FA-01b WATER QUALITY MODEL DEVELOPMENT STUDY INTERIM REPORT

SKAGIT RIVER HYDROELECTRIC PROJECT
FERC NO. 553

Seattle City Light

Prepared by:
Geosyntec Consultants, Inc.
and
Northwest Hydraulic Consultants, Inc.

March 2022
Initial Study Report

TABLE OF CONTENTS

Section No.	Description	Page No.

List of Figures

Figure No.	Description	Page No.

List of Tables

List of Acronyms and Abbreviations

°C ....degrees Celsius
3-D ....three-dimensional
BC ....British Columbia
City Light..................Seattle City Light
CoSD.........................City of Seattle datum
DEM..........................digital elevation model
Ecology ....Washington State Department of Ecology
FERC.........................Federal Energy Regulatory Commission
ft ....feet/foot
GIS ....Geographic Information System
HDR ....HDR Engineering, Inc.
ISR ....Interim Study Report
LiDAR.......................Light Detection and Ranging
LP ....licensing participant
m ....meter
msl.............................mean sea level
NAVD 88 ....North American Vertical Datum of 1988
NPS ....National Park Service
PRM ....Project River Mile
Project ....Skagit River Hydroelectric Project
QAPP ....Quality Assurance Project Plan
QSI ....Quantum Spatial, Inc.
RAWS ....Remote Automatic Weather Stations
RM ....river mile
RSP ....Revised Study Plan
SCL ....Seattle City Light
SPD ....Study Plan Determination
USGS .........................U.S. Geological Survey
USR...........................Updated Study Report
W/m^2 ....watt per square meter
WQ............................water quality

This page intentionally left blank.

1.0 INTRODUCTION

The FA-01b Water Quality Model Development Study (WQ 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. This study is one component of the overall FA-01 study, which also includes the FA-01a Water Quality Monitoring Study (WQ Monitoring Study), which is addressed in a companion report (City Light 2022a). On June 9, 2021, Seattle City Light (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 Revised Study Plan (RSP) submitted by City Light on April 7, 2021 (City Light 2021a). The modifications in the June 9, 2021 Notice were 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 [NPS], U.S. Fish and Wildlife Service, Washington State Department of Ecology [Ecology], and Washington Department of Fish and Wildlife). The June 9, 2021 Notice included City Light's intent to conduct water quality modeling using CE-QUAL-W2.

In its Study Plan Determination (SPD), FERC approved City Light's proposal in the June 9, 2021 Notice to develop a hydrodynamic water quality model (CE-QUAL-W2) to evaluate water temperatures, specifically the effects of cold-water releases from the reservoirs on water temperatures in the Skagit River downstream of Gorge Dam. FERC noted that City Light proposed, after completion of the water temperature model, to develop a nutrient and productivity component for the water quality model. In its SPD, FERC states, "…we do not recommend requiring City Light to conduct a future nutrient sampling program and develop a nutrient model for the Project reservoirs, major tributaries, and Skagit River from Gorge Dam to the Skagit estuary..." Notwithstanding, City Light is implementing the WQ Model Development Study as proposed in the RSP, with the agreed to modifications from the June 9, 2021 Notice as described in Section 2 of this study report.

This interim report on the 2021 study efforts is being filed with FERC as part of City Light's Initial Study Report (ISR). City Light will perform additional work for this study in 2022 and include a report in the Updated Study Report (USR) in March 2023.

---

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 this study is to develop of a set of hydrodynamic, temperature, and water quality (i.e., nutrients, algae, and dissolved oxygen) models in the CE-QUAL-W2 modeling platform. These models will act as a tool in scenario analyses to evaluate impacts from the Project on aquatic resources. These models will be used to simulate:

- Temperature, nutrients, dissolved oxygen, and algae concentrations within the Project reservoirs and downstream from Gorge Dam.
- The effects of different flow management scenarios on the above variables within the Project reservoirs and downstream in the Skagit River. Scenarios will be developed collaboratively with City Light and the LPs beginning in 2022.

The models will also simulate water surface elevation in the reservoirs and the river downstream as a prerequisite to simulating hydrodynamics and temperature. These water surface elevations can be compared to estimates from the instream flow model and Operations model that are being developed in other studies. The models will also simulate several additional variables related to algal growth and nutrient dynamics in the Project.

The June 9, 2021 Notice commitments incorporated within this WQ Model Development Study are identified below. Please see the FA-01a Water Quality Monitoring Study report for commitments pertaining to water quality monitoring efforts (City Light 2022a):

- City Light will modify FA-01 to include development of a CE-QUAL-W2 model to evaluate temperature impacts from the Project on aquatic resources. City Light will seek and incorporate the input of Scott Wells in the development of the CE-QUAL-W2 model. The CE-QUAL-W2 model will be used to evaluate, among other things, the impact of cold-water releases from Ross reservoir on fishery resources. City Light will schedule one or more workshops with the LPs, as needed, to collaboratively develop this model.
- City Light will also modify the study plan to initiate modeling of nutrient and productivity components after (1) the CE-QUAL-W2 model for temperature is developed, and (2) data sources and years available are evaluated against the objectives of the LPs. Concurrently City Light would continue to collect proposed water quality parameter data and develop the CE-QUAL-W2 framework and integration with Operations model and other modeling tools in order to perform a sensitivity analysis to determine the accuracy and sensitivity of the tool (and data needs) for illustrating nutrient dynamics under alternative operational scenarios.
- City Light will convene a workshop with concerned LPs to discuss parameters, frequency, monitoring locations, and temporal overlap with existing data. The workshop will also identify the parameters to be modeled by CE-QUAL-W2, potential gaps in the model, and the approach to filling the gaps.

This report focuses only on the initial development of the CE-QUAL-W2 models, which will focus on simulations of hydrodynamics and temperature. Simulation of water quality variables will be initiated in 2022.

3.0 STUDY AREA

The hydrodynamic and temperature models developed for the Project will be limited to the full-pool areas of the three Project reservoirs—Ross Lake, Diablo Lake, and Gorge Lake—including the flowing upper portions of Diablo Lake and Gorge Lake. Tributary inflows to the reservoirs will not be modeled. Instead, they will be estimated (described below) and used as inputs to the reservoir models. The Skagit River downstream of Gorge Dam will be modeled within its main river channel (i.e., its bankfull width, not its floodplain) to Project River Mile (PRM) 54, which is just below its confluence with the Baker River in Concrete, Washington. The downstream boundary of the model was extended from PRM 65, near the confluence with the Sauk River, to Concrete in January 2022.[2] Work to date has focused on modeling only to PRM 65. Characteristics of the three reservoirs and Skagit River downstream to Concrete are summarized in Table 3.0-1.

Table 3.0-1. Study area summary characteristics.

Attribute	Ross Lake	Diablo Lake	Gorge Lake	Skagit River: Gorge Dam to Concrete
Drainage Area (sq. miles)	1,008	1,135	1,172	2,737
Length (miles)	24[2]	4.5	4.5	43.0
Normal Maximum Water Surface Elevation (feet [ft])[1]	1,608.76 (1,602.5)	1,211.36 (1,205)	881.51 (875)	
Surface Area at Normal Maximum Water Surface Elevation (acres)	11,680[2]	770	240	
Usable Storage (acre-ft)	1,052,000	8,820	6,600	
Spillways	2	2	1	
Spillway Crest Elevation (ft)[1]	1,588.2 (1,582)	1,193.65 (1,187)	831.3 (825)	
Dam Crest Elevation (ft)[1]	1,621.2 (1,615)	1,224.65 (1,218)	886.3 (880.5)	

1 All elevations in the table are North American Vertical Datum of 1988 (NAVD 88) with the City of Seattle Datum (CoSD) value in parentheses. As described in Section 2.3.1 of the RSP, the CoSD requires a conversion to NAVD 88 in order to be comparable with elevations measured and presented elsewhere in analyses and discussions surrounding Project relicensing.

2 Approximately 23 miles and 11,180 acres in the U.S. and 1 mile and 500 acres in Canada.

2 The benefits of extending the CE-QUAL-W2 model downstream to PRM 54 were discussed during LP meetings on December 20, 2021 and January 25, 2022. The discussions considered: the contribution of different sources on the total instream flow; the effects of atmospheric effects on diurnal in-stream temperature patterns; and increased uncertainty associated with characterizing model inputs in downstream urban areas such as Mt. Vernon, Washington. The consultant team recommended that terminating the model at Concrete will allow all of the anticipated model use cases to be evaluated while also maintaining model accuracy and certainty objectives.

4.0 METHODS

4.1 Modeling Quality Assurance Project Plan

The drafting of the modeling Quality Assurance Project Plan (QAPP) for this water quality modeling study is underway, and the document is evolving as study goals, objectives, and model scenarios are being more clearly defined. Currently, approximately 50 percent of the modeling QAPP has been completed. A final draft for hydrodynamics and temperature is expected to be completed by May 2022.

The QAPP serves as a roadmap to ensure success of the water quality modeling study. The QAPP, which is required for environmental studies involving Ecology, outlines the procedures and methods to be implemented to ensure study goals and objectives are met specifically for environmental modeling studies. The QAPP is developed during the initial planning stages of the study, can evolve over time, and remains relevant in final documentation. The current outline for the modeling QAPP is provided below.

- Introduction
  - Issue Definition, Goals, Management Objectives
- Key Processes and Variables
- Model Development
  - Model Selection, Assumptions, and Limitations
  - Spatial Extents, Spatial and Temporal Resolution, Model Input Parameters, Simulation Period
- Model Performance and Acceptance Criteria
  - Model Uncertainty and Sensitivity, Model Calibration, Qualitative and Quantitative Methods of Model Performance
- Model Scenarios
  - Effects of different flow management scenarios on hydrodynamics and temperature within the Project reservoirs and downstream through the Skagit River to the confluence of the Sauk River
- Environmental Monitoring Data Needs for Modeling
  - Data Inventory, Gaps, Quality, and Collection Procedures
- Quality Control
  - Project Roles, Schedule, Data Management, Peer Review, QAPP Review and Approval

4.2 Model Development

4.2.1 Overview

The Project and the Skagit River downstream will be simulated with four separate CE-QUAL-W2 models—one for each reservoir and one for the river. CE-QUAL-W2 is a two-dimensional, laterally averaged, hydrodynamic and water quality model originally developed by the U.S. Army Corps of Engineers and maintained by Portland State University. The latest available version, which will be used in this modeling effort, is version 4.5 (Wells 2021a).

The two-dimensions of a CE-QUAL-W2 model are: (1) depth; and (2) horizontal distance in the path of a river channel flow. CE-QUAL-W2 achieves substantial reductions in required computing resources and model run time by averaging across the lateral dimension of a water body. In other words, when considering horizontal variation, this modeling software differentiates between regions in a water body in the upstream or downstream directions, but it assumes that a water body is homogenous across its width. Thus, CE-QUAL-W2 is well-suited for reservoirs like Ross Lake, Diablo Lake, and Gorge Lake, which fill narrow river valleys where lateral averaging is a reasonable assumption. CE-QUAL-W2 is limited in its ability to describe circular or wide lakes where wind blowing across the lake can be more important for circulation than flow from a coherent upstream inflow or a downstream outflow. Similarly, CE-QUAL-W2 is an excellent choice for the Skagit River, which exhibits unidirectional flow downstream and does not spread across a wide floodplain under a wide range of flow regimes.

The CE-QUAL-W2 software executable reads a “Control File” that: (1) directs the executable to read in separate supporting files that provide tables of information about the simulated water body; (2) specifies a range of physical and chemical constants (referred to as “model parameters”); and (3) specifies details about the model simulation (e.g., starting and ending dates of the simulated period). Thus, development of a CE-QUAL-W2 model involves development of supporting input files and specifications of values within a control file. Input files include, but are not limited to:

- Bathymetry;
- Meteorology;
- Flow in tributaries;
- Temperature in tributaries; and
- Minor input files.

The development of these files and the control file is described in this section. Separate CE-QUAL-W2 models will be created for Ross Lake, Diablo Lake, Gorge Lake, and the Skagit River downstream for computational and workflow efficiency. The following sections describe the development of these models separately where activities for each differ.

4.2.2 Bathymetry

Creation of a CE-QUAL-W2 bathymetric file is a time-intensive process and is critical for model calibration because it determines the appropriate volume-elevation curve for the water body, which, in turn, allows the accurate simulation of water level and water residence times. A bathymetry input file in CE-QUAL-W2 specifies, in order, six key pieces of information about the simulated water body:

(1) The length of a model “segment.” Segments are divisions of the distance from the inflow of the water body to its downstream boundary (i.e., a dam or the confluence with the Sauk River).

(2) The initial elevation of the water surface. A bathymetry file states the initial elevation of the water surface.

(3) The orientation of the segment relative to true north. Description of segments relative to true north and relative to one another is critical for the accurate representation of mechanical mixing due to wind.

(4) The friction of the channel bed of the segment. Model segments with flow in their bottom layers are common in rivers, and thus the specification of bed friction in each segment is required. This specification is not generally important for models of deep-water bodies like reservoirs or lakes.

(5) The thickness of each "layer" within a segment. Layers are vertical divisions of the water column in a CE-QUAL-W2 model that can be conceptualized as horizontal planes within the water body. The unique combination of a specific layer and a specific segment is known as a model "cell."

(6) The width of each model cell. This specification of a width for model cells of specified length and thickness determines their volume, which, in turn, determines the volume for the water body.

