GE-04 SKAGIT RIVER GEOMORPHOLOGY BETWEEN GORGE DAM AND THE SAUK RIVER STUDY REPORT

SKAGIT RIVER HYDROELECTRIC PROJECT
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List of Attachments

Attachment A Annotated Bibliography of Geomorphology from Sauk River Confluence to Skagit Estuary
Attachment B Scour Monitor Installation Location Mapbook
Attachment C Large Wood Inventory Detailed Areas Mapbook
Attachment D LiDAR REM Mapbook
Attachment E Historical Channel Changes Mapbook
Attachment F Aquatic Habitat Mapbook
Attachment G Tributary Fish Passage Analysis Inventory
Attachment H Side Channel Inventory Narrative by Geomorphic Reach
Attachment I Large Wood August 2021 Inventory Mapbook
Attachment J Large Wood Distribution by Geomorphic Reach
Attachment K Large Wood Initial Tag Locations December 2021
Attachment L Large Wood Transport During High Flow Events Between October 2021 and January 2022
Attachment M Channel Migration Zones for Key Tributaries Mapbook
Attachment N Predicted Outcomes of Large Wood Piece Movement
Attachment O UBC Regime Model (UBCRM) Model Application Technical Memorandum
Attachment P 1-D HEC-RAS Mobile Bed Model Development Technical Memorandum
Attachment Q Morphodynamics and Sediment Tracers 1-D (MAST 1-D) Model Development Technical Memorandum
Attachment R Sediment Yield Analysis Memorandum
Attachment S LiDAR Change Detection 2017-2022 Mapbook
Attachment T Indicators of Hydrologic Alteration Memorandum
Attachment U Off-Channel Level Loggers Memorandum
Attachment V Spatially Interpolated Risk of Scour Exceeding Redd Depth Thresholds
Attachment W Woody Debris Management Summary of Activities to Date Memorandum

List of Acronyms and Abbreviations

1-D .....one-dimensional
2-D .....two-dimensional
ABSS.....above Shovel Spur
BMM.....below Marblemount
cfs.....cubic feet per second
City Light.....Seattle City Light
cm.....centimeter
cu ft .....cubic feet
dbh.....diameter at breast height
DEM.....Digital Elevation Model
DNR .....Department of Natural Resources (Washington State)
Ecology .....Washington State Department of Ecology
FERC.....Federal Energy Regulatory Commission
FLA .....Final License Application
ft .....foot/feet
GIS .....Geographic Information System
GPS .....Global Positioning System
HEC-RAS .....Hydrologic Engineering Center River Analysis System
HSC.....Habitat Suitability Criteria
IHA .....Indicators of Hydraulic Alteration
IQR.....interquartile range
ISR .....Initial Study Report
kg.....kilogram
kHz.....kilohertz
LB .....left bank
LiDAR.....Light Detection and Ranging
LP.....licensing participant
LWD .....large woody debris
m .....meter
MAST .....Morphodynamics and Sediment Tracers
MHz .....megahertz

mm .....millimeter
NAVD 88.....North American Vertical Datum of 1988
NGVD 29.....National Geodetic Vertical Datum of 1929
NMFS.....National Marine Fisheries Service
NPS .....National Park Service
NSD.....Natural Systems Design
PAD.....Pre-Application Document
PIT.....passive integrated transponder
PME .....protection, mitigation, and enhancement
PRM.....Project River Mile
Project .....Skagit River Hydroelectric Project
QA/QC.....quality assurance/quality control
QSI.....Quantum Spatial, Inc.
RB .....right bank
RCI.....River Complexity Index
REM.....relative elevation model
RFID .....Radio Frequency Identification Device
RS-FRIS.....Remote-Sensing Forest Resource Inventory System
RSP .....Revised Study Plan
RTK.....Real-time Kinematic
SR.....State Route
SRSC.....Skagit River System Cooperative
SWIFD.....Statewide Washington Integrated Fish Distribution
UBCRM.....University of British Columbia Regime Model
USACE .....U.S. Army Corps of Engineers
USFS.....U.S. Forest Service
USGS .....U.S. Geological Survey
USR.....Updated Study Report
WDFW.....Washington Department of Fish and Wildlife
WSDOT .....Washington State Department of Transportation
WSE.....water surface elevation
WY.....water year
yr .....year

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1.0 INTRODUCTION

The GE-04 Skagit River Geomorphology Between Gorge Dam and the Sauk River Study (Geomorphology 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 [NMFS], National Park Service [NPS], U.S. Fish and Wildlife Service, Washington State Department of Ecology [Ecology], and Washington Department of Fish and Wildlife [WDFW]). The June 9, 2021 Notice included agreed to modifications to the Geomorphology Study.

In its July 16, 2021 Study Plan Determination, FERC approved the Geomorphology Study with modifications. Specifically, FERC did not require City Light to quantify the amount of sediment transported into Ross Lake on an annual basis (which was an agreed to modification in the June 9, 2021 Notice). Notwithstanding, City Light implemented the Geomorphology Study as proposed in the RSP with the agreed to modifications described in the June 9, 2021 notice. On March 8, 2022, City Light filed its Initial Study Report (ISR). The Upper Skagit Indian Tribe and NMFS filed requests for study modification. FERC's August 8, 2022 Determination on Requests for Study Modification required no modifications to the Geomorphology Study.

This study is substantially complete and a report of the study efforts is being filed with FERC as part of City Light's Updated Study Report (USR). Development of the two-dimensional mobile bed model is ongoing and a technical memorandum describing development and calibration of the model will be provided to LPs and filed with FERC in Q2 2023. This model is not critical for development of an effects analysis but will provide additional information that will help inform future adaptive management.

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

2.0 STUDY GOALS AND OBJECTIVES

The goals of the Geomorphology Study are to characterize the current condition of aquatic habitat within the 30-mile segment of the Skagit River between Gorge Dam and the Sauk River confluence and to characterize how Project-related changes in peak flows affect geomorphic processes, which will be used to evaluate the Project's contribution to cumulative effects in the reach. Specific objectives include:

- Use aerial photograph and Light Detection and Ranging (LiDAR) data and collect field data noting current conditions and changes to document:
  - Baseline channel configuration and migration patterns;
  - Distribution of aquatic habitat types, characteristics, and availability;
  - Side channels and off-channel habitat, including hydraulically-connected wetlands;
  - Substrate size and distribution;
  - Sediment sources and delivery mechanisms; and
  - Large wood input, transport and retention.
- Determine flow rates that may result in redd scour to help guide management of peak flow releases from Gorge Dam and Powerhouse.
- Investigate flows that result in geomorphic/habitat changes (process flows) for the following processes:
  - Mobilize deposits at tributary mouths along the mainstem Skagit River;
  - Mobilize riverbed and bars;
  - Erode riverbanks and result in channel migration;
  - Instigate side channel development/maintenance; and
  - Hydraulically connect side channel and off-channel habitat.

Per the June 9, 2021 Notice, additional commitments related to study efforts below the Sauk River confluence were incorporated into the Geomorphology Study and are described in this study report. These commitments, as well as the status of their implementation, are described in Section 6.2 of this study report.

3.0 STUDY AREA

The primary study area includes the 30-mile segment of the Skagit River between Gorge Dam and the Sauk River confluence (Figure 3.0-1). Side channels and off-channel habitat areas included in the primary study area were selected through a collaborative process involving the LPs, City Light staff, and study teams. There are 20 named tributary streams that drain into the Skagit River within the primary study area (Figure 3.0-2; Table 3.0-1). Fieldwork and analysis were generally limited to the tributary junctions defined as a distance of 500 feet (ft) upstream of the confluence with the Skagit River at each tributary. Additional review of previous geomorphic studies downstream of the Sauk River confluence was completed and included in an annotated bibliography found in Attachment A.

The downstream extent of the sediment transport study area is the location where the riverbed material shifts from gravel to sand (called the gravel-sand transition) around Project River Mile (PRM) 21 near Sedro-Woolley, about 11 miles upstream of the channel bifurcation at the head of the delta where the channel debouches into the estuary where tidal processes begin to dominate channel forming processes. Section 7.3 of this study report explains the rationale for choosing this location as the downstream boundary for the sediment transport modeling program.

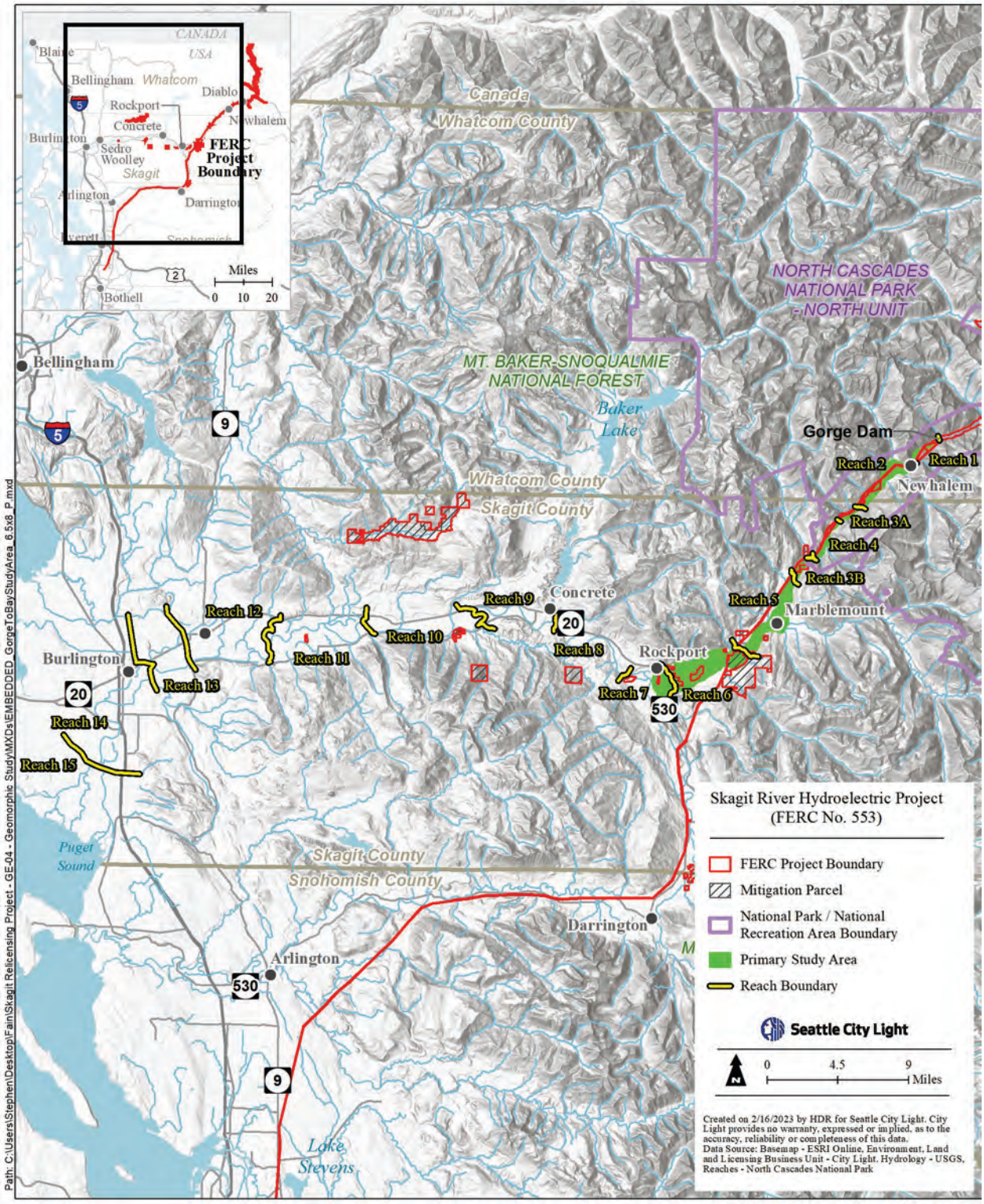


Figure 3.0-1. Overview map of the Skagit River from Gorge Dam to the estuary including geomorphic reach boundaries from Riedel et al. (2020) and highlighting the primary study area from Gorge Dam to Sauk River confluence.

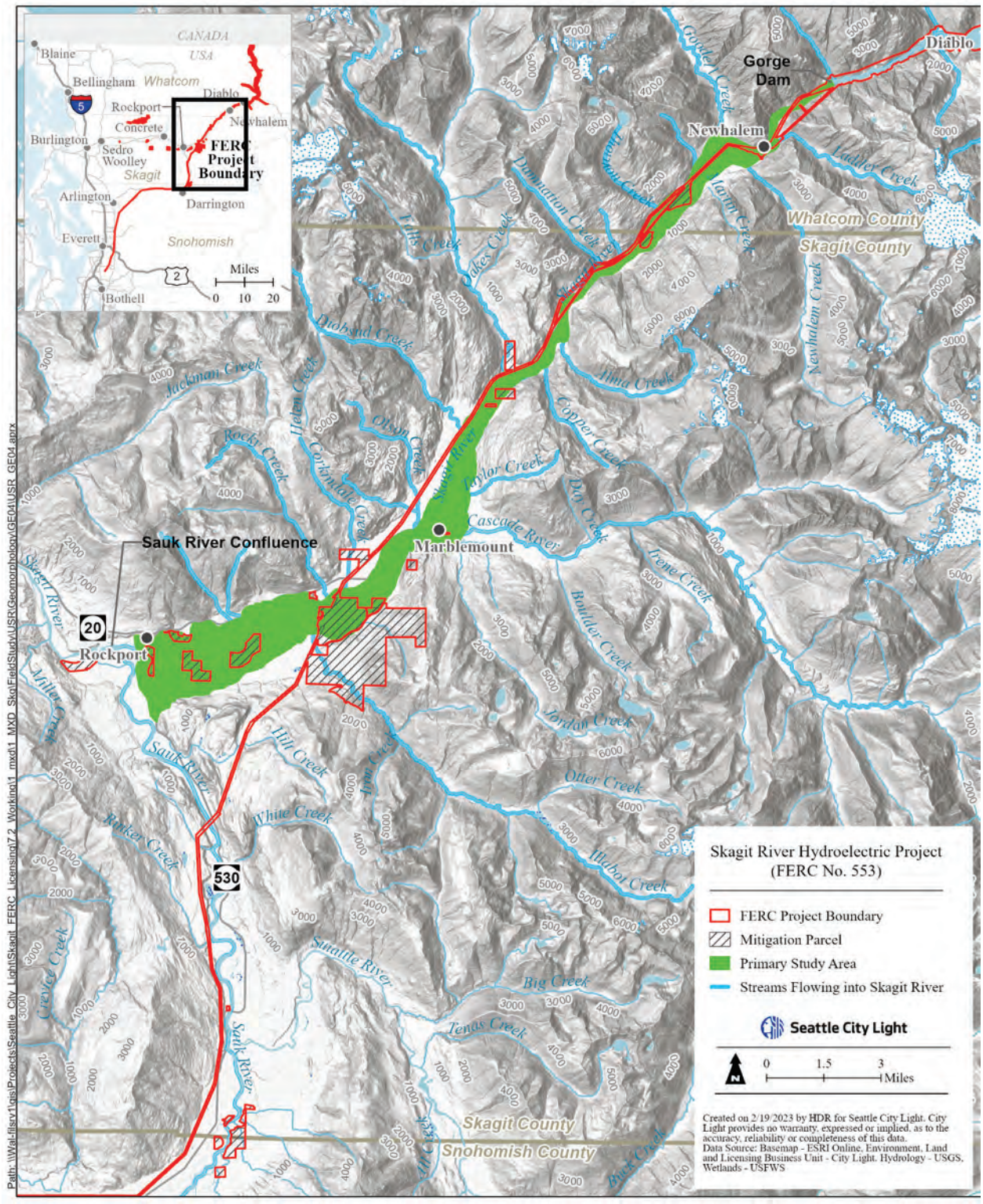


Figure 3.0-2. Overview of primary study area: Gorge Dam to Sauk River confluence.

Table 3.0-1. Tributaries in primary study area.

Tributary	Project River Mile (PRM)	Left Bank (LB) / Right Bank (RB) Looking Downstream
Ladder Creek	94.6	LB
Newhalem Creek	93.8	LB
Goodell Creek	93.3	RB
Babcock Creek	92.1	RB
Martin Creek	91.4	LB
Thornton Creek	90.5	RB
Sky Creek	88.6	RB
Damnation Creek	88.0	RB
Alma Creek	85.5	LB
Copper Creek	84.4	LB
Bacon Creek	83.2	RB
Diobsud Creek	81.0	RB
Taylor Creek	79.1	LB
Cascade River	78.2	LB
Olson Creek	77.2	RB
Corkindale Creek	74.3	RB
Rocky Creek	73.8	RB
Illabot Creek	73.0	LB
Sutter Creek	71.0	RB
Barr/Swift Creek	70.8	RB

4.0 METHODS

The Geomorphology Study included pre-field analysis of existing information, field work to inventory aquatic habitat and current geomorphic conditions in the Skagit River, redd scour monitoring, scour monitoring at tributary junctions and river bars, sediment transport modeling, and post-field analysis and report writing. This study report is organized by topic areas to present methods for the following subsections as described in the RSP:

- Geomorphic change;
- Aquatic habitat;
- Side channels and off-channel habitat;
- Substrate/sediment;
- Sediment transport;
- Large wood inventory;
- Large wood tracking and transport; and
- Process flows.

Per Section 2.6.1 of the RSP (City Light 2021), existing information providing a basis for understanding geomorphic processes in the Skagit River was compiled and included the following studies:

- A baseline fluvial geomorphology report was prepared for the Skagit River basin (Gorge Powerhouse to estuary) by the U.S. Army Corps of Engineers (USACE) that includes an estimated sediment input budget based on basin sediment budgets and suspended load data and a description of fluvial geomorphic reaches (USACE 2008).
- Channel incision was identified as a potential issue during the Project's previous relicensing in the early 1990s. Analysis of U.S. Geological Survey (USGS) gage records at that time showed incision at the Alma gage (no longer in service) and little variation to 0.4 ft of aggradation at the Newhalem gage (Riedel 1990).
- The Water Resource Inventory Areas Limiting Factors Assessment for the Skagit River (Smith 2003) identifies types of habitat/conditions that are limiting fish production in the river. Information on substrate quality, streambed stability, and large woody debris (LWD) are listed as data gaps in the upper Skagit River (Newhalem to Sauk River confluence).
- The Skagit Watershed Council produced Geographic Information System (GIS)-based analyses of relative sediment input, riparian conditions, and bank hardening areas in the Skagit River system (Beamer et. al 2000). This information was used for a reach assessment of the Middle Skagit River (Sauk River confluence to Sedro-Woolley) that analyzed potential areas for targeting habitat restoration based on habitat, geomorphology, and land uses (Smith et al. 2011).
- The Upper Skagit Indian Tribe (Hartson and Shannahan 2015) conducted a field inventory of hydromodified banks along the upper Skagit River.

- A sediment budget of the Middle Skagit River (Rockport to Sedro-Woolley) was developed by Rothleutner (2017) and included an analysis of historical channel migration rates and sediment input from river meandering.
- The Skagit Watershed Council commissioned a report on LWD in the Skagit River system (Natural Systems Design [NSD] 2017) that included a summary of existing factors affecting LWD recruitment and potential methods to analyze/inventory LWD in the watershed.
- Geomorphology, hydrology, and hydraulics studies undertaken for the Barnaby Reach restoration project provide detailed information on the Skagit River channel, off-channel areas, and floodplain in the area just upstream of the Sauk River confluence (Skagit River System Cooperative [SRSC] and NSD 2019).
- Suspended sediment monitoring by the USGS on the lower Skagit River (Curran et al. 2016) and Sauk River (Jaeger et al. 2017).
- Geomorphic mapping and landform analysis being conducted by NPS (Riedel et al. 2020).

A compilation of relevant studies describing Skagit River geomorphology downstream from the Sauk River confluence were reviewed and summarized in an annotated bibliography included in Attachment A.

The primary study area upstream of the Sauk River in which field data were collected in 2021 and 2022 is divided into seven geomorphic reaches based on landform mapping by NPS (Riedel et al. 2020). A geomorphic reach is a defined segment of the river having a relatively consistent suite of valley and channel characteristics. The geomorphic reaches are influenced by the bedrock geology, glacial history, and inputs from adjoining tributaries and hillslope processes. Study reaches vary between 1.2 and 6.7 miles in length with select subreaches identified as shorter segments with a minimum length of 1.2 miles. Figures 4.0-1 to 4.0-4 identify the reach boundaries and locations of major tributaries draining to the Skagit River within the primary study area. The longitudinal profile in Figure 4.0-5 shows channel slope relative to reach boundaries.

Reach 1 (Gorge bypass reach) is a steep, narrow valley cut into the Crystalline Core of the North Cascades (Figure 4.0-1). Bedrock geology in this zone is largely composed of relatively hard, metamorphic rock of the Skagit Gneiss Complex (orthogneiss and banded gneiss) previously buried and heated inside the crust then brought to the surface by tectonic uplift (Tabor and Haugerud 1999). The Skagit River Gorge was created by drainage from proglacial lakes that spilled over a hydrologic divide during the early Pleistocene and increased the size of the Skagit River basin by capturing drainage that formerly flowed north to the Fraser River (Riedel 2007; Riedel et al. 2022).

Reach 2 begins downstream of the Gorge bypass reach where the channel slope decreases and the valley widens at Newhalem (Figure 4.0-5) due to the influence of alpine glaciers that advanced from the Goodell Creek and Newhalem Creek watersheds (Riedel et al. 2020). Reach 2 has been further divided into subreaches for the Geomorphology Study (Figure 4.0-1): Reach 2A represents the segment from Gorge Powerhouse near PRM 94.7 to the bridge crossing at PRM 93.5, and Reach 2B continues to the downstream limit of alpine glaciation (PRM 89.4) just south of the county line separating Whatcom and Skagit counties. Major tributary streams draining into the Skagit River within Reach 2 include Ladder Creek, Newhalem Creek, Goodell Creek, Babcock

Creek, Martin Creek, and Thornton Creek. City Light maintains two former gravel mine sites in the reach at Newhalem Aggregate (Agg) Ponds and County Line Ponds as off-channel fish habitat.

Reach 3 narrows in relation to Reach 2 as a result of resistant bedrock and limited alpine glaciation (Riedel et al. 2020). Reach 3 is split into two segments that are separated by Reach 4 (Figure 4.0-2). Reach 3A begins near the county line (PRM 89.4) and continues downstream past the tributary junction with Damnation Creek to the beginning of Reach 4 at PRM 87.5.

Reach 4 is the landslide zone that spans 3.5 miles (PRM 87.5 to 84.0) between Damnation Creek and Bacon Creek. The reach is bound by two fault zones that define the regional geology and landslide deposits that confine the valley (Riedel et al. 2020). Reach 3B continues downstream of the landslide zone from PRM 84 to the change in geology where the Skagit River crosses the Straight Creek Fault (PRM 82). Alma Creek, Copper Creek, and Bacon Creek join with the Skagit River in Reach 3B.

Reach 5 continues downstream of the Straight Creek Fault (PRM 82) to just upstream of Rocky Creek (PRM 74.8). The valley widens relative to upstream reaches due to a change in the underlying bedrock geology that results in decreased erosional resistance west of the fault. The channel is incised into a series of terraces that occupy much of the valley bottom. The community of Marblemount is located on a terrace surface just upstream and across from the junction with the Cascade River at PRM 78.2. The Cascade River is the largest tributary entering the Skagit River between Gorge Dam and the Sauk River and is an important source of water, sediment, and wood to Reaches 5 and 6. Additional tributary inflows within Reach 5 include Diobsud Creek, Olson Creek, and Corkindale Creek. For this study, Reach 5 was split into two subreaches defined by segments upstream (Reach 5A) and downstream (Reach 5B) of the Cascade River (Figure 4.0-3).

Reach 6 (Barnaby Reach) begins near Rocky Creek (PRM 74.8) and continues downstream to the upstream edge of the Sauk River alluvial fan near PRM 68.1. Barr Creek and Sutter Creek both join with the Skagit River near PRM 71 and have formed coalescing debris cones that extend into the valley from the north. Tributary inflow from O'Brien Creek and Illabot Creek drain into the Skagit River floodplain from the south in the upper segment of Reach 6. A meander cutoff in the early 1900s left an abandoned channel that is now occupied by Illabot Creek where it flows north across the Skagit River floodplain (Figure 4.0-3). Downstream of Illabot Creek, the floodplain contains a series of relict meanders (Figure 4.0-4). The meander complex represents up to 5,800 years of fluvial history in the valley (Riedel 2019). The youngest of these meanders is known as Barnaby Slough and was cut off during the late 1800s to early 1900s. Barnaby Slough and adjacent floodplain features, such as Harrison Pond and Lucas Slough (collectively known as the "Barnaby Complex"), have been modified since the 1960s to create rearing habitat for hatchery steelhead. Use of the facility was discontinued in 2007, and the Barnaby Complex is the site of ongoing restoration activities to improve habitat conditions in the reach.

Reach 7 is characterized by the influence of the Sauk River alluvial fan that has formed at the confluence of the Sauk River and the Skagit River near the community of Rockport (Figure 4.0-4). State Route (SR) 530 crosses the Skagit River at Rockport and heads south across the Sauk River alluvial fan. Relict channels from the Sauk River extend upstream to the east of SR 530, including much of the low-lying area in the floodplain along Martin Road. Over a timescale of tens to hundreds of years, the position of the Sauk River confluence shifts upstream and

downstream within the valley and exerts an influence over hydraulic and geomorphic processes in Reach 6. As recent as the early 1900s, the confluence of the Sauk River was approximately 1 mile upstream of its present location and much closer to the area around Rockport. For this study, Reach 7 was split into two subreaches upstream (Reach 7A) and downstream (Reach 7B) of the Sauk River confluence near PRM 66.8 (Figure 4.0-4). Field mapping of bank conditions, aquatic habitat, and large wood inventory was limited to the segments upstream of the Sauk River confluence (Reach 7A).

Downstream of the primary study area, bed material sampling (Section 4.4), National Marine Fisheries Service (UBCRM) modeling (Section 4.5.1.1), and MAST1-D modeling (Section 4.5.1.4), extended through Reach 12. Reaches 8, 9, and 10 are described in completed NPS landform mapping (Riedel et al. 2022), while NPS landform mapping for reaches 11 and 12 is still under development as of the finalization of this study report.

Reach 8 extends from the downstream end of the Sauk fan to the Baker River confluence. The only major tributary in Reach 8 is Jackman Creek. Reach 8 is largely confined between glacial terraces, which limit floodplain width and channel migration as well as contributing sediment to the channel through gullying and small landslides. An exception is the area upstream of Jackman Creek near Van Horn, which is a sediment deposition zone due to backwater effects of the Jackman Creek fan. This area has a two-channel pattern in some areas, and has a greater channel width, sinuosity, and migration rate than the rest of Reach 8.

Reach 9 extends from Baker River to the large meander at Cape Horn. Reach 9, like Reach 8, is incised into glacial terraces and has high confinement. In upper Reach 9, the channel width and floodplain width are similar to that in Reach 8 but increase downstream as the valley widens. The Baker River, at the upstream end of the reach, is the only major tributary to Reach 9. At the Dalles, where the Concrete-Sauk Valley Road crosses the Skagit, the river flows over a bedrock spur. This bedrock sets the base level for the Skagit watershed upstream of this point (Riedel et al. 2022).

Reach 10 extends from Cape Horn to Hamilton and Cumberland Creek. Tributaries include Finney, Pressentin, Grandy, and Alder Creeks. In this reach, confinement is lower and valley width is higher than in Reach 9. Downstream of the Alder Creek confluence, there are a series of meander scrolls on the right bank floodplain.

NPS landform mapping for Reach 11 and Reach 12 is not yet complete, so these reaches are described here very briefly. Reach 11, also known as the Ross Island Reach, is a major depositional zone for gravel upstream of the gravel-sand transition. The Skagit has a multi-threaded, wandering channel pattern with a high migration rate for most of Reach 11. Tributaries include Day and Gilligan Creeks. Reach 12 runs from approximately PRM 29 to Sedro-Woolley and is characterized by a mostly single-thread channel pattern, in contrast with Reach 11.

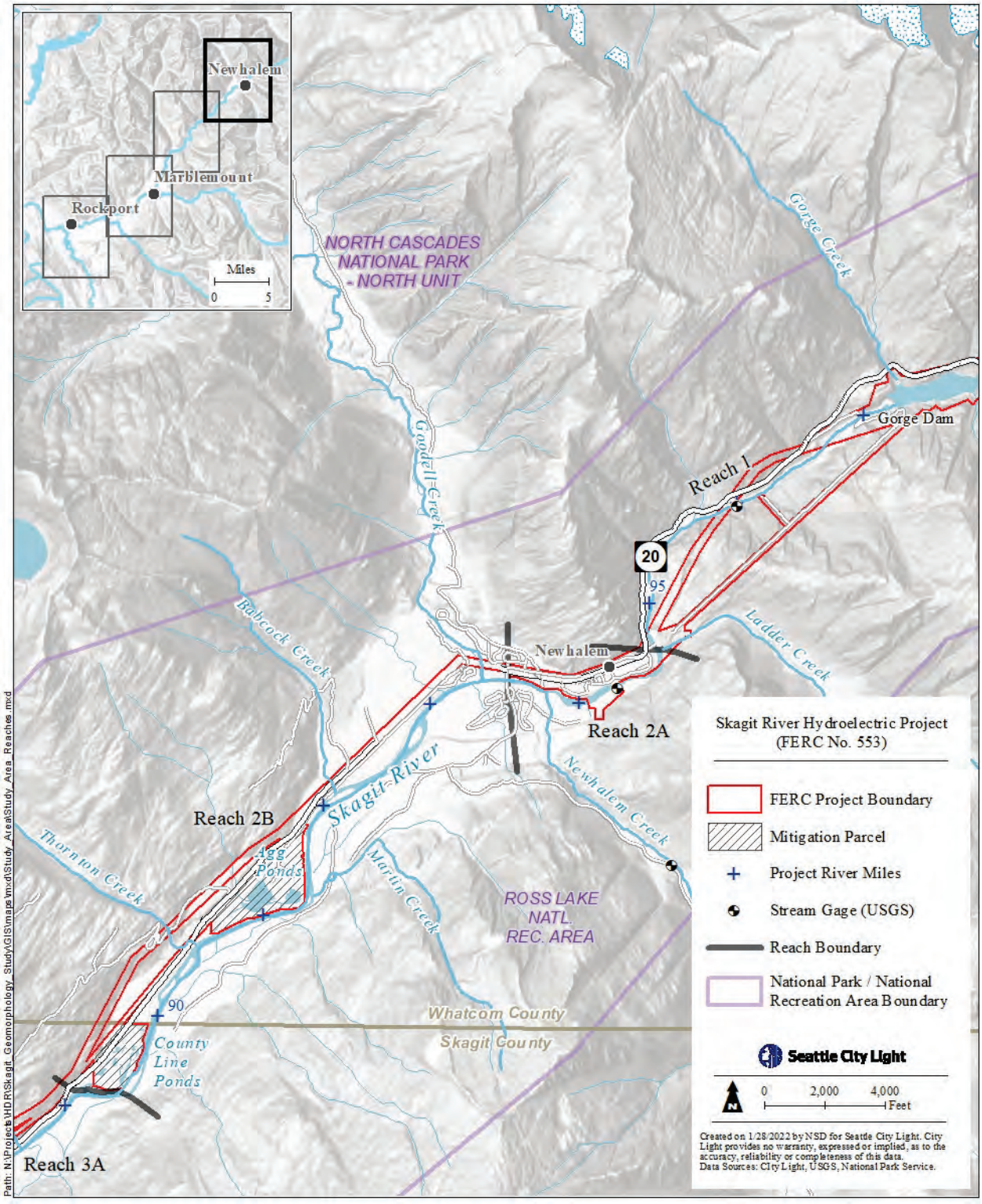


Figure 4.0-1. Northern portion of primary study area from Gorge Dam to the county line including Reach 1, 2A, and 2B.

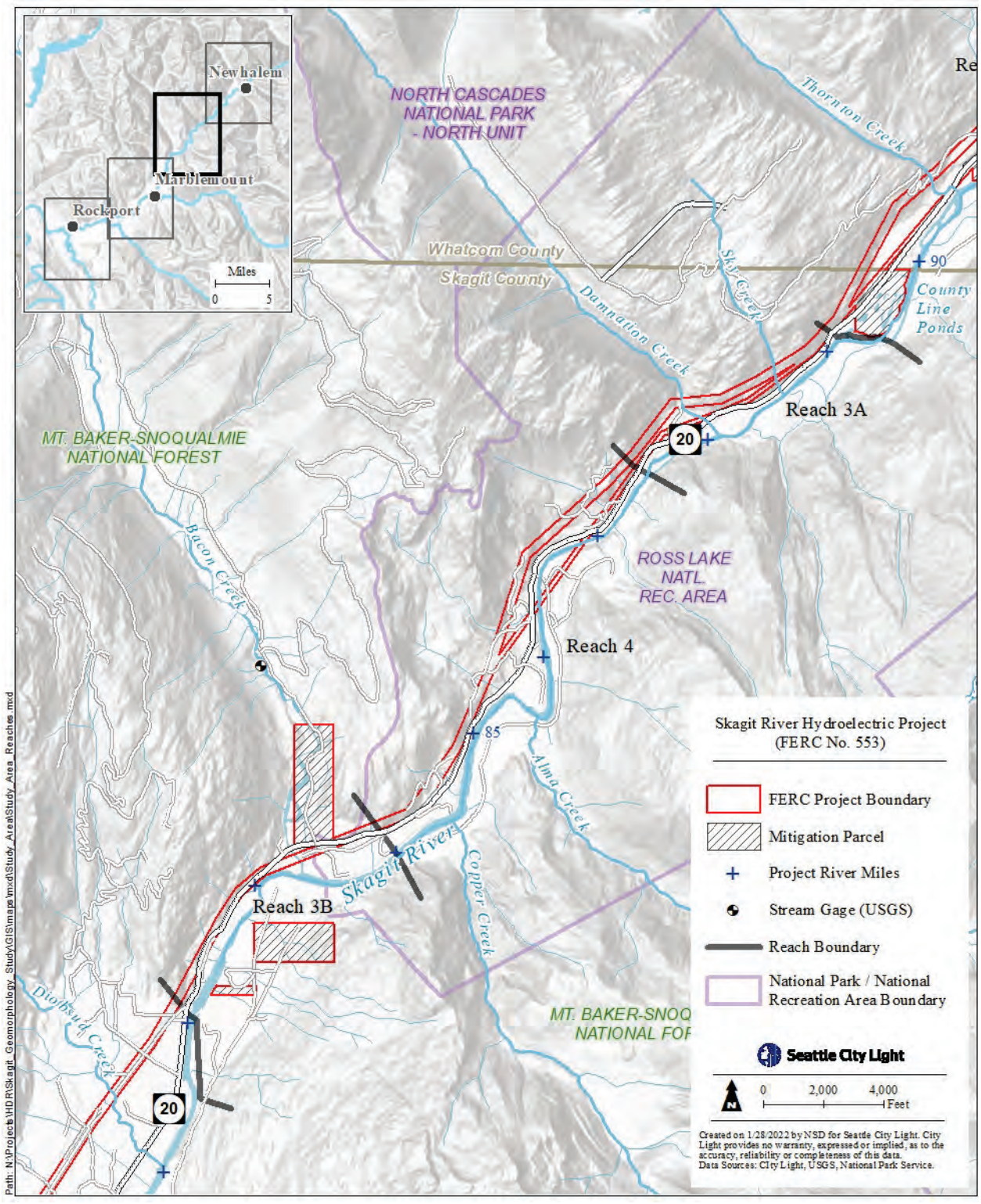


Figure 4.0-2. Primary study area reaches from county line to the Straight Creek Fault Zone near Diobsud Creek including the Narrow Upper Skagit Reaches 3A/3B and the landslide zone (Reach 4).

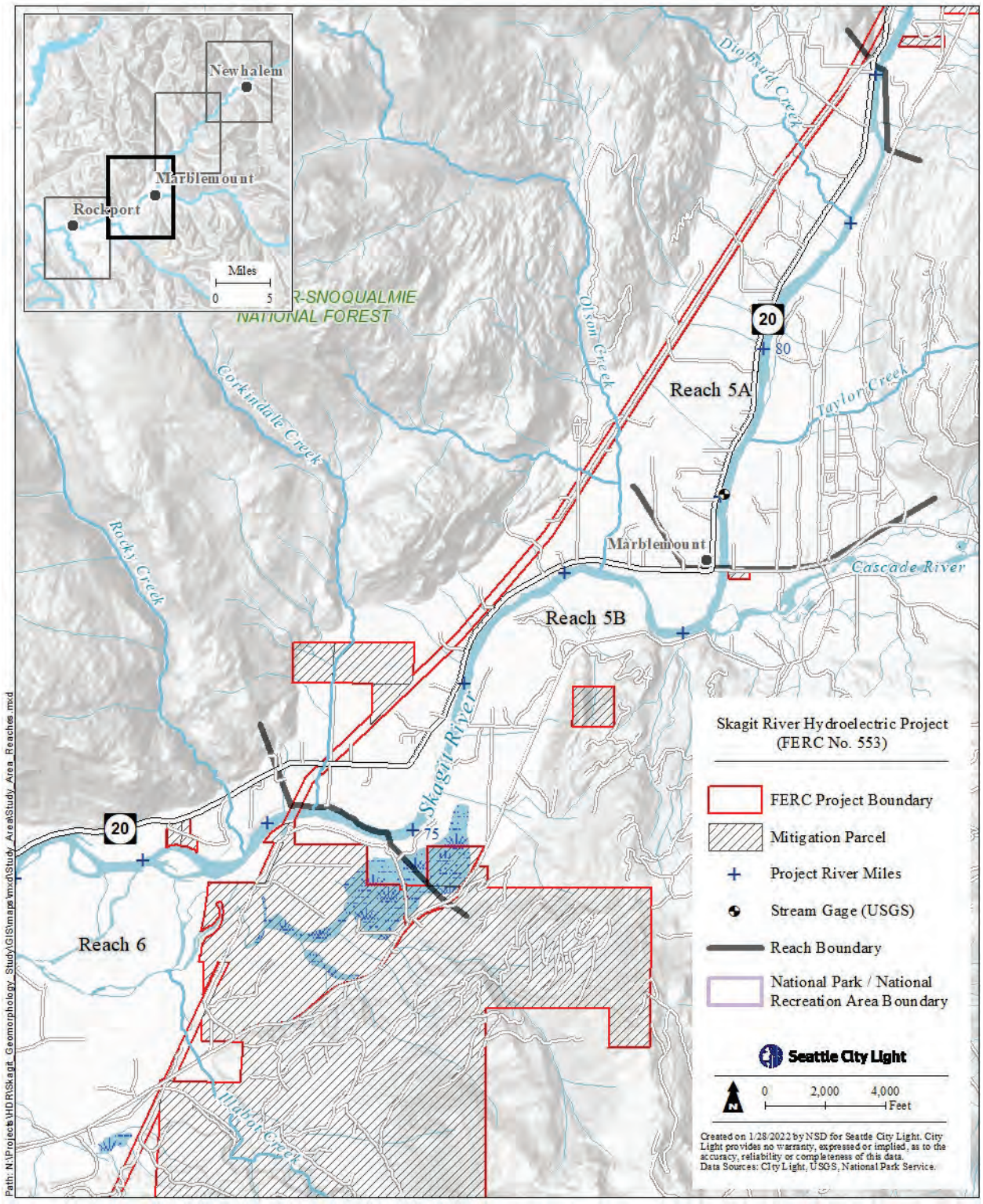


Figure 4.0-3. **Primary study area reaches from the Straight Creek Fault Zone to the Cascade River (Reach 5A), Cascade River to Rocky Creek (Reach 5B), and the upper segments of Reach 6 near Illabot Creek.**

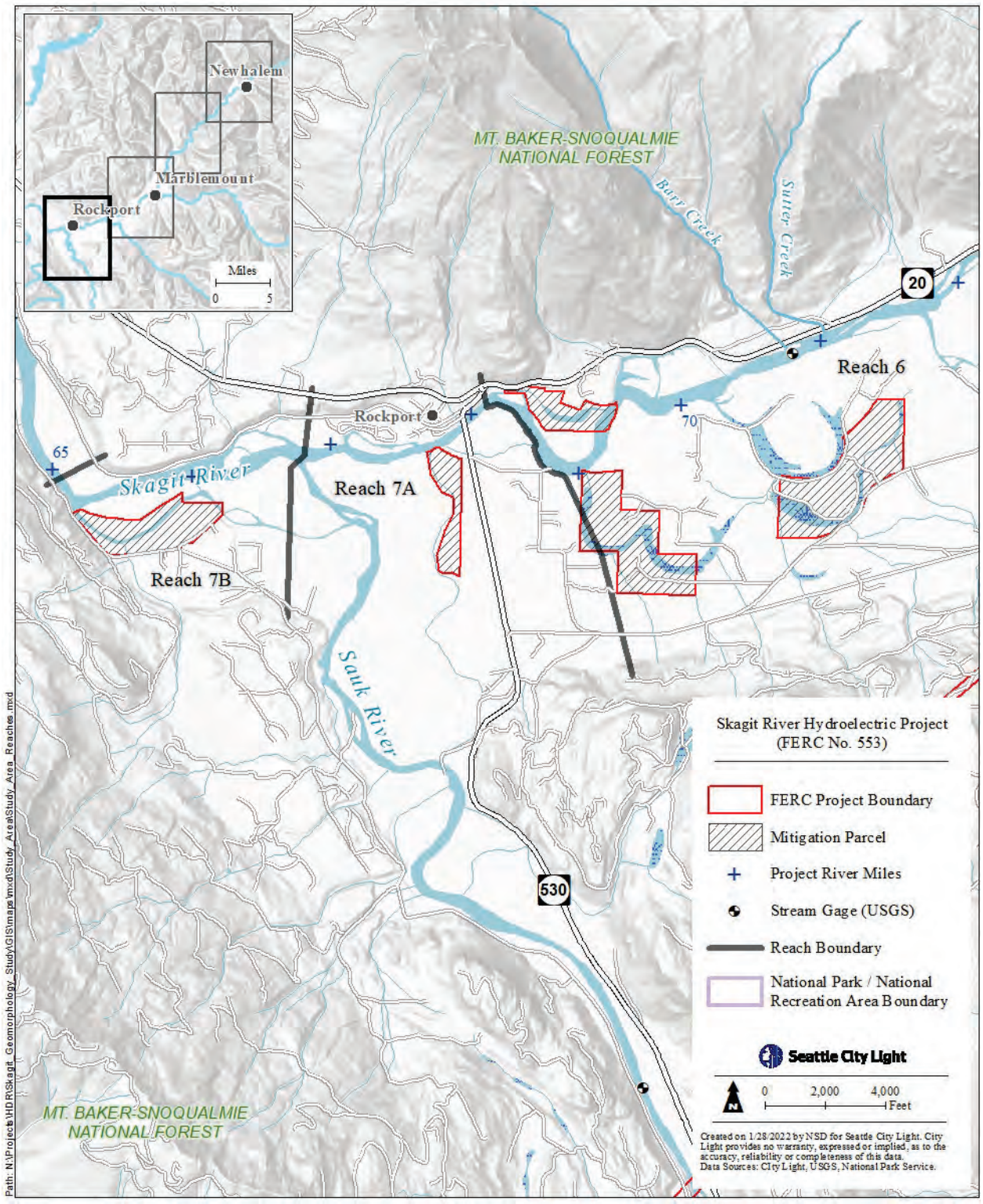


Figure 4.0-4. Downstream portion of the primary study area including the Barnaby Meanders (Reach 6) and Sauk River confluence (Reach 7A/7B).

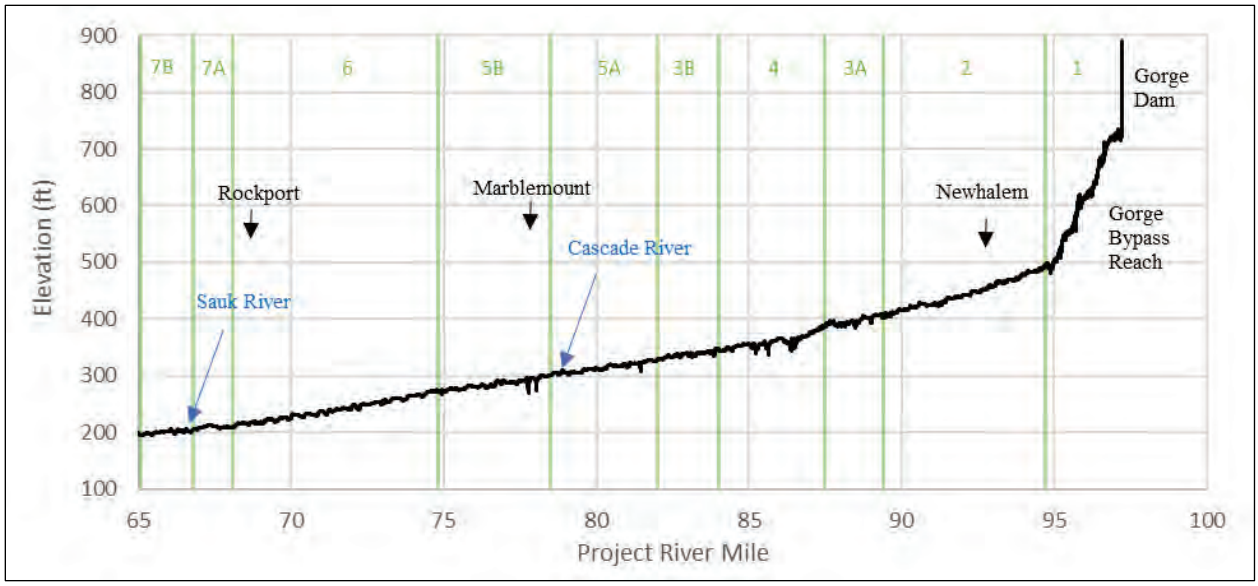


Figure 4.0-5. **Longitudinal profile of the Skagit River from Gorge Dam to the Sauk River confluence with overlay of reach boundaries. Elevation data from 2017 and 2018 topobathymetric LiDAR surface (Quantum Spatial, Inc. [QSI] 2017, 2018). Small dips in profile represent pool features in the bathymetric data.**

4.1 Geomorphic Change

The analysis of geomorphic change includes a characterization of lateral channel migration and vertical channel changes (incision or aggradation) following methods defined in Section 2.6.2 of the RSP (City Light 2021). Results are discussed in Section 5.1 of this study report.

4.1.1 Mapping Active Channels

Upstream of the Sauk River confluence, active river channels were mapped for Reaches 2-7 using LiDAR, aerial photographs, and digital aerial imagery from multiple time steps between 1944 and 2019 to evaluate historical channel conditions (Table 4.1-1). Channel features were not digitized from historical imagery in Reach 1 given the bedrock-controlled morphology that limits channel migration and increased error in georeferencing imagery in the Gorge bypass reach due to the steep topography and limited availability of stable control points.

Channel features digitized as part of previous work by SRSC were refined and used for channel reaches between the Sauk River confluence and Marblemount (SRSC 2019). Additional imagery was then compiled from the list of available imagery presented in Table 2.6-1 of the RSP to extend the data set of historical imagery for channel reaches upstream of Marblemount (City Light 2021). Several of the data sources were limited in spatial extent and did not include full coverage of the primary study area. Multiple data sources were combined to create a composite for select time periods that included imagery from different data sources that spanned two consecutive years. The resulting time series included the following years: 1944, 1963-64, 1978-79, 1998, 2006-07, and 2019 (Table 4.1-1).

Table 4.1-1. Data sources compiled for mapping active channel areas and evaluation of lateral channel migration.

Year	Map/Image Type	Scale/ Resolution	Source/Notes
1915[1]	Historical map	1:10,000	USGS
1944	Black and white stereo photos	Unknown	USACE; georeferenced by Collins and Sheikh (2002)
1963/1964	Black and white stereo photos	1:12,000	U.S. Forest Service (USFS); images downstream of Marblemount georeferenced by SRSC (2019); additional images upstream of Marblemount acquired for this study
1978	Color stereo photos	1:24,000	NPS; upstream of Bacon Creek only
1979	Color stereo photos	Unknown	USFS; downstream of Marblemount only; Georeferenced by SRSC (2019)
1998	Color stereo photos	1:24,000	NPS; upstream of Bacon Creek only
1998	Color stereo photos	Unknown	USFS; downstream of Marblemount only; georeferenced by SRSC (2019)
1998	Digital imagery	1 m^2	USGS
2006	Digital imagery	1 m	National Agricultural Imagery Program
2007	Digital imagery	1 ft	Skagit County Pictometry
2018	Digital imagery	0.5 ft	City Light (QSI 2018)
2019	Digital imagery	0.75 ft	Skagit County Pictometry

1 1915 map not digitized.
2 m = meter.

The peak flow history at USGS gaging stations at the Skagit River at Newhalem gage (12178000) and at the Skagit River at Marblemount gage (12181000) were overlaid with years selected in time series of aerial imagery in Figure 4.1-1 and 4.1-2. The gage record at Newhalem dates to 1908 and the three highest recorded flows (all greater than 40,000 cubic feet per second [cfs]) occurred prior to time series of aerial imagery used in this study. Several tributaries drain into the Skagit River between the USGS gaging stations at Newhalem and Marblemount increasing the contributing drainage area from 1,175 to 1,381 square miles, respectively (an 18 percent increase in drainage area). The gage record at Marblemount begins in 1943 and includes a period with no data during the interval 1957-1975.

Channel digitizing practices and classification codes were derived from and refined based on methods described by SRSC for the reaches downstream of Marblemount, and digitization was continued from Marblemount to the Gorge Dam using consistent rules and practices. These methods are briefly outlined below.

Digitization involved classifying areas into discrete polygons. As derived from SRSC digitization methods (SRSC 2019), polygon classes included low flow channel (water) and unvegetated area (bars). Low flow channels were further classified as comprising main channel, braid channels, or side channels. Braid channels were defined as secondary channels with flows that split around

predominantly unvegetated bars from the Skagit River's primary flowpath. Side channels were defined as secondary channels with flows that split around predominantly vegetated bars (or forested islands) from the Skagit River's primary flowpath. Unvegetated areas were further classified as comprising main channel bars or side channel bars. Active channels include areas within the river where the combination of sediment transport intensity and hydroperiod prevent establishment of vegetation and are therefore comprised of both low flow channel and unvegetated area classes. Active channel width, sinuosity, and braiding intensity were calculated for appropriate geomorphic reaches (reaches with similar confinement characteristics).

Multiple data sources were used to evaluate the historical channel alignment (Table 4.1-1), including those listed in Table 2.6-1 in the RSP (City Light 2021). Data sets were reviewed and those with the highest spatial resolution, ranging from 0.5- to 3-ft cell sizes, were incorporated. Historical aerial imagery was not orthorectified. As such, georeferencing of the historical images could not align perfectly. The root mean square of image alignment to a series of user-defined control points was generated during georeferencing and used as an indicator of accuracy, coupled with manual review.

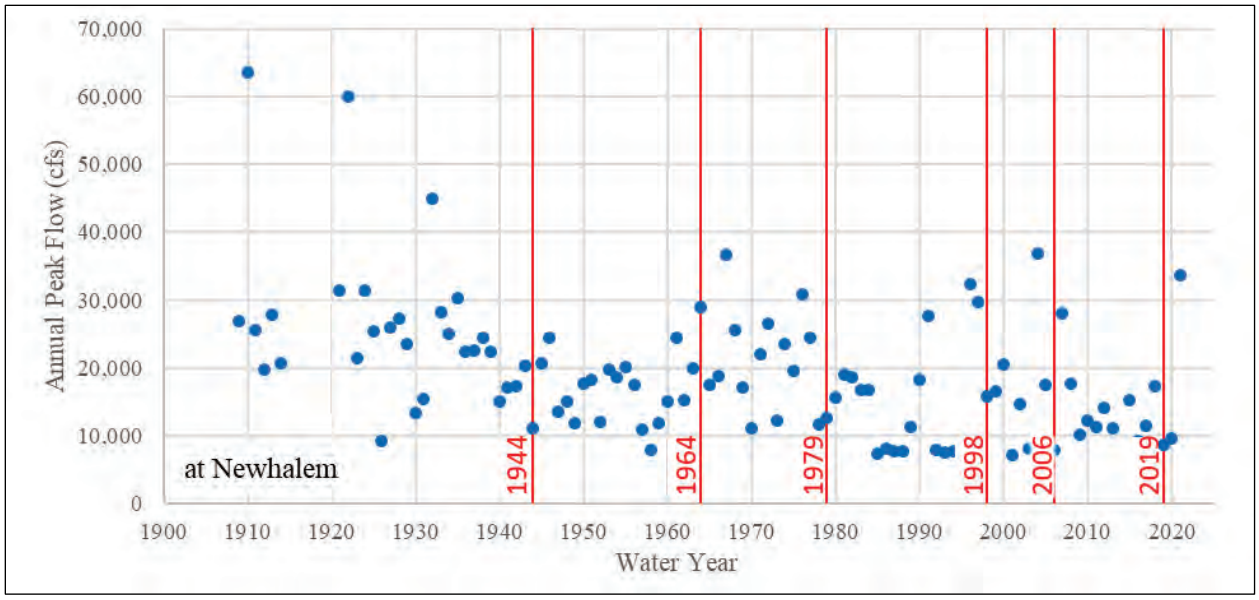


Figure 4.1-1. **Time series of annual peak flow (1908-2021) for the Skagit River at USGS gaging stations at Newhalem (USGS 12178000) with overlay of aerial photo sets used in mapping historical channel change. Preliminary data for 2021 flood shown for reference.**

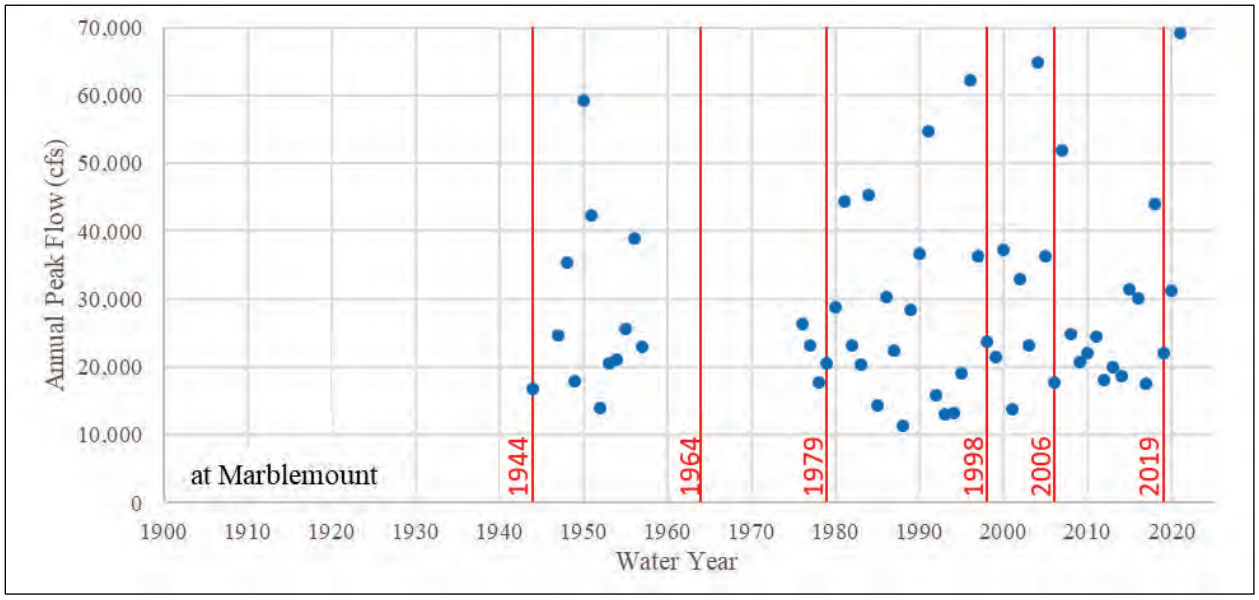


Figure 4.1-2. **Time series of annual peak flow (1943-1956; 1976-2021) for the Skagit River at USGS gaging stations at Marblemount (USGS 12181000) with overlay of aerial photo sets used in mapping historical channel change. Preliminary data for 2021 flood shown for reference.**

4.1.2 Channel Migration Rates

Areas of lateral channel migration were identified by overlying banklines from consecutive years in the time series using GIS tools in the "Channel Migration Toolbox" from Ecology (Legg et al. 2014). Areas of channel migration were delineated for each bank of the river separately. Channel migration rates were calculated by summing the difference in new channel planform area between aerial photograph years and dividing by reach length. Rates are calculated based only on eroded area where change between imagery was from vegetated floodplain to channel and do not include areas of bar building in calculations. Transects were digitized across the channel migration zone at a longitudinal spacing of 500 ft. Channel width and lateral channel migration between successive years in the time series were recorded along each transect for the period 1944-2019.

