GE-03 SEDIMENT DEPOSITION IN RESERVOIRS AFFECTING RESOURCE AREAS OF CONCERN STUDY REPORT

SKAGIT RIVER HYDROELECTRIC PROJECT FERC NO. 553

Seattle City Light

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Updated Study Report

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Attachment B	Recent History of Rhode Creek

List of Acronyms and Abbreviations

1-D .....one-dimensional
2-D .....two-dimensional
cfs.....cubic feet per second
City Light.....Seattle City Light
CoSD.....City of Seattle datum
cu yds .....cubic yards
DHSVM .....Distributed Hydrology Soil Vegetation Model
FERC.....Federal Energy Regulatory Commission
ft .....feet
GIS .....Geographic Information System
HEC-RAS .....Hydrologic Engineering Center River Analysis System
ISR .....Initial Study Report
LiDAR.....Light Detection and Ranging
LP.....licensing participant
m .....meter
mm .....millimeter
NAIP .....National Agriculture Imagery Program
NAVD 88.....North American Vertical Datum of 1988
NPS .....National Park Service
Project .....Skagit River Hydroelectric Project
RSP .....Revised Study Plan
SR.....State Route
USACE .....U.S. Army Corps of Engineers
USFS.....U.S. Forest Service
USGS .....U.S. Geological Survey
USR.....Updated Study Report

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1.0 INTRODUCTION

The GE-03 Sediment Deposition in Reservoirs Affecting Resource Areas of Concern Study (Sediment Deposition 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 [NPS], U.S. Fish and Wildlife Service, Washington State Department of Ecology, and Washington Department of Fish and Wildlife). The June 9, 2021 Notice included agreed to modifications to the Sediment Deposition Study.

In its July 16, 2021 Study Plan Determination, FERC approved the Sediment Deposition 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 Modifications required no modifications to the Sediment Deposition 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 Sediment Deposition Study as stated in the RSP is to evaluate the effects of deposition on four specific locations within Ross, Diablo, and Gorge lakes with identified recreational resources and/or Project operations impacts. The study will develop an understanding of the physical conditions (rate of deposition, grain size of deposits) under which deposition occurs at the four locations. Specific objectives are as follows:

- Describe and map the location and history of sediment deposition in the:
  - Hozomeen inlet in Ross Lake (i.e., the large arm of upper Ross Lake that has sediment contributed by the Skagit River);
  - Sourdough Creek inlet in Diablo Lake (i.e., the small arm of Diablo Lake into which Sourdough Creek flows);
  - Thunder Arm in Diablo Lake (i.e., the large arm within Diablo Lake into which Thunder Creek, Colonial Creek, and Rhode Creek flow); and
  - Stetattle Creek delta in Gorge Lake (i.e., the sediment deposited at the mouth of Stetattle Creek where it enters Gorge Lake and the sediment deposited between Stetattle Creek and the State Route [SR] 20 bridge crossing).
- Determine rate and grain size of sediment input, quantify total volume of sediment deposition in the four inlets and deltas, and estimate rate and patterns of deposition.
- Identify likely future zones and patterns of deposition with respect to recreational resources and operational impacts.

As part of the June 9, 2021 Notice, the following commitments were made by City Light with respect to this study:

- Quantify sediment supply of all size ranges (i.e., grain size distribution estimate) in Ross, Diablo, and Gorge lakes as an average annual rate by using the existing Distributed Hydrology Soil Vegetation Model (DHSVM), historical contours, and updated bathymetry information;
- Assess (map) deposition and erosion in the drawdown zone; and
- Use a one-dimensional (1-D) backwater model to estimate magnitude and location of reservoir backwater effects in the four study deltas as appropriate.

3.0 STUDY AREA

The study area for the first three study objectives includes specific portions of the Skagit River inlet near Hozomeen (Ross Lake), Thunder Arm (Diablo Lake), Sourdough Creek inlet (Diablo Lake), and Stetattle Creek delta (Gorge Lake) (Figure 3.0-1). These specific study areas include inlets/deltas at four locations with identified recreational or operational impacts in the Project Boundary:

- Hozomeen inlet at the head of Ross Lake – recreational resource: Hozomeen and Winnebago Flats boat launches;
- Thunder inlet in Diablo Lake – recreational resource: Colonial Creek Boat Launch and Boathouse;
- Sourdough inlet in Diablo Lake – City Light resources: City Light Boat Launch, City Light Boathouse, City Light Dry Dock; recreational resources: West Ferry Landing, Environmental Learning Center Canoe and Kayak Dock; and
- Stetattle Creek delta in Gorge Lake – recreational resource: whitewater training and instruction, Gorge Lake Campground Boat Launch and Dock; operational resource: City Light Diablo Powerhouse Tailrace.

Figures 3.0-2 through 3.0-5 show the extent of the depositional area that was investigated for the four specific study locations. Each figure includes the location of the resource(s) of concern. Figure 3.0-2 also includes an area south of the Hozomeen area boat launches in case, upon field review, the area has substantially more deposition that could affect the boat launch than is visible from the aerial photographs.[2] In addition to the deposition zones shown in the figures, the study area includes the watersheds of each of the creeks to help estimate current/future sediment inputs based on watershed area, geology, and extent of glacial cover.

The Skagit River inlet in the Hozomeen area includes areas within Canada (Figure 3.0-2). The study area within Canada was evaluated using remote sensing data (Light Detecting and Ranging [LiDAR], aerial photographs); field work in Canada was not necessary.

As a result of commitments in the June 9, 2021 Notice, the study area was expanded to include the drawdown zone within all three Project reservoirs.

[2] Field work showed that there was not substantial deposition around the boat launches, so the Hozomeen study area did not need to extend as far south as shown in Figure 3.0-2.

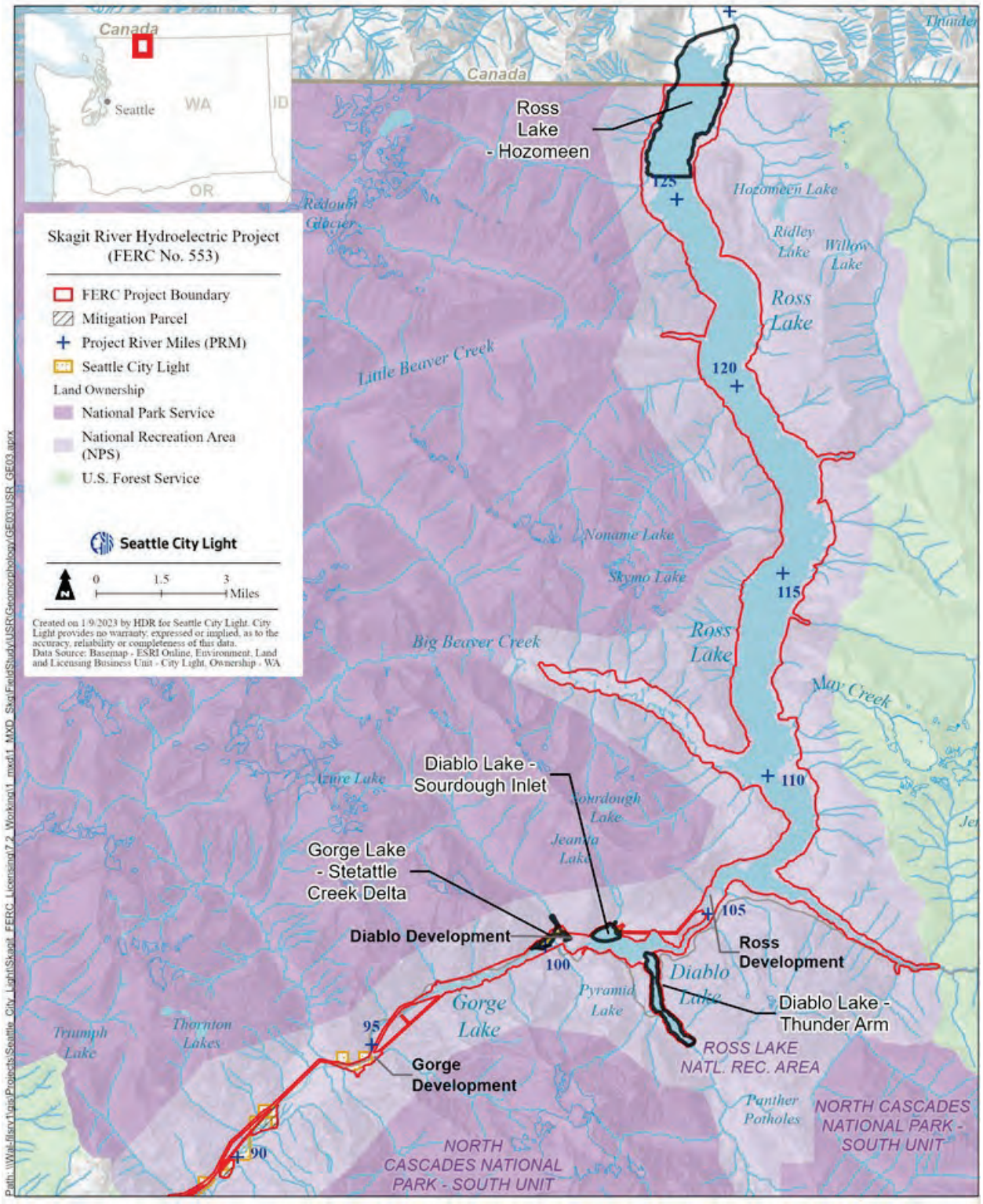


Figure 3.0-1. Overview of study area.

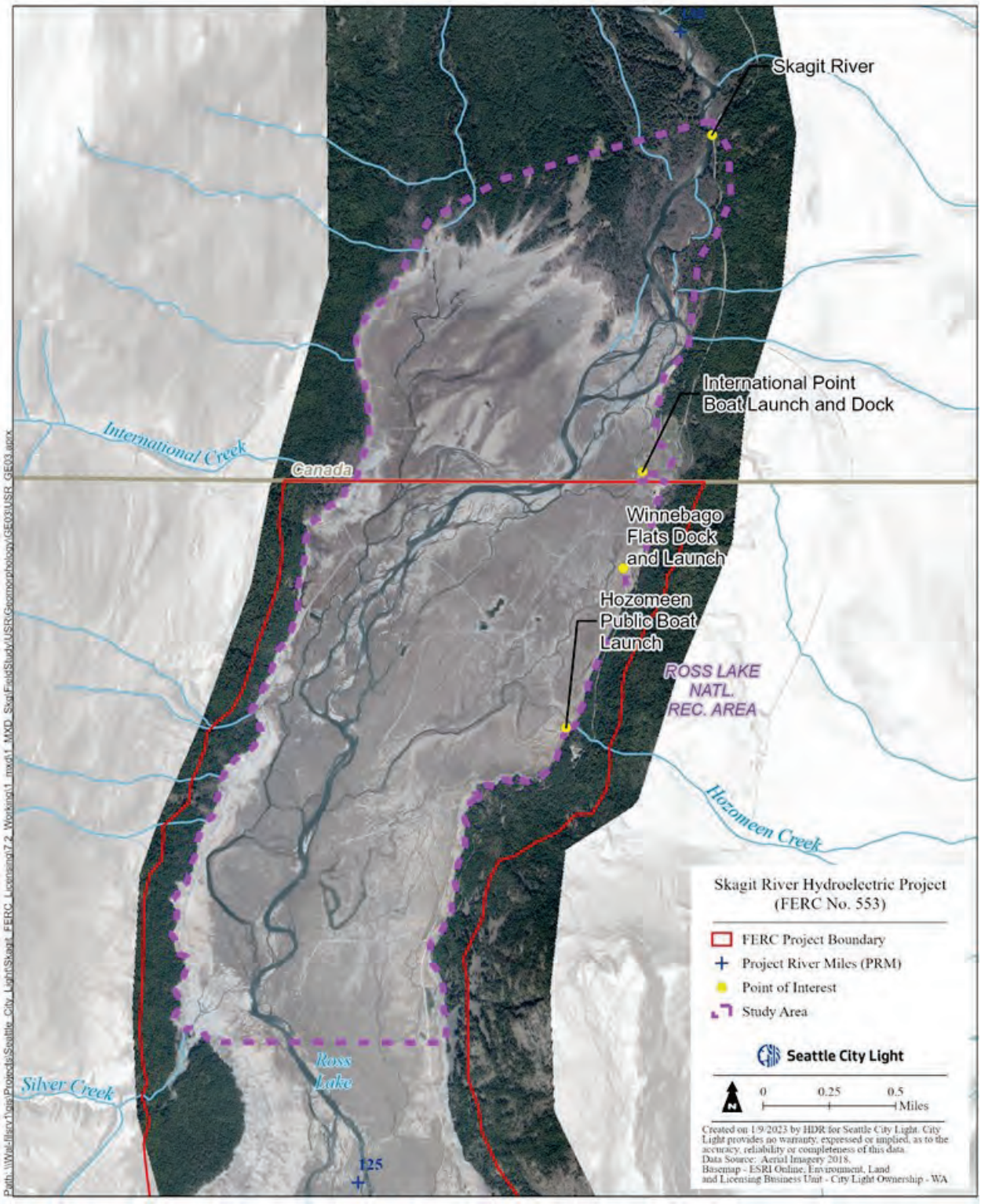


Figure 3.0-2. Study area: Ross Lake – Hozomeen inlet with Winnebago Flats dock and launch and Hozomeen public boat launch.

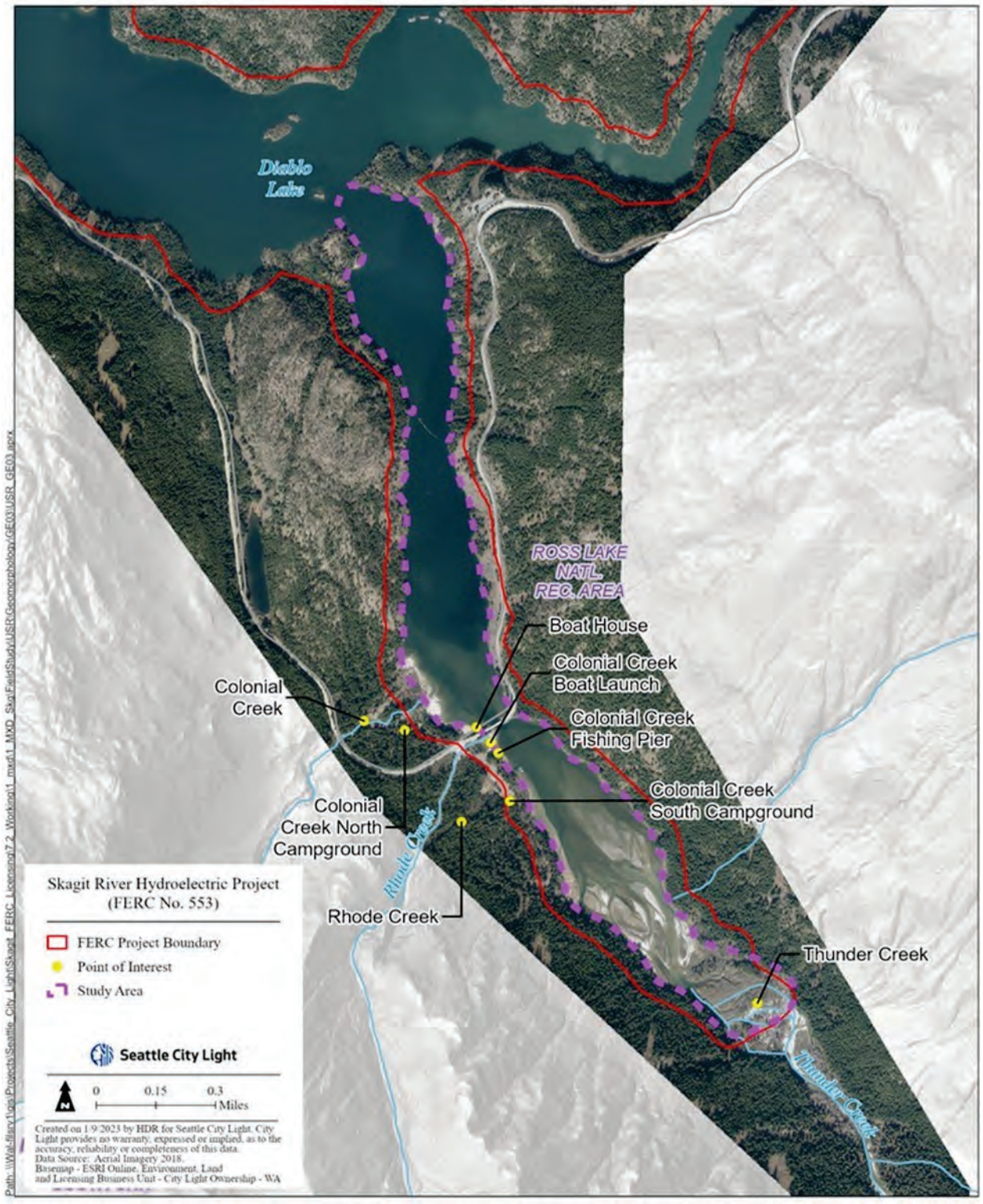


Figure 3.0-3. Study area: Diablo Lake – Thunder Arm inlet, with Colonial Creek boat launch/dock.

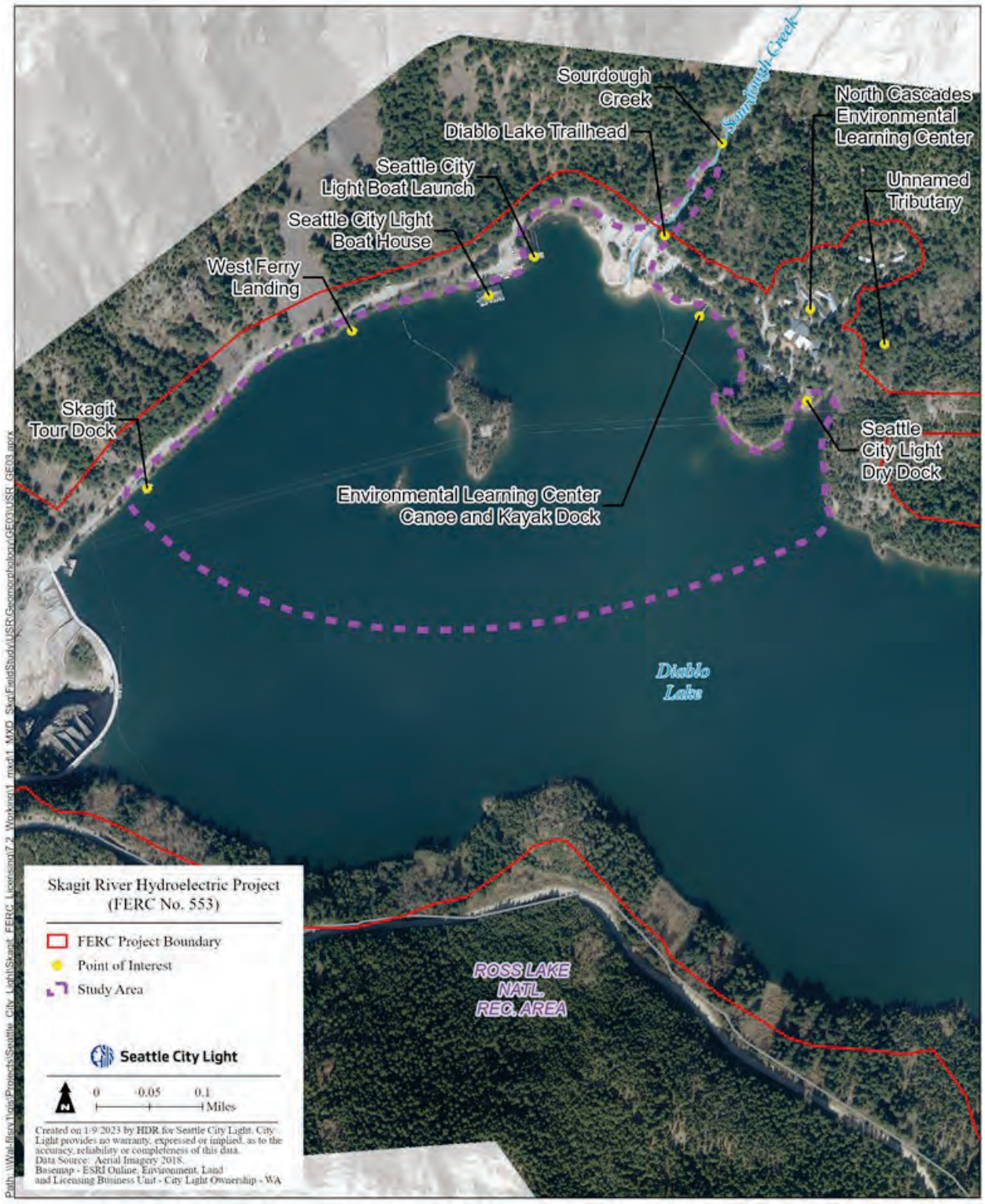


Figure 3.0-4. **Study area: Diablo Lake – Sourdough Creek inlet with City Light boat launch, City Light Boathouse, City Light dry dock, West Ferry landing, Environmental Learning Center canoe and kayak dock, and Skagit Tour dock.**

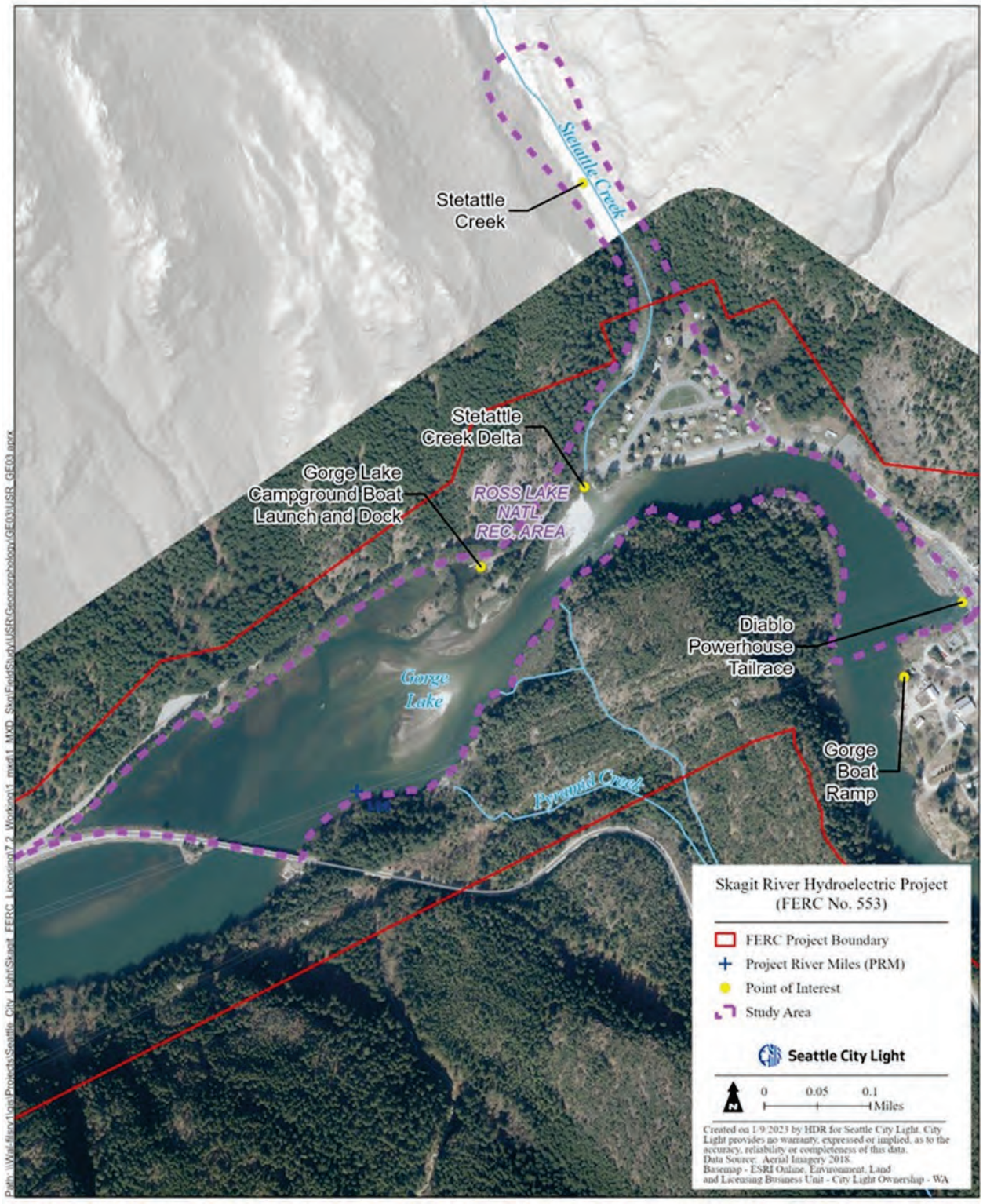


Figure 3.0-5. **Study area: Gorge Lake - Stetattle Creek delta, with Gorge Lake Campground boat launch and dock, Stetattle delta deposit, and Diablo Powerhouse tailrace.**

4.0 METHODS

The following sections describe the methods used in 2021 – 2022 in this study report. Table 4.0-1 lists the status of each RSP or June 9, 2021 Notice element of the study.

Table 4.0-1. Status of study plan and June 9, 2021 Notice elements.

Element	Status
RSP Section 2.6.1, compile and assess existing information.	Information compiled as described in Section 4.1 and used in analyses reported on in this study report.
RSP Section 2.6.2, bathymetry.	Recent (2022) bathymetry data was not collected. Alternate methods for evaluating recent sediment deposition amounts were used and are described in this study report below.
RSP Section 2.6.2.2, sediment transport and deposition zones.	Completed using methods in Section 4.2 and reported in Sections 5.1.4, 5.2.6, 5.3.3, and 5.4.6.
RSP Section 2.6.2.3, mapping of inlet area deposits.	Completed using methods in Section 4.2 and reported in Sections 5.1.2, 5.2.2, 5.3.1, and 5.4.5.
RSP Section 2.6.3, analysis deliverables.	Deliverables referenced in the RSP are provided throughout this report.
June 9, 2021 Notice: City Light will quantify sediment supply of all size ranges (i.e., grain size distribution estimate) into Ross, Diablo, and Gorge Reservoirs as an annual rate by using the existing DHSVM model, historical contours, and updated bathymetry information. Workgroup will discuss sediment size and characterization available from DHSVM model.	Sediment supply of all size ranges was estimated using a statistical regression analysis and is reported in Section 5.5. Upon further investigation, the DHSVM model was not an appropriate tool to inform this analysis, as discussed with LPs on November 9, 2021 and described in the ISR. Additional information is provided in Section 5.4 and Table 6.1-1 below.
June 9, 2021 Notice: City Light will clarify that mapping of the sediment and erosion deposition zone and tributaries are part of the existing scope of the study. Any remaining gaps will be addressed during implementation.	Completed using methods described in Sections 4.2 and 4.3 and reported in Sections 5.6.
June 9, 2021 Notice: City Light will expand the scope of GE-03 to include 1-D backwater modeling. City Light and the LPs recognize that there are limitations on the ability to calibrate aspects of this model.	Two-dimensional (2-D) backwater modeling for both Thunder Arm and Stetattle Creek have been completed and results are included in Sections 5.2.5 and 5.4.6. 2-D backwater models are more detailed than 1-D models and meet the intention of the agreement. As described in the ISR, a backwater model was not needed for Sourdough Creek because the gradient of the stream is too steep to have backwater effects, and aa backwater model was not necessary nor completed for the Hozomeen area (see discussion in Table 6.1-1).

4.1 Compile and Assess Existing Information

Existing maps, drawings, aerial photographs, LiDAR, reports, and data were collected and reviewed, including:

- Diablo Powerhouse Tailwater Remediation: Stetattle Creek Delta Geomorphology Report (Watershed GeoDynamics, in prep).
- Report on Existing Conditions of Reservoir and Streambank Erosion (Riedel 1990).
- Skagit Hydroelectric Project Erosion Control Plan (Riedel et al. 1991).
- NPS Erosion Control and Revegetation Completion Reports (NPS 2016; 2018).
- Diablo Powerhouse sediment management project (Seattle University 2008).
- Diablo Powerhouse tailwater restoration project preliminary engineering design report (R2 Resource Consultants, Inc. 2013).
- Environmental Assessment, Diablo Powerhouse tailrace restoration (NPS 2014).
- U.S. Geological Survey (USGS) stream gaging records and Project flow records.
- Historic still photographs and aerial photographs, drawings, and maps. (See Table 4.1-1 for aerial photography selected for analysis based on resolution/lake elevation of photography and dates of sediment input events, as described further in Section 5 of this study report.) Additional photo years were reviewed but not selected for analysis because they did not have the appropriate level of detail or lake levels to be useful for this analysis.
- LiDAR data sets from 2006 and 2018 (Table 4.1-1).
- Improvement of Recreational Facilities, Hozomeen Campground Lower Boat Launch Area (NPS 1999).
- Geomorphology of a Cordilleran ice sheet drainage network through breached divides in the North Cascades Mountains of Washington and British Columbia, Geomorphology (Riedel et al. 2007).
- Deposition of Mount Mazama Tephra in a Landslide-Dammed Lake on the Upper Skagit River, Washington, USA. In Volcaniclastic Sedimentation in Lacustrine Settings (Riedel et al. 2009).
- Geomorphology of the Upper Skagit watershed: Landform mapping at North Cascades National Park Service Complex, Washington (Riedel et al. 2012).
- Regional estimates of watershed sediment input. (See Section 4.3.1 for more details.)
- Contacting NPS Maintenance Supervisor to discuss Thunder Arm debris flows.

These existing sources of information were used to develop initial estimates of sediment input/deposition and rates of inlet/delta sedimentation through time.

Table 4.1-1. Project vicinity aerial photograph inventory and remote sensing resources used in analysis.

Date	Image Type	Resolution	Notes
Aerial imagery			
1990	Orthophoto quads	1 meter (m)	Source: U.S. Forest Service (USFS 1990) aerials
2006	True Color National Agriculture Imagery Program (NAIP) hi-resolution	1 m	Source: NAIP (2006)
2018	Skagit Project hi-resolution	6 inches	Source: Quantum Spatial 2018b
LiDAR and Digital Elevation Models			
2017	Skagit Topobathymetric LiDAR	0.5 m or 1 foot (ft)	USGS QL1 standards, Source: Quantum Spatial 2017a
2017	Western Washington, 3DEP North	0.5 m or 1ft	Source: Quantum Spatial 2017b
2018	Ross Lake	0.5 m or 1ft	Source: Quantum Spatial 2018a
2018	Gorge and Diablo Lake Green LiDAR	0.5 m or 1ft	Source: Quantum Spatial 2018b

4.2 Field Data Collection

The Hozomeen area (head of Ross Lake) was visited on May 12-16, 2021, to map existing conditions and surficial substrate at the head of the lake. Ross Lake was slowly filling, with lake elevations increasing from 1,535 to 1,542 feet (ft) North American Vertical Datum 88 (NAVD 88; 1,528.7 to 1,535.7 ft City of Seattle datum [CoSD])[3] over the field data collection period (Table 4.2-1).

Table 4.2-1. Ross Lake levels during Hozomeen area field visits.

Date	Ross Lake Elevation[1] (ft)	
	NAVD 88	CoSD
5/12/21	1,535	1,528.7
5/13/21	1,537	1,530.7
5/14/21	1,538	1,531.7
5/15/21	1,540	1,533.7
5/16/21	1,542	1,535.7

1 Normal maximum water surface elevation: Ross Lake = 1,608.76 ft NAVD 88 (1,602.5 ft CoSD).

In 2022, the drawdown zone of Ross Lake was revisited via boat and foot during low lake elevations to map surficial substrate in the drawdown zone, erosion/deposition processes, and to measure erosion (reported in GE-04 Skagit River Geomorphology Between Gorge Dam and the Sauk River Study Report [GE-04 Geomorphology Study; City Light 2023]) and deposition depths. Field visits took place in April and May 2022, as listed in Table 4.2-3.

[3] Note that vertical elevations reported as NAVD 88 and CoSD datum differ; both are included in this report for clarity. City Light is in the process of converting Project information from its older vertical elevation datum (CoSD) to the more current and standardized elevation datum (NAVD 88). This conversion is +6.51 ft (CoSD +6.51 = NAVD 88) at Gorge Lake, +6.36 ft at Diablo Lake, and +6.26 ft at Ross Lake.

Table 4.2-3. Ross Lake drawdown zone field data collection dates and reservoir elevations.[1]

Field Collection Date	Ross Lake Elevation[2] (ft)	
	NAVD 88	CoSD
4/7/2022	1,537	1,530.7
4/8/2022	1,537	1,530.7
4/9/2022	1,537.3	1,531
4/10/2022	1,537.6	1,531.3
4/11/2022	1,537.6	1,531.3
4/12/2022	1,537.5	1,531.2
4/13/2022	1,537.4	1,531.1
4/14/2022	1,537.3	1,531
4/15/2022	1,537	1,530.7
4/16/2022	1,536.5	1,530.2
4/17/2022	1,536	1,529.7
4/21/2022	1,534.1	1,527.8
4/22/2022	1,533.7	1,527.4
4/23/2022	1,533.2	1,526.9
4/24/2022	1,532.5	1,526.2
4/25/2022	1,532	1,525.7
4/26/2022	1,531.5	1,525.2
4/27/2022	1,531.2	1,524.9
5/10/2022	1,533.7	1,527.4
5/12/2022	1,533.8	1,527.5
5/13/2022	1,533.9	1,527.6
5/26/2022	1,542.1	1,535.8
5/27/2022	1,543.4	1,537.1
5/28/2022	1,545.2	1,538.9
5/29/2022	1,546.9	1,540.6
5/30/2022	1,548.3	1,542

1 Source: USGS (2022).
2 Normal maximum water surface elevation: Ross Lake = 1,608.76 ft NAVD 88 (1,602.5 ft CoSD).

Sourdough Creek and Thunder Arm, both in Diablo Lake, were visited on August 31-September 7, 2021, to map surficial substrate, survey, and collect pebble count data. Diablo Lake elevation ranged from 1,206-1,207 ft NAVD 88 (1,199.6-1,200.6 ft CoSD).

Stetattle Creek and the Stetattle Creek delta were visited on several occasions to document existing conditions of the stream and delta, to map and sample substrate size, and to observe the delta during low Gorge Lake conditions. Field visits took place on September 17-18, 2018, December 20, 2018, and April 4, 2019. Flow in the Skagit River and Gorge Lake levels on field visit dates are shown in Table 4.2-2.

Table 4.2-2. Skagit River flow and Gorge Lake levels during Stetattle Creek field visits.

Date	Skagit River Flow[1]	Gorge Lake Elevation[2] (ft)	
		NAVD 88	CoSD
9/17/18	3,200	878.1	871.6
9/18/18	3,100	877.4	870.9
12/20/18	3,260	877.5	871.0
4/4/19	2,800	830.9	824.4

1 Diablo Powerhouse outflow plus any spill; cubic ft per second (cfs).
2 Normal maximum water surface elevation: Gorge Lake = 881.51 ft NAVD 88 (875 ft CoSD).

4.2.1 Surficial Substrate Mapping and Ross Drawdown Process Mapping

Surficial sediment size was mapped in the study areas and the Ross Lake drawdown zone based on visual observation for exposed sediment and areas in shallow water where substrate size could be observed. Dominant and sub-dominant size classes were recorded using the following categories: bedrock, boulder, cobble, gravel, sand, fines (silt/clay), and manmade (e.g. concrete structures). For areas covered by deep or opaque water in Diablo Lake, a Petit Ponar sampler was deployed from a boat to obtain a surface grab sample. Petit Ponar samples were taken to characterize the delta areas of Sourdough Creek (10 samples) and Thunder Creek (7 samples). Areas with similar-sized dominant and subdominant sediment (e.g., cobble/gravel) were drawn on a set of laminated 2018 aerial photograph maps for later transfer to Geographical Information System (GIS) polygons.

In the Ross Lake drawdown zone, the dominant erosion/deposition type was mapped based on visual estimates on 2018 aerial photographs, LiDAR, and field observations. The following categories were mapped:

- Erosion (dominant process is erosion, little deposition);
- Deposition (dominant process is deposition, little erosion or re-working);
- Lacustrine re-working (substrate re-worked by wave action and is a mix of erosion and deposition over time); and
- Fluvial re-working (active river deltas that are subject to erosion and deposition at different water surface and flow levels).

4.2.2 Soil Probes

In 2022, a total of 58 soil core and/or probes were taken at several depositional locations in the drawdown zone of Ross Lake to provide data on deposition depths. Soil texture and depth to refusal was noted at each core location, and material was screened by a cultural resources specialist to ensure no cultural material was disturbed. Depth to refusal was assumed to be the depth of deposition at each location; the maximum length of the soil probe was 5 ft; therefore, if no hard surface was encountered by the probe, it was assumed that deposits were greater than 5 ft in depth.

4.2.3 Pebble Counts

On September 17 and 18, 2018, pebble counts were collected at seven locations within Stetattle Creek and the Stetattle Creek delta area, four sites in Sourdough Creek/delta, and one location on Thunder Creek. No pebble counts were taken in the Hozomeen area due to concerns about disturbing cultural resources.

Wolman (1954) pebble counts of 100 particles were taken at sites composed of primarily coarse-grained (gravel-cobble-boulder) material. At each site, 100 particles were selected by walking along a grid pattern covering the facies to be sampled. Each particle was passed through a gravelometer and binned by half phi size class into < 2 millimeter (mm), 2 mm, 4 mm, 5.7 mm, 8 mm, etc., up to over 1,080 mm size for the largest boulders sampled.

Two shovel samples were taken of finer-grained sand-fine gravel substrate at the upstream end of the Stetattle Creek delta. The shovel samples were returned to the Seattle Public Utilities materials processing lab and sieved to obtain information on grain size.

Results of the pebble counts and shovel samples were entered into an Excel® spreadsheet for analysis and graphing.

4.2.4 Stream Profile and Cross Section Surveying

In Sourdough Creek, a stream thalweg profile was surveyed on September 6, 2021 (Diablo elevation 1,207 ft NAVD 88 [1,200.6 ft CoSD]) using a laser level and tape from as deep in Diablo Lake as was wadable to a point upstream of the road crossing to supplement the LiDAR data (because Diablo Lake was full when the LiDAR was flown).

4.3 Sediment Retention in Lakes and Delta Deposition Rates

The City Light team developed a sediment yield relationship based on measured fine sediment yield from basins in the North Cascades and Canada and a statistical predictive relationship using a multiple linear regression model based on basin characteristics (see details in Section 4.5.4 of the GE-04 Geomorphology Study [City Light 2023]). The model selection analysis determined that the best model includes terms for mean annual precipitation, relief represented using Steepness Index, and basin geology represented with three parameters: (1) bedrock ratio, (2) the area of unconsolidated sediment, and (3) the area of glaciated stratovolcano. Reservoir trap efficiency calculations were used to determine what proportion of the fine sediment delivery to each reservoir would be expected to pass downstream.

This regression equation and a bedload suspended sediment yield ratio based on basin size was used to estimate total sediment yield to each of the three reservoirs (Ross Lake, Diablo Lake, and Gorge Lake) as well as the Hozomeen, Thunder Arm, Sourdough, and Stetattle Creek delta study areas. The total sediment yield was partitioned into grain size classes based on the surficial substrate mapping in major deltas in each reservoir (described in Section 4.2.1). Sediment retention in each reservoir was calculated based on reservoir trap efficiency (see GE-04 Geomorphology Study [City Light 2023]).

In addition, an estimate of coarse-grained sediment supply to the Stetattle Creek delta was made based on comparison of change in topography/bathymetry through time in the Stetattle delta area.

4.4 Backwater Effects Analysis

HEC-RAS hydraulic modeling was used to assess backwater effects in Thunder Creek and Stetattle Creek. A 1-D HEC-RAS model was originally proposed for this analysis, but a 2-D model was developed for these two streams as described below. The 2-D model provides additional detail of hydraulic patterns in areas of complex hydraulics and was determined to be more appropriate during the analysis phase.

A 2-D hydraulic model of the lower 0.5 miles of Stetattle Creek and the Skagit River near the confluence with Stetattle Creek was prepared by Alden Labs.

A 2-D HEC-RAS (Hydrologic Engineering Center River Analysis System) model (Version 6.2) was developed to assess hydraulic conditions and potential backwater effects of reservoir operation on Thunder Creek. A detailed description of model development, calibration, and results is provided in Attachment A.

The model terrain used 50 ft by 50 ft grid cells with 25 ft by 25 ft grid cells in the main channel of Thunder Creek and was based on the 2018 LiDAR data (Quantum Spatial 2018b). A modified representation of the valley-spanning log jam similar to that formed in the 2003 flood event was also run for comparison of hydraulics with and without a log jam in place (Figure 4.4-1). Roughness (a model input parameter that represents resistance to flow from substrate and vegetation) was varied from 0.03 to 0.07 to capture the potential variability in backwater effects with different roughness values. Roughness in streams varies with flow depth as roughness elements become less dominant with deeper flows. Flows from a 2 year to 100 year recurrence interval peak flow and the 2003 flood of record were run, with lake levels varying from 1,194 to 1,212 ft NAVD 88 (1,187.6 to 1,205.6 ft CoSD). A summary of the input parameters run through the model are shown in Table 4.4-1.

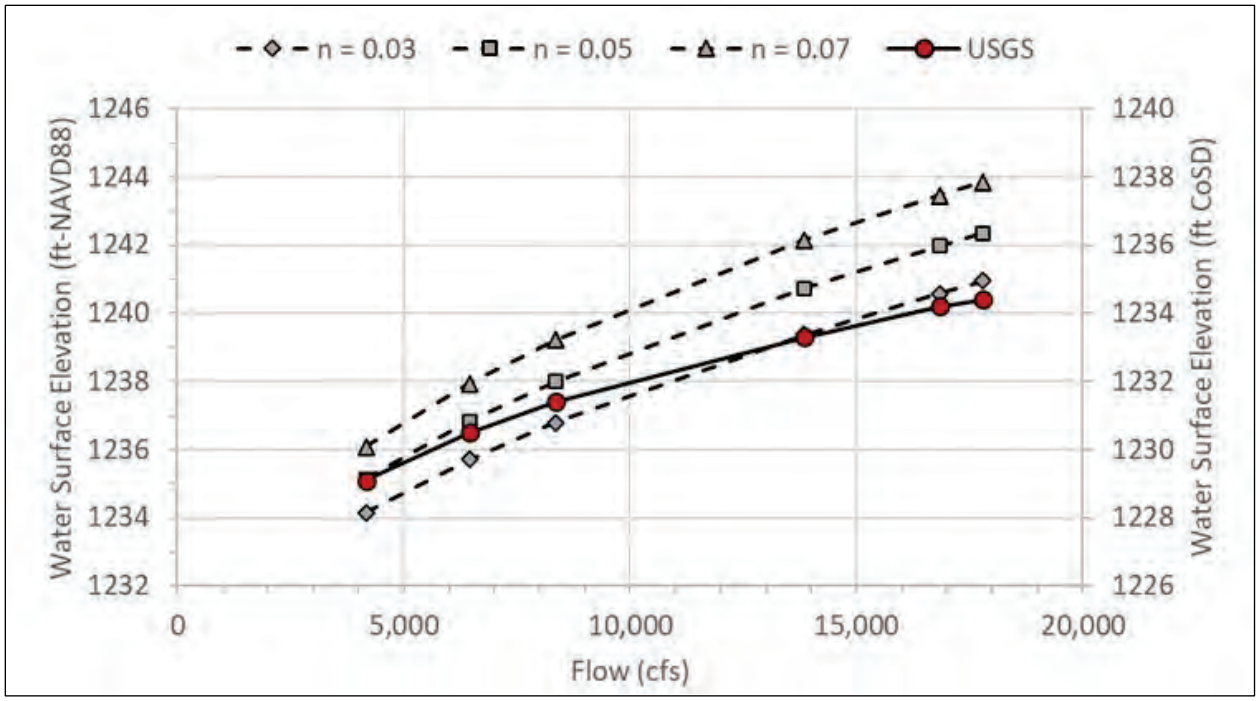


Figure 4.4-1. Calibration results by roughness factor at the USGS Thunder Creek gage (12175500).

Table 4.4-1. Simulation combinations analyzed in the Thunder Creek HEC-RAS model.

Parameter	Variation
Flows	Q2, Q5, Q10, Q50, Q100, and the 2003 flood
Varied uniform roughness	0.03, 0.05, and 0.07
Terrain	Combined topographic-bathymetric surface and combined surface with a modified representation of a valley spanning wood jam
Diablo Lake level	Comparison of simulations analyzing greatest backwater effects by varying the Diablo Lake water surface elevation from 1,194 to 1,212 ft NAVD 88 (1,187.6 to 1,205.6 ft CoSD)

A hydraulic modeling was not developed for Sourdough Creek because the stream is very high gradient, so there can be no substantial backwater effects (see analysis of Sourdough Creek in results section for details). A hydraulic model was not developed for the Skagit River at the upper end of Ross Lake because the detailed calibration data needed to develop a 1-D topographic hydraulic model for the Skagit River in the Hozomeen area is unavailable, and no issues with sediment deposition were noted at boat launches in the Hozomeen area.

4.4.1 Stetattle Creek and Thunder Creek Sediment Transport Analysis

In Stetattle Creek, output from the 2-D hydraulic model of the Stetattle Creek/Skagit River confluence was used to calculate sediment transport potential based on critical shear stress of particles that could be entrained under a given flow within the lower 0.5 miles of Stetattle Creek and within the Skagit River near the confluence with Stetattle Creek. The 2-D HEC-RAS output from the Thunder Creek analysis was used to calculate sediment transport potential for Thunder Arm.

The critical diameter (largest diameter of the substrate that can be moved under given flow conditions) was computed for each cell in the 2-D model output using the method described in Appendix B of Engineering Manual 1110-2-1418 "Channel Stability Assessment for Flood Control Projects" (U.S. Army Corps of Engineers [USACE] 1994). This method is based upon the Manning's equation and assumes a Shields number of 0.045, and roughness height (k) equal to 3 times the median grain size (D_{50}). For this analysis, the Shields number was adjusted to 0.03 for both streams based on a study of bed-load transport in similar gravel bed streams (Mueller et al. 2005). Additionally, studies have shown the assumption that $k = 3D_{50}$ was considered too low; the ratio $k = 6.8D_{50}$ is more appropriate for use in gravel-bed streams (Clifford et al. 1992) and was, therefore, applied. Application of the adjustments noted above resulted in the following relationship for calculation of the critical diameter:

$$D_{crit} = 0.686\frac{V^3}{\sqrt{d}}$$

where:

D_{crit} = critical diameter (mm)

V = Velocity (ft/s)

d = Depth (ft)

5.0 RESULTS

The results presented in this study report include field data collection and data analysis through 2022 for the Hozomeen inlet at the head of Ross Lake, Thunder Arm inlet in Diablo Lake, Sourdough Creek inlet at Diablo Lake, and Stetattle Creek delta in Gorge Lake study areas as well as sediment deposition in all three reservoir areas.

5.1 Hozomeen

5.1.1 Hydrology and Lake Level

The Skagit River upstream from Ross Lake has a drainage area of approximately 380 square miles. Flows are highest from May to July in response to snowmelt, with the highest peaks in June.

Water surface elevation in Ross Lake varies seasonally in response to inflow, outflow, and power needs. Lake elevation curves (2007-2019) and annual percent exceedance curves of water surface elevations for Ross Lake from 1991 to 2018 are provided in Figures 5.1-1 and 5.1-2. Exceedance values refer to the value that is exceeded for the specified percent of the time. For example, the 40 percent exceedance elevation in Ross Lake is 1,595.26 ft NAVD 88 (1,588.96 ft CoSD), which means that the reservoir elevation was above this level 40 percent of the time for the period 1991-2018 and lower than this level 60 percent of the time.

Ross Lake is drawn down as much as 120 ft seasonally, with normal maximum water surface elevation generally maintained between July 31 and Labor Day each year. License Article 403 of the existing license requires that City Light: (1) fill Ross Lake as soon as possible after April 15; (2) achieve normal maximum water surface elevation by July 31; and (3) maintain normal maximum water surface elevation through Labor Day subject to adequate runoff, anadromous fish protection flows downstream of the Project, flood protection, spill minimization, and firm power generation needs.

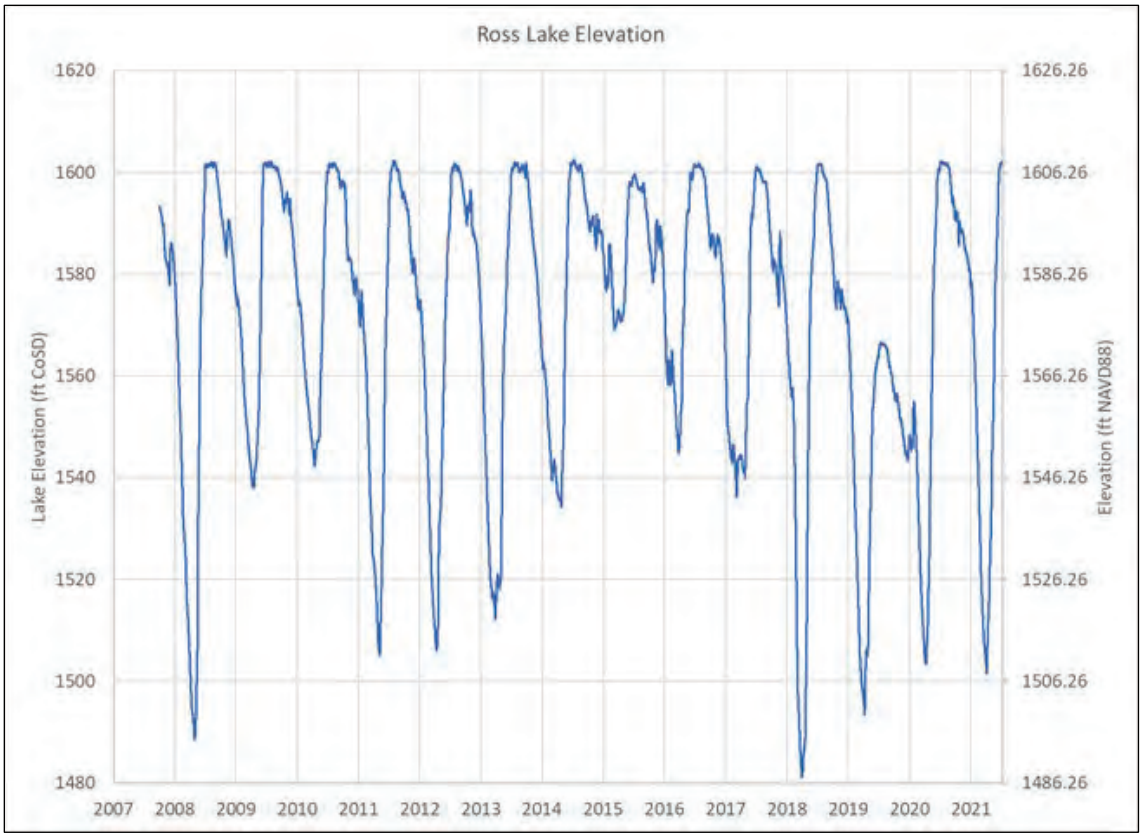


Figure 5.1-1. Ross Lake elevation, 2007-2021.