A water body in CE-QUAL-W2 is described by one bathymetry file. One water body is modeled in each of the four separate CE-QUAL-W2 models developed in this study, and thus four bathymetry files have been developed. Activities specific to each water body are described below.

Digital Elevation Models (DEM) of bathymetry for each of the four CE-QUAL-W2 models have been developed from the best available data for each waterbody. City Light is in the process of collecting additional bathymetry data from portions of Ross, Diablo, and Gorge lakes that are expected to be incorporated into the models in 2022. The existing data sources currently being used for each model are discussed in the sections that follow.

4.2.2.1 Ross Lake

Segmentation

Ross Lake was divided into 178 segments for the Skagit River (main) branch and 34 segments for the Ruby Arm branch. The Skagit River branch segments have a mean length of 711.94 ft with a range of 213.26 – 1,519.03 ft; the Ruby Arm segments have a mean length of 544.62 ft with a range of 240.06 – 1,194.23 ft. These mean segment lengths were chosen to be long enough to limit the number of segments (and thus computing time to run the model) yet short enough to define the bathymetry (and, in turn, the reservoir volume), with adequate resolution.

The development of model segments was configured using an automated process followed by manual refinement to ensure that the model segmentations accurately cover the shapes of the waterbodies. In the automated process, the model grid shapefiles were developed using Python libraries called "pygridtools" (Hobson 2018) and "pygridgen" (Hetland 2018). Pygridtools is a high-level interface for curvilinear-orthogonal grid generation, manipulation, and visualization, which depends on pygridgen for the generation of new grids. Inputs to the tool consisted of the boundary outline of the reservoir, which was developed in Geographic Information System (GIS), and the specification of a 820.21 ft approximate segment length. Accompanying parameter values in the boundary coordinate shapefile indicated points representing the four corners of the pseudo-rectangular, curvilinear segments. The segment shapes were then defined by the length of the water body divided by 820.21 ft as the initial length of each segment. The resulting segments were exported to shapefiles for further manual refinements that focused on angular sections of shoreline and the confluence of the Ruby Arm with the Skagit River branch (e.g., Figure 4.2-1).

Initial Water Surface Elevation

The initial water surface elevation was set at 1,480.3 ft NAVD 88 (1,474.04 ft CoSD). This will be adjusted based on observed water levels on the dates when model runs begin.

Segment Orientation

Segment orientation was produced by the automated methods described above and spot checked manually to verify quality.

Bed Friction

The Chézy bed friction factor was set at 70 for the reservoir model segments. This is an accepted default value for CE-QUAL-W2 models (Wells 2021b).

Layer Thickness

Layer thicknesses were set at 3.28 ft (1 meter [m]), which was selected as a compromise between the large layer thicknesses that would decrease computation time (by decreasing the number of cells) and smaller layer thicknesses that would allow for finer resolution of vertical variation in model results (e.g., thermal stratification). The current vertical layers of 3.28 ft are well suited for capturing thermal stratification in the Project reservoirs.

Cell Widths

Cell widths in the bathymetry file were determined from a volume-elevation curve developed for each segment of the reservoir. With the cell length and height fixed following the steps described above, the width of each cell is determined by dividing the volume at a given elevation by that height (1 m) and the cell length. This requires development of a volume-elevation curve for each segment of the reservoir. These volume-elevation curves were constructed from a DEM of the terrain beneath Ross Lake and near its shoreline to an elevation higher than its full-pool elevation (Figure 4.2-2).

The DEM of the Ross Lake bathymetry was created by merging 40-ft bathymetry contour maps from the 1960s (U.S. Geological Survey [USGS] 1963a; 1969a; 1969b) and Light Detection and Ranging (LiDAR) (topo-bathymetry) data collected on behalf of City Light in 2018 (Quantum Spatial Inc. [QSI] 2018a) and reprocessed by HDR Engineering, Inc. (HDR) in 2020 (HDR 2020) when the lake was drawn down to an elevation of approximately 1,499.3 ft NAVD 88 (1,493.04 ft CoSD). The LiDAR data were used wherever possible, but LiDAR surveys cannot collect information below the water surface—this information was only available for portions of Ross Lake that were exposed when the reservoir was drawn down. USGS contour data (USGS 1963a; 1969a; 1969b) were hand digitized as line shapefiles (Figure 4.2-3) and densified to 3-ft contour intervals to match the resolution of the LiDAR DEMs. To be able to combine the contour data with the LiDAR data, the contour data were interpolated onto a grid with a 3-ft horizontal resolution.

The vertical datum for the contour data was set as the mean sea level (msl), in feet. The vertical datum for the LiDAR, however, was NAVD 88, in feet. The relationship between msl and NAVD 88 at Seattle was used to convert msl to NAVD 88 for the contour DEM. Mean sea level is 4.3 ft above NAVD 88 at Seattle, so 4.3 ft was added to the contour DEM. The lowest elevation for the collected LiDAR for Ross Lake was approximately 1,485 ft. Values above 1,490 ft in the contour DEM and values below 1,500 ft in the LiDAR DEM were set to no data. The 10-ft vertical gap between the two datasets provided a buffer to account for uncertainties in the contour DEM. The two DEMs were merged in ArcMap using the mosaic raster tool with the blend method, and the gaps were filled using raster in a Python tool.

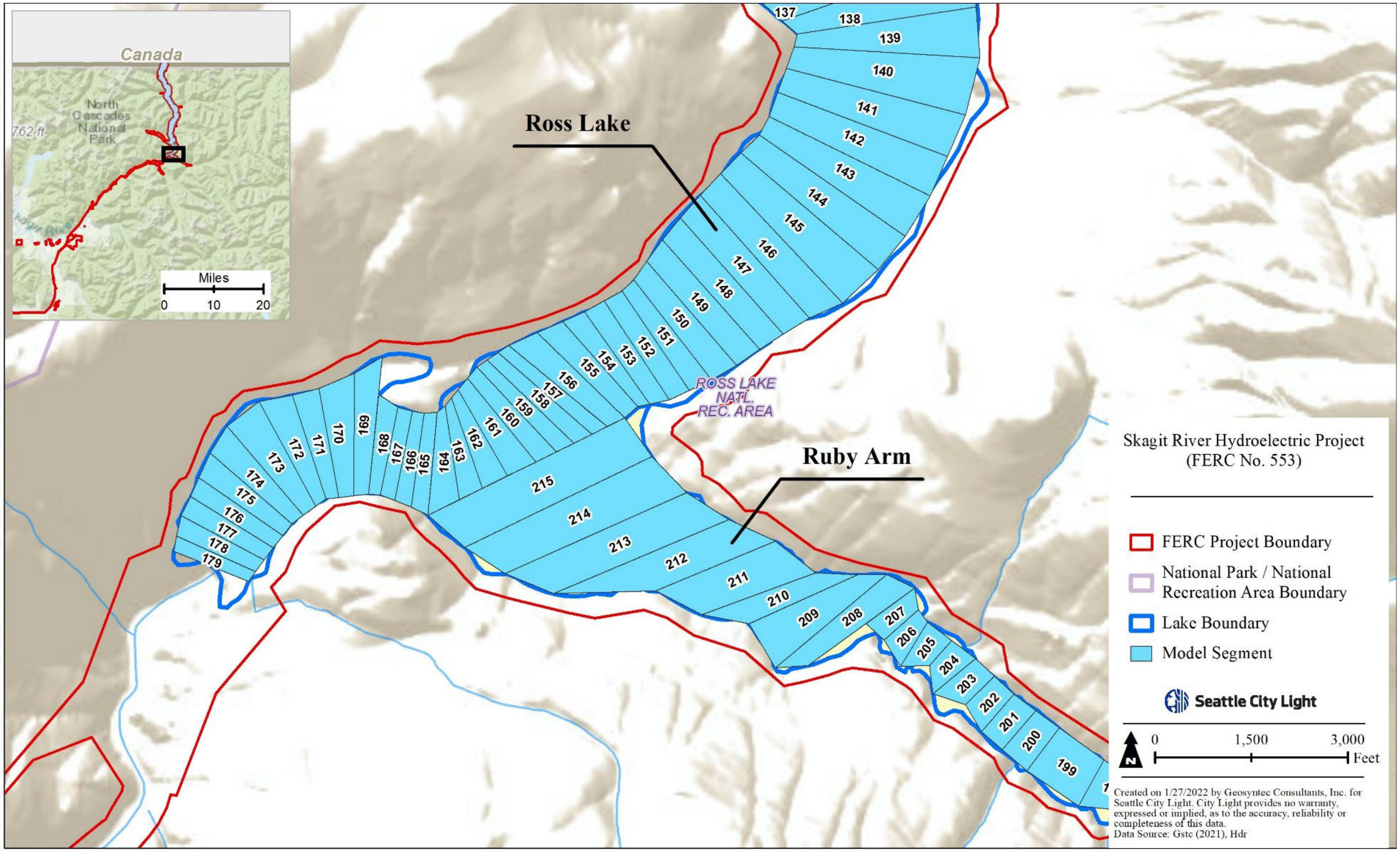

Figure 4.2-1. Example of segmentation of Ross Lake. View is scaled so that individual segments can be identified clearly in the downstream portion of the reservoir.

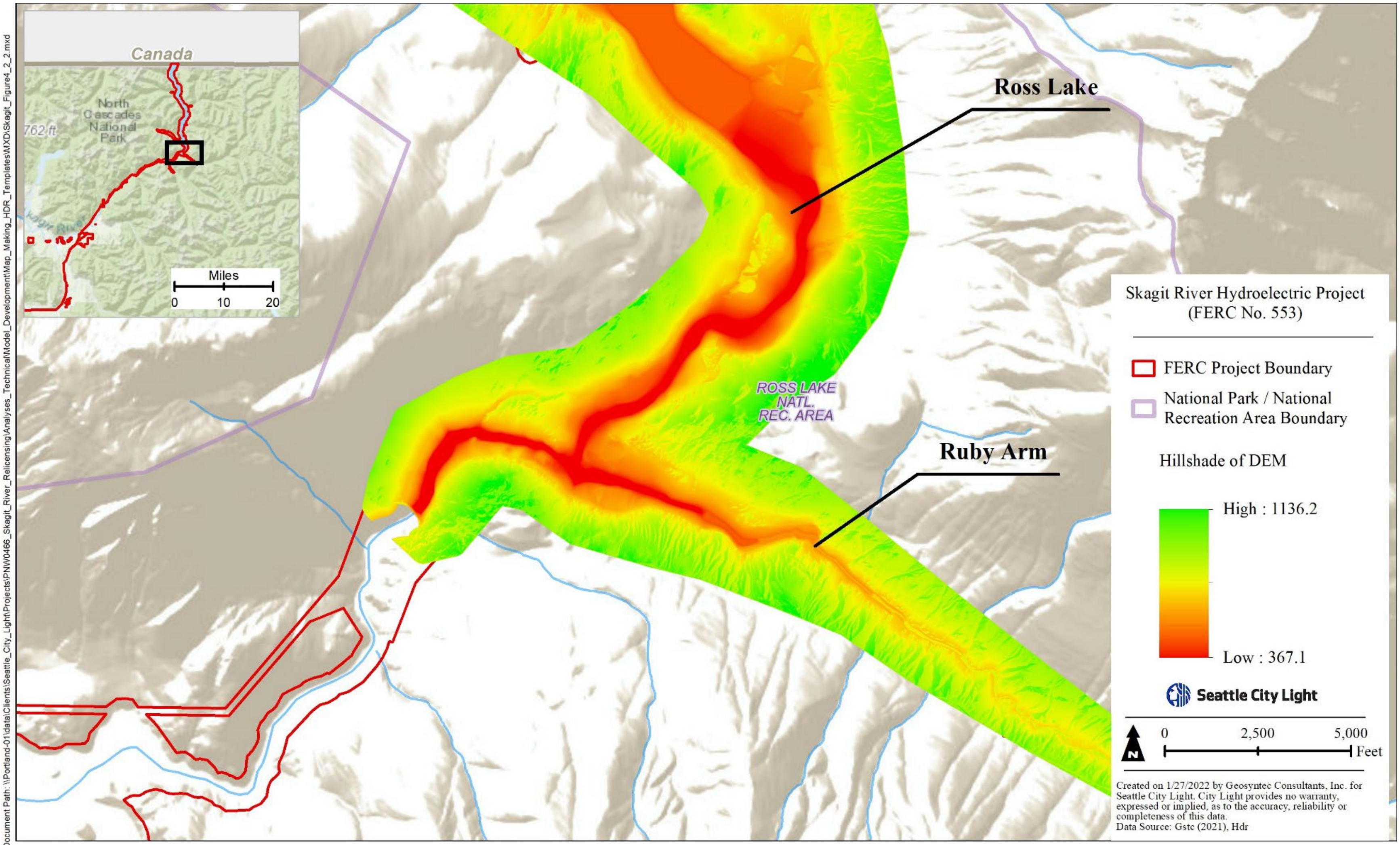

Figure 4.2-2. Example of hill shade visualization of final DEM for central Ross Lake.