Channel migration rates were compared to peak flow conditions between aerial photograph years (Figure 4.1-1 and 4.1-2) and changes to sediment inputs and large wood loading to determine conditions that contribute to bank erosion and channel migration. Channel migration history over the existing license period was represented by historical channel occupancy maps and maps illustrating historical channel positions. Bank protection was considered when analyzing channel migration.

4.1.3 Streambank Characterization

Locations of eroding riverbanks were mapped in the field as part of geomorphic reconnaissance in 2021. Grain size of eroded bank material were described by visual estimate of percent boulder, cobble, gravel, sand, and fines (silt/clay). The location and extent of bank protection limiting channel migration processes were mapped using the existing GIS database from the Upper Skagit Indian Tribe (Hartson and Shannahan 2015) and verified in the field as part of geomorphic reconnaissance.

4.1.4 LiDAR Change Detection

Recent geomorphic changes were mapped from a comparison of LiDAR data collected in 2022 with an earlier dataset of topobathymetric LiDAR collected in 2017 and 2018. The 2017/2018 data were derived from the composite topobathymetric surface developed for the FA-02 Instream Flow Model Development Study (City Light 2023a). The 2017/2018 terrain model developed for the FA-02 Instream Flow Model Development Study integrates supplemental survey data to fill void areas that had no LiDAR returns in the 2017 and 2018 datasets. Approximately 6 percent of the wetted channel area in the 2022 LiDAR were void areas with no LiDAR returns. Selected void areas in the 2022 LiDAR dataset were filled using interpolated values for locations within eroding bank segments that were converted from floodplain or terrace to channel bed between 2017/18 and 2022. This interpolation was applied to prevent undercounting of sediment inputs from bank erosion. Other void areas located within the 2017/18 channel areas were left unfilled (no data) as the interpolated values would be an unreliable indicator of change.

A GIS raster dataset was calculated to represent changes between the 2017/2018 and the 2022 LiDAR. Results were displayed in a GIS mapbook and tabulated to calculate sediment inputs from channel migration. A polygon dataset of feature types was used as a mask layer to classify geomorphic changes from the LiDAR change detection. The mask layer delineated the floodplain area into the following categories:

- Active channel areas from the earlier LiDAR period;
- Eroded areas of the floodplain that were converted to active channel; and
- Vegetated floodplain areas that remained floodplain in 2022.

An additional map layer was created to delineate subreach areas and divide the geomorphic reaches into smaller units that averaged 1 to 2 miles in length. Results from the LiDAR difference raster were summarized by category and subreach using the zonal statistics tool in ArcGIS.

LiDAR change detection analysis omitted the Gorge bypass reach (Reach 1) from the results. Review of the 2022 LiDAR data revealed that there was a spill event that routed flows over 4,000 cfs through the Gorge bypass reach on the date of the LiDAR acquisition (4/29/2022). No LiDAR returns were available for much of Reach 1 due to turbidity and turbulence of the flow. Updated 2022 aerial photos were used in place of LiDAR to compare with 2018 imagery and document the presence/absence of bank erosion or other geomorphic change in Reach 1.

4.1.5 Changes to USGS Rating Curves

Changes in stage-discharge relations were quantified by comparing stage-discharge information from historical stream flow measurements to the latest, shift-adjusted rating curve for gaging stations on the Skagit River at Newhalem (USGS gage 12178000) and Marblemount (USGS gage 12181000). Stage residuals were calculated by extracting the difference between the observed gage height for each field measurement and the expected gage height for a given flow based on current rating. Similar approaches have been applied in previous studies to assess long-term trends in river bed elevation at gaging station locations (James 1991; Juracek and Fitzpatrick 2009; Anderson et al. 2019). A positive stage residual indicates that the stage associated with the measured discharge was higher at the time of the measurement than it would be at present. A negative stage residual indicates that the stage associated with the measured discharge was lower at the time of the measurement than it would be at present.

Vertical channel changes are inferred from the time series of stage residuals. An increasing trend in the stage residuals is associated with periods of channel aggradation and decreasing conveyance capacity. A decreasing trend in the stage residuals is associated with periods of channel incision and increasing conveyance capacity.

4.1.6 Changes to Longitudinal Profiles

Historical topographic maps based on USGS 1915 and 1947 provide a reference for evaluating channel changes to the longitudinal profile and identify segments of the channel that have incised or aggraded over the historical period. The 1915 and 1947 surveys recorded water surface contours at 5-ft intervals. Point features were digitized in GIS where these water surface contours crossed the channel. Point values extracted from the 1915 and 1947 maps were located along the centerline of the channel alignment in 2017/2018 LiDAR and attributed with the nearest PRM.

USGS map accuracy standards specify that 90 percent of points should be within half of the contour interval of the actual elevation (USGS 1999). Given the contour interval of 5 ft, elevation data from the 1947 maps should be considered accurate to within +/- 2.5 ft, which could change the results in most reaches from net incision to net aggradation. Methods of data collection for the

1915 profile data are unknown, and the range of uncertainty is assumed to be greater than that of more recent topographic data.

The 1947 topography was derived from photogrammetric methods based on aerial photos acquired at a scale of 1:27,700. The 1947 images covering most of the study area were acquired 8/26/1947, and the corresponding flows at the Newhalem and Marblemount gaging stations were 2,670 cfs and 3,270 cfs, respectively. No details on survey dates or flow estimates were identified for the 1915 profile survey.

Elevation data from the 1915 and 1947 contours were adjusted by 3.78 ft to convert values from the National Geodetic Vertical Datum of 1929 (NGVD 29) (sea level) to the same North American Vertical Datum of 1988 (NAVD 88) vertical datum used for LiDAR and hydraulic model outputs (NGVD 29 elevation + 3.78 ft = NAVD 88 elevation). The datum adjusted 1915 and 1947 water surface elevation (WSE) profiles were then compared to hydraulic model output from the FA-02 Instream Flow Model Development Study (City Light 2023a) to assess vertical channel changes. The 90 percent daily exceedance flow simulation from the FA-02 Instream Flow Model Development Study (2,500 cfs at Newhalem and 2,970 cfs at Marblemount) most closely aligned with the flows assumed for the 1947 imagery and was used for the profile comparison for both 1915-2018 and 1947-2018.

Additional data from 1975 channel cross-sections were available for reaches downstream of Marblemount. The 1978 cross-section data were originally collected for use in the Flood Insurance Study for Skagit County (FEMA 1984) then later used in an updated hydraulic model developed for a USACE (2013) Flood Risk Management Study. Cross-section data in the updated Hydrologic Engineering Center River Analysis System (HEC-RAS) model adjusted elevations from the 1975 survey to the NAVD 88 vertical datum. The adjusted 1975 cross-section data were extracted from the HEC-RAS model and compared to channel cross-sections and profile data from the 2022 topobathymetric LiDAR data to assess geomorphic channel change. There were no data available at five out of the 35 sections between PRM 65-79 due to voids in the 2022 LiDAR data coverage.

The overlay of longitudinal profiles, observed changes to USGS rating curves, and relative elevation map based on 2017 and 2018 LiDAR data (QSI 2017, 2018) were then used to analyze channel evolution stage between Gorge Dam and the Sauk River based on the Stream Evolution Model in Cluer and Thorne (2013).

4.2 Aquatic Habitat

The purpose of the Aquatic Habitat Section of this report is to summarize existing information on the status and location of habitat units, as well as other mainstem, side channel, and tributary features. The goals and objectives that are associated with aquatic habitat from the list above include the documentation of the following:

- Distribution of aquatic habitat types, characteristics, and availability;
- Substrate size and distribution;
- Large wood input, transport and retention; and
- Process flows that mobilize riverbed and bars.

Some of these objectives integrate information from other studies. The substrate and cover information come from field work conducted under the FA-02 Instream Flow Model Development Study (City Light 2023a) and FA-05 Skagit River Gorge Bypass Reach Hydraulic and Instream Flow Model Development Study (FA-05 Bypass Instream Flow Model Development Study; City Light 2023c). Modeling output from the FA-02 Instream Flow Model Development Study were used to identify and validate channel unit types and the distribution of edge habitat. The large wood input, retention/presence information comes from the Large Wood Section within this Geomorphology Study and were into the Aquatic Habitat analysis as well.

4.2.1 Habitat Mapping

Per the description in Section 2.6.3 of the RSP (City Light 2021), aquatic habitat in the mainstem and side channels of the Skagit River was evaluated using digital resources prior to field verification. The pre-field evaluation was designed to digitize channel units on the Skagit River between Gorge Dam and the confluence with Sauk River using remote sensing data. These data were also used to characterize the habitat in the Gorge bypass reach above the Gorge Powerhouse. The data sources used for this effort included multiple LiDAR data sets, aerial imagery, WSE profiles, and landform mapping data sets. Table 4.2-1 lists the specific resources that were included in the desktop analysis of aquatic habitat. The terrain model used to generate the relative elevation models (REM) is a mosaic of the LiDAR data sets from 2017 and 2018 identified in Table 4.2-1 along with field-collected bathymetric and topographic data to fill gaps in terrain coverage. The terrain model was developed as part of the FA-02 Instream Flow Model Development Study (City Light 2023a). This REM is not the same one used by NPS for landform mapping (Riedel et al. 2020) as this surface was created from more recent data.

Channel unit classifications in the mainstem were based on relevant literature sources (Table 4.2-2). Channel units included those within the mainstem, as well as blind and flow-through side channels and off-channel habitat that do not experience frequent scouring flows and are noted as having fine sediment and low velocity. Constructed features are also denoted in each reach with ponds and channels noted separately, but the amount of habitat on a total area percentage basis was small. Tributary mouths were assessed as part of the fish passage evaluation as described in Section 2.6.3 of the RSP (City Light 2021). The data sets identified in Table 4.2-1 were used to determine the boundaries of each channel unit. The size and detail on the channel unit boundaries were based on the resolution of the data sets rather than on any specific minimum size criteria. The combination of the REM, the terrain dataset, and the WSE allowed for visualization of the bedform, which aided in identification of unit boundaries, specifically pools. Aerial photos were also used to look for evidence of turbulence in surface flow and channel features, such as log jams that would likely cause scour or other deformations of the channel bed. Table 4.2-2 includes the classifications used for channel units along with their descriptions and applicable references.

The process for digitizing the channel units used the 2017 and 2018 topobathymetric LiDAR to first create a wetted edge polygon based on the wetted extents at the time of the LiDAR flights. The wetted extent polygon was then split into individual channel units using the editor in ArcMap. The classification for each channel unit was then assigned according to the classifications listed in Table 4.2-2.

Table 4.2-1. Data resources used in Aquatic Habitat desktop evaluation.

Data Type	Year	Extent	Notes/Reference	Flow at Time of Flight (cfs)[1]
Topobathymetric LiDAR	2018	Gorge Dam to PRM 75.9	REM in development; (QSI 2018)	6,000 to 7,500
Topobathymetric LiDAR	2017	PRM 75.9 to Sauk River	REM created and used (QSI 2017)	8,000
Aerial Imagery	2018	Gorge Dam to PRM 75.9	0.5 ft Quantum Spatial image (QSI 2018)	6,000 to 7,500
Aerial Imagery	2017	PRM 75.9 to Sauk River	Skagit County data set (no report, May 2017 identified in metadata)	5,310 to 14,900 during May 2017
Water Surface Profile	2018	Gorge Dam to Sauk River	Created during hydraulic model calibration (City Light 2023a)	6,000 to 7,500
Landform Mapping	2016	Gorge Dam to Sauk River	NPS data layer (Riedel et al. 2020)	Multiple flows from March 2016 - June 2017
Drone Footage	2021	Bypass Reach	NHC data layer (NHC 2021)	Local tributary runoff, photos were taken following high flow releases
Terrain Dataset	2021	Bypass Reach	FA-05 Bypass Instream Flow Model Development Study product from the 2018 LiDAR Digital Elevation Model (DEM) (City Light 2023c)	N/A – data were from channel bed

1 Flows are presented at USGS Skagit River at Marblemount gage (12181000).

Table 4.2-2. Channel unit classifications used for aquatic habitat.

Channel Unit	Description	Reference(s)
Pool	Obvious scoured depression in bed, often with notable pool tail crest.	Beechie et al. 2005; Bisson et al. 1988
Glide	Steeper than pools but less steep than runs, no obvious depression in the bed and little surface turbulence.	Beechie et al. 2005
Riffle	Turbulent flow, shallow, generally 1-4 percent gradient.	Bisson et al. 1988
Run	Generally, 1-4 percent gradient (steeper than glides), laminar flow.	
Rapid	Turbulent flow, generally > 4 percent gradient.	Bisson et al. 1988
Cascade	Steep unit > 4% gradient with series of drops and step pools noted in the WSE profile.	Bisson et al. 1988
Backwater	Slow water unit formed along the bank of mainstem.	Hawkins et al. 1993; Bisson et al. 1988

Channel Unit	Description	Reference(s)
Blind Side Channel	Side channel to the mainstem with less flow than the mainstem and separated by an island with permanent vegetation; connected at one end of the channel per surface water connection depicted in 2018 and 2019 aerial photos and field observations from August 2021.	Side channels to be included in the survey were presented during engagements with the LPs
Flow-Through Side Channel	Side channel to the mainstem with less flow than the mainstem and separated by an island with permanent vegetation; connected at both inlet and outlet per surface water connection depicted in 2018 and 2019 aerial photos and field observations from August 2021.	Side channels to be included in the survey were presented during engagements with the LPs
Off-Channel Habitat	Off channel habitats are floodplain water bodies that do not experience frequent scouring flows and exhibit characteristics more like a ponded wetland than flowing channel. Characteristics include fine sediments (silt and sand) as dominate substrate, aquatic vegetation, and slow water velocities or ponded water during non-flood flows.	
Constructed Channel Feature	Those channels or ponds known to be constructed, expanded, or enhanced	Sources: City Light 2020, 2021; Smith and Ramsden 2006

After the initial desktop-based channel unit mapping was completed, the study areas were surveyed by boat or foot in the field during August 2021 (multiple dates between August 12 and 27) to validate unit classifications and boundaries (except for the Gorge bypass reach which was only evaluated using remotely sensed data). Flows during this time frame ranged from 2,500 cfs to 4,200 cfs on the USGS Skagit River at Marblemount gage (12181000) (Figures 4.2-1 and 4.2-2). At the USGS Concrete gage (12194000), flows ranged from 5,500 cfs to 11,300 cfs. Bacon Creek flows (USGS gage 12179900) ranged from 100 to 200 cfs, while the Cascade River (USGS gage 12182500) fluctuated between 380 and 900 cfs. Any differences between the assigned unit classifications or unit boundaries and the observed conditions in the field were logged with Global Positioning System (GPS) coordinates and notes describing the needed edits. Revisions were made in ArcMap to the channel unit polygons using points and descriptions collected in the field. Cover and substrate data were mapped as a part of the FA-02 Instream Flow Model Development Study (City Light 2023a), and velocity and depth information were also integrated from the same model.

Quality assurance/quality control (QA/QC) procedures were implemented by two senior staff members on the study team (a Senior Fish Biologist and a Principal Geomorphologist) to verify the boundaries and classifications of the habitat map layer. Channel units were then used as the spatial basis to characterize quantity and quality of habitat across the study area. Unit boundaries were applied to the data collected on substrate, cover, velocity and depth (from the FA-02 Instream Flow Model Development Study [City Light 2023a]) and large wood to summarize habitat conditions throughout the study area. Analytical procedures were then applied to these data sets to calculate metrics to be used to summarize the current habitat conditions in the mainstem and floodplain habitats.

The FA-02 Instream Flow Model Development Study was conducted to develop a flow-habitat evaluation tool to analyze instream flows and aquatic habitat for the Skagit River between the Skagit River at Newhalem USGS gage (12178000) and the Sauk River confluence (City Light 2023a). This study required the development of two distinct models: (1) a two-dimensional (2-D)

numerical hydraulic model (the Upper Skagit Hydraulic Model); and (2) a habitat model (the Upper Skagit Habitat Model). The Upper Skagit Habitat Model integrates water depth and velocity outputs from the Upper Skagit Hydraulic Model with biological Habitat Suitability Criteria (HSC) to produce flow-habitat relationships for the study reach for 37 fish species and life stages of interest. Please refer to the FA-02 Instream Flow Model Development Study report for details on the development of the Upper Skagit Hydraulic Model and Upper Skagit Habitat Model.

Analysis of the unit specific data used the same reaches that were designated as part of the NPS Landform Study (Riedel et al. 2020), with some of the reaches divided into subreaches (see Section 4.0 of this study report). The original seven reaches from the landform survey were divided into 10 subreaches for further summary and analysis based on differences in sediment transport and geomorphic context. Figures 4.0-1 through 4.0-4 above show the reaches and subreaches used in the summary of aquatic habitat data for the mainstem Skagit River.

Habitat metrics in the analysis include those used in the Puget Sound Status and Trend Monitoring Program (Beechie et al. 2017) for large rivers and other metrics commonly used to describe habitat quality. Table 4.2-3 includes the metrics proposed to summarize the quantity and quality of aquatic habitat. These metrics can be calculated with available data and are included in Section 5.2 of this study report. Centerline length and area by channel unit classifications were calculated from the composite surface and water surface profile used in FA-02 Instream Flow Model Development Study (City Light 2023a). Edge habitat metrics rely on output from the Upper Skagit Hydraulic Model (velocity and depth). Per Section 2.6.3 in the RSP (City Light 2021), depth data were provided and validated as part of the FA-02 Instream Flow Model Development Study (City Light 2023a). Pool depth and edge habitat were analyzed using the 80 percent annual exceedance flow (2,981 cfs at USGS Skagit River at Newhalem gage [12178000]).

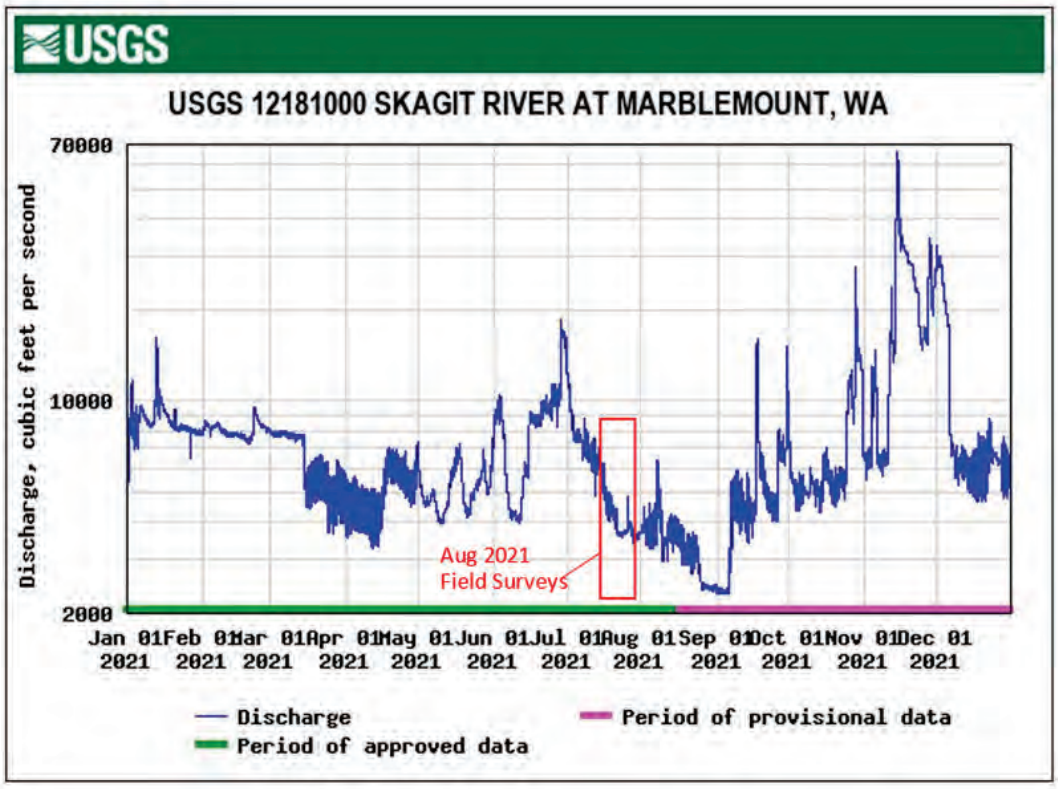


Figure 4.2-1. Skagit River flows during 2021 (USGS 12181000).

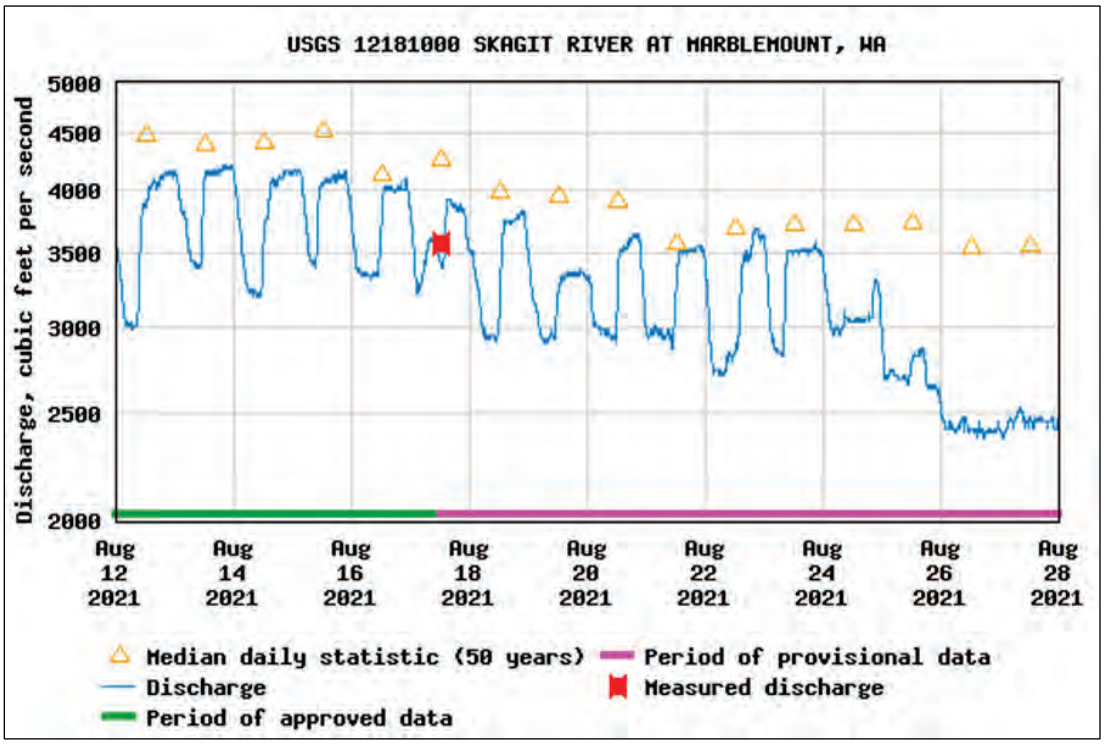


Figure 4.2-2. Skagit River flows during the 2021 habitat mapping field survey (USGS 12181000).

Table 4.2-3. Habitat metrics for aquatic habitat mapping summary.

Habitat Metric	Description	Metric
Centerline length	Length of the mainstem channel	miles
Area by channel unit classifications	Area of each channel unit summed across the classification	square ft ($ft^{2)}$
Area of edge habitat	Area of habitat with less than 0.15 meter per second velocity and less than 0.6 m depth	ft^2
Area of edge habitat with cover	Area of habitat with less than 0.15 meter per second velocity and less than 0.6 m depth that also has cover mapped	ft^2
Percent hydromodified	Proportion of length on right and left banks that is hydromodified	percent
Percent actively eroding	Proportion of length on right and left banks that is actively eroding	percent
Dominate substrate	Proportion of pool habitat with specific class of substrate	percent
Number of log jams	Number of jams with greater than 10 qualified pieces	number
Number of key pieces	Number of qualified key pieces	number
Number of bar apex jams	Number of apex jams	number
Percent pool area with cover	Percent of total pool surface areas with cover	percent
Pools per mile with cover	Number of pools with greater than 10 percent cover divided by the length of centerline	number/mile
Pools per channel width	Pool frequency scaled by bankfull width	number/(reach length/bankfull width)
Average pool depth	Average of each pool depth summed for the reach	ft
Wetted width[1]	Width of each channel unit	ft
Bankfull width	Average bankfull width	ft
Bankfull depth	Average bankfull depth	ft
Number of channel units per mile	Number of total channel units per mile of centerline	number/mile
Percent cover	Percent of surface area with cover	percent

1 Wetted width was calculated for each channel unit, but only reported as part of ArcGIS deliverable. Area values were calculated from the 2017 and 2018 LiDAR with flows of 8,000 cfs and 6,000-7,500 cfs respectively.

Cover data were provided as part of the FA-02 Instream Flow Model Development Study (City Light 2023a). Cover included the following categories: undercut banks, overhanging vegetation, rootwads, log jam/submerged brush pile, log(s) parallel to bank, aquatic vegetation, short (less than 1 ft) terrestrial grass, tall (greater than 3 ft) dense grass (e.g., reed canary grass), and vegetation greater than 3 vertical ft above stage zero flow (WDFW and Ecology 2016). Information on hydromodifications was available in a 2015 data set from the Upper Skagit Indian Tribe (Hartson and Shannahan 2015) and was summarized by percent of bank length across reaches. Percent length of channel actively eroding pertains to areas where the study team noted disturbance of vegetated banks or indicators of bank instability (Bauer and Burton 1993) and was calculated by comparing changes in bank alignment between the 2006 and the 2022 aerial photos, changes in the terrain surfaces between the 2017-2018 and 2022 LiDAR as part of the Geomorphic

Change Section in this study, as well as through observations made in the field. Additional information, such as pools per bankfull channel width (mainstem length divided by the bankfull width were used to normalize pool frequency and spacing by channel size), were used to describe habitat quality and are included in Section 5.2.1 of this study report.

4.2.2 Tributary Analysis

Tributary assessments were focused on the level of fish passage at the confluence with the Skagit River and field surveys in the lower 500 ft of each tributary were conducted in August 2021 when flows were projected to be at seasonal low conditions. Flows during August 2021 ranged from 2,390 to 5,400 cfs at the USGS Skagit River at Marblemount gage (12181000). Figure 4.2-3 shows the 2021 water year with daily flows, with the survey timing identified. The August 2021 data collection events took place during the low flow period for the 2021 water year. Additionally, Figure 4.2-4 shows the flows in August 2021, as well as the average August daily flows, through the period of record. For most of the dates in August, the flows were below the mean flow for that date across the period of record. Therefore, flow conditions were representative of common low flow conditions during the surveys.

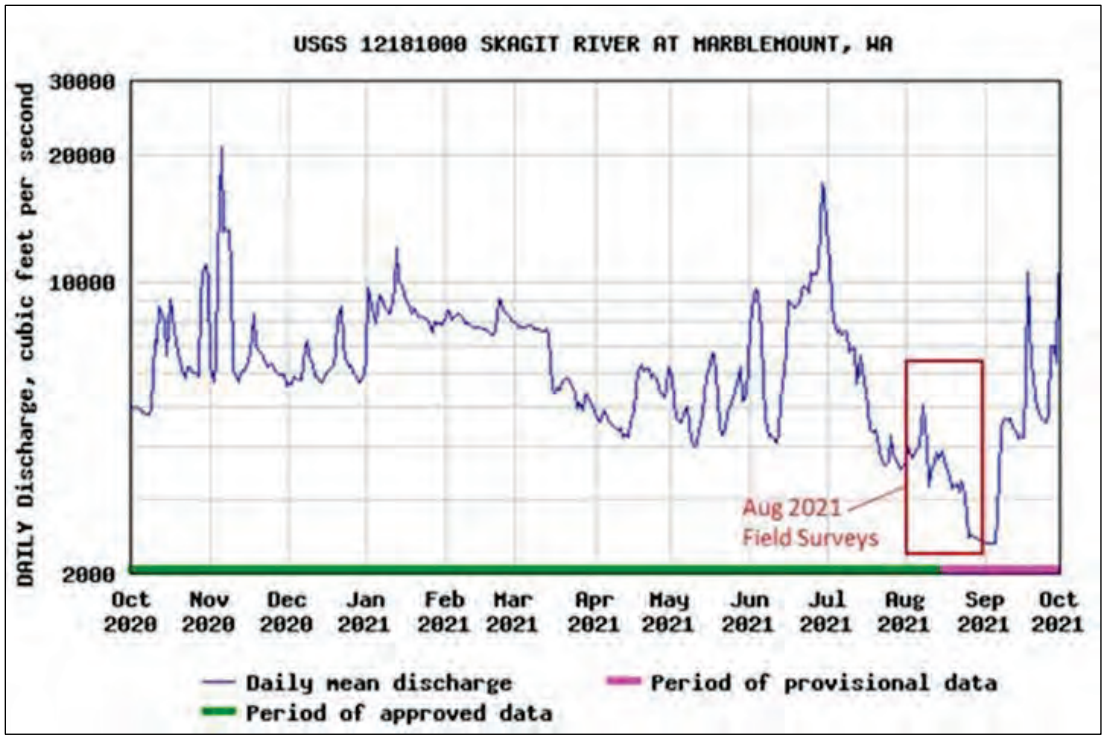


Figure 4.2-3. Skagit River flows during the 2021 water year at USGS Skagit River at Marblemount gage (12181000).

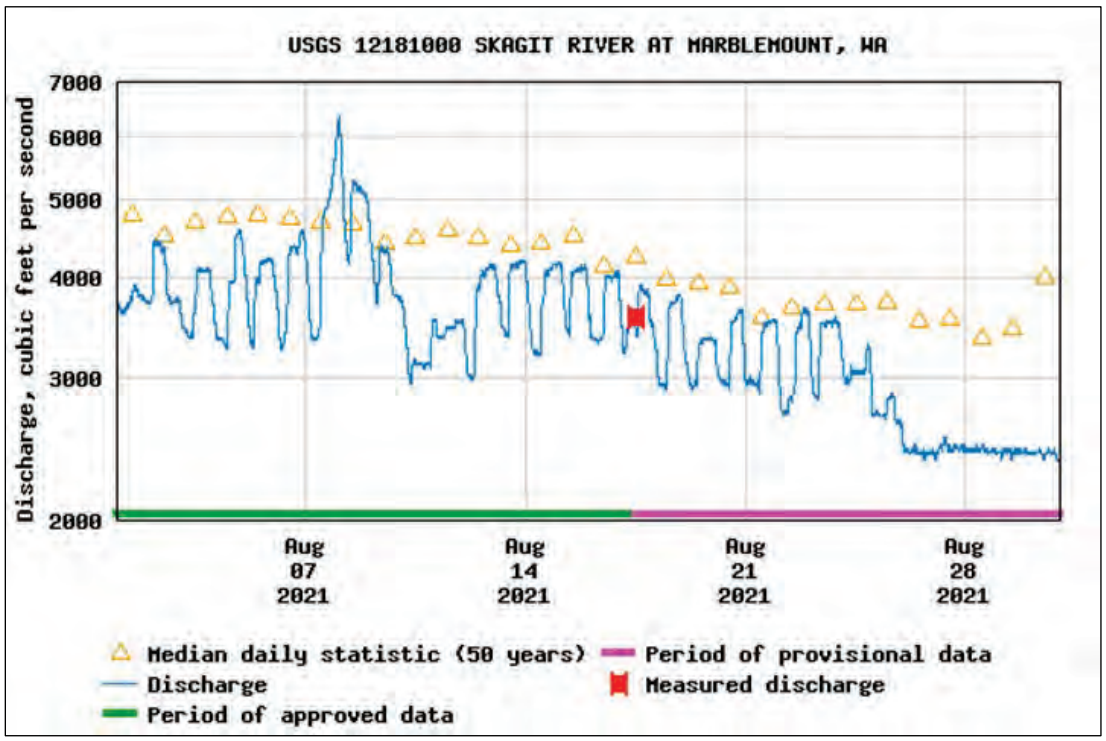


Figure 4.2-4. Skagit River flows during August 2021 at USGS Skagit River at Marblemount gage (12181000).

Surveys were designed to assess potential fish passage issues at tributary mouths. Additional information on tributary habitat for a subset of streams that flow under transmission lines is available in the GE-02 Erosion and Geologic Hazards at Project Facilities and Transmission Line Right-Of-Way Study (GE-02 Erosion and Geologic Hazards Study; City Light 2023d). Per Section 2.6.3 of the RSP (City Light 2021), water depths were measured at each tributary and compared to minimum water depths required for adult migration to assess passage (City Light 2021). Based on further literature review, the survey methods were expanded to include stream width and stream gradient. According to Reiser et al. (2006), in a study evaluating typical leaping and swimming capabilities of adult salmonids in Ward Creek, Alaska, the typical minimum swimming water depth for all five species of Pacific salmon and steelhead is 0.56 ft; however, this can be affected by extenuating circumstances, such as linear distance of shallow water depths, proximity to pools large enough for adults to rest in and submerge gills in, and deterioration of adult spawners at time of passage (WDFW 2019).

Minimal regulatory guidance exists around solely using water depth as an indicator of fish passage, and no specific depth criteria are present in the WDFW Fish Passage Manual (WDFW 2019) as surveys occur throughout varying times of the year and flow levels fluctuate widely. Therefore, water depth profiles, stream width, and stream gradient were all collected, as well as the presence of any other potential natural or artificial barriers per WDFW guidance. Assessment of fish passage issues was primarily guided by the WDFW Fish Passage Inventory, Assessment, and Prioritization Manual (WDFW 2019).

Field surveys used a range finder attached to a monopod, a prism, and a stadia rod to obtain water depth, wetted width, and vertical and horizontal distance measurements following guidance by WDFW (2019). Bankfull width measurements were collected instead of wetted width if no surface water was present in the stream. Bankfull width measurements followed collection criteria as outlined in WDFW (2019).

4.3 Side Channels and Off-Channel Habitat

The purpose of this section of the study report is to characterize the existing condition and distribution of these habitats, as well as discuss the processes involved in the formation and loss of side channel habitats through time. The goals and objectives that are associated with side channel and off-channel habitat include documentation of the following:

- Side channels and off-channel habitat, including hydraulically-connected wetlands;
- Substrate size and distribution;
- Large wood input, transport, and retention;
- Process flows that instigate side channel development/maintenance; and
- Process flows that hydraulically connect side channel and off-channel habitat.

Some of these objectives integrate information from other studies. The substrate and cover information comes from field work conducted under the FA-02 Instream Flow Model Development Study (City Light 2023a) and were incorporated into this Geomorphology Study Report. The large wood input, retention/presence information comes from within this Geomorphology Study in the Large Wood Section and were incorporated into this section of the

study report as well. Per Section 2.6.4 of the RSP (City Light 2021), information from the TR-02 Wetland Assessment (City Light 2022b) was reviewed to further inform the analysis of side channel and off-channel habitat.

4.3.1 Existing Condition Side Channel Field Methods

Side channels included in the field survey effort were identified by a collaborative process with City Light and LPs in July 2021. As part of this process, and as described in Section 2.6.4 of the RSP (City Light 2021), an initial map of side channels and off-channel habitat was made. This data layer was built using the green LiDAR and geo-referenced aerial photos. The map also integrated information from the NPS landform mapping project (Riedel et al. 2020) and the TR-02 Wetlands Assessment (City Light 2022b). Following the initial presentation of the map of proposed side channel and off-channel habitat for survey, LPs were invited to comment, as well as make additions or deletions. Information gained from LPs during these conversations was utilized in the planning of the field survey effort. Surveys of the side channels identified by City Light and LPs were then conducted in August 2021. The surveys focused on assessing how connected each side channel was to the river and geomorphic and salmonid habitat characteristics of the side channels.

Each side channel inlet and outlet was surveyed. Measurements included water depth, dominant and subdominant substrate size, and presence of large wood and hydromodifications. At select locations, pebble counts and relative datum cross sections were collected. Side channels were walked and characterized, focusing on documenting features, such as presence of pools, large wood, overhanging vegetation, beavers, juvenile salmonid use, measuring representative depths, substrate size, and noting conditions, such as recent erosion or colonization by vegetation.

Side channel types were classified as perennial, seasonal, or inactive based on field observations. A side channel was classified as perennial if it was wetted during the August 2021 survey. More refined analysis assessing the connectivity of side channels at standardized flow recurrences was accomplished using hydraulic modeling results from the FA-02 Instream Flow Model Development Study (City Light 2023a).

Additional information on substrate and fish cover collected as part of the FA-02 Instream Flow Model Development Study (City Light 2023a) were also incorporated in this Geomorphology Study side and off-channel analysis.

As described in the June 9, 2021 Notice, City Light installed “continuous stage readers and temperature loggers in the floodplain to validate floodplain connectivity.” A selection of 20 side channel and off-channel monitoring sites were selected in a series of small group working sessions that included City Light and LPs. The 20 field sites identified for this study are spatially distributed between Newhalem and the Sauk River and are supplemental to an existing network of hydrologic monitoring installed in Reach 6 by SRSC as part of the Barnaby Reach Restoration Project (SRSC and NSD 2019). HOBO U20 water level loggers were deployed inside of PVC stilling wells at each monitoring location over a range of dates between 11/29/2021 and 5/20/2022. Gage datums were surveyed in the field to adjust stage readings to water surface elevations referencing the NAVD 88 vertical datum. Additional details of the floodplain data logger sites and methodology is presented in a technical memorandum included as Attachment U.

4.3.2 Existing Condition Side Channel Desktop Analysis Methods

Side channels and off-channel features were digitized using REM based on August 2020 and March 2021 WSE profiles collected as part of hydraulic model calibration for the FA-02 Instream Flow Model Development Study. The terrain model used for the REMs is discussed in Section 4.2.1 Habitat Mapping methods and was created as part of the FA-02 Instream Flow Model Development Study (City Light 2023a). Delineations were further refined using field observations to help confirm elevations from REMs and to define the limits of side channels where LiDAR resolution was insufficient. One side channel, Pressentin Side Channel, was digitized from 2022 LiDAR because it was constructed in 2021, so it was not present in older LiDAR datasets. The digitized features were used to calculate an approximate area for each side channel. The approximate area of each side channel is presented in the results to aide in understanding the relative size of each feature.

To assess connectivity of side channels and off-channel features the Upper Skagit Hydraulic Model results were used to evaluate the connection of inlets and outlets to the mainstem Skagit River. Features were considered connected if mainstem flow with depth 0.5 ft or greater entered the channel inlet or outlet. The analysis was focused on annual exceedance flows to evaluate the frequency of connections. The November 2020 flood was also used as a higher than annual flow to see if more disconnected connections became engaged.

4.3.3 Time Series Analysis of Side Channel and Off-Channel Habitat

Methods for the time series analysis of side channel and off-channel habitats are described in Section 4.1 of this study report as well as in Section 2.6.4 of the RSP (City Light 2021). The same sets of photographs were used for the identification of side channel and off-channel habitats as those used for geomorphic and channel change. Since REM data for each time step in the time series was not available, aerial photos and maps were the primary data sources for this analysis. Variance in the relative quality and season during which the photos were captured affect the level of detail in observed side channels for each time step. For example, the photos used from 2006 were taken during the leaf-off stage, while other photo sets were captured when leaves were still present in the canopy. This may result in a higher level of detail in the side-channels mapped for 2006 as compared to other years. Conversely, photos from earlier periods (e.g., 1944) were of lower resolution and may show a lower level of detail in the side channels mapped as compared to other years.

Mapped areas and lengths of side channel and off-channel habitat were then used to calculate the metrics shown in Table 4.3-1 (where feasible). Braids were identified as channels of the mainstem that were separated from the thalweg by gravel bars at time of image capture. Side channels were identified as those separated from the mainstem flow by islands with permanent vegetation. The River Complexity Index (RCI) has been used to measure the relative level of habitat diversity and quality in paleochannels and integrates sinuosity (the relationship between channel length and valley length) and the number of junctions with braids or side channels within a given length of channel (Brown 2002). See Figures 4.1-1 and 4.1-2 for annual peak flow information surrounding date of image capture.

Table 4.3-1. Side channel and off-channel metrics for time series analysis.

Metric	Description	Unit
Length of side channel	Length of flow-through and blind side channel habitat	miles
Area of side channel/off-channel habitat	Area of side channel and off-channel habitat	ft^2
Braid ratio	Length of channel in braids divided by length of mainstem	ratio
Length of side channel/length of mainstem	Length of side channel divided by length of mainstem	ratio
Braid node density	Number of intersections of braids with mainstem per mile of mainstem length	number/mile
Side channel node density	Number of side channel junctions per mile of mainstem length	umber/mile
River Complexity Index (RCI)[1]	RCI = S(1+J) S= Sinuosity J = number of junctions in the reach	Number

1 The RCI (Brown 2002) integrates the sinuosity (or relative meander pattern) with the number of joins or junctions in the channel to summarize channel complexity.

4.4 Substrate/Sediment

The investigation of channel substrate described in this section is intended to document both local variability and along-channel trends in the composition of the channel boundary, as described in Section 2.6.5 of the RSP (City Light 2021). This information will contribute to understanding the interaction of sediment supply and channel hydraulics in the river and the effects of existing sediment composition and sediment transport processes on salmonid habitat quality. This section describes methods used to document existing sediment characteristics in the study area.

Substrate conditions vary substantially over small distances in rivers (e.g., from the upstream head of a bar to the downstream tail of a bar), and so it is important to have data describing both local heterogeneity and river-scale trends in bed material composition. When evaluating river-scale trends, the best approach is to focus sediment sampling in a characteristic geomorphic environment that most represents typical dominant bed material in the channel. Another important distinction to quantify is the difference between the character of the surface and subsurface sediment. The surface material of riverbed gravel and cobble deposits—the armor layer—is characteristically coarser than the subsurface material, and both the surface and the subsurface material play important roles in governing aquatic habitat, sediment transport, channel form, and channel stability. Three principal methods were applied to provide a robust view of bed material sediment through the study area: Wolman (1954) pebble counts of the surficial material, bulk samples of the material below the armor layer, and facies mapping covering the active channel.

Pebble counts were completed to characterize the grain size distribution of the surficial bed material in July and August 2021 for the primary study area from the Sauk River confluence upstream, and in April 2022 between the Sauk River confluence and PRM 20 between Sedro-Woolley and Burlington. Pebble counts were repeated for select sites in the primary study area in July and August 2022 to evaluate if the November 2021 flood impacted the grainsize distribution of the surficial material in a detectable way. One pebble count was performed on material exposed

in an eroding bank at PRM 88.2 in order to characterize the lithologies of pre-regulation bed material.

Bulk samples were collected to characterize the grain size distribution of the subsurface material. As with pebble counts, samples were collected in July and August 2021 for the primary study area from the Sauk River confluence upstream; in April 2022 between the Sauk River confluence and PRM 20; and at select repeated locations in the primary study area in July and August 2022.

A total of 54 bulk samples with an additional 8 repeat samples and 72 pebble counts with an additional 26 repeat samples were collected from bar head locations that were believed to represent typical structural bed material in each reach (e.g., Figure 4.4-1), or pockets of material believed to be typical bedload in steep reaches where the structural bed material is interpreted to be rarely mobilized. Sample sites were selected from aerial photos, and field notes documenting the relationship of the sampled material to surrounding bed material were recorded. Figures 4.4-2 and 4.4-3 show locations of sediment samples collected and Table 4.4-1 lists the geomorphic position of each sediment sample. Ultimately, over 32,000 pounds (14,500 kilograms [kg]) of sediment was handled in the process of collecting the bulk samples, and over 9,800 grains were measured for the pebble counts.



Figure 4.4-1. Examples of typical sediment sample locations, including the head of an island bar at PRM 90.2 (top) and head of a bank-attached point bar at PRM 78.4 (bottom).

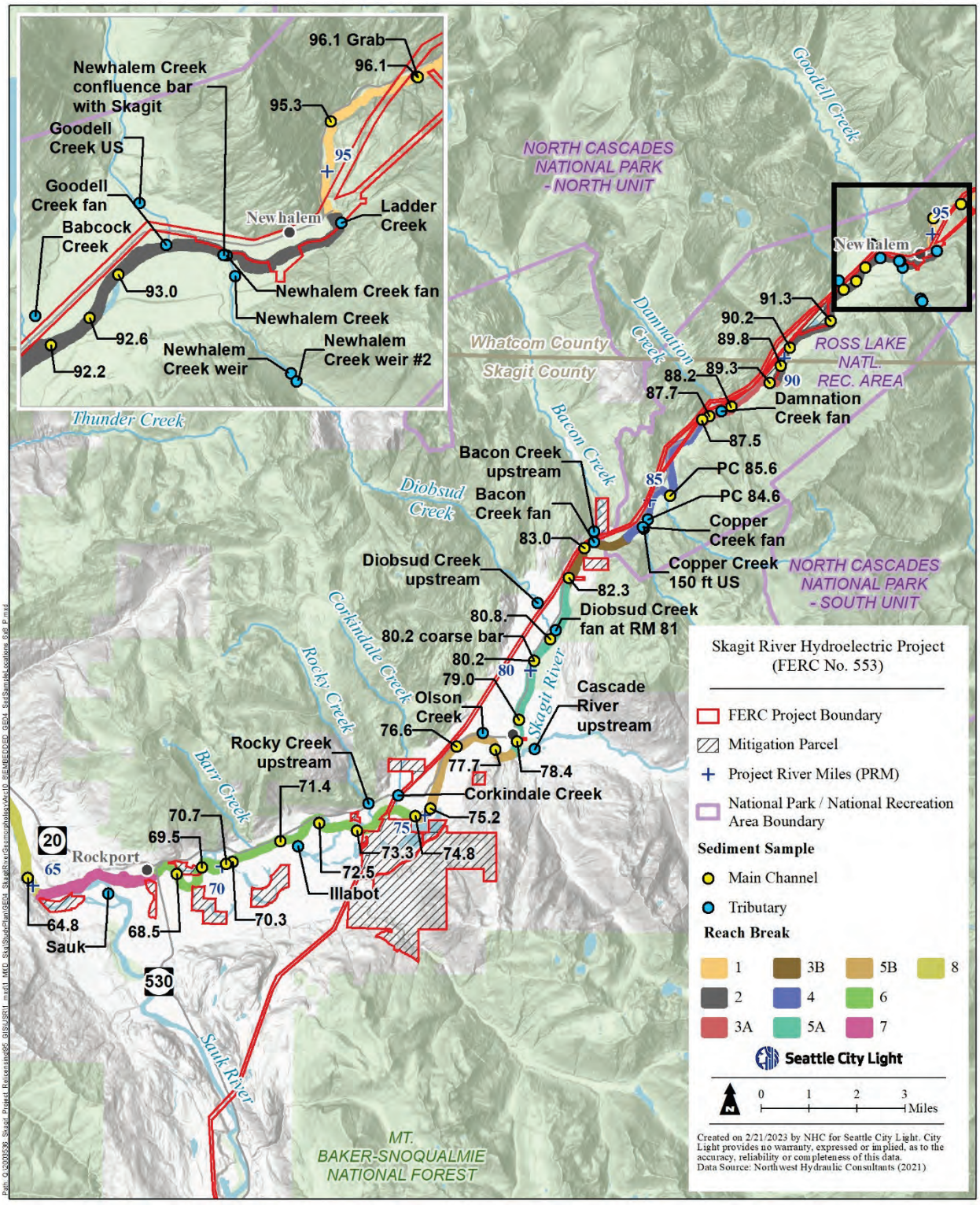


Figure 4.4-2. Overview of sediment sample locations in primary study area.

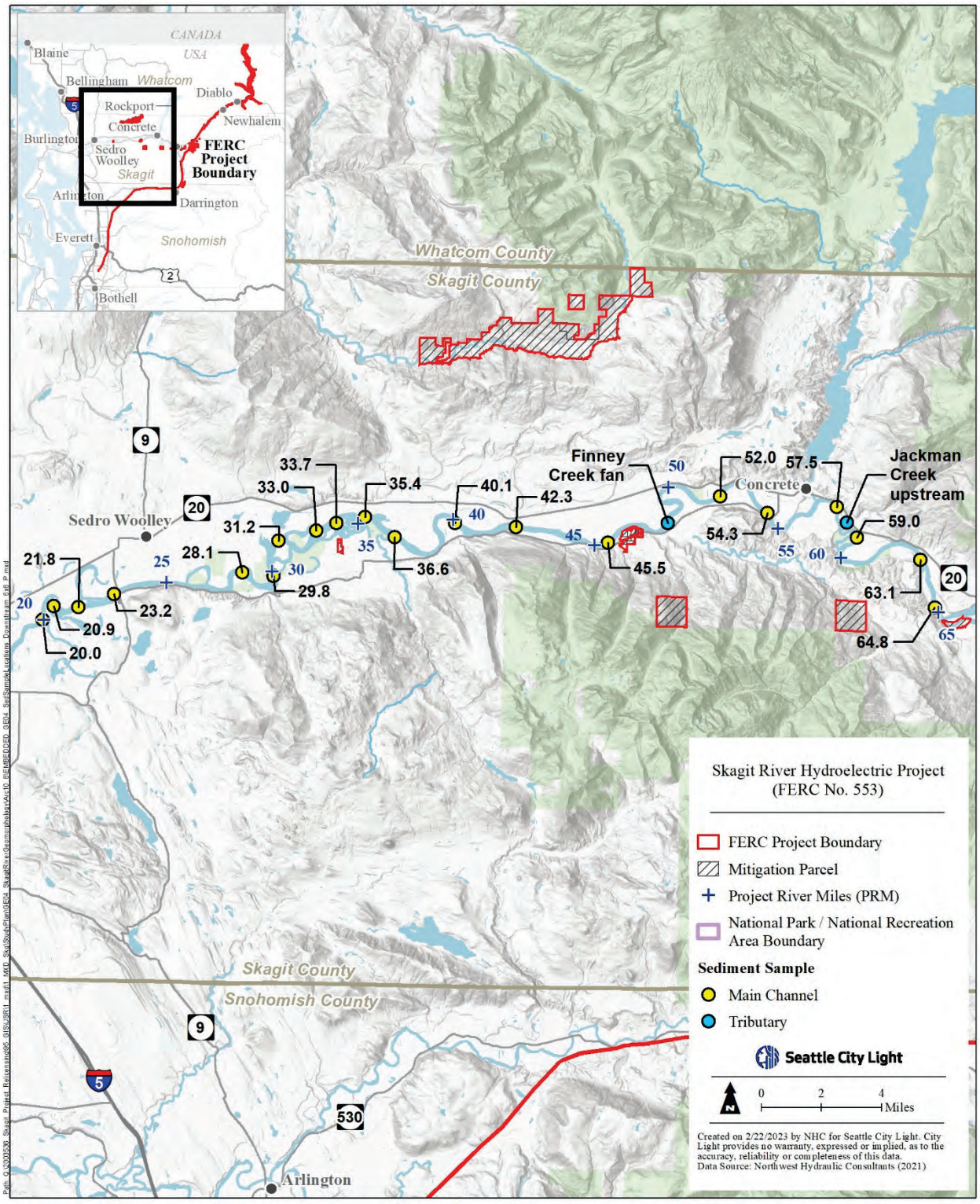


Figure 4.4-3. Overview of sediment sample locations downstream of Sauk River confluence.

Table 4.4-1. Locations of sediment samples.

Sample Location (PRM or Tributary)	Sample Type(s)	Geomorphic Position
96.1	Bulk and pebble count	Pocket fine mid-channel bar deposit in lee of boulders. Believed to represent throughput bedload in reach.
95.3	Pebble count	Relatively fine-grained point bar.
93	Bulk and pebble count	Riffle crest bar head.
92.6	Bulk and pebble count	Head of point bar; anomalously coarse, some soil development beginning between cobbles, moss establishing on large cobble to small boulder, heavy periphyton growth.
92.2	Bulk and pebble count	Head of mid-channel island bar, similar to typical material in channel across riffle upstream.
91.3	Bulk and pebble count	Head of stabilizing island bar at riffle crest.
90.2	Bulk and pebble count	Head of stabilizing island bar at riffle crest.
90.1	Pebble count	Head of newly formed mid-channel bar, off right bank side channel. Repeat sample paired with 90.2 (location changed slightly between 2021-2022).
89.8	Bulk and pebble count	Head of riffle crest bar.
89.3	Bulk and pebble count	Head of mid-channel bar, extremely bimodal (large gravel and cobble and sand).
88.2	Pebble count	Material exposed in lower half of eroding bank. Interpreted to be bed material deposited before regulation.
87.7	Bulk and pebble count	Head of large island bar, light moss and periphyton development, characteristic of typical bed material in reach.
87.55	Pebble count	Head of newly formed mid-channel bar, downstream of eroding bank, repeat sample paired with 87.5 (location changed slightly between 2021-2022).
87.5	Bulk and pebble count	Mid-channel bar in lee of island, clearly developed by material deposited out of transport in the right bank channel, some moss, periphyton, and small willow establishing.
84.6	Bulk and pebble count	Head of point bar, relatively high topographic position due to higher flow at time of sampling.
83	Bulk and pebble count	Head of point bar that extends into riffle downstream.
82.3	Bulk and pebble count	Head of riffle crest bar.
80.8	Bulk and pebble count	Head of point bar on right bank just downstream of Diobsud Creek confluence.
80.2	Bulk and pebble count	Head of compound point bar.
80.2	Pebble count	Head of coarse point bar landward of compound point bar.
79	Bulk and pebble count	Head of island bar.
78.4	Bulk and pebble count	Middle of very long point bar on inside of meander.
77.7	Bulk and pebble count	Head of compound point bar at riffle crest.
76.6	Pebble count	Across large geomorphically-controlling riffle.

Sample Location (PRM or Tributary)	Sample Type(s)	Geomorphic Position
75.2	Bulk and pebble count	Head of riffle crest point bar.
74.8	Bulk and pebble count	Middle of very long point bar on inside of meander.
73.3	Bulk and pebble count	Head of stabilizing mid-channel bar that is transitioning towards a point bar. Similar to material at site and upstream but coarser than material in channel downstream. Some periphyton but very little moss growth.
72.5	Bulk and pebble count	Head of large island bar at backwater upstream of revetment where river impinges against SR 20.
71.4	Bulk and pebble count	Head of riffle crest point bar.
70.3	Bulk and pebble count	Head of riffle crest point bar.
70.1	Pebble count	Across whole area of compound point bar.
69.5	Bulk and pebble count	Head of actively growing point bar.
68.5	Bulk and pebble count	Head of riffle crest point bar.
64.8	Bulk and pebble count	Head of very large island bar at riffle crest caused by flow expansion.
63.1	Pebble count	Middle/upstream half of island bar in lee of island. Finer than other bars in general area.
59.0	Bulk and pebble count	Mid-upstream end of large point bar across from eroding bank, characteristic of active bar material in reach.
57.5	Pebble count	Mid-upstream end of point bar, characteristic of active bar material in reach.
54.3	Bulk and pebble count	Head of mid-channel bar near right side of channel. Downstream of bridge/bedrock constriction. Bar material relatively coarse for reach but obviously mobile in 2021 flood; cobble deposited over bases of willows at bar center.
52.0	Pebble count	Head of mid-channel bar near left side of channel. In slight flow expansion zone; relatively fine for reach.
45.5	Bulk and pebble count	Mid-upstream end of large island bar at outside of bend with bank eroding at inside of bend. Relatively coarse for reach. Center of bar has mature vegetation established.
42.3	Pebble count	Head of large, stable mid-channel bar.
40.1	Bulk and pebble count	Head of narrow bar on upstream-inside of meander, immediately downstream of bank erosion zone on same bank.
36.6	Pebble count	Head of point bar at gentle bend.
35.4	Bulk and pebble count	Head of large point bar at upstream end of anastomosing reach.
33.7	Pebble count	Head of point bar on large island in anastomosing reach.
33.0	Bulk and pebble count	Head of large point bar opposite flow split and eroding bank of island. In anastomosing reach.
31.2	Bulk and pebble count	Head of island bar near right bank. Immediately downstream of junction between two large channels in anastomosing reach.
30.2	Pebble count	Head of mid-channel bar.