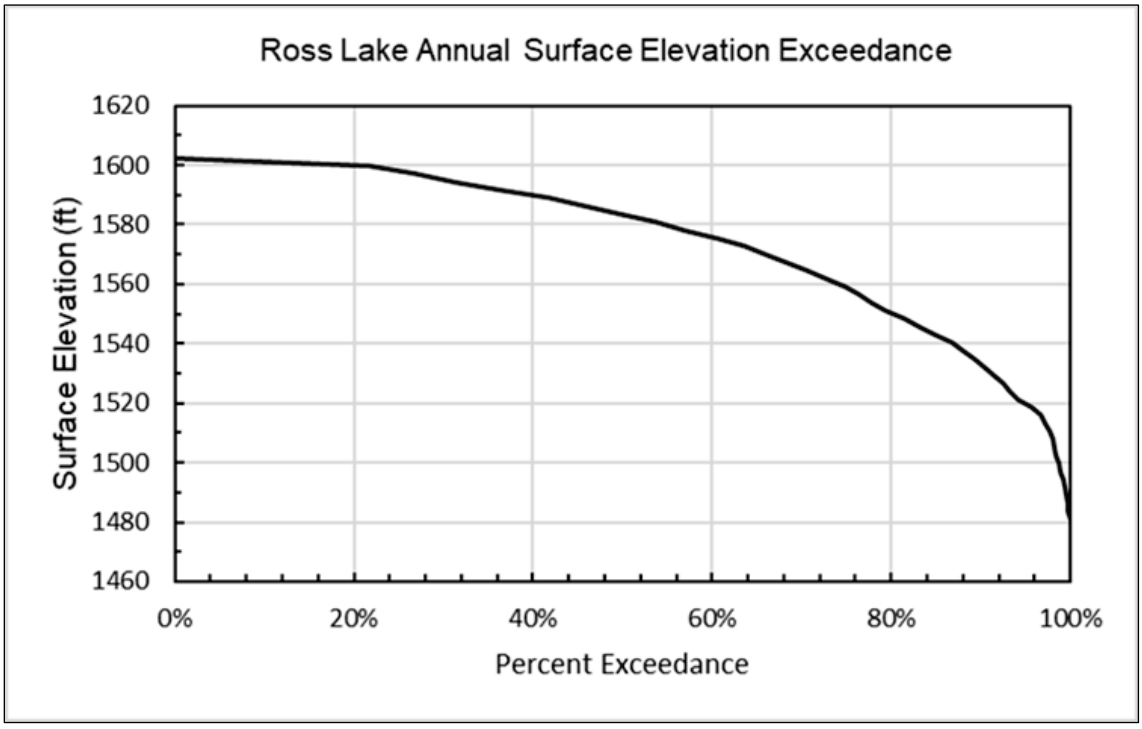


Figure 5.1-2. Annual percent exceedance curve of water surface elevations for Ross Lake, based on the period 1991–2018 (elevations in CoSD).

5.1.2 Surficial Substrate

Surficial substrate in the Hozomeen area is primarily fine-grained sediment (silt/clay) with areas of boulder/cobble/gravel around the margins of Ross Lake that are subject to wave activity during the summer months (Figure 5.1-3). There is gravel, sand, and some cobble material in stream and river channels within the area. Based on observations of exposed tree stumps, most of the area showed little evidence of deposition or erosion (Figure 5.1-4). Fine-grained deposition of 1 ft to 4 ft was observed along the main Skagit River channel in two areas based on tree stump exposure—one area is between elevation 1,575-1,577 ft NAVD 88 (1,568.7-1,570.7 ft CoSD), and another is between 1,563-1,570 ft NAVD 88 (1,556.7-1,563.7 ft CoSD), as seen on Figures 5.1-3 and 5.1-4.

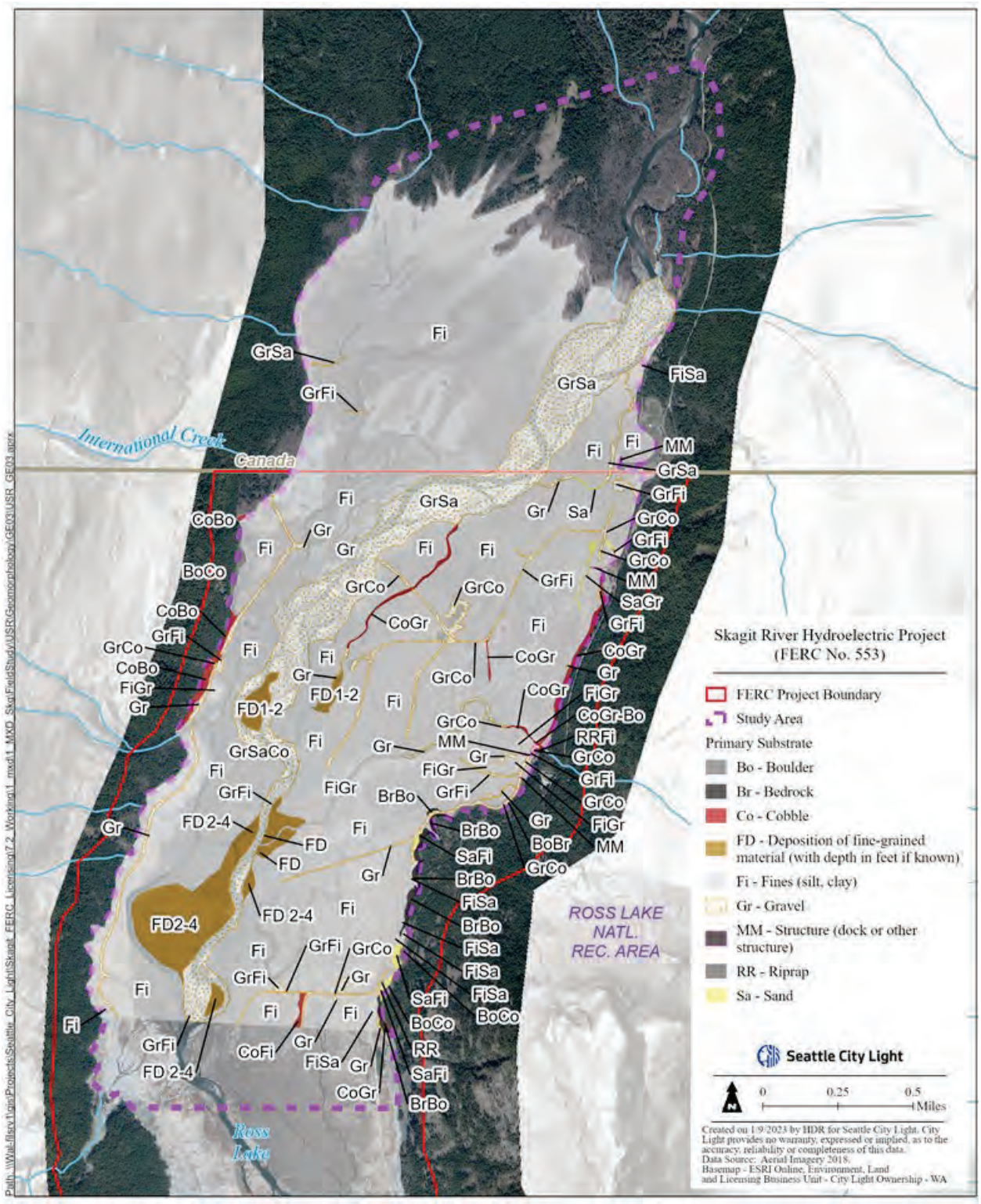


Figure 5.1-3. Surficial substrate in the Hozomeen area.



Fine-grained substrate with old gravel road in foreground



Deposition around tree stumps

Figure 5.1-4. Photos of substrate in the Hozomeen area.

5.1.3 Hozomeen Area Boat Launches

The two public boat launches within the U.S. in the Hozomeen area were visited to determine if sediment deposition was occurring in the vicinity of the ramps. The end of the Hozomeen ramp has been excavated to improve boat access at lower pool elevations; there does not appear to be substantial recent deposition in the area (Figure 5.1-5). The Winnebago Flats boat ramp ends at a stream channel (during low lake elevations) and, likewise, has little recent deposition.



Hozomeen boat ramp



Winnebago Flats boat ramp

Figure 5.1-5. Photos of ends of public boat ramps in the U.S. portion of the Hozomeen area.

5.1.4 Sediment Transport, Deposition Rates, and Expected Future Trends in the Hozomeen Area

Field and aerial photograph observations suggest that there are low levels of sediment input and deposition at the upper end of Ross Lake. These observations are consistent with estimates of sediment input based on the regional regression analysis that yield a total average input of 10,100 cubic yards (cu yds) /year of sediment with 1,900 cu yd/year of gravel and 8,200 cu yds/year of sand, silt, and clay material. This material is deposited over a long, fairly broad area (see discussion and Figure 5.6-1 in Section 5.6 below) resulting in very low deposition rates in the upper end of Ross Lake. The low gradient of the Skagit River upstream of Ross Lake (0.2 percent) results in deposition of the majority of cobble and coarser sediment upstream from the lake delta.

Future deposition trends will likely be similar to past deposition characteristics with deposition of gravel and sand, as well as silt in the fluvial reworking zone (see Section 5.6 below) and slow deposition of silt in the rest of the Hozomeen area. Hozomeen Creek and other small tributaries will bring in small amounts of gravel, sand, and fines, which will continue to be deposited in the stream channels established in the drawdown zone.

5.2 Thunder Arm

Thunder Arm is a long, narrow embayment on the south side of Diablo Lake (Figure 5.2-1). SR 20 crosses the arm. The Colonial Creek Campground and Boat Launch as well as the NPS boathouse and a temporary barge launch landing used occasionally by City Light is located on the western shore of Thunder Arm.

There are three primary sources of inflow and sediment to Thunder Arm: Thunder Creek, Rhode Creek, and Colonial Creek. Thunder Creek drains a large watershed that includes runoff from 51 glaciers (12.8 percent of the basin; Chennault 2004). The glaciers contribute fine-grained sediment to the runoff, particularly during the summer and early fall. Rhode Creek and Colonial Creek are steep streams that have built alluvial fans on the western shores of Thunder Arm.

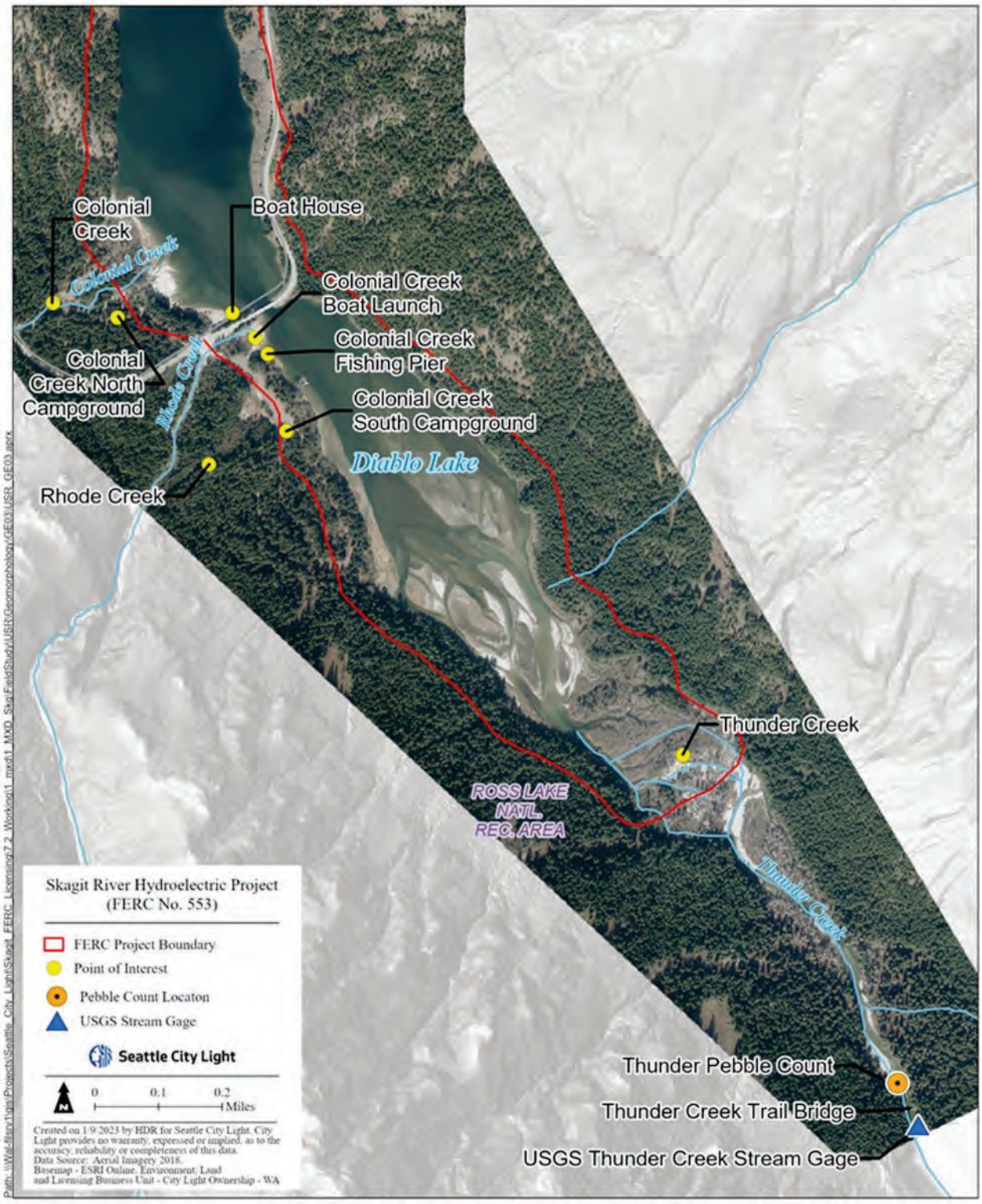


Figure 5.2-1. Thunder Arm of Diablo Lake.

5.2.1 Hydrology and Lake Level

The volume of sediment input and location of sediment deposition in Thunder Arm is dependent on incoming sediment carried by streams and lake levels in Diablo Lake. USGS maintains a stream gage on Thunder Creek. Colonial and Rhode creeks are not gaged. In addition to streamflow, debris flows occur in Rhode and Colonial creeks.

5.2.1.1 Thunder Creek Flow

Thunder Creek has a drainage area of approximately 105 square miles at the USGS gage located 0.4 miles upstream from Diablo Lake. The gage is located just upstream from the Thunder Creek trail bridge.

Mean daily flows in Thunder Creek are highest from May through July in response to snowmelt (Figure 5.2-2). Glacial melt keeps flows relatively high through October in contrast to non-glacial streams in the Pacific Northwest. Lowest flows generally occur in February and March when much of the watershed is covered in snow.

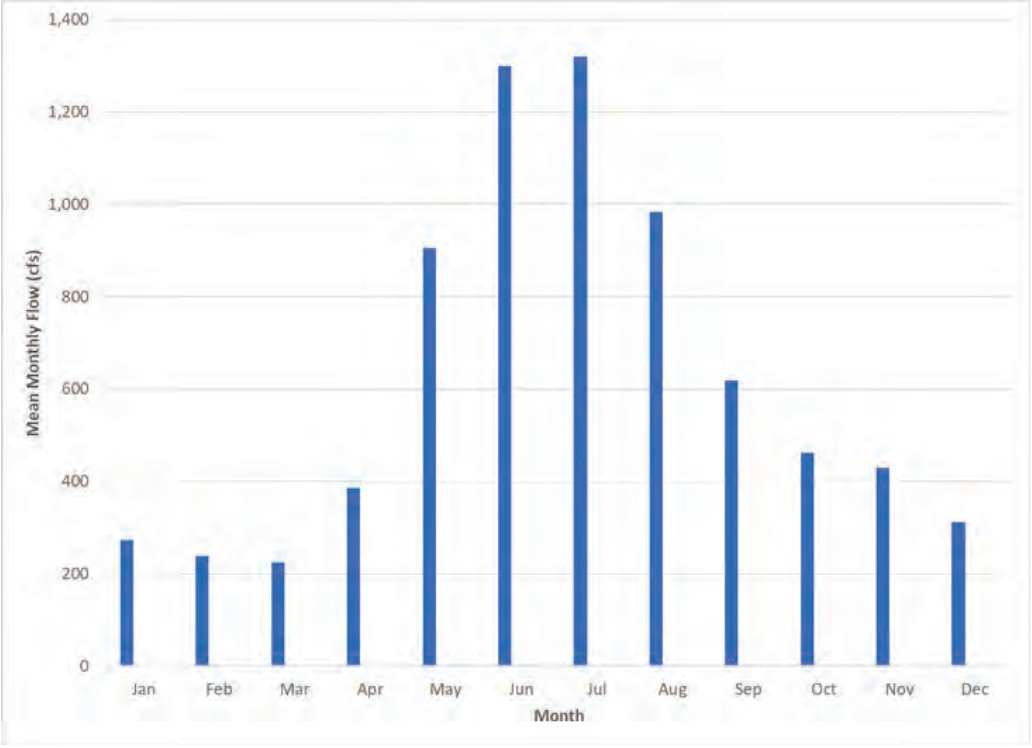


Figure 5.2-2. Thunder Creek mean monthly flows (1931-2020).

In addition to suspended sediment carried from glacial sources during normal daily flows, high flow events have enough energy to transport coarser gravel and cobble as bedload. Annual peak flow events for the period of record (1931-2022) are shown in Figure 5.2-3. Figure 5.2-4 shows timing of peak flows during the year; the flow of record (~18,000 cfs) occured in October 2003 in response to a major regional rainfall event. The November 14, 2021 peak flow was estimated at 8,000 cfs by the USGS. Other large peaks occured from rain and rain-on-snow events. A peak flow recurrence interval for the gage is included in Table 5.2-1.

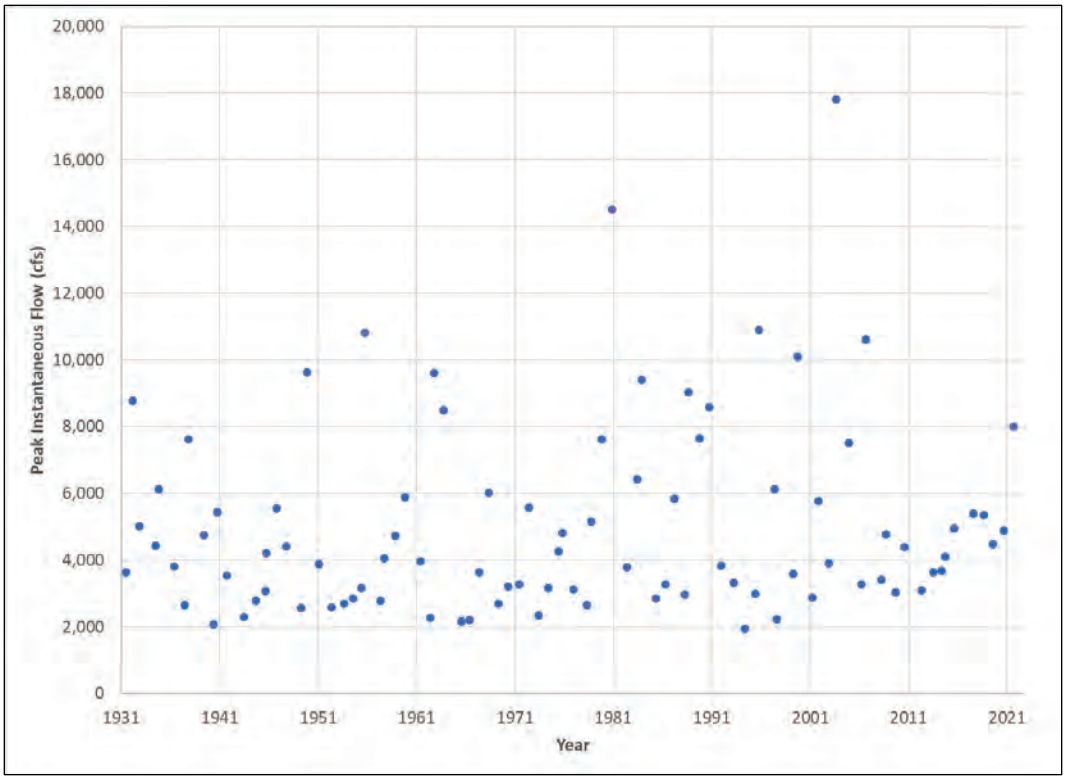


Figure 5.2-3. Thunder Creek peak instantaneous flows (1931-2022).

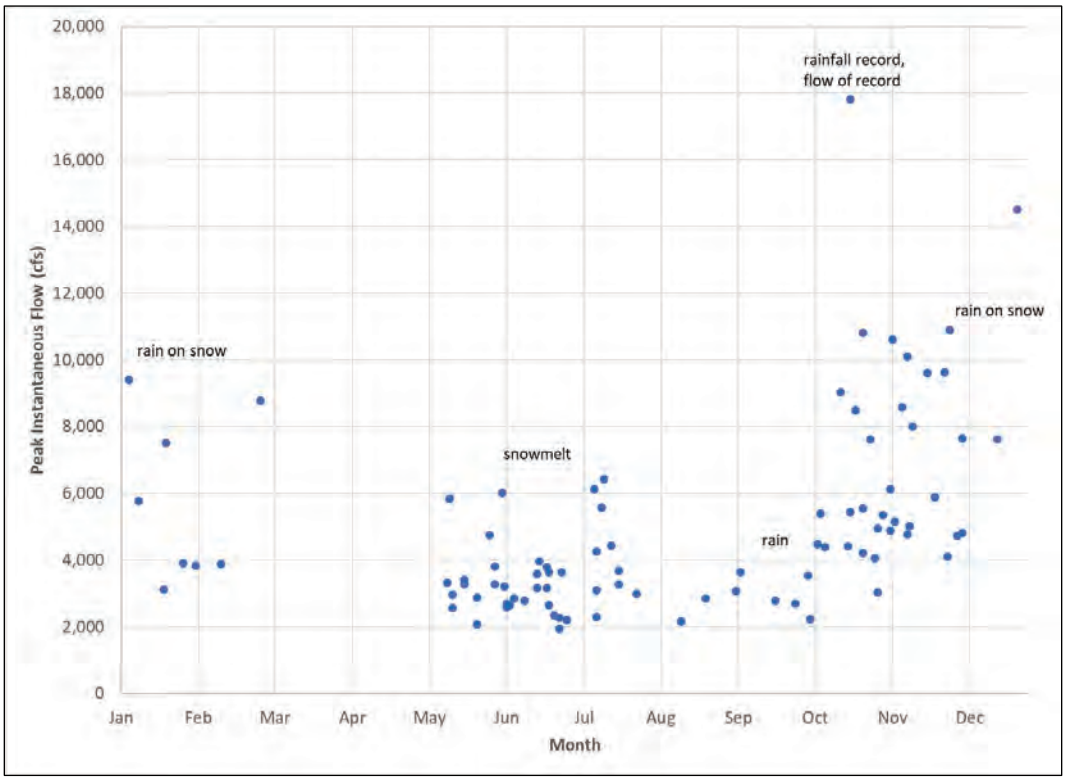


Figure 5.2-4. Thunder Creek peak flow timing.

Table 5.2-1. Thunder Creek annual peak exceedance flows.

Recurrence Interval (years)	Percent Exceedance Probability	Annual Peak Flow (cfs)
2	50%	4,170
5	20%	6,440
10	10%	8,340
50	2%	13,800
100	1%	16,800

5.2.1.2 Diablo Lake Levels

Water surface elevation in Diablo Lake is generally held between approximately 1,206 and 1,211 NAVD 88 (1,199.6 and 1,204.6 ft CoSD) and varies up to 5 ft daily in response to inflow, outflow, and power needs. The annual percent exceedance curves of water surface elevation for Diablo Lake from 1991 to 2018 is provided in Figure 5.2-5.

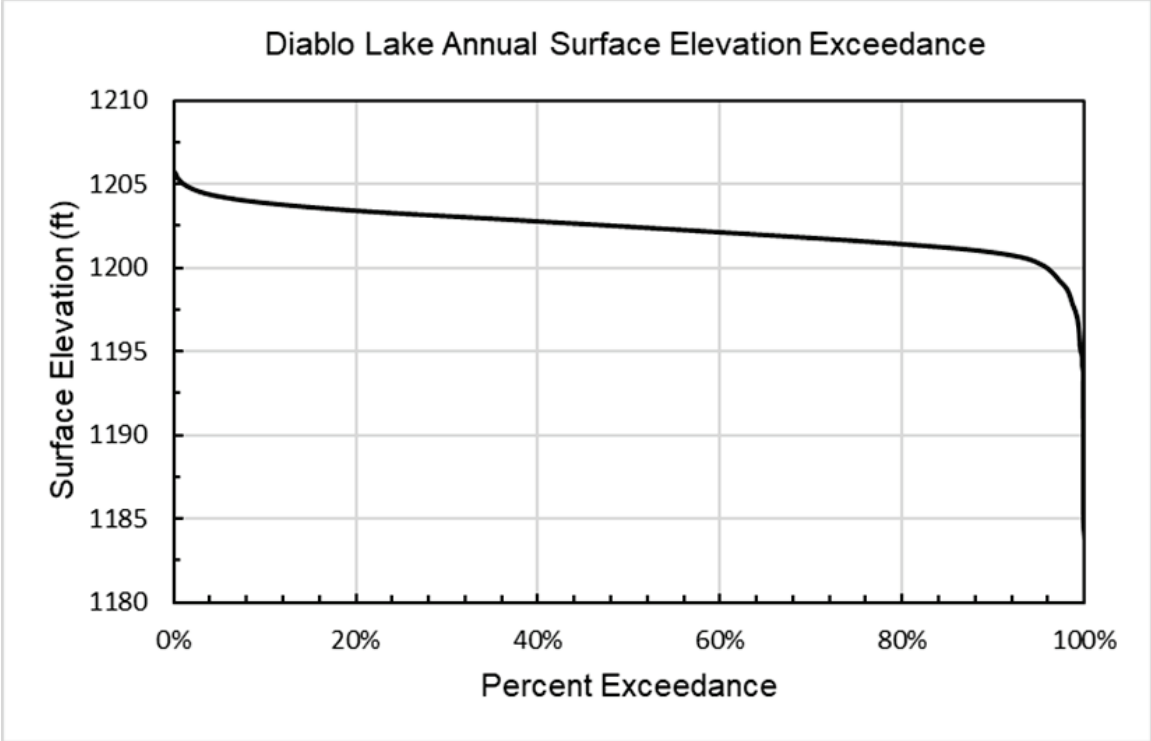


Figure 5.2-5. Annual percent exceedance curve of water surface elevations for Diablo Lake, based on the period 1991–2018 (elevations in CoSD).

5.2.2 Surficial Substrate

Surficial sediment in Thunder Arm is dominated by fine-grained sediment in the main part of the arm (Figure 5.2-6). The fine sediment grades to sand and then gravel and cobble where Thunder Creek enters the lake forming a delta. The Rhode Creek alluvial fan is also building out into Diablo Lake and grades from boulder to cobble to gravel to sand in a downstream direction. Rhode Creek fan deposits occur on both sides of SR 20. Colonial Creek fan deposits include cobble and gravel in areas that are currently active and gravel and sand in areas of past deposition.

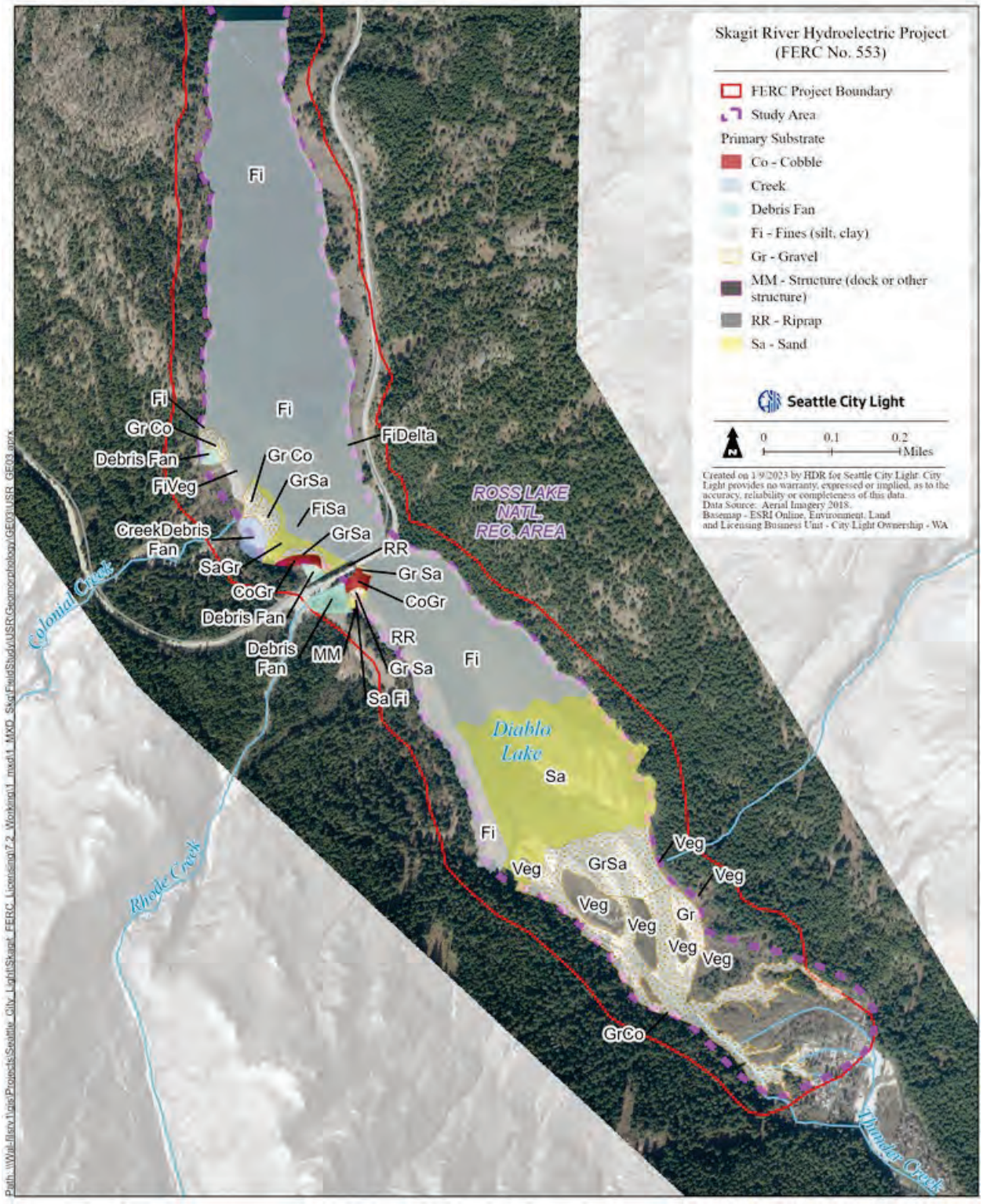


Figure 5.2-6. Surficial substrate in Thunder Arm.

One pebble count was made in Thunder Creek on a point bar just downstream from the trail bridge/USGS gage area. The sample was composed of 58 percent cobble and 42 percent gravel with a median grain diameter of 700 mm (Figure 5.2-7).

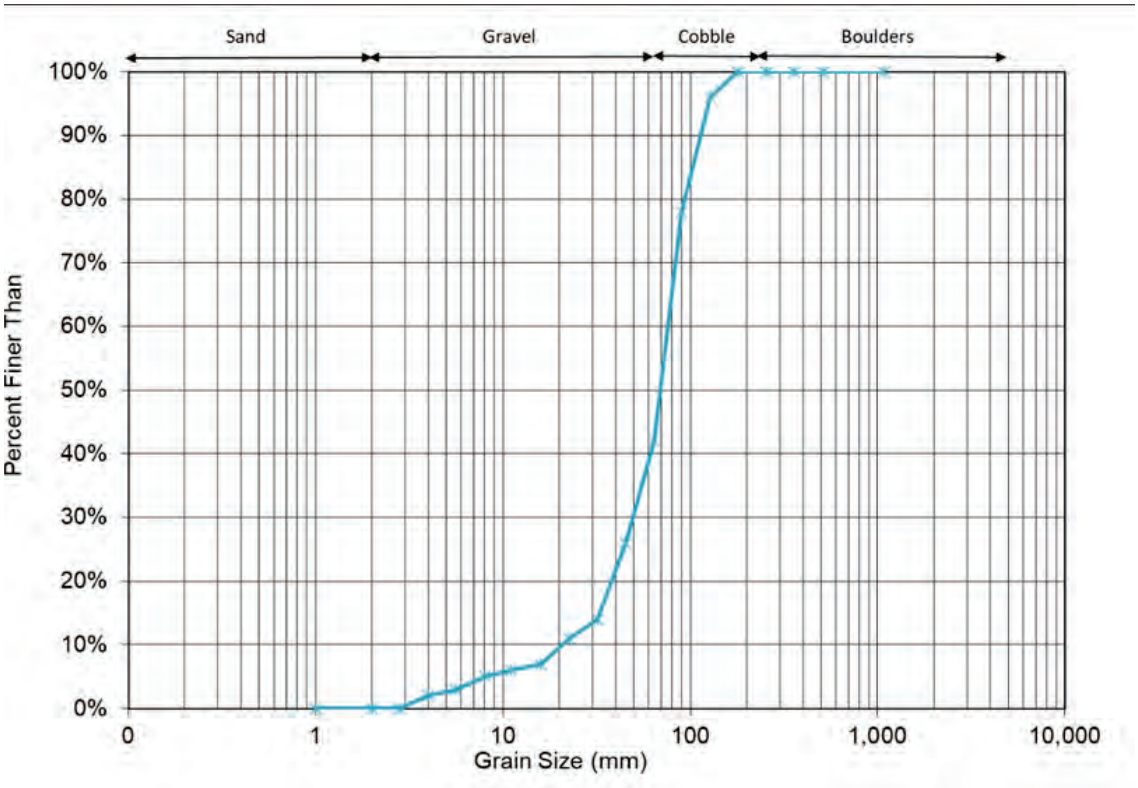


Figure 5.2-7. Thunder Creek substrate sample grain size distribution.

5.2.3 Thunder Arm Changes Through Time

Three sets of aerial photographs (1990, 2006, and 2018) were compared to determine how deposits in Thunder Arm changed through time (Figure 5.2-8). Lake levels and water clarity vary in each of the aerial photographs but general sediment deposition patterns and trends can still be determined. The October 20, 2003 peak flow event (17,800 cfs instantaneous peak—largest flow on record) resulted in substantial areas of deposition in Thunder Arm. Many bars developed in the Thunder Creek delta at the confluence of the creek and Diablo Lake and a large log jam filled the northern meander bend at the mouth of the stream as seen in the 2006 aerial photographs (Figures 5.2-9 and 5.2-10). Deposition in the delta continued through time resulting in the formation of vegetated islands at the upper end of the delta and additional deposition in the delta by 2018. The deposits from the 2003 flood and the formation of a large channel spanning log jam appear to have resulted in aggradation within the stream. Some floodplain trees that were alive in the 1990 aerial photograph were dead in the 2006 photo. The zone of dead trees extends approximately 0.5 miles upstream from the normal maximum water surface elevation of Diablo Lake and was mapped as North Pacific Lowland Riparian Forest and Woodland Group in the TR-01 Vegetation Mapping Study (City Light 2022b). These trees are up to 15 feet higher in elevation than normal maximum water surface elevation of Diablo Lake and are likely affected by backwater effects including deposition (see discussion in Section 5.2.5).

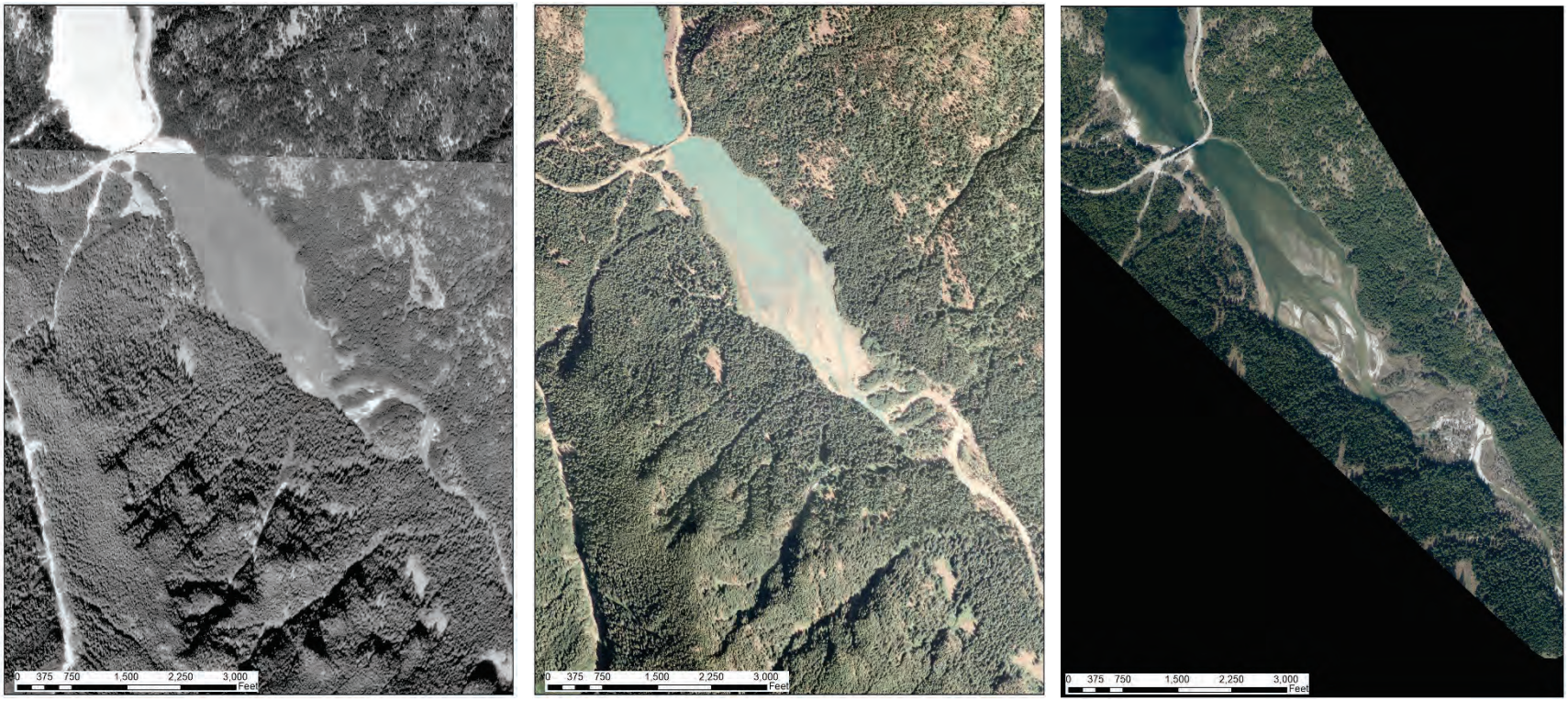


Figure 5.2-8. Thunder Arm changes through time.

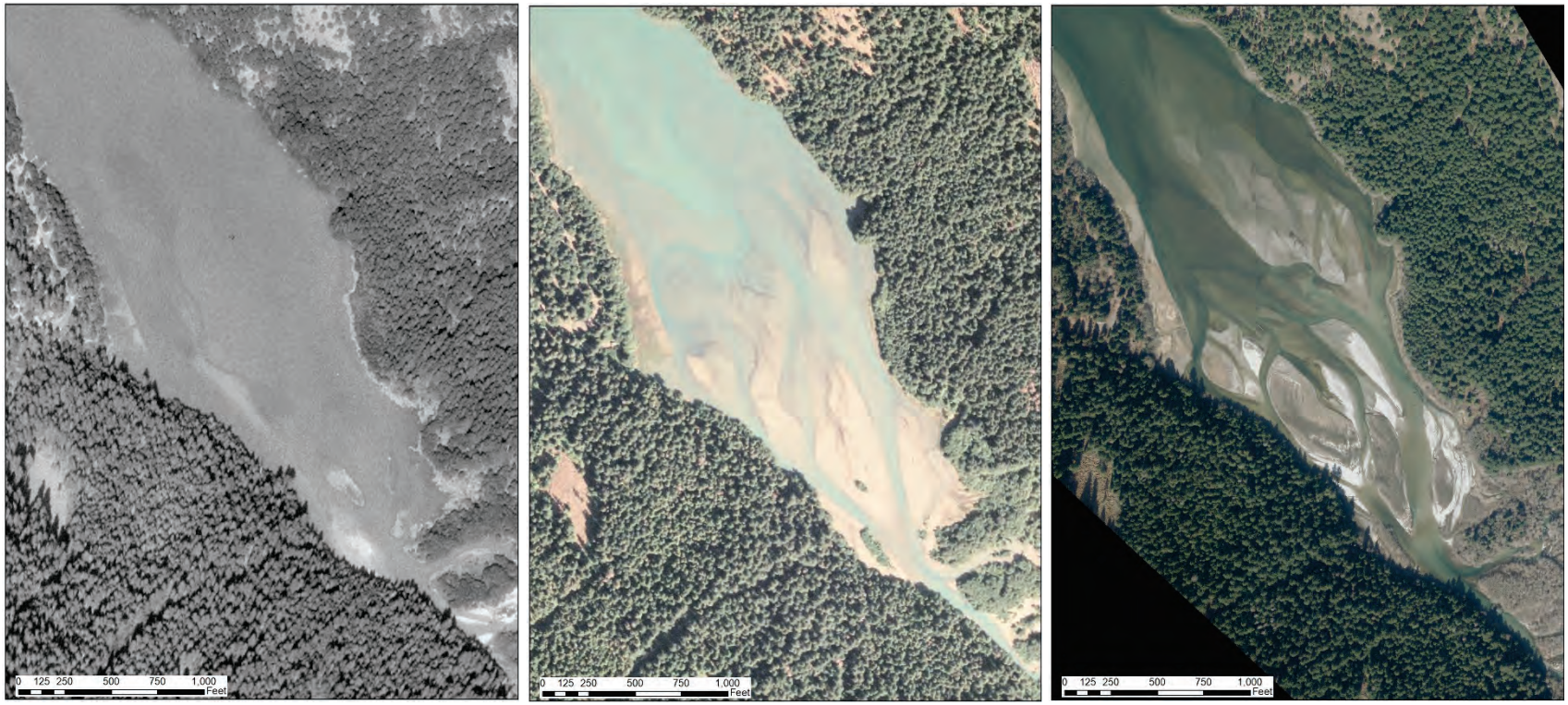
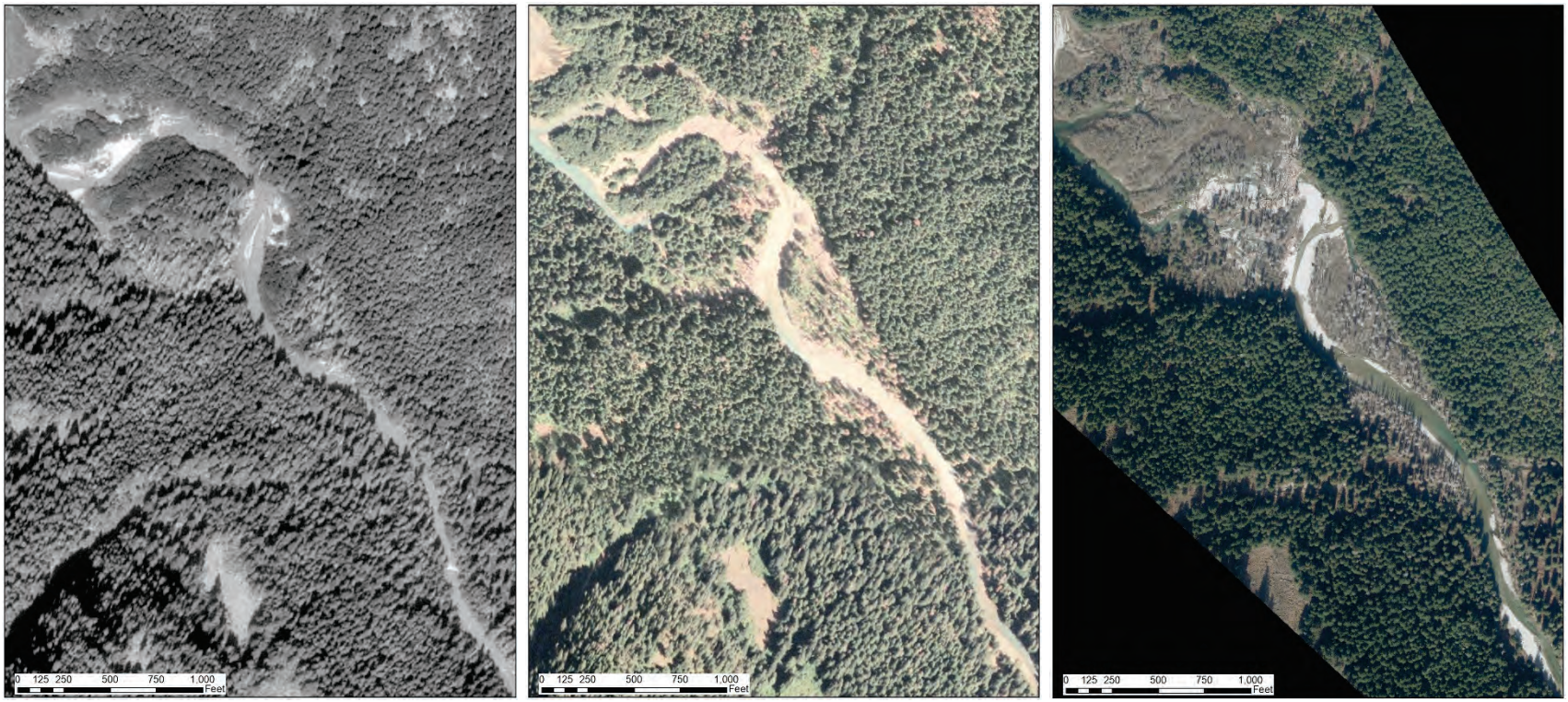


Figure 5.2-9. Thunder Arm upper delta through time.



1990 2006 2018

Figure 5.2-10. Mouth of Thunder Creek through time.

5.2.4 Colonial Creek Campground Boathouse and Boat Ramp and Temporary Barge Landing

Deposition at the boathouse, temporary City Light barge landing (on-going occasional use), and boat ramp at the Colonial Creek Campground limits the usefulness of these facilities, particularly at low lake levels. Observations at the facilities, located directly north and south of SR 20, respectively, suggest that the primary source of sediment at all three of these facilities is Rhode Creek. SR 20 and the Colonial Creek Campground southern entrance road are constructed in the depositional zone of the Rhode Creek fan (Figure 5.2-11). Alan Schoblom, the NPS Skagit District Maintenance Supervisor, says that during most fall/winter seasons sediment coming down Rhode Creek plugs the culvert under the campground entrance road (shown as an orange circle on Figure 5.2-11) and then splits, flowing over SR 20 toward the boathouse/temporary barge landing and over the campground access road toward the boat launch (Schoblom 2021). Typically, 50 to 100 cu yd of sediment and debris are deposited during each event. Deposits in the lake near the boathouse/temporary barge landing and boat ramp include gravel, sand, and fines (Figures 5.2-12 through 5.2-14). Riedel (2016) documented that Rhode Creek follows the Thunder Lake Fault, producing large quantities of gravel and boulders that are delivered via debris flows (see Attachment B). Riedel notes that sometime after 1956, the Rhode Creek channel appears to have been moved north by the USFS during construction of Colonial Creek campground. As a result, the stream takes a steeper route in an unstable channel, with tens of thousands of cu yds of sediment coming down the creek approximately every decade from 1972-2004. Construction and frequent cleaning of the catch basin by NPS upstream of the campground access road has led to more frequent but smaller magnitude depositional events (approximately 1,000 – 5,000 cu yds roughly every 5 years).

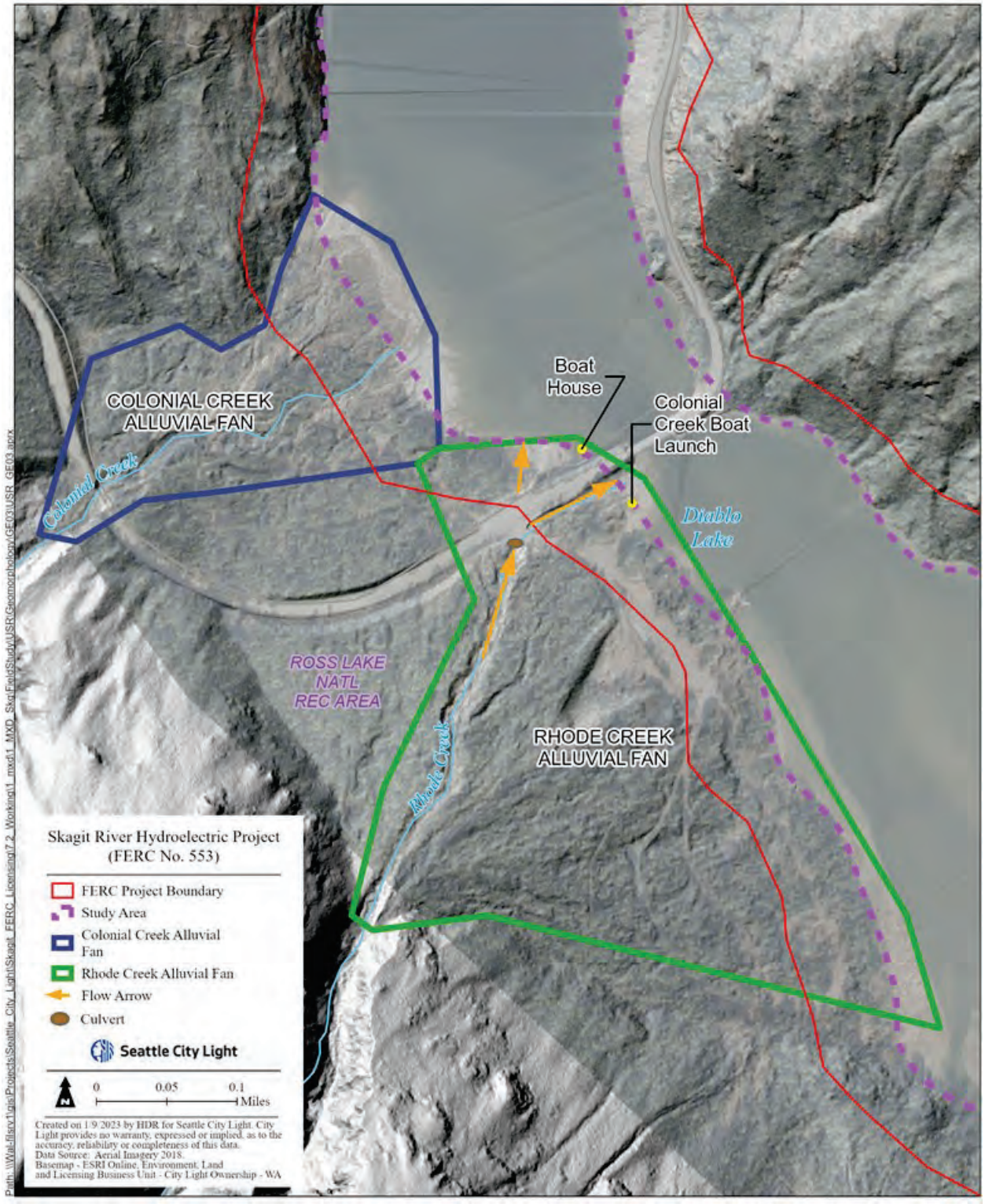


Figure 5.2-11. Rhode Creek and Colonial Creek depositional fans.