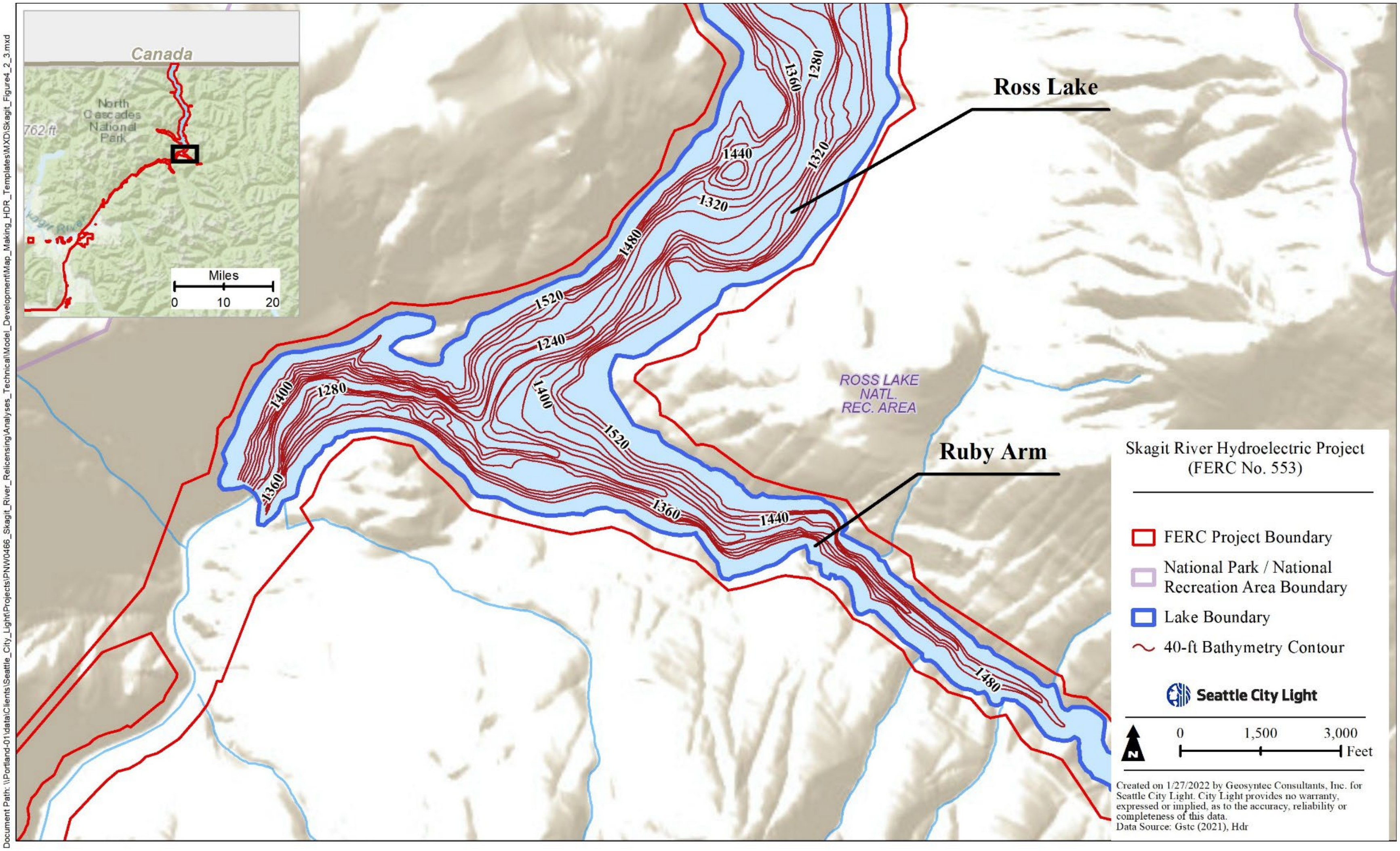

Figure 4.2-3. Example of digitized contours for central Ross Lake.

4.2.2.2 Diablo Lake

Segmentation

Diablo Lake was divided into 60 segments for the Skagit River (main) branch and 25 segments for the Thunder Arm branch. The Skagit River branch segments have a mean length of 396.98 ft; the Thunder Arm branch segments have a mean length of 488.85 ft with a range of 318.23 – 816.93 ft. Segments were developed in the same manner described above for Ross Lake.

Initial Water Surface Elevation

The initial elevation of the water surface was set at 1,214.62 ft NAVD 88 (1,208.26 ft CoSD). This will be adjusted based on observed water levels on the dates when model runs begin.

Segment Orientation

Segment orientation was produced by the automated methods described above for Ross Lake and spot checked manually to verify quality.

Bed Friction

The Chézy bed friction factor was set at 70 for the model segments (Wells 2021b).

Layer Thickness

Layer thicknesses were set at 3.28 ft (1 m), as in Ross Lake, described above.

Cell Widths

Cell widths were determined as described above for Ross Lake. Diablo Lake bathymetric and topographic data consist of LiDAR data collected in 2018 and 2016 (QSI 2018b; QSI 2017a; QSI 2017b) and reprocessed by HDR (HDR 2020) and USGS contour bathymetry data from the 1960s (USGS 1963a; USGS 1963b). The 2018 LiDAR for Diablo Lake consisted of LiDAR collected for Thunder Arm only and this was used in its entirety. The 2016 LiDAR and contour DEM were used for coverage over the rest of the reservoir. Elevation data for the 2016 LiDAR data below 1,254 ft NAVD 88 (approximately 1,248 ft CoSD) were set to no data. Likewise, elevations for the contour DEM above 1,204 ft NAVD 88 (approximately 1,198 ft CoSD) were set to no data. The larger vertical gap, 50 ft, was used to accommodate more uncertainty with the contour DEM associated with steeper terrain around Diablo Lake than around Ross Lake. The two LiDAR datasets were merged and then the resulting LiDAR dataset was merged with the contour DEM. In the final merged DEM, the 2018 LiDAR took first priority, the 2016 LiDAR took second priority, and the contour data took third priority. A 100-ft horizontal buffer was used between the two LiDAR datasets to allow for smooth interpolation between the two datasets.

4.2.2.3 Gorge Lake

Segmentation

Gorge Lake is approximately 4.5 miles long and was divided into 45 segments. The mean segment length is 492 ft (range: 164 – 1,050 ft). Separate branch(es) may need to be defined for the Stetattle and Reflector Bar reaches, beginning near the State Route 20 crossing, to account for notable changes in bed slope within the more riverine Stetattle reach. The current model segmentation for George Lake is shown in Figure 4.2-4.

Initial Water Surface Elevation

The initial elevation of the water surface was set at 881.51 ft NAVD 88 (875 ft CoSD) corresponding to the normal maximum water surface elevation. This will be adjusted based on observed water levels on the dates when model runs begin.

Segment Orientation

Segment orientation was produced by automated methods and spot checked manually to verify quality.

Bed Friction

The Chézy bed friction factor was set at 70 for the model segments (Wells, 2021b).

Layer Thickness

The vertical layer thicknesses were set at 3.28 ft (1 m), identical to Ross Lake and Diablo Lake. This may be further reduced in the Stetattle and Reflector Bar reaches as needed during model refinement to confirm an acceptable level of wetted top-width representation.

Cell Widths

Cell widths for each segment at each layer height were produced by automated methods based on a DEM of Gorge Lake bathymetry developed from multiple data sources. The 2018 topobathymetric LiDAR dataset (QSI 2018b), which was applied to the DEM where it was available, generally covers segments 2 through 20 within the Reflector Bar and Stetattle reaches and also covers shallow and dry-ground areas within the remainder of the reservoir. It is common for topobathymetric LiDAR datasets to contain areas where the LiDAR system failed to acquire data (returns) from wetted channel areas. Returns are the reflected laser pulses sensed by the LiDAR system that are used to map topographic surfaces, and bathymetric channel bed returns are limited by turbidity, depth, obstructions, and bottom surface reflectivity. A void is an area where no returns were detected. The spatial location of voids is a product that accompanies the LiDAR data. There are voids, in the 2018 topo-bathymetric LiDAR where depths exceed the limit of the technology. A limited 2016 standard LiDAR dataset (QSI 2017b) was also used to extend the bathymetry DEM landward to include the surrounding terrain.

Within Stetattle reach segments 6 through 18, single beam bathymetric data from a 2017 survey (True North Surveying, Inc. 2017) was used to fill the voids. A few small voids in segments 2 through 6 where the 2017 survey data were not available were interpolated (i.e. filled based on values at the edges of the voids in the topobathymetric LiDAR data).

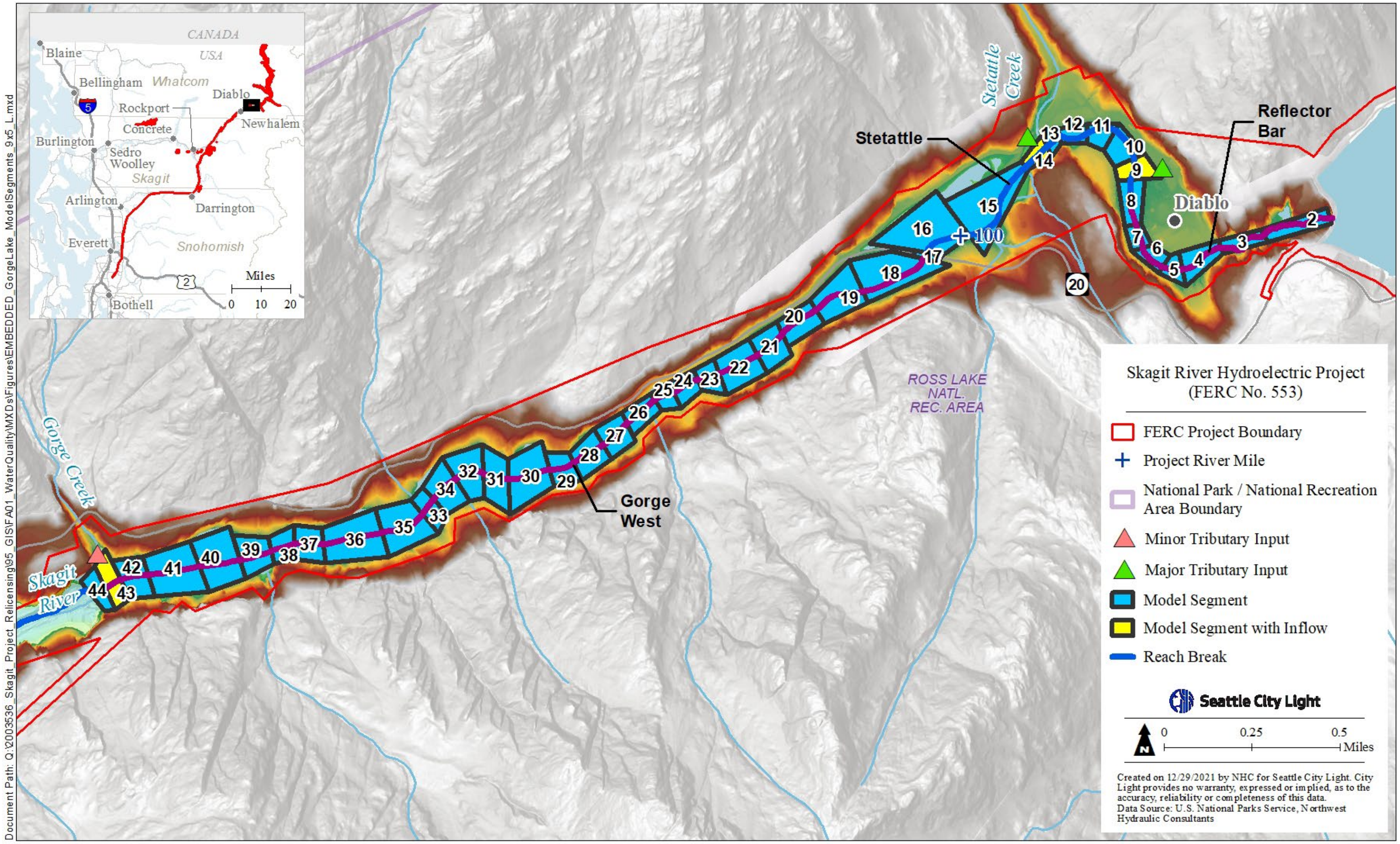

Figure 4.2-4. Current model segmentation for Gorge Lake.

Bathymetry for the West Zone of the reservoir was defined using historic topographic map contours. The 1960s contour data used for the Diablo and Ross reservoirs were not used for Gorge Lake because the 40-ft contour interval data is not of an adequate resolution to define the reservoir's shallower topography. Instead, digitized 5-ft contour mapping conducted in 1915, before the construction of Gorge Dam, was used. A sample of these data, taken from record file "USGS 1915 Skagit River Profile Survey_Plate3.jpg," is provided below as Figure 4.2-5. Because the vertical datum of the 1915 data was not easily verified, it was shifted vertically to tie into the higher accuracy LiDAR data where the two datasets overlap. It is recognized that two major construction efforts on Gorge Dam in 1921 and 1961 may have modified this topography to some extent and that 100 years of dam operations have likely resulted in some localized sedimentation effects. As mentioned previously in Section 4.2.2, it is expected that newer bathymetry of the reservoir will be collected and used to define the grid as part of subsequent modeling effort of this reservoir.

The mean top width for all Gorge Lake model segments is 394 ft (range: 164 – 1,148 ft).