Sample Location (PRM or Tributary)	Sample Type(s)	Geomorphic Position
28.1	Bulk and pebble count	Head of point bar. Bar surface somewhat coarse for reach but subsurface relatively fine.
23.2	Bulk and pebble count	Head of mid-channel bar downstream of bridge.
21.8	Bulk and pebble count	Head of right bank bar.
20.9	Pebble count	Mid-upstream part of large mid-channel bar.
20.0	Bulk and pebble count	Head of point bar.
Alma Creek Fan	Bulk and pebble count	Point bar that is a pocket deposit interpreted to be comprised of throughput bedload. Finer than typical structural bed material (boulder).
Babcock Creek	Bulk and pebble count	Riffle crest across thalweg of dry creek.
Bacon Creek Fan	Bulk and pebble count	Relatively coarse active lobes of fan.
Bacon Creek Upstream	Bulk and pebble count	Middle of point bar.
Cascade River	Bulk and pebble count	Head of island bar connected to riffle crest.
Copper Creek Fan	Pebble count	Across confluence bar formed at and downstream of creek outlet.
Copper Creek Upstream	Pebble count	Across whole channel.
Corkindale Creek	Bulk and pebble count	Riffle crest across thalweg of dry creek.
Damnation Creek Fan	Bulk and pebble count	Relatively coarse active lobe of fan.
Diobsud Creek Fan	Bulk and pebble count	Head of active lobe of fan.
Diobsud Creek Upstream	Bulk and pebble count	Head of riffle crest point bar.
Finney Creek Fan	Pebble count	Inside of slight bend on Finney Creek, within backwater influence of Skagit River.
Goodell Creek Fan	Bulk and pebble count	Across active lobe of fan.
Goodell Creek Fan	Bulk and pebble count	Head of island bar.
Illabot Creek Upstream	Bulk and pebble count	Head of island bar, within backwater influence of Skagit River.
Jackman Creek Upstream	Pebble count	Head of right bank bar upstream of estimated backwater influence of Skagit River. Representative of channel material to slightly coarser.
Ladder Creek Fan	Bulk and pebble count	Across terrace bar formed by recent aggradation-degradation episode.
Newhalem Creek Fan	Pebble count	Across coarse lobes of confluence fan.
Newhalem Creek Upstream	Pebble count	Pockets of mobile bed material just downstream of bridge, finer than structural boulder bed material in reach.
Olson Creek Upstream	Bulk and pebble count	Riffle crest across thalweg of dry creek.
Rocky Creek Upstream	Bulk and pebble count	Pocket bar deposit typical of transported bedload upstream of channel spanning large wood jam; finer than structural bed material.
Sauk River	Bulk and pebble count	Head of riffle crest point bar.
Sauk River (2)	Pebble count	Head of first riffle crest upstream from the confluence, repeat sample paired with Sauk River (location changed slightly between 2021 and 2022 because channel migrated/avulsed).

4.4.1 Pebble Count Methods

Pebble counts (n=100) were collected following a standard Wolman (1954) random-walk procedure and used gravelometer templates to measure particles in half-phi size classes up to a b-axis diameter of 180 millimeters (mm). The b-axis of particles larger than 180 mm was measured using a tape or measured increments on the side of the gravelometer and recorded in half-phi size bins. Pebble counts were collected from locations adjacent to bulk samples from areas with a visually similar grain size distribution to the location of the bulk sample.

In addition to the standard particle size measurements, the lithology of each measured particle was also recorded. Lithology classes were defined to be readily field-identifiable and provide indications of the source area for the particle. The study team worked with Jon Riedel (retired North Cascades National Park Geologist) to determine these lithology classes, which are identified in Table 4.4-2. A simplified lithology map is shown in Figure 4.4-4.

Table 4.4-2. Lithology classes used in pebble counts.

Lithology Class (Class Code)	Geologic Domain	Characteristic Geologic Units (Haugerud and Tabor 2009)	Principal Tributary Basin(s)	Notes
Cherty Conglomerate (Cc)	Eastern Cascades	MzPzh, Kps, Ktf	Upper basin	
Panther Creek Conglomerate (Cp)	Eastern Cascades	KJos	Upper basin	
Metasedimentary (Ms)	Eastern Cascades	MzPzh, Km, Ktf, TKm	Upper basin	Includes well-indurated marine sedimentary
Banded Gneiss (Gb)	Central Crystalline Core	Knmg, Kswg, TKmm, TKsg	Upper basin, Ladder Ck Newhalem Ck, Cascade R, Sauk R	
Orthogneiss (Go)	Central Crystalline Core	TKgo, TKmo, TKsn, TKso, TKto	Upper basin, Ladder Ck, Newhalem Ck, Goodell Ck, Alma Ck, Cascade R.	
Granodiorite & Other Intermediate to Felsic Intrusives (GD)	Central Crystalline Core	Kg, KJya, Kmd, Kt, Ktm, QTcp, Tcai, Tcas, Tei, TKmd, TKrb	Upper basin, Goodell Ck, Damnation Ck, Bacon Ck, Copper Ck, Cascade R, Illabot Ck, Sauk R	
Napeequa Schist (Sn)	Central Crystalline Core	Kns, TKns	Newhalem Ck, Alma Ck, Copper Ck, Bacon Ck, Cascade R, Illabot Ck, Sauk R	May be conflated with Blueschist, especially from units Kcs and TKcs
Mafic & Ultramafic (M, UM)	Central Crystalline Core & Western Group	KJb, KJts. KJya, Knmg, Knu, TKhg, TKhm, TKmm, TKnu, TKsx	Cascade R, Sauk R	

Lithology Class (Class Code)	Geologic Domain	Characteristic Geologic Units (Haugerud and Tabor 2009)	Principal Tributary Basin(s)	Notes
Greenschist (SG)	Western Cascades & Central Crystalline Core	Kcs, Kes, TKcs, TKhg	Bacon Ck, Diobsud Ck, Cascade R, Olson Ck, Corkindale Ck, Illabot Ck, Sauk R	
Blueschist & Other Schists (SB)	Western Cascades	Kcs, Kes, KJb, Kncs, TKcs	Corkindale Ck, Rocky Ck, Olson Ck, Cascade R, Sauk R	May be conflated with Napeequa Schist
Darrington Phyllite (Ked)	Western Cascades	Ked	Diobsud Ck, Olson Ck, Corkindale Ck, Illabot Ck, Sauk R, Finney Ck	Higher grade material may be conflated with Blueschist
Conglomerate of Bacon Creek (Cb)	Western Cascades	Tes	Bacon Ck	May be conflated with other conglomerates
Volcanics, General (V)	Western Cascades & Central Crystalline Core (minor)	Qcav, Qtcc, Tcaf, Tcao, Tev	Upper basin, Goodell Ck, Bacon Ck, Sauk R	Older volcanics may be conflated with Metavolcanic
Vesicular Volcanics (Vs)	Western Cascades	Qcav	Sauk R	Distinctive tracer to Sauk River
Volcanic Breccia of Bacon Creek (Vb)	Western Cascades	Unmapped	Bacon Ck	Distinctive material with dark gray matrix and angular clasts
Clastic Sedimentary (Sed)	Western & Eastern Cascades	JTrc, KJn, KJos, Kps, Ktf, PDc, Tees, Tes	Upper basin, Bacon Ck, Corkindale Ck, Rocky Ck, Sauk R	
Other Conglomerate & Metaconglomerate (C, CM)	Western & Eastern Cascades, Central Crystalline Core	Km, PDc, Tees, Tes, TKcs, TKm, TKmm	Upper basin, Cascade R, Jackman Ck.	
Metavolcanic (Mv)	Western & Eastern Cascades	KJb, Kpv, MzPzh, PDc, TKhg	Upper basin, Ladder Ck, Bacon Ck, Cascade R, Diobsud Ck, Illabot Ck, Ladder Ck, Jackman Ck, Finney Ck	Likely includes many other lithologies with fine textured dark matrix material
Quartz & Quartzite (Qz)	All	Various	NA	
Other or Not Identifiable (X)	NA	NA	NA	

1 Geologic unit codes follow Haugerud and Tabor (2009).

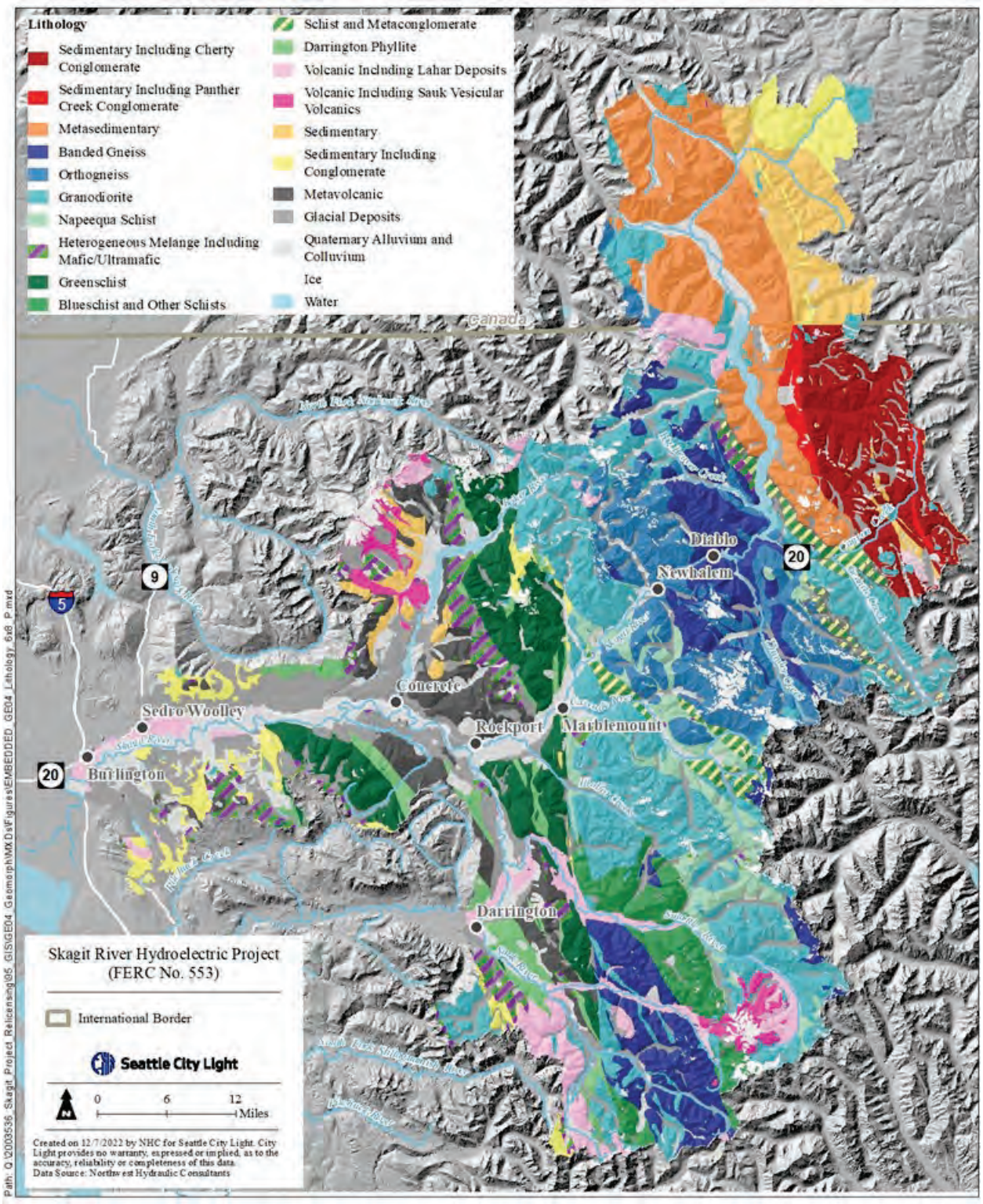


Figure 4.4-4. **Overview of lithologies in the Skagit basin showing source areas for pebble count lithology classes. Data simplified from Haugerud and Tabor (2009) and Cui et al (2017).**

4.4.2 Bulk Sample Methods to Characterize Sub-surface Material

Bulk samples of the material below the surface armor layer were collected following the method of Church et al. (1987). To do this, the surface armor layer was removed, and then a pit was excavated until either the practical sampling limit of 440 pounds (200 kg) or a volume sufficient that the largest particles in the deposit made up no more than 1 percent of the sample weight was obtained (the 1 percent criterion). The bulk sample material was field-sieved to separate material at the 32 mm size. Material larger than 32 mm was divided into half-phi grainsize classes using a gravelometer, and the weight of each class was measured in the field. A 30- to 45-pound sub-sample of the material smaller than 32 mm was retained for grainsize analysis following American Society for Testing and Materials standards. Sieve analysis of this material was performed by Materials Testing & Consulting, Inc. Field and lab grainsize distributions for each bulk sample were then combined based on the split ratio of the material; water weight was assumed to be evenly distributed through the fraction of the sample smaller than 32 mm.

4.4.3 Hybrid Grainsize Classification Method

Since the practical sampling limit of 200 kg determined for this study was below the recommended 1 percent criterion for many samples (Church et al. 1987), the hybrid method of Rice and Haschenburger (2004) was applied to characterize the coarse tail of the bulk grainsize distribution. The decision to apply this method was made in consultation with LPs during the July 20 and July 27, 2021 Geomorphology Work Group meetings. This method assumes that the surface and subsurface material come from the same source grainsize population and that the surface armor layer formed through selective horizontal removal of fine sediment (winnowing). This implies that the ratio of the weight of a specified match fraction (between the surface and subsurface samples) and each larger grainsize fraction in the surface material can be used to determine the distribution of the coarser material more reliably than would be possible with only the undersized sample. Selection of the match fraction was determined by identifying the largest grainsize fraction meeting the 1 percent sample size criterion. In other words, the match fraction was chosen as the largest grainsize for which the cumulative weight of the sample through that size class (smallest to largest) was greater than the 1 percent criterion for material of that size. For 440-pound (200 kg) samples, the match fraction was most frequently 64 to 91 mm, and occasionally 91 to 128 mm.

4.4.4 Comparison of 2021 and 2022 Grainsize Distributions

Grainsize data from bulk samples and pebble counts collected in 2021 and 2022 were paired at repeat sampling sites to evaluate whether meaningful changes in the grainsize distribution occurred as a result of high flows in November 2021. Paired sample t-tests were performed on the grainsize quantiles (D_{10}, D_{16}, D_{50}, D_{84}, D_{90}) to determine if the mean of the quantile values had changed at a quantifiable level of statistical significance. Comparison of grainsize distribution data was conducted on all of the repeat sites and on subsets of the data. For bulk sampling sites, t-tests were also performed on the armor layer ratio (surface D_{50}/subsurface D_{50}). Further analysis isolated the effects of tributary sites by explicitly comparing them to mainstem Skagit sites. The power ($1-\beta$) of the t-tests was calculated post hoc to quantify the tests' ability to detect existing change. Quantile-Quantile plots visualizing 2022 grainsize distribution quantiles as functions of 2021 quantiles were created to elucidate patterns in the data and to identify the direction of change (coarsening or fining). In theory, two perfectly equal distributions should line up on the one-to-one line in a Quantile-Quantile plot. The magnitude of change (2022 mean quantile – 2021 mean

quantile) in grainsize distributions exhibiting statistically significant change was calculated to show effect size as well as direction of change.

4.4.5 Facies Mapping

Methods for the facies mapping are reported in the FA-02 Instream Flow Model Development Study (City Light 2023a). This mapping covered large portions of the mainstem Skagit River. These data were analyzed in this Geomorphology Study to understand spatial heterogeneity of the bed material. The substrate is reported by code, providing a dominant and subdominant grainsize class, as well as the percent coverage of the dominant grainsize class per the Washington State Instream Flow Study Guidelines (Beecher et al. 2016). Pebble counts were not utilized in the facies mapping exercise, so the estimates are based purely on visual methods.

In order to extract relevant grain size metrics from the coded substrate data, a series of logical clauses were applied to the codes to predict the D_{84} and D_{50} grain size. There were two methods used to calculate the D_{84}, as illustrated by the following example (Table 4.4-3). First, if the dominant grain size class was mapped to be smaller than the subdominant grain size class (example: 27.5 = sand dominant [50 percent], large cobble subdominant), then the D_{84} was calculated as the weighted average between the largest grain size in the dominant class and the median grain size of the subdominant class using the percent coverage for the weight. Otherwise, if the dominant grain size class was larger than the subdominant class (example: 76.5 = large cobble dominant [50 percent], medium cobble subdominant), then the D_{84} was assigned the largest grain size of the dominant class. Example initial grain sizes interpreted using this approach are specified in Table 4.4-3. Where possible, the predicted grain size was compared to the metrics of 37 spatially correlated Wolman pebble counts collected in 2021 (Section 4.4.1). These comparisons to measured data provided the opportunity to calibrate the predictive logical expressions using an iterative approach.

Table 4.4-3. Examples of interpreted (pre-calibration) facies mapping relation to grainsize.

Facies Code	Dominant Grainsize	Subdominant Grainsize	Percent Dominant	Interpreted D_{50} (mm)	Interpreted D_{84} (mm)
27.6	Sand (0.5-2.5 mm)	Large cobble (152-304 mm)	60%	45	90
36.7	Fine gravel (2.5-13 mm)	Small cobble (76-152 mm)	70%	27	45
45.7	Medium gravel (13-38 mm)	Coarse gravel (38-76 mm)	70%	23	38
76.5	Large cobble (152-304 mm)	Small cobble (76-152 mm)	50%	147	304
87.5	Boulder (>304 mm)	large cobble (152- 304 mm)	50%	304	609

4.5 Sediment Transport

Sediment transport and sediment augmentation studies completed as a part of this geomorphic study focus on understanding the existing conditions of sediment transport and how patterns of sediment transport and channel morphology may be expected to respond to different inputs of flood flows, sediment, or both factors (channel process sensitivity). To do this, a modeling program was developed in collaboration with LPs (based on commitments in the June 9, 2021 Notice and RSP [City Light 2021]) to improve understanding of existing conditions and channel process sensitivity related to bedload transport, channel profile changes (aggradation and degradation), cross section shape and area, side channel formation and decay, lateral channel migration, and stage-discharge rating adjustments. Bed material load was addressed with these models, while changes to washload were considered through the lens of sediment yield, as described in Section 4.5.4 of this study report.

Empirical data regarding sediment mobility and sediment transport have also been collected. These data include scour monitoring of select riffle crest locations and locations of known important spawning activity, and the deployment and recovery of Radio Frequency Identification Device (RFID)-tagged particle tracers. Concurrent and ongoing efforts by the USGS to monitor bedload movement using direct sampling and acoustic techniques (Anderson 2022) provide limited supplementary information for quantifying sediment transport.

4.5.1 Sediment Transport Modeling Program

The RSP specified that this study would include both one dimensional (1-D) and two-dimensional (2-D) mobile bed sediment transport modeling (City Light 2021). In addition, the June 9, 2021 Notice specified that hydraulic modeling and sediment transport studies would be extended downstream of the Sauk River confluence. Based on the commitments in the June 9, 2021 Notice, details of the modeling program were developed in collaboration with LPs in a series of workshops held on July 20, July 27, September 28, and November 9, 2021. Conversation at these meetings resulted in some minor variances relative to commitments in the June 9, 2021 Notice, which were approved by FERC in its August 8, 2022 Determination on Requests for Study Modification.

The modeling program includes the nested development of four kinds of models to represent key aspects of the Skagit River channel processes. Key questions regarding river processes that can be addressed with sediment transport modeling were identified in consultation with LPs at the September 28, 2021 Sediment Transport Sub-Group work session and October 12, 2021 Geomorphology Work Group meeting. These questions, and the applicable models to inform answers to them, are listed in Table 4.5-1; these questions framed the modelling and are guiding development of model application. In addition, Attachment C of the RSP identified that the modeling program would be developed to provide a tool to show how any sediment added to the Skagit River as part of any potential protection, mitigation, and enhancement (PME) would be routed through the river and how far downstream it would generate noticeable effects (City Light 2021). Model extents (Figure 4.5-1) were selected based on preliminary understanding of which processes and questions are most important in each area of the Skagit River. These models are described in more detail below.

Table 4.5-1. Applicable models to inform key questions for sediment transport modeling.

Key Question	UBCRM	1-D HEC RAS	2-D HEC RAS	MAST 1-D
1. How sensitive is channel width (and therefore side channel prevalence) to channel forming discharge in each reach? What impact could plausible alternative flow release regimes have on channel width?	**X**			**X**
2. How sensitive is channel width (and side channel prevalence) to bed material supply in each reach? How does channel width vary if both Qw and Qb vary?	**X**			**X**
3. How sensitive are the channel profile and local stage-discharge relationships to variability in bed material input (both quantity and caliber) and to variability in the flow regime?		**X**		**X**
4. How sensitive is the grainsize distribution of the bed material to variability in bed material input and flow regime?		**X**	**X**	**X**
5. What flows are required to mobilize/scour sediment in tributary fans? In spawning areas? Around side channel offtakes?			**X**	
6. How does wood density affect local and reach-scale sediment transport processes?		**X**	**X**	
7. To what extent may changes in flood regime and sediment supply trigger feedback loops that further impact sediment mobility and downstream movement?	**X**	**X**	**X**	**X**

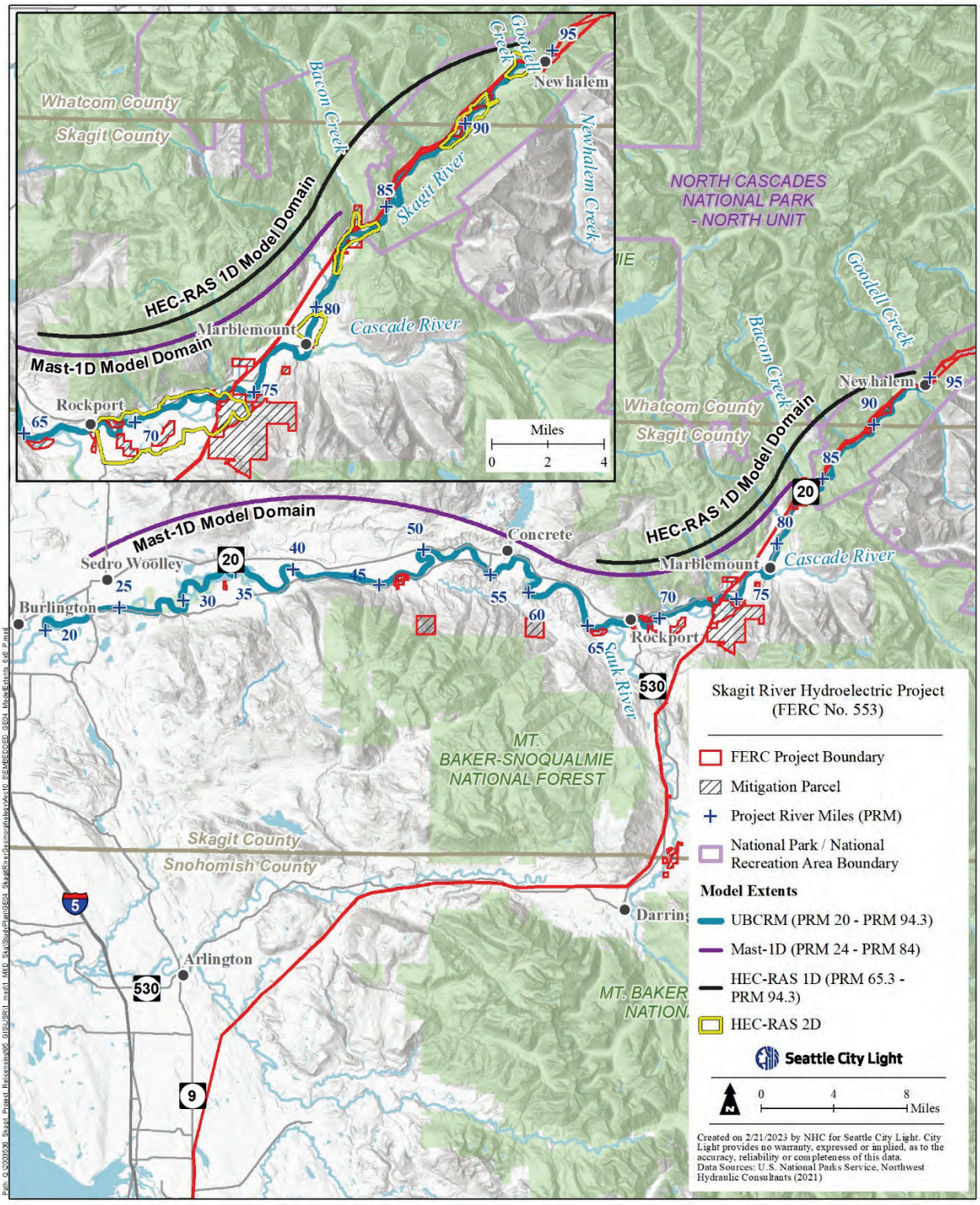


Figure 4.5-1. Sediment transport model extents. All models span the floodplain.

4.5.1.1 UBCRM

The University of British Columbia Regime Model (UBCRM) (Eaton 2007; Millar et al. 2014) provides a means to rapidly assess river channel hydraulic geometry and propensity for multi-channel morphologic adjustments based on prescribed hydrologic and sediment loading scenarios. Base UBCRM parameterizations were developed for each hydrologically and geomorphically distinct reach of the Skagit River between Newhalem and PRM 20, several miles upstream of the gravel-sand transition. For the area upstream of the Sauk River, these reaches are defined in Section 3 of this study report. UBCRM reaches were defined based on similar criteria for the reach between the Sauk River and the gravel-sand transition. They align with geomorphic reaches used by Smith et al. (2011) and Rothleutner (2017). This modeling effort is intended to fulfill commitments in the June 9, 2021 Notice to include evaluation of lateral channel mobility in reaches where that may be an important process and to study controls over geomorphic processes downstream of the Sauk River.

UBCRM provides estimates of channel width-to-depth ratios and channel patterns as a function of sediment loading, slope, bank material strength, and hydrologic conditions. It provides these estimates assuming that the input discharge is the channel forming discharge for the channel, and the output channel geometry represents equilibrium with that channel forming discharge. Daily flood quantiles interpolated to each geomorphic reach calculated for the 1988-2020 period were used as input channel forming flows (NHC 2023). Specifically, the historical regulated 10-year daily discharge was used as the current channel forming discharge upstream of the Sauk River, and the historical regulated 5-year daily discharge was used as the current channel forming discharge downstream of the Sauk River. The historical regulated 2-year daily discharge was also tested as a possible channel forming discharge using the calibration procedure described below, but it was found to be too low to form the observed channel morphology.

UBCRM has been calibrated by adjusting the bank strength parameter until the computed channel widths were equal to those measured by the ongoing morphometric mapping activities. This calibration represents existing conditions, with channel geometry assumed to be equilibrated to the channel forming discharges identified above. Calibration was successful for all reaches except 7A, where the Sauk delta affects the slope of the Skagit River and prevents the reach from fully equilibrating to Skagit River hydrology and sediment supply. After calibration, UBCRM was applied to evaluate general channel hydraulic geometry and planform sensitivity to a wide plausible range of possible channel forming hydrology and sediment supply conditions. Complete details of the UBCRM model parameterization, calibration, and application are described in Attachment O.

4.5.1.2 One-Dimensional Mobile Bed HEC-RAS Model

A 1-D mobile bed USACE HEC-RAS (version 6.3) model (1-D HEC-RAS model) was developed to quantify long-term sediment transport and channel bed profile evolution of the Skagit River, as described in Section 3.2.2 of Attachment C of the RSP (City Light 2021). Model cross sections were cut from the same 2017/18 topobathymetric surface used in the Upper Skagit Hydraulic Model (City Light 2023a) and included both the channel and floodplain areas. Cross section locations and spacing were set to capture hydraulic and sediment transport characteristics throughout the study reach, extending from PRM 94.5 at Newhalem (NPS Reach 2) downstream to PRM 65 near the confluence of the Sauk River (NPS Reach 7). Depending on the channel

topography and complexity, cross section spacing ranged from about 340 ft to 680 ft, with the average spacing of about 500 ft. Bed material characteristics in the model were specified using surface and sub-surface bed material data collected along the modeled reach in 2021 (Sections 4.4 and 5.4.1). Details of the model development and calibration are described in Attachment P. Specific aspects of the 1-D model setup and initial applications are provided below:

- Initial model testing was conducted by running 45 years of historical flows (October 1, 1977 through September 30, 2022, which corresponds to the period when daily flows are consistently available for both the USGS Skagit River at Marblemount gage (12181000) and USGS Skagit River at Newhalem gage (12178000) to assess long-term model application performance and stability.
- Hydraulic model calibration was based on comparing modeled water surface profiles with available measured river and overbank stage data for the November 2020 and November 2021 flood events.
- Sediment transport calibration was based on comparative topobathymetric surveys in 2017, 2018, and 2022 (Sections 4.1.4 and 5.1.2), measured changes in USGS stage-discharge rating curves (where available, Sections 4.1.5 and 5.1.3), and a qualitative comparison of model-predicted locations of sediment throughput (as indicated by the lack of in-channel bar features) and storage (as indicated by the presence of in-channel bar features).
- Tributary sediment inflows were initially computed from tributary sub-models for a series of steady flows with equilibrium upstream sediment supply. This was done by computing appropriate bed material sediment transport relationships from slope-area hydraulic calculations and tributary bed material grain size characteristics in each tributary sub model. The computed sediment rating curves were then adjusted to provide the best agreement with the available measured sediment transport data and observed bed changes.
- Model sensitivity and performance was assessed by varying hydraulic roughness parameters and tributary sediment inflows.
- Spin-up runs were required prior to each mobile bed simulation to remove initial condition effects and reach a dynamic equilibrium prior to model application for a given simulation.

Upon completion of these tasks, the 1-D HEC-RAS model was applied to describe the existing conditions of the bed material sediment budget for the modeled reach of the river. The model can be applied to quantify long-term evolution (i.e., several decades) of hydraulic and bed profiles for several alternative flow release schedules, flood operations, and other river management once these have been defined.

4.5.1.3 Two-Dimensional Mobile Bed HEC-RAS Models

A suite of five 2-D mobile bed HEC-RAS (version 6.3) models (2-D mobile bed models) of six subreaches of the Skagit River between Newhalem and the confluence of the Sauk River are in development, as described in Section 3.2.1 of Attachment C of the RSP (City Light 2021). These six subreaches were identified based on discussions with LPs and aim to quantify erosion and deposition processes related to key morphologic and habitat features identified in this reach. The six subreaches are located at approximately the following locations, where PRM 69 and PRM 73 have been combined into a single modeling domain:

(1) PRM 69 (upstream of Sauk River confluence);

(2) PRM 73 (downstream of powerline crossing);

(3) PRM 79 (Marblemount);

(4) PRM 83 (Bacon Creek confluence);

(5) PRM 90 (Countyline); and

(6) PRM 93 (Goodell Creek confluence).

Reach lengths for each 2-D mobile bed model vary from approximately 1 to 6 miles to capture the key morphologic features of interest, which include tributary deltas, key spawning bars, and side channel connections. The 2-D bathymetric surface is the same that was used in the FA-02 Instream Flow Model Development Study (City Light 2023a). This section summarizes initial parameterization of the 2-D mobile bed model, which is still under development. A complete model development and calibration report will be provided after model development and calibration have been completed, expected in Q2 2023.

Through a suite of grid-cell-size tests, a geometry with base cell size of 100-ft sides and the use of breaklines to provide 50-ft refinement cells along the main channel, side channels, tributaries, and geomorphic features was selected. The larger grid size used in the 2-D mobile bed model in contrast to the Upper Skagit Hydraulic Model developed for the FA-02 Instream Flow Model Development Study (City Light 2023a), which is fixed bed 2-D HEC-RAS model of the river, was required to provide reasonable model runtimes for mobile bed model simulations, and it was adequate to address the key questions for the sediment transport modeling program (refer to Table 4.5-1) where the larger spatial scale of primary sedimentary features in the channel (100s of ft) is resolved. A constant 4-second timestep was chosen to be used for all the models, which satisfies the Courant condition.

Locations for 2-D mobile bed model boundaries were carefully selected to reduce the potential for numerical artifacts. Locations for tributary boundaries were selected to be upstream of the effects of backwater caused by the mainstem Skagit River.

Reasonable roughness coefficient values for the subdomains of the models representing in-channel (i.e., gravel bed material) and overbank (i.e., forested floodplain) regions were used to obtain calibration of the hydraulic models (Figure 4.5-2). The two-value roughness delineation was based on aggregating and refining a variation of the Upper Skagit Hydraulic Model roughness delineations (City Light 2023a). The aggregation was based on combining channel features together (e.g., main channel, gravel bar, side channel, slough, Sauk River, tributary, and wetland) and combining everything else outside of these channel features together (e.g., forest, riprap, roads, and vegetated gravel bars).

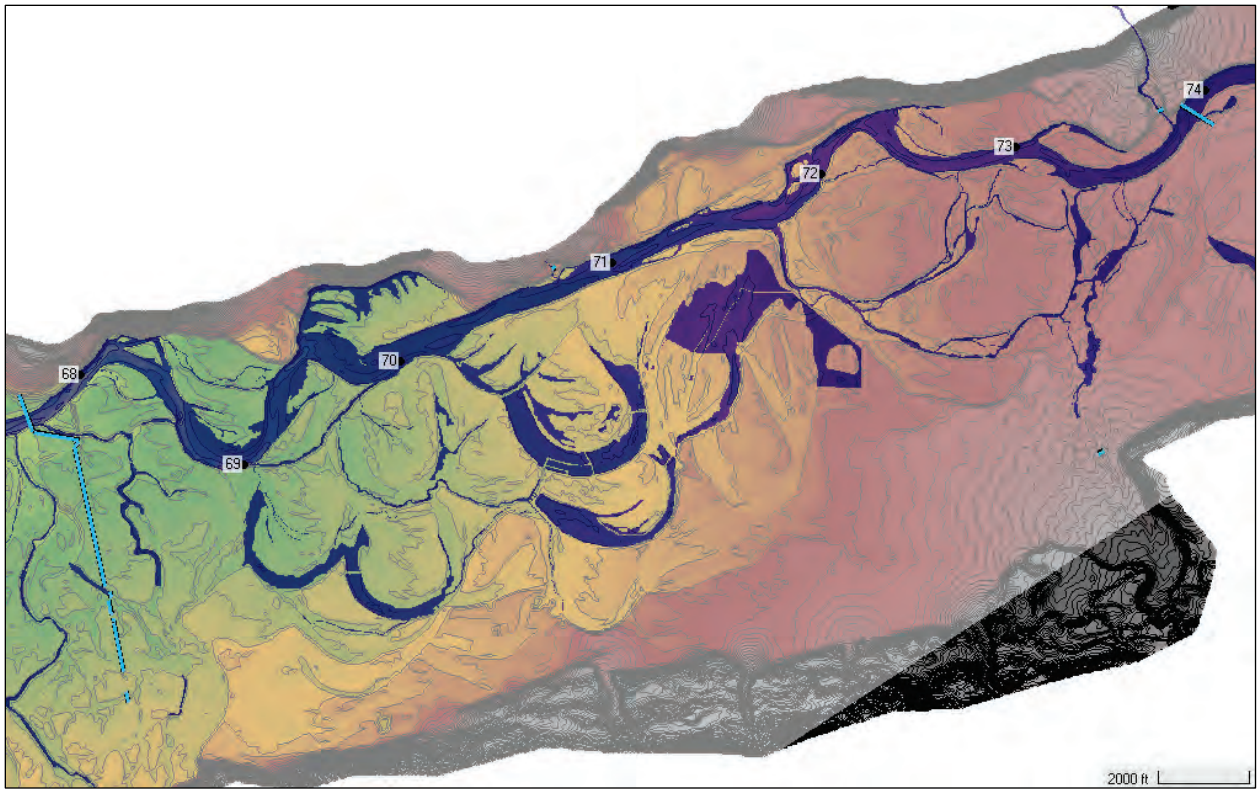


Figure 4.5-2. **Example of 2-value roughness layer aggregated from the Upper Skagit Hydraulic Model roughness layer for the combined PRM 69 and PRM 73 model; the blue overlay represents a single channel value and everything else is denoted as forest. The blue lines represent upstream, downstream, and tributary boundaries. PRM are labeled.**

The Geomorphology Study modeling aims to simulate sediment and geomorphic changes that rely on flows that are approximately at and above the bankfull flow discharge. Therefore, to calibrate the Geomorphology Study models, the high-water marks and USGS stream stage elevations from the November 2020 and November 2021 flood events were used. Because each subdomain model covers only a portion of the river, hydraulic calibration directly using these data is limited to only a few observations of WSE (surveyed high-water marks and USGS gage data) to calibrate each model (Table 4.5-2). This table demonstrates the need for an alternative approach for hydraulically calibrating the models.

Table 4.5-2. **Number of available high-water marks (and USGS gage locations) within each domain.**

Modeling Domain	Nov. 2020 Flood	Nov. 2021 Flood
PRM 93	1	1
PRM 90	3	4
PRM 83	1	2
PRM 79	1 (1)	1 (1)
PRM 69 and PRM 73	5 (1)	7 (1)

Therefore, to calibrate the models more accurately to roughness, a tangential 2-D model was developed using the Upper Skagit Hydraulic Model modeling domain (City Light 2023a), which extends from Newhalem to below the confluence with Sauk River. Rather than using the Upper Skagit Hydraulic Model breaklines and grid sizing, this model specifically used the breaklines developed for each 2-D mobile bed subdomain model. Between subdomains, additional breaklines were added for consistency of transferring flows from upstream to downstream for each subdomain model. This approach allows for use of all the measured WSE data and specifically uses the same grid geometry that was used in the 2-D mobile bed model simulations. This approach also reduces the chances for hydraulic boundary condition effects at each of the subdomain models. Calibration focused on the November 2020 flood and November 2021 flood (with more focus on the 2021 flood, which had a higher discharge). The roughness delineated varied the two-value layer by testing combinations of in-channel roughness from 0.02 to 0.04 and overbank roughness from 0.07 to 0.10. The minimum (modeled minus observed) mean and mean absolute error for both the November 2020 and November 2021 flood events suggest a combination of channel and floodplain roughness of 0.03 and 0.07, respectively.

Hydraulic model verification was performed by comparing the 2-D mobile bed model modeled WSE with the Upper Skagit Hydraulic Model modeled WSE and the 1-D HEC-RAS model modeled WSE (Figure 4.5-3). The 1-D centerline was used to extract WSEs from the 2-D mobile bed and Upper Skagit Hydraulic Model. The modeled surfaces are generally within ± 0.5-ft (Table 4.5-3). The most dissimilar results are around the Shovel Spur location, which has the most uncertainty in bed elevation and boulder-controlled rapids and is not within any of the 2-D mobile bed model subdomains. Computing the mean and mean absolute error for the cross sections within each subreach model, the results show a downstream trend that suggests that the roughness should be decreasing.

Table 4.5-3. Mean and mean absolute error statistics for comparing the Geomorphology model with the Upper Skagit Hydraulic Model.

Result	Nov. 2020 Flood	Nov. 2021 Flood
Mean	0.5	0.2
Mean absolute error	0.6	0.5

The bed of the Skagit River and its tributaries are composed of spatially varying sediment sizes at the surface and within the subsurface. Field samples from summer 2021 (Sections 4.4 and 5.4.1) were used to define the bed gradation and stratigraphy in the mobile bed models. For each model domain, locally representative samples were averaged to determine a single surface and single subsurface gradation. For tributaries, the bed material was separated to represent the sampled gradation of tributary bed materials. As an example, a bed material sample at the tributary fan was only used to represent the fan, while a bed material sample upstream on the tributary was used to represent the tributary channel (typically down to SR 20) as shown in Figure 4.5-4.

Sediment inflow at the upstream boundary for each 2-D mobile bed model reach utilizes results from 1-D HEC-RAS model mobile bed model. Using the 1-D HEC-RAS model mobile bed timeseries of flow, sediment, and gradation for every simulated hour, a sediment discharge and gradation rating curve is being developed for each model domain. These curves relate a single flow

and sediment mass input to specific sediment gradations. This approach provides the least cumbersome way to adjust the sediment input under simulated flow release and sediment management alternatives.

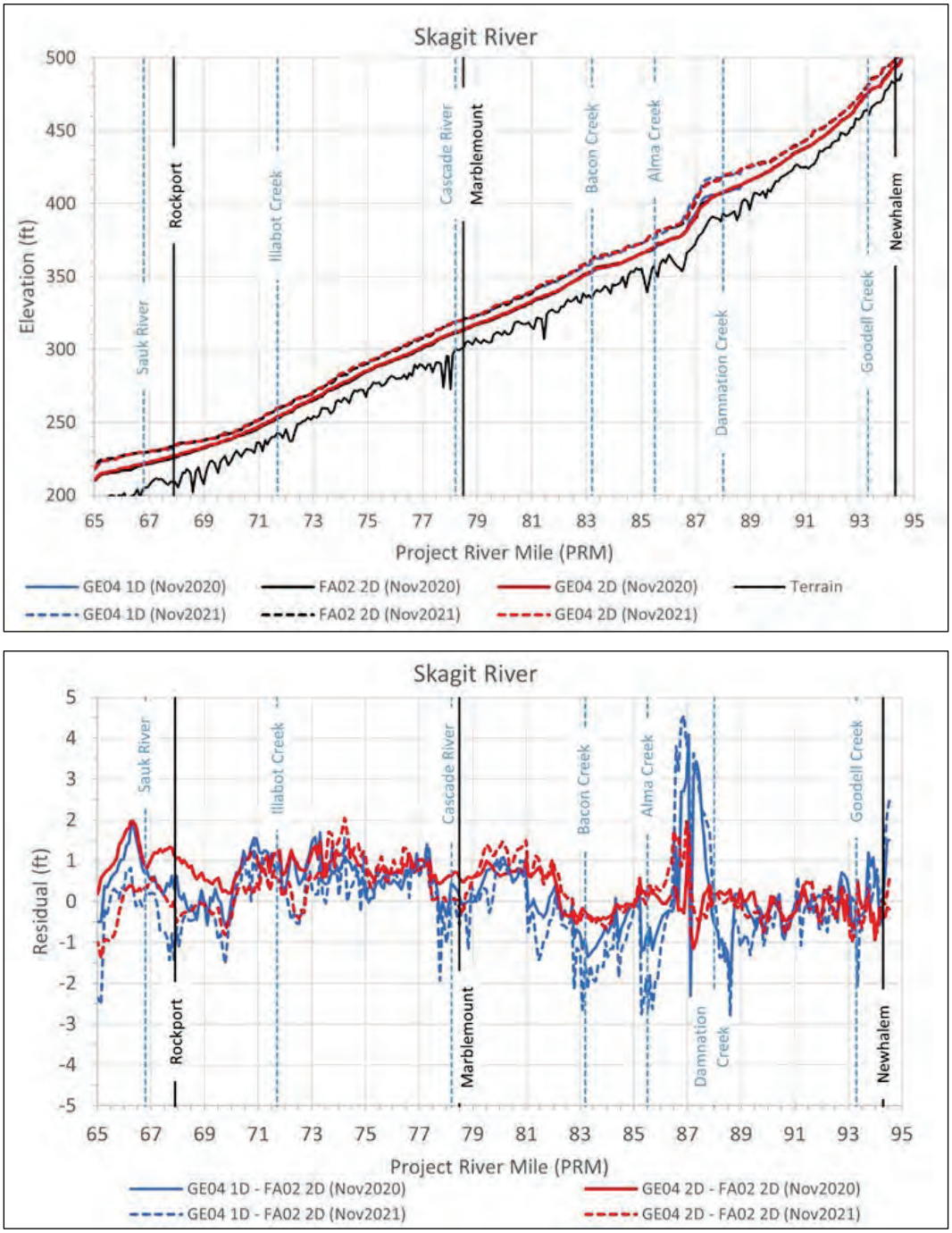


Figure 4.5-3. **Modeled water surface elevations for the 1-D HEC-RAS model, 2-D mobile bed model, and Upper Skagit Hydraulic Model (top) and residuals of water surface elevations for the 1-D and 2-D mobile bed geomorphology study models minus the Upper Skagit Hydraulic Model (bottom).**

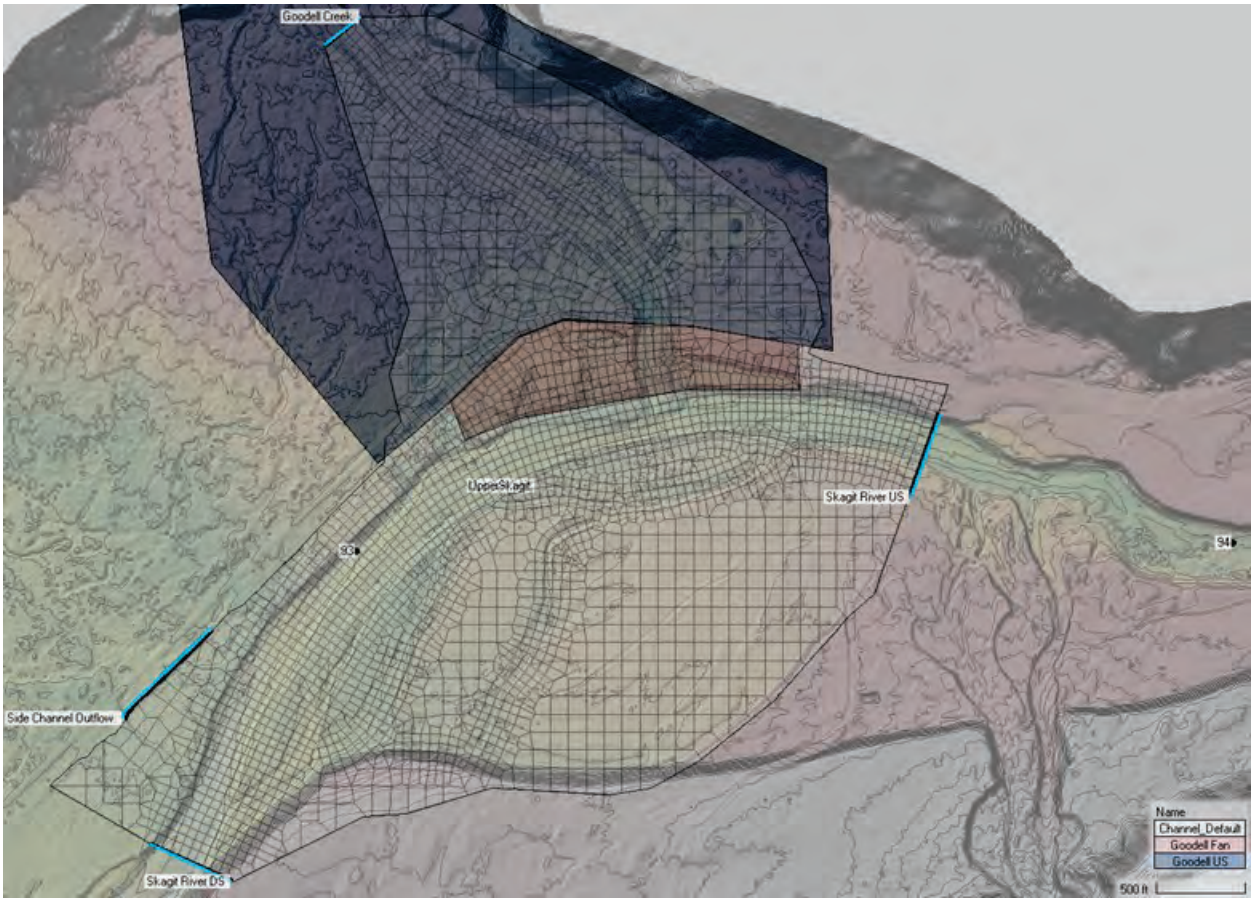


Figure 4.5-4. Example spatial distribution of channel (default), tributary fan, and tributary upstream sediment gradations at PRM 93. The blue lines represent labeled boundary conditions.

Sediment transport validation of the 2-D mobile bed model is underway and will primarily be based on demonstrating qualitative agreement of patterns and magnitudes of observed and computed zones of bed material erosion or deposition with those zones of measured bed change as determined through a comparison of the 2018 and 2022 LiDAR surfaces. Overbank regions in the 2-D mobile bed model domain are characteristically heavily forested floodplain surfaces. Root strength and vegetated soil strength are not simulated in the 2-D mobile bed model, so erosion of these surfaces cannot be simulated with the present mobile bed modeling technology. That said, the 2-D mobile bed model, calibrated to properly simulate inundation extents, WSE, and depth of flow in the overbank regions provides a rational approach for computing depth, flow velocities, and boundary shear stress in the overbank regions. Deposition of sand-sized bed material sediments, transported as suspended sediment in the overbank regions, can be simulated with the 2-D mobile bed model. Shear stress and overbank flow velocities computed by the 2-D mobile bed model can also be utilized to assess if the hydraulic conditions are conducive to deposition of fine suspended sediment (i.e., fine sands, silt, and clay), as well as erosion of floodplain surfaces for specified critical shear stress or critical flow velocities of the vegetated overbank regions. Bank erosion and geotechnical bank failure are not directly simulated in the 2-D mobile bed model.

Upon completion of these tasks, the 2-D mobile bed models will be applied to quantify erosion and depositional characteristics on bar surfaces, and side channel connections within each subreach, for several alternative flow release schedules, flood operations, and other river management scenarios.

A technical memorandum describing development and calibration of the 2-D mobile bed models will be provided in Q2 2023.

4.5.1.4 MAST 1-D

A Morphodynamics and Sediment Tracers (MAST) 1-D model of the Skagit River, from above the Bacon Creek confluence at PRM 84 through Sedro-Woolley at PRM 24, was developed to quantify width adjustments of the Skagit River to existing and potential future operational flow release scenarios and to evaluate patterns of bed material mobility, channel-floodplain sediment exchange, and (downstream of the Sauk River confluence) channel profile adjustments. This model is intended to fulfill commitments in the June 9, 2021 Notice to evaluate lateral channel mobility and channel hydraulics and sediment transport downstream of the Sauk River, with modifications as described in Section 7.0.

Attachment Q describes details of the MAST 1-D model development and calibration. MAST 1-D is an academic research code (Lauer et al. 2016; De Rego et al. 2020) and coding development was required for applications to the Skagit River system including adding the ability to link multiple reaches with contrasting hydrology, confinement, hydraulics, and bed material, and the addition of representations of tributaries. Hydraulic calculations within MAST 1-D are simplified relative to 1-D HEC-RAS, but MAST 1-D has unique capabilities of simulating channel width response to a range of hydrologic and sediment loading conditions and explicitly tracking sediment exchange between the channel and floodplain. Because MAST 1-D is a one-dimensional model, its outputs do not directly show planimetric lateral channel migration, but interpretation of width changes in conjunction with mapping of historical channel movement patterns (see Section 4.1 of this study report) allows for quantification of expected bank erosion patterns. As it provides information on channel width variability and channel-floodplain sediment exchange, application of MAST 1-D is complementary to the long-term profile and side channel connectivity modeling using 1-D or 2-D HEC-RAS, as well as width and multi-channel propensity modeling with UBCRM.

MAST 1-D sediment model calibration was based on comparisons of computed channel widths over selected time periods of interest, as determined through the ongoing morphometric mapping activities (Section 5.1.1 of this report); observed subsurface grain size distributions (Section 5.4.1); and morphologic sediment budget estimates between Bacon Creek and the Sauk River (Section 5.5.3). Model sensitivity testing to changes in specified hydraulic roughness, reference shear stress, bank material strength, bed material grain size, and Skagit River and tributary sediment inflow loadings has been completed to assess model performance.

As with the other models, the calibrated MAST 1-D model is available to evaluate potential channel response to several alternative flow release schedules, flood operations, and other river management scenarios.

4.5.2 Observational Bed Mobility Data

4.5.2.1 Scour Monitoring to Evaluate Redd Scour Risk and Active Layer Thickness

An analysis of initiation of gravel transport at key/representative spawning locations using scour monitors and accelerometers was conducted to determine the flow rate that initiates movement or results in substrate scour to redd depth. A pilot redd scour monitoring project was initiated at three locations in August 2019 to help determine the feasibility of using various scour monitor/accelerometer techniques in the Skagit River. This initial monitoring work was expanded in 2020 from the three original sites to ten sites focused on areas of known important spawning activity (e.g., Figure 4.5-5), as described in Section 2.6.5 and Attachment B of the RSP (City Light 2021).

In August 2021, the monitoring project was expanded to include a total of 19 scour arrays, the locations of which are shown in Figure 4.5-6. The purpose of this extension was to provide data at select locations representative of typical/controlling sediment transport, at the mouths of tributaries (to meet commitments in the June 9, 2021 Notice), and at bulk sample locations for select tributaries. Six of these locations included riffle crests in the mainstem channel where scour monitoring aided in development and calibration of the 1-D sediment transport model. Other arrays included the confluence fans of Goodell and Bacon creeks (the Newhalem Creek fan did not have substrate suitable for scour monitor installation) and locations on Cascade River and Bacon Creek to aid in calibrating estimates of tributary sediment loads. Attachment B includes a map set showing individual scour monitor installation locations.



Figure 4.5-5. Example location of redd-focused scour monitoring array located along the left bank line (right side of image at site ABSS1 [above Shovel Spur]).

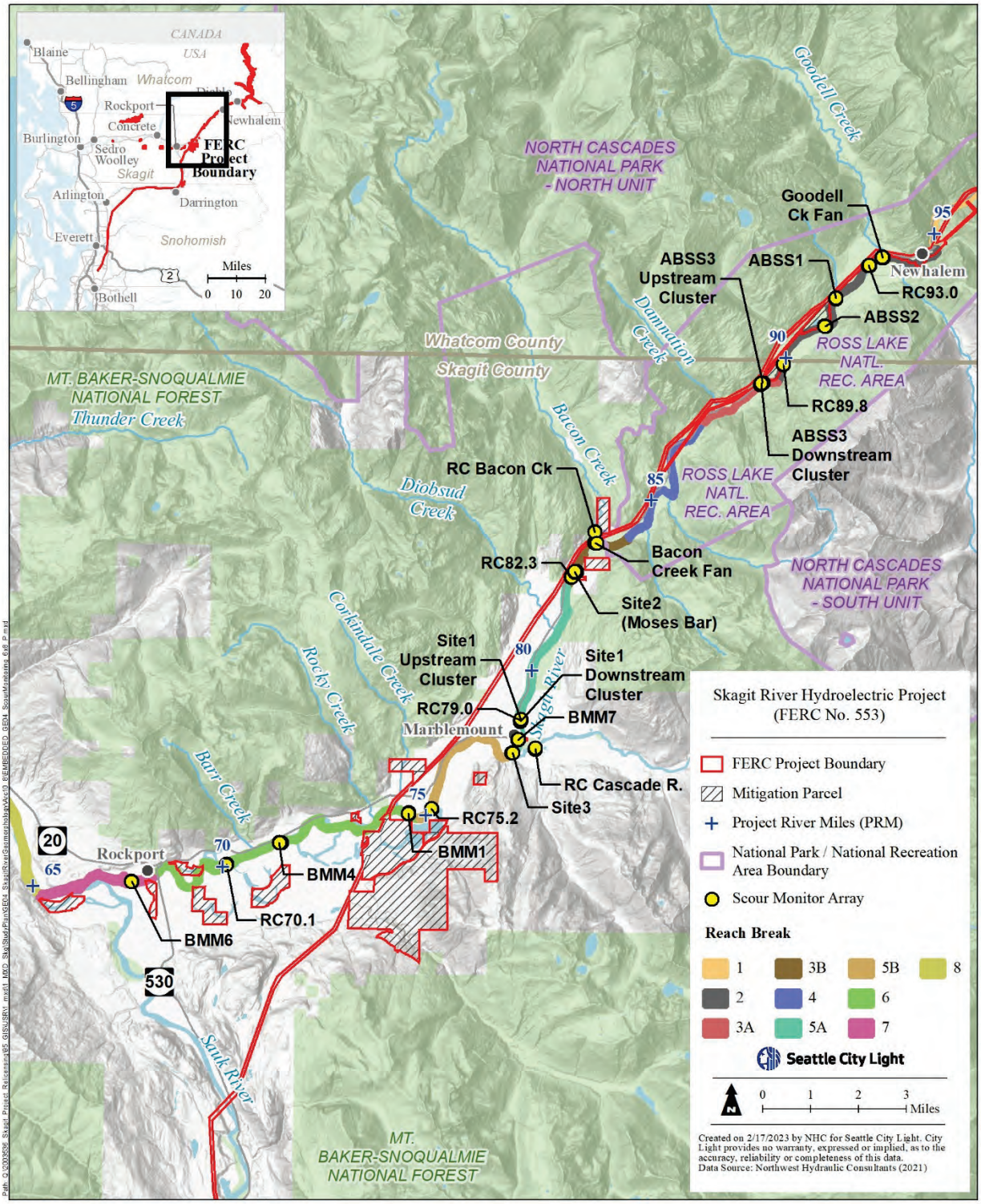


Figure 4.5-6. **Scour monitor installation locations. Site names reflect location and time of installation. 'Site' prefixes were installed in 2019, BMM (Below Marblemount) prefixes were installed in 2020 below Marblemount, ABSS (above Shovel Spur) prefixes were installed in 2020 upstream of Shovel Spur; these are all located at spawning areas. RC sites were installed in 2021 on Riffle Crests.**

Three types of scour monitoring devices were installed in the arrays. These included sliding bead scour monitors, golf ball scour monitors, and accelerometer arrays, which are described in detail in Attachment B of the RSP (City Light 2021). A typical site installation includes three sliding bead scour monitors, four golf ball scour monitors, and four accelerometer arrays (which record data for one year and have been replaced each year following initial installation).