Figure 5.2-12. Rhode Creek deposition just downstream from culvert that routinely plugs (SR 20 on left).



Figure 5.2-13. Rhode Creek deposition near Colonial Creek boathouse and temporary barge landing (SR 20 in background on right).



Figure 5.2-14. Rhode Creek deposition near the Colonial Creek boat ramp.

5.2.5 Diablo Lake Backwater Effects on Thunder Creek

The HEC-RAS model results of Thunder Creek and Thunder Arm were used to extract water surface elevation profiles along the Thunder Arm delta from downstream of the SR 20 bridge to upstream of the USGS gage to help understand the extent of backwater effects of Diablo Lake elevation on Thunder Creek. The difference in water surface elevation between very low lake level (1,194 ft NAVD 88 [1,187.6 ft CoSD]) and high lake level (1,212 ft NAVD 88 [1,205.6 ft CoSD]) under 2 year, 10 year, and 100 year flow levels are shown in Figure 5.2-15. The backwater effects of the SR 20 bridge opening are shown by the increase in water surface at the bridge crossing under the low reservoir conditions for all flows, including those with high lake level. At high flows, such as the 2003 flood event, the bridge has 2.8-4 ft of an impact on the lake water surface elevation upstream from the bridge. Differences in water surface elevation between the high and low lake level model runs converge at about Station 11,500 for all model runs. The combined effect of lake elevation and SR 20 bridge constriction results in backwater effects up to this location.

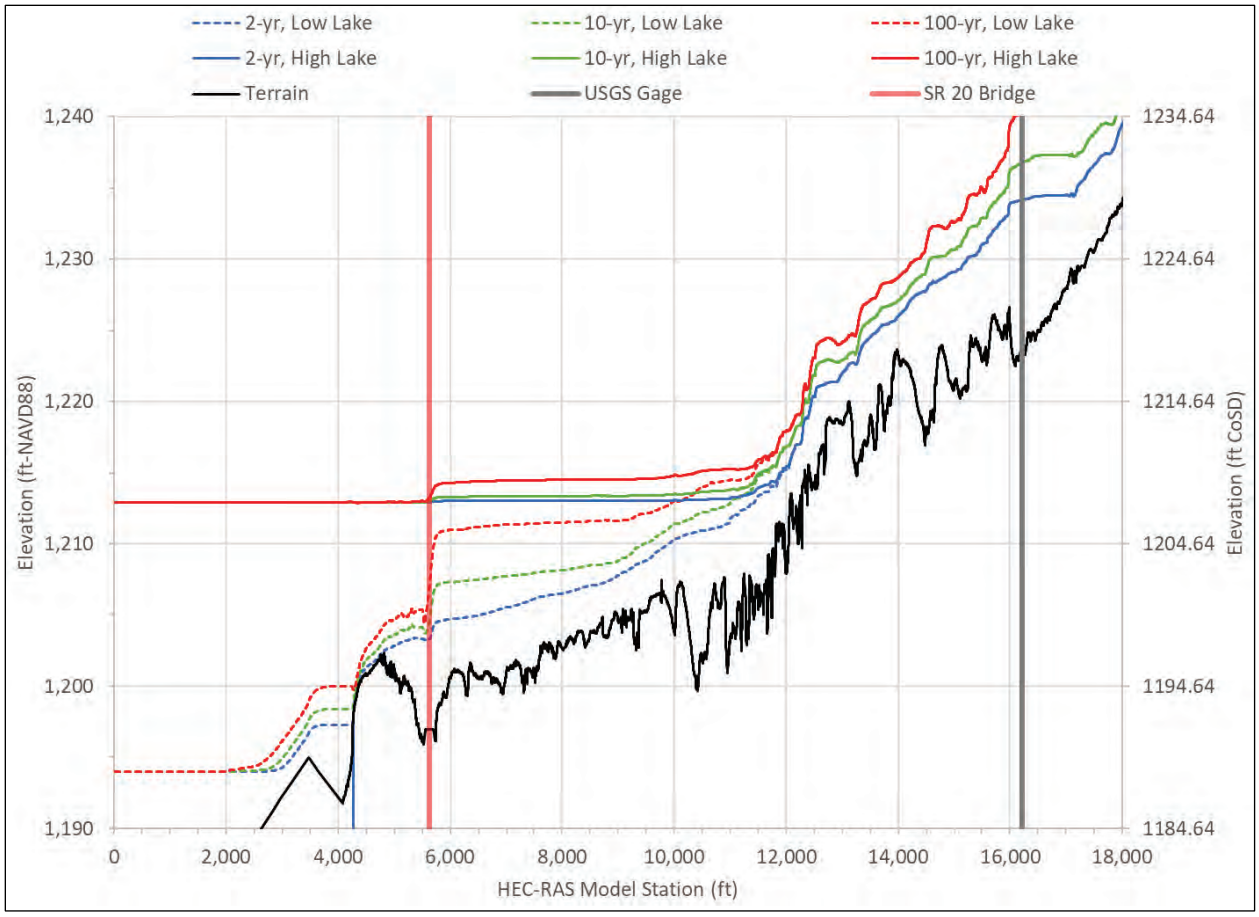


Figure 5.2-15. Comparison of water surface elevations for low (1,194 ft NAVD 88) and high (1,212 ft NAVD 88) lake levels for the 2 year, 10 year, and 100 year floods (roughness value 0.03).

Indirect and continuing effects of the backwater on Thunder Creek were considered as a result of aggradation and wood accumulations at the upper end of the Thunder Creek delta. Aggradation upstream of the 2003 log jam can be observed in the channel and on aerial photographs as far as 0.5 miles upstream from the jam. Stage-discharge records from the USGS gage (approximately 0.65 miles upstream from the log jam) show that there was little channel change in bed elevation from the 1930s through 2003 (Figure 5.2-16). Aggradation resulting from the 2003 flood caused an increase in stage that persisted until fall 2020. In water years 2021 and 2022, there were two more distinct increases in the stage-discharge relationships, with peak flows of 4,870 cfs and 8,000 cfs during this period. Given the coincidence of the first major increase in stage occurring at the time of the 2003 flood, it is reasonable to hypothesize that the sediment and wood deposited at the Thunder Creek delta has caused an increase in base level at the head of Diablo Lake. This change in the bed elevation appears to have propagated upstream. Adjustments to the bed profile at the USGS gaging station in 2021 and 2022 likely have occurred as a result of continuing aggradation, but possibly as a result of local large wood influences.

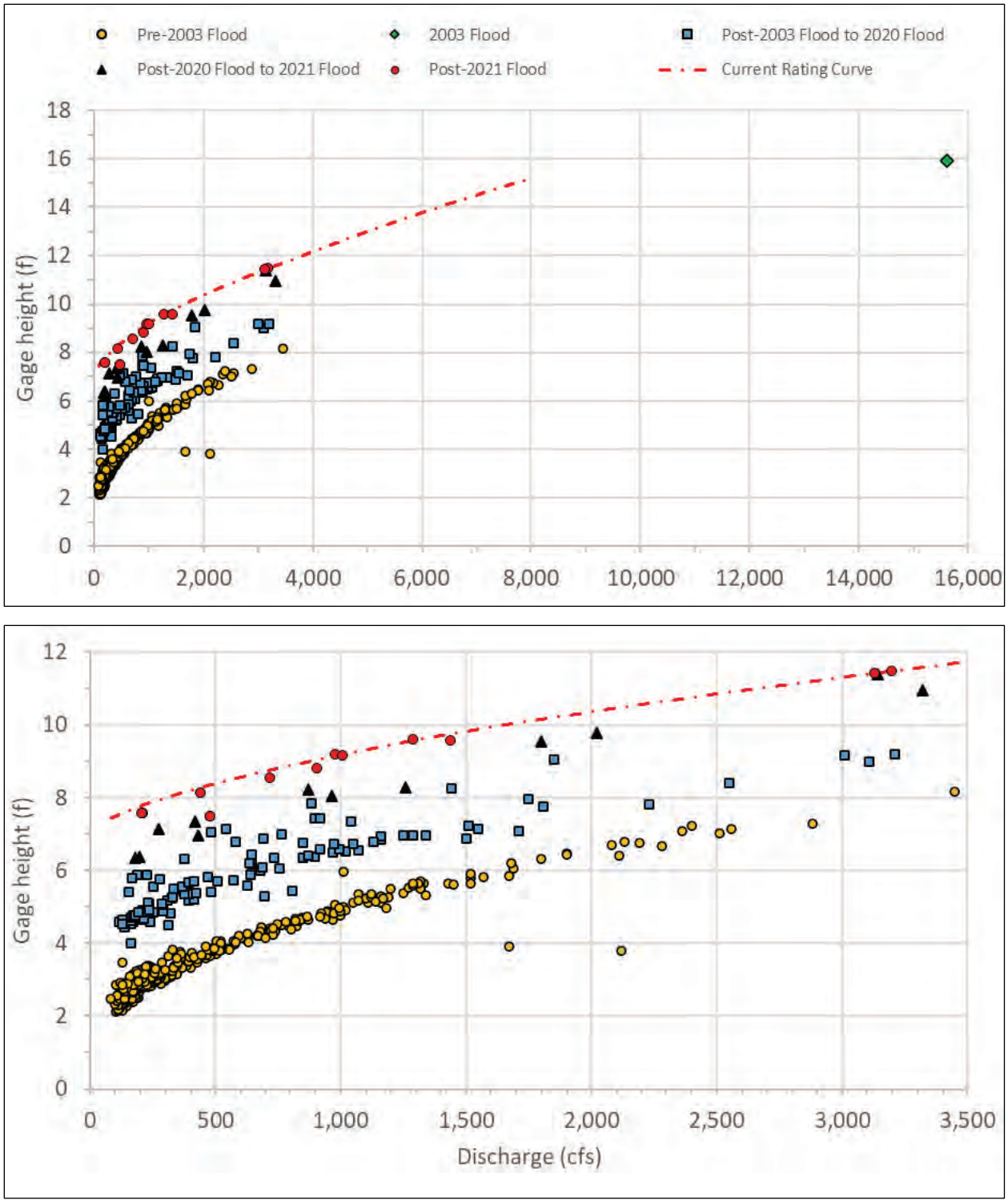


Figure 5.2-16. **Stage-discharge rating curve from USGS field observations at the USGS Thunder Creek gage (12175500). The top graph shows all measurements, the bottom shows lower discharges to make clear the relative changes in stage.**

5.2.6 Sediment Transport, Deposition Rates, and Expected Future Deposition Trends in Thunder Arm

Sediment movement in Thunder Creek and the Thunder Arm was assessed using the output from the 2-D HEC-RAS hydraulic model output to predict the grain size of sediment that could be mobilized under the 2 year, 10 year, and 100 year peak flow (Figures 5.2-17 through 5.2-19).

The 2 year recurrence interval peak flow is predicted to mobilize cobble, gravel, and finer material within the Thunder Creek channel, with small gravel mobilized through the channel in the upstream end of the delta (Figure 5.4-37). Sand and fines are predicted to settle in Thunder Arm. These results are consistent with observed substrate during the 2021 field mapping (Figure 5.2-6 above) that was completed following several years with moderate (2 year and lower) peak flow conditions.

Under the 10 year peak and 100 year peak flow conditions, gravel transport can occur further out in the delta and under the SR 20 bridge constriction due to higher velocities in these areas (Figures 5.2-18 and 5.2-19).

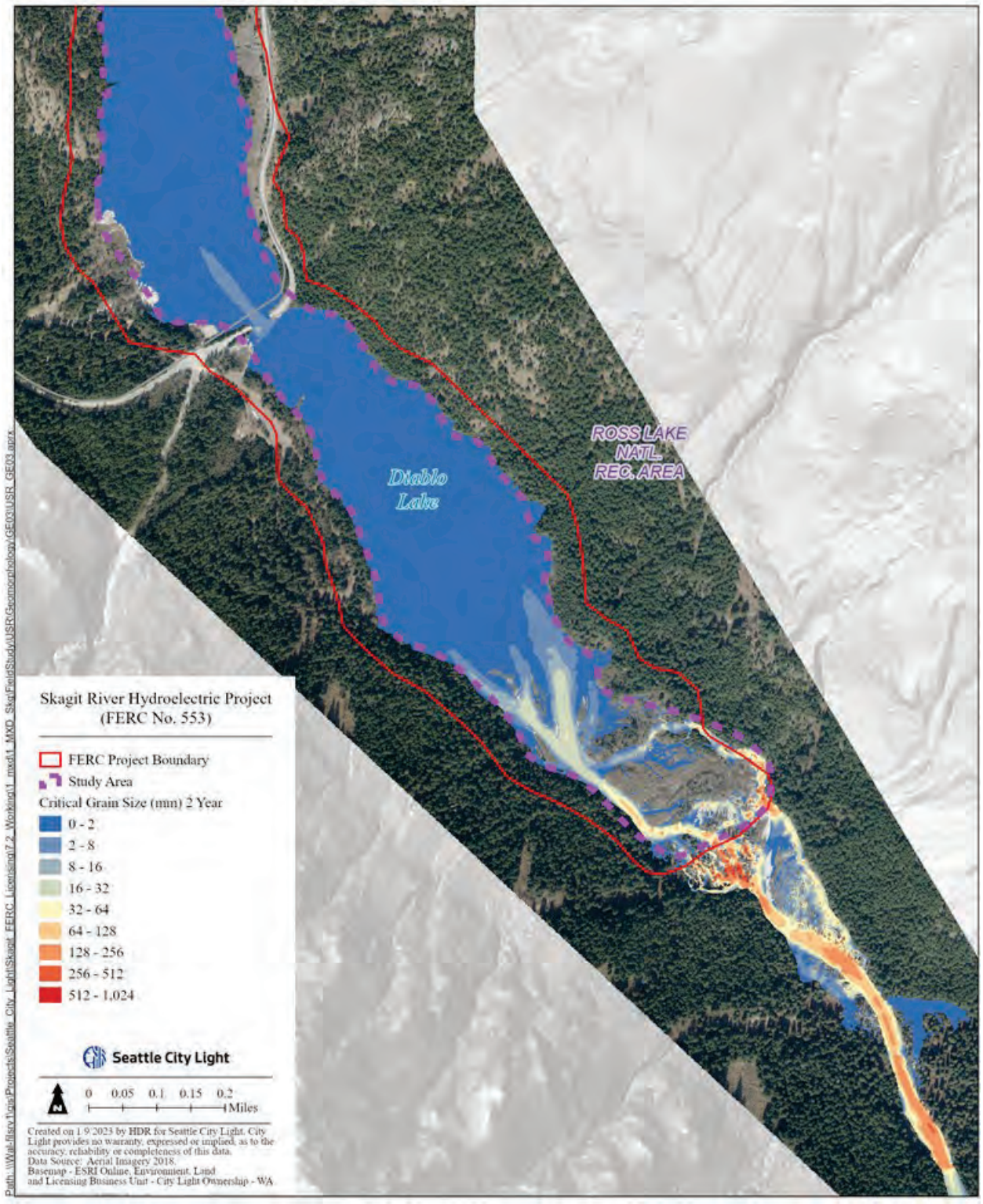


Figure 5.2-17. Critical grain size (mm) with 2 year peak flow in Thunder Creek and high lake level.

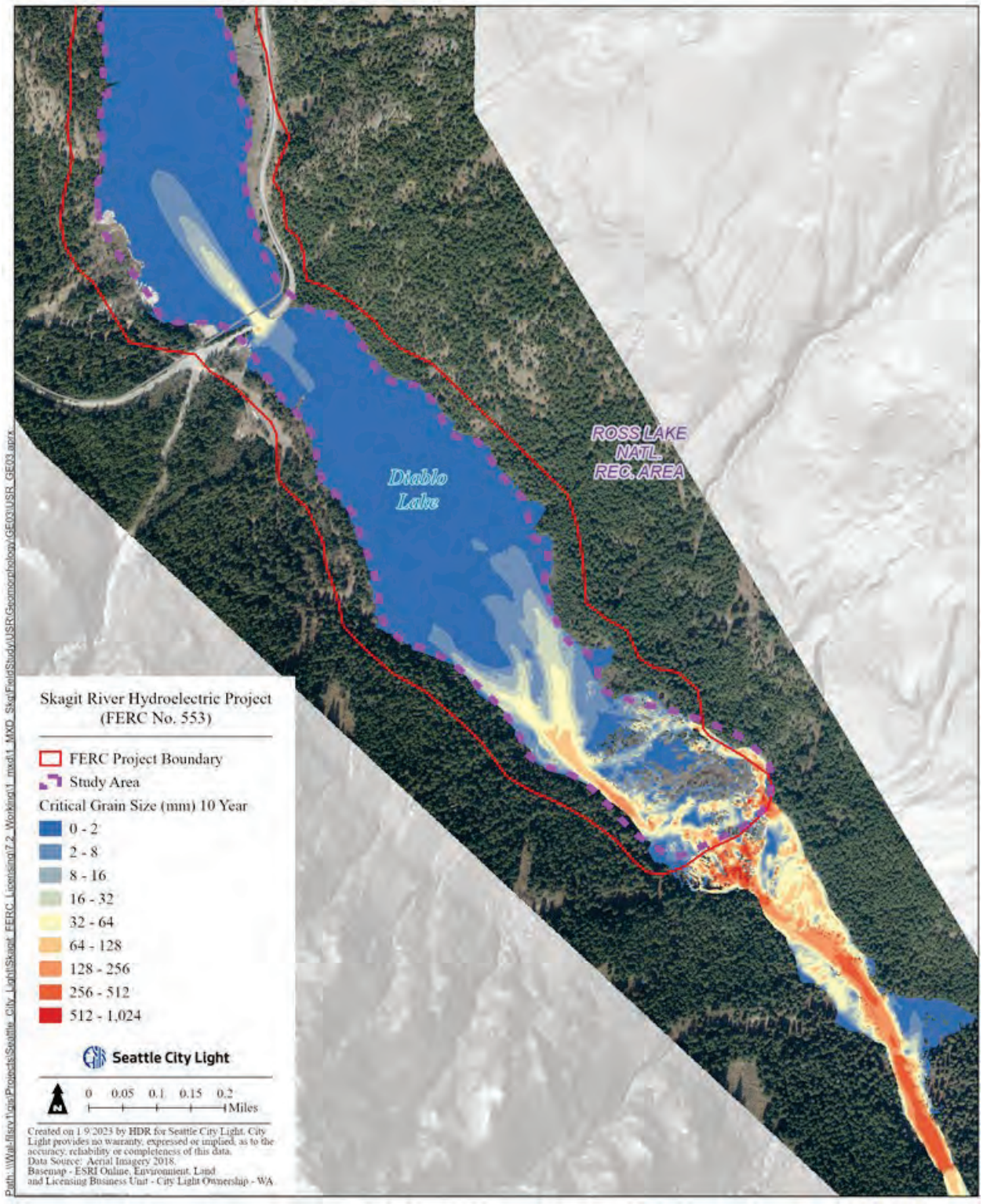


Figure 5.2-18. Critical grain size (mm) with 10 year peak flow in Thunder Creek and high lake level.

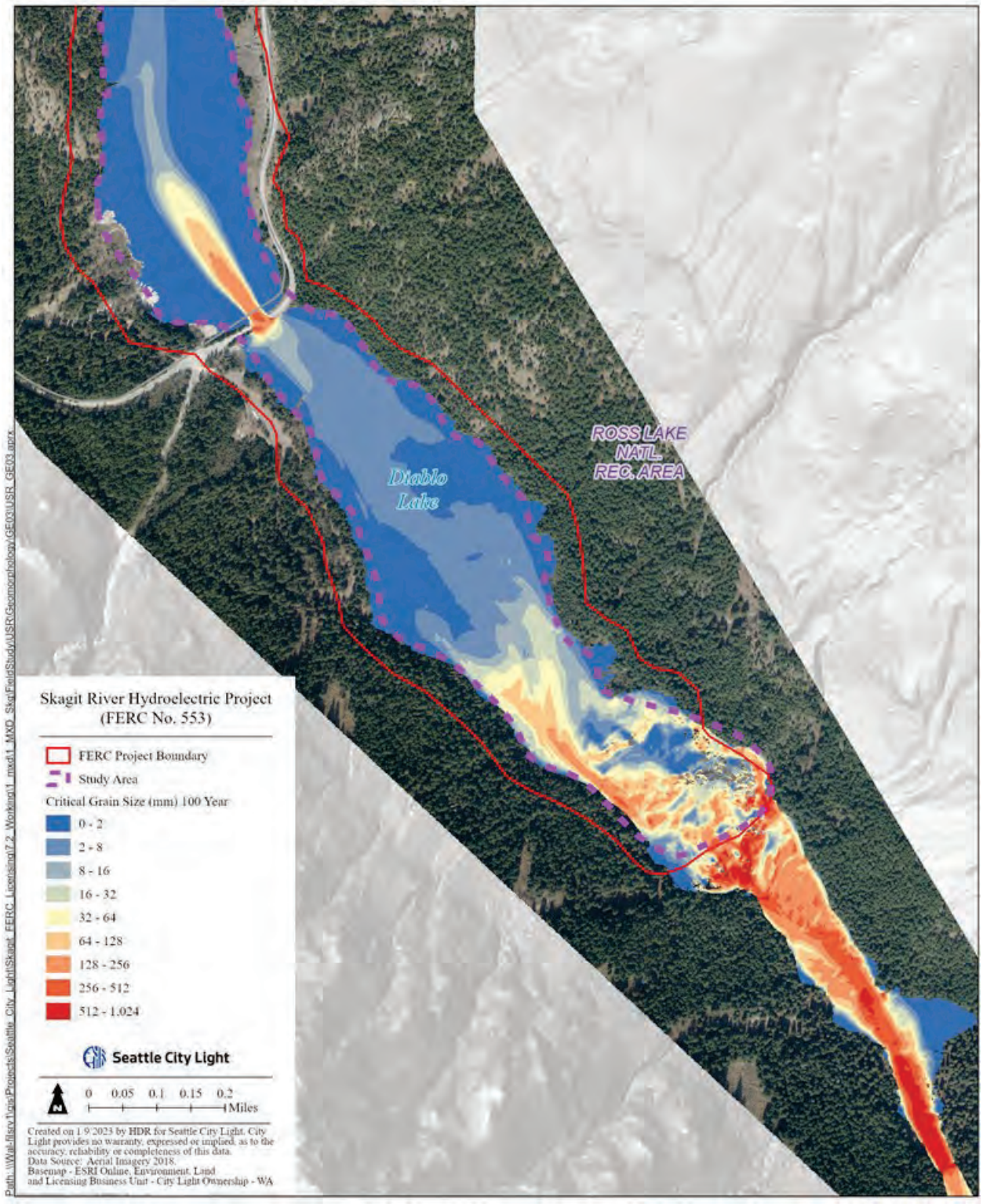


Figure 5.2-19. Critical grain size (mm) with 100 year peak flow in Thunder Creek and high lake level.

An average annual input rate of 238,500 cu yds of sediment was estimated to be supplied to Thunder Arm from Thunder Creek based on the regional regression equation, with 35,600 cu yds of gravel and coarser sediment and 202,900 cu yds of sand, silt, and clay material.

It is expected over the term of the new license that the Thunder Creek delta will continue to aggrade, with gravel and coarser sediment being deposited within Thunder Creek and at the head of the Thunder, Colonial, and Rhode creek deltas and sand and finer material deposited further downstream in Thunder Arm. The 2-D hydraulic model shows that the constriction at the SR 20 highway bridge is a hydraulic control; it is anticipated that fine sediment will continue to aggrade at the Colonial Creek boat launch from Thunder Creek and sand, gravel, and cobble will continue to aggrade at the boat launch from intermittent input from chronic Rhode Creek debris flows. Rhode Creek debris flows will also continue to transport cobble, gravel, and sand to the Rhode Creek delta that is continuing to build toward the Colonial Creek boathouse and temporary barge landing along the north side of SR 20.

5.3 Sourdough Creek

Sourdough Creek is a tributary to the north side of Diablo Lake between the City Light boathouse and the North Cascades Institute. Facilities in the area include the City Light boathouse, fuel dock, boat ramp, woody debris extraction pad, and barge landing; parking areas for public use; and North Cascades Institute swim area and boating facilities. Sourdough Creek is a high gradient (10 percent) stream that has formed an alluvial fan; the parking lots and woody debris extraction pad are built on past fan deposits (Figure 5.3-1). A vented ford was constructed by NPS across Sourdough Creek on the Environmental Learning Center access road between 2006 and 2009.

No gaging records are available for Sourdough Creek. Diablo Lake elevations are shown in Figure 5.2-5 above.

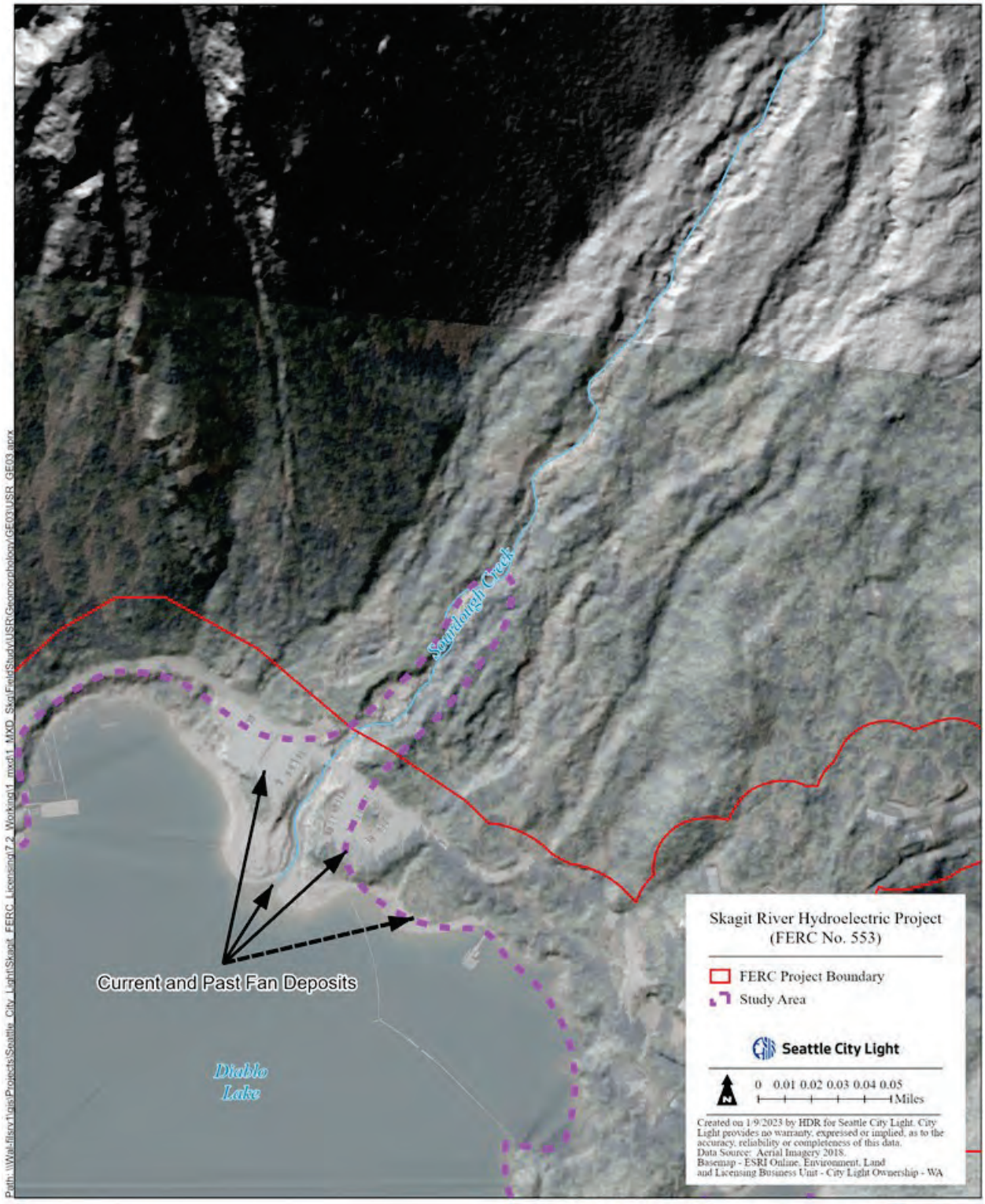


Figure 5.3-1. Sourdough Creek alluvial fan.

5.3.1 Surficial Substrate

Surficial substrate in Sourdough Creek includes boulder, cobble, and gravel material and generally fines in a downstream direction from boulder/cobble upstream of the road crossing to gravel in Diablo Lake (Figure 5.3-2). Substrate becomes finer off the face of the delta, with sand grading to silt and clay in the main body of the lake.

Pebble counts in Sourdough Creek and the delta confirmed the fining-downstream pattern and were dominated by cobble and gravel sized particles with boulders in the stream and sand in the delta area (Figure 5.3-3). Median grain diameter ranged from 50 mm in the stream to 11 mm in the finer-grained delta sample.

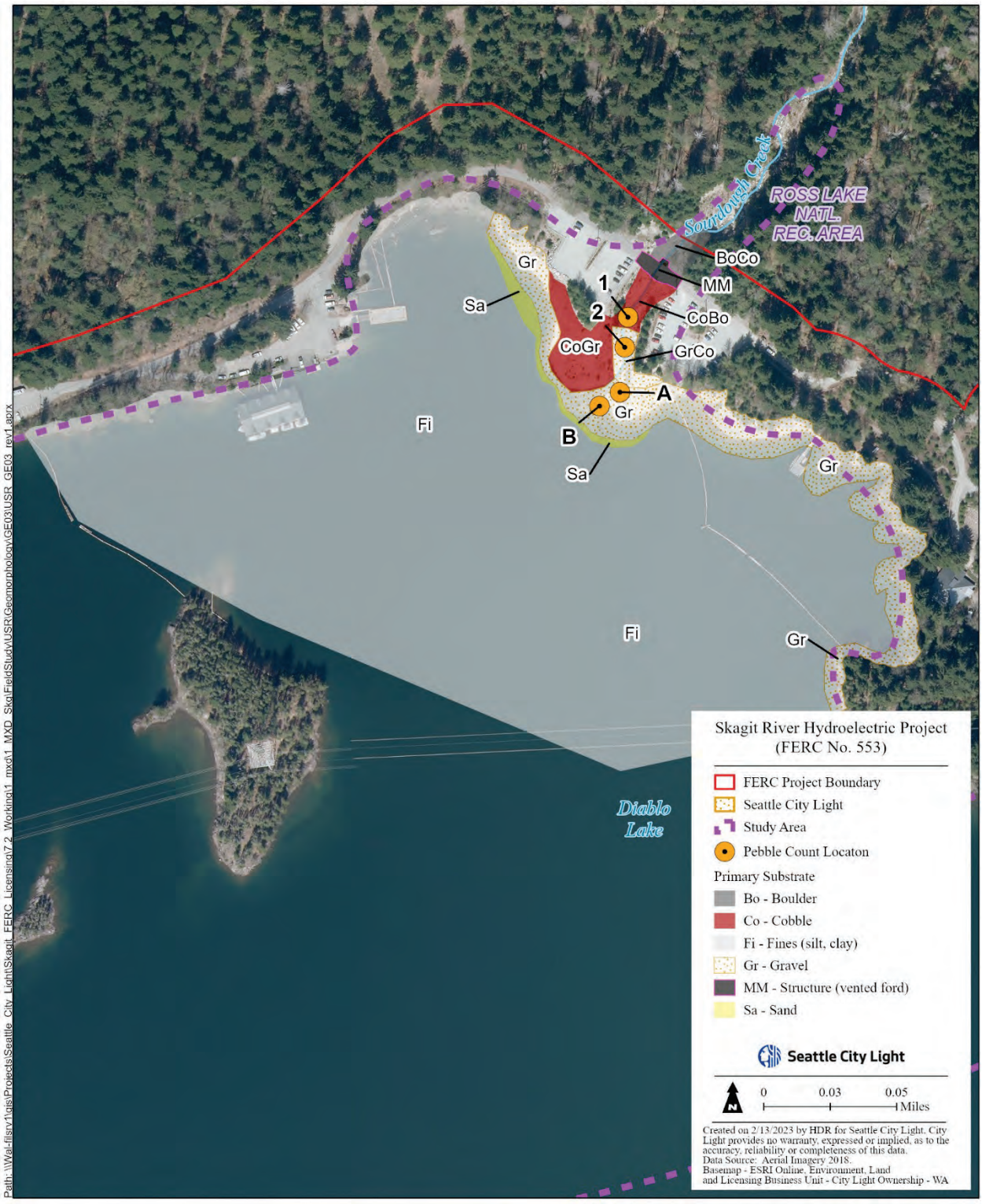


Figure 5.3-2. Surficial substrate in the Sourdough Creek delta area (early fall 2021 field data collection).

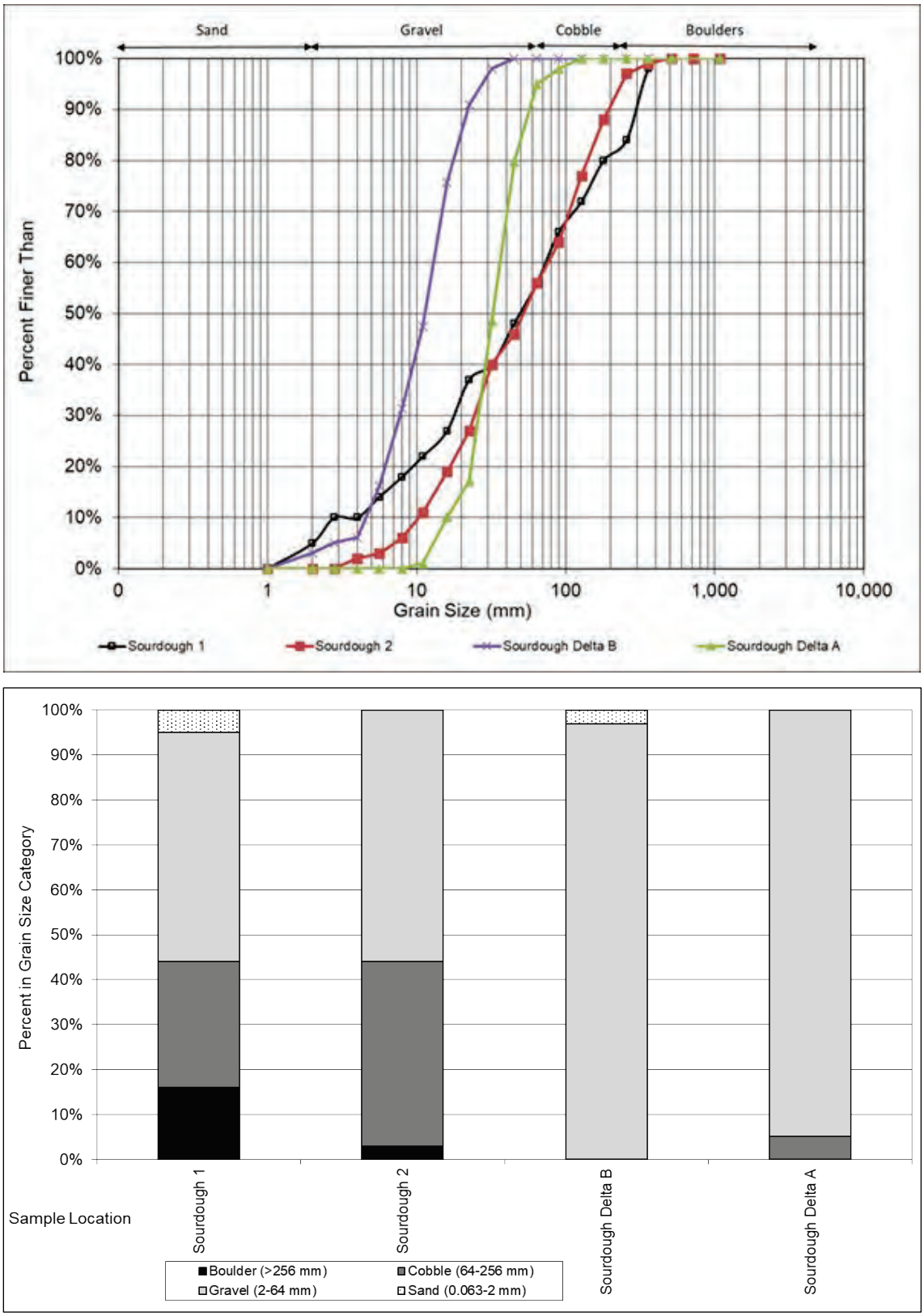


Figure 5.3-3. Sourdough Creek substrate samples grain size distribution (top) and percent in each grain size category (bottom).

5.3.2 Delta Changes Through Time

Three sets of aerial photographs were compared to determine how the Sourdough delta changes through time (Figure 5.3-4). The main Sourdough Creek channel has not substantially changed position since 1990. Between 2006 and 2019, a concrete crossing structure (vented ford) was constructed by NPS approximately 250 ft upstream from the mouth of Sourdough Creek with metal grates on the upstream side to help capture sediment and debris flows coming down the stream and to maintain vehicle access. This structure also provides a grade control. The stream has been confined to a single central channel since construction of the crossing structure and parking lots. NPS reports that most sediment and debris sluice through the structure, and the structure needs cleaning every few years (Schoblom 2021).

The delta grew between 1990 and 2006, likely in response to the large 2003 storm event. Based on the aerial photographs, the front edge of the delta advanced up to 70 ft into Diablo Lake from 1990-2006. Between 2006 and 2018, the edge of the delta advanced another 20 to 45 ft into the lake. Note that these distances are based on the visible leading edge of delta deposits in the aerial photographs. Differences in lake levels and water visibility at the time the photos were taken likely result in errors associated with absolute measurements using this method, but the conclusion that the delta grew through time is evident.

In fall 2021, a debris torrent and flooding event occurred on Sourdough Creek. Large volumes of small boulders, cobbles, and gravel came down Sourdough Creek, filled the vented ford with sediment, covered and blocked the road, and caused a channel avulsion that damaged the shoreline access road and deposited gravel and cobble on the shoreline east of the Diablo Boathouse. The debris torrent also caused major changes in the alluvial fan and nearshore bathymetry in Diablo Lake near the fan (NPS 2022; Figure 5.3-5). A longitudinal profile of Sourdough Creek was compiled from LiDAR elevation data (upstream from the lake surface) supplemented with 2021 field-measured elevations within the lake since the available LiDAR data measured the surface elevation of Diablo Lake instead of the underwater portions of the delta (Figure 5.3-6). The steep gradient of the stream, coarse nature of the sediment supply, and grade control structure suggest that any backwater effects from Diablo Lake extend less than 100 ft upstream from the lake. No evidence of sediment or debris deposits were observed that suggest backwater effects extend farther upstream. No further analysis of backwater effects on Sourdough Creek are needed to confirm these conclusions.

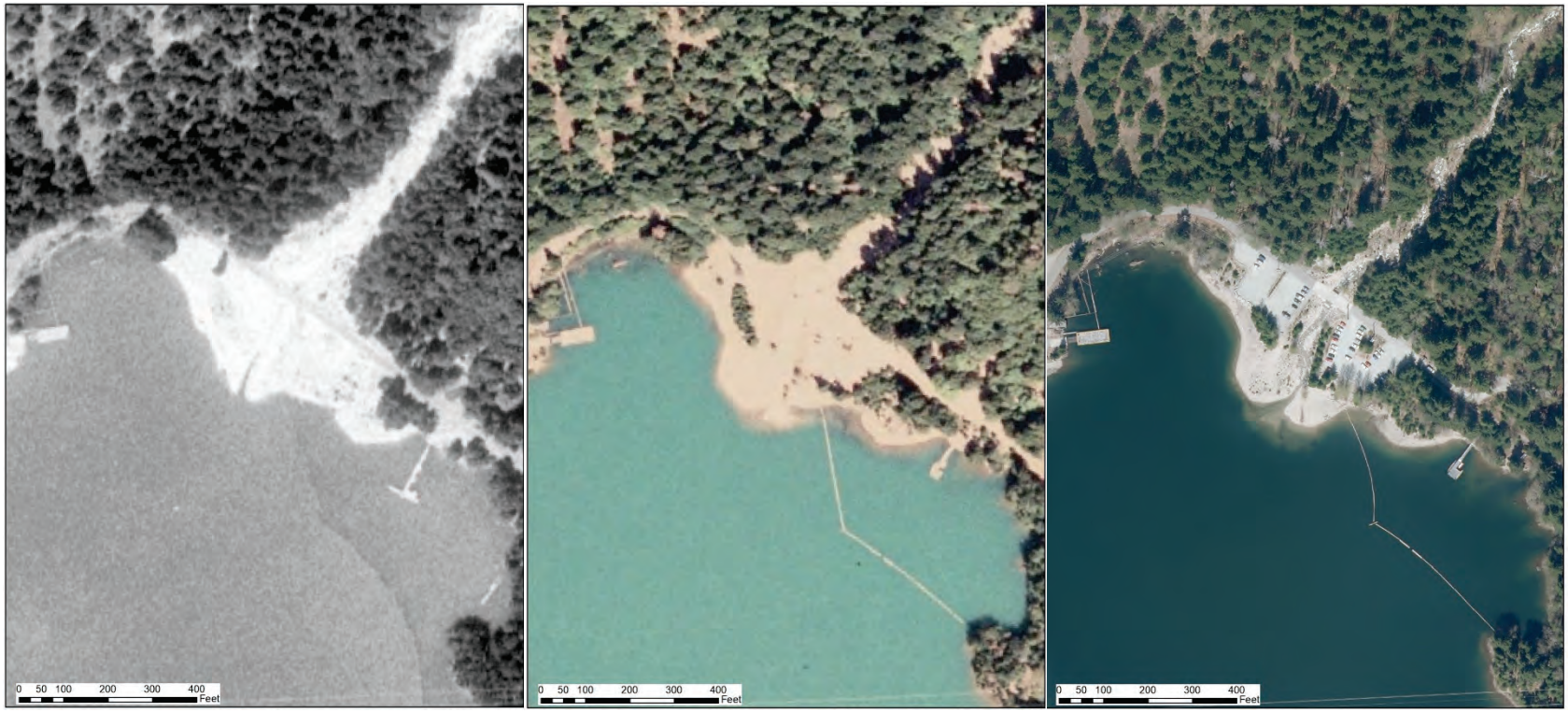


Figure 5.3-4. Sourdough Creek delta changes through time.



Downstream from vented ford.



New deposition in bay opposite Diablo Boathouse.

Figure 5.3-5. Sourdough Creek following fall 2021 debris torrent/flood event.

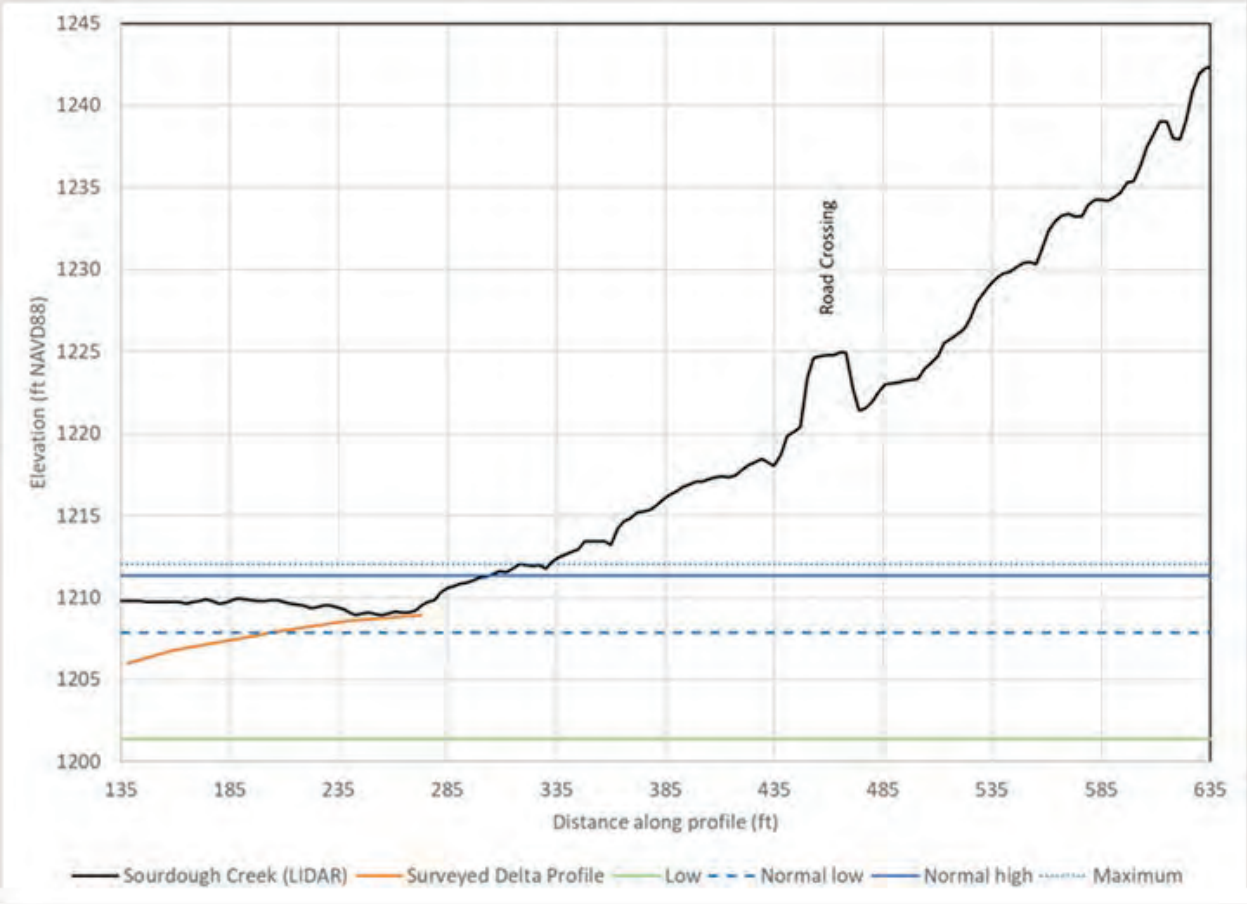


Figure 5.3-6. Sourdough Creek profile.

5.3.3 Sediment Transport, Deposition Rates, and Expected Future Trends in Sourdough Creek Delta

Because Sourdough Creek sediment input and deposition is controlled by debris flows/torrents, fluvial sediment transport analyses were not conducted. No bathymetric or LiDAR datasets were found to enable computations of deposition rates in the Sourdough Creek area.

The regional regression analysis yielded an average annual estimate of 2,000 cu yds/year from Sourdough Creek, with 600 cu yds/year of boulder, cobble, and gravel material and 1,400 cu yds/year of sand, silt, and clay material. Because sediment input from Sourdough Creek is primarily driven by debris flows, the actual amount of sediment input each year can vary widely, from little input in years with no debris flows to large amounts of boulder, cobble, gravel, sand, and fines in years with active debris flows, such as 2021.

Future sediment deposition trends in Sourdough Creek are expected to be highly variable both in amount of sediment input as well as location of deposits because Sourdough Creek is an alluvial fan with sediment input via debris torrent. The LiDAR imagery shown on Figure 5.3-1 (above) shows the historic, multiple debris torrent paths and deposition areas on the fan. Continued maintenance of the road, vented ford, recreation areas, parking lots, and City Light boathouse, boat ramp, and barge landing areas should be anticipated.

5.4 Stetattle Creek

A detailed analysis of the Stetattle Creek delta area with similar objectives to this study was completed for City Light in a previous, separate study (Watershed GeoDynamics, in prep). Those results are summarized here.

5.4.1 Basin Characteristics

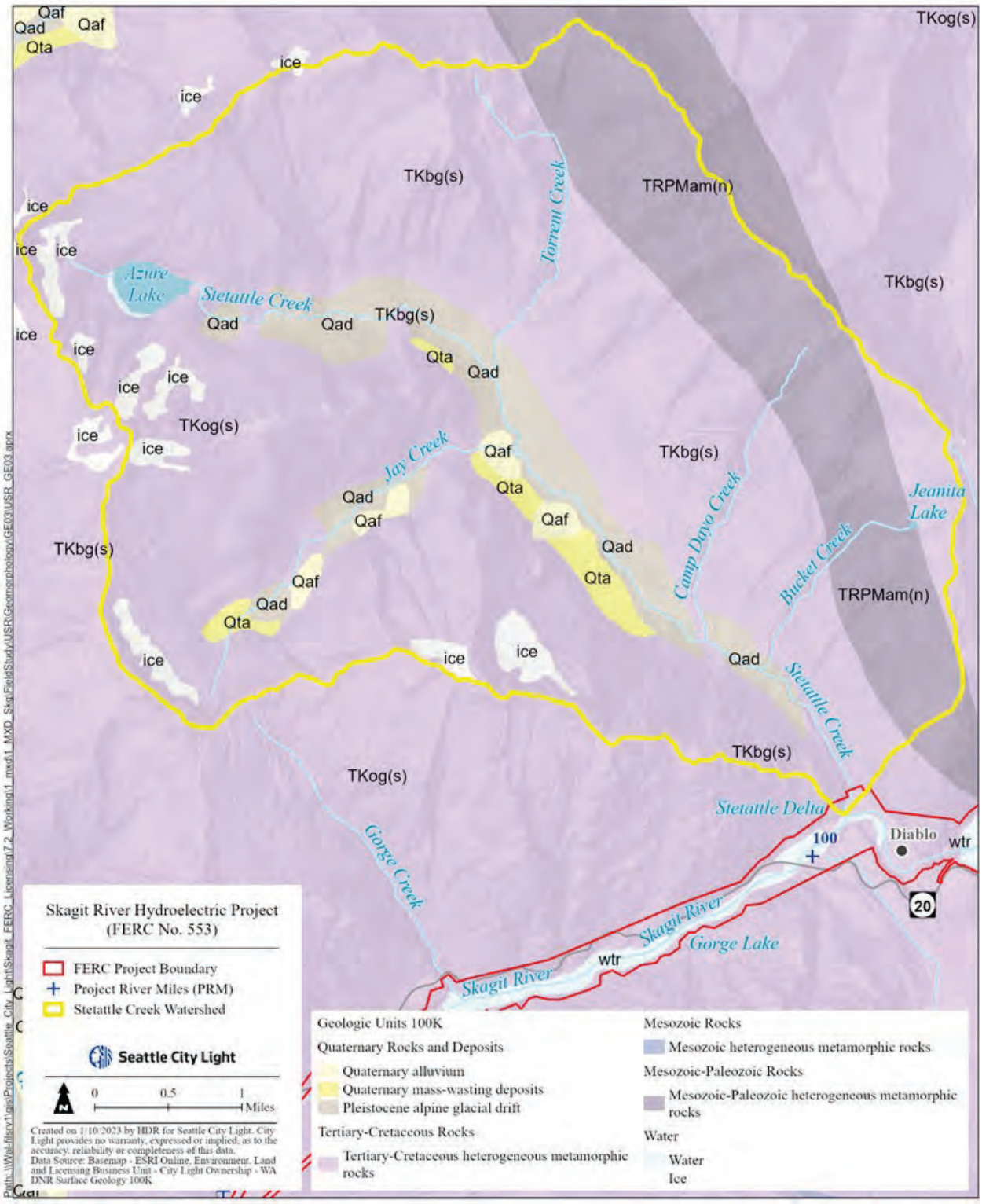
The Stetattle Creek watershed is in the North Cascades region of Washington State and encompasses 22.8 square miles. The basin is within the Ross Lake National Recreation Area and is primarily undeveloped except for hiking trails and the Hollywood residential area, which is located on the historic alluvial fan at the mouth of the creek (see discussion in Section 5.4.4 of this study report).