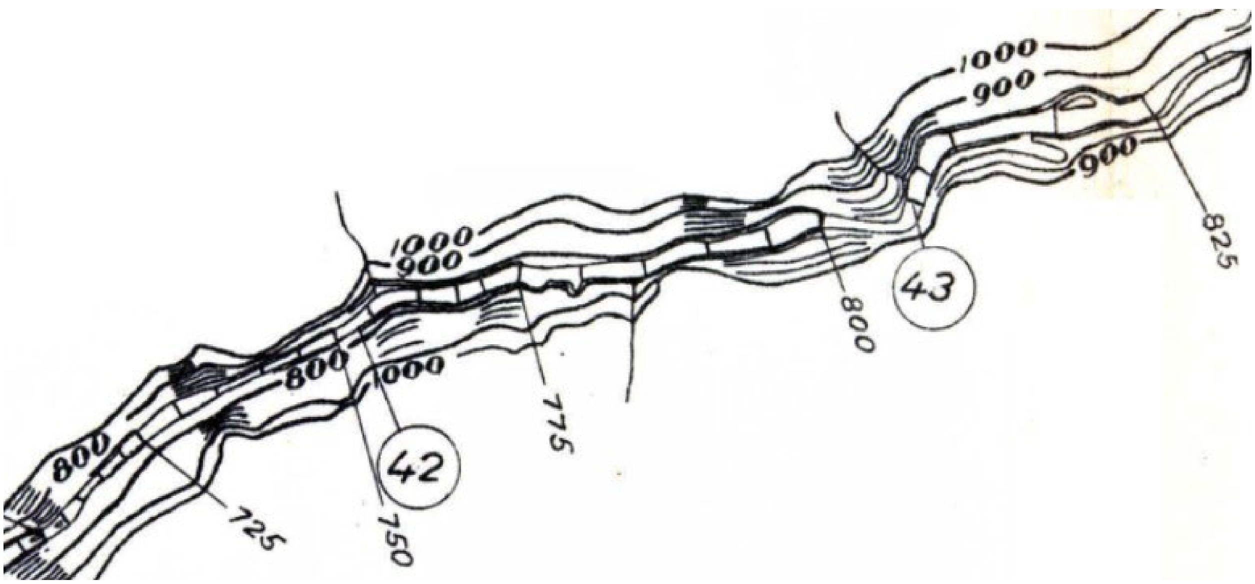

Figure 4.2-5. Example of 1915 5-ft contours used for Gorge Lake bathymetry.

4.2.2.4 Skagit River: Gorge Dam to Sauk River Confluence[3]

Segmentation

The Skagit River from the Gorge Lake Dam to the Sauk River confluence near Rockport is approximately 32 miles long and was divided into 130 segments. The mean segment length is 1,312 ft (range: 394 – 2,247 ft). It is anticipated that many of these segments will be further subdivided during model refinement to improve the definition of changes in channel morphology (e.g., pool transitions). Five branches are currently defined to account for notable changes in slope, as depicted in the Skagit River profile plot below (Figure 4.2-6). The Gorge Bypass Reach immediately downstream of Gorge Dam is not currently included in the Skagit River model but

[3] Details on the model extension to PRM 54 at Concrete, Washington are under development and will be reported in the USR.

will be added during the first quarter of 2022, as needed to facilitate simulation of flows resulting from Gorge Lake spills. This reach is more complex than the ensuing downstream reaches and will require a different modeling approach due to its steeper slope and unique hydraulic characteristics, in which the upper portion of the reach is commonly dry depending on Gorge Dam spill.

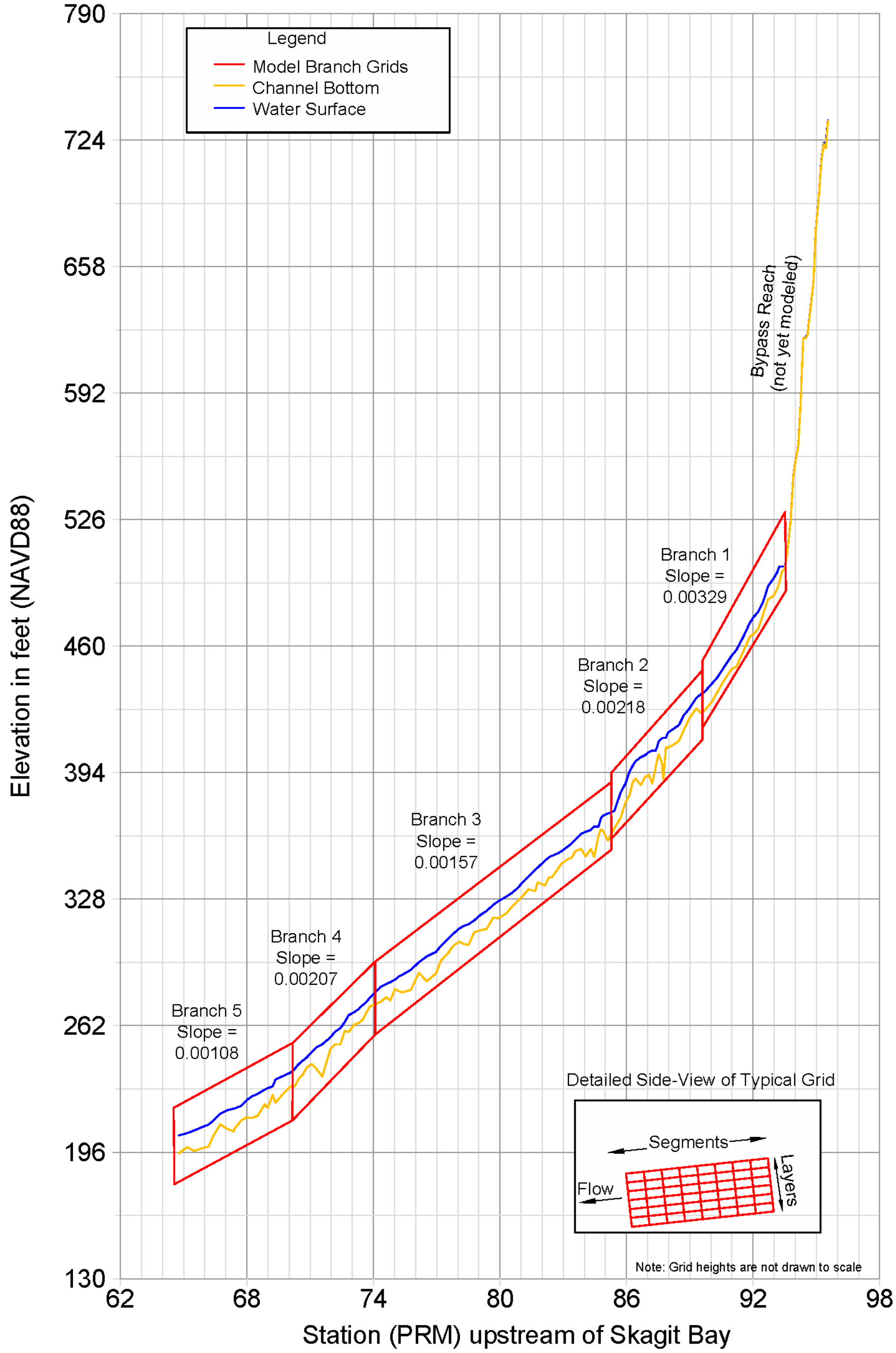

Figure 4.2-6. **Profile plot of the Skagit River between Gorge Dam and the Sauk River confluence. Five branches are currently defined in the Skagit River model to account for notable changes in hydraulic slope.**

Initial Water Surface Elevation

The initial elevation of the water surface in the Skagit River model varies. An initial discharge of 4,000 cfs (approximate mean summer flow for the Skagit River near Marblemount) was specified for the segments, and normal depth[4] was assumed to compute the initial water surface elevation for each segment using Manning's equation and the average river slope for that reach. This will be adjusted based on observed water levels on the dates when model simulations begin.

Segment Orientation

Segment orientation was produced by automated methods and spot checked manually to verify quality.

Bed Friction

The initial Manning's bed friction factor was set to 0.035 for the model segments for debugging purposes and these will next be revised during model water-level calibration to provide as much consistency with the roughness coefficients being used for the FA-02 Instream Flow Model Development Study's hydraulic modeling effort (City Light 2022b), while also matching available water-level observations. While CE-QUAL-W2 allows the use of either the Chézy or Manning's bed friction coefficient, which are related to one another through hydraulic radius, Manning's coefficient tends to be used more often in riverine environments and was therefore used in the Skagit River model.

Layer Thickness

The vertical layer thicknesses range from 0.82 – 3.28 ft (0.25 – 1 m) in the river branches. While vertical stratification is not a concern in the riverine reaches, which are well mixed, variation in vertical layer width is also used to define the channel geometry (i.e., side slope). A single rectangular layer, similar to a flume, could be used but it would not accurately represent the wetted channel width at varying flows. As a result, layer thicknesses of less than 3.28 ft (1 m) were used as needed to define the channel geometry, and 3.28 ft (1 m) thicknesses have been used for deeper reaches. The quality of the channel geometry definition will be confirmed by comparing simulated to observed wetted top widths as part of grid refinement.

Cell Widths

Cell widths for each segment at each layer height in the Skagit River were also produced by automated methods based on a DEM of the reach. The DEM of the reach, which spans from Gorge Dam to approximately 1.5 miles downstream of the Sauk River confluence (≈32 river miles [RM]), was developed from a combination of standard and topobathymetric LiDAR (QSI 2017a and 2018b), boat-based bathymetric (sonar) surveys, and terrain data from an existing hydraulic model of the Barnaby reach of the Skagit River. Like the 2018 topobathymetric LiDAR data set used for the reservoirs, the 2017 topobathymetric LiDAR dataset covering the river also contain voids. The 2017 and 2018 topobathymetric LiDAR includes approximately 105 acres of voids within the main channel, which account for approximately 10 percent of the main channel area.

---

4 "Normal depth" is the depth of flow that would occur if the flow was not changing longitudinally (uniform) or temporally (i.e., steady), and is commonly predicted using the Manning's equation.

To address the data gaps (i.e., voids) and to replace suspect surface values, two bathymetric survey efforts were conducted: the first over two separate weeks in October 2020 and March 2021 for voids in the 2017 and 2018 surfaces between Gorge Powerhouse and PRM 73.4; and the second over a week in September 2021 for voids within the Barnaby Reach surface between PRM 73.4 and the confluence with the Sauk River. Detailed documentation of the bathymetric void infilling is covered in Attachment E to the FA-02 Instream Flow Model Development Study Interim Report (City Light 2022b). Elevations for the Gorge bypass reach, located between Gorge Dam and Gorge Powerhouse, were applied directly from LiDAR data (QSI 2017a), and voids were filled using a 2017 single beam bathymetric survey covering the Gorge dam plunge pool (True North Surveying, Inc. 2017). The mean top width for all segments developed from the resulting DEM is 381 ft (range: 148 – 928 ft).

4.2.3 Meteorology

The CE-QUAL-W2 model requires a meteorological input file that contains a time series of:

- Air Temperature;
- Dew Point Temperature;
- Wind Speed;
- Wind Direction;
- Cloud Cover; and
- Incident Short Wave Solar Radiation.

The separate water bodies simulated in each of the four models required independent meteorology input files (Table 4.2-1). NPS provided a list of 22 active climate stations inside North Cascades National Park and Ross Lake National Recreation Area and 24 active climate stations outside the parks. These have start dates ranging from 1931 to 2014, and they measure different combinations of air temperature, precipitation, relative humidity, soil temperature, soil moisture, wind speed, wind direction, snow depth, snow-water equivalent, and solar radiation. Two stations from the Remote Automatic Weather Stations (RAWS) program, Hozomeen and Marblemount, were selected based on their temporal coverage and available measurements. Data were downloaded from the Western Regional Climate Center (2021) and data were processed for recent durations during which data were most complete (Table 4.2-1).

Table 4.2-1. Meteorology stations.

Model	Station	Program	Coordinates	Elevation[1] (ft)	Duration[2]
Ross Lake	Hozomeen	RAWS	49.1083 - 121.1833	1,704 (1,698)	Feb. 2018 – Oct. 2021
Diablo Lake	Marblemount	RAWS	48.5944 - 121.5611	361 (355)	Jan. 2011 – Oct. 2021
Gorge Lake	Marblemount	RAWS	48.5944 - 121.5611	361 (355)	Jan. 2011 – Oct. 2021
Skagit River	Marblemount	RAWS	48.5944 - 121.5611	361 (355)	Jan. 2011 – Oct. 2021

1 Elevations shown relative to NAVD 88, with elevations relative to CoSD in parentheses. All elevations are rounded to the nearest foot.

2 Data are available as early as 2004 and 2003 for Hozomeen and Marblemount Stations, respectively. However, filling large data gaps will require substantial effort to estimate values of meteorological variables prior to the duration shown.

For the Hozomeen site the data coverage completeness was around 98 percent between January 1, 2020 and October 31, 2021, with a maximum of 33 hours of continuous missing data. For the Marblemount site, the data coverage completeness was >99 percent between January 1, 2020 and October 31, 2021, with a maximum of 9 hours of continuous missing data. Missing data were filled using linear interpolation for short time period gaps (i.e., <6 hours) and, for gaps of a few days, available data from a few days before and after the missing hours were used to preserve the temporal variation of the variables. Most of the meteorological variables required by the CE-QUAL-W2 model were available at the RAWS stations except dewpoint temperature and cloud cover, which were calculated using measured variables.

The dewpoint temperature was computed based on relative humidity and air temperature by rearranging Equation 4.1-1 (Singh 1992):

$$RH = \left[\frac{112 - 0.1T + T_d}{112 + 0.9T}\right]^8$$

Eq. 4.1-1

Where: RH is the measured relative humidity at the two stations (dimensionless);
T is the air temperature in Celsius (°C); and
T_d is the dewpoint temperature (°C).