The sliding bead scour monitors, the smallest monitors constructed, use ¾-inch steelhead corkies strung on $^{3}/_{32}$-inch stainless steel aircraft cable. The advantages of these monitors are ease of installation and the ability to measure finer-scale scour since each bead is ¾ inches in diameter. These devices were generally not durable enough to handle the sediment transport in the Skagit River, and so installation of them was discontinued in summer 2021.

Golf ball scour monitors are similar in design to the sliding bead scour monitors but use plastic perforated heavy-duty golf balls in place of the Corkies. The golf balls are approximately 1.7 inches in diameter, so they record scour at a coarser scale than the Corkies but proved to be generally durable through the whole deployment period (summer 2018- summer 2022).

Arrays of two accelerometers were constructed using a design modified from Gendazak et al. (2013). Accelerometers measure x-y-z orientation at given time steps and thus, record the time when movement takes place (which can be correlated with flow at that time), but they only record when scour reaches the depth at which they are buried (in the armor layer and at a depth of 7 inches, an average Chinook redd depth). To assemble accelerometer arrays, Hobo Pendant G® accelerometers were inserted into 4-inch lengths of 1¼-inch-diameter PVC pipe (Nominal Pipe Size, so the outer diameter is about 1.66 inches). A piece of $^{1}/_{8}$-inch stainless steel aircraft cable was threaded through a hole drilled through the PVC pipe, through the eye on the accelerometer, and then crimped in place with a double cable stop. Two accelerometer pipe setups were threaded through each anchor, with one set at 10 inches from the anchor and the other set at 17 inches from the anchor. The result was two independent cables with accelerometers set 7 inches apart from each other. This allowed for the accelerometers to be inserted into the gravel with the top accelerometer measuring movement of surface substrate (initiation of movement) and the bottom accelerometer measuring movement of material 7 inches below the surface. The accelerometers were set to record at 30-minute intervals. This allows for 1.2 years of record to be stored before the onboard memory fills.

During the summers of 2020 and 2021, data were downloaded from the 2019-2020 and 2020-2021 accelerometers and the devices were replaced. Bed elevation at each of the surviving scour monitors was recorded using Real-time Kinematic (RTK) survey equipment, as was the depth of fill on top of the newly installed monitors. If golf balls moved from the vertical position, the number of moved (or exposed) golf balls was recorded to determine scour depth. The majority of the 2019-2020 small bead scour monitors did not survive or were not recoverable in 2021, so staff only installed golf ball monitors in addition to accelerometers at the 2021 riffle crest monitoring arrays.

In August 2022, the scour monitoring equipment was retrieved, and the accelerometer data was downloaded. Bed elevation at each of the scour monitor locations was recorded using RTK survey equipment (except for monitors under excessive tree canopy). Due to channel shifts and relatively high flows during the field effort, some scour monitors could not be safely retrieved or adequately

searched for in the deep, swift waters. This mostly pertains to several unexposed or potentially scoured golf ball chains at Riffle Crest Site 70.1 and BMM6, leaving the minimum scour depth of these five monitors unknown. All surviving accelerometers were retrieved from the scour array locations, except for three accelerometer pairs at Spawning Site BMM4, where retrieval proved unfeasible at digging depths greater than 3 ft. At other sites, if no RFID signal was acquired at the accelerometer RTK location, a hole was dug to a depth that was both safe and feasible, usually a minimum of 12 inches, before it was inferred that the accelerometer had scoured away. Of the retrieved accelerometers, less than 10 percent of the loggers failed to download due to logger malfunction. In those cases, scour initiation was either left unknown (NA) or inferred from the second accelerometer in the pair (for example, if the bottom accelerometer recorded scour, then it was inferred that the top accelerometer tilted as well).

The minimum scour depth of each monitor was interpreted from bed mobility indicators, such as accelerometer activity or deployed golf balls, as well as the armor layer thickness estimated in the field and the observed initial burial depth. Following the guidance of Gendaszek et al. (2013), changes in tilt that exceeded 15 degrees from the initial deployed orientation were inferred to be indicative of accelerometer disturbance and scour to the depth at which that device was buried. Raw accelerometer files were filtered through manually to assess both the degree of tilt and timing of initial tilt, and to record any subsequent activity for accelerometers reburied after initial scour. Timing was then compared to discharge using the FA-02 Instream Flow Model Development Study (City Light 2023a) flow routing model to determine whether the scour occurred during the time of a flood or during likely spawning activity. Scour depth of the top accelerometer was estimated as the sum of the armor layer thickness, recorded during deployment, plus the depth below the base of the armor layer of the top of the PVC, plus 2 inches (assuming that at least half of the 4-inch PVC must be exposed to cause greater than 15 degrees of tilt). Scour depth of the bottom accelerometer was estimated using the same method but adding 7 inches (spacing between top and bottom PVC). The minimum scour depth if total scour took place was the distance from the top accelerometer to the anchor, or 17 inches, plus the armor layer thickness. If golf balls were deployed, the minimum scour depth was determined by adding the thickness of the armor layer above the first buried ball, recorded the year prior or at the time of deployment, and the displacement length of the deployed balls (number of balls deployed multiplied by 1.7 inches).

Scour data were analyzed to understand event scour, instantaneous active layer thickness, and redd scour risk. Event scour and instantaneous active layer thickness were evaluated by comparing normalized scour depth (d_s/D_{90}) to dimensionless shear stress τ^* (also referred to as normalized shear stress), following the approach of previous work that has found the event active layer thicknesses correlate to dimensionless shear stress τ^* (Wilcock et al. 1996; Haschenburger 1999; DeVries 2002; Brenna et al. 2019):

$$\tau^* = \frac{\tau}{(\rho_s - \rho_w) g D_{50}}$$

where τ is the shear stress exerted on the bed, ρ_s is the density of the sediment, ρ_w the density of water, g acceleration due to gravity, and D_{50} is the median grain size of the surface material. Regression relations were developed relating normalized event scour ($d_{s\ (event)}/D_{90}$) as a function of τ^* to evaluate event scour depth. Instantaneous active layer thickness was defined as equivalent to the event scour result up to a maximum normalized scour depth of two times the D_{90}.

Due to the variability in the relation between dimensionless shear stress (τ^*) and scour depth, a probabilistic model is more useful for understanding redd scour risk than the deterministic regression models described above. Logistic regression is an appropriate tool to predict the probability of a binary outcome based on a continuous input variable, and so was applied to evaluate the likelihood of scour to redd depths (redd scour risk). Based on the understanding that dimensionless shear stress (τ^*) and event scour depth (d_s) are closely related, the probability of scour exceeding thresholds related to redd depth was evaluated as a function of τ^*.

The egg burial depth criteria of DeVries (1997) were applied as key ds thresholds to consider in the analysis; these are specified in Table 4.5-4. The binary logistic regression calculator of Statistics Kingdom (2017) was used to complete the regression analysis, relating τ^* independently to the probability of exceeding each threshold scour depth. To assess the potential risk of scour with increasing flows, the logistic regression equations were applied to map the local probability of scour from 2-D hydraulic model results (discussed in Section 4.5.1.3) and facies mapping information (discussed in Section 4.4.5) for a range of flows from 10,000 through 70,000 cfs. Scour probability was evaluated at the thresholds outlined in Table 4.5-4, between 15 and 50 centimeters, to span the depth of redd pockets for salmon species and steelhead that spawn in the river. Critical dimensionless shear stress (τ^*) was calculated for flows between 10,000 and 70,000 cfs (in increments of 10,000 cfs) using the facies mapping grainsize distributions (Section 4.4.5) and shear stress results of 2-D Upper Skagit Hydraulic Model steady-state simulations (without tributary inflows) to calculate τ^*.

Table 4.5-4. Threshold scour depths used in redd scour risk assessment (DeVries 1997).

d_s threshold	Importance
5.9 in (15 centimeters [cm])	Top of redd pocket for Chinook, Chum, Coho, and Pink salmon and steelhead (initiation of egg loss)
10 in (25 cm)	Middle of pocket for Chum, Coho, and Pink salmon and steelhead t redds
14 in (35 cm)	Bottom of pocket for Chum, Coho, and Pink salmon and steelhead t (100% egg loss expected); Middle of pocket for Chinook Salmon redds.
20 in (50 cm)	Bottom of pocket for Chinook Salmon redds

4.5.2.2 Particle Tracing

Tracer particles provide information on the size of sediment a river is competent to move and the magnitude of sediment particle displacement between the time of their deployment and recovery. Together, these data provide one of the important inputs to development of a morphologic sediment flux estimate (Section 4.5.3). Previous work has utilized tracer particles of various bed sediment size fractions to estimate the displacement length and corresponding virtual velocity of each size fraction on an event-based or longer timescale (e.g., Ferguson et al. 2002; Milan 2013; Mao et al. 2017; Brenna et al. 2019; McQueen et al. 2022). Tracer particles are also very useful in identifying hotspots of erosion and deposition.

Tracer particles were deployed at six locations along the river in early November 2021 (Figures 4.5-7 through 4.5-9). These sites include the confluence bars and delta fans of Ladder Creek, Newhalem Creek, Goodell Creek, and Bacon Creek (also referred to as the Bacon Creek Downstream deployment site), as well as the riffle crest scour monitor sites on Bacon Creek (Bacon Creek Upstream deployment site) and at PRM 89.8. Early onset of significant flooding, prior to the winter of 2021-2022, prevented deployment of tracer particles at four other planned riffle crest locations downstream of Bacon Creek. A total of 552 particles were deployed at the six sites (Table 4.5-5). The deployed tracer particle sizes matched the distribution of the 45 mm and larger subsurface material present at each site, except additional particles were deployed to provide duplicates (n=2 to 4) of larger size classes that would be represented by only one or fewer particles.

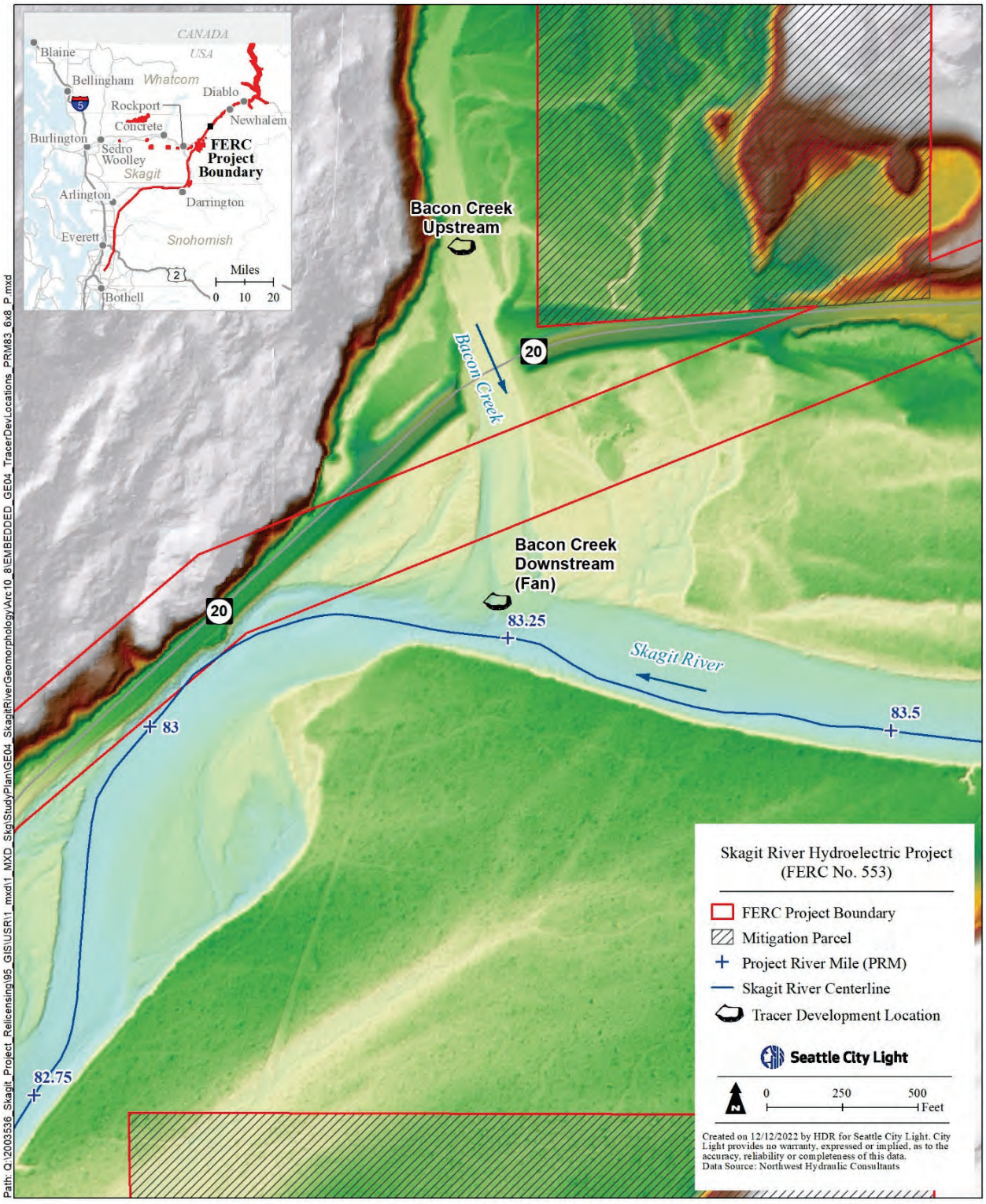


Figure 4.5-7. Tracer particle deployment locations on and near Bacon Creek.

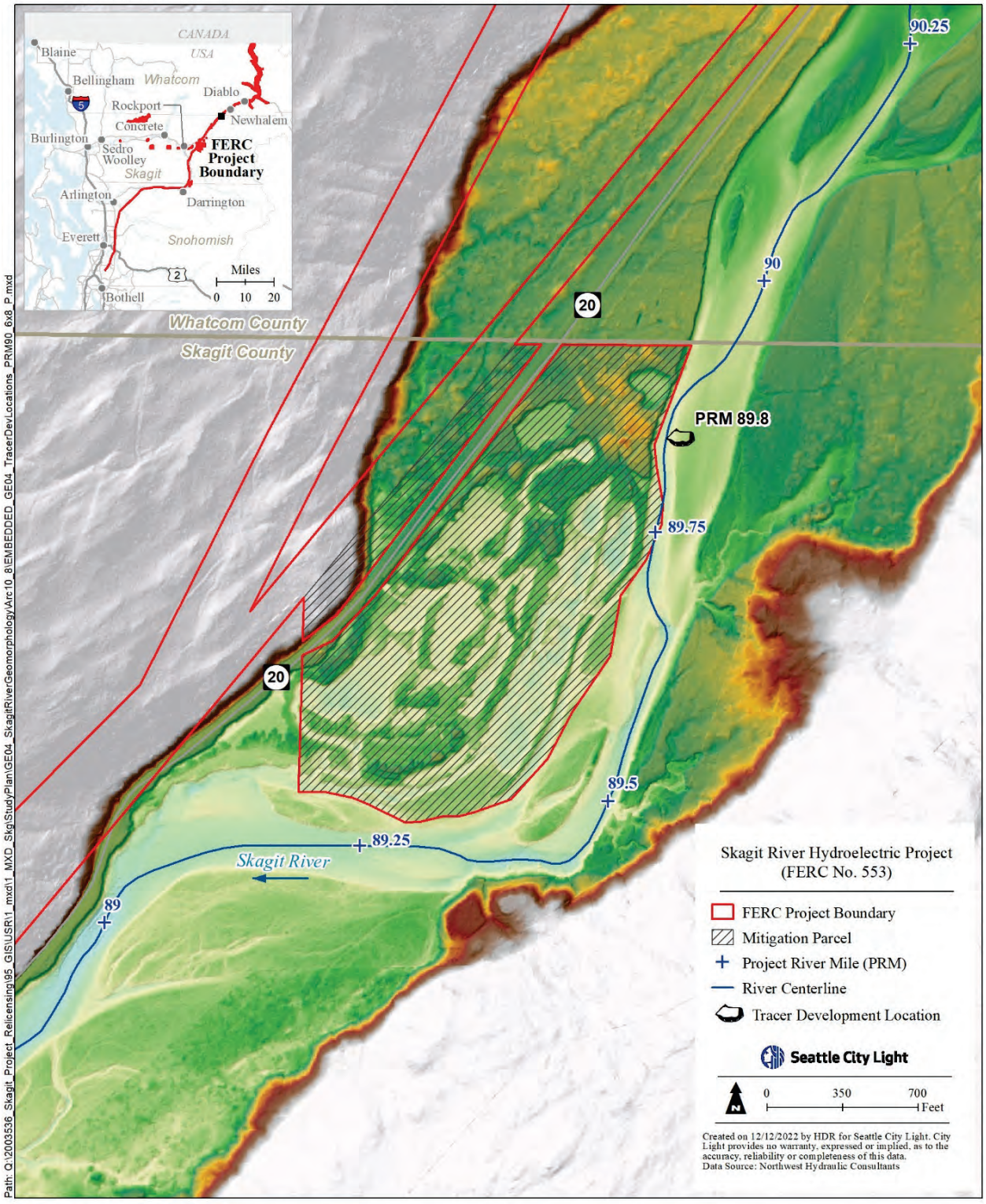


Figure 4.5-8. Tracer particle deployment location near Project River Mile (PRM) 89.8.

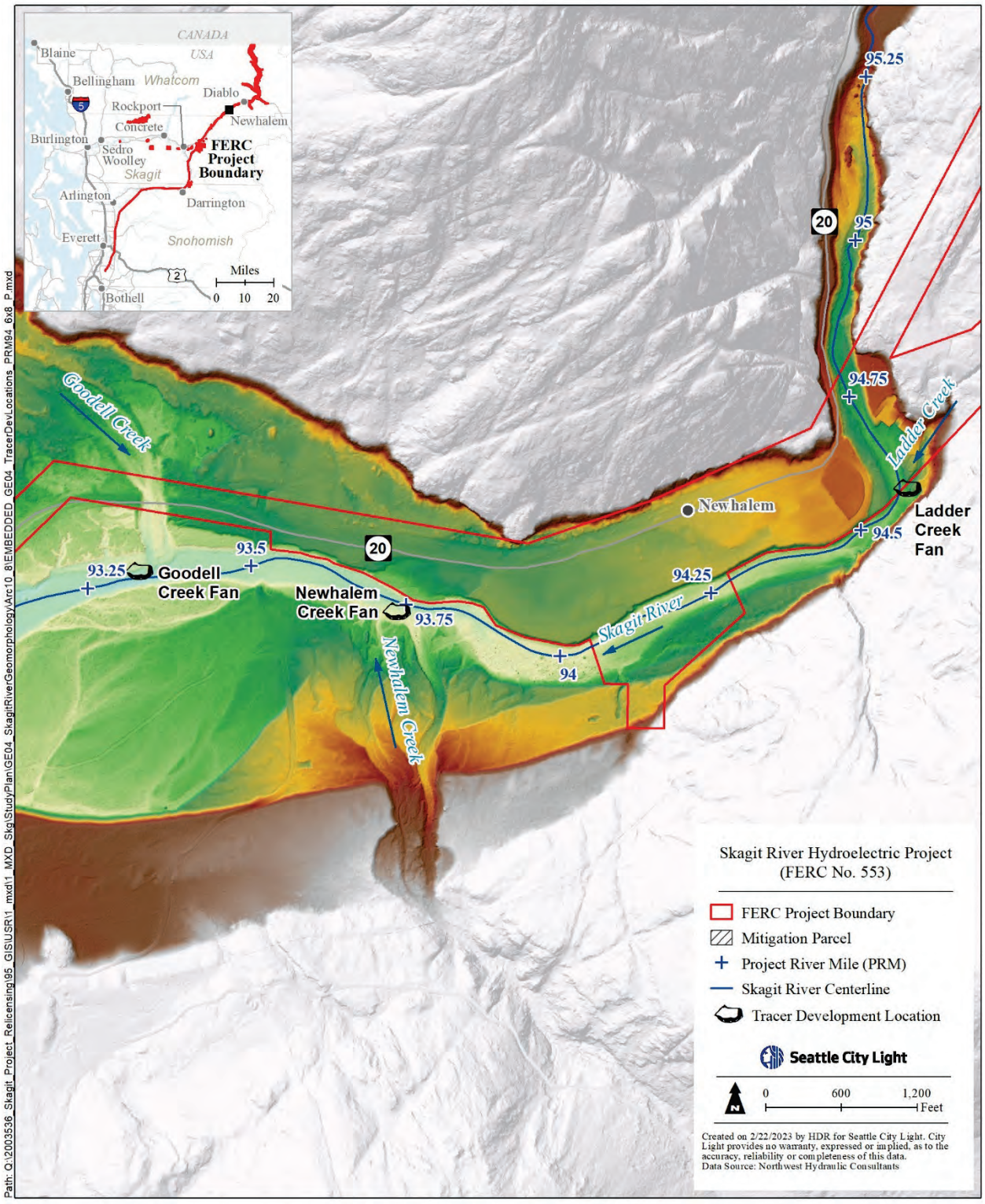


Figure 4.5-9. Tracer particle deployment locations near the Goodell, Newhalem, and Ladder creek fans.

Table 4.5-5. Number and sizes of tracer particles deployed at the six sites.

	45-64 mm	64-91 mm	91-128 mm	128-180 mm	180-256 mm	256-360 mm	360-512 mm	512-712 mm	Total
Bacon Creek Downstream (Fan)	12	23	20	22	6	2	0	0	85
Bacon Creek Upstream	23	23	16	17	12	4	0	0	95
PRM 89.8	31	29	24	7	4	0	0	0	95
Goodell Creek	19	27	17	10	10	4	0	0	87
Newhalem Creek	32	29	15	7	4	4	5	2	98
Ladder Creek	23	25	16	12	8	5	3	0	92
Total	140	156	108	75	44	19	8	2	552

Particles were tagged by placing RFID tags into holes drilled into the particles. The RFID tags are passive, half-duplex 1.3-inch (32-mm) long, supplied by Oregon RFID, and originally manufactured by Texas Instruments. The tags operate at a Low Frequency (LF) band of the Radio Frequency spectrum (134.2 kilohertz [kHz]), which allows good penetration of the Radio Frequency waves through water and sediment media. These tags are passive and are thus energized by the magnetic field of the antenna by which they are being detected. Therefore, they have no onboard batteries and offer reliable operation for many years. Reliable detection ranges for these tags can be achieved to approximately 6 ft.

Two methods were used to drill $^{3}/_{16}$-inch-diameter and roughly 1.5-inch-deep holes in particles for the installation of RFID tags. Method 1 was utilized for the smallest, 64-mm sized particles and consisted of using a Jet Floor standing drill press with a $^{3}/_{16}$-inch drill bit. To reduce friction/heat of the drill bit and particle, water cooling was used during the drilling process. A water pump was placed into a custom sump and directed water at the hole with a hose positioned over the drill bit and particle. In addition to cooling, the water entrained debris from the hole, thus facilitating the drilling process. Method 2 consisted of using a Hilti TE 6-A22 cordless rotary hammer. A gripping device was fabricated based on the design of Slaven et al. (2014) to securely hold 91-mm particles when being drilled. Method 2 was also used for drilling the tracer particles larger than 91 mm near their deployment location in the field. Figure 4.5-10 shows method 1 and method 2 for tracer particle drilling.



Figure 4.5-10. Method 1 (left) and method 2 (right) for tracer particle drilling.

West System 105 marine-grade epoxy resin and 205 Fast Hardener were used to secure passive integrated transponder (PIT) RFID tags into the drilled particle holes. The two compounds were mixed and injected into the drill hole via a syringe filling up approximately half of the drilled hole. A RFID tag was placed into the hole and covered with additional epoxy mixture to fill any remaining voids and securely fasten the tag into the tracer particle.

The tagged particles were deployed at the six deployment locations by physically throwing the smaller particles along an imaginary line between the bank and the channel centerline and by rolling the heavier particles into the channel. The serial numbers of the deployed particles at each location were recorded along with the tracer particles that these were inserted into. Coordinates of the particle deployment locations were collected and recorded with a RTK GPS.

To the best of the study team's knowledge, the Skagit River is the largest river where RFID particle tracing has been employed. To manage the tracer recovery effort in face of the depths and velocities and large search area resulting from the size of the Skagit River, two methods were utilized for recovering the deployed particles. Recovery method 1 was developed for scanning large swaths of river area either via a boat at the deeper river areas (Figure 4.5-11) or via manual deployment at wadeable portions of the river (Figure 4.5-12). To this end, recovery method 1 (Figures 4.5-11 and 4.5-12) was developed around the IS1001 LF passive RFID system provided by Biomark. This system is a low-frequency, passive system suitable for detecting the 32-mm RFID tags. The system is comprised of the IS 1001 Reader with a Bluetooth enabled datalogger, the IS1001 cord antenna, and appropriate junction boxes. The system was powered by two 12-Volt batteries connected in series to provide the minimum required 24-Volt reader operational voltage. The system is supplied in a weatherproof case with appropriate waterproof connections for the junction box and cord antenna.

The cord antenna was routed into a custom 10- by 6-ft frame constructed from 3-inch diameter PVC pipe. This created a 10- by 6-ft antenna loop, which could detect a particle located within this loop at a given time and allowed for covering relatively large areas of the river. The custom frame was fixed to a pontoon vessel (cataraft), which provided floatation for the antenna. The antenna was initially fixed to the underside but was subsequently placed on top of the pontoon to reduce

drag and improve its stability and decrease the minimum depth in which the raft could be operated. The pontoon also offered space for securely mounting the case containing the reader unit and power supply, as well as a separate RTK-GPS receiver, which was programmed to provide GPS coordinates every 10 ft of displacement. These GPS tracking coordinates were transmitted via Bluetooth in real time to a Carlson datalogger in the boat towing the pontoon vessel.

Logging of the tag detection data was performed using the BioLogic software, also provided by Biomark. The BioLogic software was loaded onto a portable tablet, which was connected to the RFID datalogger via Bluetooth. The Bluetooth connectivity allowed recording of the serial number of a tagged particle remotely up to about 100 ft away, thus enabling a system operator in the boat to record tag detections with the RFID system on the pontoon in tow. The BioLogic software also automatically appended the date and time stamp of a tag detection and the GPS coordinates provided by the integrated tablet GPS receiver. The GPS location(s) of the one or two closest points tracked by the RTK-GPS were also recorded upon each tagged particle detection.



Figure 4.5-11. Tagged particle recovery method 1 using pontoon reader in tow behind boat.



Figure 4.5-12. Tagged particle recovery method 1 using pontoon reader in manual search.

Recovery method 2 was employed for manually searching shallow or dry areas of the Skagit River such as exposed river bars (Figure 4.5-13). Recovery method 2 used the BioMark HPR Plus Handheld PIT Tag Reader with the BP Plus Portable Antenna, which is a portable system allowing the user to scan the surrounding bed for tagged particles. The HPR Plus reader features an integrated GPS receiver and automatically attaches the coordinates of a detected particle to its tag serial number, along with the detection date and time stamp.



Figure 4.5-13. Tagged particle recovery method 2 using handheld reader.

Search efforts along the river were initially concentrated at the particle deployment locations, to evaluate whether the deployed particles had been mobilized, and at targeted areas downstream of the deployment locations. Targeted search areas were identified using geomorphic judgement and a difference map between the most recent 2022 and previous 2017/2018 topobathymetric LiDAR (see Sections 4.1.4 and 5.1.2). This map highlighted potential particle deposition areas and areas of erosion where particles would not be expected and aided in determining anticipated particle travel paths. Portions of the river estimated to be deeper than the anticipated 6-ft detection range of the system were generally avoided. Furthermore, the continuous points tracked at 10-ft intervals by the RTK-GPS receiver provided a guide for targeting search locations and minimizing duplicative search effort.

The location of each recovered tagged particle was determined through an analysis of the integrated tablet GPS coordinates and the RTK-GPS coordinates of the tracked points matching the detection of that tagged particle. Specifically, if the field-recorded RTK-GPS point coordinates, matching the detection, fell within approximately 70-ft of the tablet GPS (expected 30-ft accuracy of the handheld GPS plus an estimated 40-ft distance between tablet and pontoon), then the field-recorded RTK-GPS point was used for assigning the location of that tagged particle. If the recorded RTK-GPS point was located outside the 70-ft distance, then the coordinates from the tablet-integrated GPS were used. The locations of the recovered particles were then assessed by

accounting for the extents of the search areas. The locations of a few particles, as determined from either the tablet GPS or the RTK-GPS, were evaluated to be outside the searched area bounds. The final locations for these particles were corrected to match the coordinates of the closest point within the search area boundary.

Determination of the search areas involved different techniques for the pontoon reader and the handheld reader. The search areas covered by the pontoon were based on processing the RTK-GPS track into polygons using GIS. The search areas covered by the handheld reader were delineated on field maps by the reader operators during the field campaign and digitally delineated as polygons in GIS following the field campaign. The total area, including both areas that were and were not searched, where particles could have been deposited was estimated based on delineating the active channel. This delineation of the main channel was informed by hydraulic analysis and sediment characteristics, an assessment of the difference map between the most recent 2022 and previous 2017/2018 topobathymetric LiDAR, and the locations of the recovered particles. A comparison of the searched and total areas was used to estimate the search intensity.

The estimation of the tagged particle travel distance (L) considered their initial deployment and final recovery locations and the streamlines estimated by a 2-D hydraulic model. This travel distance was determined by delineating the 2-D hydraulic model streamline passing through the recovery location of a particle, starting from its recovery location and terminating at the deployment location of that tagged particle (Figure 4.5-14).

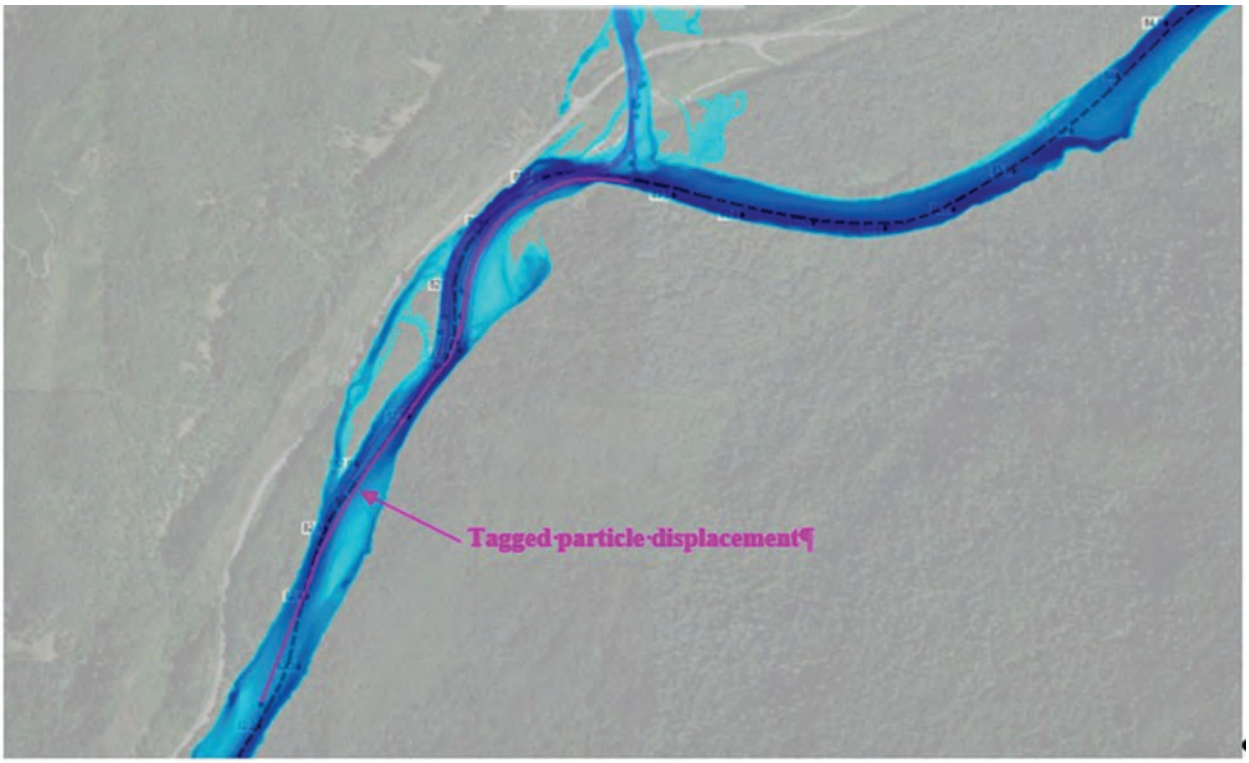


Figure 4.5-14. Delineation of the displacement for a tagged particle deployed at the Bacon Creek Downstream (Fan) site and recovered near PRM 82.2.

The tagged particle displacements were assessed based on the framework outlined by Church and Hassan (1992), which correlates them with the particle diameter. Within this framework, the normalized displacement of a particle, L_n, correlates with the normalized diameter D_n using the following relation: $L_n = 1.77(1\text{-}\log D_n)^{1.35}$.

In this relation, L_n denotes the particle displacements normalized by the mean displacement distance, L_{50}, of the size class that contains the bed surface median diameter, $D_{50,s}$. The particle diameter, D_n, is the particle diameter, D, normalized by the median diameter, D_{50}, of the bedload grain size distribution. The assumption that the Church and Hassan (1992) or a similar size-specific relationship is applicable to particle sizes other than those of the tracer particle sizes allows estimating the expected average displacement of these untagged and typically smaller particle sizes through extrapolation. This estimate can then provide a representative, average particle displacement by weighted averaging of the applicable relationship using the proportion of each size fraction in the transported mixture as the weights. Formally, the average displacement distance for the whole gravel and coarser fraction of the subsurface bed material (L_{avg}) is estimated as:

$$L_{avg} = \left(\sum_i (L_i \cdot Y_i)\right) / \left(\sum_i (Y_i)\right)$$

where L_i is the average displacement of the ith sediment size fraction representing proportion Y_i of the total gravel and coarser grainsize distribution. Finally, L_{avg} values measured on the Skagit River were compared to predictions of Beechie (2001) to show consistent results for the Skagit River with other observations from western North America.

4.5.2.3 Washington State Department of Transportation Bedload Measurements and Acoustic Bedload Monitoring

Parallel to this effort, the USGS in cooperation with Washington State Department of Transportation (WSDOT) is studying bedload transport on the Skagit River. They installed hydrophones at Marblemount and Car Body Hole in fall 2020 to record acoustical signals of bedload movement. They collected bedload transport data during moderate flow conditions on March 1, 2022 (discharge 12,000 cfs) and July 1, 2022 (Discharge 17,000 cfs), but did not collect bedload transport measurements during flood conditions. As of the filing of this study report, no data of the acoustic signal are yet available. The bedload transport measurements were used to inform calibration of the 1-D HEC-RAS and MAST1-D sediment transport models.

4.5.3 Morphologic Bedload Flux Estimates

In addition to direct measurement of bedload transport, it is possible to estimate bedload transport rates from the pattern of empirically observed bed mobilization. These data, along with the calibration period bedload sediment budget described in Section 4.5.5, provide both a robust measure of existing sediment transport conditions in the river and key calibration data for the sediment transport models. Estimates of sediment flux developed using observations of bed mobilization patterns are called morphologic bedload flux estimates. This approach combines understanding of bar deposition and bank erosion sediment exchanges, the thickness of the active layer across the channel, and the virtual velocity of mobilized sediment (Popov 1962a, 1962b; Neill 1971, 1983; Haschenburger and Church 1998; Church 2006; Mao et al. 2017; Brenna et al.

2019). In this study, the study team measured scour during flood events (Sections 4.5.2 and 5.5.1), particle displacement distances (Sections 4.5.2 and 5.5.2), and bar and bank sediment exchanges (Sections 4.1.4 and 5.1.2), allowing calculation of all of the key parameters needed for a morphologic flux estimate.

The directly observable morphologic sediment flux is the cross-channel flux of sediment resulting in measurable changes in the channel bathymetry. It was calculated from the reach-average cross-sectional area of scour and fill (a_m) in the LiDAR geomorphic change detection data as the average of the volume of bar deposition and bank erosion normalized to the length of the analysis segment

$$a_m = \frac{0.5\times(|\Delta S_c|+|\Delta S_b|)}{L},$$

where L is the length of channel over which the change in storage terms were evaluated. In the case of a laterally mobile channel, as is assumed in this framework, this equation properly represents the a_m term; however, in the case of simple aggradation or degradation with no bank erosion, this will underestimate a_m by a factor of 50 percent. The physical changes in the channel boundary accomplishing the directly observable morphologic sediment flux are assumed to occur in a single direction over a longer time period than the sediment budget. Therefore, each parcel of eroded or deposited material is only moved once in the morphologic budget calculation. Said another way, the study team assumed no deposition and re-erosion of material in the observable morphologic flux value.

In contrast, the event active layer across the channel (d_s) is a zone where sediment mobilization may occur in any event in which the threshold of motion for the bed is exceeded (Church and Haschenburger 2017), which may include multiple instances over the several-year period of the sediment budget considered here. The scour monitoring program (Sections 4.5.2 and 5.5.1) measured event active layer thicknesses for the November 2021 flood at "Riffle Crest" sites intended to be representative of typical locations in the channel, while observations of event active layer thickness are available for relatively sheltered spawning locations for the period from 2019-2022.

The study team estimated the thickness of the active layer for the peak flood in each water year of the calibration period using reach-averaged (excluding rapids) τ^* values and the regression relation predicting normalized scour depth from normalized shear stress described in Section 5.5.1.2:

$$\frac{d_s}{D_{90}} = 170\ {\tau^*}_{max}^{1.73}$$

Reach-average d_s/D_{90} are consistently less than 2, the limit of active layer thickness found by DeVries (2002). Localized areas with higher τ^* values may experience net erosion or deposition exceeding 2 times the D_{90}. These areas are reflected in the observed scour and fill term of the sediment flux estimate (a_m).

The active layer thicknesses for each year of the calibration period are then summed to produce composite active layer thickness ($d_{s\,(composite)}$) which is then multiplied by the reach average width (w_{bf}) to produce the cumulative cross sectional area of mobilized active layer material $a_s = d_{s\,(composite)} \times w_{bf}$.

Based on strong agreement between particle tracing observations on the Skagit River and Beechie's (2001) regression relation predicting annual virtual velocity from bankfull width, the study team estimated the virtual velocity v_b for mobilized particles from a modified version of Beechie's regression relation incorporating new data for the Skagit River:

$$v_b = 15 + 20.8W_{bf}$$

Uncertainty bounds for this relation are calculated as described in Section 5.5.2. In application to the sediment flux calculated using the morphologic method, the study team assumed the annual virtual velocity is the path length for each instance in which an individual parcel of sediment is mobilized.

The morphologic estimate of sediment flux is then calculated as $Q_{bo} = v_b(a_m + a_s)$.

4.5.4 Fine Sediment Yield Analysis

This section considers the quantity of fine sediment supplied to the Skagit River, which is transported by very different mechanisms than the coarser bed material that is a focus of this study. Sediment transport that reshapes the bed and banks in the primary study area is dominated by movement of cobble and gravel sized sediment as bedload, and so most of the empirical and modeling approaches to understand sediment transport in this section focus on that coarser material. Finer sediment (sand and finer) primarily moves in suspension through the primary study area and only begins to form the channel bed and banks as the river approaches the estuary. However, understanding fine sediment yield can be useful to help estimate cobble and gravel yields, as described in Section 4.5.5.1.

Because of the different transport mechanisms, the bedload transport focused modeling tools described in Section 4.5.1 are inappropriate for understanding fine sediment yield. Therefore, a different approach is appropriate to understand fine sediment dynamics.

This was done by completion of a study of known sediment yield values for surrounding river basins and subbasins (Figure 4.5-15), development of a multiple linear regression model to estimate sediment yield for the subbasins of the Skagit River above the Project, and application of reservoir trap efficiency calculations to determine what proportion of the fine sediment delivery to each reservoir would be expected to pass downstream. These results have been integrated with results of the GE-03 Sediment Deposition in Reservoirs Affecting Resource Areas of Concern Study (City Light 2023e).

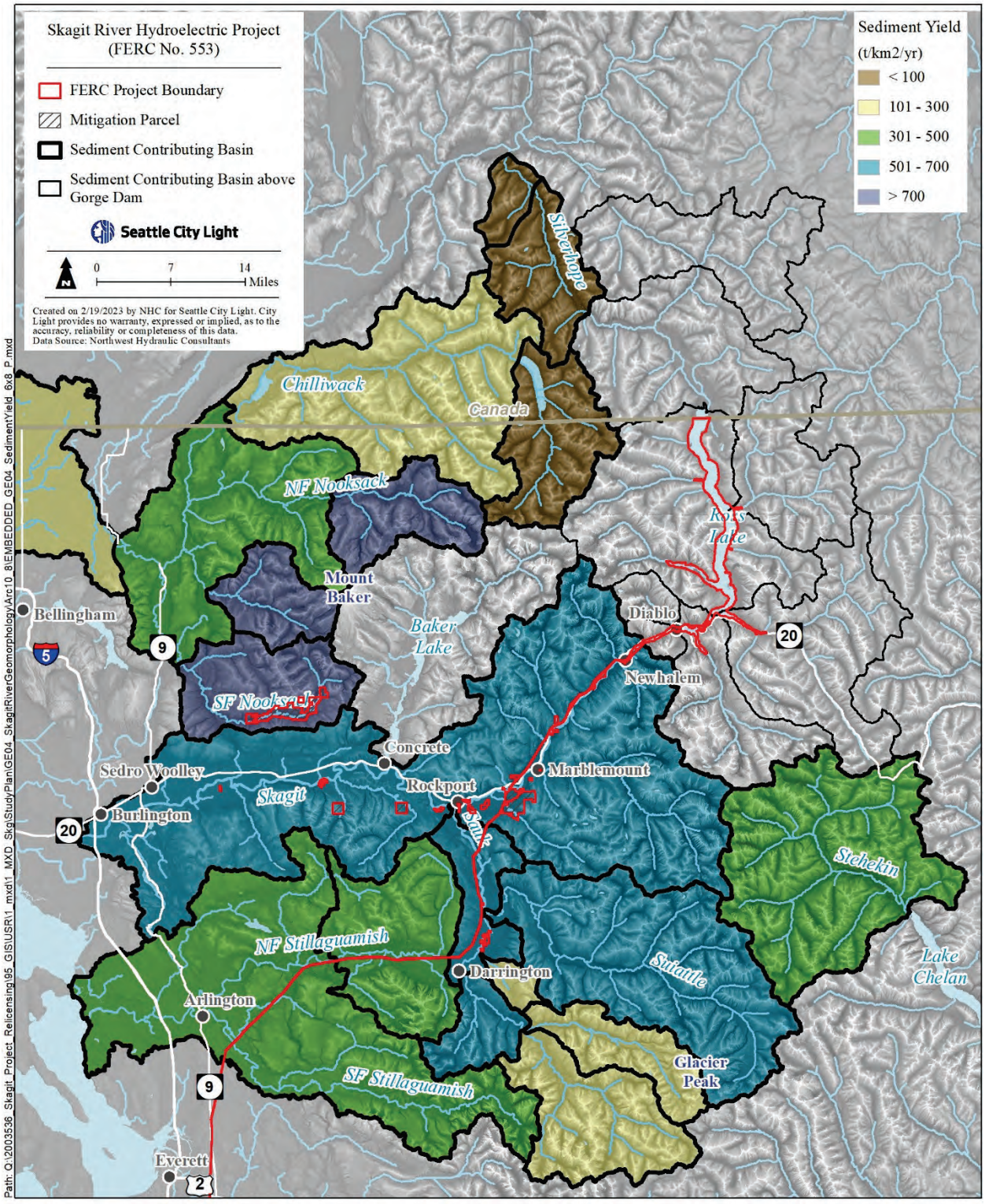
Fine sediment supply is commonly characterized as specific sediment yield; that is, a quantity of sediment exported from a given catchment area over a given period. It is often reported in units of tons per square mile per year. Sediment yield in a given catchment is a function of many factors including the erodibility of underlying bedrock and surficial geologic units, the topography of the basin, the character of vegetation, glacial and periglacial influences, sediment trapping in lakes,

precipitation, natural disturbances (including fire and landslides), and anthropogenic disturbances (including forest and agricultural practices and road building) (e.g., Church and Slaymaker 1989; Milliman and Syvitski 1992; Pierce et al. 2004; Czuba et al. 2011; O'Connor et al. 2014; Renard et al. 2017). The amount of fine sediment intercepted by the Project was estimated by documenting available data to describe the sediment yield for the Skagit River at Mount Vernon and extrapolating available sediment yield data to the area upstream of Gorge Dam (the upper Skagit) using a multiple linear regression approach designed to account for spatial variability in the underlying controls on sediment yield. Complete details of the multiple linear regression model development and model selection procedure are reported in Attachment R.

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: bedrock ratio, the area of unconsolidated sediment, and the area of glaciated stratovolcano.

Mean annual precipitation was calculated from the PRISM (2015) 30-year normal values. Mean annual precipitation varies from less than 500 mm per year (20 inches per year) in areas of the Puget Lowlands and north and east of Ross Lake to nearly 4,000 mm per year (160 inches per year) in areas of the western and central Cascades (Figure 4.5-16).

Steepness Index can be thought of as measuring the deviation of the stream network's longitudinal profiles from an expected typical concave profile, and is often closely related to tectonic uplift and erosion rates of bedrock (e.g., Whipple et al. 2007; Ouimet et al. 2009; Hu et al. 2010; Norton et al. 2010; Castillo et al. 2014; Vezzoli et al. 2020). It was calculated using the AutoKSnProfiler functionality of the Topographic Analysis Kit for TopoToolbox (Forte and Whipple 2019) using a reference concavity of θ=0.5, after quantile-regression smoothing of the stream profiles. The central Cascades characteristically have high values of Steepness Index compared to the Puget Lowlands, Western Cascades, and Eastern Cascades (Figure 4.5-17).



Note: Data for larger aggregate basins overlapping subbasins (e.g., Skagit River at Mount Vernon and Nooksack River at Ferndale) are not shown.

Figure 4.5-15. Suspended sediment yield for the smallest-scale subbasins considered in the suspended sediment yield analysis.

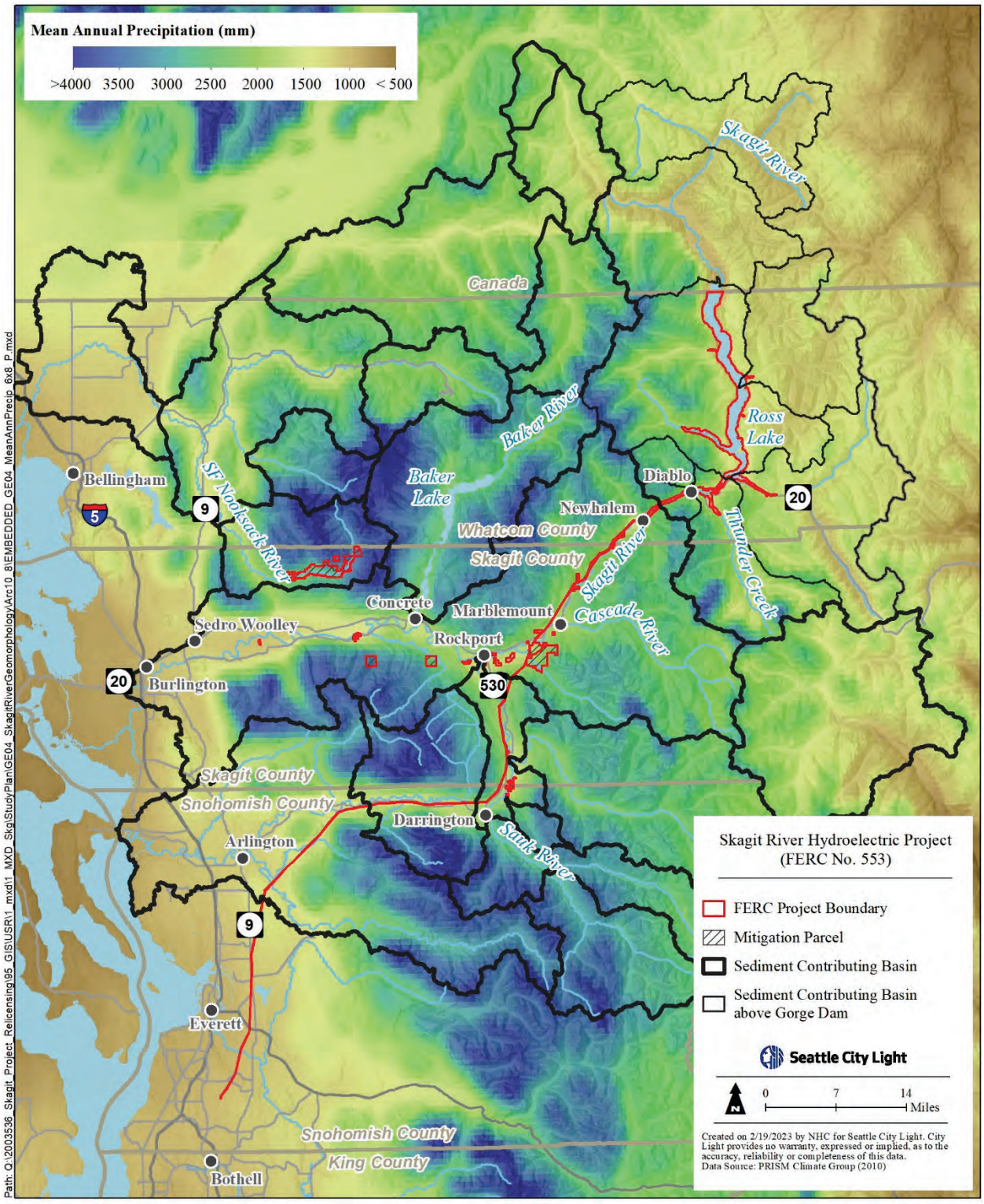


Figure 4.5-16. Mean annual precipitation for basins considered in the fine sediment yield analysis.

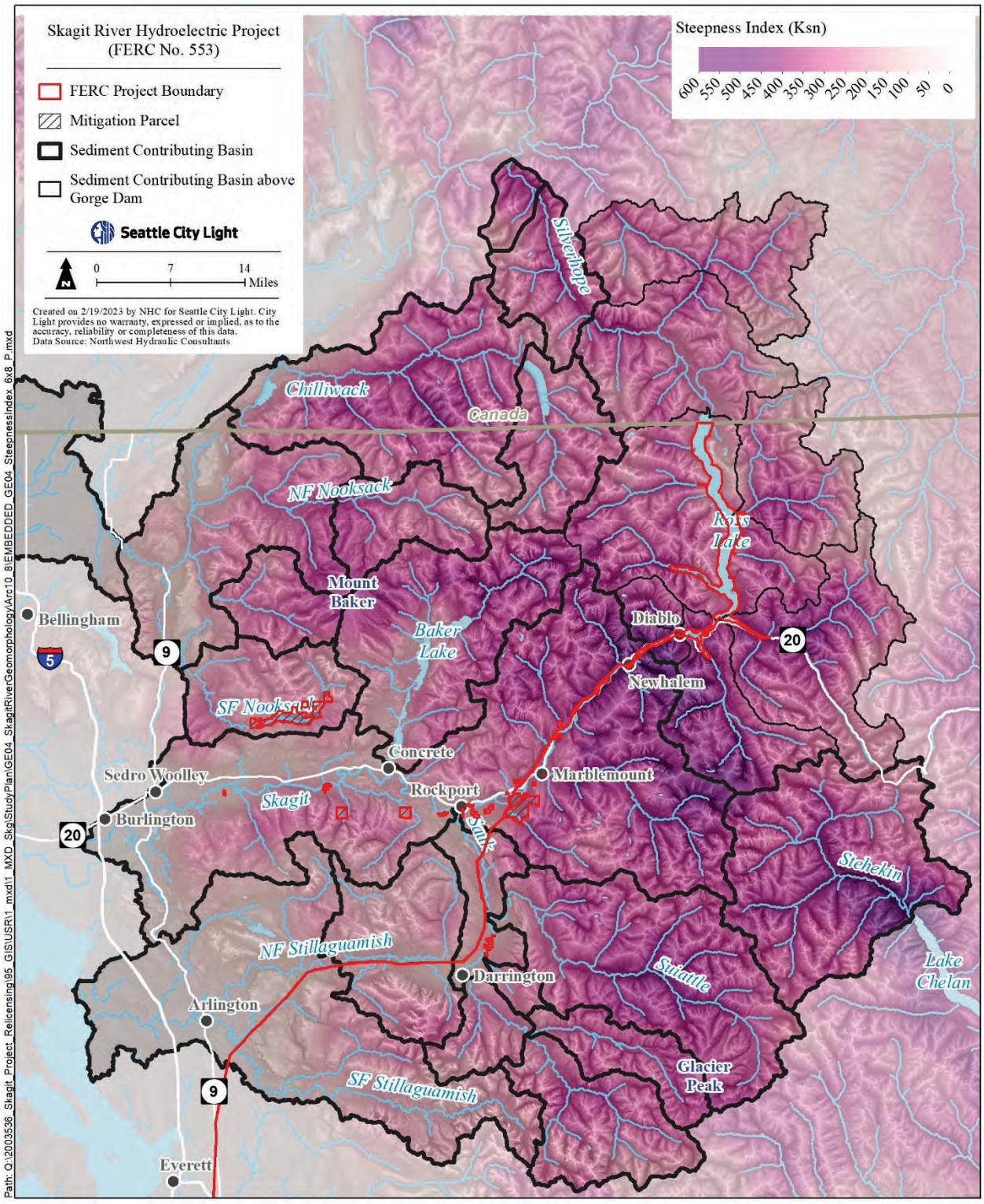


Figure 4.5-17. Steepness Index (Ksn) for the subject basins (m0.9 computed using θ=0.5).

Basin geology was defined by generalizing 1:100,000 scale geologic mapping in Washington State (Division of Geology 2010) and 1:250,000 scale geologic mapping in British Columbia (Cui et al. 2017). Each mapped geologic unit was classified as belonging to one of the following generalization groups: glacier ice, intrusive igneous and high grade metamorphic, unconsolidated lowland deposits (alluvium and continental glacial drift), unconsolidated alpine deposits (landslides and alpine glacial drift), Quaternary volcanics, and softer bedrock (sedimentary, low grade metamorphic, and tertiary volcanic), as shown in Figure 4.5-18. The study area is commonly divided into four principal geologic provinces: the Puget Lowlands, which include the bottom portions of the largest rivers; the Western Cascades, which are dominantly comprised of softer bedrock and volcanic rocks; the Central Crystalline Core, which is comprised of intrusive igneous and high-grade metamorphic rocks; and the Eastern Cascades, which are comprised of older sedimentary, metasedimentary, and metavolcanic rocks. In addition to these parameters, the area occupied by the physical massif of a glaciated stratovolcano (Mt. Baker and Glacier Peak) was manually delineated. "Bedrock Index" was computed as the fraction of the total bedrock area that is occupied by the softer, more erodible rocks (volcanics, sedimentary, and low-grade metamorphic rocks). The area of unconsolidated sediment and the area of glaciated stratovolcano were calculated as the fraction of total basin area consisting of unconsolidated material and within the manually delineated extent of the glaciated stratovolcano massif, respectively.

