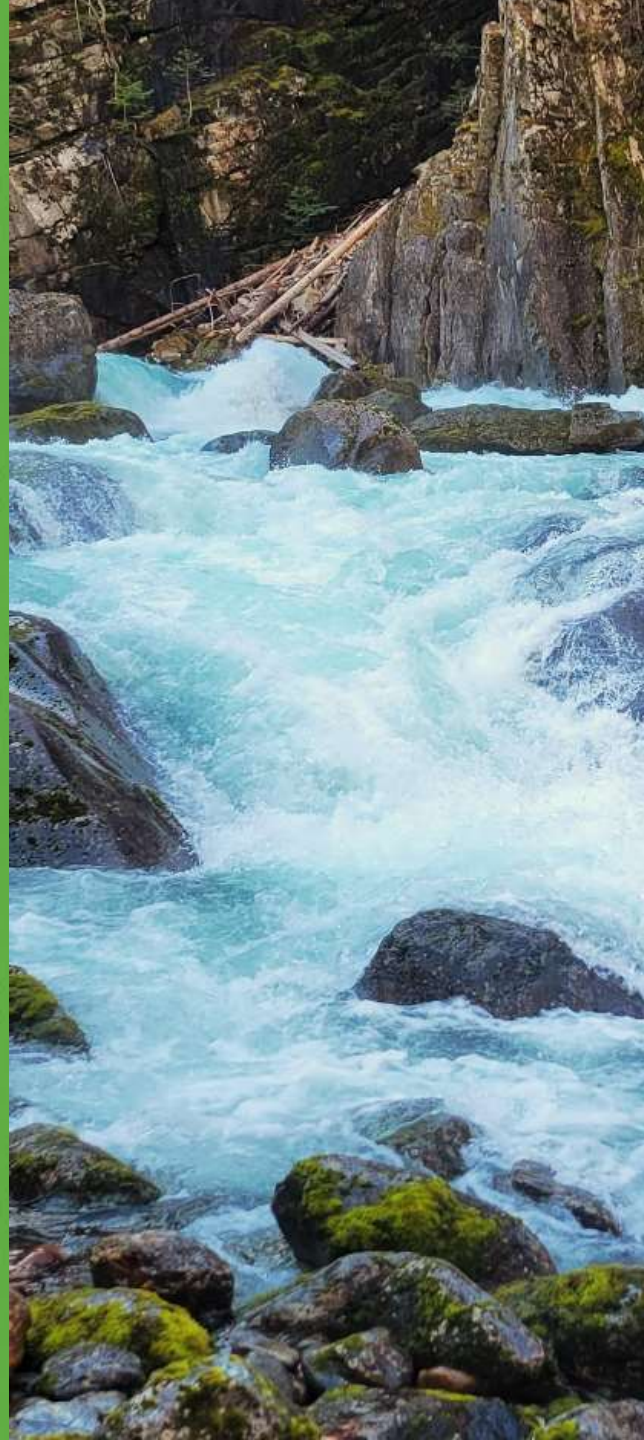
COLLECTION OF FLOW MAGNITUDE, DEPTH, ELEVATION, AND VELOCITY DATA



FISH PASSAGE METHODS AND TOOLS

- Data collection
  - Flow
  - Depth
  - Velocity

FLOW MEASUREMENT

- Proposed Transects and Cableways
  - GG-2
  - AA-1
  - II
  - EE
  - BRIDGE



DEPTH MEASUREMENT

- Depth monitoring locations identified using site investigation and initial/uncalibrated 2D model
- Deployment of level probes at 12 select locations
  - 5 at each feature (total of 10)
  - 2 at selected flow measurement transects
- Locations refined further after observations of features at ~1,200 cfs

UPSTREAM FEATURE

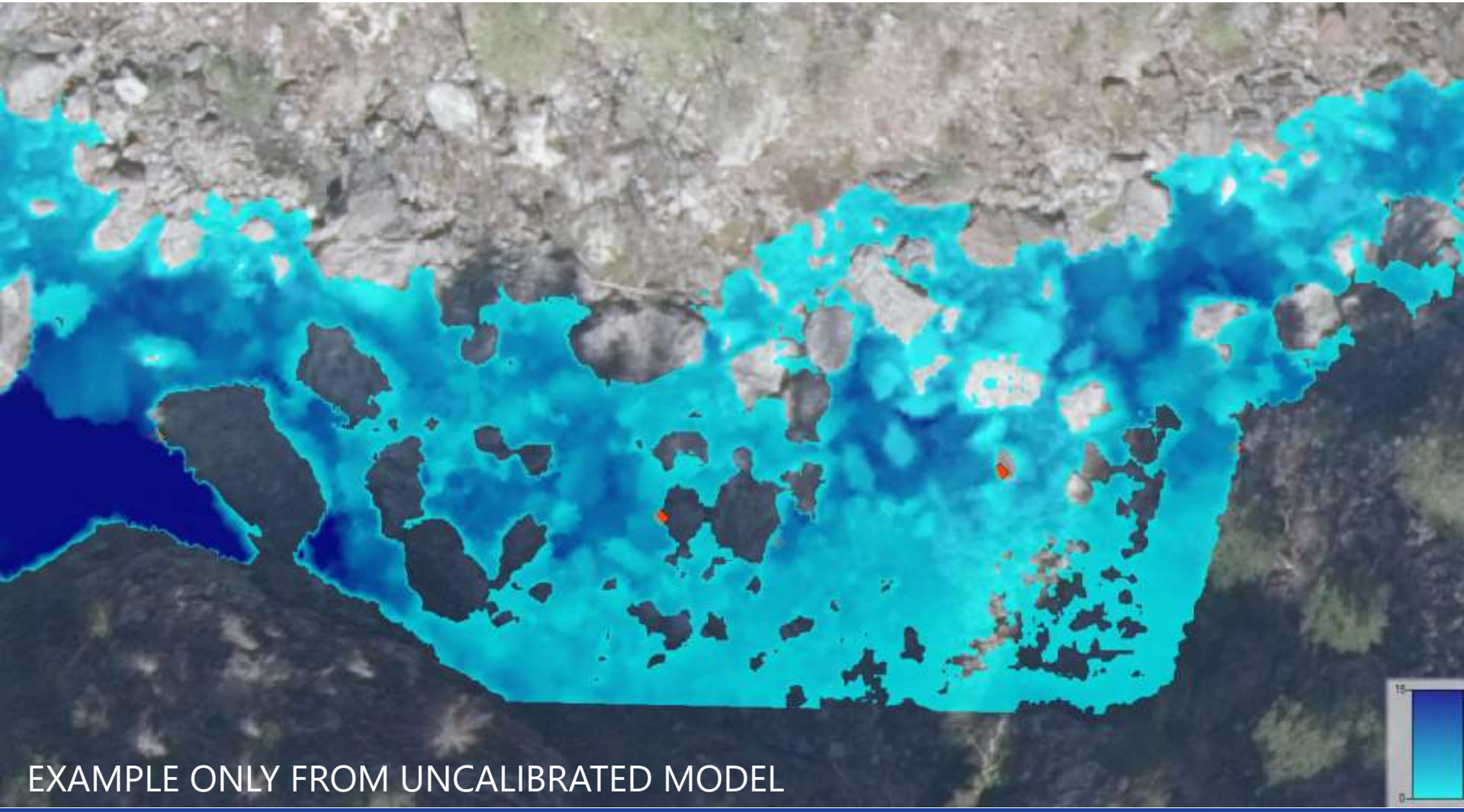


UPSTREAM FEATURE

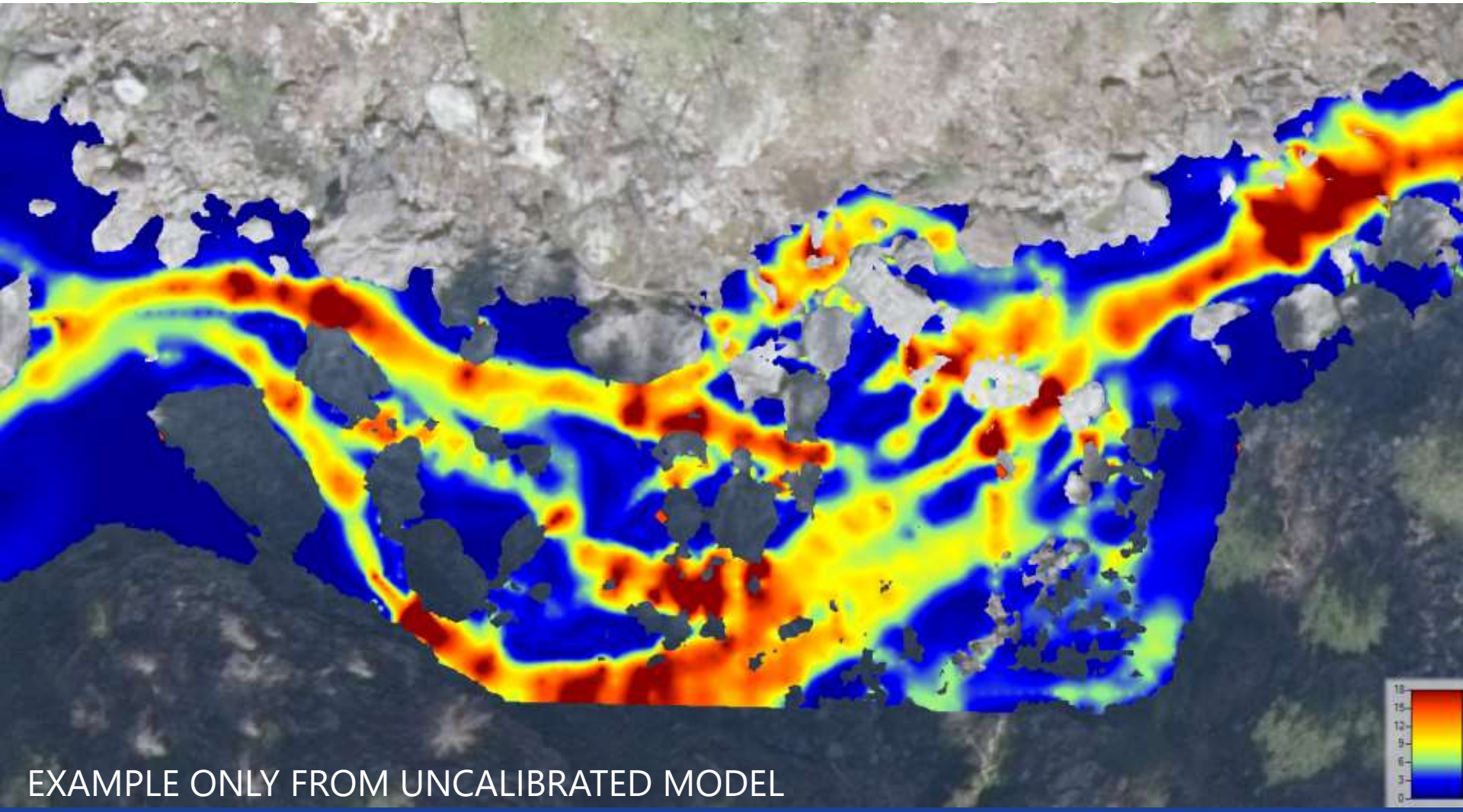


EXAMPLE ONLY FROM UNCALIBRATED MODEL

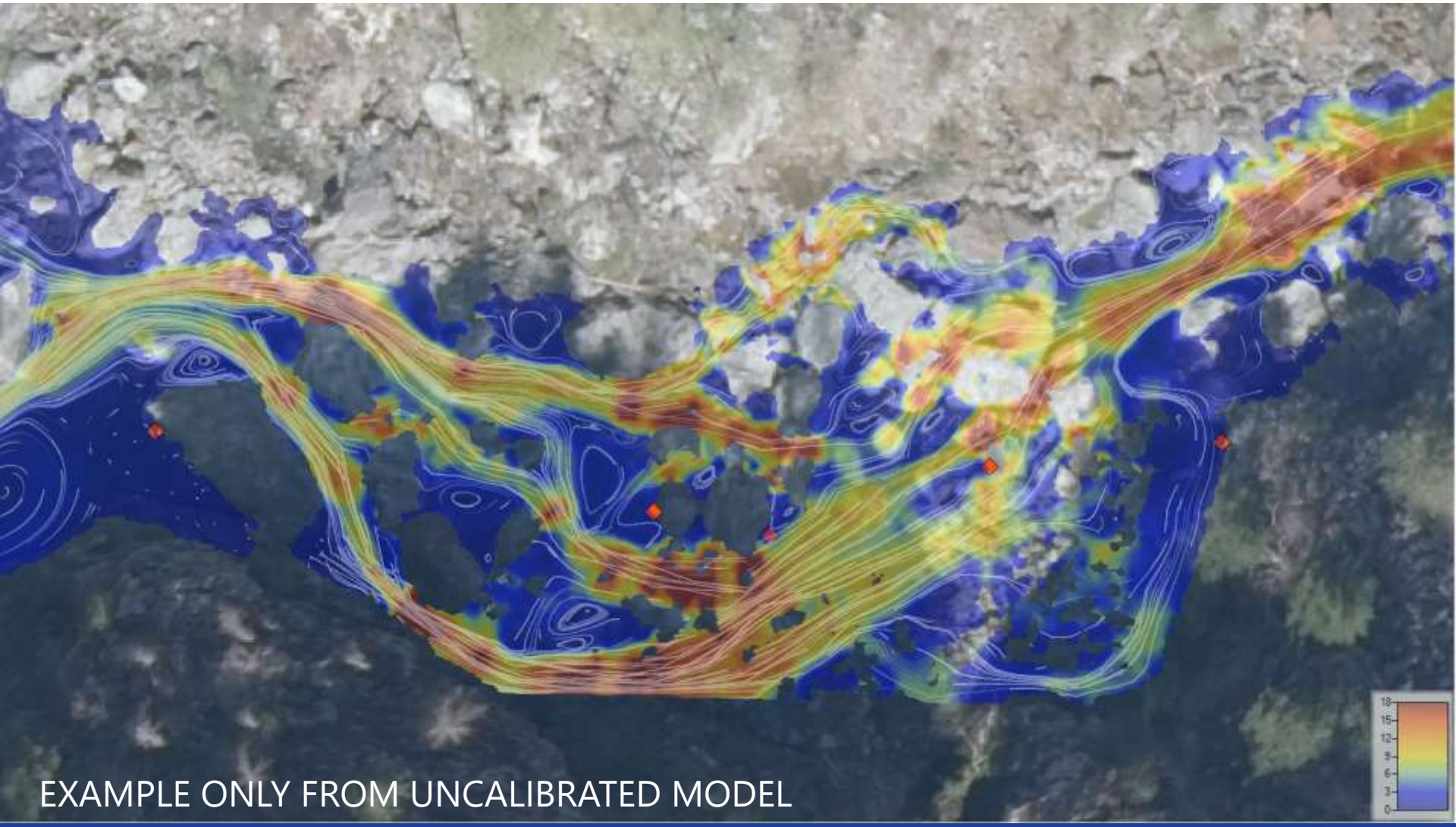
UPSTREAM FEATURE



UPSTREAM FEATURE



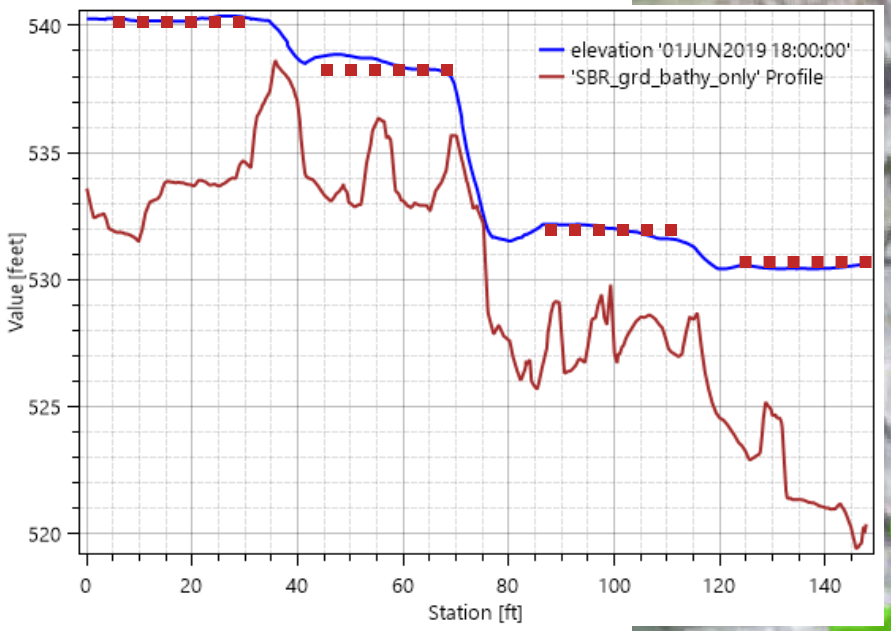
UPSTREAM FEATURE



DOWNSTREAM FEATURE

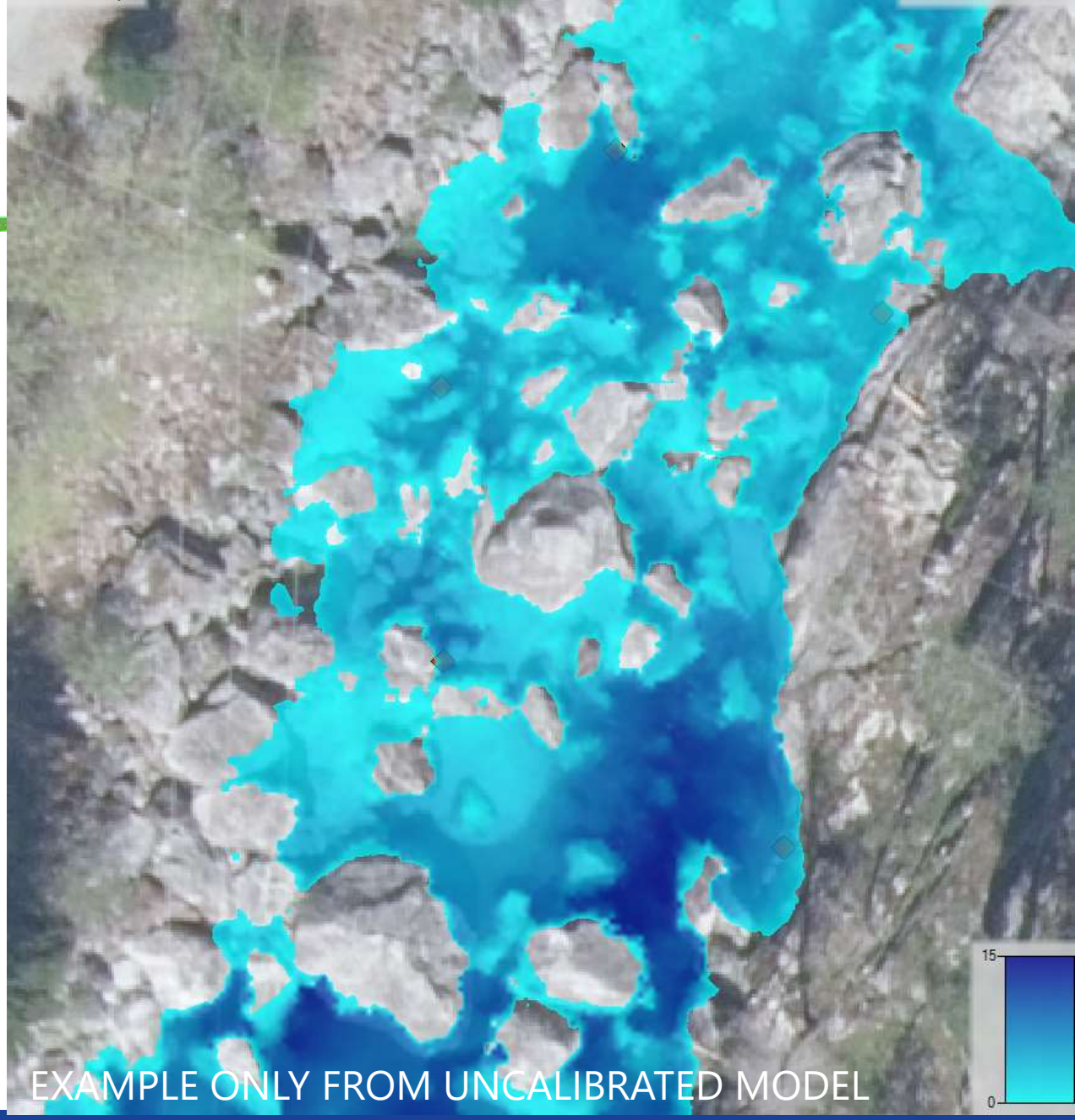


DOWNSTREAM FEATURE



EXAMPLE ONLY FROM UNCALIBRATED MODEL

DOWNSTREAM FEATURE



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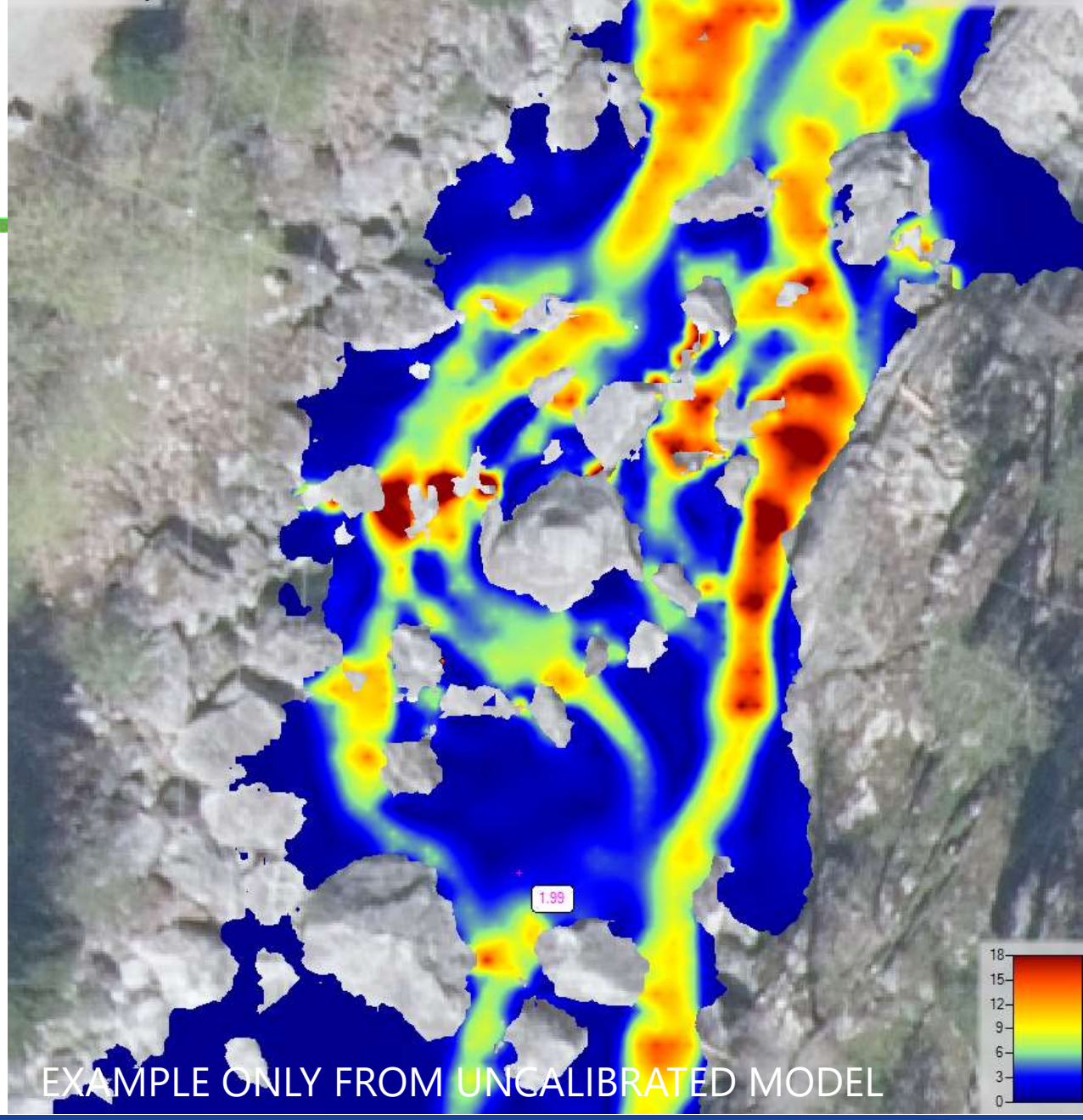

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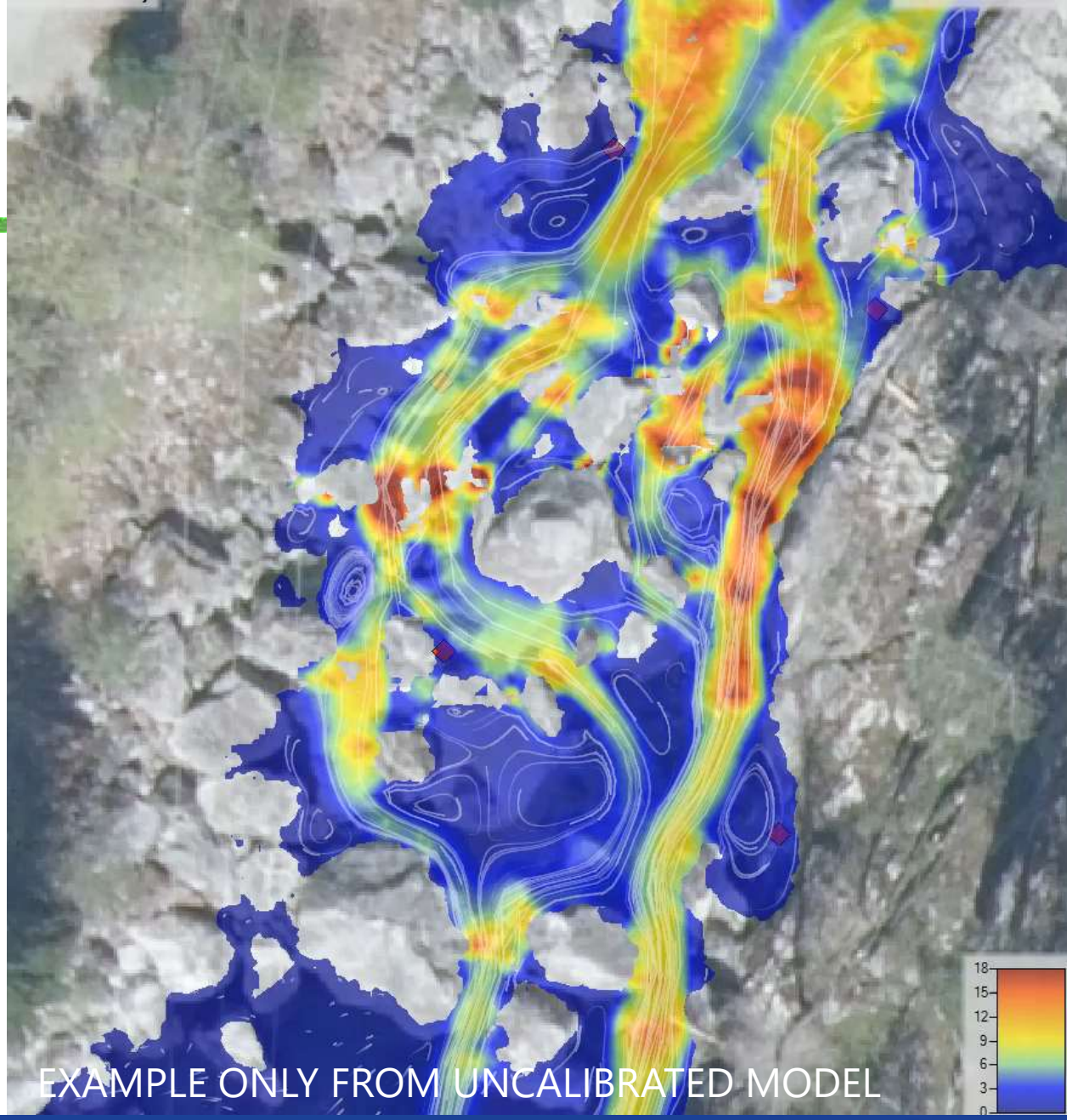

VELOCITY MEASUREMENT

- Difficult and unsafe access at flows above 50 cfs
- High levels of turbulence and multi-directional flow
- Conventional methods likely inadequate
- Potential options
  - Approximation using hydraulic modeling tools
  - UAV with Particle tracking

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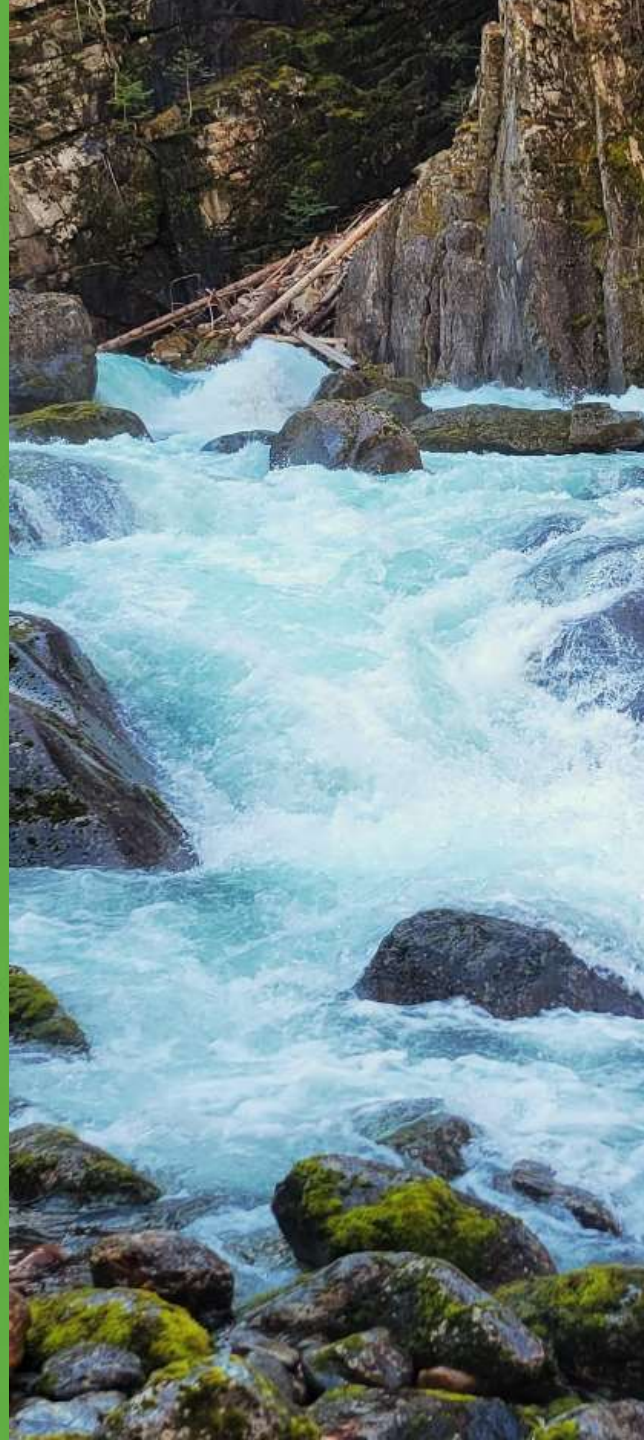
EXAMPLE FISH PASSAGE EVALUATION PROJECTS



FISH PASSAGE METHODS AND TOOLS

- Numerous examples of fish passage evaluation methods and complexities exist
- Standardized methods provide insight consistent with their purpose and within a range of applicable conditions
- Custom methods suit more unique site-specific conditions
- Not intended to replace or replicate results and conclusions from long-term monitoring programs

FISH PASSAGE METHODS AND TOOLS

- Example fish passage evaluations
  - Clearwater River
  - Mission Creek
  - Nelson Dam Removal
  - Example fish passage simulation technique

SF CLEARWATER RIVER

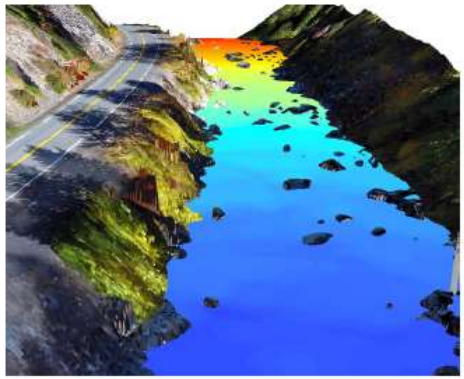
CRAMER FISH SCIENCES
An Employee Owned Consulting Company

nhc
northwest hydraulic consultants

SOUTH FORK CLEARWATER RIVER

MP 28 Hypothesized Velocity Barrier

Final Report



Prepared for:

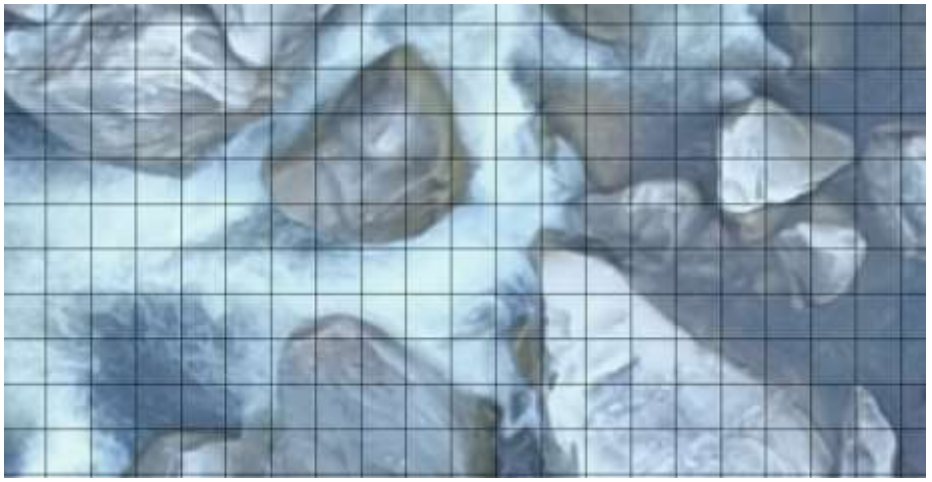
Mark Johnson, Nez Perce Tribe

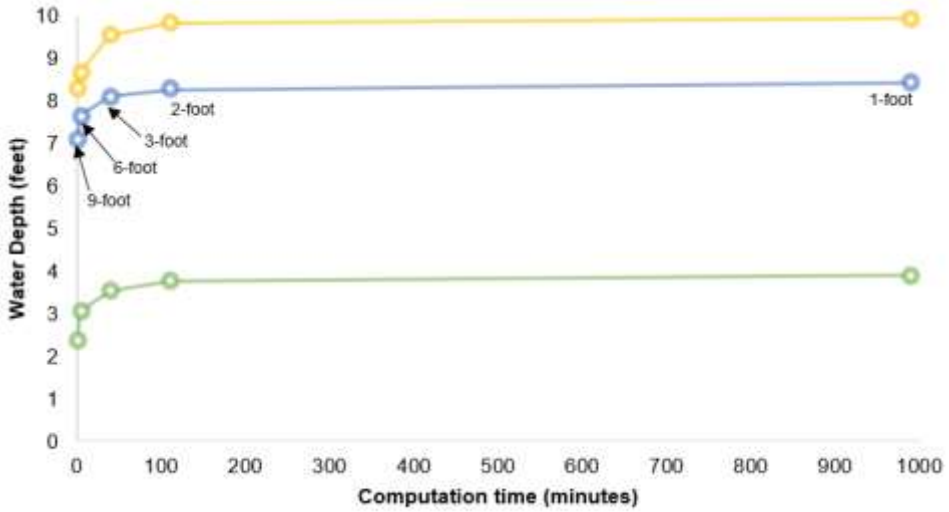
Prepared by:

Ray Timm, Lucius Caldwell, Dana Stroud, and Phil Roni – Cramer Fish Sciences

Andrew Nelson, Chris Long – Northwest Hydraulic Consultants

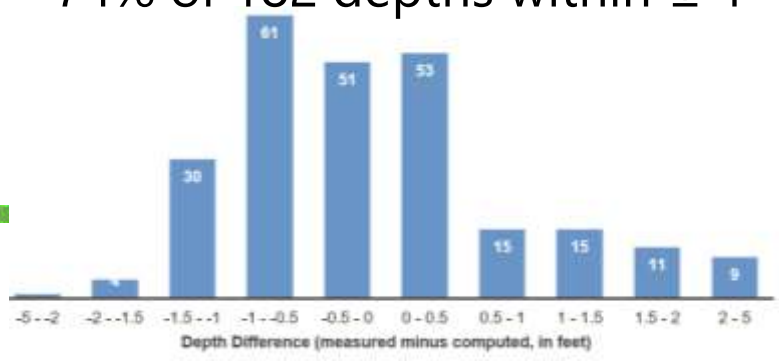
January 18, 2017





SF CLEARWATER RIVER

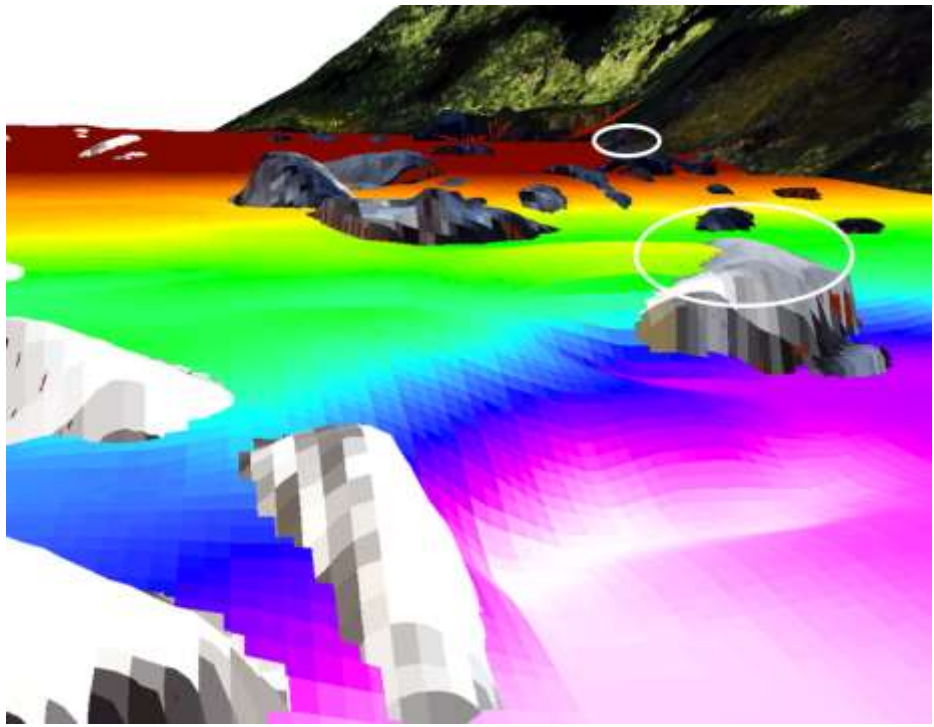
- 74% of 182 depths within ± 1′



- May 5, 2016 (~1074 cfs)

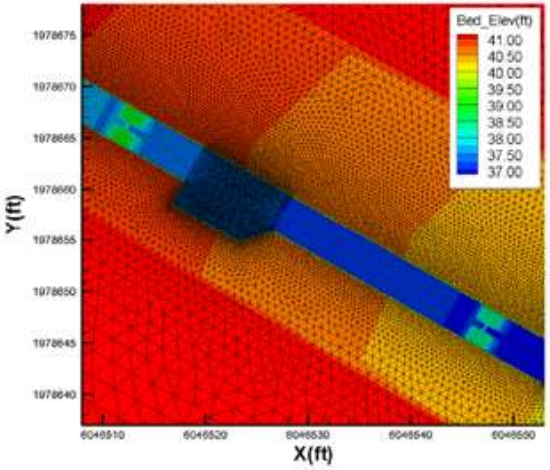


- Calibrated RAS model (1100 cfs)

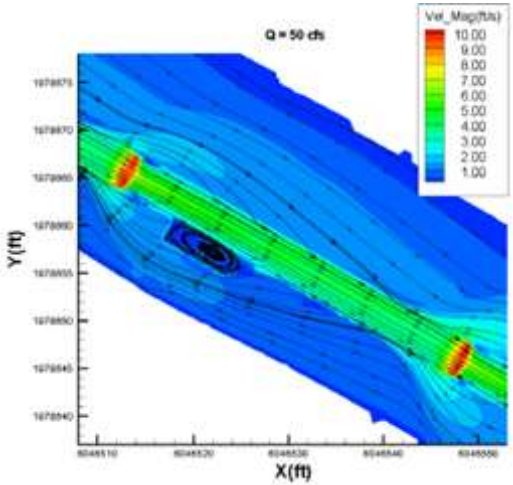


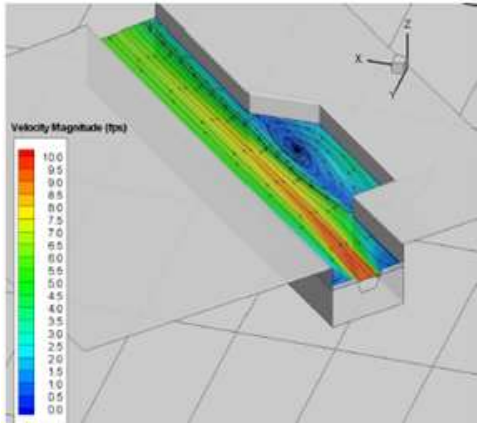
MISSION CREEK

- 1D, 2D, 3D, and physical model development
- 2D model calibrated from physical model results
- 2D model results used to perform energy expenditure simulation informing steelhead passage









TRABUCO CREEK PHYSICAL MODEL STUDIES

- Metrolink Rail Crossing
  - 1:6 Fishway Model
  - 1:20 Comprehensive Model
  - Fish Passage around 30-ft Barrier
  - Objective: Fish Passage
  - Target: California Steelhead



Metrolink Existing Barrier



1:20 Comprehensive



1:6 Fishway



I-5 Comprehensive



I-5 Fishway Entrance

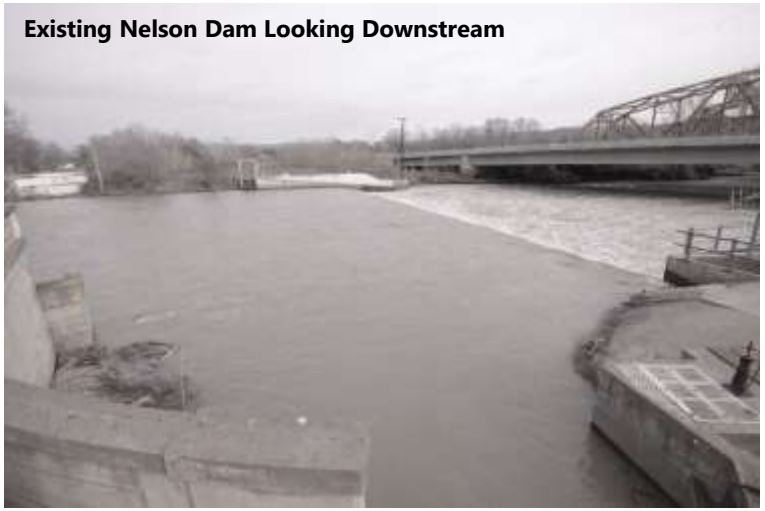


I-5 Fishway

- I-5 Crossing
  - 1:8 Fishway Model
  - 1:25 Comprehensive Model
  - Fish Passage through Existing Concrete Culverts and Stilling Basin
  - Objective: Fish Passage
  - Target: California Steelhead

NELSON DAM REMOVAL PHYSICAL MODEL STUDIES

- 1:24 Scale Model
- Objective: Dam Removal & Fish Passage
- Fish Channel and Sluiceway







NELSON DAM REMOVAL FISH PASSAGE EVALUATION

Figure 2-3. Swim Distance vs. Flow Velocity for 250 mm and 1,000 mm Salmonids

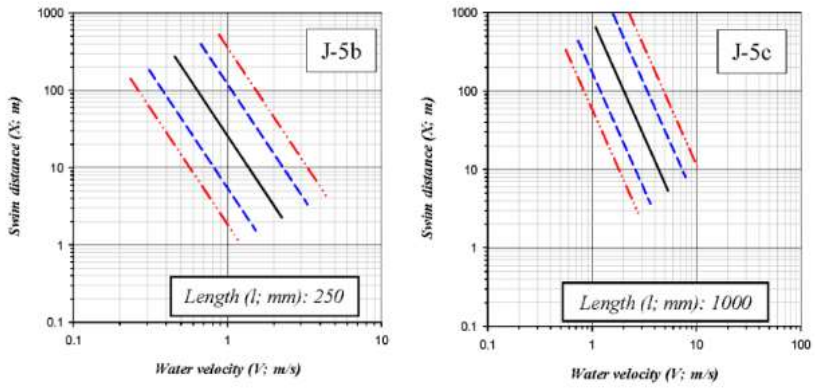
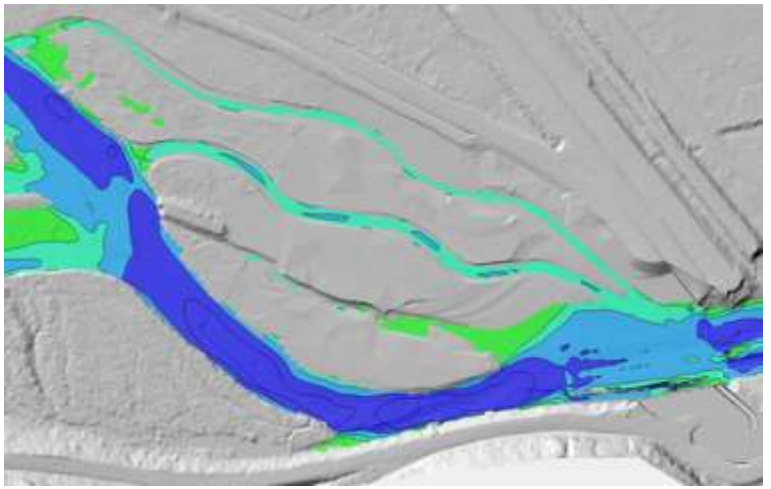
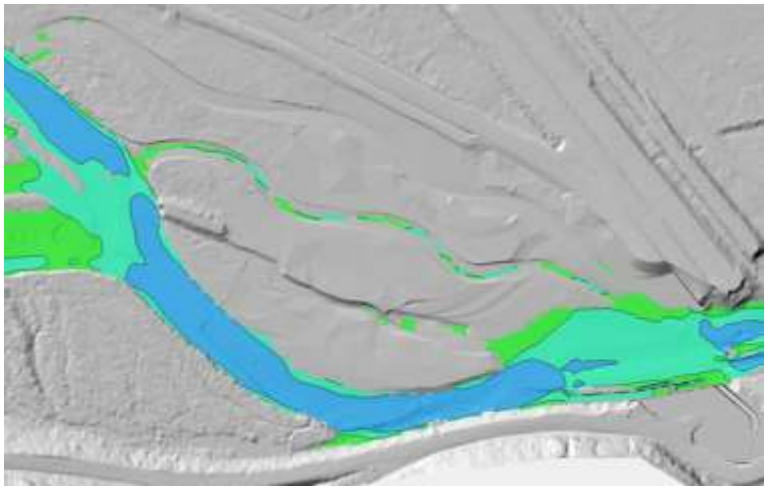


Table 4-8. Swimming Speeds For 250-mm, 1,000-mm, And 710-mm Salmonids for 75th Percentile

Fish Length	Time	Water Velocity (fps)	Swim Distance (ft)	Correlated Swim Speed (fps)
250mm[a] (10 inches)	5 seconds	9.5	16.4	12.8
	20 seconds	6.9	45.9	9.2
	3 minutes	4.3	229.6	5.5
	30 minutes	2.1	1,312.0	2.9
710mm[b] (28 inches)	5 seconds	18.0	30.5	24.1
	20 seconds	12.7	86.2	17.0
	3 minutes	7.3	450.9	9.8
	30 minutes	4.0	2,418.5	5.4

[a] Obtained from Katopodis and Gervais (2016), Appendix E, Charts J-5b and J-5c.
[b] Interpolated from Katopodis and Gervais (2016) data using dimensionless length ratio.





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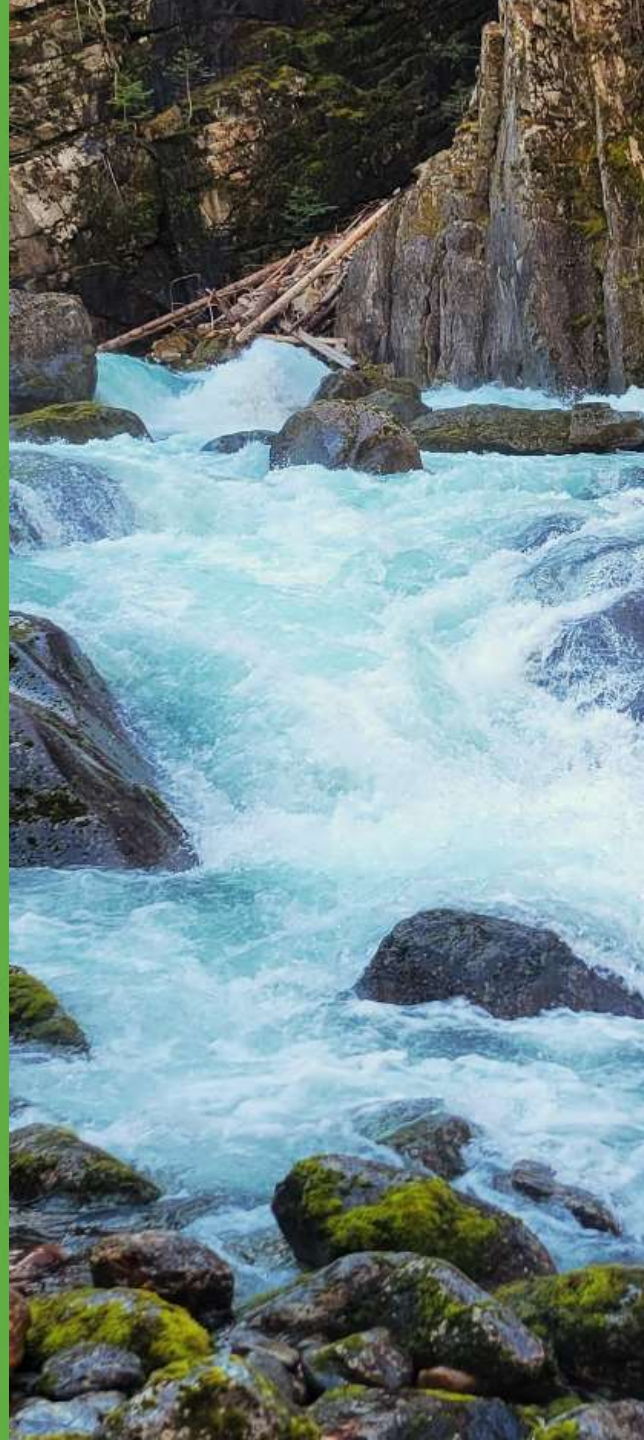
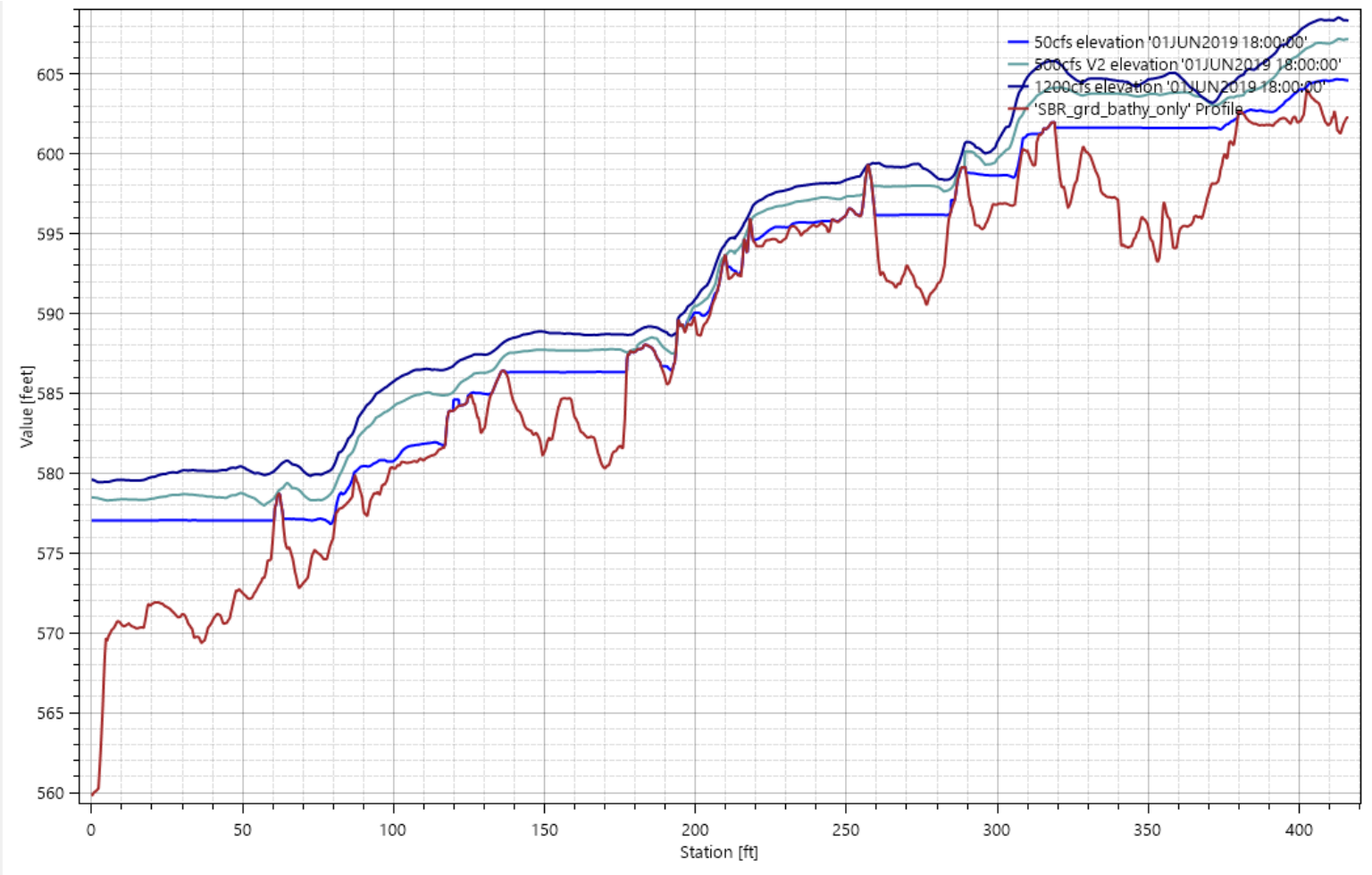
USE OF HYDRAULIC MODELS TO SUPPORT FISH PASSAGE INTERPRETATIONS



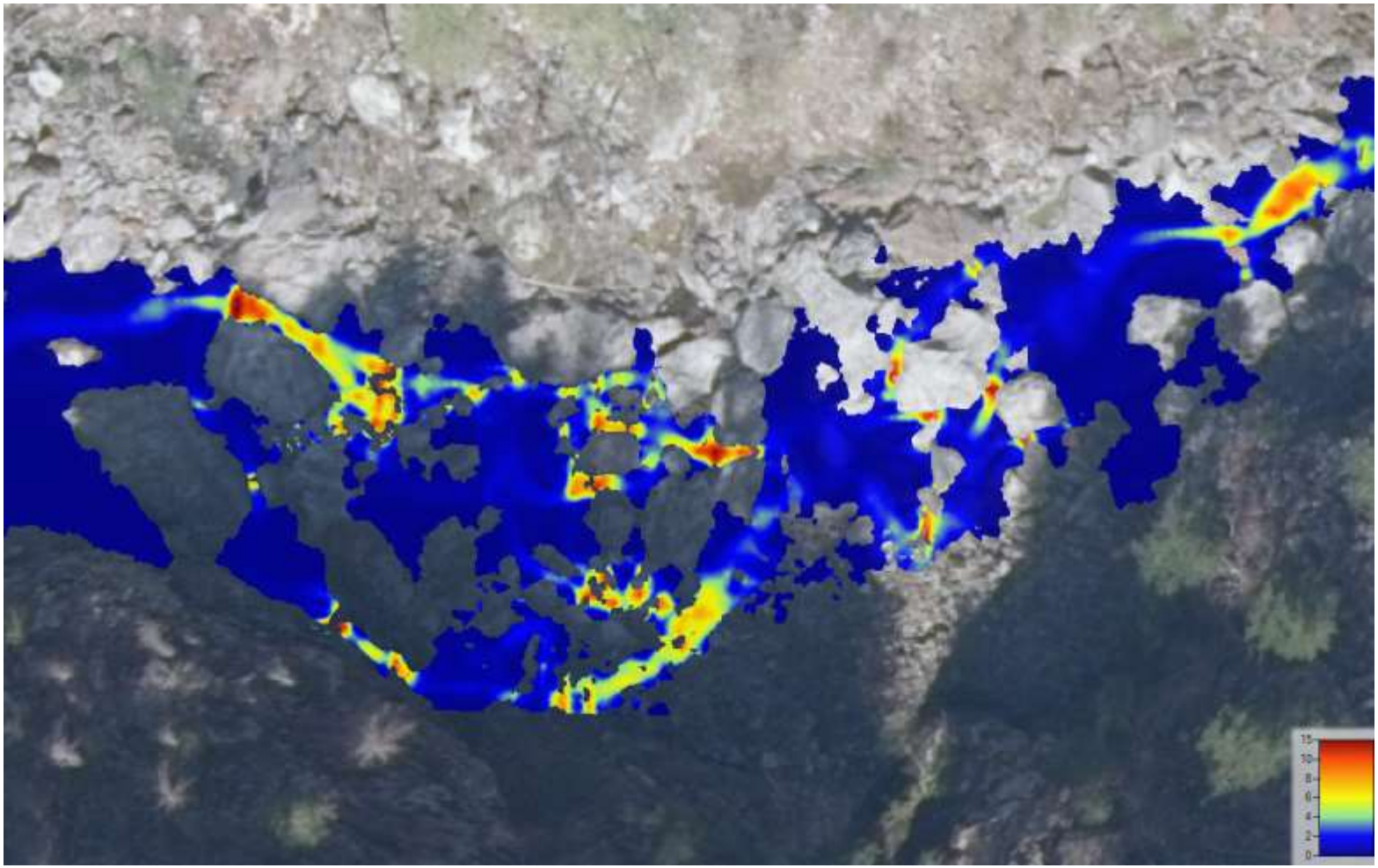
THE ROLE OF HYDRAULIC MODELING IN THE PROPOSED STUDY

- Informs data collection methods
- Informs development of hydraulic pathways that may provide passage
- Informs transition between plunging and streaming flow regimes – leaping vs swimming conditions
- Provides a tool to study trends across the range of flows experienced at the site
- Not intended to be a quantitative tool to dictate pass or fail

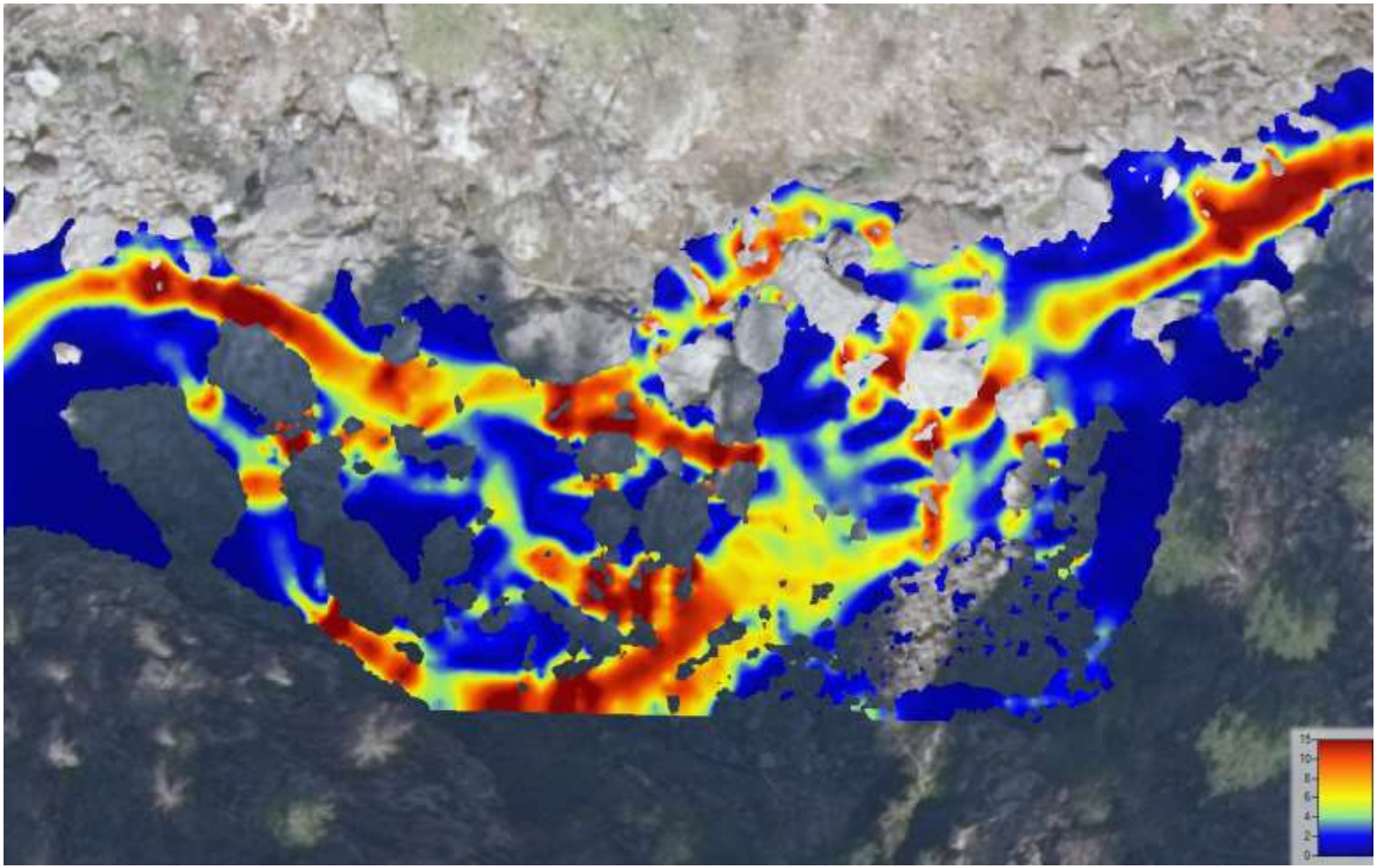
UNCALIBRATED HEC-RAS MODEL – WSEL PROFILE



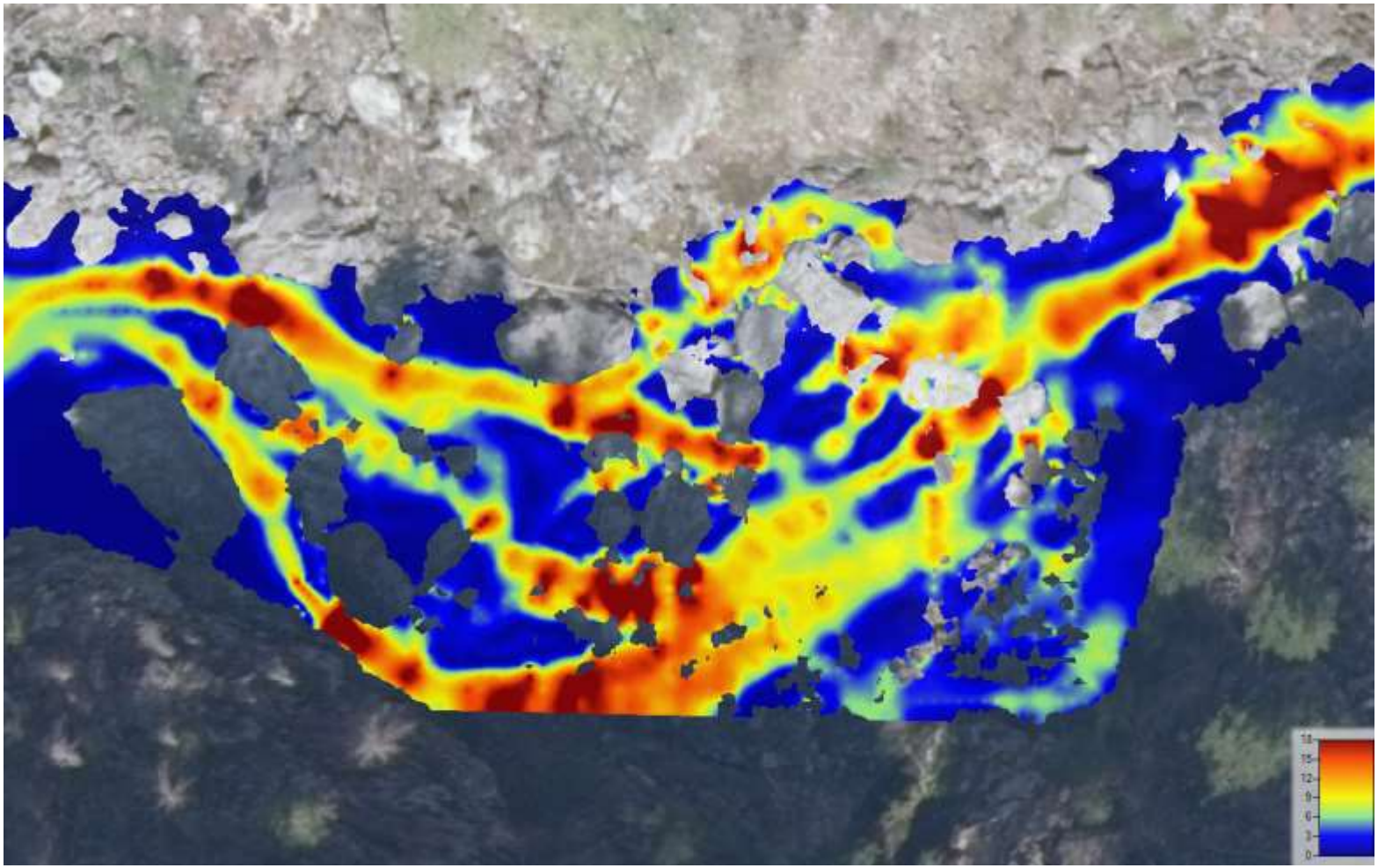
UNCALIBRATED HEC-RAS MODEL – 50 CFS



UNCALIBRATED HEC-RAS MODEL – 500 CFS



UNCALIBRATED HEC-RAS MODEL – 1200 CFS



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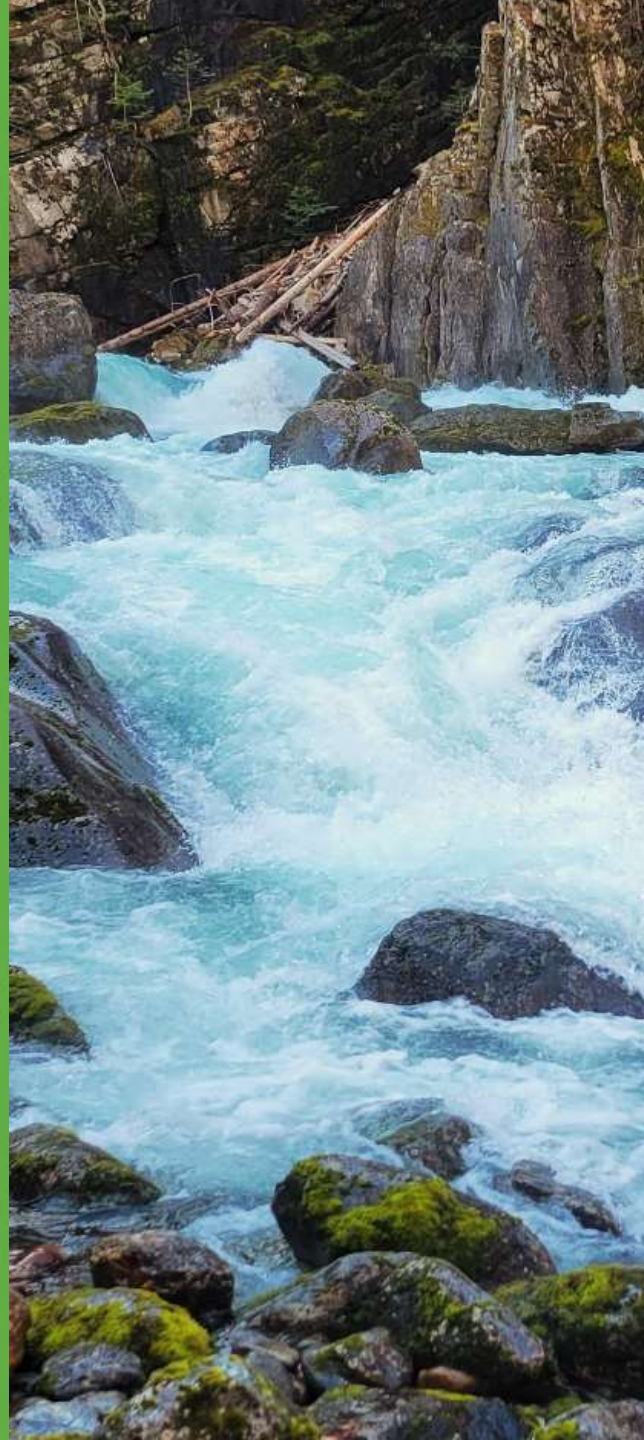
SELECTION AND APPLICABILITY OF MODELING PLATFORMS



HYDRAULIC MODEL SELECTION

All models are wrong, but some models are useful. So the question you need to ask is not "Is the model true?" (it never is) but "Is the model good enough for this particular application? – George Box

HYDRAULIC MODEL SELECTION

- All model applications are influenced by
  - Physical environment, digital terrain, and selected mesh size
  - Calibration – effort and available data
  - Hydraulic complexity
  - Understanding of model limits
  - Experience of the user

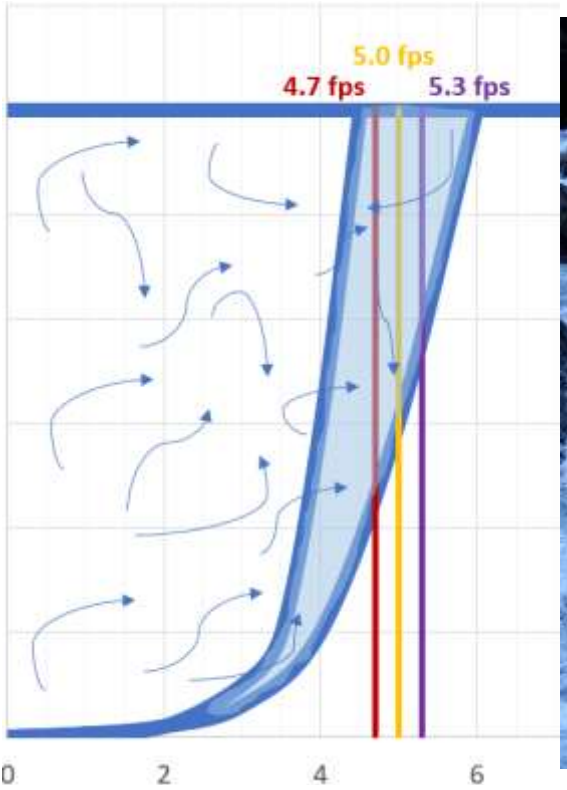
2D MODELS MOST COMMON IN WESTERN WA

- Flo-2D, difference
- River2D, element
- RiverFlow2D, volume
- Telemac-2D, volume/element
- Mike21, volume
- SRH-2D, volume
- HEC-RAS 2D, volume

MODEL COMPARISON

	HEC-RAS	SRH2D	RiverFlow2D	River2D	Telemac2D	Delft3D	PC-SWMM
Floodplain Modeling							
Large domain mesh (computation speed)							
Dam break							
Levee Breach							
Bridge Pressure Flow							
Bridge Piers							
Hydraulic structures (culverts, weirs)							
Tidal Influence							
Fish Habitat							
Ice Cover							
Graphical Display							
Sediment Transport							
FEMA Approved							
Temperature							
Active Development							
Support							
Cost/Licensing							
		can port into RiverFlow2D	can port into SRH2D	can port into Telemac2D	can be port into 3D		

DEPTH AVERAGED VELOCITY IN BYPASS REACH





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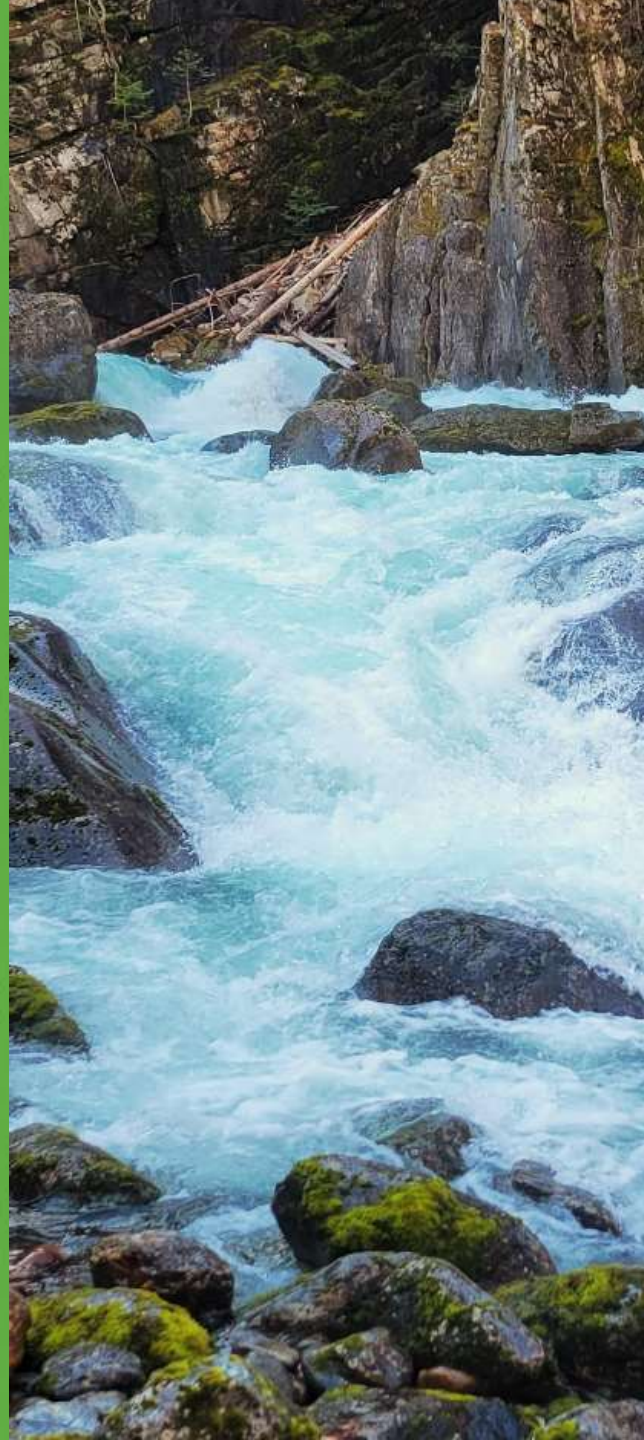
HEC-RAS 2D



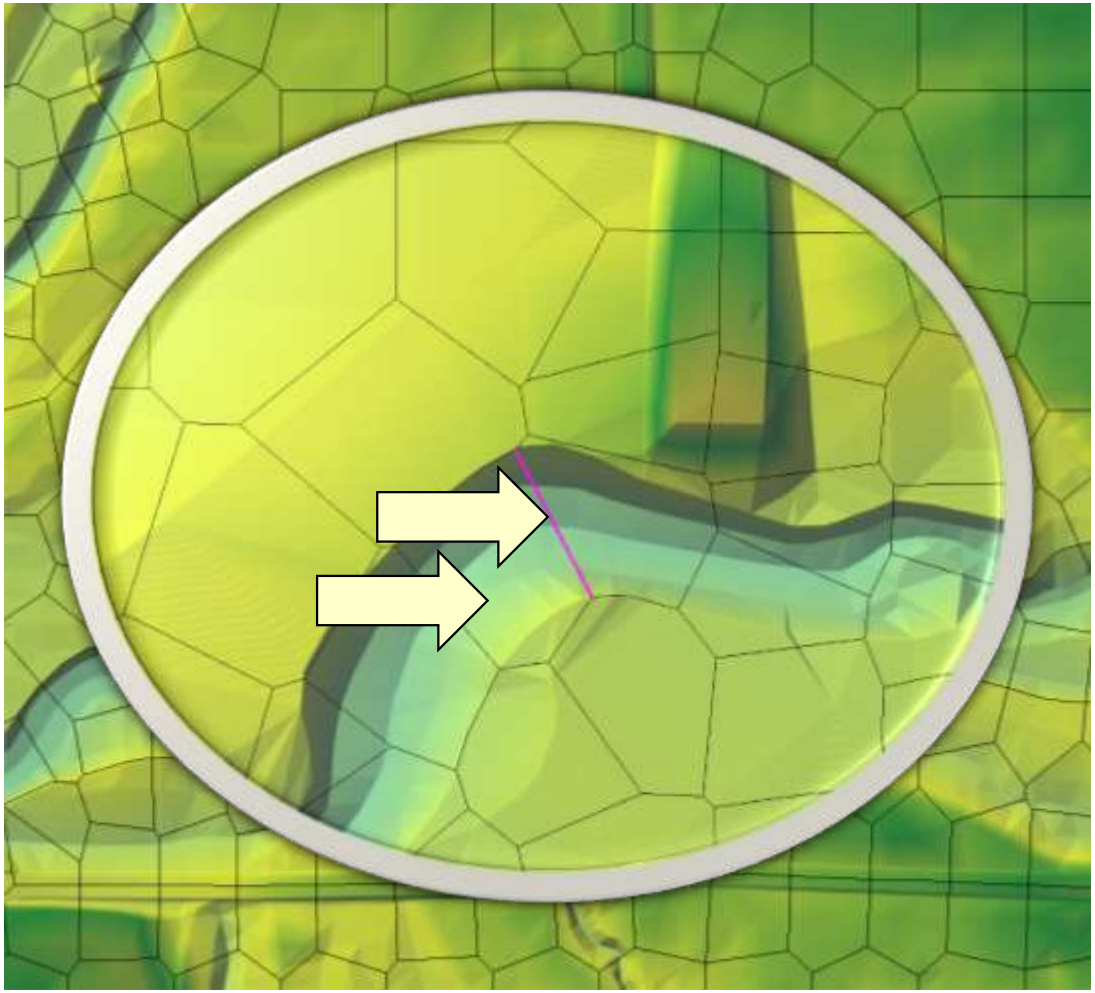
HEC-RAS 2D VERSIONS

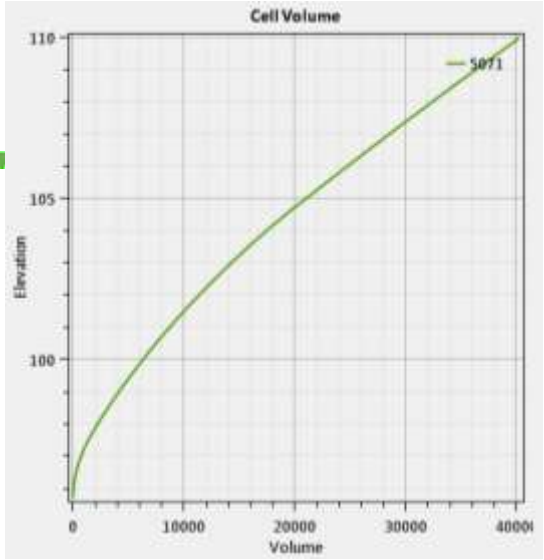
- 4.2 Alpha 2 *(2013)*
- 5.0 Beta *(2014)*
- 5.0 *(2016)*
- 5.0.1 through 5.07 *(2016-2019)*
- 6.0 Beta 3 *(March 2021)*

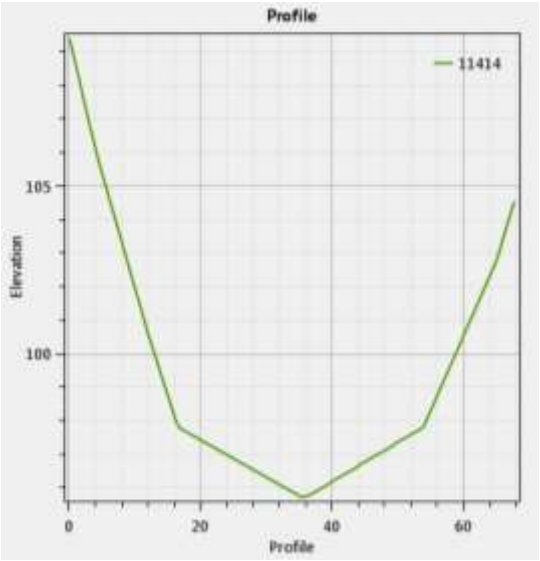
HEC-RAS 2D FEATURES

- SWE – Finite Volume (implicit)
- Wetting/drying robust, sudden rush (dam break)
- Subcritical, supercritical, mixed flow
- 1D-2D coupled
- Structured and unstructured mesh
- High-resolution subgrid model
  - hydraulic property tables vs. primitive geometry at higher resolution

HIGH RESOLUTION SUBGRID MODEL

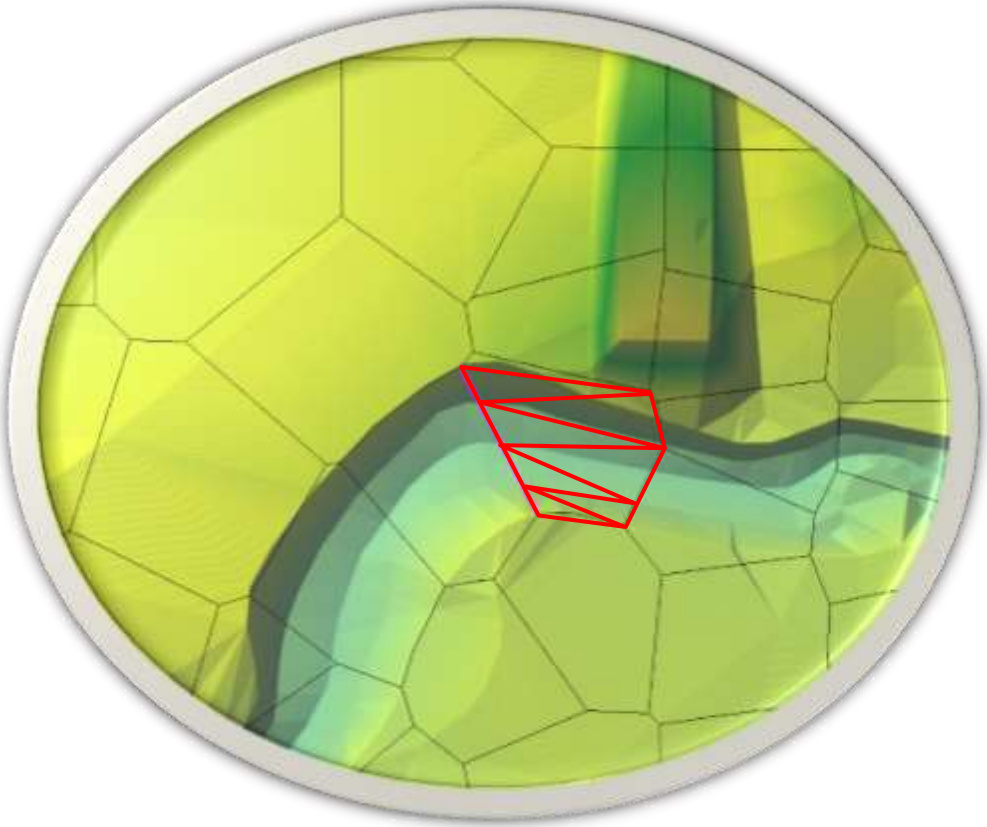


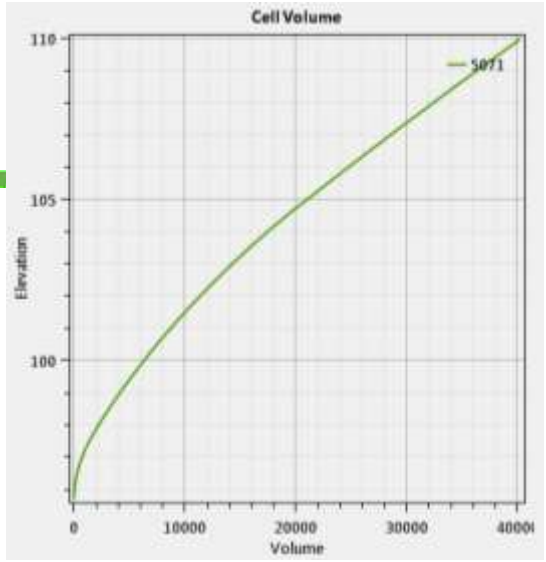


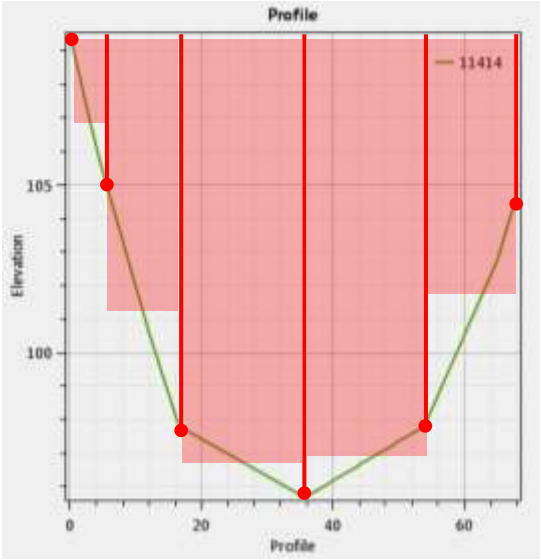


HIGH RESOLUTION SUBGRID MODEL

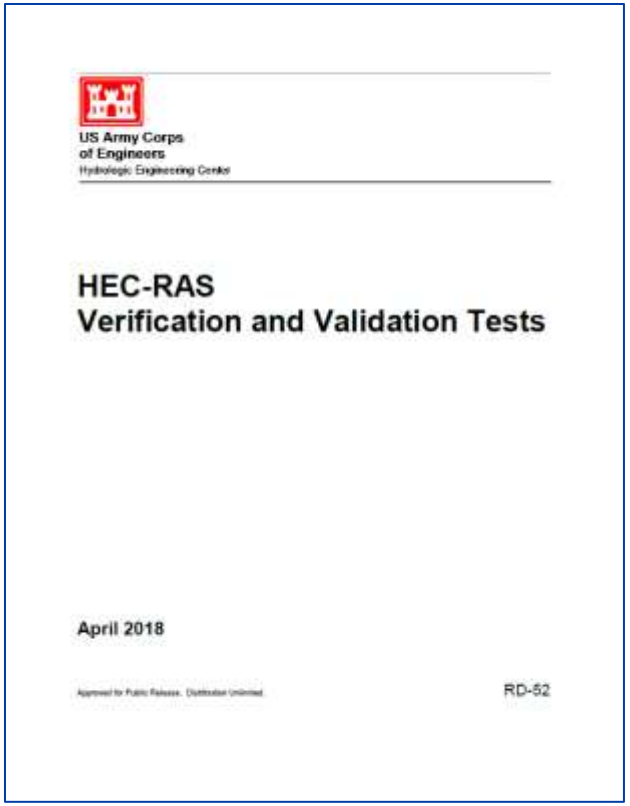
- Larger cells without loss of resolution







HEC-RAS TESTING

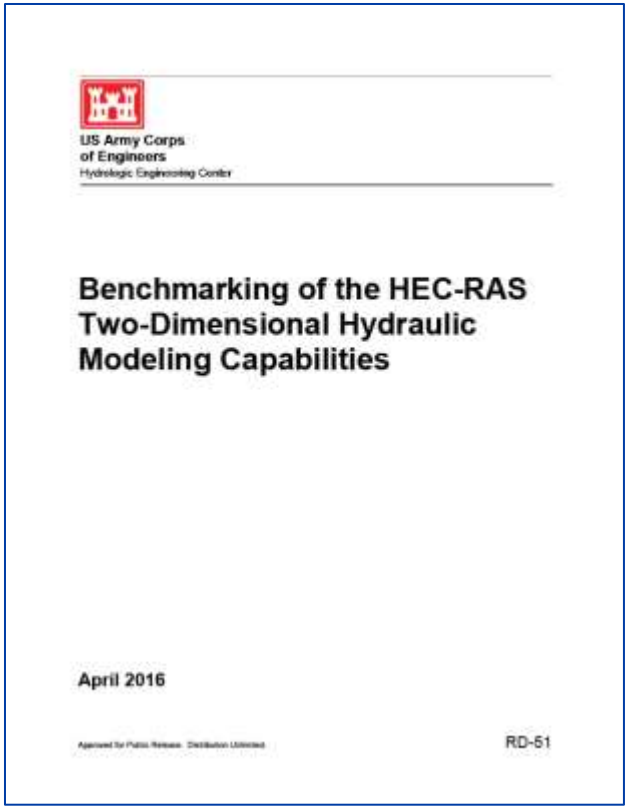

US Army Corps
of Engineers
Hydrologic Engineering Center

HEC-RAS
Verification and Validation Tests

April 2018

Approved for Public Release. Distribution Unlimited.