Cloud cover is used to compute the long-wave atmospheric radiation in the CE-QUAL-W2 model (Wells 2021b). The cloud cover was computed based on net and clear-sky short wave solar radiation by rearranging Equation 4.1-2 (Wunderlich 1972):

$$\phi_{s\_net} = \phi_{s\_clearsky}(1 - 0.65C^2)$$

Eq. 4.1-2

Where: $\Phi_{s\text{-}net}$ is the measured net short wave solar radiation in watts per sq. meter (W/m^2);
$\Phi_{s\text{-}clearsky}$ is the clear-sky short wave solar radiation (W/m^2); and
C is the cloud cover fraction between 0 and 1 (dimensionless).

The clear-sky solar radiation was estimated using a method developed by Annear and Wells (2006) that estimates the clear-sky short wave solar radiation using five different models. These were calibrated using the short-wave solar radiation measured in clear-sky days at the Marblemount monitoring site, and the best-fit model was used to compute cloud cover fraction for the entire simulation period using Equation 4.1-2. Solar radiation at the Hozomeen meteorological station was judged to be unreliable and was not used.

4.2.4 Flow Input Files

CE-QUAL-W2 requires input files containing time series of flow into the simulated water body via each tributary and out of the water body via its downstream boundary and other withdrawals. These files are created in two major steps. First, the inflows[5] and outflows that need to be included in the model must be defined. Second, existing data must be used to develop time series for these inflows and outflows. These two tasks are connected; often, available data influence the inflows that can be included in the model.

4.2.4.1 Ross Lake and Diablo Lake

As mountain lakes at a northern temperate latitude, Ross Lake and Diablo Lake are fed by numerous streams of varying sizes. Of these, the Skagit River, Big Beaver Creek, and Ruby Creek (which flow into Ross Lake) and Thunder Creek (which flows into Diablo Lake) are gaged by the USGS. Additionally, Ross Dam outflows are both the only meaningful outflows from Ross Lake and the main inflow to Diablo Lake; Diablo Dam plays the same role for Diablo Lake and Gorge Lake downstream.

The inflows to the reservoirs via the >20 ungaged, named tributaries cannot be neglected, yet these tributaries are too numerous to estimate the flow in each individually. Consequently, tributary inflow regions were developed around Ross Lake and Diablo Lake to define catchment areas that, for the purposes of developing model input files, would be considered as contributing runoff into a single inflow to the water bodies (Figure 4.2-7). This delineation of catchment areas defined the number of tributaries and, in turn, inflow time series that were developed for the Ross Lake and Diablo Lake models.

[5] CE-QUAL-W2 divides inflows to a water body as “branch inputs” if they enter the main branches of a model (i.e., the main arms of a reservoir) in the longitudinal direction and “tributaries” if they are minor streams that enter a segment of the model in the lateral direction. Some tributaries mentioned in this passage are classified as branch inputs when implemented in CE-QUAL-W2, but this distinction is not relevant for comprehension by the non-modeler, so the inflows are termed “tributaries” in this report.

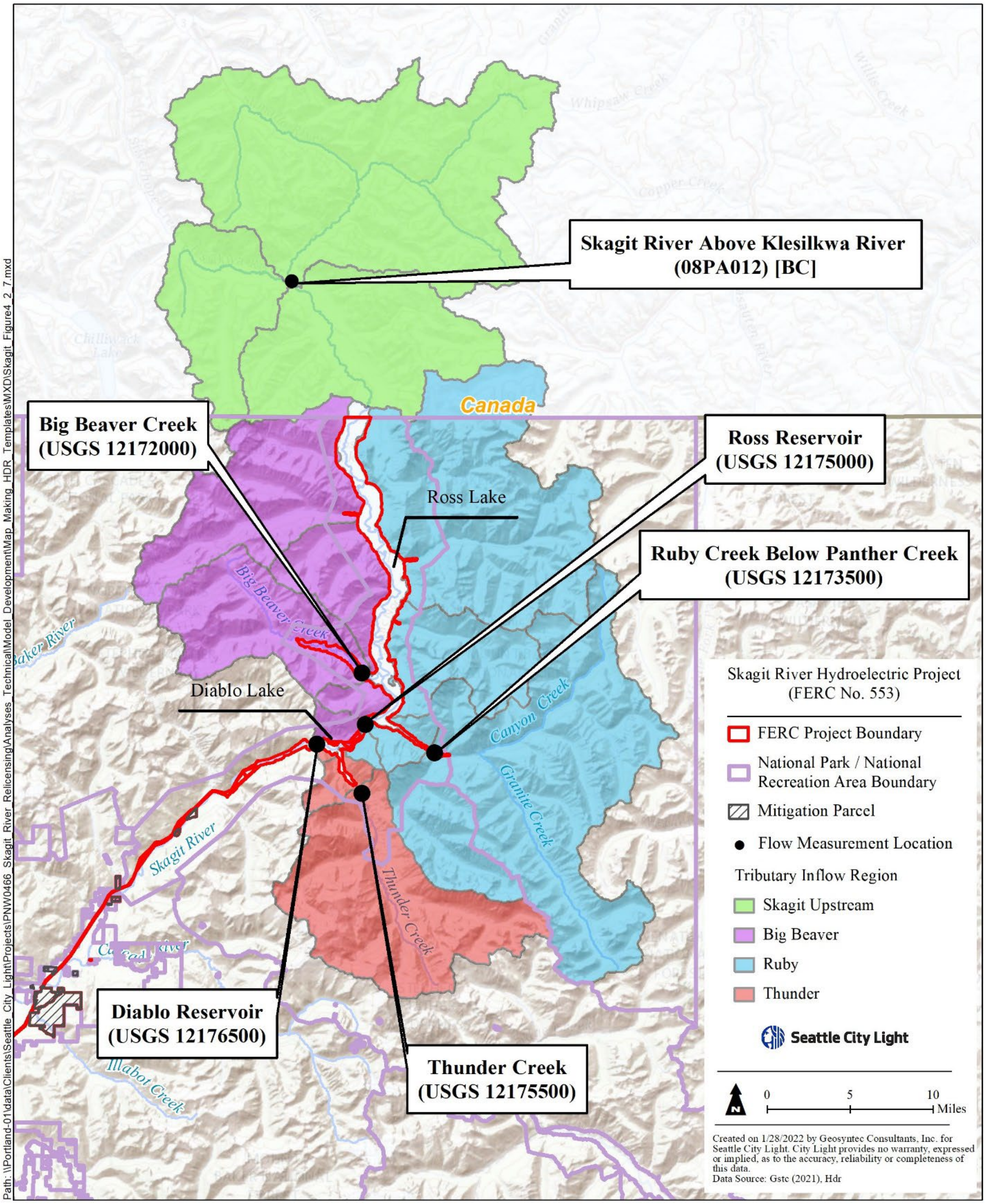

Figure 4.2-7. Tributary inflow regions surrounding Ross Lake and Diablo Lake.

For gaged tributaries—Big Beaver Creek, Ruby Creek, and Thunder Creek—inflow regions corresponded to the watersheds of these creeks upstream of the USGS gages. These watersheds were determined by beginning with the 1/3 arc-second n49w123 1 x 1 degree DEM created by the USGS and the Canada three-dimensional (3-D) DEM created by Natural Resources Canada. These DEMs were pre-processed, merged, projected into Universal Transverse Mercator Zone 10 using ArcGIS 10.7, and inspected for any gaps or errors. Watersheds were delineated in ArcGIS (ArcMap 10.7) following the Watershed Delineation with ArcGIS 10.2.x guideline from Trent University (Trent University 2014), which uses these steps:

(1) Create a Depression-less DEM. The Fill tool in Hydrology toolbox in ArcGIS 10.7 was used to remove any cells in the final DEM raster that did not have an associated drainage value. These cells in the DEM are commonly known as imperfections or sinks. The result is a DEM surface raster without any small imperfections.

(2) Create a Flow Direction Grid. A flow direction raster was created from the DEM surface raster in Step 1 using the D8 method (Greenlee 1987) of the Flow Direction Tool in Hydrology toolbox in ArcGIS 10.7. The D8 method assigns an integer between 1 and 255 to each grid of the DEMs raster with respect to the location of the steepest downslope neighbor cells. The final product in Step 2 is an integer raster with values ranging from 1 to 255.

(3) Create a Flow Accumulation Grid. The number of upstream cells flowing into each of the grids was calculated using the Flow Accumulation tool in the Hydrology Toolbox in ArcGIS 10.7. The final product is a raster surface where the higher values represent areas of lower elevation into which water flows naturally.

(4) Snap Watershed Outlet (Pour) Points. Tributaries of the Skagit River were identified, and a point shapefile of the discharged location was created. Then, the Snap Pour Point tool in ArcGIS 10.7 was used to snap the outlet of each tributary to its most downstream grid (i.e., highest value) in the flow accumulation raster surface in Step 3. Finally, the pour points were inspected and adjusted to ensure the most downstream grid of each tributary is selected.

(5) Delineate Watershed. The Watershed Tool in the Hydrology Toolbox was used to delineate the drainage area of the tributaries using the Flow Direction and the Pour Points rasters in Steps 2 and 4. Then, drainage areas raster was simplified and converted to a vector drainage area file for further geoprocessing using the Raster to Polygon tool in ArcGIS 10.7.

For ungaged tributaries, the above process was repeated. It led to the delineation of 763 watersheds, far too many to effectively characterize within the CE-QUAL-W2 modeling framework. Many of the watersheds, therefore, were consolidated into larger inflow regions and assigned a single outflow location into Ross or Diablo Lake. The practical effect of this is the assignment of, for example, the attribution of the total volumetric flow in Hozomeen Creek, Lightning Creek, and other small tributaries that enter the northeastern portion of Ross Lake into Hozomeen Creek alone, which was assigned to flow into a specific segment of the Ross Lake model. This led to 10 individual inflows to the Ross Lake model and seven to the Diablo Lake model (Figures 4.2-8, 4.2-9, and 4.2-10).

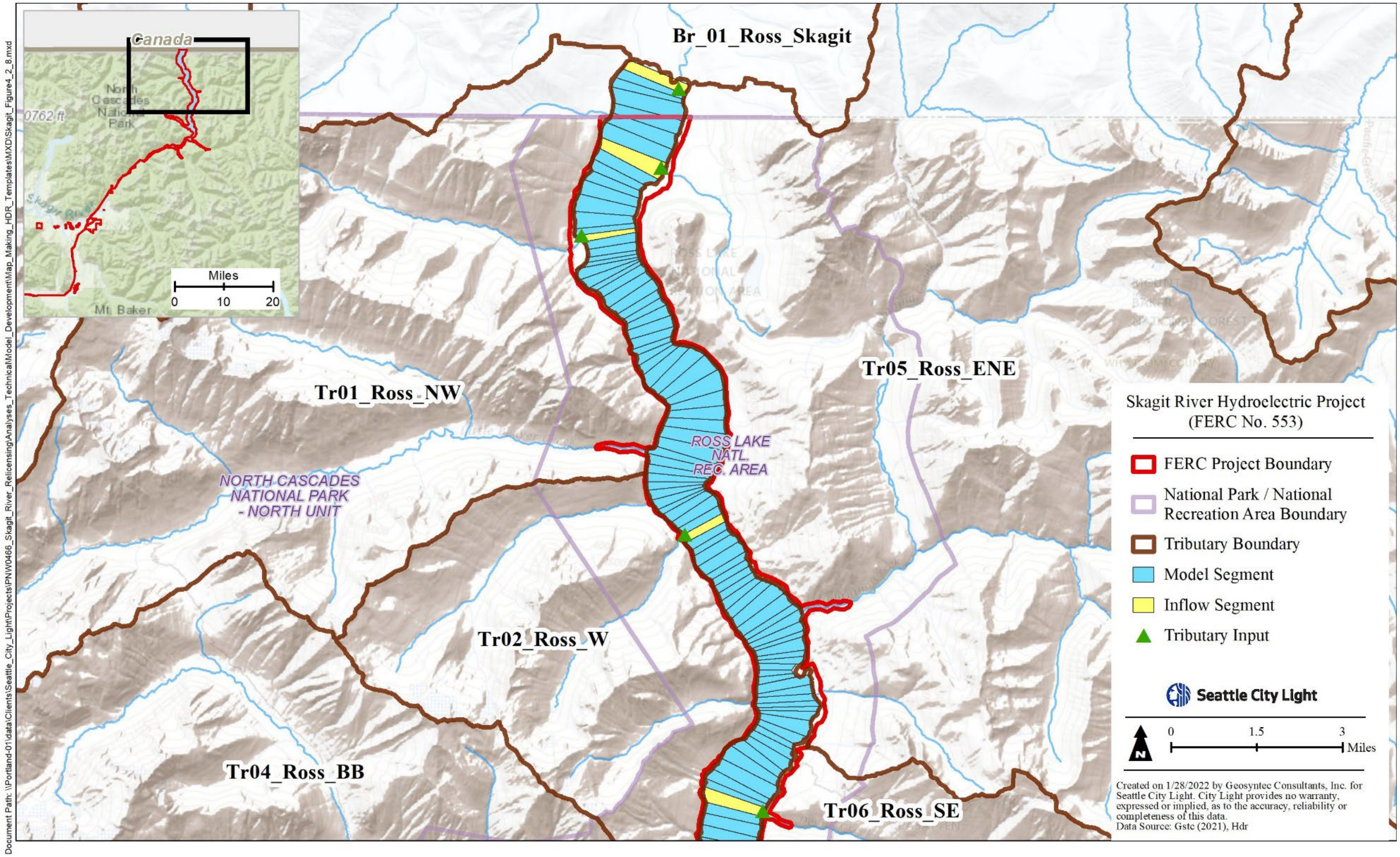

Figure 4.2-8. Entry points of tributary inflow regions into northern Ross Lake.