The Project does not trap all of the suspended sediment that enters the reservoirs. Reservoir trap efficiency was calculated to estimate the proportion of different grainsizes that pass through the reservoirs downstream. As the Skagit River enters the impoundments upstream from each of the Project dams, the flowing water slows, which reduces shear velocity, resulting in sediment deposition in the reservoirs but not all material settles out. Visually observed turbidity is common in the Skagit River downstream from Gorge Dam/Powerhouse and attests to flushing of fine sediment past Gorge Dam, indicating some suspended sediment does pass the Project. This interpretation is supported by trap efficiency calculations for various grainsizes of material reported in Table 4.5-6. Ross Lake traps essentially all sand entering it and most (greater than 90 percent) silt and clay. About 80 percent of sand and 60 percent of silt and clay entering Diablo Lake are trapped there, and about 25 percent of sand and a trivial amount (calculated to be 0 percent) of silt and clay are trapped in Gorge Lake. Because the reservoirs are ordered from largest to smallest in the upstream to downstream direction, the study team assumed that all material passing each upstream reservoir also passes through the downstream reservoirs.

Table 4.5-6. Trap efficiency calculations for different grainsizes.

Reservoir	Gross Storage (acre-feet)	Average outflow (acre-ft per year)	Capacity / Inflow Ratio	Calculated Trap Efficiency (%)		
				Sand	Mixture	Silt &Clay
Ross	1,432,000	2,325,385	0.62	100	97	93
Diablo	88,800	2,762,662	0.018	81	70	58
Gorge	8,200	3,328,805	0.003	23	9	0

Note: Trap efficiencies calculated based on the Summit County Soil and Water Conservation District modified Brune (1953) curves published by Verstraeten and Poesen (2000).

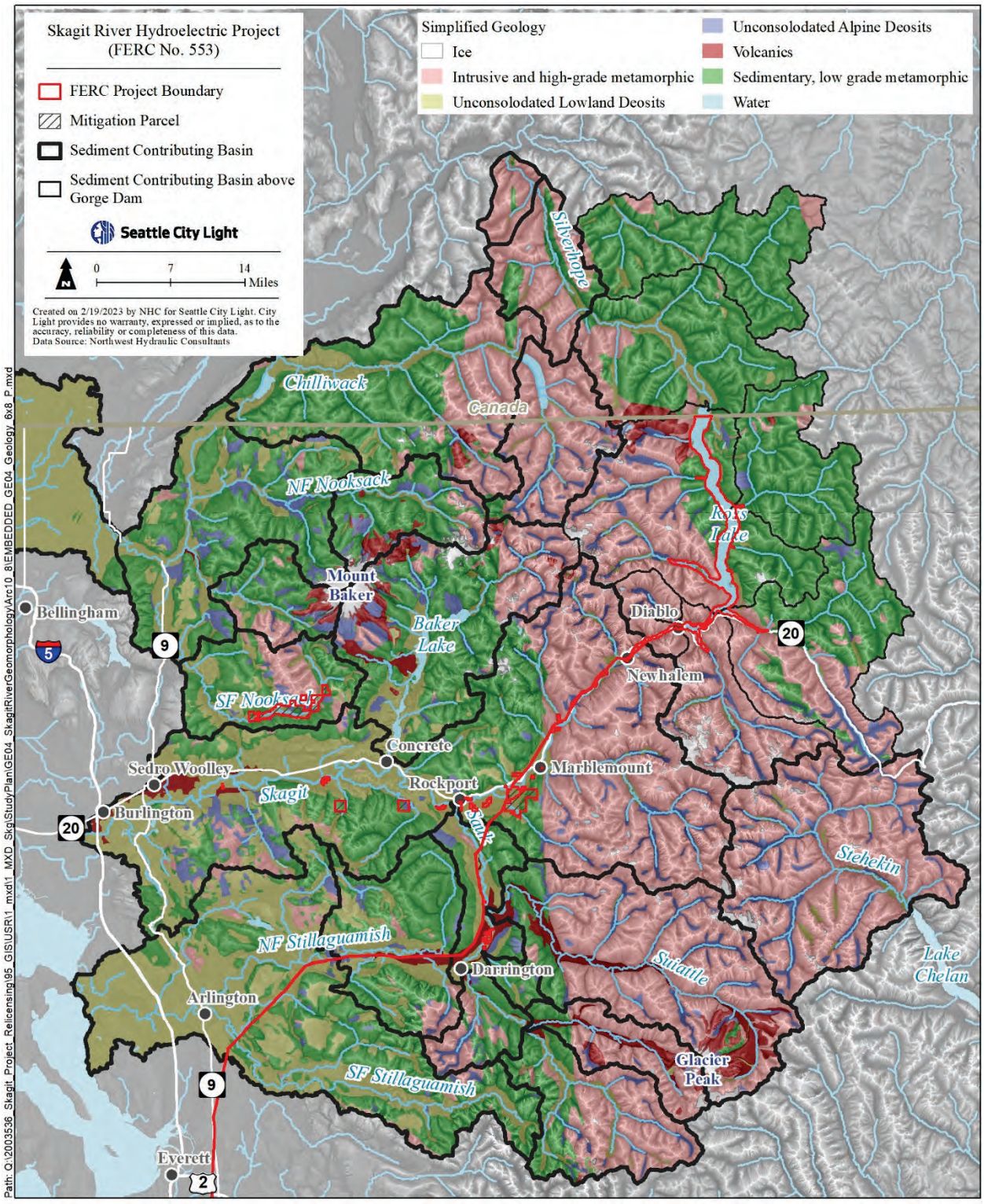


Figure 4.5-18. Generalized geology for the basins considered in the suspended sediment yield analysis.

4.5.5 Calibration Period Bedload Sediment Budget

A sediment budget framework provides an approach to translate observations of change in sediment storage (Sections 4.1.4 and 5.1.2) into estimates of sediment flux that can be used, along with the morphologic bedload flux estimates described in Section 4.5.3, to provide calibration data for the sediment transport models and a robust measure of existing sediment transport conditions. A morphologic sediment budget for the Skagit River between the Sauk River confluence and the Gorge Powerhouse was developed integrating observed change in storage between green-band topobathy LiDAR datasets collected in April of 2017/18 and 2022 (described in Sections 4.1.4 and 5.1.2), and estimated tributary inputs of gravel and cobble derived from a combination of previously published estimates, hydraulic-based sediment transport functions, and scaling from suspended sediment yields estimated by applying the North Cascades suspended sediment yield regression relation described in Sections 4.5.4 and 5.5.4. Because morphodynamic change within the channel occurs as a result of erosion, transport, and deposition of gravel- and cobble-sized sediment, the sediment budget focuses on those grainsizes.

A morphologic sediment budget is based on the principle of conservation of mass and tracks inputs, outputs, and change in storage of sediment within a reservoir. This can be represented mathematically in the general form:

$$Q_{bo} = Q_{bi} - \Delta S$$

Where $Q_{bo}$is the quantity of bed material exported from the reach, Q_{bi} is the quantity of material supplied to the reach, and ΔS is the change in storage within the channel. This may be elaborated to discriminate particular inputs or change in storage reservoirs, for example:

$$Q_{bo} = Q_{bi_c} + Q_{bi_t} - (\Delta S_c + \Delta S_b)$$

Where Q_{bi_c} represents sediment input from the mainstem upstream, Q_{bi_t} represents sediment input from tributaries, ΔS_c represents change in storage within the active channel, and ΔS_b represents change in storage through bank erosion. Aggradation within the active channel is represented as a positive value of ΔS_c, and degradation, a negative value. Erosion of banks is represented as a negative value of ΔS_b, as it provides a net source of sediment to the down-channel flux.

Comparison of the multitemporal topobathymetric LiDAR datasets (Sections 4.1.4 and 5.1.2) gives high-confidence results for the $\Delta S_c + \Delta S_b$ terms of the sediment budget. These were defined by assigning a 0.5-ft level of detection, then computing volumes of cut and fill that occurred within the area that started and remained channel through the 2017-2022 period, which defines ΔS_c. The volume of sediment eroded from the area that started as floodplain and became channel over the comparison time period (bank erosion inputs, ΔS_b) was estimated by calculating the total volume of eroding material and then adjusting the total volume to account for erosion of sand from the floodplain. To do this, field observations of the stratigraphy of eroding banks were related to total measured bank heights, and a percentage of sand and finer sediment for individual eroding banks was estimated as the ratio of observed sand depth to total bank height. These observations included most significant areas of bank erosion sediment recruitment to the channel. Reach-average values for sand content from bank erosion inputs were calculated as the length-weighted average of

observations from individual eroding banks. Bank erosion inputs ΔS_b were then calculated as the total volume of bank erosion input less that volume times the sand proportion.

Change in channel storage (ΔS_c) and bank erosion inputs (ΔS_b) were calculated for a series of 19 analysis cells corresponding to the NPS reach boundaries and subreach breaks at select major tributaries. Because the change-in-storage terms are known, the sediment budget can be propagated to define bed material fluxes through the analysis domain if Q_{bi_c} is known (in this case Q_{bi_c} can be assumed to be functionally zero for the Skagit River due to the impact of Gorge Dam) and either:

- Q_{bi_t} is known for each tributary input, or
- Q_{bo} is known at any point within the analysis domain.

The budget is then solved mathematically for each analysis cell working progressively away from the point where four of the five parameters are known. For example, if the downstream boundary Q_{bo}flux is known, the input flux to the downstream-most analysis cell can be computed as

$$Q_{bi_c} = Q_{bo} + (\Delta S_c + \Delta S_b) - Q_{bi_t}$$

Q_{bi_c} for the downstream-most cell is Q_{bo} for the next cell upstream, hence the procedure can be calculated to iteratively solve for all analysis cells in the study domain.

A morphologic sediment budget is typically expressed in volumetric units, while suspended sediment yield and hydraulic based sediment transport functions give results in terms of mass. A typical bulk density of the sediment deposits is therefore needed to relate change in storage volumes to key methods of estimating sediment inputs. A value of 1.45 tons per cubic yard (1.73 tons per cubic meter) was used for this purpose. This value is on the low side of the range reported by Bunte and Abt (Milhous 2001 as cited in Bunte and Abt 2001), consistent with previous estimates of bulk density for the gravel bed reach of the Fraser River (McLean and Church 1999), and slightly lower than values for compacted alluvial gravel in the Chilliwack Fan (Tunnicliffe et al. 2012a).

No long-term measure of sediment flux is available within the sediment budget domain, but various tools are available to estimate sediment fluxes in different locations:

- Tributary bed material inputs may be estimated by a bedload to suspended load ratio from the suspended sediment yields that have been estimated for each tributary using the regression relation developed to predict suspended sediment yield above Gorge Dam (Sections 4.5.4 and 5.5.4).
- Tributary bed material inputs, in select cases where bed materials samples are available and the assumption of transport-limited conditions is met, may be estimated from hydraulic-based sediment transport functions, as have been implemented in HEC-RAS and MAST 1-D sediment transport models of the Skagit River.
- Sediment flux along the mainstem may be estimated by morphologic methods that combine the measured bank erosion and bar sedimentation volumes, estimates of the active layer

thickness, and estimates of the virtual velocity of mobilized particles. Bank erosion and bar sedimentation volumes are normalized to the channel length and the active layer thickness, multiplied by the channel width, so both give a cross-sectional area of mobilized sediment. This area is multiplied by the virtual velocity to derive a flux.

- Sediment flux along the mainstem may also be estimated by hydraulic sediment transport computations as implemented in HEC-RAS and MAST 1-D. The flux in any given location depends, in large part, on the upstream tributary inputs (grain size and quantity).

The following sections document the methods used to develop tributary input estimates from the suspended sediment yield regression and the morphologic sediment flux.

4.5.5.1 Tributary Inputs (Qbit) from Suspended Sediment Yield

Sections 4.5.4 and 5.5.4 describe a multiple linear regression relation developed to predict suspended sediment yield in the North Cascades as a function of basin relief, geology, and precipitation. The primary focus of this work was to estimate suspended sediment yield above Gorge, Diablo, and Ross dams, but it is also useful for understanding relative expected sediment yields for other tributary basins that enter the Skagit River downstream of the dams.

It is possible to use the suspended sediment yield regression relation to develop an understanding of relative bedload yields for the different basins if the ratio between suspended sediment and bed material or bedload sediment is known. As a first-order approximation of this value, the study team applied the regression relations of Turowski et al. (2010), where the proportion of the total yield transported in suspension is estimated as a function of drainage area. Information is available for several locations directly relevant to understanding Skagit River tributaries, validating applicability of the relation for the North Cascades: the Nooksack River near Deming, WA, which has a basin area of 589 mi^2 (1526 km^2) and 50 to 90 percent suspended load (Anderson et al. 2019); the Chilliwack River above Chilliwack Lake, which has a basin area of 129 mi^2 (334 km^2) and about 82 percent suspended load (Tunnicliffe et al. 2012); Fitzsimmons Creek, in Whistler, BC, which has a basin area of 37 mi^2 (95 km^2) and about 41 percent suspended load (Schiefer et al. 2010) with conditions similar to some of the steepest alpine tributary catchments; and Sullivan Creek, which has a basin area of 70 mi^2 (182 km^2), 64 to 73 percent suspended load (Cienciala et al. 2020), and conditions more similar to northern and eastern tributaries to Ross Lake. All three of these sites plot within the typical range of variability in Turowski et al.'s (2010) dataset (Figure 4.5-19).

Based on the general agreement between Turowski et al.'s (2010) dataset and local validation information, their basin-area based approach (equation 7 in Turowski et al. 2010) was used to estimate the partitioning of suspended load and bedload for the Skagit River tributaries. The bedload values reported in Turowski et al. (2010) and calibration datasets include a substantial proportion of sand, which does not play a morphologically important role in shaping the Skagit River channel as it moves as throughput load in the mainstem and only accumulates on the bed in interstices between gravel and cobble particles. A cobble-gravel scaling factor of 0.625 ± 0.125 (0.5 to 0.75), the value of which was estimated from tributaries where cobble-gravel and sand ratios are known (City Light 2023e), was therefore applied to the bedload yield estimate to estimate the yield of gravel and cobble material.

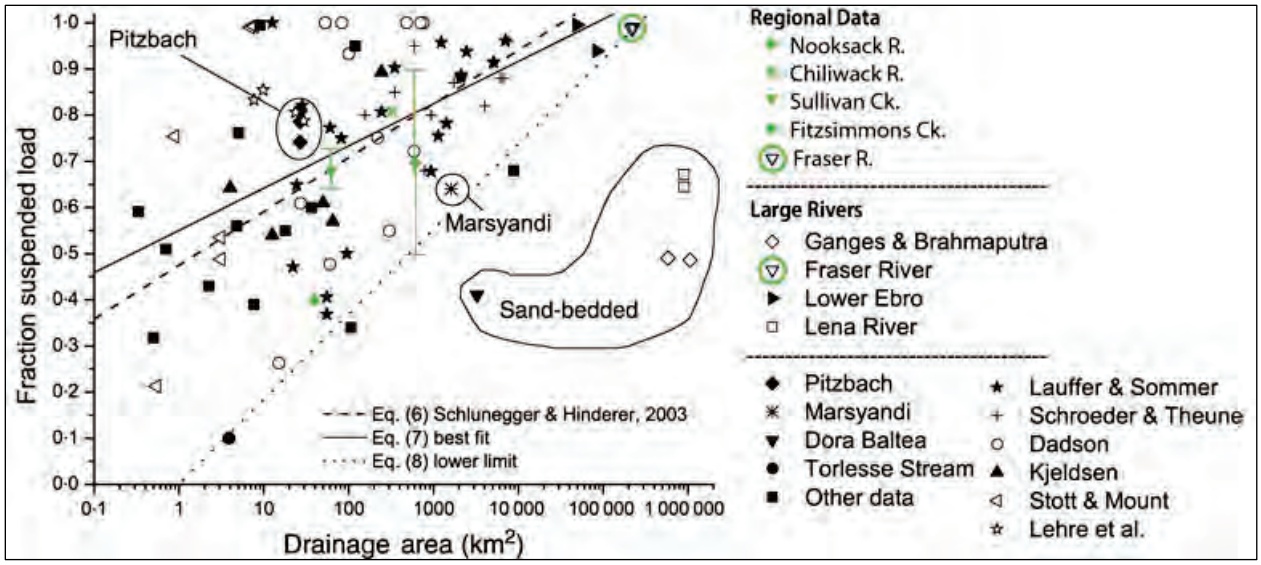


Figure 4.5-19. Relation between drainage area and fraction of suspended load adapted from Turowski et al (2010). Regional data (sources described in text) are shown in green to validate applicability of Turowski's relation to the North Cascades.

4.5.5.2 Tributary Inputs (Qbit) Estimated from Hydraulic-based Sediment Transport Calculations

Some tributaries cross areas of floodplain surrounding the Skagit River with a low gradient. In these cases, their coarse sediment contribution to the river is mediated through long-term storage in the creek fans and floodplain between the creek and river. Fortunately, these are also locations where the underlying assumptions of traditional hydraulics-based sediment transport calculations are best met. In these cases, the best estimate of the tributary cobble-and-gravel yield Q_{bit} term of the sediment budget was estimated from 1-D HEC-RAS models of each tributary described in Attachment P.

4.5.5.3 Integrated Tributary Inputs (Qbit) Estimate

Table 4.5-7 shows the best estimate and range of reasonable estimates of Q_{bit} for each tributary. These were determined by inductively integrating information from independently determined measurements and estimates, the 1-D HEC-RAS model, and estimates based on the calculated suspended sediment yield for each basin. Except as indicated in notes for specific tributaries (which include references to all other available estimates of sediment yields for them), the following rule set was used to complete this integration:

- The bedload yield estimate times the upper bound cobble-gravel adjustment factor of 0.75 was used to calculate the upper bound cobble-gravel yield estimate.
- The best cobble-gravel yield estimate was determined by the bedload yield estimate times the central cobble-gravel adjustment factor of 0.625, except where long reaches of the tributary cross the floodplain at a low gradient, in which case the HEC-RAS calculated cobble and gravel yield was used.

- The lower bound cobble-gravel yield estimate was calculated by first checking whether the regression-based bedload yield times the lower bound cobble-gravel adjustment factor was less than the best cobble-gravel yield estimate. If it was, that value was used. If it was not (in some cases where HEC-RAS-calculated cobble and gravel yield was used for the best estimate), then a value of 0.5 times the best estimate cobble-gravel yield was used to account for the order-of-magnitude uncertainty in uncalibrated hydraulic-based sediment transport computations.

Table 4.5-7. Estimated tributary sediment inputs to Skagit River.

Tributary or Mainstem Location	Basin Area (mi^2)	Regression Estimated Suspended Sediment Yield (tons/yr)	Fraction of Total Load		Regression Based Yield Estimate (tons/yr)		HEC-RAS Calculated Gravel and Coarser Yield (tons/yr)	Integrated Cobble and Gravel Yield Estimate (tons/yr)		
			Suspended	Bedload	All Bedload	Gravel and Coarser		Upper Bound	Best Estimate	Lower Bound
Skagit River at Hozomeen	383	12,000	0.83	0.17	2,500	1,600	--	1,900	1,600	1,300
Skagit River at Gorge Dam	1,172	660,000	0.87	0.13	100,000	60,000	--	70,000	60,000	50,000
Ladder Creek[1]	7	34,000	0.67	0.33	17,000	10,000	--	13,000	10,000	8,000
Newhalem Creek[2]	28	78,000	0.72	0.28	30,000	19,000	--	22,000	19,000	15,000
Goodell Creek[3]	39	120,000	0.73	0.27	40,000	30,000	--	30,000	20,000	20,000
Babcock Creek[4]	2	5,000	0.61	0.39	3,200	2,000	40	2,400	40	20
Martin Creek	1	1,300	0.58	0.42	900	600	--	700	600	500
Thornton Creek	4	4,700	0.65	0.35	2,600	1,600	--	1,900	1,600	1,300
Sky Creek	1	2,100	0.60	0.40	1,400	900	150	1,100	100	100
Damnation Creek[5]	5	6,700	0.65	0.35	3,600	2,200	--	2,700	2,200	1,800
Alma Creek[6]	8	18,000	0.67	0.33	9,000	6,000	--	6,700	5,600	4,500
Copper Creek[6]	4	5,700	0.64	0.36	3,200	2,000	--	2,400	2,000	1,600
Bacon Creek[7]	51	110,000	0.75	0.25	40,000	20,000	--	30,000	20,000	20,000
Diobsud Creek	27	51,000	0.72	0.28	20,000	12,000	--	15,000	12,000	10,000
Taylor Creek	2	3,100	0.62	0.38	1,900	1,200	60	1,400	100	30
Cascade River[8]	185	370,000	0.80	0.20	100,000	60,000	--	70,000	60,000	30,000
Olson Creek	7	10,000	0.66	0.34	4,900	3,100	3,600	3,700	3,600	2,500
Corkindale Creek	5	15,000	0.65	0.35	7,900	5,000	130	5,900	100	100
Rocky Creek	10	23,000	0.68	0.32	11,000	6,700	1,400	8,100	1,400	700
Illabot Creek	44	59,000	0.74	0.26	21,000	13,000	300	16,000	300	100
Sutter Creek	2	2,600	0.61	0.39	1,600	1,000	160	1,200	200	100
Barr Creek	3	3,800	0.63	0.37	2,300	1,400	230	1,700	200	100
Sauk River[9]	734	1,070,000	0.85	0.15	190,000	120,000	--	160,000	120,000	90,000

1 Preserved depositional features and damage to vegetation indicate that the November 2021 flood deposited (and subsequently scoured most of) ~4,000 cubic yards (yd^3) of sediment on Ladder Creek fan. Summer 2021 observations suggest similar aggradation-degradation episodes had occurred a couple of additional times in the past several years. Using 2 × D_{90} from fan to estimate active layer thickness in braided reach above waterfalls and virtual velocity (v_b) of 20 bankfull widths per year = 3,000 ft for that reach, and assuming 2 bed mobilizing events gives a total estimate of 50,000 yd^3 between 2018 and 2022 or about 10,000 yd^3/yr.

2 Anecdotal record of annual to biannual excavation to bypass sediment past City Light weir (Adams 2022) sets minimum bound gravel-coble yield for Newhalem Creek of ~500-1000 yd^3/yr. Using 2×D_{90} from channel above weir to estimate active layer thickness and v_b of 20 bankfull widths per year = 1,000 ft for that reach, and assuming 2 bed mobilizing events gives a total estimate of 9,000 yd^3 between 2018 and 2022 or about 2,000 yd^3/yr.

3 Herrera (2017) measured 250,000 yd^3 lake storage between 2003 and 2014, assumed this was all bedload (this assumption is probably reasonable, but with high sand fraction and perhaps higher sand fraction than assumed in the cobble-gravel adjustment factor given the landslide lake accumulation environment). This gives 25,000 yd^3/yr bedload. Further, Herrera measured 16,000 yd^3 of large cobble and gravel accumulation on fan between 2006 and 2009, suggesting a minimum cobble gravel supply of ~5,000 yd^3/yr. Best estimate assigned using Herrera's measured lake accumulation bedload × median cobble-gravel adjustment factor (0.625) + observed cobble-gravel accumulation on fan; minimum determined by lake accumulation bedload × lower bound cobble-gravel adjustment factor (0.5) + observed gravel and cobble accumulation on fan. As a check on this value, using 2×D_{90} from head of the fan and bar cut and fill of 294 ft^3/ft to estimate active layer thickness and v_b of 20 bankfull widths per year = 3,600 ft for that reach, and assuming 2 bed mobilizing events gives a total estimate of 108,000 yd^3 between 2017 and 2022 or about 22,000 yd^3/yr.

4 At time and location of observation, bed of creek was sand dominated with very little gravel-sized material, interpret potential for big shifts depending on mass wasting in basin, path across creek fan, and interaction with Goodell Creek fan on multi-centennial timescale.

5 Preserved depositional features and damage to vegetation indicate that the November 2021 flood generated a debris flood that deposited (and subsequently scoured about half of) ~5,000 yd^3.

6 Field evidence suggests bed mobilized in low frequency, high magnitude debris flood/flow events. Little activity in November 2021 flood.

7 2 ft active layer thickness observed across channel and morphologically-detectable sediment exchange of 351 ft^3/ft, given the 150-ft channel width and assumption of 20 bankfull widths per year virtual velocity (supported by particle tracing showing widespread movement into Skagit River from deployment site 1,000 ft upstream), this gives a value of 80,000 yd^3 transport between 2017 and 2022 or about 16,000 yd^3/yr.

8 Paulsen (1997) estimates 44,000 tons/yr bedload for Cascade River. This value is below the lower bound estimate determined from the regression approach (Section 4.5.5.1). 0.625 × the Paulson bedload value used as the lower bound estimate. Winter 2021-22 active layer thickness (which included two events between 9,000 cfs (greater than 2 yr recurrence) and 11,000 cfs [approximately5 yr recurrence]) measured by scour monitoring array was 0.67 ft given the 210-ft channel width and assumption of 20 bankfull widths per year virtual velocity; this gives a value of 19,000 yd^3 transport. In addition to this a morphologically detectable flux (bar deposition and bank erosion) of 128 ft^3/ft occurred between 2017 and 2022 with the same virtual velocity assumption, this gives a value of 4,000 yd^3 per year, giving an estimate of 23,000 yd^3 for 2021-22.

9 Measured suspended sediment yield (Jaeger et al., 2017) used instead of regression predicted. Bedload fraction strongly supported by USGS measurements over a range of flows (0.14) and estimate of plausible true range of 10-20 percent (Anderson 2022). Anderson also notes an additional 45,000 m^3/yr (85,000 tons/yr) eroded downstream of gage between 2005 and 2016; the upper bound estimate adds this assuming 50 percent is bedload (and 37.5 precent cobble gravel) and 50 percent suspended. A morphologic flux estimate using 1,206 ft^3/ft of morphologically detectable change and 2 × D_{90} to estimate active layer thickness and v_b of 20 bankfull widths per year = 13,000 ft for that reach, and assuming 3 bed mobilizing events gives a total estimate of 1,000,000 yd^3 between 2017 and 2022 or about 200,000 yd^3/yr.

4.6 Large Wood Inventory

The purpose of this section of the report is to characterize large wood within the study area. This inventory was completed in accordance with Section 2.6.6 of the RSP (City Light 2021). Large wood transport and retention methods are addressed in Section 4.7 of this study report. The study team performed a historical aerial photograph inventory, August 2021 field inventory, and July 2021 high resolution drone imagery of individual large wood pieces and log jams. The methods used for performing these inventories is detailed in the following sections.

4.6.1 Historical Aerial Photograph Inventory

The study team identified pieces of large wood pieces and log jams using seven remote sensing data sets presented in Table 4.6-1 that span the course of the current and previous FERC licenses. Due to limitations in resolution and spatial extent of remotely sensed data sets, 1979 and 1998 do not include all of the primary study area; however, the coverage provided in 1979 and 1998 was still sufficient to characterize the large wood in the primary study area for each time period.

Table 4.6-1. Remote sensing imaging with resolution 0.5-1.4 ft in the study area.

Year	Image Type	Resolution (ft)	Source	Study Length Covered (miles)
1979	Color stereo photos	1.0	SRSC	11.0
1998	Color stereo photos	1.4	USFS/SRSC	11.8
2009	Digital imagery	1.0	Skagit County	27.5
2011	Digital imagery	1.0	Skagit County	27.5
2018/2019	Digital imagery	0.5/0.75	City Light/Skagit County	30.1
2021	Digital imagery	0.75	City Light/Skagit County	27.9
2022	Digital imagery	0.5	City Light/Skagit County	30.6

Large wood pieces were inventoried in color stereo photos and digital imagery using the following criteria.

- Piece was within the bankfull channel of the Skagit River mainstem, side channels, or tributaries. Within tributaries, piece must be within 500 ft upstream of tributary confluences with the Skagit River mainstem.
- Large wood pieces longer than 25 ft and wider than one ft diameter at breast height (dbh) were included in the inventory. Large wood was digitized as a line feature in ArcMap. Width and length were measured using the measure tool.

The following attributes were assigned to each of the pieces:

- **Adjacent Tributary:** Named tributaries that are within 1,000 ft of a large wood polyline.
- **Length:** Length of large wood piece in ft.
- **Width:** Diameter of large wood piece in ft.

- **Jam Member:** Located in or out of a mapped log jam.
- **Orientation:** Orientation of large wood piece relative to flow. Classified as either parallel, perpendicular, or oblique to flow.
- **Rootwad:** Presence or absence of a rootwad, where visible.

Log jams were defined by a minimum of five large wood pieces that met the required size criteria. Log jams were digitized as polygons. Log jam polygons were created by outlining the outer perimeter of the log jam being mapped. The following attributes were assigned to each of the log jams:

- **Adjacent Tributary:** Named tributaries that are within 1,000 ft of large wood polyline.
- **Area:** Area of log jam in square ft.
- **Type:** The type was classified as bar top (bt), bar apex (ba), meander jam (mj), side channel (sc), or submerged jam (sj) for aerials from 2011 to 2022.
- **Change:** Difference in size of the log jam between years classified as building, decaying, stable, or variable.

Due to the 3-ft resolution of topobathymetric LiDAR, it was difficult to recognize individual pieces of large wood. The study team attempted to use the method for characterizing log jams using a difference in raster method presented in Abalharth et al. (2015). The low pulse return density resulted in a low-resolution DEM in many places, which made it difficult to implement the method.

QA/QC procedures were implemented by two senior staff members of the study team (a Science Lead and a Principal Geomorphologist) to verify the identification of large wood and log jams in historical aerial photographs.

4.6.2 August 2021 Field Inventory

In August 2021, the study team performed a large wood tally and log jam tally for the majority of the primary study area and detailed field survey of ten 0.5-mile areas. The Gorge bypass reach was inventoried using high resolution drone imagery from 2021 collected for the FA-05 Bypass Instream Flow Model Development Study (City Light 2023c). All data and photographs were collected on a GPS-enabled iPad in ArcGIS Collector. Flows during August 2021 ranged from 2,390 cfs to 5,400 cfs at the USGS Skagit River at Marblemount gage (12181000) and were representative of average low flow conditions.

4.6.2.1 Large Wood and Log Jam Tally

A large wood and log jam tally was completed for 26.5 of the 30.1 miles of the mainstem Skagit River, all 56 side channels addressed in Section 5.3 of this study report, and 500 ft above the confluence of 20 tributaries listed in Table 3.0-1. The large wood and log jam tally was not completed in the mainstem of the Skagit River between PRM 86.6-87.7 due to a section of rapids that prevented access. The Gorge bypass reach was inventoried using high resolution drone imagery from July 2021 collected for the FA-05 Bypass Instream Flow Model Development Study (City Light 2023c). For all other reaches, large wood that was equal to or greater than 25 ft and one ft dbh was tallied and geolocated. For large wood that was found within log jams, the number

was counted exactly between 5 and 9 pieces. For all log jams greater than 9 pieces, the study team estimated to a bin class of 10-49 (small), 50-99 (medium), or 100 plus pieces (large), and geolocated.

Additionally, individual tallied large wood pieces were assigned the following attributes:

- **Length:** Estimated length was binned as 25-49 ft, 50-74 ft, 75-99 ft, or 100 plus ft.
- **Diameter at Breast Height (dbh):** Estimated dbh was binned as 1-1.9 ft, 2-2.9 ft, 3-3.9 ft, or 4 plus ft categories.
- **Rootwad:** Presence or absence of a rootwad.

4.6.2.2 Large Wood Inventory Detailed Areas

Ten 0.5-mile areas within the primary study area were selected for a detailed large wood inventory. These detailed areas were selected to be representative of various channel morphologies present within the primary study area; they were agreed upon by LPs in a July 2021 Geomorphology Work Group meeting. The name of the detailed areas and associated geomorphic reach number is shown in Table 4.6-2. For these detailed areas, in addition to mapping the location, abundance, and size of large wood, attributes were collected to characterize the adjacent tributary, jam member, orientation, function, decay class, bank erosion, species, stratigraphy, mobility, and residual pool depth. Each individual large wood piece was assigned a geotagged polyline representative of its location and each log jam was assigned a geotagged polygon representative of its perimeter. Attributes that were collected for log jams include average height, location in active channel, number of pieces, occupied percentage, type, and residual pool depth. Large wood and log jam features that spanned more than one channel unit type were assigned to the channel unit type that contained the most length or area of the individual feature. An exception was made for large wood and log jam features that spanned a "Main Channel Wet" channel unit; in this case the feature defaulted to the "Main Channel Wet" classification. This was decided because it is geomorphically important to note if a large wood feature is interacting with the wetted channel even if it is not the entirety of the wood feature. The location of these large wood inventory detailed areas is shown in Attachment C. Seven of the ten detailed wood inventory areas overlap with proposed 2-D sediment modeling areas.

Table 4.6-2. Large wood inventory detailed areas and geomorphic reaches.

Detailed Wood Inventory Area	Geomorphic Reach	Project River Mile (PRM) Range for Detailed Areas
Rockport	7A	67.4 – 67.9
Barnaby West	6	68.6 – 69.1
Barnaby East	6	69.5 – 70.0
Sutter	6	71.0 – 71.5
Cascade	5B	77.4 – 77.9
Bacon South	3B	82.5 – 83.0
Bacon North	3B	83.0 – 83.5
County Line	2B	89.4 – 89.9
Thornton	2B	90.1 – 90.6
Goodell	2B	93.0 – 93.5

The following attributes were assigned to each of the individual large wood pieces identified in the detailed reach:

- **Length:** Length of the piece in ft.
- **Diameter at Breast Height (dbh):** Diameter of the piece at breast height in ft measured to the nearest tenth of a foot.
- **Rootwad:** Presence or absence of a rootwad.
- **Rootwad Diameter:** Average diameter of rootwad in ft.
- **Adjacent Tributary:** Named tributaries that are within 1,000 ft of large wood polyline.
- **Jam Member:** Located in or out of a mapped log jam.
- **Orientation:** Orientation of large wood piece relative to flow.
- **Function:** Geomorphic function of large wood piece. These include hydraulic cover, pool forming, key piece in log jam, and log jam members.
- **Decay Class:** Level of decomposition defined as either 1 (fresh), 2 (intermediate), or 3 (rotten). Class 1 refers to wood that is very firm and often has bark and limbs. Class 2 refers to wood that is firm and often has some bark and limbs. Class 3 refers to wood that is softer and has no or very little bark and limbs.
- **Bank Erosion:** Whether the piece was recruited locally from bank erosion or not. This was determined based on the presence of the rootwad being on the bank, as well as signs of local bank erosion, such as scour and exposure of tree roots.
- **Species:** Identity of tree species. If species could not be determined large wood piece was defined as “Unknown.”
- **Stratigraphy:** Location of wood in the channel. Classified as either low flow channel (lf), partially or fully submerged (psu or su), gravel bar (gb), or floodplain (fp).

- **Mobility:** Estimate of large wood piece stability based on how embedded the piece was in the substrate and where in relationship to flow it was located. Mobility was classified as either stable (st), partially stable (int), or not stable (nst).
- **Pool Depth:** Residual depth of associated pool in ft (if pool is present). Measured in the field.

The following attributes were assigned to each of the log jams identified in the detailed reach:

- **Height:** Average height of log jam above the riverbed in ft.
- **Wetted Channel:** Whether the log jam was engaged with the wetted channel.
- **Number of Pieces:** Estimated number of pieces in the log jam (binned as 5-9, 10-49, 50-99, or 100 plus). At least 5 pieces of the log jam were greater than 25 ft and 1 ft dbh.
- **Occupy Percentage**: The percentage of the mainstem or side channel that the log jam occupies.
- **Type**: The type was classified as bar top (bt), bar apex (ba), meander jam (mj), side channel (sc), and submerged jam (sj).
- **Pool Depth**: Residual depth of associated pool in ft (if present).

4.6.3 Stability of Large Wood between April 2018 and June 2022

Aerial imagery from 2018/2019 to 2022 and the August 2021 field inventory were used to assess the stability of large wood in the Skagit River primary study area. Large wood with a dbh greater than one ft and a length greater than 25 ft that were seen in the aerial imagery and field inventory were digitized and assigned length, diameter, rootwad, and volume. Volume for each piece of large wood was calculated using equations developed by Abbe (2000) in cubic meters and converted to cubic feet (cu ft). These equations take into account the combination of the volume of the rootwad and the trunk.

The study team assessed stability between 2018/2019 and May 2021. In this period, the highest flood was 31,300 cfs at the USGS Skagit River at Marblemount gage (USGS 12181000). This flow represents a typical fall flood. To gain an approximate number of stable pieces, 5-ft buffers were created around each piece seen in the 2018 and 2019 imagery (neither 2018 nor 2019 imagery covers the entire study area). The intersect tool in ArcMap was used to find large wood pieces in 2021 that intersected these buffers. The study team assumed any of these intersected pieces to be the same as the 2018/2019 pieces and marked them as stable. Large wood movement in the 2021 imagery and 2022 imagery were also compared.

Large wood that was present in both the May 2021 imagery and the August 2021 field inventory detailed area were marked as stable for that period. Large wood present in both the August 2021 field inventory and the June 2022 imagery was marked as stable for that period. Large wood that was present in both May 2021 and August 2021 remained stable throughout spring flows. The largest spring flow in 2021 was recorded as 18,500 cfs at the USGS Skagit River at Marblemount gage (12181000). Large wood that was present in both August 2021 and June 2022 remained stable throughout the November 2021 floods, which had a peak of 63,400 cfs at the USGS Skagit River at Marblemount gage (12181000). For the May 2021 to August 2021 and August 2021 to June

2022 time periods, stability was compared to piece length, diameter, rootwad diameter, and total volume.

4.6.4 Large Wood in Reservoirs

Large wood in reservoirs was inventoried by City Light in accordance with Section 2.0 of Attachment C in the RSP (City Light 2021). The Woody Debris Management Summary of Activities to Date Memorandum (Attachment W to this study report) discusses the most up to date summary of this task and includes information from Ross and Diablo lakes wood collection, holding, and Skagit River wood placement annually from 2017 to 2022. Under current practice, City Light inventories reservoir wood by length, dbh, and rootwad presence to a maximum classification of greater than 20 ft in length and 12 inches in diameter. The wood data collection and recommendations memo suggest classifying large wood by decay class and additional length classes up to 100 ft or greater in length and 36 inches or greater in diameter.

4.7 Large Wood Tracking and Transport

The purpose of this section of the report is to address large wood tracking, transport, retention, and augmentation. This was completed in accordance with the June 9, 2021 Notice and Section 2.6.8 and Attachment C of the RSP (City Light 2021). The completion of the transport, recruitment, and augmentation sections utilizes hydraulic modeling results from FA-02 Instream Flow Model Development Study (City Light 2023a).

4.7.1 Large Wood Tracking

The large wood tracking was completed in accordance with the June 9, 2021 Notice and Section 2.6.8 and Attachment C of the RSP (City Light 2021). The method used for large wood tracking was discussed with LPs during the July and October 2021 Geomorphology Work Group meetings with the LPs. The primary goals of the large wood tracking include:

- Identify and characterize what size of large wood moves in a flood peak;
- Determine distance and location of where the large wood moves and accumulates; and
- Determine characteristics of large wood that is most stable.

Active RFID (radiotags) manufactured by Lotek were used for tracking wood movement (Figure 4.7-1). The read range is greater than 1,000 ft when above water, and approximately 15 ft when below water. The tags have a lifespan of three to five years and frequency of 166.520 megahertz.

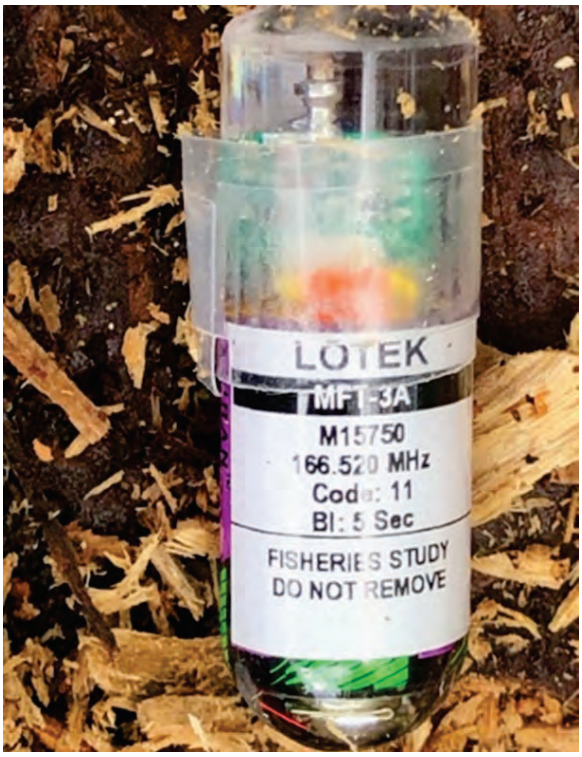


Figure 4.7-1. Lotek MFT-3A radiotag used to track large wood.

During the October 2021 Geomorphology Work Group meeting with the LPs, the study team presented a plan for tagging a variety of pieces in the mainstem, tributaries, and side channels throughout the primary study area. The pieces that had a radiotag installed included a distribution of lengths and diameters, species, orientation, location in the active channel, presence as racked or individual piece, and rootwad presence/absence. The study team installed the radiotags in the large wood with the following procedure:

- A piece of large wood greater than 1-ft dbh and 25-ft length was identified;
- Bark was removed from the area where the radiotag was installed;
- A hole of 1-inch by 3.5-inch dimensions was drilled in the wood (Figure 4.7-2);
- Clear silicone caulk was installed on top of the radiotag (Figure 4.7-2);
- A metal plate was screwed on top of the caulk (Figure 4.7-2);
- Antennae was laid out and stapled along the wood (Figure 4.7-2); and
- When possible, bark was replaced in the area where the tag and antennae were located.



Figure 4.7-2. Large wood installation of radiotags. Hole drilled and radiotag inserted (left). Hole filled with waterproof adhesive and metal brace screwed on top of hole and antenna stapled to log surface where bark was removed (right).

4.7.2 Large Wood Transport

The large wood transport analysis was completed in accordance with the June 9, 2021 Notice and Section 2.6.8 of the RSP (City Light 2021). Large wood transport analysis utilized the results of the large wood tracking effort (Section 4.7.1) as well as the FA-02 Instream Flow Model Development Study outputs (City Light 2023a).

4.7.2.1 Large Wood Transport Analysis

Transport of individual tagged large wood pieces were associated to flood events using the results of the large wood tracking effort and discharge data from USGS Skagit River at Newhalem gage (12178000). Large wood piece movement was associated to the peak discharge value that occurred at USGS Skagit River at Newhalem gage (12178000) between each instance of when the piece's location was known. For analysis, the study team assumed that the piece moved only once during the peak discharge event. Large wood stability for pieces that did not move during peak discharge values was also recorded.

4.7.2.2 Large Wood Transport Analysis with Hydraulic Model Results

Large wood tracking data was associated to several flood events to inform large wood transport data. Additionally, the FA-02 Instream Flow Model Development Study provided this study team with hydraulic model outputs for various flows in the primary study area. Using these two data

sets, the large wood transport results from the October 28-29, 2021, and November 15-16, 2021 flood events were associated to hydraulic model outputs that closely matched the peak discharge values during the October 2021 and November 2021 flood events.

Hydraulic model output runs provided by the FA-02 Instream Flow Model Development Study (City Light 2023a) are in the format of 3-ft resolution velocity, depth, and shear stress data that cover the extent of the primary study area. This study team used the depth and velocity data to examine the correlations between large wood piece geometry, mobility observed in the field, and magnitude of depth or velocity acting on the piece. The study team also used the depth and velocity data to create a model of the forces acting on an individual piece of large wood and examined how these forces compare with the mobility of each piece observed in the field. The volume of each piece with a rootwad was calculated by using established methods (Abbe 2000). The study team created a conceptual model to predict whether an individual large wood piece would be mobile or stable depending on the modeled depth and velocity of flow at the piece's initial and final locations, as well as the piece's geometry and predicted density. This conceptual model assumed all pieces were in the position of lying on the bed, not entrenched, and parallel to flow with the rootwad upstream. If a rootwad was not present, then the piece was assumed to be parallel to flow. The conceptual model accounted for drag force on the rootwad, buoyancy force on the piece, gravitational force on the piece, and frictional force from the bed on the piece depending on the depth and velocity values associated with the large wood piece at the location being analyzed (Figure 4.7-3). The drag coefficient used to calculate frictional force was assumed to be 0.5. Large wood tracking points that were not scanned in the field in their exact location for both flood events were excluded from this analysis. For each flood event using this analysis, three transport scenarios and their associated locations were examined. For large wood that was observed to be stable in the field after a flood event, hydraulic model data was extracted and analyzed from the one location where each piece was stable. For large wood that transported after a flood event, hydraulic model data was extracted and analyzed from both the initial location of the piece before the flood event and the final location of the piece after the flood event.

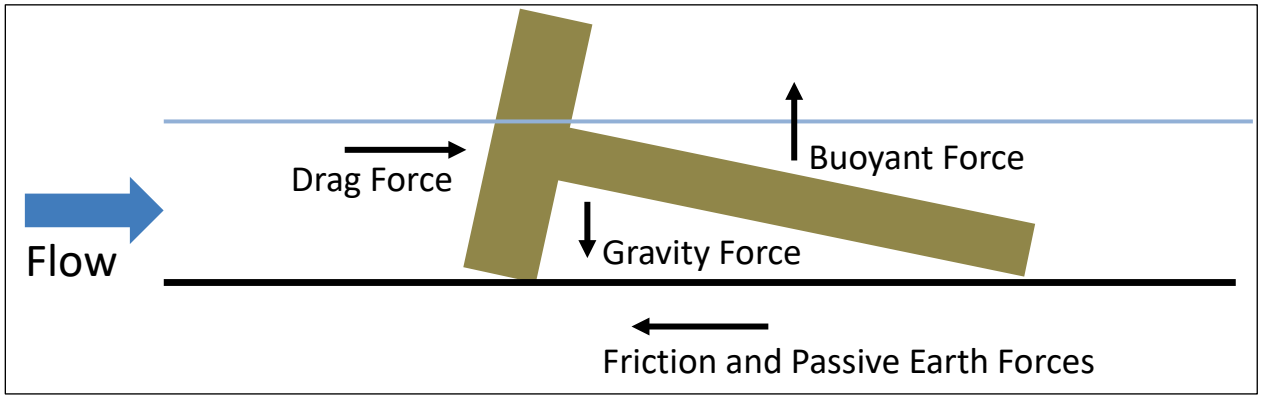


Figure 4.7-3. Primary forces acting on a piece of large wood.

4.7.3 Large Wood Recruitment

The purpose of the large wood recruitment study was to evaluate the potential for large wood loading from tributaries and bank erosion. The large wood recruitment study effort was completed in accordance with section 2.6.6 of the RSP (City Light 2021). The study effort was informed by bank erosion rates discussed in detail in Section 4.1.2, the TR-01 Vegetation Mapping Study (City Light 2022a), FA-02 Instream Flow Model Development Study (City Light 2023a), and vegetation data from the Washington State Department of Natural Resources (DNR) (DNR 2020).

Large wood recruitment potential was determined within the mainstem of the Skagit River primary study area and tributaries to the Skagit River primary study area that showed evidence of being a significant contributor of large wood. Determination of tributaries that showed evidence of being significant contributors of large wood to the Skagit River was based on the criteria that five or more large wood pieces were inventoried within 500 ft of the confluence with the Skagit River in the 2021 field inventory effort. Additionally, tributaries had to show evidence of historical channel migration with the aerial photo datasets that were available. The tributaries selected for this analysis were Goodell Creek, Bacon Creek, Diobsud Creek, and Cascade River. Although Newhalem Creek and Damnation Creek also met the criteria near their confluences with the Skagit River, they were not examined because migration was hard to identify in the canyon and steep slopes of these creeks.

Large wood recruitment potential was determined in the study areas discussed previously across three different time periods: 1998 to 2006, 2006 to 2019, and 2019 to 2039. Two different methods were used to determine the large wood recruitment potential for these three periods of analysis.

Large wood recruitment potential for the periods spanning 1998 to 2006 and 2006 to 2019 used the same method of analysis. Eroded bank area in the mainstem Skagit River for these two time periods was determined using data provided by the channel migration rates study effort discussed in detail in section 4.1.2. Eroded bank area in the tributaries selected for this analysis was completed separately for this section of the study. This was done following the same methods outlined in section 4.1.2 but using the four tributaries selected for recruitment analysis as the study area. Vegetation data for this analysis was provided by the Washington State DNR, Remote-Sensing Forest Resource Inventory System (RS-FRIS) (DNR 2020). This system uses regression analysis to relate forest plot measurements with remote sensing characteristics. Two datasets that were created from the RS-FRIS that were used in the large wood recruitment analysis are raster datasets that predict the density of trees with a stem greater than eleven inches in diameter and the density of trees with a stem greater than 31 inches in diameter at a resolution of $1/10^{th}$ of an acre. These two datasets were collected using remote sensing data from 2019.

Eroded bank areas for the two periods between 1998 and 2019 did not have any underlying vegetation data as the vegetation data being used for this analysis was from 2019. Aerial imagery for 1998 and 2006 was available. To determine large wood recruitment potential within these historical eroded bank areas, land classes were created to represent the average density of trees for a certain land class type visible in aerial imagery. A minimum of three or more sample land class polygons were created for each land class type in the primary study area using 2019 aerial photos. The average tree density for trees with either a stem diameter greater than 11 but less than 31 inches or greater than 31 inches was extracted from each sample land class polygon using the zonal statistics tool. These values were then averaged across each sample land class polygon and

assigned to each representative land class type (Table 4.7-1). Using these representative land class tree density values, the study team calculated the total number of trees recruited into the channel for each historical eroded area polygon depending on its determined land class type and total area. These were then summed to calculate the total number of trees recruited into the channel and tributaries that are greater than an 11-inch and 31-inch stem diameter for the 1998 to 2006 and 2006 to 2019 time periods. An example of this process displaying land class types and historical eroded bank area polygons overlaying 1998 aerial imagery is provided in Figure 4.7-4.

Table 4.7-1. Tree density values for each land cover class.

Land Class Type	Number of Trees per acre Greater than 11 inches (0.92 ft) dbh	Number of Trees per acre Greater than 31 inches (2.6 ft) in dbh
Forested	134	4.64
Vegetated Bar	28.5	0.385
Non-Vegetated Bar	0.970	0.0338
Clearcut	1.24	0.0326

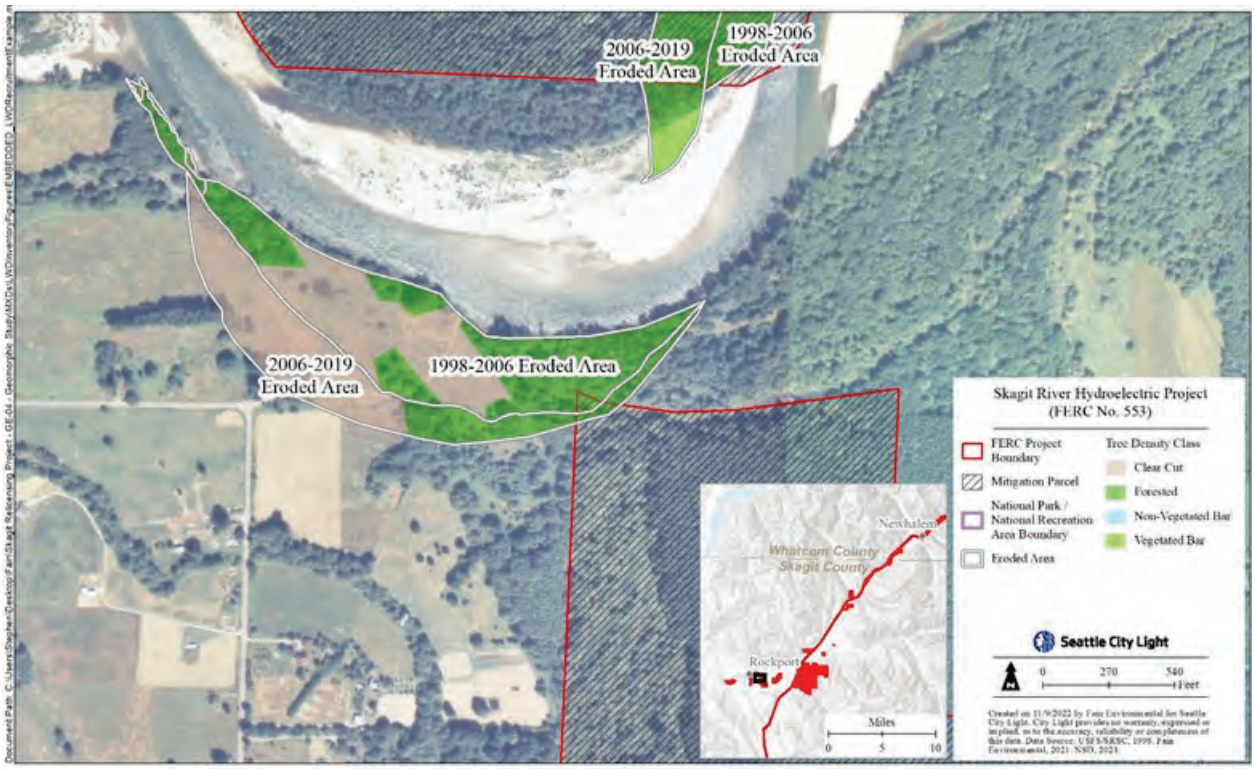


Figure 4.7-4. Example of historically eroded bank areas for the time periods 1998 to 2006 and 2006 to 2019 with underlying land class type. Basemap is aerial imagery from 1998.

Large wood recruitment potential for the period spanning 2019 to 2039 used a different method of analysis than what was used for 1998 to 2019. Eroded bank area for this period had to be extrapolated from present channel migration rates. The study team used channel migration rates using data from 1998 to 2019 rather than the entire channel migration rates study period of 1944

to 2019. Data from a more recent period better approximates the present-day channel dynamics. Channel migration rates in the tributaries examined for the large wood recruitment analysis were calculated separately using the methods described in Section 4.1.2 but using the tributaries as the study area instead of the Skagit River mainstem. Vegetation data was provided by the greater than 11-inch dbh and greater than 31-inch dbh datasets created using the Washington DNR RS-FRIS. Future eroded area polygons for the period 2019 to 2039 were created by extrapolating the 1998 to 2019 channel migration rate transects from the 2019 bank line to a predicted position using the 1998 to 2019 channel migration rate metrics. These positions were then used to estimate a future eroded bank area from 2019 to 2039. Using the future eroded bank area polygons, the RS-FRIS stem density datasets were used to calculate the estimated number of trees greater than an 11-inch stem diameter and the number of trees greater than a 31-inch stem diameter that underlie the predicted eroded bank area in the mainstem and tributaries. This metric was calculated by multiplying the average stem density underlying each future bank erosion polygon by the total area of that polygon, resulting in the number of trees that could potentially be recruited for the 2019 to 2039 period. An example of this process displaying the future eroded bank area polygons, the greater than 11-inch dbh data, and aerial imagery from 2019 are displayed in Figure 4.7-5.