The topography of the North Cascades in the Stetattle Creek area reflects multiple alpine glaciations overlain on a relatively young, uplifted, and faulted landscape. The glaciers carved deep valleys, steep valley walls, and jagged horns and arêtes. Stetattle Creek has several remnant ice fields, avalanche chutes, and areas of rockfall and talus that are actively contributing sediment to the creek.

Stetattle Creek is underlain by rocks of the North Cascades Metamorphic Core Domain; these rocks have high levels of metamorphism and are more resistant to weathering and erosion, resulting in the high peaks of the North Cascades. These geologic units include gneiss, orthogneiss, and schist, which underlie the Project dams, Gorge Lake, Diablo Lake, and the southern part of Ross Lake. While resistant to erosion, the steep valleys formed in these hard rocks are subject to rockfalls, landslides, and avalanches. Geologic units in the Stetattle Creek area include (Figure 5.4-1):

- Qad – Alpine drift (glacial deposits) from Fraser-age alpine glaciers;
- Qaf – alluvial fan deposits;
- Qta – talus;
- Tkgs(s), Tkog(s), TRog(sn) – Skagit Gneiss including banded and orthogneiss;
- TRPMam(n) – Napeequa Schist;
- ice – perennial ice field; and
- wtr - lakes.

Stetattle Creek is a relatively steep tributary to the Skagit River with an average gradient of 2 percent near the confluence with the Skagit River (Figure 5.4-2). Gradient generally increases in an upstream direction with an average gradient of 6 percent in the middle reaches and over 30 percent in the headwaters. The high gradient results in transport of coarse-grained material, up to boulder size, through the stream and into the Stetattle Creek delta in the Project vicinity. The Skagit River near the confluence with Stetattle Creek is relatively low gradient, with an average gradient of less than 0.1 percent between SR 20 and the Diablo Powerhouse and with a local maximum gradient of 0.3 percent at the Stetattle Creek confluence.



Source: Washington Department of Natural Resources online geologic mapping downloaded from https://www.dnr.wa.gov/programs-and-services/geology/publications-and-data/gis-data-and-databases.

Figure 5.4-1. Stetattle Creek watershed geology.

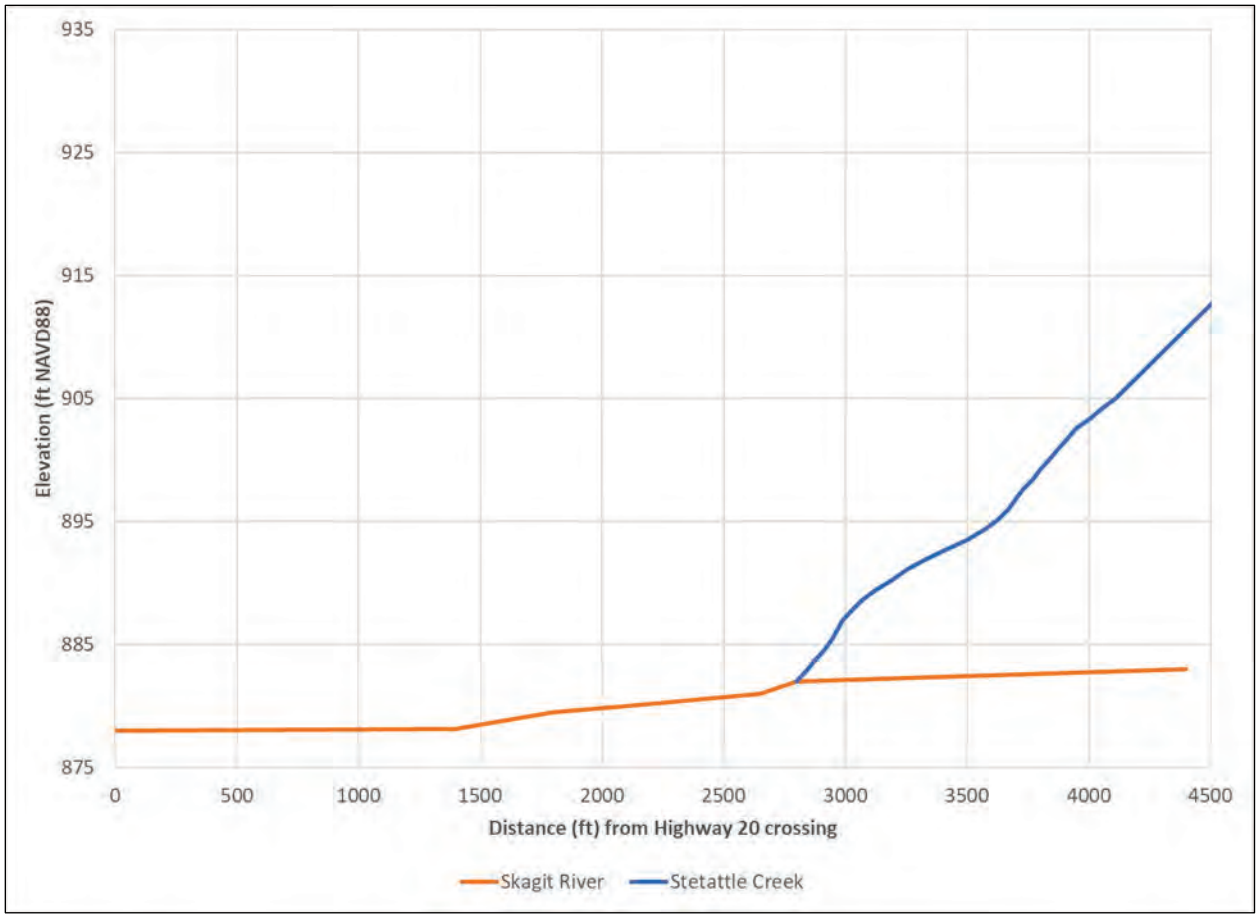


Figure 5.4-2. Skagit River and Stetattle Creek profiles (elevations in NAVD 88).

5.4.2 Hydrology and Lake Level

Transport and deposition of sediment in Stetattle Creek and the Skagit River is controlled by stream/river flow rates and the elevation of Gorge Lake (as well as stream gradient as discussed in the previous section). Stetattle Creek is an unregulated stream; flows in the Skagit River at the confluence with Stetattle Creek are controlled by storage in the upstream Ross and Diablo lakes. Flow in the Skagit River at the project site is the sum of outflow from Diablo Powerhouse plus any spill over Diablo Dam.

5.4.2.1 Stetattle Creek Flow

Streamflow in Stetattle Creek was recorded at a stream gage operated by the USGS from 1933-1982. The gage was located approximately 0.5 miles upstream from the confluence with the Skagit River. Mean monthly flows over the period of record ranged from 100 cfs in March to over 350 cfs in June and were generally highest during snowmelt (May-June-July) and lowest in September and March when either rainfall is lowest (September) or just prior to snowmelt (March; Figure 5.4-3). Daily flows in Stetattle Creek vary depending upon recent precipitation and snowmelt patterns (Figure 5.4-4), and they generally follow the mean monthly flow pattern with variations for rainfall or snowmelt events.

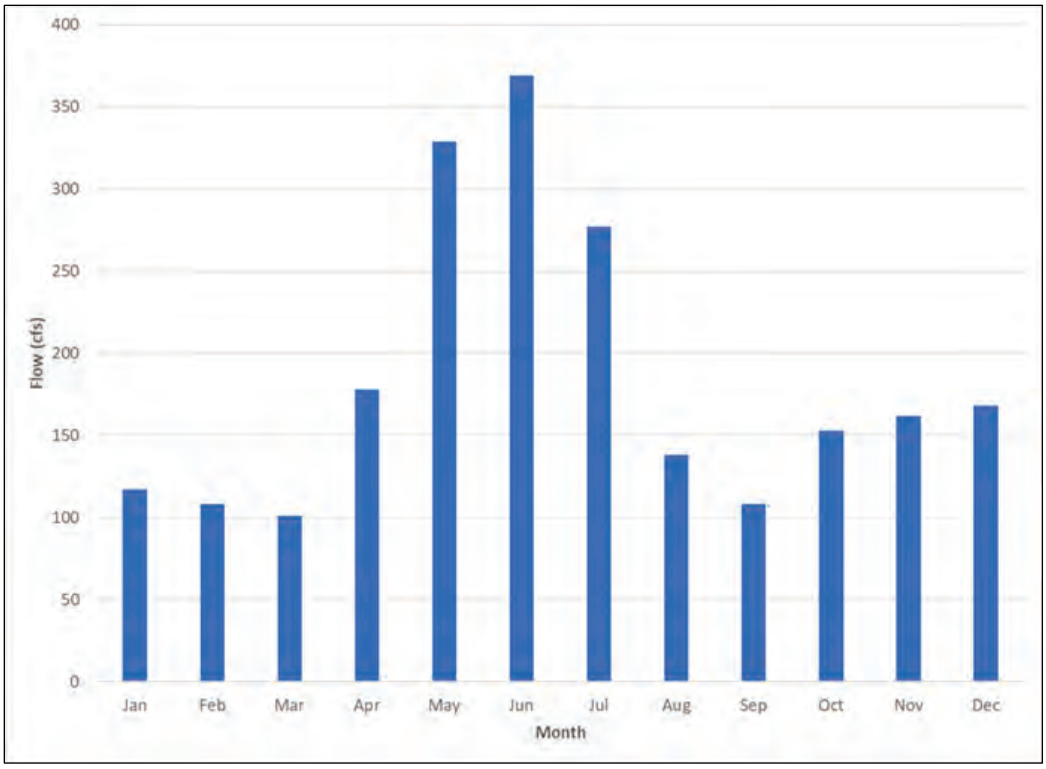


Figure 5.4-3. Stetattle Creek mean monthly flow (USGS 12177500—period of record 1933-1982).

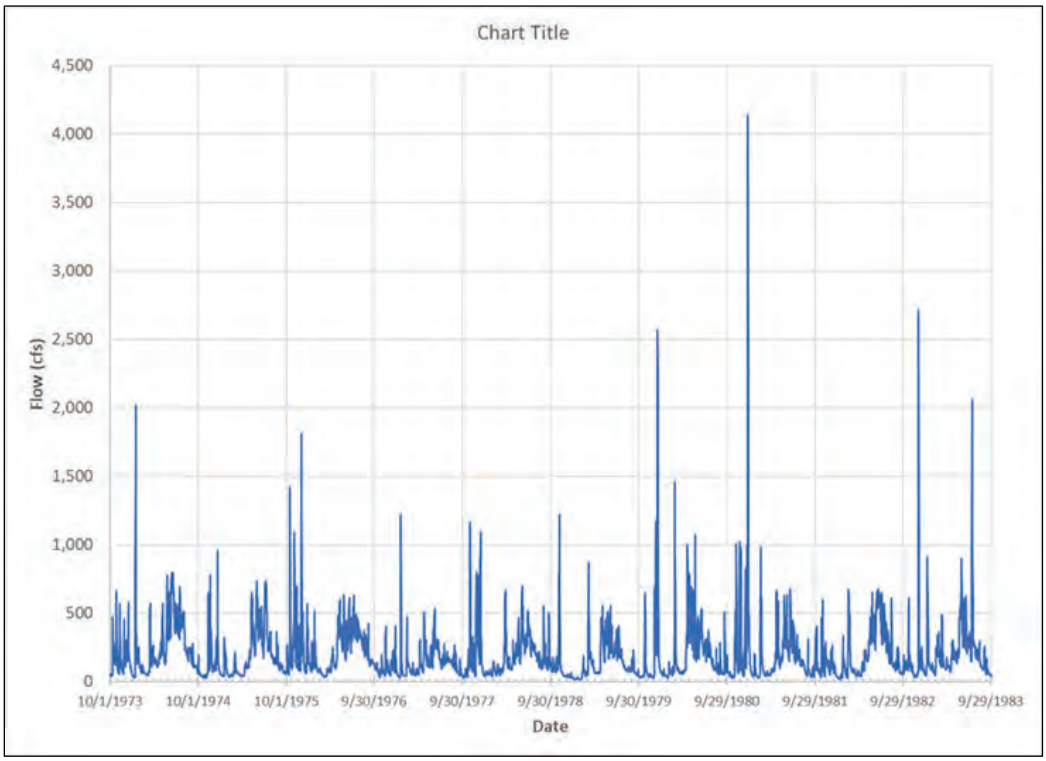


Figure 5.4-4. Stetattle Creek mean daily flow variation example (USGS 12177500—period of record 1973-1983).

Bedload transport and geomorphic change occur primarily during high flow conditions when velocities are high enough to transport coarse-grained material on the streambed. Annual peak flows in Stetattle Creek for the period of record (1933-1982) ranged from less than 1,000 cfs to over 9,000 cfs, with the highest peak flows occurring in November and December as a result of rain-on-snow events and more moderate peak flows occurring as a result of rainstorms from October through February or snowmelt during June and July (Figure 5.4-5). Peak flow recurrence intervals and exceedance probabilities were calculated for the period of record (Table 5.4-1). The 2 year peak flow (50 percent chance of occurring during a given year) is calculated to be 2,000 cfs, and the 20 year peak flow (5 percent chance of occurring during a given year) is 6,490 cfs.

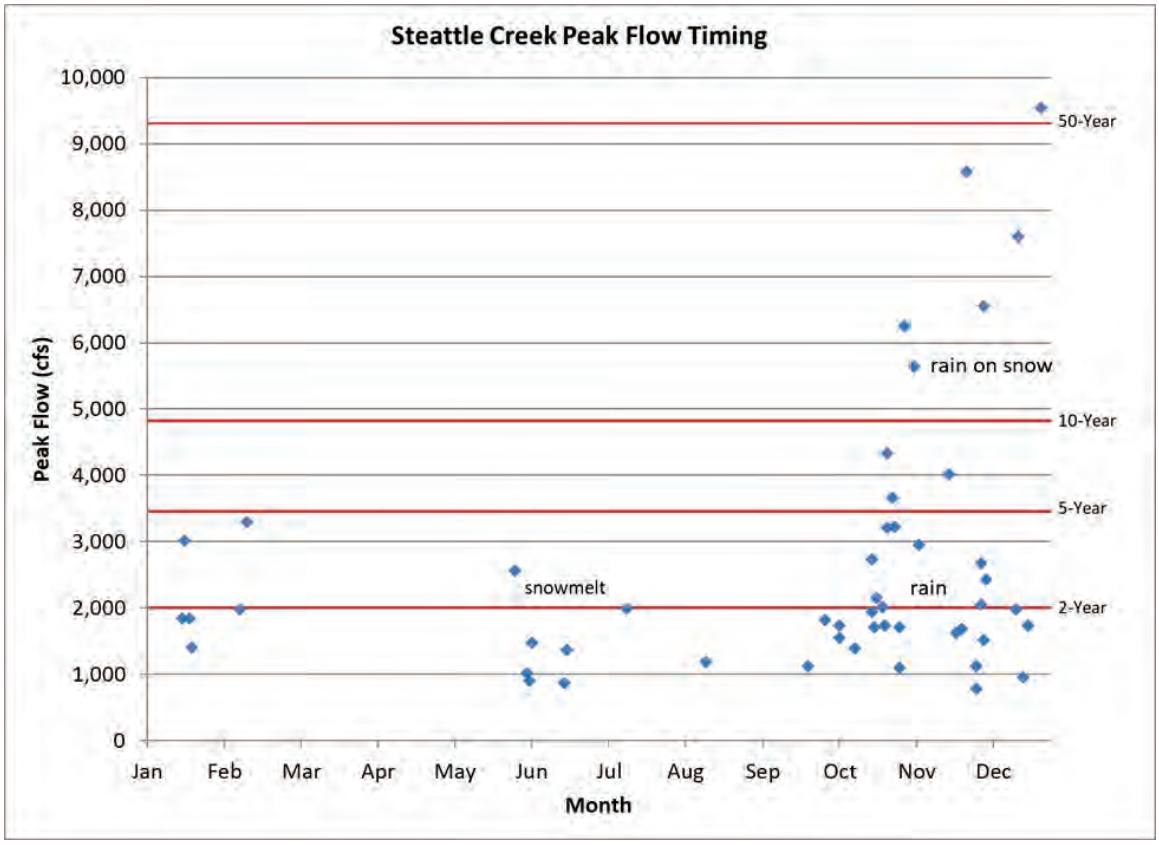


Figure 5.4-5. Stetattle Creek peak flow timing (USGS 12177500—period of record 1933-1982).

Table 5.4-1. Stetattle Creek peak flow recurrence interval and percent chance exceedance.[1]

Recurrence interval (years)	Percent chance exceedance	Flow (cfs)
100	1%	12,000
50	2%	9,310
20	5%	6,490
10	10%	4,820
5	20%	3,460
2	50%	2,000

1 Data from USGS gage 12177500 period of record 1933-1982. Bulletin 17B analysis.

5.4.2.2 Diablo Powerhouse Flow and Spill

Flow in the Skagit River at the confluence with Stetattle Creek is controlled by flow through the Diablo Powerhouse and spill over Diablo Dam. The annual flow duration curve showing percent of time flow is exceeded is shown in Figure 5.4-6; the 50 percent exceedance flow is approximately 3,500 cfs.

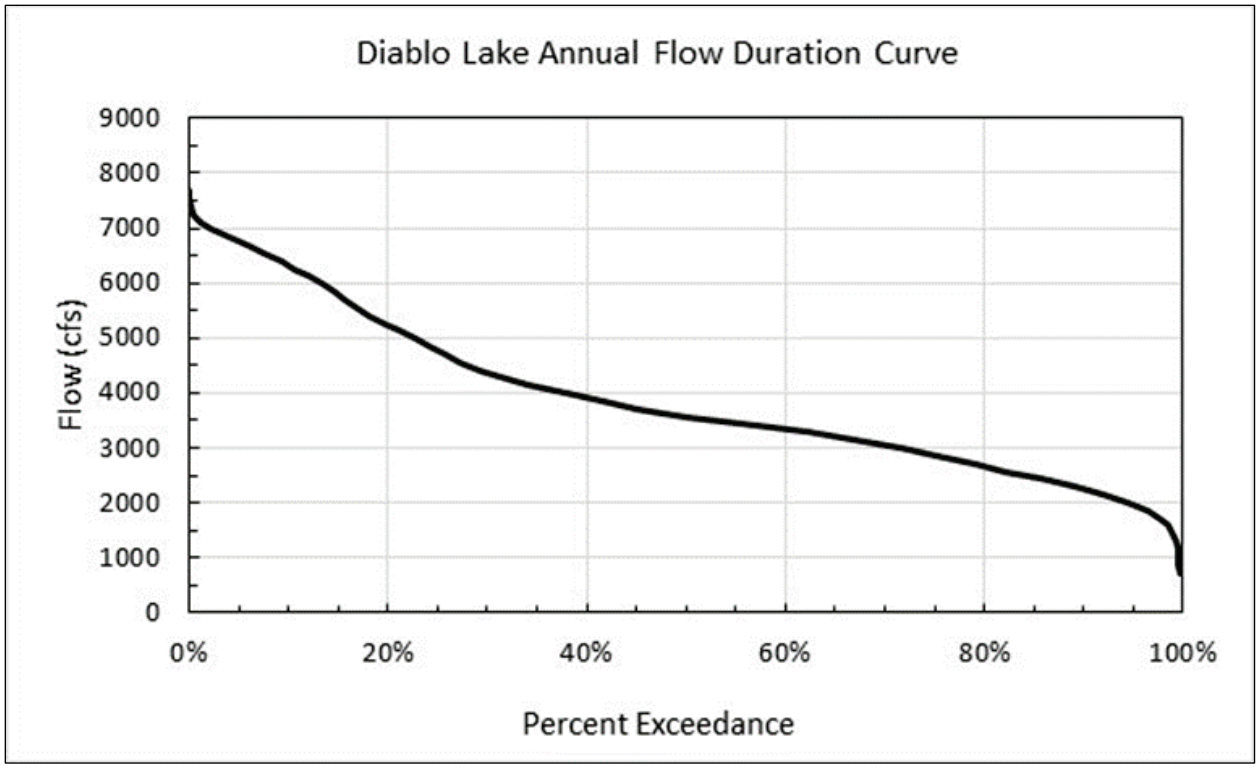


Figure 5.4-6. Annual flow duration curve for Diablo Lake outflows (1991-2018).

Based on the 2-D hydraulic model, the current primary hydraulic control for the Diablo Dam tailwater is the constriction formed by the Stetattle Creek delta at the confluence with the Skagit River and (secondarily) the delta deposits formed further upstream of SR 20. The tailwater elevation has changed through time (Figure 5.4-7), with a substantial increase in tailwater elevation between 1999 and 2000 and another increase between 2003 and 2004. Both increases corresponded to large high flow events that likely caused a large input of sediment from Stetattle Creek that was deposited within the Skagit River. A high flow event in 2006 did not substantially change the tailwater elevation. Two test flushing spills occurred in June 2007 and resulted in a reduction in the tailwater elevation—a spill of 22,800 cfs on June 20, 2007 resulted in a 9-inch reduction in tailwater elevation, and a higher spill of 32,000 cfs on June 27, 2007 reduced the tailwater elevation by another 6 inches. The tailwater elevation has been declining slightly in the past few years.

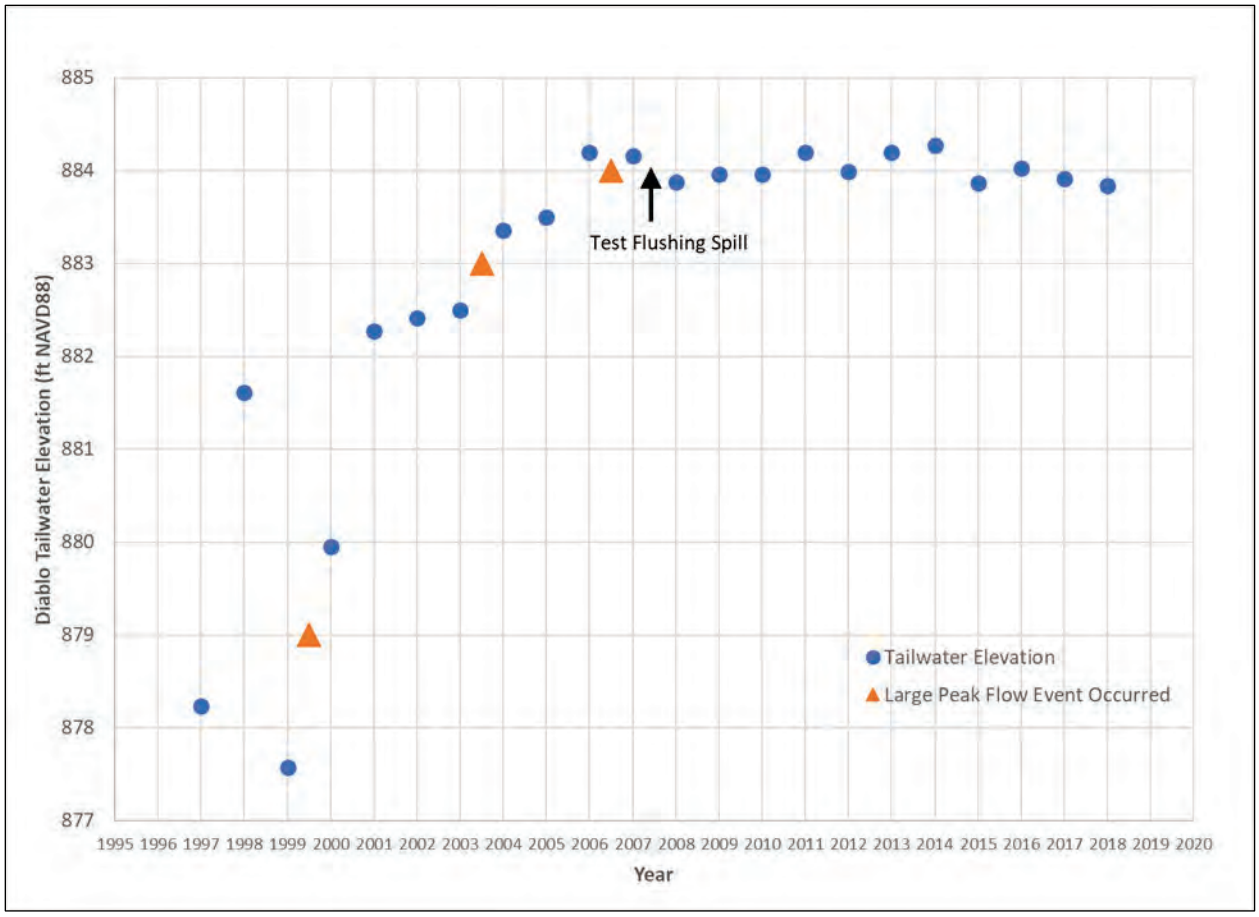
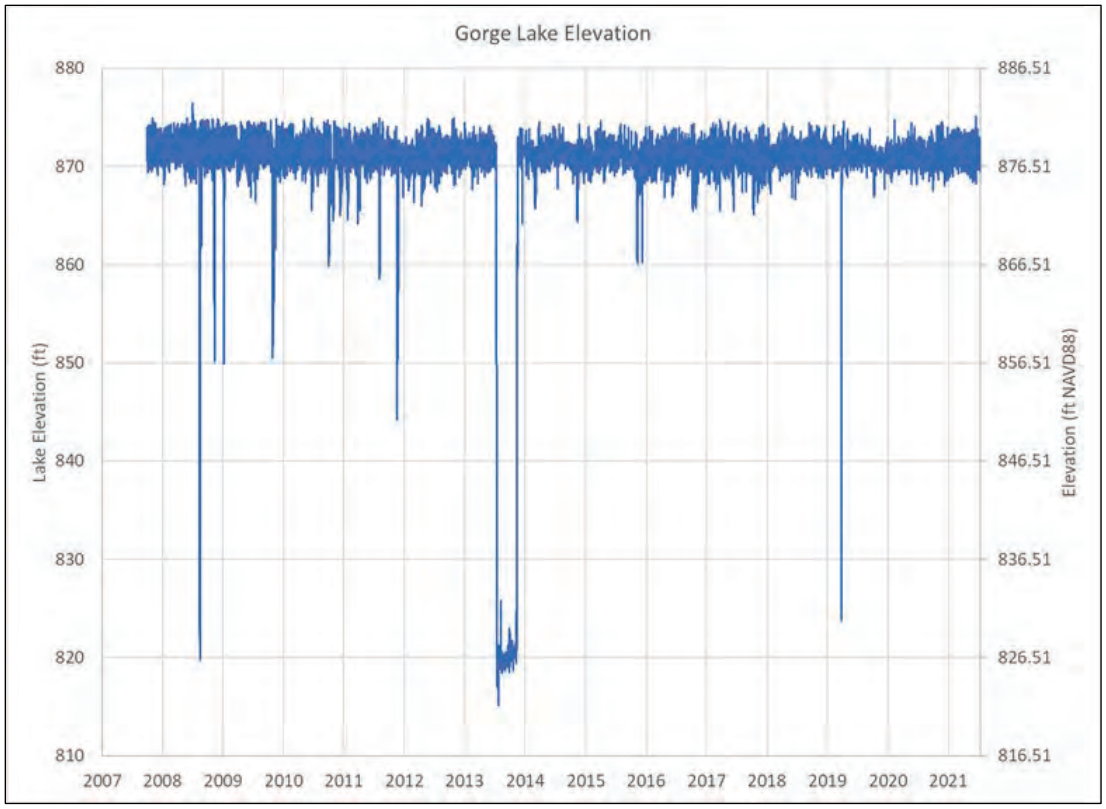


Figure 5.4-7. Changes in Diablo tailwater elevation (elevations in NAVD 88).

5.4.2.3 Gorge Lake Elevation

Gorge Lake elevation varies based on operations of Gorge Powerhouse. Prior to 1961, Gorge Lake elevation was much lower than at present; construction of Gorge High Dam raised the level of Gorge Lake to the current operational levels. Under current conditions, Gorge Lake generally varies between approximate elevation of 876.5-882.5 ft NAVD 88 (870-876 ft CoSD), but it is occasionally drawn down lower for maintenance or operational needs (Figure 5.4-8). The annual surface elevation exceedance curve is shown in Figure 5.4-9.



Note: lengthy drawdown in 2013 was for Project maintenance activities.

Figure 5.4-8. Gorge Lake elevation variation, 2007-2021.

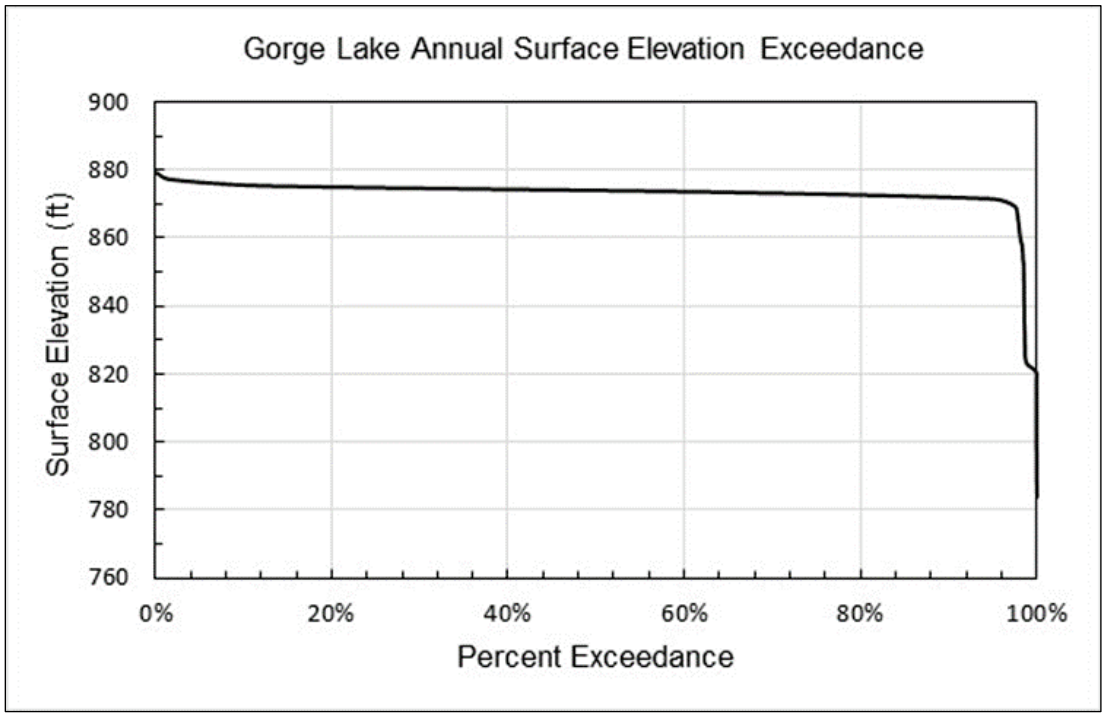


Figure 5.4-9. Annual percent exceedance curve of water surface elevations for Gorge Lake, based on the period 1991-2018 (elevations in CoSD).

5.4.2.4 Asynchronous Peak Flows in Stetattle Creek and the Skagit River

Under current conditions with the Project operating normally, large peak flows in Stetattle Creek and the Skagit River do not occur simultaneously. When a large storm is forecast for the region, system control operations generally draw down Gorge Lake to capture the anticipated high flows coming in from Stetattle Creek. During the storm event, Stetattle Creek has a large peak flow that delivers water and sediment to the confluence with the Skagit River. Flows in the Skagit River are relatively low because Skagit River inflow is being stored in the upstream Ross and Diablo lakes. If the flood is very large and upstream lake storage fills, spill over Ross or Diablo dams may occur, but this is generally well after the peak in Stetattle Creek.

One effect of these asynchronous peak flows is that bedload sediment coming down Stetattle Creek is deposited at the confluence with the Skagit River and in the secondary delta just downstream from the confluence (at the elevation of Gorge Lake). While the deposition of the largest particles (e.g., boulders) would occur even if flows in the Skagit River were high, because the Skagit River is much lower gradient and would not have enough energy to transport boulders, the regulated flows in the Skagit River exacerbate the effect and coupled with the water level in Gorge Lake result in deposition of all of the coarse-grained sediment. When flows subsequently increase in the Skagit River, the deposited sediment becomes armored with a lag deposit, which protects the underlying deposits and results in on-going aggradation.

5.4.3 Sediment Supply

Sediment supply to the Stetattle Creek delta comes primarily from the Stetattle Creek watershed, although small amounts of sediment may be supplied from stored sediments between Diablo Dam and the Stetattle Creek confluence. The Stetattle Creek watershed has many unvegetated areas of mass wasting (rockfalls, landslides, debris torrents), avalanche chutes, and perennial ice that are actively contributing sediment to the drainage (Figure 5.4-10). Due to the underlying geology (primarily gneiss, alpine glacial deposits, and talus slopes) and steep topography, there is an abundant source of coarse sediment to Stetattle Creek. The gneiss underlying most of the watershed is a relatively hard rock that is not abraded very quickly by transport in the stream but produces primarily sand-sized particles (rather than silt and clay) when it does break down. Evidence of local sediment inputs, such as discrete mass wasting events, can be seen within the Stetattle Creek streambed; angular particles have not been transported far from the source slide and are readily differentiated from rounded particles that have been transported from upstream sources or from alpine glacial deposits (Figure 5.4-11 and 5.4-12). The steep gradient and high peak flows in Stetattle Creek allow even boulder-sized rocks to be transported to the delta in the Skagit River.

There are no direct measurements of sediment input or transport in Stetattle Creek. Two methods were used to estimate long-term average annual sediment input from the watershed:

- Estimate of sediment supply based on the regional sediment input regression and watershed characteristics; and
- Estimate of coarse-grained sediment supply based on comparison of change in topography/bathymetry through time in the Stetattle delta area.

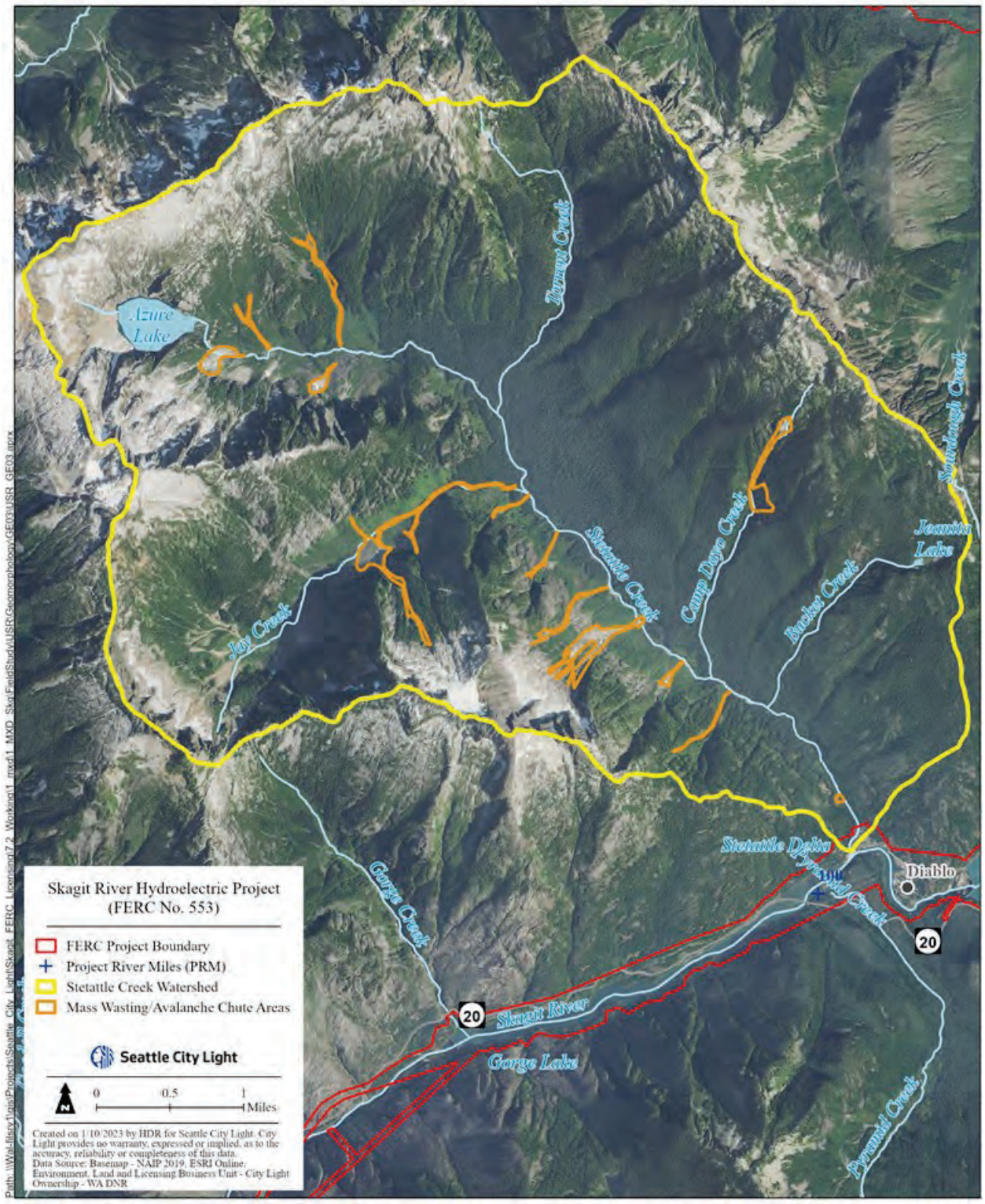


Figure 5.4-10. Mass wasting and avalanche chute areas contributing sediment to Stetattle Creek.



Figure 5.4-11. Stetattle Creek mass wasting site near former USGS gage location.



Figure 5.4-12. Stetattle Creek coarse substrate, near mass wasting site showing angular particles (local source) and rounded particles (transport from upstream source).

5.4.3.1 Estimated Stetattle Creek Sediment Load Based on Regional Sediment Regression

Based on the regional sediment regression analysis, Stetattle Creek has an estimated average annual sediment yield of 42,800 cu yds/year. Of this total, approximately 34,400 cu yds are calculated to be sand, silt, and clay, and 8,400 cu yds/year is calculated to be boulder, cobble, and gravel.

5.4.3.2 Comparison of Topography and Bathymetry in Stetattle Creek Delta

Based on Civil3D modeling of estimated topographic contours in the pre-construction period compared to 2017 bathymetric data, at least 257,000 cu yd of sediment has been deposited in the upper reaches of Gorge Lake as of 2017. There are two significant deposition locations. The first is at the mouth of Stetattle Creek (upper delta) and the second is in the area between Stetattle Creek and the SR 20 causeway (lower delta). Approximately 32,000 cu yd have been deposited in the upper delta and approximately 215,000 cu yd have been deposited in the lower delta.

These volumes were determined in Civil3D by using existing, limited topographical and bathymetric survey data and historical aerial photography prior to construction of Gorge High Dam from several sources. Because of the limited detail and approximation needed to recreate a historical terrain surface, the calculated volumes should be considered an estimate using best known available data. However, enough historical information was available to make a reasonable approximation of volume and to illustrate the depositional patterns.

In order to convert the total volume estimates to average annual deposition rates, the construction history of upstream and downstream dams needs to be considered. The first Gorge Dam was completed in 1924, but the wooden crib dam was not high enough to cause deposition in the study area. The second Gorge Dam (concrete) was completed in 1950 and, likewise, was not high enough to cause impoundments in the study area. It was not until the completion of Gorge High Dam in 1961 that water impounded in Gorge Lake caused deposition in the study area. The upstream Diablo Dam was completed in 1929, so all coarse-grained sediment deposited in the study area is from Stetattle Creek. Therefore, the Civil3D estimated 257,000 cu yd accumulated between 1961 and 2017 (56 years), which is an average of 4,590 cu yd/year. Note that this does not include the majority of the fine sand, silt, and clay portion of the load from Stetattle Creek (or any fine sediment from Diablo Lake) that is deposited farther downstream in Gorge Lake or transported through the lake.

5.4.4 Stetattle Creek Delta Development

Construction and operation of the Project and the levee protecting the Hollywood residential area have altered sediment deposition patterns in the lower 0.5 miles of Stetattle Creek and at the confluence of Stetattle Creek and the Skagit River. Current Stetattle Creek deposits in the Skagit River include the relatively coarse-grained delta that is evident at the mouth of Stetattle Creek, as well as the gravel and sand deposits that are accumulating at the head of Gorge Lake in the area just upstream from the SR 20 crossing and finer-grained sediment that is accumulating over the historic Davis Ranch area and near the campground boat launch. The location and timing of deposition of the sediment coming from Stetattle Creek is controlled by a relatively complex interaction of flow and sediment input rates from Stetattle Creek, flow in the Skagit River, and the elevation of Gorge Lake as described in Section 5.4.2.4 of this study report.

Changes in the lower part of Stetattle Creek can be seen by comparing the photos in Figures 5.4-13 (early 1900s) through 5.4-15 (2018), all taken from or near the bridge crossing at the mouth of the creek. The 1955 photo shows the newly constructed levee; the 2018 photo shows how vegetation has grown on the levee and the coarse stream deposits in the channel just upstream from the bridge. Figure 5.4-16 shows the boulder and cobble deposits in a mid-channel bar located between 400-800 ft upstream from the mouth; this bar is continuing to grow and is diverting water to both sides of the stream, resulting in levee erosion on the left bank.

Growth of the Stetattle Creek delta at the confluence with the Skagit River and the secondary deposits downstream can be seen in the photos and maps in Figure 5.4-17 through 5.4-31. Prior to the construction of Gorge High Dam in 1961, the primary delta at the confluence of Stetattle Creek and the Skagit River grew as the coarsest bedload sediment (boulders) were deposited in the lower gradient Skagit River. Smaller cobble and gravel material was transported downstream in the Skagit River to the head of Gorge Lake, which was much farther downstream than the current lake location. Since 1961, a secondary delta of cobble, gravel, and sand has been building upstream of the SR 20 bridge crossing. This can be seen as a growth of a series of mid-channel islands, which are currently diverting the main flow of the river toward the left and right banks approximately halfway between Stetattle Creek and the bridge. Bank erosion is occurring on the left bank at this location as the main flow is directed at erodible areas of the shoreline. The primary and secondary delta have increased water elevations upstream of Stetattle Creek; vegetation on the left bank downstream from the Diablo Powerhouse tailrace has been dying, presumably due to the higher water levels (Figure 5.4-30)



Figure 5.4-13. Stetattle Creek looking upstream from mouth, early 1900s (City Light).



Figure 5.4-14. Stetattle Creek looking upstream from road bridge, 1955 (City Light).



Figure 5.4-15. Stetattle Creek looking upstream from road bridge, 2018.



Figure 5.4-16. Deposition in Stetattle Creek leveed area, approximately 800 and 400 ft upstream from mouth, 2018.



Figure 5.4-17. Stetattle Creek delta looking downstream, circa 1920 (City Light).



Note: Arrows show location of Stetattle Creek channel.

Figure 5.4-18. Stetattle Creek delta looking downstream during Gorge Lake drawdown, April 2014 (City Light).



Figure 5.4-19. Stetattle Creek delta looking upstream, early 1900s (undated; City Light).

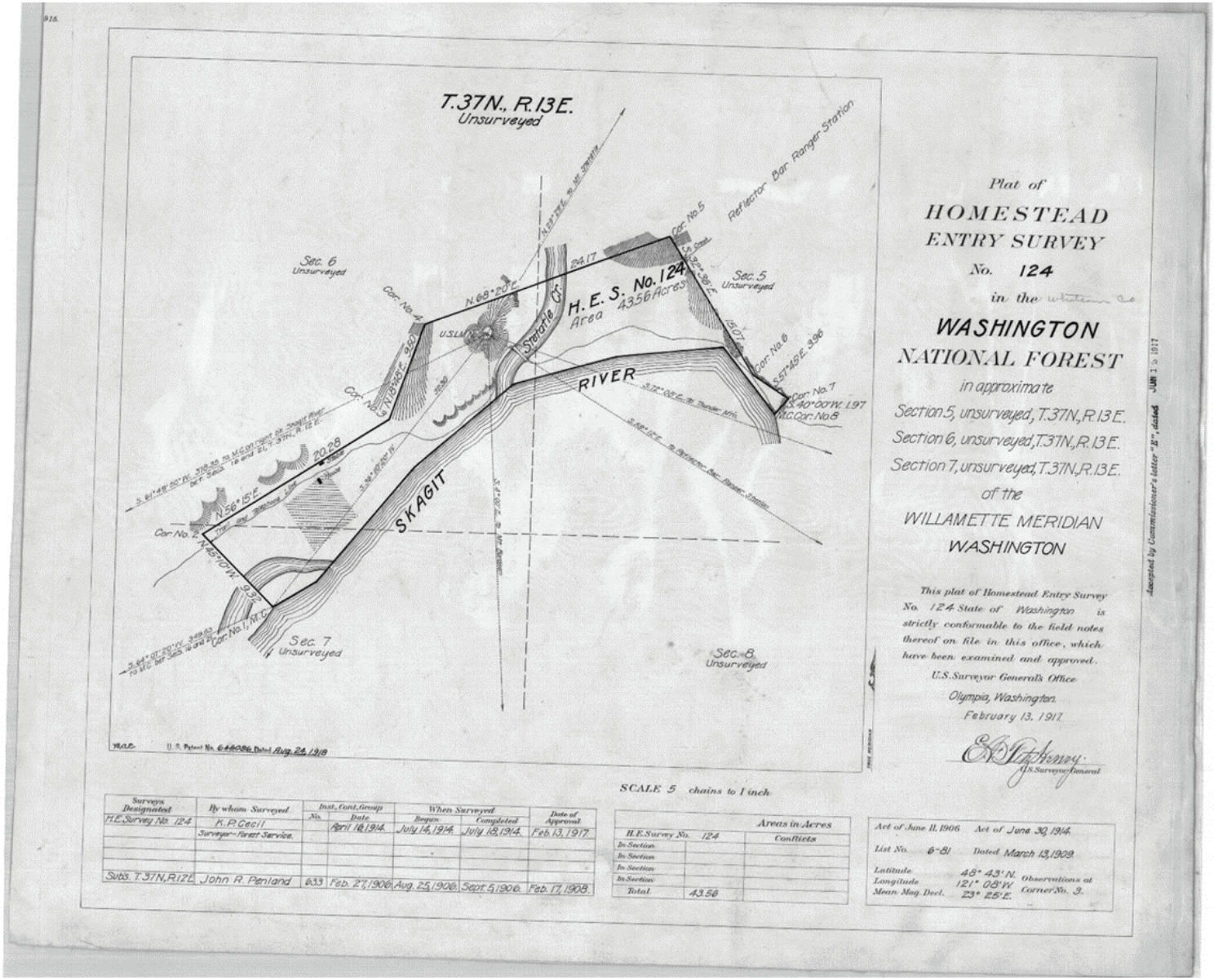


Figure 5.4-20. Stetattle Creek and Skagit River confluence, 1917 map (City Light).

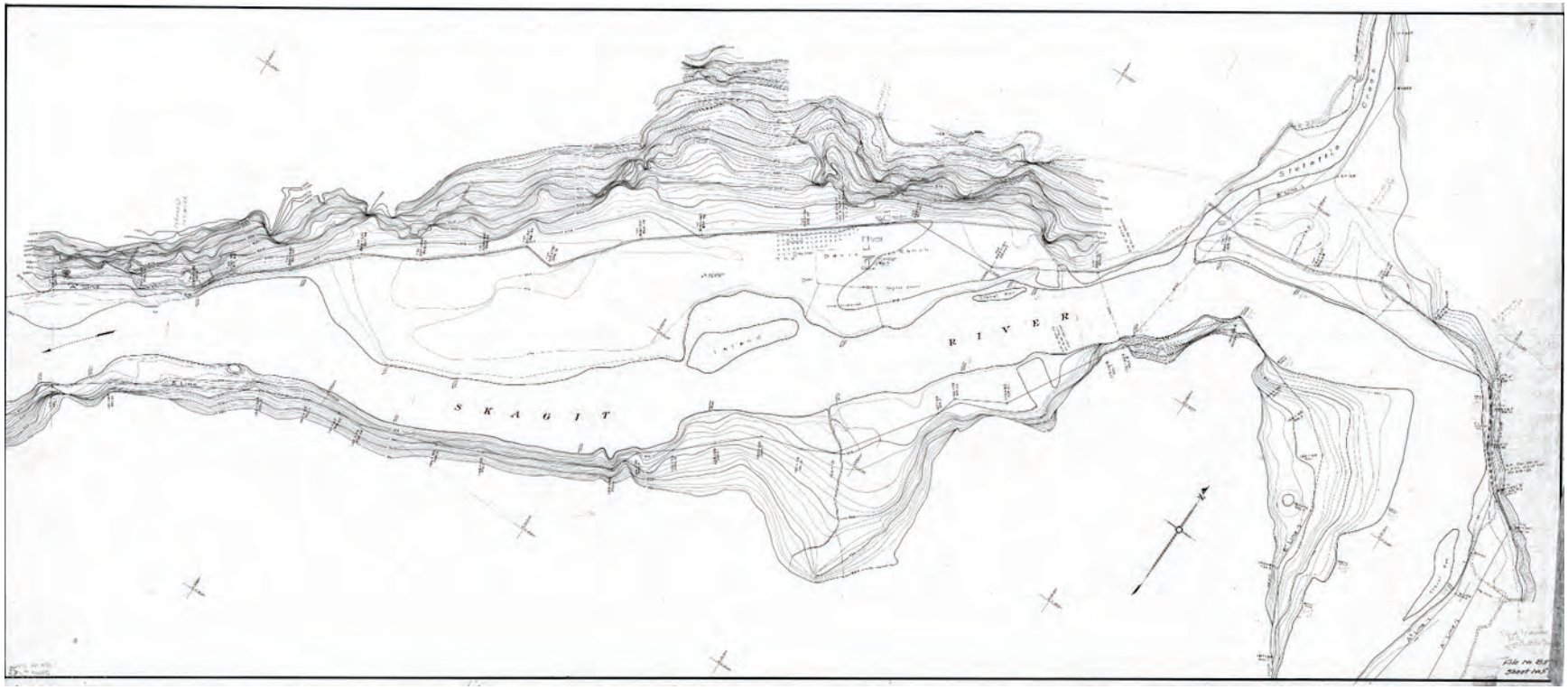


Figure 5.4-21. Stetattle Creek and Skagit River confluence, circa 1919 topographic map (City Light).