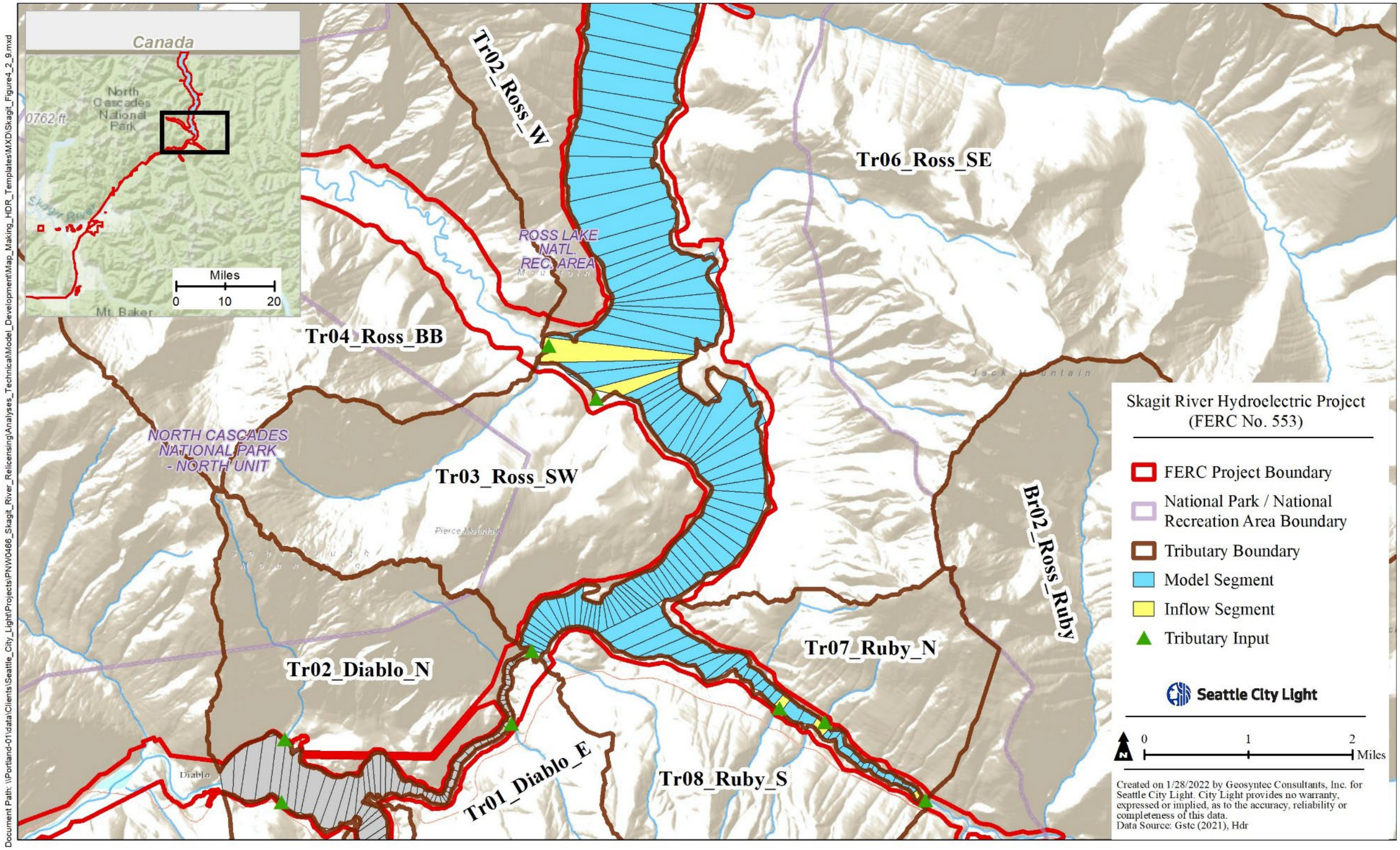

Figure 4.2-9. Entry points of tributary inflow regions into southern Ross Lake.

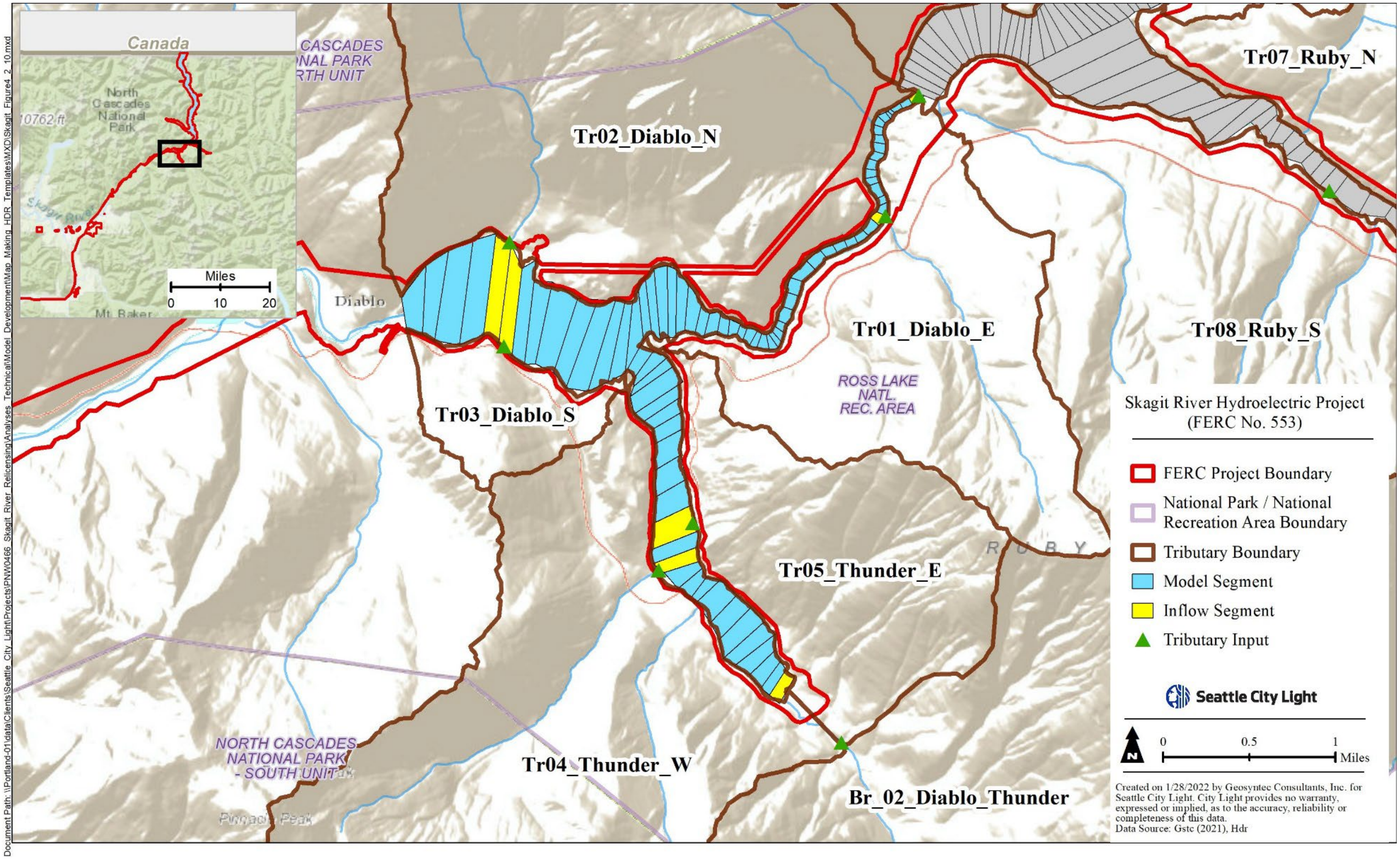

Figure 4.2-10. Entry points of tributary inflow regions into Diablo Lake.

Once the inflow regions were defined, their areas were calculated in GIS and then the flow in each was estimated from the flow at a nearby USGS gage and the ratio of the drainage areas between the gaged watershed and the ungaged watershed of interest (Table 4.2-2). The Skagit River gage (Water Survey of Canada gage 08PA012) is located immediately upstream of the Skagit River's confluence with the Klesilkwa River, which joins the Skagit River from the west after draining a significant area. Consequently, the Klesilkwa River flow and the flow into the Skagit River between its confluence with the Klesilkwa River and the upstream end of Ross Lake were both estimated based on the gaged Skagit River flow. These three flows were summed to create an estimate of the Skagit River inflow to Ross Lake. Dam outflows were taken from City Light dam operations data.

Table 4.2-2. Sources of flow data for Ross Lake and Diablo Lake tributary inflow regions.

Inflow Region	Area (sq. miles)	Gage	Estimation	Inflow Location
Ross Lake Tributaries				
Skagit River	391.73	Skagit	Sum of gaged values and prorated estimates of Klesilkwa flows and inflows between Klesilkwa and Ross Lake	Skagit River inflow to Ross Lake
Northwest	81.71	Big Beaver	Prorated by watershed area relative to Big Beaver	Silver Creek
West	32.13	Big Beaver		No Name Creek
Southwest	7.44	Big Beaver		S. of Pierce Creek
Big Beaver	65.18	Big Beaver	None (USGS values used)	Big Beaver Creek
Northeast	161.71	Ruby	Prorated by watershed area relative to Ruby	Hozomeen Creek
Southeast	45.28	Ruby		Devils Creek
Ruby East	212.94	Ruby	None (USGS values used)	Ruby Creek
Ruby North	3.56	Ruby	Prorated by watershed area relative to Ruby	Lone Tree Creek
Ruby South	5.89	Ruby		Lillian Creek
Diablo Lake Tributaries				
Ross Lake	1,008	Ross Dam	Sum of powerhouse and spillway flows	Ross Dam outflow to Diablo Lake
East	2.37	Ruby	Prorated by watershed area relative to Ruby	Horsetail Creek
North	5.46	Big Beaver	Prorated by watershed area relative to Big Beaver	Sourdough Creek
South	0.66	Thunder	Prorated by watershed area relative to Thunder	None; center of inflow region used
Thunder South	110.36	Thunder	None (USGS values used)	Thunder Creek
Thunder West	5.48	Thunder	Prorated by watershed area relative to Thunder	Colonial Creek
Thunder East	2.95	Thunder		None; center of inflow region used

4.2.4.2 Gorge Lake and Skagit River Downstream to RM 54, Below Baker River Confluence

Development of inflow time-series for the Gorge Lake and Skagit River mainstem models is still in progress. The primary inflow to Gorge Lake is the regulated powerhouse outflow from Diablo

Dam, which enters from the right bank at the beginning of the Stetattle reach (i.e., not the head of the waterbody which begins at Diablo Dam). One major stream, Stetattle Creek, which has a basin area of approximately 22.8 square miles, will be represented as a lumped tributary input to the reservoir model with the larger 27.5 square mile area tributary to the Stetattle reach. The smaller Gorge Creek will also be defined as a specific tributary inflow. All other inflow to the reservoir will be lumped as distributed inflow, calculated as part of the water balance being performed to match USGS water-level records. The yellow segments in Figure 4.2-4 signify the tributary inflow locations to the Gorge Lake model.

Inflows to the Skagit River mainstem model between Gorge Dam and the Sauk River confluence include the outflows from Gorge Dam and multiple tributary inputs (see Table 4.2-3 and Figure 4.2-11). The relative contribution of flows from the Project varies along the reach, with non-Project discharges contributing approximately 10 percent of annual average flows at Newhalem and increasing downstream to as much as 37 percent of the annual average flow downstream of the Cascade River and 62 percent downstream of the Sauk River confluence (City Light 2021b).

Inflows to the steep Gorge bypass reach located between Gorge Dam and Newhalem are infrequent, and characterization of these flows will need to be defined. Flow time-series for tributary inputs will be based on available USGS flow records and/or scaling records from comparable/adjacent basins, depending on the period of simulation.

Table 4.2-3. Sources of flow data for Gorge Lake and the Skagit River downstream to the Sauk River confluence.