RD-52


US Army Corps
of Engineers
Hydrologic Engineering Center

Benchmarking of the HEC-RAS
Two-Dimensional Hydraulic
Modeling Capabilities

April 2016

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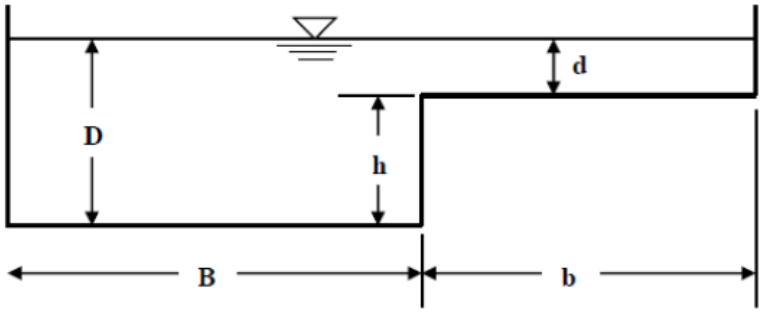
RD-51

HEC-RAS VALIDATION TESTING



- Flow in a compound channel

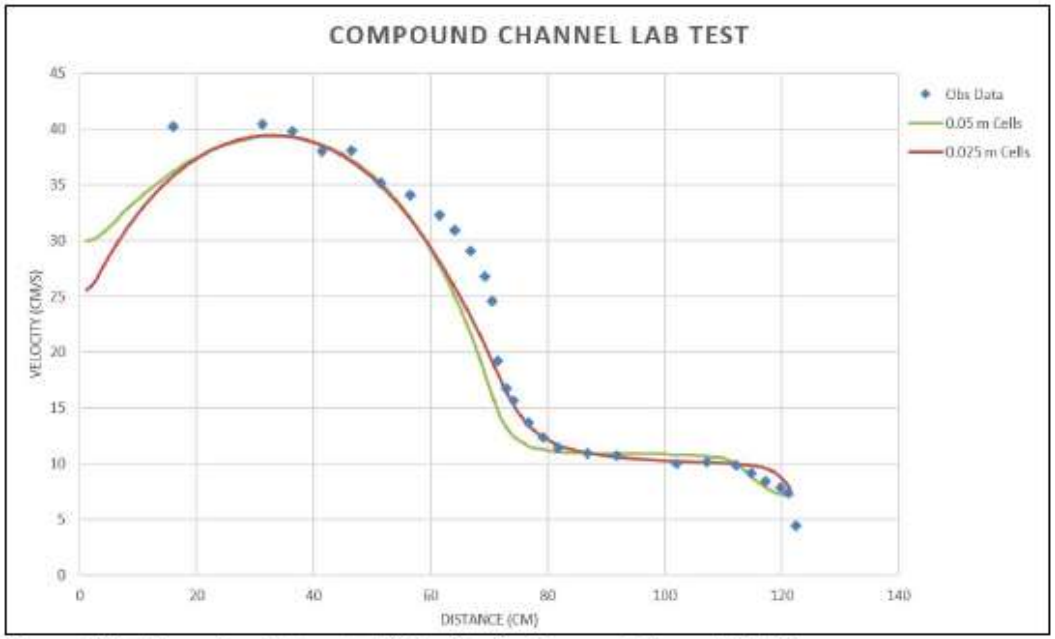
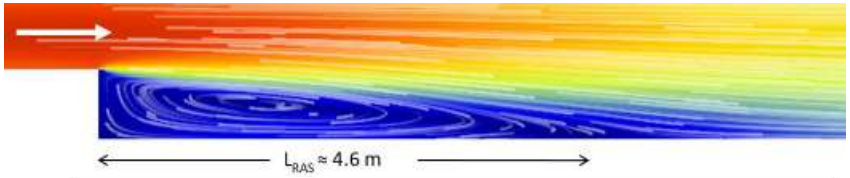


Figure 4-32. Observed and Computed Velocities for Compound Channel Test Case

HEC-RAS VALIDATION TESTING



- Flow in a rectangular channel with sudden expansion

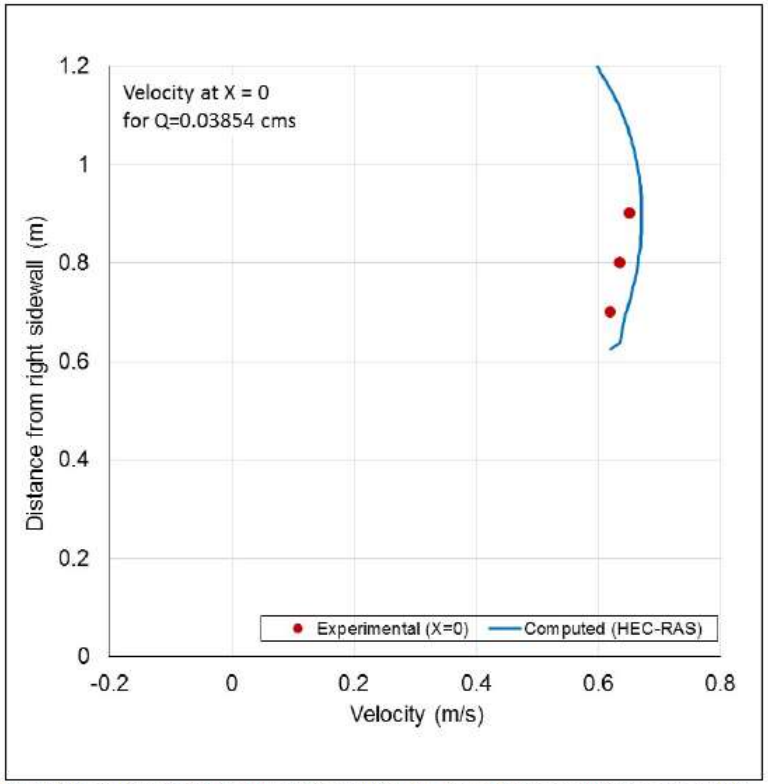


Figure 4-41. Velocity Profile (computed and experimental), at X = 0 (just upstream of the expansion) for Q = 0.03854 cms

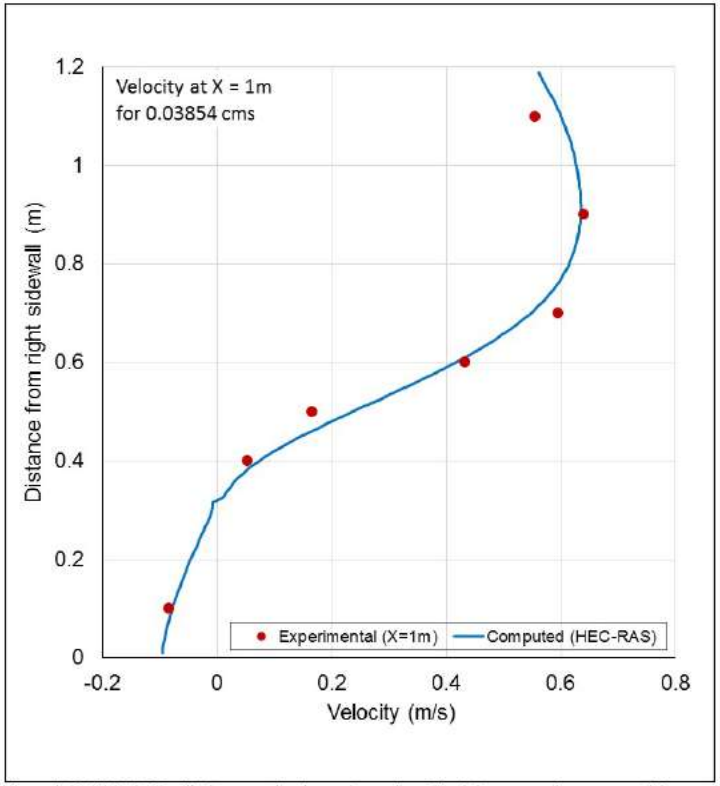


Figure 4-42. Velocity Profile (computed and experimental), at X = 1 (one meter downstream of the expansion) for Q = 0.03854 cms

HEC-RAS VALIDATION TESTING

- Flow in a rectangular channel with sudden expansion

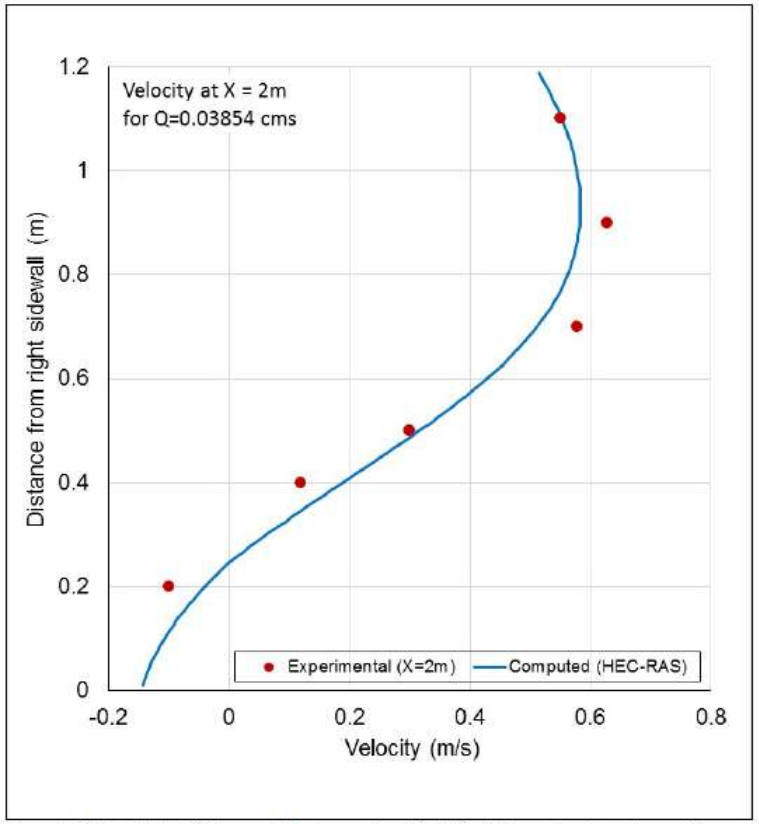


Figure 4-43. Velocity Profile (computed and experimental), at X = 2 (two meters downstream of the expansion) for Q = 0.03854 cms

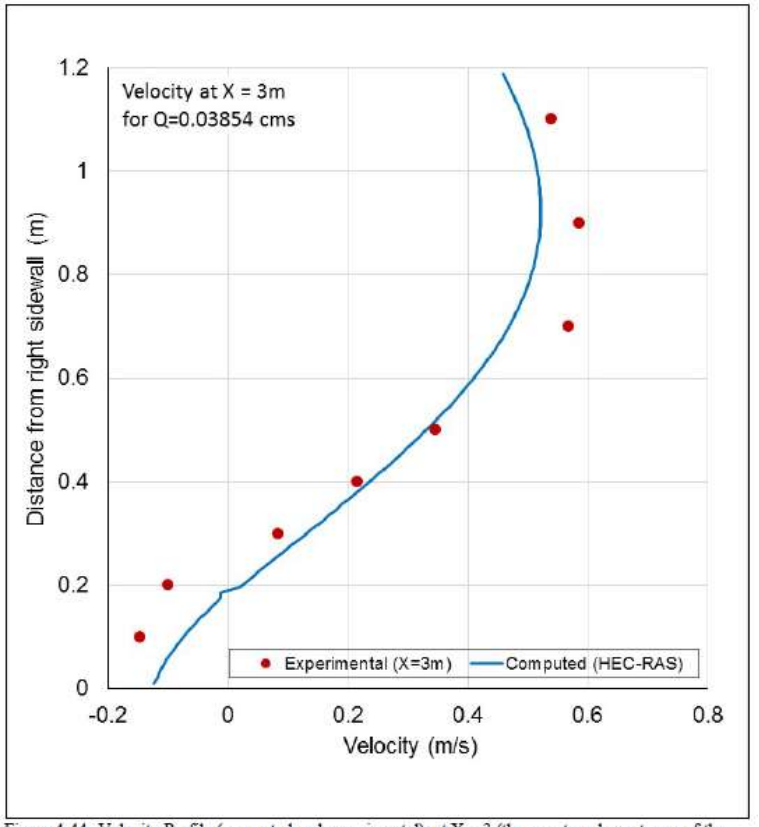


Figure 4-44. Velocity Profile (computed and experimental), at X = 3 (three meters downstream of the expansion) for Q = 0.03854 cms

HEC-RAS VALIDATION TESTING

- Flow in a rectangular channel with sudden expansion

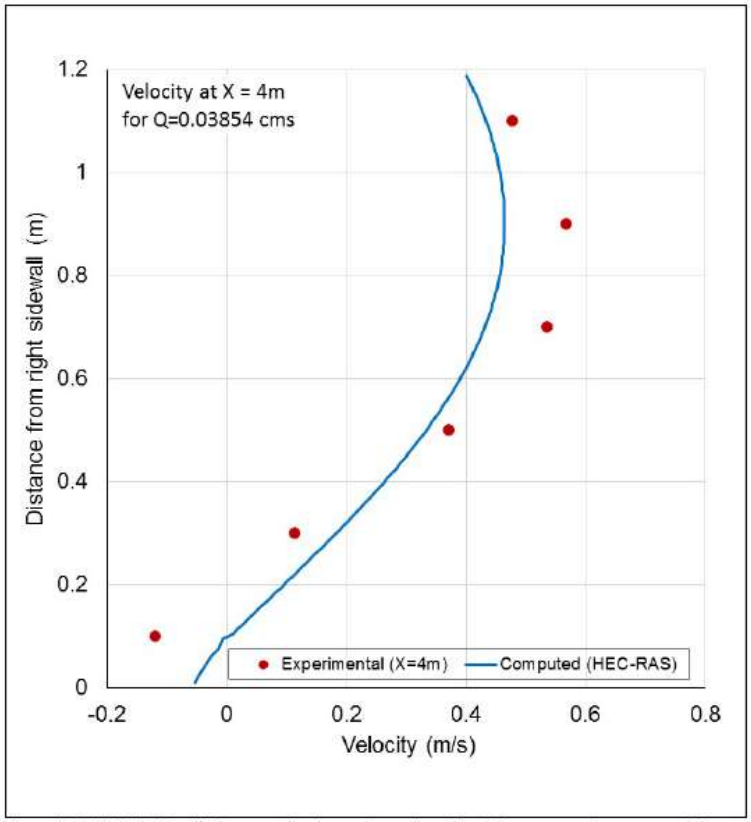


Figure 4-45. Velocity Profile (computed and experimental), at X = 4 (four meters downstream of the expansion) for Q = 0.03854 cms

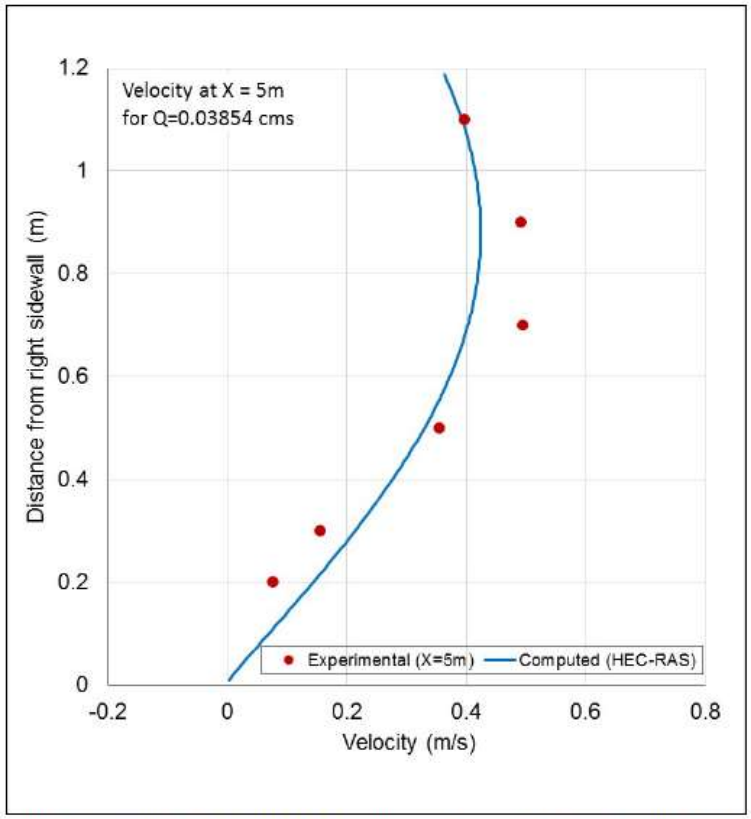


Figure 4-46. Velocity Profile (computed and experimental), at X = 5 (five meters downstream of the expansion) for Q = 0.03854 cms

HEC-RAS VALIDATION TESTING

- Rectangular channel with 180-degree bend

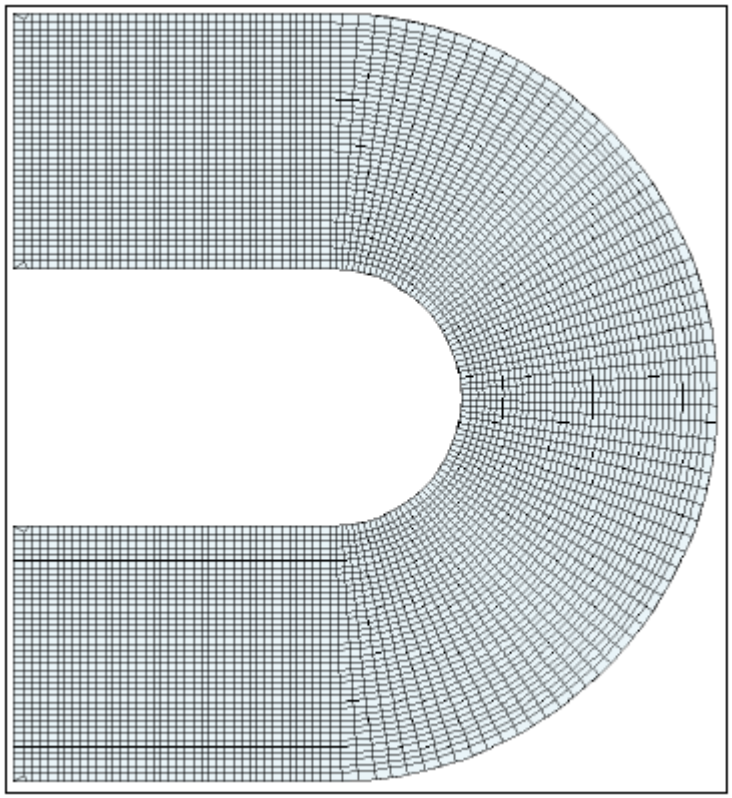


Figure 4-54. Curvilinear Computational Mesh for the 180-degree Bend Test Case

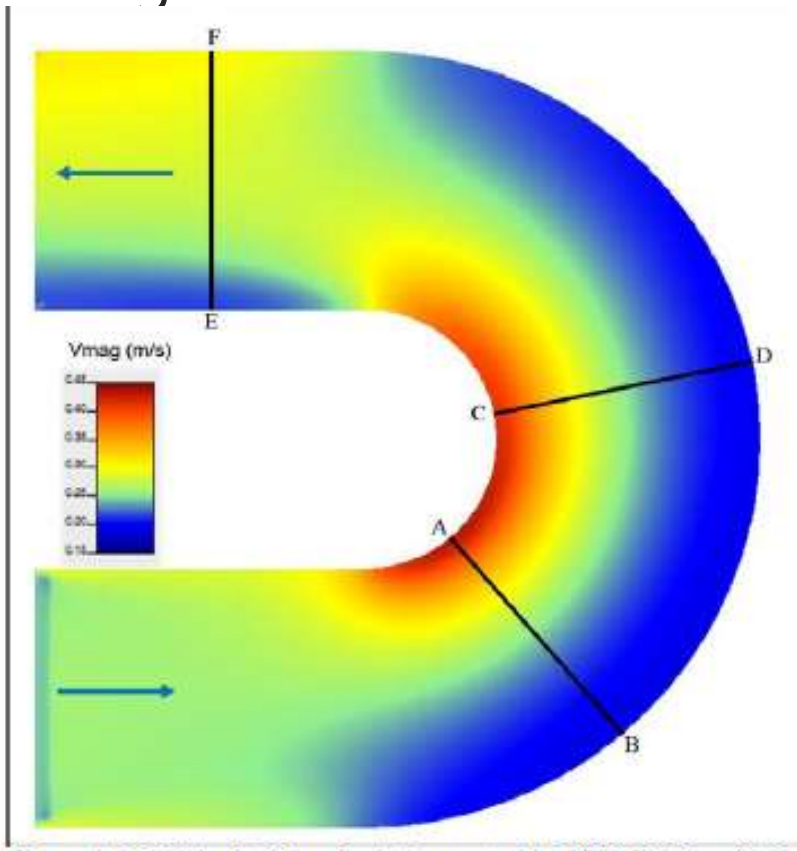


Figure 4-55. Velocity Magnitude (computed by HEC-RAS), with Faster Velocity

HEC-RAS VALIDATION TESTING

- Rectangular channel with 180-degree bend

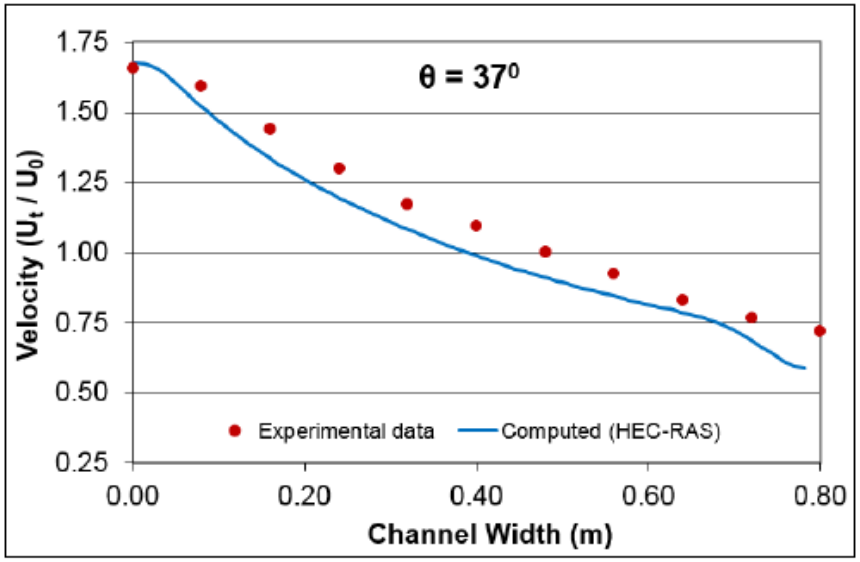


Figure 4-56. Velocity Profile (computed and experimental), at Section A-B in Figure 4-55 (with entrance velocity $U_0 = 0.265$ m/s)

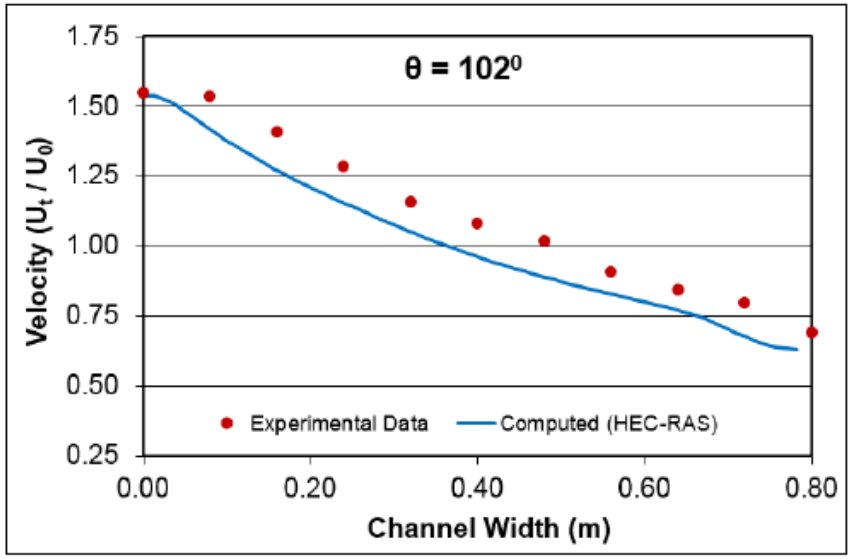
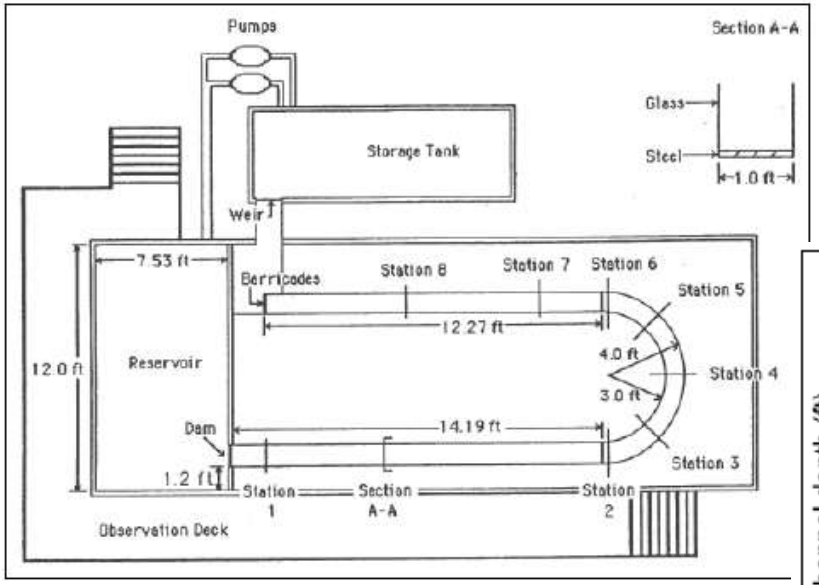


Figure 4-57. Velocity Profile (computed and experimental), at Section C-D in Figure 4-55 (with entrance velocity $U_0 = 0.265$ m/s)

HEC-RAS VALIDATION TESTING

- Dam break in channel with 180-degree bend



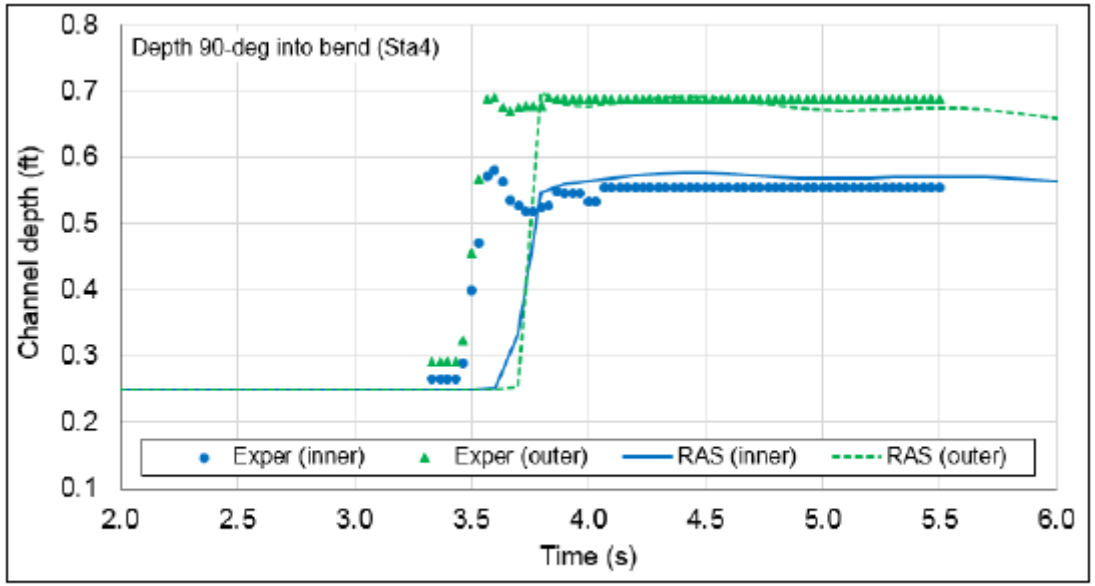


Figure 4-70. Depth Hydrograph (computed and experimental), at Station 4 in Figure 4-68 (midway through bend, 90-degrees)

HEC-RAS VALIDATION TESTING

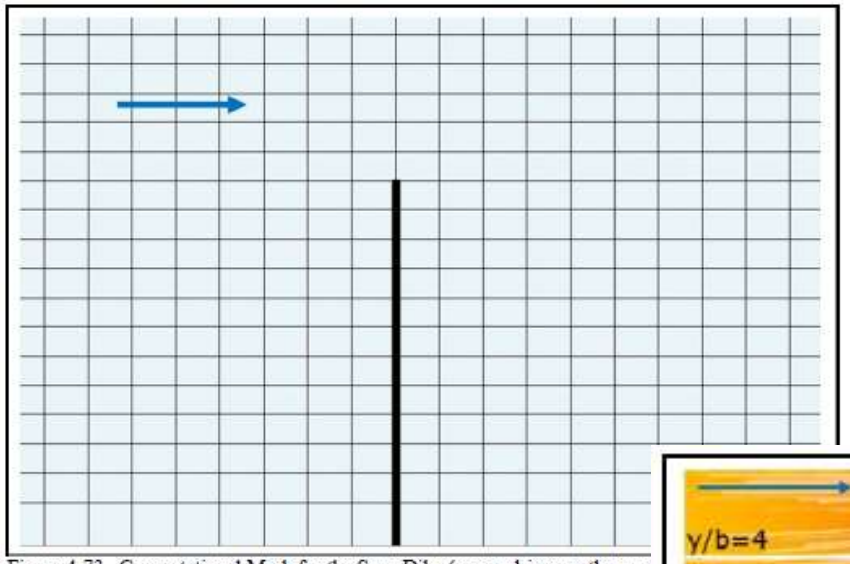


Figure 4-73. Computational Mesh for the Spur-Dike (zoomed-in near the spu

- Flow around a Spur-Dike

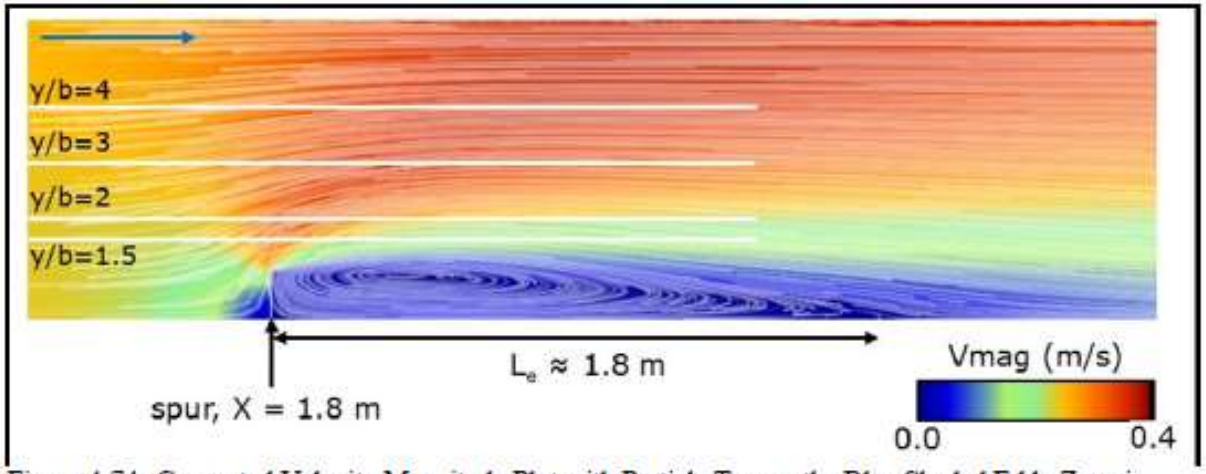
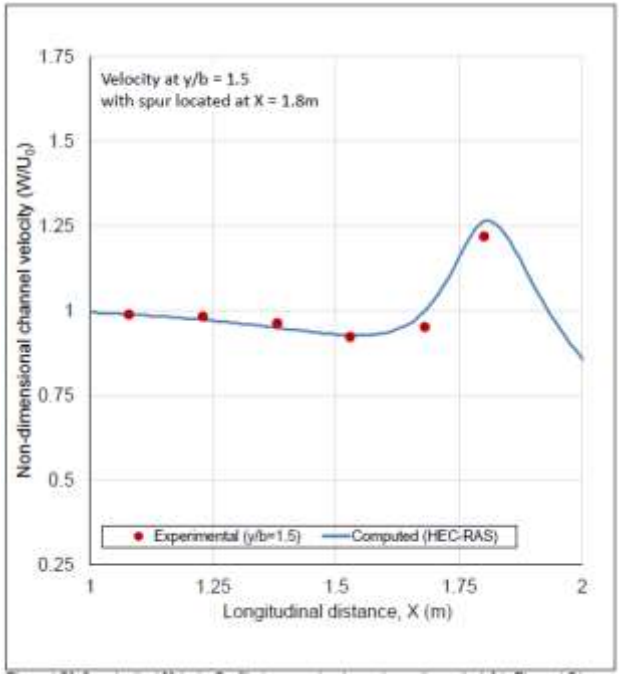
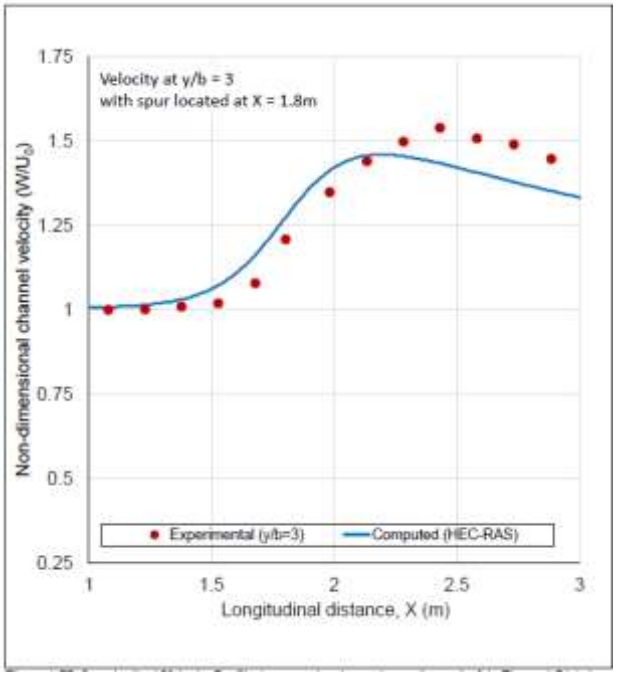


Figure 4-74. Computed Velocity Magnitude Plot with Particle Traces, the Blue Shaded Eddy Zone is Clearly Evident Downstream of the Spur-Dike

HEC-RAS VALIDATION TESTING

- Flow around a Spur-Dike





HEC-RAS VALIDATION TESTING

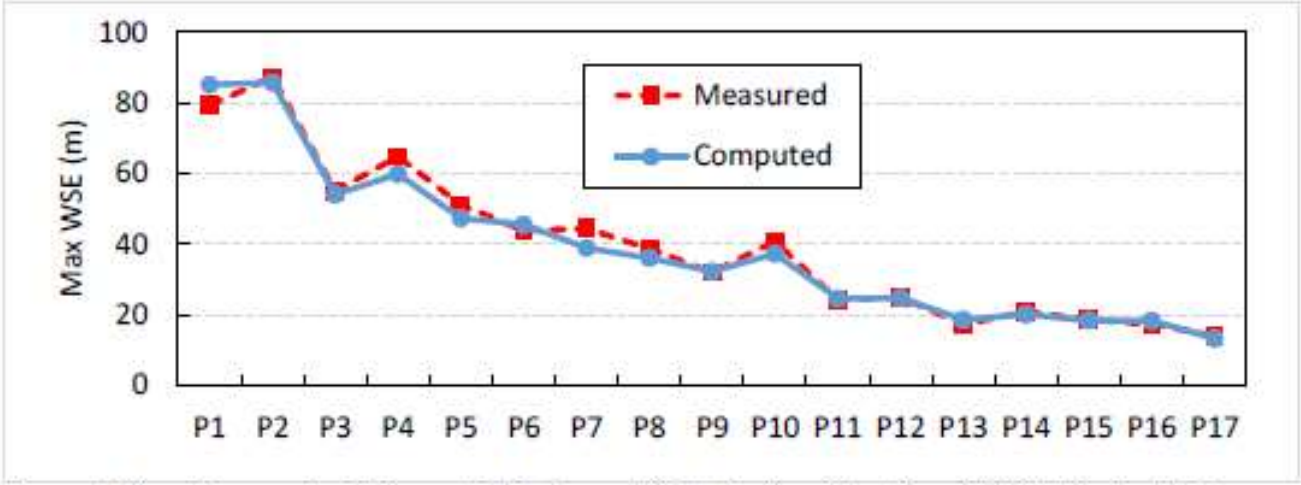


Figure 4-99. Measured and Computed Maximum Water Surface Elevations (WSEL) for the High-Water Marks Collected by the Police after the Malpasset Dam Break

- Malpasset Dam Break

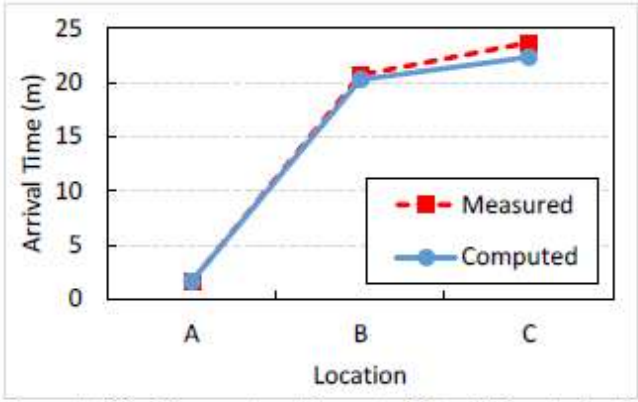
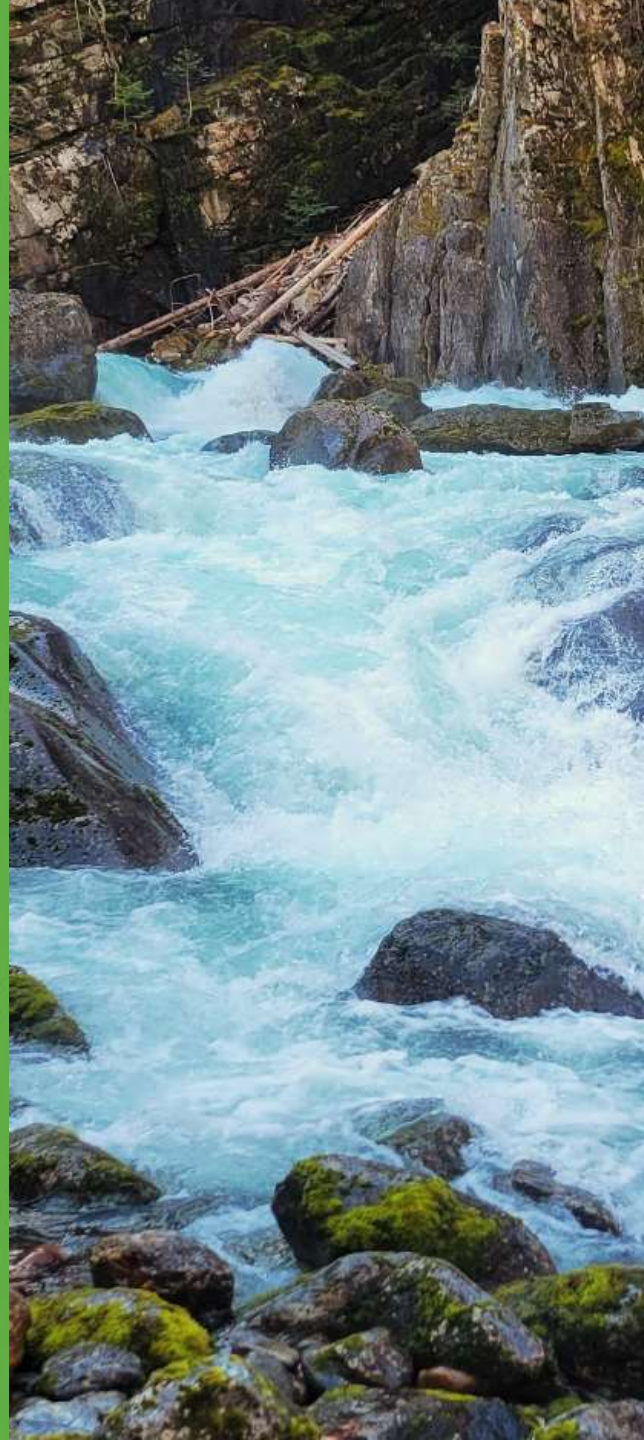


Figure 4-100. Measured and Computed Flood Wave Arrival Times for the Malpasset Dam Break at Three Locations where Electric Transformers were Damaged

Seattle City Light

SRH-2D

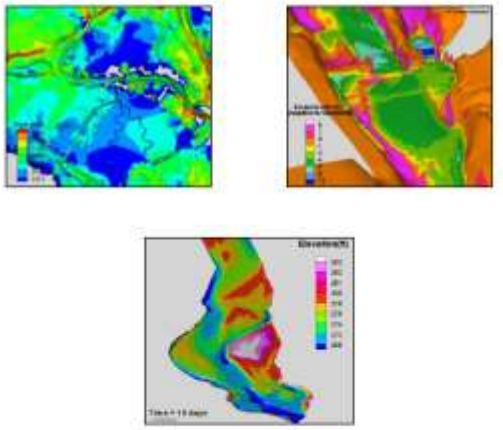


SRH-2D VERIFICATION CASES

RECLAMATION
Managing Water in the West

SRH-2D version 2: Theory and User's Manual

Sedimentation and River Hydraulics – Two-Dimensional River Flow Modeling



U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

November 2008

Two-Dimensional Depth-Averaged Flow Modeling

with an Unstructured Hybrid Mesh

by

Yong G. Lai[1]

ABSTRACT

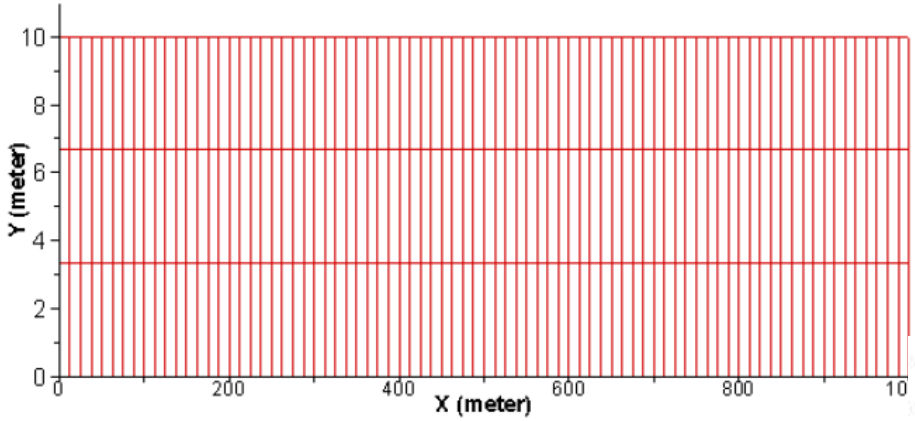
An unstructured hybrid mesh numerical method is developed to simulate open channel flows. The method is applicable to arbitrarily-shaped mesh cells and offers a framework to unify many mesh topologies into a single formulation. The finite-volume discretization is applied to the two-dimensional depth-averaged St. Venant equations, and the mass conservation is satisfied both locally and globally. An automatic wetting-drying procedure is incorporated in conjunction with the segregated solution procedure that chooses the water surface elevation as the main variable. The method is applicable to both steady and unsteady flows and covers the entire flow range: subcritical, transcritical and supercritical. The proposed numerical method is well suited to natural river flows with a combination of main channels, side channels, bars, floodplains and in-stream structures. Technical details of the method are presented, verification studies are performed using a number of simple flows, and a practical natural river is modeled to illustrate issues of calibration and validation.

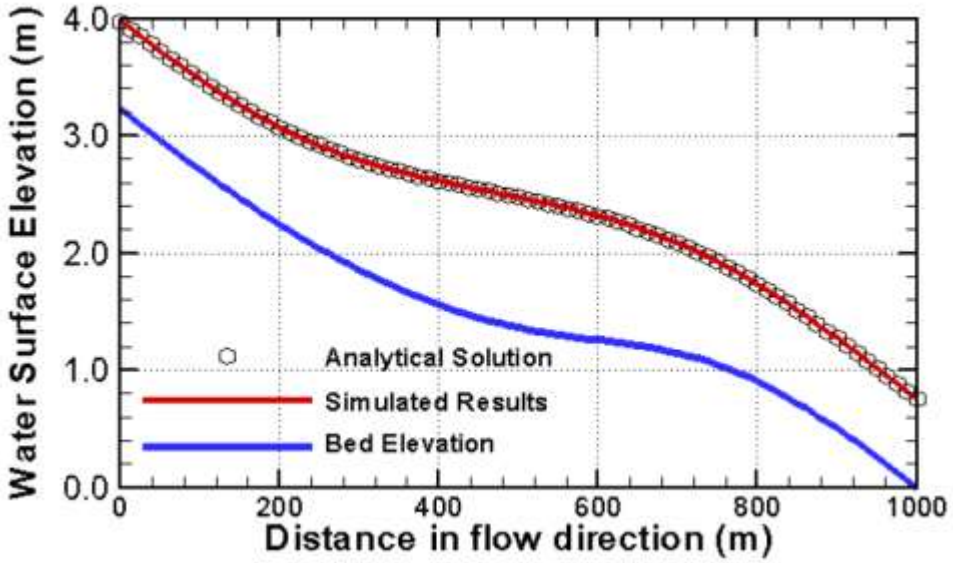
KEYWORDS: 2D Model, Depth-Averaged Model, Hybrid Mesh, Unstructured Mesh

[1]Hydraulic Engineer, Sedimentation and River Hydraulics Group, Technical Service Center, Bureau of Reclamation, Denver, CO 80225; PH: 303-445-2560; FAX: 303-445-6351; email: ylai@do.usbr.gov

SRH-2D VERIFICATION CASES

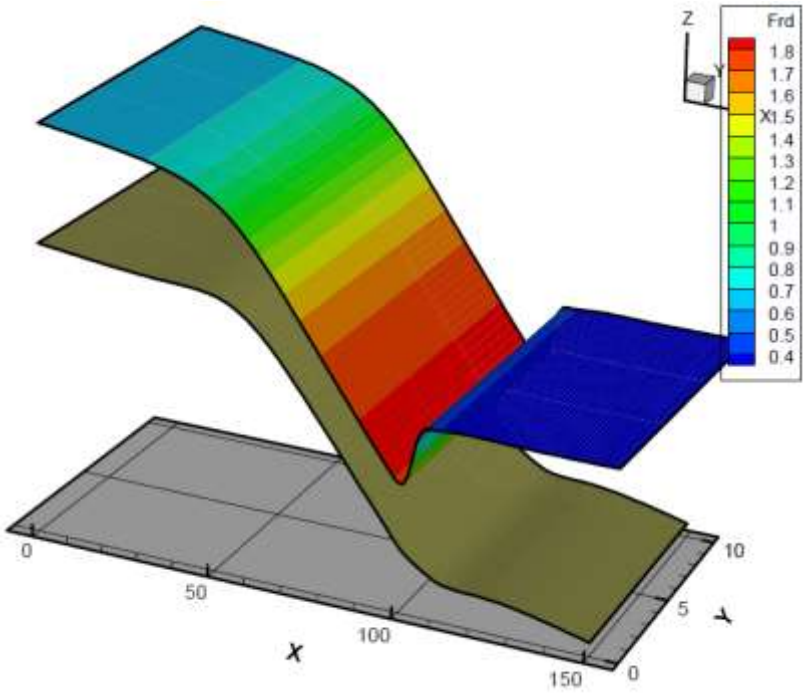
- Subcritical Flow in a 1D Channel

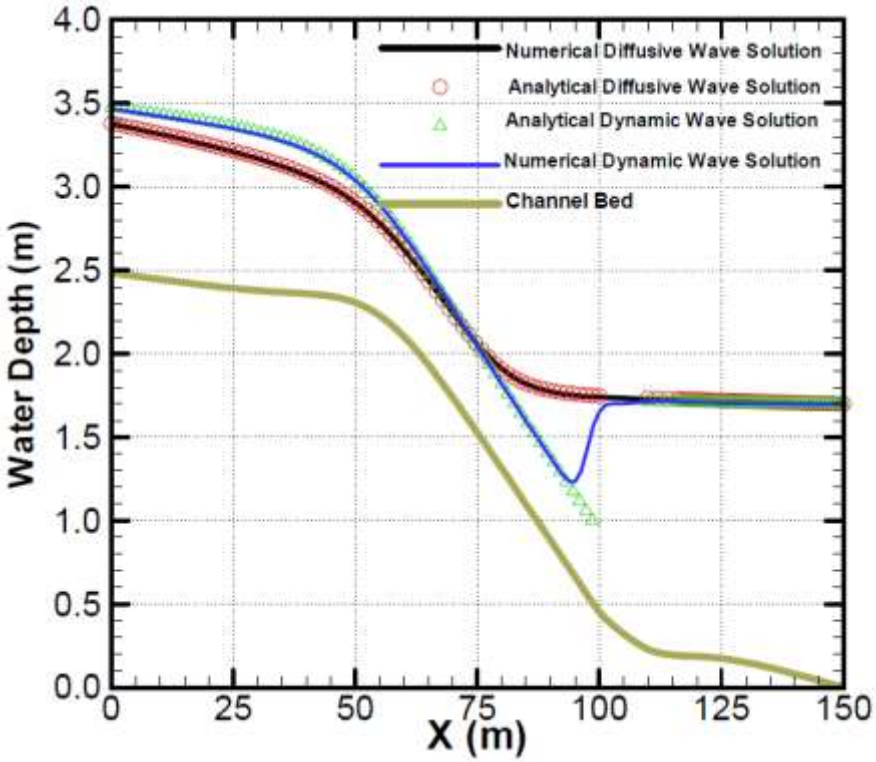




SRH-2D VERIFICATION CASES

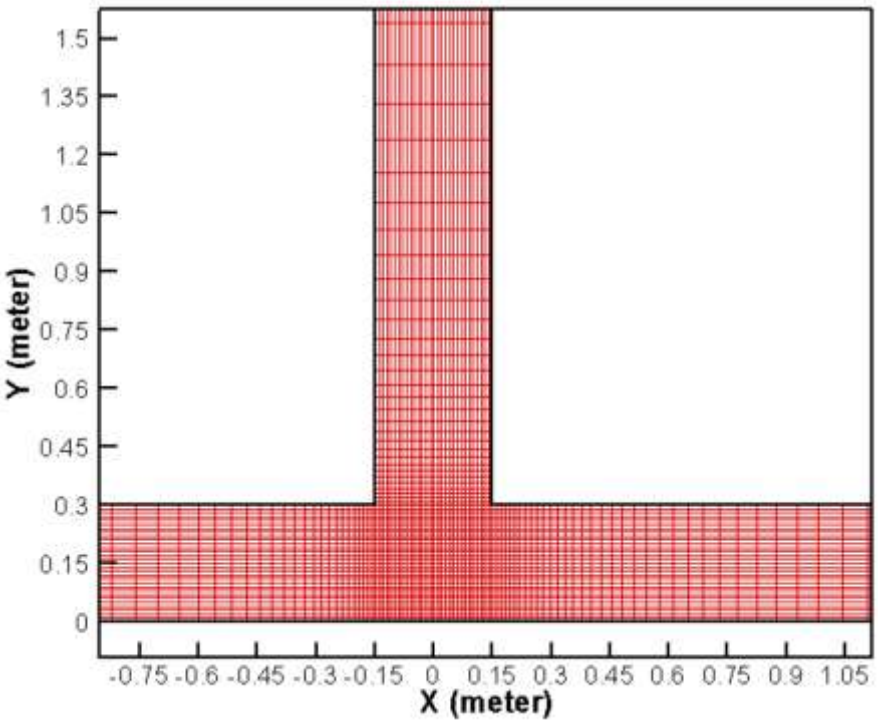
- Transcritical Flow in a 1D Channel

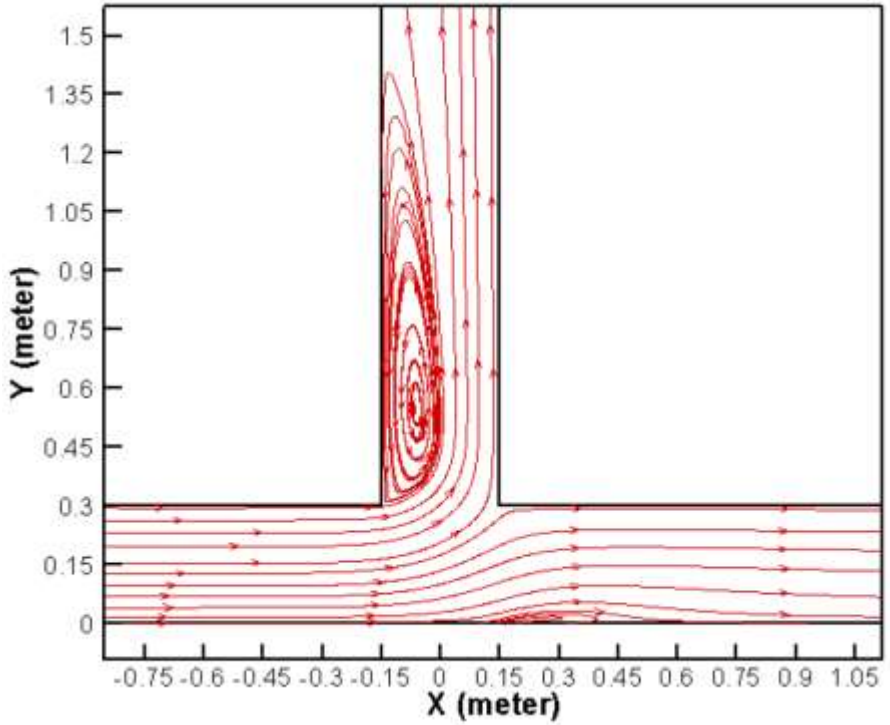




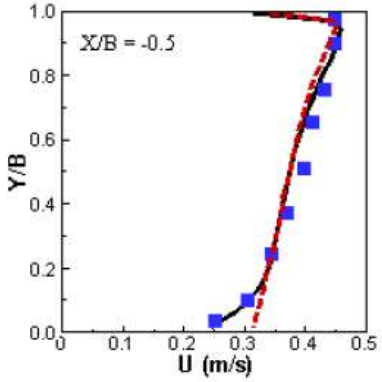
SRH-2D VERIFICATION CASES

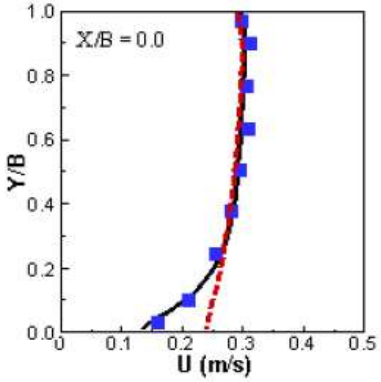
- 2D Diversion Flow in a Channel

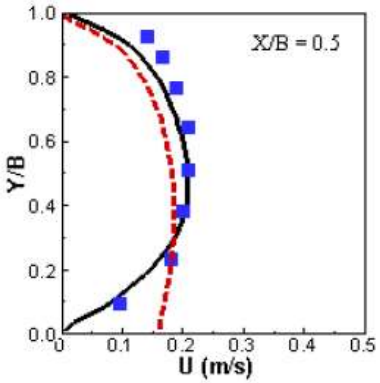


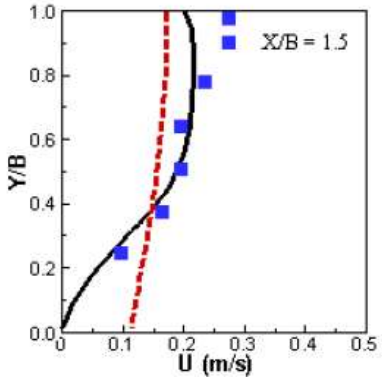


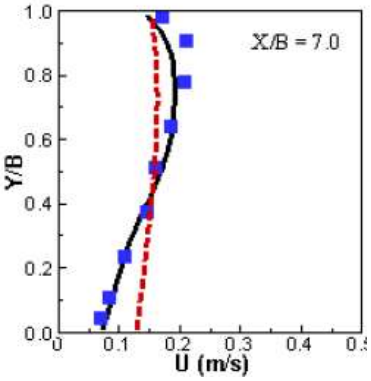
SRH-2D VERIFICATION CASES

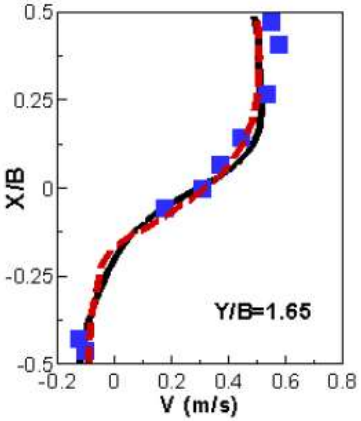


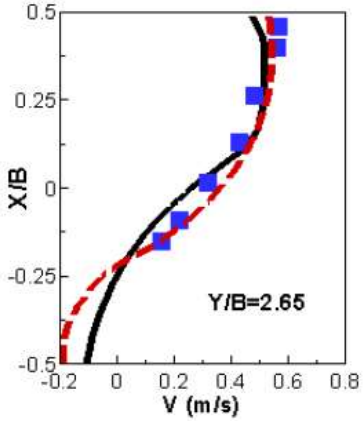


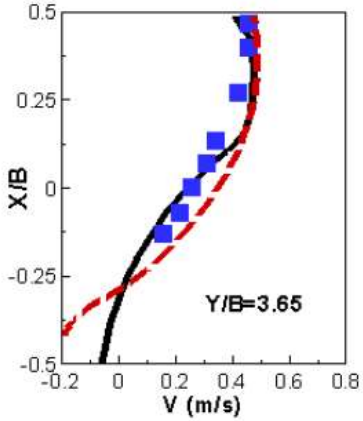






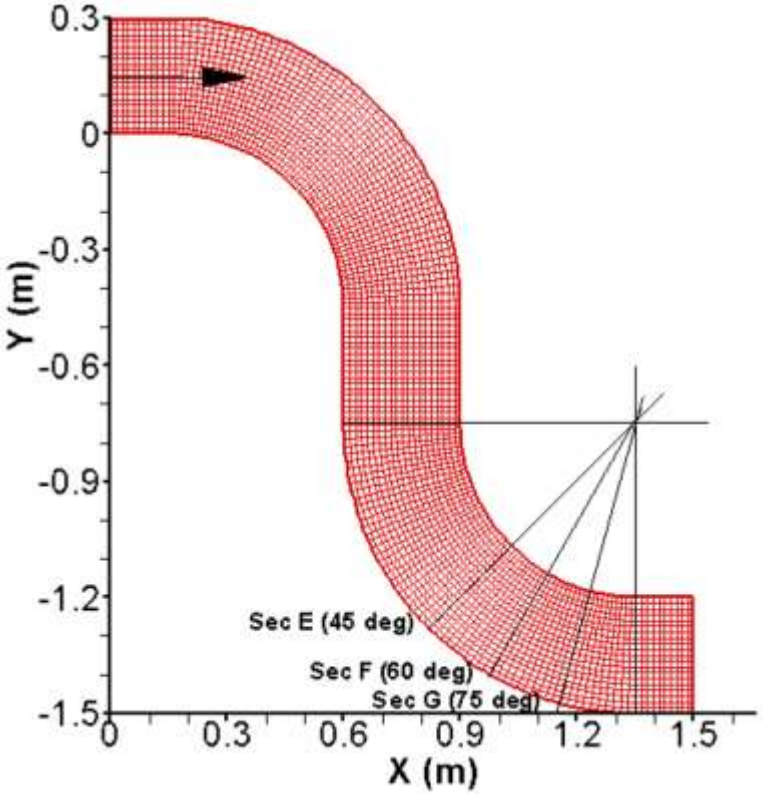


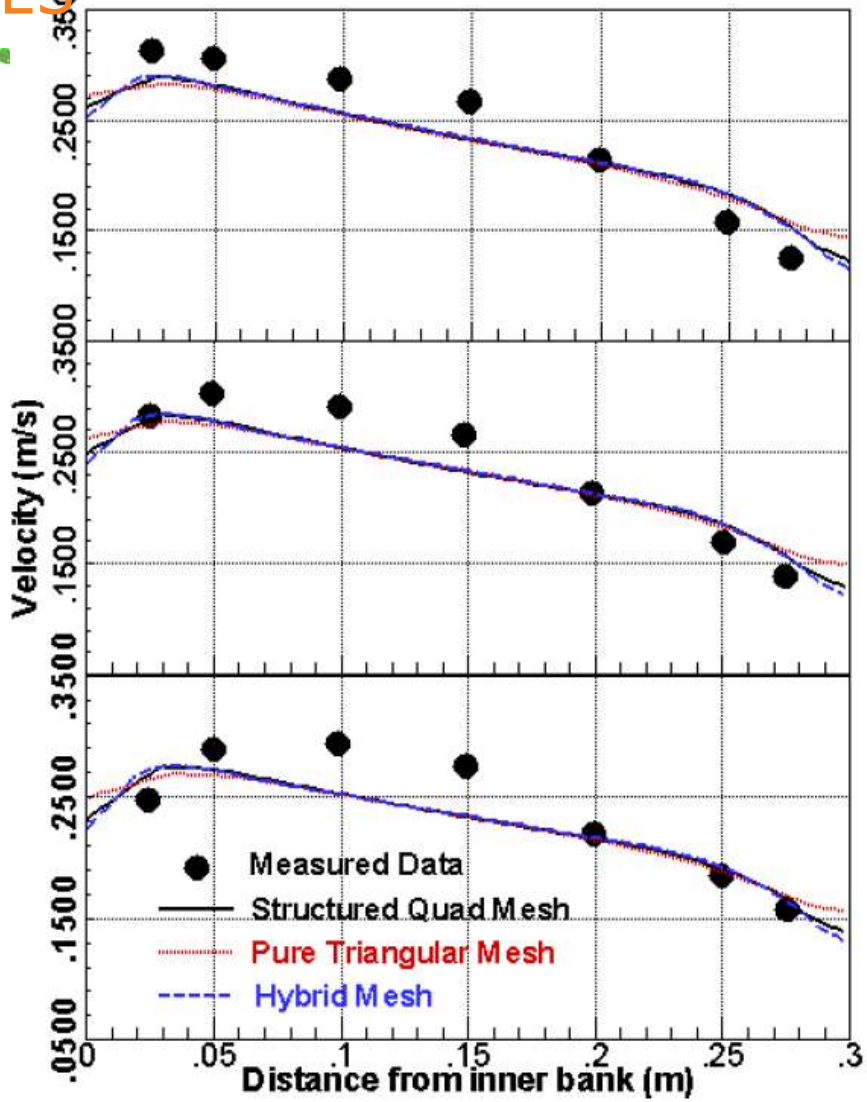




SRH-2D VERIFICATION CASES

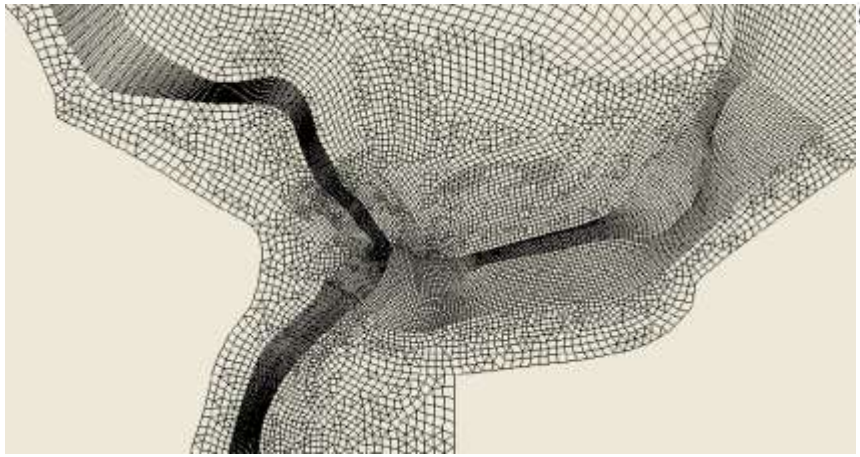
- Meandering Channel with 90° bends

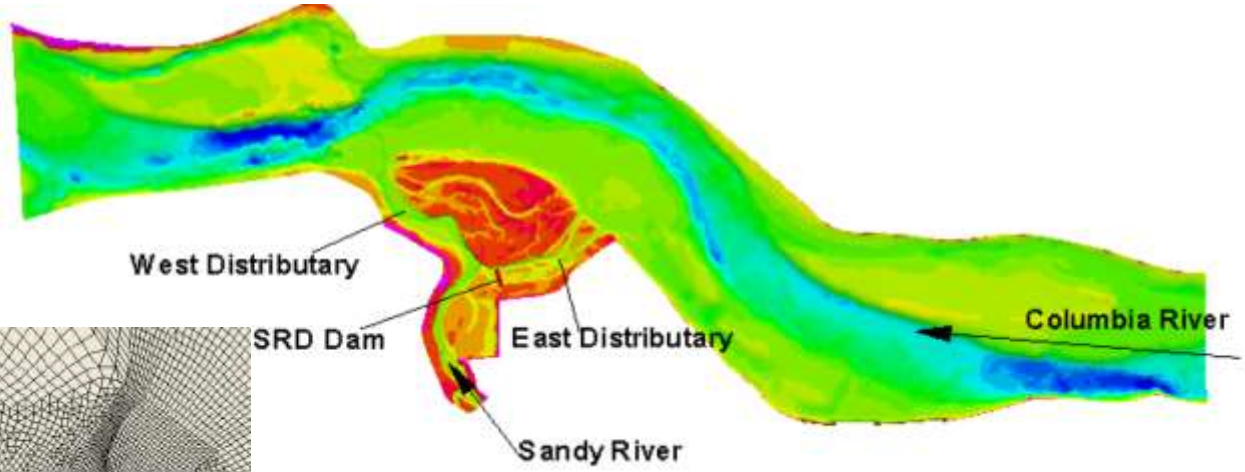




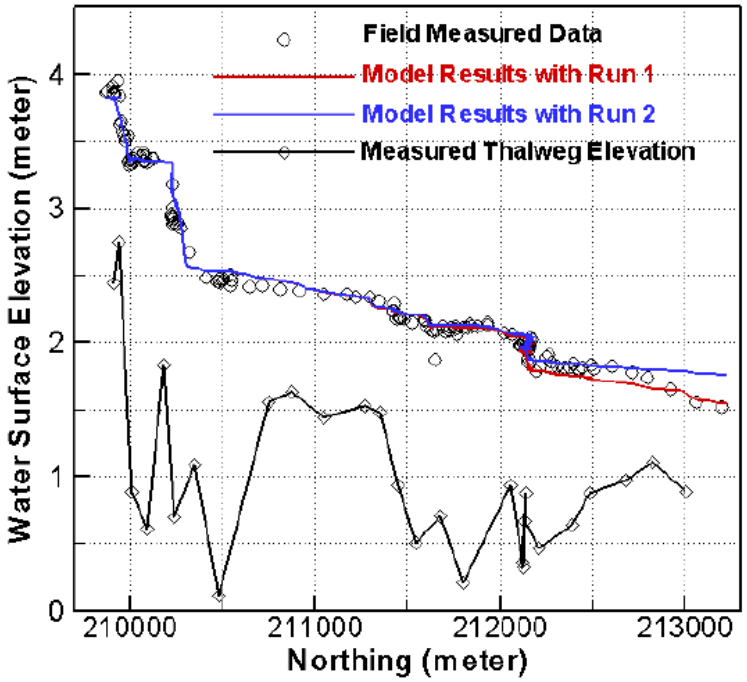
SRH-2D VERIFICATION CASES

- Sandy and Columbia River confluence

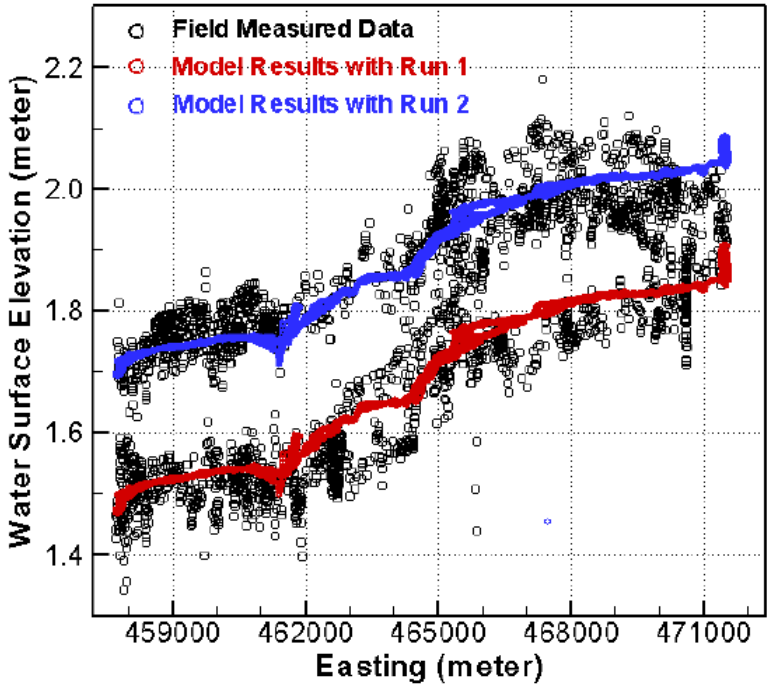




SRH-2D VERIFICATION CASES

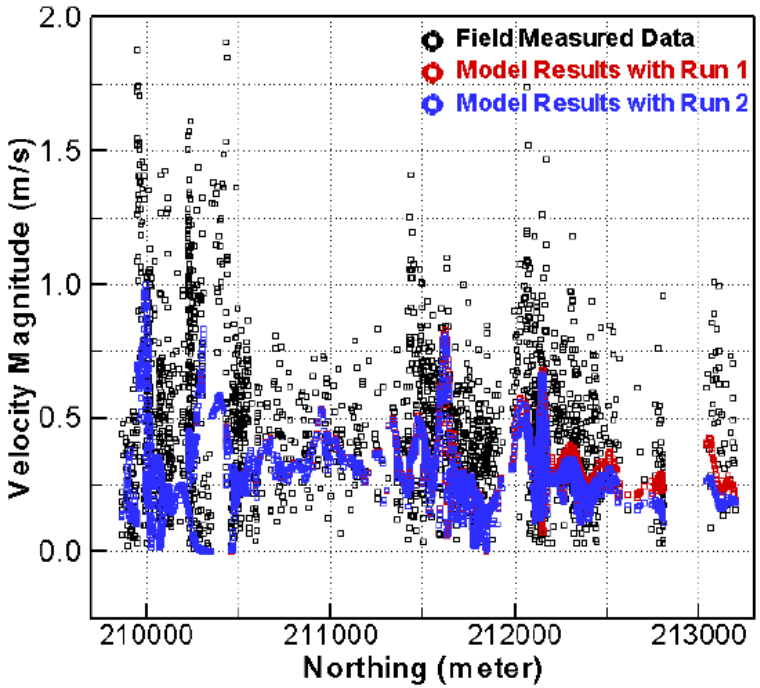


- Sandy River

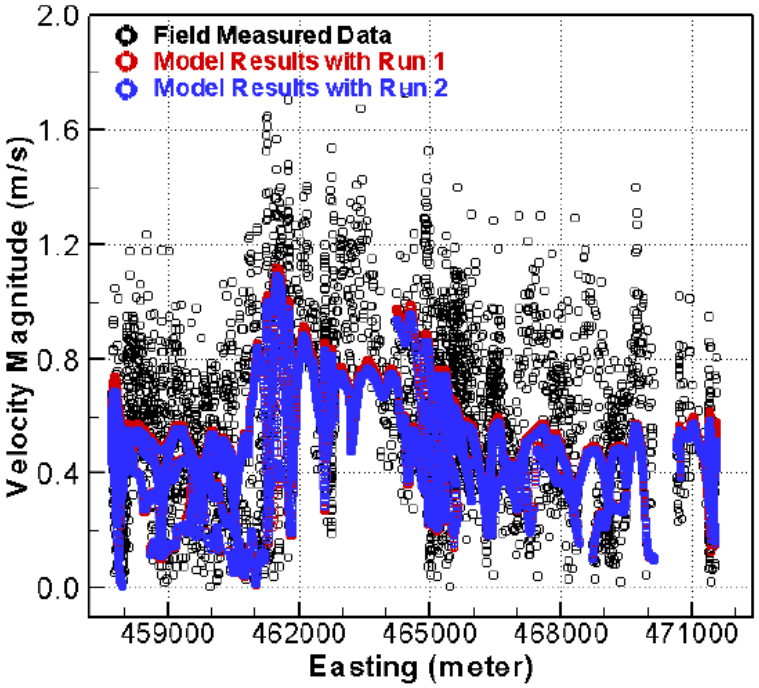


- Columbia River

SRH-2D VERIFICATION CASES



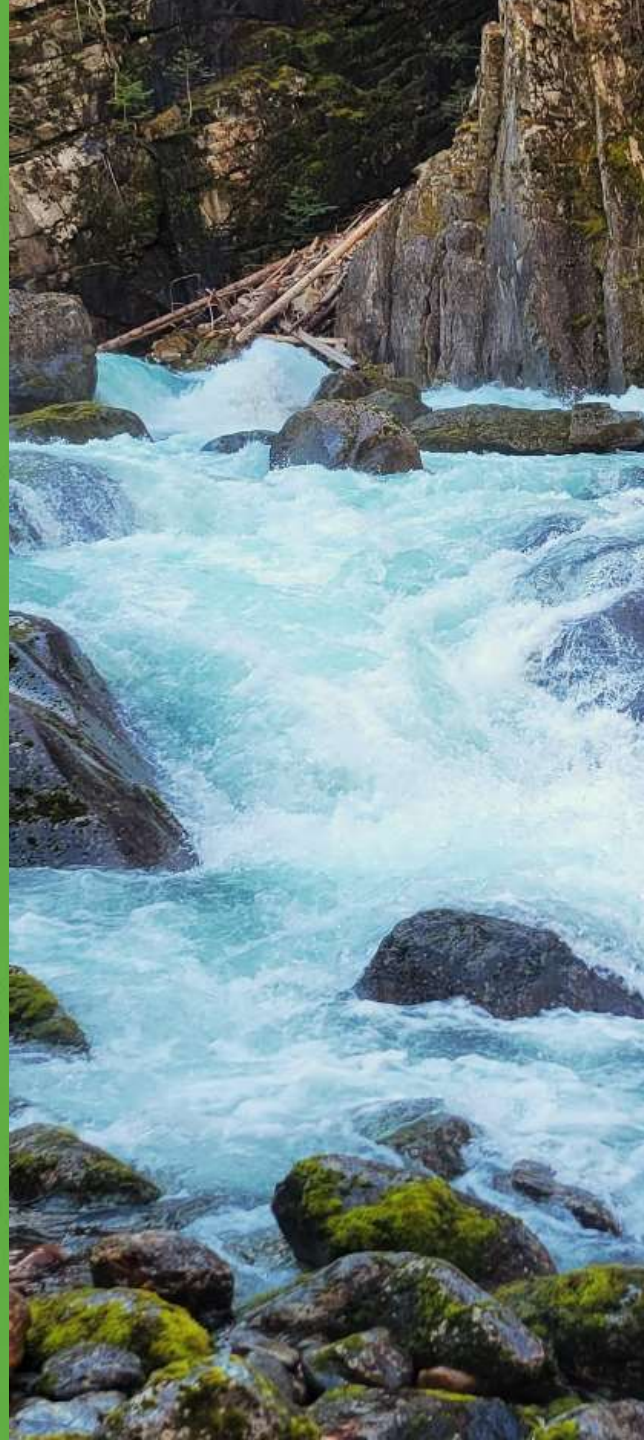
- Sandy River



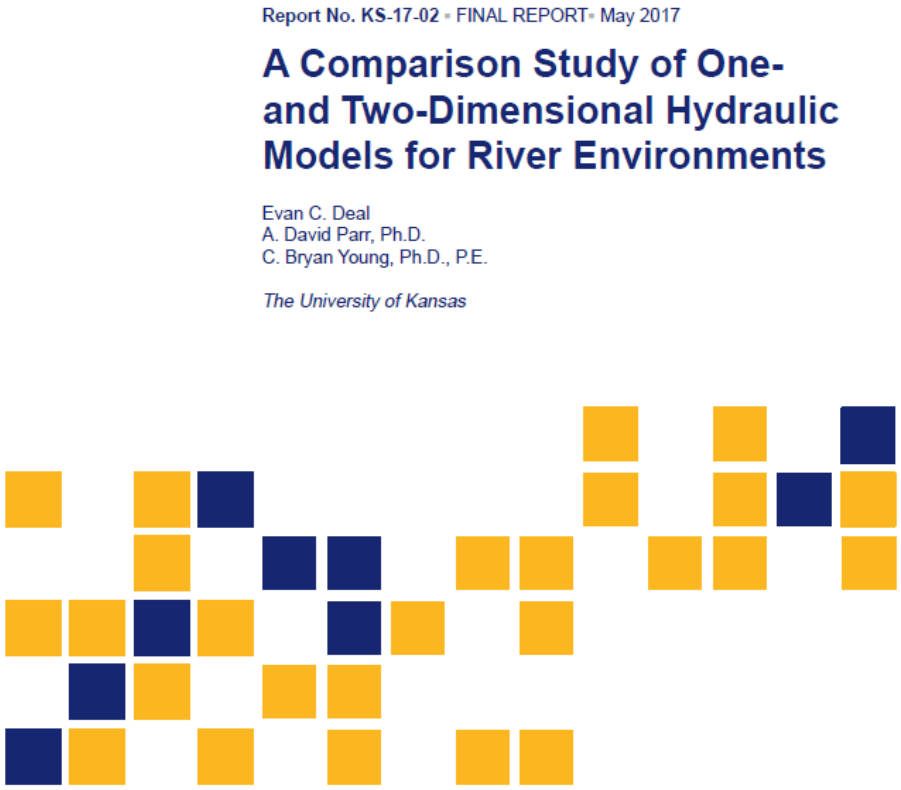
- Columbia River

Seattle City Light

COMPARISON OF HEC-RAS AND SRH-2D



HYDRAULIC MODEL COMPARISON



Report No. KS-17-02 • FINAL REPORT • May 2017

A Comparison Study of One- and Two-Dimensional Hydraulic Models for River Environments

Evan C. Deal
A. David Parr, Ph.D.
C. Bryan Young, Ph.D., P.E.