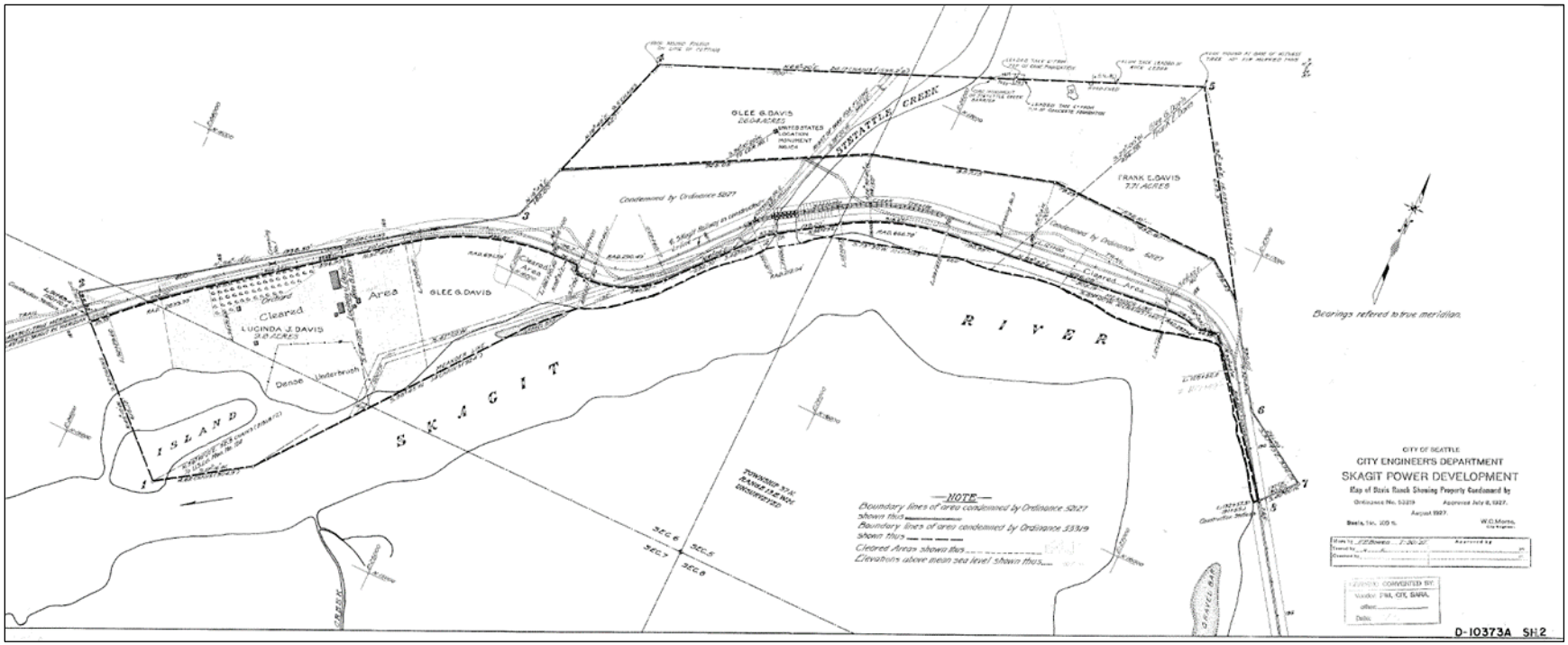


Figure 5.4-22. Stetattle Creek and Skagit River confluence, 1927 map (City Light).



Figure 5.4-23. Stetattle Creek Delta area, 1945 (photo credit KS Melson, City Light).

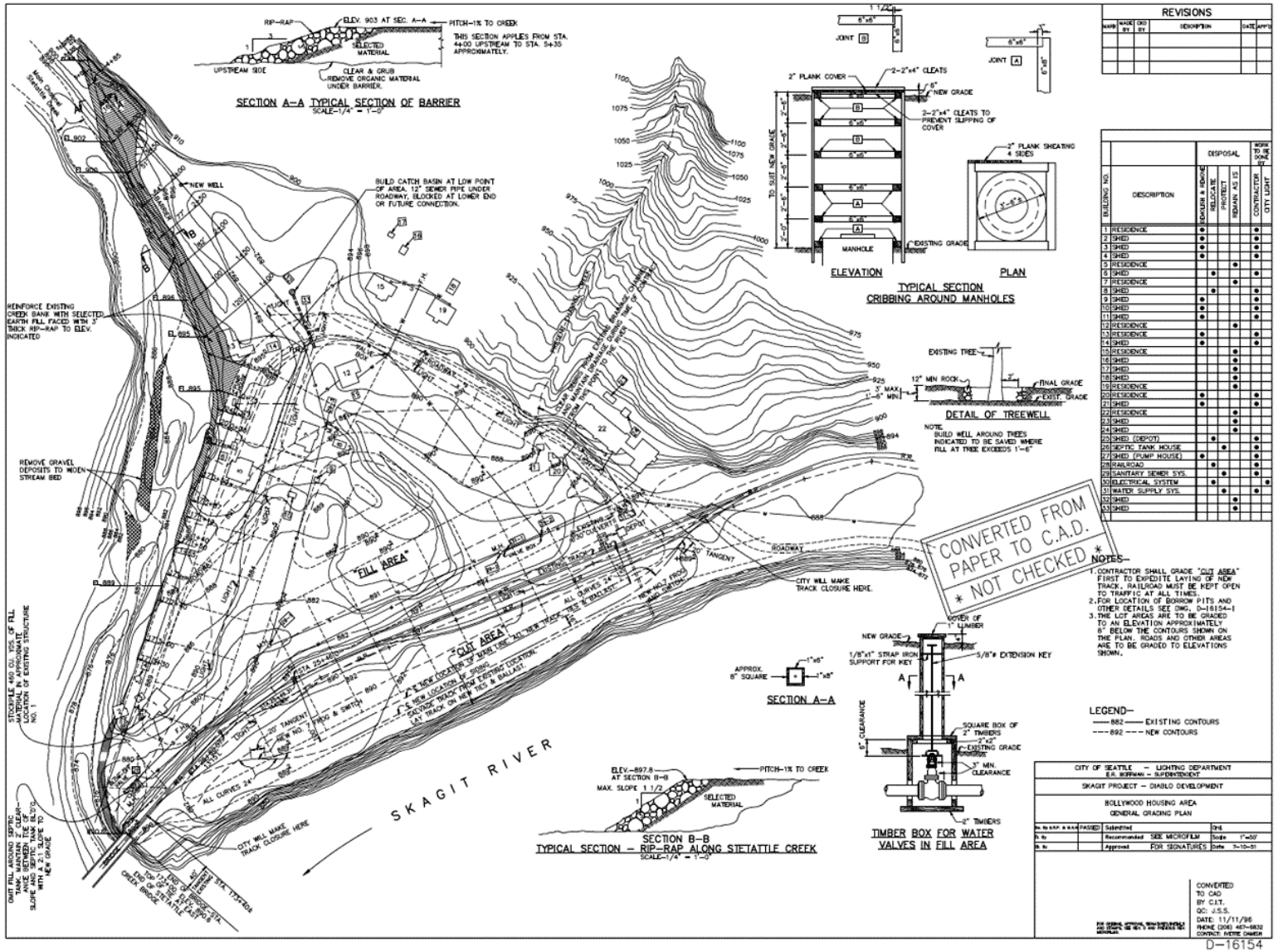


Figure 5.4-24. Stetattle Creek and Hollywood development plans, 1951 (City Light).



Figure 5.4-25. Stetattle Creek Delta area, August 1955, prior to Gorge High Dam (City Light).



Figure 5.4-26. Stetattle Creek Delta area, August 1990.



Figure 5.4-27. Stetattle Creek Delta area, July 22, 1998.



Figure 5.4-28. Stetattle Creek Delta area, circa 2008.



Figure 5.4-29. Stetattle Creek Delta area oblique photo, August 2013 (Gorge Lake drawdown).



Figure 5.4-30. Stetattle Creek delta area, 2018.



Figure 5.4-31. Stetattle Creek delta area, April 4, 2019 oblique photo (Gorge Lake drawdown).

5.4.5 Surficial Substrate

Stetattle Creek is a high gradient system that transports up to boulder-sized material to the mouth of the stream. Pebble count and grab sample data taken during this and previous studies show surficial grain size in the delta area varies greatly between different areas (Table 5.4-2, Figure 5.4-32 through 5.4-35).

Substrate within the lower portions of Stetattle Creek include boulder, cobble, and gravel material. The mid-channel bar that has been building between 400-800 ft upstream from the confluence has a median (d_{50}) grain size of 159 mm and is primarily boulder and cobble material (Figure 5.4-36).

Substrate on the primary delta at the confluence of Stetattle Creek and the Skagit River is very coarse-grained on the western (downstream) side, with median grain size of 90-200 mm. There are finer-grained deposits building into the deep pool on the eastern (upstream) side of the delta that have a median grain size of 3-21 mm and are composed primarily of sand and gravel.

No grain size samples were taken on the secondary delta, but visual estimates showed these deposits are composed primarily of gravel and sand.

Table 5.4-2. Stetattle Creek and delta grain size parameters.

Sample	Armor D_{65} (mm)	Armor D_{50} (mm)	Boulder (>256 mm)	Cobble (64-256 mm)	Gravel (2-64 mm)	Sand (0.063-2 mm)
Stetattle Mid Channel Bar 6	201	159	18%	72%	3%	7%
Stetattle Delta 1	118	93	3%	66%	31%	0%
Stetattle Delta 2	277	201	39%	46%	16%	0%
Stetattle Delta 5	89	74	0%	59%	41%	0%
Stetattle Delta 4	29	21	0%	4%	94%	2%
Delta Fines Site 4 - Sample B	18	9	0%	0%	77%	22%
Delta Fines Sample A	6	3	0%	0%	51%	47%

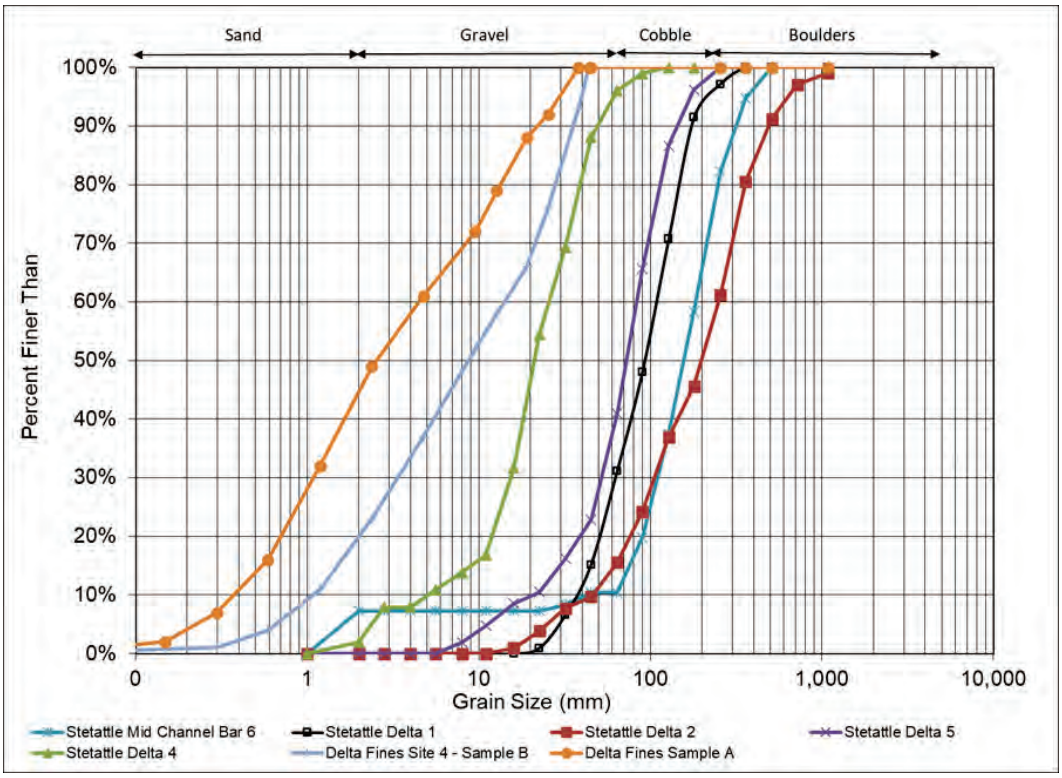


Figure 5.4-32. Stetattle Creek and delta substrate samples grain size distribution, September 2018.

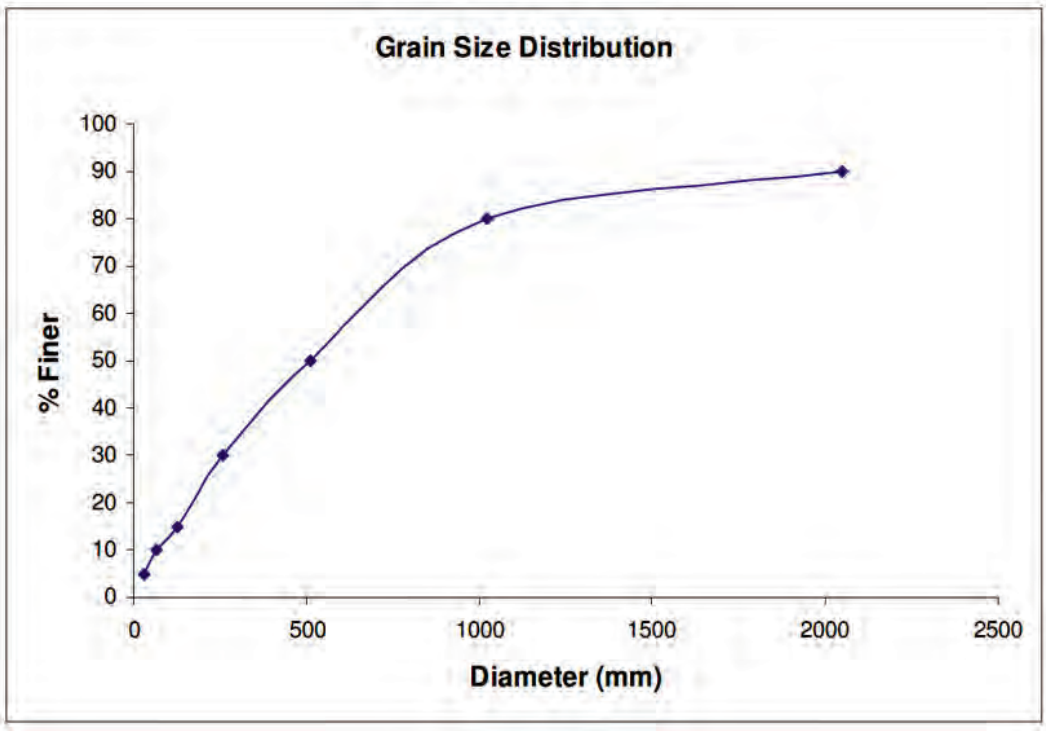


Figure 5.4-33. Stetattle Creek delta substrate sample, October 27, 2007 (4 months after spill event; from Seattle University 2008).

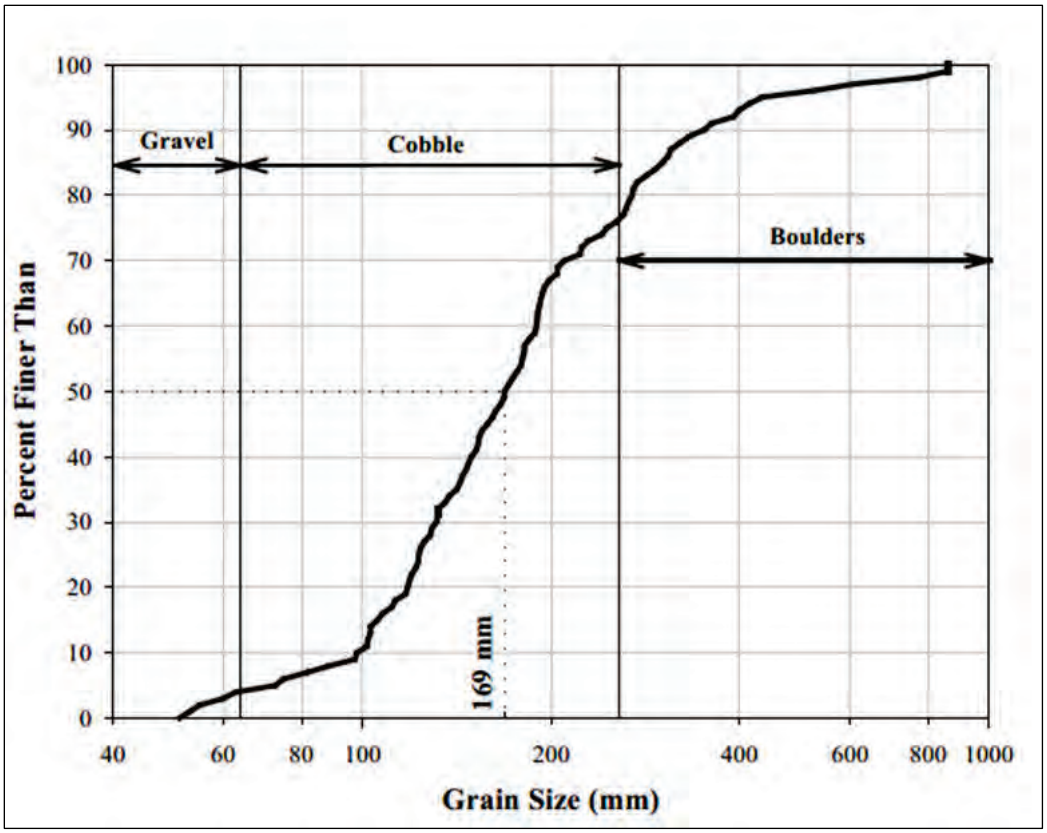


Figure 5.4-34. Stetattle Creek delta substrate sample, August 8, 2011 (R2 Resources, Inc. 2013).

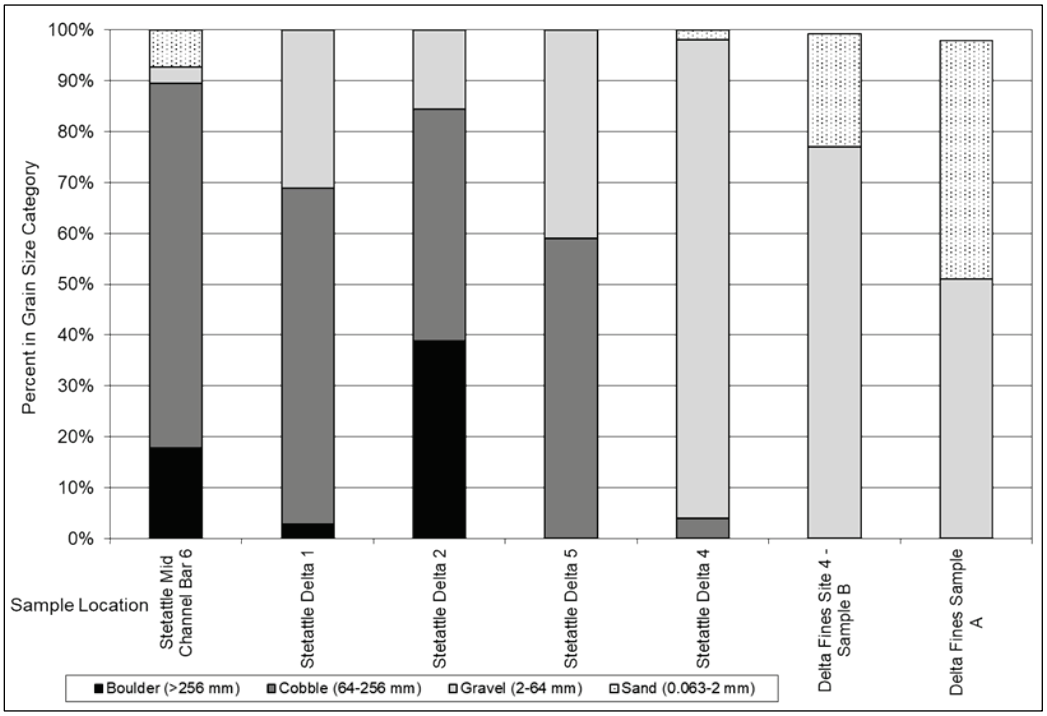


Figure 5.4-35. Stetattle Creek and delta substrate samples percent boulder, cobble, gravel, sand, 2018.

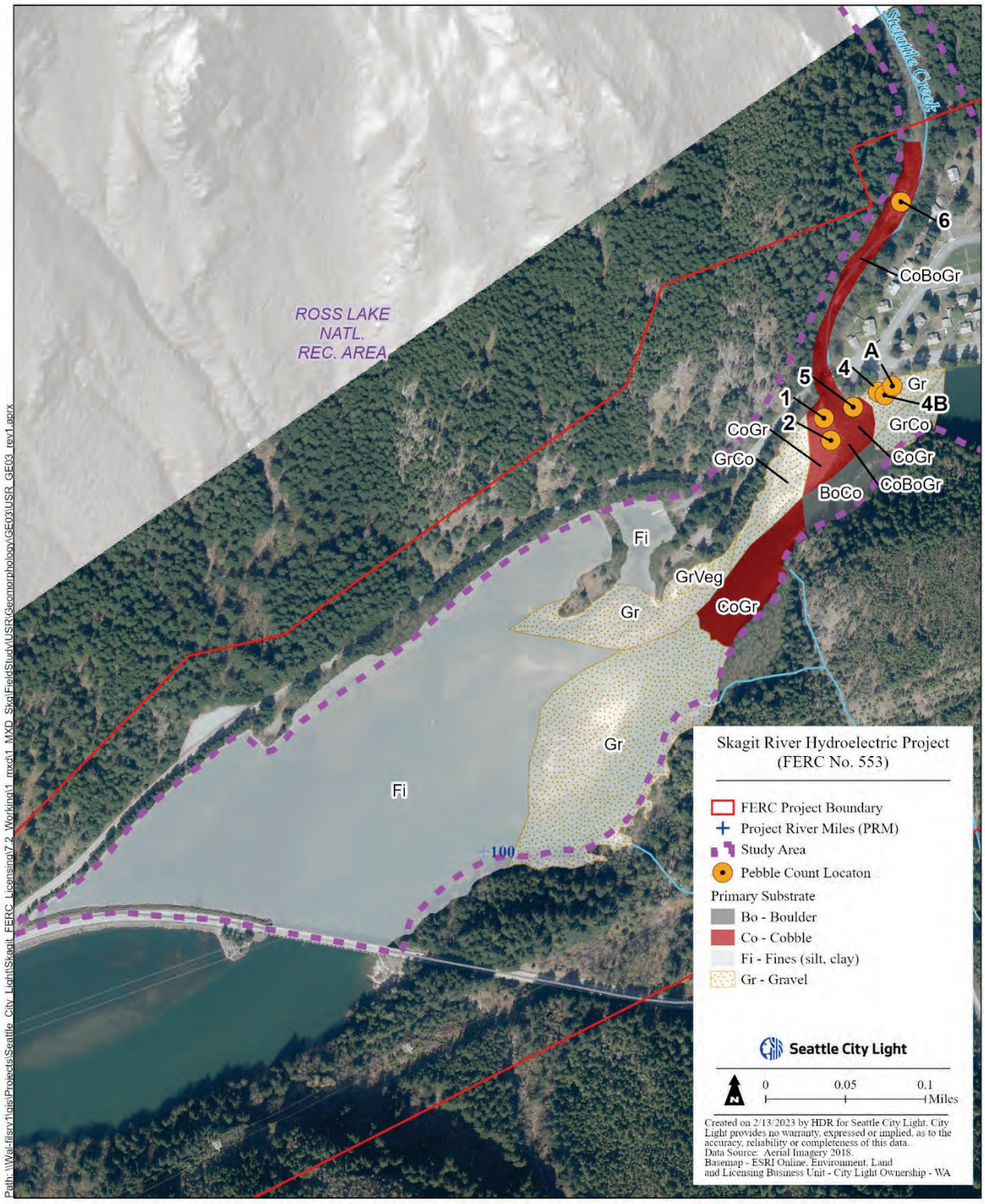


Figure 5.4-36. Surficial substrate in the Stetattle Creek delta area.

5.4.6 Sediment Transport Analysis

Sediment movement in lower Stetattle Creek and the delta area was assessed using the output from the 2-D hydraulic model to predict the critical grain size of sediment that could be picked up and transported under a variety of flows in Stetattle Creek and the Skagit River. Since peak flows in Stetattle Creek and the Skagit River are asynchronous (see discussion in Section 5.4.2.4 of this study report), the model was run with either peak flows in Stetattle Creek and low flows (3,500 cfs) in the Skagit River or high flows in the Skagit River and lower flows (500 cfs) in Stetattle Creek.

In Stetattle Creek, flows of 2,000 cfs (approximately a 2 year recurrence interval peak flow) are predicted to mobilize material up to 64 mm in size (coarse gravel and smaller particles), with cobble transport in some portions of the stream (Figure 5.4-37). In the primary delta, where Stetattle Creek enters the Skagit River, the coarse gravel material is predicted to settle out in the main channel with finer material on the upstream and downstream margins of the delta. Material up to boulder size can be transported under flows of 5,000 cfs (approximately 10 year recurrence interval, Figure 5.4-38) and large boulders under flows of 7,000 cfs (approximately 20 year recurrence interval, Figure 5.4-39). These findings are consistent with observations in Stetattle Creek and the primary delta, where cobble material show signs of frequent transport, and fresh deposits of cobble and boulder were seen on the delta covering small alders (Figure 5.4-40).

In the Skagit River, the critical grain diameter analysis suggested that only smaller material (gravel and finer) could be transported in the narrowest parts of the main channel under normal flows of 3,500 cfs (half powerhouse capacity, Figure 5.4-41) and, under flows of 6,000 cfs (approximately full powerhouse capacity, Figure 5.4-42), the gravel could be transported downstream into the secondary delta closer to the SR 20 bridge where deposits of gravel and cobble were observed. Under spill conditions (30,000 cfs), material up to coarse gravel and cobble size can be transported into the secondary delta (Figure 5.4-43).

These critical grain size analyses show that Stetattle Creek has a much higher competence to transport material than the Skagit River under existing conditions. Stetattle Creek can carry larger-sized material than the Skagit River, resulting in deposition of cobble and boulder material on the primary delta and gravel and finer material on the secondary delta.

Growth of the primary delta toward the opposite (left) bank of the Skagit River is limited due to the bedrock on the left bank that forms an immovable constriction and results in a narrow, high velocity chute that minimizes deposition. As a result, the delta is growing upstream and downstream from the confluence as material is deposited in the upstream deep pool and downstream secondary delta. These depositional trends will continue in the future.

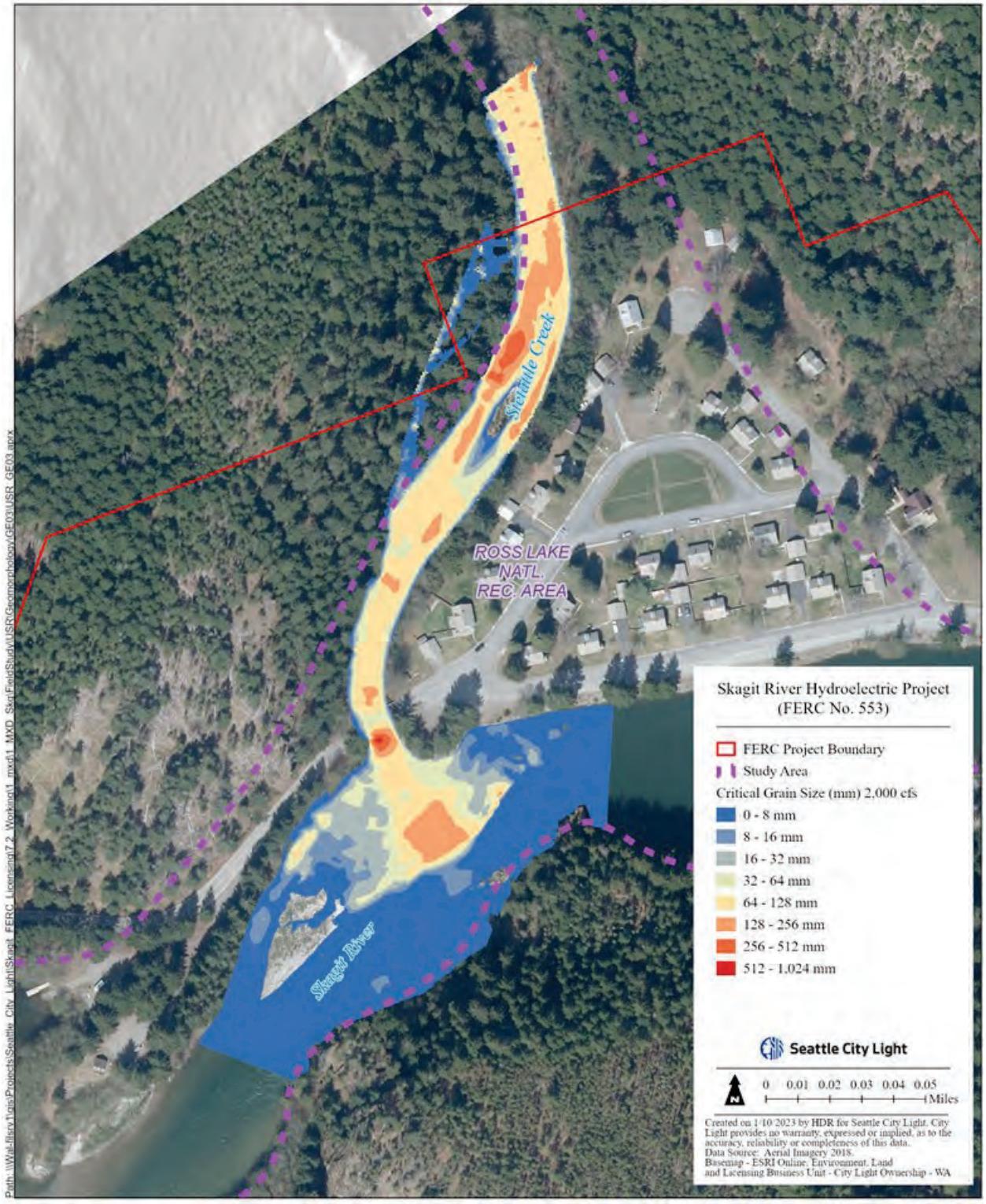


Figure 5.4-37. Critical grain size (mm) with flow of 2,000 cfs in Stetattle Creek.

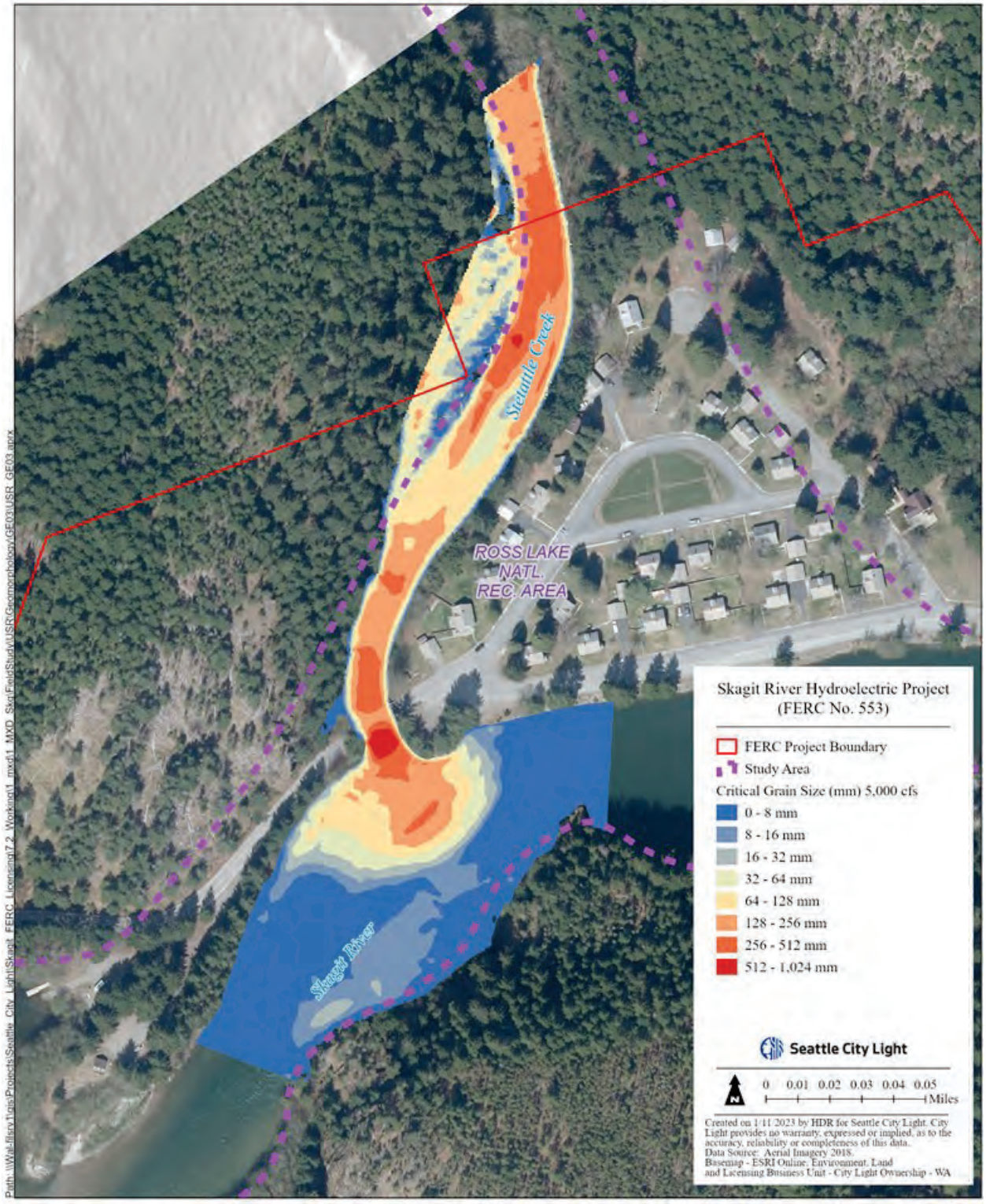


Figure 5.4-38. Critical grain size (mm) with flow of 5,000 cfs in Stetattle Creek.

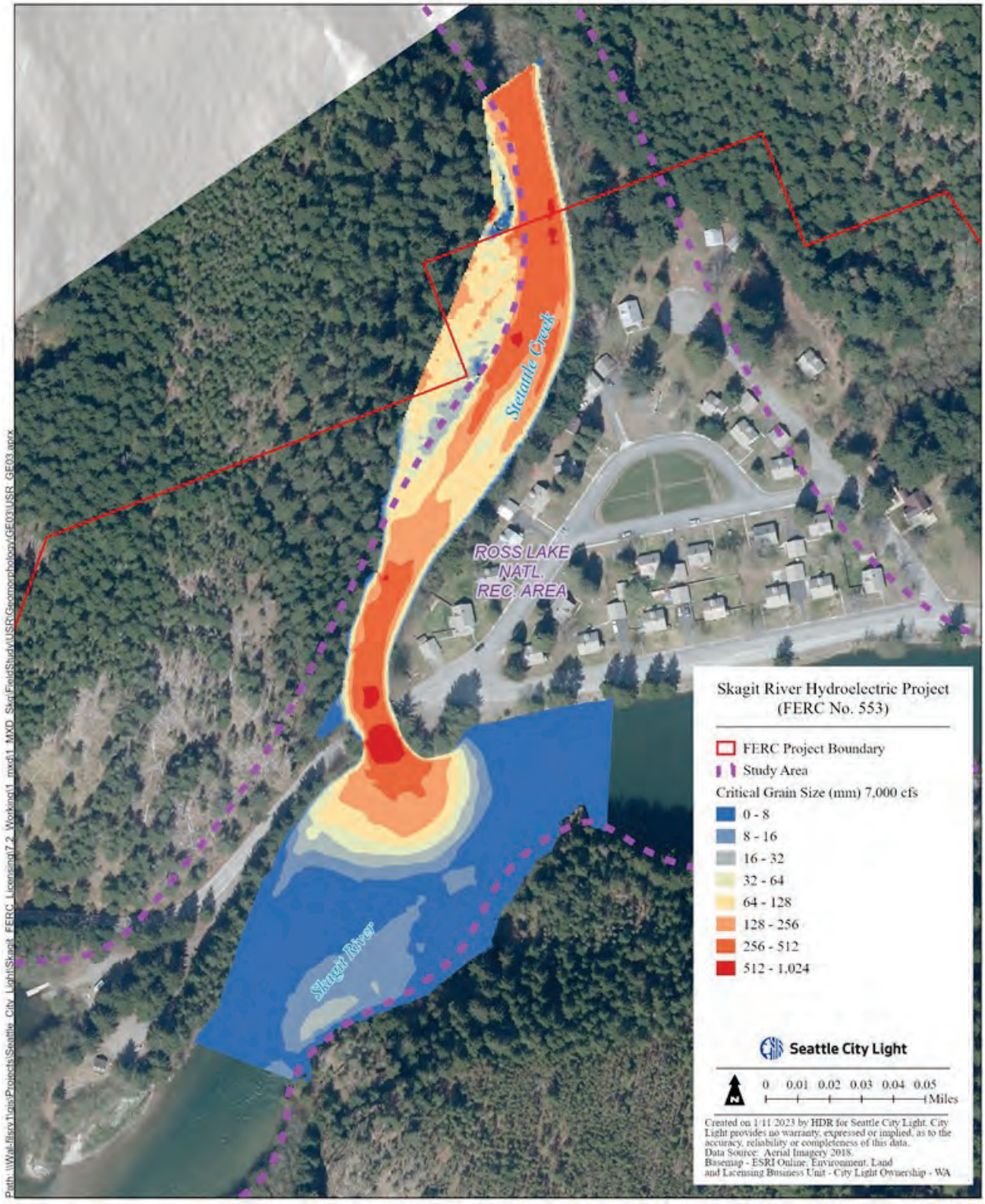


Figure 5.4-39. Critical grain size (mm) with flow of 7,000 cfs in Stetattle Creek.



Figure 5.4-40. Stetattle Creek delta 2018 showing recent deposition of cobbles and boulders on young alders.

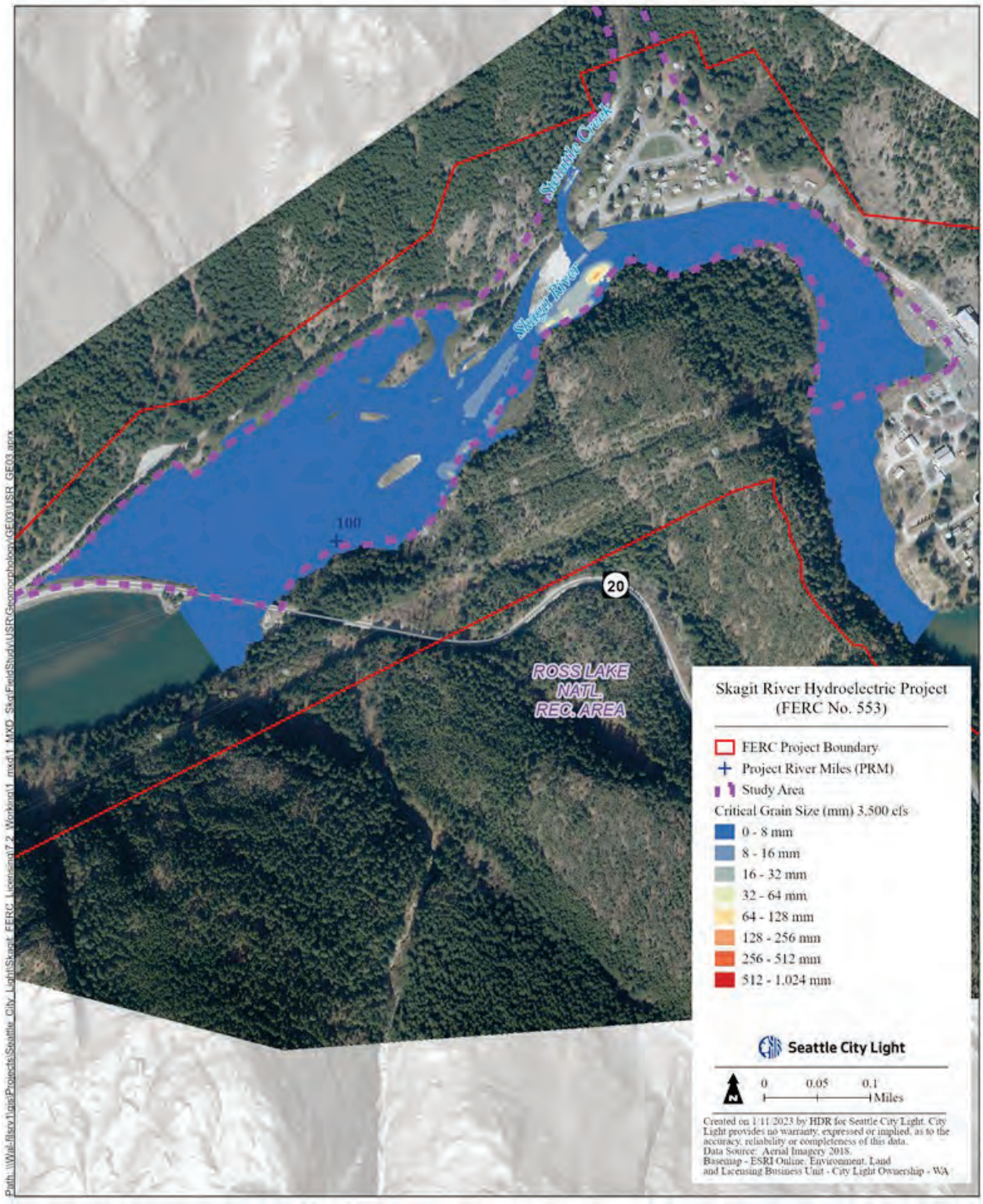


Figure 5.4-41. Critical grain size (mm) with flow of 3,500 cfs in Skagit River.

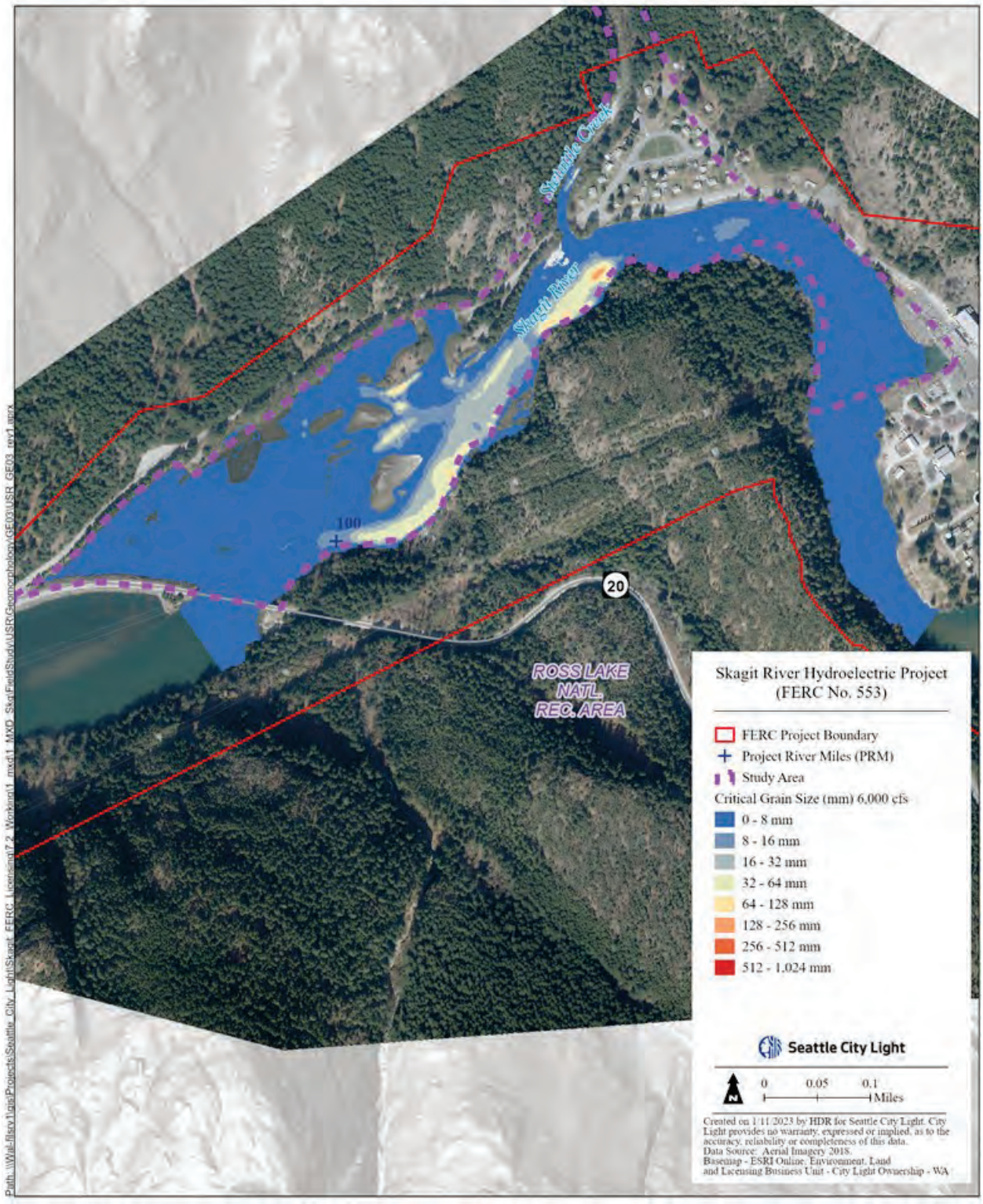


Figure 5.4-42. Critical grain size (mm) with flow of 6,000 cfs in the Skagit River.

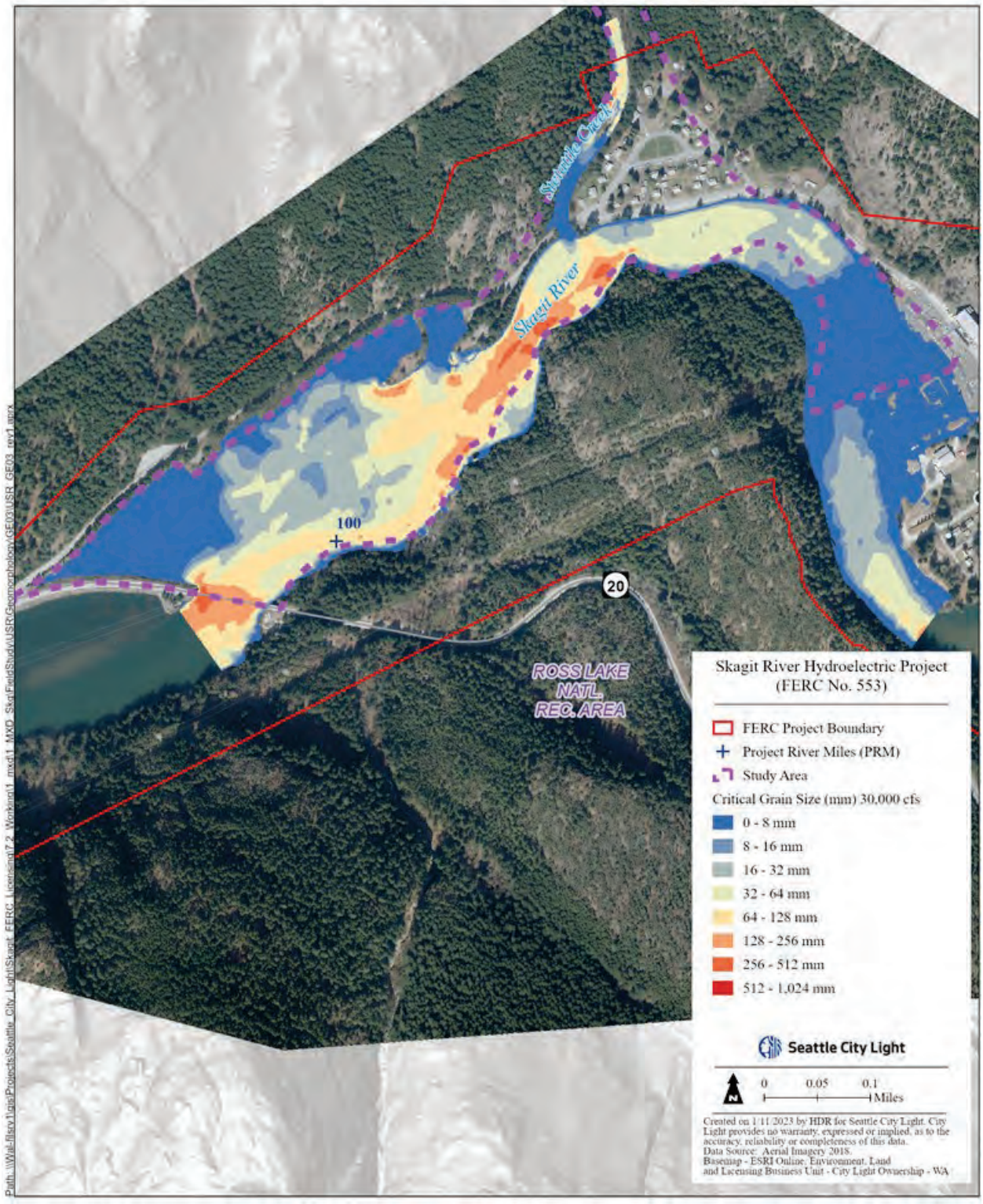


Figure 5.4-43. Critical grain size (mm) with flow of 30,000 cfs in the Skagit River.

5.4.7 Gorge Lake Boat Launch

The Gorge Lake boat launch is located in an embayment on the north side of Gorge Lake near the campground. This embayment is a location of fine sediment deposition. In addition, gravel deposition in the secondary delta area results in very shallow water depths at the outlet to the boat launch embayment, which precludes many large boats from using the launch to reach the lake, particularly when Gorge Lake levels are low.

5.5 Sediment Retention Rates in Project Reservoirs

Average annual sediment retention rates within the three Project reservoirs were estimated using a regional regression analysis and calculated trap efficiencies (Table 5.5-1).

Table 5.5-1. Estimated average annual reservoir sediment retention rates.