Inflow Region	Area (sq. miles)	Gage	Estimation	Inflow Location
Gorge Lake				
Diablo Lake (spill to Reflector Bar)	1,135	Diablo Dam	Diablo spillway flows + estimation of baseflow	Diablo Dam
Diablo Lake (powerhouse to Stetattle Reach)	1,135	Diablo Dam	Diablo powerhouse flows	Diablo Dam powerhouse
Stetattle Reach	27.5	Big Beaver, Newhalem, or Thunder	Prorated by watershed area relative to Big Beaver, Newhalem, or Thunder Creek	Stetattle Creek
West Zone (Gorge Lake Local)	7.0	Gorge Lake	Based on water-balance to observed USGS water-level record	Distributed
West Zone (Gorge Creek)	2.7	Bacon or Newhalem	Prorated by watershed area relative to Bacon or Newhalem Creek	Gorge Creek
Skagit River: Gorge Dam to Sauk River Confluence				
Gorge Lake (spill to Bypass Reach)	1,172	Gorge Dam	Gorge spillway flows	Gorge Dam
Bypass Reach	11.3	Newhalem	Prorated by watershed area relative to Newhalem Creek	Distributed
Gorge Lake (powerhouse to Newhalem Reach)	1,184.4	Gorge Dam	Gorge dam spillway flows	Gorge Dam powerhouse outflow to Skagit River
Newhalem Reach	90.4	Newhalem	Sum of powerhouse and prorated inflow by watershed area relative to Newhalem gage (26.9 mi^2)	Newhalem Creek
Damnation and Landslide Reaches	24.9	Bacon or Newhalem	Prorated by watershed area relative to Bacon or Newhalem Creek	Damnation Creek
Bacon Reach	54.6	Bacon	Prorated by watershed area relative to Bacon Creek gage (49.7 mi^2)	Bacon Creek
Cascade Reach (Diobsud/Upper)	38.8	Bacon	Prorated by watershed area relative to Bacon Creek	Diobsud Creek
Cascade Reach (Cascade River/Lower)	190.2	Cascade	Prorated by watershed area relative to Cascade River gage (172 mi^2)	Cascade River
Barnaby Reach (Rocky Creek)	17.6	Bacon	Prorated by watershed area relative to Bacon Creek	Corkindale Creek
Barnaby Reach (Illabot Creek)	63.2	Bacon	Prorated by watershed area relative to Bacon Creek	Illabot Creek
Sauk Alluvial Fan	750.7	Sauk River	Prorated by watershed area relative to Sauk River gage (714 mi^2)	Sauk River

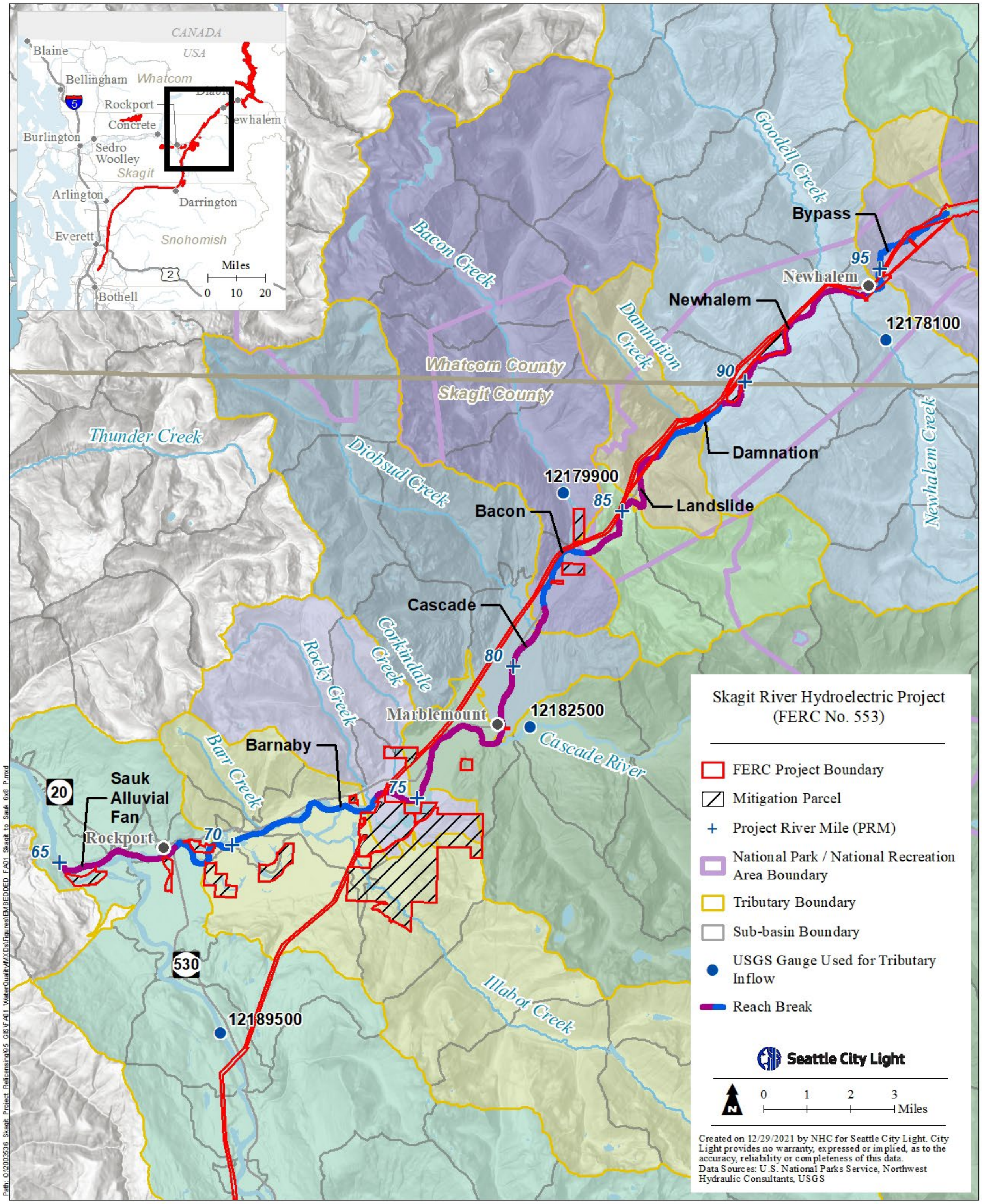

Figure 4.2-11. Entry points of tributary inflow regions into the Skagit River below Gorge Dam.

4.2.4.3 Flow Data Availability

The duration of available inflow data is a major constraint on the duration of model simulations. Flow data availability are summarized in Table 4.2-4. Limited data exist from time periods decades ago (e.g., the 1950s), but these are not useful for development of a model that represents present conditions.

Table 4.2-4. Availability of flow data.

Gage	Number[1]	Record Start	Record End
Ross Lake Inflows			
Skagit River above Klesilkwa	08PA012	Mid-2019	Present
Big Beaver Creek	12172000	June 27, 2018	Present
Ruby Creek	12173500	April 30, 2018	Present
Diablo Lake Inflows			
Ross Dam	None	January 1, 1997	Present
Thunder Creek	12175500	October 1, 1989	Present
Gorge Lake Inflows			
Diablo Dam	None	January 1, 1997	Present
Skagit River Gages and Inflows			
Gorge Dam	None	January 1,1997	Present
Skagit River at Newhalem	12178000	October 5, 1987	Present
Newhalem Creek	12178100	October 1, 1989	Present
Skagit River below Babcock Creek	12178600	November 10, 2020	Present
Skagit River below Damnation Creek	12178900	September 26, 2020	Present
Skagit River above Alma Creek	12179000	June 11, 2020	Present
Bacon Creek	12179900	November 3, 1998	Present
Skagit River above Diobsud Creek	12180300	June 9, 2020	Present
Skagit River at Marblemount	12181000	October 1, 1987	Present
Cascade River	12182500	June 7, 2006	Present
Skagit River at Corkindale	12183900	June 9, 2020	Present
Skagit River near Rockport	12184700	October 1, 2015	Present

1 The Skagit River above Klesilkwa is operated by the Water Survey of Canada. The other gages are USGS gages.

4.2.5 Temperature Input Files

In addition to input files describing flow of water into and out of simulated water bodies, CE-QUAL-W2 requires separate input files that contain time series of water quality constituents that will be modeled. Insofar as the models under development will simulate water temperature, temperature time series are required in the same tributaries for which inflows were specified. Substantial temperature monitoring efforts in recent years have created a robust inventory of temperature data in tributaries around Ross Lake, Diablo Lake, Gorge Lake, and the Skagit River, as described in the Management and Evaluation of Existing Water Quality Data Draft Report, Attachment D to the FA-01a WQ Monitoring Study report (City Light 2022a). Using those data, inflow files were developed as indicated in Tables 4.2-5 and 4.2-6. When data were not available in an inflow region, a nearby record was used. Therefore, some temperature records are used to provide temperature inputs for multiple inflow regions.

Table 4.2-5. Sources of tributary temperature data for Ross Lake and Diablo Lake tributary inflow regions.

Inflow Region	Water Temperature Record Used
Ross Lake Tributaries	
Skagit River	Skagit River at Swing Bridge
Northwest	Silver Creek NPS Sensor
West	Silver Creek NPS Sensor
Southwest	Big Beaver USGS Gage
Big Beaver	Big Beaver USGS Gage
Northeast	Hozomeen Creek
Southeast	Big Beaver USGS Gage
Ruby East	Ruby Creek USGS Gage
Ruby North	Granite Creek
Ruby South	Granite Creek
Diablo Lake Tributaries	
Ross Lake	Ross Dam Log Boom
East	Granite Creek
North	Granite Creek
South	Granite Creek
Thunder South	Thunder Creek USGS Gage
Thunder West	Thunder Creek USGS Gage
Thunder East	Thunder Creek USGS Gage

Table 4.2-6. Sources of tributary temperature data for Gorge Lake and Skagit River tributary inflow regions.

Inflow Region	Water Temperature Record Used
Gorge Lake Tributaries	
Diablo Lake (spill to Reflector Bar or powerhouse to Stetattle Upper Reach)	Diablo Dam Log Boom
Stetattle Reach	Stetattle Creek City Light and STS Study Sensor
West Zone (Gorge Lake Local)	Stetattle Creek City Light and STS Study Sensor
West Zone (Gorge Creek)	Stetattle Creek City Light and STS Study Sensor
Skagit River Tributaries	
Gorge Lake (spill to Bypass Reach or powerhouse to Newhalem Reach)	Gorge Dam Log Boom
Bypass Reach	Newhalem Creek City Light and STS Study Sensor
Newhalem Reach	Newhalem Creek City Light and STS Study Sensor
Damnation Reach	Bacon Creek NPS Sensor
Landslide Reach	Bacon Creek NPS Sensor
Bacon Reach	Bacon Creek NPS Sensor
Cascade Reach (Diobsud/Upper)	Bacon or Rocky Creek NPS Sensors
Cascade Reach (Cascade River)	Cascade River NPS Sensor
Barnaby Reach (Rocky Creek)	Rocky Creek NPS Sensor
Barnaby Reach (Illabot Creek)	Illabot Creek NPS Sensor
Sauk River Alluvial Fan	Sauk River City Light Sensor

A CE-QUAL-W2 model does not require an input file describing water temperature in the outflow of a water body. Instead, the model calculates temperatures at the outflows of dams or at the downstream extent of the modeled river reach. However, time series of temperatures in outflows from Ross Dam, Diablo Dam, and Gorge Dam are required as upstream inputs to Diablo Lake, Gorge Lake, and the Skagit River, respectively. Additionally, these time series can be useful for calibrating the Ross Lake, Diablo Lake, and Gorge Lake models, respectively. Because water temperature is not measured continuously in dam outflows, temperature time series of dam outflows will be created using the time series measured by thermistors positioned at the log boom locations upstream of the dams. Temperature records at the surface and at the depth of the penstock openings of each dam will be extracted from the database created as part of the Management and Evaluation of Existing Water Quality Data Report, Attachment D to the FA-01a WQ Monitoring Study report (City Light 2022a), and these will be averaged after weighting them by the outflows via the spillway (surface) and the powerhouses (depth) at each time for which flow and temperature are available. The depth range of the water column from which the penstock openings withdraw water will be assumed to be narrow; only temperatures corresponding to the depth of the penstock openings will be used. This is acceptable because, when the water column is stratified, water will be withdrawn from a narrow depth range due to buoyancy resistance to mixing. When the water column is well-mixed, it will be isothermal and errors in the withdrawal depth are not important.

These will be used as upstream input files for the Diablo Lake, Gorge Lake, and Skagit River models.

4.2.6 Other Input Files

CE-QUAL-W2 requires several additional input files in the initial stages of model development. They are each discussed briefly here:

- Withdrawal Outflow file: This will not be used in the models of the Project and the river downstream because no significant withdrawals from the reservoirs or the rivers are known in the reaches modeled.
- Gate Outflow file: Modeling control structures as gates is expected to be unnecessary to achieve model calibration.
- Wind Sheltering file: This file describes the extent to which the effective wind speed on the water surface may be reduced due to topographic sheltering in individual model segments. It is expected to be important in model calibration, but initial estimates will be used during model development.
- Shade file: This file describes the extent to which topography or vegetation might shade the water bodies with enough frequency to reduce the actual incident short-wave solar radiation on the water surface. It may be used during model calibration, but initial estimates will be used during model development.

4.2.7 Model Control File

The CE-QUAL-W2 model control file is divided into brief, discrete sections known as control "cards." Several control cards describe the nature of the model input files (e.g., the number of segments and layers or the segments into which tributaries flow), and these will not be reiterated here. Other control cards specify model parameterizations that will be initially set to default values provided in the CE-QUAL-W2 manual (Wells 2021b) and adjusted as needed during calibration.

Key parameters are:

- Latitude and longitude: The center of each reservoir or the center of the modeled reach of the Skagit River will be used.
- Elevation of the reservoir bottom: The elevation of the base of a dam or of the riverbed at the confluence with the Sauk River will be used.
- Longitudinal eddy viscosity and diffusivity: Initially each set to 1 meter squared per second.
- Bottom heat exchange: Initially set to the default value of 0.3 watts per square meter per degree Celsius.
- Sediment temperature: Initially set to the long-term average air temperature stated in the meteorological input file.
- Light extinction: Initially set to the recommended default value of 0.45 inverse meters.
- Maximum vertical eddy viscosity: Initially set to the default value of 1 square meter per second.

- Number of outlet structures: Each dam will have two outlet structures—the spillway and the penstocks. Elevations and widths of each will be taken from the latest available documentation of the Project.