The University of Kansas

- HEC-RAS 1D
- HEC-RAS 2D
- SRH-2D

Kansas Department of Transportation

MODEL COMPARISON TESTS

1. Basic Flow Around a Bend
2. Turbulence and Roughness Sensitivity Tests
3. Mixed Flow Regime Test
4. Bridge Flume (short model)
5. Bridge Flume (long model)
6. Noedesha Floodplain Study
7. Sumner County Study
8. Butler County Study

MODEL COMPARISON CONCLUSIONS

1. 1D models are still useful
2. 2D models require judgement and sensitivity
3. 2D models can aid setup of 1D models
4. 2D model response to roughness change concerning
5. Difference 2D vs 1D model results at bridge openings
6. WSEL computed with RAS2D typically > SRH-2D
7. Useful application of 1D/2D models

MODEL COMPARISON POINTS

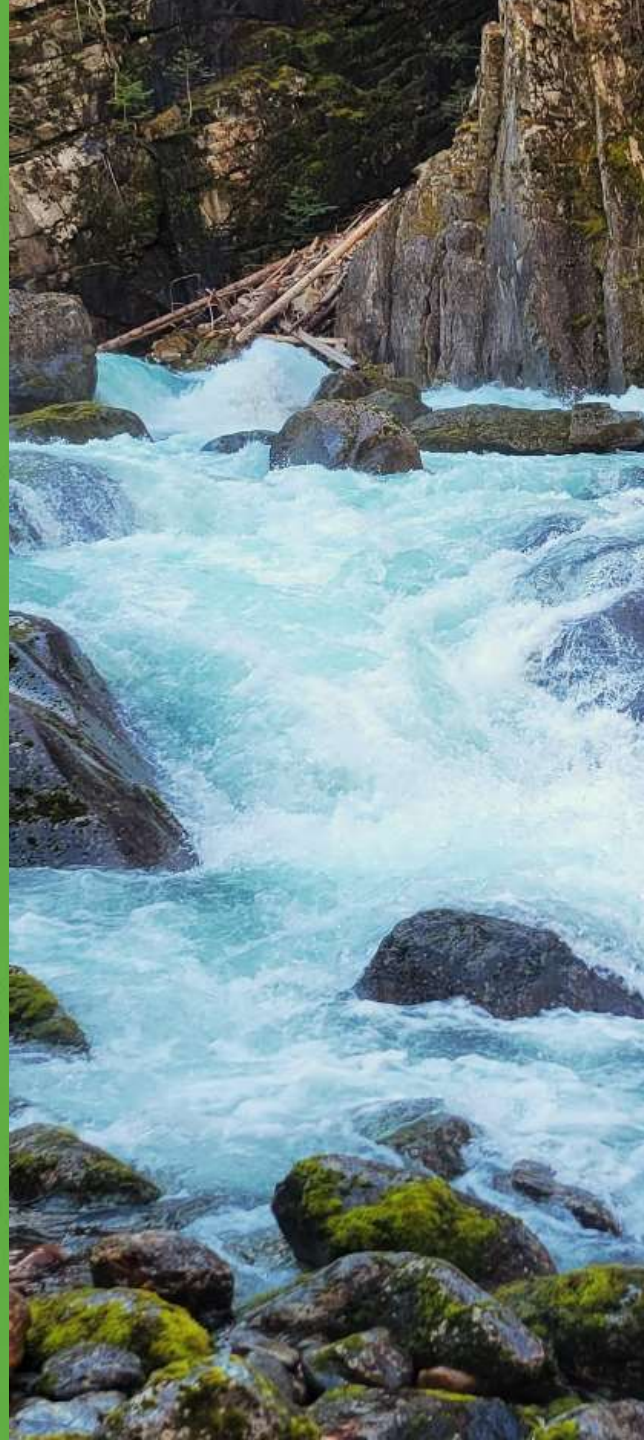
1. Runtime: RAS2D faster than SRH-2D
2. Pre/Post-Processing: RAS2D built in, SRH-2D requires 3rd party, RAS2D more readily interfaces with GIS
3. Setup: Similar
4. Accuracy: Comparisons made; both models strong
5. Flexibility: Comparisons made; each has strengths
6. Support: Similar; both models federally funded
7. Manning's n: Research needed for values in 2D models

MODEL COMPARISON POINTS

8. Channel vs Overbank: Both have options
9. Cell size: Requires user experience; rules of thumb
10. Modeling piers: Both have options
11. Timestep: Requires user experience, sensitivity testing
12. Breaklines: Both have options
13. Hydrology: Useful application of 1D models
14. Bridge overtopping: 1D models recommended

Seattle City Light

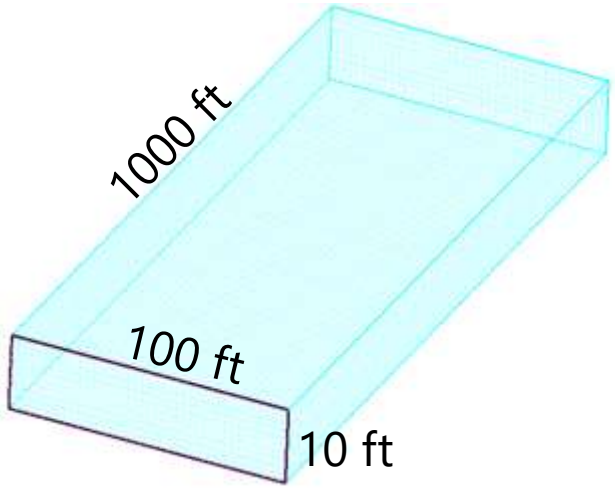
USE OF 3D CFD MODEL PLATFORMS FOR FEATURE ASSESSMENT



USE OF 3D CFD MODELS

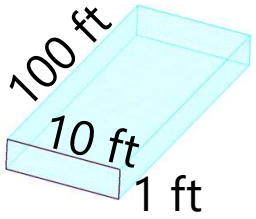
- 3D CFD model good for detailed simulations in small reach (“near field”), but not for long reaches
- Practical size of 3D modeling reach becomes smaller when flows and water depth reduce
- For small flows, 3D model may cover a short reach with a few pools
- For long reaches (“far field”), 2D models are more practical used

USE OF 3D CFD MODELS



High flow, H = 10 ft.

- Cell size = 1 ft.
- L = 1000 ft
- W = 100 ft
- Number of cells = 1 million



Low flow, H = 1 ft.

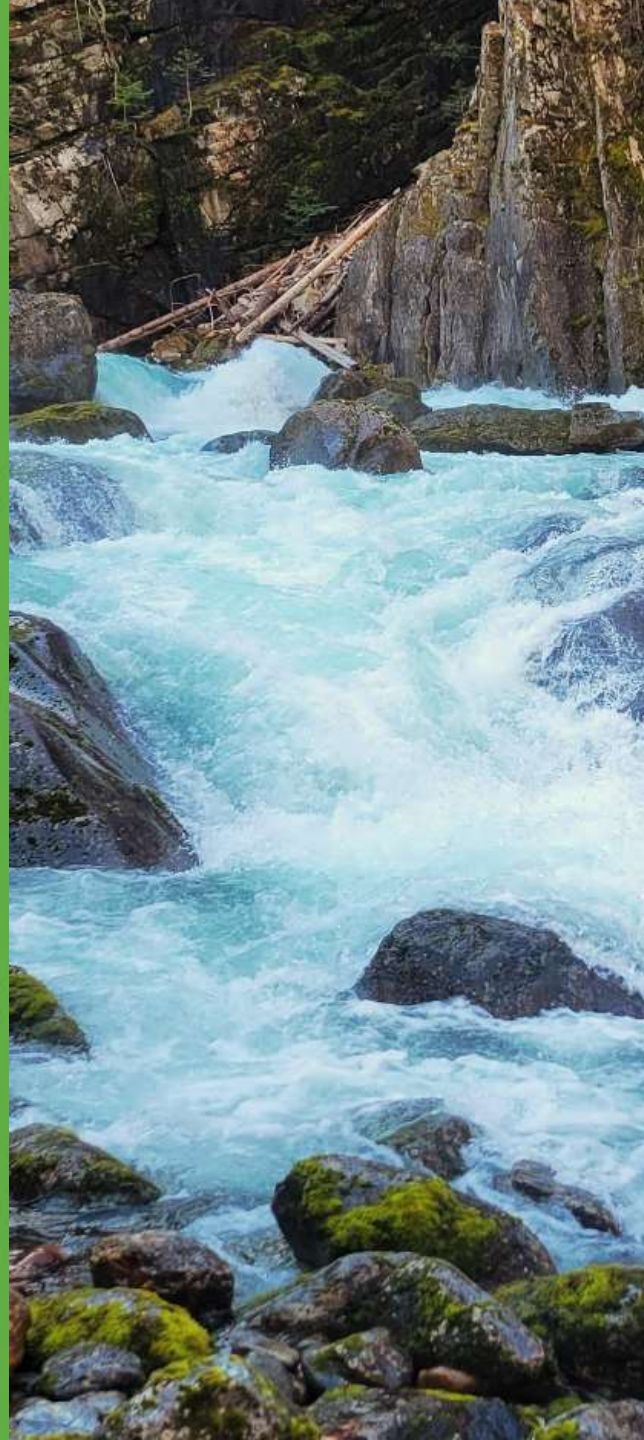
- Cell size = 0.1 ft.
- L = 100 ft
- W = 10 ft
- Number of cells = 1 million

USE OF 3D CFD MODELS

- 3D CFD model good for detailed simulations in small reach (“near field”), but not for long reaches
- Practical size of 3D modeling reach becomes smaller when flows and water depth reduce
- For small flows, 3D model may cover a short reach with a few pools
- For long reaches (“far field”), 2D models are more practical used

Seattle City Light

BREAK



DISCUSSION

- Concurrence on the proposed study plan

CLOSING

- Schedule
- Action items
- Next steps

Skagit River Hydroelectric Project
Seattle City Light (City Light)
Fish Passage Evaluations and Modeling in the Bypass Reach – Technical Meeting
May 17, 2021, 1:00 PM to 5:00 PM

DRAFT Meeting Summary

Disclaimer: These notes are provided to serve as high-level summary of the meeting and as a communication tool for the benefit of committee continuity. They are not intended as a formal record of the meeting.

Attendance

Licensing Participants (LPs):
Brock Applegate, Washington Department of Fish and Wildlife (WDFW)
Stuart Beck, Swinomish Indian Tribal Community (Swinomish)
Curtis Clements, Upper Skagit Indian Tribe (USIT)
Jeff Garnett, US Fish and Wildlife Service (USFWS)
Kiza Gates, WDFW
Rick Hartson, USIT
Jonathan Kohr, WDFW
Mike Larrabee, NPS
Kyle Taylor Lucas, Cooks Ferry Indian Band and Tulalip Tribes
Logan Negherbon, NMFS
Jim Pacheco, Washington Department of Ecology (Ecology)
Dudley Reiser, Swinomish Tribe
Kara Symonds, Skagit County
Larry Wasserman, Swinomish Tribe
Erik Young, Skagit Fisheries Enhancement Group (SFEG)

Seattle City Light (City Light):
Michael Aronowitz, City Light
Jeff Fisher, City Light
Erin Lowery, City Light

Federal Energy Regulatory Commission (FERC):
Matt Cutlip, FERC

Consultant Team:
Michael Garello, Consultant Team
Meghan Gavin, Cascadia Law
Danielle Hanson, Consultant Team
Becky Holloway, Consultant Team
Bao Le, Consultant Team
Malcolm Leytham, Consultant Team
Chris Long, Consultant Team
Angie Scangas, Consultant Team
Jose "Pepe" Vasquez, Consultant Team

Facilitation Team:
Joy Juelson, Facilitation Team
Alex Sweetser, Facilitation Team

Meeting Materials

Available upon request

- Meeting Agenda
- Meeting PowerPoint Slides: Fish Passage Evaluations and Modeling in the Bypass Reach

Action Items

Action	Responsibility	Deadline
LP Action Items		
There was general concurrence from LPs on the selection of the HEC-RAS 2D model to meet both the instream flow/habitat objectives and the evaluation of passage at natural feature objectives of the FA-05 Study Plan. Ecology and WDFW will brief their federal partners to seek concurrence on this decision and notify City Light.	Ecology and WDFW	End of this week
There was general concurrence from LPs to add an additional planned flow release of approximately 250 cfs to the already proposed flow releases of 50, 500, and 1,200 cfs, as well as to maintain the numbers of bypass reach transects (5) to support development of the hydraulic model. Ecology and WDFW will brief their federal partners to seek concurrence on this decision and notify City Light.	Ecology and WDFW	End of this week
City Light Action Items		
Follow up with the photogrammetrist to determine if as part of LiDAR reclassification to a high-resolution raster surface, determine if development of a Triangular Irregular Network (TIN) would provide better interpolation between points thus resulting in a surface with greater resolution and accuracy for modeling purposes.	City Light	As soon as possible
Convey to City Light management FERC's request that any material changes to the study be filed with FERC as soon as possible.	City Light	As soon as possible
Facilitation Team Action Items		
Prepare draft meeting summary and send to LPs for review.	Triangle Associates	Next Week

Summary of Issues Discussed, Action Items, and Decisions

Welcome, Introductions, Agenda Overview

The Facilitator, Joy Juelson, welcomed participants. She led a roll call and explained that the agenda and meeting purpose had been set in coordination with Ecology and City Light. Joy explained that this is the third meeting in a series of technical meetings scheduled to inform time sensitive data collection this summer. The purpose of the first meeting on April 28th was to share information on the instream flow models and the purpose of the second meeting on May 12th was to discuss habitat suitability criteria (HSC) curves and the periodicity table. Additionally, HDR and Triangle Associates will be reaching out soon to schedule future technical workshops and planning meetings.

Joy noted the intent of the meeting summaries is to serve as a high-level review of what was discussed, track issues and discussion topics across meetings, and identify areas of agreement. They are not technical documents (though the meetings are technical in nature) or verbatim records of what was said.

The objectives for this meeting were to:

- Review fish passage evaluation study objectives and discuss fish passage evaluation methods.
- Discuss the role of hydraulic modeling in fish passage evaluations methodology and provide examples of how hydraulic models have been used at other projects.
- Address concerns regarding the use HEC-RAS 2D as a fish passage evaluation tool.

- Discuss and reach concurrence with LPs on study design to identify areas of agreement, areas that need to be updated, and areas for future conversations.

Evaluation of Fish Passage in the Bypass Reach

Mike Garello, Consultant Team, presented the Fish Passage Evaluations and Modeling in the Bypass Reach meeting slides (see meeting slides for details). He noted the intent of this meeting was to have a discussion on the approach for these studies and how modeling will be accomplished.

Mike Garello explained the purpose of this evaluation is to gain a more detailed understanding of feature geometry in the bypass, characterize hydraulic pathways that could potentially provide fish passage, better understand conditions that promote or impede fish passage, and to inform concurrent studies.

- In response to a question about use of different HEC-RAS 2D model domains and resolution, one for habitat and one for fish passage, Mike clarified they will use the same model for each.
- Jim Pacheco, Ecology, noted there is not a lot of fish habitat in the high elevation reach and a higher mesh size could be used. Chris discussed how there did not appear to be a significant change when reducing model resolution to differentiate fish passage and habitat, so the same resolution will be used on all hydraulic features.
- In response to a question about how visual fish observations will be incorporated, Mike noted visual observations will be incorporated and additional research is needed on flows and their impact on fish passage. By understanding the relationship between flow and fish passage, this study will inform other studies such as the Passage Facility Alternatives Study.
- Rick Hartson, Upper Skagit Tribe, and Kyle Taylor Lucas, Cooks Ferry Indian Band and Tulalip Tribes, expressed concern over the quick timing of the meeting and narrow distribution list. Jim Pacheco explained that he set the schedule of the three instream flow meetings to resolve time-sensitive issues that require resolution prior to approval of the study design. Joy noted decisions at these meetings are technical decisions that resolve study design issues and that policy decisions will be elevated at future meetings.
- In response to a question about this study's ability to identify flows that allow fish passage, Mike explained that this study can provide a range of flows that may allow fish passage but will not provide a definitive answer on the flows required for fish passage.

Observable Discharges

Malcolm Leytham, Consultant Team, provided an overview of observable discharges and the proposed data collection program. The data will be used for calibration of the hydraulic model and inform visual assessment of fish passage. There are two components to data collection: 1) controlled releases; and 2) water level loggers to assess discharge and opportunistic spills over a longer timeframe. Malcolm reviewed several transect maps to demonstrate the uncalibrated RAS model (see meeting slides for graphics).

- Malcom noted that water level recorders and time lapse cameras will likely be installed in the coming weeks and stay through November. The goal is for them to capture higher flows during the late spring/early summer snowmelt season and fall and early winter. Mike explained that there will be two cameras in a fixed position taking photos on a regular timeframe. The cameras will be useful for visualizing controlled releases and providing photo documentation of flows at flow meters. Additionally, the cameras will be used for monitoring opportunistic spills, which they intend to include in the analysis.

- In response to a question about when controlled releases are being proposed, Malcolm noted release times are not fixed, but they are aiming for between the last week of June and the third week in July.
- In response to a question about whether baseflow measurements are being used for calibration and verification or for historical purposes, Malcolm clarified baseflows are not useful for calibration and are being used to document conditions.

Fish Passage Evaluation Methods and Tools

Michael Garello provided an overview of the fish passage evaluations methods and tools. He discussed biological and ecohydraulic metrics that could be used to calculate swimming fatigue curves around hydraulic features (see meeting slides for details).

Site Inspection, Surveying, and Visual Observation

Chris Long, Consultant Team, provided an overview of site inspection and visual observation methods. LiDAR will be used to provide the topography that will form the basis of the model. The data collection methods used will be supported by site inspection and photo or video documentation. Several examples of outputs were presented (see meeting slides for graphics).

Mike Garello noted that for site inspection and visual observation the minimum range of flows is 5 cfs to 1200 cfs. However, there are anticipated opportunities to collect data up to 5,000 cfs.

Collection of Flow Magnitude, Depth, Elevation, and Velocity Data

Mike Garello provided an overview of data collection methods for flow magnitude, depth, elevation, and velocity. Depth monitoring locations were identified using site investigation and the initial uncalibrated 2D model. Locations were further refined after observing features at ~1,200 cfs. Several examples from the uncalibrated model were presented to demonstrate depth and flow (see meeting slides for graphics). Velocity measurements are difficult and there are unsafe conditions above 50cfs. Additionally, high levels of turbulence and a multi-directional flow mean conventional data collection methods are likely inadequate. Potential options to get around these challenges include approximation with hydraulic modeling or utilizing an Unmanned Aerial Vehicle (UAV).

Chris Long briefly presented examples of modeling results from other fish passage evaluation projects.

- Stuart Beck, Swinomish, recommended the development of a Triangular Irregular Network (TIN) as part of LiDAR reclassification to a high-resolution raster surface. Chris noted the consulting team can follow-up with a photogrammetrist to determine if developing a TIN would increase surface resolution and accuracy for modeling purposes.
- In response to a question about how biological analysis will support modeling, Mike clarified that there are several methods for biological analysis. He provided an example developed from Katopodis and Gervais (2016), which showed swim distance and speeds for fish based on fish size, time, and water velocity.
- Brock Applegate, WDFW, requested the field team to look for lamprey attachment sites during sampling and installation of meters and loggers.

Action Item: Follow up with the photogrammetrist to determine if as part of LiDAR reclassification to a high-resolution raster surface, development of a Triangular Irregular Network (TIN) would provide better interpolation between points thus resulting in a surface with greater resolution and accuracy for modeling purposes.

Use of Hydraulic Model to Support Fish Passage Interpretations

Mike Garello provided an overview of the use of the hydraulic models to support fish passage interpretations. He explained that modeling will inform data collection methods, development of hydraulic pathways that may provide passage, inform transitions between leaping vs swimming conditions, and will provide a tool to study trends across a range of flows. The models are not intended to be a quantitative tool for dictating fish passage as a pass or a fail. Mike presented several examples of the HEC-RAS 2D model, including output graphics and the model's ability to identify pathways at different flows (see meeting slides for graphics).

Selection and Applicability of Modeling Platforms

Chris Long provided an overview of how HEC-RAS 2D was selected and the applicability of hydraulic models, which are influenced by multiple factors. Several 2D models were assessed based on their strengths and limitations.

Chris Long compared HEC-RAS with SRH-2D and reviewed verification studies of these two models.

- Stuart Beck, Swinomish, noted that one study showed that HEC-RAS 2D was not good at predicting the location of hydraulic jumps and tended to predict jumps too soon compared to SRH-2D.

Use of 3D CFD Model Platforms for Feature Assessment

Jose "Pepe" Vasquez, Consultant Team, provided an overview of the use and application of 3D CFD models. 3D CFD models are good for detailed simulations of small reaches, but not good for long reaches, which is why 2D models were selected to model the longer bypass reach.

- Jim Pacheco noted it is unclear if the passage areas are too large for a 3D model. In response, it was stated that the passage features are too large for 3D modeling but that a 3D model could be used to model flow at the scale of an individual boulder.
- Meeting participants suggested using 3D models in isolated passage spots or for verification of passage at individual features. However, it would be difficult to implement another model at such a small scale and impractical to use different models. Concurrence was not reached on this suggestion.
- In response to a question about how a 2D model could inform management decisions, Jim noted the graphics could show velocity near river features, which will enable managers to better evaluate passage. Mike clarified that biometrics will also be used to inform passage scenarios.

LP Discussion on Study Design

Meeting participants were asked to evaluate their comfort level around the proposed approach for using the HEC-RAS 2D model.

- There was general concurrence from LPs on the selection of the HEC-RAS 2D model to meet both the instream flow/habitat objectives and the evaluation of passage at natural feature objectives of the FA-05 Study Plan.
- In response to a suggestion to develop and utilize 3D models to evaluate specific areas of passage or blockage, there was general agreement that it was not practical to use multiple models and methods in different sections.
- In response to a question about whether both upstream and downstream passage will be evaluated at the plunge pool where a proposed fish passage facility could be built, Mike clarified that the fish passage study would assess the location of the facility, as well as upstream and downstream passage at the plunge pool.

Meeting participants discussed the suite of controlled releases that were proposed at a previous meeting. These proposed flow releases were 50, 300, 500, and 1,200 cfs.

- Malcolm noted that the proposed 300 cfs controlled release appeared to be too high based on the model and proposed setting it to 250 cfs instead. After discussing the proposed change, there was general concurrence from LPs to use 250 cfs as the additional planned flow release (to the already proposed flow releases of 50, 500, and 1,200 cfs) and to maintain the numbers of bypass reach transects (5) to support development of the hydraulic model.
- LPs from Ecology and WDFW noted they will need additional time to consider this change and brief their federal partners to seek concurrence on this decision.

Matt Cutlip, FERC, expressed concerns about these areas of concurrence being resolved before the FERC study plan determination and requested City Light to file any material changes to the study with FERC as soon as possible.

Action Item: There was general concurrence from LPs on the selection of the HEC-RAS 2D model to meet both the instream flow/habitat objectives and the evaluation of passage at natural feature objectives of the FA-05 Study Plan. Ecology and WDFW will brief their federal partners to seek concurrence on this decision and notify City Light.

Action Item: There was general concurrence from LPs to reduce the proposed 300 cfs planned flow to 250 cfs. This would be added to the already proposed flow releases of 50, 500, and 1,200 cfs. Additionally, there was general concurrence from LPs to maintain the numbers of bypass reach transects (5) to support development of the hydraulic model. Ecology and WDFW will brief their federal partners to seek concurrence on this decision and notify City Light.

Action Item: Convey to City Light management FERC's request that any material changes to the study be filed with the FERC as soon as possible.

Review Action Items and Next Steps

The facilitator reviewed the action items and areas of concurrence from the meeting.

Action Item: *Triangle will prepare a draft meeting summary and send to LPs for review.*

The meeting was adjourned at 5:05 p.m.

SKAGIT RIVER GORGE BYPASS REACH HYDRAULIC AND INSTREAM FLOW MODEL DEVELOPMENT STUDY REPORT

ATTACHMENT H

FA-05 WORKSHOP 3 MATERIALS

Seattle City Light

DRAFT MEETING AGENDA

Skagit Hydroelectric Project Relicensing Meeting

FA-05 Gorge Bypass Reach Hydraulic and Instream Flow Model Development, Workshop #3

August 26, 2021, 8:30 am – 1:30 pm

WEBEX

Webex Meeting Link: https://triangleassociates.my.webex.com/meet/jjuelson

Call in Information: +1-510-338-9438,,629101299## USA Toll

MEETING PURPOSE

- Review Controlled and Uncontrolled Spill Data Collection
- Review Model Terrain Development
- Provide Overview of Hydraulic Model Development Approach

FACILITATOR

Thomas Christian, Triangle Associates

AGENDA

8:30 – 8:45 (15 minutes)	**Introduction** – *Facilitator, Triangle* ▪ Roll Call Introduction ▪ Background and Context ▪ Review Action Items from Previous Meeting
8:45 – 9:00 (15 minutes)	**Study Overview** – *Erin Lowery, City Light and Chris Long, NHC* ▪ Background ▪ Review Meeting Objectives and Agenda
9:00 – 10:00 (60 minutes)	**Controlled Spill Monitoring: Transect Data** – *Donnie Jones, NHC* ▪ Observed Flows ▪ Depth and Velocity Measurements Questions and Discussion (30 minutes)
10:00 – 10:15 (15 minutes)	**Break**
10:15 – 11:00 (45 minutes)	**Controlled Spill Monitoring: UAV Data** – *Chris Long, NHC* ▪ Observed Surface Velocities at Hydraulic Features ▪ Orthoimagery Questions and Discussion (15 minutes)
11:00 – 11:30 (30 minutes)	**Level Logger Data** – *Malcolm Leytham, NHC* ▪ Data Collected ▪ Discuss use of level logger data for model development Questions and Discussion (15 minutes)
11:30 – 11:45 (15 minutes)	**Break**

11:45 –12:15 (30 minutes)	**Terrain** – *Donnie Jones, NHC* ▪ Terrain Development ▪ Model Implementation Questions and Discussion (15 minutes)
12:15 – 1:15 (60 minutes)	**Hydraulic Model Development Approach** – *Donnie Jones, NHC* ▪ Roughness ▪ Mesh ▪ Calibration and Validation Questions and Discussion (30 minutes)
1:15 – 1:30 (15 minutes)	**Action Item Review and Agenda Items for Next Meeting –** *Triangle and NHC*
1:30	**Meeting Adjourned**

Action Items From FA-05 Bypass Reach Workshop (5/17)

Action Items

Action	Responsibility	Timeframe
LP Action Items		
There was general concurrence from LPs on the selection of the HEC-RAS 2D model to meet both the instream flow/habitat and evaluation of passage at natural feature objectives of the FA-05 Study Plan. Ecology and WDFW will brief their federal partners to seek concurrence on this decision and notify City Light.	Ecology and WDFW	Complete
There was general concurrence from LPs to add an additional planned flow release of approximately 250 cfs (to the already proposed flow releases of 50, 500, and 1,200 cfs) and to maintain the numbers of bypass reach transects (5) to support development of the hydraulic model. Ecology and WDFW will brief their federal partners to seek concurrence on this decision and notify City Light.	Ecology and WDFW	Complete
City Light Action Items		
Follow up with the photogrammetrist to determine if as part of LiDAR reclassification to a high-resolution raster surface, determine if development of a Triangular Irregular Network (TIN) would provide better interpolation between points thus resulting in a surface with greater resolution and accuracy for modeling purposes.	City Light	Complete
Convey to City Light management FERC's request that any material changes to the study be filed with the Commission as soon as possible.	City Light	Complete
Facilitation Team Action Items		
Prepare draft meeting summary and send to LPs for review.	Triangle	Complete



SKAGIT RIVER GORGE BYPASS REACH HYDRAULIC AND INSTREAM FLOW MODEL DEVELOPMENT – WORKSHOP 3

August 26, 2021

STUDY STATUS UPDATE

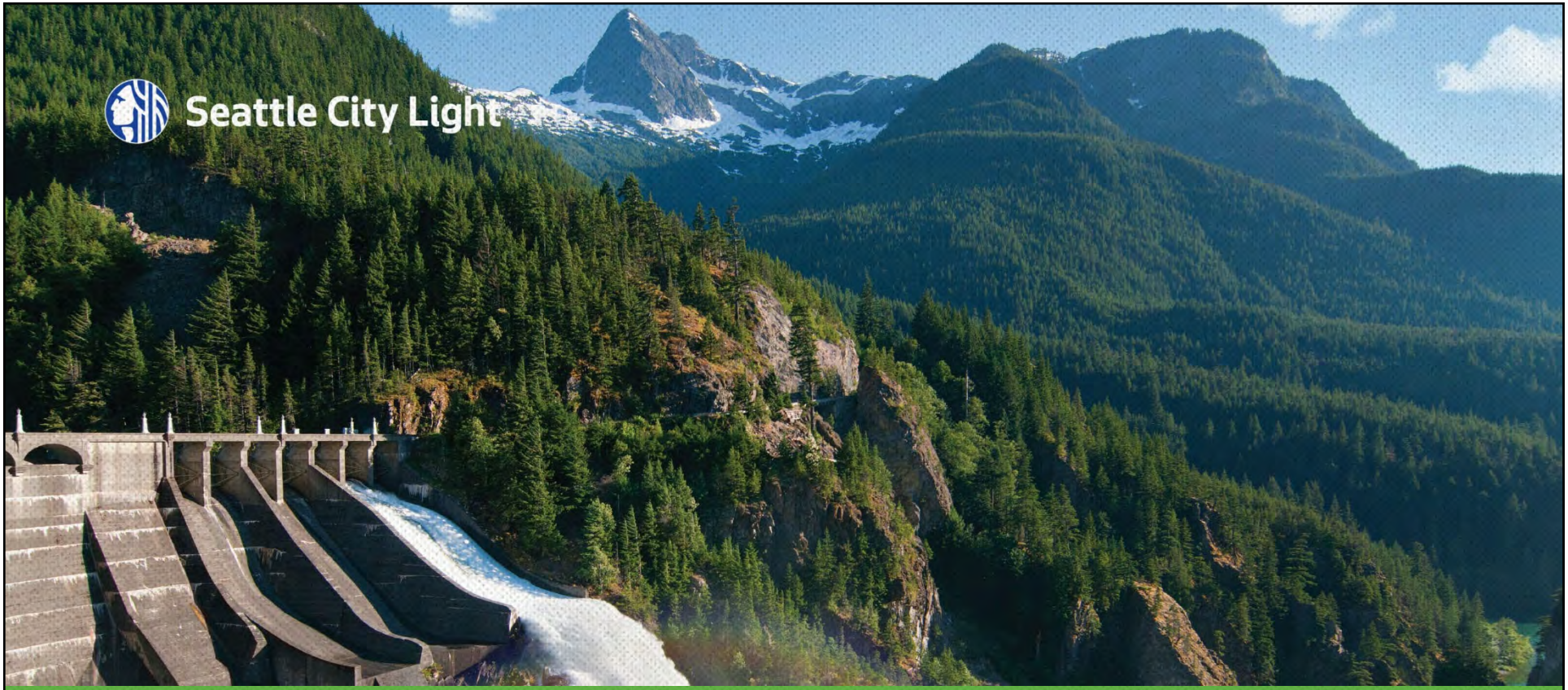
- FA-02 study currently more advanced than FA-05
  - FA-02 started field data collection August 2020
- FA-05 model will develop more quickly than FA-02
  - More limited in size
  - Less calibration data
- Just finished intense week of field data collection
- Presentation focus
- Limited update on hydraulic modeling

STUDY ROAD MAP/SCHEDULE

	May	June	July	August	September	October	November	December	January	February		
Field Data Collection											Initial study report March 2022	Alternative scenario identification and evaluation: February - September 2022
Hydrometric data collection for model calibration												
Substrate and cover data collection												
Hydraulic Model Development												
Modify terrain data												
Hydraulic model construction												
Hydraulic model calibration/validation												
Biological and Habitat Information												
Review, field validation and selection of HSCs												
Integration with hydraulic data												
Workshops (HSC focused workshops not shown)	↑			↑			↑			↑		

WORKSHOPS

Workshop	Date	Topics
~~1A~~	~~May 2021~~	~~Overview development of hydraulic and instream flow model for the Gorge Bypass Reach~~
~~2~~	~~July 2021~~	~~Updates to biological and habitat metrics based on discussions and input from FA-02 Workshop 1~~
3	August 2021	Field monitoring debrief and hydraulic model development kickoff
4	November 2021	Hydraulic model calibration ongoing
5	February 2022	Final hydraulic model calibration results and discussion of future model application



CONTROLLED SPILL MONITORING TRANSECT DATA

August 26, 2021

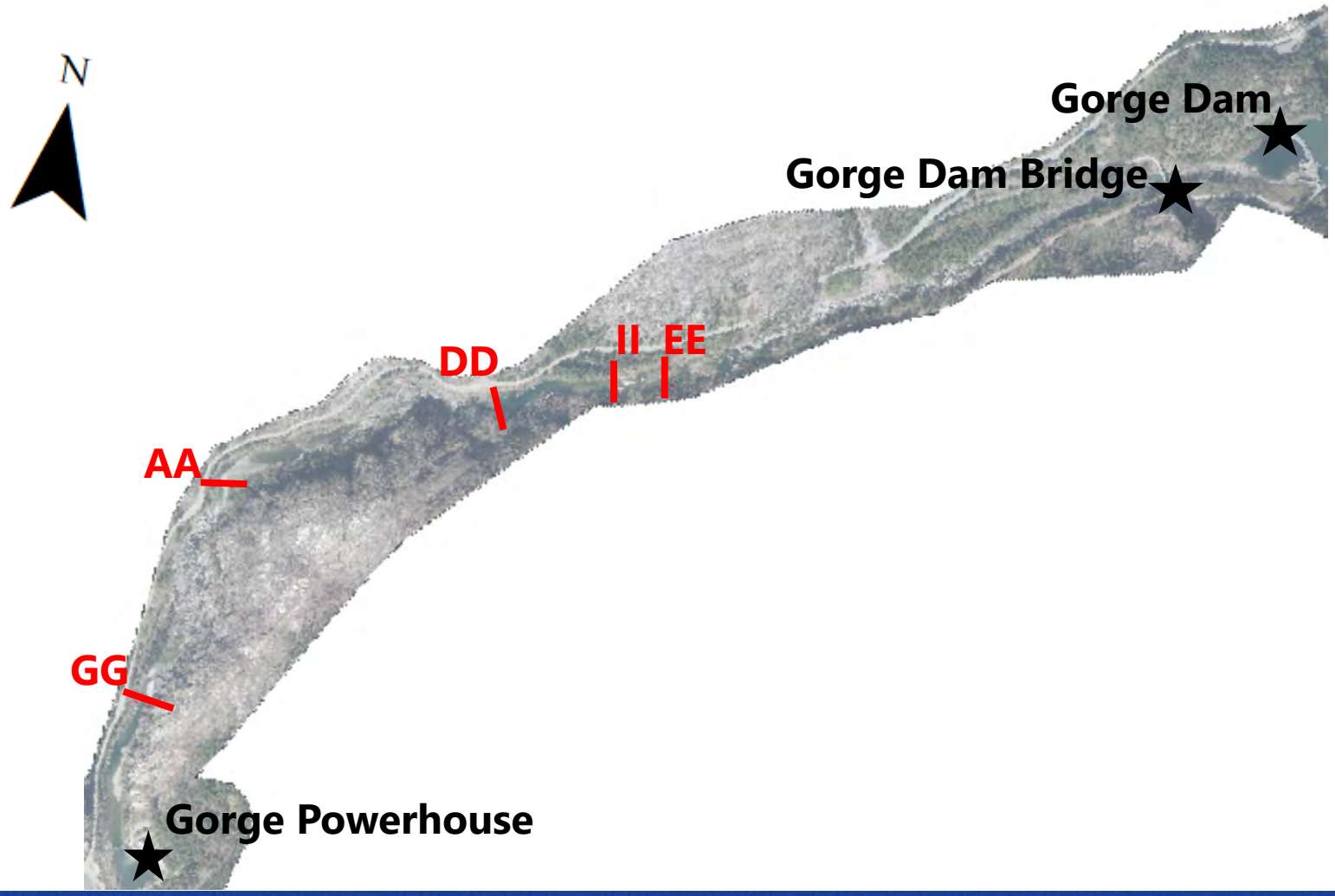
OVERVIEW

- Purpose
- Transect Locations
- Instruments
  - ADCP
  - ADV
  - Deployment
- Measurements
  - Methodology
  - Observed Flows
  - Observed Depths and Velocities

PURPOSE

- Determine controlled spill flows
  - Expected releases of 1200, 500, 250, and 50 cfs
- Collect velocity and depth data for model calibration

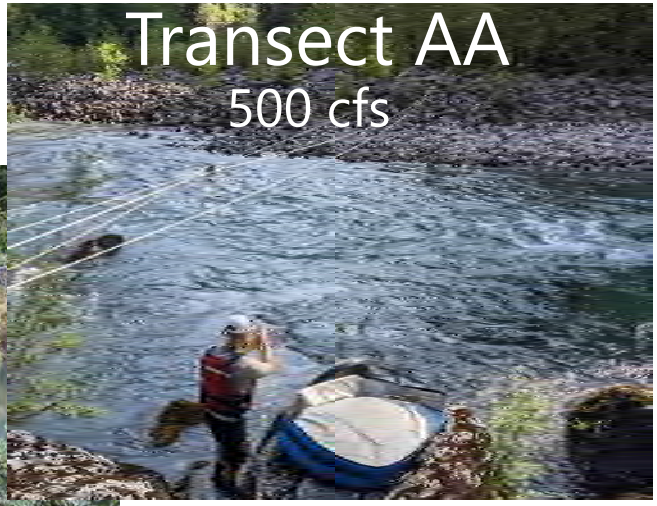
TRANSECT LOCATIONS



TRANSECT LOCATIONS





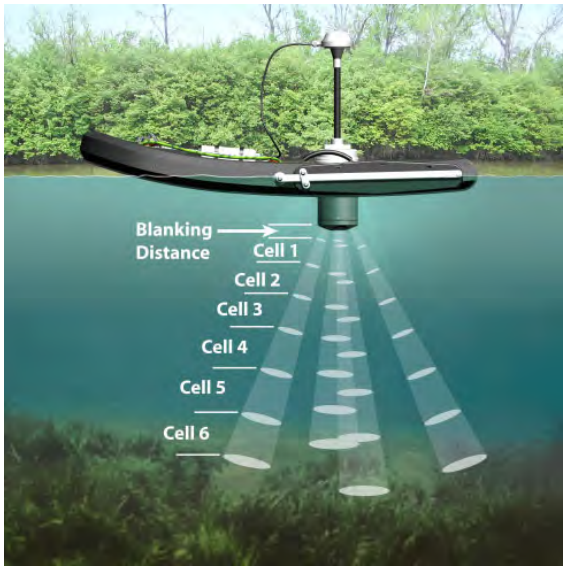


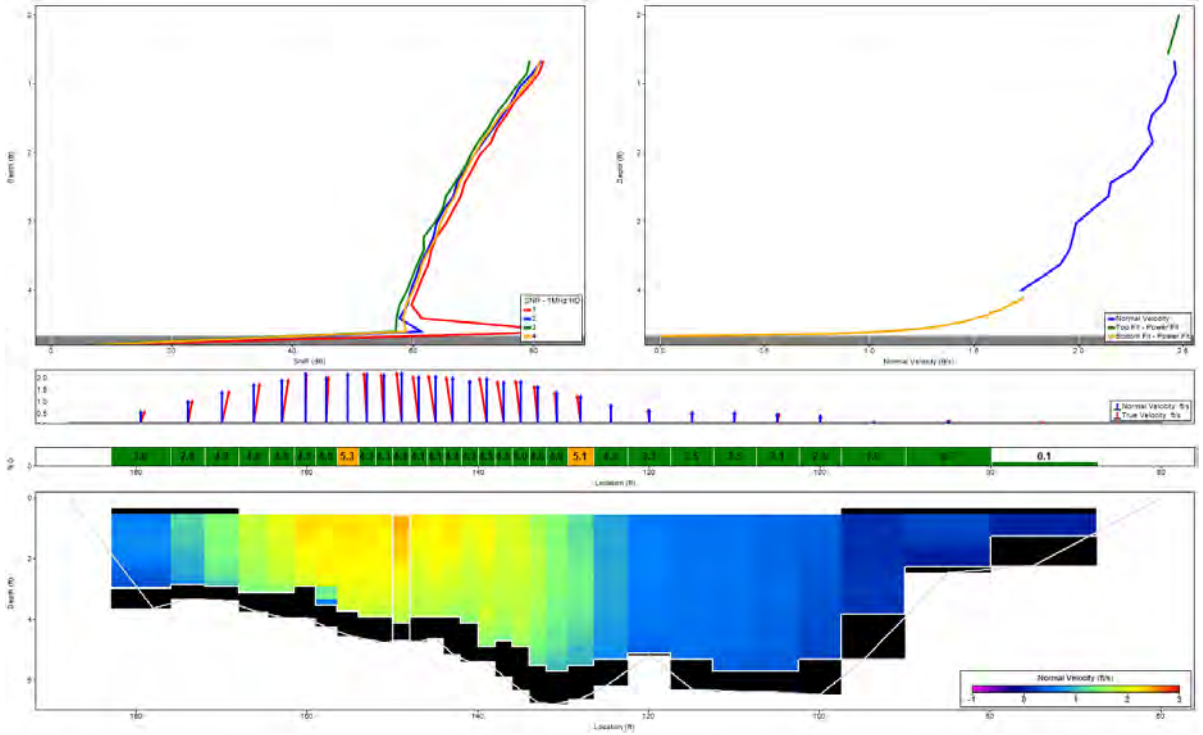




INSTRUMENTATION - ADCP

- ADCP (Acoustic Doppler Current Profiler) – Sontek RiverSurveyor M9
  - Velocity and depth profiling
  - Depths >1ft



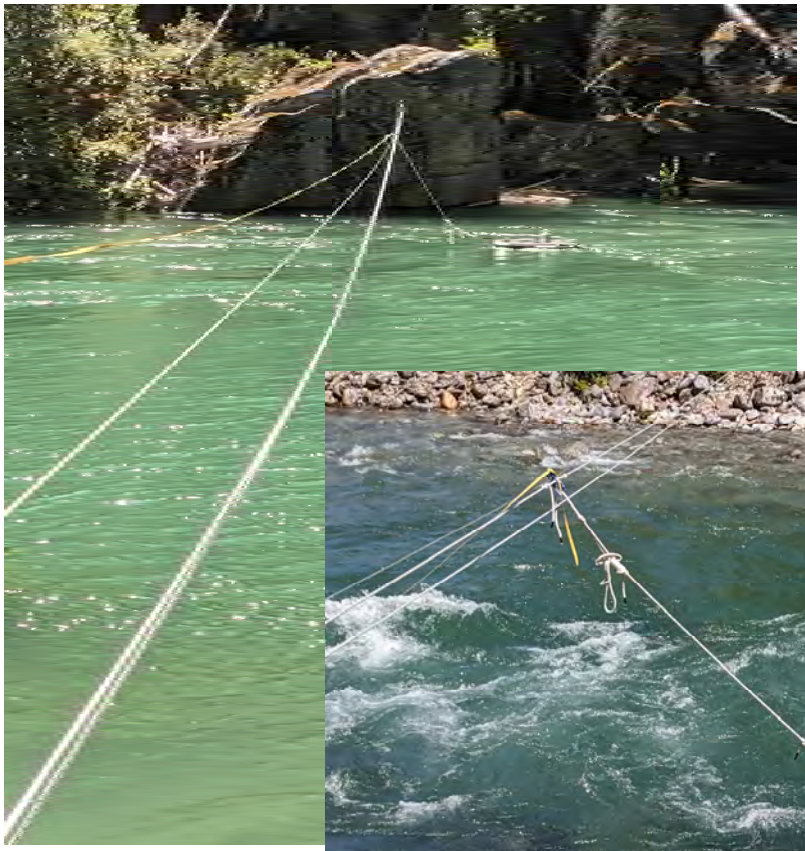


INSTRUMENTATION - ADV

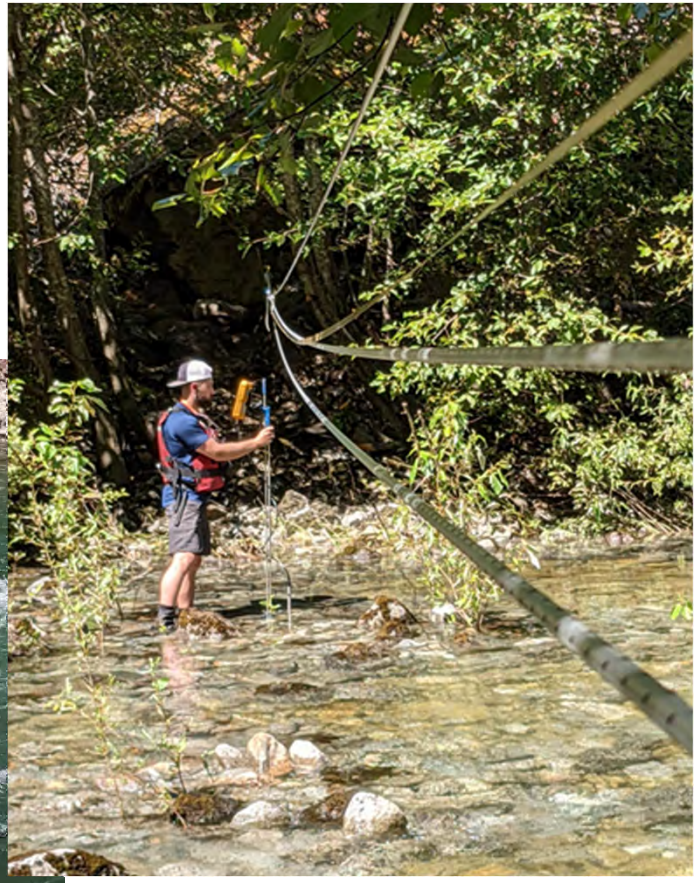
- ADV (Acoustic Doppler Velocimeter) – Sontek FlowTrackerII
  - Point velocities
  - Depth with rod
  - Shallow depths



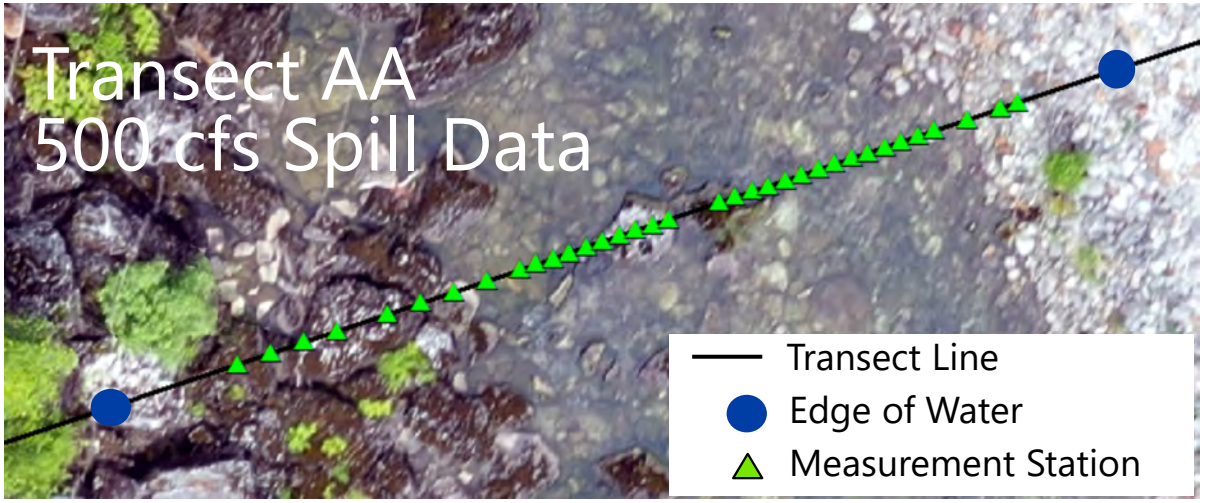
INSTRUMENTATION - DEPLOYMENT

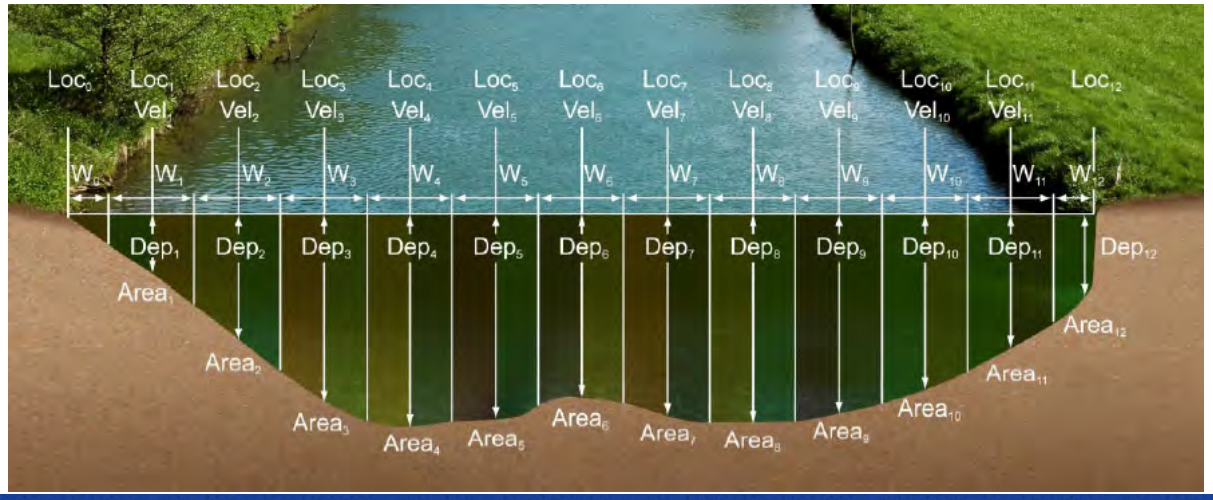




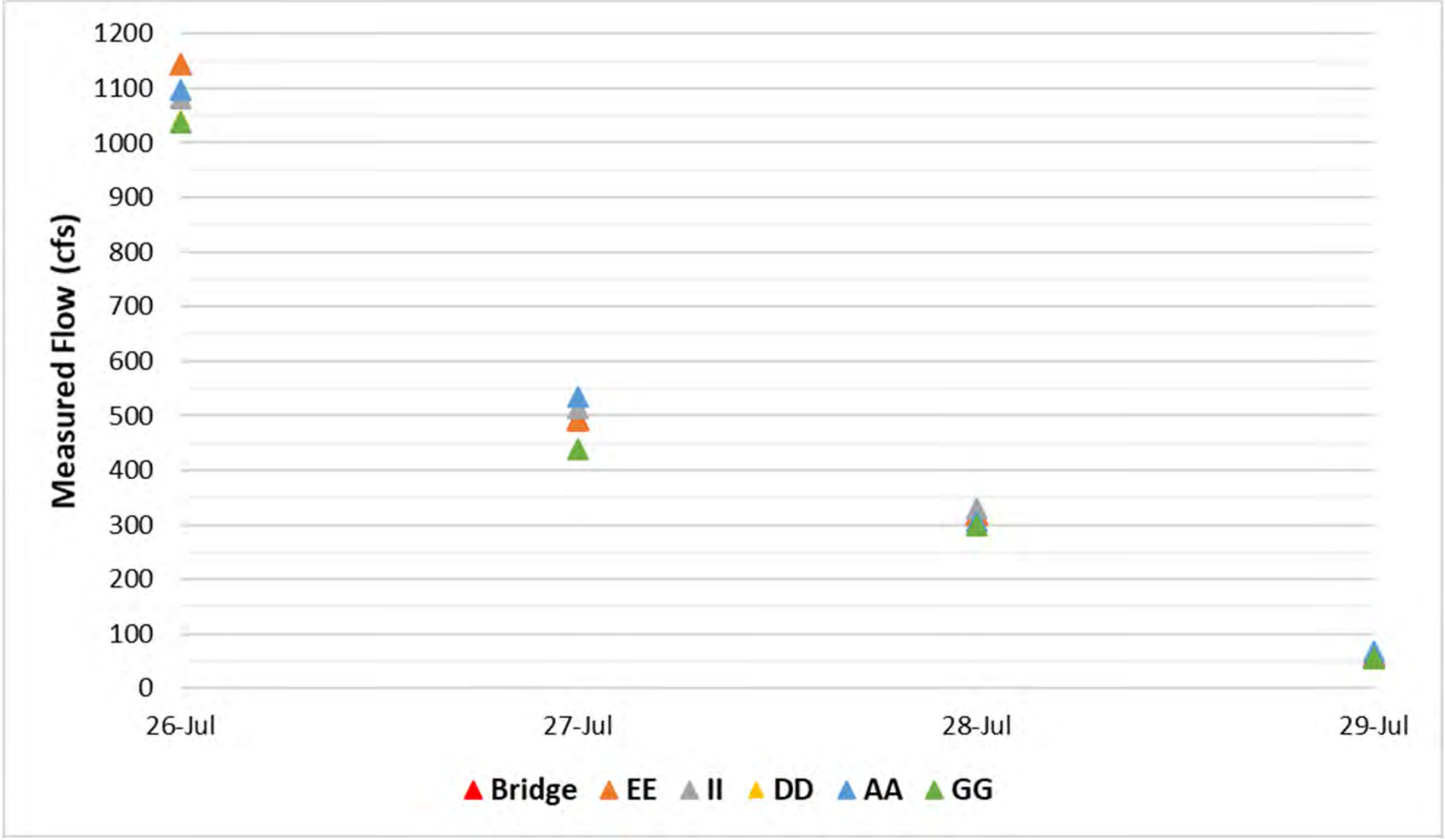


MEASUREMENTS - METHODOLOGY



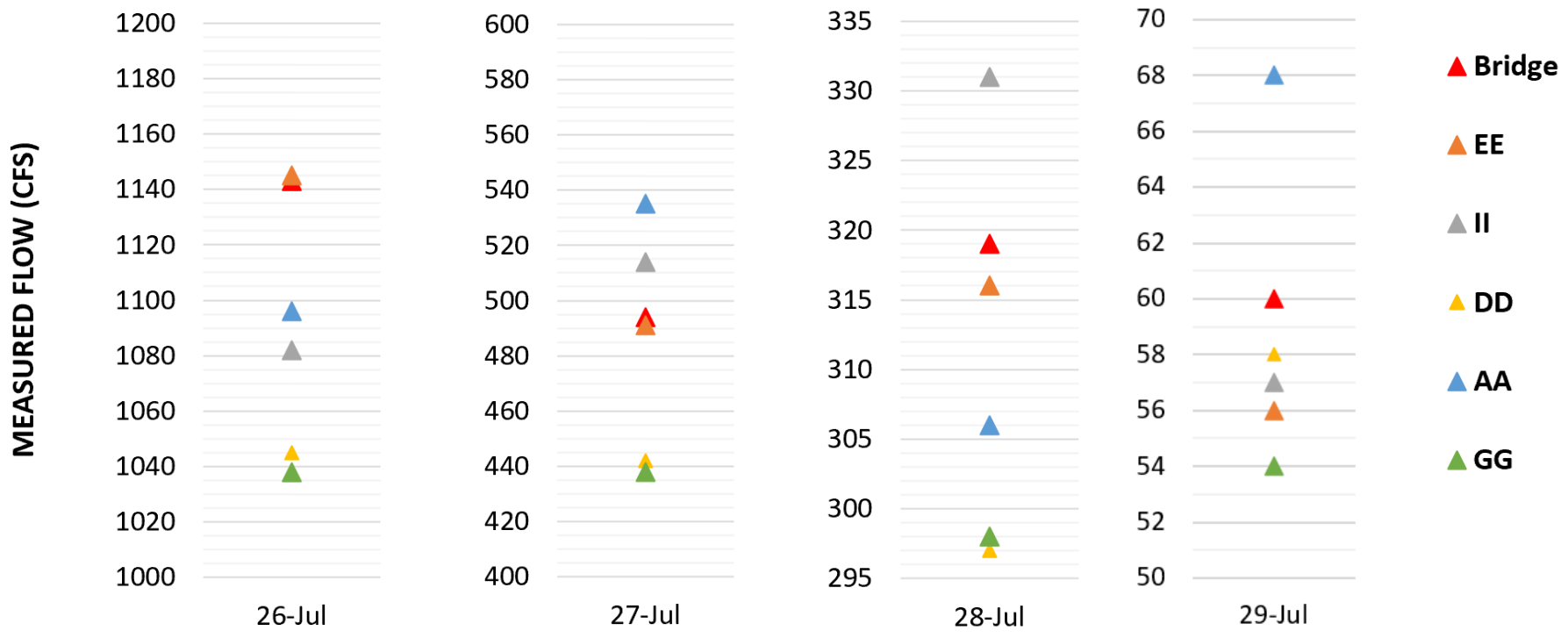


MEASUREMENTS - OBSERVED FLOWS



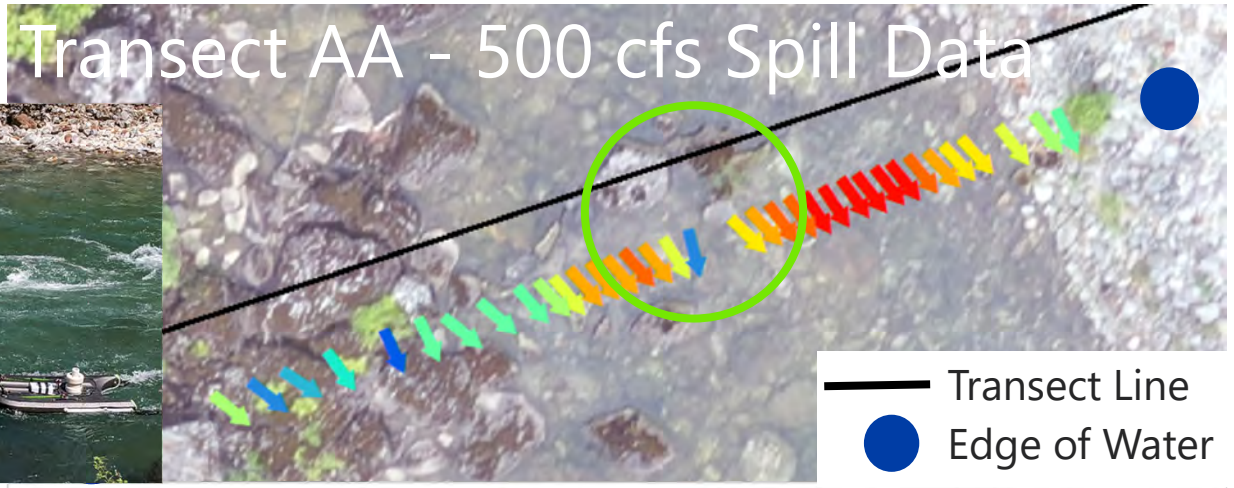
MEASUREMENTS - OBSERVED FLOWS

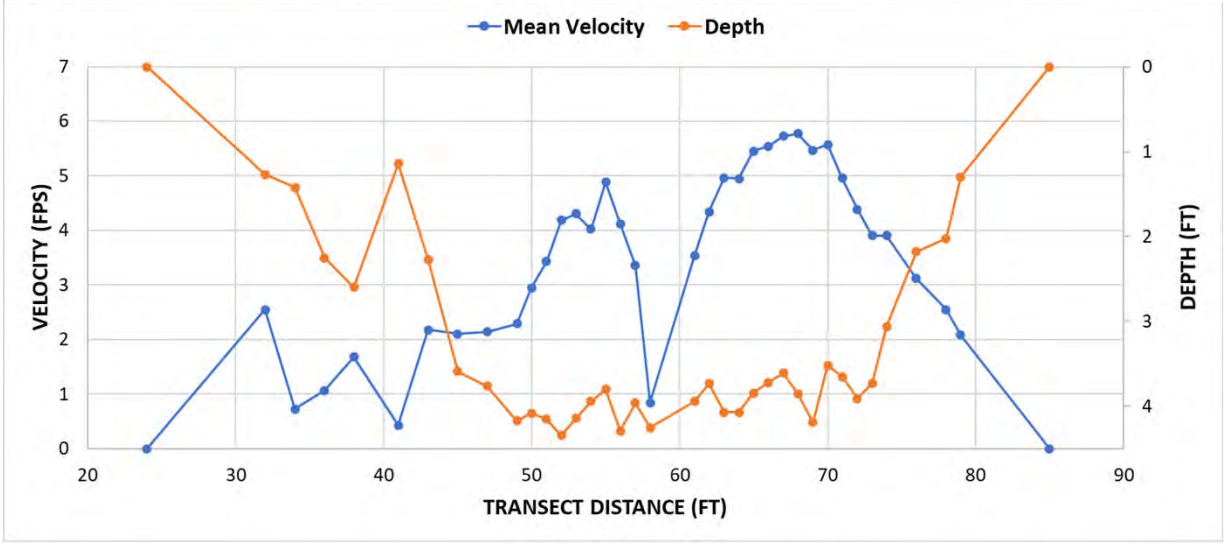
TARGET RELEASE (CFS)	1200	500	250	50
SCL REPORTED RELEASE (CFS)	1095-1097	435-445	246-258	Log Chute (~50 cfs)



MEASUREMENTS – DEPTHS AND VELOCITIES





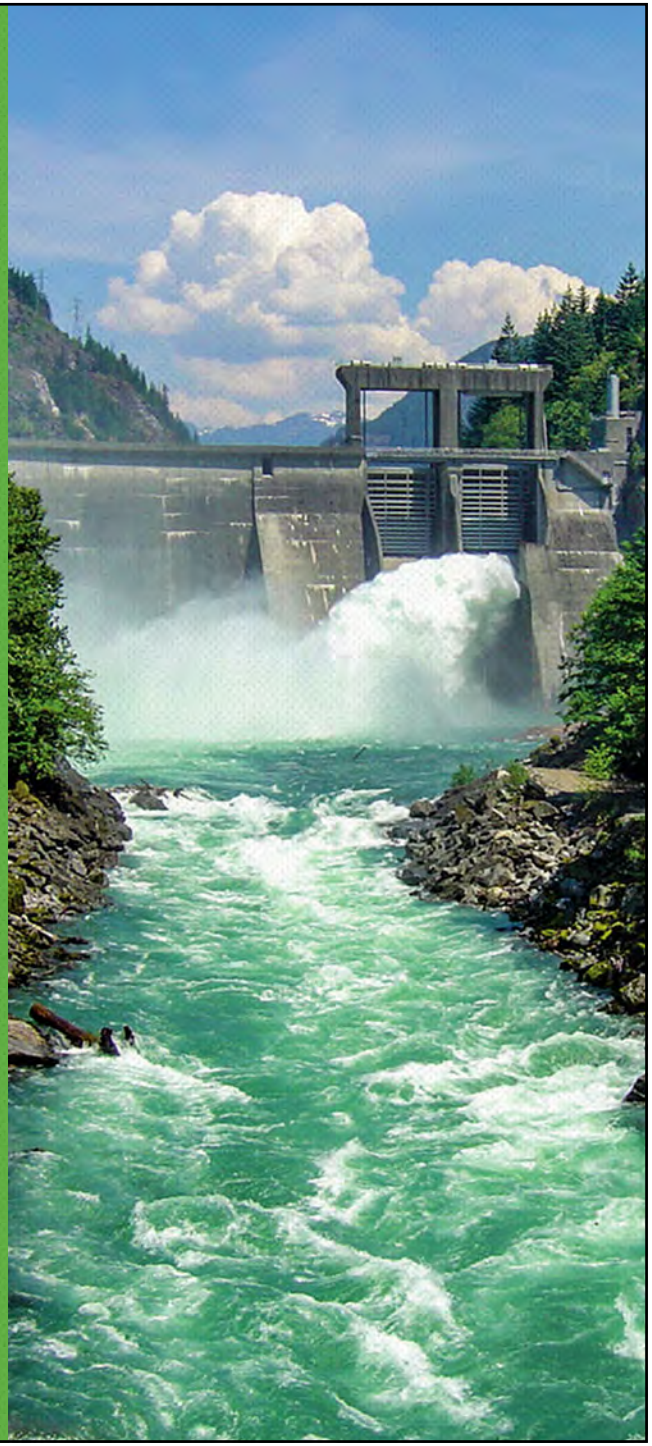


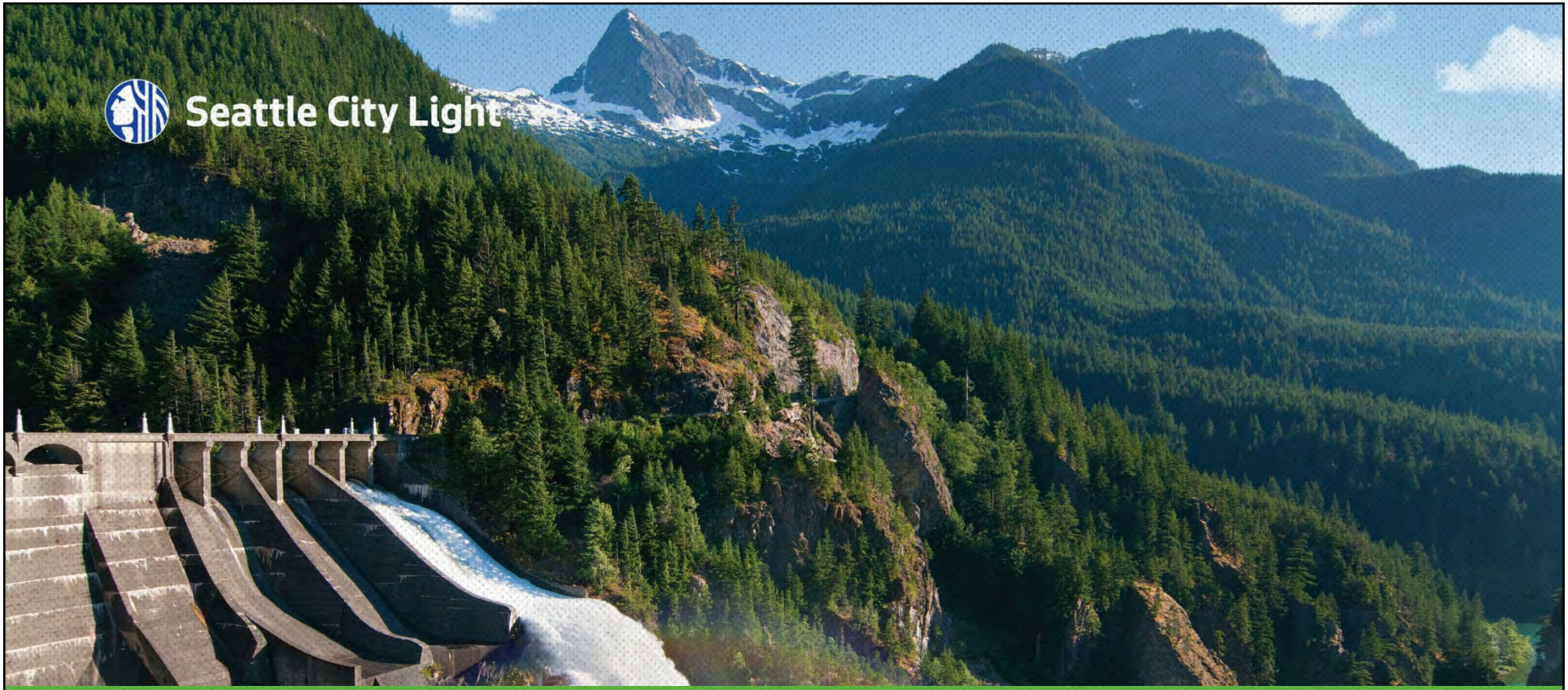
Velocity (FT/S)

- 0 - 0.5
- 0.5 - 1.0
- 1.0 - 1.5
- 1.5 - 2.0
- 2.0 - 2.5
- 2.5 - 3.0
- 3.0 - 3.5
- 3.5 - 4.0
- 4.0 - 4.5
- 4.5 - 5.0
- 5.0+

Seattle City Light

DISCUSSION





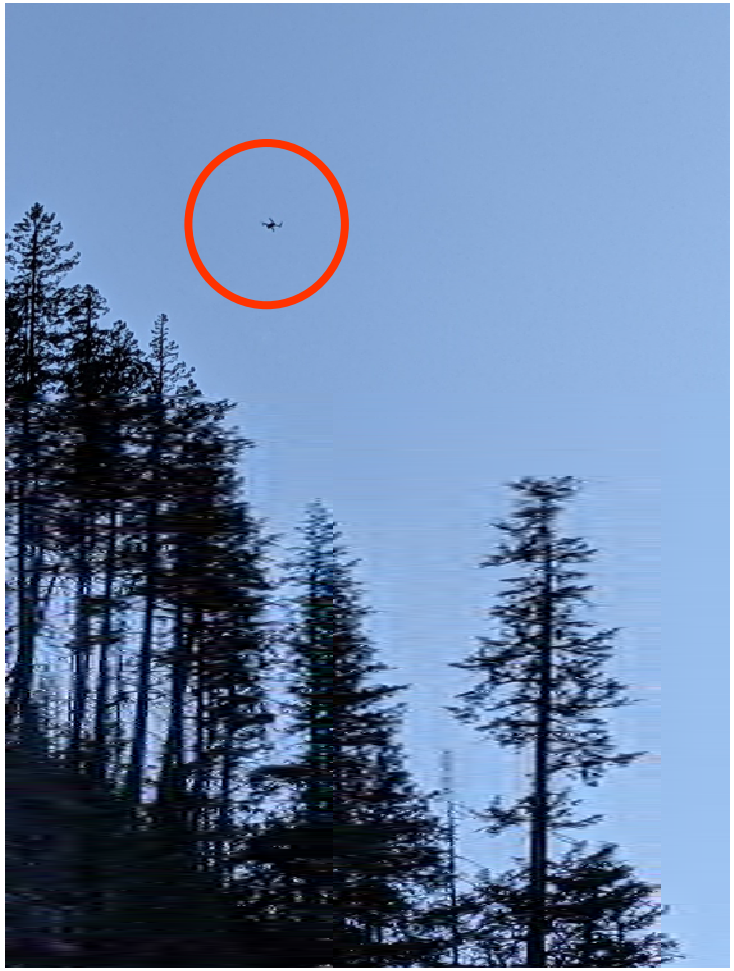
CONTROLLED SPILL MONITORING
UAV DATA

August 26, 2021

OVERVIEW

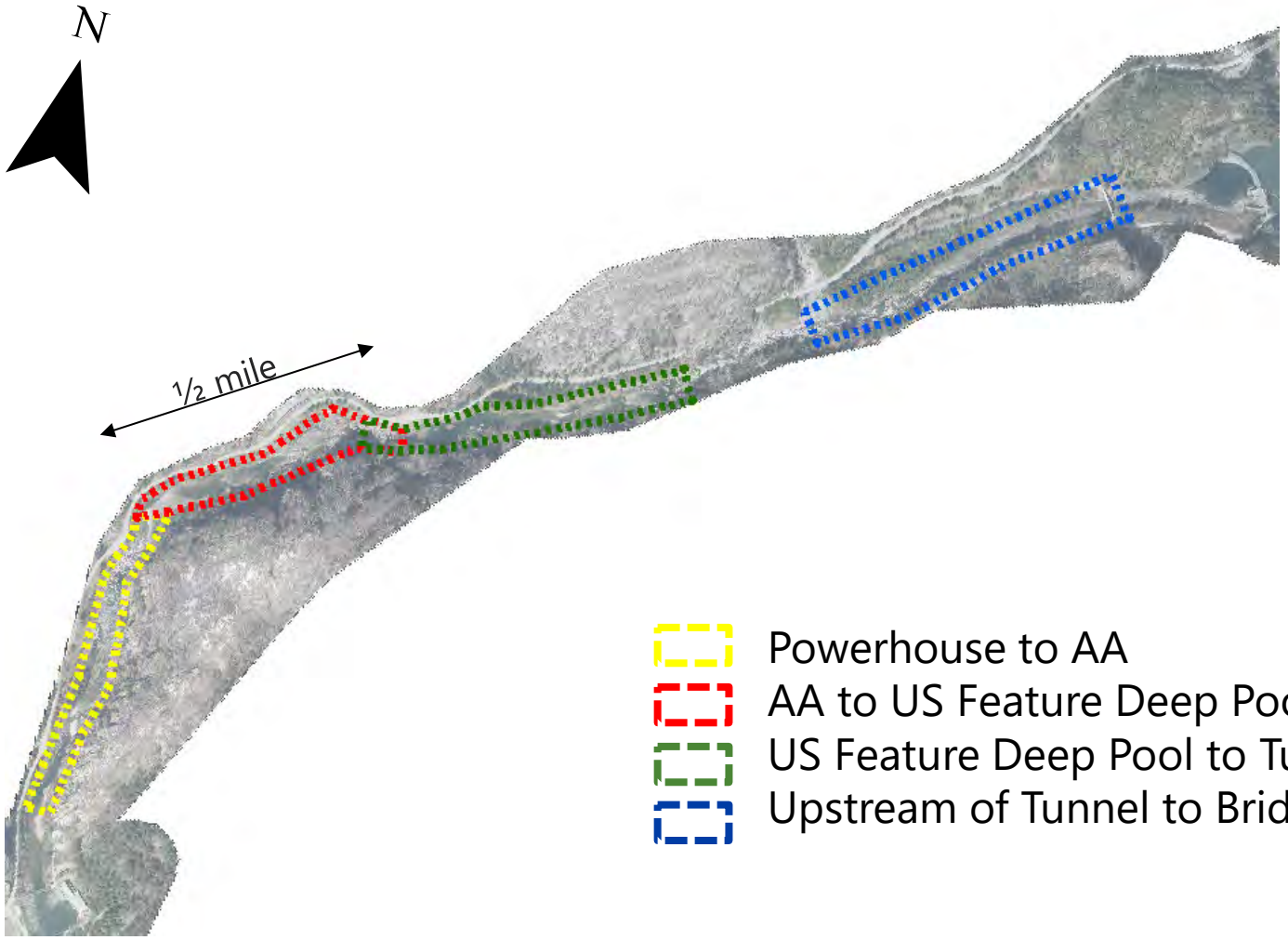
- UAV photos
  - Deployment
  - SfM
  - Geo-reference
  - Application
- UAV videos
  - LSPIV
  - Methodology
  - Locations
  - Application