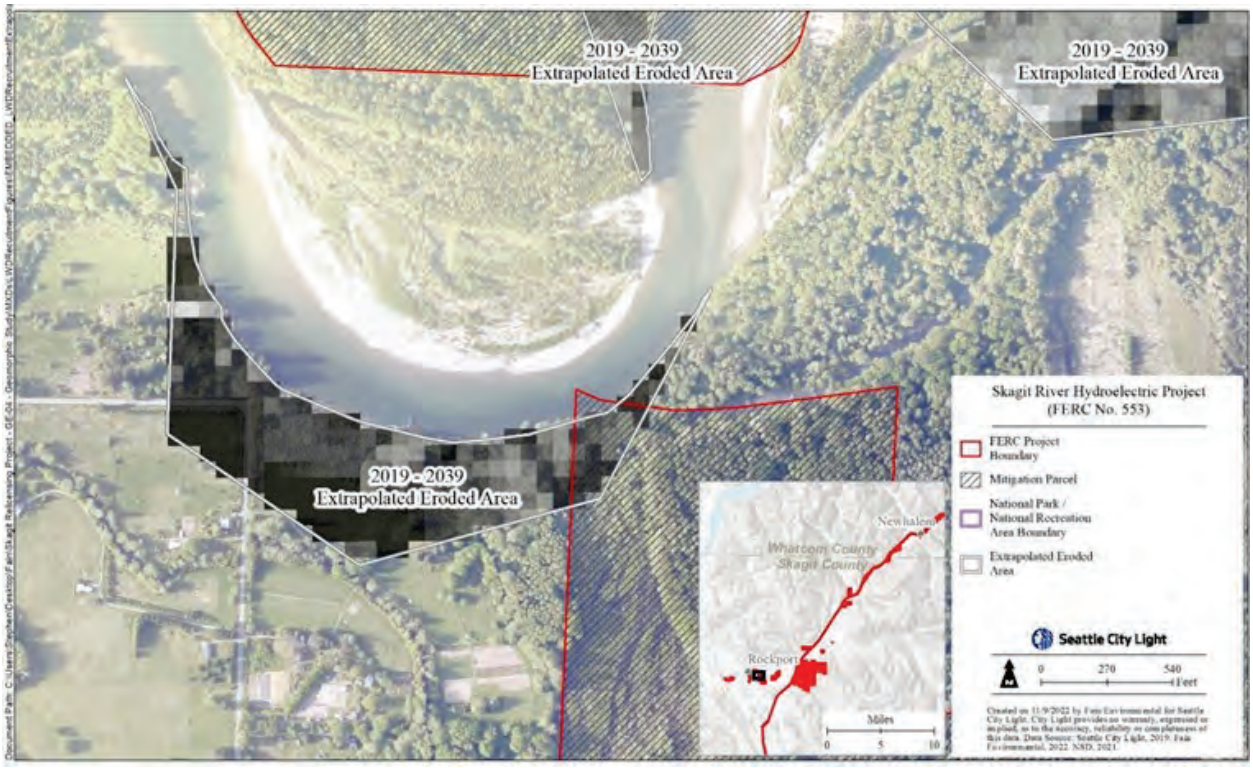


Figure 4.7-5. Example of future eroded bank areas for the period 2019 to 2039 with underlying greater than 11-inch dbh dataset. Basemap is aerial imagery from 2019.

This study presents an approximation of past and future wood recruitment in the primary study area. The study team assumes that all forested areas have the same density of trees greater than 31 inches and greater than 11 inches (Table 4.7-1). These standardized values do not capture the complexity of natural systems. Some areas may be dominated by old growth, where others may have been logged in the past 40 years. This study assumes that the tributaries will continue to follow their past migration patterns. This analysis does not consider differences in terrain, ground

composition, and hard boundaries, both man-made and natural, that might limit lateral migration. This study also does not approximate the percentage of large wood recruited in tributaries that transports to the mainstem Skagit River.

4.7.4 Large Wood Augmentation

As described in the June 9, 2021 Notice, City Light will determine locations and methods for wood augmentation within six months of the FA-02 Instream Flow Model Development Study model being completed. The information will be used as part of the Final License Application (FLA) and PME development process to assess potential wood augmentation and habitat restoration plans for the new license. Additional discussion is provided in Section 6.7.4.

4.8 Process Flows

As described in Section 2.6.7 of the RSP (City Light 2021), process flows are identified as high flow events that support a variety of geomorphic processes and habitat values. Based on information and analysis described in sections above, flows associated with the following processes were investigated:

- Flows that mobilize river bar deposits;
- Flows that mobilize deposits at tributary mouths;
- Flows that erode river banks and contribute to channel migration
- Flows that instigate side channel development/maintenance; and
- Flows that hydraulically connect side channel and off-channel habitat.

The evaluation of process flows integrates results developed from hydraulic models and sediment transport models with observational bed mobility data from scour monitors and particle tracers to characterize flows that initiate bedload movement at river bars, tributary mouths, and riverbanks. The methodology applied to these sediment transport analyses is described above in Section 4.5.

Flows that erode river banks and contribute to channel migration and development/maintenance of side channel habitat were evaluated using results from the analysis of geomorphic change using historical aerial imagery and recent LiDAR data as described in Section 4.1.

Connectivity of side channel and off-channel habitat was evaluated using a combination of hydraulic model results from the FA-02 Instream Flow Model Development Study (City Light 2023a). Data from floodplain water level loggers were integrated with hydraulic model results and field observations to refine evaluation of connectivity at side channel junctions (Section 4.3.1 and Attachment U).

The Indicators of Hydrologic Alteration (IHA) software program was used to investigate the timing and duration of different types of high flow events under unmanaged (unregulated) conditions. Unregulated daily flows at USGS gaging stations at Newhalem, Marblemount, and Concrete were estimated for the 32-year period spanning water years (WY) 1989-2020 using calculated inflows at upstream reservoirs developed for use in the Skagit Operations Model. A detailed discussion of the development of the flow data for the Skagit River Hydroelectric Project

is included in Appendix 1 of the Skagit Operations Model Logic and Validation Report (Attachment A to OM-01 Operations Model Study, City Light 2023f).

The IHA analysis calculated a suite of hydrologic parameters describing: (1) monthly flow magnitude; (2) magnitude and duration of annual extreme (min/max) water conditions; (3) timing of annual extreme water conditions; (4) frequency and duration of high and low pulses; and (5) rate and frequency of water condition changes or reversal. A second suite of parameters were calculated to represent Environmental Flow Components (EFCs) representing different types of flow events considered necessary to sustain the ecological integrity of a river system (Mathews and Richter 2007): (1) extreme low flows; (2) low flows; (3) high flow pulses; (4) small floods (peak flow events exceeding the unregulated 2-year recurrence interval); and (5) large floods (peak flow events exceeding the unregulated 10-year recurrence interval).

IHA calculates the mean values and coefficient of variation for each parameter and characterizes hydrologic alteration as the magnitude and percentage of change in mean values between the unregulated and regulated flow series. A technical memorandum included as Attachment T describes additional detail of the data and methods used in the IHA analysis.

5.0 RESULTS

Existing information collected as part of the pre-field analysis informed the implementation of this study and is integrated into analyses described below. Additional reports on Skagit River geomorphology downstream from the Sauk River confluence are summarized in Attachment A.

Study results are organized by topic areas in the following subsections as described in the RSP (City Light 2021):

- Geomorphic change (Section 5.1);
- Aquatic habitat (Section 5.2);
- Side channels and off-channel habitat (Section 5.3);
- Substrate/sediment (Section 5.4);
- Sediment transport (Section 5.5);
- Large wood inventory (Section 5.6);
- Large wood transport (Section 5.7); and
- Process flows (Section 5.8).

5.1 Geomorphic Change

5.1.1 Historical Channel Migration and Planform Characteristics

Results of channel migration patterns mapped from aerial imagery of the period 1944-2019 show moderate changes in planform channel characteristics for geomorphic reaches between Newhalem and Marblemount and more pronounced channel migration activity in the reaches between Marblemount and the Sauk River confluence. Downstream variability in channel characteristics is summarized in Table 5.1-1. Attachment D presents a mapbook showing floodplain elevations relative to the low flow WSE of the active channel based on composite of recent (2016-2018) LiDAR data.

A series of historical maps and aerial imagery used in in mapping of active channel polygons are presented in Attachment E. Channel width measured from aerial imagery shows reach scale variability between the more confined, less dynamic reaches 2 through 5 and more dynamic reaches 6 and 7 (Figure 5.1-1). The time series of active channel width by reach shows slowly decreasing trends since 1944 (Figure 5.1-2). The average width combined for all reaches between Newhalem and the Sauk River decreased by 8 percent. Reaches 3A, 3B, and 7A were most sensitive with decreased channel widths of 18, 12, and 15 percent, respectively (Table 5.1-2).

Channel sinuosity remained steady in all reaches over the period 1944-2019 with only minor adjustments of +/- 2 percent (Table 5.1-3). There were earlier channel adjustments in the early 1900s resulting in bend cutoffs that reduced sinuosity in Reach 6 near Barnaby Slough and Illabot Creek. The Illabot bend cutoff occurred after 1915 and resulted in a 22 percent decrease in length and sinuosity in Reach 6 between 1915 and 1944.

Table 5.1-1. Summary of reach characteristics.

Reach	Gradient	Channel Length (miles)	Sinuosity	Average Active Channel Width (ft)	Length of Hydro-modified Banks (ft)		Percentage of Banks with Hydro-modifications	
					Left	Right	Left	Right
1	0.0189	2.5	N/A	N/A	N/A	N/A	N/A	N/A
2A	0.0036	1.2	1.10	216	0	0	0%	0%
2B	0.0031	4.1	1.11	324	0	570	0%	3%
3A	0.0015	1.9	1.10	234	0	3,680	0%	37%
4	0.0022	3.5	1.21	233	0	4,340	0%	23%
3B	0.0018	2	1.16	325	620	2,270	6%	21%
5A	0.0015	3.5	1.05	325	630	0	3%	0%
5B	0.0014	3.7	1.27	382	180	3,210	1%	16%
6	0.0018	6.7	1.21	537	180	7,210	1%	20%
7A	0.0004	1.3	1.04	520	0	1,430	0%	21%

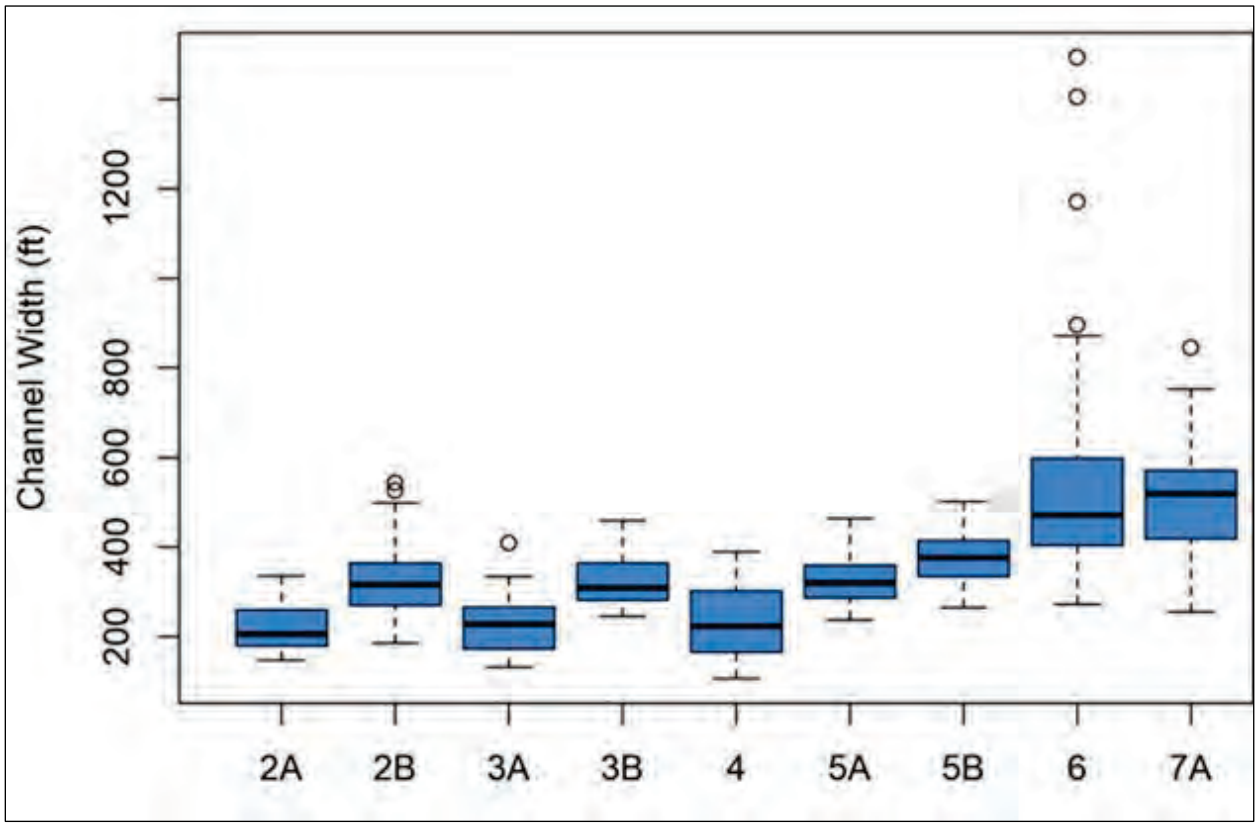


Figure 5.1-1. Variability in 2019 active channel width, by reach. Horizontal bars represent the median value of transects in a given reach, boxes show the interquartile range (IQR) and whiskers extend to 1.5 x IQR.

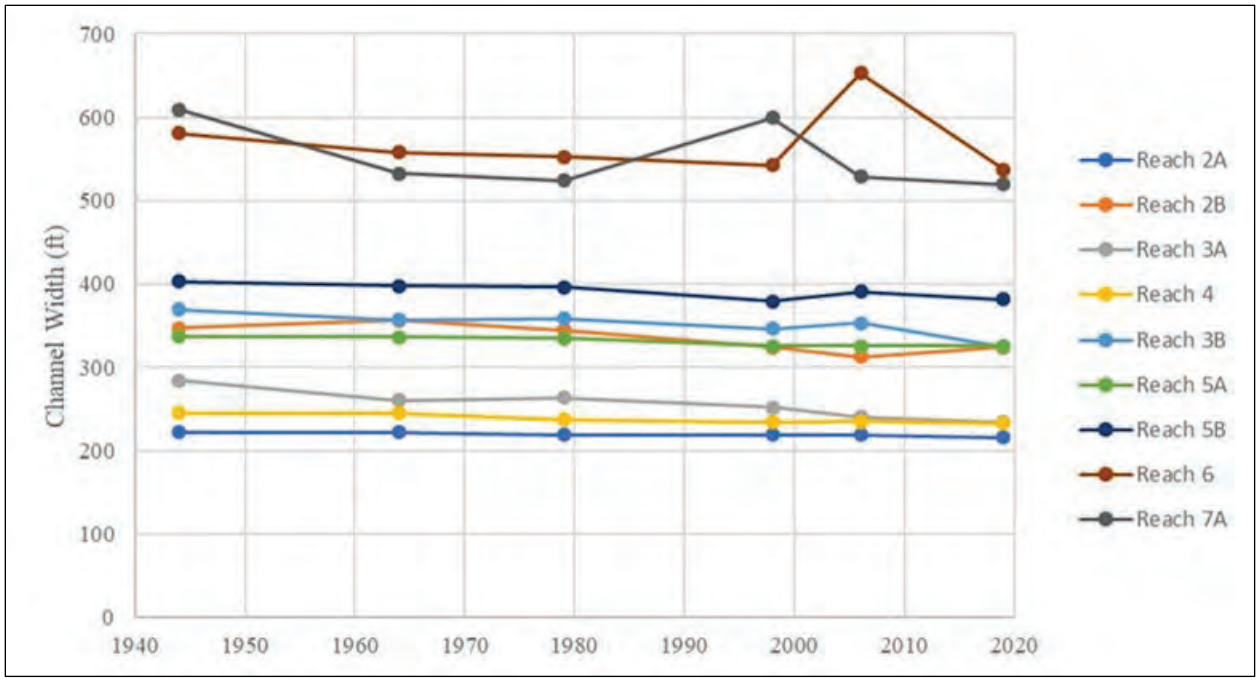


Figure 5.1-2. Trends in active channel width by reach, 1944-2019.

A time series comparing the 1915 topographic map with subsequent aerial imagery for the period 1944-2019 along with maps showing the historic channel positions and channel occupancy are included in Attachment E. Lateral migration rates (1944-2019) by reach are summarized in Table 5.1-4.

The peak flow history at USGS gaging stations in the Skagit River at Newhalem (USGS gage 12178000) and at Marblemount (USGS gage 12181000) are overlaid with years selected in time series of aerial imagery in Figure 4.1-1 and 4.1-2 and summarized by interval in the historical time series of aerial imagery in Table 5.1-5.

Measurement of lateral migration distances between intervals in the historical time series illustrates the downstream variability among reaches (Figure 5.1-3). Historical trends in lateral migration rate are summarized by reach in Figure 5.1-4 and illustrated in maps comparing 1944 imagery with 2019 imagery in Figures 5.1-5 through 5.1-15. Key findings from the evaluation of historical channel changes are summarized by reach below.

Table 5.1-2. Active channel width changes through time based on historical aerial imagery.

Reach	1944	1963/64	1978/78	1998	2006	2019	Change 1944-2019
2A	222	222	219	219	219	216	-3%
2B	347	356	344	324	313	324	-7%
3A	284	261	264	252	240	234	-18%
4	245	245	237	235	235	233	-5%
3B	369	357	359	346	353	325	-12%
5A	337	336	335	326	325	325	-3%
5B	403	398	396	379	390	382	-5%
6	581	558	552	542	653	537	-8%
7A	609	533	524	599	529	520	-15%

Table 5.1-3. Channel sinuosity changes through time based on historical aerial imagery.

Reach	1944	1963/64	1978/78	1998	2006	2019	Change 1944-2019
2A	1.09	1.10	1.10	1.10	1.09	1.10	0.8%
2B	1.09	1.09	1.10	1.11	1.11	1.11	1.0%
3A	1.11	1.09	1.14	1.08	1.09	1.10	-0.8%
4	1.22	1.20	1.21	1.21	1.21	1.21	-0.3%
3B	1.17	1.14	1.15	1.15	1.16	1.16	-1.7%
5A	1.05	1.05	1.05	1.05	1.05	1.05	0.1%
5B	1.29	1.26	1.27	1.27	1.27	1.27	-1.9%
6	1.22	1.23	1.23	1.18	1.19	1.21	-0.4%
7A	1.05	1.04	1.04	1.04	1.04	1.04	-1.6%

Table 5.1-4. Summary of lateral migration rates (1944-2019) by reach.

Reach	Eroded Area 1944-2019 (acres)	Average Lateral Migration (ft)	Lateral Migration Rate (ft/yr)
2A	0	0	0.0
2B	13.5	27	0.4
3A	1.5	7	0.1
4	0.7	3	0.0
3B	2.9	7	0.1
5A	1.8	4	0.1
5B	12.9	29	0.4
6	248	305	4.1
7A	7.3	47	0.6

Table 5.1-5. Summary of peak flow (1944-2019) by time series interval.

	at Newhalem (USGS Gage 12178000)		at Marblemount (USGS Gage 12181000)	
Reach	**Peak Flow (cfs)**	**Date**	**Peak Flow (cfs)**	**Date**
1944-1964	28,900	7/9/1964	59,300[1]	11/27/1949
1964-1979	36,700	6/21/1967	26,400[1]	7/14/1976
1979-1998	32,300	12/2/1995	62,300	11/29/1995
1998-2006	36,800	10/22/2003	64,300	10/20/2003
2006-2019	28,100	11/8/2006	52,000	11/6/2006

1 Based on partial record; no data at Marblemount 1957-1975.

Reach 1 (Gorge bypass reach) lateral channel migration was not assessed because Reach 1 is bedrock controlled.

Reach 2A represents the transition where the Skagit River emerges into the lower gradient valley that has been widened by alpine glaciation (Figure 5.1-5). The channel is confined by terraces and armored by large cobble and boulder-sized sediments along the bank. No detectable observations of lateral channel migration were recorded in Reach 2A over the period 1944-2019.

Reach 2B continues from the bridge at Newhalem Campground downstream to the County Line. Overall, lateral migration in Reach 2B averaged 0.4 ft/yr. Observation of historical channel changes in reach 2B include:

- A gradual decrease in connectivity between the mainstem and a side channel along the left bank downstream of Goodell Creek (side channel 92.8-L; further described in Section 5.3.1 of this study report) due to sedimentation and encroaching vegetation (Figure 5.1-5; Attachment E, sheet 2); Pronounced sedimentation at the side channel between 1998 and 2006 imagery suggests that sediment inputs from the 2003 Goodell Creek landslide could be an important contributing factor to the decline in side channel connectivity.
- Little to no change in the island between the mainstem and side channel at PRM 92.8.
- Growth of a mid-channel bar at PRM 92 that has developed into a vegetated island near the confluence with Babcock Creek and deflected flow laterally into the banks opposite the developing island causing toe scour and lateral bank migration of 5 ft/yr from 1964-1979 with ongoing toe scour that maintains a near vertical bank to the north of the developing island.
- Historical channel migration between PRM 90 and 91 led to development of a side channel complex near the confluence with Thornton Creek (Figure 5.1-6; Attachment E, sheet 3). Historical mapping in 1915 shows an anabranching channel pattern with two islands or mid-channel bars in this segment at that time. The upper bar from PRM 90.5 to 91 grew in the downstream direction between 1915 and 1944, then stabilized with vegetation between 1944 and 1964. Secondary channels connecting with the Thornton side channel complex appear better defined in imagery prior to 1998 but have since narrowed with sedimentation and vegetation encroachment. A secondary channel spilling laterally from the mainstem into the

side channel has grown in recent years and showed evidence of widening in 2021 field reconnaissance.

- Clearing of riparian vegetation and extraction of gravel from the floodplain at the County Line Ponds resulted in channel widening between PRM 89.2 and 89.8 from 1944-1964. Subsequent formation of a mid-channel bar has formed an island near PRM 89.5. Flow deflected toward the right bank upstream of the island breached the berm separating the pond from the mainstem between 1998 and 2006, allowing a portion of the flow to spill laterally into the pond complex.
- Toe scour along the right bank is creating localized bank migration toward the pond complex from PRM 89.8 to 90.

Reach 3A is confined by resistant bedrock, large debris fans, and riprap that lines the channel along SR 20. Observations within this reach include:

- An alluvial terrace flanks the channel along the left bank from the county line to the confluence with Sky Creek, but the bank has been stable throughout the record of aerial imagery.
- A side channel near Damnation Creek was more clearly connected with the mainstem in the 1915 map and 1944 imagery, then becomes less connected over time, as the side channel is affected by sedimentation and vegetation encroachment (Figure 5.1-7).
- Minor amounts of localized bank erosion were observed downstream of Damnation Creek between PRM 87.6 and 87.8 from 1964-1979 and 1979-1998 where sediment deposition has formed bars within the channel upstream of the valley confinement entering the landslide zone.

Reach 4 is the confined valley segment within the landslide zone. Observations within this reach include:

- The channel is composed of coarse sediment and boulders, and riprap armors the banks in segments along SR 20.
- Minor changes in channel planform have occurred downstream of Alma Creek near PRM 85.4 (Figure 5.1-8).

Reach 3B is a continuation of the narrow valley segment downstream of the landslide zone and includes the confluence with Bacon Creek (Figure 5.1-9). Historical channel changes in Reach 3B are minor and include:

- Development of a bar extending from the left bank downstream and across from Bacon Creek (PRM 89) associated with lateral migration towards an island on the opposite (right) bank between 1964 and 1979; subsequent development of a pond in the abandoned channel separated from the mainstem by the vegetated bar is apparent by 1998.
- Formation of a log jam at the inlet to a side channel along the right bank downstream of Bacon Creek between 1979 and 1998 and subsequent sediment deposition and vegetation encroachment decreasing connectivity with the side channel over time.

Reach 5A enters a widened valley downstream of the Straight Creek Fault; however, the channel is inset within 10- to 20-ft-high banks flanked by alluvial terraces marked by relict channel features. Only one area of localized bank erosion was recorded. Observations from the record of historical imagery include:

- Sedimentation and vegetation encroachment limiting side channel connectivity upstream of Diobsud Creek at PRM 81.6 (Figure 5.1-10); the side channel is well defined in 1915 USGS map, had a unvegetated channel connecting to the mainstem in 1944 imagery, and vegetation became progressively established at the upstream connection beginning with the 1964 imagery (Attachment E, sheet 6).
- Sedimentation and vegetation encroachment on the tributary fan at the confluence with Diobsud Creek; moderate deposition noted along right bank at confluence between 1944 and 1964, then establishment of vegetation stabilized the deposits between 1964 and 1979.
- Localized erosion along the left bank across from Diobsud Creek at PRM 81 concurrent with the bar growth on the opposite bank at the confluence. Erosion began between 1944 and 1964, continued between 1964 and 1979, then shifted the focus of bank erosion slightly downstream of the tributary confluence between 1979 and 1998 (Attachment E, sheet 6). No detectable erosion was noted in the periods since 1998.
- Sedimentation and vegetation encroachment limiting side channel connectivity downstream of Diobsud Creek at PRM 80.8; similar to the side channel upstream at PRM 81.6, the side channel at PRM 80.8 is well defined in 1915 USGS map, had an unvegetated channel connecting to the mainstem in 1944 imagery, and vegetation became progressively established at the upstream connection beginning with the 1964 imagery (Attachment E, sheet 6).

Reach 5B continues from the confluence with the Cascade River downstream to Rocky Creek (Figure 5.1-11). Observations within this segment include:

- Right bank erosion downstream of the Cascade River (PRM 77.6) between 1944-1964 and subsequent armoring of the eroding bank by riprap.
- Left bank erosion between PRM 77.4 and 77.6 resulting in development of a split flow channel that has persisted since the 1990s (Attachment E, sheet 7).
- Toe scour and lateral bend migration on the left bank between PRM 74.4 and 75 between 1979 and 1998 (then continuing at lower rate between 1998 and 2006) and concurrent toe scour and bend migration into the terrace on the opposite (right) bank downstream of Corkindale Creek (Figure 5.1-12; Attachment E, sheet 8).

Reach 6 represents the most dynamic segment of the study area and includes areas with large meander cutoffs near Illabot Creek and Barnaby Slough. Key observations from the record of historical maps and imagery within this reach include:

- A large-scale bend cutoff abandoned the meander known as Barnaby Slough in the early 1900s (prior to 1915 topographic map) and shortened the channel length between PRM 70.5 and 71. The bend cutoff at Barnaby Slough is further discussed in previous work by SRSC and NSD (2019).

- A second bend cutoff then occurred upstream and abandoned the meander near Illabot Creek (PRM 73 to 73.5) between 1915 and 1944 (Attachment E, sheet 9).
- The new channel that cut off the bend near Illabot Creek split into two flow paths around a developing island and erosion along the right bank near PRM 73 produced lateral migration to the north between 1944 and 1964 that was subsequently halted by placement of riprap (Figure 5.1-13).
- The left bank to the south of developing island erosion eroded between PRM 73.2 and 73.4 from 1944 to 1964, was relatively stable from 1964-1979, then eroded further over a long segment extending from PRM 73 upstream to Rocky Creek near PRM 74 between 1979 and 1998. Ongoing left bank erosion in this segment downstream of Rocky Creek has continued episodically (Attachment E, sheet 9).
- The right bank is armored by riprap near the next bend downstream where the channel is parallel to the embankment along SR 20 between PRM 72 and 72.5.
- The left bank between the two armored sections has adjusted by migrating laterally over 1,000 ft since 1944 near PRM 72.5; toe erosion drove bank erosion between 1944 and 1964. A mid-channel bar then formed resulting in additional left bank erosion between 1964 and 1979; ongoing migration toward the left bank has since formed an extensive point bar on the opposite bank that has grown progressively over time (Attachment E, sheet 9).
- Bank protection on the right bank along SR 20 near RM 72 deflects flow to the opposite bank and the left bank has been progressively eroding near the confluence with Illabot Creek.
- The channel segment adjacent to Barnaby Slough has remained relatively static with only localized areas of left bank erosion across from a developing bar near the confluence with Barr Creek and Sutter Creek (PRM 70.6 to 71).
- A meander across from Barnaby Slough has progressively migrated downstream further shortening channel length and forming the relict channel features containing wetlands on the north side of the valley near Washington Eddy (Attachment E, sheet 10). In 1915, the outer bank was located near PRM 70.2 and then migrated 460 ft in a downstream direction between 1915-1944 (16 ft/yr), 420 ft from 1944-1964 (21 ft/yr), 440 ft from 1964-1979 (29 ft/yr), 440 ft from 1979-1998 (23 ft/yr), 170 ft from 1998-2006 (21 ft/yr), and 480 ft from 2006-2019 (37 ft/yr).
- Riprap previously armored the left bank downstream of Washington Eddy until the 1990s when erosion flanked the riprap and initiated a period of rapid lateral migration along the meander bend at PRM 69 near Martin Road (Figure 5.1-14; Attachment E, sheet 11); lateral migration of the meander bend near PRM 68.8 progressed 290 ft toward Martin Rd from 1998-2006 (36 ft/yr) and 290 ft from 2006-2019 (22 ft/yr).

Reach 7 continues along the margin of the Sauk River alluvial fan.

- The right bank is armored throughout this segment near the Rockport bridge and the segment upstream of the bridge appears to have been armored prior to the 1944 imagery.
- Channel dynamics in this reach have been dominated by westward migration of the Sauk River along the alluvial fan over the period 1944-2019.

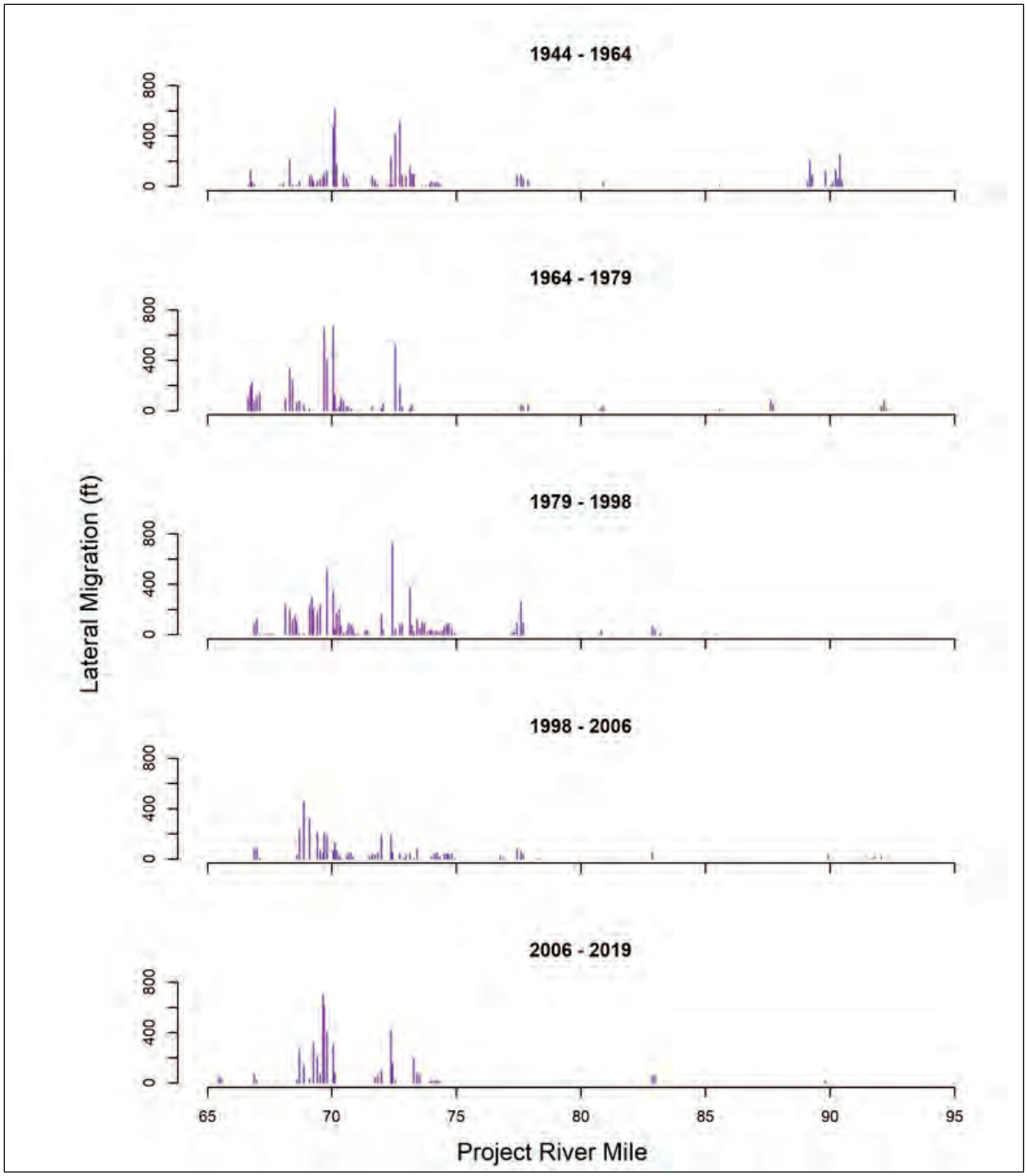


Figure 5.1-3. Downstream trends in lateral migration distance over the period 1944-2019.

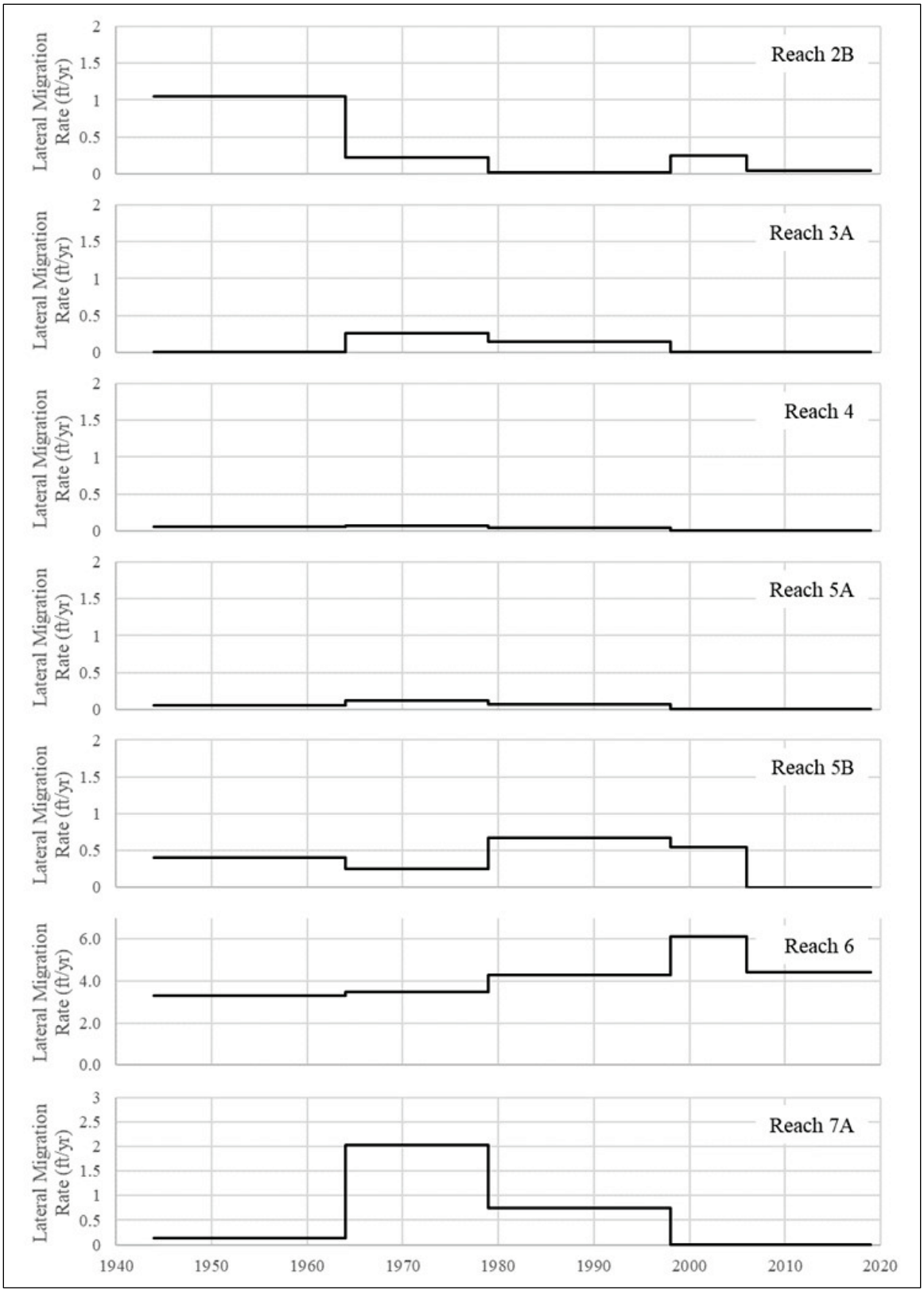


Figure 5.1-4. Time series of lateral migration rates by reach over the period 1944-2019. Reach 2A not shown (no lateral migration 1944-2019).

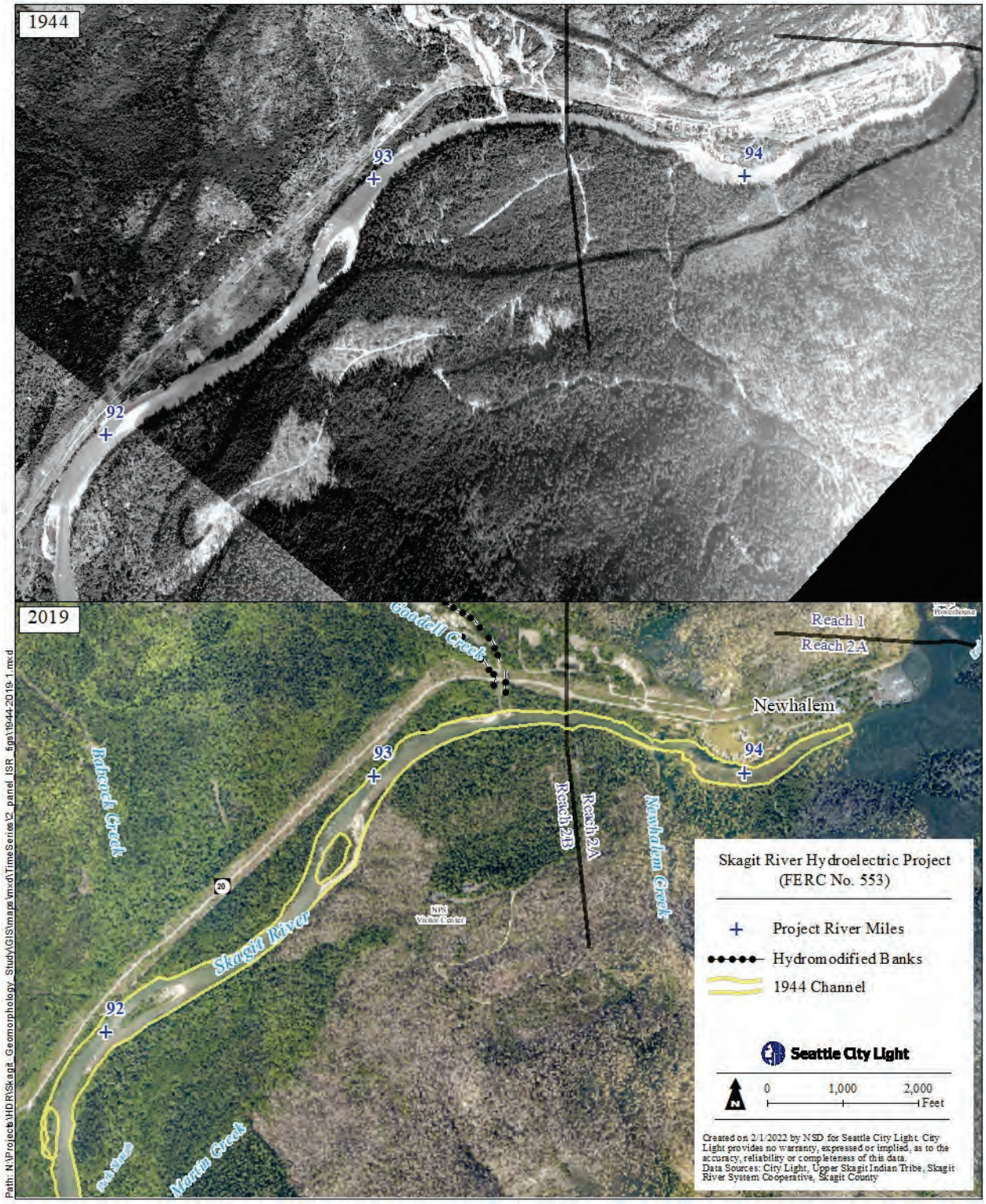


Figure 5.1-5. Comparison of 1944 and 2019 imagery in Reach 2A and upper segment of Reach 2B.



Figure 5.1-6. Comparison of 1944 and 2019 imagery in lower segment of Reach 2B.



Figure 5.1-7. Comparison of 1944 and 2019 imagery in Reach 3A and upper segment of Reach 4.

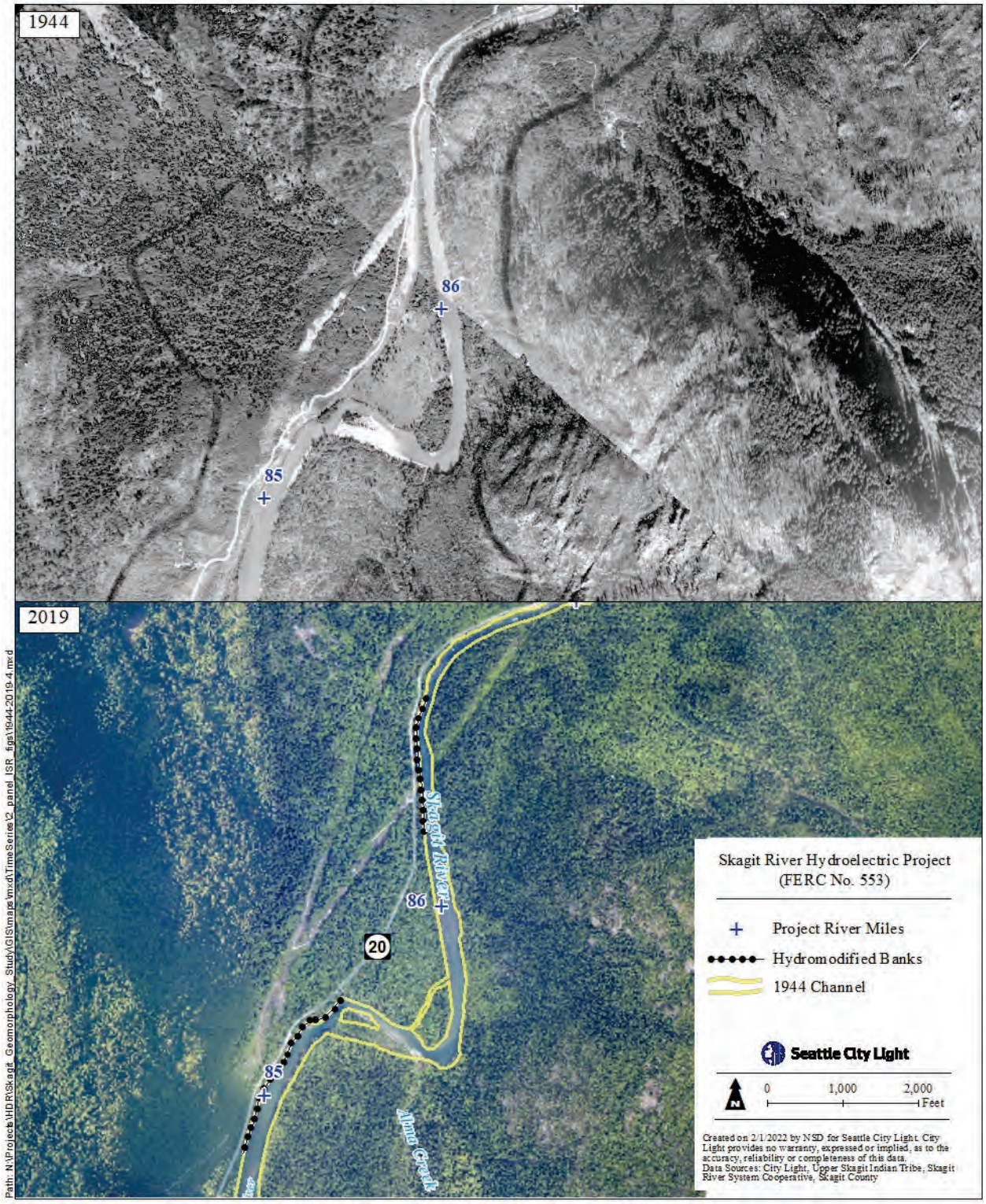


Figure 5.1-8. Comparison of 1944 and 2019 imagery in Reach 4.



Figure 5.1-9. Comparison of 1944 and 2019 imagery in Reach 3B.

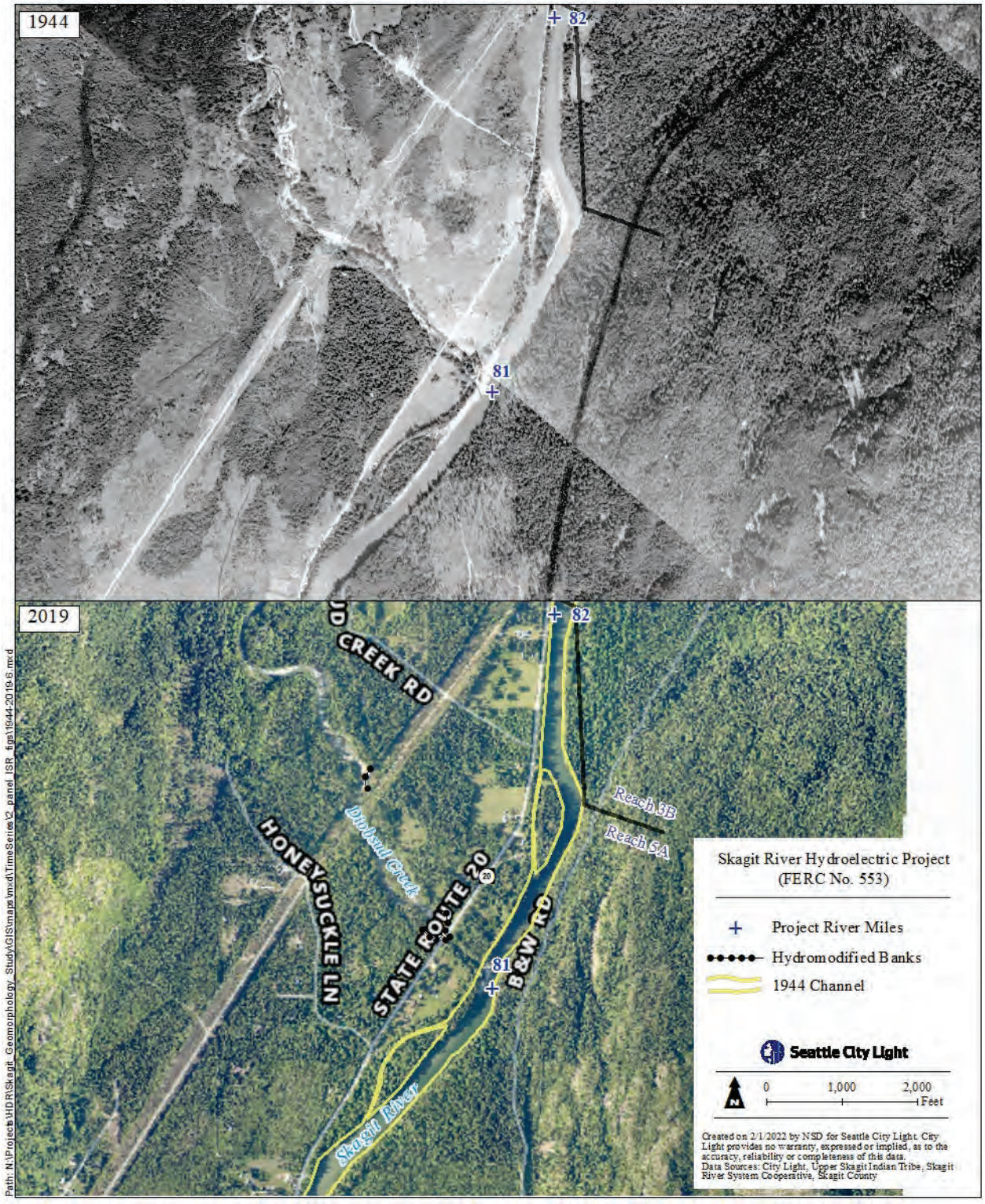


Figure 5.1-10. Comparison of 1944 and 2019 imagery in upper segment of Reach 5A.

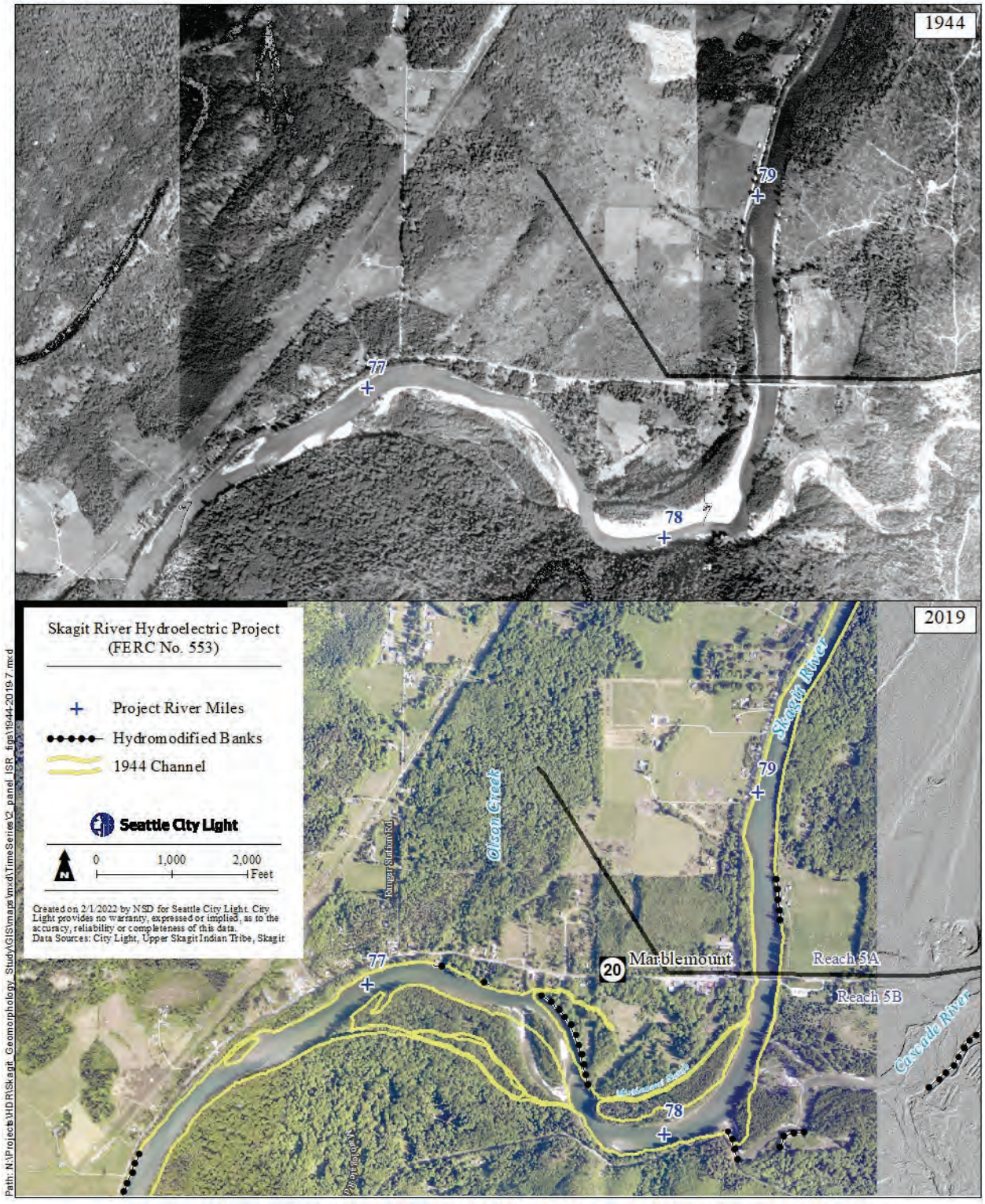


Figure 5.1-11. Comparison of 1944 and 2019 imagery in Reach 5A and upper segment of Reach 5B.

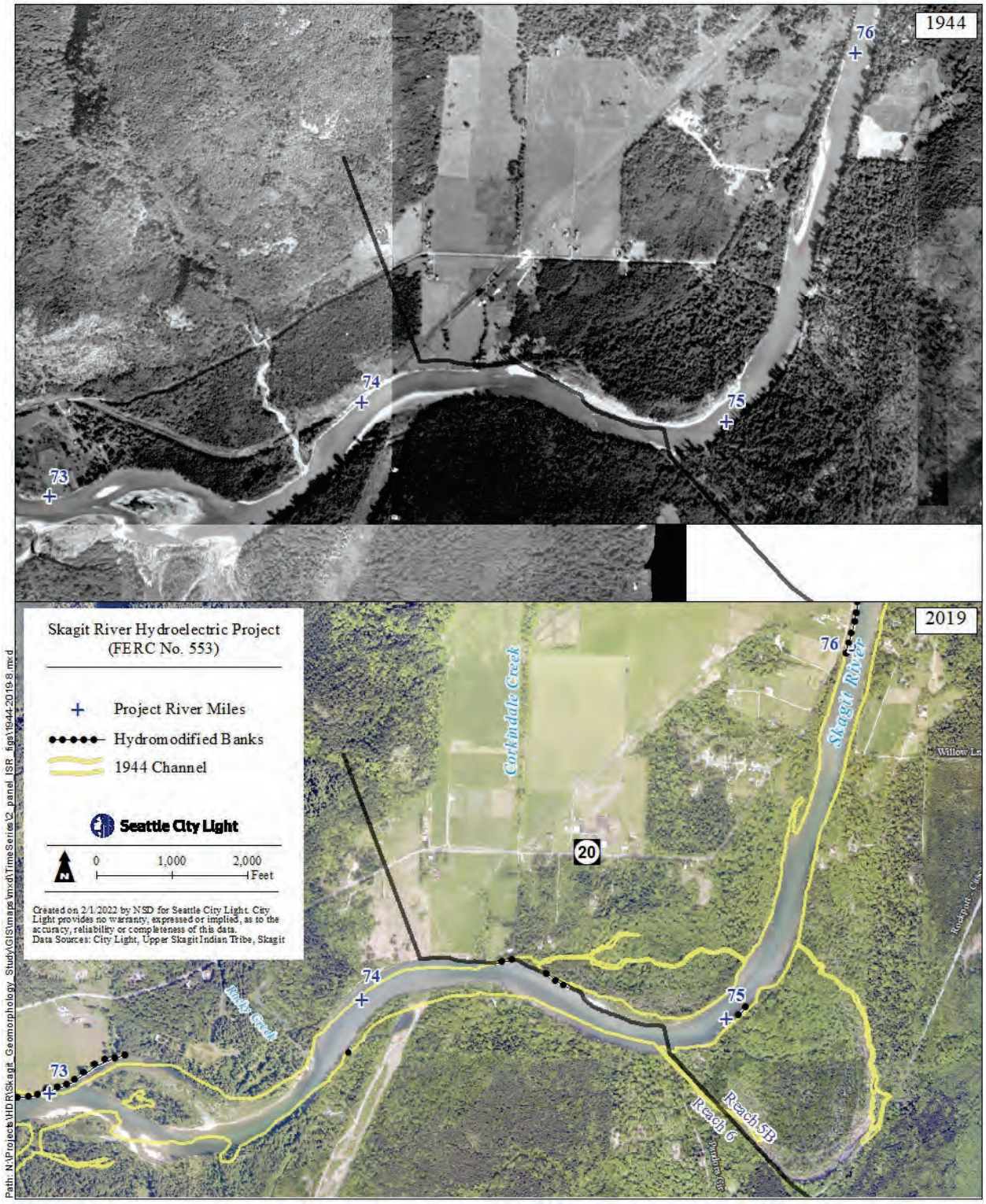


Figure 5.1-12. Comparison of 1944 and 2019 imagery in lower segment of Reach 5B and upper segment of Reach 6.