Reservoir	Estimated average annual reservoir sediment retention rate (cu yd/year)			
	Total	Boulder, cobble, gravel	Sand	Silt/clay
Ross Lake	160,600	19,400	10,900	130,300
Diablo Lake	191,300	35,600	21,400	134,300
Gorge Lake	35,600	18,100	17,500	0 (very small amount)

5.6 Ross Lake Drawdown Zone Substrate and Erosion/Deposition Process Mapping

Surficial substrate in the Ross Lake drawdown zone and dominant erosion or deposition process is shown on Figures 5.6-1 through 5.6-6. Substrate on the maps is color coded by and labeled with dominant substrate size. Dominant erosion/deposition processes are overlain in a hatched/striped pattern on the map so that both substrate and dominant process can be seen at once. Note that the substrate and process units were mapped on the area exposed when the 2018 aerial photographs were taken on April 25, 2018. This was during a very low drawdown, with Ross Lake water surface elevation at 1,493.16 ft NAVD 88 (1,486.86 ft CoSD). See Figure 5.1-1 above (Quantum Spatial 2018b). This low drawdown exposed large areas of fine-grained sediment in the upper end of Ross Lake; drawdown level at a particular time or during a particular year affects the percentage of total area calculations discussed in the following section.

Substrate ranged from bedrock to fine-grained silt/clay. The percentage of the total area mapped from the 2018 aerials is shown in Table 5.6-1. Fine-grained sediment covered over 60 percent of the drawdown area and was mapped in lower elevation areas of the reservoir that are normally inundated, in the upstream one-third of the reservoir between Hozomeen and Arctic Creek, and in low elevation areas near major tributary deltas. Much of the normal drawdown zone slopes are underlain by gravel-cobble mixes (19 and 9 percent respectively). Bedrock was exposed in areas where thin soil overlaying shallow bedrock was eroded, likely areas where glacial scour occurred during the Pleistocene and left bedrock knobs or hillsides. Lag boulders occur primarily as secondary substrate in areas where boulders were part of the former soil/geologic units (e.g., talus, glacial till) that have been eroded through time in the reservoir fluctuation zone. Sand occurred primarily in deltas of larger tributaries, most notably Big Beaver Creek delta area.

Table 5.6-1. Ross Lake drawdown zone dominant substrate distribution.

Dominant Substrate	Percent of drawdown zone area
Fines	61%
Sand	4%
Gravel	19%
Cobble	9%
Boulder	1%
Bedrock	6%
Other (rip rap, manmade)	< 1%

The Ross Lake drawdown zone was also partitioned according to the dominant erosion or deposition process that occurs as the lake level rises and falls seasonally and as waves and tributaries re-work the exposed sediments (Figure 5.6-1 through 5.6-6 and Table 5.6-2). The majority of the 2018 exposed reservoir area was dominantly a deposition zone, with deposition occurring primarily in areas covered with fine-grained deposits in the upstream end of Ross Lake (Hozomeen area) and in lower elevation or flatter areas of the reservoir.

Table 5.6-2. Ross Lake drawdown zone dominant erosion/deposition process.

Dominant Substrate	Percent of drawdown zone area
Deposition	45%
Erosion	15%
Fluvial Reworking	32%
Lacustrine Reworking	8%

The fluvial re-working process areas are dominated by active river/stream delta activity and denote locations where flowing water alternately deposits or erodes sediments as the lake level rises and falls seasonally. Deposition takes place in these areas at and below the stream/lake water interface; stream erosion and re-working takes place on exposed sediments when the lake is drawn down.

Drawdown zone areas dominated by erosion processes occur along the upper elevation portions of the drawdown zone where wave action is concentrated (Figure 5.1-2 above) and finer-grained sediment is winnowed out and transported downslope or out into the lake. Reservoir drawdown areas between the higher-elevation-dominantly-erosion and low-elevation-dominantly-deposition zones were mapped as lacustrine reworking areas. In these areas, wave action moves sediment downslope, but some deposition from upslope erosion also occurs.

Soil probes and cores were taken in five locations mapped as deposition or fluvial reworking zones to help determine the depth of deposits. These locations are shown on Figures 5.6-1 through 5.6-6 as green circles and include Hozomeen, Cat Island, Lightning Creek delta, Big Beaver delta, and the northwest end of Ruby Arm. Core/probe depth was limited to 5 ft, so areas with deposits over 5 ft deep were noted as such. The range of core/probe depth and general soil texture in each area is shown in Table 5.6-3. Note that these depths do not imply that thicker deposits were present, but core locations were chosen in some of the areas to determine depths near the edges of deposits.

Table 5.6-3. Ross Lake range of soil core/probe depth by area.

Area	Range of core/probe depth (ft)	Soil texture
Hozomeen	1.3 to over 5	Fines (silt/clay) to fine sand
Cat Island	0.8-1.95	Silt to fine gravel
Lightning Creek delta	0.5 to over 5	Fines (silt/clay) to fine sand
Big Beaver delta	1.1-3.2	Sandy
Northwest end of Ruby Arm	0.25-0.7	Fines (silt/clay) to sand

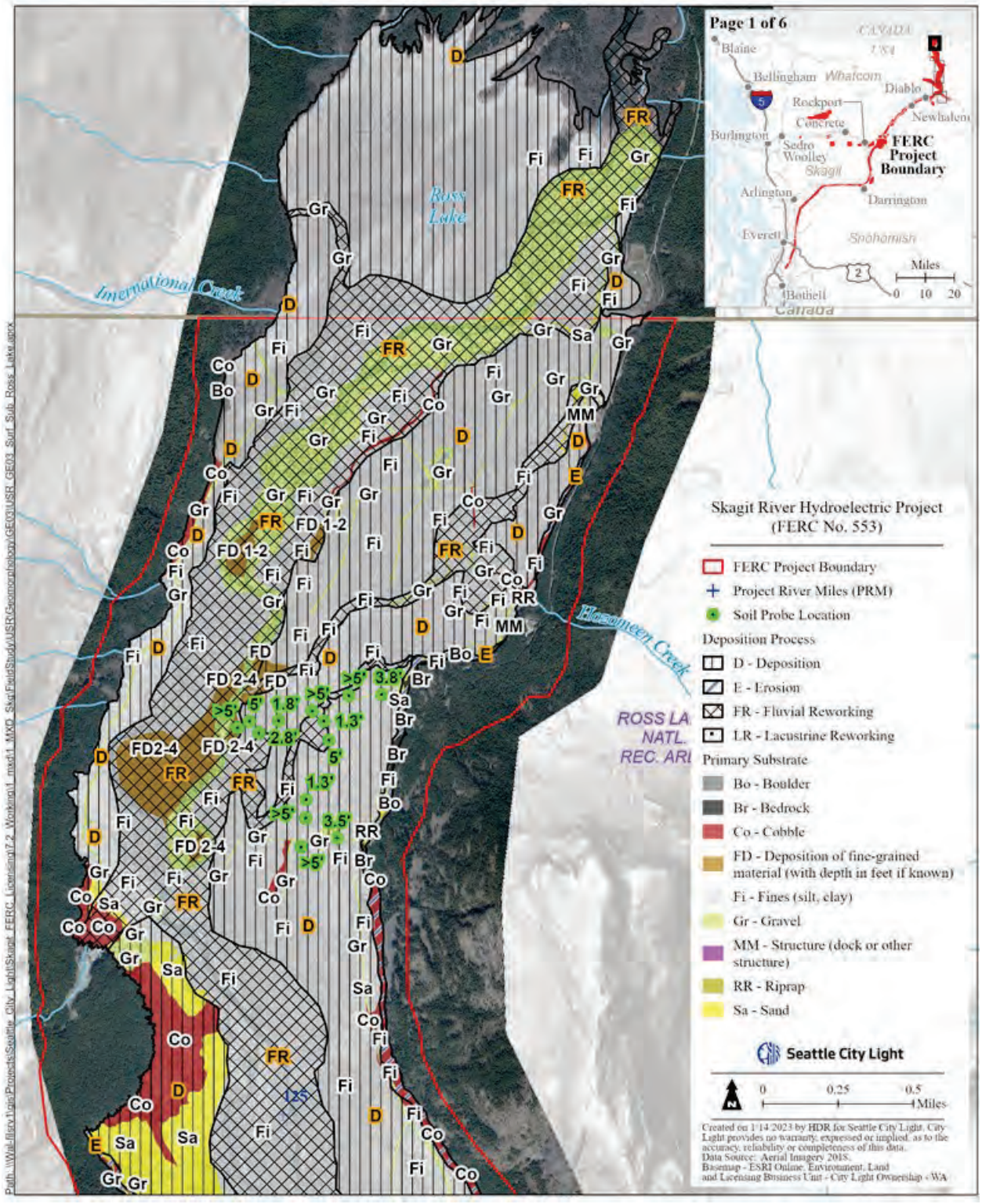


Figure 5.6-1. Substrate and erosion/deposition process in the Ross Lake drawdown zone (page 1 of 6).

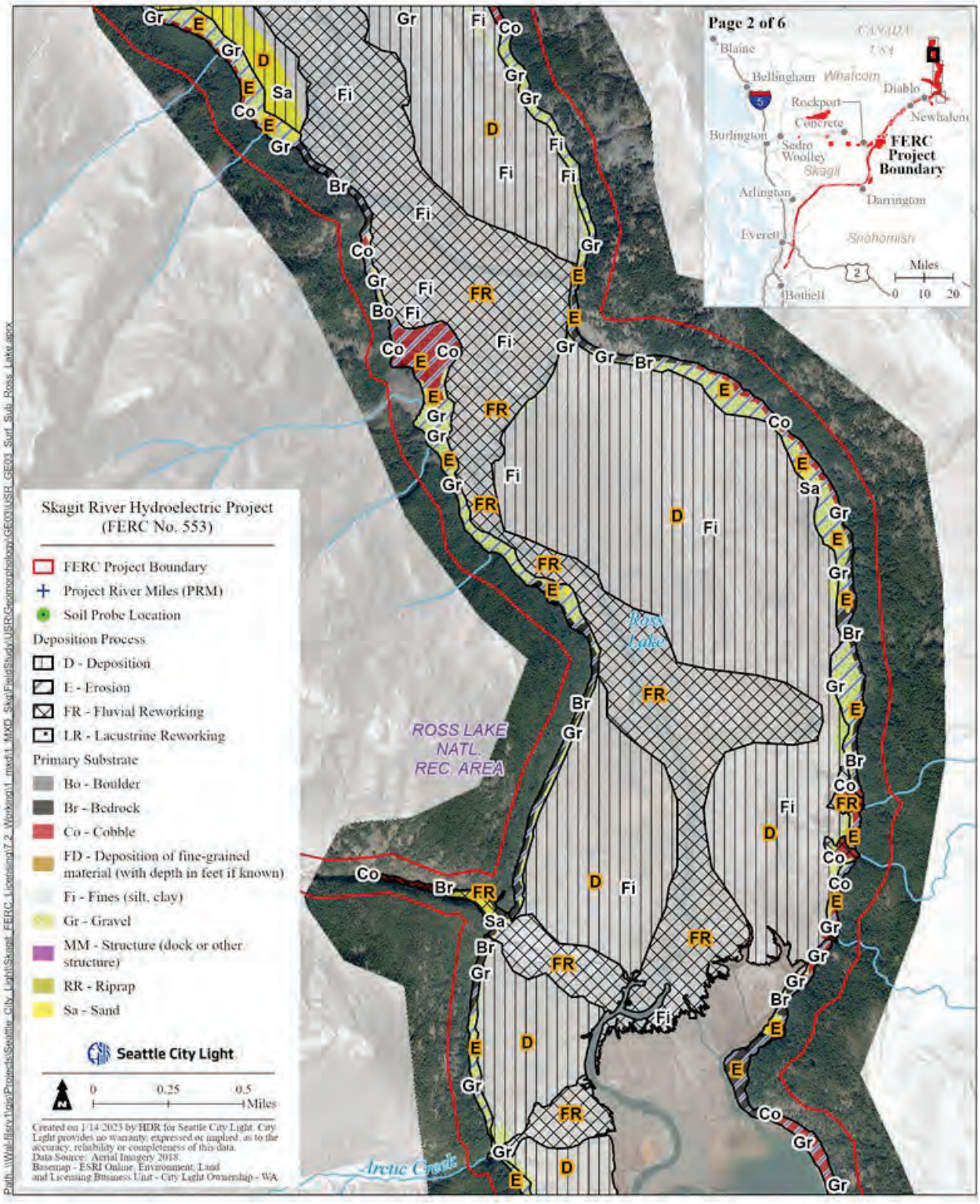


Figure 5.6-2. Substrate and erosion/deposition process in the Ross Lake drawdown zone (page 2 of 6).

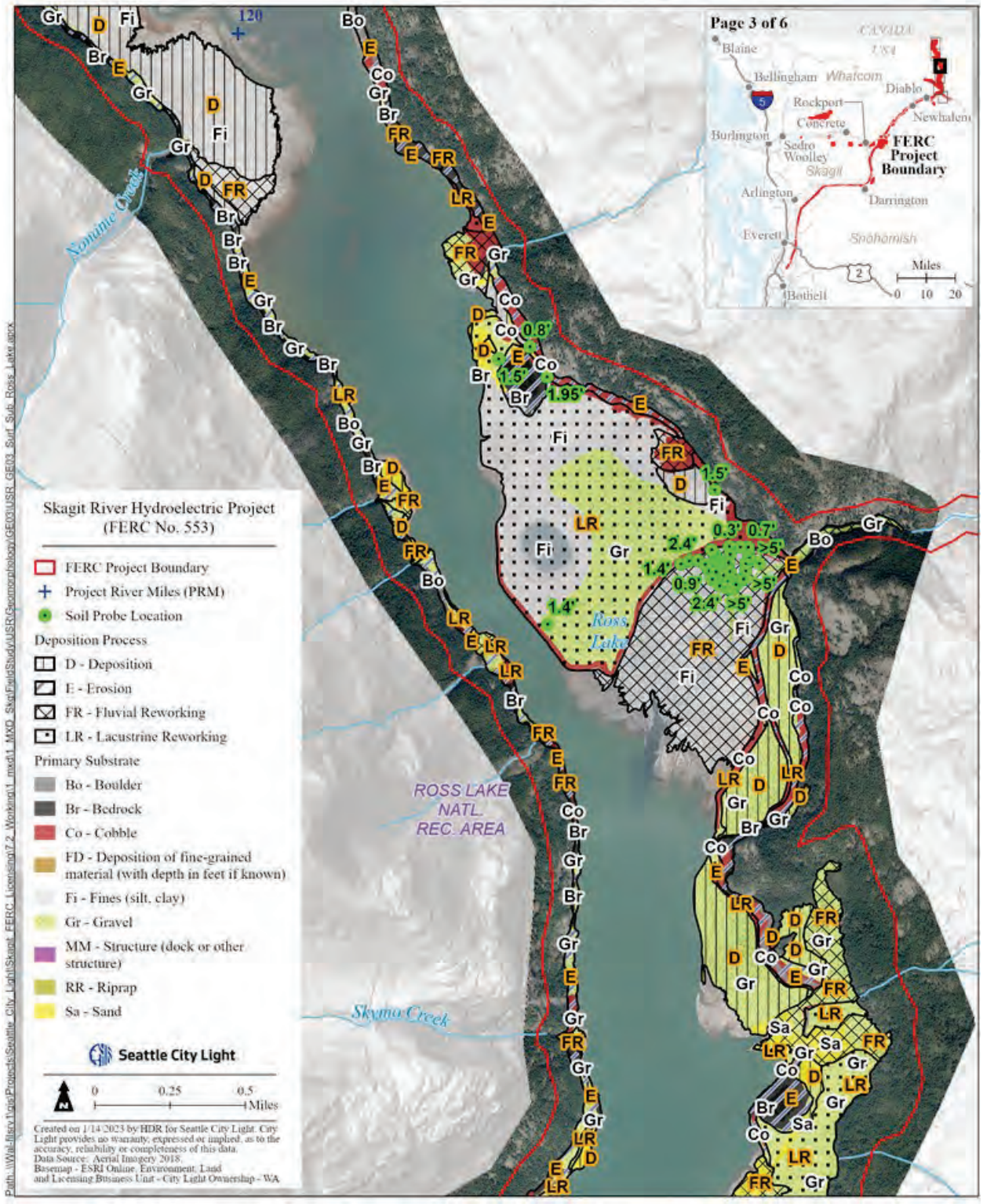


Figure 5.6-3. Substrate and erosion/deposition process in the Ross Lake drawdown zone (page 3 of 6).

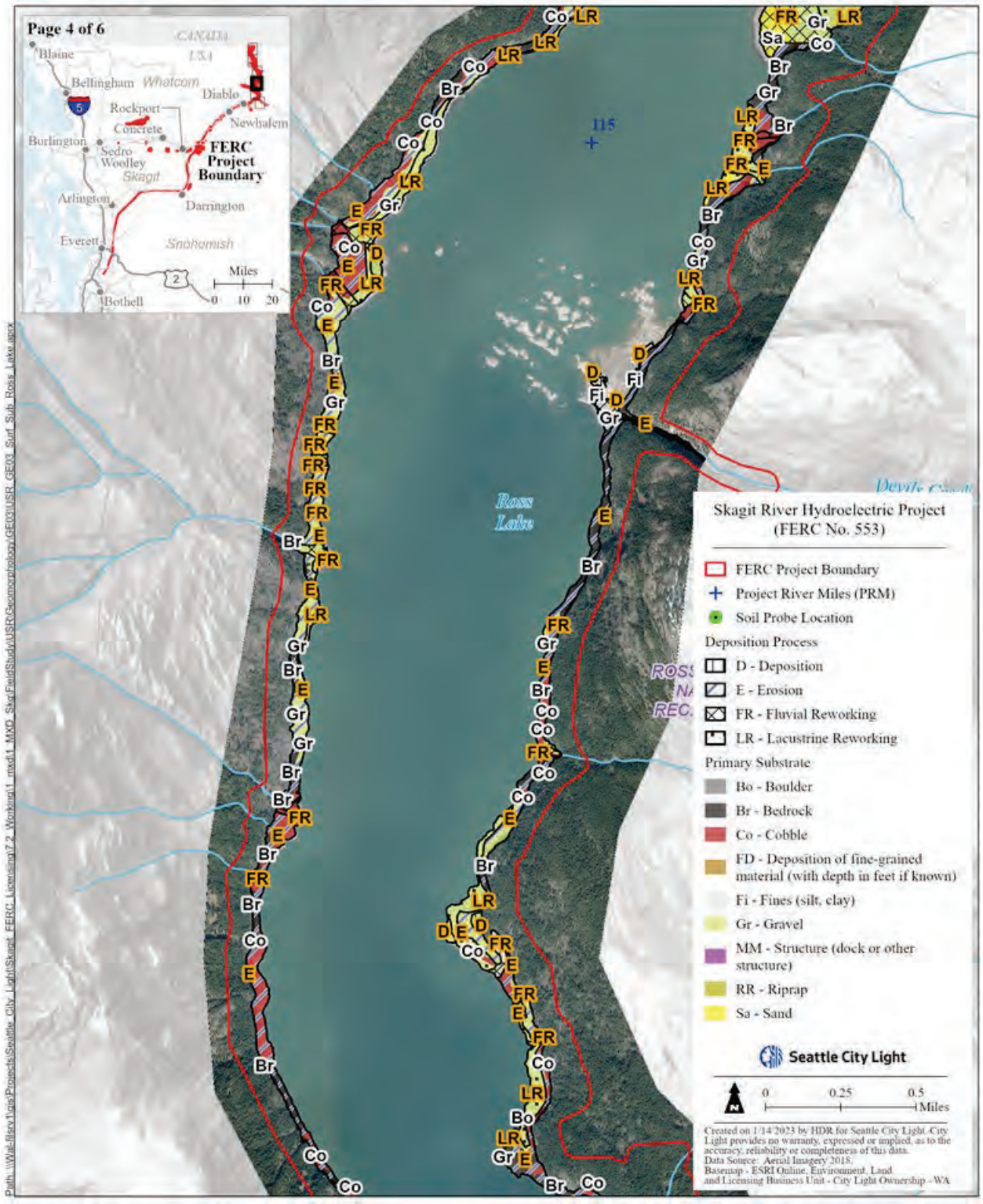


Figure 5.6-4. Substrate and erosion/deposition process in the Ross Lake drawdown zone (page 4 of 6).

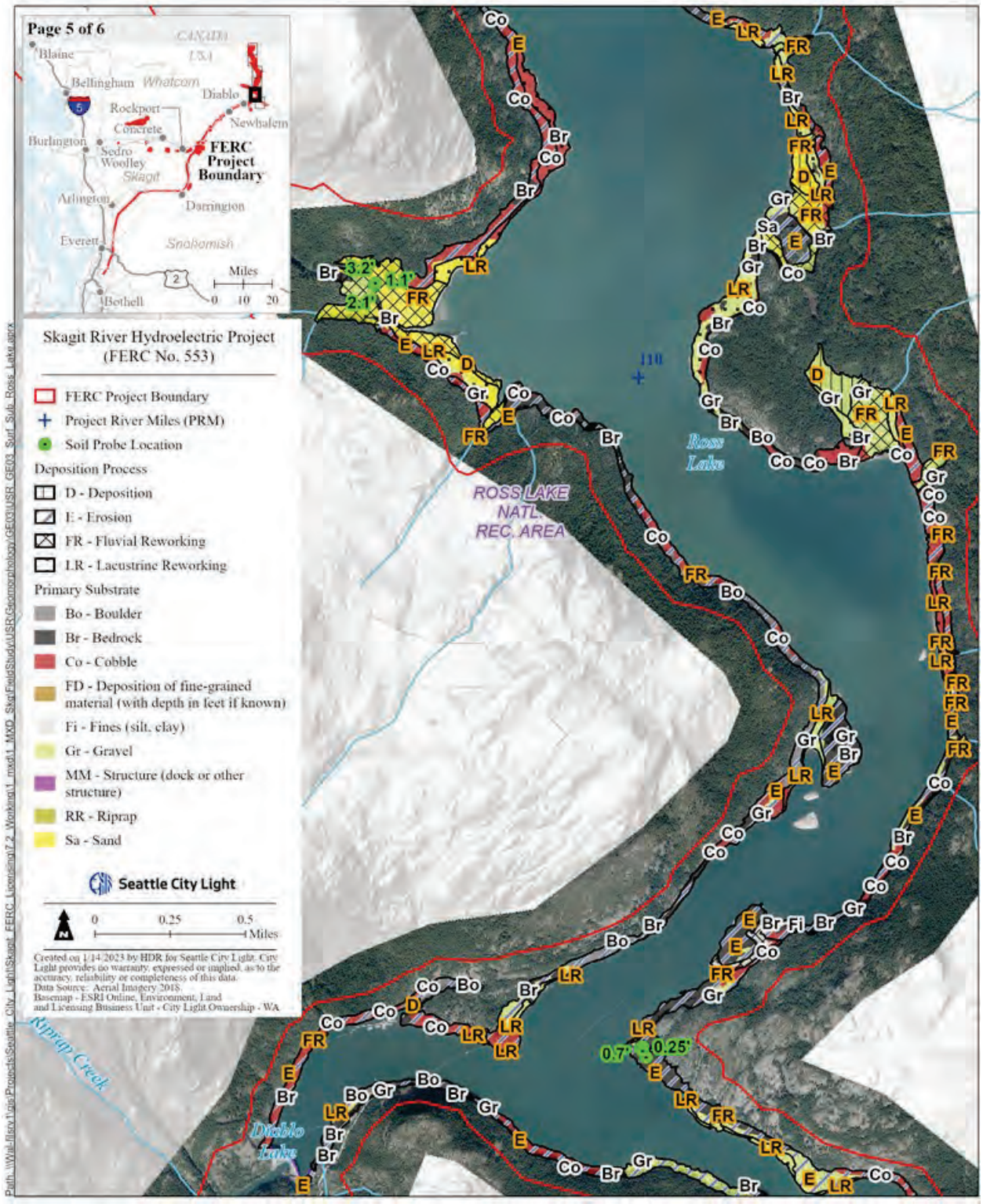


Figure 5.6-5. Substrate and erosion/deposition process in the Ross Lake drawdown zone (page 5 of 6).

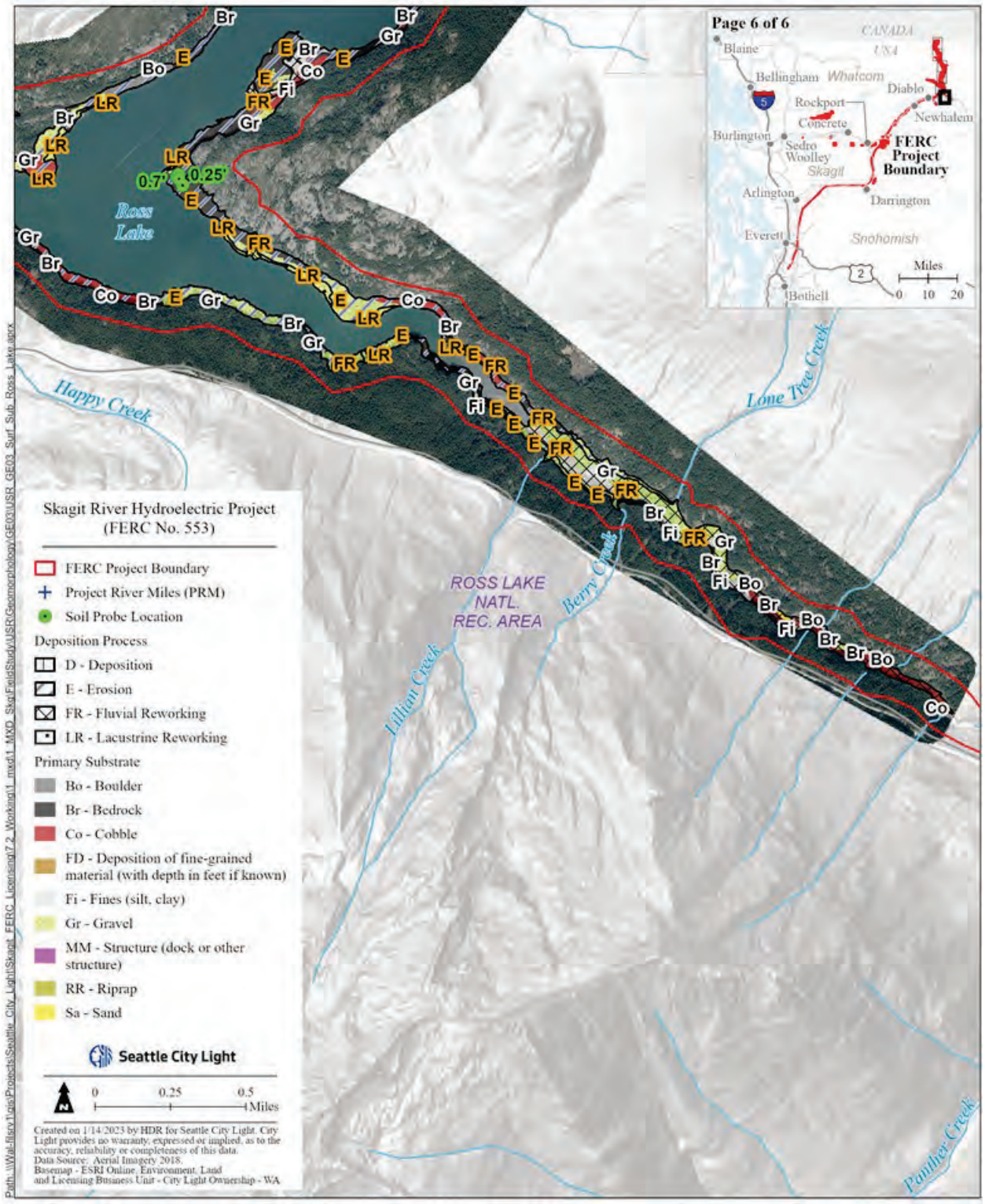


Figure 5.6-6. Substrate and erosion/deposition process in the Ross Lake drawdown zone (page 6 of 6).

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. The overall goal of the Sediment Deposition Study is to evaluate the effects of deposition on four specific locations within Ross, Diablo, and Gorge lakes with identified recreational resources and/or Project operations impacts. This study report includes data from the 2021 and 2022 field seasons and subsequent analyses. Each of the study objectives was met as described in Section 4.0 above and further summarized below.

- Describe and map the location and history of sediment deposition in the:
  - Hozomeen inlet in Ross Lake (Section 5.1);
  - Sourdough Creek inlet in Diablo Lake (Section 5.2);
  - Thunder Arm in Diablo Lake (Section 5.3); and
  - Stetattle Creek delta in Gorge Lake (Section 5.4).
- Determine rate and grain size of sediment input, quantify total volume of sediment deposition in the four inlets and deltas, and estimate rate and patterns of deposition (Sections 5.1 through 5.4);
- Identify likely future zones and patterns of deposition with respect to recreational resources and operational impacts (Sections 5.1.4, 5.2.6, 5.3.3, and 5.4.6);
- Quantify sediment supply of all size ranges (i.e., grain size distribution estimate) in Ross, Diablo, and Gorge lakes as an average annual rate by using the regional sediment yield regression analysis[4] (Sections 5.1 through 5.4);
- Assess (map) deposition and erosion in the Ross Lake drawdown zone (Section 5.6); and
- Use a backwater model to estimate magnitude and location of reservoir backwater effects in the four study deltas as appropriate (Thunder Arm, Section 5.2.5 and Stetattle Creek Section 5.4.5).

The analysis of sediment deposition patterns in the four areas where deposition was hypothesized to be causing impacts to recreational or operational resources found the following:

- In the Hozomeen area, sediment deposition rates are very low and are not causing impacts to any boat launches or other recreational facilities. It is anticipated that these conditions will continue in the future.
- Sourdough Creek is a steep tributary with an alluvial fan and episodic debris flows/torrents that deliver large amounts of boulders, cobble, gravel, and sand to the Sourdough Creek inlet. The resulting sediment deposits can fill the vented ford, block the access road to North Cascade Institute facilities, and affect adjacent parking lots and the woody debris extraction area. Future debris flows/torrents and associated maintenance of the vented ford, access road, parking

[4] DHSVM was determined not to be an appropriate tool to estimate regional sediment yield. Bathymetric data was unavailable to complete the planned estimate of sediment retention in each reservoir and delta analysis area. Instead, a regional regression analysis was used to estimate sediment input to meet the objectives of the study.

facilities, and boat/barge/woody debris extraction facilities are expected over the term of the new license; climate change may result in more frequent events.

- Deposition from three separate sources is affecting Thunder Arm. Thunder Creek enters at the upstream end of Thunder Arm and depositional patterns are affected by the backwater from Diablo Lake and the SR 20 highway bridge constriction. A large log jam developed in 2003, and subsequent deposition appears to have resulted in the death of low elevation cedar groves up to 0.5 miles upstream from the log jam. The Thunder Creek stream gage also shows evidence of aggradation since the 2003 event. Deposition of finer-grained sediment in Thunder Arm results in shallow water and limits boat water access to the boat launch, boathouse, and City Light temporary barge landing. Deposition of cobble, gravel, and sand from episodic debris flows in Colonial Creek and Rhode Creek is also limiting land access to and the usefulness of the boat launch, boathouse, and temporary barge landing and has the potential for covering these facilities in the future.
- Stetattle Creek provides boulder, cobble, gravel, and finer sediment to the Skagit River downstream from the Diablo Powerhouse. The supplied sediment is larger than flow in the Skagit River can carry, resulting in development of a coarse-grained (boulder/cobble) primary delta at the mouth of Stetattle Creek and a finer-grained (gravel, sand) secondary delta upstream from the SR 20 crossing. Hydraulic modeling shows that both of these deltas are affecting backwater elevations and resulting hydraulic capacity of the Diablo Powerhouse, and the Skagit River does not have the competence to move the accumulated sediment. Deposition in the secondary delta is also affecting access to the Gorge Lake boat launch and dock. These depositional trends will continue in the future.

Mapping of dominant/subdominant substrate size was completed in the Ross Lake drawdown zone, as well as mapping of dominant erosion/deposition process areas in the drawdown zone.

6.1 Status of June 9, 2021 Notice

As part of the June 9, 2021 Notice, several commitments were made by City Light to augment the Sediment Deposition Study. The status of each of these commitments is summarized in Table 6.1-1.

Table 6.1-1. Status of Sediment Deposition Study modifications identified in the June 9, 2021 Notice.

Study Modifications identified in the June 9, 2021 Notice: As Written	Status
Assess sediment sequestration quantity and character in all three project reservoirs; add a comprehensive sediment survey in reservoirs. City Light will quantify sediment supply of all size ranges (i.e., grain size distribution estimate) into Ross, Diablo, and Gorge Reservoirs as an annual rate by using the existing DHSVM model, historical contours, and updated bathymetry information. Workgroup will discuss sediment size and characterization available from DHSVM model.	As described in the ISR, the DHSVM model is not an appropriate tool to use to estimate sediment supply to the reservoirs, so it was not used for this study. Additionally, updated bathymetric data was not available to inform this analysis. Instead, a fine sediment yield regression relationship was developed as described in the November 9, 2021 Geomorphology Work Group Standing Meeting. Integration of this regression analysis with the results from other studies (notably the GE-04 Geomorphology Study) should provide sufficient detail to adequately inform the development of any Protection, Mitigation and Enhancement measures.

Study Modifications identified in the June 9, 2021 Notice: As Written	Status
Assess deposition and erosion in the drawdown zone. City Light will clarify that mapping of the sediment and erosion deposition zone and tributaries are part of the existing scope of the study. Any remaining gaps will be addressed during implementation.	Sediment erosion and deposition zones within the drawdown zones were mapped using remote sensing and field-based methods in 2022. Details of methodology were developed in consultation with LPs.
Use a 1-D backwater model instead of the geomorphic 'inflection point" to estimate the magnitude and location of the reservoir backwater effect. City Light will expand the scope of GE-03 to include this modeling. City Light and the LPs recognize that there are limitations on the ability to calibrate aspects of this model.	In the ISR, City Light proposed that the reservoir backwater effect would be analyzed in the four delta study areas using the most appropriate method for each particular area. The following work was performed: ▪ Hozomeen inlet: As described in Section 5.1 above, no issues with sediment deposition were noted at boat launches in the Hozomeen area, and while existing detailed topographic LiDAR were available, there were not sufficient hydraulic data available to calibrate a hydraulic model in the Skagit River upstream from Hozomeen. Therefore, a 1-D HEC-RAS model was not developed. ▪ Sourdough Creek: the longitudinal profile measured from 2018 LiDAR and 2021 survey data shows that due to the steep gradient of Sourdough Creek, and the grade control/drop at the existing road crossing structure, the backwater effect cannot extend up Sourdough Creek (see Section 5.3). A 1-D HEC-RAS model is not needed, and there is no hydrologic data to calibrate the model. ▪ Thunder Arm: a 2-D HEC-RAS model was developed for Thunder Arm. This is appropriate because Thunder Creek is relatively low gradient, there is evidence of backwater effects (see Section 5.2), and there is existing detailed topographic (LiDAR) and hydraulic (USGS gage) data available for Thunder Creek to enable calibration of the model. 2-D backwater models are more detailed than 1-D models and meet the intention of the agreement. ▪ Stetattle Creek: a 2-D HEC-RAS model (more detailed than a 1-D HEC-RAS model) was developed as part of a previous study and was used to analyze backwater effects.

7.0 VARIANCES FROM FERC-APPROVED STUDY PLAN AND PROPOSED MODIFICATIONS

As stated in the Sediment Deposition Study Interim Report (City Light 2022a), three variances from the FERC-approved study plan were adopted during study implementation as summarized below:

- Field efforts, analysis, and reporting extended into 2022.
- Existing detailed topographic LiDAR data available for Thunder Creek were sufficient to analyze sediment transport/deposition using a 2-D HEC-RAS model (more detailed than a 1-D model), so field-surveyed cross sections and slope were not needed (Section 2.6.2.2 of the RSP).
- Existing detailed topographic LiDAR data for the Skagit River upstream from Ross Lake were used for the analysis of sediment transport/deposition; these data extend approximately 2 miles upstream from the head of Ross Lake and are of sufficient detail for the analysis. No field-surveyed cross sections or slope were measured. No pebble counts were made in the Skagit River outside of the U.S. due to limitations of field work in Canada.

Changes to the methods committed to as part of the June 9, 2021 Notice that were also described in the Sediment Deposition Study Interim Report are summarized below:

- Further investigation of the DSHVM highlighted that the model was not the appropriate tool to be used to estimate sediment supply into the reservoirs. A comparison of historical contours with updated bathymetry and a fine sediment yield regression analysis would be developed.
- Sediment erosion and deposition zones within the drawdown zones would be mapped using remote sensing and field-based methods.
- A 1-D model for the Hozomeen inlet and Sourdough Creek areas were not needed (see Table 6.1-1).
- 1 1-D model for the Thunder Arm area and a 2-D model for the Stetattle Creek area (previously developed) would be used to analyze the backwater effects.

Lastly, the following modifications to methods committed to as part of the June 9, 2021 Notice since the filing of the ISR are summarized below:

- City Light quantified the sediment supply of all sizes using a statistical regression analysis, as described in Section 5.5 and in Table 6.1-1. Updated bathymetric information was not available to provide for a comparison of historical contours. Integration of this regression analysis with the results from other studies (notably the GE-04 Geomorphology Study) should provide sufficient detail to adequately inform the development of any Protection, Mitigation and Enhancement measures.

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SEDIMENT DEPOSITION IN RESERVOIRS AFFECTING RESOURCE AREAS OF CONCERN STUDY REPORT

ATTACHMENT A

THUNDER CREEK BACKWATER EXTENTS REPORT

Northwest Hydraulic Consultants Inc.
12787 Gateway Drive S.
Seattle, WA 98168
Tel: (206) 241-6000

www.nhcweb.com

NHC Reference 2003536

March 2023

HDR Engineering Inc.
929 108th Avenue NE, Suite 1300
Bellevue, WA 98004

Attention: Jenna Borovansky, HDR (Jenna.Borovansky@hdrinc.com)
Copy to: Matt Wiggs, HDR (matthew.wiggs@hdrinc.com)
Kathy Dubé, Watershed Geodynamics (kdube@watersheddynamics.com)
Via email: Jenna.Borovansky@hdrinc.com

Re: **GE-03 Sediment Deposition in Reservoirs Affecting Resource Areas of Concern Study Thunder Creek Backwater Extents Report, Rev. 4**

1 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 GE-03 Sediment Deposition in Reservoirs Affecting Resource Areas of Concern Study (GE-03 Sediment Deposition Study). As part of work supporting City Light (City Light) for the GE-03 Sediment Deposition Study, Northwest Hydraulic Consultants (NHC) has evaluated the hydraulic and geomorphic characteristics of the Thunder Creek delta as Thunder Creek approaches Diablo Lake Reservoir.

The main objective of this work was to identify the extent of lake backwater effects during floods in Thunder Creek. Secondary objectives of this work include evaluating the following questions:

- Will the deposition of sediment and wood continue, further causing backwater of Thunder Creek?
- Is the deposition caused by extraordinary events or a continuous process?
- Have backwater effects contributed to the observed death of near-channel cedar trees upstream of the reservoir?

2 Project Location and General Geomorphic Observations

One study area for the GE-03 Sediment Deposition Study is located at the mouth of Thunder Creek as it meets Diablo Lake (Figure 2-1). The drainage area is approximately 108 square miles that brings water, sediment, and wood down from the North Cascades. Elevations in the basin vary from 1,210 feet (ft) at the mouth of Thunder Creek up to 9,112 ft at Buckner Mountain. The upper basin of Thunder Creek is located in the North Cascades National Park, while the lower 5.5 miles of the creek is located in the Ross Lake National Recreation Area.

The scope for this work is limited to desktop analyses, although NHC staff did visit Thunder Creek on personal time during a weekend break from the summer 2022 Project field activities. Available aerial imagery was downloaded, geo- and orthorectified as needed, and reviewed. Observations of the aerial imagery indicate a few things (Figure 2-2, Figure 2-3, and Figure 2-4). First, the delta has grown as a result of sediment and wood being transport to and deposited at the delta. Determining change in extent or an approximation in volume would require further desktop analysis and would have high uncertainty. Growth of the delta is most prominently punctuated as a result of the 2003 flood and has become more complex with multiple flow paths.

Quite a few trees have died along the river upstream from the wood jam and this becomes evident starting in the 2006 imagery. Personal communication with Kathy Dubé indicated that the trees are cedars. It is likely that the death of these trees is related to deposition of wood and sediment associated with the 2003 flood. The mid-channel bars deposited during the 2003 flood at the mouth of Thunder Creek have begun to vegetate. Google Earth imagery (not presented) was also reviewed as several dates since 2003 show how the wood jam has evolved over time. What these images show is that the wood jam had a fairly dense raft of wood blocking the main channel. Behind the raft was a wedge of sediment deposits that are posited to be sand and gravel. The raft is still evident in 2009, however the sediment wedge appears to have been transported and new pools exist. Two years later (2011) a new dominant flow path was created to the west of the log raft, which is where the channel generally persists today.

Construction of the North Cascades highway (State Route 20) began in 1959 and was opened to the public in 1972 (History Link). The State Route (SR) 20 bridge can be seen in the June 2, 1972 imagery (Figure 2-4); it is assumed the bridge was completed in the 1960s. The opening under the bridge is on the order of 150 ft, while the valley section in this area before construction was 500-600 ft. The implications of narrowing this section are further explored in the hydraulic analysis (Section 6 Hydraulic Results).

Reviewing the historic imagery away from the study area a few observations can be made. Glacial extents, and therefore ice mass, have diminished since the 1940s, which is corroborated by scientific research (Pelto 2008). Although mass movements are common in the Pacific Northwest (e.g., the 2003 Oso Slide), there are no obvious major landslides in the vicinity of the study area. However, there is a steep gully just upstream and to the east of delta that appears to frequently contribute sediment to Thunder Creek. The retreat of glaciers and loss of permanent snow field extents can be observed by the relatively bare ground in the earlier images, which have become covered with shrubs and trees in more recent images.

Forest fires are part of the natural ecosystem. The images do not suggest large fires in recent history. A review of fire history on CalTopo.com show that three small fires have occurred in the past decade: the 2015 Goode fire; the 2015 Thunder Creek fire; and the 2021 Moraine Lake fire (Figure 2-5). One study

noted that fire frequency in the basin did not significantly change over millennial time scales, but the return intervals were highly variable (Prichard 2003).

The U.S. Geological Survey (USGS) 1/3 arc-second digital elevation model (DEM) was also reviewed for the Thunder Creek watershed. No major landslides were observed on the DEM in the vicinity of the study area. There are likely smaller landslides that are difficult to distinguish given the coarseness of the DEM. In the headwaters upstream from the study area the channel is narrowly confined, with few areas where the valley expands near tributaries. As Thunder Creek approaches the delta, the valley expands and then constricts again at the alluvial fan created by Colonial and Rhode Creeks. This change in valley width suggests that an alluvial fan naturally existed in the vicinity of today's delta. The collection of sediment cores would be required to determine the amount of deposition due to the natural alluvial fan versus dam-induced delta deposition. NHC was unable to find any historic maps or atlas that pre-date the dam.

Based on average channel slopes (Figure 2-6), the channel type of Thunder Creek 15,200 ft (about 3 miles) upstream from the SR 20 bridge and beyond is primarily step-pool with locations of cascades (*sensu* Montgomery and Buffington 1997). The channel through the upper reaches is primarily single-thread with localized areas containing mid-channel islands and wood jams. The channel type is primarily pool-riffle from the delta upstream to about 3 miles. The channel transitions from single-thread to multi-thread with numerous overbank flow paths as Thunder Creek reaches the delta.

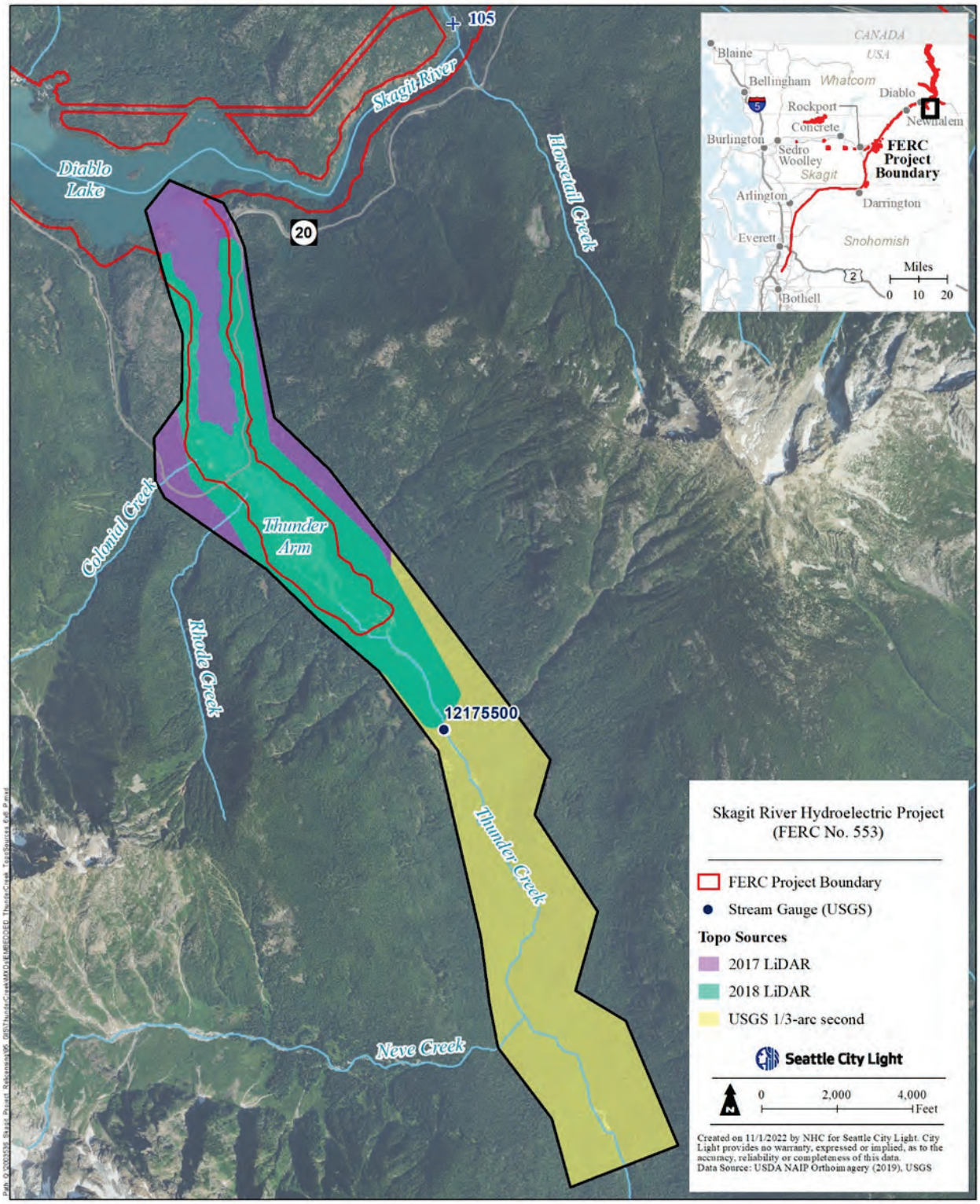


Figure 2-1. Topographic surface sources used in the hydraulic analysis.