UAV DEPLOYMENT

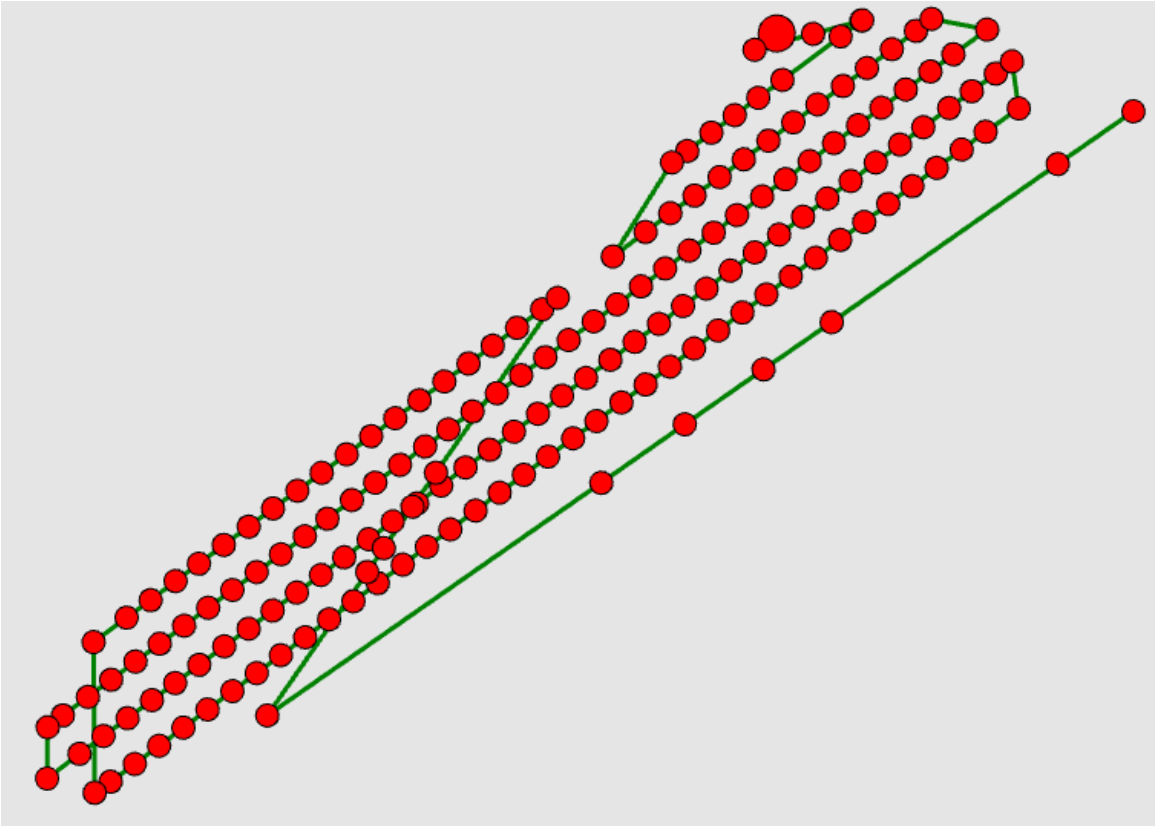




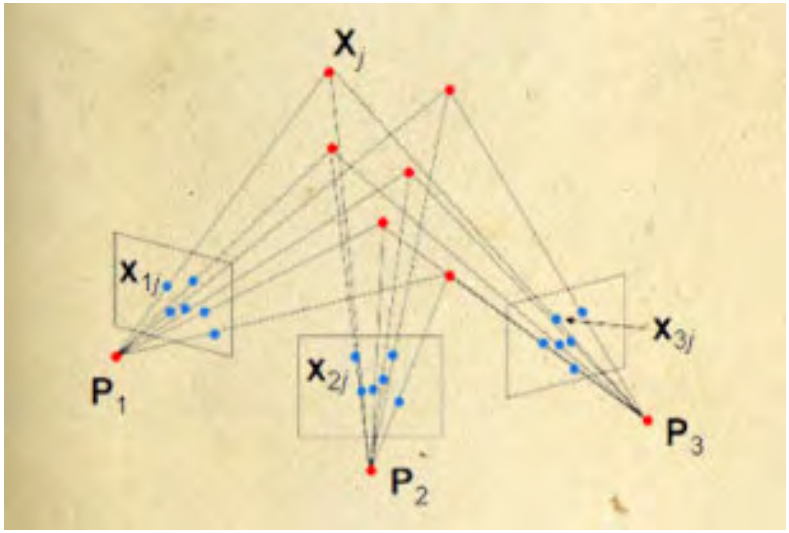
UAV DEPLOYMENT - ZONES



UAV DEPLOYMENT – EXAMPLE MISSION PLAN



STRUCTURE FROM MOTION

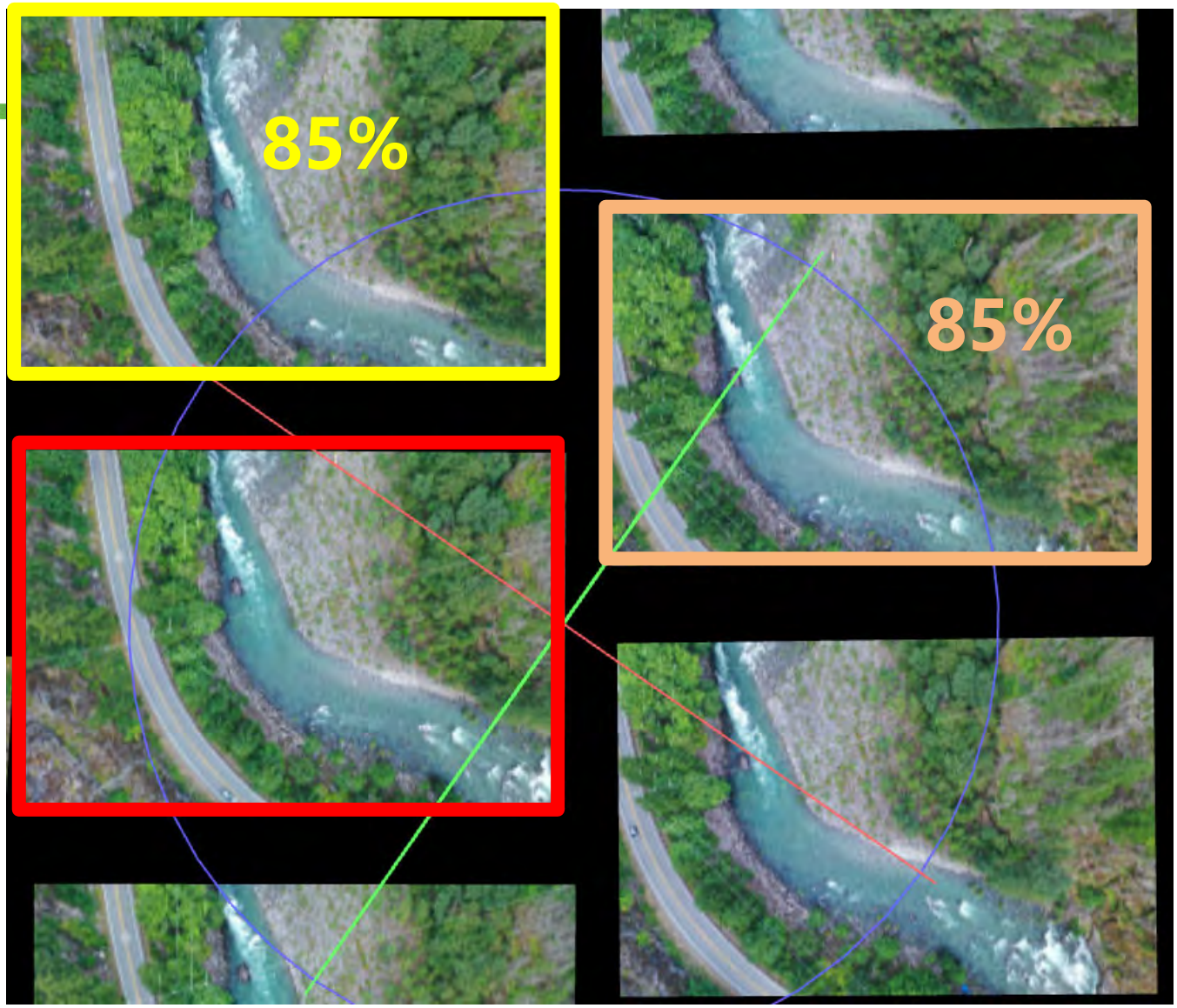


- SfM is workflow and set of algorithms used to determine 3D coordinates of an object space from a series of overlapping photos

STRUCTURE FROM MOTION

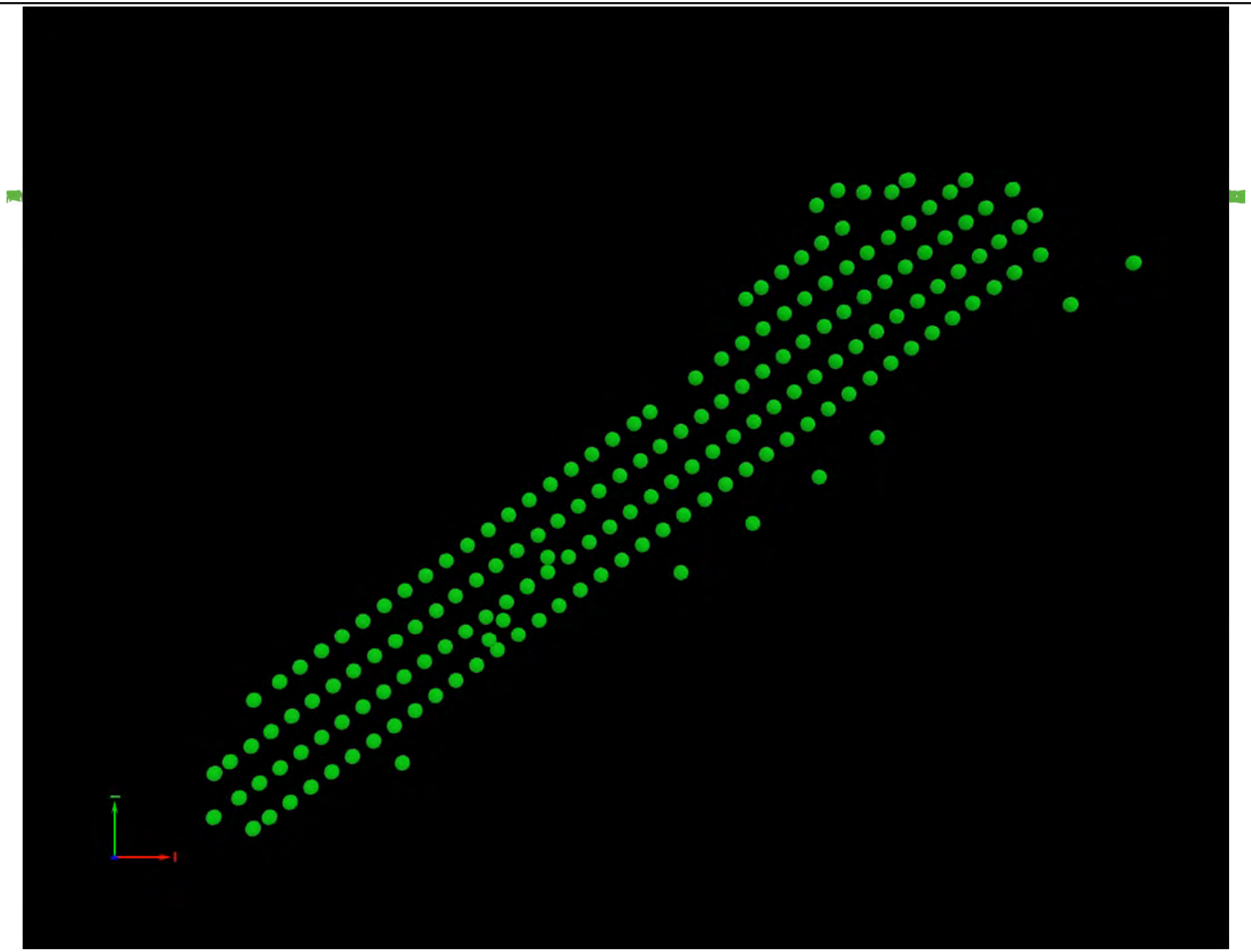
- Form of photogrammetry
  - 3D structure resolved from a series of overlapping, offset 2D images
  - Requires high image overlap
- Fundamentally different than traditional photogrammetry
  - No a priori knowledge necessary (camera 3D location & pose or GCPs)
  - No control required (but no scale, orientation, position)
- Match multiple features in multiple overlapping images

OVERLAP

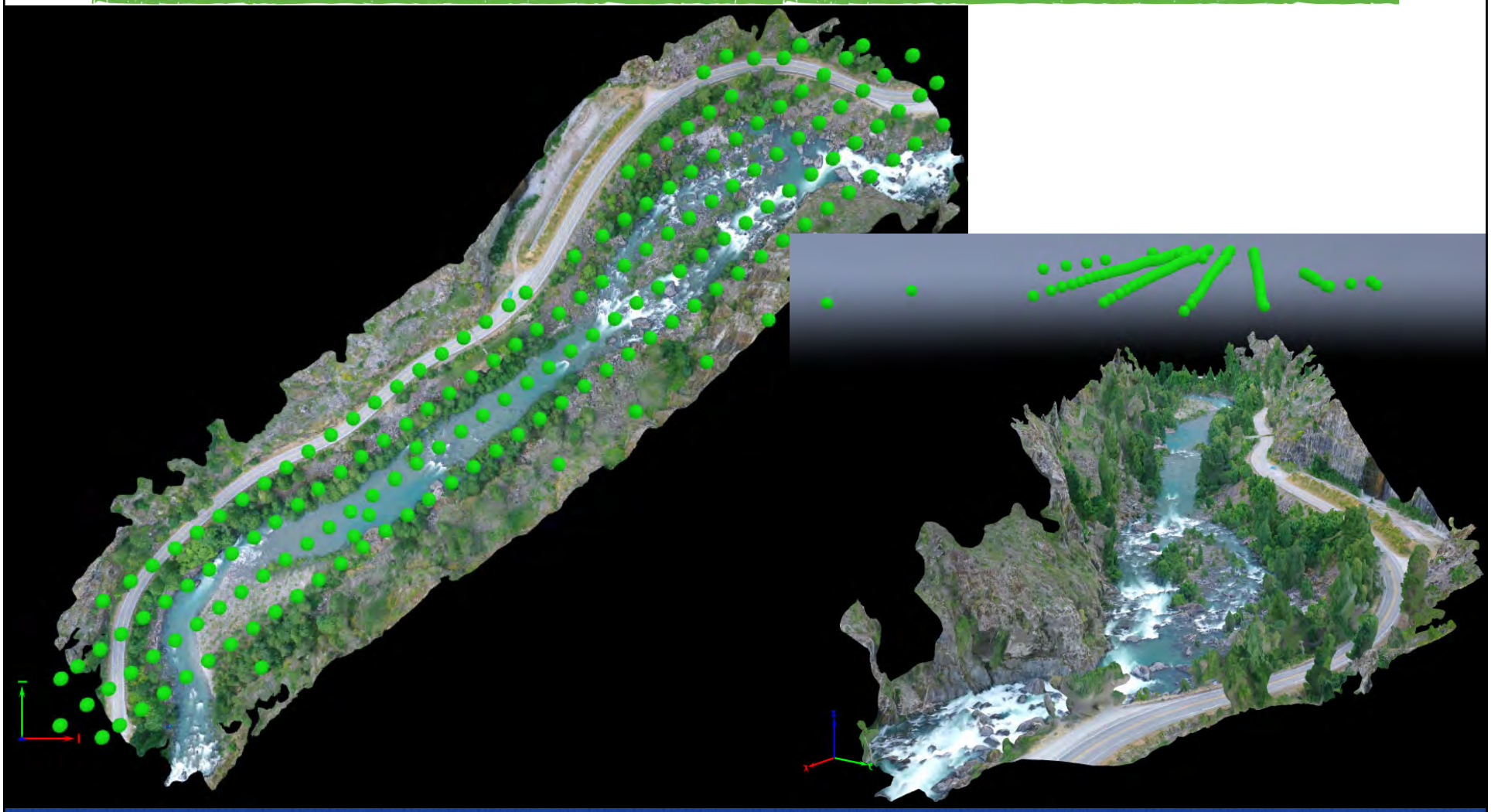


STRUCTURE FROM MOTION

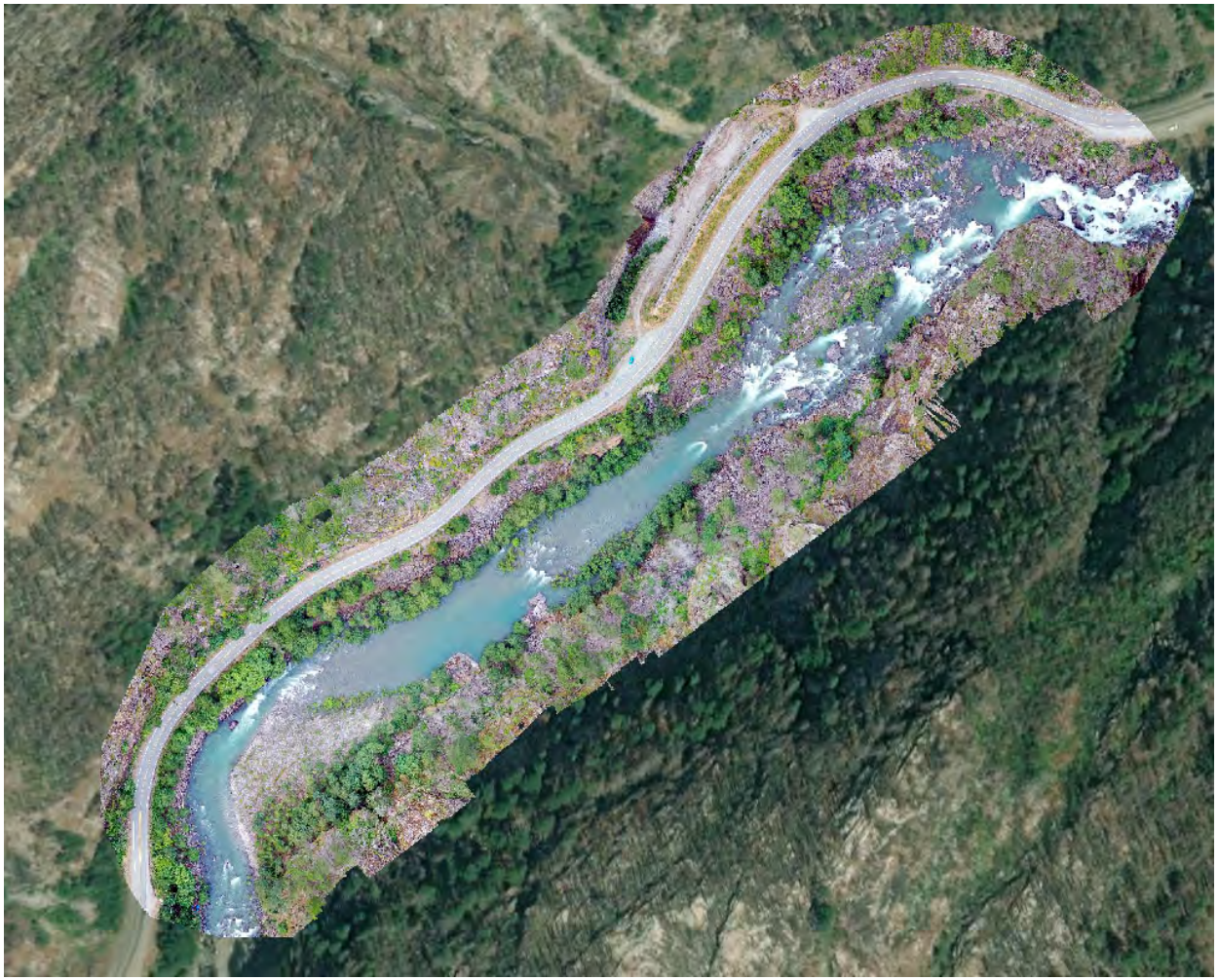
- SfM process automated and bundled – Pix4D
- Result is a 3D model of keypoints
- 3D model -> 2D surface and orthomosaic
- Orthomosaic NOT result of the stitching together imagery, but rather projection of individual pixels from the original imagery



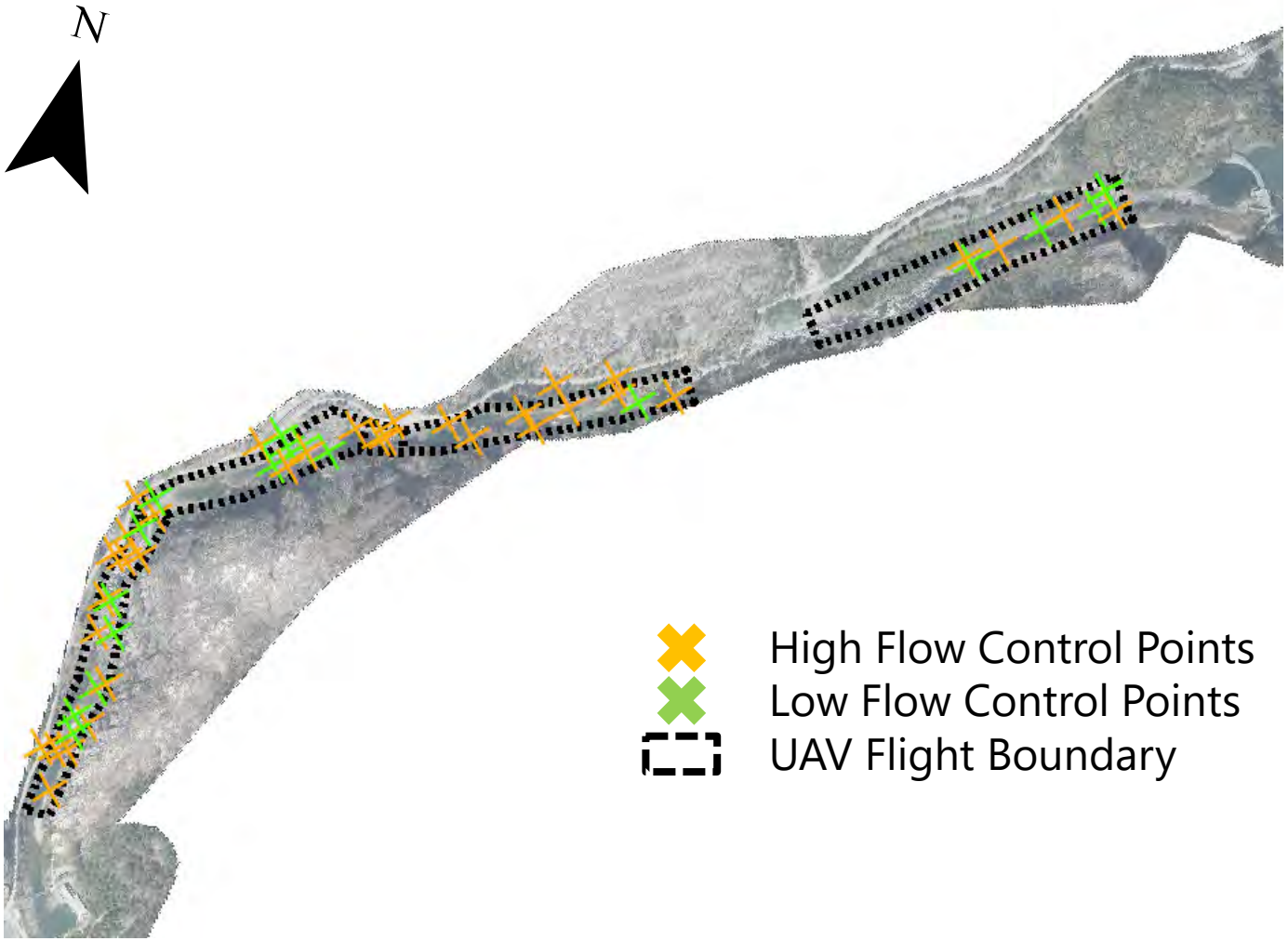
SFM – POINT CLOUD



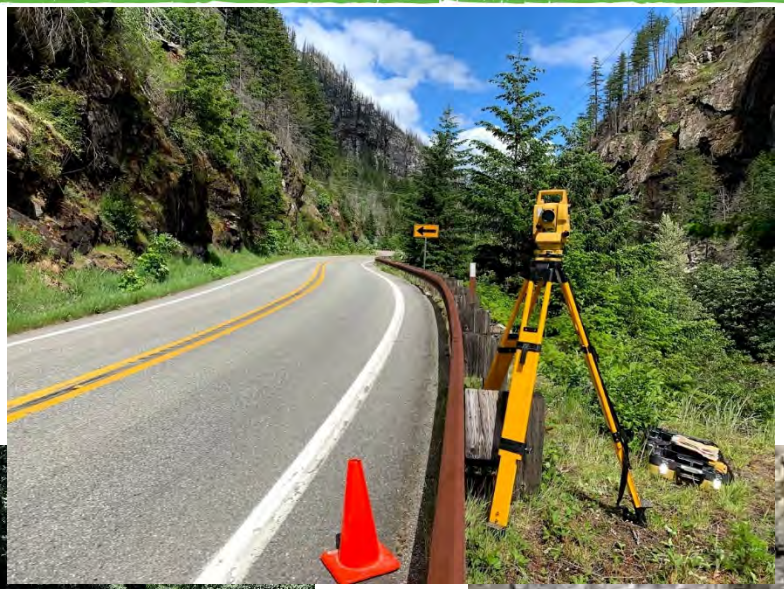
SFM – COMPOSITE ORTHOMOSAIC



SFM MODEL – GEOREFERENCING



SURVEY – GEOREFERENCING





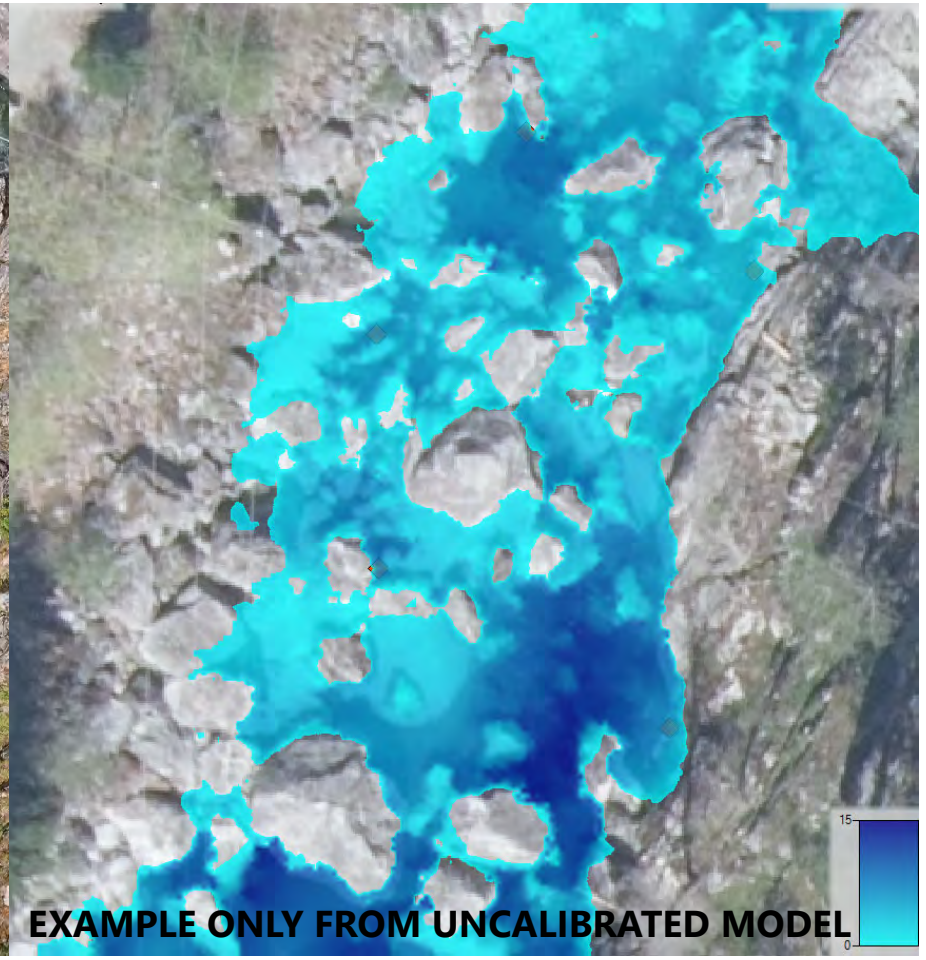


UAV APPLICATION - VISUALIZATION



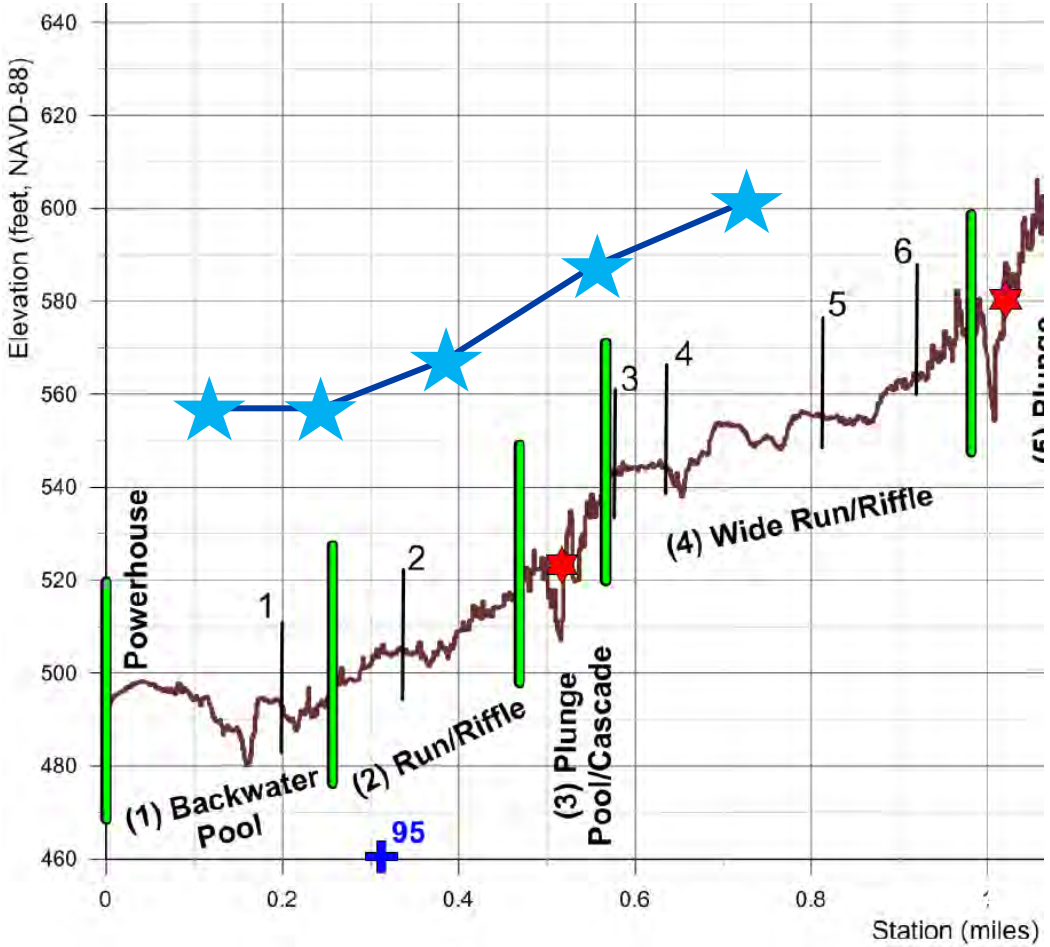
UAV APPLICATION – COMPARE WITH MODEL





EXAMPLE ONLY FROM UNCALIBRATED MODEL

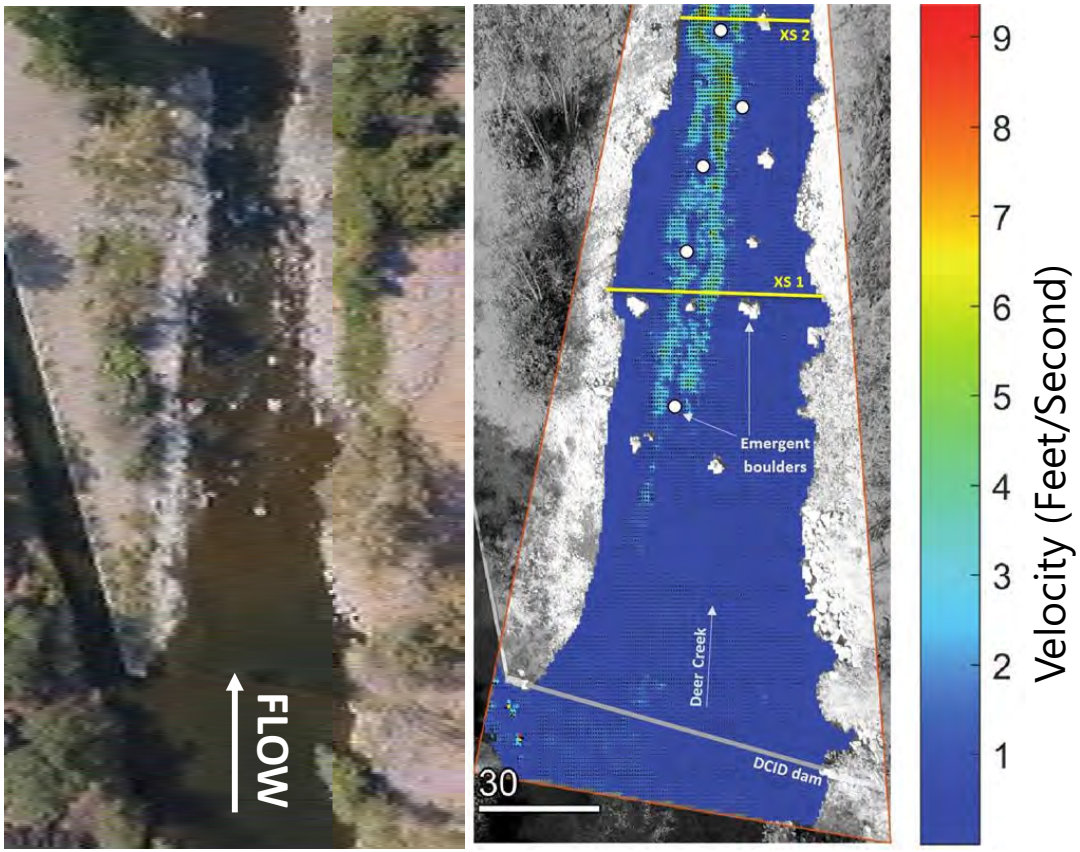
UAV APPLICATION – WSEL PROFILE





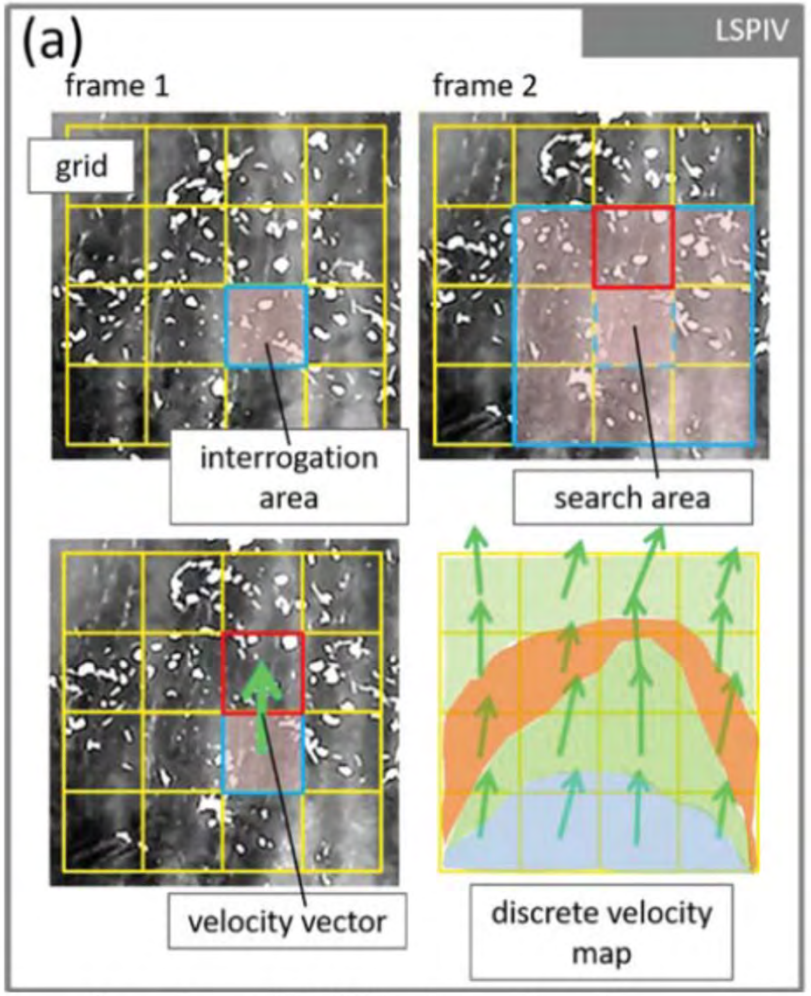
LSPIV - GOAL

- **L**arge **S**cale **P**article **I**mage **V**elocimetry
- Surface velocity vectors
- Uses:
  - Ground truth numerical model
  - Another view of fish passage potential
- LSPIV vector density comparable to numerical model mesh resolution



LSPIV - PRINCIPLE

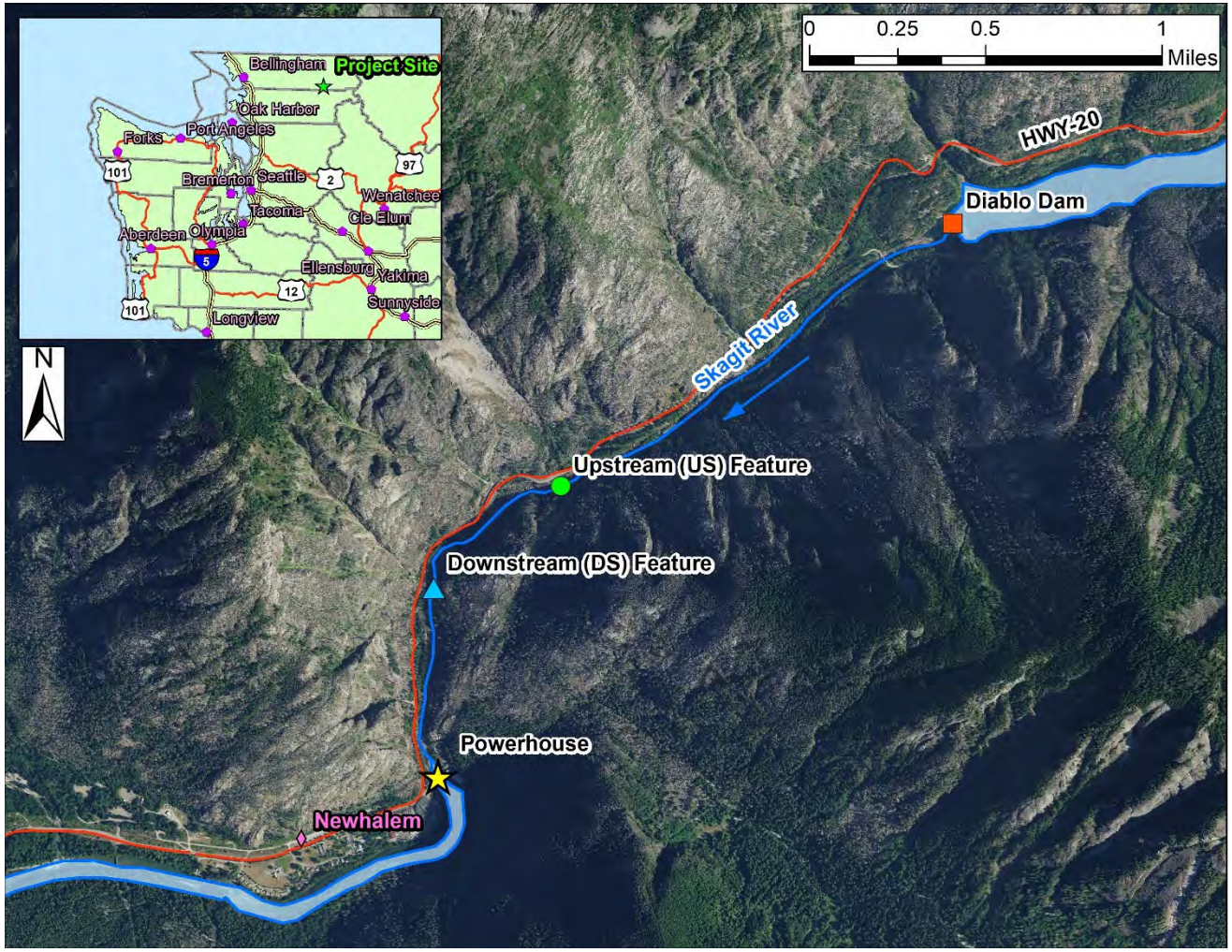
- Seed flow with buoyant tracer particles that follow the flow streamlines
  - Seed material must contrast with water to be visible in camera
- Capture the tracer movement on video with known frame rate
- Calculate tracer movement within interrogation areas for every successive pair of video frames



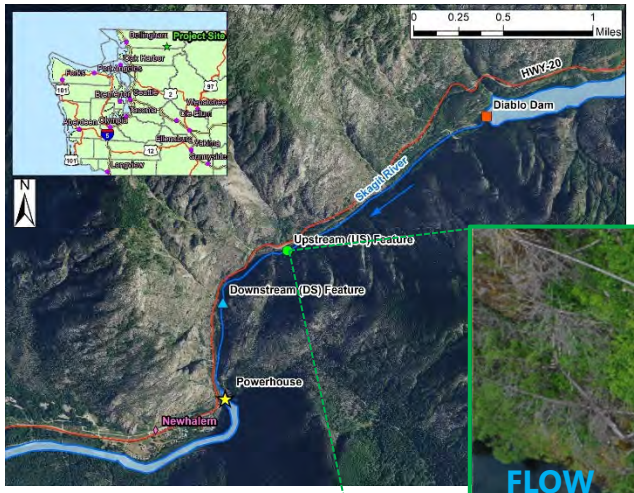
Source: Tauro et al., (2017 –Water Resources Research)

LSPIV – PROJECT SITE

- Upstream (US) feature
- Downstream (DS) feature



LSPIV – UPSTREAM (US) FEATURE



- Image at Base Flow



LSPIV – DOWNSTREAM (DS) FEATURE



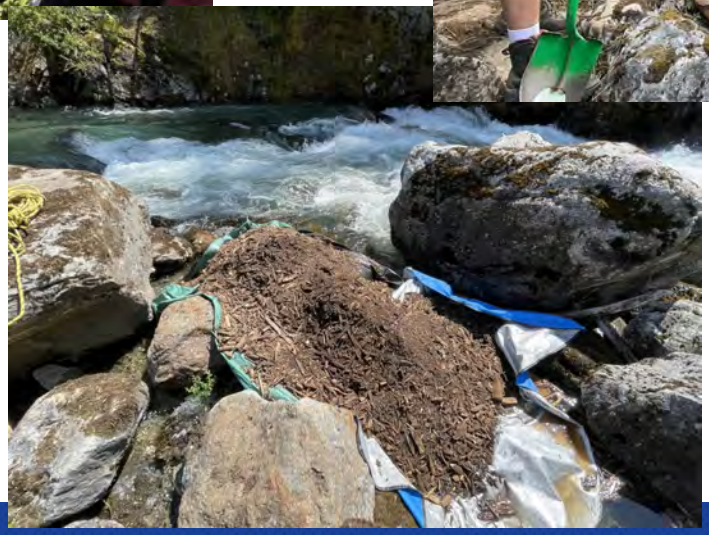
- Image at Base Flow



LSPIV – SEEDING MATERIAL



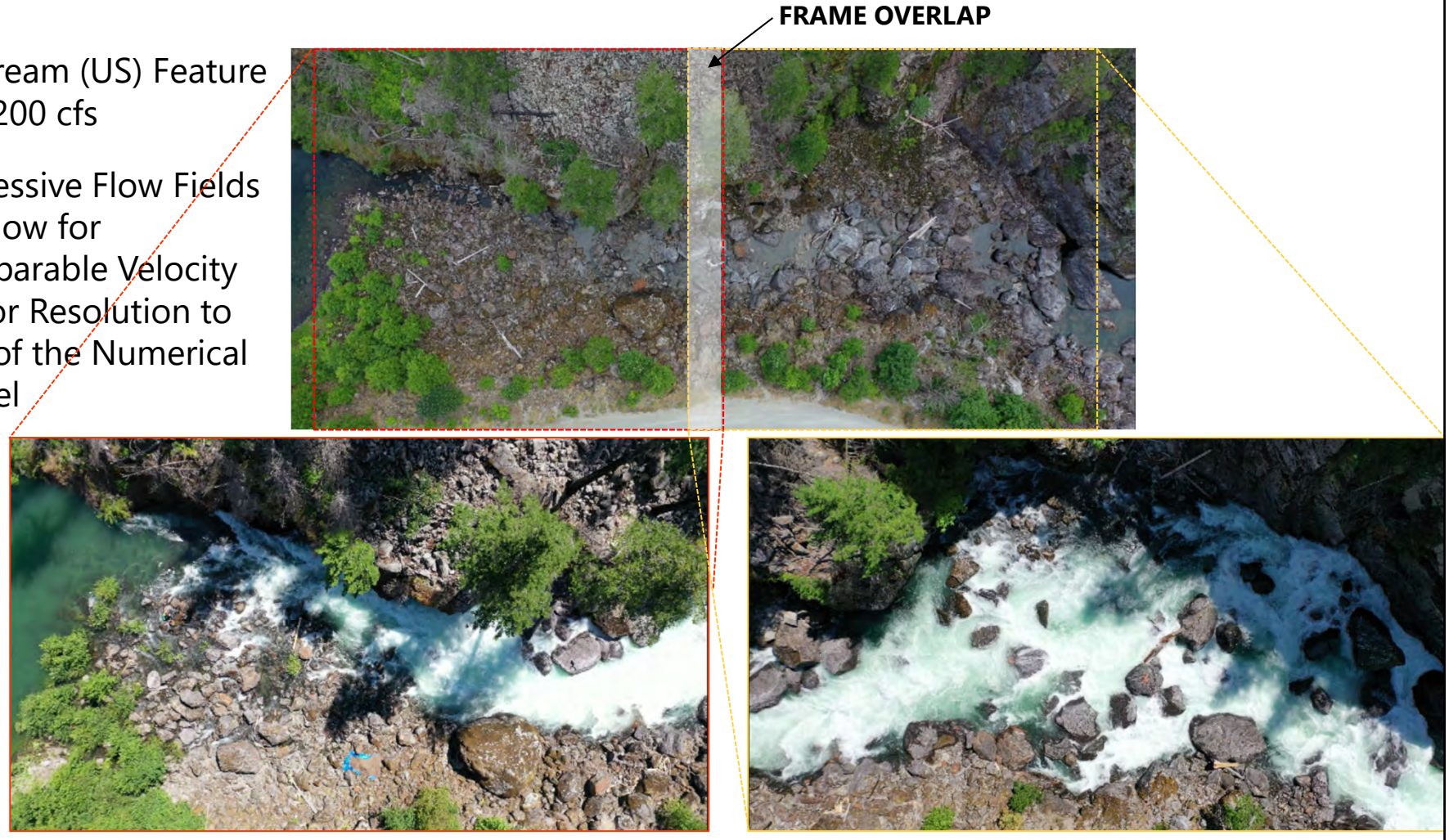




- Bark Chips
- Buoyant
- Good Contrast to Whitewater

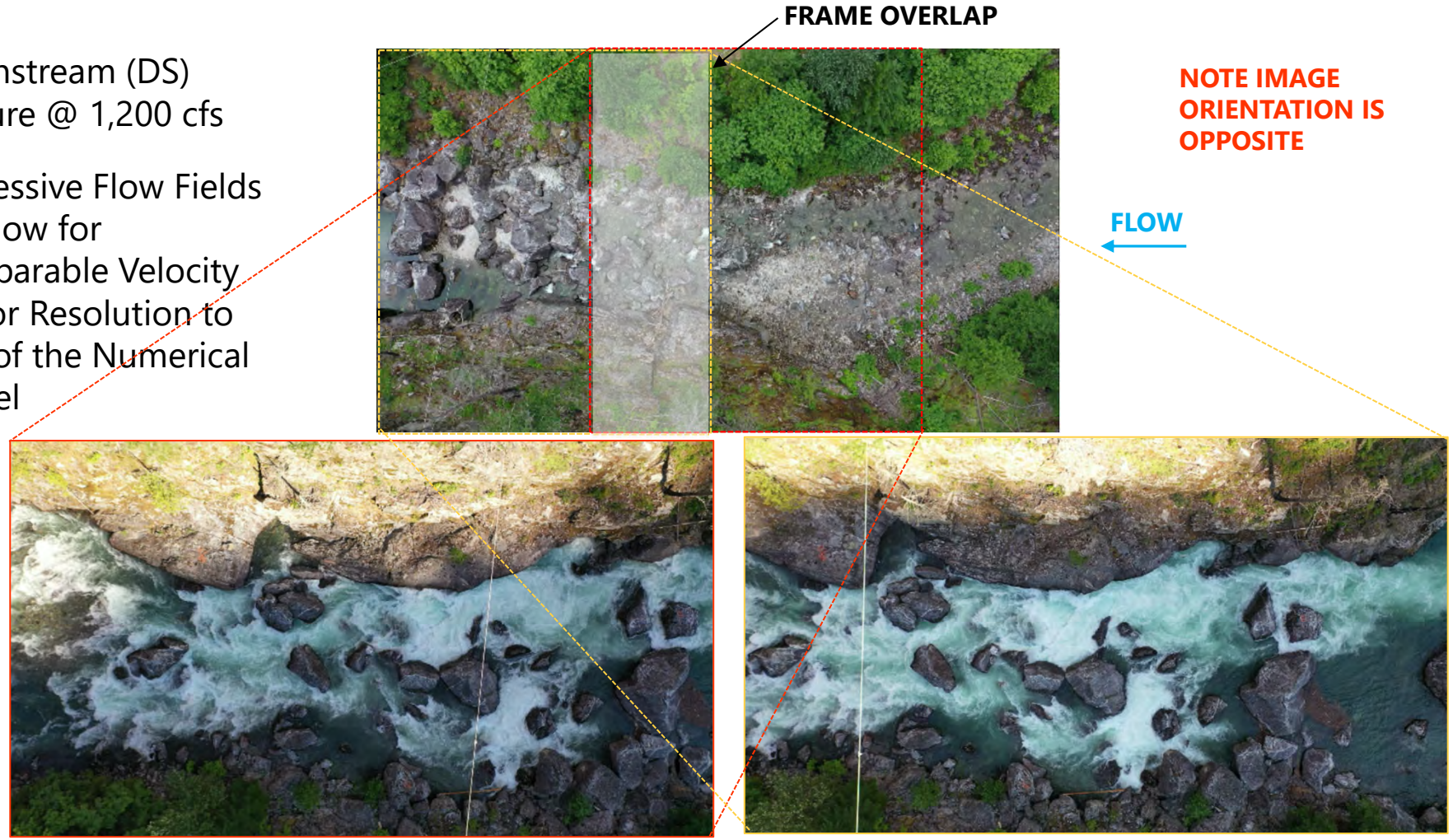
LSPIV – UAV VIDEO CAPTURE

- Upstream (US) Feature @ 1,200 cfs
- Successive Flow Fields to Allow for Comparable Velocity Vector Resolution to that of the Numerical Model



LSPIV – UAV VIDEO CAPTURE

- Downstream (DS) Feature @ 1,200 cfs
- Successive Flow Fields to Allow for Comparable Velocity Vector Resolution to that of the Numerical Model

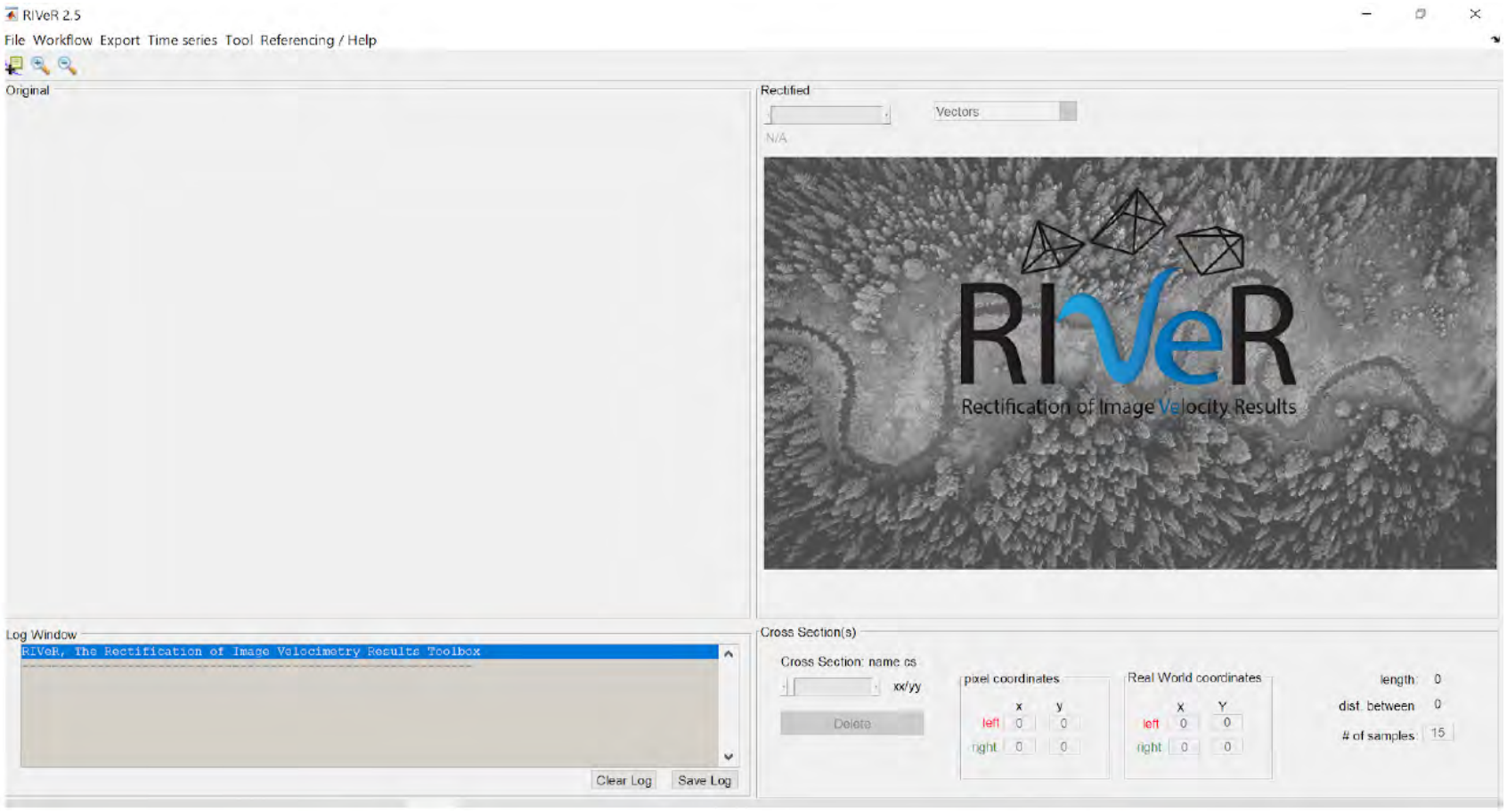


LSPIV – CAPTURED VIDEO



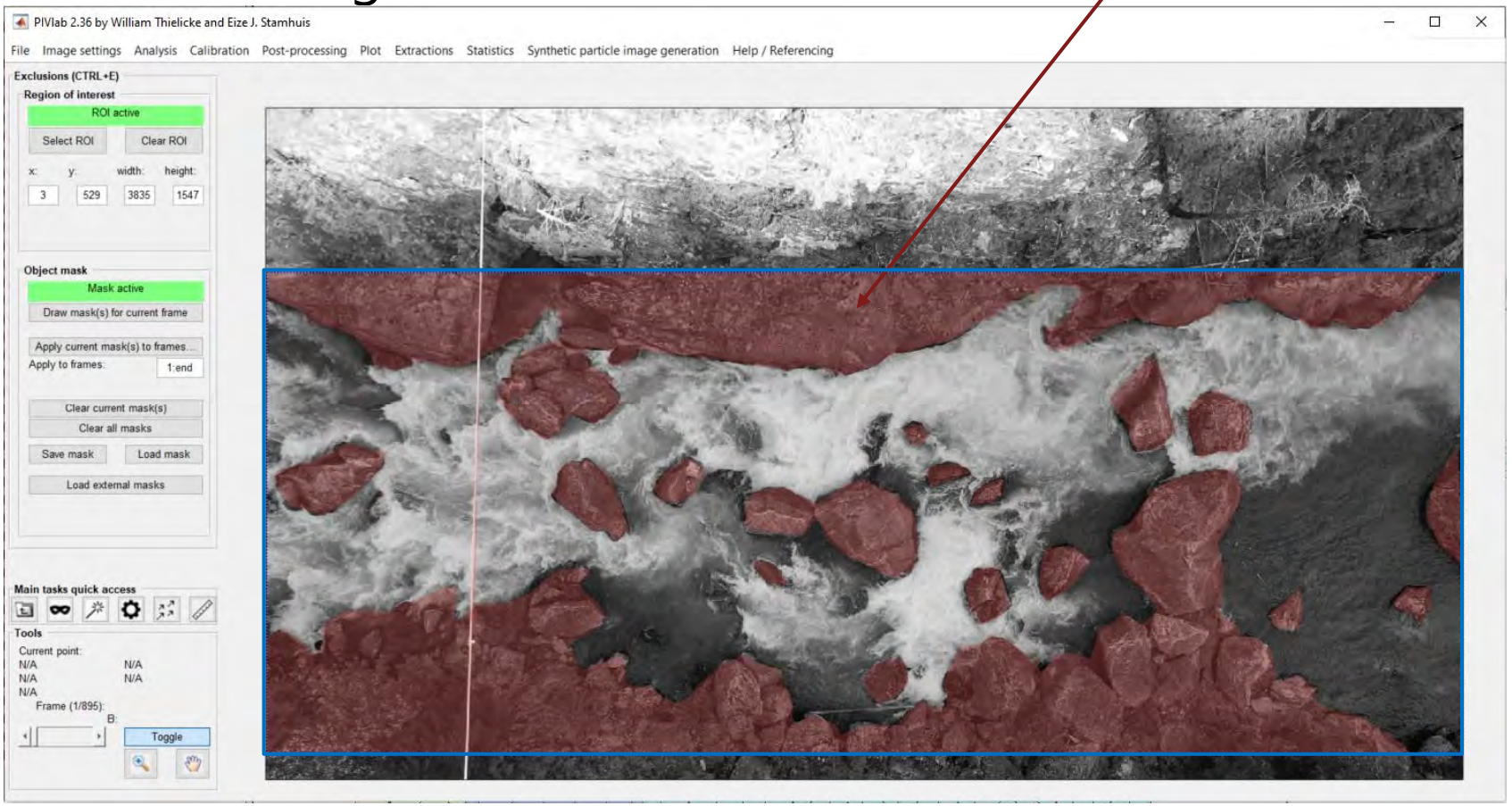
LSPIV – ANALYSIS

- RIVeR Software



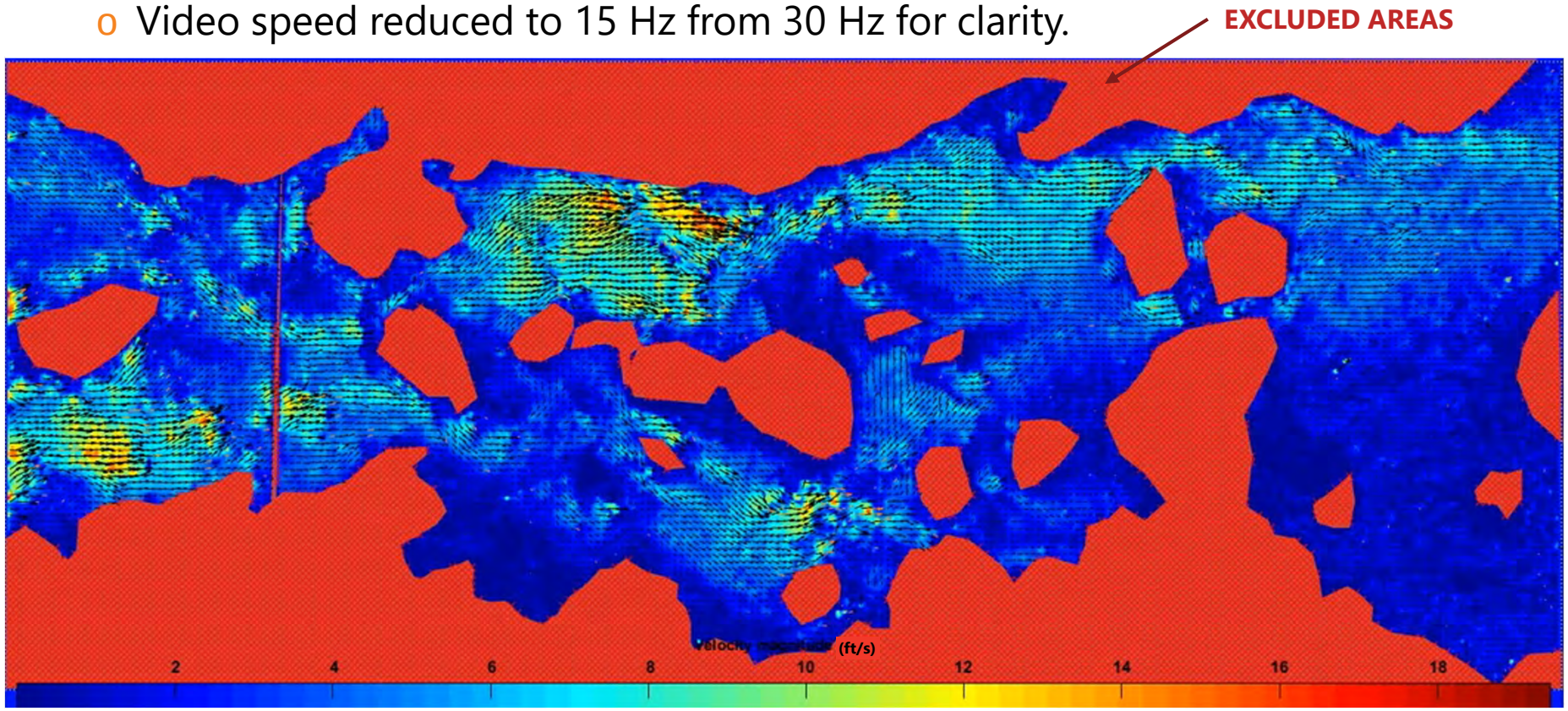
LSPIV – ANALYSIS

- Mask Out Regions With No Flow



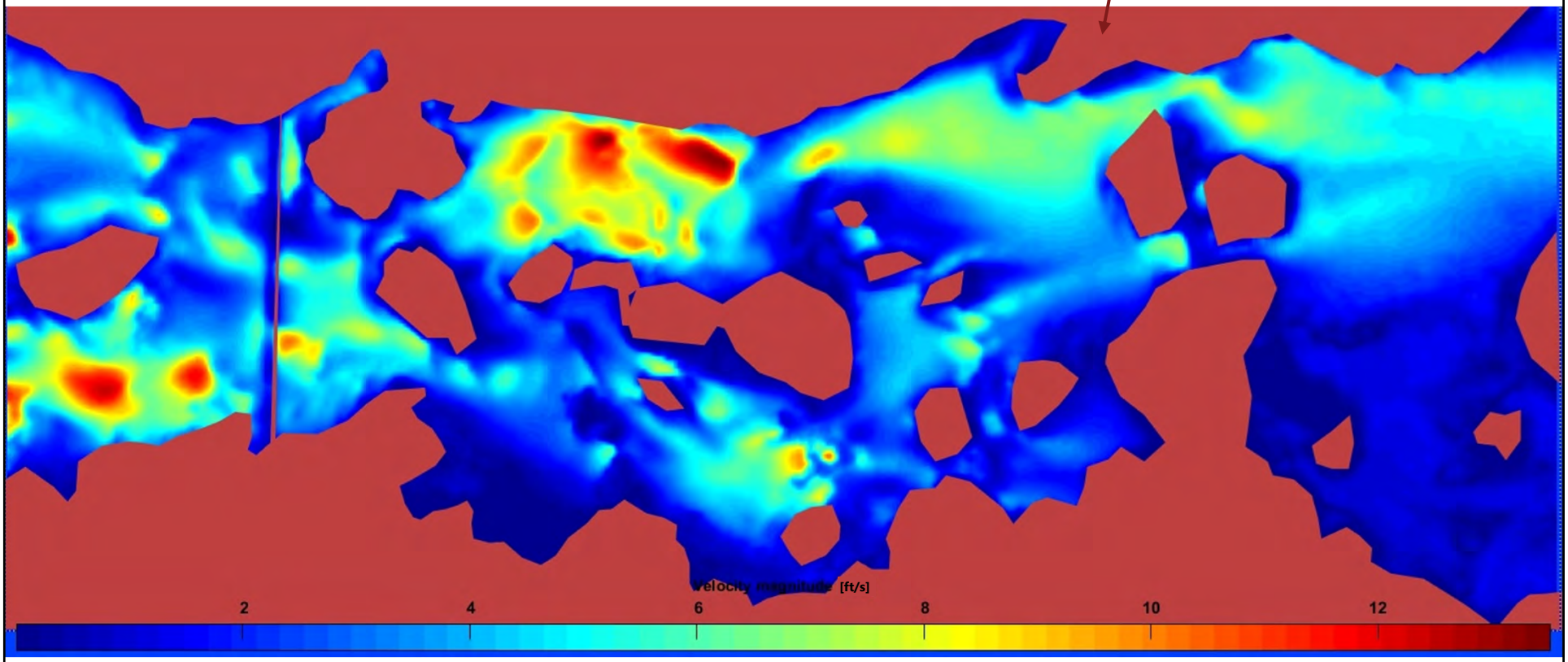
LSPIV – RESULTS

- Instantaneous Raw Velocity Vectors
  - Velocity vector spacing: 1.1 feet; Video shows only every second vector for clarity.
  - Video speed reduced to 15 Hz from 30 Hz for clarity.