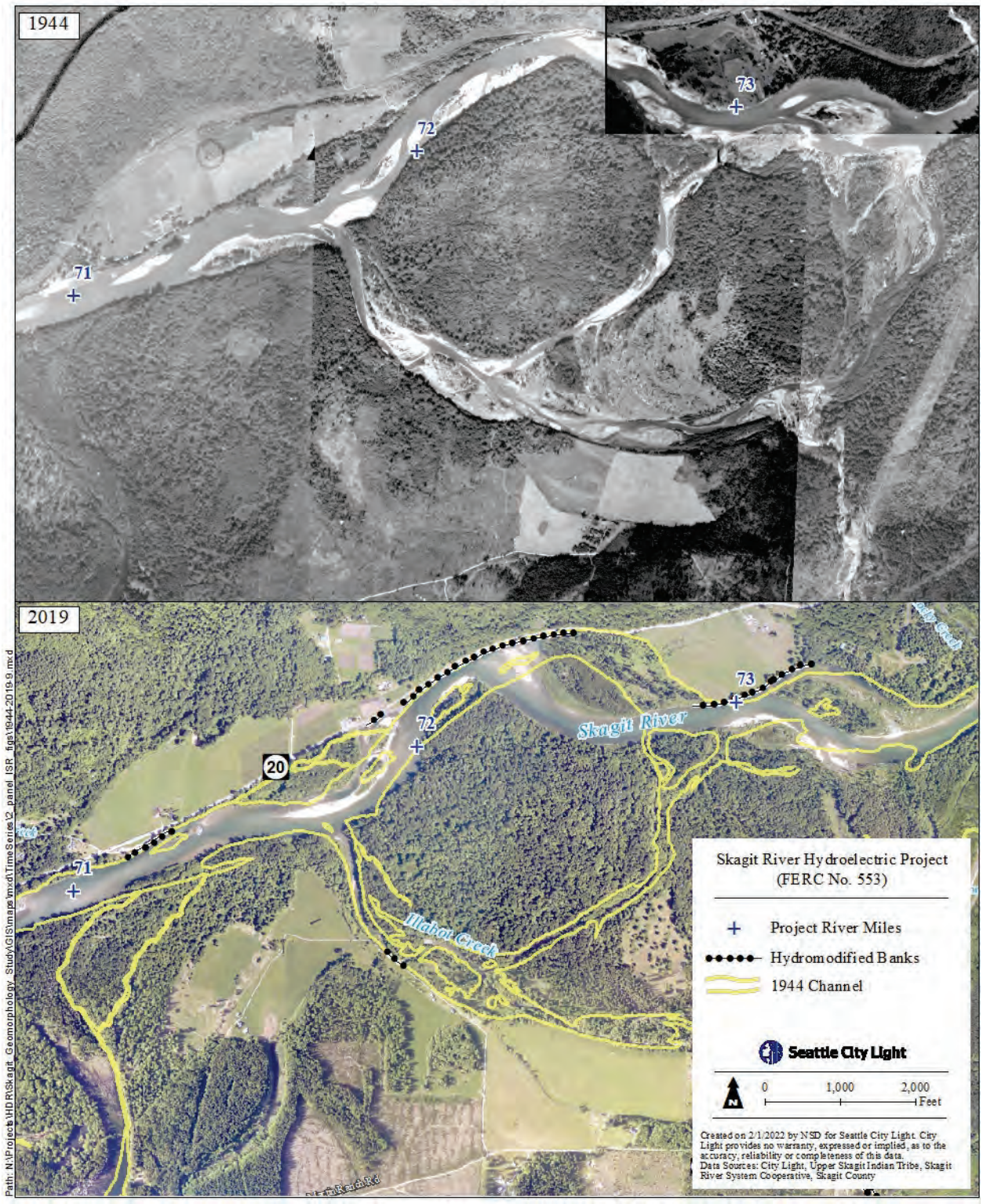


Figure 5.1-13. Comparison of 1944 and 2019 imagery in middle segment of Reach 6.

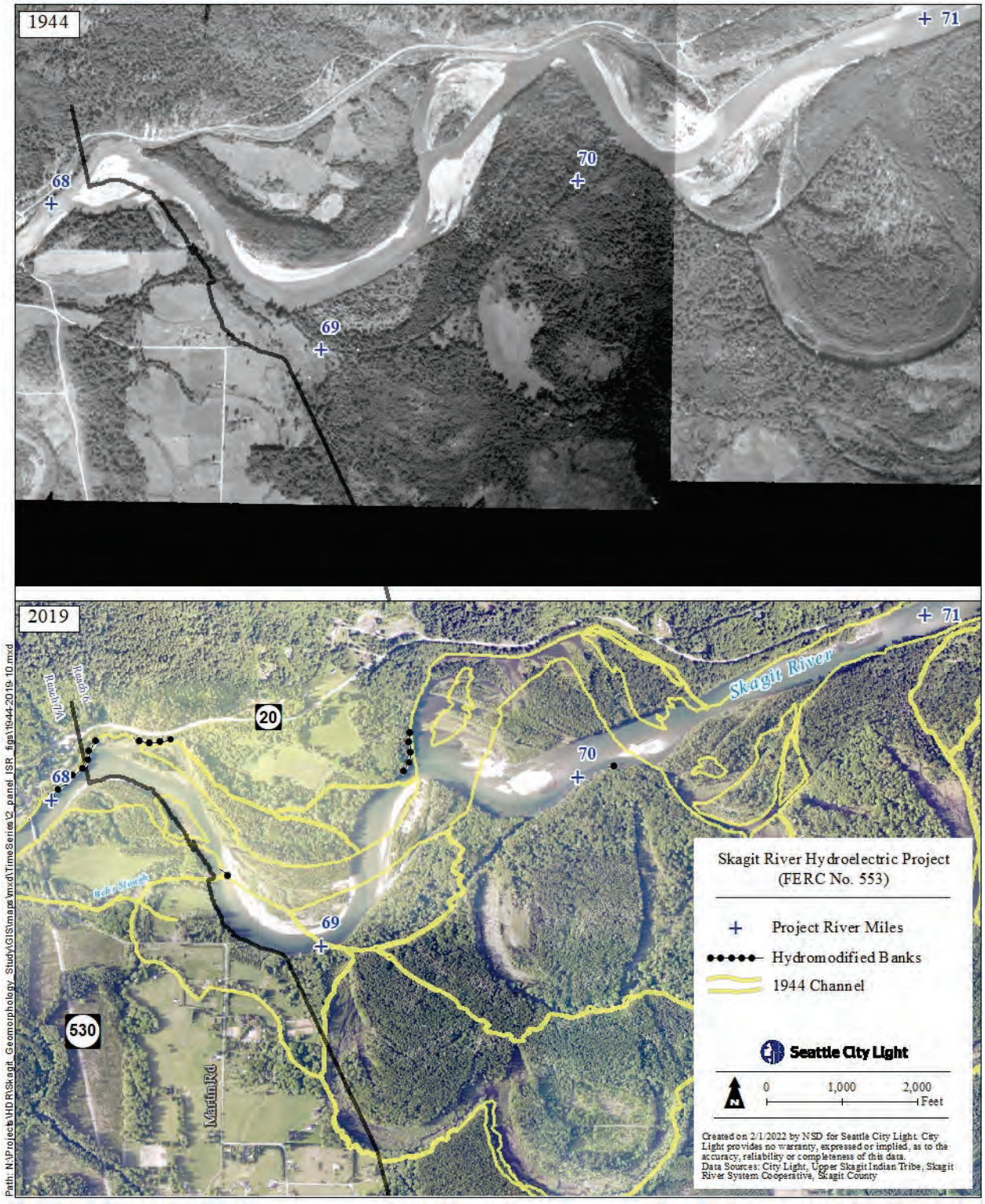


Figure 5.1-14. Comparison of 1944 and 2019 imagery in lower segment of Reach 6.



Figure 5.1-15. Comparison of 1944 and 2019 imagery in Reach 7A.

5.1.2 LiDAR Change and Sediment Inputs from Channel Migration 2017/18-2022

A map series presented in Attachment S shows the DEM of Difference derived from comparison of LiDAR datasets collected in 2017/18 and 2022. The map series highlights areas of sediment deposition and erosion representing geomorphic change between the two datasets. Table 5.1-6 summarizes the annual peak flows observed during the period 2017-2022 for USGS gaging stations at Newhalem and Marblemount. For study reaches covered by 2018 LiDAR (upstream of PRM 76), the DEM of Difference primarily represents geomorphic change associated with the November 2021 flood in which peak flow reached 34,800 cfs at Newhalem and 63,400 cfs at Marblemount (Table 5.1-6). For study reaches covered by 2017 LiDAR (downstream of PRM 76), the DEM of Difference represents the combined response to the November 2021 flood as well as an earlier flood event in November 2017 that reached a peak streamflow of 44,100 cfs at Marblemount.

Table 5.1-6. Summary of annual peak flows during the interval between 2017/18 and 2022 LiDAR data.

Water Year	USGS Newhalem gage (12178000)		USGS Marblemount gage (12181000)	
	Peak Streamflow (cfs)	Date	Peak Streamflow (cfs)	Date
2018	17,400	11/23/2017	44,100	11/23/2017
2019	8,720	4/19/2019	22,000	11/27/2018
2020	9,620	6/26/2020	31,300	2/1/2020
2021	13,900	6/28/2021	25,300	11/5/2020
2022	34,800	11/16/2021	63,400	11/15/2021

Comparing the observed peak flows to flood quantiles estimated for a naturalized or unregulated condition (see NHC 2023) suggests that the peak flows observed in November 2021 would have an annual return period of between 2 and 5 years in the naturalized flow series at Newhalem and a return period between 5 and 10 years in the naturalized flow series at Marblemount. The November 2017 flood peak is estimated to have an annual return period of less than 2 years in the naturalized flow series at Newhalem and a return period between 2 and 5 years in the naturalized flow series at Marblemount.

The area of observed bank erosion during the interval between 2017/18 and 2022 LiDAR data are summarized below in Table 5.1-7. Downstream trends in lateral migration rates for the period 2017/18 to 2022 show a similar pattern as described for the historical record with only localized areas of bank erosion resulting in low rates of channel migration in geomorphic Reaches 2A-5B and more dynamic channel changes with higher migration rates in Reach 6.

Table 5.1-7. Summary of bank erosion and lateral migration rates during the interval between the 2017/18 and 2022 LiDAR data.

Reach	Eroded Area (acres)	Average Lateral Migration (ft)	Lateral Migration Rate (ft/yr)
2A	0.0	0	0.0
2B	2.1	4.3	1.1
3A	0.4	1.6	0.4
4	0.6	1.3	0.3
3B	1.9	8.2	2.0
5A	0.3	0.6	0.1
5B	2.6	5.7	1.1
6	43.4	53.3	10.7

There are no LiDAR change detection results for the Gorge bypass reach (Reach 1) due to void areas in the 2022 LiDAR. Geomorphic change between 2018 and 2022 was assessed by comparison of 2018 and 2022 aerial imagery and showed only minor geomorphic adjustments in Reach 1 with localized areas of sediment deposition and erosion associated with mobilization of alluvial bars. The framework of boulders that make up the two boulder cascades in Reach 1 appears to have remained stable in response to the high flows released into the Gorge bypass reach during the November 2021 flood. Localized adjustment of boulder sized material in the Gorge bypass reach is discussed within the FA-04 Fish Passage Technical Studies Program (City Light 2023b).

Volumes of sediment erosion and deposition normalized by channel length are summarized in Table 5.1-8 and shown graphically in Figure 5.1-16. As noted for areas of bank erosion, the magnitude of volumetric changes increases markedly in Reach 6 compared to the less dynamic reaches upstream. The net change in sediment volumes within the 2017/18 active channel and eroded areas converted from floodplain to channel between 2017/18 and 2022 reveals a pattern of net sediment deposition for Reaches 2A through 5B. Within these reaches, the volume of deposition through bar development exceeded the volume of erosion through bed scour and bank erosion (Figure 5.1-17).

The DEM of Difference showed only minor geomorphic adjustments and no detectable bank erosion in Reach 2A. Bed scour was noted at the base of the alluvial fan extending into the channel from Goodell Creek at the upstream end of Reach 2B. The channel segment downstream of Goodell Creek had areas of bed scour; however, there was deposition within the side channel downstream of PRM 93 such that the net channel change was relatively neutral in this segment (Figure 5.1-18). Continuing downstream, the volume of sediment deposition within the channel exceeded the volume of erosion from bed scour and bank erosion resulting in positive values of net channel change for the remaining segments of Reach 2B. Localized areas of bank erosion in Reach 2B were noted along a portion of a forested island upstream of the Agg Ponds at PRM 91.7 (Figure 5.1-19) and widening of a side channel in the Thornton Creek side channel complex near PRM 90.7 (Figure 5.1-20); however, sediment volumes from bank erosion were small relative to deposition within the channel. The depositional trend in Reach 2B was most pronounced

downstream of Thornton Creek near County Line Ponds. Additional floodplain deposition was notable at the County Line Ponds where sediment was transported into the pond through a breach in the right bank berm near PRM 89.7 (Figure 5.1-21).

Geomorphic changes in the confined channel segments in Reach 3A between 2018 and 2022 were limited to minor adjustments of the channel bed with volumes of sediment deposition exceeding the volume of bed scour and bank erosion. Deposition was most pronounced in the segment downstream of Damnation Creek where flow splits around a mid-channel bar before entering the upper end of Reach 4 at Shovel Spur Rapid. Continuing downstream, LiDAR change detection results reveled only minor channel adjustments in Reach 4.

Geomorphic Reach 3B included an area of dynamic channel changes downstream of the tributary confluence with Bacon Creek where the right bank eroded into a forested island near PRM 83 (Figure 5.1-22). The erosion also appears to have scoured the bed at the adjacent side channel junction and increased connectivity with the side channel that parallels SR 20 downstream of Bacon Creek. The sediment volume mobilized by localized bed scour and bank erosion was exceeded by deposition and bar development within the active channel resulting in a net depositional response for Reach 3B.

The depositional trend continued downstream through Reach 5A. Localized areas of bed scour were noted at the base of the tributary alluvial fan at Diobsud Creek and in the mainstem channel area upstream. Bank erosion rates were very low in Reach 5A with only small, localized areas of toe scour.

Dynamic channel changes near the tributary confluence with the Cascade River at Marblemount reshaped geomorphic features in the upstream segment of Reach 5B (Figure 5.1-23). Channel bed scour was noted along the left bank downstream of the Cascade River and continuing downsteam of the side channel junction near PRM 77.7. Bank erosion was identified along the left bank of the side channel downstream of PRM 77.7 and along the right bank of the main channel opposite the side channel junction near PRM 77.4. Sediment deposition filled a portion of the channel along the right bank upstream of PRM 78, within the left bank side channel downstream of PRM 77.7 and in the main channel at the side channel junction (PRM 77.4). Collectively, the geomorphic adjustments in the upper segment of Reach 5B were relatively balanced with a minor depositional response. Note that the DEM of Difference shows an area of net sediment removal along the constructed channel completed in 2021 at Pressentin Park; however, the constructed channel feature was excluded from calculations of geomorphic change in this study.

Results from the lower segment of Reach 5B between Marblegate Slough and Corkindale Creek (PRM 74.4-76.0) show a shift towards net sediment loss where the combined volumes of bank erosion and bed scour exceed volumes of deposition from bar development within the channel. Bank erosion within this segment was primarily along the left bank terrace downstream of PRM 75.

Within Reach 6, the DEM of Difference shows a net export of sediment driven by large volumes of sediment mobilized by bank erosion and transported downstream (Figure 5.1-17). The imbalance between sediment deposition and erosion is most pronounced in segments of Reach 6 between Rocky Creek and Illabot Creek (PRM 71.4-74.4). Bank erosion from toe scour was

observed along the outside of all meander bends in these segments (Figures 5.1-24 and 5.1-25). A segment of bank armor near PRM 73 washed out in November 2021 resulting in bank erosion behind the riprap. Bank armor along SR 20 near PRM 72 sustained damage in both the November 2017 and November 2021 flood events. Geomorphic changes downstream of Illabot Creek were more moderate but continued to show a net export of sediment. Localized scour was observed around a stable logjam upstream of Sutter Creek and the left bank eroded across from Barr Creek (Figure 5.1-26). The channel segment downstream of Barnaby Slough to the SR 530 bridge at Rockport also had extensive areas of bank erosion on the outside of meander bends; however, these sediment losses were offset by substantial deposition on bars within the channel resulting in a net channel change that was depositional (Figure 5.1-27). Much of the in-channel deposition in lower segments of Reach 6 is likely attributable to the net export of sediment from reaches upstream between Rocky Creek and Barnaby Slough.

Table 5.1-8. Geomorphic changes between 2017/18 and 2022 LiDAR normalized by channel length and summarized by analysis segment.

Analysis Segment ID	PRM	Geomorphic reach	2017/18 Active Channel		Bank Erosion 2017/18-2022 (yd^3 yd^{-1})	Net Channel[1] Change (yd^3 yd^{-1})	Floodplain (yd^3 yd^{-1})	Net Total[2] Change (yd^3 yd^{-1})
			Depositional Areas (yd^3 yd^{-1})	Erosional Areas (yd^3 yd^{-1})				
2	93.5-94.7	2a	7.76	-3.67	0.00	4.08	-0.11	3.98
3	92.6-93.5	2b	10.21	-9.06	-0.17	0.98	0.75	1.73
4	91.1-92.6	2b	16.06	-4.39	-3.61	8.06	5.65	13.70
5	90.0-91.1	2b	13.24	-3.12	-1.64	8.48	5.48	13.96
6	89.4-90.0	2b	25.34	-4.18	-3.42	17.74	19.00	36.74
7	88.5-89.4	3a	4.07	-1.58	0.00	2.48	1.97	4.45
8	87.5-88.5	3a	12.47	-3.77	-1.74	6.96	2.69	9.66
9	85.6-87.5	4	5.47	-1.29	-0.02	4.16	0.04	4.20
10	83.9-58.6	4	6.60	-2.85	-0.69	3.07	0.53	3.60
11	82.2-83.9	3b	22.64	-7.16	-7.31	8.17	5.11	13.28
12	80.4-82.2	5a	13.54	-8.16	-0.37	5.01	0.93	5.94
13	78.5-80.4	5a	10.07	-0.93	0.00	9.14	0.87	10.01
14	76.0-78.5	5b	16.15	-9.82	-3.24	3.09	3.06	6.15
15	74.4-76.0	5b	8.75	-7.74	-6.67	-5.66	-11.72	-17.38
16	72.3-74.4	6	28.31	-23.59	-38.17	-33.45	-1.80	-35.25
17	71.4-72.3	6	75.30	-31.11	-67.61	-23.42	1.48	-21.94
18	70.4-71.4	6	23.48	-19.31	-15.58	-11.41	-50.33	-61.74
19	68.1-70.4	6	94.91	-23.72	-67.52	3.67	3.69	7.36
20	66.8-68.1	7A	22.79	-31.84	-5.16	-14.22	2.50	-11.72
21	65.1-66.8	7B	62.74	-95.89	-7.54	-40.69	0.79	-39.89

1 Net Channel Change = 2017/18 active channel area + bank erosion areas between 2017/18 and 2022.
2 Net Total Change = net channel change + floodplain areas.
3 Negative volumes in floodplain are a likely artifact of LiDAR returns in ponded areas and potential source of error.

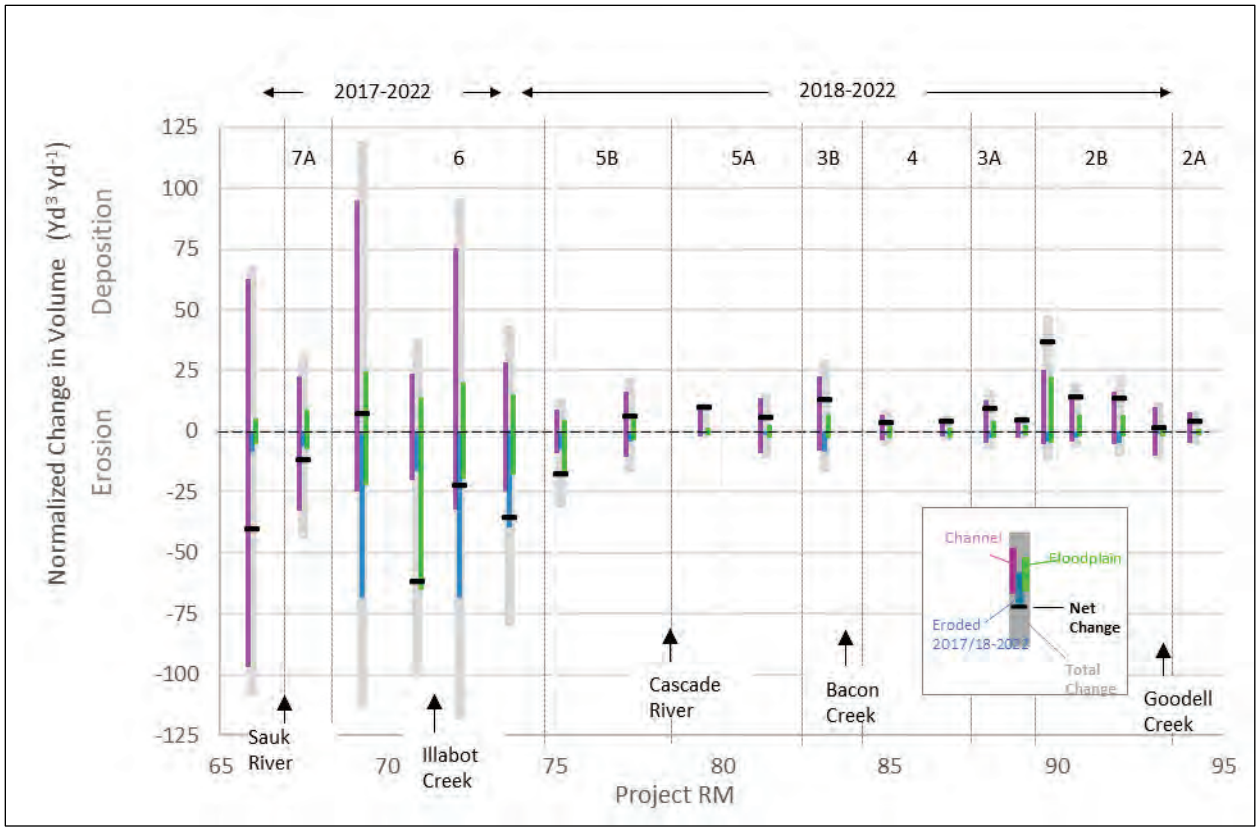


Figure 5.1-16. **Change in sediment volumes by subreach and normalized by channel length for the period 2017/2018 to 2022. Sediment erosion and deposition is categorized by active channel (purple), eroded area (blue) and vegetated floodplain (green) areas. Horizontal bars show the net change in all areas.**

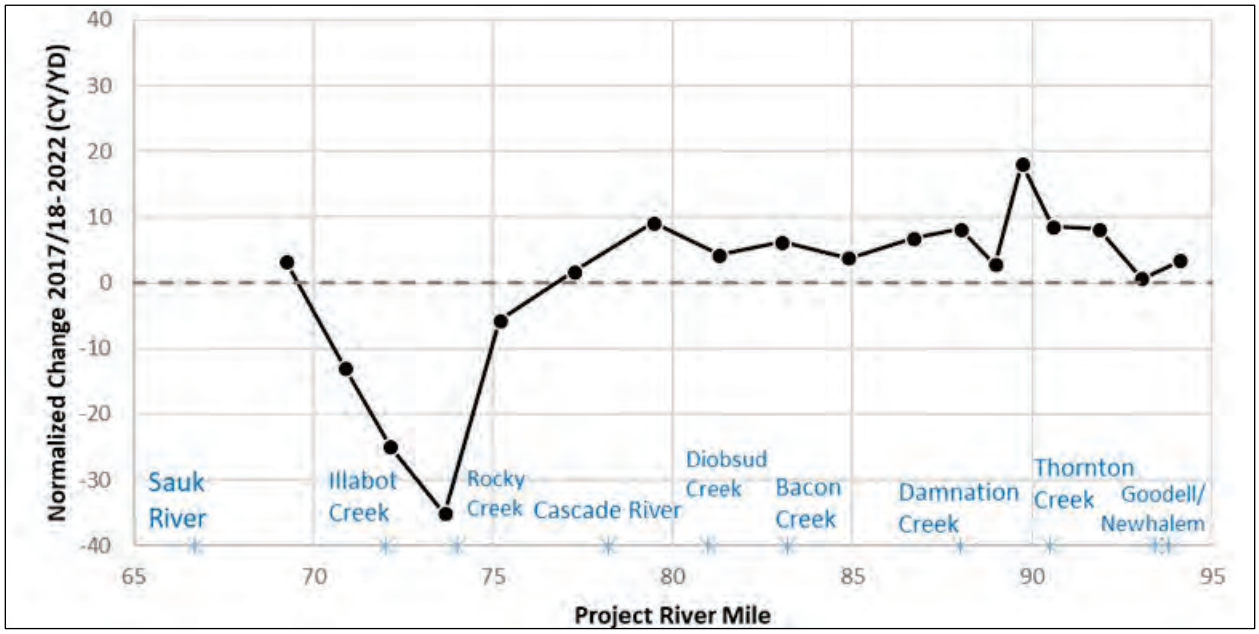


Figure 5.1-17. **Net change in sediment volumes for active channel areas (2017/2018 channel combined with the areas of bank erosion between 2017/2018 and 2022).**

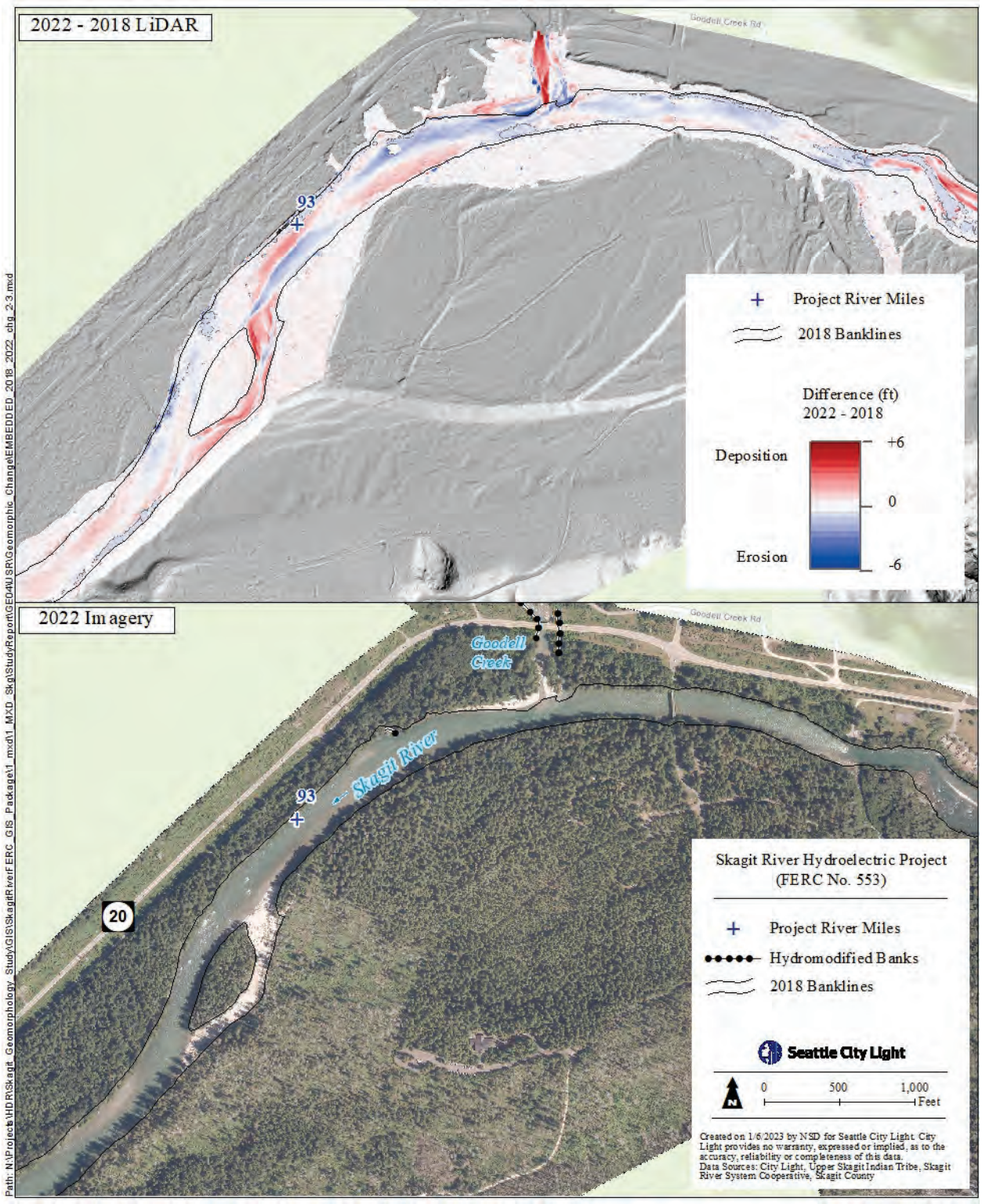


Figure 5.1-18. DEM of Difference (2022 – 2018 LiDAR) for near the tributary confluence with Goodell Creek (Reaches 2A/2B).

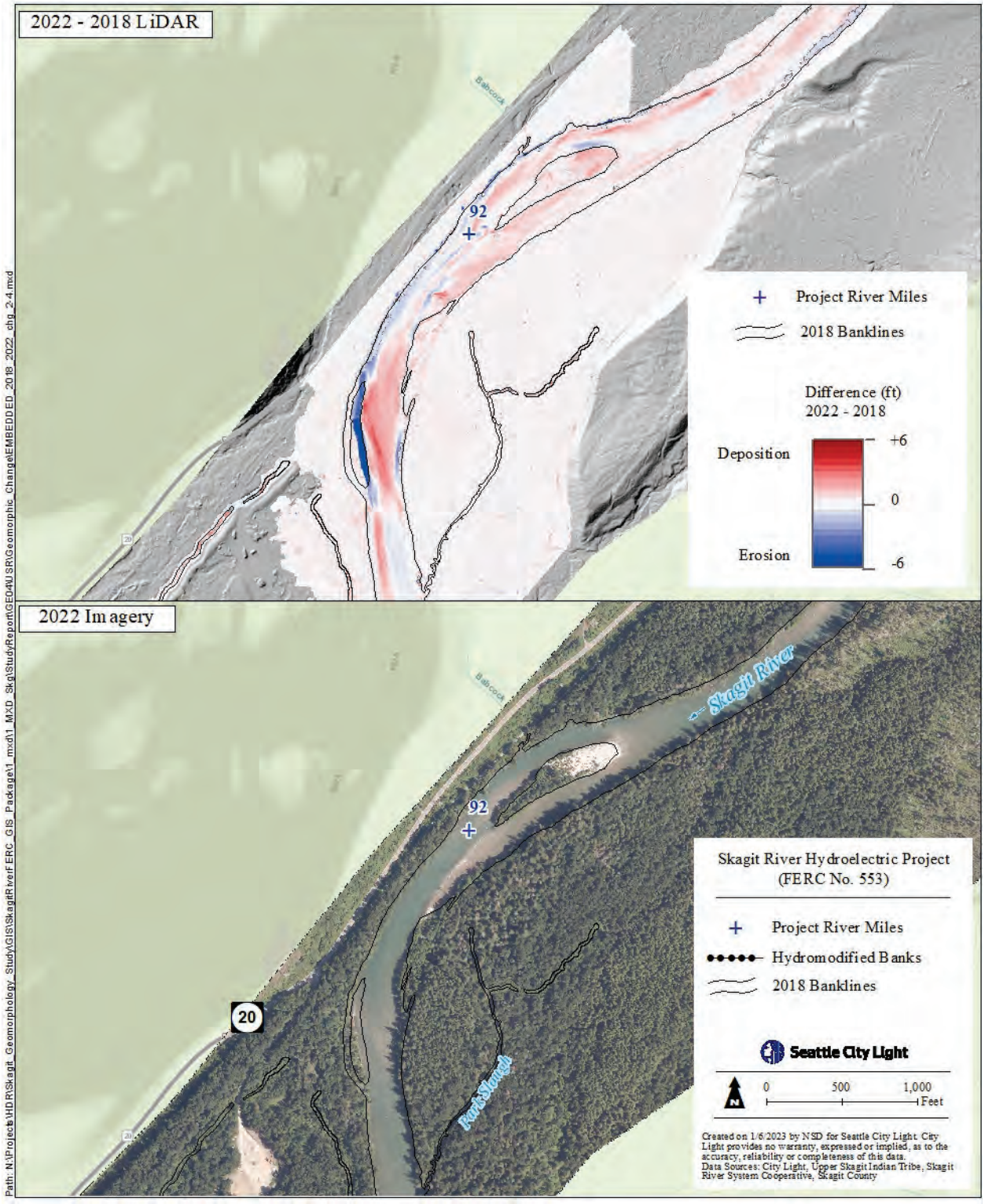


Figure 5.1-19. DEM of Difference (2022 – 2018 LiDAR) for a portion of Reach 2B between Goodell Creek and the Newhalem Agg Ponds.

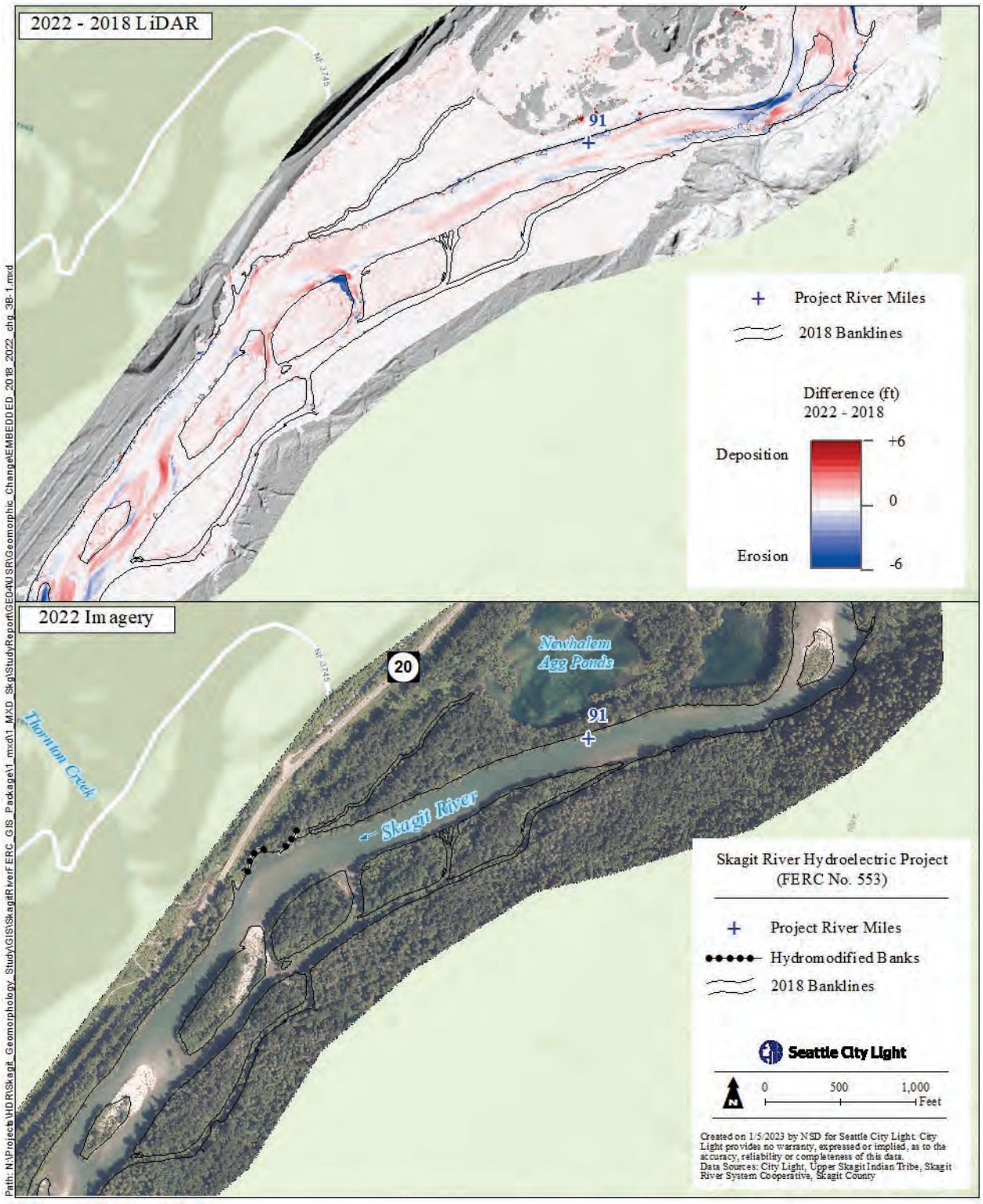


Figure 5.1-20. DEM of Difference (2022 – 2018 LiDAR) for a portion of Reach 2B near the Newhalem Agg Ponds and Thornton Creek.

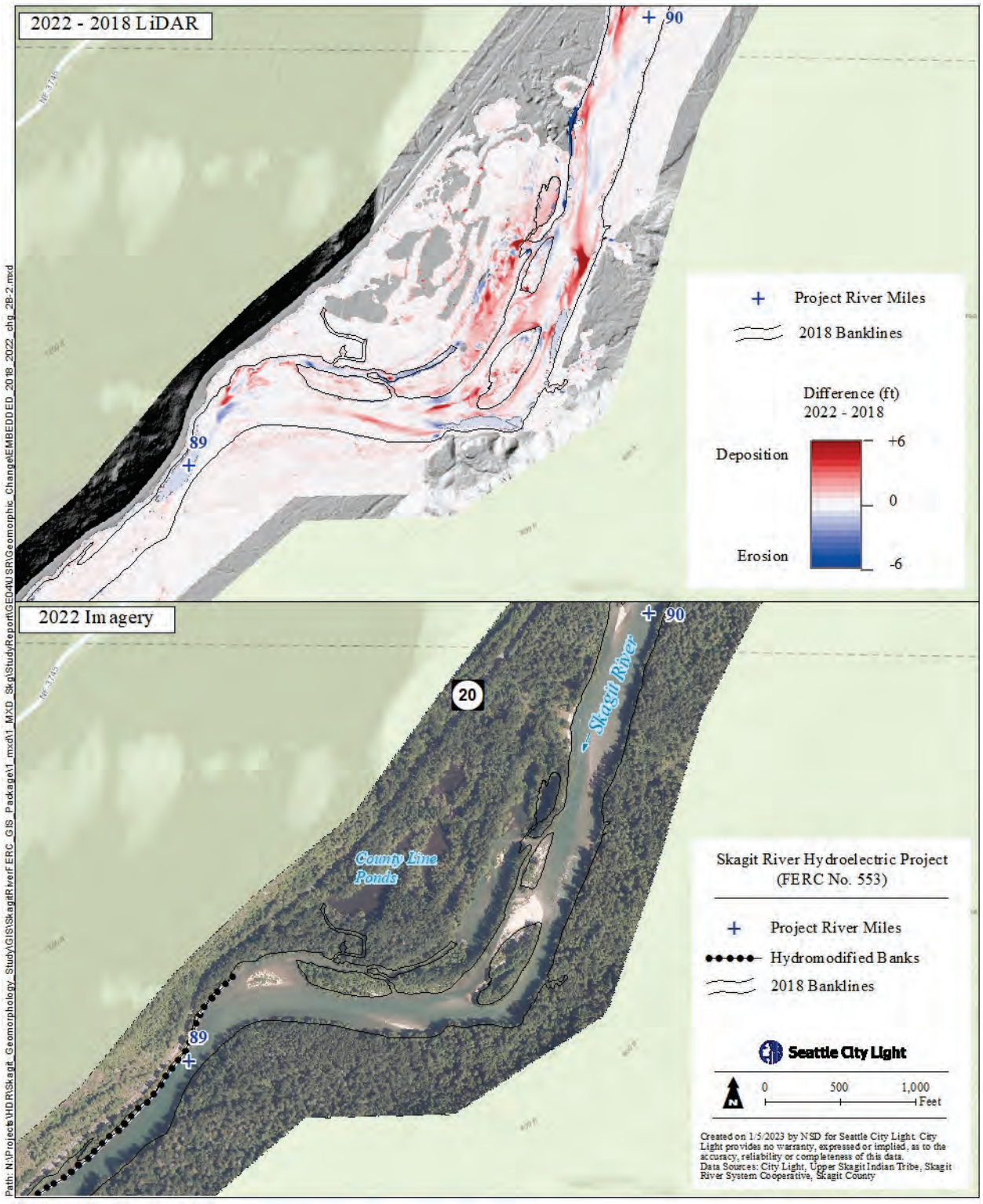


Figure 5.1-21. DEM of Difference (2022 – 2018 LiDAR) for a portion of Reach 2B near the County Line Ponds.

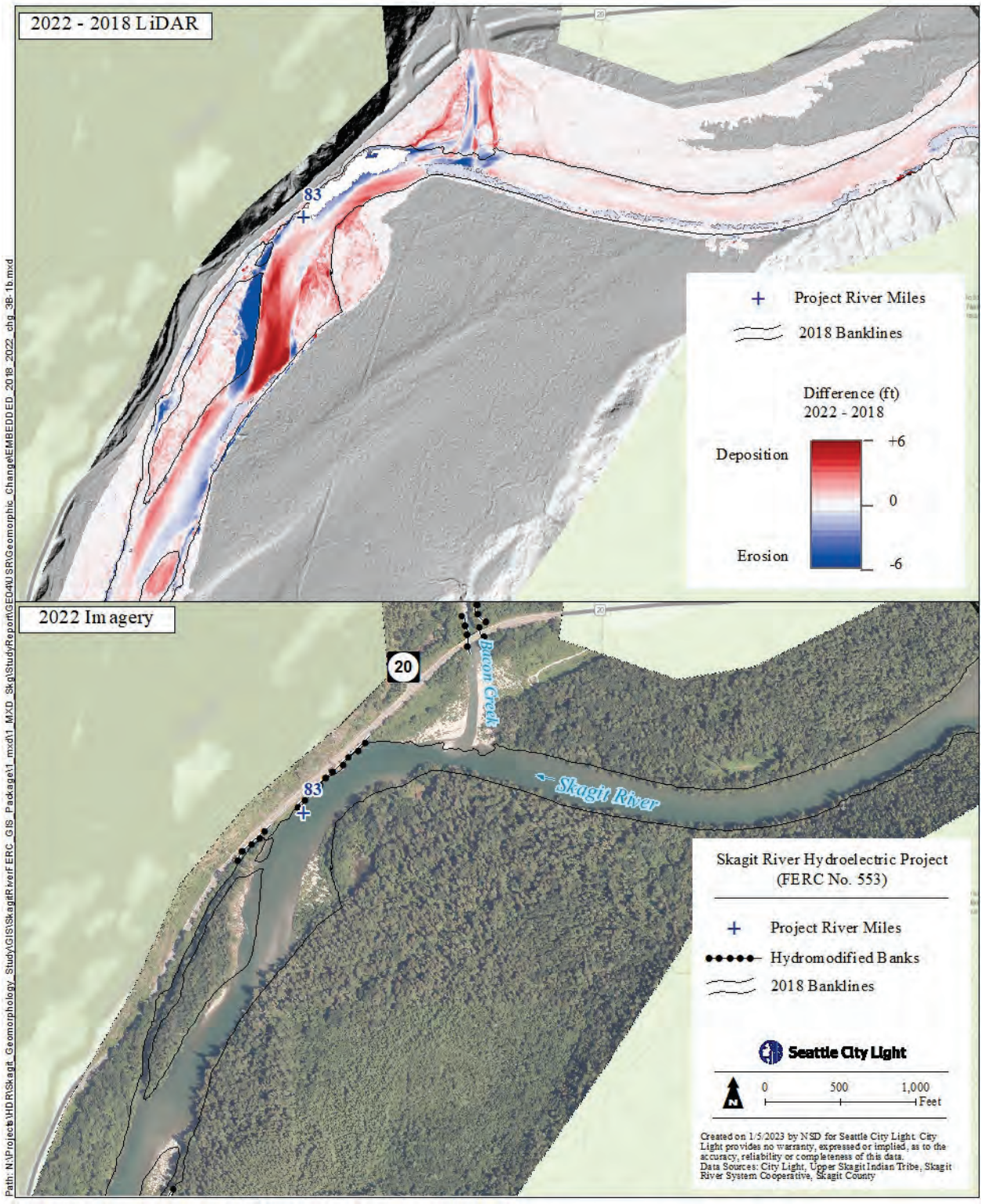


Figure 5.1-22. DEM of Difference (2022 – 2018 LiDAR) for a portion of Reach 3B near the tributary confluence with Bacon Creek.

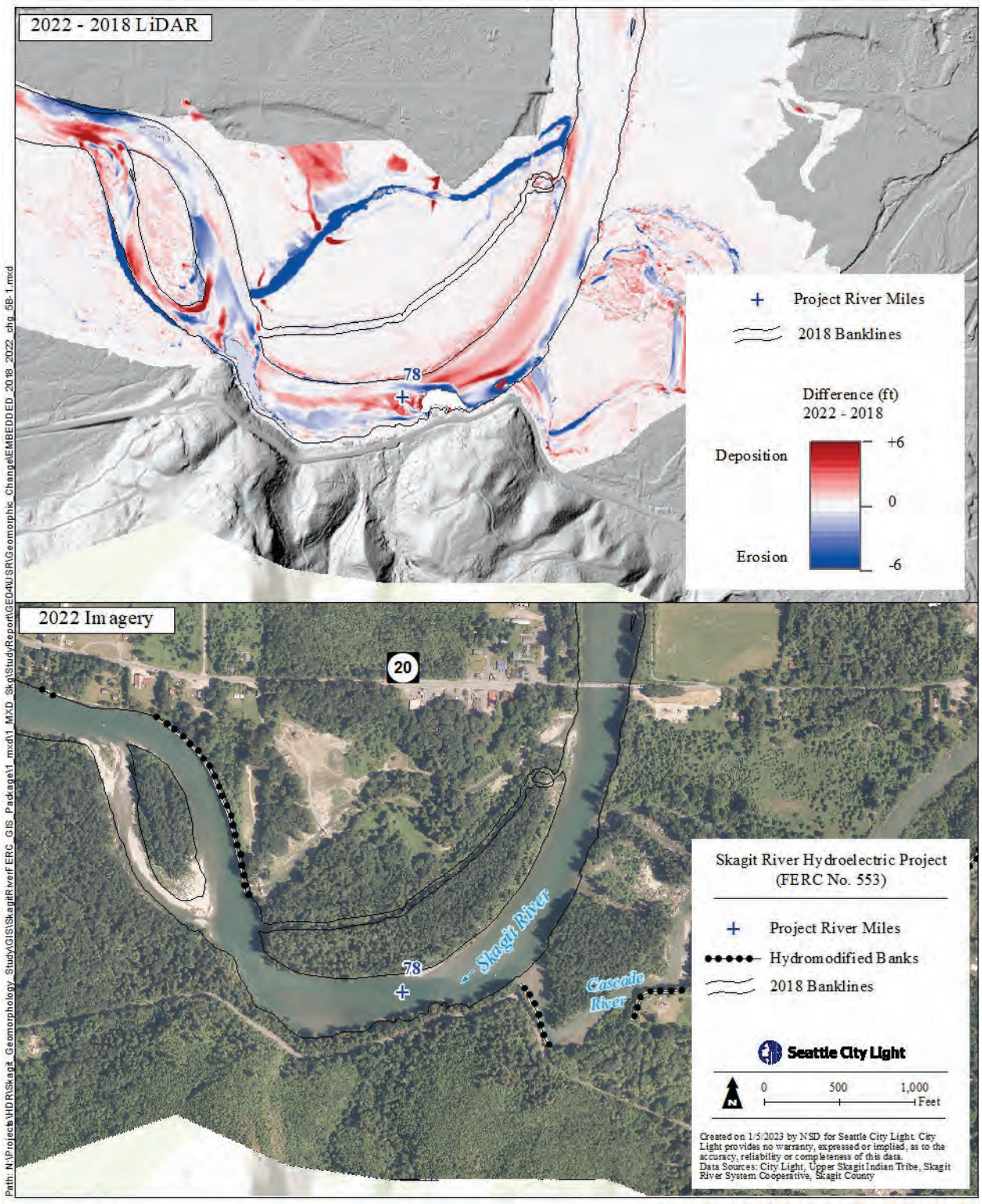


Figure 5.1-23. DEM of Difference (2022 – 2018 LiDAR) for a portion of Reach 5B near Marblemount and the tributary confluence with the Cascade River.

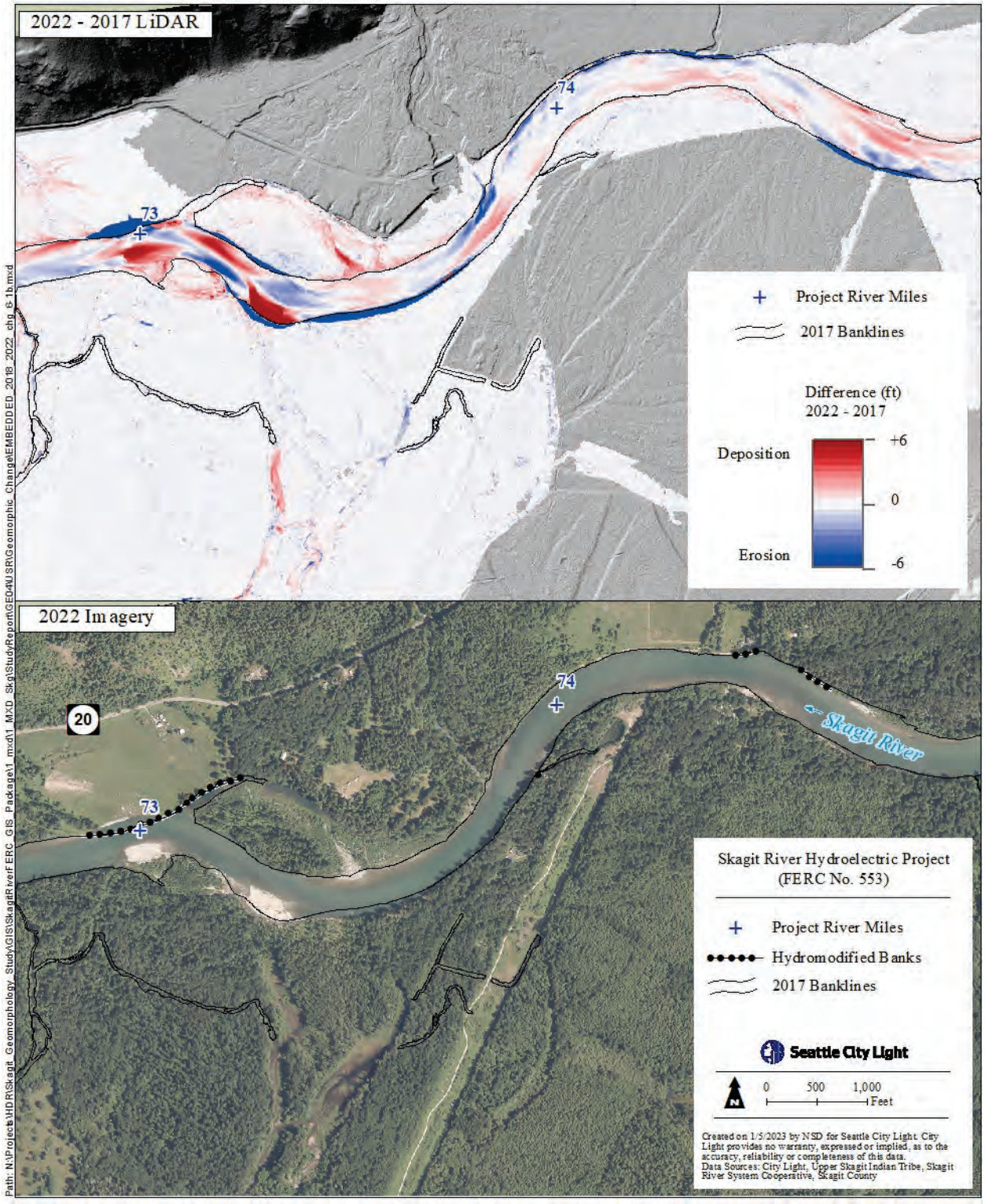


Figure 5.1-24. DEM of Difference (2022 – 2018 LiDAR) for a portion of Reach 6 between Illabot Creek and Corkindale Creek.

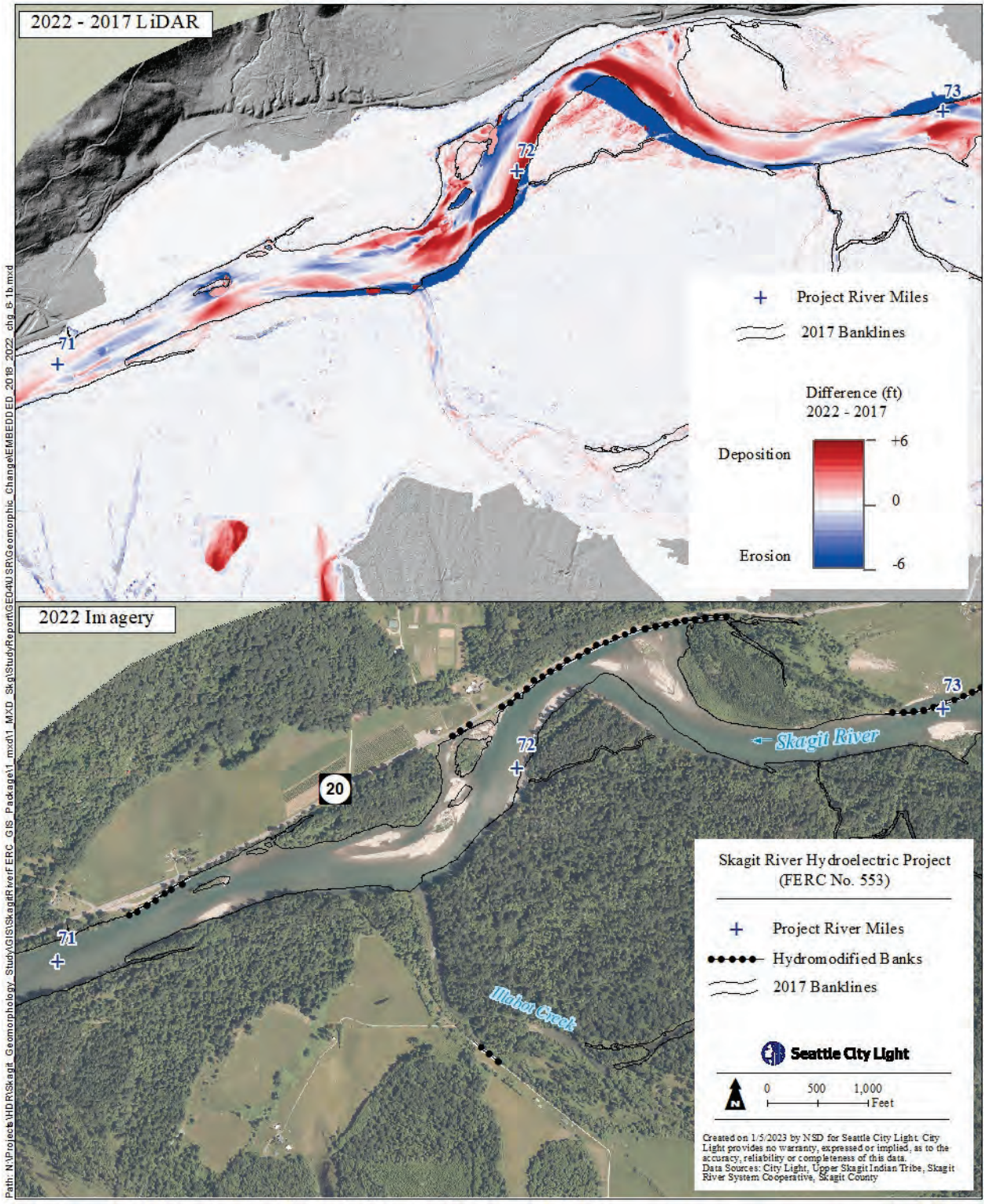


Figure 5.1-25. DEM of Difference (2022 – 2018 LiDAR) for a portion of Reach 6 near the tributary confluence with Illabot Creek.