4.3 Debugging and Calibration

Model debugging is the process of iteratively running the model and resolving syntax or logical errors that may have occurred when developing input files or specifying parameters in the control file. When modeling with CE-QUAL-W2, the preprocessor utility is used to test the model for errors before running it on the model executable. The model will be debugged until preprocessor errors have been eliminated and preprocessor warnings are eliminated or deemed acceptable. This debugging practice is consistent with industry standards.

The first calibration activity will be the matching of simulated water surface elevation levels to water levels that have been observed at the dams or the USGS gages on the Skagit River. The customary method of achieving a "water balance" is to use the CE-QUAL-W2 water balance utility to calculate the difference in inflows at each time step during the simulation that would be required to resolve the difference in water levels. Then, those flows are added to the water body via a "distributed tributary," which is a conceptual tributary whose flow is divided evenly among the cells. This is meant to resolve small errors in inflows. These errors and, consequently, the distributed tributary flows, may be somewhat substantial in the Ross Lake and Diablo Lake models since a large fraction of tributary inflows will be estimated.

Temperature calibration will involve comparison of temperature profiles simulated by the model to vertical profiles and thermistor chain data collected in the reservoirs and the temperature measurements recorded at the USGS Skagit River gages and those currently operated by Meridian Environmental Inc. on behalf of City Light. The approach and results of temperature calibration will be discussed in detail in the modeling report submitted as part of the USR in 2023.

5.0 PRELIMINARY RESULTS

At the time of submission of this report, the Ross Lake and Diablo Lake initial models are complete and debugging and water level calibration are underway. The Gorge Lake and Skagit River model grids have been assembled, and model refinement, inflow time-series development, and model debugging are underway. Thus, model results are forthcoming in the months ahead—the results of this model development to date consist of the completed bathymetry, meteorology, flow, and temperature input files and the model control file described above.

Once model development, calibration, and sensitivity analysis are completed, hydrodynamic and temperature results will be available for further analysis.

6.0 SUMMARY

Model development of the Ross Lake and Diablo Lake initial models is nearly complete with model debugging and water level calibration underway and temperature calibration to follow in early 2022. Model development of the Gorge Lake and Skagit River models is in progress and will be completed by early 2022. Both model geometries have been developed, and both models will use the same meteorology input file that has been developed from the Marblemount RAWS data. Development of the flow and temperature input files for both models is still in progress. Once model development is completed, debugging and calibration (hydrodynamic and temperature) efforts will begin during the first quarter of 2022.

6.1 Status of June 9, 2021 Notice

The June 9, 2021 Notice identified items of discussion related to the implementation of this WQ Model Development Study. The status of these is summarized in Table 6.1-1.

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

Study Modifications Identified in the June 9, 2021 Notice	Status
Seattle City Light ("SCL") will modify FA-01 to include development of a CE-QUAL-W2 model to evaluate temperature impacts from the Project on aquatic resources. SCL will seek and incorporate the input of Scott Wells and the Oregon and Washington USGS Water Science Centers in the development of the CE-QUAL-W2 model. The model will be developed and implemented within the two-year study timeframe. The CE-QUAL-W2 model will be used to evaluate, among other things, the impact of cold-water releases from Ross reservoir on fishery resources. Action item: SCL will schedule one or more workshops with the LPs, as needed, to collaborative develop this model.	The CE-QUAL-W2 model of hydrodynamics and temperature is expected to be developed and calibrated within the two-year timeframe, pending sufficient availability of input data. The model may be used to evaluate, among other things, the impact of cold-water releases from Ross Lake on temperature in the reservoirs and river downstream. Dr. Scott Wells is under contract to serve as an additional technical expert on CE-QUAL-W2 development. City Light is actively discussing CE-QUAL-W2 model development and calibration with LPs in a series of Water Quality Resource Work Group meetings.
SCL will provide a QAPP that meets Ecology's standards and judge existing data based on the QAPP. If the existing data cannot be confirmed, the data will be reviewed on a case-by-case basis in collaboration with the LPs. Action item: SCL to provide provisional data summary by the end of July 2021 to identify gaps and ensure those gaps are addressed through data collection in the study time frame, followed by a full summary in the Initial Study Report. Action item: The existing data will be reviewed to determine data gaps that need to be filled through the implementation of the study plan.	The QAPP, which is based on Ecology's Standard Operating Procedures, was included as an attachment to the Water Quality Monitoring Study RSP. City Light submitted the provisional data summary to LPs on September 3, 2021. The full water quality data summary and analysis is attached to the FA-01a Water Quality Monitoring Study interim report.
SCL will modify FA-01 to clarify that SCL will evaluate measures of biological productivity including primary producers and will collaborate with the LPs to develop a sampling study. In addition, SCL will execute an expanded benthic macroinvertebrate sampling program to include the Project reservoirs, Skagit River to the estuary	City Light has worked with LPs in the Water Quality Resource Work Group to (1) develop a sampling plan that allows for the modeling of a range of water quality parameters, including nutrient dynamics to address questions of productivity, and (2) arrive at a sampling plan for BMI and invertebrate drift, in the Project

Study Modifications Identified in the June 9, 2021 Notice	Status
(through reference reach sampling mutually agreed to by SCL and the LPs), varying seasons, varying habitat types, and invertebrate drift. The sampling program will be developed in collaboration with the LPs and informed by NPS Appendix A.[6]	reservoirs, tributaries to the reservoirs in the reservoirs' varial zones, and the Skagit River downstream of the Project, including a downstream expansion of sampling sites. As of the filing of this ISR, the scope of the WQ Monitoring Study has been significantly expanded in consultation with LPs to include additional data collection to support development and calibration of the CE-QUAL-W2 model and BMI/invertebrate drift data.
SCL will modify the study plan to conduct an initial assessment of nitrogen and phosphorous in the Project Reservoirs, representative major reservoir tributaries, and Skagit River to the estuary (through mutually agreed sampling program including reference reaches). An assessment for nutrient data collection will be developed in coordination with tributary habitat sampling, water quality modeling, and the food web study. The sampling design will be developed in collaboration with the LPs. SCL will also modify the study plan to initiate modelling of nutrient and productivity components after 1) the CE-QUAL-W2 model for temperature is developed, and 2) data sources and years available are evaluated against the objectives of the LPs. Concurrently SCL would continue to collect proposed water quality parameter data and develop the CE-QUAL-W2 framework and integration with Operations model and other modelling tools in order to perform a sensitivity analysis to determine the accuracy and sensitivity of the tool (and data needs) for illustrating nutrient dynamics under alternative operational scenarios. SCL anticipates that this effort will be initiated during the second year of study and completed prior to the filing of the Updated Study Report.	City Light has worked with LPs in the Water Quality Resource Work Group to (1) develop a sampling plan that allows for the modeling of a range of water quality parameters, including nutrient dynamics to address questions of productivity, and (2) arrive at a sampling plan for BMI and invertebrate drift, in the Project reservoirs, tributaries to the reservoirs in the reservoirs' varial zones, and the Skagit River downstream of the Project, including a downstream expansion of sampling sites. As of the filing of this ISR, the scope of the WQ Monitoring Study has been significantly expanded in consultation with LPs to include additional data collection to support development and calibration of the CE-QUAL-W2 model and BMI/invertebrate drift data.
SCL will convene a workshop with concerned LPs to discuss parameters, frequency, monitoring locations, and temporal overlap with existing data. This workshop will occur in August 2021 after the data gaps in the QA/QC analysis are presented by SCL. The workshop will also identify the parameters to be modeled by CE-QUAL-W2, potential gaps in the model, and the approach to filling the gaps. Where the model will not adequately describe the effects of Project operation scenarios on water quality parameters, empirical data collection requirements will be developed by SCL in collaboration with the LPs and informed by NPS Appendix A.	City Light is currently discussing CE-QUAL-W2 model development and calibration in Water Quality Resource Work Group meetings. As of the filing of this ISR, the scope of the WQ Monitoring Study has been significantly expanded in consultation with LPs, to include additional data to support development and calibration of the CE-QUAL-W2 model and BMI/invertebrate drift data. Existing data, as well as sampling already identified in the RSP, were factored into decision-making about what parameters should be sampled and the general locations of sampling. Refinements are underway to select final monitoring locations based on field reconnaissance.

6 Taylor-Goodrich, K.F. Re: North Cascades National Park Service Complex comments on Seattle City Light's Revised Study Plan for the relicensing of the Skagit Project (#553), Appendix A. Letter to K.D. Bose, Secretary, Federal Energy Regulatory Commission, May 5, 2021.

7.0 VARIANCES FROM FERC-APPROVED STUDY PLAN AND PROPOSED MODIFICATIONS

This WQ Model Development Study is consistent with references to temperature modeling contained in the June 9, 2021 Notice and approved by FERC in its SPD dated July 16, 2021. There are no variances from or modifications to the agreed-upon approach for the WQ Model Development Study.

8.0 REFERENCES

Annear, R.L., and S.A. Wells. 2007. A comparison of five models for estimating clear-sky solar radiation. Water Resources Research, 43, W10415, doi:10.1029/2006WR005055.

Greenlee, D.D. 1987. Raster and Vector Processing for Scanned Linework. Photogrammetric Engineering and Remote Sensing 53 (10): 1383–1387.

HDR, Inc. 2020. LiDAR Data Processing and Management. Memorandum. April 10, 2020.

Hetland, R. 2018. Pygridgen. Github, (city and state unknown). Full date unknown. [Online] URL: https://pygridgen.github.io/pygridgen/index.html. Accessed 15 October 2021.

Hobson, P. 2018. Pygridtools. Github, Portland, OR. Full date unknown. [Online] URL: https://pygridtools.readthedocs.io/en/latest/index.html. Accessed 15 October 2021.

Quantum Spatial, Inc. (QSI) 2017a. Skagit Topobathymetry, Washington. Topobathymetric LiDAR Technical Data Report, Prepared for Skagit River System Cooperative, July 17, 2017.

_____. 2017b. Western Washington 3DEP LiDAR – North AOI. Technical Data Report. Acquisition 2016, Prepared for U.S. Geological Survey (USGS), September 29, 2017.

_____. 2018a. Ross Lake, Washington and British Columbia, Canada, LiDAR Technical Data Report. Prepared for Seattle City Light. June 22, 2018.

_____. 2018b. Upper Skagit, Gorge Lake and Diablo Lake, Washington, Topobathymetric LiDAR and Orthoimagery Technical Data Report. Prepared for Seattle City Light. August 17, 2018.

Seattle City Light (City Light). 2021a. Revised Study Plan (RSP) for the Skagit River Hydroelectric Project, FERC Project No. 553. April 2021.

_____. 2021b. Summary table of geomorphic reach characteristics provided at the October 1, 2021 LP Meeting for the Skagit River Hydroelectric Project FA-01a Water Quality Monitoring Study, FERC Project No. 553.

_____. 2022a. FA-01a Water Quality Monitoring Study, Interim Report for the Skagit River Hydroelectric Project, FERC Project No. 553. Prepared by Meridian Environmental, Inc. and Four Peaks Environmental, Inc. March 2022.

_____. 2022b. FA-02 Instream Flow Model Development Study, Interim Report for the Skagit River Hydroelectric Project, FERC Project No. 553. Prepared by Northwest Hydraulic Consultants, Inc. and HDR Engineering, Inc. March 2022.

Singh, V.P. 1992. Elementary hydrology. Prentice Hall, Englewood Cliffs, NJ.

Trent University. 2014. Watershed Delineation with ArcGIS 10.2.x. Trent University Library Maps, Data and Government Information Centre. Full date unknown.

True North Surveying, Inc. 2017. March and April, 2017 single beam bathymetric surveys titled "River Maintenance at Stetattle" and "Gorge Plunge Pool Bathymetry." Prepared for Seattle City Light. Provided as 24 sheets in DWG file with 0.25 foot interval contour lines and PDFs "Stetattle 1 of 2.pdf" and "Stetattle 2 of 2 .pdf."

U.S. Geological Survey (USGS). 1963a. Ross Dam Quadrangle. Map. N4837.5-W12100/7.5, DMA 1781 II NE-Series V891. U.S. Department of the Interior. Reston, Va.

_____. 1963b. Diablo Dam Quadrangle. Map. N4837.5-W12107.5/7.5, AMS 1781 II NW-Series V891. U.S. Department of the Interior. Reston, Va.

_____. 1969a. Hozomeen Mountain Quadrangle. Map. N4852.5-W12100/7.5, AMS 1781 I NE-Series V891. U.S. Department of the Interior. Reston, Va.

_____. 1969b. Pumpkin Mountain Quadrangle. Map. N4845-W12100/7.5, AMS 1781 I SE-Series V891. U.S. Department of the Interior. Reston, Va.

Wells, S.A. 2021a. CE-QUAL-W2: A Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 4.5. User Manual: Part 1, Introduction, Model Download Package, How to Run the Model. Department of Civil and Environmental Engineering, Portland, Oregon. June 2021.

_____. 2021b. CE-QUAL-W2: A Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 4.2.2. User Manual: Part 3, Input and Output Files. Department of Civil and Environmental Engineering, Portland, Oregon. February 2021.

Western Regional Climate Center. 2021. RAWS USA Climate Archive. Reno, Nevada. December 2021.

Wunderlich, W. 1972. Heat and Mass Transfer between a Water Surface and the Atmosphere. Tennessee Valley Authority, Division of Water Control Planning, Water Research Laboratory, Norris, TN. Rpt. No. 14, Rpt. Publication No. 0-6803.

This page intentionally left blank.