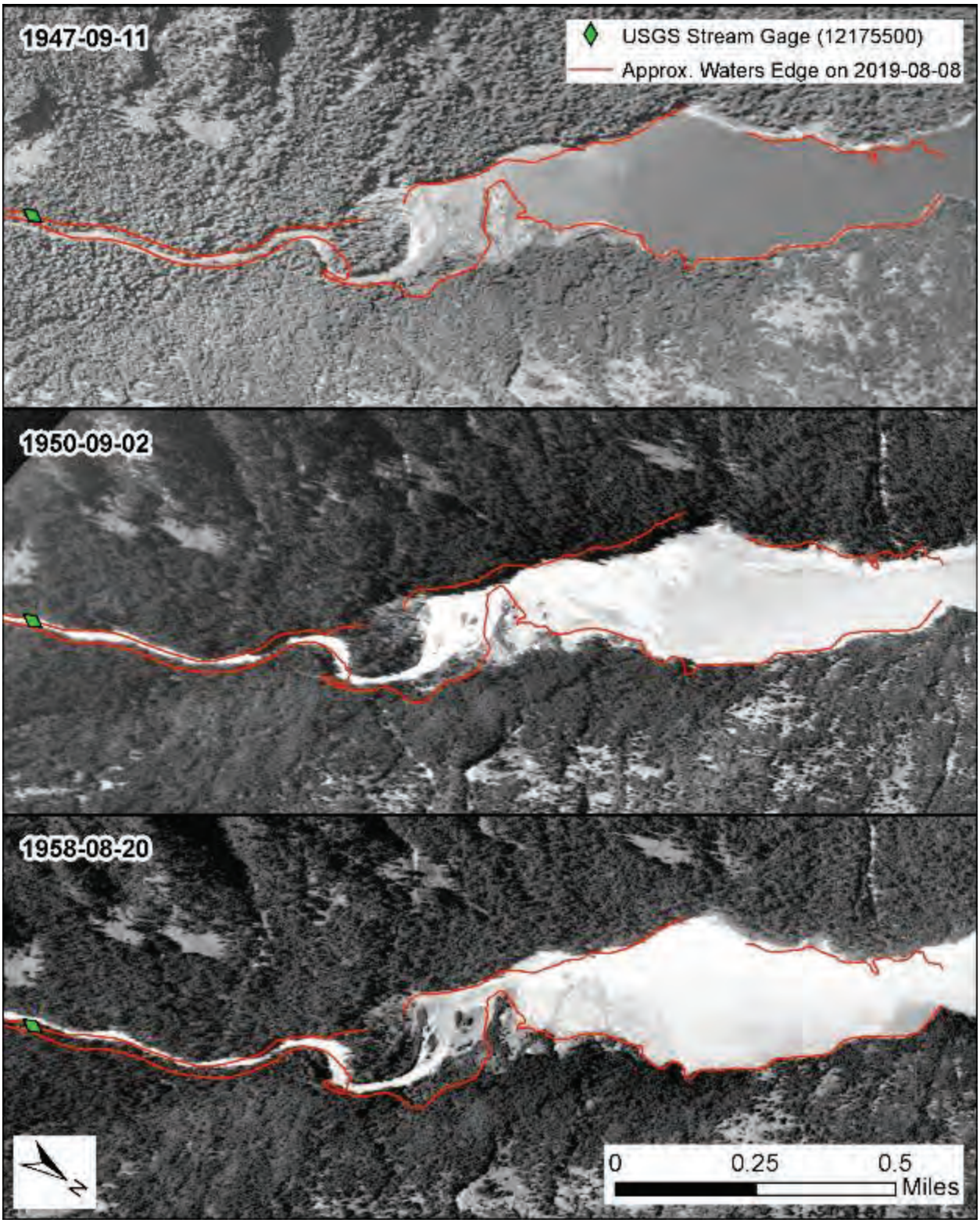


Figure 2-2. **Aerial imagery of Thunder Creek delta (Figure 1 of 3). Aerial imagery downloaded from USGS Earth Explorer on 2022-11-02.**

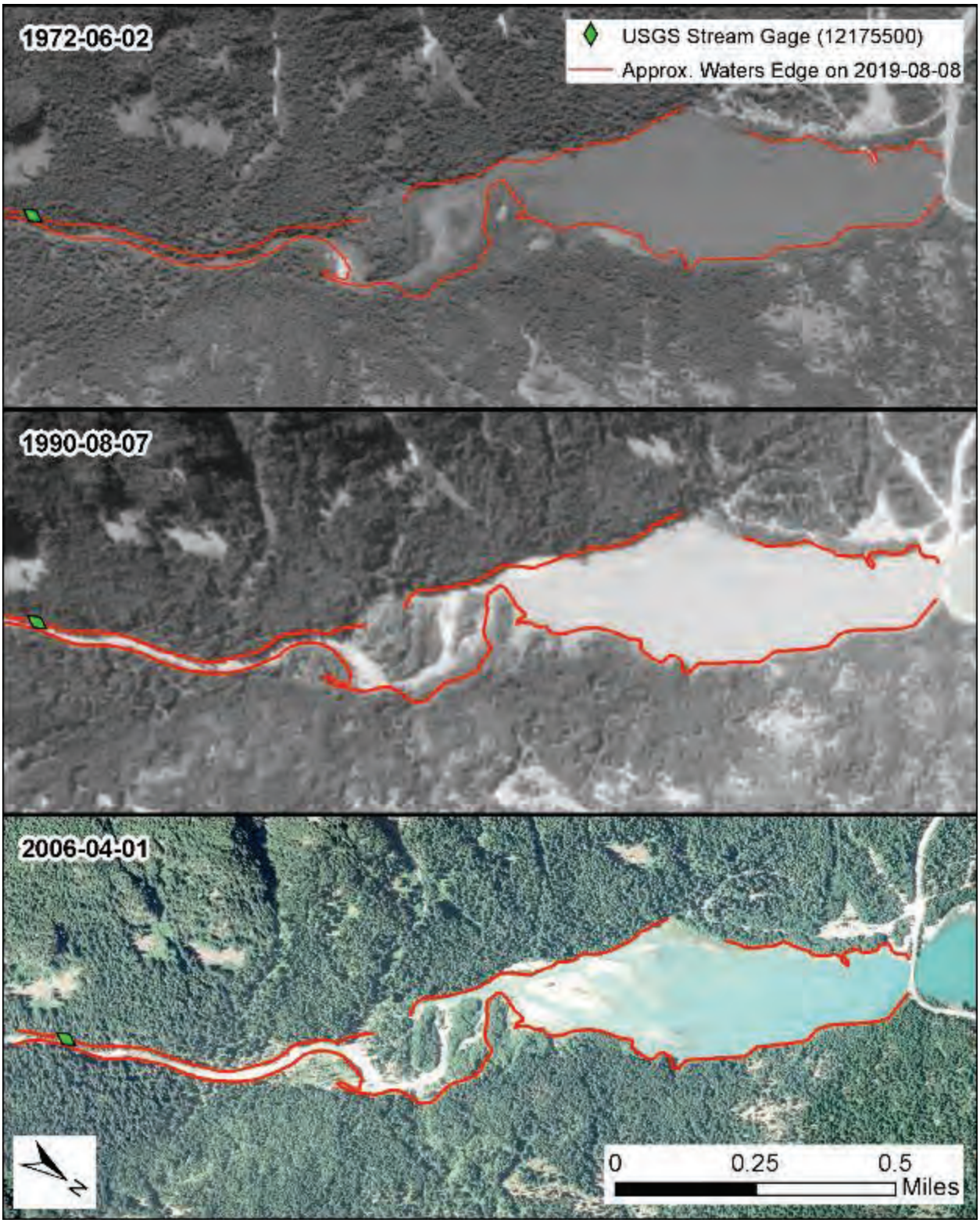


Figure 2-3. **Aerial imagery of Thunder Creek delta (Figure 2 of 3). Aerial imagery downloaded from USGS Earth Explorer on 2022-11-02.**

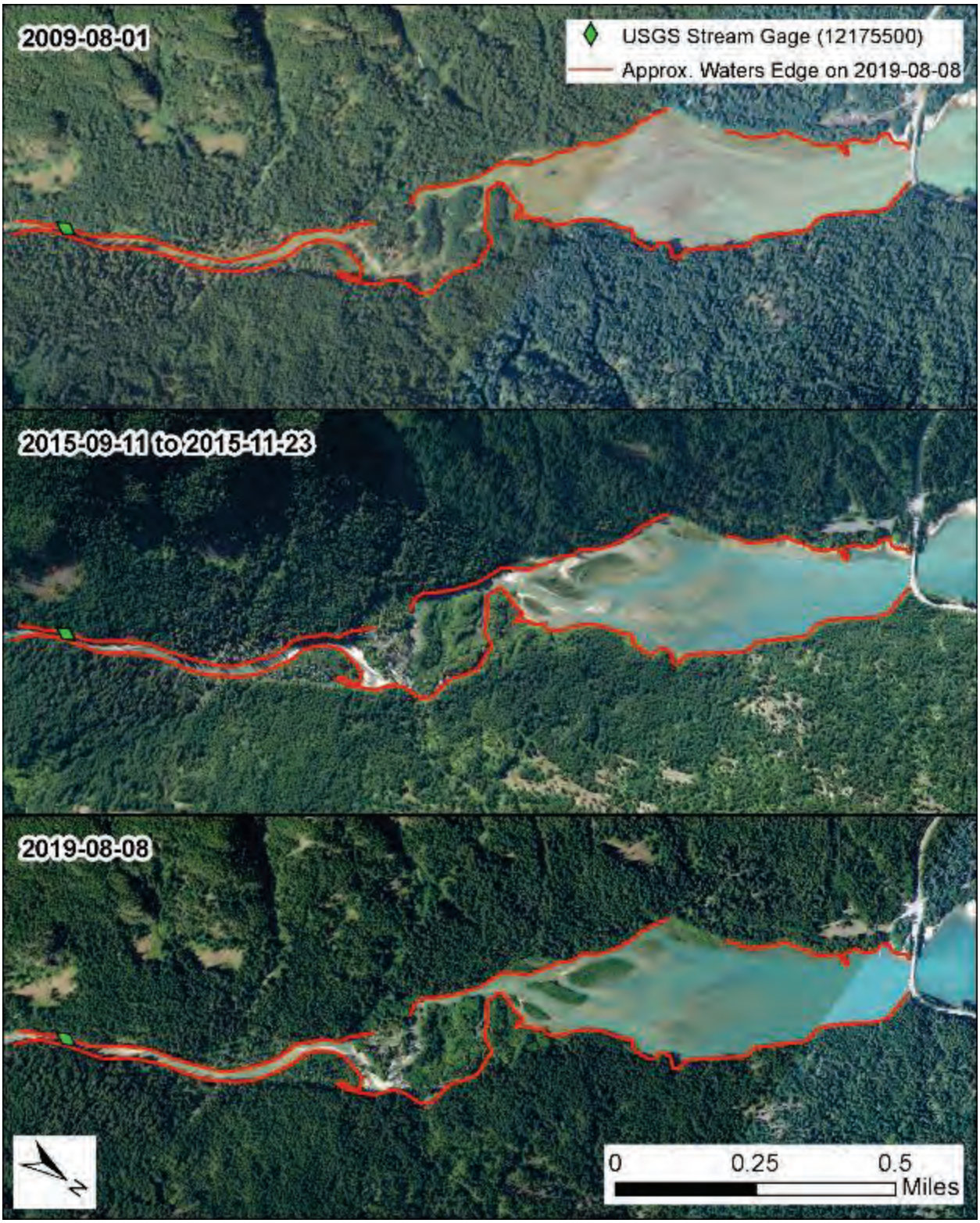


Figure 2-4. **Aerial imagery of Thunder Creek delta (Figure 3 of 3). Aerial imagery downloaded from USGS Earth Explorer on 2022-11-02.**



Figure 2-5. Fires in recent history within the Thunder Creek watershed are limited to the Thunder Creek Fire, Goode Fire, and the Moraine Lake Fire.

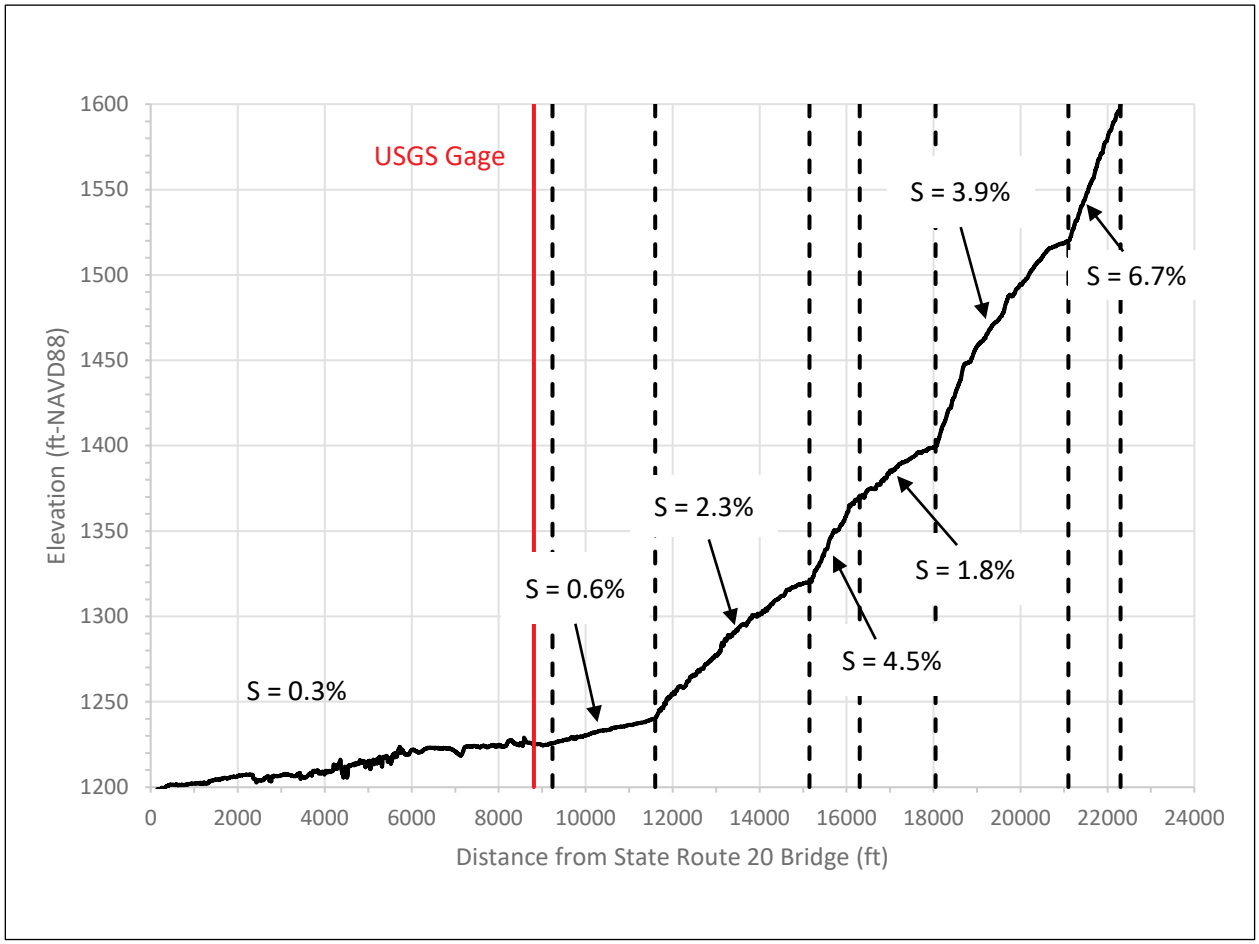


Figure 2-6. Longitudinal elevation profile for Thunder Creek with a breakdown of approximate slopes for locations where the channel has a significant break in slope.

3 Hydrologic Data Review

3.1 Available Data

Hydrologic data for understanding and modeling the Thunder Creek hydraulics is informed by two data sources. The USGS stream gage (12175500) upstream on Thunder Creek provided historic stage and flow information; images in the vicinity of the gage show a relatively narrow single channel (Figure 3-1). These data include peak flows for water years 1931 to 2021 (Figure 3-2) and 15 minute readings from 1989 to present. There are also 422 field measurements of stage-discharge relationships with a few records starting in the 1930s. The gage is located on the left bank, just upstream from the Thunder Creek trail bridge and lies just beyond the 2018 LiDAR where the best available data is the USGS 1/3-arc second DEM (Figure 2-1).

The second source used in this study was hourly Lake Diablo water surface elevations. The sensor for this gage is located at Diablo Dam and the data were provided by City Light. This gage is the same as the USGS water surface elevation gage 12176500. This gage is approximately 3.5 miles away from the study area.

3.2 Flow Analyses

Peak flows for the USGS Thunder Creek gage (12175500) show that around 66 percent of the recorded events are less than 5,000 cfs, 28 percent of the events are between 5,000 and 10,000 cfs, and that only 7 percent of the events are greater than 10,000 cfs (Figure 3-2). The highest flow of record was associated with an atmospheric river event on and around October 20, 2003, which resulted in a peak flow of 17,800 cfs. The second largest flow was 14,500 cfs in 1980.

Using the peak flow dataset, a Bulletin 17B analysis was performed using HEC-SSP to determine exceedance probabilities (Figure 3-3) for specific design storms with recurrence intervals of 2-years, 5-years, 10-years, 50-years, and 100-years (Table 3-1).

Daily mean flow data for the period of record was also analyzed to characterize seasonal trends and cycles of the mean daily flow of Thunder Creek. The period of record includes water years 1930 through 2022. A daily discharge annual summary hydrograph (Figure 3-4) indicates the daily maximum, minimum, and mean flows recorded for each day, as well as the 25/75 percent and 5/95 percent exceedance flows for each calendar day. The data indicates increasing flows in the March through August time frames driven by snowmelt runoff during the spring and early summertime periods. Wintertime flows from November through March are highly variable, with peak flows typically driven by atmospheric river events and rain or rain on snow events leading to the higher peak flow events for most water years. The cumulative daily flow percent time exceedance statistics are provided in Table 3-2. The mean daily flow is approximately 430 cfs. Mean daily flows exceed 84 cfs approximately 99 percent of the time, while mean daily flows exceed 2,390 cfs approximately 1 percent of the time.

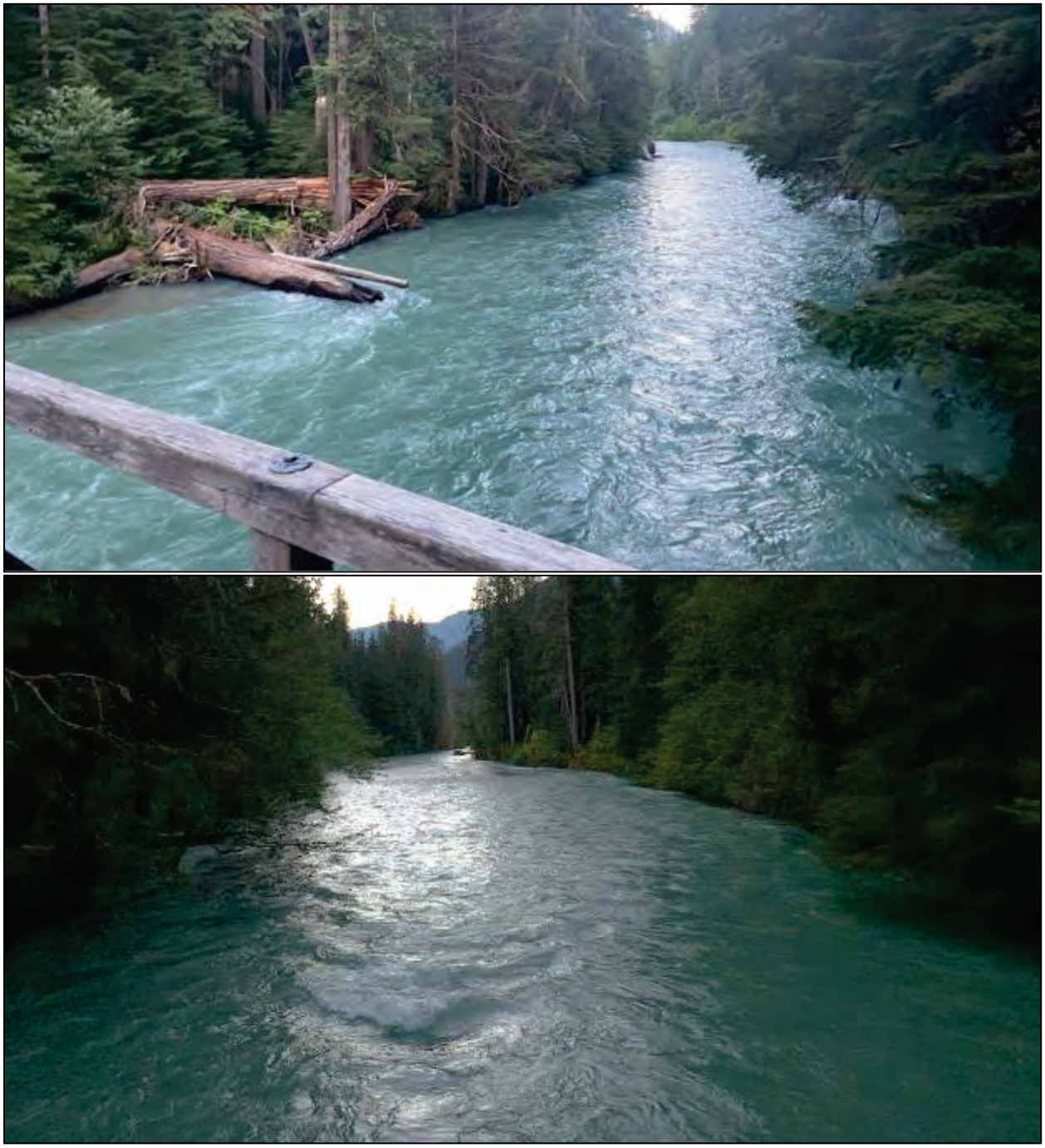


Figure 3-1. **Photos taken on 29 July 2022 looking upstream (top; photo credit: NHC) and downstream (bottom; photo credit: Sam Michels-Boyce) from the Thunder Creek trail crossing near the USGS gaging station. Flow was approximately 1,910 cfs.**

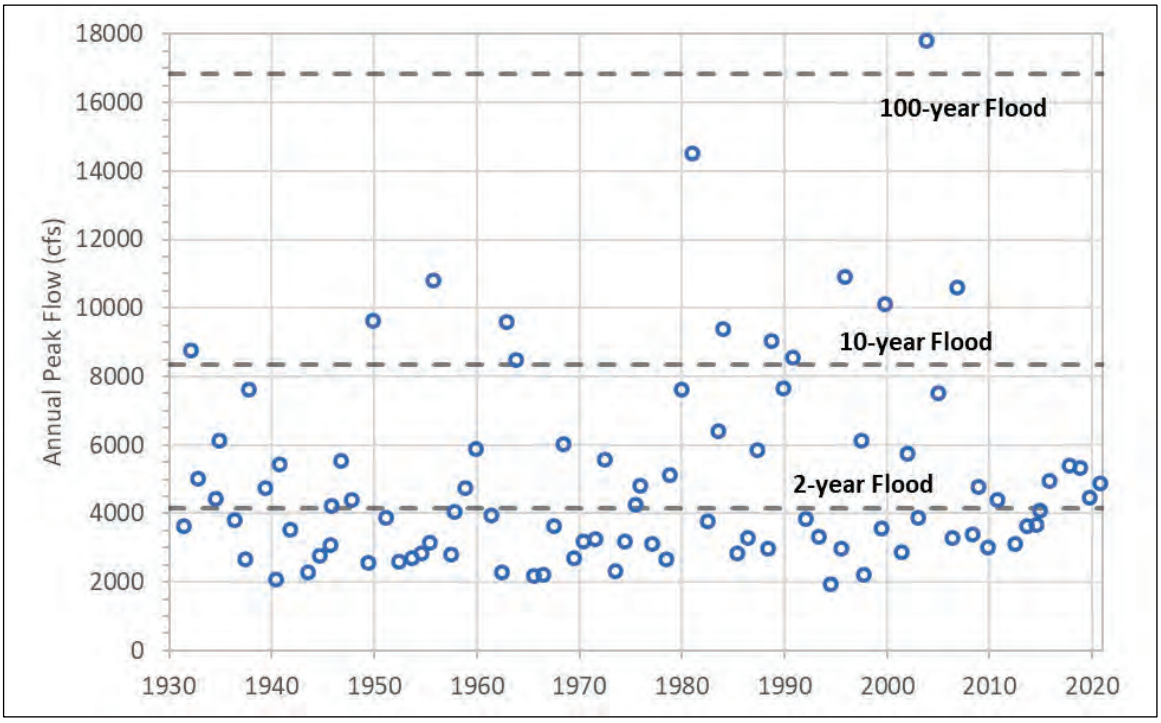


Figure 3-2. Annual peak flow at the USGS Thunder Creek gage (12175500) for water years 1931 to 2021.

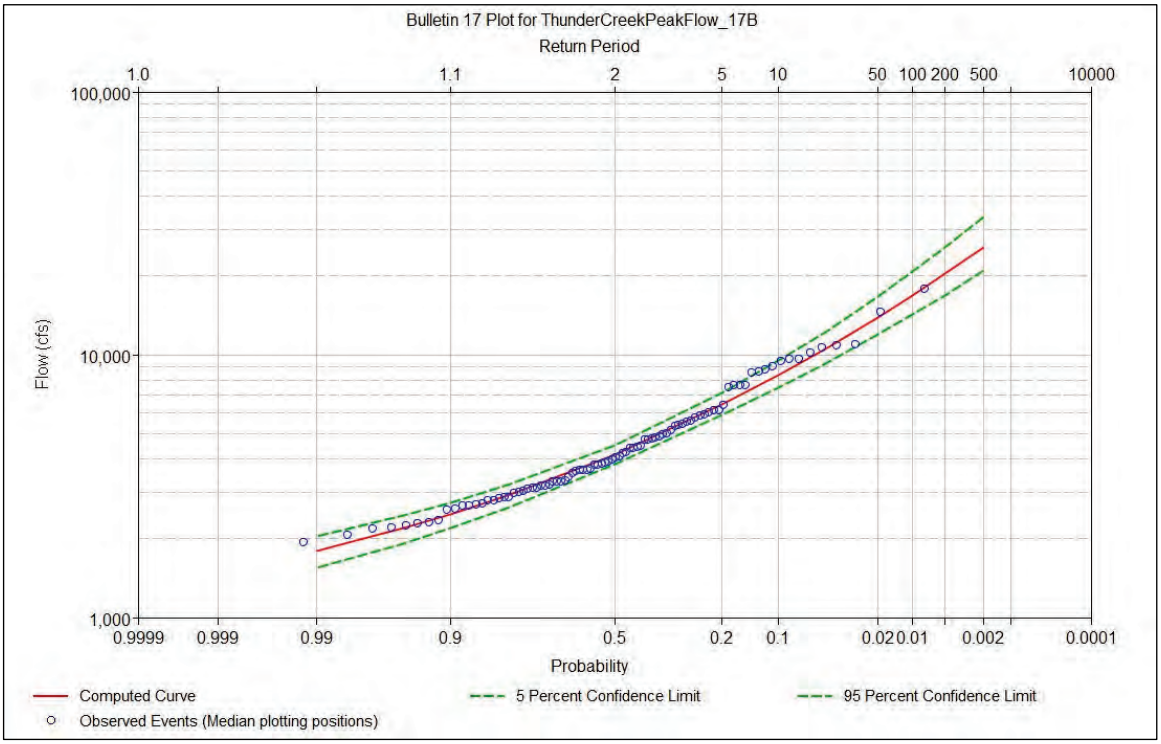


Figure 3-3. USGS Thunder Creek gage (12175500) annual peak exceedance probability (processed in HEC-SSP).

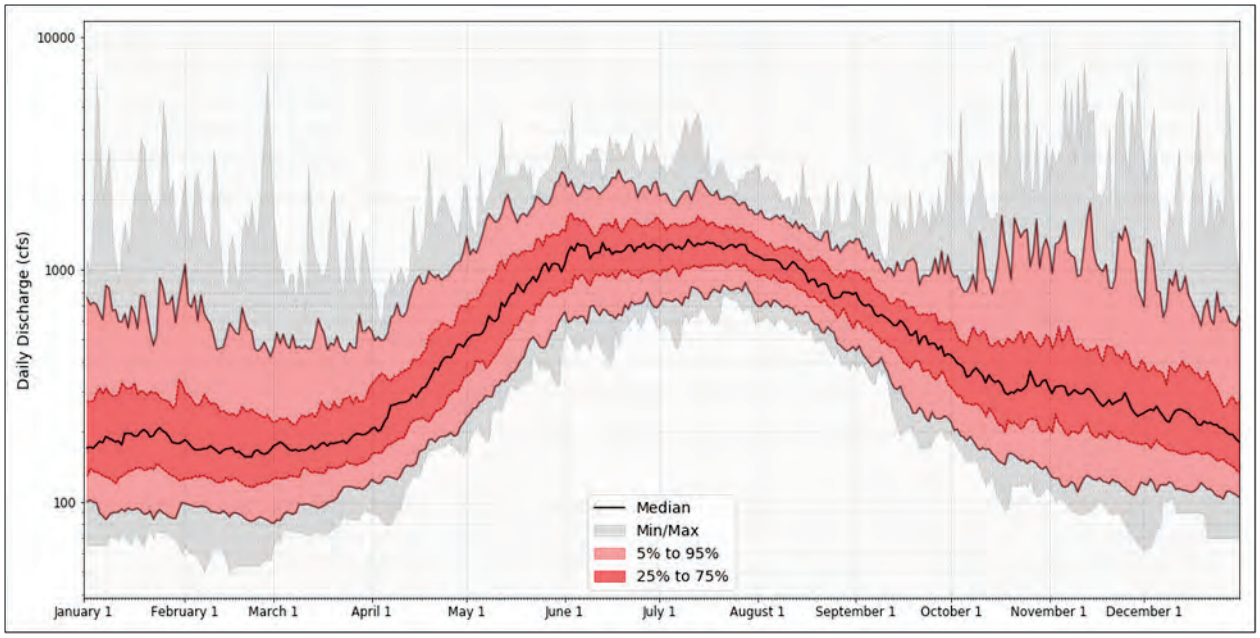


Figure 3-4. **Daily discharge statistics for each day of the year; record analyzed for water years 1930 through 2022.**

Table 3-1. **Peak flow analysis using Bulletin 17B in HEC-SSP.**

Percent Exceedance Probability	Recurrence Interval	Annual Peak Flow (cfs)
50%	2	4,170
20%	5	6,440
10%	10	8,340
2%	50	13,800
1%	100	16,800

Table 3-2. **USGS Thunder Creek gage (12175500) percent exceedance of daily mean flow duration.**

Percent Exceedance Probability	Flow (cfs)
99%	84
95%	116
50%	430
25%	914
10%	1,370
2%	2,060
1%	2,390

3.3 Stage-Discharge Analysis

There are 422 field measurements of stage and discharge at the Thunder Creek USGS gaging station. These data provide a direct comparison of measurements on a revolving cycle, which can be used to analyze geomorphic changes at a given location. A jump in the stage for a similar discharge indicates that there has been a change in the shape of the cross section, most often an increase or decrease in the average bed elevation. These jumps might be associated with localized bed aggradation or incision, or possibly a longer-term change in the overall bed profile.

Plotting the stage-discharge relationship for Thunder Creek shows that there are four distinct breaks in the record (Figure 3-5). The earliest measurements, pre-2003 flood, all group together and show that the channel changed little at this location from the 1930s through 2003. The 2003 flood caused an obvious jump in stage and that roughly persisted until fall 2020. In water years 2021 and 2022 there were two distinct jumps in the stage-discharge relationships. At the start of the 2021 water year (WY) there was a flood on 11/5/2020 with a peak flow of 4870 cfs. Similarly, about a year later, the 2021 WY started with a flood on 11/14/2021 with a preliminary peak flow estimate of 8000 cfs.

Given the coincidence of the first major jump occurring at the time of the 2003 flood, it is reasonable to posit that the sediment and wood deposited at the delta has caused a base level control on the bed profile. This increase in the bed elevation on the delta has propagated upstream and with subsequent floods additional sediment deposition is causing an adjustment to the bed profile and stage-discharge relationship at the USGS gaging station.

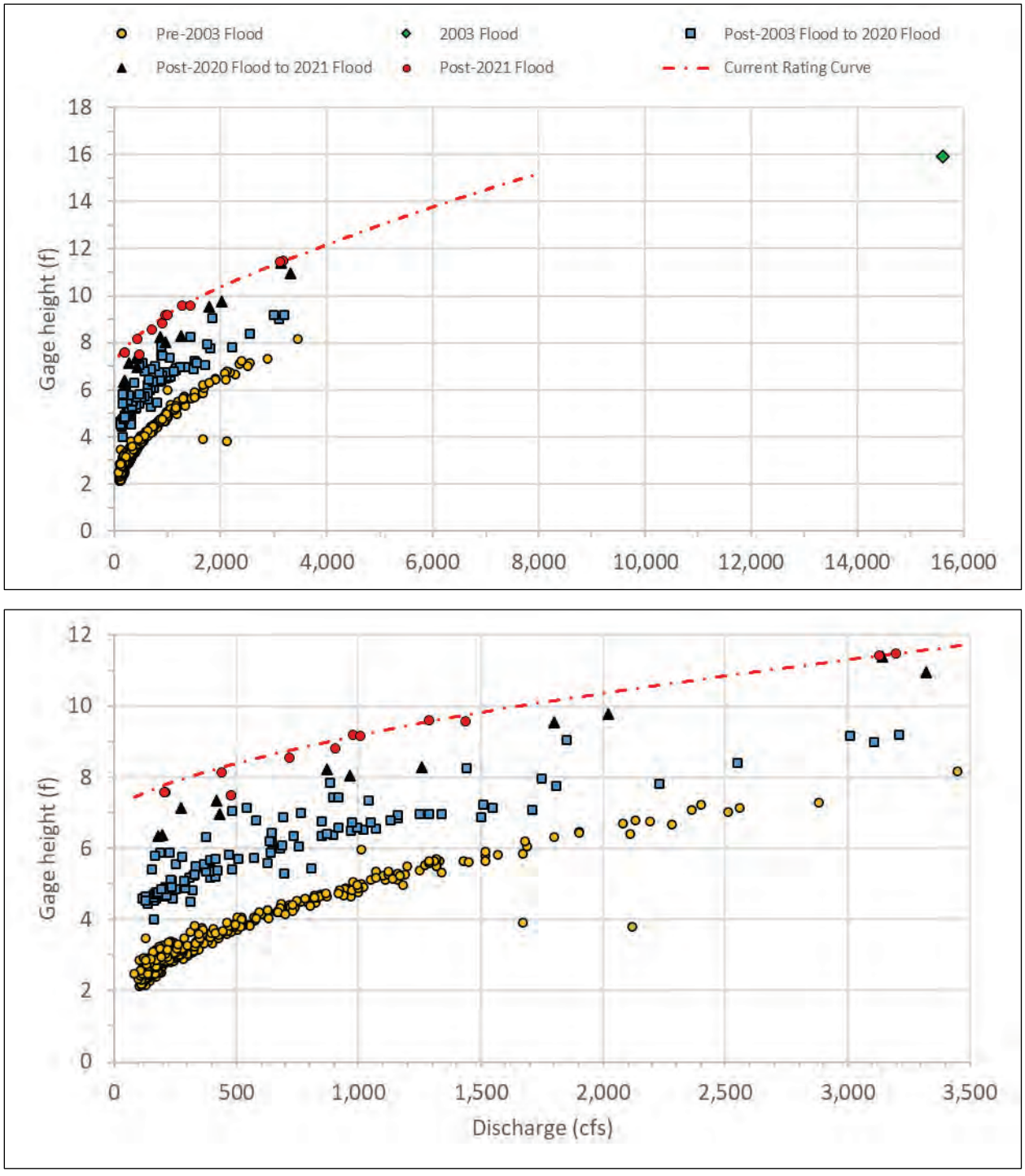


Figure 3-5. **Stage-discharge rating curve from USGS field observations at the Thunder Creek gage (12175500). The top graph includes shows all measurements, the bottom zooms in to the lower discharges to make clear the relative changes in stage.**

3.4 Lake Elevation Analysis

Hourly lake elevations were provided by City Light at the Diablo Dam for the record from January 1, 1997 to December 1, 2019 (Figure 3-6). These data were analyzed to determine statistical parameters that could be used to inform the hydraulic model (Table 3-3). The mean water surface elevation during this time period was 1,207.9 ft North American Vertical Datum 88 (NAVD 88). Minimum and maximum elevations were 1,199.4 and 1,212.9 ft NAVD 88, respectively. The 10 percent exceedance water surface elevation of 1,209.5 ft NAVD 88 was used for the hydraulic analysis as the relatively high lake stand. The peak stage recorded during the October 20, 2003 flood was 1,211.8 ft NAVD 88. Given the 3.5 mile distance from the mouth of Thunder Creek to the gage, it is likely that water surface elevations were somewhat higher than recorded at the location of the gate at the dam. A water surface elevation of 1,212.0 ft NAVD 88 was used in the modeling as a means to approximate the maximum backwater extents during this flood.

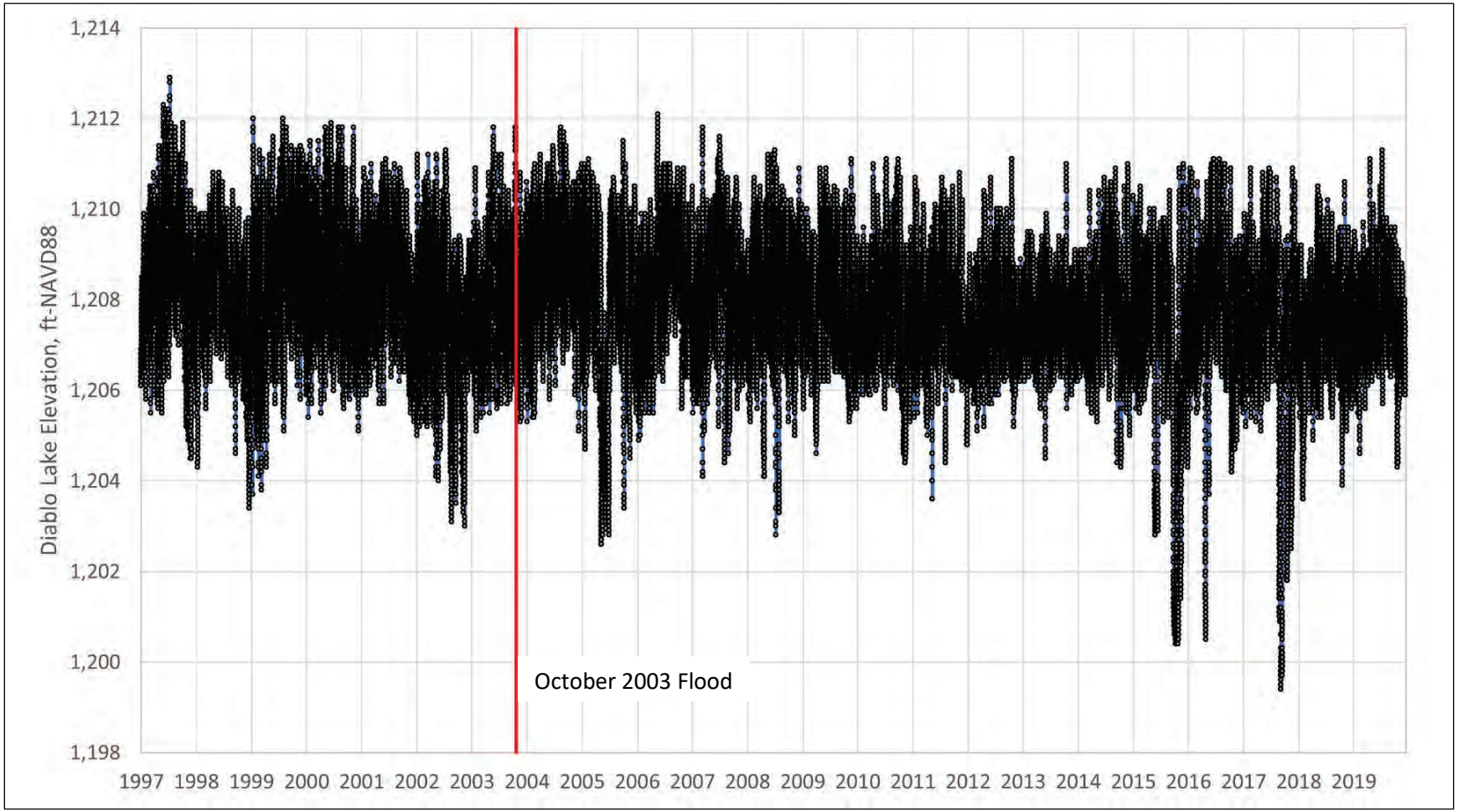


Figure 3-6. Hourly Diablo Lake elevations from 1997 to 2020 as recorded at the dam.

Table 3-3. Lake level statistics for Diablo Lake.

Statistic	Elevation (ft NAVD 88)
Minimum	1,199.4
Maximum	1,212.9
10% Exceedance	1209.5
Mean	1,207.9
Median	1,209.9
90% Exceedance	1,206.5
Standard deviation	1.3

4 Topographic Data Development

A DEM surface was created for the area of interest using three datasets (Figure 2-1). The portion of the study area downstream of the USGS gage was covered by two separate LiDAR sources: one flown in 2017 and one flown in 2018. Due to the lack of spatial coverage extending upstream to the USGS gaging station, NHC also incorporated USGS 1/3-arc second DEM (10 meter DEM), date unknown. The three datasets were mosaicked together with the LiDAR being given the higher priority so that it drew atop the DEM. The final surface was produced in NAD 1983 (HARN) State Plane Coordinates Washington North, NAVD 88, U.S. Feet with a grid resolution of 3 ft.

Within the Thunder Creek arm of Diablo Lake there was also a need to represent the bathymetric terrain. A thorough online search provided two webpages with unknown sources of bathymetric contours:

- https://fishing-app.gpsnauticalcharts.com/i-boating-fishing-web-app/fishing-marine-charts-navigation.html?title=Diablo+Lake+boating+app#13.82/48.7077/-121.0980
- https://usa.fishermap.org/depth-map/diablo-lake-whatcom-wa/

The first reference above had contours that ended too far into the lake to provide reliable information to inform the model. The second reference included contours up to and slightly upstream of the SR 20 bridge (Figure 4-1). Inspecting these contours, a high point is noticed approximately 4,300 ft downstream from the SR 20 bridge. This feature seems unlikely given a basic understanding of the historical geomorphology of the region. During a conversation with Kathy Dubé on September 7, 2022, she indicated that the high point in the bathymetric contours seems unrealistic given her experience boating through that area. Furthermore, NHC analyzed the 2018 LiDAR point data in more details and it showed that consistent and arguably reliable bathymetric LiDAR returns could be detected around 6-10 ft below the water surface in the vicinity (Figure 4-2). Given the uncertainty in using the Fishermap contours, the bathymetry with the arm was modified; details are further explained in Section 6.3 Terrain Modification.

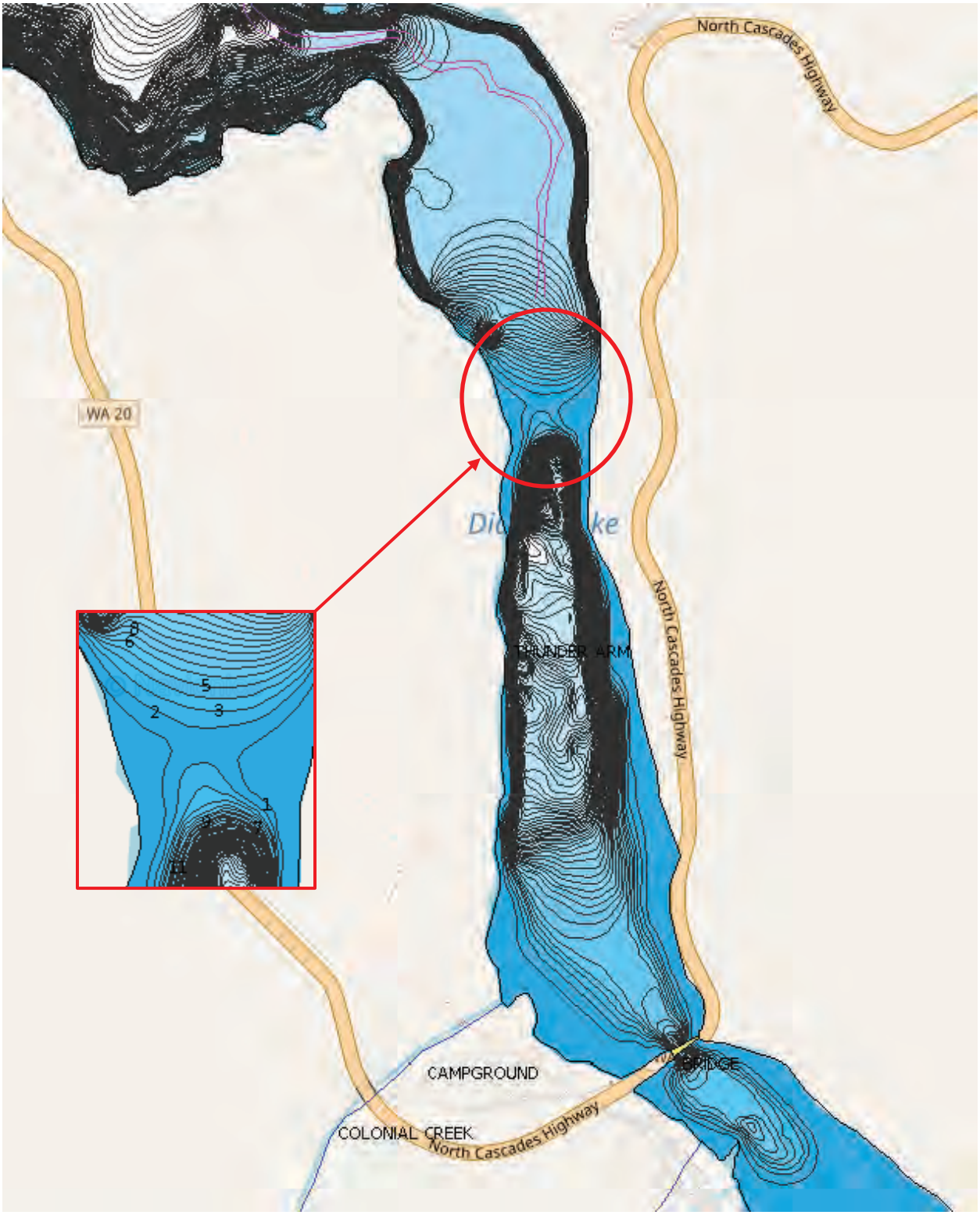


Figure 4-1. **Fishermap bathymetric contours for the Thunder Creek arm, screenshot taken on November 1, 2022.**

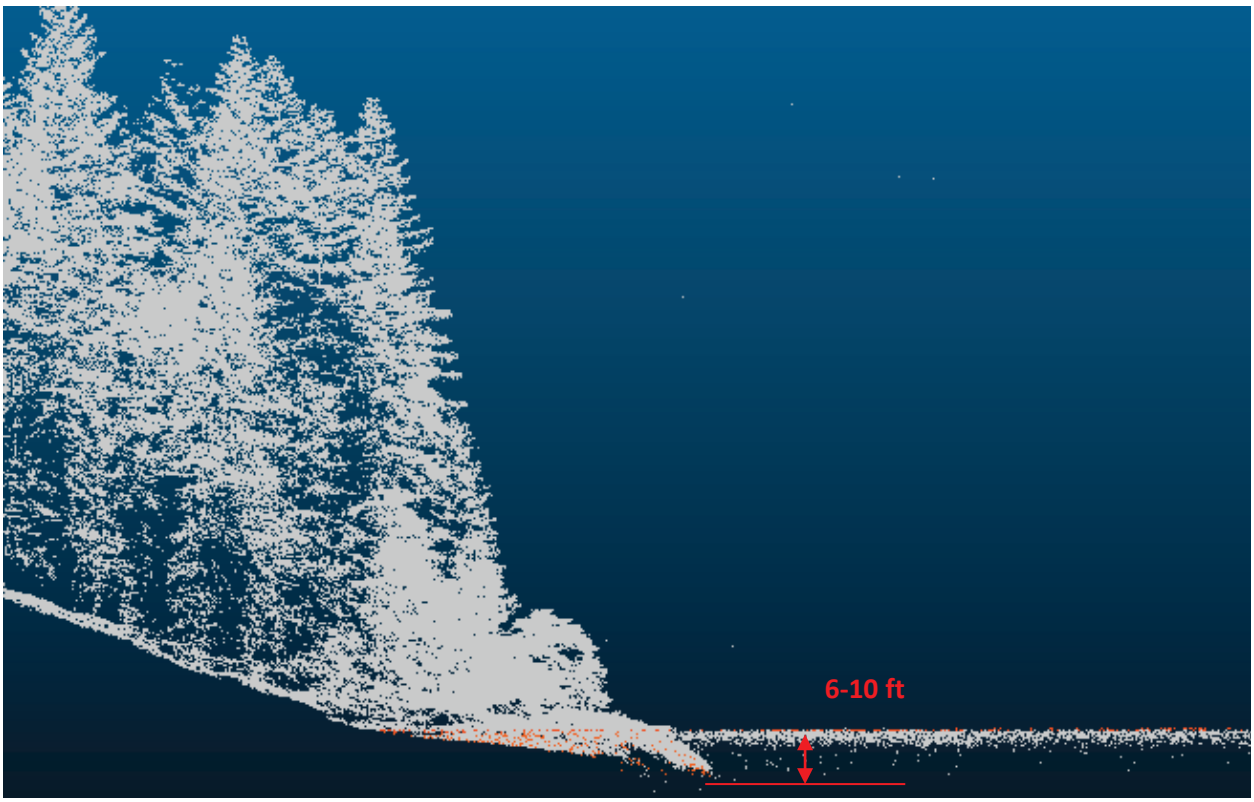


Figure 4-2. Cross section view of 2018 LiDAR points near the Fishermap bathymetric contour high point in Figure 5-2. Points show that the bathymetry is likely lower than illustrated by Fishermap.

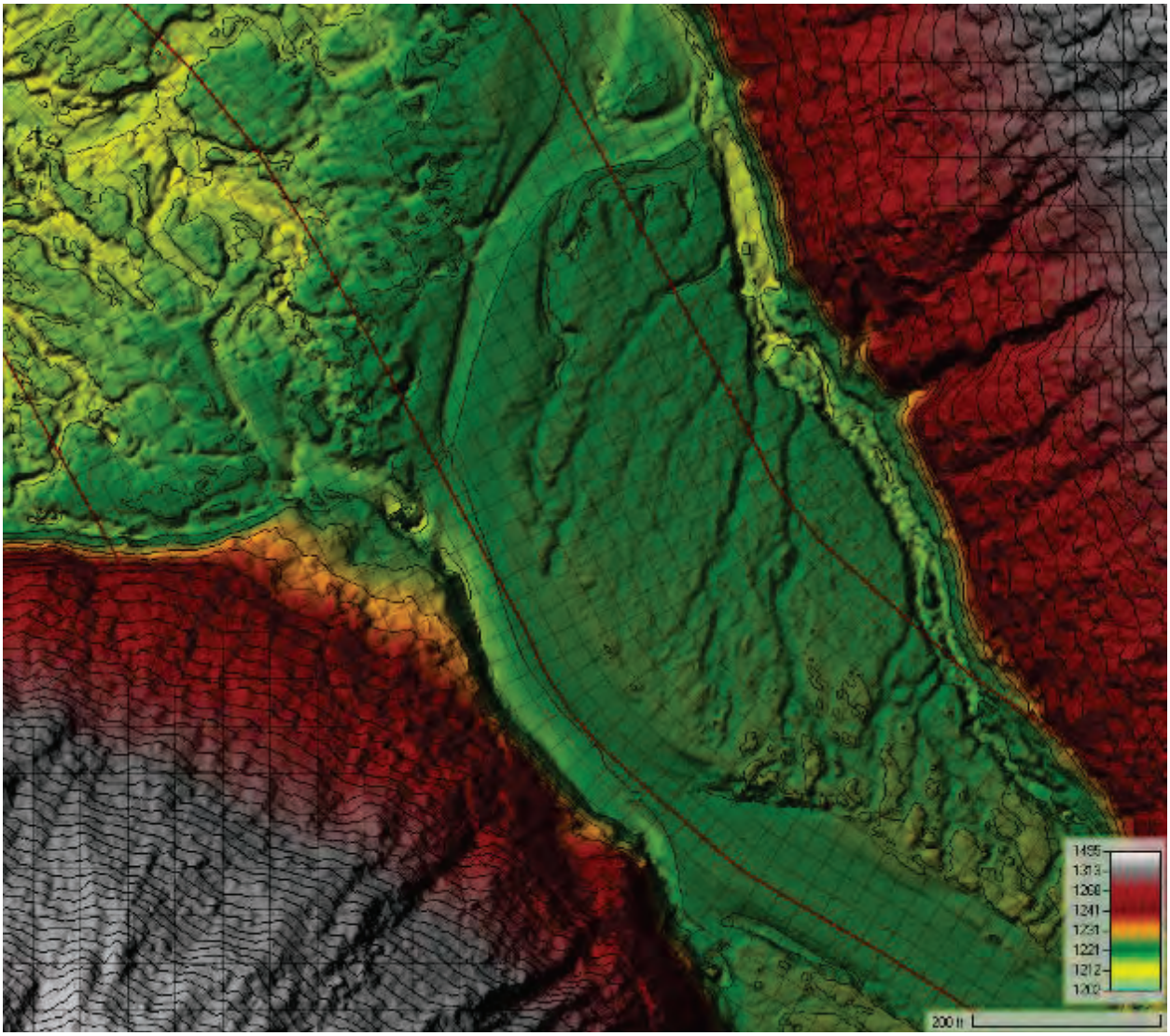
5 Hydraulic Analysis

5.1 Model Selection

A two-dimensional (2-D) HEC-RAS model (version 6.2) was developed to assess hydraulic conditions across the Project area. HEC-RAS was developed by the U.S. Army Corps of Engineers (USACE 2022) and is widely accepted as a standard for hydraulic and flood hazard studies.

5.2 Model Geometry

HEC-RAS solves the shallow water equations by using an implicit finite volume algorithm. HEC-RAS 2-D is unique in that it uses a subgrid approach where the details of the terrain are incorporated into elevation volume curves developed for each grid cell. For the basis of the geometry mesh of the 2-D hydraulic model, a rectilinear grid of 50 ft by 50 ft cells was created from the topographic basemap described in Section 2. Additional detail was created by using breaklines along the main flow path to orient cells to better capture hydrodynamics and define cells at a reduced size with 25 ft sides (see Figure 5-1 for an example).