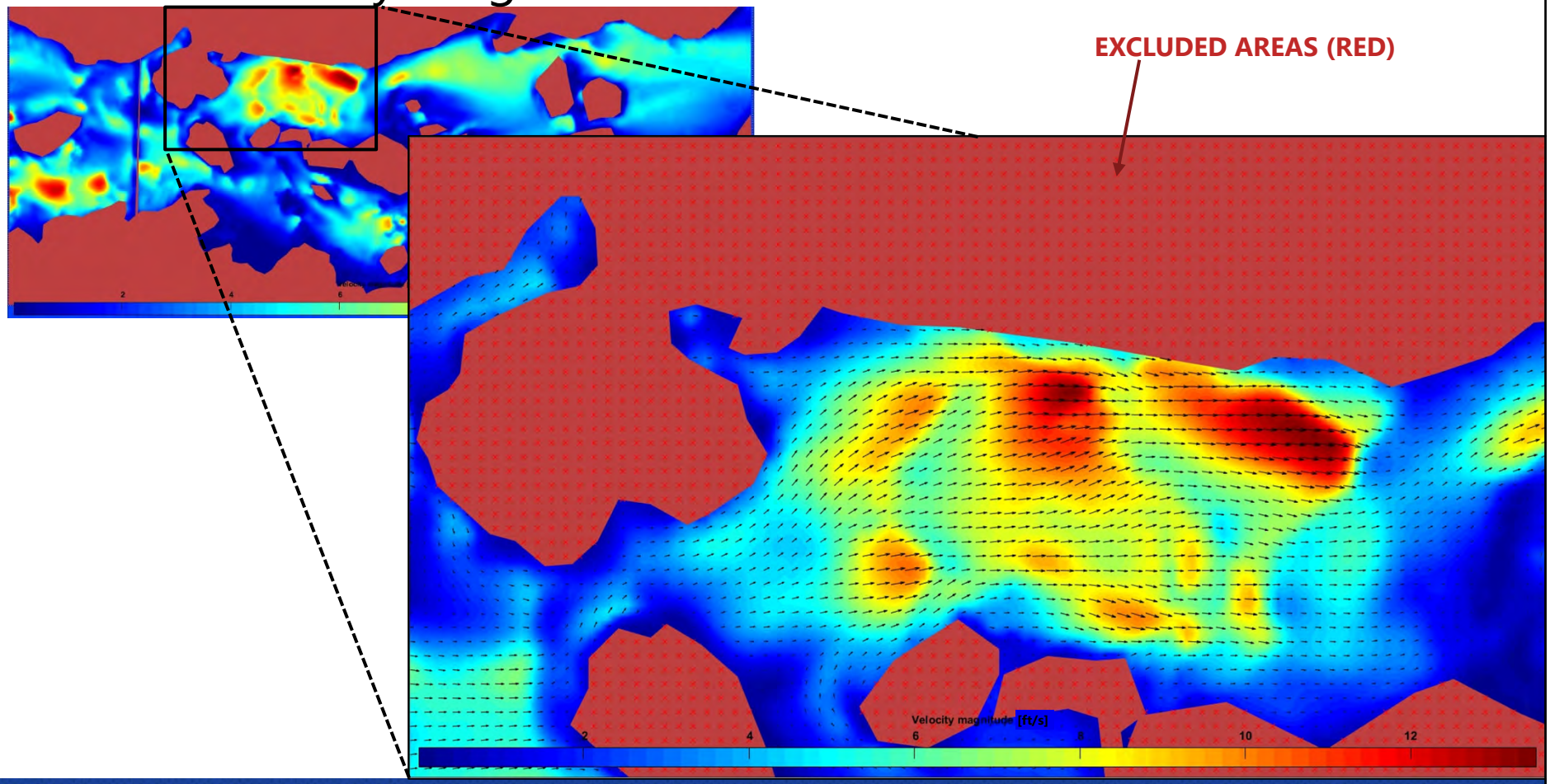
LSPIV – RESULTS (CONT'D)

- Mean Velocity Magnitude



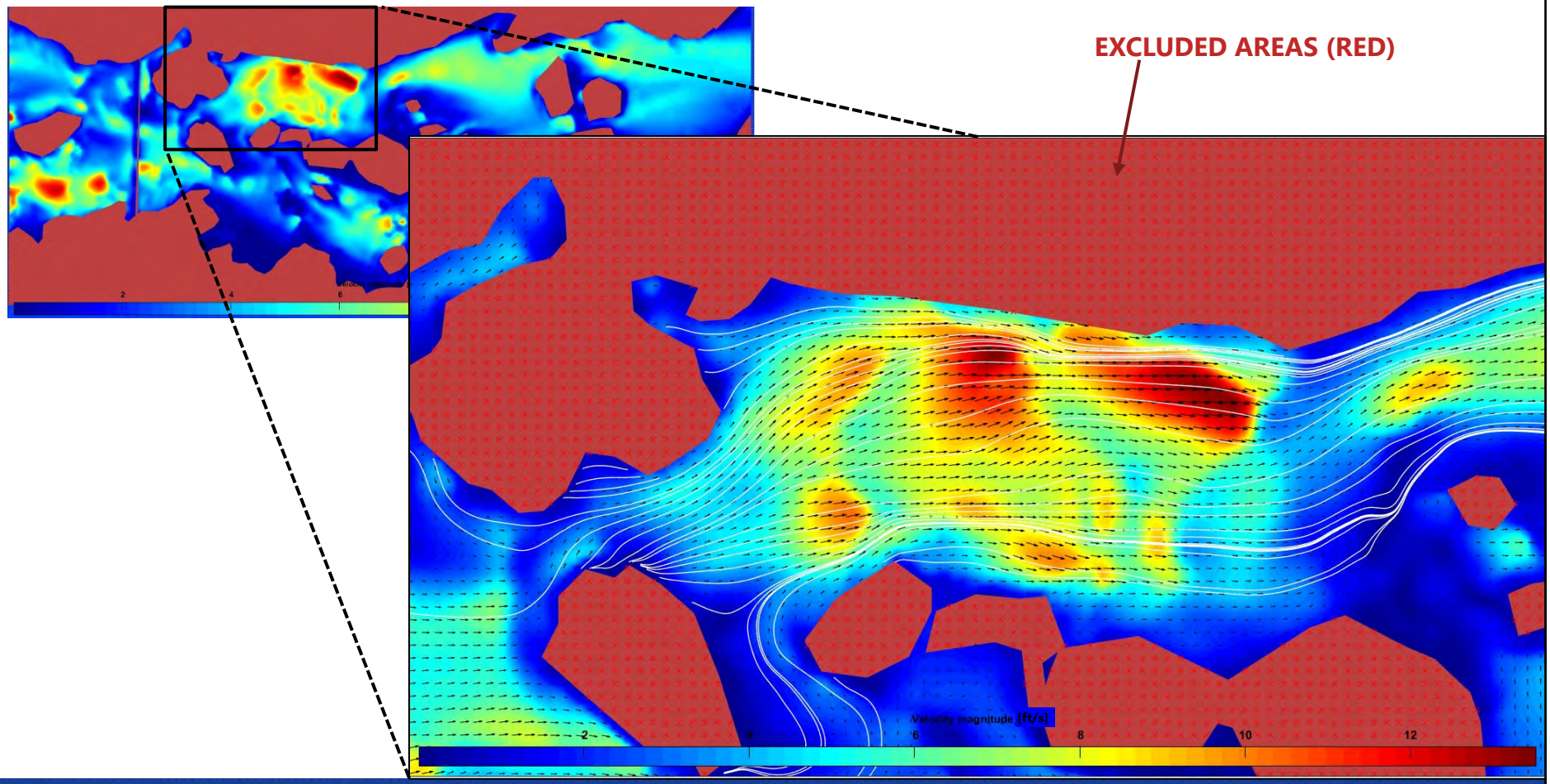
LSPIV – RESULTS

- Mean Velocity Magnitude



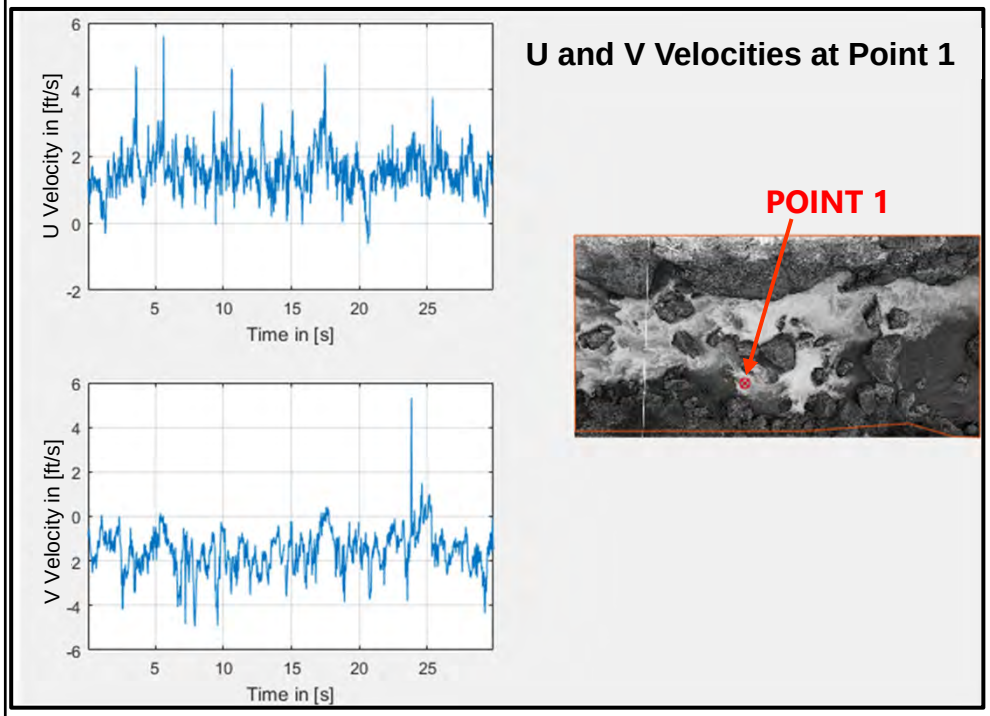
LSPIV – RESULTS

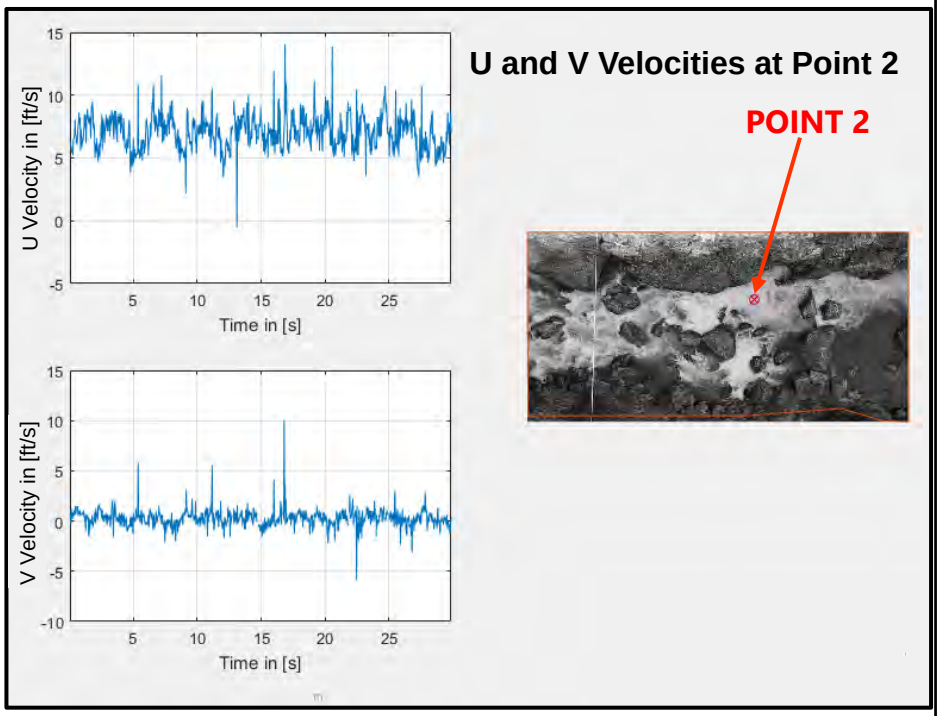
- Streamlines



LSPIV – RESULTS

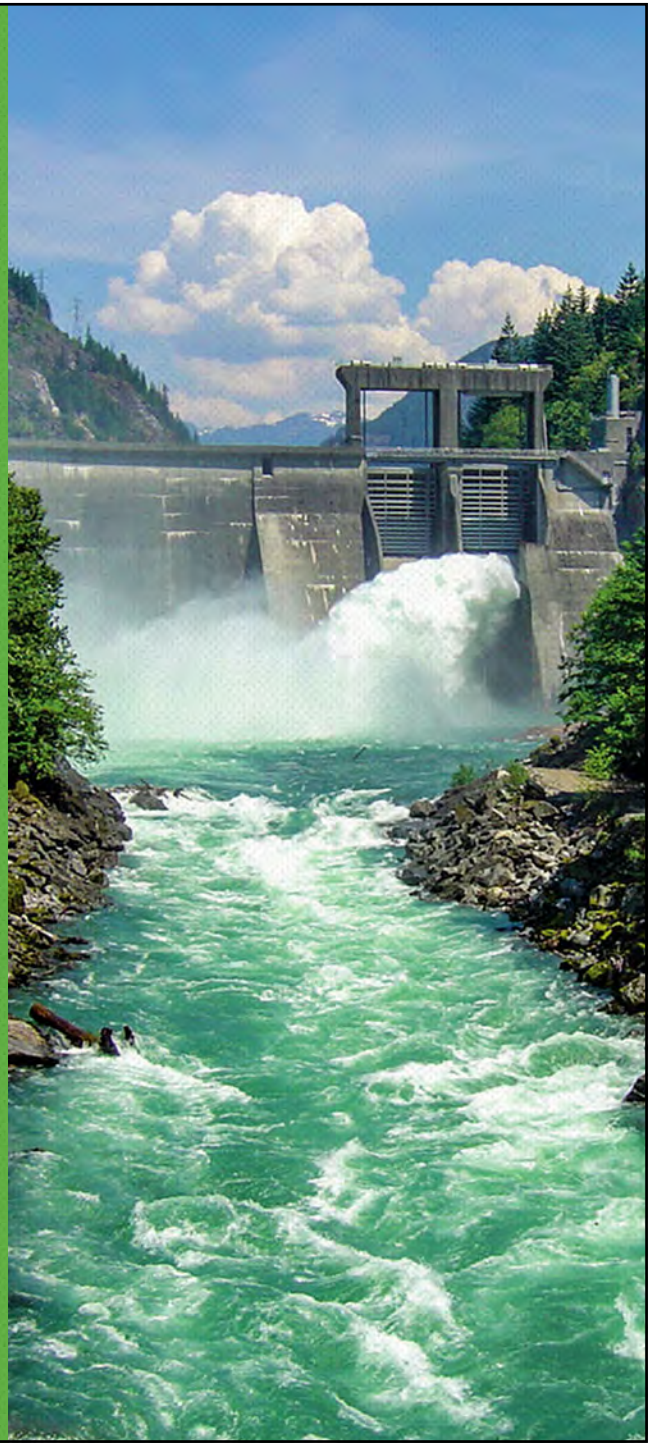
- Streamwise (U) and Transverse (V) Velocity Components at a Point Over the Video Duration

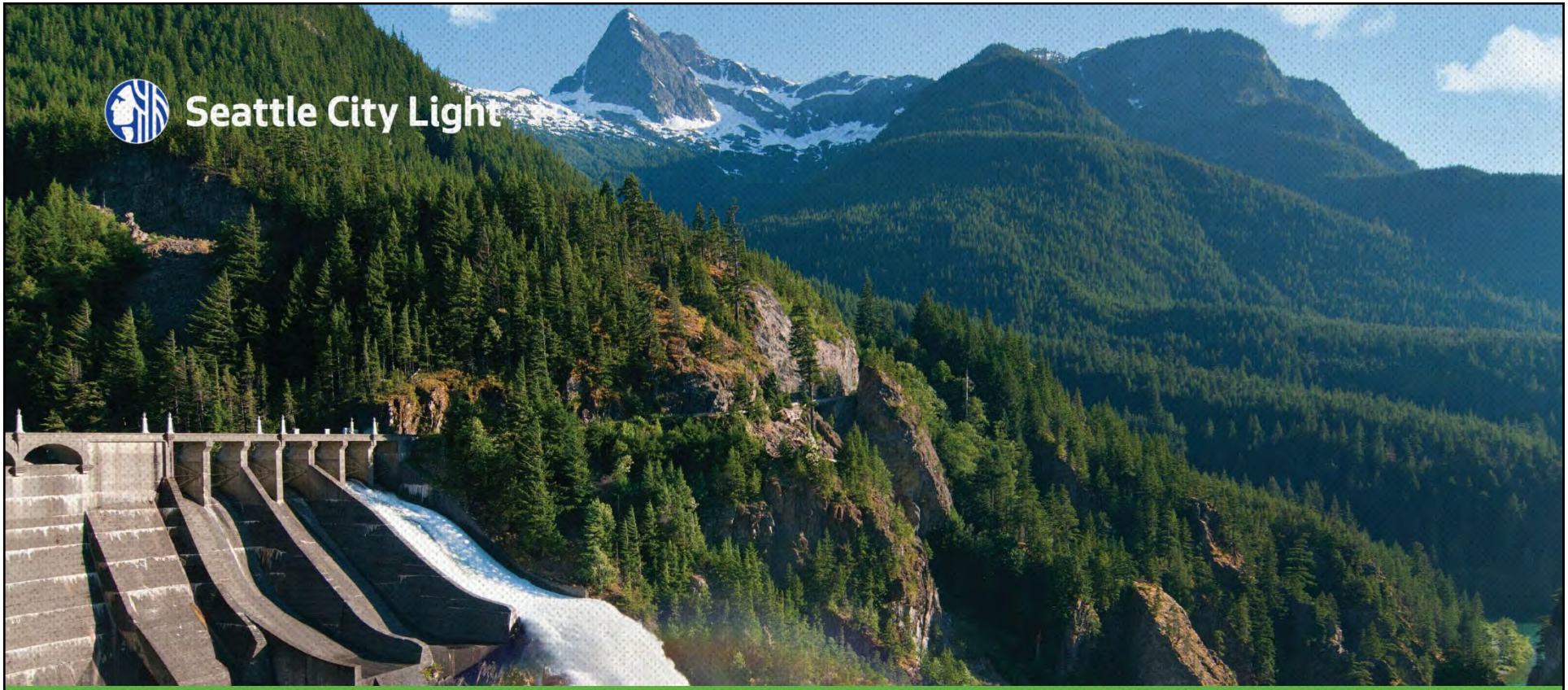




Seattle City Light

DISCUSSION





LEVEL LOGGER DATA

August 26, 2021

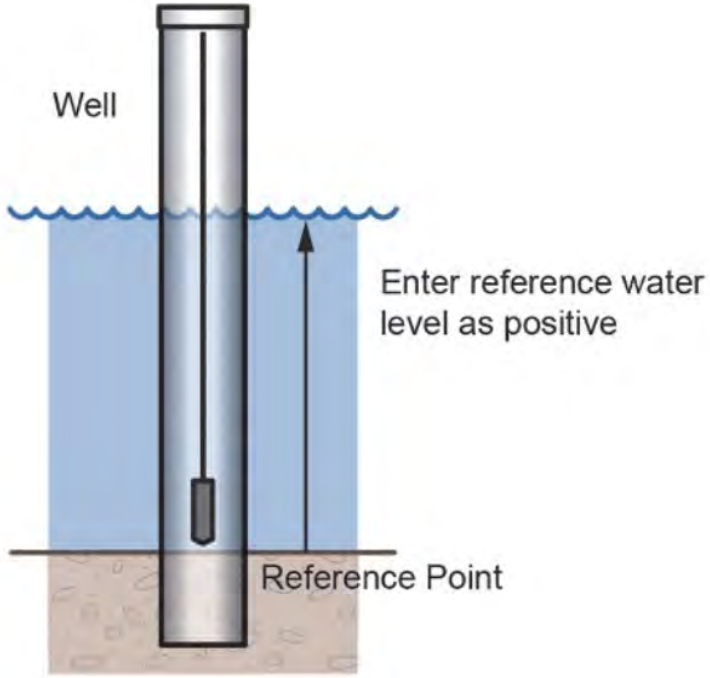
OVERVIEW

- Instrumentation
  - Onset HOBO Level Loggers
  - Installation
  - WSEL datum corrections
- Data Collected
  - Controlled spill events (26 July – 29 July)
  - Unplanned spill event (28 June – 2 July)

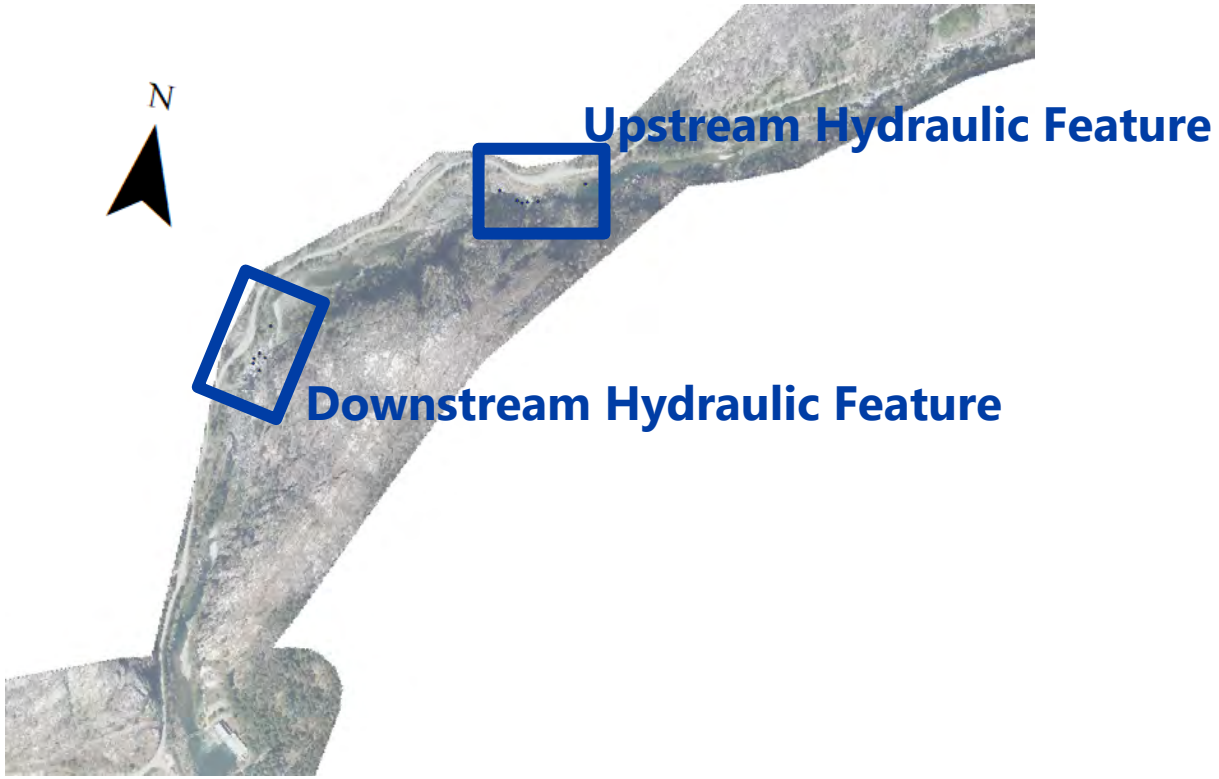
INSTRUMENTATION

- Onset HOBO Level Logger
  - Measures pressure
  - Computes depth
  - Barometric correction

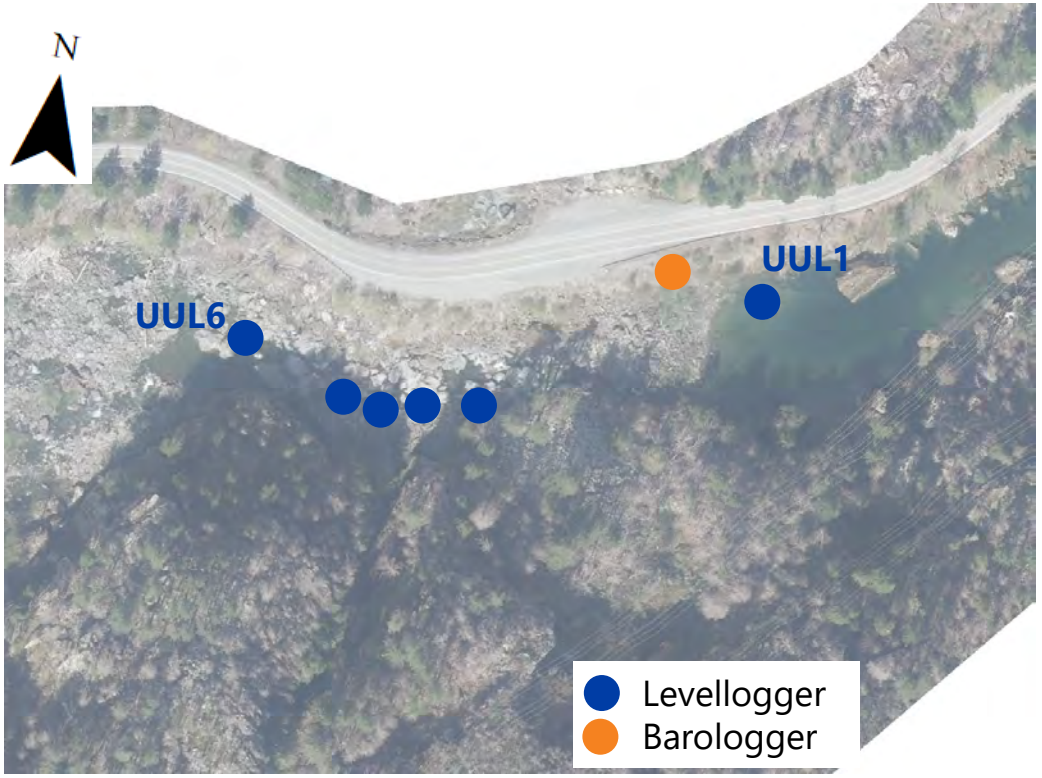




INSTALLATION

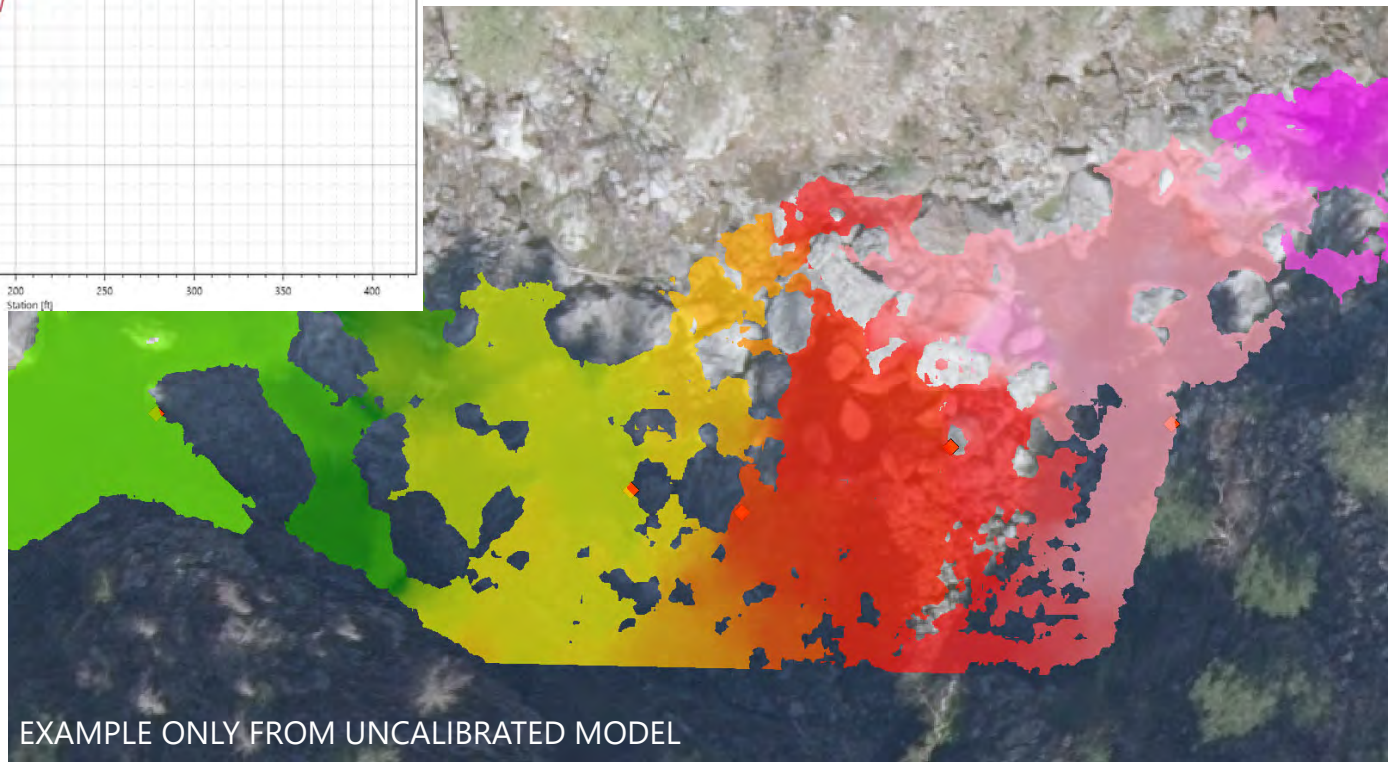


INSTALLATION – UPSTREAM FEATURE



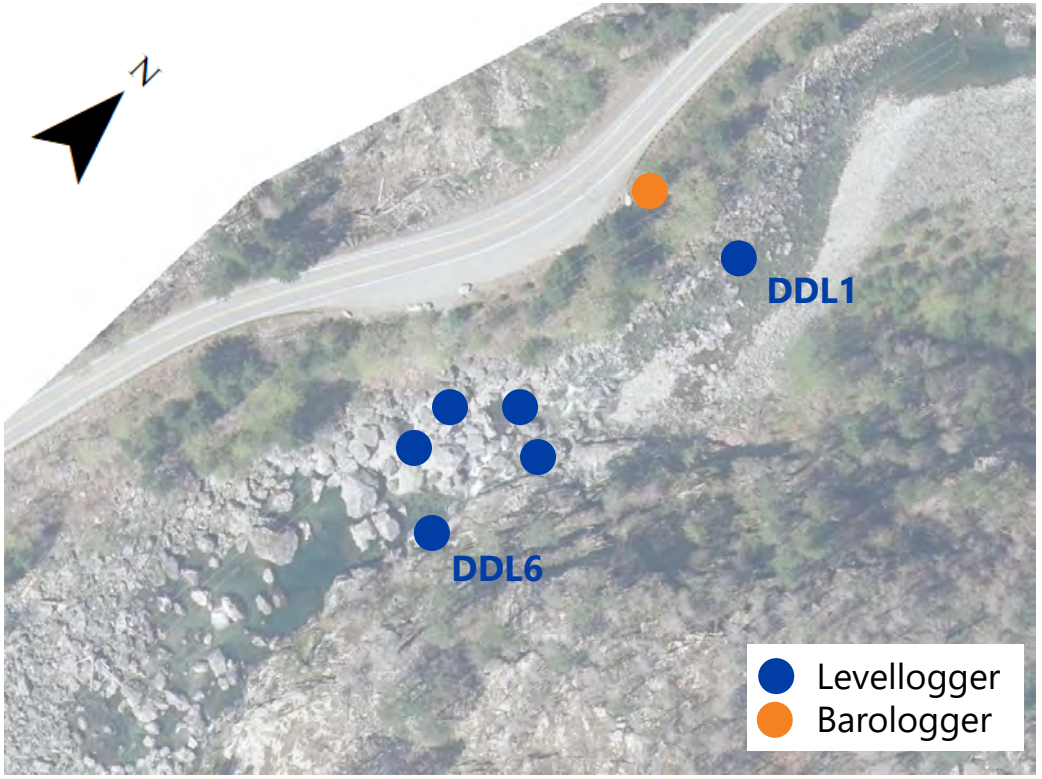
UPSTREAM FEATURE



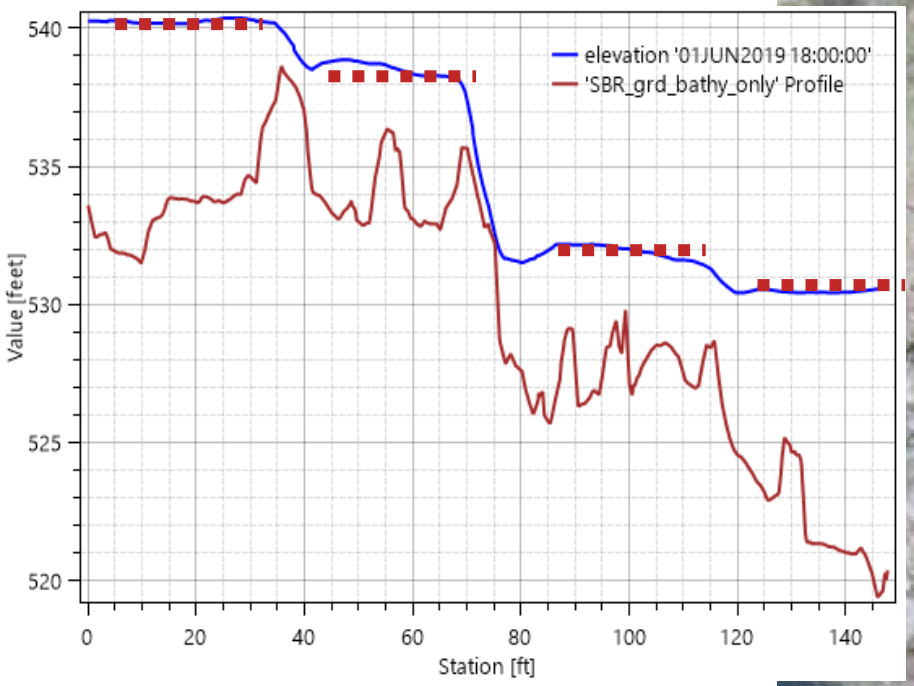


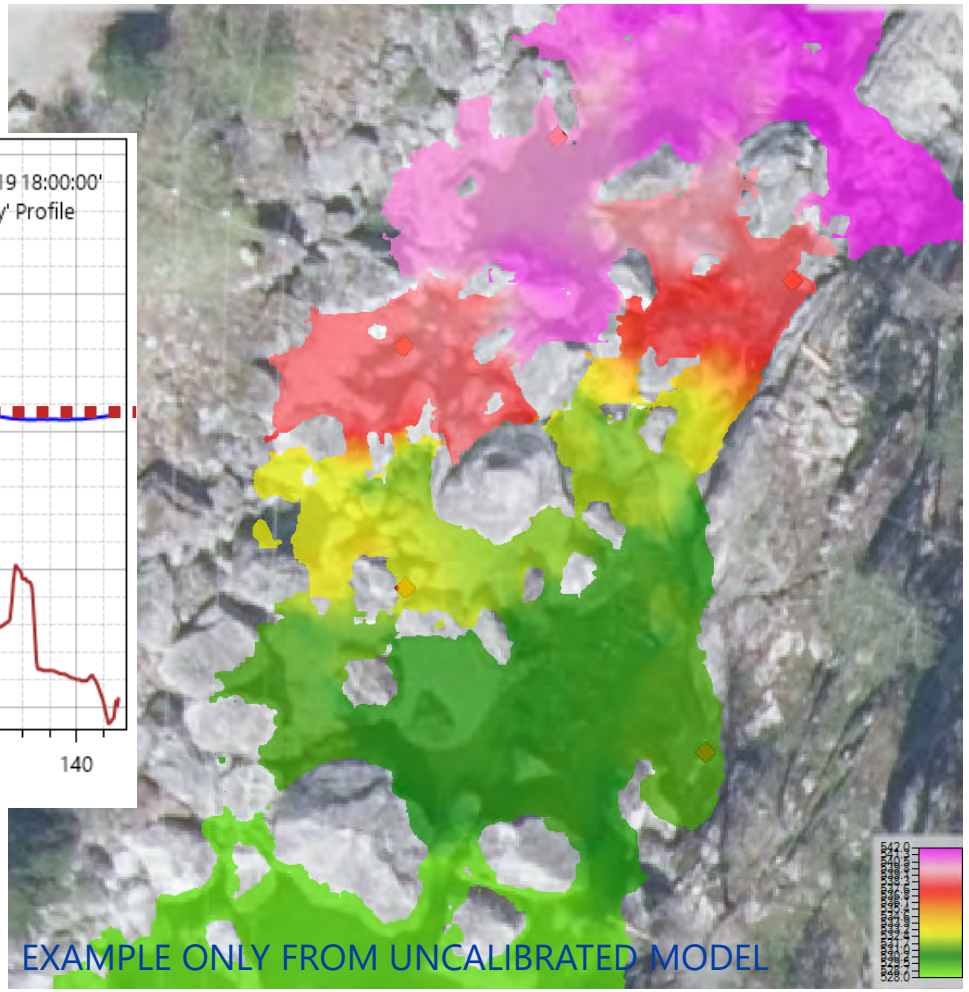
EXAMPLE ONLY FROM UNCALIBRATED MODEL

INSTALLATION – DOWNSTREAM FEATURE



DOWNSTREAM FEATURE





INSTALLATION







WSEL DATUM CORRECTIONS

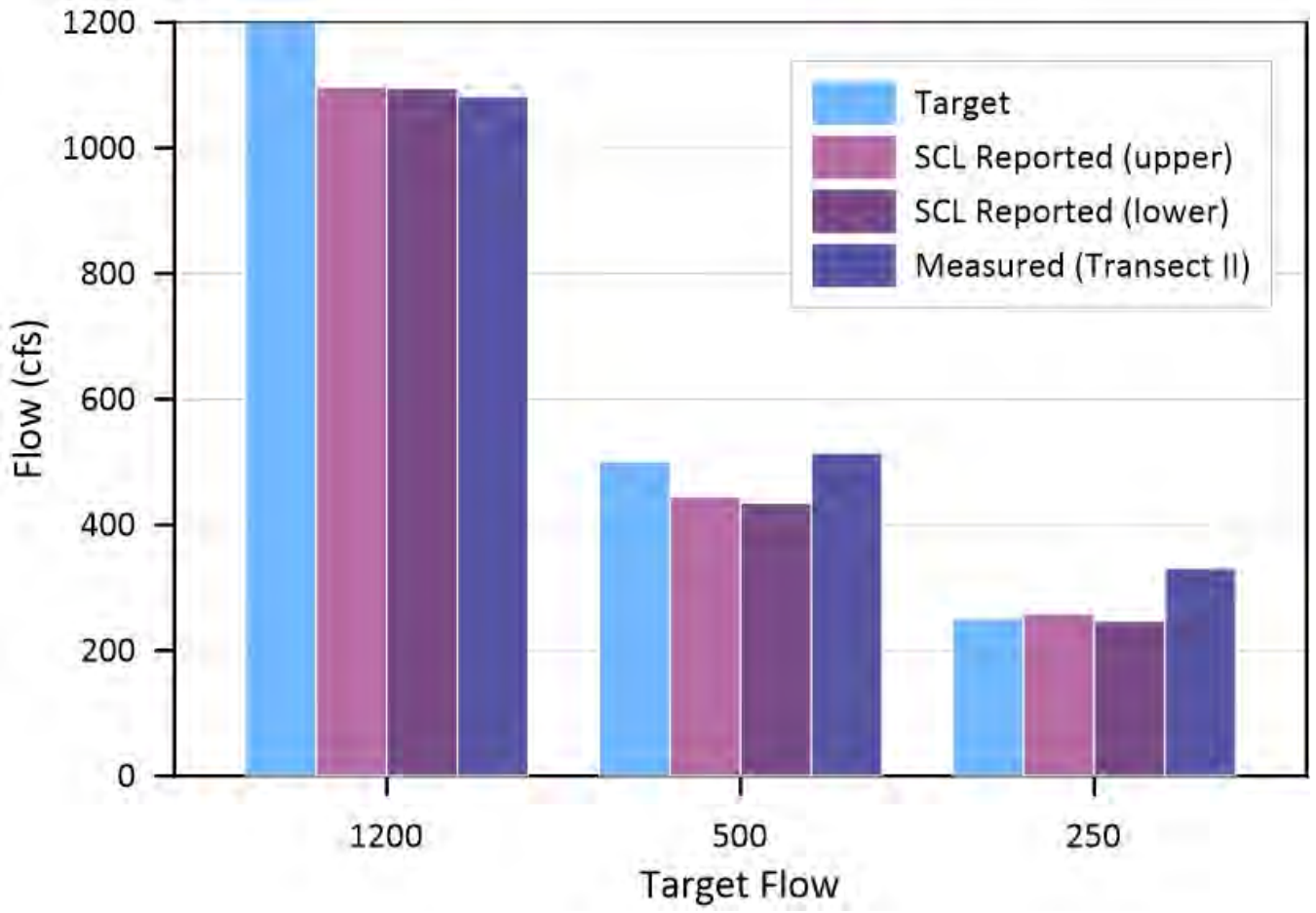
- Total station survey to reference bolt gives bolt elevation to NAVD88.
- Measure down from bolt to water surface gives water surface elevation to NAVD88.
- Subtract HOBO water depth to give HOBO "zero" to NAVD88.



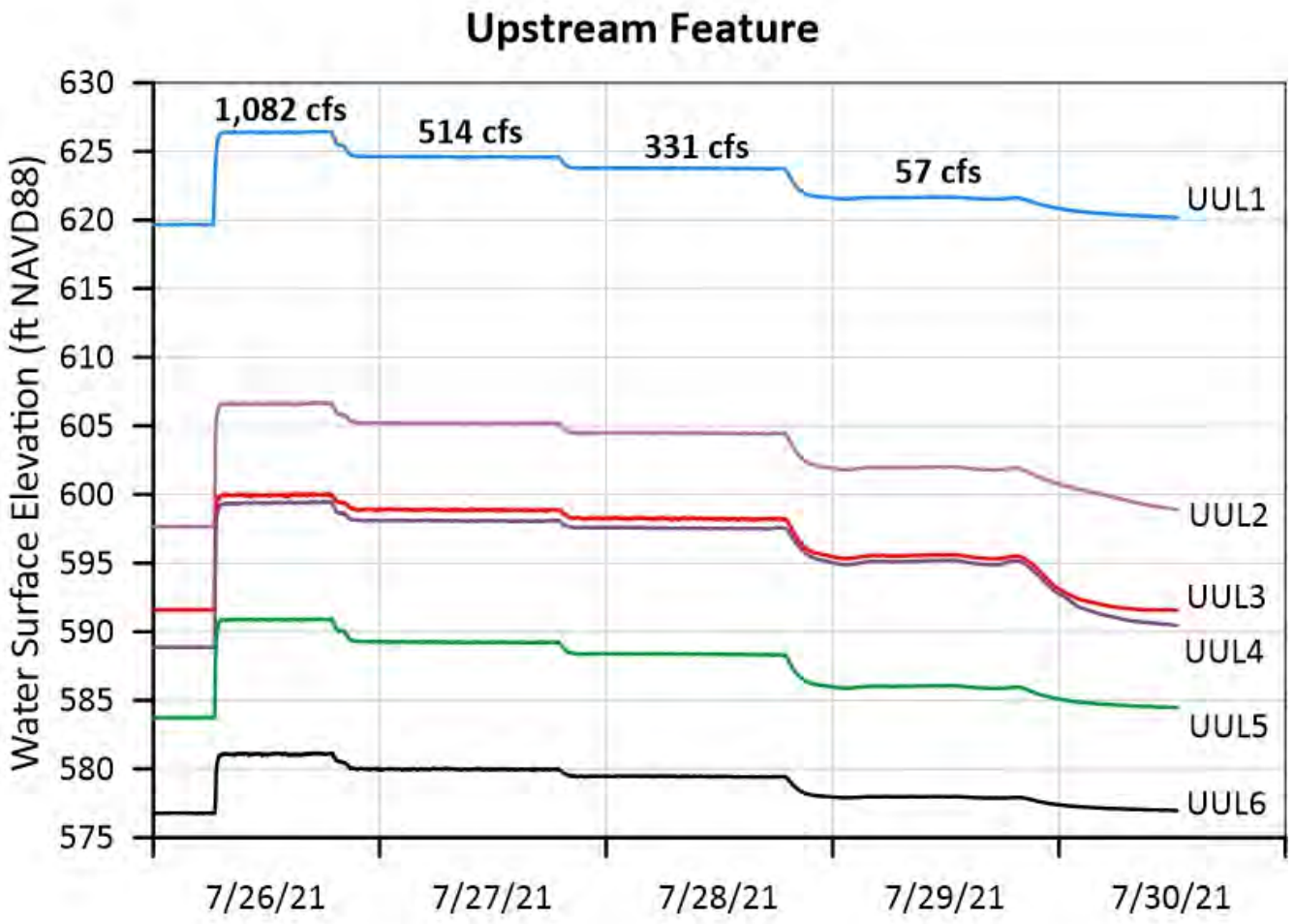
DATA COLLECTION

- Initial deployment 28 May 2021
- Measurement interval:
  - 10-minute 28 May – 25 July
  - 5-minute since 25 July
- Monthly downloads (~ 45-day logger data capacity)

CONTROLLED RELEASE – DATA COMPARISON



CONTROLLED SPILL DATA – UPSTREAM FEATURE



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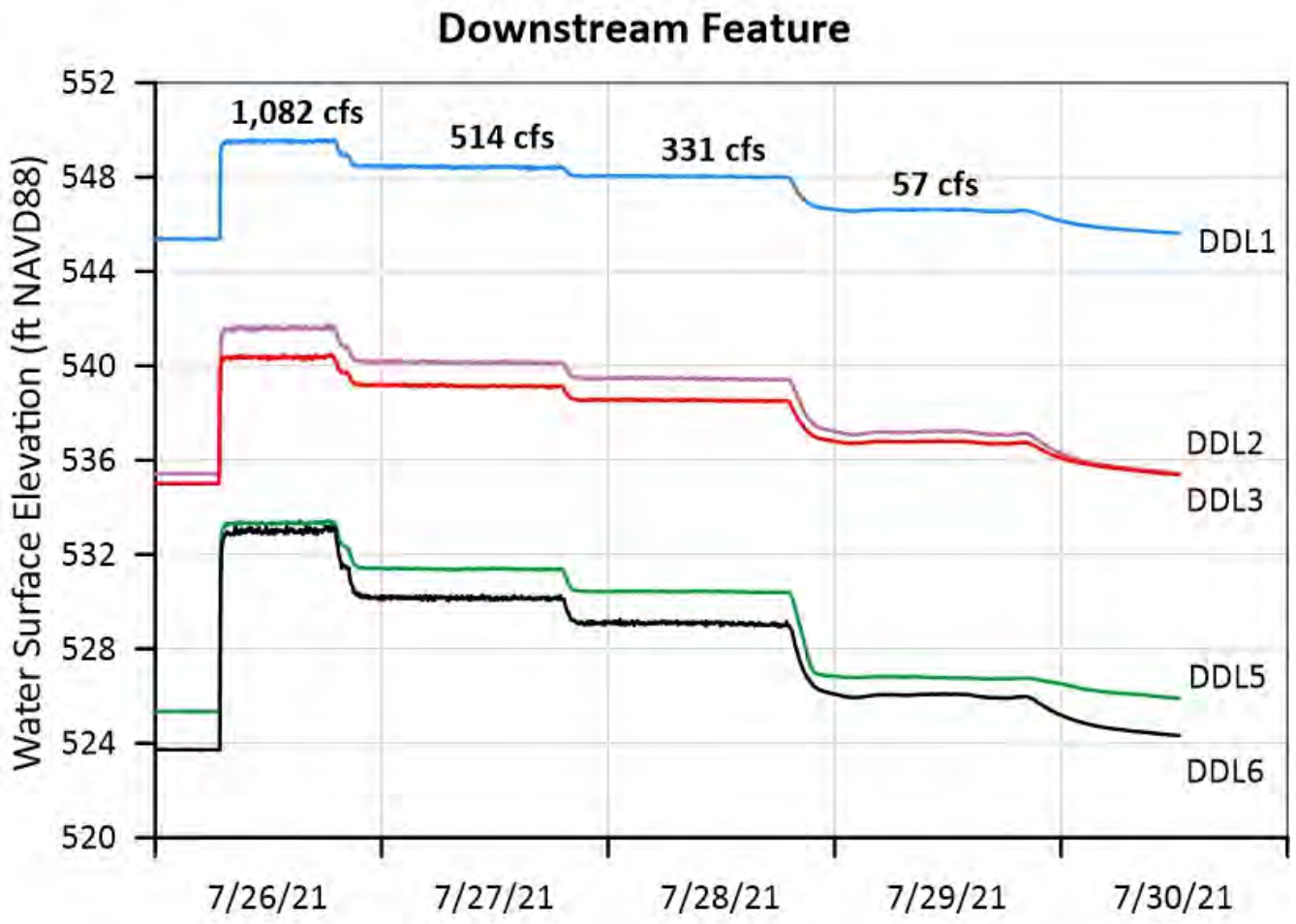
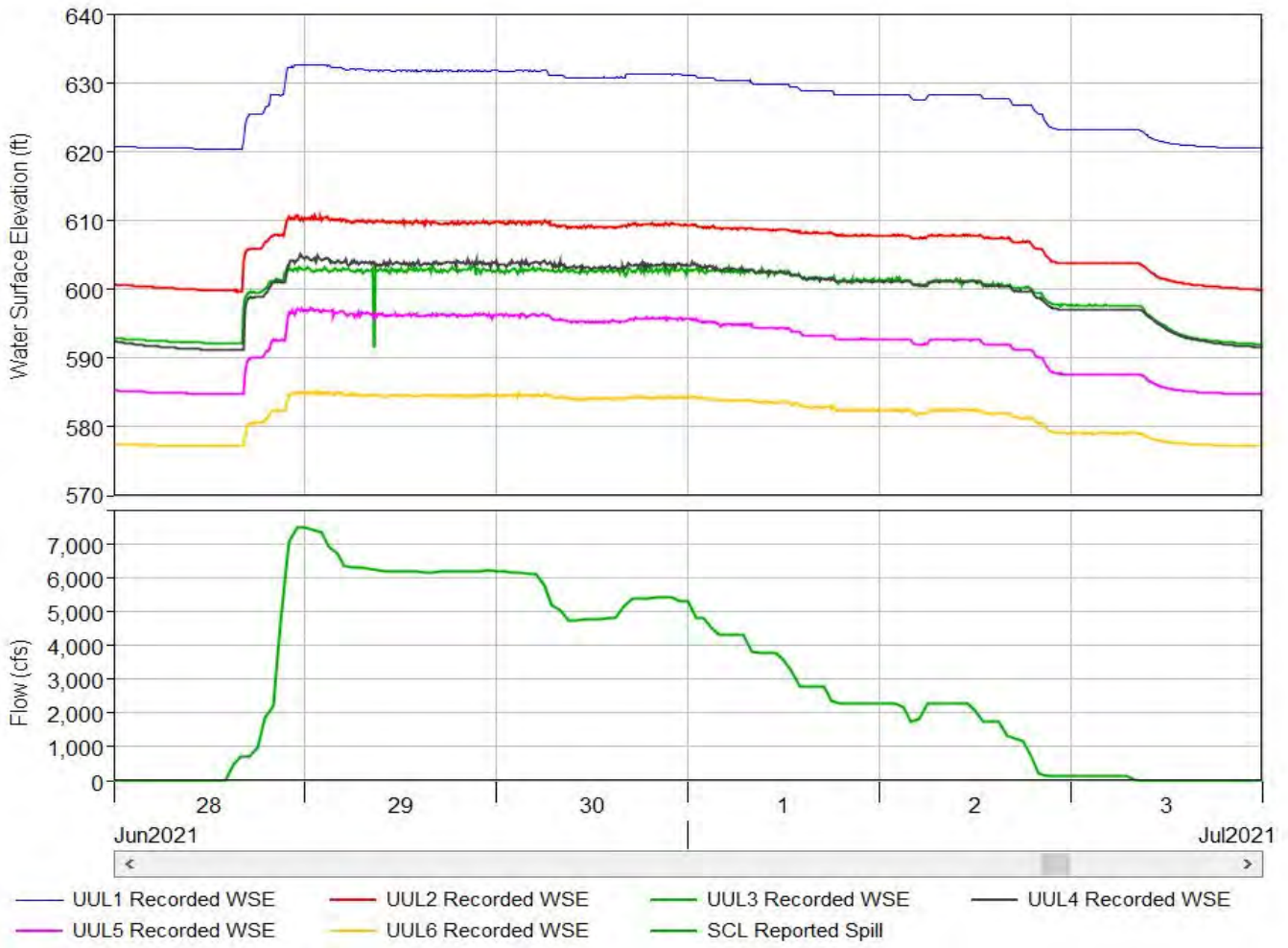
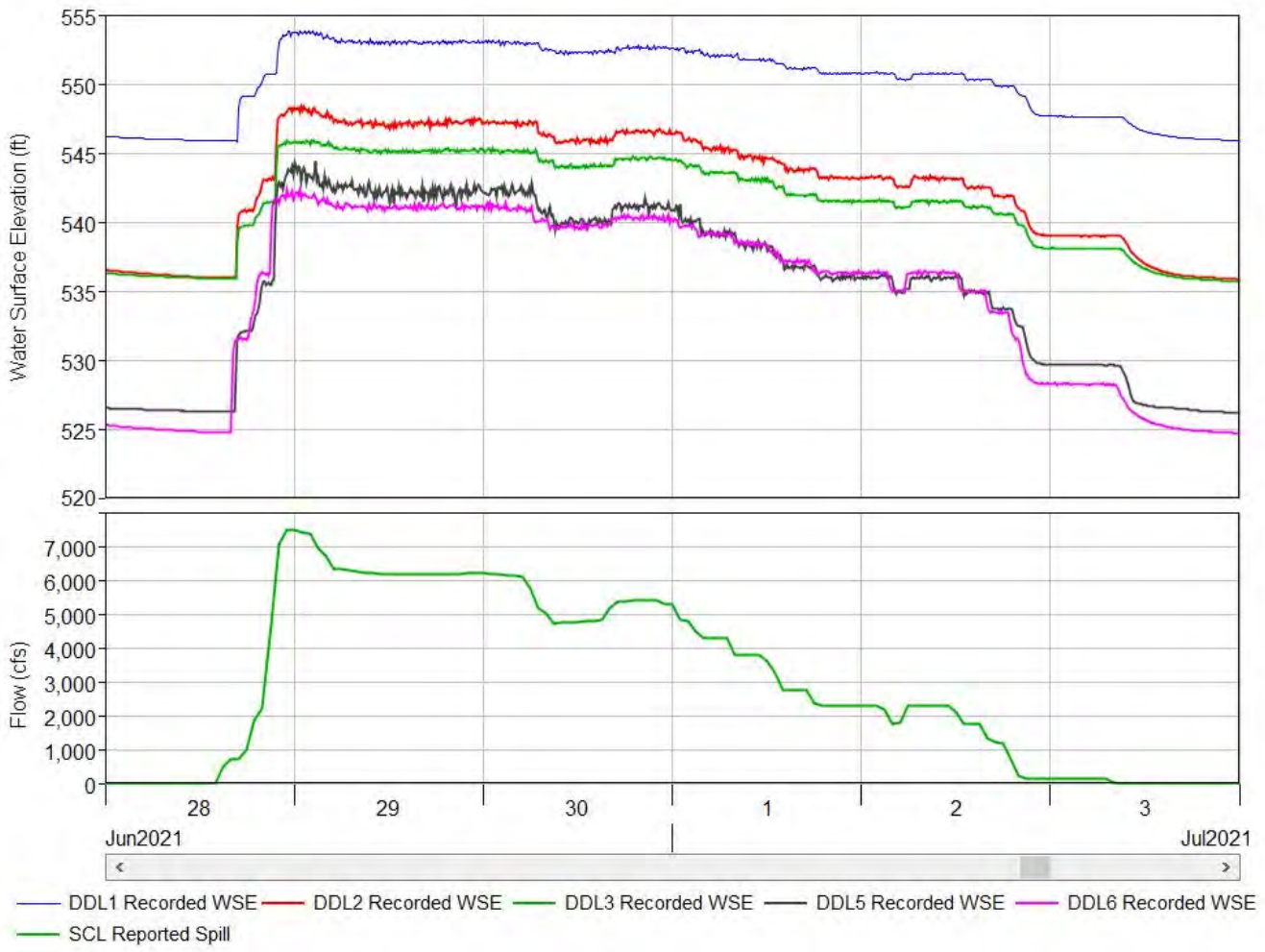


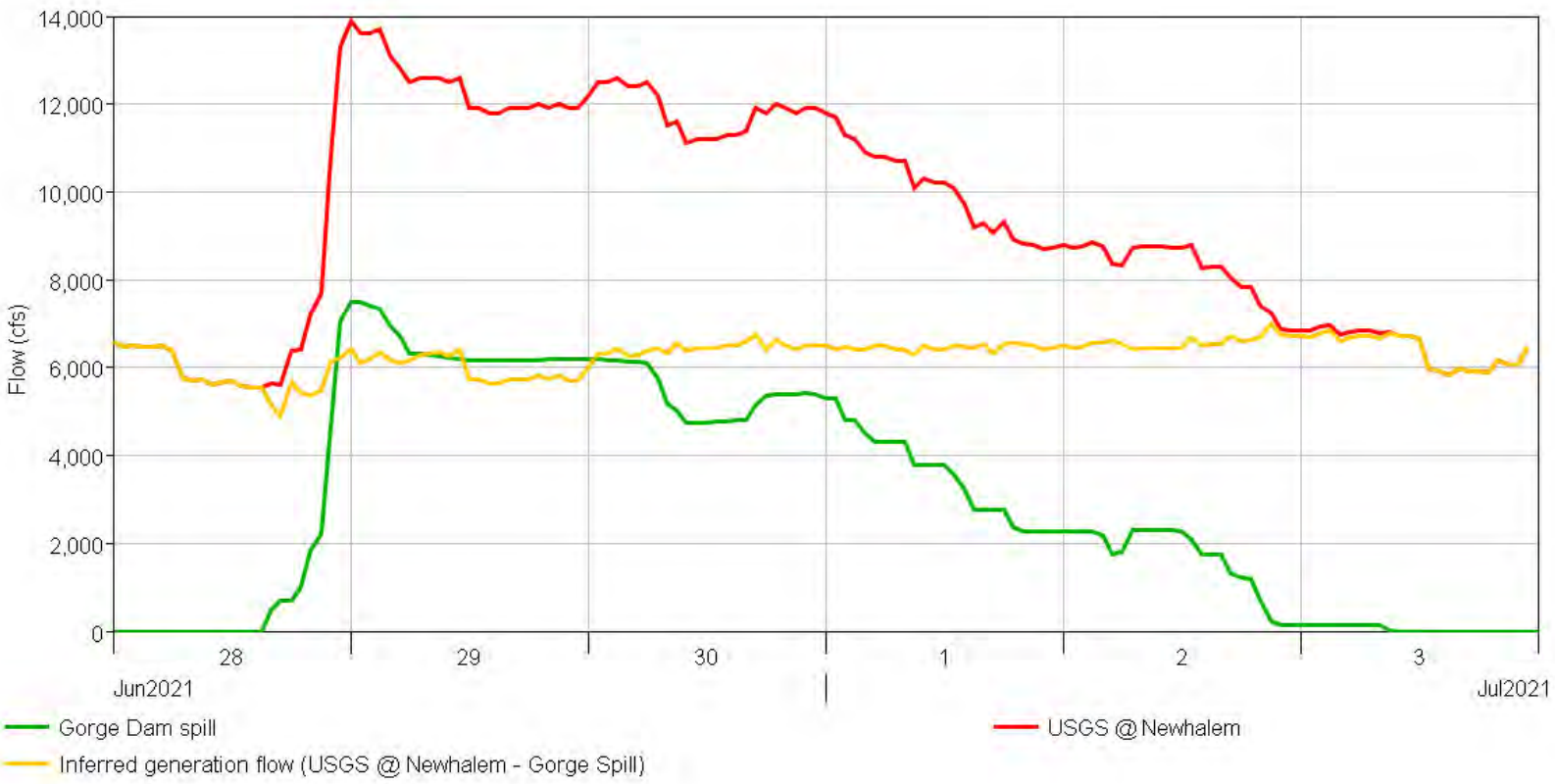
JUNE/JULY SPILL DATA – UPSTREAM FEATURE



JUNE/JULY SPILL DATA – DOWNSTREAM FEATURE



JUNE/JULY SPILL DATA – DATA CHECK



DOWNSTREAM FEATURE – 4,700 CFS



DOWNSTREAM FEATURE – 300 CFS



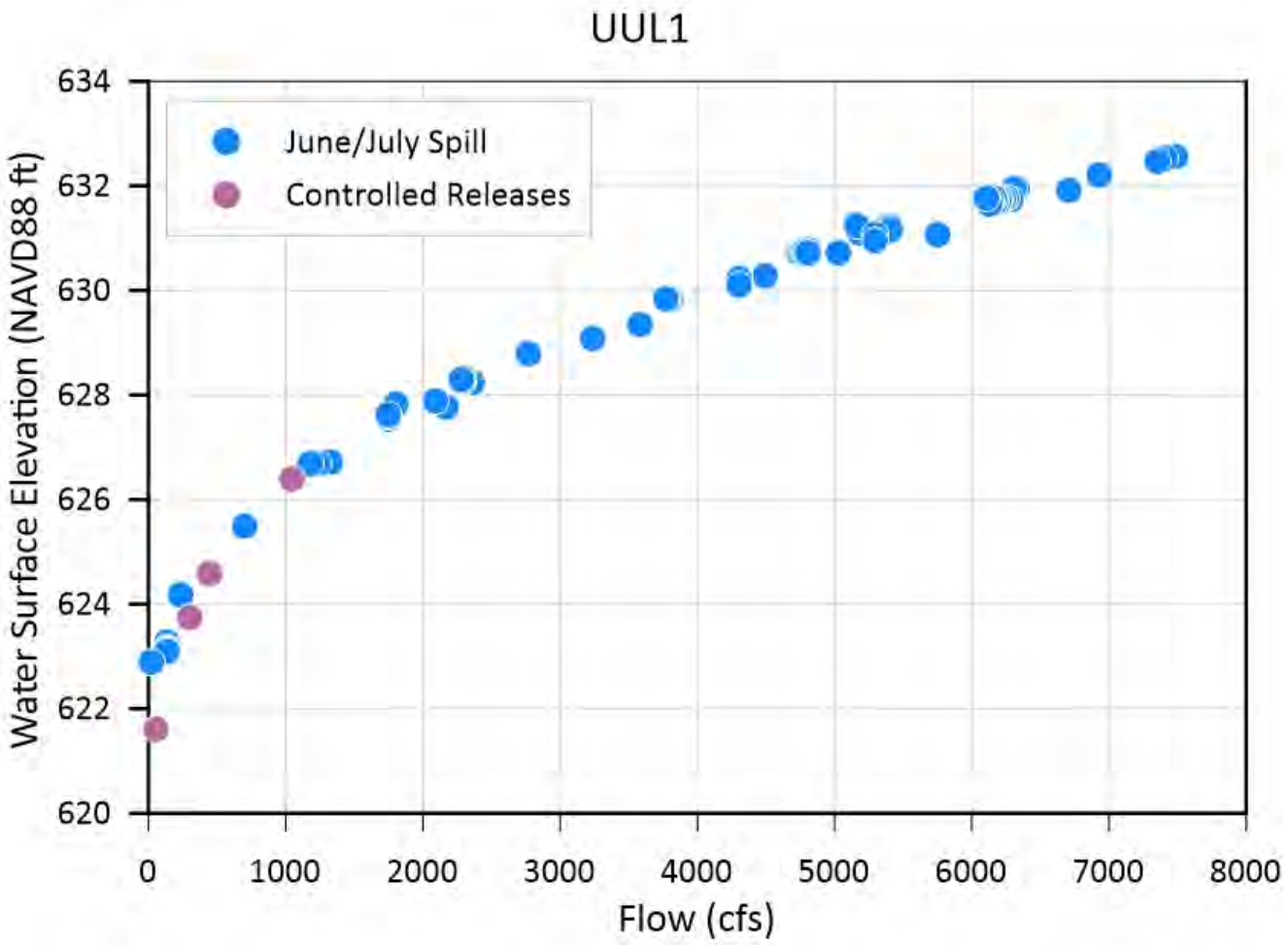
UPSTREAM FEATURE – 4,700 CFS



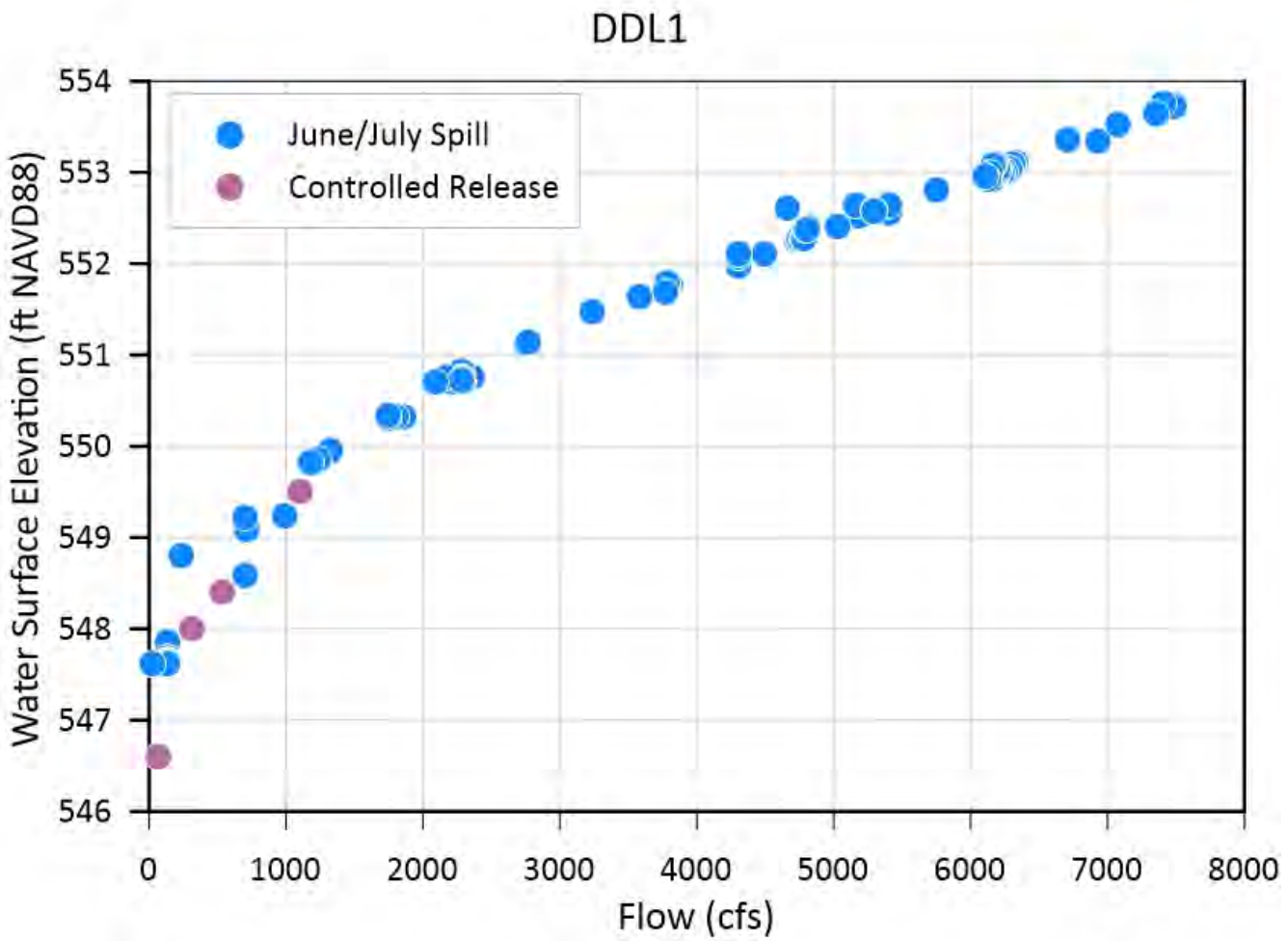
UPSTREAM FEATURE – NO SPILL



LOGGER RATING – UUL1

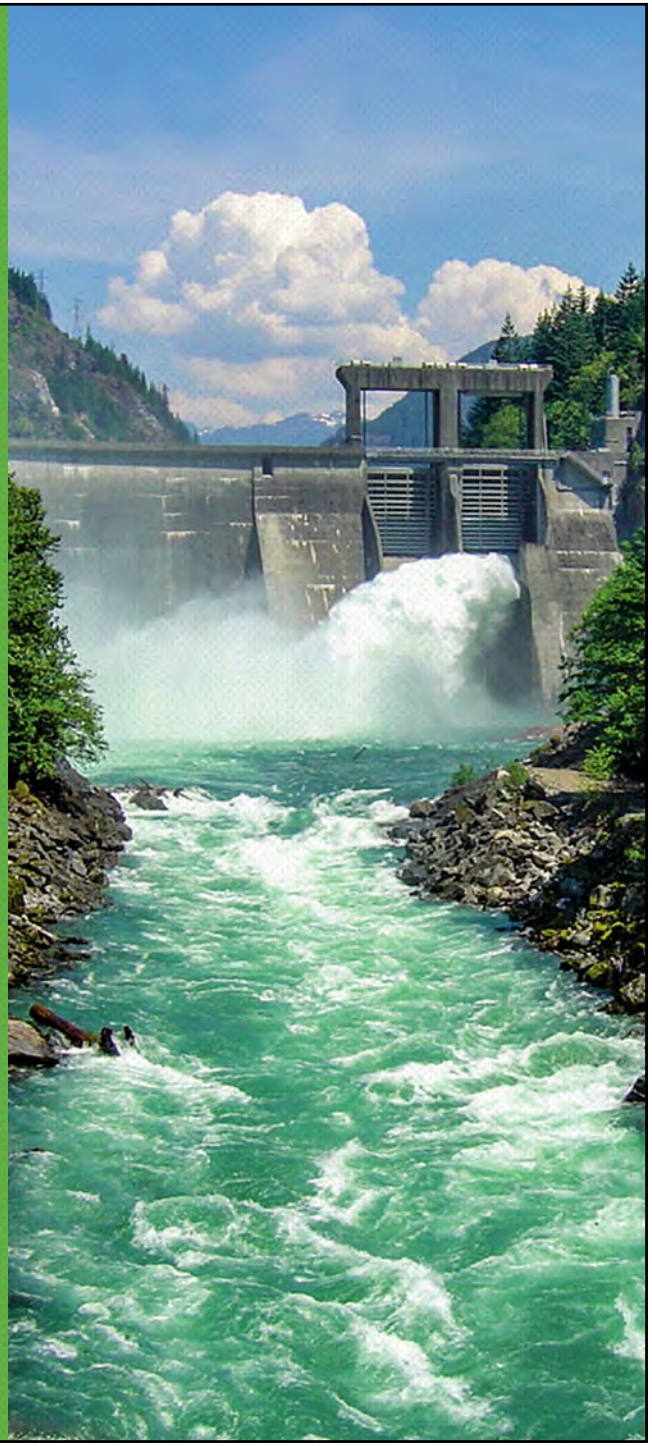


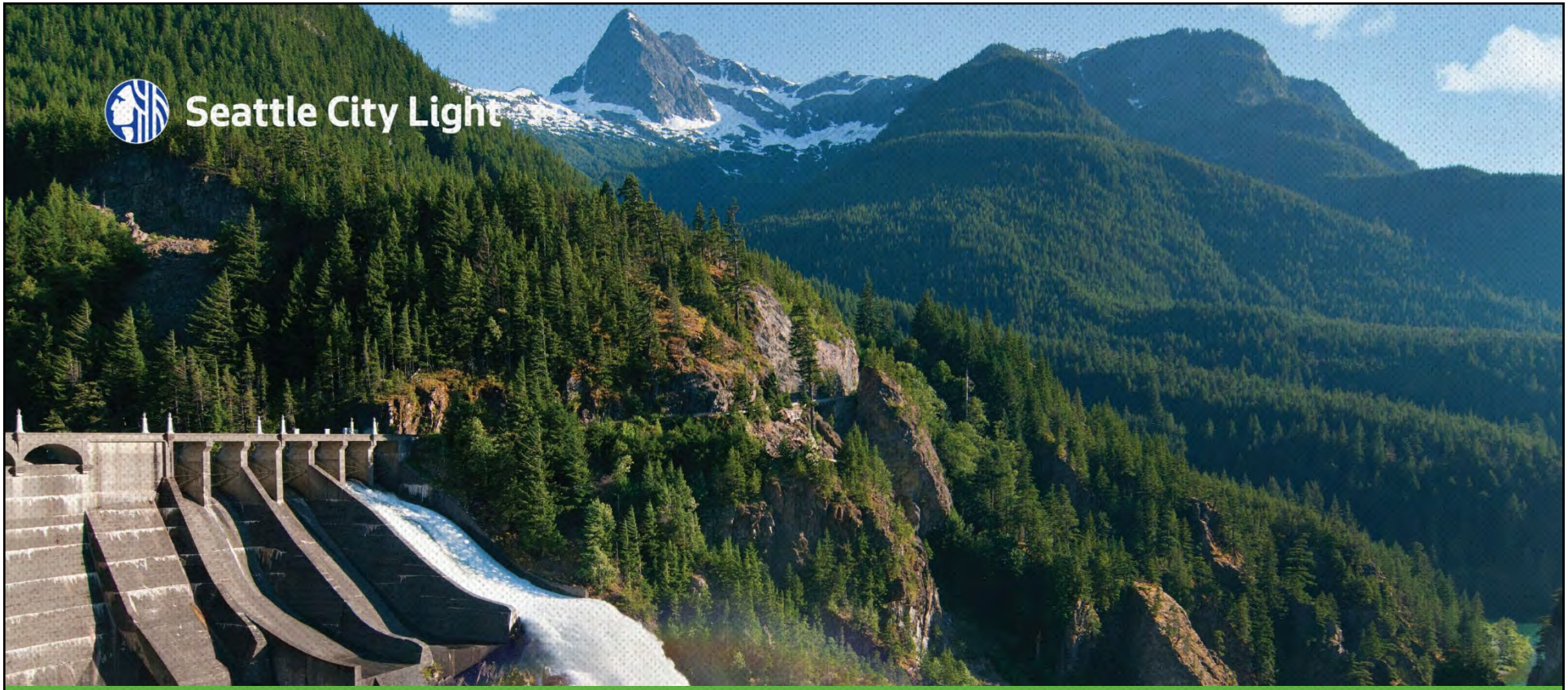
LOGGER RATING – DDL1



Seattle City Light

DISCUSSION



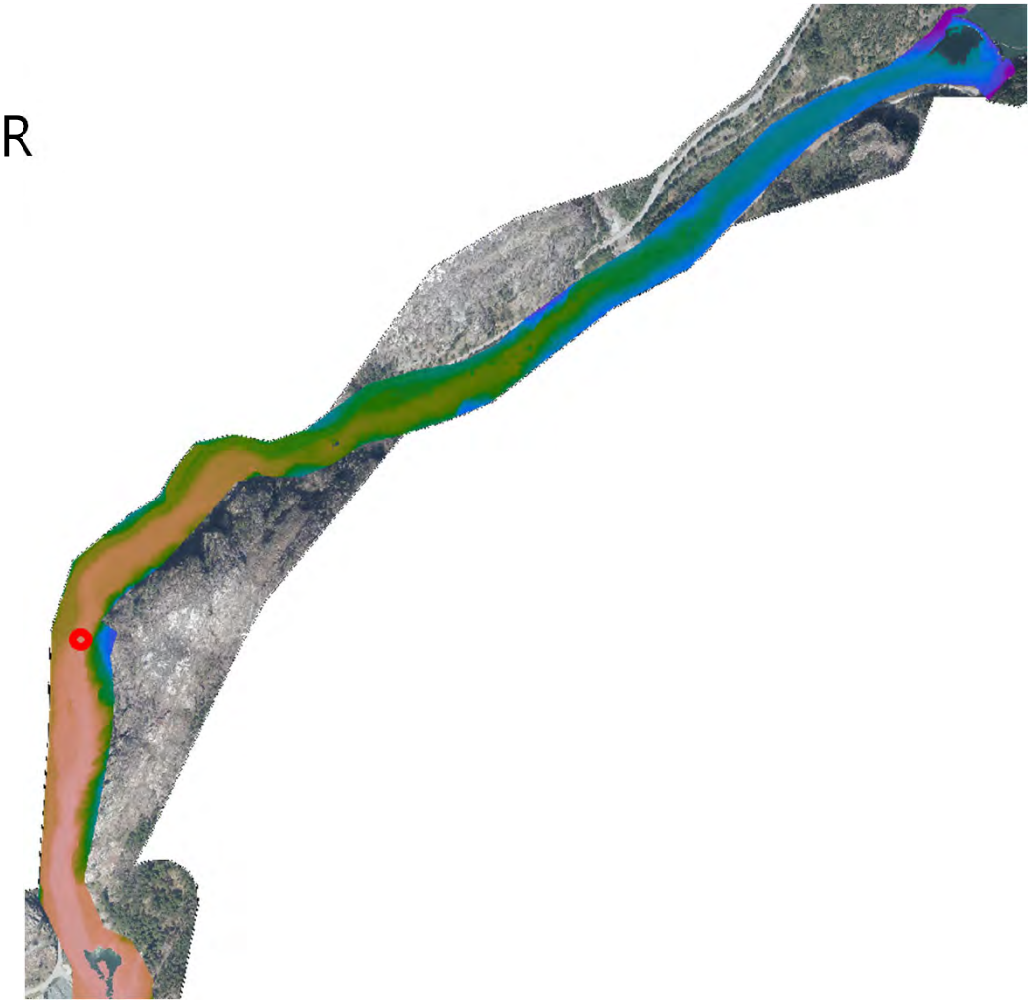


HYDRAULIC MODEL TERRAIN

August 26, 2021

OVERVIEW

- Quantum Spatial 2018
  - Water Penetrating LiDAR
- 3 voids
  - Gorge Dam plunge pool
  - Gorge Powerhouse tailrace
  - 20'x50'x25+' deep hole
- 0.52 points/ft^2 density
- NVA = 0.201'
- Bathy VA = 0.366'
- Original Resolution = 3ft

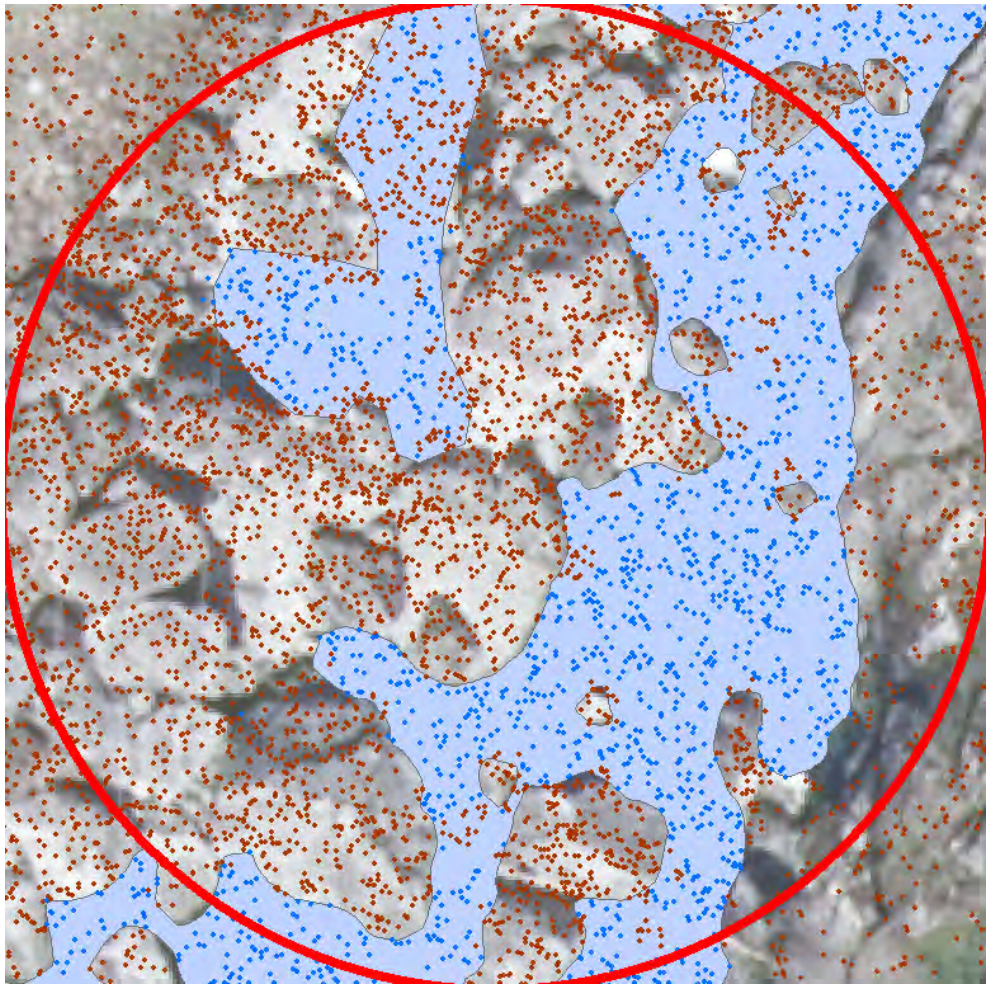


SAMPLE LIDAR DENSITY



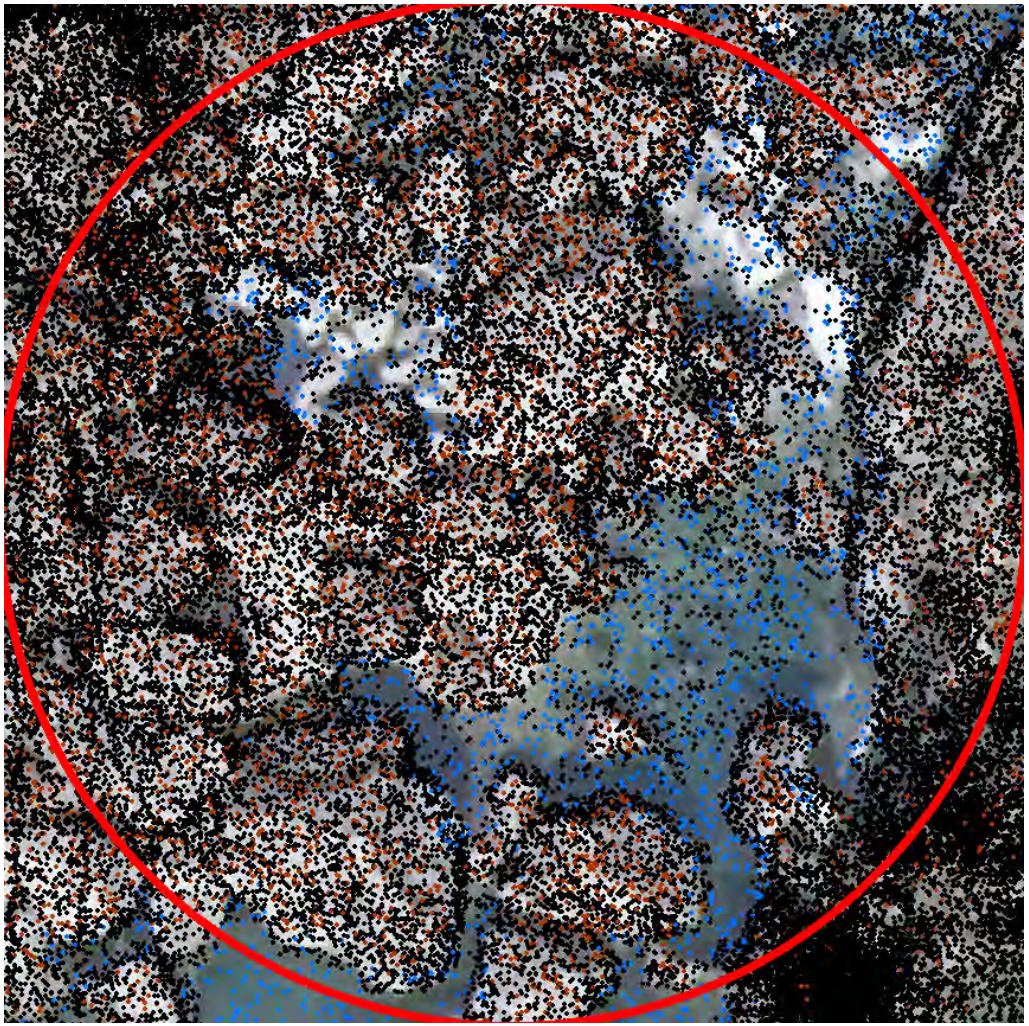
LIDAR DENSITY

- Avg density
  - 6 pulses/m^2
- Pulse spacing
  - 0.41 m
- 2 X pulse spacing
  - 2.7 feet