Cells in the channel have sides of 25 ft, while cells beyond the channel have 50 ft sides. The red lines represent breaklines. Elevations are in ft NAVD 88 and contours are 5 ft.

Figure 5-1. Example of the varied grid used in the HEC-RAS model.

5.3 Terrain Modification

As noted in Section 4 Topographic Data Development, the bathymetry within the Thunder Creek arm as represented by the LiDAR does not extend to the USGS gage nor does it provide a complete bathymetric surface of the Thunder Arm of Diablo Lake. Additionally, the available bathymetric contours found online are unreliable. Therefore, NHC manually modified the bathymetric terrain within HEC-RAS (Figure 5-2). These changes allow for a more accurate backwater representation within the Thunder Creek arm.

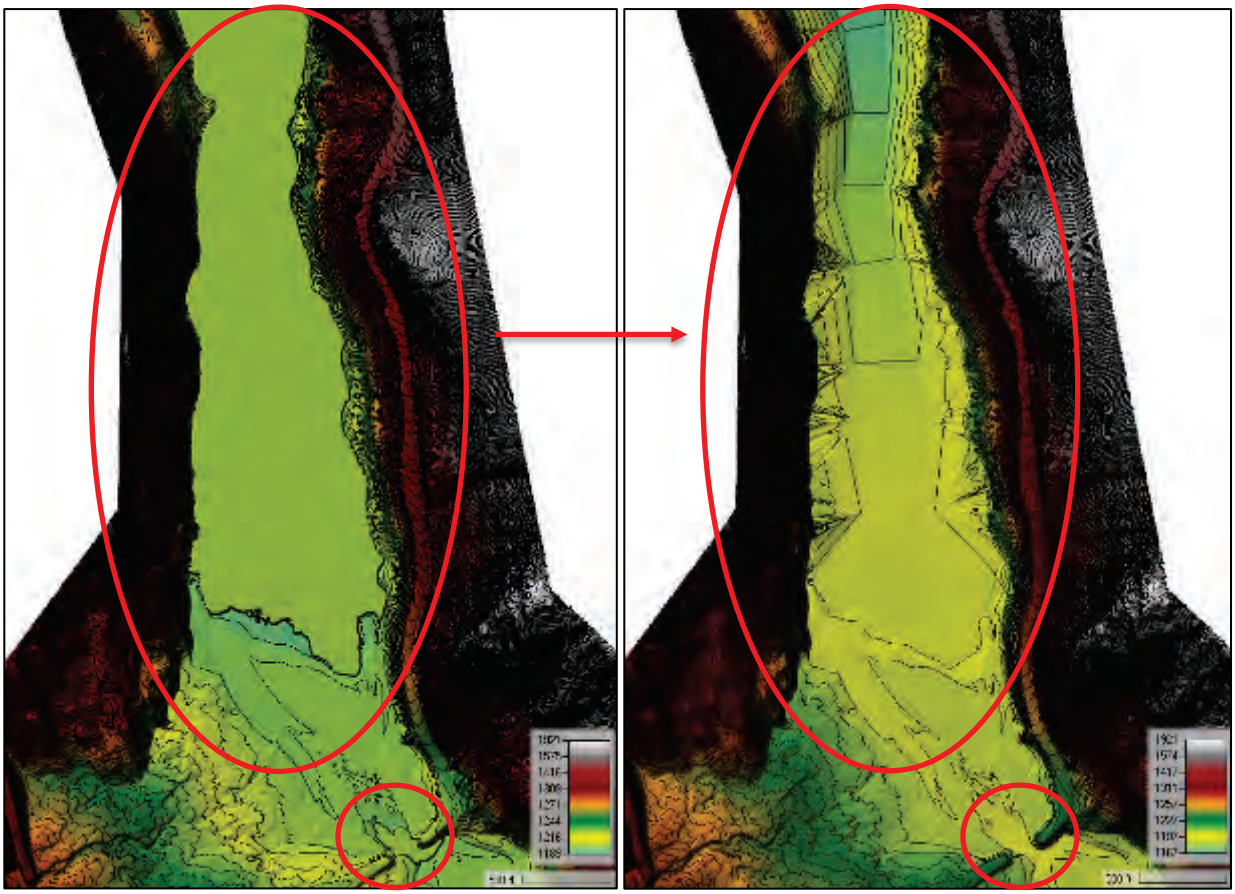


Figure 5-2. Bathymetric modification downstream from the SR 20 bridge, elevations in NAVD 88 and contour lines are 5 ft.

5.4 Roughness

2-D models provide the ability to spatially vary roughness parameters to better reflect the variations in bed material, vegetation, and channel form resistance. Through analyzing aerial imagery and site visits it was determined that the in-channel spatial variability of roughness was relatively uniform and that the overbank roughness is greater than the in-channel portion. For this analysis and given the overall uncertainty of spatial roughness – a uniform Manning's *n* roughness was assigned to the entire domain. To capture the range of potential variability in backwater effects, three different roughness values (0.03, 0.05, and 0.07) were analyzed for each of the flow combinations.

5.5 Boundary Conditions

Boundary conditions provide points for flows to enter or leave the modeling domain and should be located far enough from the areas of interest to limit the effects of boundary condition assumptions on the results. The Thunder Arm model used two boundary conditions: 1) one inflow boundary approximately 2,000 ft upstream from the USGS gaging station; and 2) one outflow boundary condition near the mouth of the Thunder Creek arm in Lake Diablo. The slope of the energy gradeline at the upstream boundary was estimated based on the approximate slope of the channel profile at this location, which was 0.01 ft/ft.

Any water entering or exiting from additional flow paths, groundwater, or local hillslopes was neglected. The downstream lake boundary was set as a constant elevation based on the 90 percent exceedance elevation of 1,209.5 ft NAVD 88 for the hydraulic roughness calibration model simulations (refer to Section 4.2).

5.6 Model Parameters

The full momentum equations (Saint Venant) were used. Given the relatively fine resolution of the mesh a timestep of 0.5 or 1.0 seconds was selected for each simulation. The combination of 25 ft cells, 1.0 second timestep, and modeled velocities generally less than 20 ft/s indicate that the selected modeling parameters meet the recommended Courant number criteria for model cell computations. The models were run with a 6 hour hydraulic warm up and four hours for the main simulation. These conditions allowed each model simulation to approach steady-state equilibrium. At the completion of each simulation, models were checked for minimal overall volume accounting errors and water surface elevation errors. Given the lack of measured velocity distribution data in the channel and overbank regions for calibrating momentum diffusion parameters, RAS's "turbulence" parameters were not utilized. Turbulence parameters do not significantly influence computed water surface elevations and thus modeled backwater extents up Thunder Creek.

5.7 Sensitivity and Simulation Combinations

In the previous sections a number of different scenarios for model setup were described, which includes variations in peak flow and roughness (Table 5-1). In addition to those variations, it was decided to include a simulation that would predict the greatest potential for backwater during the 2003 flood that recruited significant wood to the delta. To do this, the terrain was modified in the vicinity of the wood jam to include a complete barrier elevated to 1,224.0 ft NAVD 88 (Figure 5-3). For this combination, the inflow was held constant at 17,800 cfs and only the 0.07 roughness was simulated. The lake water surface elevation was then varied from 1,204.0 to 1,212.0 ft NAVD 88. This process allows us to see the inflection point of the backwater influences and provides the greatest backwater potential.

Table 5-1. Simulations combinations analyzed in the HEC-RAS model.

Parameter	Variation
Flows	Q2, Q5, Q10, Q50, Q100, and the 2003 flood
Varied uniform roughness	0.03, 0.05, and 0.07
Terrain	Combined topographic-bathymetric surface and combined surface with a modified representation of a valley spanning wood jam
Lake level	Constant 1,209.5 ft NAVD 88 for most runs with two simulations analyzing least and most backwater effects by varying the lake water surface elevation from 1,194 (minimal lake effect) to 1,212 (high lake level) ft NAVD 88

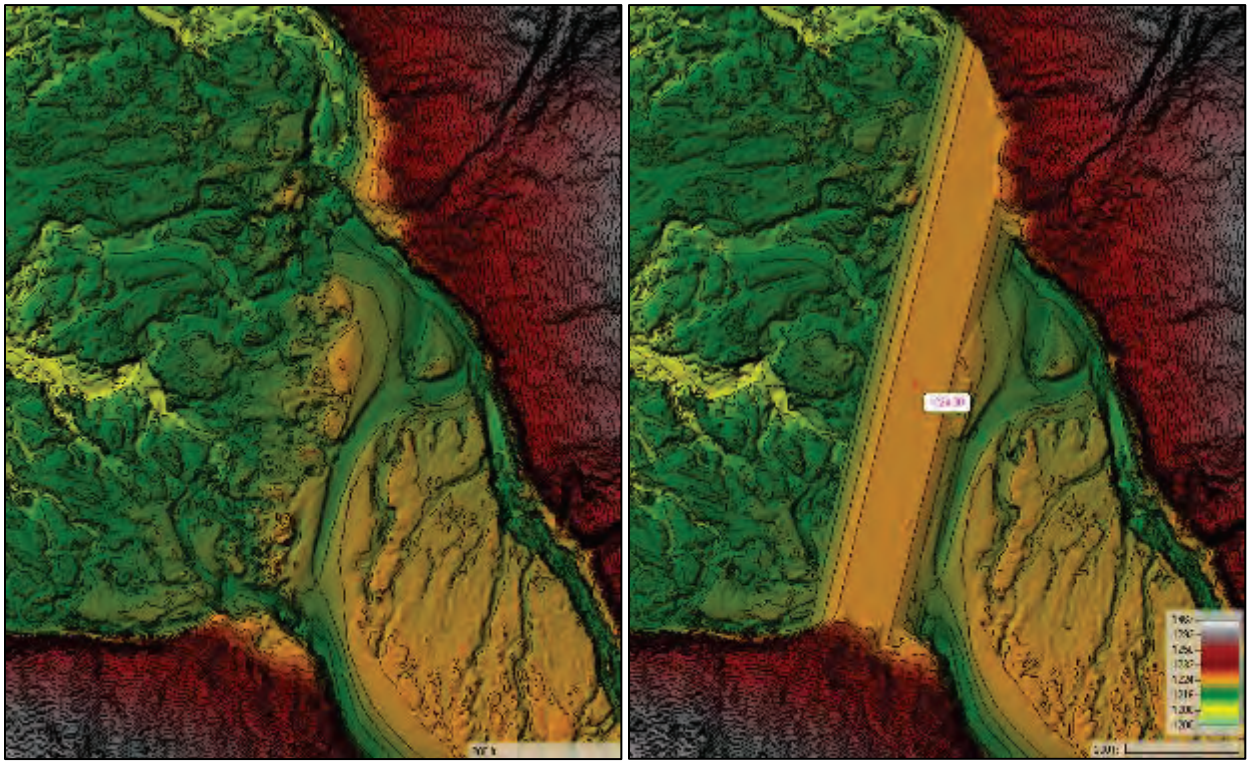


Figure 5-3. Modified terrain representing potential backwater effects if the 2003 flood had a valley spanning wood jam that spanned the valley width. Contours are 2 ft.

5.8 Approximate Calibration

Calibration data for the hydraulic analysis is limited to approximated water surface elevations at the USGS gaging station. Field measurement records for this station go back to 1931, however, the majority of these records are less than 3,000 cfs. Also, as noted in Section 3 Hydrologic Data Review, the stage-discharge relationship has been changing. To most accurately estimate water surface elevations that represent the surface used in the model (ca 2018) at modeled flood flows, only measurements from 2017 to 2021 that were greater than 1,000 cfs (11 measurements) and the 2003 flood measurement (1 measurement) were used. A rating curve was fit to these data using a power function, for which water surface elevations (WSEs) were estimated for each of the design floods (2-year, 5-year, etc.) by adding the datum shift to NAVD 88 (1,224.0 ft).

For calibration of the Thunder Creek HEC-RAS model there were three roughness values tested: 0.03, 0.05, and 0.07. Each roughness was run in combination with the 2-year, 5-year, 10-year, 50-year, and 100-year floods, and the 2003 flood peak flow. These floods provided modeled water surface elevations along Thunder Creek. Modeled WSEs were then extracted for each simulation at the centerline of the channel near the USGS gage. Cross-referencing these results with the approximate WSE estimates (Figure 5-4), it appears that the roughness coefficient of 0.05 reasonably matches for flows less than the 10-year flood. At flows greater than the 10-year flood, it appears that a roughness coefficient of 0.03 provides a reasonable estimate.

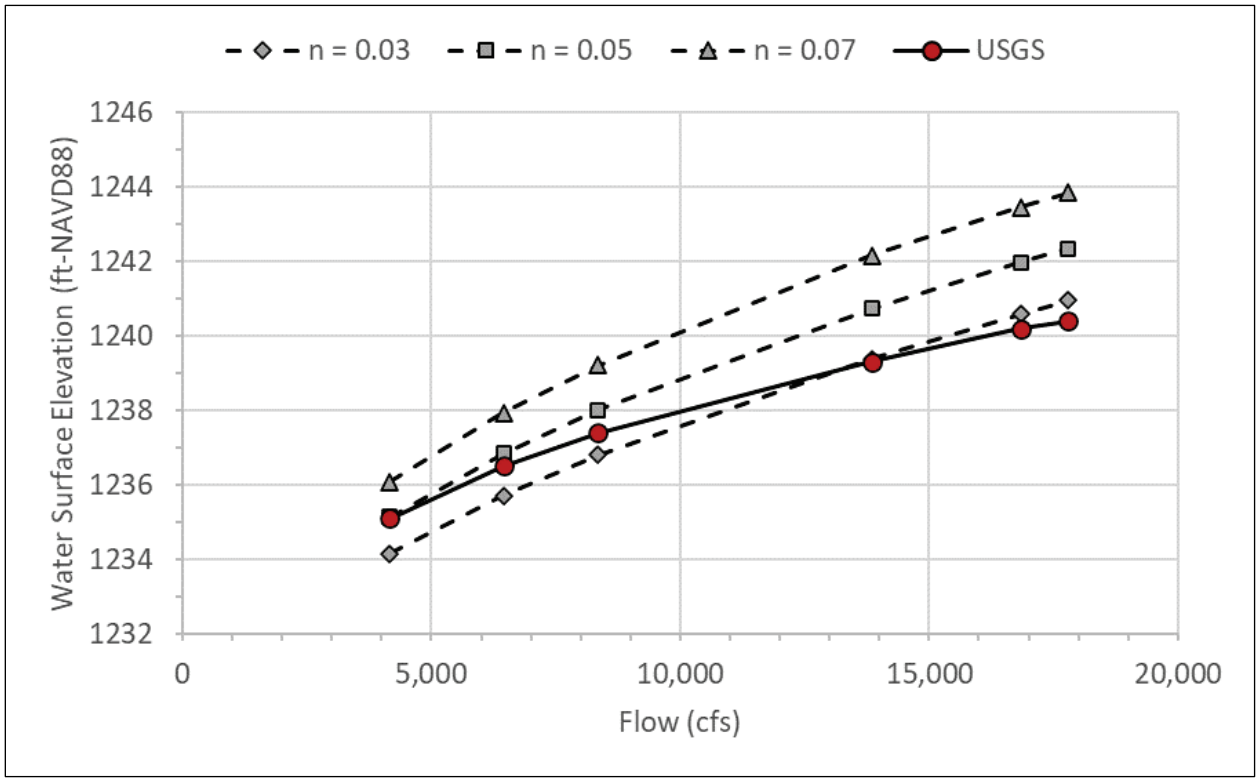


Figure 5-4. Approximate roughness calibration at the USGS Thunder Creek gage (12175500).

6 Hydraulic Analysis Results

Results of the hydraulic analysis were selected to address the objectives of this work and depending on the circumstances; therefore, roughness values may not match the calibration analysis (Figure 5-4). Profile plots showing water surface elevations for multiple flood scenarios were extracted from the model using an approximate thalweg alignment that extends from downstream of the SR 20 bridge and upstream to the model boundary (Figure 6-1). Locations of note on this figure include the SR 20 bridge around station 5,625 ft, the log jam between stations 12,000 and 13,200 ft, and the USGS gage at 16,215 ft.

Water surface elevation plots for the 0.03 roughness at each of the modeled floods show that that the constriction under the bridge has a significant control on water surface elevations upstream of the bridge (Figure 6-2). At low flood flows, such as the 2-year flood (4,170 cfs), the bridge has around 0.2-0.4 ft of an impact on the water surface elevation, depending on the roughness. At high flow, such as the 2003 flood (17,800 cfs), the bridge has around 2.8-4.0 ft of an impact on the water surface elevation, depending on the roughness. However, the effect of the bridge-caused backwater is limited to the downstream end of the Thunder Creek delta. These results are demonstrated by the convergence of water surface elevations at around station 11,500 ft for the 2003 flood using low and high reservoir levels (Figure 6-3). High flows within the reservoir will be less impacted by low roughness values since the flood flows will be running across relatively deep water and the impact of the bridge embankment and constriction will be on areas upstream of the bridge. Lower values of roughness, however, do have implications for velocity and the model approximates a maximum flood velocity through the bridge greater than 11 ft/s. In a very low lake

level (around 1,194 ft NAVD 88), the estimated through bridge velocity is around 19 ft/s. The potential impact of these high velocities on bridge embankment and abutment stability has not been assessed as part of these studies.

A key objective of this study was to determine the maximum backwater upstream of Thunder Arm possible. To do this a series of maximum (2003) flood simulations at each roughness value was compared with existing terrain versus the possibility of the 2003 flood and wood jam deposits that completely span that portion of the valley (refer to Figure 5-3). The results of this analysis showed that all water surface elevations (for each roughness) converge around station 14,500 ft, or approximately 1,500 ft upstream from the log jam (Figure 6-4).

One of the objectives of this study was to assess the potential implications of the 2003 deposition as it relates to the die back of cedar trees on the delta. The modeling indicates that during common floods (i.e., 2-year event) the regions where cedar tree die back has been observed is inundated by 2 or more feet of water (Figure 6-5). Cursory review of flood duration data suggests floods on the order of 2-year events have a duration of hours with some floods in the 15-min record being on the order of days, so although the base of the trees are inundated the duration is limited. The potential change in water table level associated with the log jam may be more significant factor influencing the die back, however, that was not investigated in this work.

Based on hydraulically modeled results, the backwater influence of the log jam or a valley spanning log jam does not extend upstream to the USGS gage location. However, aerial image and stage gage analyses suggest that the log jam is enhancing sediment deposition immediately upstream of the log jam, resulting in the observed and ongoing upward shift of the stage-discharge rating curve at the USGS gage. Localized logs or sediment deposition that have been observed near the gage site may also be contributing to the upward shift of the stage-discharge rating curve. Repeat LiDAR or other terrain mapping surveys are not available to confirm the locations and magnitudes of any ongoing sediment deposition in this portion of Thunder Creek. The USGS gage is also located just outside of the 2017/2018 LiDAR survey, and it must be recognized that the 10 meter DEM may not represent channel and overbank terrain accurately at the gage location.

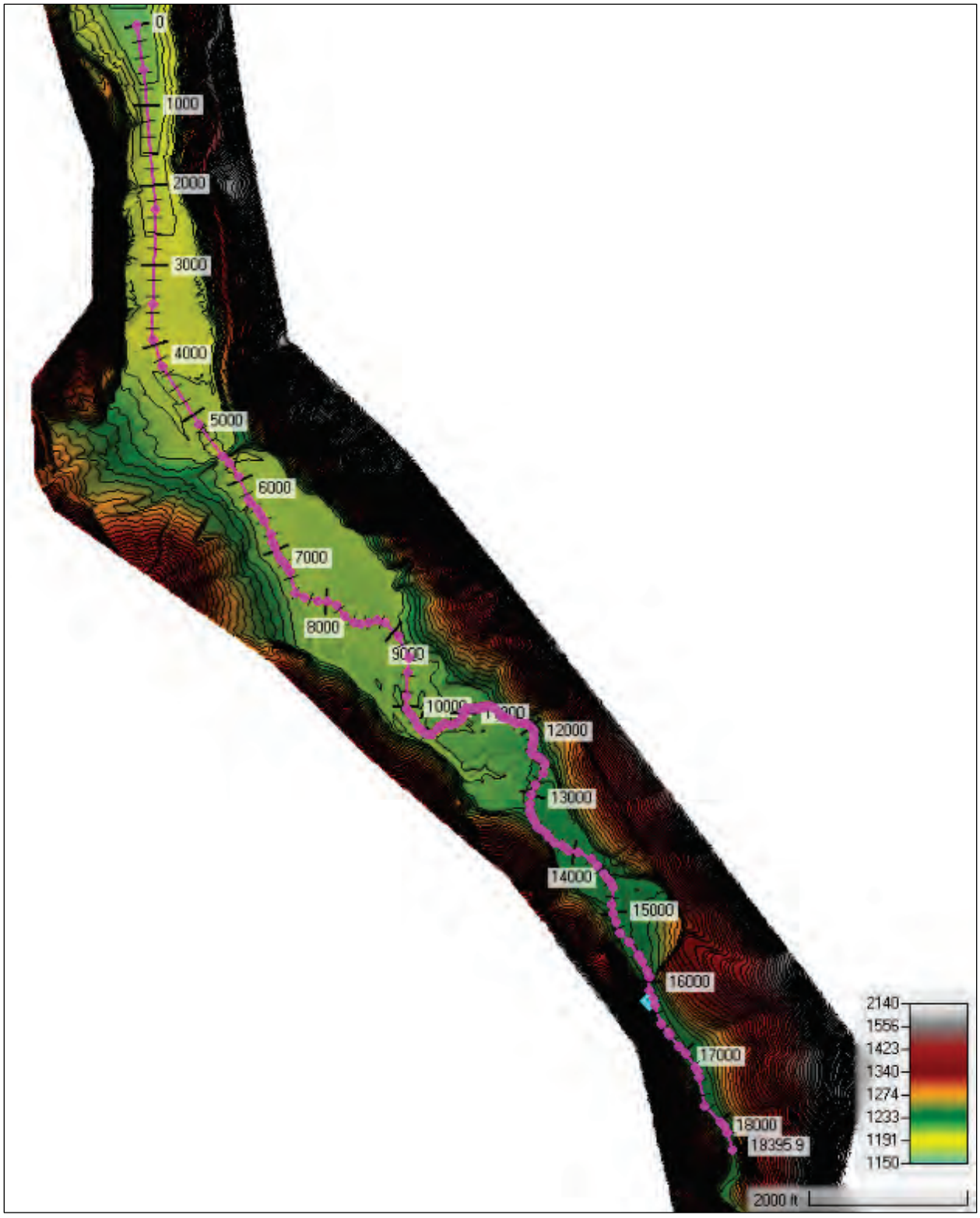


Figure 6-1. Centerline used to extract water surface elevations. The blue diamond represents the location of the USGS Thunder Creek gage (12175500). Contours are 10 ft.

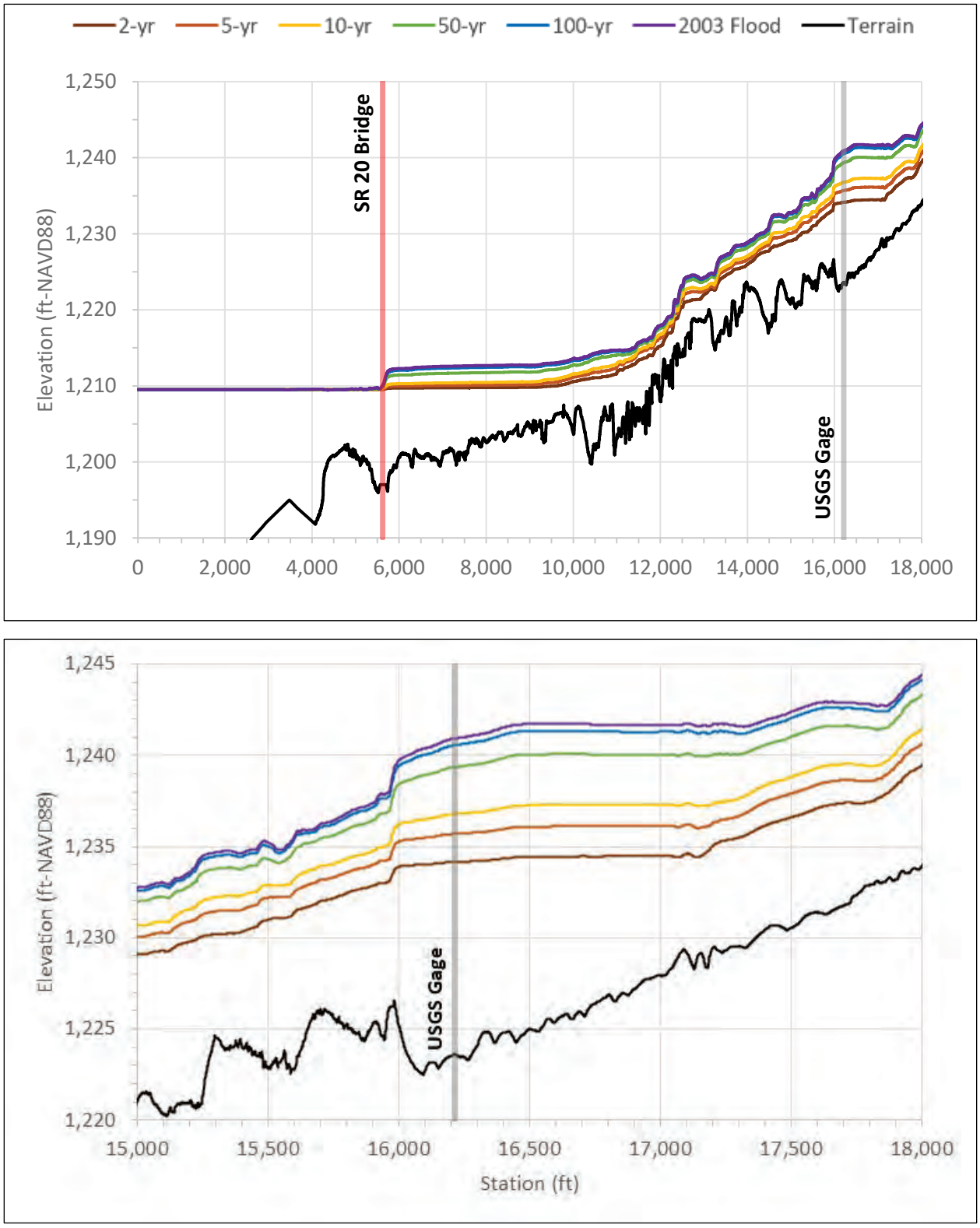


Figure 6-2. Water surface elevation profiles for variable floods using a roughness value of 0.03.

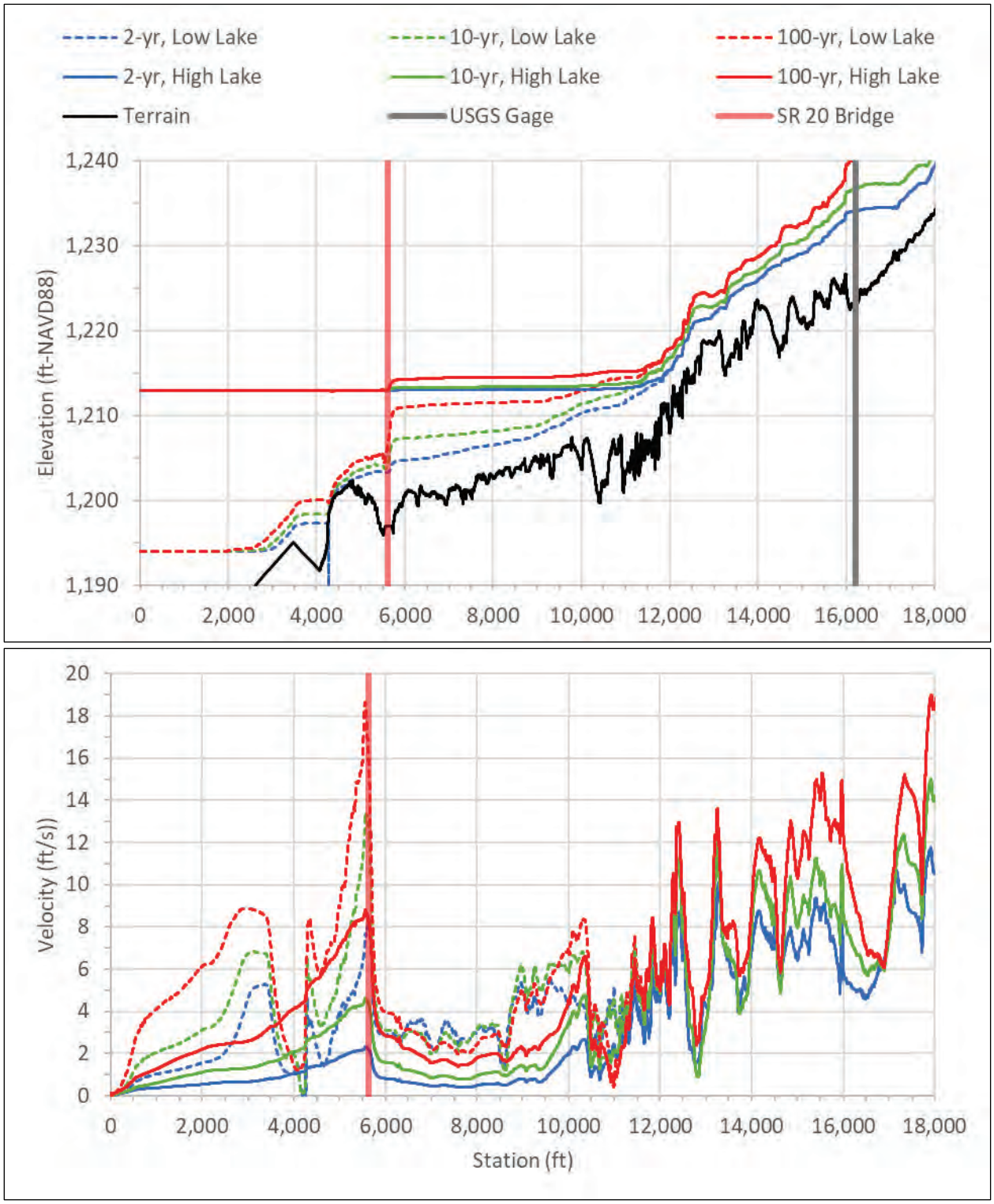


Figure 6-3. **Comparison of water surface elevations (top) and velocities (bottom) for low (1,194 ft NAVD 88) and high (1,212 ft NAVD 88) lake levels for the 2-year, 10-year, and 100-year floods. The roughness is 0.03 for all presented results.**

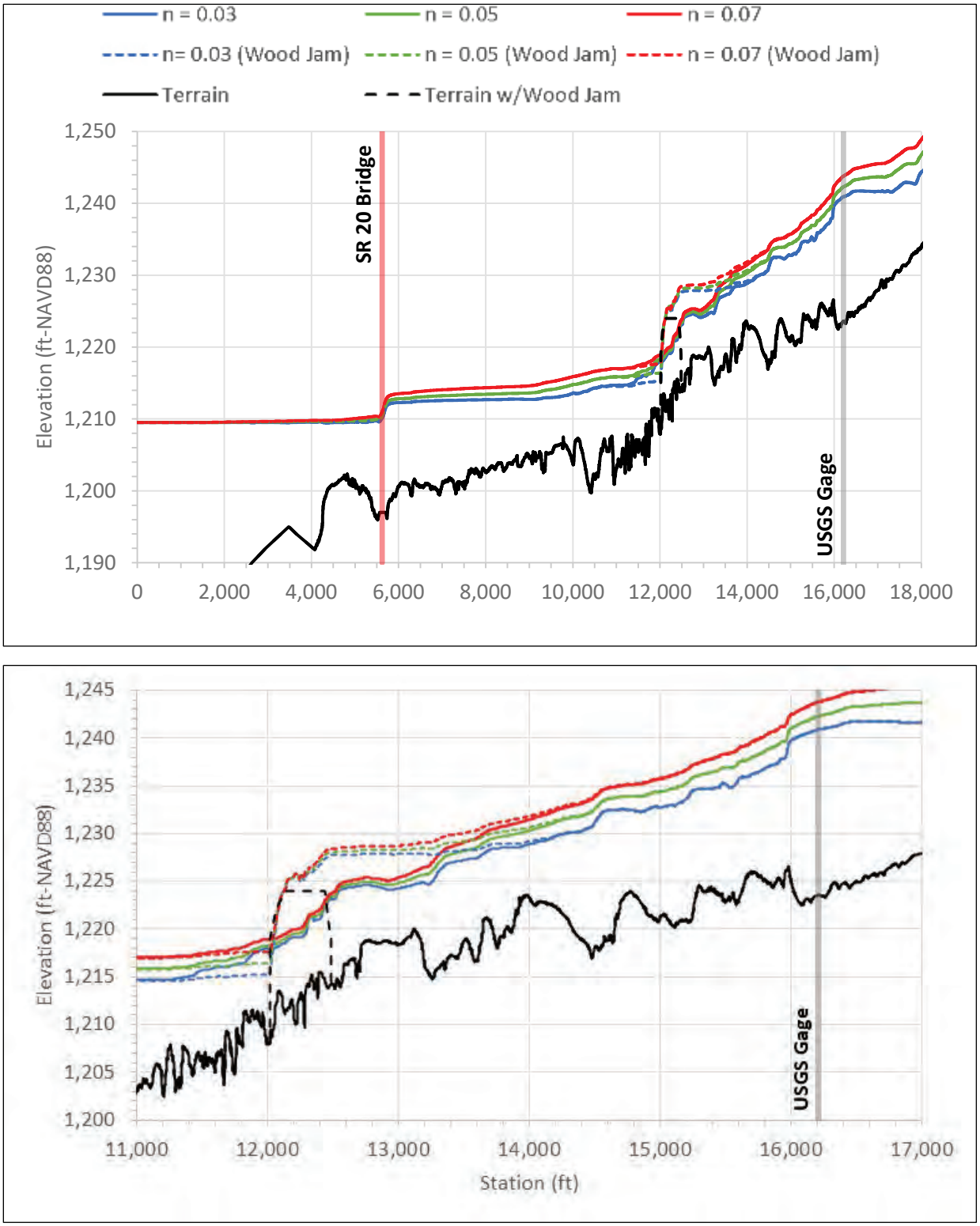


Figure 6-4. **Water surface elevation profiles for flood results using roughness values for 0.03, 0.05, and 0.07 for the model terrain and with the terrain modified with a valley spanning wood jam.**

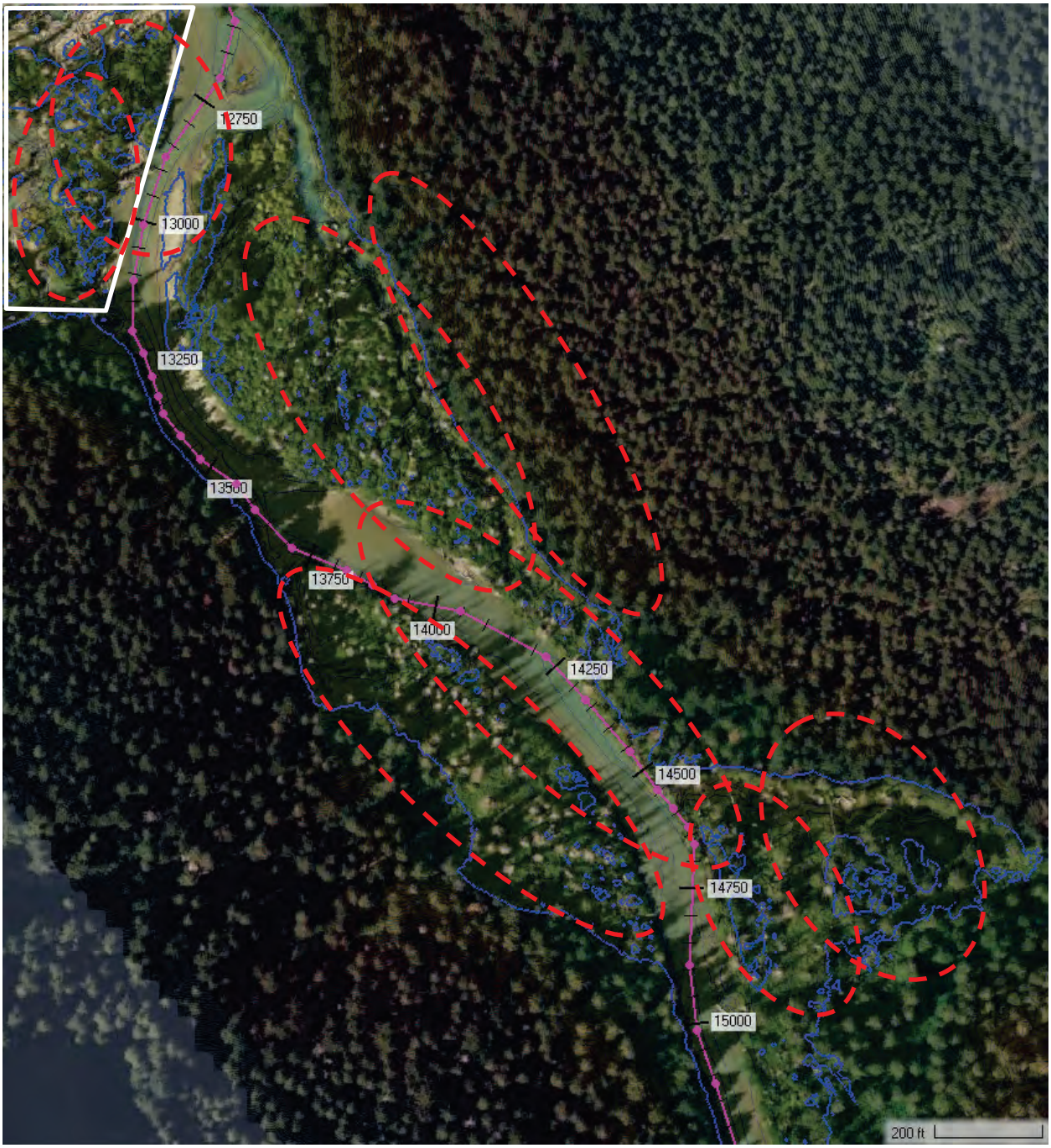


Figure 6-5. **Aerial imagery and hydraulic inundation for the 2-year flood (4,170 cfs) using a roughness of 0.05 showing approximate location of dead cedar trees (circled in dashed red) and general location of log jam (white solid line). Faint contour lines are 2 ft intervals.**

7 Conclusions and Discussion

Aerial imagery starting in 1947 (post-dam construction) shows that the delta has been growing since that time. The growth of the delta is most prominently punctuated as a result of significant accumulation of wood and sediment transported during the 2003 flood (flood of record). Analysis of the measured stage-discharge relationships at the USGS Thunder Creek gage (12175500) shows sediment deposition and aggradation on the delta and downstream of the gage site starting with the 2003 flood event and have been continuing since that time.

Following are specific responses to each of the key objectives of this study:

- *What are the extents of lake backwater effects during floods in Thunder Creek?*

The effects of lake levels generally have a direct influence on backing water up to the existing log jam. Deposition upstream of the log jam has likely occurred as indicated by the rapid response and shift of the USGS gage stage discharge relationship following the 2003 flood event. These compounding and longitudinally continuous effects result in backwater influences up to the vicinity of the USGS stream gage.

- *Will the deposition of sediment and wood continue, further causing backwater of Thunder Creek?*

Low to moderate flows have eroded 1-2 channels through the 2003 deposits, which may indicate that low to moderate flows do not contribute to significant aggradation upstream from the log jam. This does not dismiss that low flows don't carry sediment, as the sediment that they carry contributes to the progradation of the delta into the reservoir. In contrast, at high flows, the log jam causes a significant obstruction to flow, resulting in reduced energy upstream and likely contributing to further aggradation upstream of the log jam. The constriction at the bridge during high flows compounds the backwater effects of the reservoir, which contributes to deposition on the Thunder Creek delta, but not as far upstream as the log jam. Rhode Creek flows in just upstream of SR 20 and has a small alluvial fan protruding into the reservoir; the relatively small fan is presumed to have little to no influence on upstream hydraulics at typical lake levels. Colonial Creek has a larger alluvial fan than Rhode Creek, but is downstream from SR 20 and it is therefore believed this creek has no influence on the hydraulics or sedimentation at the Thunder Creek delta. These fans are included in the terrain for the Diablo Arm portion of the HEC-RAS model so any backwater effects of the fans are accounted for in the analysis.

- *Is the deposition caused by extraordinary events or is it a more continuous process?*

Review of the geomorphology and hydraulics for the Thunder Creek delta suggest that both small (i.e., 2-year and 5-year magnitudes) and large (i.e., 10-year magnitude and greater) floods have played a key part in the dynamics of the delta. The 2003 flood (100-year magnitude) brought a significant amount of wood and sediment to the delta. The racking and amount of wood in the delta today make it easier for additional wood and sediment to accumulate at this location during low to moderately sized floods. Additionally, the general high point in the terrain caused by the 2003 deposits has effectively raised the base level of the terrain at the apex of the delta for larger floods. This change has led to a rise in the thalweg upstream, as noted by the ongoing and continuous changes in in the stage-discharge relationship at the USGS gage (Figure 3-5).

- *What are the underlying causes to the death of the cedar trees?*

Based on the available aerial imagery, the cedar trees started dying prior to the 2006 imagery and it is most likely related to the deposition of sediment and wood during the 2003 flood. During the 2003 flood the reservoir elevations rose to nearly 1,212 ft NAVD 88; the backwater from this reservoir elevation alone would have been sufficient to back water up to where the log jam formed. As noted earlier, the SR 20 bridge causes a constriction to flood flows, which further exacerbates backwater effects to just downstream of the log jam. Ultimately, the reservoir contributed to the deposition of the sediment and wood transported during the 2003 flood, which in turn led to deposition upstream from the delta and, as suggested by the change in stage-discharge rating curves, as far upstream as the USGS gaging station. Although hydraulic modeling results for the 2-year flood using the best calibration roughness of 0.05 shows that the floodplain has overbank flows in the vicinity of the dead cedar trees (Figure 6-5), the duration of surface flows is not long enough to have caused the die back. It is probable that a change in water table and/or potentially sedimentation around the root zone is influencing their mortality. A botanist with a background in cedar trees should be consulted to further understand these implications.

The following additional observations are noted from our analysis of the geomorphology and hydraulic characteristics of Thunder Creek and its delta at Diablo Lake:

- The extents of backwater impacts during the 2003 flood are uncertain given terrain data for that time period is unavailable; however, the stage-discharge analysis suggests that there was around 2 ft of aggradation at the USGS gaging station.
- The channel morphology on the delta has become more complex with multiple flow paths through time as is typical for delta development.
- Vegetation has established on the emergent bars and delta sediments deposited during and after the 2003 flood.
- The HEC-RAS results indicate that the SR 20 bridge causes up to 4 ft increase in flood profiles immediately upstream of the bridge and to the approximate downstream extent of the emergent subaerial delta deposits near HEC-RAS station 10,000 (Figure 6-1).
- Pre-2003 terrain does not exist which limits our analysis to demonstrate the implications of the backwater due to deposition and log jam formation associated with the 2003 flood.

DISCLAIMER

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SEDIMENT DEPOSITION IN RESERVOIRS AFFECTING RESOURCE AREAS OF CONCERN STUDY REPORT

ATTACHMENT B

RECENT HISTORY OF RHODE CREEK

Recent History of Rhode Creek

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April 15, 2016

The purpose of this report is to document the recent activity of Rhode Creek near Colonial Campground in Ross Lake NRA. Rhode Creek is a small first order stream with a history of channel instability and frequent debris flows. The creek has produced numerous debris flows in the past 50 years due to its geologic setting and human manipulation. The upper part of Rhode Creek follows the Thunder Lake Fault, which has given the stream a steep, straight profile capable of carrying voluminous debris flows to Diablo Lake. The fault zone also produces large quantities of gravel and boulders. In an undisturbed state this stream is thought to produce debris flows every 20 years or so that have of volume of 20,000-30,000 cubic yards. Major events occurred in 1972, 1984 and 2004.

In 1956, almost 30 years after Diablo Lake was created, Rhode Creek met the lake several hundred feet to the southeast of its present location (Figure 1). At that time there were no large debris fans extending into Diablo Lake where it met the stream. Sometime soon after 1956, Rhode Creek channel appears to have been moved to the north by the US Forest Service during construction of Colonial Creek Campground in the late 1950s. The old channel was blocked by a levee to prevent it from flowing through the new campground. This action forced the creek to take a steeper, more direct route to Diablo Lake down a channel that has been very unstable. Along with a series of large rainfall events in 1972, 1983, 1995, and 2004, the channel relocation led to the deposition of several tens of thousands of cubic yards of new sand and gravel into Diablo Lake on either side of the new western highway bridge abutment (Figure 1). Much of the sediment was deposited on the debris cone where Rhode Creek gradient drops at the campground entrance off of highway 20. The box culvert beneath the campground entrance road is too small to hold the debris flow deposits and is often fills with sediment, leading to material being carried along and across the highway and into Diablo Lake. Some events such as the one in 1983 buried the highway at the entrance in 6 ft of rubble. These events have led to the growth of the gravel fan 100 ft or more into the lake on the north side of the highway in the past 50 years.

USFS records show that the new stream channel was unstable and in 1978 USFS engineers designed a system that included placement of several gabion baskets at three locations in the channel to try and slow channel widening and downcutting. These structures were not effective and the channel's width and depth grew steadily during smaller rainstorms in in the late 1980s and early 1990s (Table 1). Over-aggressive removal of these deposits by the NPS to create a catch-basin at the head of the culvert led to more channel growth and more frequent, but smaller, depositional events at the entrance road. Unlike the previous large events the movement of gravel from the channel occurred roughly every 5 years and each event left from 1,000- 5,000 cubic yards. The NPS removed much of the material from these events, but some made it into Diablo Lake on both sides of the highway.

In summary, the present location and activity of Rhode Creek are the result of natural conditions (fault zone producing large debris flows and large rainfall events) and management actions (flooding of valley by Diablo Lake 1929, relocation of creek channel late1950s, construction of highway ~1972, and debris removal after recent depositional events. The 2004 flood and debris flow deposition sent some flow to the south through the campground and into Diablo Lake near the present amphitheater. It is not known if Rhode Creek will attempt to expand use this route in the future. It is also possible that a large depositional event at the canyon mouth could send Rhode Creek directly to Highway 20 to the north of its current location.

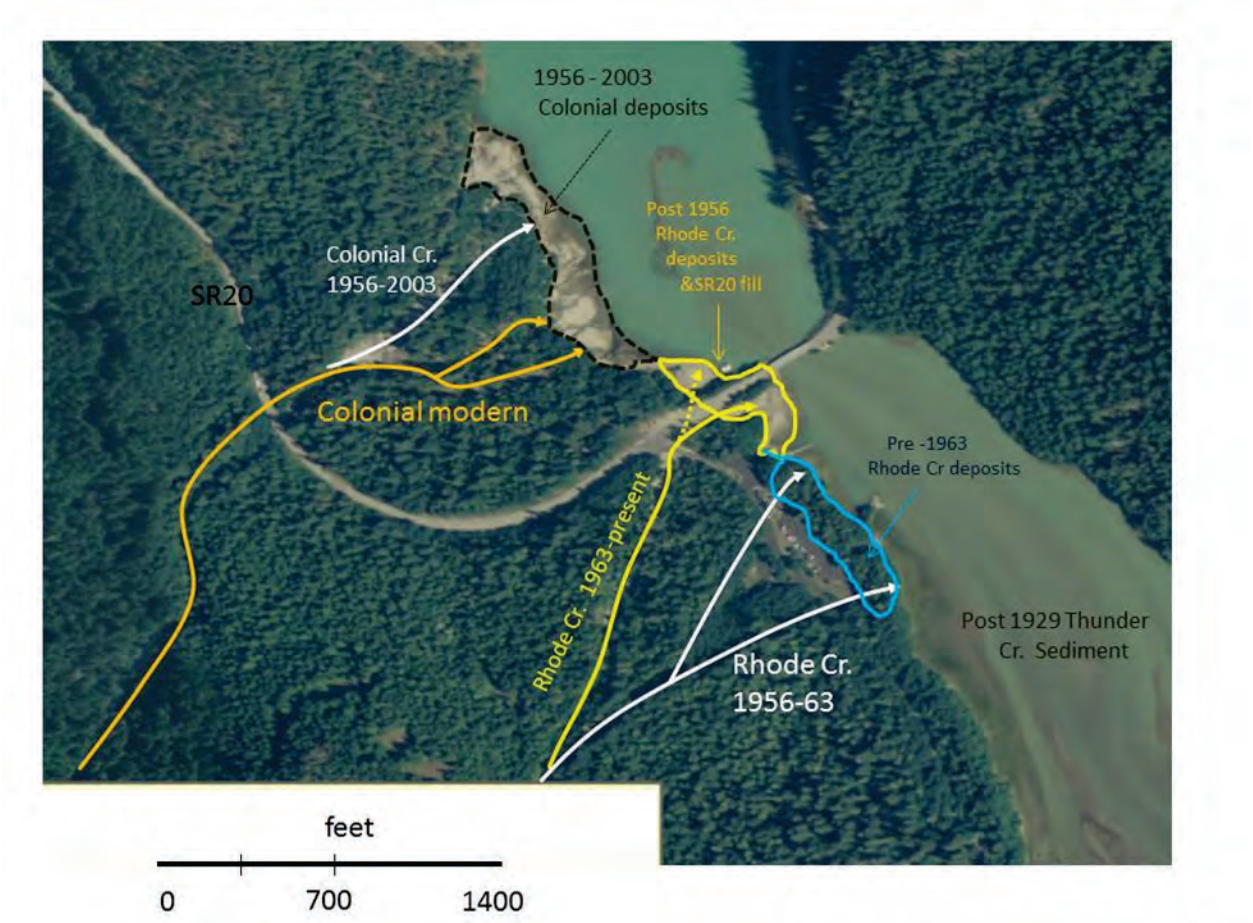


Figure 1. **Recent geomorphic changes near the mouths of Colonial and Rhode Creeks based on air photos taken in 1956, 1978, 2006 on 2009 image.**

Table 1. Chronology of NPS actions to remove debris from mouth of Rhode Creek (1968-2016).

Year	Relative Event Size and Timing	NPS Actions
1971	Small	Debris removed
1974	Large	Box Culvert repaired, debris removed
1975	Small	Debris removed
1976	Moderate spring?	Box culvert repaired, debris removed
1977	Moderate	Several thousand cubic yards of debris removed
1978	Small spring	Debris removed from entrance road, gabion baskets installed left bank near SR20, trash rack installed on entrance box culvert
1979	None	Improvements to box culvert
1980	Small	700 cubic yards of debris removed
1983	Small	Debris removed
1984	Large	10-20,000 cubic yards of debris removed
1989	Moderate fall	9,000 cubic yards of debris removed
1990	Moderate fall	9,000 cubic yards of debris removed
1995	Moderate fall	Debris removed
2004	Large fall	Debris removed, deposition at canyon mouth leads creek to flood campground to south
2015	Moderate fall	Debris removed, Channel incision on north side of highway