- Ground
- Bathymetry

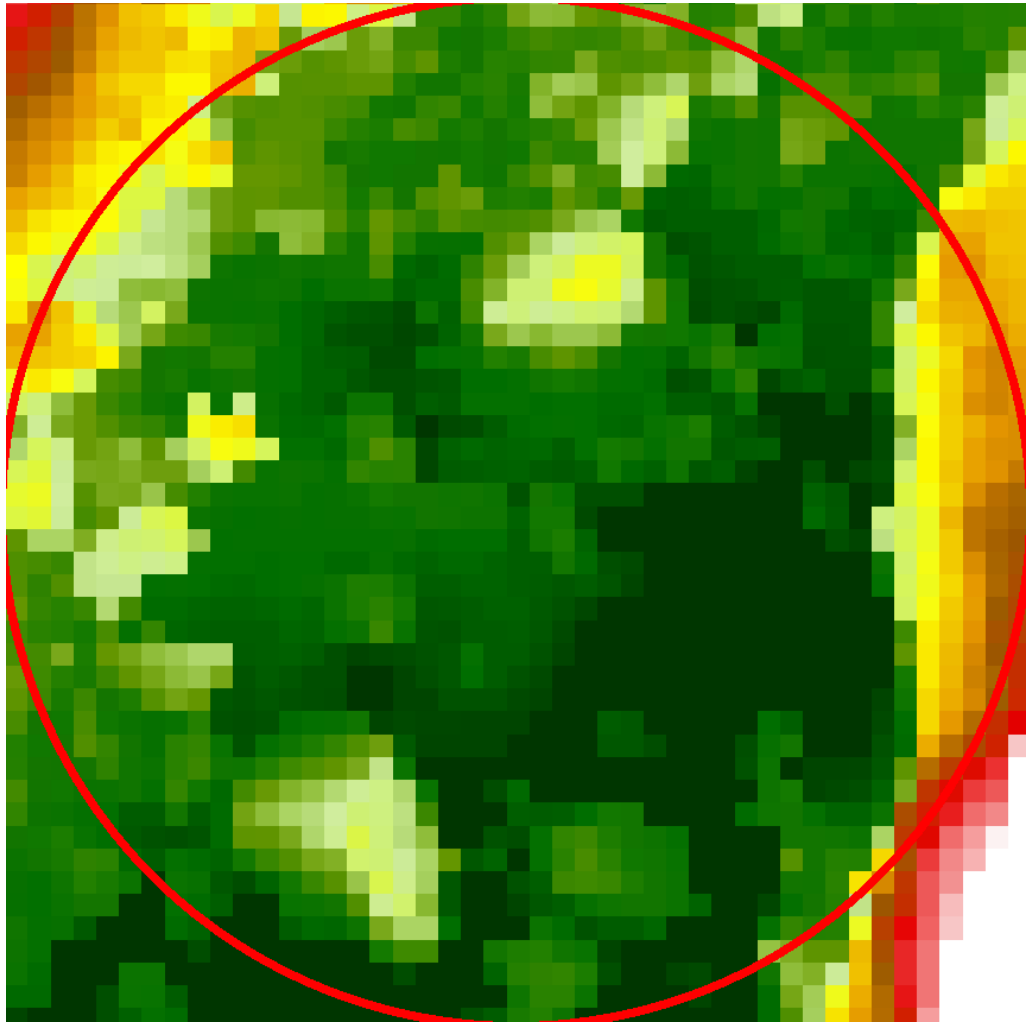
LIDAR DENSITY



- Unassigned
- Ground
- Bathymetry

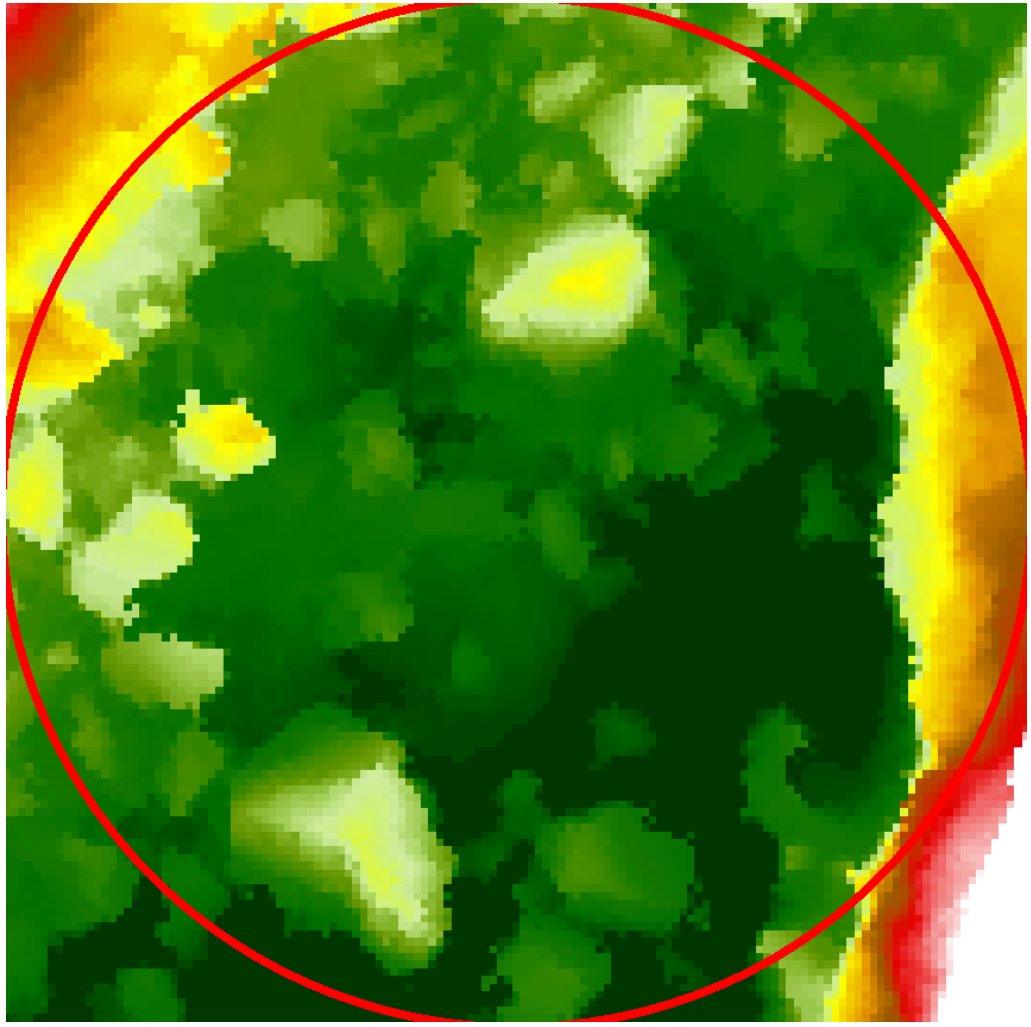
ORIGINAL RESOLUTION

- 3′ raster



TARGET RESOLUTION

- 1′ raster

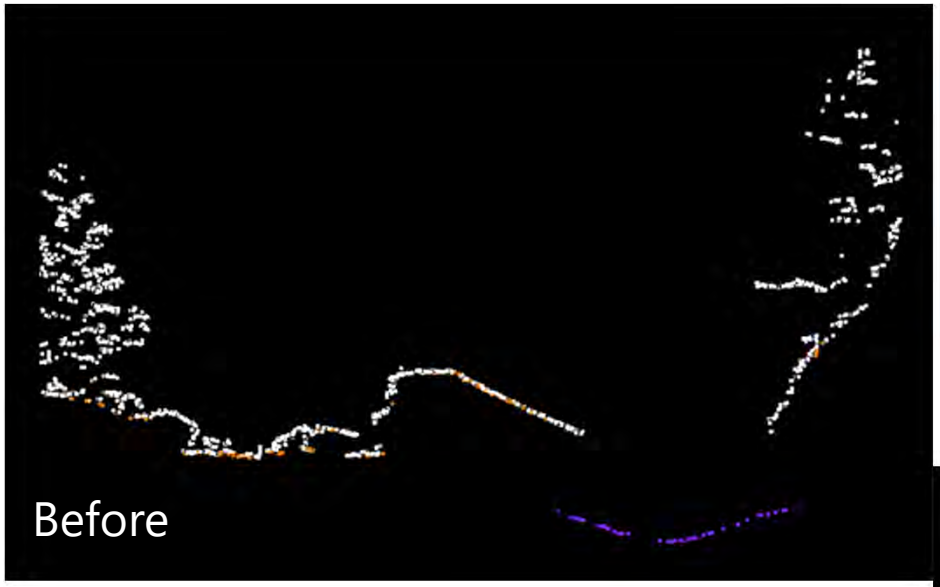


TERRAIN REFINEMENT

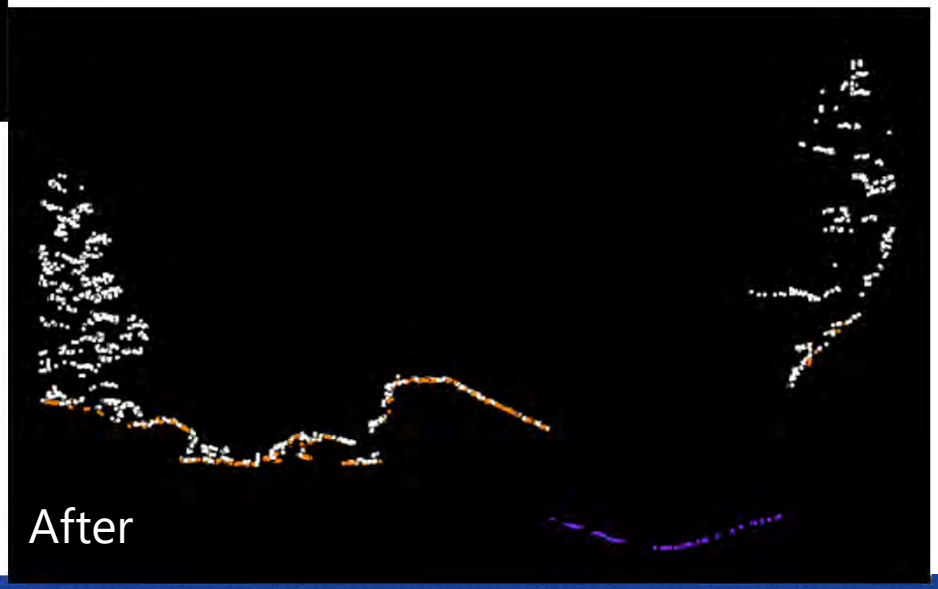
- Focus areas
  - Hydraulic features
  - Dry Channel



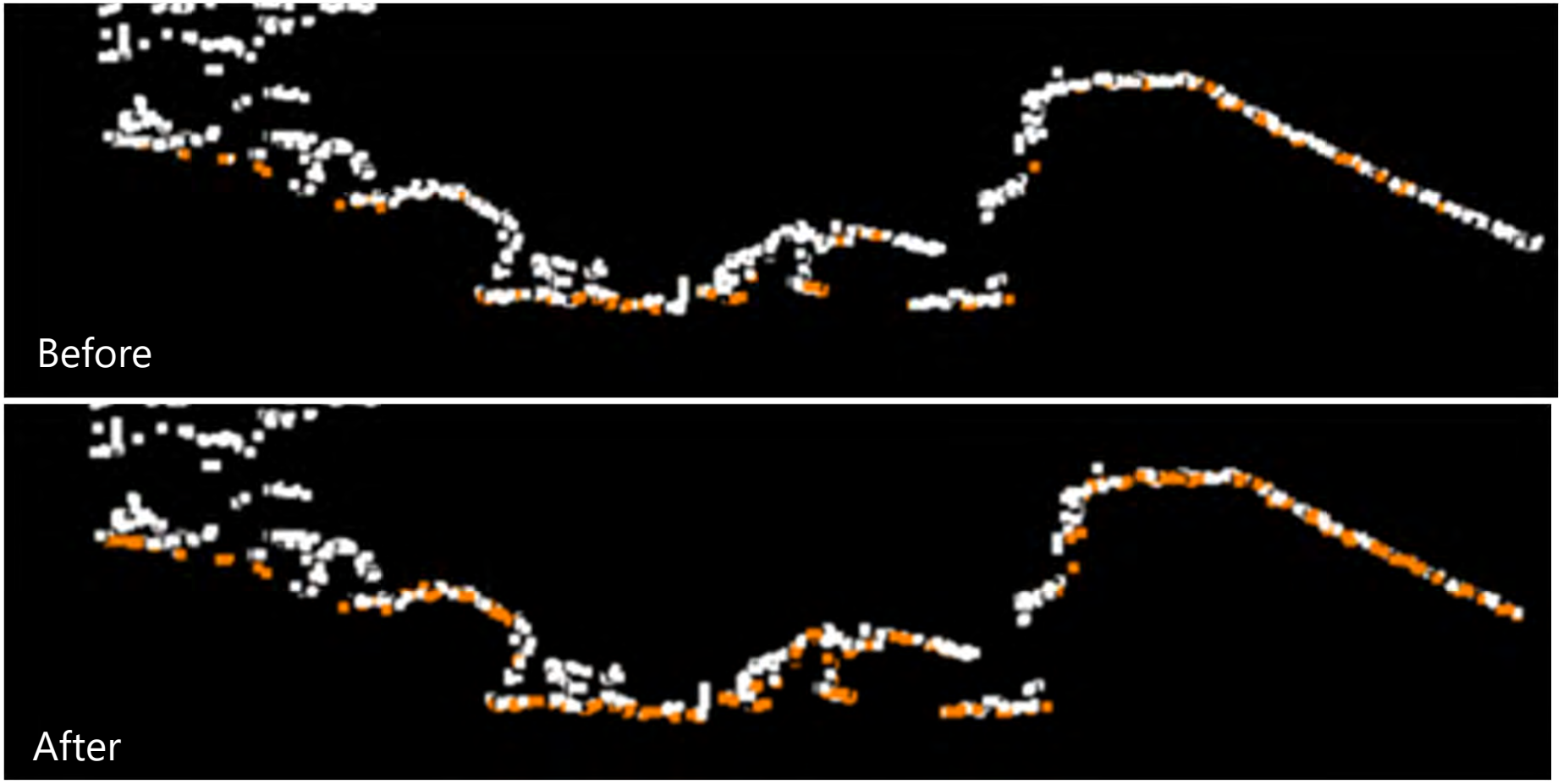
POINT RECLASSIFICATION



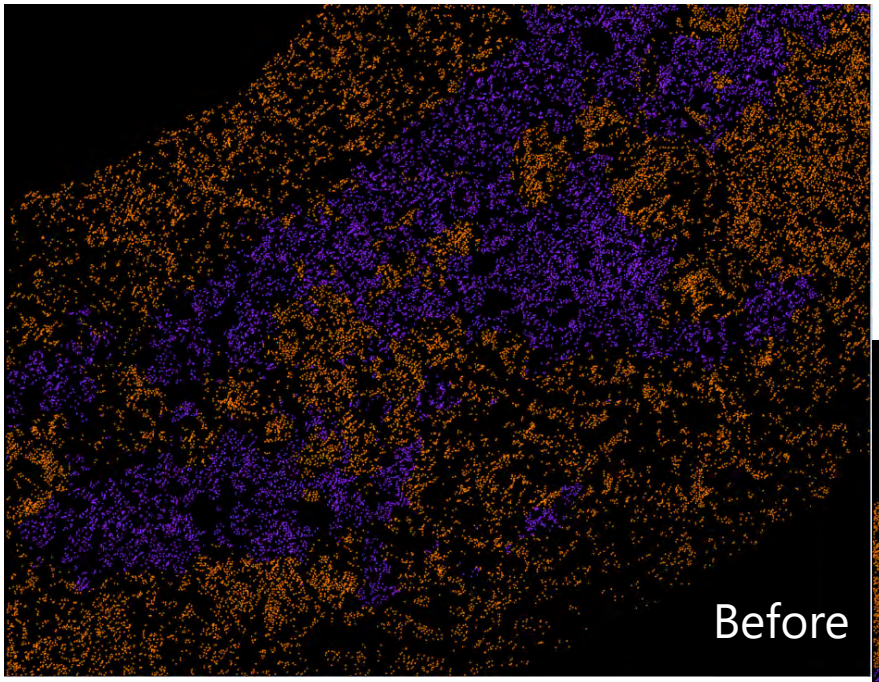
- White = Default
- Orange = Ground
- Purple = Bathymetric Bottom



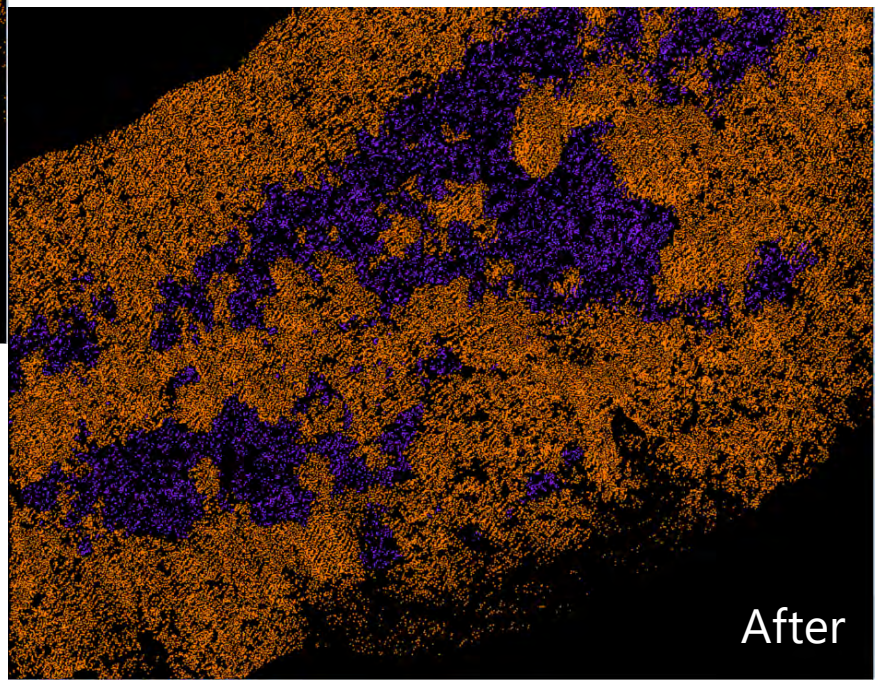
POINT RECLASSIFICATION



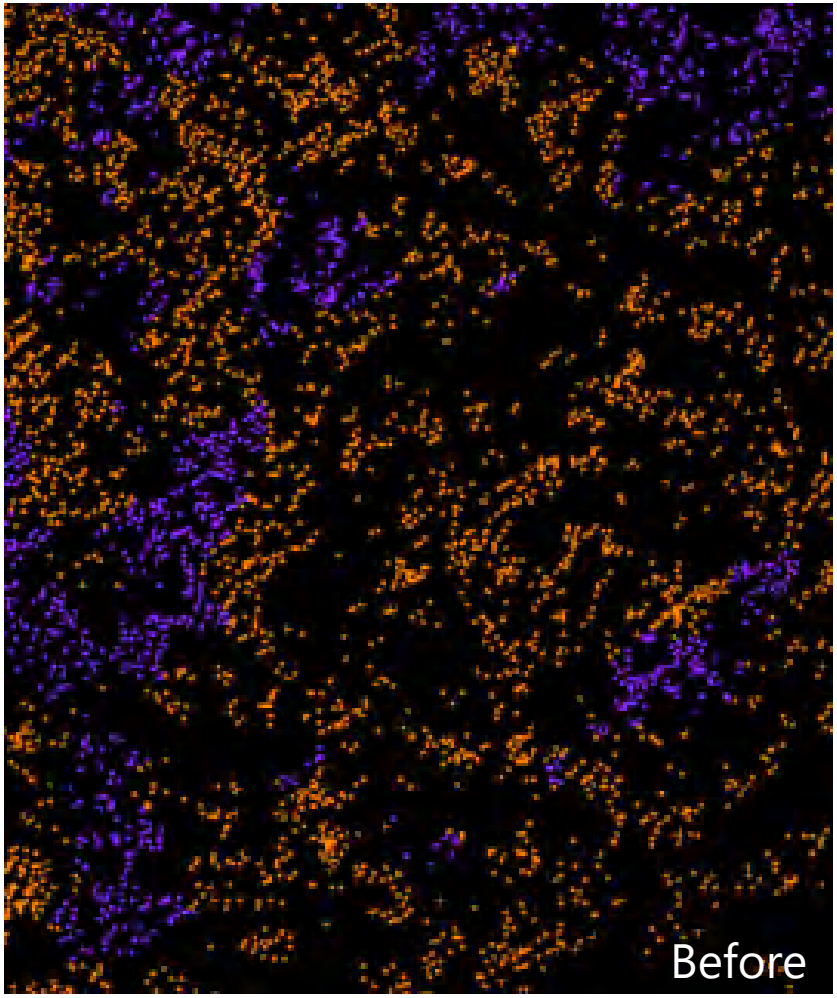
POINT RECLASSIFICATION

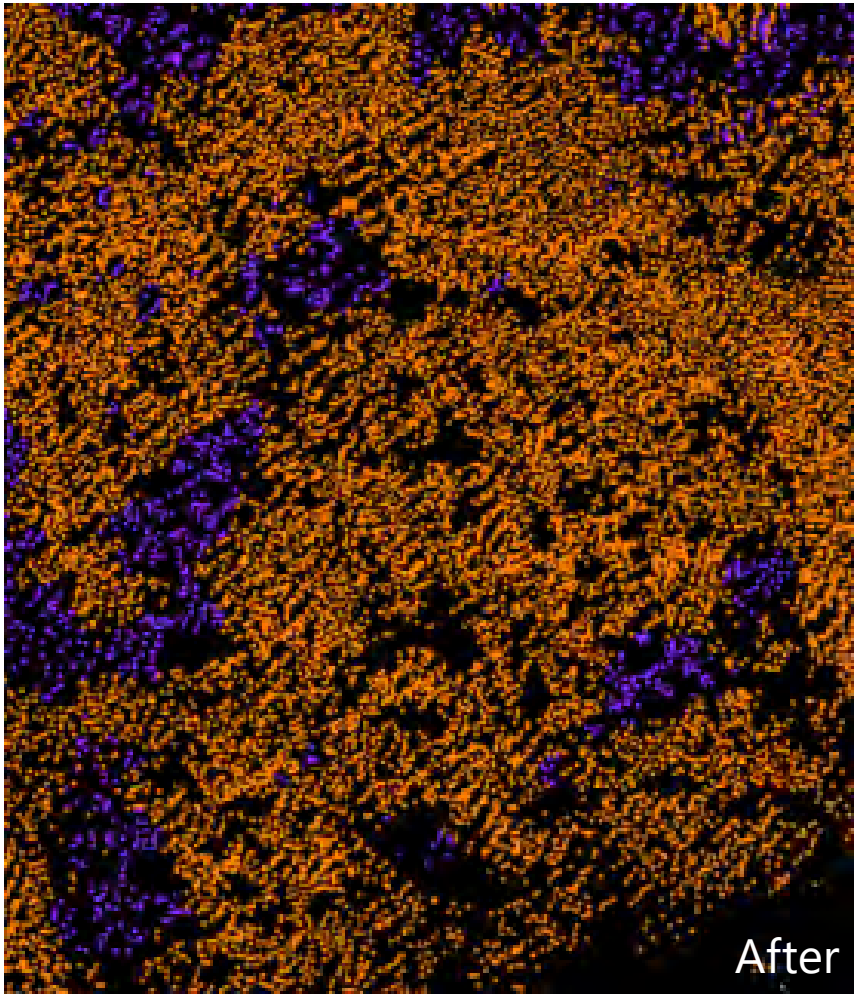


- Orange = Ground
- Purple = Bathymetric Bottom



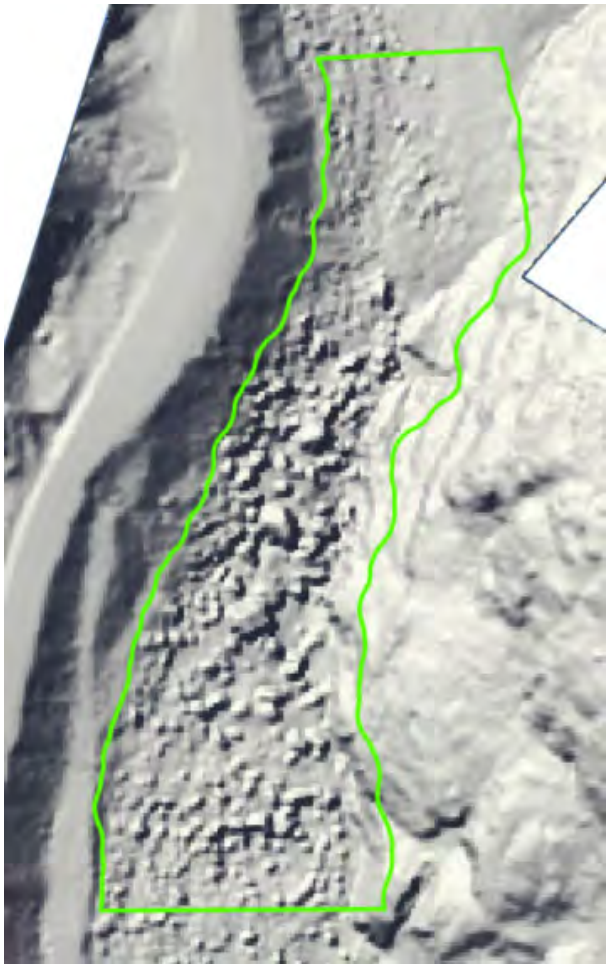
POINT RECLASSIFICATION



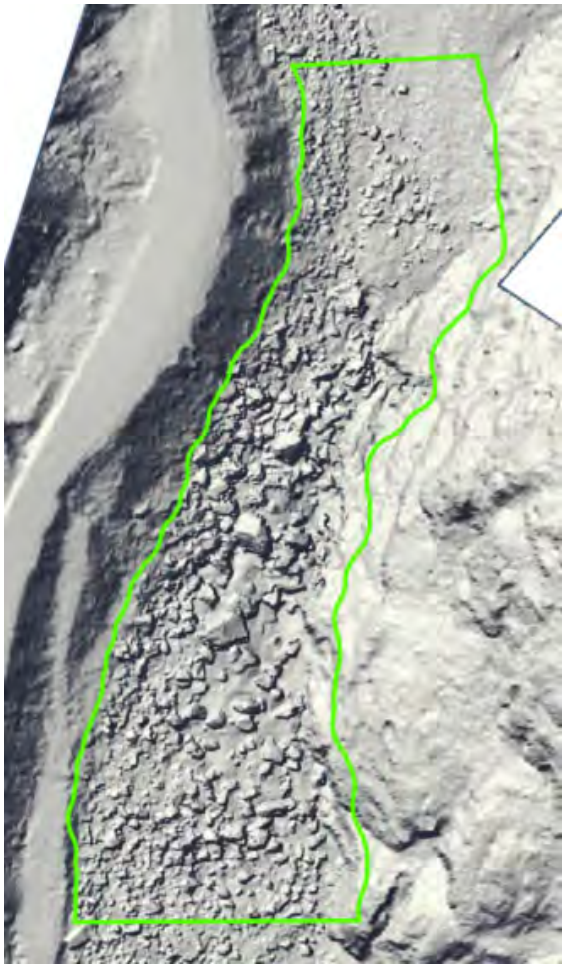


FOCUS AREA 1 – 1’ GRID

Before (3ft Cell Resolution)

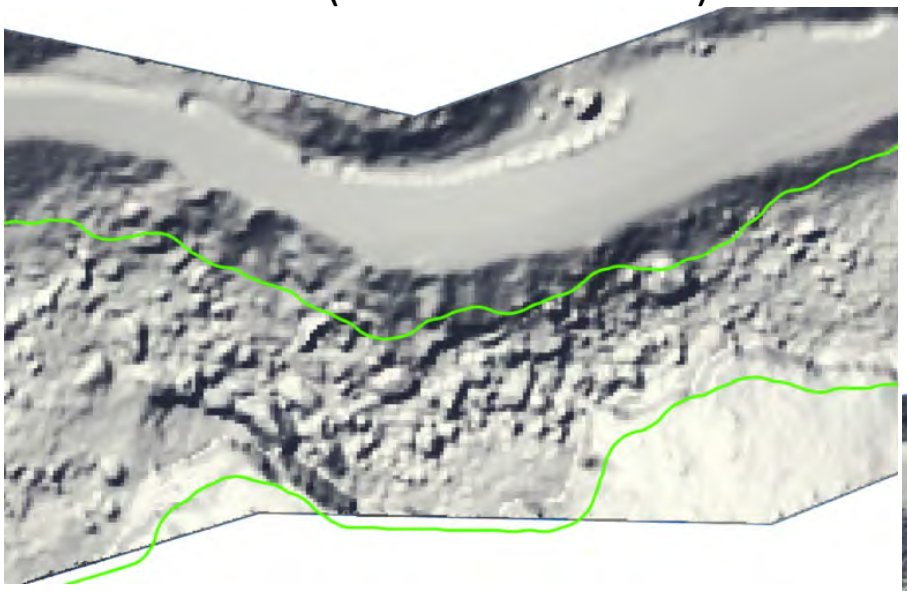


After (1ft Cell Resolution)

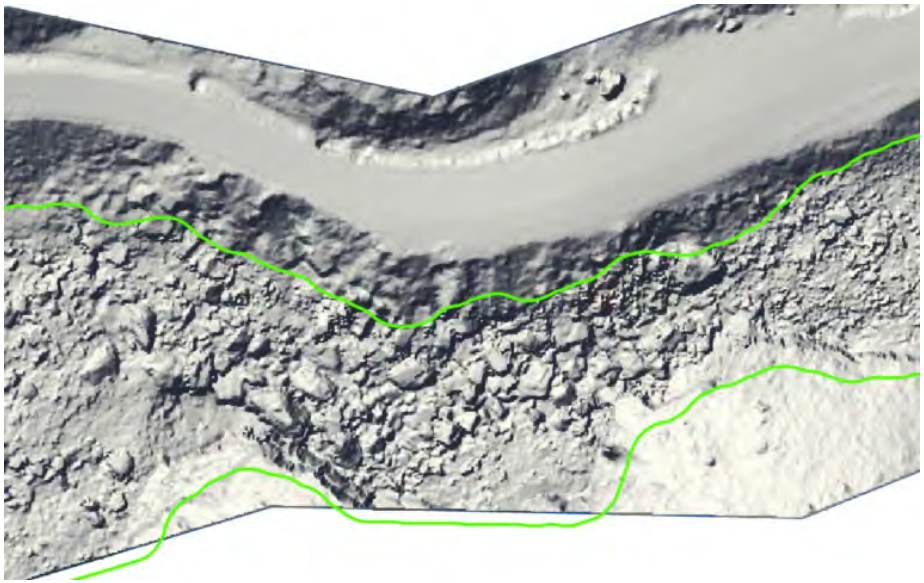


FOCUS AREA 2 – 1’ GRID

Before (3ft Cell Resolution)

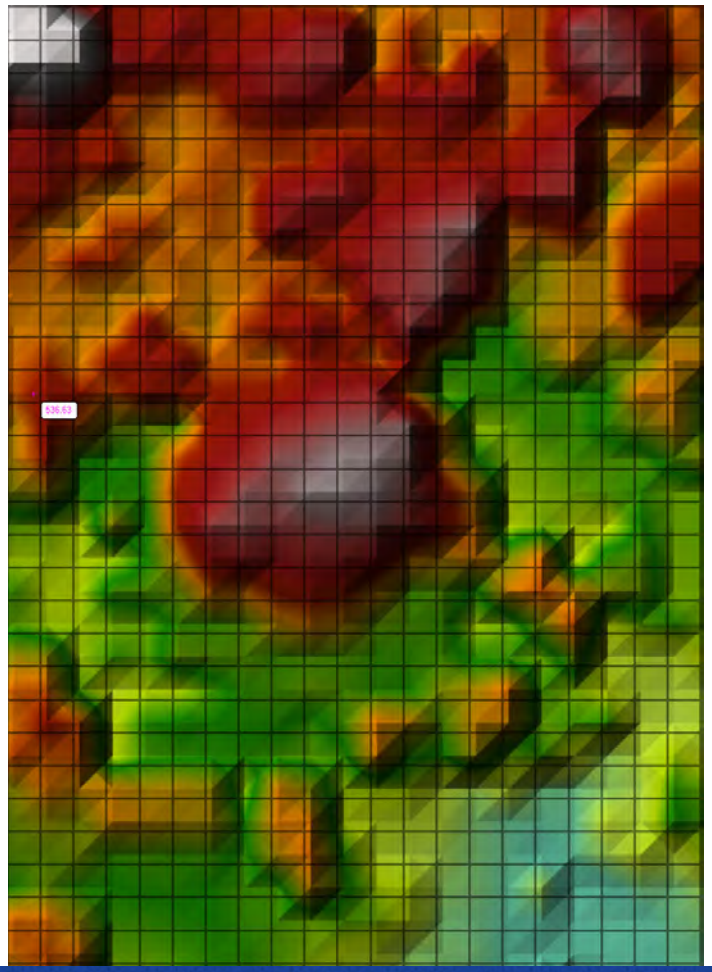


After (1ft Cell Resolution)

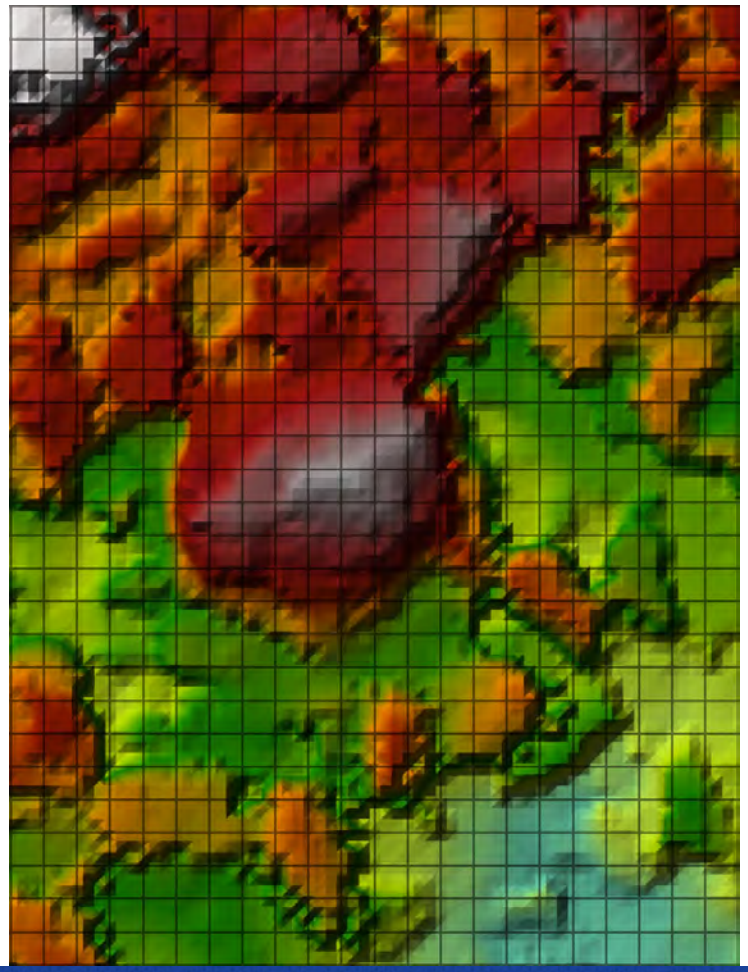


MODEL IMPLEMENTATION

3ft Resolution

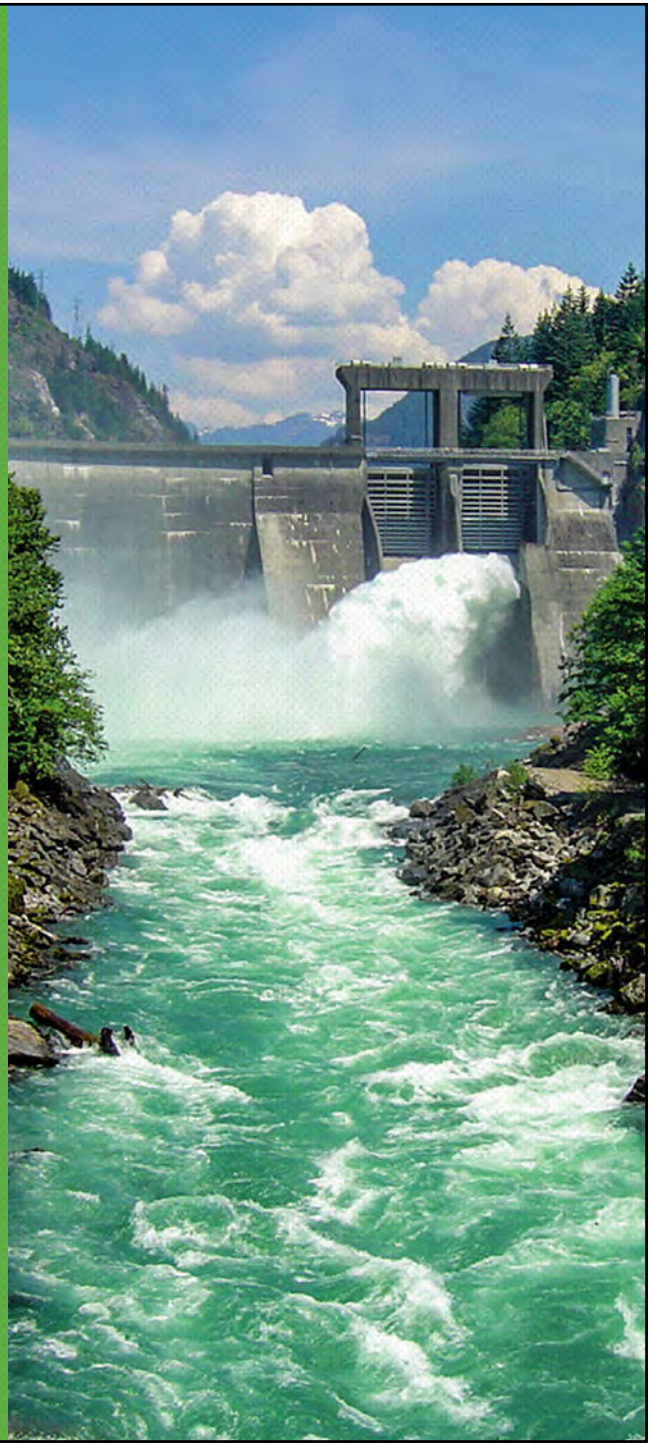


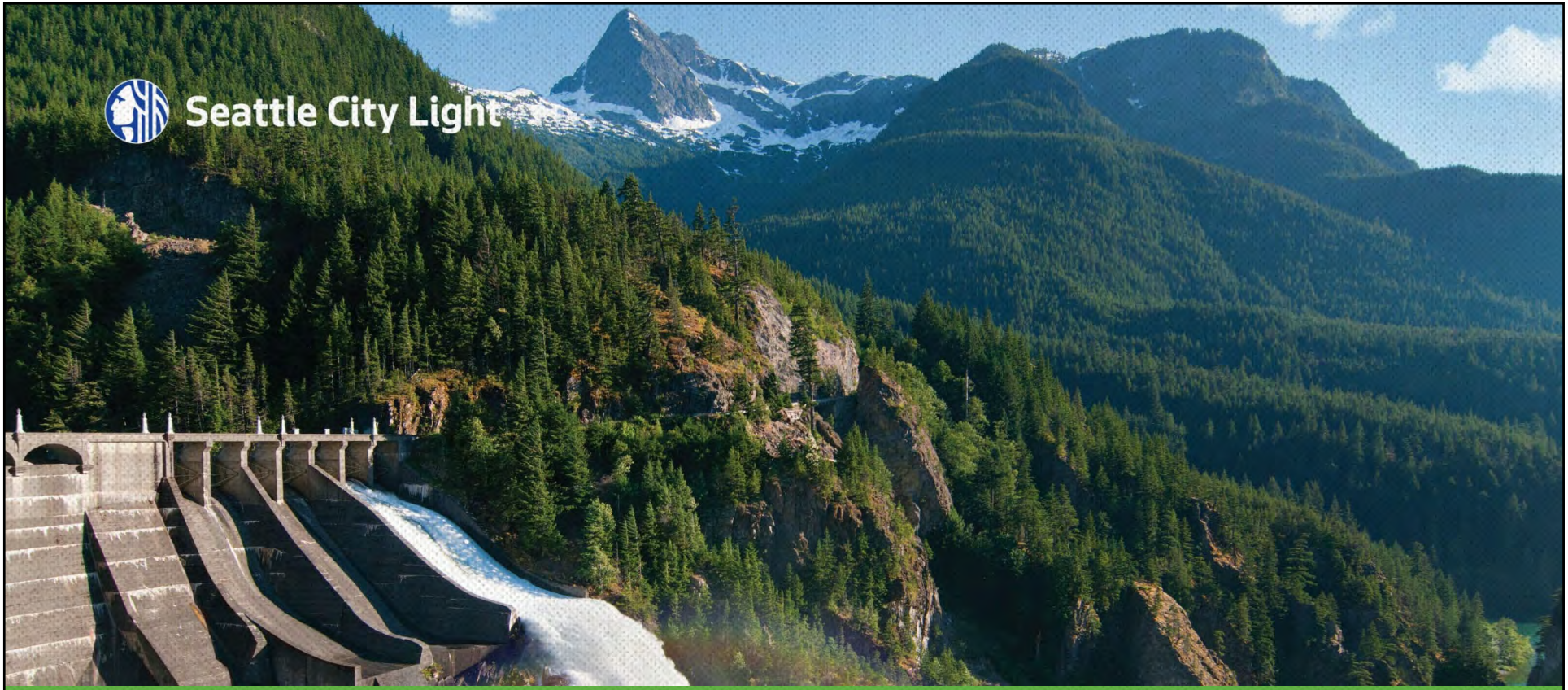
1ft Resolution



Seattle City Light

DISCUSSION





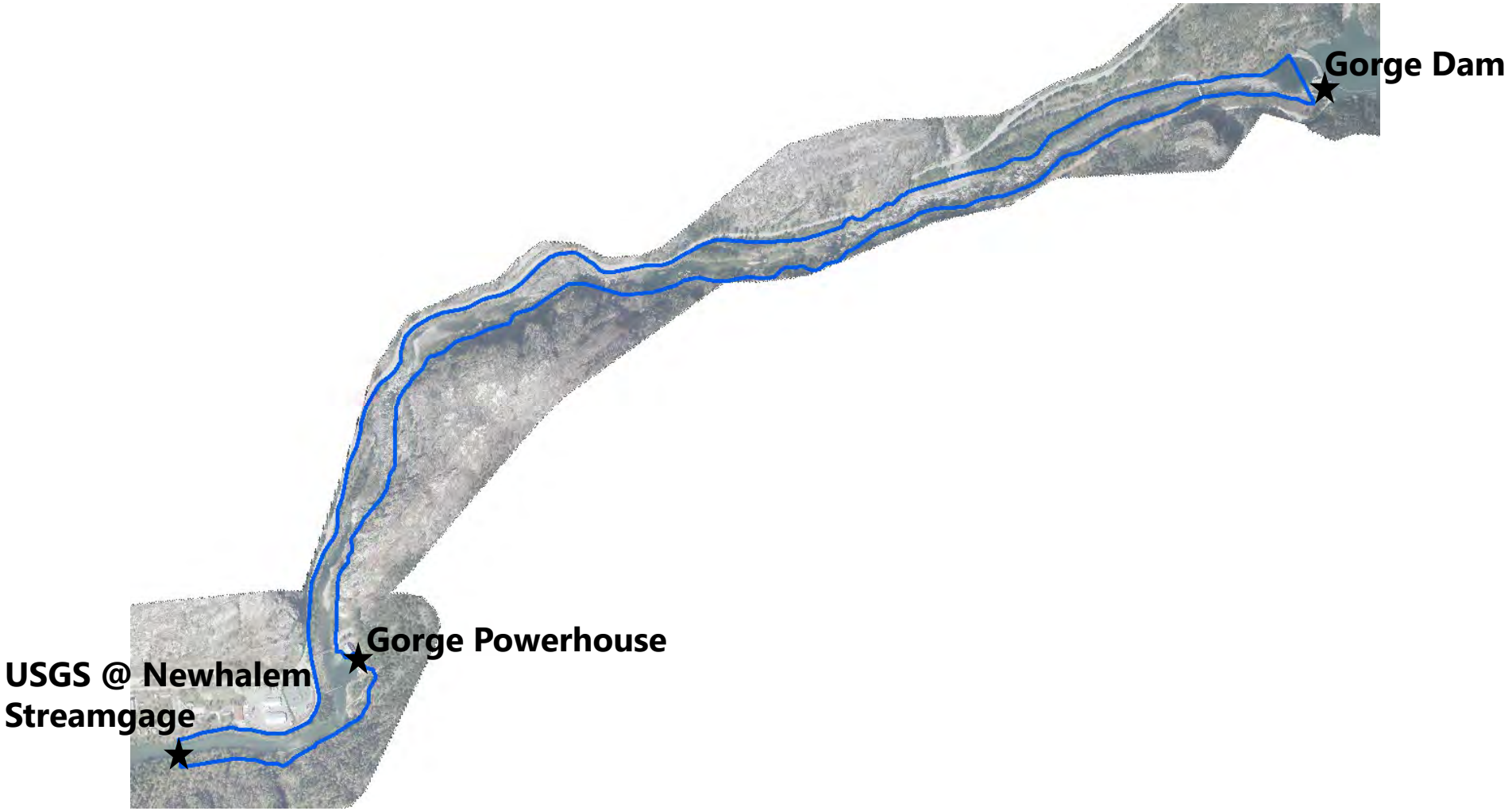
HYDRAULIC MODEL DEVELOPMENT APPROACH

August 26, 2021

OVERVIEW

- Mesh
  - Model Extent
  - Cell size
- Roughness Categories
- Turbulence
- Calibration and Validation
- 2D Model Context

MODEL EXTENT



CELL SIZE – MODEL PRECISION/ACCURACY

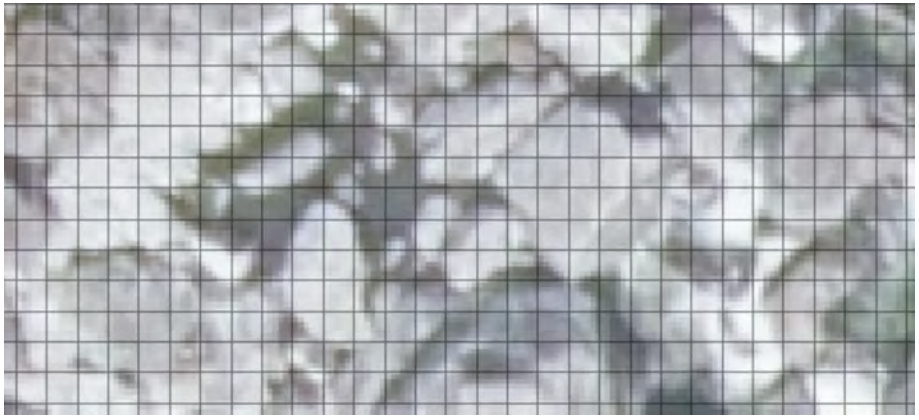
1′ Cells



2′ Cells

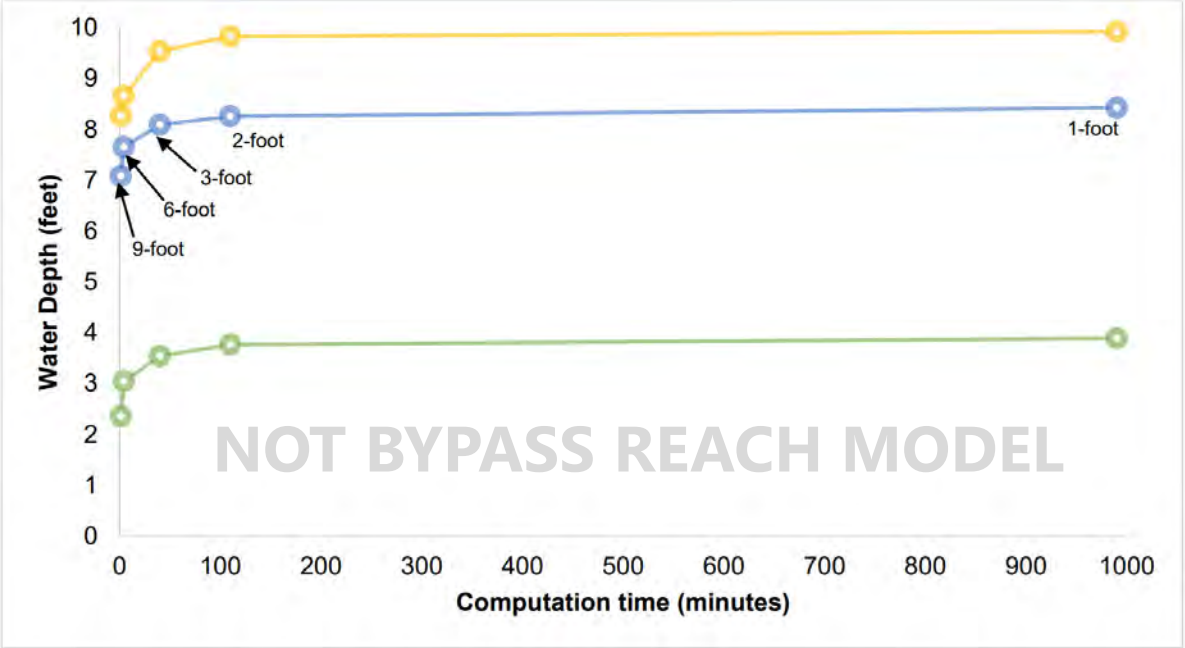


3′ Cells



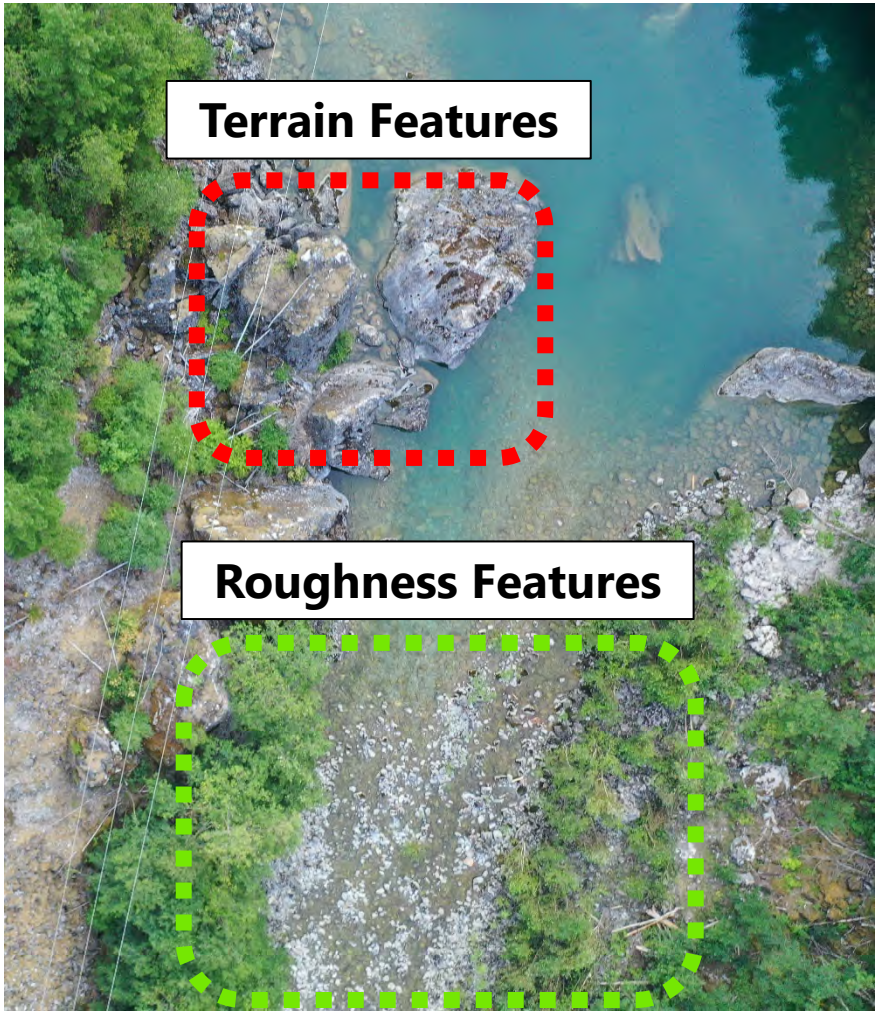
CELL SIZE – MODEL EFFICIENCY

- More cells = longer runtime
  - 3′ – 500,000 cells
  - 2′ – 1,100,000 cells
  - 1′ – 4,500,000 cells
- Timestep selection



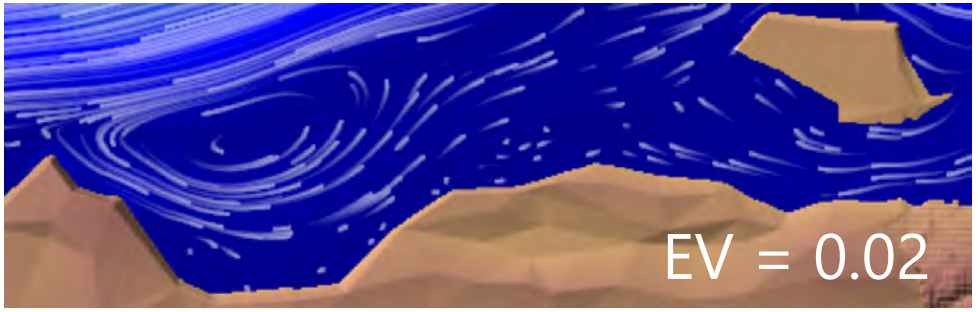
ROUGHNESS CATEGORIZATION

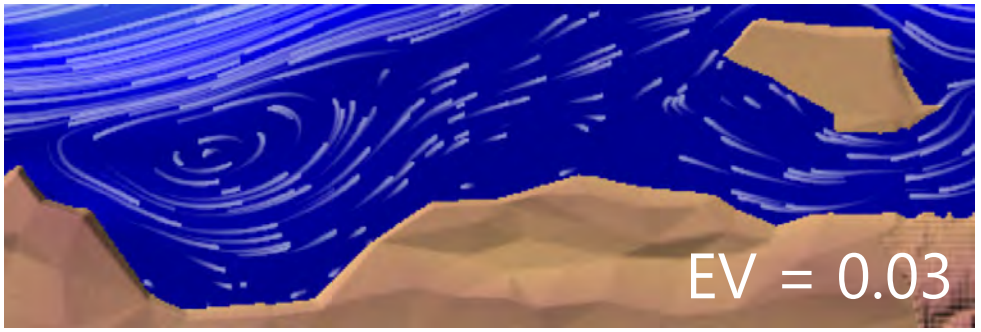
- Influencing factors
  - Substrate vs Grid Size
  - Vegetation
- Roughness values determined through calibration

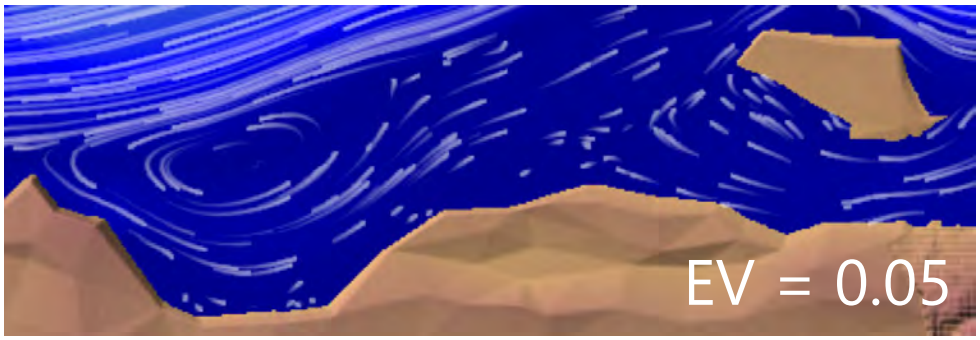


TURBULENCE

- Momentum transfer due to chaotic motion
  - Represented by numerical diffusion in model
- Eddy viscosity coefficient
  - Calibrates best to spatially distributed velocities
  - Affects WSEL and velocity





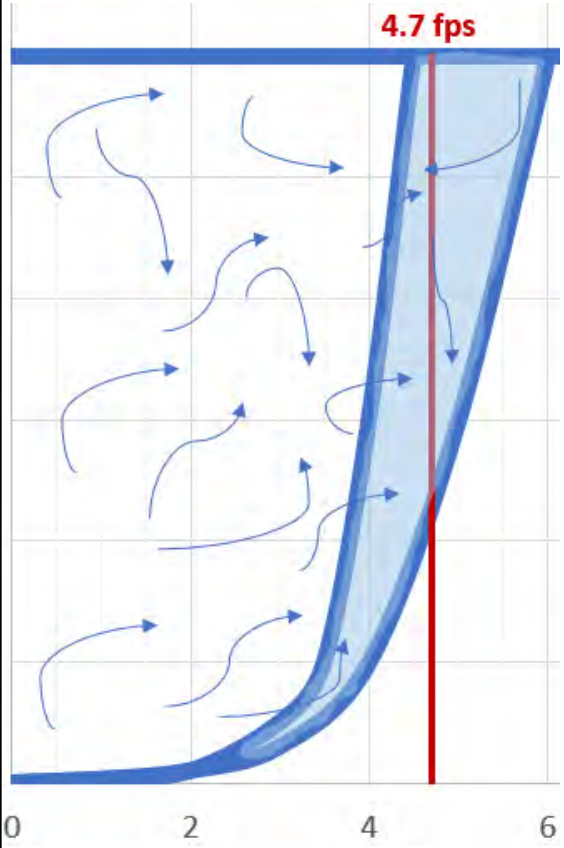


CALIBRATION AND VALIDATION

- Information
  - Continuous WSEL profiles from 4 controlled releases
  - Level loggers
    - 4 controlled releases
    - 1 unplanned spill
  - 5 transects from 4 controlled releases
- Parameters
  - Roughness
  - Turbulence
- Some measurements reserved for model validation

2D MODEL CONTEXT

- Depth-averaged

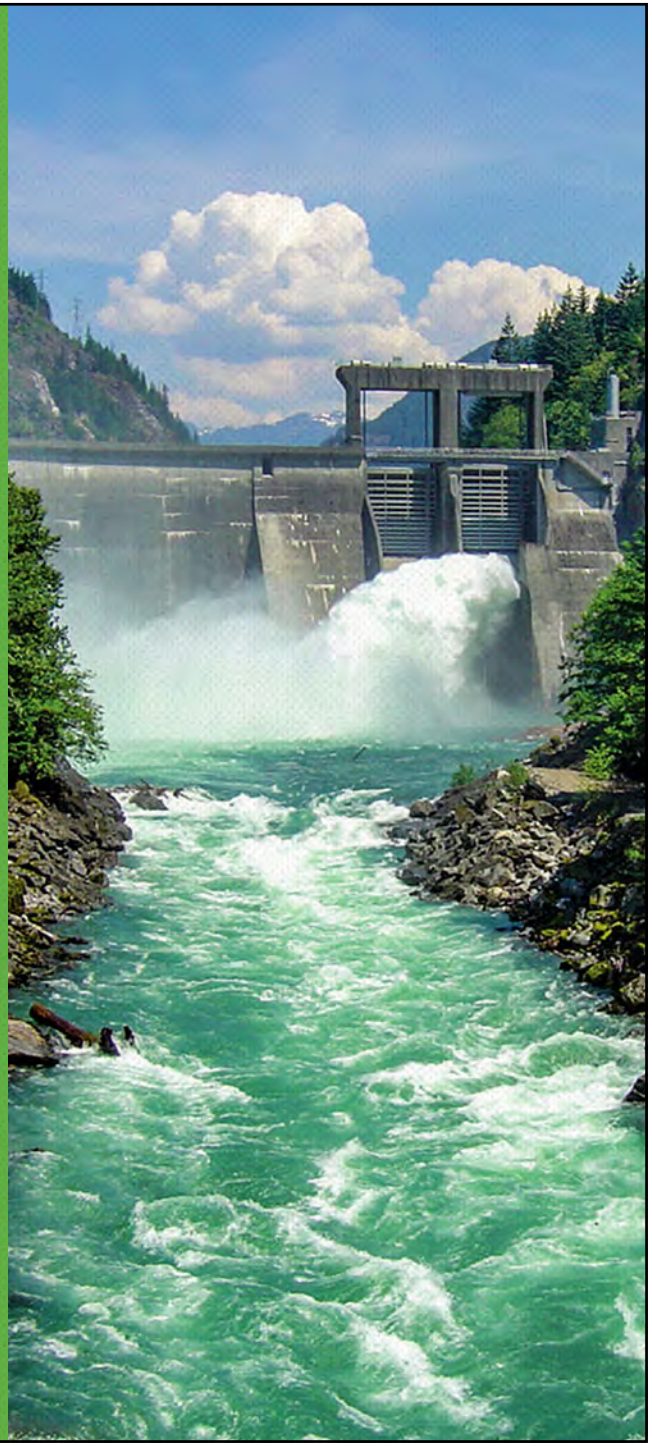




U/S Feature - April 12, 2021 – 1200 cfs

Seattle City Light

DISCUSSION



Skagit River Hydroelectric Project
Seattle City Light (City Light)
FA-05 Gorge Bypass Reach Hydraulic and Instream Flow Model Development, Workshop #3
August 26, 2021

Meeting Summary

Disclaimer: These notes are provided to serve as a high-level summary of the meeting and as a communication tool to benefit work group continuity. They are streamlined and focused on action items, unresolved issues, future discussion items, and high-level discussion points. They are not intended as a formal record of the meeting.

Attendance

Licensing Participants (LPs):
Brock Applegate, Washington Department of Fish and Wildlife (WDFW)
Stuart Beck, Kleinschmidt Group (for Swinomish Tribe)
Curtis Clement, Upper Skagit Indian Tribe (USIT)
Kiza Gates, WDFW
Kirk Gehl, Nlaka'pamux Nation Bands Coalition
Rick Hartson, USIT
Jonathan Kohr, WDFW
Kevin Lautz, WDFW
Jim Myers, National Marine Fisheries Services (NMFS)
Jim Pacheco, Washington Department of Ecology (Ecology)
Duncan Pfeifer, WDFW
Ashley Rawhouser, National Park Service (NPS)
Dudley Reiser, Kleinschmidt Group (for Swinomish Tribe)
Kara Symonds, Skagit County
Amy Trainer, Swinomish Tribe
Stan Walsh, Skagit River System Cooperative (SRSC)
Erik Young, Skagit Fisheries Enhancement Group (SFEG)

Seattle City Light (City Light):
Andrew Bearlin, City Light
Erin Lowery, City Light
Vanessa Lund, City Light Consultant

Cascadia Law:
Matt Love, Cascadia Law

Consultant Team:
Jenna Borovansky, Consultant Team
Danielle Hanson, Consultant Team
Becky Holloway, Consultant Team
Donnie Jones, Consultant Team – NHC
Bao Le, Consultant Team
Malcolm Leytham, Consultant Team – NHC
Chris Long, Consultant Team – NHC
Theo Malone, Consultant Team

Facilitation Team:
Thomas Christian, Facilitation Team
Alex Sweetser, Facilitation Team

Meeting Materials

Meeting materials are stored in this folder on the Skagit SharePoint site.

- Meeting Agenda
- Meeting Slides: Skagit River Gorge Bypass Reach Hydraulic and Instream Flow Model Development Workshop 3

Action Items

Action	Responsibility	Deadline
LP Action Items		
None identified at this meeting		
City Light Action Items		
Consultant Team will provide a technical memorandum about the confidence/variance of observed flows. It will include a longitudinal profile of the flow data.	City Light	Before next workshop
City Light will provide LPs a technical memo on flow stabilization for their reference.	City Light	Before next workshop
Facilitation Team Action Items		
Prepare draft meeting summary and send to LPs for review.	Triangle	Two weeks

Summary of Issues Discussed, Action Items, and Decisions

Welcome, Introductions, Agenda Overview

The facilitator, Thomas Christian, welcomed the group and led a roll call. He briefly walked through the agenda and reviewed action items from the last *Gorge Bypass Reach Hydraulic and Instream Flow Model Development Workshop* held on May 17, 2021.

Erin Lowery, City Light, noted this meeting is intended as an information-sharing meeting on hydraulic model development. There will be room on each agenda item for questions and discussion. He reviewed the meeting objectives, which were to:

- Review controlled and uncontrolled spill data collection
- Review model terrain development
- Provide an overview of the hydraulic model development approach

Study Overview

Chris Long, Consultant Team, provided a status update on the Instream Flows studies (see slides 1–4). He noted the FA-02 study is more advanced because field data collection started in August 2020 and field data collection for FA-05 only happened in the last month. However, progress on FA-05 will quickly jump ahead due to the limited size and ~~scope of~~ quantity of calibration data for the model.

- In response to a question, Chris clarified that the modeling team just started synthesizing the field data collected in July 2021 and profiles from the model will not be presented today.

Chris reviewed the study road map and noted there will still be a monthly collection of data from level loggers. Referencing the standing workshop calendar, Chris explained the next workshop will likely be in early November 2021 and will cover ongoing model calibration. Another workshop to present the finalized model is anticipated for February 2022.

Controlled Spill Monitoring: Transect Data

Donnie Jones, Consultant Team, provided a presentation on controlled spill monitoring data (see slides 5–17). He explained the purpose of the controlled spill flows was to collect velocity and depth data for model calibration through expected releases of 1200, 500, 250, and 50 cfs. Donnie presented the transect locations, described the methodologies for the Acoustic Doppler Current Profiler (ADCP) they used to collect the data, observed flows data in the Bypass Reach, and measured depths and velocities.

Questions/Discussion

- In response to a question about how the ADCP collected data, Donnie explained they used a station-to-station~~ary data~~ instead of moving-vessel approach ~~it~~. This approach allowed them to collect 40 seconds of data at each sampling location to average out temporal fluctuations.
- In response to a question about the gains and losses of observed flows, Chris and Donnie noted losses were most notable in transects DD and GG. They hypothesize this loss was caused by groundwater conversion ~~within these transects~~at the Afternoon Creek pool. Chris elaborated this hypothesis was not due to observations but based on the quality, pattern, and confidence of the data.
- Jim Pacheco, Ecology, expressed that the bridge transect was expected to be the most stable, but had an inconsistent distribution of measured flows across targeted releases. Donnie explained ~~the~~ flow ~~within~~at this transect was not as uniformly distributed as expected and that larger features, such as the ~~bridge~~abrupt shotcrete walls at the channel margins, made it difficult to characterize the ~~channel~~flow field at high discharges.
- Jim Pacheco shared that Ecology often uses a dual-state discharge method and said it would be helpful if the model could recognize gains and losses of flows within the river reaches. Chris clarified that sources and sinks can be added to the model during the model calibration phase.
- In response to a question from Curtis Clement (USIT) about which transect the consultant team has the most confidence in, Donnie noted they have the most confidence in the data at transect II, and the bridge transect under certain conditions.
- LPs requested that City Light revise the observed flows graph on slide 15 to show the confidence of the data at each observation. Additionally, LPs requested this include a longitudinal profile of the flow data.

Action Item: The Consultant Team will provide a technical memorandum about the confidence/variance of observed flows. It will include a longitudinal profile of the flow data.

Controlled Spill Monitoring: UAV Data

Chris Long presented the controlled spill monitoring UAV data collection and data analysis methodologies (see slides 18–51). He explained the drone flew Monday through Friday in one week and collected data ~~for~~in four different zones in ~~a~~ pre-planned missions. Then, they used overlapping photos from the drone to develop a 3D structure of the study area, which could be added as a layer beneath the hydraulic model to compare the model simulation to field observations.

Chris explained they will be using ~~the~~ Large Scale Particle Image Velocimetry (LSPIV) analysis ~~tool~~ to measure surface velocity, ground-truth (but not calibrate) the numerical model, and provide another view of potential fish passage through the Bypass Reach. The LSPIV software tracks "seeding material" – objects floating on the surface of the water – in a video and calculates the speed and orientation of the objects across video frames to calculate the direction and magnitude of the river's flow. ~~It can also~~

~~demonstrate turbidity.~~ Seeding material can be natural or artificially added, such as bark chips, as was done for this study.

Questions and Discussion

- In response to a question from Stuart Beck, consultant for Swinomish Tribe, about the drone's height above the river, Chris clarified the drone was about 250ft above ground level for the LSPIV videos and 300-350ft for the still photos.
- In response to a question if the surface velocities from the LSPIV tool could be used to help refine the 2D hydraulic model, Chris explained these measures could help to ground truth the model, but would not be as useful for model calibration. The LSPIV outputs are for surface water velocity, whereas the 2D model's output is depth averaged, which means the values would not align. Additionally, the LSPIV output shows active turbulence, which alters the surface flow values.
- In response to a question about the cost~~s~~ and utility of using the UAV to track gravel movement, Chris explained the UAV itself only costs a couple hundred dollars ~~and is not expensive~~, but the analysis software, which costs between $3,000 – $6,000, and paying the field crews is what costs the most. This means data collection is inexpensive, but planning and post-processing the data is expensive. ~~Chris noted there are several ways they could track gravel movement, but it is not currently being tracked.~~

Level Logger Data Collection

Malcolm Leytham, Consultant Team, provided an overview of the level logger equipment, instrument~~level logger~~ installation, and ~~level logger~~ data collection methodologies and results (see slides 52–75). He noted they installed six level loggers at the upstream feature and six level loggers at the downstream feature. Additionally, the Consultant Team believes they have gotten the data necessary to calibrate the model ~~up to~~at ~~4~~6,000 cfs after the large uncontrolled spill event in June. Malcolm noted they are still processing the level logger data.

Questions and Discussion

- Rick Hartson, USIT, expressed concern about the ability of the level loggers to ~~date data~~measure at higher flows and the accuracy of high flow data. Malcolm responded that due to safety and logistical considerations, they ~~we~~are unable to measure velocities ~~with the level loggers~~ at the uncontrolled high-flow event; however, the model will use the level logger data for river ~~height~~stage, and they have photos as a qualitative reference for this event. ~~Additionally, the level logger data will be used for calibration.~~ He explained the level loggers will remain in place until November or December in case there is another high flow event this fall. However, they have a good dataset from the uncontrolled release event.
- In response to a question from Ashley Rawhouser about the travel time between Gorge Dam and the Newhalem Gage and how this may affect stabilization time, Malcolm answered the travel time is about an hour. Malcolm explained the stage stabilization time is longer and closer to four to five hours, which was considered when planning field data collection. Andrew Bearlin, City Light, noted City Light can provide a technical memo on flow stabilization to LPs for their reference.

Action Item: City Light will provide LPs a technical memo on flow stabilization for their reference.

Terrain

Donnie Jones presented on the hydraulic model terrain development ~~and data outputs~~ (see slides 76–91) including~~. Additionally, he provided~~ an overview of the methods for refining the model to a 1ft raster and point reclassification results. As part of terrain refinement, Donnie noted there ~~needs to be~~is a manual assessment of unassigned LiDAR points, which ~~cannot~~will not be done in wetted areas but ~~is possible~~ in dry areas only.

Questions and Discussion

- In response to a question from Johnathan Kohr, WDFW, Malcolm explained the terrain outputs ~~from this part of the model~~ are primarily for ~~terrain layout in the~~ model topography and not for habitat cover. Bao Le, Consultant Team, clarified that ~~a full cover map of~~ substrate and habitat cover~~age~~ is being field mapped separately and will follow Ecology guidelines.
- In response to a question from Rick Hartson about ~~lost data due to~~ the ~~model's~~ inability to increase LiDAR point density in wetted areas, Donnie explained the LiDAR data was collected in baseflow (dry) conditions and that most of the wet areas were shallow pools ~~of flows~~ between rocks and cobble. For these areas, the impact of ~~loss~~lesser ~~of~~ data resolution is minimal ~~due to it being a case of diminishing returns~~.

Hydraulic Model Development Approach

Donnie presented the approach for developing the hydraulic model (see slides 92–101). The model extent is from ~~the~~ Gorge Dam to the Newhalem stream gage. Donnie noted that smaller cell sizes results in ~~a~~ better resolution, but at the cost of~~greatly~~ increasinge the model~~'s~~ run time. ~~The~~He illustrated from a pervious hydraulic model analogous to the Bypass Reach that the largest increase in computational runtime with ~~small~~least accuracy gains ~~i~~was ~~in~~ between the 2ft to 1ft resolution. Donnie also explained ~~the~~ roughness values will be determined ~~through~~during model calibration. ~~Lastly, Donnie noted any remaining measures will be reserved for model validation after the model is calibrated.~~

Questions and Discussion

- In response to a question from Kevin Lautz, WDFW, about if roughness is ~~being~~ scaled by depth, Donnie explained that in HEC-RAS roughness is scaled to flow magnitude, which is related to flow depth. If roughness scaling is included, it would be through this method with a roughness coefficient.
- In response to a question about using a 1ft raster resolution for the entire model, Donnie noted ~~this will not be an issue with their software. However,~~ the 1ft resolution can be selectively applied in different areas where it offers greater improvements.
- In response a question about the model being calibrated to 7,000 cfs, Malcolm explained the level logger record~~ model becomes~~ is unsteady at this flow. Instead, there is a 6,000 cfs stable period that calibration could be based on. ~~Chris added that extremely high flows become very turbid and chaotic, so there is a concern about false accuracy in the model at these higher flows.~~
- In response to a question, Donnie clarified grid sizes will vary by focus area.

- In response to a question, Donnie clarified actual water velocity varies both vertically and horizontally. The model provides a vertical (depth) average ~~of~~ velocity.
- In response to a question, Donnie clarified that air entrainment is not represented in the model.
- Rick Hartson noted turbulence is very important for fish passage and asked how this model will inform the wider fish passage and river modeling toolset. Donnie responded it depends on how well the model outputs for velocity, depth, and water surface elevation match data to corresponding locations. Additionally, the model can better characterize larger features and is less accurate with smaller features and cobble. Chris added that the model ~~appears smooth because the velocity and heigh measures are averaged, which means this model~~ does not simulate the true chaotic and periodic nature of turbulence. This requires the ~~team on the~~ FA-04 Fish Passage Technical Studies Program team~~will need~~ to understand the model limitations and that model outputs are not absolute for fish passage estimates. This model will be one of the ~~many~~several tools the team uses to assess fish passage. Jim Pacheco added this indicates unpassable velocity measures in the model may be passable in the real world due to the high level of variance caused by turb~~idity~~ulence.

General Question

- In response to a question from Stuart Beck about the risk of fish stranding or trappings when ramping down flows after a controlled release, Erin Lowery, City Light, clarified dam operators are meeting ramping rates rules that are inclusive of several considerations for fish. However, there is potential for gravel bar and pothole stranding. Stuart expressed concern about ramping rates not specifically being addressed in the Bypass Reach and the potential for pothole stranding within the Bypass Reach.

Review Action Items and Next Steps

The Consultant Team noted a topic for the next FA-05 Workshop will be to discuss model calibration. The facilitator noted Triangle is working with City Light to establish a standing meeting calendar and the next Flows Work Group meeting will likely fall into that standing calendar time.

Action Item: Consultant Team will provide a technical memorandum about the confidence/variance of observed flows. It will include a longitudinal profile of the flow data.

Action Item: City Light will provide LPs a technical memo on flow stabilization for their reference.

Action Item: Triangle will prepare a draft meeting summary and send to LPs for review.

The meeting was adjourned at 1:00 p.m.

SKAGIT RIVER GORGE BYPASS REACH HYDRAULIC AND INSTREAM FLOW MODEL DEVELOPMENT STUDY REPORT

ATTACHMENT I

FA-05 WORKSHOP 4 MATERIALS

Seattle City Light

DRAFT MEETING AGENDA

Skagit Hydroelectric Project Relicensing: Flows Work Group Meeting

FA-05 Gorge Bypass Reach Hydraulic and Instream Flow Model Development, Workshop #4

November 2, 2021, 8:30 a.m. – 1:15 p.m.

WEBEX

Webex Meeting Link:
https://triangleassociates.my.webex.com/triangleassociates.my/j.php?MTID=med4871c742b1d1e0d00da4363e231b79

Call in Information: +1-510-338-9438,,25565666087#74985787# USA Toll

MEETING PURPOSE

- Review selection and associated uncertainty of flows used for model calibration
- Review model development and sensitivity analyses
- Present current progress of model calibration
- Outline remaining work for completing model calibration and validation
- Provide updates on substrate and cover mapping and HSC and periodicity development
- Preview hydraulic model integration with biological/habitat data

RESOURCES

- NOA Commitments
- Flows Work Group Discussion Tracker

FACILITATION TEAM

Joy Juelson, Triangle Associates, Facilitation
Alex Sweetser, Triangle Associates, Documentation

AGENDA

8:30 – 8:45 a.m. (15 minutes)	**Introduction** – *Facilitator, Triangle* ▪ Roll Call Introduction ▪ Background and Context ▪ Review Action Items from Previous Meeting
8:45 – 9:00 a.m. (15 minutes)	**Study Overview** – *Erin Lowery, City Light and Chris Long, NHC* ▪ Background ▪ Review Meeting Objectives and Agenda
9:00 – 9:45 a.m. (45 minutes)	**Present and Discuss Calibration Flow Selection and Uncertainty Analysis** – *Donnie Jones, NHC* ▪ Late June 2021 Spill ▪ July 26-29 Controlled Spill Events Questions and Discussion (30 minutes) ▪ Discussion topic: Assessing uncertainty of uncontrolled spill event. – *Rick Hartson (15 minutes)*

9:45 – 10:45 a.m. (60 minutes)	**Update and Discuss Model Development and Sensitivity Analysis** – *Donnie Jones, NHC* ▪ Model Terrain ▪ Model Geometry Overview ▪ Sensitivity Tests ▪ Final Mesh Selection Questions and Discussion (15 minutes)
10:45 – 11:00 a.m. (15 minutes)	**Break**
11:00 – 12:30 p.m. (90 minutes)	**Present and Discuss Model Calibration and Validation**– *Donnie Jones, NHC* ▪ Observed data ▪ Calibration Procedure ▪ Current Progress ▪ Future Progress Questions and Discussion (20 minutes)
12:30 – 1:00 p.m. (30 minutes)	**High-level Overview of the Development of Biological/Habitat Data and Integration with Hydraulic Model** – *Ty Ziegler, HDR and Chris Long, NHC* ▪ Update on substrate and cover mapping ▪ Update on HSC and periodicity development ▪ Preview of Biological/Aquatic Habitat Integration ▪ Preview of hydraulic data generation for fish passage analysis Questions and Discussion (10 minutes)
1:00 – 1:15 p.m. (15 minutes)	**Review Action Items and Discussion Tracker and Develop Agenda Items for Next Meeting –** *Triangle and NHC*
1:15 p.m.	**Meeting Adjourned**

Action Items From FA-05 Workshop 3 (8/26)

Action Items

Action	Responsibility	Timeframe
City Light Action Items		
Consultant Team will provide a technical memorandum about the confidence/variance of observed flows. It will include a longitudinal profile of the flow data.	City Light	Before next workshop
City Light will provide LPs a technical memo on flow stabilization for their reference.	City Light	Before next workshop
Facilitation Team Action Items		
Prepare draft meeting summary and send to LPs for review.	Triangle	Complete



Seattle City Light

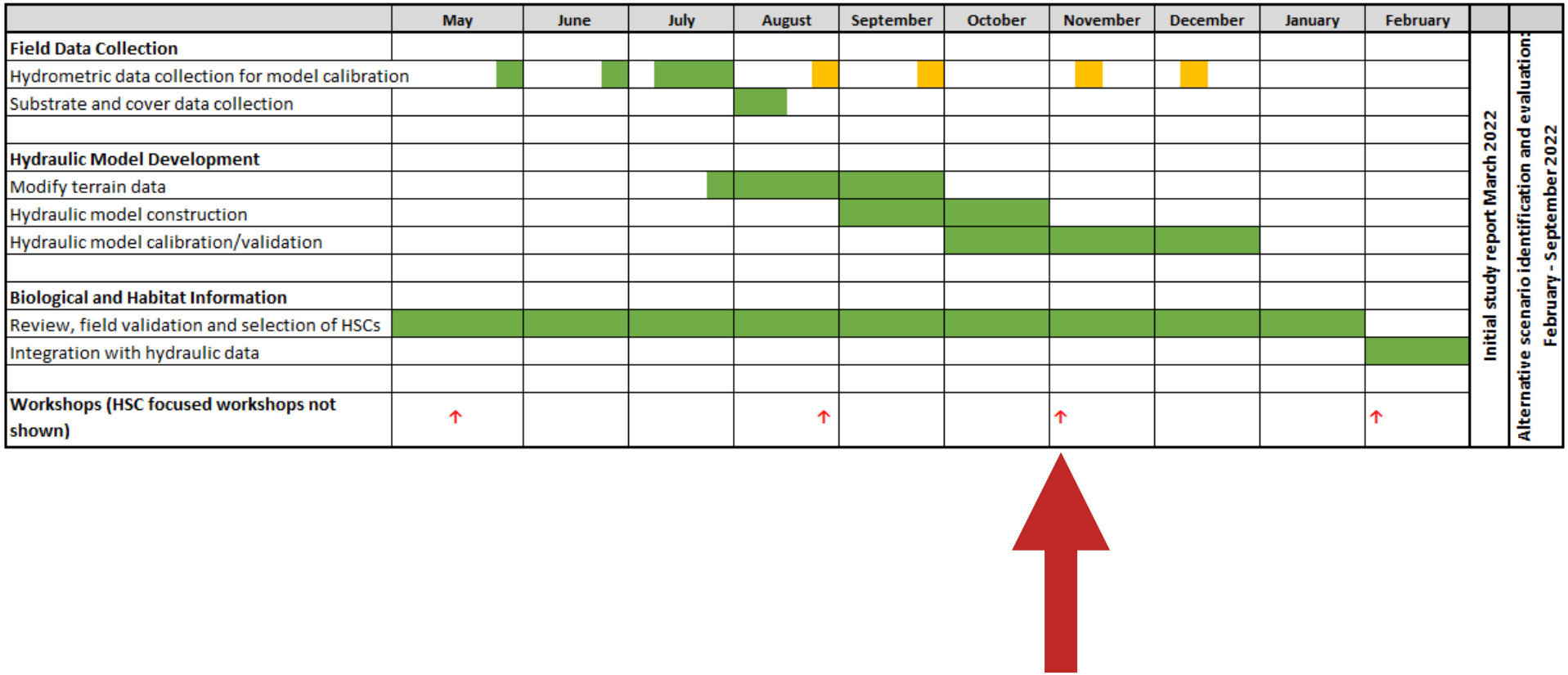
SKAGIT RIVER GORGE BYPASS REACH HYDRAULIC AND INSTREAM FLOW MODEL DEVELOPMENT – WORKSHOP 4

November 2, 2021

WORKSHOPS

Workshop	Date	Topics
~~1A~~	~~May 2021~~	~~Overview development of hydraulic and instream flow model for the Gorge Bypass Reach~~
~~2~~	~~July 2021~~	~~Updates to biological and habitat metrics based on discussions and input from FA-02 Workshop 1~~
~~3~~	~~August 2021~~	~~Field monitoring debrief and hydraulic model development kickoff~~
4	November 2021	Hydraulic model calibration ongoing
5	February 2022	Final hydraulic model calibration results and discussion of future model application

STUDY ROAD MAP/SCHEDULE



WORKSHOP 4 AGENDA

- Calibration flow selection and uncertainty
- Model development and sensitivity analysis
- Model calibration and validation
- Development and integration of biological/habitat data



CALIBRATION FLOW SELECTION AND UNCERTAINTY ANALYSIS

November 2, 2021

OVERVIEW

- Late June spill
  - Basis for spill calculations
  - Sources of uncertainty
- July 26-29 Controlled Releases
  - Measurement data
  - Uncertainty quantification
  - Possible flow loss in Bypass Reach

GORGE DAM – OUTLET WORKS



07/28/2021 19:00
~50 cfs

GORGE DAM – OUTLET WORKS



07/28/2021 18:00
~250 cfs

GORGE DAM – JUNE 2021 SPILL



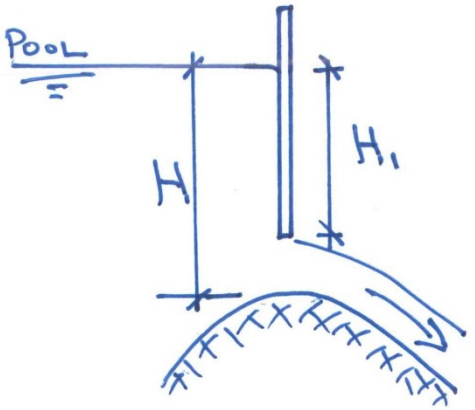
06/30/2021
~ 4700 cfs

GORGE DAM – SPILL CALCULATIONS

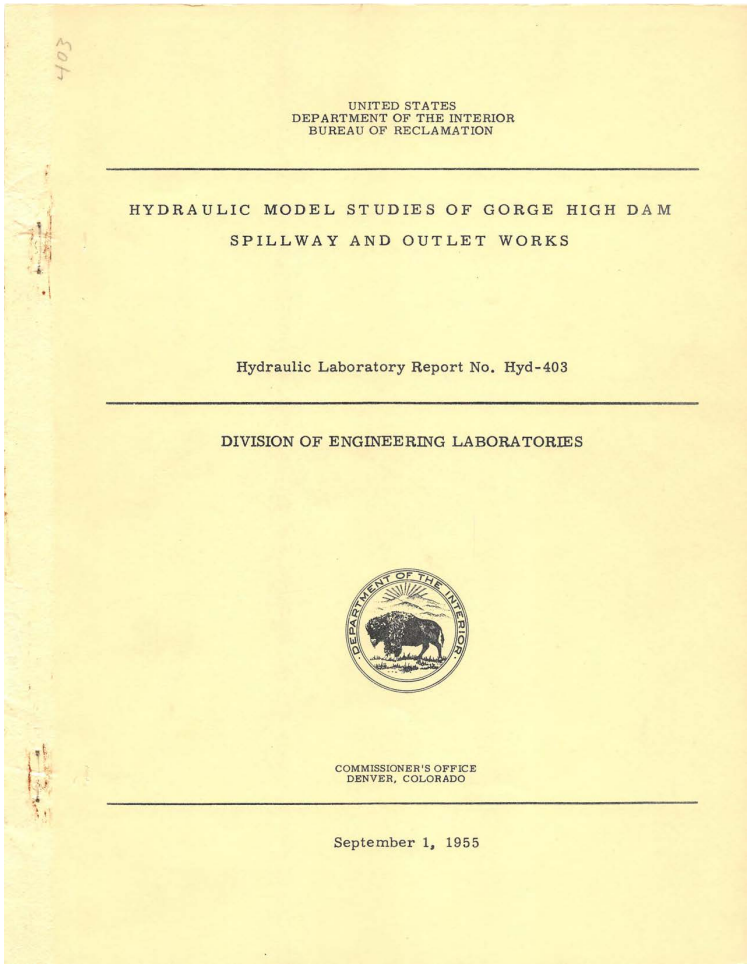
$$Q = CW\sqrt{2g}(H^{1.5} - H_1^{1.5})$$

Q = discharge (cfs)
C = coefficient of discharge
W = gate width (feet)
H = head on gate seat (feet)
H_1 = head on gate lip (feet)

Gate Opening = H – H_1



GORGE DAM – SPILLWAY RATING



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UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

HYDRAULIC MODEL STUDIES OF GORGE HIGH DAM
SPILLWAY AND OUTLET WORKS

Hydraulic Laboratory Report No. Hyd-403

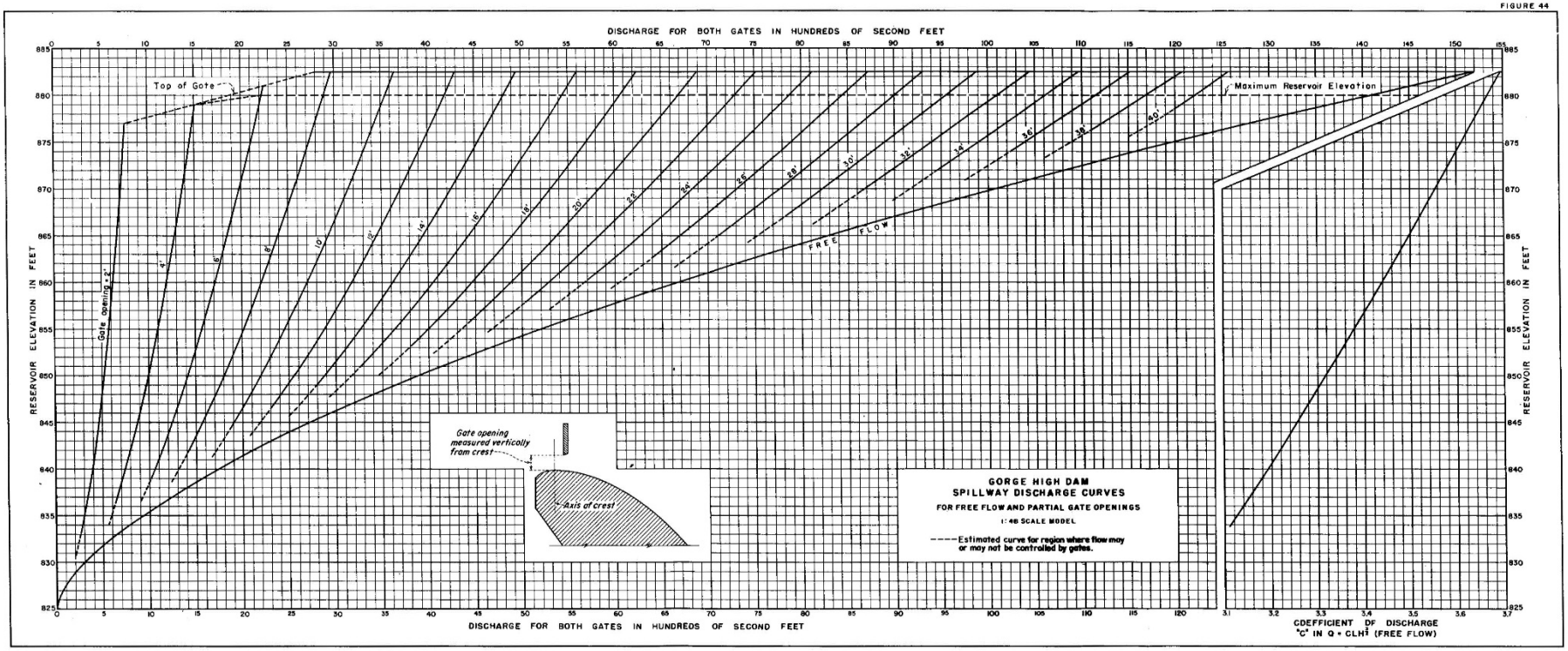
DIVISION OF ENGINEERING LABORATORIES

COMMISSIONER'S OFFICE
DENVER, COLORADO

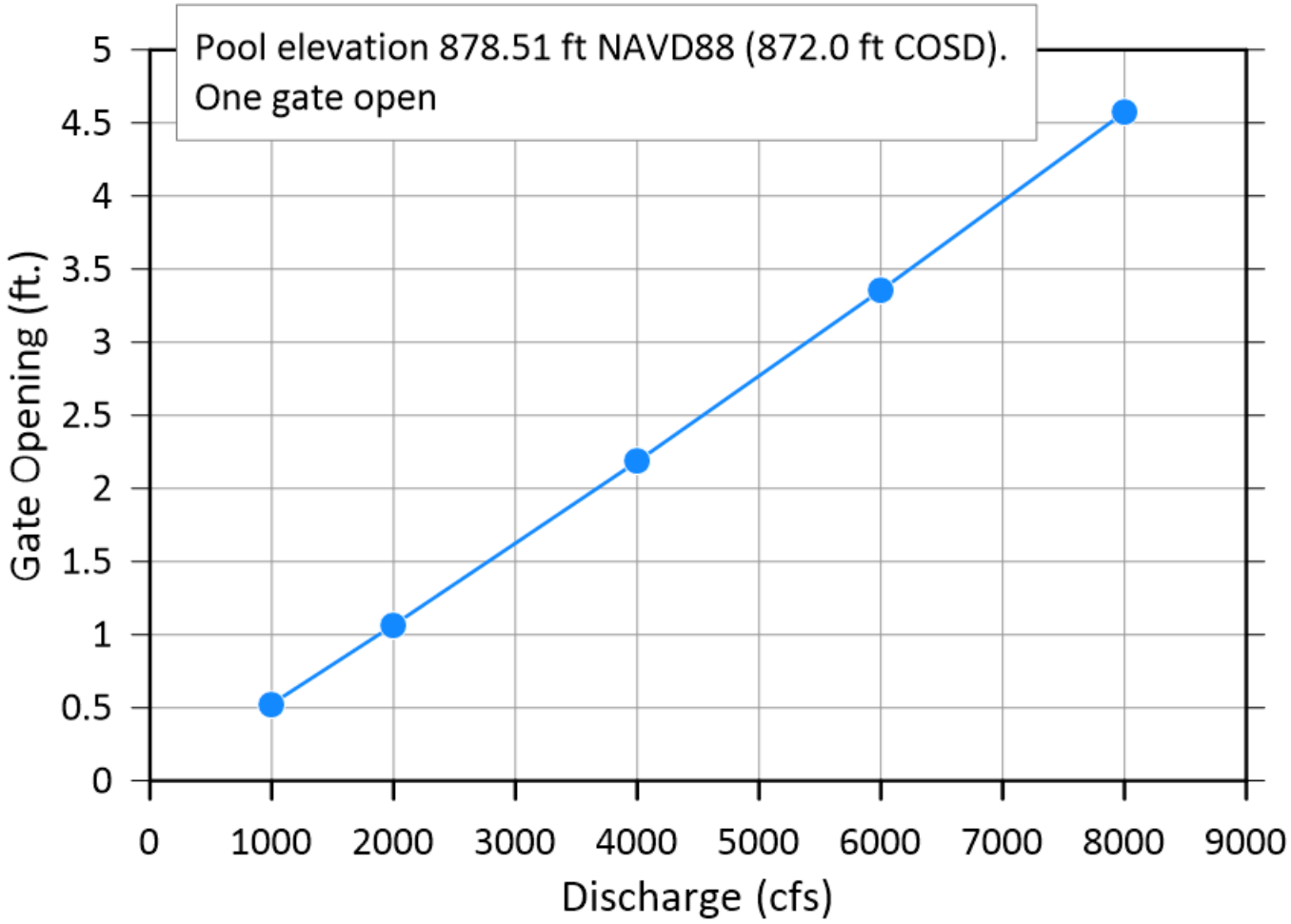
September 1, 1955

- Spillway rating from USBR hydraulic model study.
- Well-established theoretical discharge relationship.
- Laboratory experiments predict discharges to +/- 2% (e.g. Hager and Bremen, J. Hydr. Eng., ASCE, 1988).

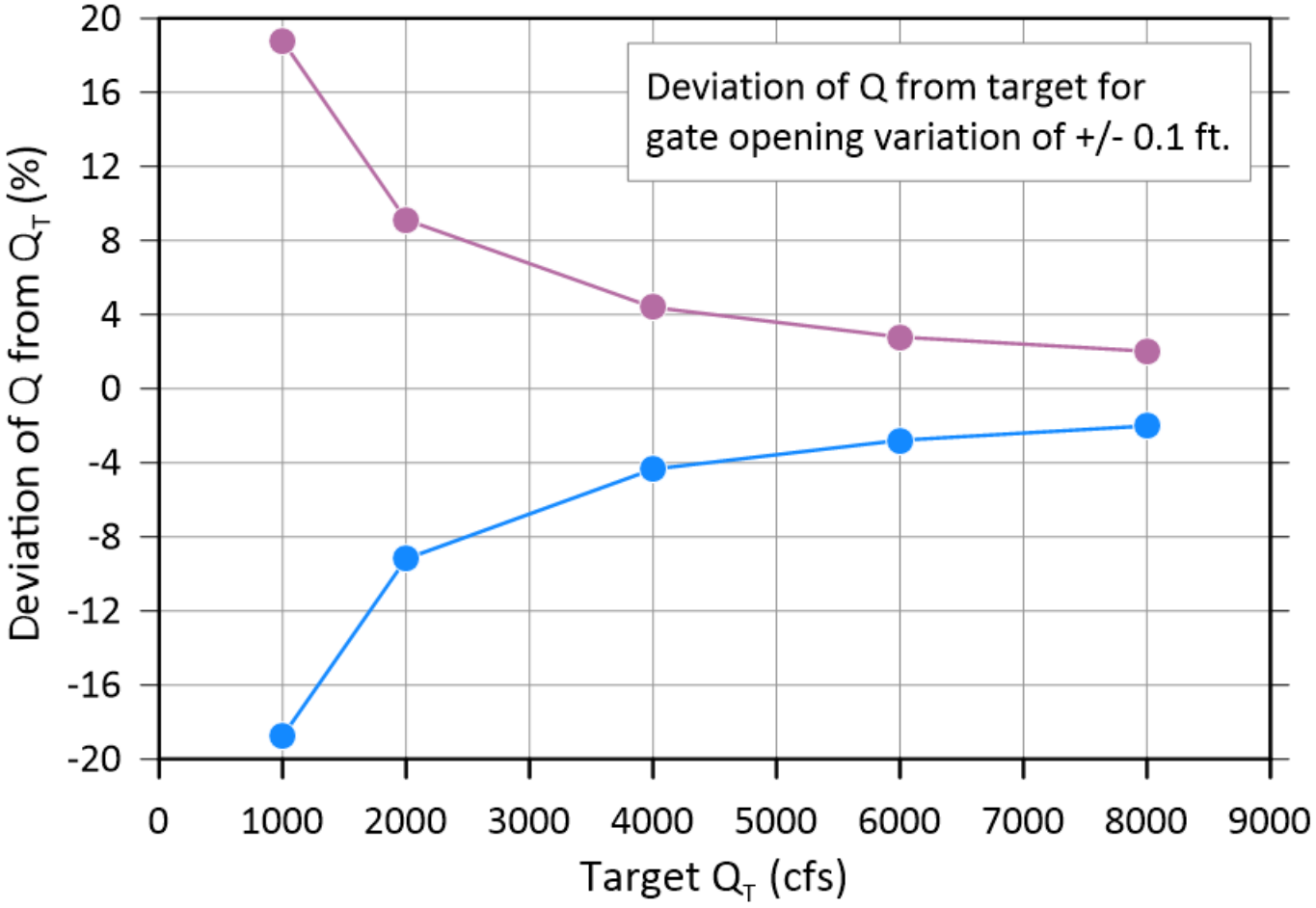
GORGE DAM – SPILLWAY RATING



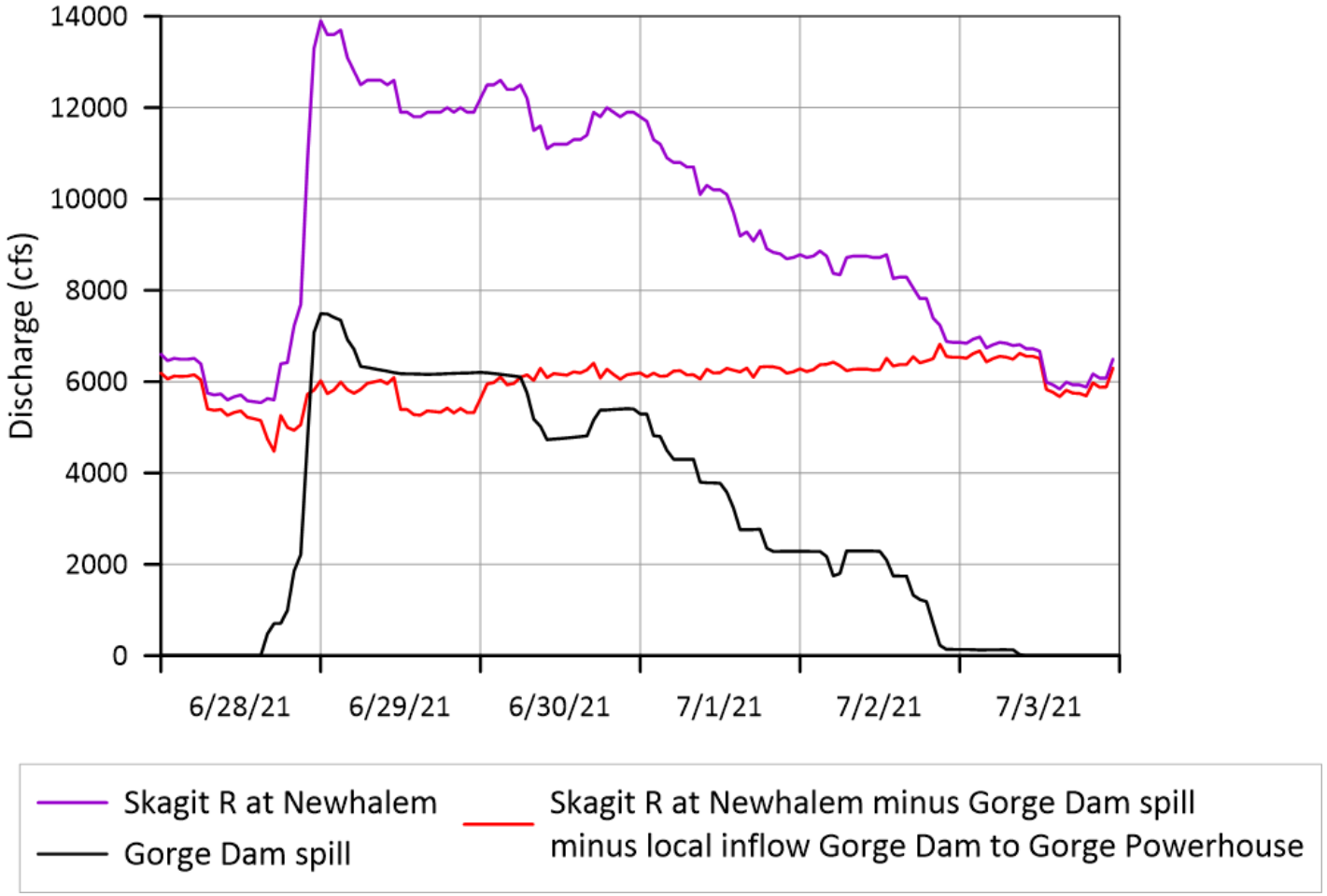
GORGE DAM – SINGLE GATE RATING



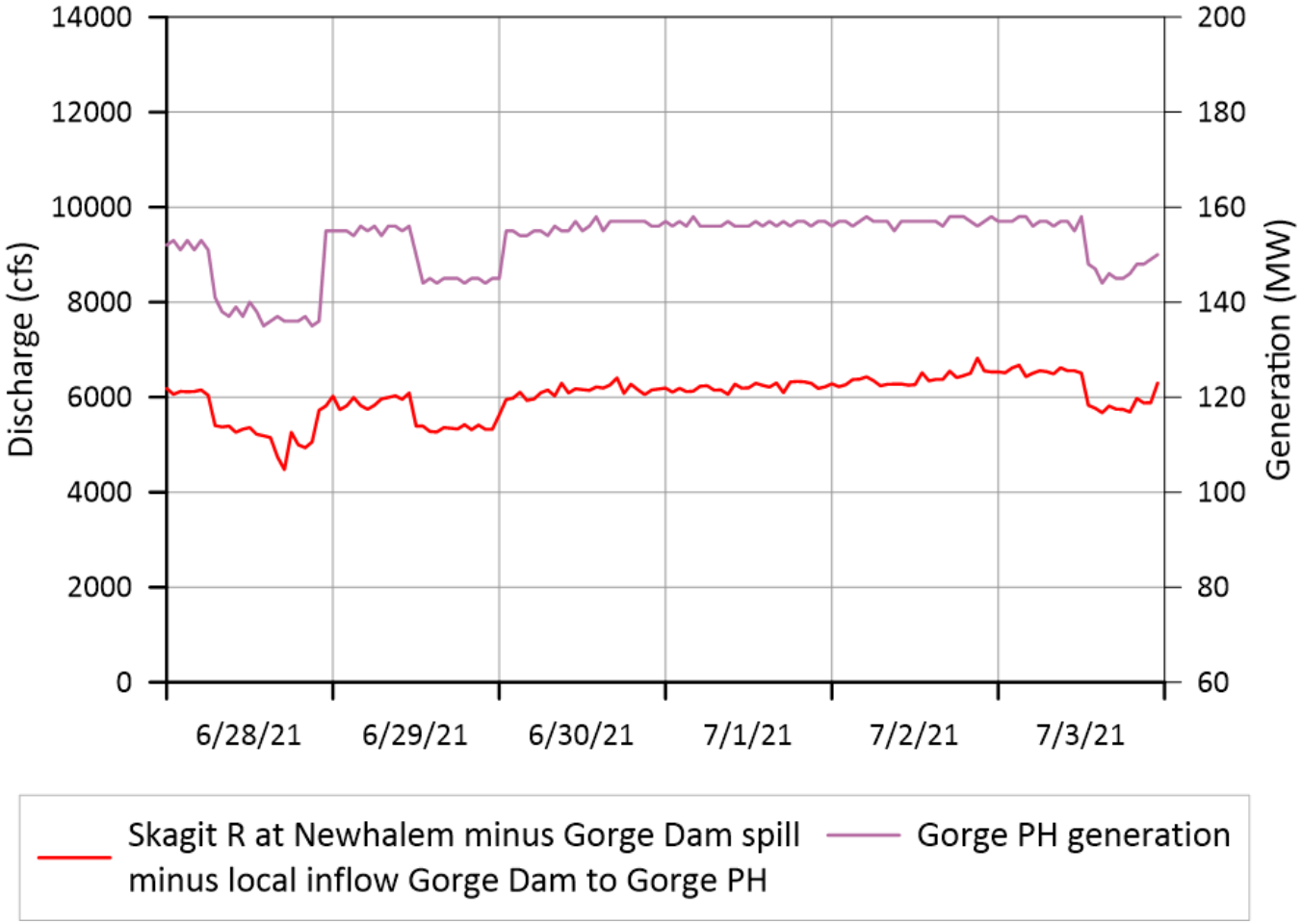
GORGE DAM – DISCHARGE SENSITIVITY TO GATE OPENING



JUNE/JULY SPILL DATA – CONSISTENCY CHECK



JUNE/JULY SPILL DATA – CONSISTENCY CHECK



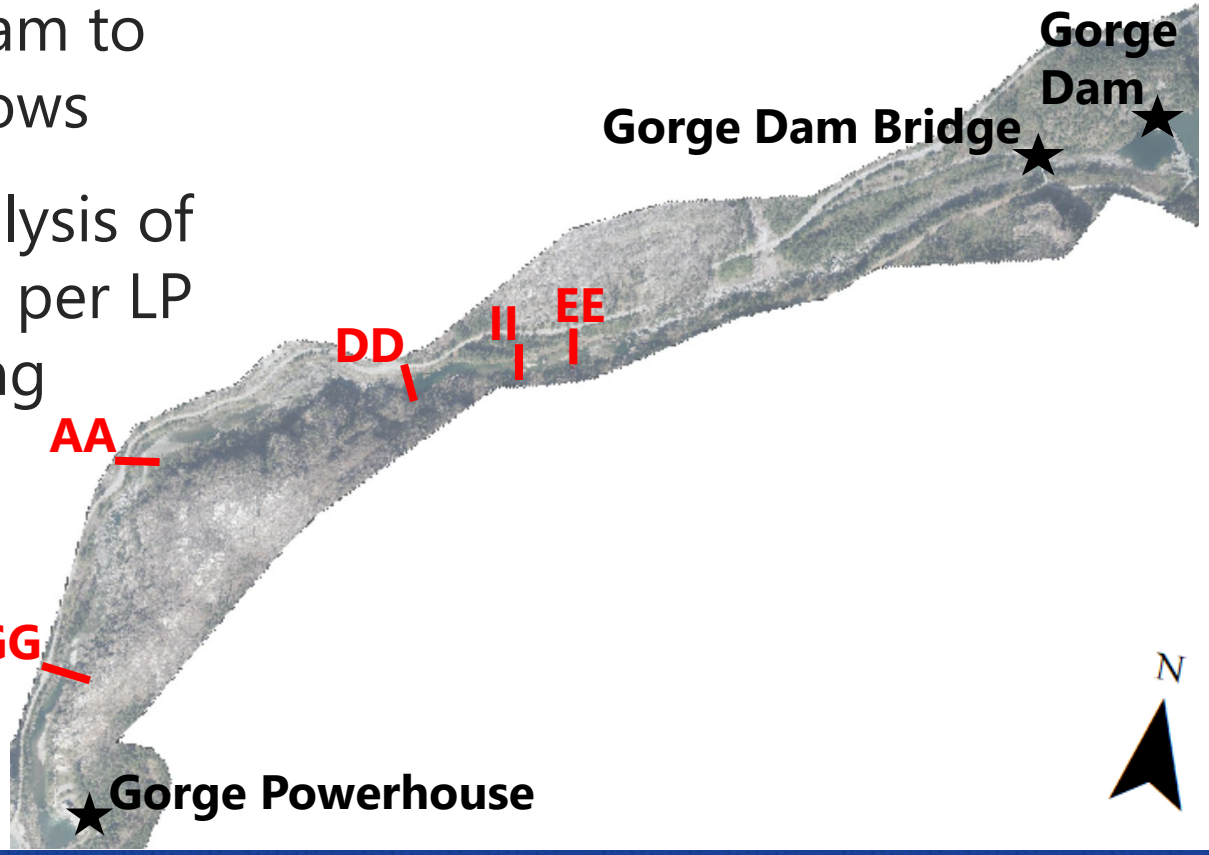
Seattle City Light

DISCUSSION



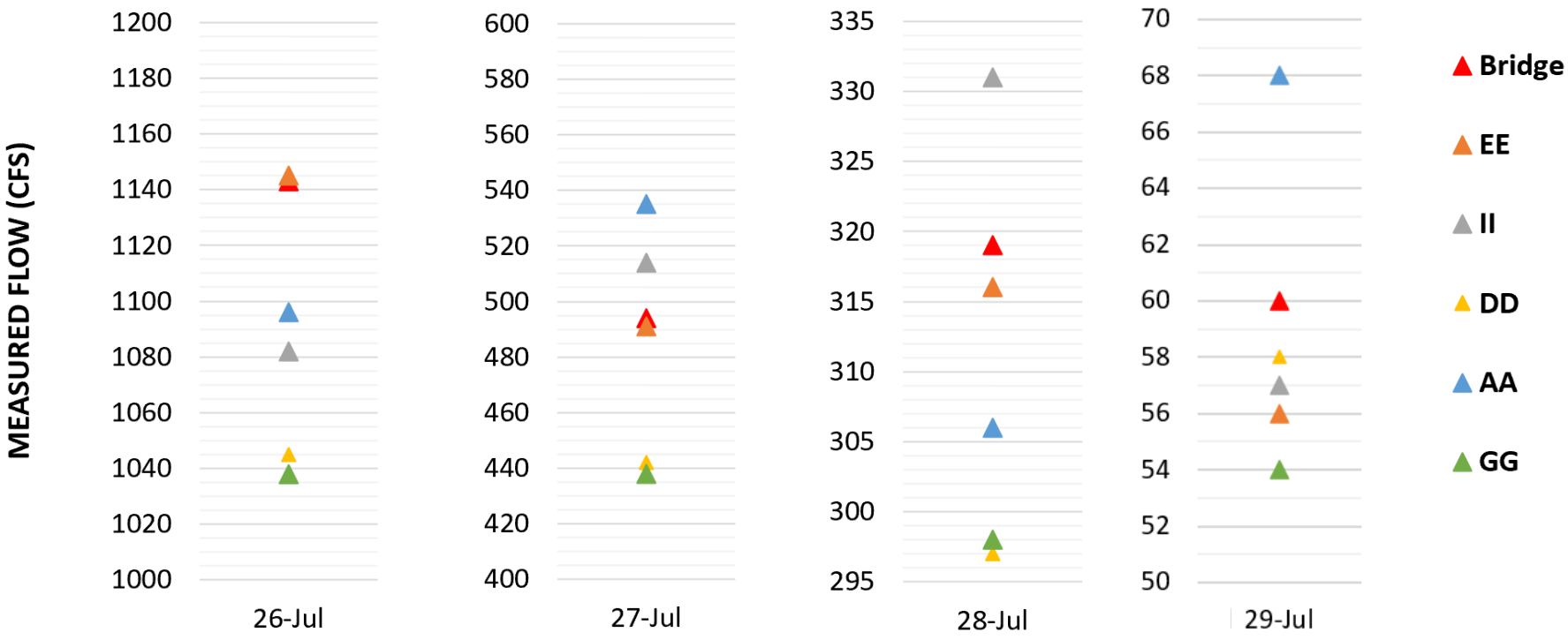
JULY 26-29 CONTROLLED RELEASE FLOWS

- Discharge measured at transects and bridge below Gorge Dam to verify release flows
- Uncertainty analysis of measured flows per LP request following Workshop 3



JULY 26-29 CONTROLLED RELEASE FLOWS

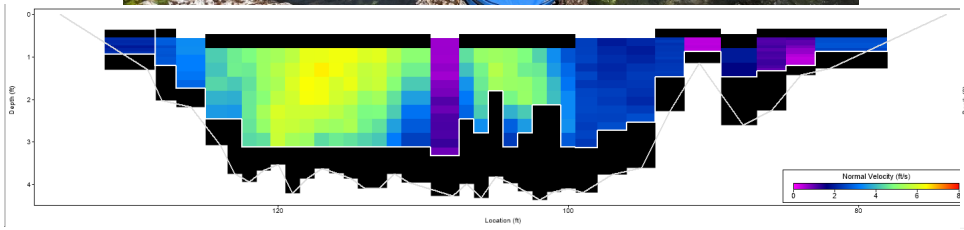
TARGET RELEASE (CFS)	1200	500	250	50
SCL REPORTED RELEASE (CFS)	1095-1097	435-445	246-258	Log Chute (~50 cfs)



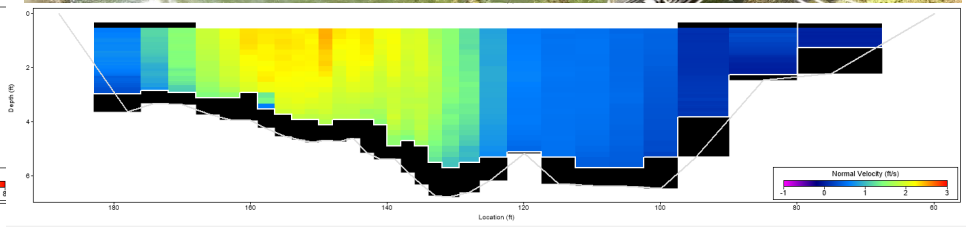
JULY 26-29 DISCHARGE MEASUREMENT UNCERTAINTY

- Discharge quality at transects
  - Transect AA not used - poor conditions
  - Transects II, DD, and bridge most reliable
  - Transects EE and GG acceptable


Transect AA – 500 cfs

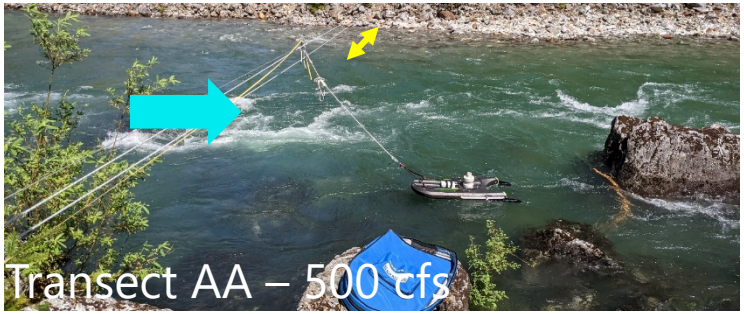


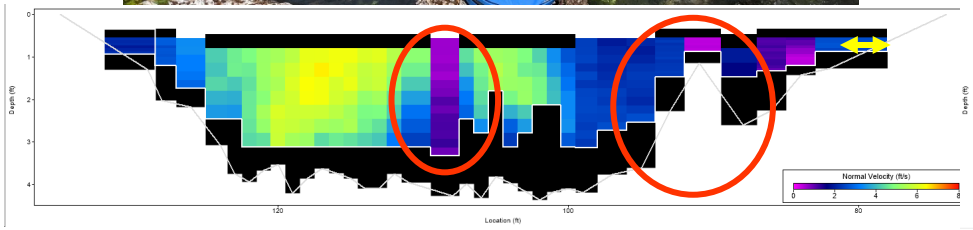

Transect II – 500 cfs

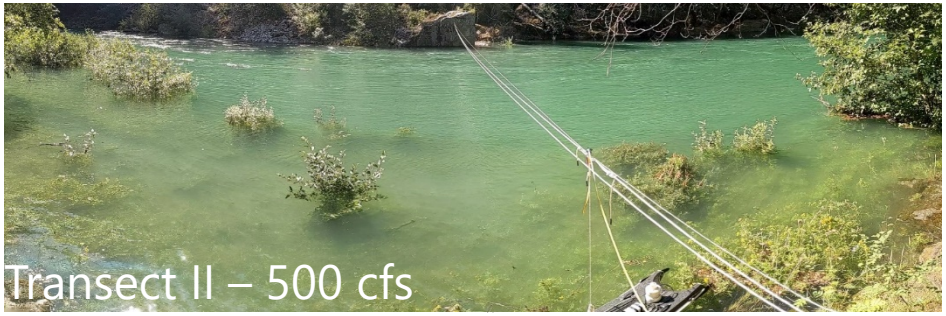


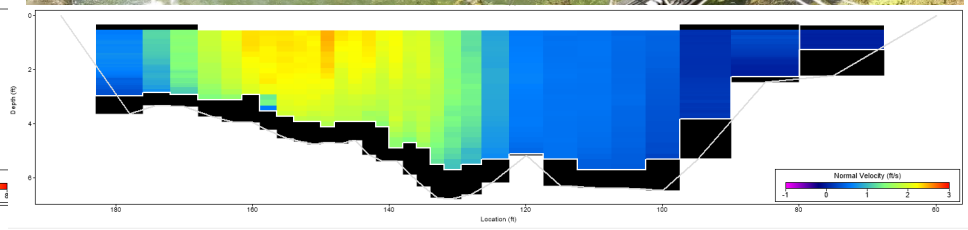
JULY 26-29 DISCHARGE MEASUREMENT UNCERTAINTY

- Quantified uncertainty
  - Change in depth and velocity between stations
  - Angle of primary flow direction
  - Estimated distance to far edge of water

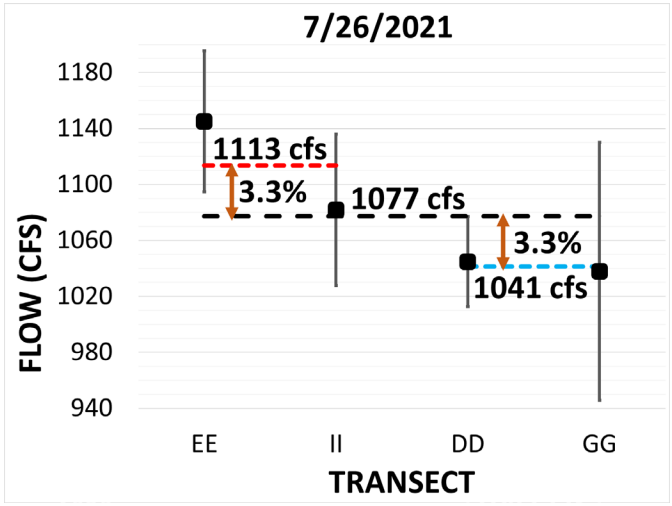


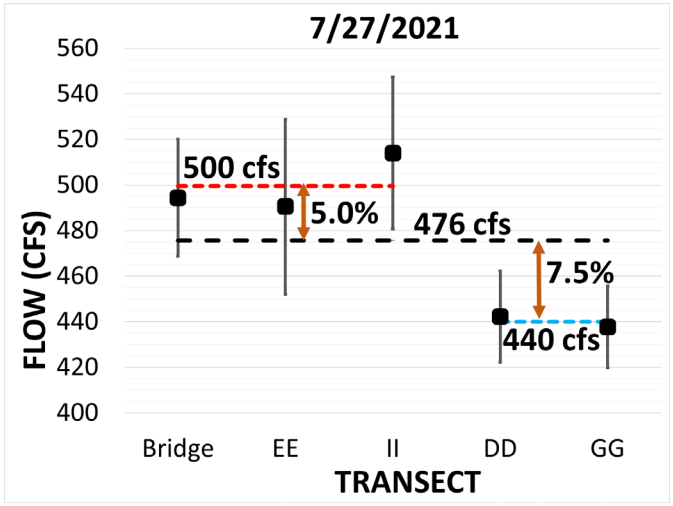


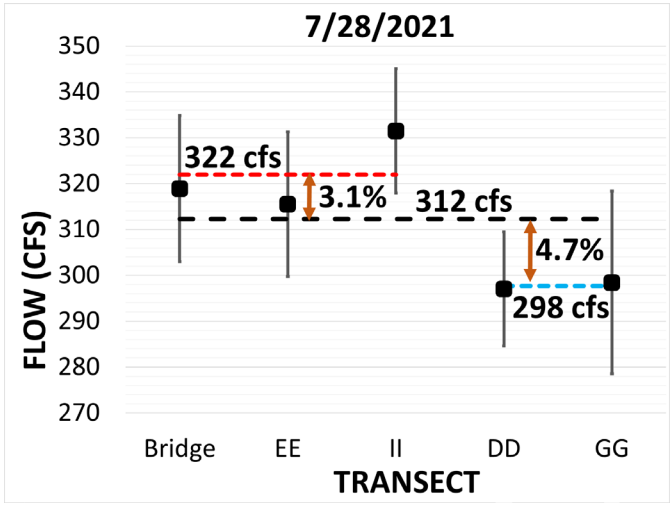


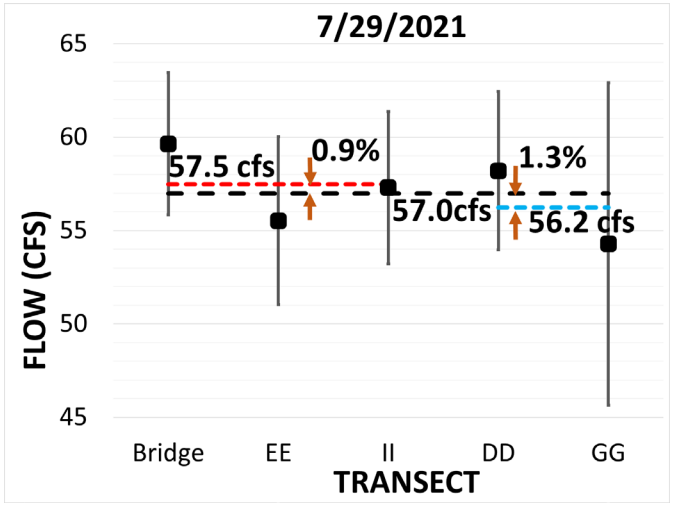


JULY 26-29 DISCHARGE MEASUREMENT UNCERTAINTY









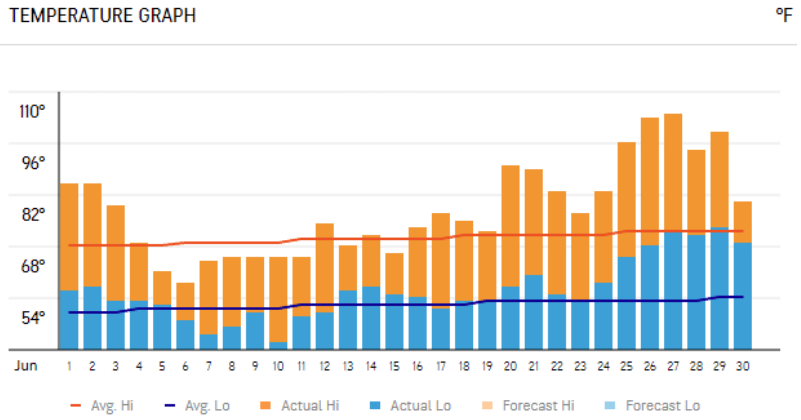
- Measured Transect Flow
- Bypass Reach Mean Flow
- Mean Flow Above Afternoon Creek Pool
- Mean Flow Below Afternoon Creek Pool

POTENTIAL FOR FLOW LOSS

- Coarse material deposits provide groundwater storage and subsurface flow paths
  - Landslide material along Afternoon Creek pool



- Dry antecedent conditions
  - Late June heat dome
  - Low July base flow (<10 cfs)

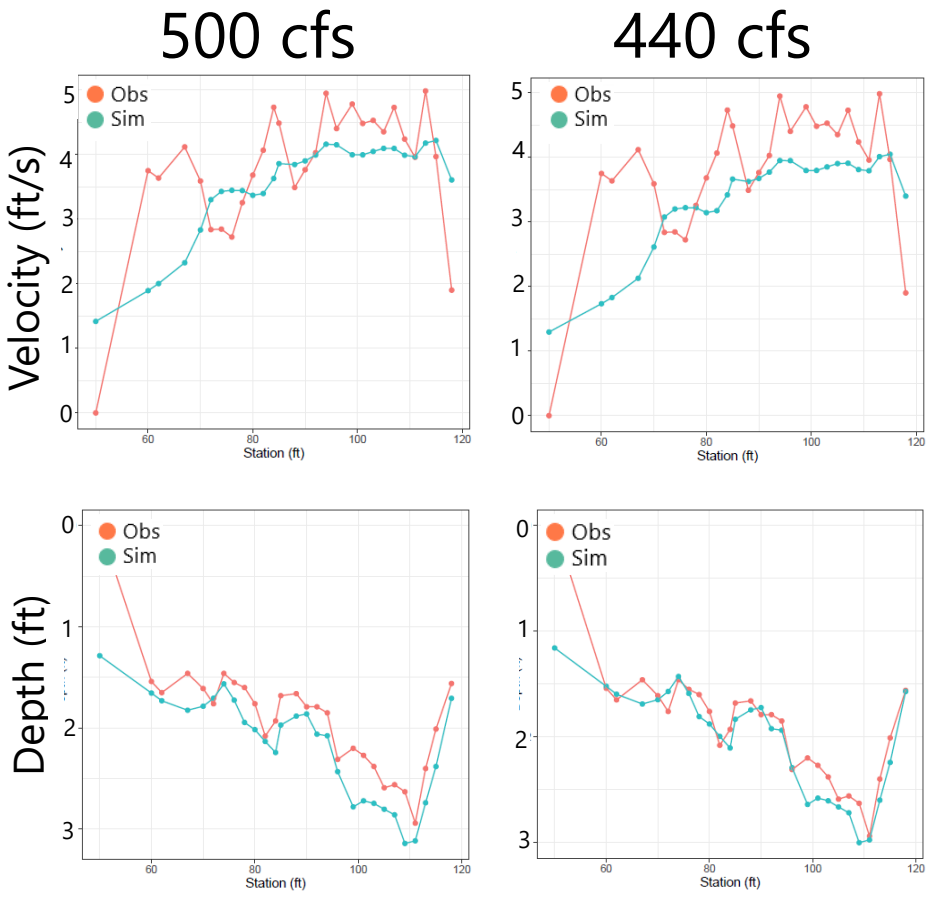


MODEL CALIBRATION FLOWS

Calibration Simulation	U/S Mean Flow (cfs)	D/S Mean Flow (cfs)
July 26, 2021	1113	1041
July 27, 2021	500	440
July 28, 2021	322	298
July 29, 2021	57	57

CALIBRATION FLOW SENSITIVITY

Transect EE



Seattle City Light

DISCUSSION





MODEL DEVELOPMENT AND SENSITIVITY ANALYSIS

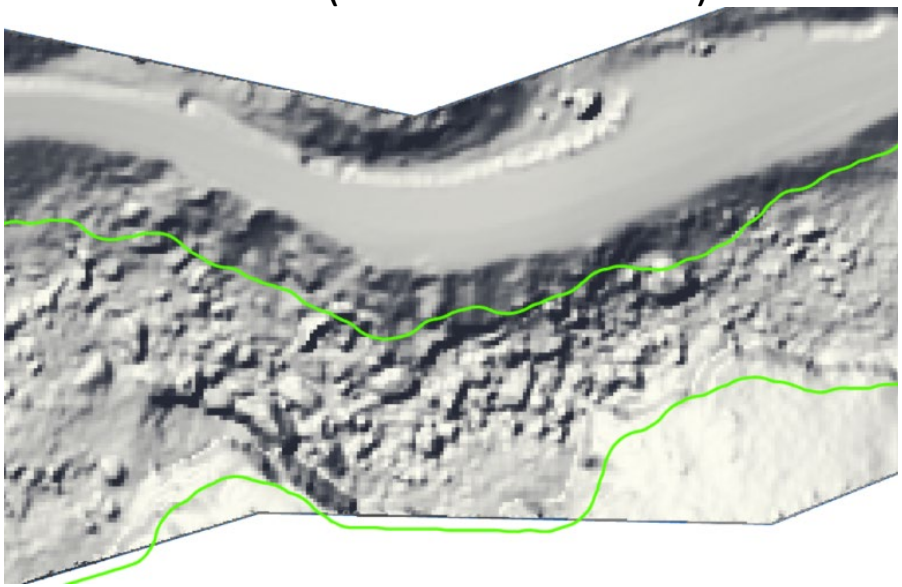
November 2, 2021

OVERVIEW

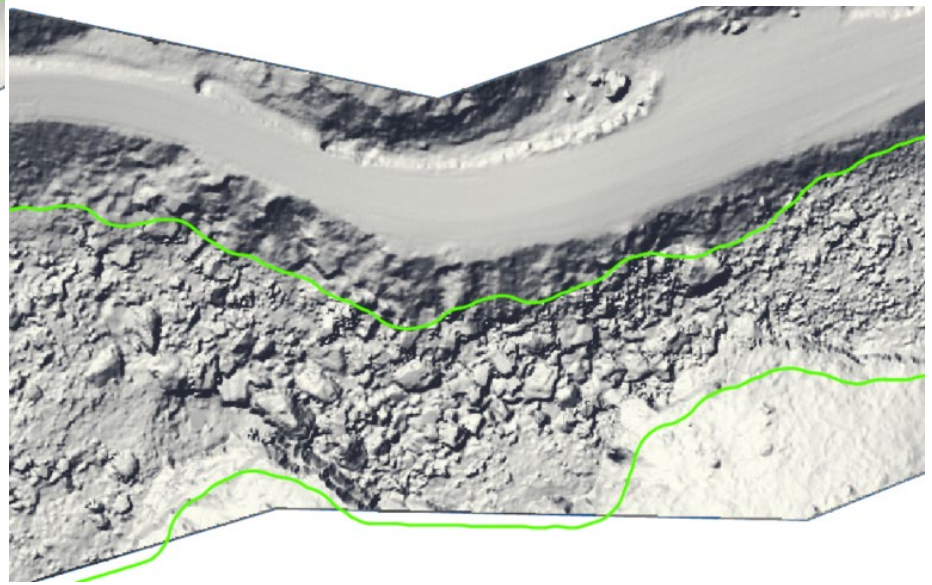
- Model Terrain
- Model Geometry
- Sensitivity Tests
- Base Model Selection

TERRAIN REFINEMENT

Before (3ft Cell Resolution)

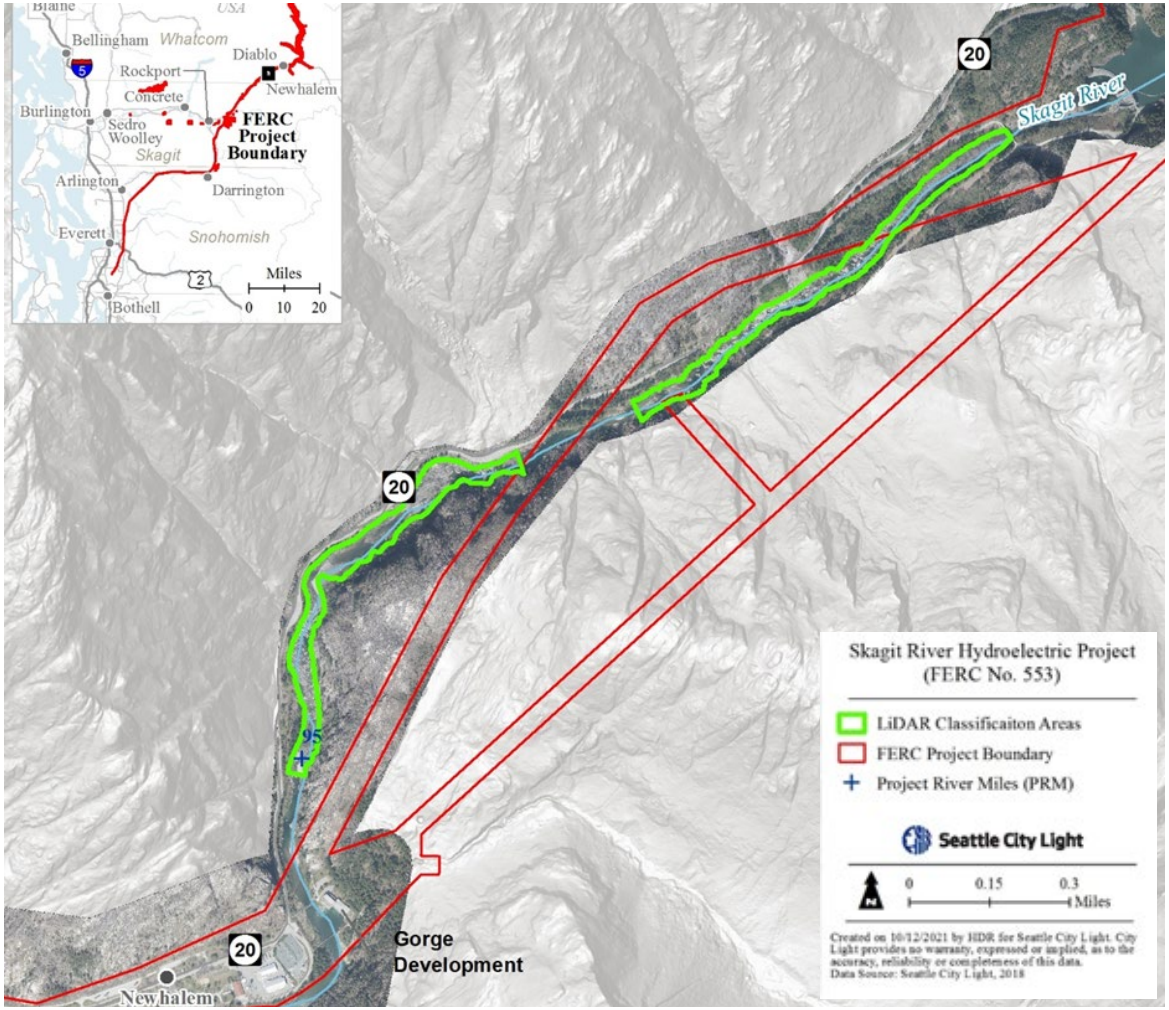


After (1ft Cell Resolution)



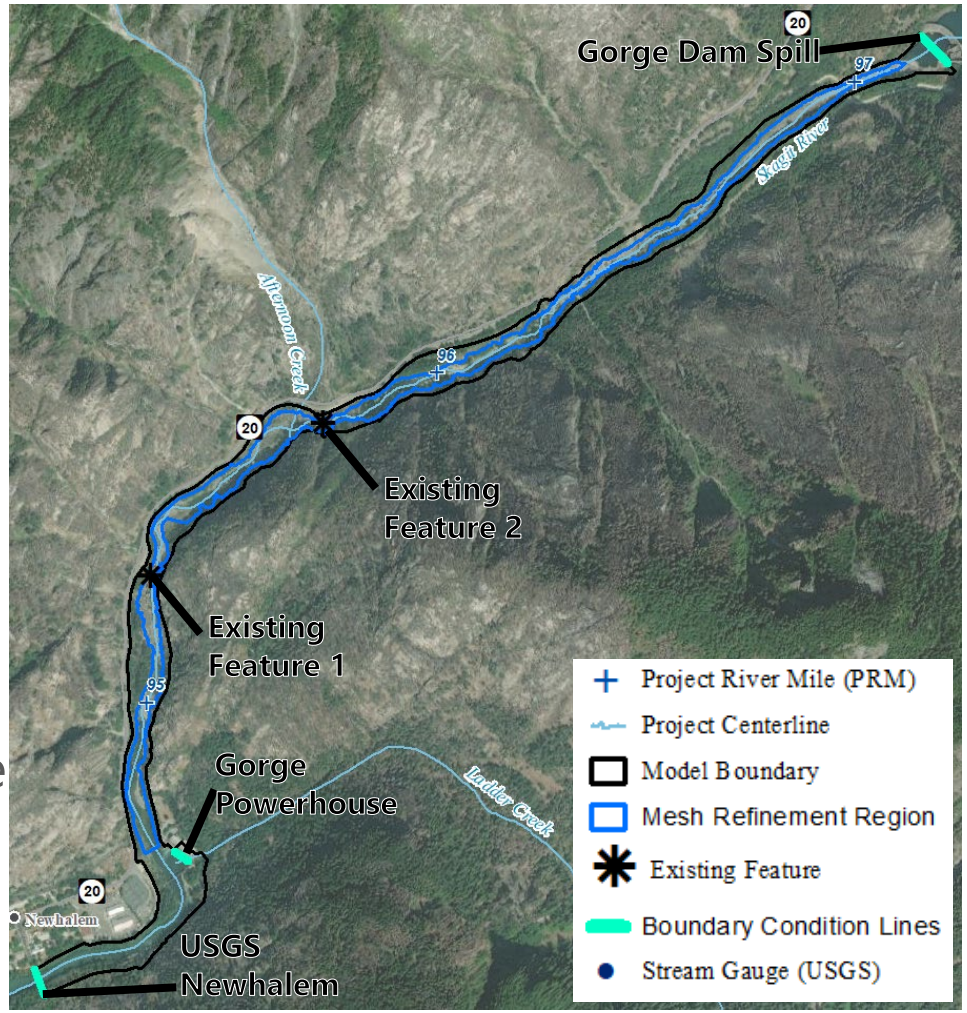
TERRAIN REFINEMENT

- Refinement extents
  - Dry Channel
  - Bank toe below vegetation
- Areas not reclassified
  - Afternoon Creek Pool
  - Gorge Dam Pool
  - Powerhouse pool/backwater



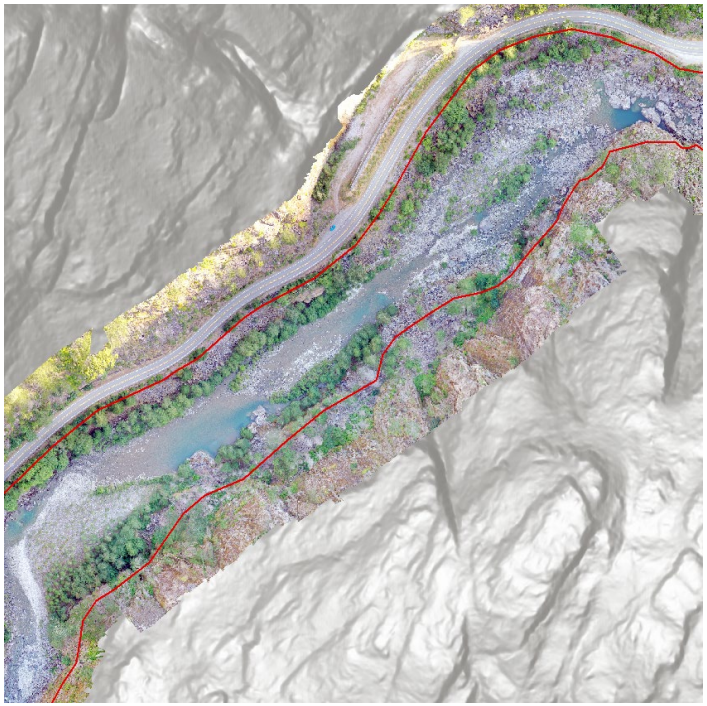
MODEL GEOMETRY

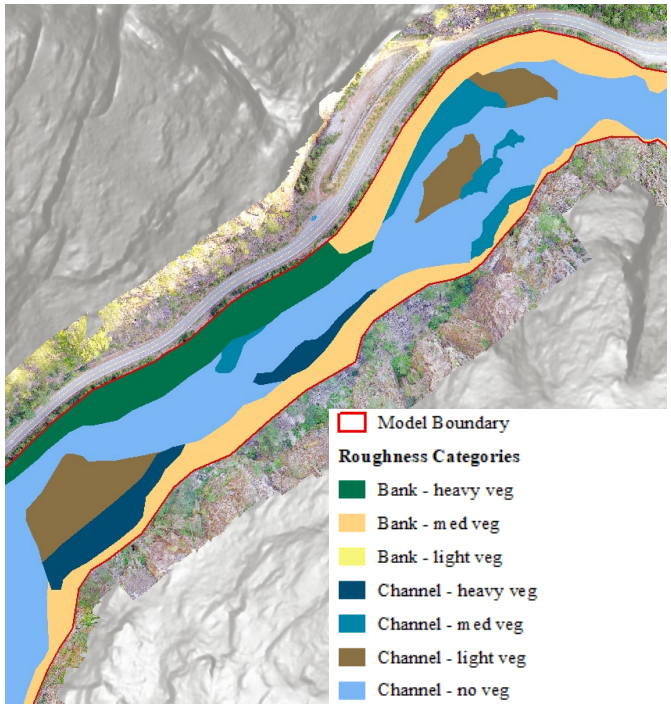
- Model Domain
  - Gorge Dam spill pool to USGS Newhalem
- Boundary Conditions
  - Gorge Dam spill
  - Gorge Powerhouse release
  - USGS Newhalem stage
- Channel refinement region
  - Channel and unvegetated bank toe
  - Covers 1’ terrain refinement



ROUGHNESS DELINEATION

- Channel and overbank – orthoimagery and preliminary model results
- Vegetation - orthoimagery





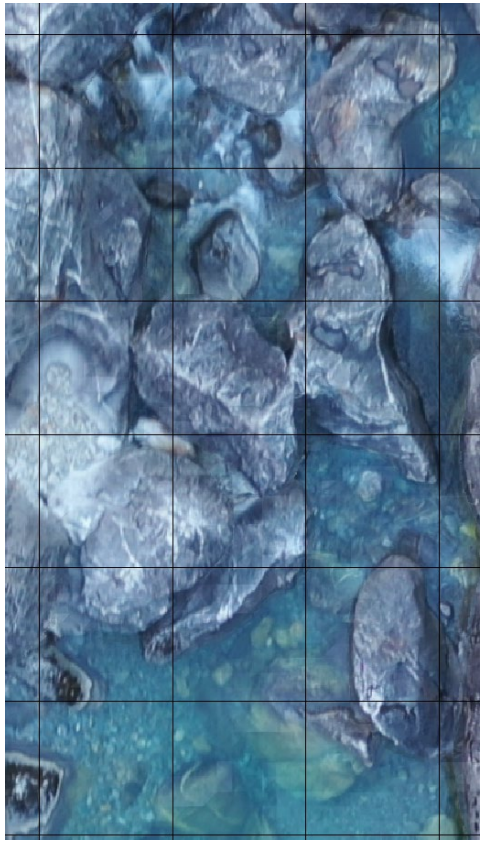
SENSITIVITY TESTS

- Cell Size
  - Timestep
- Roughness coefficient (Manning's n)
- Turbulence

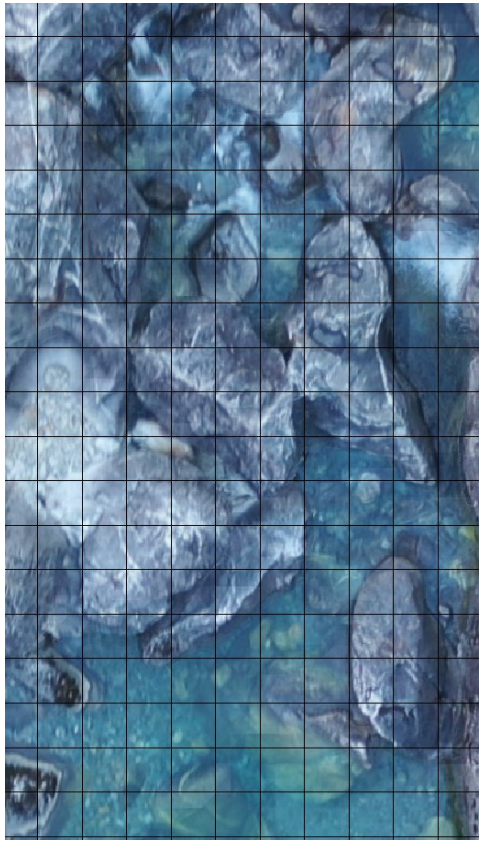
CELL SIZE SENSITIVITY

- Tested 9′, 6′, 3′, 2′, and 1′ cell size

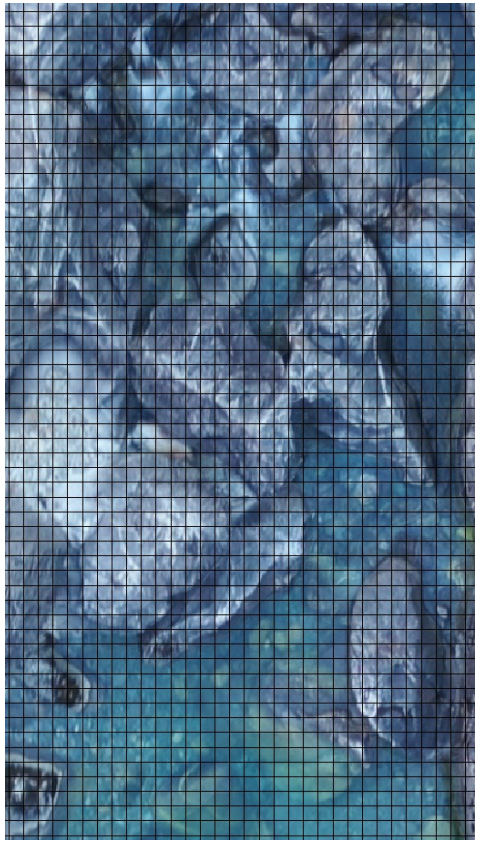
9′ Cells



3′ Cells



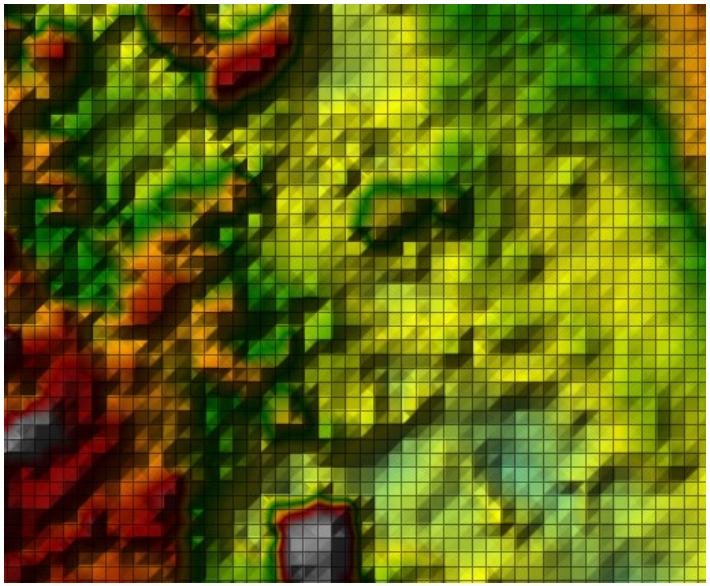
1′ Cells



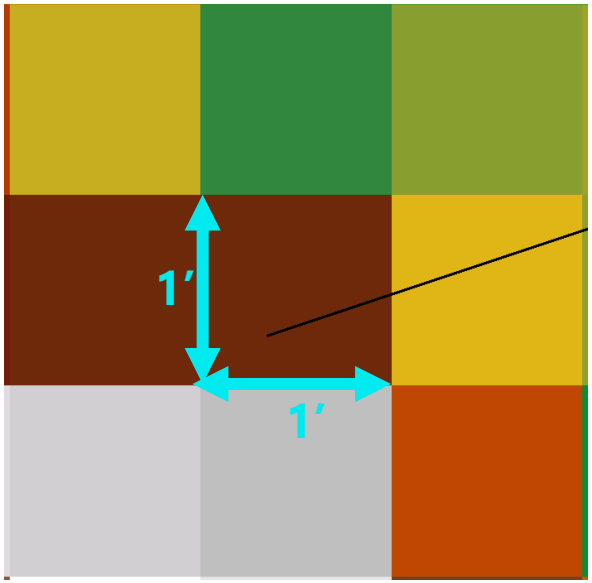
CELL SIZE SENSITIVITY

- 1-foot minimum cell size
  - Restricted by terrain resolution

1-ft Mesh Cells

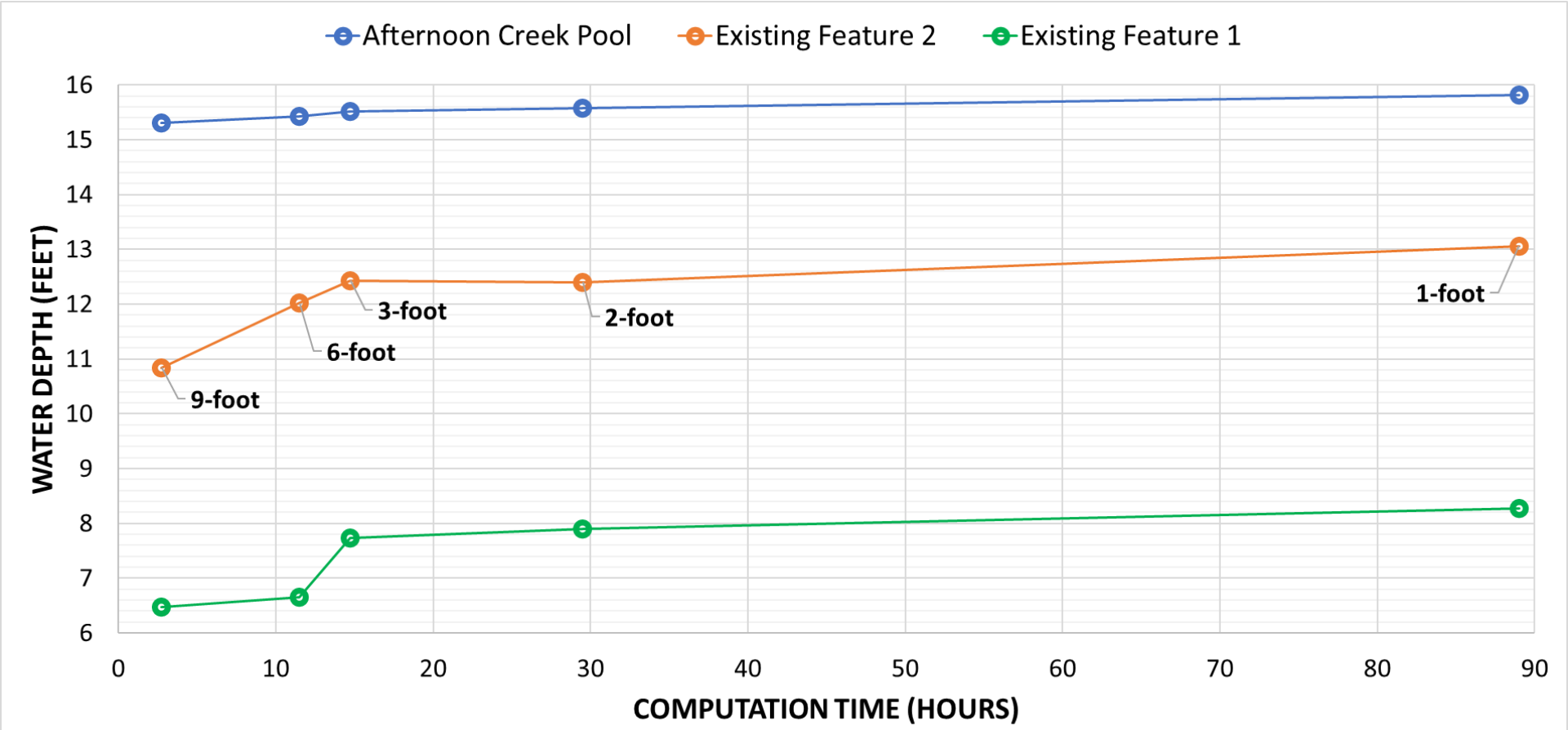


Terrain Resolution



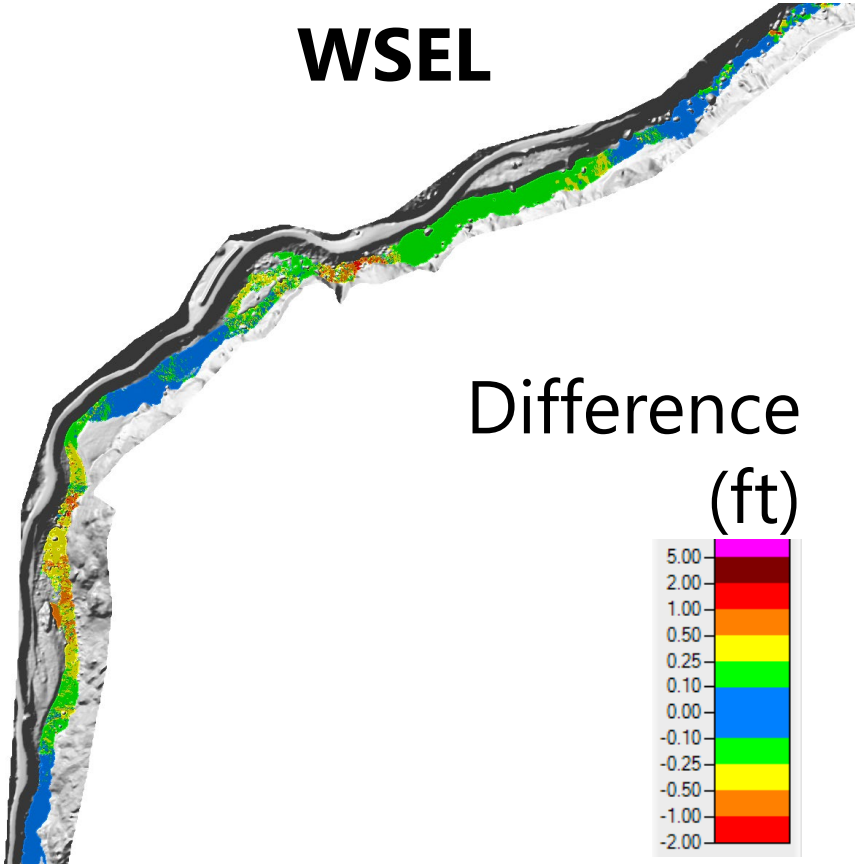
CELL SIZE SENSITIVITY

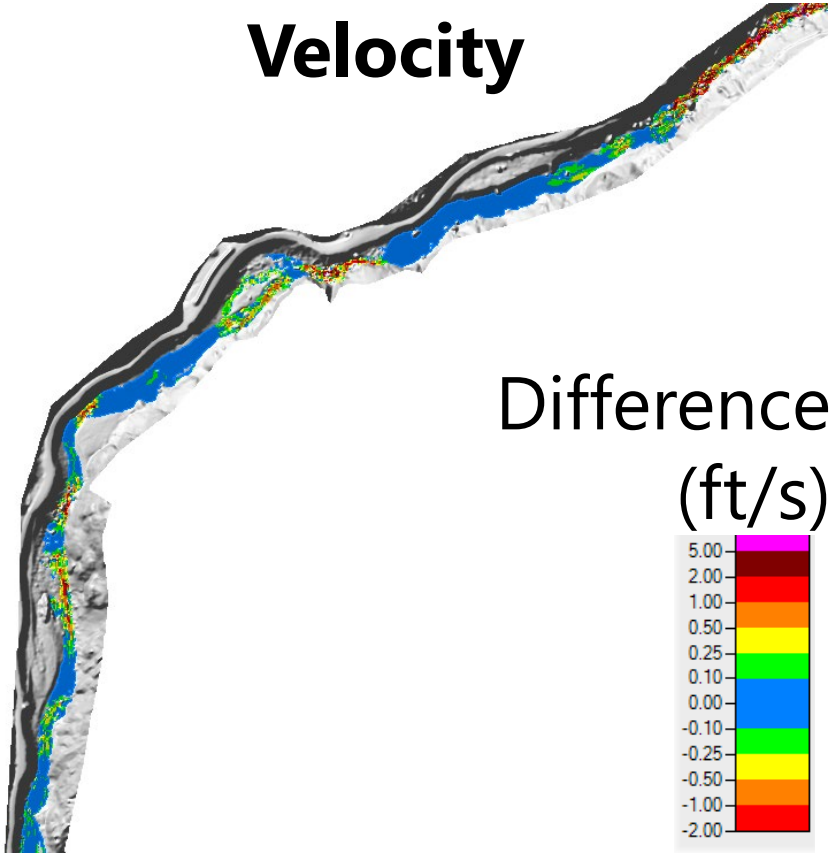
- Model results sensitive up to 1’ resolution



2’ VS 1’ CELL SIZE

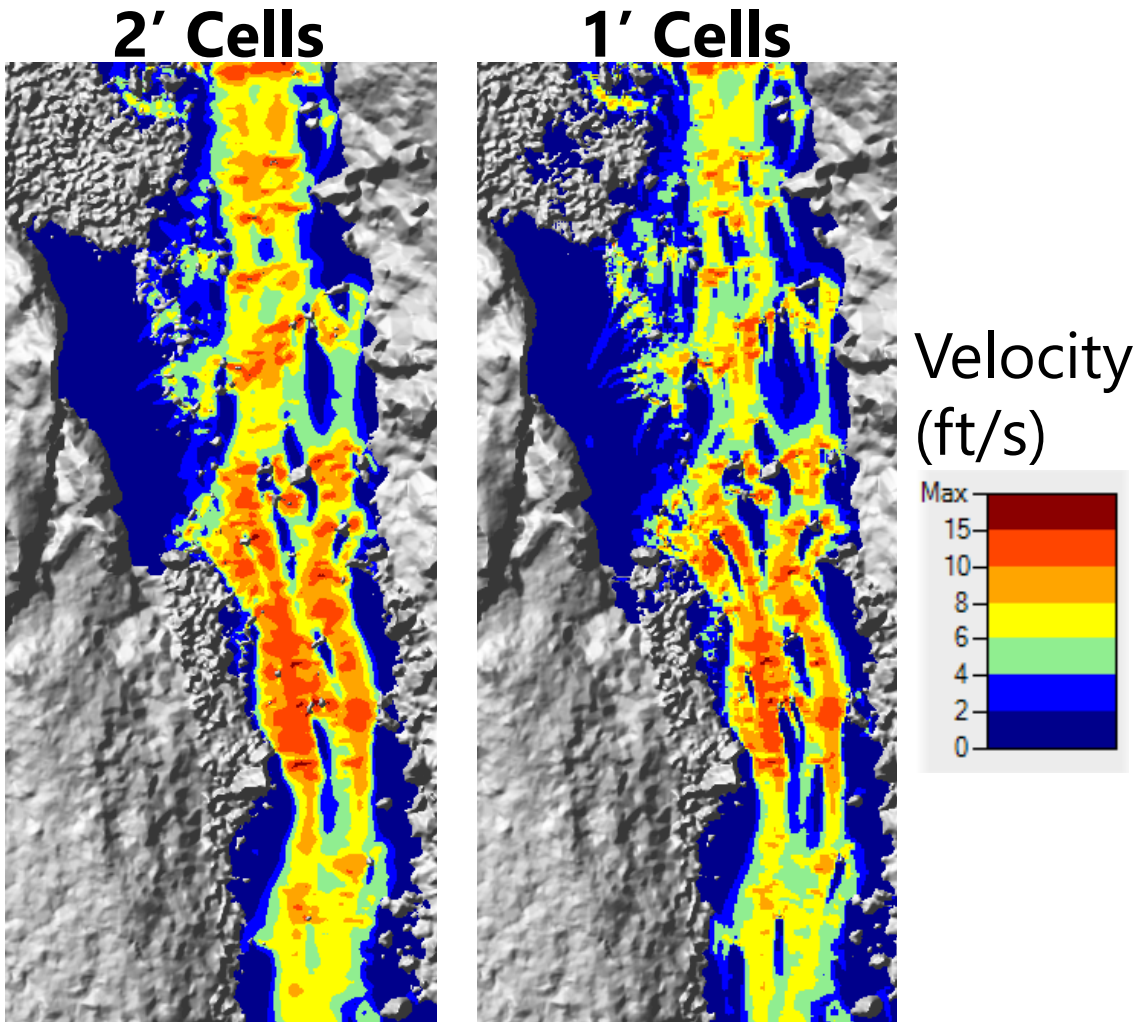
- Spatial results of cell size testing





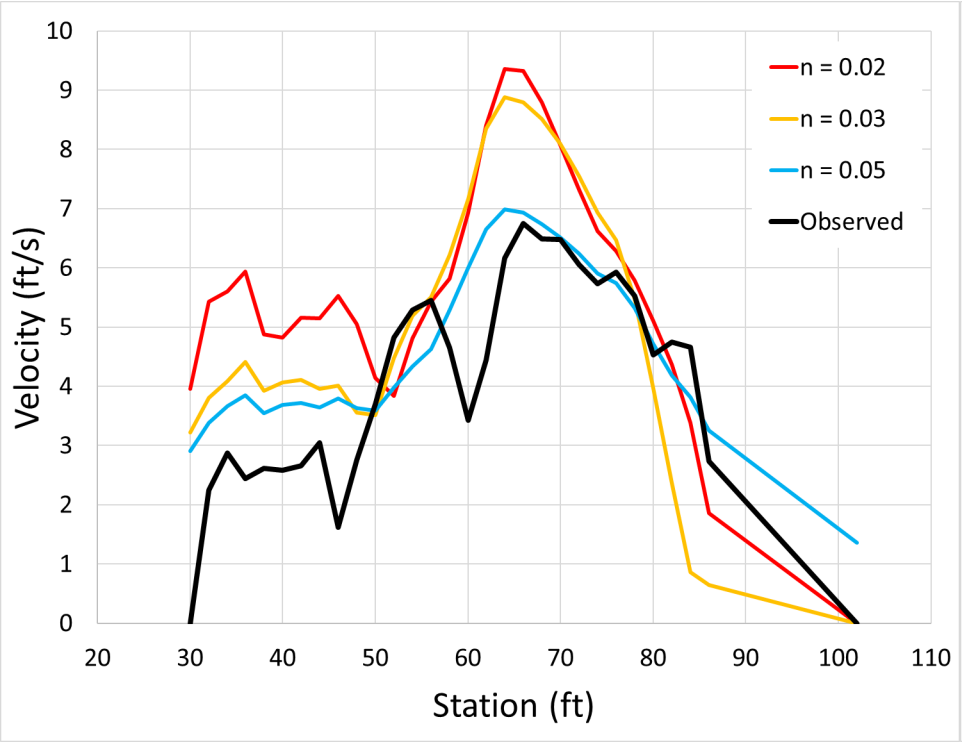
CELL SIZE SENSITIVITY

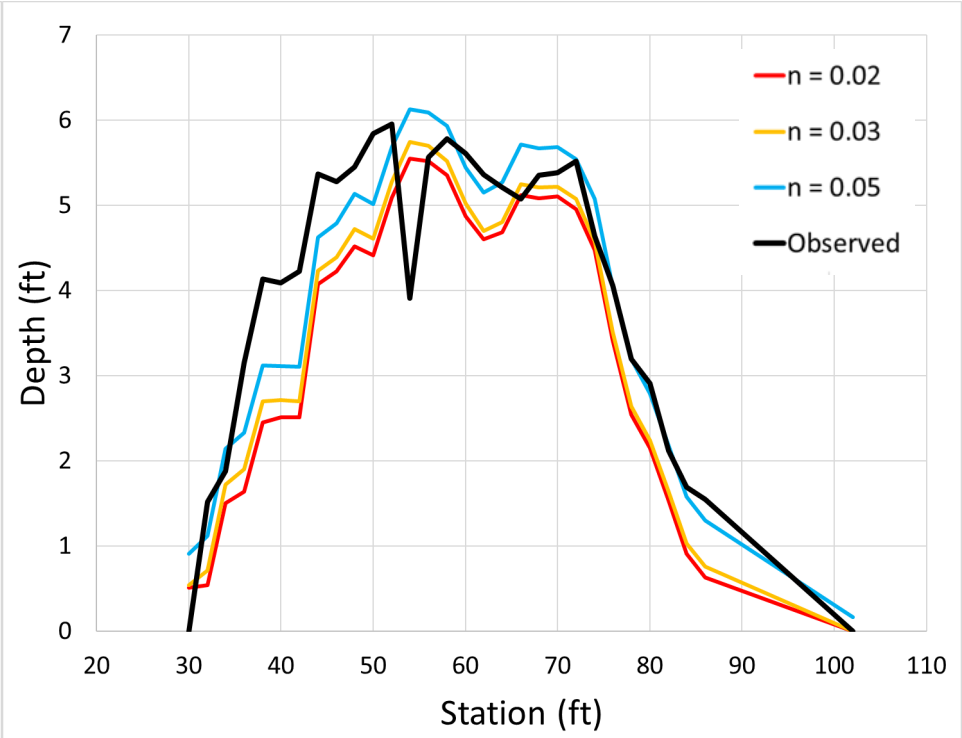
- Cell size impacts characterization of channel geometry
  - Velocity distribution



CHANNEL ROUGHNESS

Channel Roughness Sensitivity

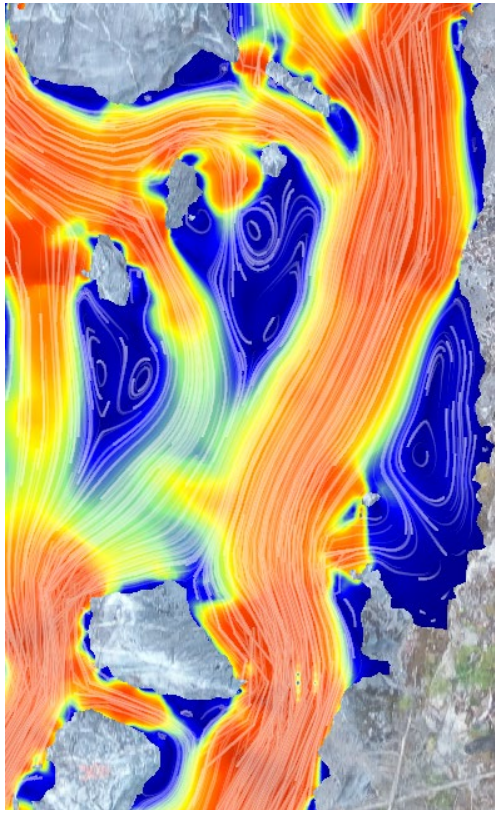




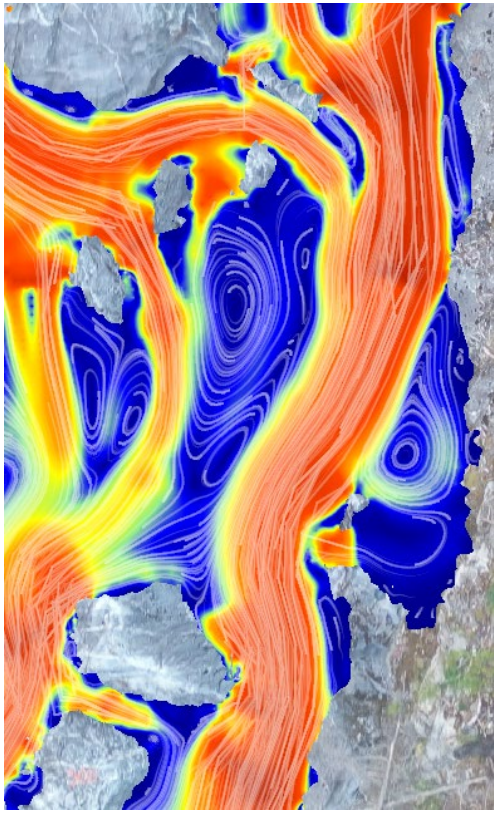
TURBULENCE SENSITIVITY

- More turbulence =
  - Stronger eddies
  - High velocity paths narrower and stronger

Turbulence Off



Max Allowable Turbulence Coefficients



BASE MODEL SELECTION

- 1′ channel cell size
  - 0.2 second timestep
- Default turbulence parameters
  - May be adjusted during model calibration

Seattle City Light

DISCUSSION





MODEL CALIBRATION AND VALIDATION

November 2, 2021

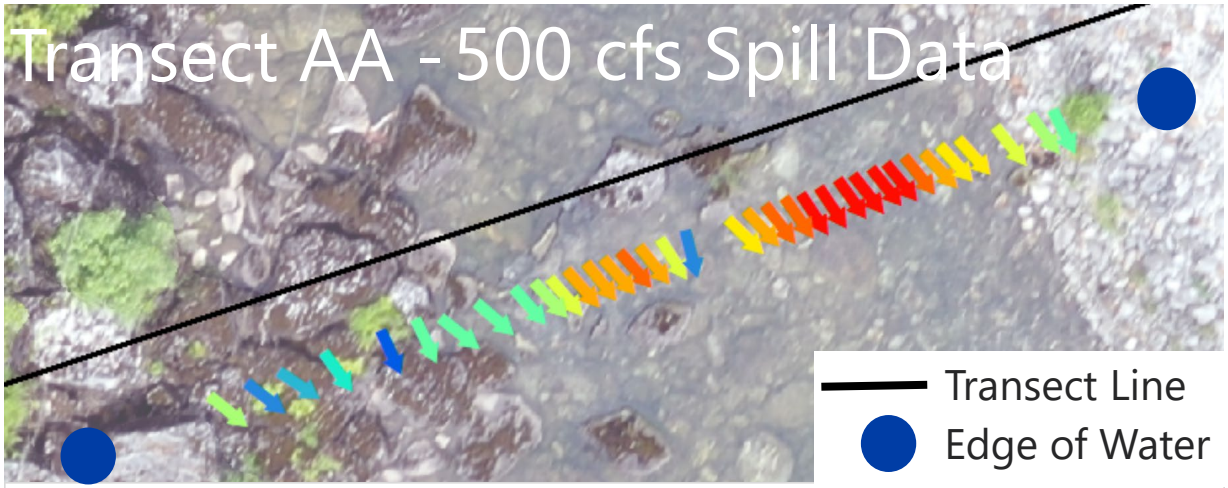
OVERVIEW

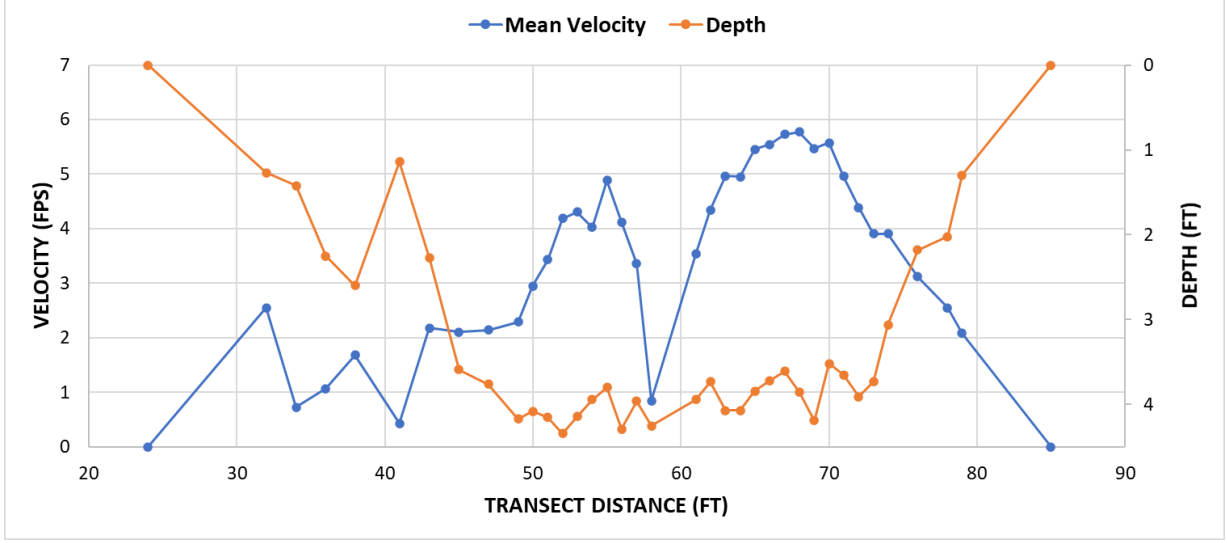
- Observed Data
- Calibration Procedure
- Current Status
- Future Trajectory

OBSERVED DATA

- Observations at 4 discharges + dry
  - Transects (5)
  - Level Loggers (12)
  - Drone-based ortho-images
  - Drone-based video

TRANSECT

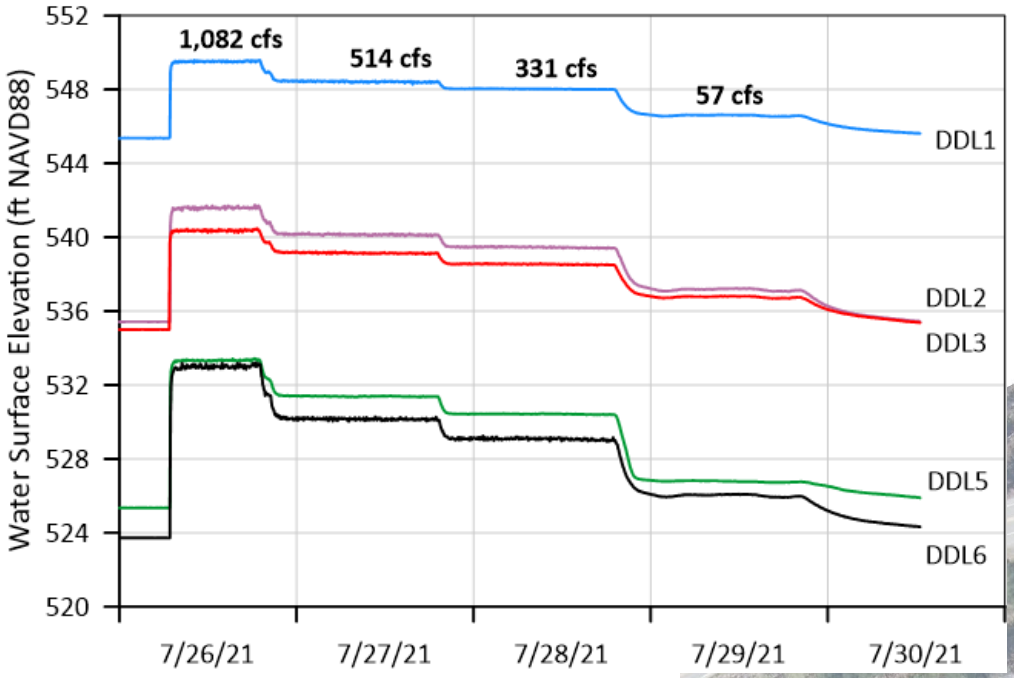


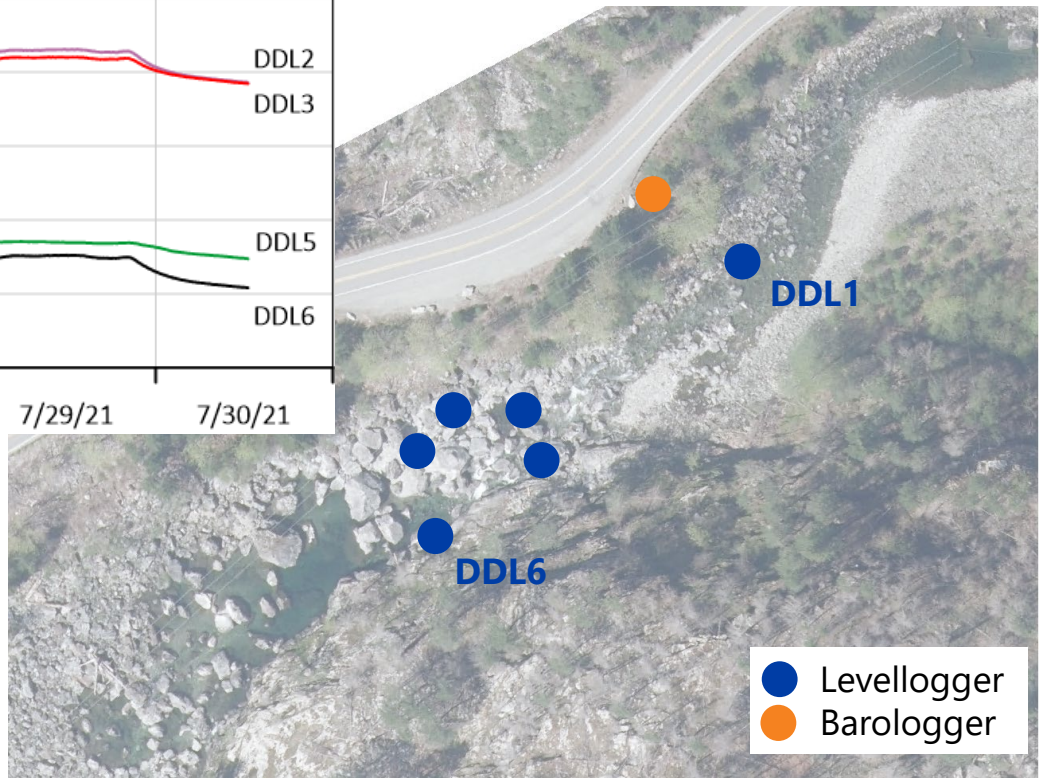


Velocity (FT/S)

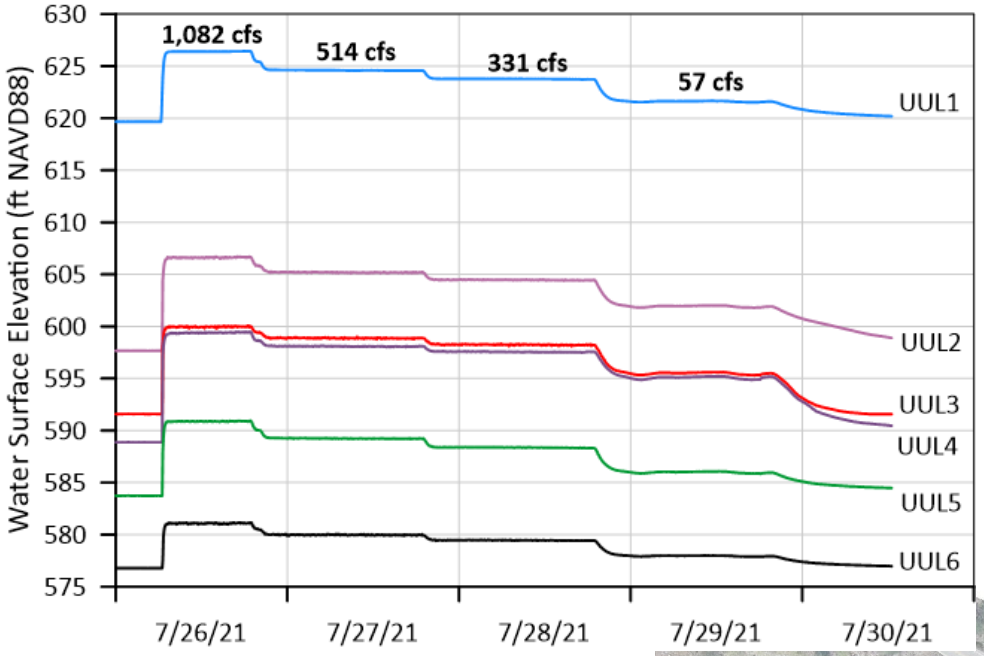
- 0 - 0.5
- 0.5 - 1.0
- 1.0 - 1.5
- 1.5 - 2.0
- 2.0 - 2.5
- 2.5 - 3.0
- 3.0 - 3.5
- 3.5 - 4.0
- 4.0 - 4.5
- 4.5 - 5.0
- 5.0+

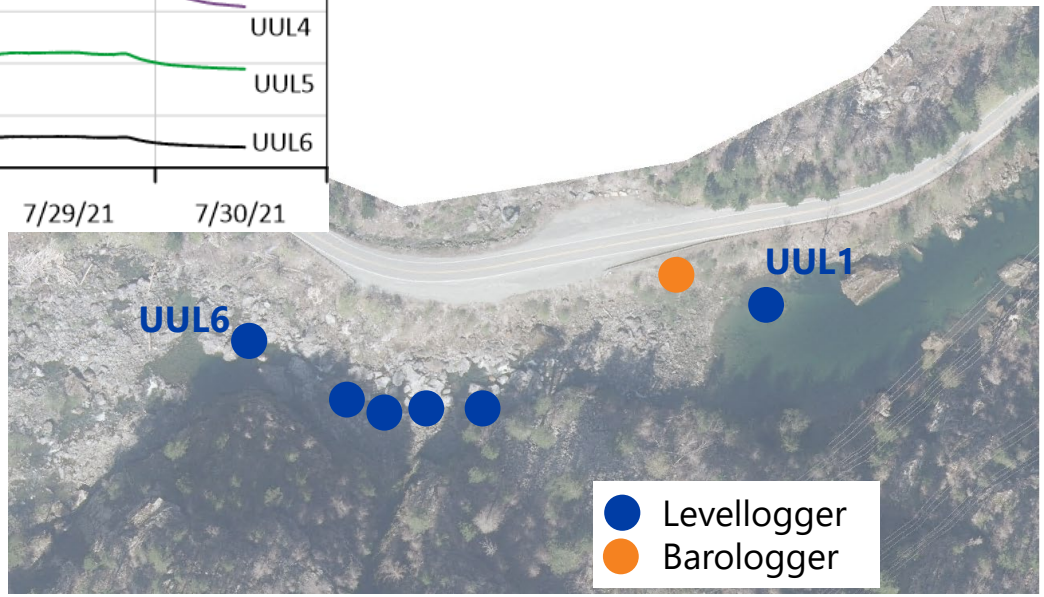
EXISTING FEATURE 1 WATER LEVELS



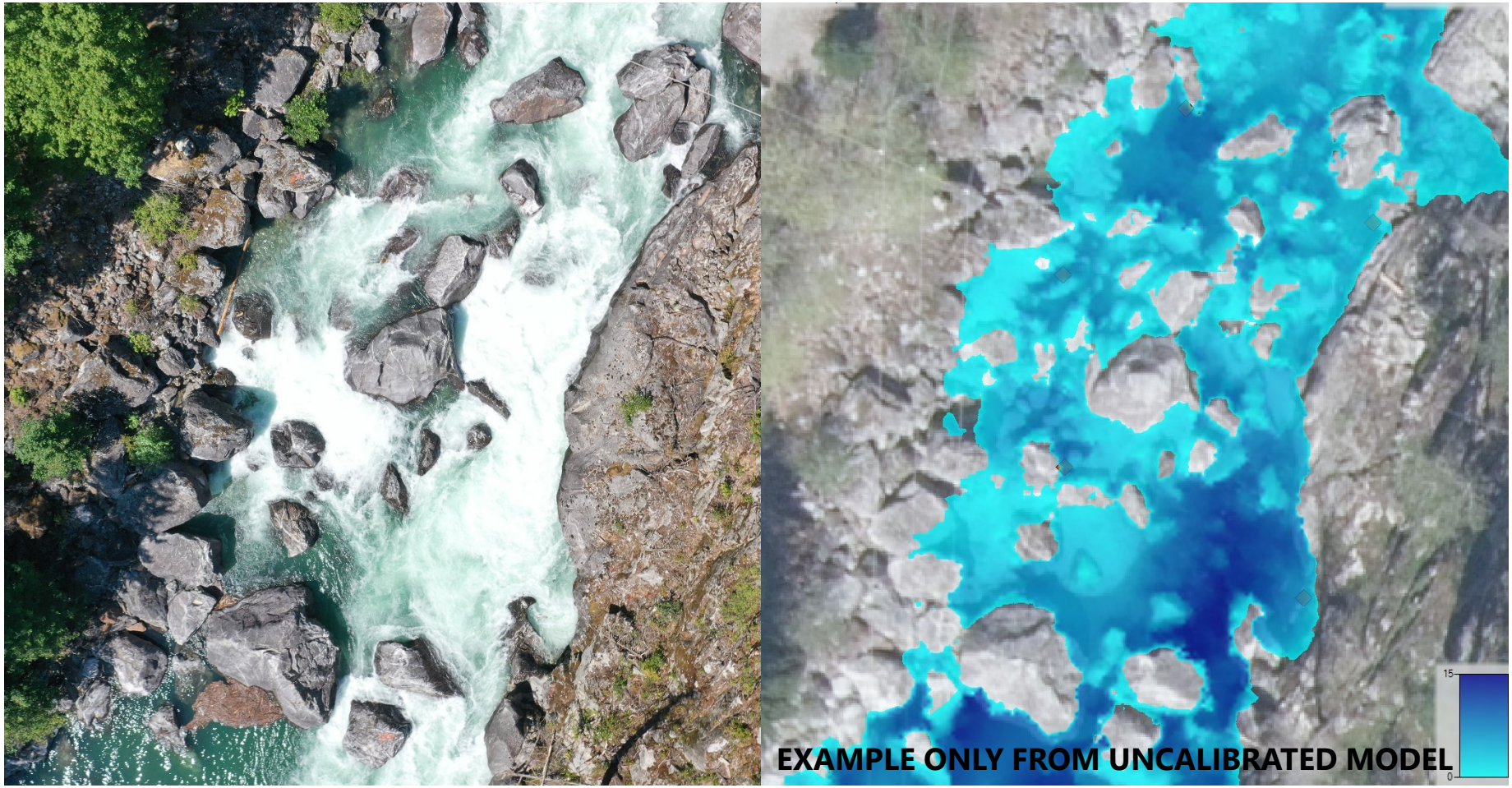


EXISTING FEATURE 2 WATER LEVELS

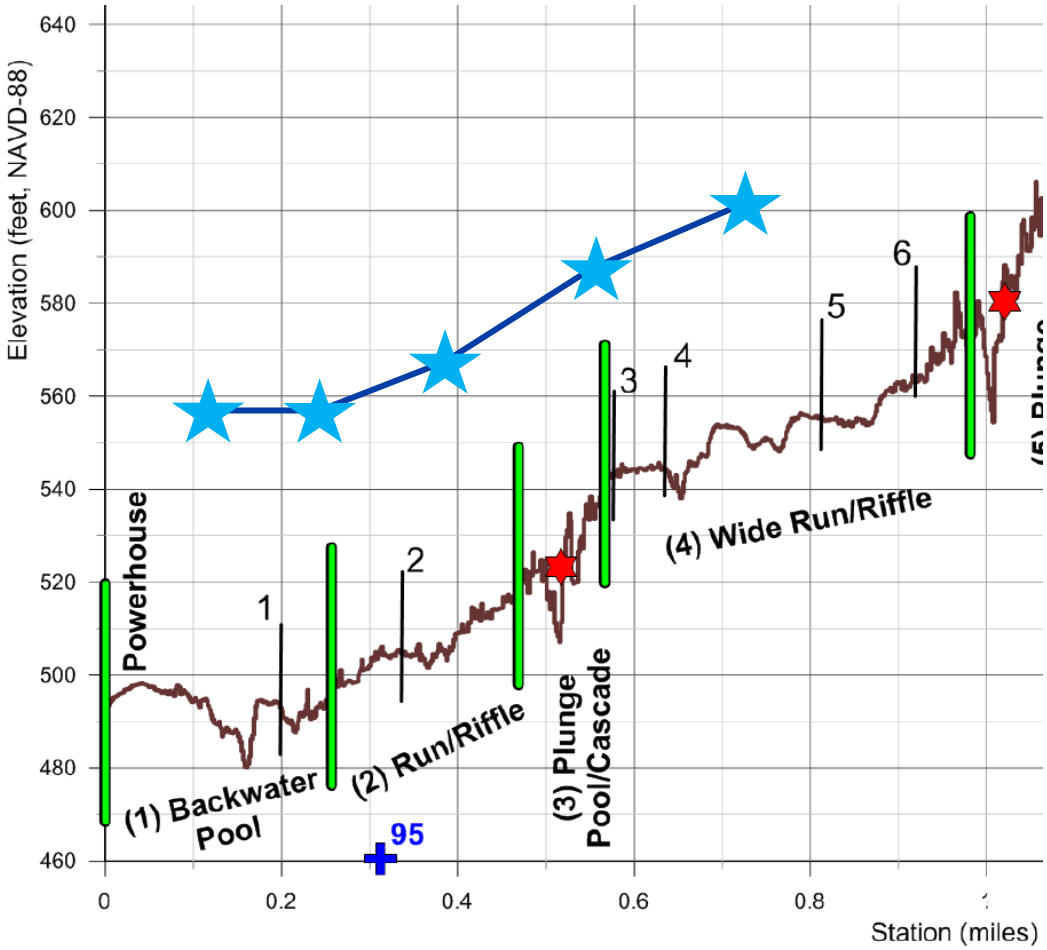




DRONE-BASED ORTHOIMAGERY – INUNDATION EXTENTS

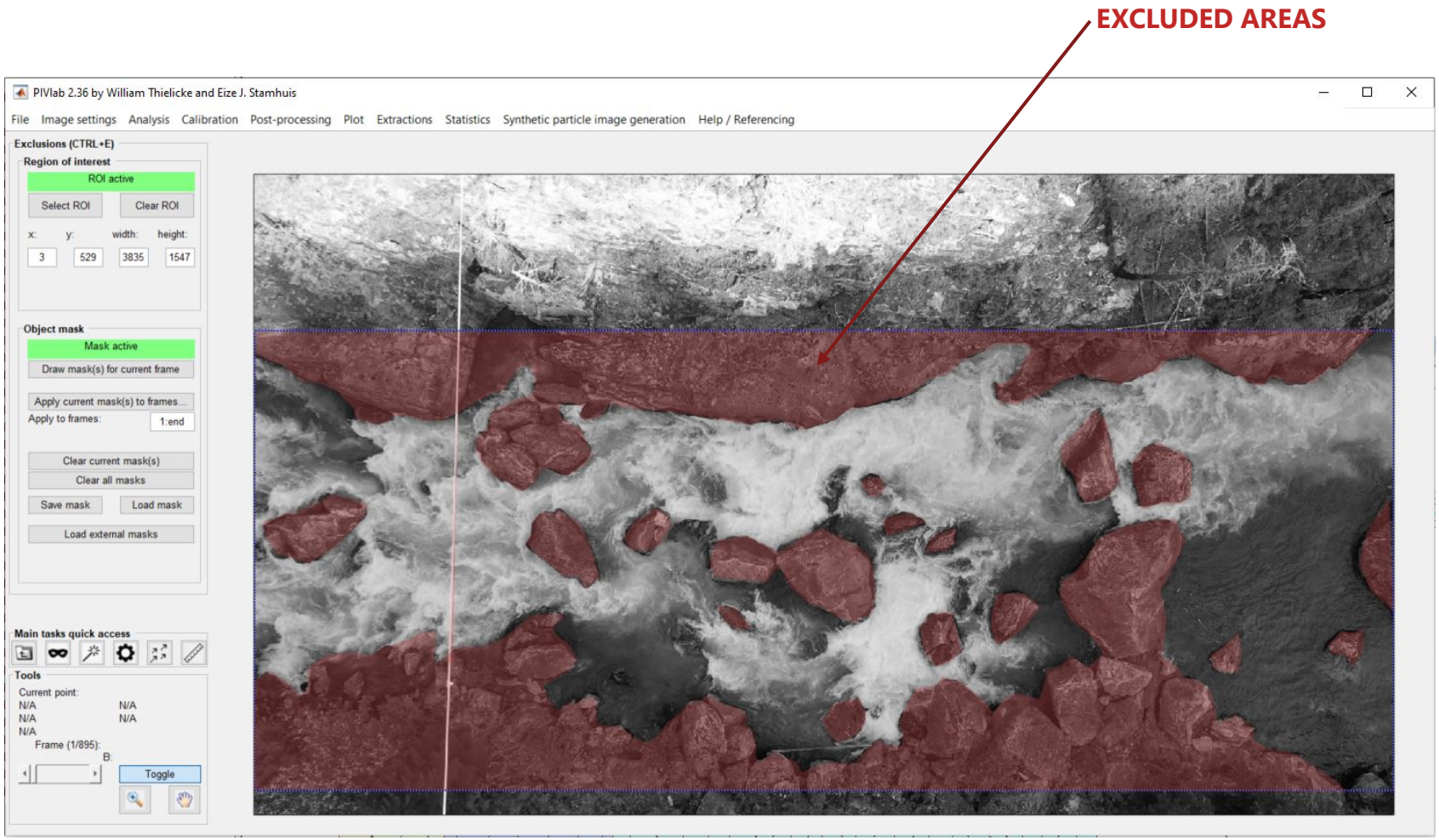


DRONE-BASED ORTHOIMAGERY – WSEL PROFILE



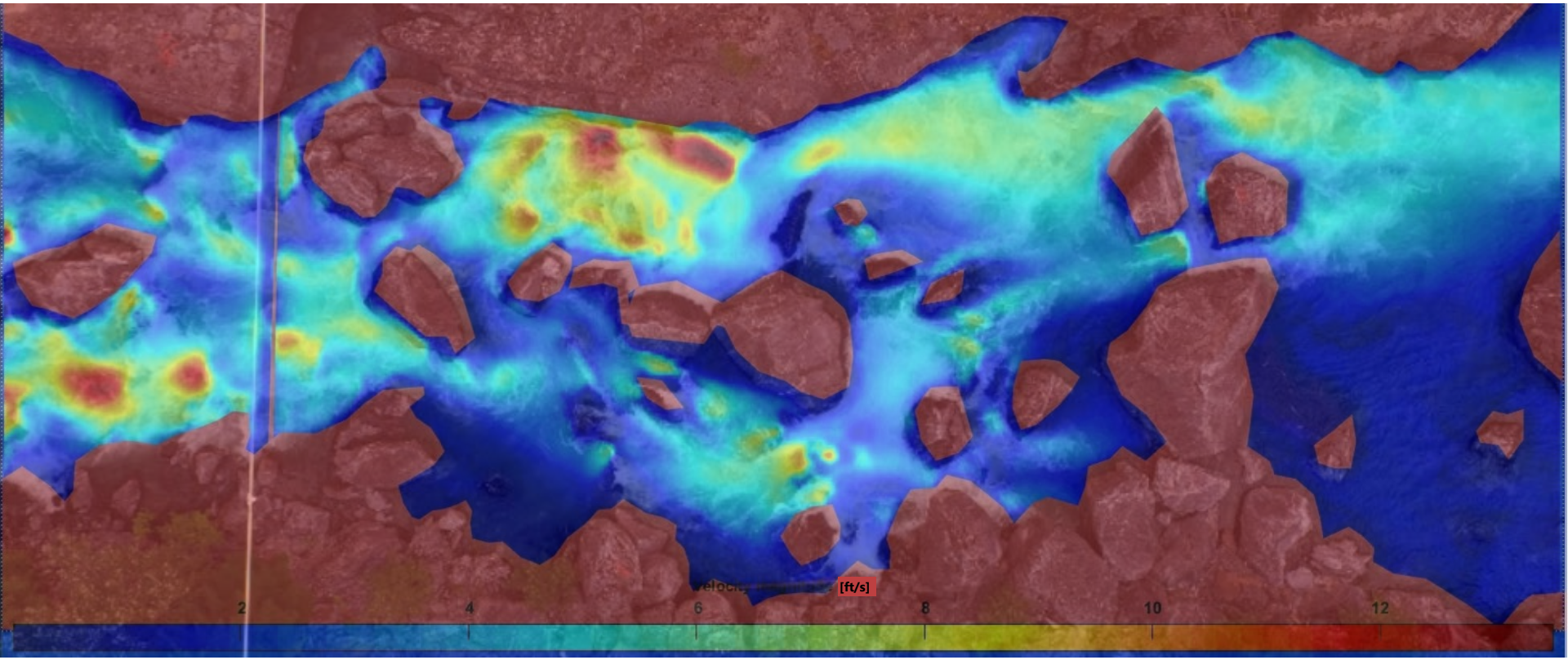


DRONE-BASED VIDEO - LSPIV

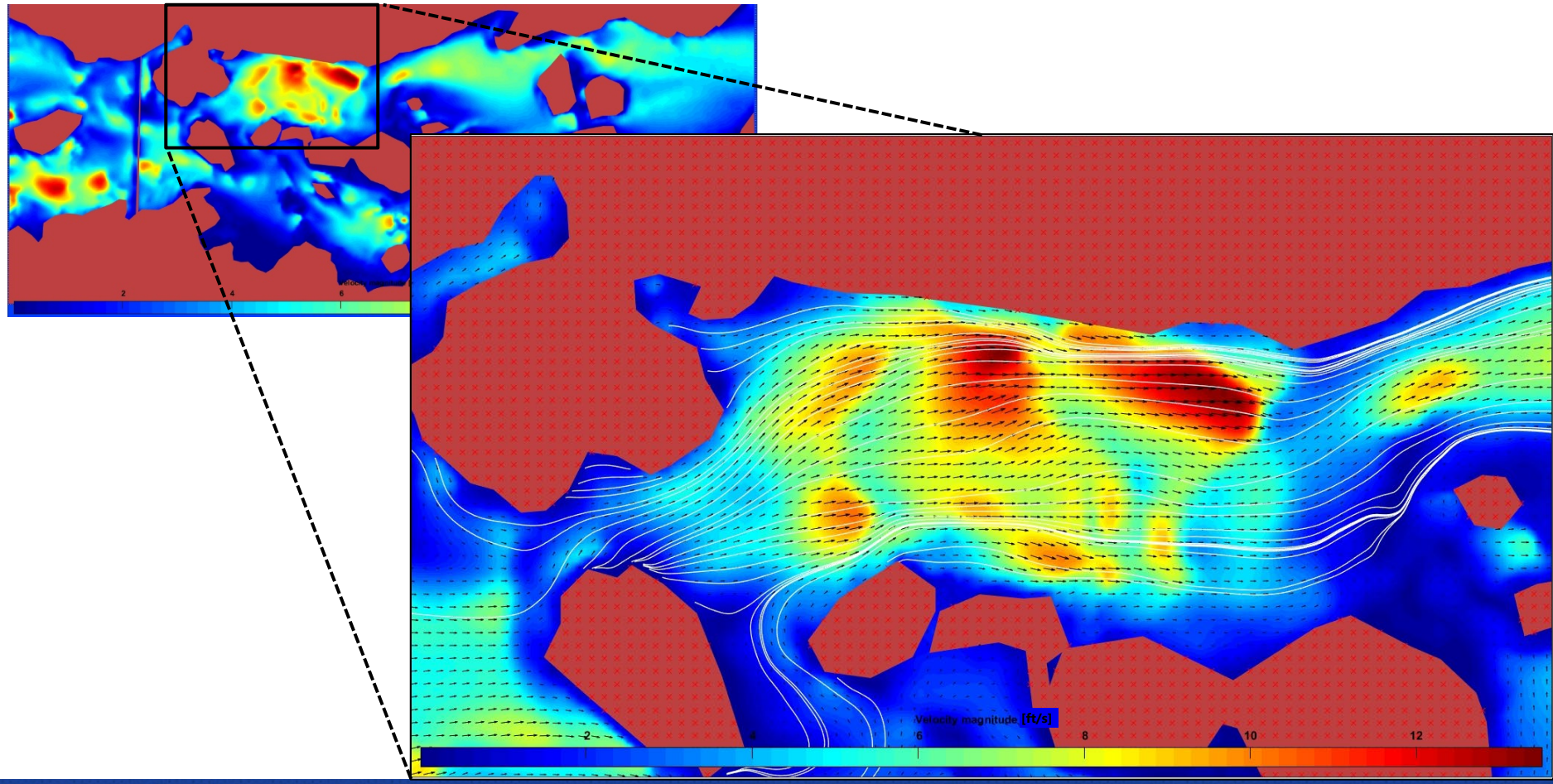


DRONE-BASED VIDEO - LSPIV

- Mean Velocity Magnitude

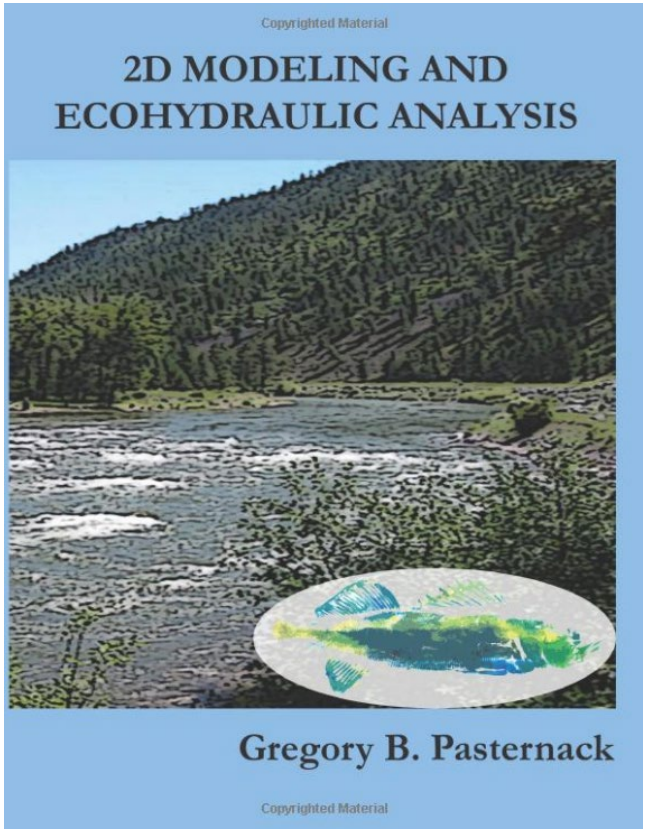


DRONE-BASED VIDEO - LSPIV



PERFORMANCE EVALUATION

- Performance evaluation standards lacking for 2D models
- Pasternack
  - http://pasternack.ucdavis.edu/
- Most common: WSEL, V_{mag}
  - Deviation, correlation, regression statistics



QUANTITATIVE PERFORMANCE INDICATORS

- Observed vs. Modeled WSEL(Depth) & V_{mag}
  - Deviation statistics (raw, %)
  - Coefficient of determination (r^2)
  - Regression line slope ~1:1
  - Zero intercept of regression line; offset?
  - Relative cross-sectional pattern ->spatial associations model error
  - Observed vs. Modeled hydraulic phase-space plots (D vs V_{mag})
- NO quantitative standards for these performance indicators have been proposed or adopted through scientific consensus

PERFORMANCE EVALUATION

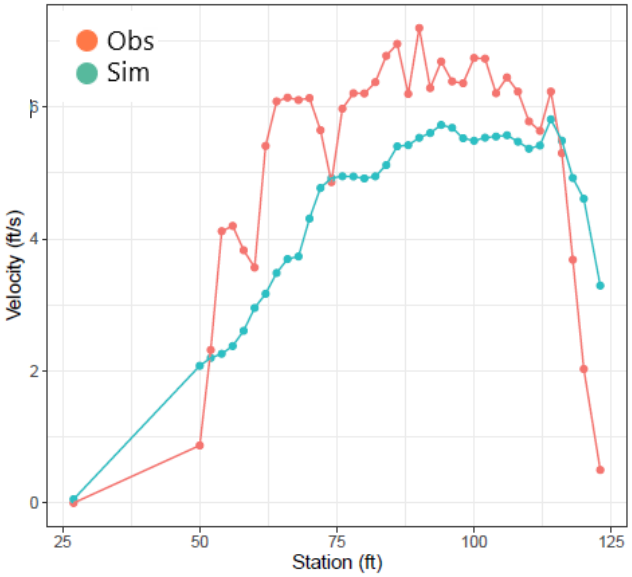
- Performance never perfect!
  - Uncertainty in observed data
  - Assumptions & simplifications in SWE and solution procedures
- Performance testing -> characterizing uncertainty

CURRENT STATUS

- Compare to transect and level logger data
- Focus on roughness delineation and values
- No turbulence adjustment

TRANSECT EE EVALUATION - VELOCITY

1200 cfs



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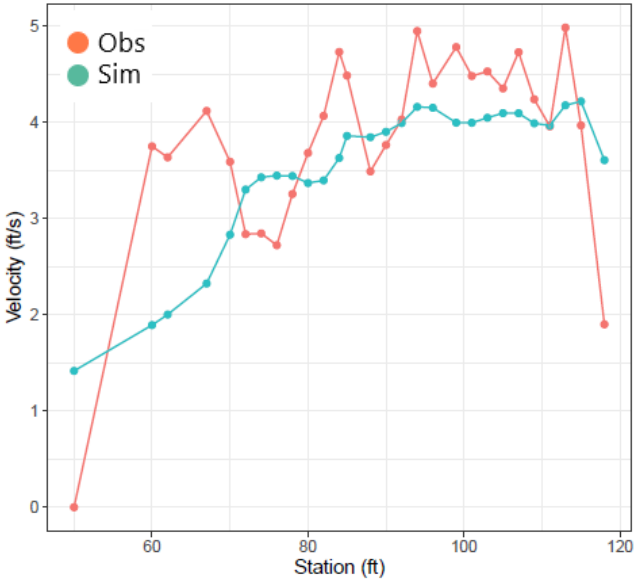

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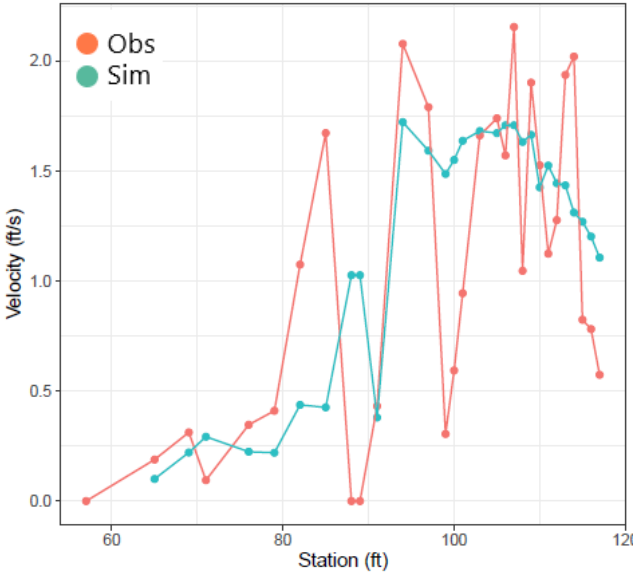

TRANSECT II EVALUATION - VELOCITY

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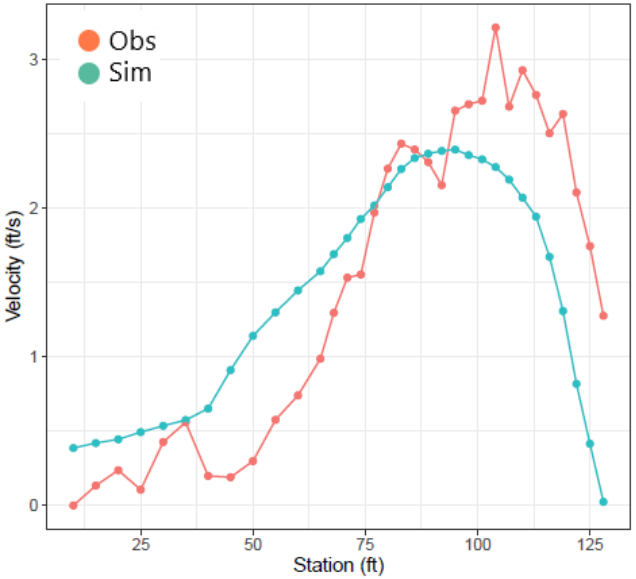

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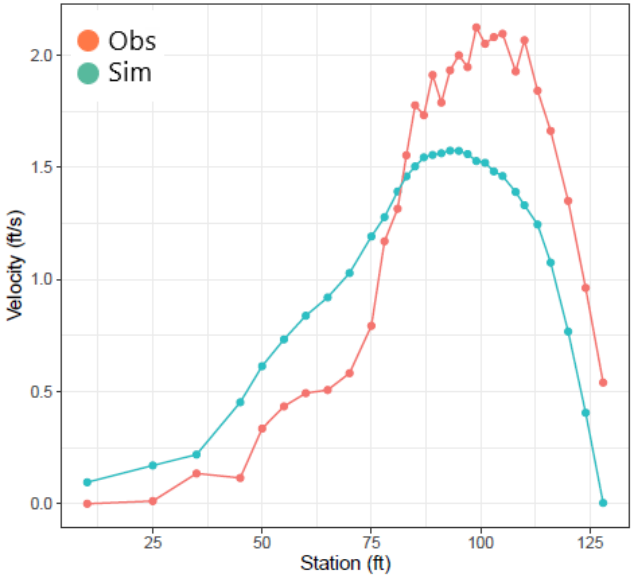

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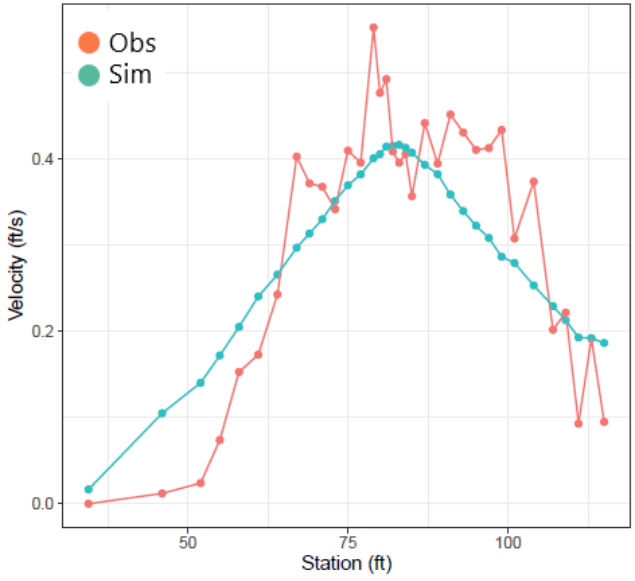

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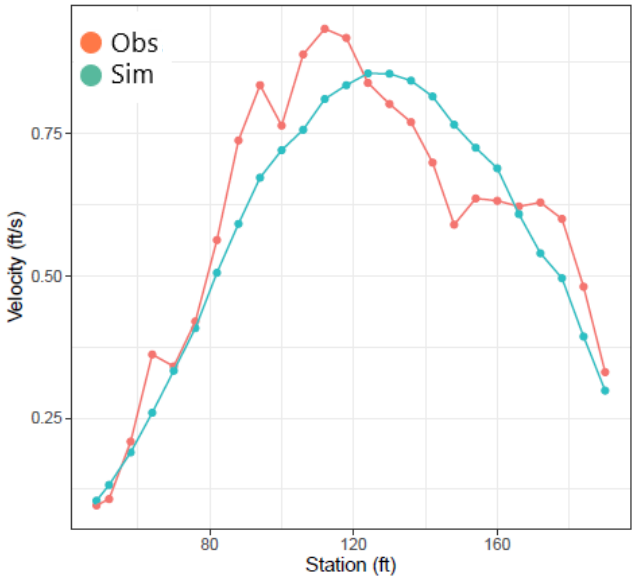

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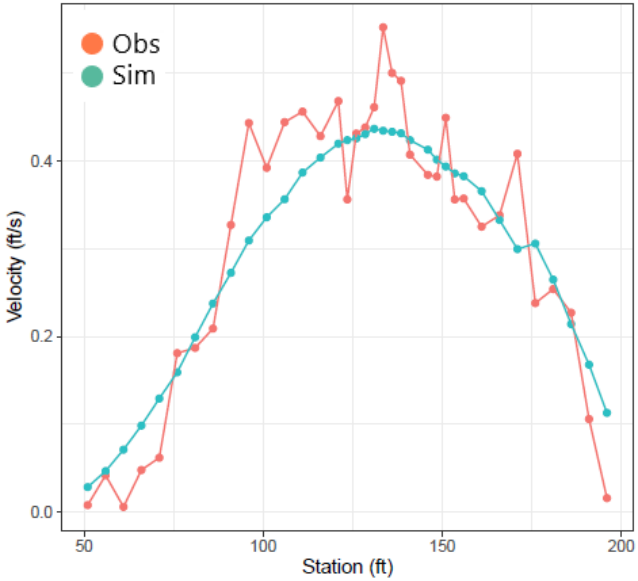

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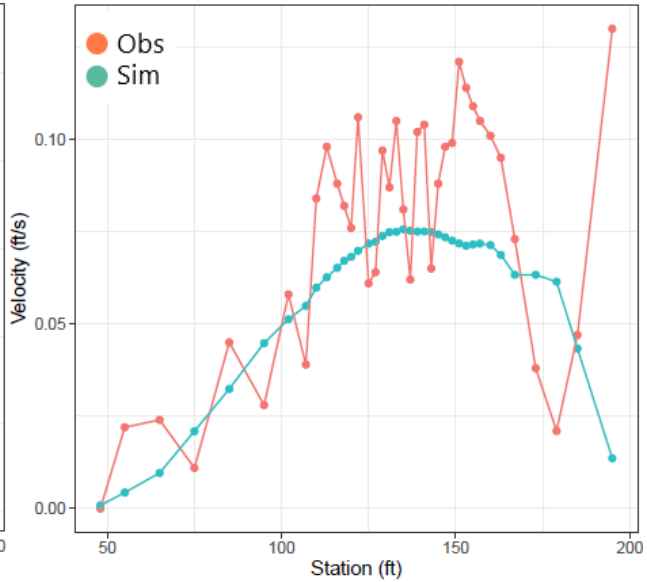

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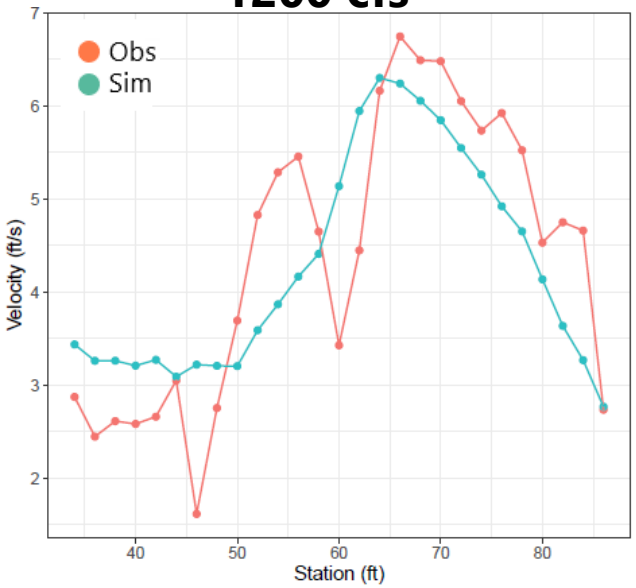

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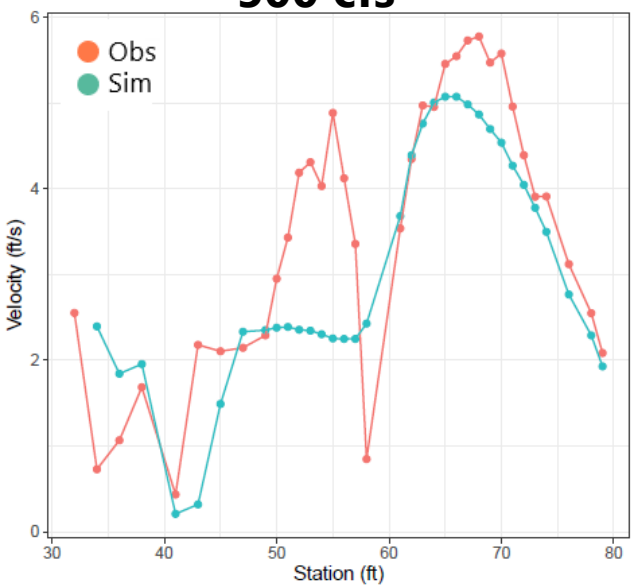

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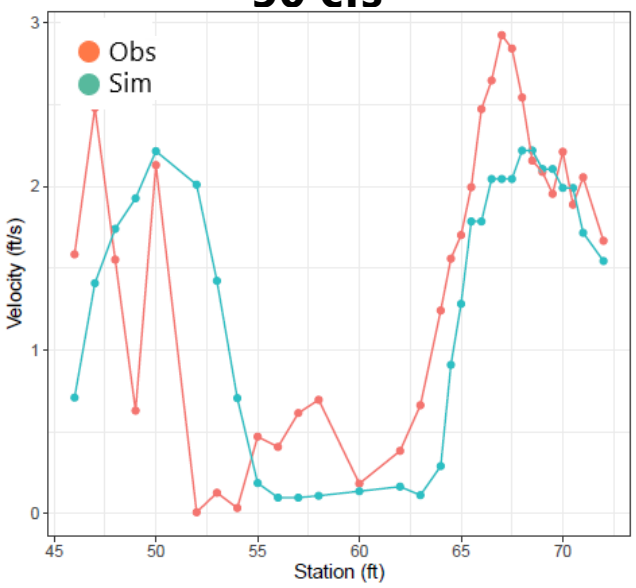

TRANSECT GG EVALUATION - VELOCITY

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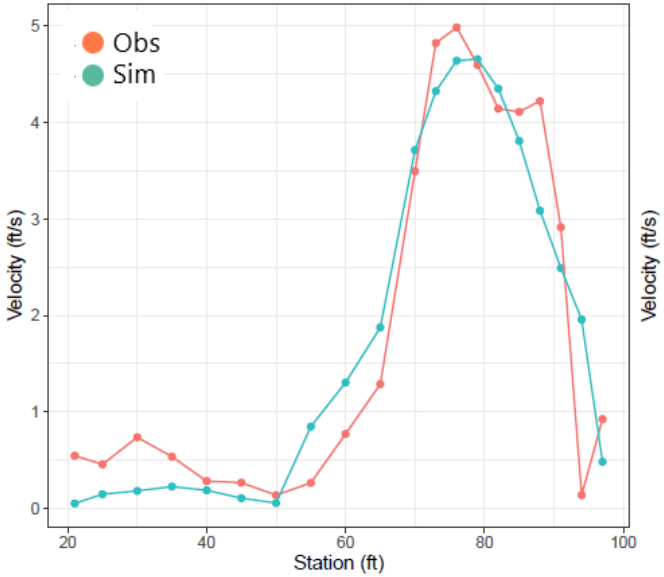

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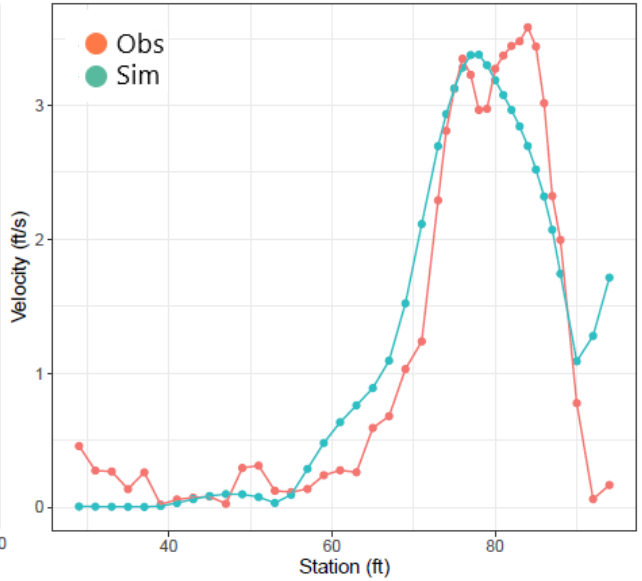

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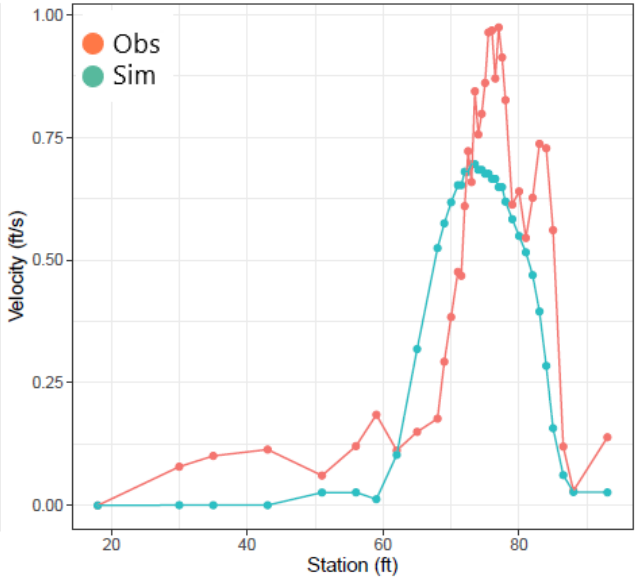
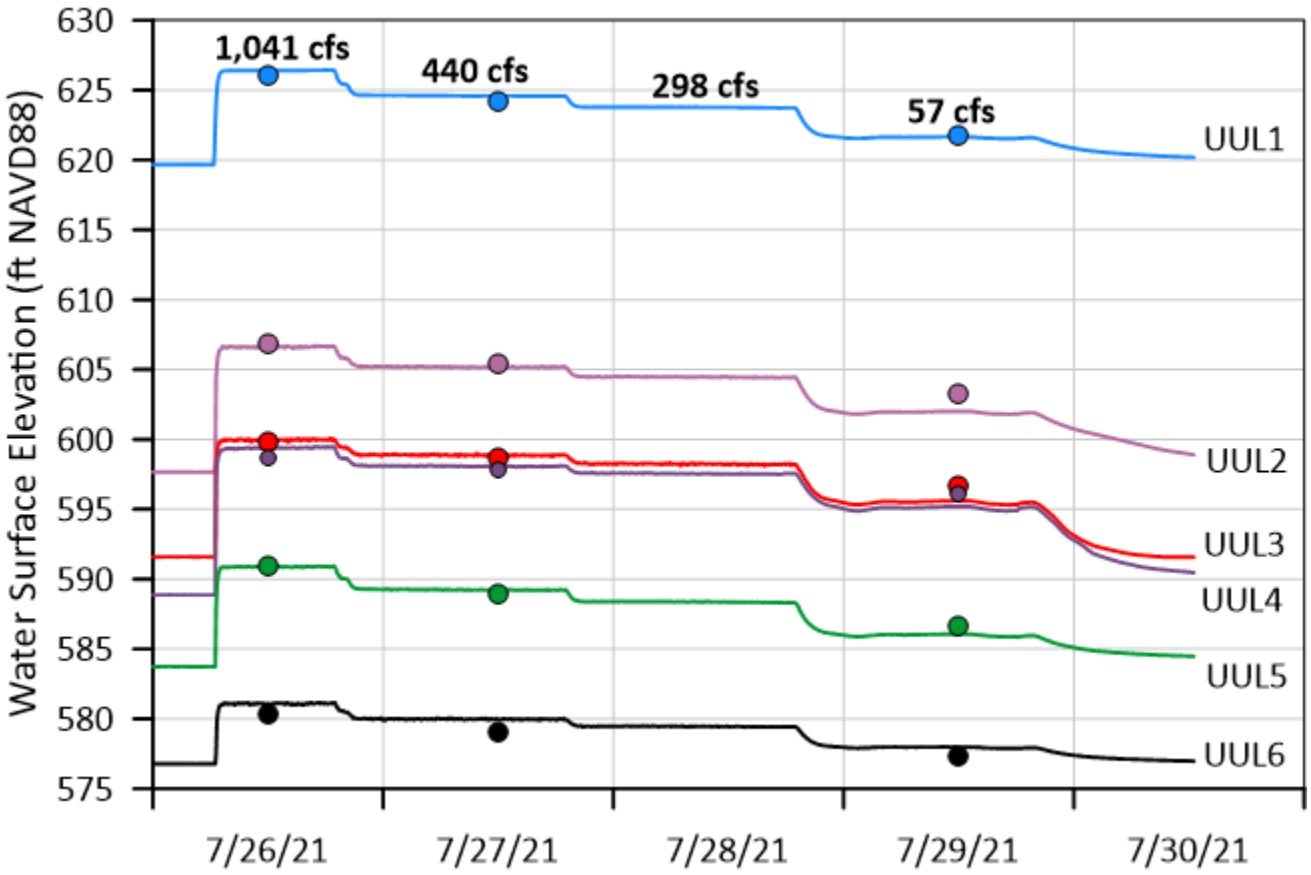
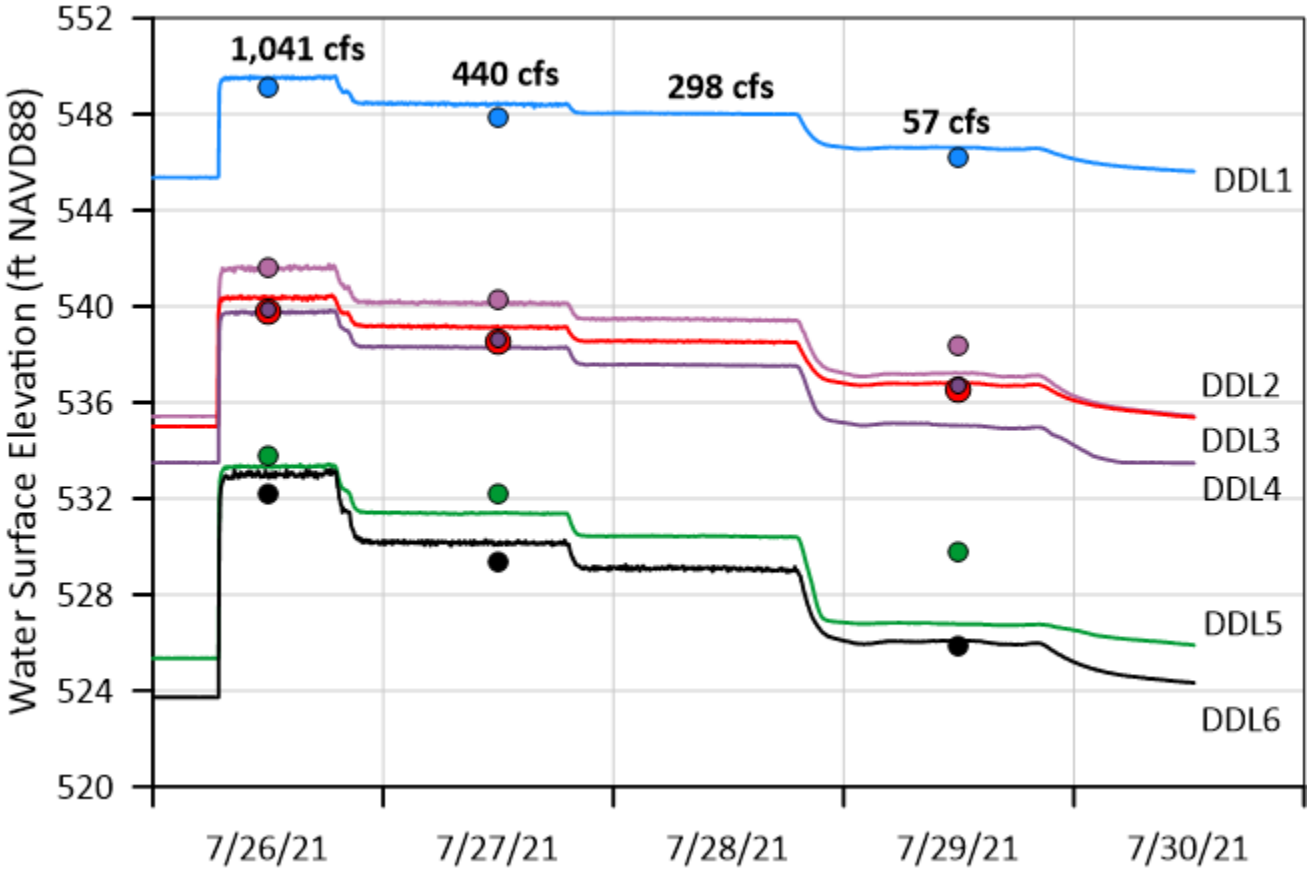


CURRENT PROGRESS – EXISTING FEATURE 2 EVALUATION



CURRENT PROGRESS – EXISTING FEATURE 1 EVALUATION



FUTURE TRAJECTORY

- Further calibration to observed transect data
  - Roughness delineation and magnitude
  - Turbulence
- Water surface elevation profiles
  - Longitudinal roughness variation in channel
- Level logger data
  - Calibrate to 6200 cfs at Existing Features
- Validate model output with 250 cfs observations
- LSPIV – qualitative verification

Seattle City Light

DISCUSSION





DEVELOPMENT OF BIOLOGICAL/HABITAT DATA AND INTEGRATION WITH HYDRAULIC MODEL

November 2, 2021

OVERVIEW

- Substrate and Cover Mapping Update
- HSC and Periodicity Development Update
- Aquatic & Biologic Habitat Integration Preview
- Hydraulic Data Generation for Fish Passage Analysis

SUBSTRATE/COVER MAPPING

- Field-based substrate/cover mapping occurred during July – October 2021. This data is currently being QC'd.
- Next steps will focus on filling in data gaps for areas that were difficult to access and where visibility was poor due to turbidity and/or depth. This process will be taking place over the next month to create a more complete map of substrate and cover for the bypass reach and mainstem.
- Mapping data will be shared with Geomorphology Team.

HABITAT SUITABILITY CRITERIA (HSC)

- HSC Development – Small Group Technical Meetings
  - Comprised of LPs, City Light, and Consultant team members
  - Initial focus of the group has been on developing preliminary HSC curves based on existing curves, studies and/or literature.
  - Future efforts will focus on species/life stages where field validation data is being collected.
  - HSC curves to be used for both bypass reach and below Gorge Powerhouse instream flow modeling.
  - Anticipate review of preliminary HSC curves with LPs in early January 2022.

HSC FIELD VALIDATION STUDIES

- Focus species / life stages
  - Steelhead spawning (Spring)
  - Chinook, Pink, Chum spawning (Fall/Winter)
  - Steelhead, Chinook, Bull Trout juveniles
- Data from these studies will be used to help validate (and/or potentially modify) existing HSC curves that will be used in the habitat modeling.

PERIODICITY

- Periodicity Technical Group Meetings
  - Periodicity is used to help focus habitat model results on periods that are relevant to each species/life stage being modeled.
  - Smaller technical working group comprised of LPs, City Light, and Consultant team members has been meeting to review existing information and recommend modifications to the preliminary periodicity table.
  - Periodicity is relevant to not only the FA-02 and FA-05 instream flow model studies, but several other fisheries-related studies.

AQUATIC & BIOLOGIC HABITAT INTEGRATION PREVIEW

- Calculate combined HSI and UA (not ***W***UA)
  - Substrate & cover layers
  - Modeled depths & velocities for each flow scenario
  - HSI curves for depth, velocity, substrate and cover per fish species and life stage
  - Calculate HSI and UA values
    - Calculate HSI at each point by multiplying:
      - (DEPTH HSI) * (VELOCITY HSI) * (SUBSTRATE HSI) * (COVER HSI)
    - Calculate UA values at each point by multiplying:
      - AREA * combined HSI
- Output: tabular and/or maps

HYDRAULIC DATA GENERATION FOR FISH PASSAGE ANALYSIS (FA-04)

- Per the RSP – "The calibrated hydraulic model will be run for a range of flows determined in consultation with LPs and study team fish passage specialists to generate hydraulic data to support the fish passage evaluation. The evaluation of fish passage will be conducted as part of the Fish Passage Study (FA-04)."
- Also providing:
  - Drone photos of Bypass Reach (controlled releases)
  - LSPIV raster maps (controlled releases)
  - Recorded level logger data (full record)

Seattle City Light

DISCUSSION



Skagit River Hydroelectric Project
Seattle City Light (City Light)
Flows Work Group
FA-05 Gorge Bypass Reach Hydraulic and Instream Flow Model Development, Workshop #4
November 2, 2021

Draft Meeting Summary

Disclaimer: These notes are provided to serve as a high-level summary of the meeting and as a communication tool to benefit work group continuity. They are streamlined and focused on action items, unresolved issues, future discussion items, and high-level discussion points. They are not intended as a formal record of the meeting.

Attendance

Licensing Participants (LPs):
Brock Applegate, Washington Department of Fish and Wildlife (WDFW)
Stuart Beck, Kleinschmidt Group (for Swinomish Tribe)
Steve Copps, National Marine Fisheries Services (NMFS)
Susannah Erwin, National Park Service (NPS)
Kiza Gates, WDFW
Kirk Gehl, Nlaka'pamux Nation Bands Coalition
Rick Hartson, Upper Skagit Indian Tribe (USIT)
Jonathan Kohr, WDFW
Ashley Rawhouser, NPS
Dudley Reiser, Kleinschmidt Group (for Swinomish Tribe)
Alison Studley, Skagit Fisheries Enhancement Group (SFEG)
Kara Symonds, Skagit County
Stan Walsh, Skagit River System Cooperative (SRSC)

Federal Energy Regulatory Commission (FERC):
Matt Cutlip, FERC

Seattle City Light (City Light):
Andrew Bearlin, City Light
Erin Lowery, City Light

Consultant Team:
Danielle Hanson, Consultant Team - HDR
Donnie Jones, Consultant Team – NHC
Bao Le, Consultant Team – HEC
Malcolm Leytham, Consultant Team – NHC
Chris Long, Consultant Team – NHC
Ty Ziegler, Consultant Team – HDR

Facilitation Team:
Joy Juelson, Facilitation Team
Alex Sweetser, Facilitation Team

Meeting Materials

Meeting materials are stored on the Skagit SharePoint site.

- Meeting Agenda
- Meeting Slides: FA-05 Gorge Bypass Reach Hydraulic and Instream Flow Model Development, Workshop #4
- Memo: GHD/Bypass Reach Model Flow Testing (Test 0)
- Memo: GHD/Bypass Reach Model Flow Testing (Test 1)
- Memo: GHD/Bypass Reach Model Flow Testing (Test 2)
- Memorandum: Gorge Bypass Reach Discharge Measurement Uncertainty Analysis

Action Items

Action	Responsibility	Deadline
LP Action Items		
None identified at this meeting.		
City Light Action Items		
Confirm with the FA-04 Fish Passage Study Team that the study's passage analysis at existing features will assess passage (both hydraulically and temporally) for each target species.	City Light	Before next workshop
Provide information to support comparison of bypass reach controlled releases vs. unregulated flows to LPs.	City Light	Before next workshop
Facilitation Team Action Items		
Prepare draft meeting summary and send to LPs for review.	Triangle	Two weeks

Summary of Issues Discussed, Action Items, and Decisions

Welcome, Introductions, Agenda Overview

The facilitator, Joy Juelson, welcomed the group and led a roll call. She briefly walked through the agenda and reviewed action items from the last *Gorge Bypass Reach Hydraulic and Instream Flow Model Development Workshop* held on August 26, 2021.

Study Overview

Erin Lowery, City Light, explained that today's meeting is the fourth of five *Gorge Bypass Reach Hydraulic and Instream Flow Model Development* (FA-05) workshops. The next meeting will be in February 2022. He noted the initial hydraulic model for the Bypass Reach has been completed, and this meeting will discuss the model's calibration.

Chris Long, Consultant Team, reviewed the purpose of the meeting, outlined in the agenda. He explained that the Consultant Team is approximately halfway through model calibration. As part of the meeting, the team will outline and discuss the calibration flow selection and the uncertainty analysis with LPs. To address an action item from the last FA-05 workshop on the Gorge Bypass Reach Discharge Measurement Uncertainty Analysis, NHC developed and shared a memorandum, included in the meeting materials. Additionally, Ty Ziegler, Consultant Team, will discuss the development and integration of biological and habitat data being collected and reviewed as part of the study's Habitat Suitability Criteria (HSC) curves.

Present and Discuss Calibration Flow Selection and Uncertainty Analysis

Malcolm Leytham, Consultant Team, presented on calibration flow selection and the uncertainty analysis (see slides 5–16), including an overview of a high flow late June spill and controlled releases between July 26-29. Additionally, he explained the methodology for spillway discharge calculations.

- In response to a question about the 878.51 pool elevation used for the single gate rating, Malcolm explained there is no difference in the pool elevation because it is a fixed value with variable discharges.
- In response to a question about variable pool elevations at different locations in Gorge Lake, Malcolm clarified that this should be accounted for in the pool elevation measurement location.

Controlled release flows (July 26-29)

Donnie Jones, Consultant Team, gave an overview of flows data collected during the controlled releases between July 26-29th. He explained that discharge was measured at five transects and the bridge below the Gorge Dam. Discharge measurements at transects II, DD, and the bridge were the most reliable, and discharges from transects EE and GG were acceptable. Measured discharges from transect AA were not used.

- Donnie clarified that measured depths and velocities at Transect AA were of high quality and will be used for model calibration. However, there was a higher degree of computed discharge uncertainty, which is why the discharge measurements from transect AA were not used.
- In response to a question about the data collection methods, Donnie explained the Consultant Team used a station-by-station method using USGS standard ~~statistical~~ methods. Data is continuously collected from a stationary position over 40 seconds at each station; there is not a need for repeat measurements.
- In response to a question, Donnie explained that when the sampling raft is tethered, there is generally less than a foot of lateral movement~~, which is why the minimum cell size is half a foot for their measurements~~.
- In response to a question about measurement stations, Donnie explained that ADCP measurements were spaced such that each measurement sampled 5% or less of the total flow at a transect.
- Donnie and Chris Long clarified that all the data collected at Transect AA is useful for measuring depth and velocity. The measured uncertainty does not mean there is a lack of confidence in the depth and velocity measurements. Instead, the uncertainty is around the ~~discharge at those depths and velocities compared to the~~ calculated discharge.

Additionally, Donnie presented the uncertainty analysis of measured flows, as requested by LPs at the previous FA-05 workshop. Discharge was presented in longitudinal plots, with uncertainty presented in black bars on the graph. Measured discharges were compared to the 1) mean flows in the Bypass Reach, 2) mean flows above Afternoon Creek, and 3) mean flows below Afternoon Creek. Lower mean flows below Afternoon Creek indicate potential flow loss at transects DD and GG.

- Malcolm and Donnie explained that it is difficult to hit lower flow release targets through the spillway gates and log chute. Due to this difficulty at the controlled release flow range, they could not reliably use City Light's reported releases from the spill gates.
- In response to a question, Donnie noted spills were held for approximately 12 hours. Erin Lowery added that the three memos provided by City Light engineers (see meeting materials) explain the methodology used to determine when equilibrium was reached so that flows were stabilized. Any gains or losses of flows ~~in data collection~~ occurred when the flow was at equilibrium.

- Donnie explained that the Consultant Team worked with John Riedel, NPS (*retired*), to consider possible explanations for the loss of flow. They theorized that flow loss may reflect groundwater storage and subsurface flow paths through coarse material deposited throughout the Bypass Reach. Additionally, dry conditions in late June due to the heat dome and low base flows in July provided more potential for groundwater storage.
- In response to a question about the small difference in U/S and D/S mean flows on July 29th, Chris Long noted thate ~~historical temperatures in June led to increased flows from melting ice. This may have led to the~~ subsurface pathways may have filled~~ing~~ during the higher flows earlier in the week. ~~The measures indicate a clear trend of loss occurring after Afternoon Creek.~~
- In response to an LP question, Malcolm explained there is no plan to collect additional data to test for flow loss in the bypass reach during periods of higher groundwater saturation ~~due to the extensive field program and the late June uncontrolled release~~.

Update and Discuss Model Development and Sensitivity Analysis

Donnie Jones presented on the development of model terrain, model geometry, sensitivity tests, and base model selection (see slides for technical details 28-41).

Since the last meeting, the model terrain was refined to a 1-foot resolution and the channel cell size was set to one ft based on sensitivity testing. Deep pools were not refined due to the negligible impact on hydraulic model calculations. Roughness delineation was developed through orthimagery and preliminary model results.

- In response to a question about an inconsistency ~~the channel roughness dip in depth~~ in modeled velocity compared to field observations at Transect AA ~~60 feet~~, Chris Long explained the terrain used in the sensitivity analysis was the original 3-foot terrain~~, but not refined terrain~~. This terrain has been reclassified at a 1-foot resolution, and the inconsistency ~~dip~~ may be caused by a channel feature that will be captured at the increased resolution.

Present and Discuss Model Calibration and Validation

Chris Long presented an overview of observed data, the calibration procedure used to calibrate the model, the status of model calibration and validation, and the process for the study moving forward.

Observed data

Chris Long explained data was collected in the last week of July at four discharges over five transects and 12 level loggers in the Bypass Reach. The level loggers were evenly divided between the two existing features and placed in coordination with the Fish Passage Technical Studies Program (FA-04) team. Additional data was gathered with drone-based orthoimagery and used to compare the model to observed conditions.

- In response to a question, Chris noted that the Consultant Team has not yet ground-truthed model velocities at the Existing Features with surface velocities derived from drone video. Since the drone products will be digital, they plan to use spatial analyses to determine differences.

Current Status

Donnie Jones presented the status of the Bypass Reach model calibration and walked through the velocity comparison at each transect. Additionally, he presented the current progress to evaluate the two existing features in the Bypass Reach. Moving forward, further calibration of observed data is needed for roughness delineation, velocity magnitude, and turbulence. Level logger data will be used to calibrate the model to 6200 cfs at the existing features, and model outputs will be validated with 250 cfs observations.

High-level Overview of the Development of Biological/Habitat Data and Integration with Hydraulic Model

Ty Ziegler, HDR, gave a high-level overview of biological and habitat data collection and its integration with the hydraulic model. He noted field-based substrate and cover mapping occurred between July – October 2021, and once it is quality controlled, the next step will be filling in data gaps. Then, the mapping data will be shared with the Geomorphology Team.

Ty explained that a small technical group of LPs, City Light, and Consultant Team members has met several times to review existing Habitat Suitability Criteria (HSC) curves and/or develop HSC curves using other studies and literature review (as appropriate). Field validation data will be collected in 2021 to help validate HSC curves for several species/life stages. The resulting preliminary HSC curves will be used for flow-habitat assessments in both the Bypass Reach and below Gorge Powerhouse. He noted the small group anticipates reviewing the preliminary HSC curves in early January and will meet on November 4th to update the Flows-HSC Work Group.

Ty noted another small technical group of LPs, City Light, and Consultant Team members has been meeting to discuss periodicity, which is used to help focus habitat model results on periods that are relevant to each species/life stage being modeled. Periodicity will not only tie into the FA-02 and FA-05 studies but several other fish-related studies.

Chris Long provided a preview of aquatic & biological habitat integration and hydraulic data generation for the FA-04 Fish Passage Study (see slides 73-74). He noted that the calibrated hydraulic model will be used to generate hydraulic data to support the fish passage evaluation. In addition to the hydraulic model, the FA-05 Consultant Team will provide drone photos of the bypass reach, LSPIV raster maps, and the full record of recorded level logger data.

Questions and Discussion

- LPs requested that City Light confirm with the FA-04 Fish Passage Study Team that the study's passage analysis at existing features will assess passage (both hydraulically and temporally) for each species of concern. This was added as an action item.
- In response to a question, Erin Lowery explained the model is of current scenarios and is being developed to explore different future scenarios. It will be integrated with the operations model once that is developed.
- LPs requested that City Light provide information to support comparison of Bypass Reach controlled releases vs. unregulated flows to LPs. This was added as an action item.
- An LP representative from USIT expressed concern about model calibration for velocity at higher flow events and requested more information on data collection efforts for more uncontrolled high flow events. Consultant Team members explained they had collected a full data set with higher flows, which should be adequate. Model calibration results for high flow events will be presented at the next meeting.

Action Item: Confirm with the FA-04 Fish Passage Study Team that the study's passage analysis at existing features will assess passage (both hydraulically and temporally) for each species of concern.

Action Item: Provide information to support comparison of Bypass Reach controlled releases vs. unregulated flows to LPs.

Review Action Items and Next Steps

Erin Lowery provided an overview of next steps and explained that City Light is nearing the point they will be integrating and cross-walking across different studies. As tools are developed, workshops will shift to discussions with LPs about this integration. He noted the next meeting is anticipated for the standing Flows Work Group calendar hold for February and will focus on model calibration.

Action Item: Triangle will prepare a draft meeting summary and send to LPs for review.

The meeting was adjourned early at 12:00 p.m.