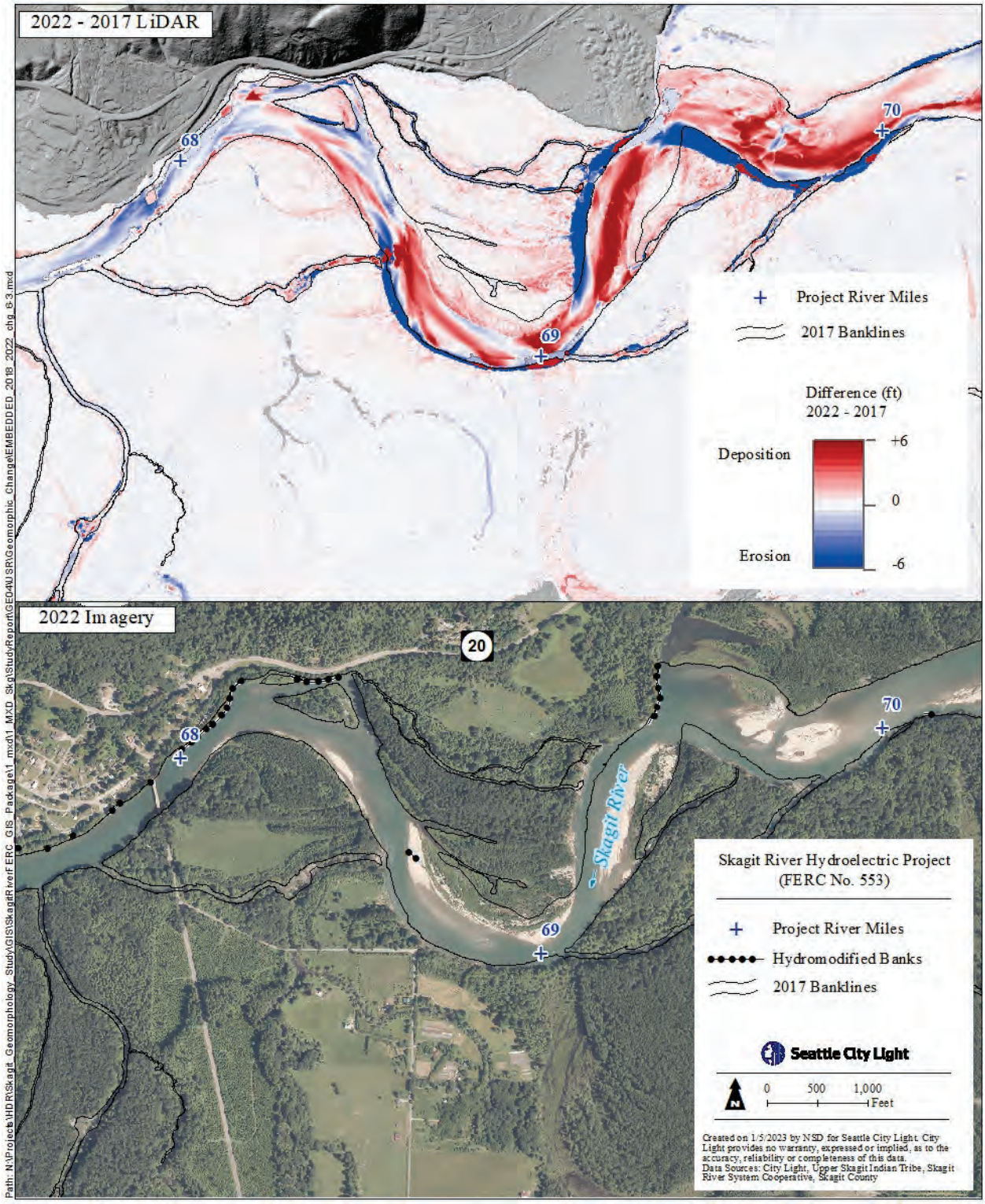


Figure 5.1-26. DEM of Difference (2022 – 2018 LiDAR) for a portion of Reach 6 near Rockport.

5.1.3 Changes to USGS Rating Curves

The time-series plot of the stage-discharge residual analysis for the Skagit River at Newhalem and Marblemount are shown below in Figure 5.1-27. Results suggest that the channel geometry has been relatively stable at the USGS gaging sites over the period of record. Stage residuals at both sites indicate an increasing trend with approximately 0.6 ft of aggradation since the 1980s with step-wise changes observed in response to flood events. The channel response to the recent flood in November 2021 is consistent with this trend in that stage residuals suggest an increase in channel bed elevation of 0.4 ft and 0.2 ft at Newhalem and Marblemount, respectively

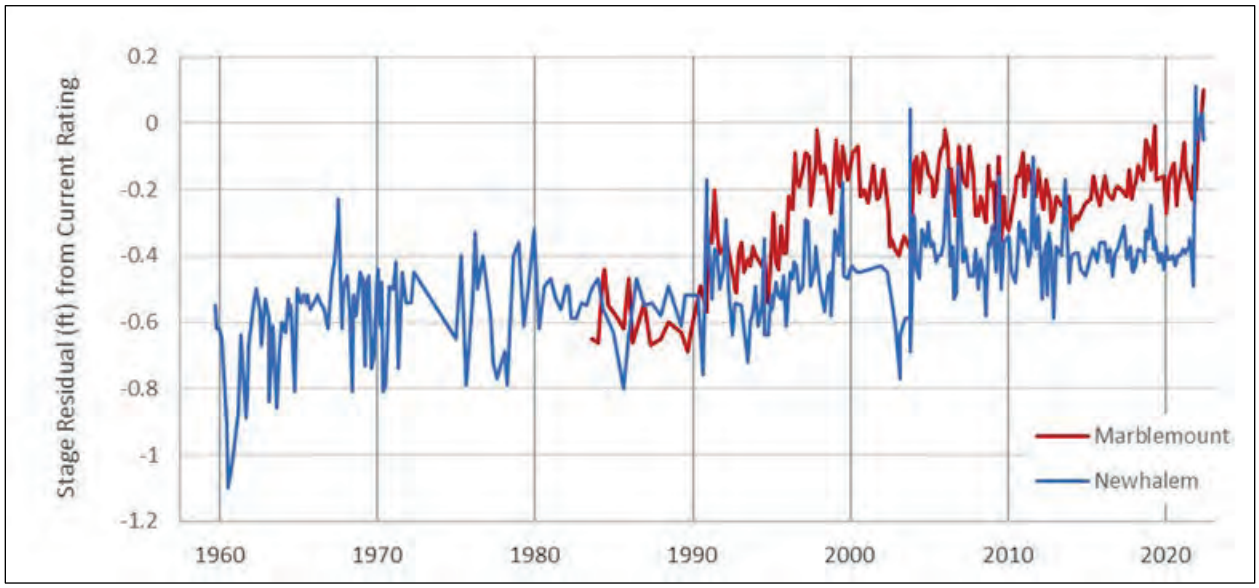


Figure 5.1-27. Stage residuals from historical field measurements compared to the current USGS rating curves at Newhalem and Marblemount.

5.1.4 Changes to Longitudinal Profiles

Channel profile adjustments are an important mechanism by which river channels respond to changes that disrupt the balance between the sediment supply and sediment transport capacity (Lane 1955; Brandt 2000). Water surface profiles from historical data sources were evaluated to investigate vertical channel changes and potential areas of channel incision and/or aggradation. The 1915 and 1947 profiles are shown below in Figure 5.1-28 with the low flow (90 percent daily exceedance probability) water surface profile simulated in the FA-02 Instream Flow Model Development Study. Changes calculated as the difference between elevation at individual contours in the 1915 and 1947 maps and the concurrent elevation from the nearest location in the existing conditions model output are shown in Figures 5.1-29 and 5.1-30, respectively. Table 5.1-9 summarizes vertical channel changes by reach.

Results derived from contours on historical topographic maps from 1915 and 1947 yielded inconclusive results. The WSE in the 1915 map series plots well below the existing conditions profile downstream of Rocky Creek suggesting around 8 ft of aggradation in Reaches 6 and 7 (Figure 5.1-29 and Table 5.1-9). This result is inconsistent with interpretation of abandoned channel features in LiDAR topography and more likely an artifact of survey error or uncertainty associated with historical data sources and not a result of actual geomorphic channel change. The

1915 profile steps upward between Illabot Creek and Rocky Creek where a bend cutoff avulsion abandoned a series of meanders sometime between 1915 and 1947. Upstream of Rocky Creek the 1915-2018 comparison continues an aggregational trend in Reaches 4 through 5B with average increases in WSE of 1 to 3 ft. Upstream of Shovel Spur Rapid, the 1915-2018 comparison shows the opposite trend with nearly 2 to 4 ft of incision between Thornton Creek and Damnation Creek (Reaches 2B and 3A).

The comparison between water surface profiles from the 1947 map series and the existing conditions hydraulic model shows a general decrease in elevation between 1947 and 2018 that suggests potential for channel incision that averaged around 1 ft of incision in Reaches 2B and 3A, 3 ft of incision in Reach 4, and 0 to 1 ft of incision in Reaches 3B through 7 (Figure 5.1-30 and Table 5.1-9).

A third data source representing historical channel elevations was derived from 1975 cross-section surveys acquired as part of the FEMA Flood Insurance Study. Historical channel bed elevations extracted from 1975 cross-section surveys were plotted with a profile of the minimum channel elevation from 2022 topobathymetric LiDAR in Figure 5.1-31. 1975 cross-sections were limited to geomorphic reaches downstream of Marblemount (Reaches 5B through 7). Changes derived from the comparison at individual sections are plotted in Figure 5.1-32 and summarized by reach in Table 5.1-9. The change in minimum channel bed elevation between 1975 and 2022 suggest the channel segments downstream of Marblemount have generally aggraded between 2 and 3 ft over the recent 47-year period.

Collectively, results from the historical profile comparisons yield different patterns of change for geomorphic reaches upstream and downstream of Shovel Spur Rapid. Available data from Reaches 2B and 3A were consistent in suggesting incision over the historical period. Results from Reaches 4, 3B, and 5A suggest aggradation between 1915 and 1947 followed by incision since 1947. Results from Reaches 5B, 6, and 7 suggest a relatively large amount of channel aggradation (7 to 8 ft) would have needed to occur between 1915 and 1947 followed by a period of channel incision between 1947 and 1975 and subsequent return to aggradation between 1975 and 2022. The inconsistent trends observed in the historical data sources lead to a conclusion that uncertainty in results derived from water surface contours on 1915 and 1947 maps likely exceeds the magnitude of actual channel changes and that results derived from historical elevation data are inconclusive for the period prior to 1975.

Recent changes in the thalweg profile were evaluated from comparison of the 2017/2018 and 2022 topobathymetric LiDAR. Results show an average aggradation of 0.3 ft for the combined reaches between Newhalem and the Sauk River. The thalweg elevation in Reach 2B (downstream of Goodell Creek) increased 0.59 ft and the profile increased 0.66 ft in Reach 3B including the segment downstream of Bacon Creek (Table 5.1-9). The aggradational trends observed in recent LiDAR comparisons are consistent with observations from comparison with the 1975 channel cross-sections and with the stable to slightly increasing trend noted from USGS rating curves.

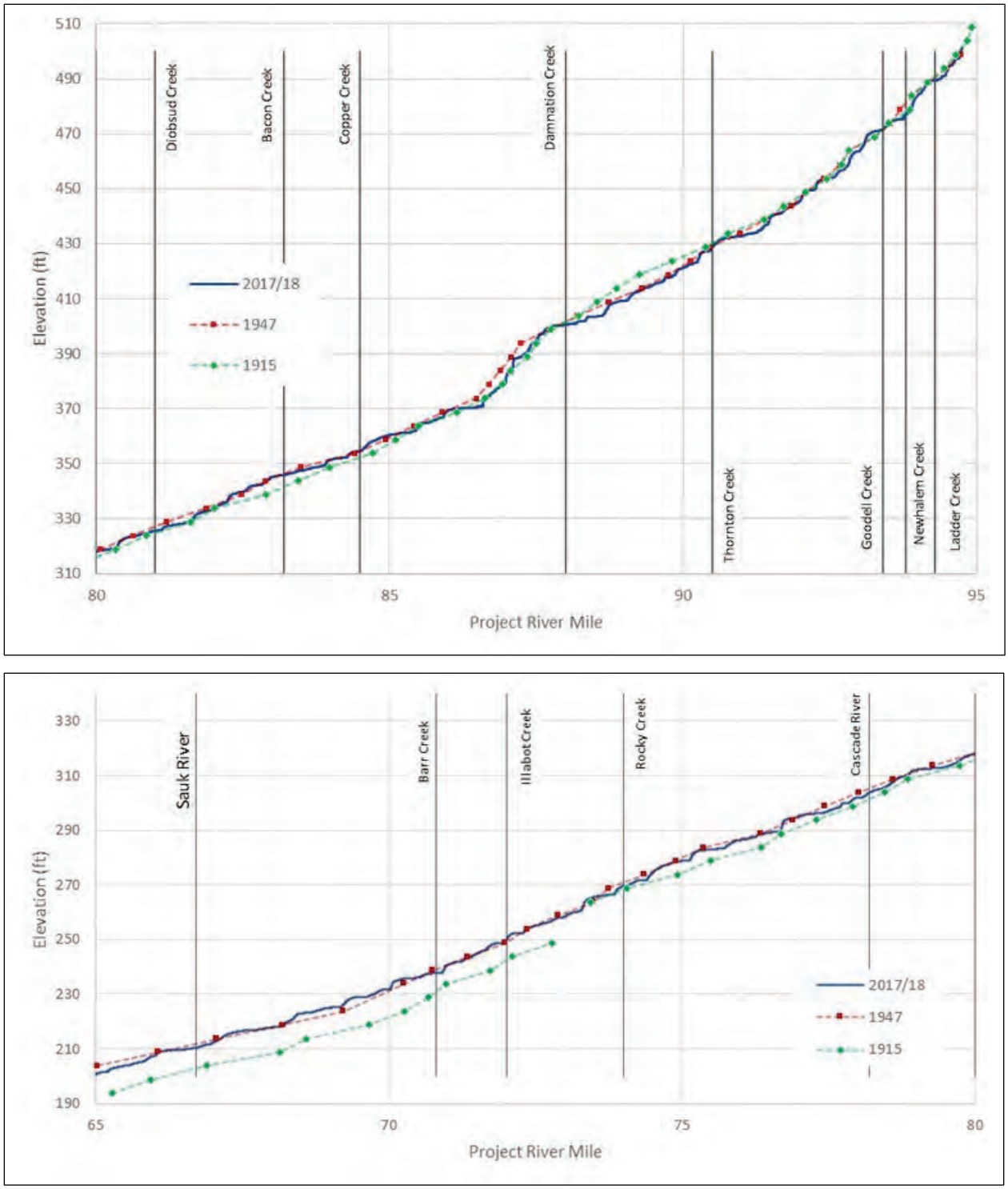


Figure 5.1-28. **Longitudinal profiles of water surface elevation from 1915 and 1947 historical maps and existing conditions hydraulic model (2017-18) output. The large offset between 1915 profile and 1947 downstream of Rocky Creek is interpreted to be a potential artifact of survey error or uncertainty in the historical data.**

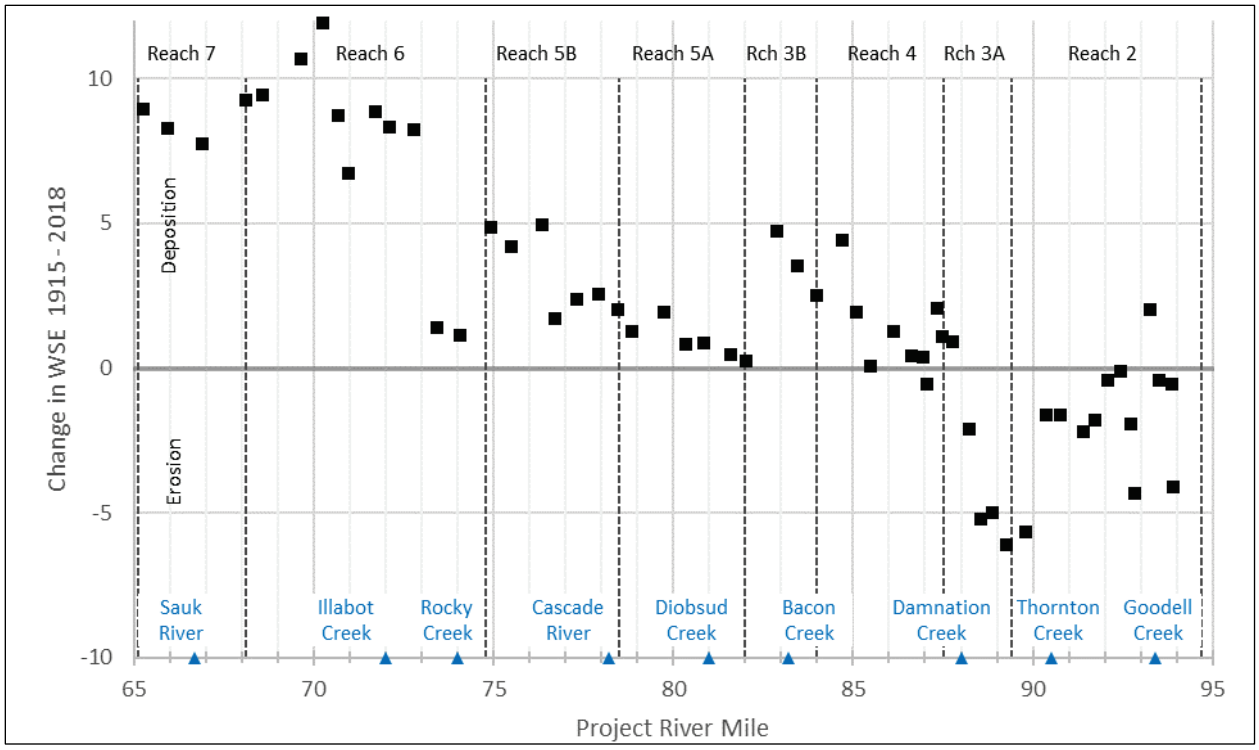


Figure 5.1-29. Change in water surface elevation between 1915 historical maps and existing conditions hydraulic model (2017-18) output.

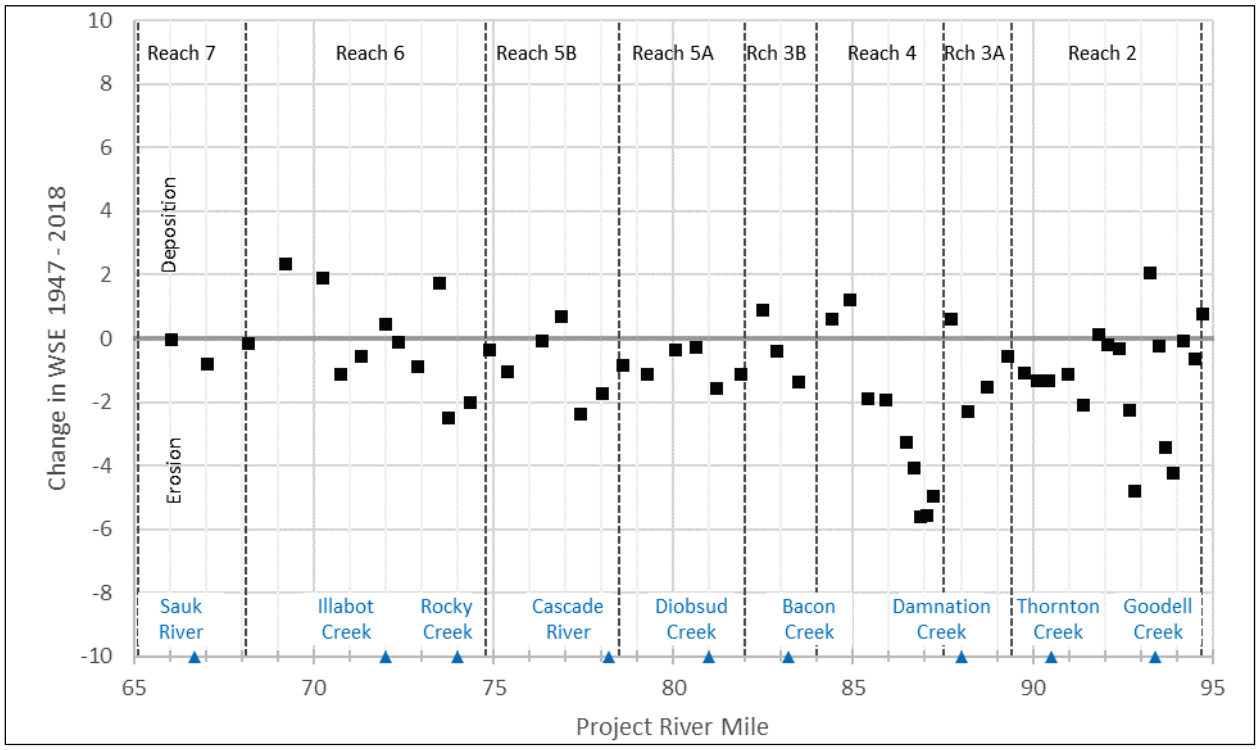


Figure 5.1-30. Change in water surface elevation between 1947 historical maps and existing conditions hydraulic model (2017-18) output.

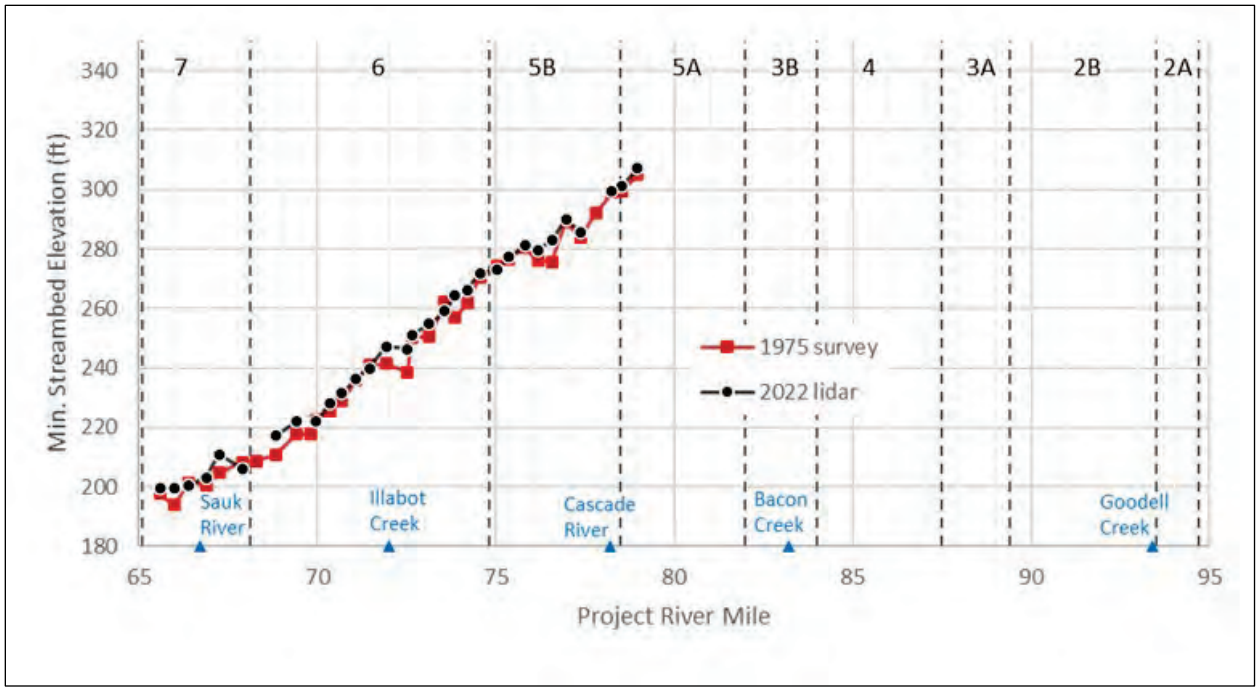


Figure 5.1-31. Longitudinal profiles of minimum channel bed elevation from 1975 cross-section surveys and 2022 topobathymetric LiDAR.

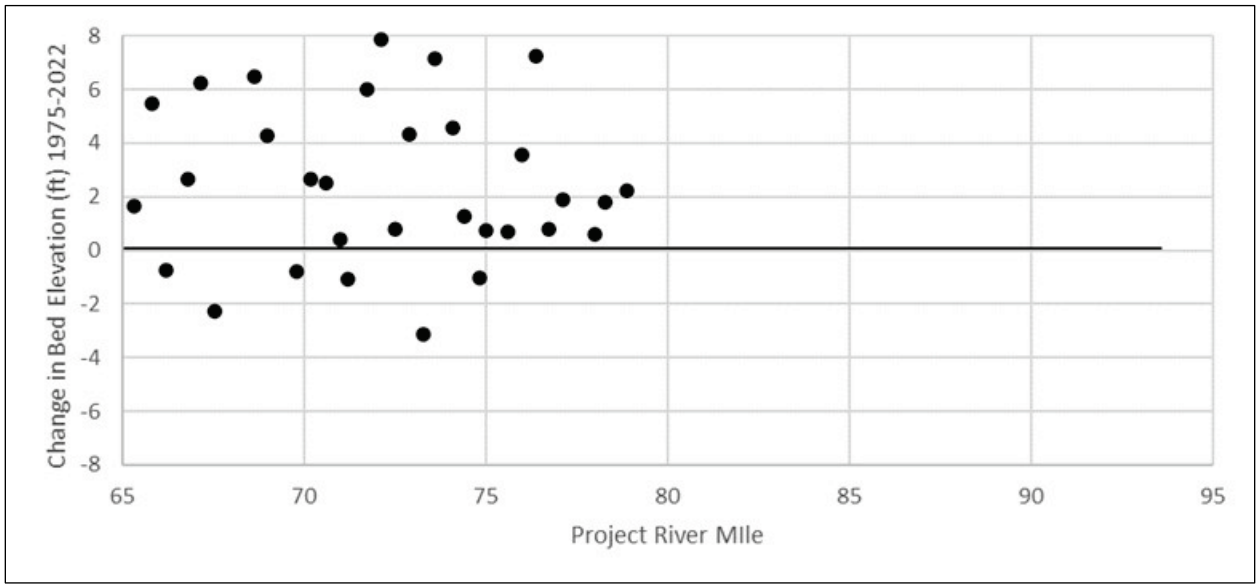


Figure 5.1-32. Change in minimum channel bed elevation between 1975 cross-section surveys and 2022 topobathymetric LiDAR.

Table 5.1-9. Summary of changes in water surface elevations 1915-2018, 1947-2018, and thalweg elevations 1975-2022, 2017/18-2022.

Reach ID	Avg. Change in Water Surface Elevation (ft)		Avg. Change in Thalweg Elev. (ft)		
	1915-2018		1947-2018	1975-2022	2017/18-2022
2A	N/A	N/A	N/A		+0.25
2B	-1.7	-1.3	N/A		+0.59
3A	-3.5	-1.0	N/A		+0.38
4	+1.2	-2.8	N/A		+0.72
3B	+2.8	-0.3	N/A		+0.66
5A	+1.1	-0.9	N/A		+0.45
5B	+3.2	-0.8	+1.84		+0.24
6	+7.7	-0.1	+2.89		+0.34
7	+8.0	-0.8	+2.16		-0.44

5.2 Aquatic Habitat

5.2.1 Habitat Mapping

Habitat mapping results are presented by reach and subreach from upstream to downstream. The quantity and distribution of aquatic habitat provide a sense of availability and diversity of units between each reach. Channel unit areas including side channel (both blind and flow through) and off-channel areas are based on the wetted extent polygon originally derived from the 2017 and 2018 LiDAR flights which were captured at 8,000 cfs and 6,000 to 7,500 cfs, respectively. Inundation areas will vary depending on river discharge, as will areas of individual channel units or side channels.

The amount of habitat and the relative proportion of habitat are presented in Figures 5.2-1 and 5.2-2 for Reaches 1 through 7A. Maps of all reaches with designated channel units are presented in Attachment F. Reach length and area normalized by length are presented in Table 5.2-1 to provide context for relative reach size and width. The area of channel unit types are summarized by reach in Table 5.2-2. The number of channel units per mile, a measure of habitat diversity, are presented in Table 5.2-3. Average depth, bankfull depth and bankfull width are reported in Table 5.2-4 and provide a relative comparison for reach cross-sectional area and channel capacity during channel forming flows.

Reaches 6 and 2B are the largest, with Reach 6 containing more than twice the surface area as the next largest reach. Reach 6 is also the longest reach with about double the length of the next largest reach (Table 5.2-1), but even normalized by length, it provides the largest amount of habitat. As described in Section 4.0 of this study report, the reaches exhibit large differences in geomorphic characteristics. Reach 6 is lower in the watershed than most of the other reaches, carries more flow due to additional tributary inputs and flows through a less confined area, so the reach has the potential for more side and off-channel habitat.

By far, the most common channel unit classification by area is glide habitat and, generally, this proportion increases in a downstream direction (with the exception of Reach 6). This channel unit type represents the largest portion of habitat area for all the reaches shown in Figure 5.2-2, except for Reaches 1 and 2A. Reach 1 was characterized using available information but has very little flow, as it is the Gorge bypass reach, and is generally a series of connected pools with some riffle, cascade and rapid habitat in between. With higher flows, due to the gradient in the reach, it would most likely be a series of rapids and riffles with some pools in between. Reach 2A, which also has a steeper gradient, has large portions of both rapid and run habitat. Reaches 2B and 6 have the largest proportion of off-channel and side channel habitat and Reach 7A also has a larger portion of side channel habitat. The lower reaches (6 and 7A) have lower gradients and more flow, which results in less riffle and rapid habitat and more slow water habitat.

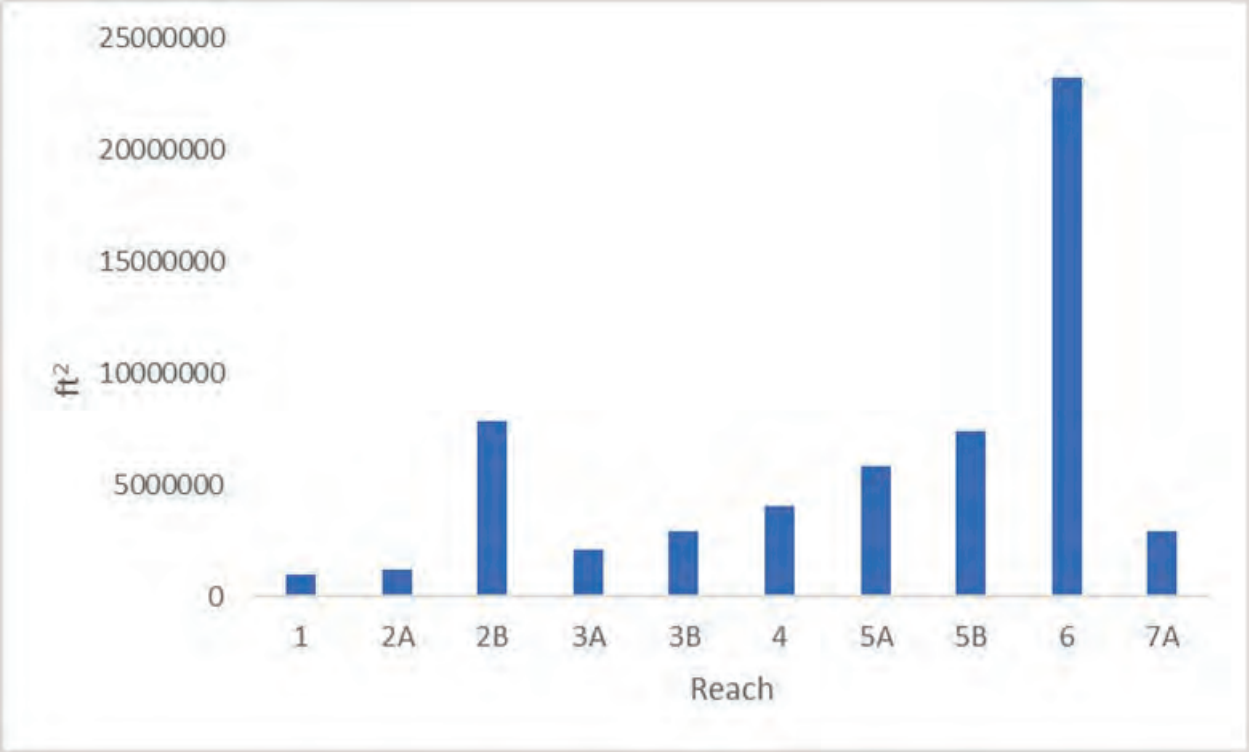


Figure 5.2-1. Total area of aquatic habitat by reach.

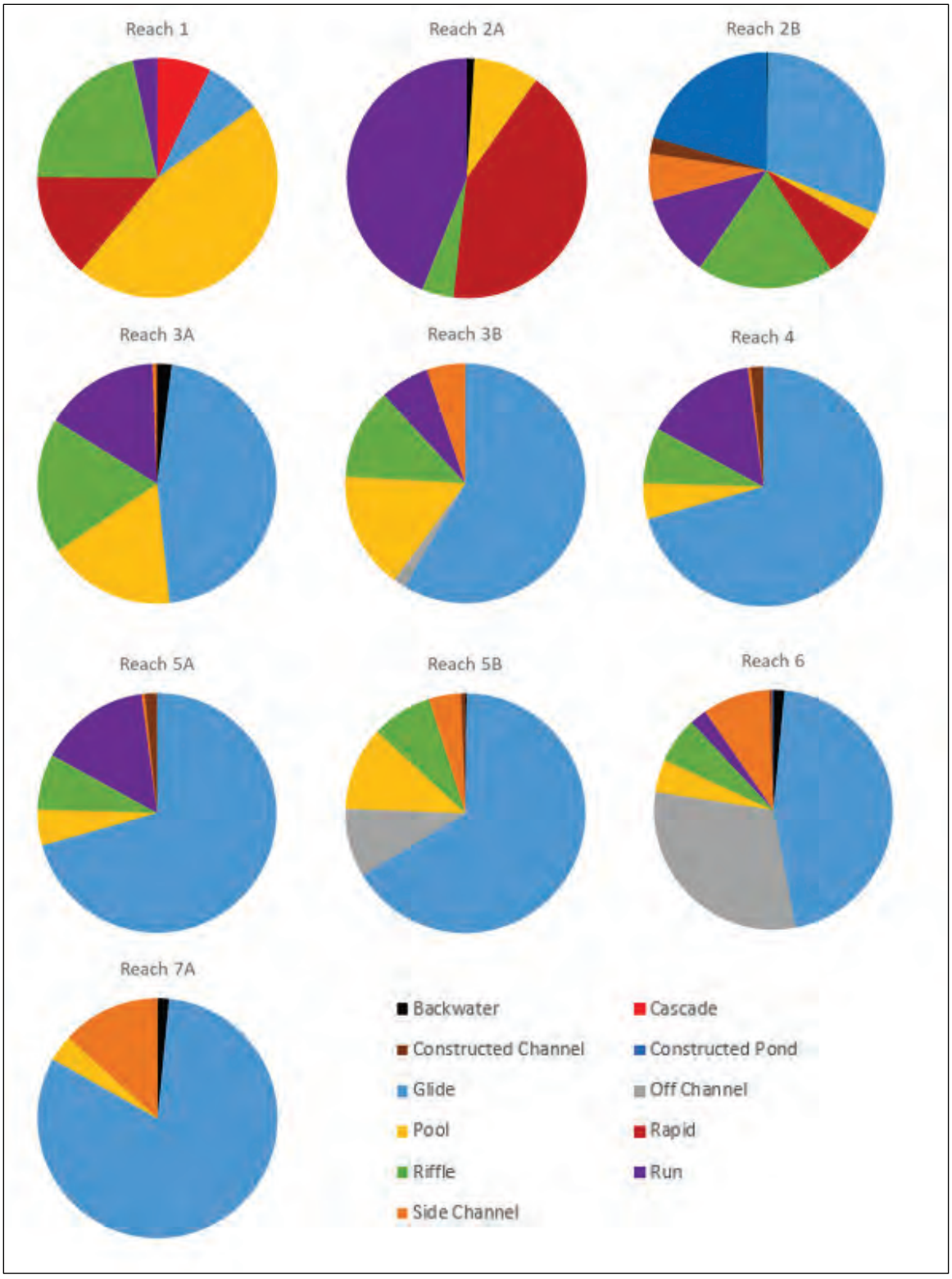


Figure 5.2-2. Distribution of the area of channel unit classes by reach (Blind and flowthrough channels are combined in this figure).

Channel unit density in terms of channel unit total and channel units per mile are included in Table 5.2-3. The density and diversity of channel units can be seen by looking at both Table 5.2-2 and 5.2-3. In terms of the diversity (number of habitat types), Reach 2B is the most diverse and also has a relatively high density of channel units at 15 units per mile. Some of this diversity is attributed to the existence of side channel and off-channel areas that are relics of past human alteration, such as the Agg Ponds and Park Slough, an engineered chum spawning channel, but there is also naturally occurring side channel and off-channel habitat. Reach 6 has the highest density of units but does not contain any rapid habitat, which is expected given its low gradient and the absence of bedrock in the reach. Reach 4 is also fairly diverse, but much smaller than Reaches 2B and 6, and with a lower density of habitat units. Reach 1 contains a higher number and density of habitats relative to all reaches except Reach 6, but due to its reduced flow levels, the habitat units are disconnected by dry stretches and not accessible to anadromous fish. Reach 7A has both the least diversity and density of all the reaches mapped.

Table 5.2-1. Reach length and area normalized by length.

Reach	Area (ft^2)	Length (miles)	Area Normalized by Length (ft^2/mi)
1	1,033,911	2.54	407,052
2A	1,259,521	1.16	1,085,794
2B	7,899,597	4.09	1,931,442
3A	2,126,914	1.92	1,107,768
4	4,066,343	3.51	1,158,502
3B	2,986,184	1.96	1,523,563
5A	5,844,664	3.52	1,660,416
5B	7,468,833	3.69	2,024,074
6	23,832,743	6.72	3,546,539
7A	2,981,566	1.27	2,347,690

Table 5.2-2. Summary of area by channel unit classification by reach (ft^2).

Reach	Backwater	Off-channel	Pool	Blind Side Channel	Flow Through Side Channel	Constructed Channel	Constructed Pond	Run	Glide	Rapid	Riffle
1	0	0	477,223	0	0	0	0	34,448	79,132	145,581	222,979
2A	12,880	0	110,897	0	0	0	0	553,475	0	527,933	54,337
2B	13,732	1,619,702	185,900	60,461	446,587	176,316	1,619,702	887,090	2,436,726	591,805	1,481,278
3A	41,700	0	365,571	13,215	0	0	0	330,427	986,309	0	389,691
4	35,452	0	533,436	9,942	12,737	0	0	435,313	2,114,880	460,439	464,144
3B	0	48,507	471,395	14,373	141,427	0	0	197,052	1,746,575	0	366,853
5A	0	0	281,459	23,934	0	97,702	0	873,328	4,128,236	0	440,096
5B	12,938	633,235	846,259	20,837	304,167	45,506	0	0	4,977,496	0	616,344
6	342,016	7,829,118	1,034,709	111,346	1,987,354	94,174	42,023	531,872	12,950,309	0	1,412,794
7A	45,184	0	105,385	396,501	0	0	0	0	2,434,496	0	0

Table 5.2-3. Number of channel units by reach.

Reach	Number of Channel Units	Length of Reach (miles)	Number of Channel Units per Mile
1	42	2.54	17
2A	12	1.16	10
2B	60	4.09	15
3A	27	1.92	14
4	22	3.51	6
3B	16	1.96	8
5A	16	3.52	5
5B	27	3.69	7
6	124	6.72	18
7A	5	1.27	4

Average metrics, such as pool depth and bankfull characteristics, allow for a comparison of habitat availability for adult steelhead holding and juvenile salmon feeding as well as channel capacity during bankfull flows. Adult holding for steelhead was also analyzed in Upper Skagit Habitat Model. Average pool depth and maximum pool depth are tied to holding habitat for adult spawners, as well as feeding areas for larger juveniles. Bankfull width and depth provide a measure of channel capacity during bankfull flows. These data also provide information on the relative size of each reach and the cross-sectional profile of the channel. Average and maximum pool depth and bankfull depth were extracted from the Upper Skagit Hydraulic Model output at the flow closest to the August sampling dates. Table 5.2-4 shows the average and maximum pool and bankfull depths, bankfull width by reach as extracted from the composite surface used in the model development, as well as the number of pools, pool frequency and pools per channel width.

Table 5.2-4. Bankfull width, number of pools, pool frequency, and pools per channel width by reach.

Reach	Average Pool Depth (ft)	Average Maximum Pool Depth (ft)	Average Bankfull Depth (ft)	Average Bankfull Width (ft)	Number of Pools	Pool Frequency (number/ mile)	Pools per Channel Width (number)
1	6.2	15.3	N/A	133	18	7	0.04
2A	3.9	7.0	6.9	216	4	3.4	0.12
2B	3.8	7.9	6.1	324	6	1.5	0.09
3A	6.4	12.1	9.1	234	6	3.1	0.14
4	5.7	13.9	10.0	325	4	1.1	0.07
3B	5.3	11.7	8.7	233	5	2.6	0.12
5A	6.8	16.0	8.3	325	3	0.9	0.05
5B	6.6	15.1	8.4	382	8	2.2	0.16
6	4.4	9.1	5.9	537	16	2.4	0.24
7A	6.1	13.2	6.8	520	1	0.8	0.08

Aquatic habitat capacity and quality is affected by mean and maximum pool depth. The average mean pool depths (mean pool depths averaged across all pools in the reach) range from 3.8 to 6.8 ft, so they are fairly consistent across reaches. Average maximum pool depth ranges more widely, from 7.0 to 16.0 ft, with the deepest values in Reaches 5A, 1 and 5B. The average maximum depths in Reach 1 are influenced by the deep pool at the head of the reach (65 ft deep).

Aquatic habitat quality is influenced by pool frequency, pool depth cover, key pieces of large wood and log jams, substrate characteristics, as well as the amount of edge habitat. Pool frequency is summarized by both pools per mile and pools per channel width. Pool frequency across reaches is relatively constant on a per mile basis with most reaches having 0.8 to 3.4 pools per mile (Table 5.2-4). The GE-02 Erosion and Geologic Hazards Study also includes similar habitat metrics for tributary reaches, however, since these are on a smaller scale than the mainstem, the metrics are slightly different (City Light 2023d). On a per channel width basis, pool frequency ranges from 0.04 to 0.24 across reaches. Reaches 2A and 3A have the highest pool frequency while Reaches 5B and 6 have the highest number of pools scaled by bankfull width.

Large wood in the study area is an important contributor to pool creation, as well as providing cover and nutrient inputs for aquatic species. Substantial data on large wood distribution and characteristics are provided in Section 5.6. The density of log jams, as well as the presence of apex jams (a subset of log jams) and pool forming wood, are indicators of structure and habitat quality for aquatic species. Selected wood metrics are presented in Table 5.2-5 summarizing the levels of large wood by reach. The majority of reaches have relatively low levels of pool-forming wood as compared to the total number of pieces, although it is noted that the data likely underestimate pool forming wood. Normalizing by reach length, Table 5.2-5 shows that in general, reaches farther downstream in the Skagit River (upstream of the Sauk River confluence in the primary study area) have more wood and more functional (e.g. pool-forming, bar forming, flow separating) wood. Section 5.6 and 5.7 presents additional detail on large wood loading and wood dynamics in the Skagit River.

Table 5.2-5. Total pieces, log jams, apex jams, and geomorphically functional wood by reach.

Reach	Total Large Wood Pieces	Pieces (number / mile)	Log Jams (number)	Jam Density (number / mile)	Apex Jams[2] (number)	Pool-Forming Wood[1] (number of pieces)	Pool-Forming Wood (number / mile)
1	131	51.6	1	0.4	0	0	0
2A	52	44.8	2	1.7	0	0	0
2B	363	88.8	10	2.4	4	27	6.6
3A	57	29.7	1	0.5	0	0	0.0
4	57	16.2	1	0.3	0	2	0.6
3B	236	120.4	5	2.6	1	31	15.8
5A	150	42.6	2	0.6	1	0	0.0
5B	827	224.1	23	6.2	6	35	9.5
6	1908	283.9	27	4.0	7	60	8.9
7A	414	326.0	9	7.1	0	4	3.1

1 Pool presence was not observed for every piece; total count is an underestimate.
2 Apex jams are a subset of log jams that have a specific function of forming bars in the main channel.

Similar to wood, cover also plays a role in the quality of rearing and spawning habitat for fish species (Beechie et al. 2005, Cram et al. 2012, Cram et al. 2017). For the purposes of this study, cover includes the following: undercut banks, overhanging vegetation, rootwads, log jam/submerged brush pile, log(s) parallel to bank, aquatic vegetation, short (less than 1ft) terrestrial grass, tall (greater than 3ft) dense grass (e.g., reed canary grass), vegetation greater than 3 vertical ft above stage zero flow (WDFW and Ecology 2016). Cover data provides information regarding habitat available for rearing, hiding cover for juveniles and holding habitat for spawning fish. Cover metrics calculated in Table. 5.2-6 includes percent cover for all habitat units, percent pool areas with cover, and area of edge habitat with cover. Total percent cover varies by reach with Reach 6 having the most at 30 percent and Reach 1 having the least with 6 percent. Reach 1 cover may be artificially low due to the low flows in that reach at the time of the survey. Percent pool area with cover is more directly related to rearing and holding habitat and Reaches 2B, 3A, 4 and 7A have above 20 percent cover. Reaches 1 and 2A have the lowest percent pool area with cover at 4 and 10 percent, respectively. Pools per mile with greater than 10 percent cover identifies the density of high-quality pool habitat by reach and allows for scaling of the metrics by reach length. Reach 3A has the highest density of pools with cover (2.6 pools per mile) likely due to the channel gradient and width while Reach 5A has the lowest density with 0.6 pools with cover per mile. Any overhanging vegetation observed in the aerial photos was noted as cover during the cover assessment, so would need to be considered in the interpretation of results.

Edge habitat has been noted as a critical component for rearing juvenile Chinook Salmon, as well as other salmon in the Skagit River (Beechie et al. 2005). Edge habitat is used by juvenile salmon to escape the main current of the river, hide from predators, and to rear and grow. The amount of cover, area of edge habitat, and area of edge habitat with cover are reported in Table 5.2-6. The area of edge habitat in Reach 1 is affected by low flows in that reach at the time of the survey and may be larger than it would be at higher flows. As would be expected based on reach size, Reach 6 has the greatest area of edge habitat by total area and normalized by length, although Reaches 3A, 5B and 4 have the largest percentages of edge habitat with cover (greater than 50 percent) indicating that the quality of edge habitat may be higher in those reaches.

Channel substrate also plays an important role in spawning habitat for adult salmonids and affects habitat use by juveniles. Specific substrate sizes are used by each species for spawning, so information on grain size can help to evaluate the quality of spawning habitat (see FA-02-Instream Flow Model Development Study [City Light 2023a] for more detail). The combination of substrate and cover, especially in river margins and edge habitat, can also influence the rearing habitat capacity and the distribution of juvenile salmonids. Substrate data for facies mapping, collected as part of the FA-02 Instream Flow Model Development Study, is summarized by reach in Table 5.2-7 but does not integrate the pebble count data discussed in Section 5.4 as those data only apply to discrete locations. Table 5.2-7 summarizes the percent cover of the dominant substrate across each reach. Cobble and boulder make up a large portion of the dominate surface substrate, although sand is also present in all reaches. Limitations for facies mapping data are noted in Section 5.4.

Table 5.2-6. Percent cover and edge habitat metrics by reach.

Reach	Percent Cover	Percent Pool Area with Cover	Pools Per Mile with Cover (number/mile)	Area of Edge Habitat (ft^2)	Area of Edge Habitat per mile (ft^2/mile)	Edge Habitat with Cover (ft^2)	Percent of Edge Habitat with Cover
1	6	4	2.0	230,375[1]	90,699	9,490	4.1
2A	15	10	1.7	39,112	33,717	16,686	42.7
2B	27	25	1.0	198,449	48,521	97,606	49.2
3A	18	22	2.6	79,929	41,630	45,948	57.5
4	18 20	1.1	127,026	64,809	64,311	50.6	N/A
3B	20	14	2.0	80,336	22,888	36,992	46.1
5A	21	11	0.6	132,088	37,525	101,303	76.7
5B	18	17	1.4	201,322	54,559	106,734	53.0
6	30	15	1.5	612,536	91,151	133,754	21.8
7A	15	24	0.8	105,084	82,743	30,025	28.6

1. Area of edge habitat is increased by low flows in reach due to flow management

Table 5.2-7. Substrate summary of percent cover by dominate substrate by reach.

Reach	Silt, Clay, Organic	Sand	Sm Gravel (0.1-0.5")	Med Gravel (0.5-1.5")	Lrg Gravel (1.5-3")	Sm Cobble (3-6")	Lrg Cobble (6-12")	Boulder (>12")	Bedrock
1	0%	1%	0%	1%	1%	5%	7%	80%	4%
2A	0%	3%	0%	0%	1%	0%	5%	88%	3%
2B	9%	14%	0%	0%	8%	35%	27%	7%	0%
3A	1%	1%	0%	0%	10%	15%	45%	27%	0%
4	0%	2%	0%	2%	4%	42%	12%	36%	0%
3B	3%	7%	0%	4%	19%	35%	17%	13%	1%
5A	0%	1%	0%	3%	16%	53%	12%	15%	0%
5B	1%	3%	1%	3%	12%	33%	21%	26%	0%
6	7%	10%	2%	5%	17%	22%	29%	8%	0%
7A	1%	7%	3%	4%	23%	3%	59%	0%	0%

Aquatic habitat conditions can be impacted by human modifications, including banks that have been hydromodified or excessively eroding banks that are caused or affected by human actions on the landscape (Hartson and Shannahan 2015, Beamer and Henderson 1998, Beechie et al 2005). Table 5.2-8 identifies the proportion of bank length in each reach that is hydromodified or actively eroding. There are some areas where banks have been hydromodified and are actively eroding, but those data are not included in the table below. In Reach 1, data are not reported for hydromodification or active erosion. This reach is a bedrock controlled reach, and there is not likely to be extensive hydromodification given the geomorphic setting. Conditions in Reach 1 were largely assessed remotely and due to the steep banks, the margin of error on the quantification of active erosion is likely larger than the amount of erosion in the reach. Consequently, the data are not reported since they are likely to be unreliable. See Attachment E to this study report and GE-02 Erosion and Geologic Hazards Study Report (City Light 2023d) for more detail on specific areas with both erosion and hydromodification. Substrate conditions downstream of actively eroding areas can also indicate whether and where erosion may be affecting fish habitat. As shown in Table 5.2-8, hydromodification is much more common on the right bank of the Skagit River, which may be due to higher levels of development and the presence of SR 20. Reaches 3A, 3B, 4 and 7A have the highest proportion of hydromodified banks on river right, followed by Reaches 6 and 5B. Reaches 2A, 2B, and 5A have little to no hydromodifications as mapped using 2015 data (Hartson and Shannahan 2015). Active erosion is present on both banks mostly in Reach 6, which is also the longest reach. There is also active erosion noted in Reach 7A on the right bank and Reach 4 on the right bank. Reaches 6 and 7A are naturally less confined, from a geomorphic perspective, than some of the other reaches, so may be more prone to erosive processes.

Table 5.2-8. Percent of bank length hydromodified and percent of bank length actively eroding by reach.

Reach	Percent Hydromodified (%)		Percent Actively Eroding (%)	
	Left Bank	Right Bank	Left Bank	Right Bank
1[1]	N/A	N/A	N/A	N/A
2A	0	0	0	0
2B	0	3	1	2
3A	0	37	0	0
4	6	21	0	9
3B	0	23	0	0
5A	3	0	0	0
5B	1	16	0	0
6	1	20	32	13
7A	0	21	0	14

1. Field data are not available for Reach 1 as habitat characterization utilized remote sensing data.

5.2.2 Tributary Analysis

A summary of water depths, widths, and gradients found within each tributary that was explored for fish passage can be found in Table 5.2-10. Gradients are averaged across the entire approximate 500-linear ft reach. Widths are of the wetted channel unless the stream was dry, in which case bankfull width measurements were taken, as wetted width is a criterion of fish passability (WDFW 2019). Some tributaries (Bacon Creek, Goodell Creek, Ladder Creek, Newhalem Creek) were too deep or swift at time of survey (during the August 2021 field visit) for surveyors to cross or obtain true thalweg measurements. In these cases, water depth measurements were taken near the accessible bank and width measurements were estimated based on remote sensing data and visual verification in the field. In the case of Goodell Creek, a survey could not be completed due to deep, swift waters coupled with steep, erosive banks making the survey inaccessible. A full inventory of tributaries assessed, linear distance surveyed, water depth and relative elevation profiles, and field photos can be found in Attachment G. Average negative slopes were recorded for three tributaries: Babcock Creek, Napoleon Side Channel, and Sauk Side Channel 1. This occurred because each stream had very low overall gradients with sections of backwatering, leading to slightly negative overall slope values across the survey. Absolute gradients of these tributaries were less than one percent and are noted as approximately zero percent in Table 5.2-9.

Table 5.2-9. Summary of tributary water depth values and average widths.

Tributary	Avg. Gradient (%)	Min. Water Depth (ft)	Max. Water Depth (ft)	Avg. Water Depth (ft)	Average Width (ft)
Alma Creek	5.25	0.50	2.45	1.55	28[2]
Babcock Creek	~0	0.00	3.17	1.04	5
Bacon Creek	1.17	1.49	2.20	1.69	54
Barr Creek	4.25	0.15	1.78	0.75	15
Copper Creek	6.37	0.47	1.66	0.84	11
Corkindale Creek	2.07	0.00	0.49	0.03	16[1]
Damnation Creek	5.16	0.80	2.75	1.26	20
Diobsud Creek	0.14	0.60	3.29	1.37	37
Goodell Creek[3]	3-6%	N/A	N/A	N/A	30
Illabot Creek	2.93	0.50	3.70	1.73	17
Ladder Creek	2.68	0.70	5.50	2.27	16
Martin Creek	0.86	0.00	2.35	0.53	9
Napolean Side Channel	~0	1.66	2.36	2.08	51
Newhalem Creek	2.90	1.50	3.90	2.12	30[2]
Olsen Creek	1.67	0.00	0.49	0.05	39[1]
Rocky Creek	2.83	0.23	1.27	0.75	19
Sauk Side Channel 1	~0	1.34	2.18	1.69	35
Sky Creek	18.65	0.16	2.60	0.90	9[2]
Sutter Creek	4.33	0.00	0.00	0.00	17
Thornton Creek	2.67	0.38	2.74	1.31	33

1 Bankfull width measurement; bankfull widths were taken instead of wetted widths when stream channels were dry.
2 Estimated value.
3. Values from field data from the GE-02 Erosion and Geologic Hazards Study (City Light 2023d).

5.3 Side Channels and Off-Channel Habitat

5.3.1 Current Side Channel Condition

Current side channel condition results are provided for side channels and off-channel areas that were identified in a collaborative process with City Light and LPs during July 2021. Results are organized by geomorphic reach and include a summary of the side channels and off-channel areas in the Skagit River between the Gorge Dam and the Sauk River confluence. A more detailed narrative describing each side channel is available in Attachment H. Summary tables are provided at the end of each reach subsection and include side channel IDs, local side channel names, side channel and off-channel area type, approximate area, and inlet and outlet characteristics. Side channel IDs are assigned based on river mile and bank (left or right looking downstream). Side channel areas presented in the summary tables are approximate and based on field observations and interpretation of REMs. Inlet and outlet connections are based on hydraulic modeling results from the FA-02 Instream Flow Model Development Study (City Light 2023a) and indicate surface water connection with the mainstem Skagit River. For the purpose of assessing connection to the mainstem river, some side channels are broken up into subsections. Where this occurs, a secondary number is attributed to the side channel ID. For example, if side channel 75-R were broken into two sections, the IDs would be listed as 75-R-1 and 75-R-2.

5.3.1.1 Reach Summaries of Side Channel Habitat

Reach 1

Reach 1 spans from the Gorge Dam to the Newhalem Powerhouse and does not contain any side channels or off-channel habitat.

Reach 2A

Reach 2A begins at the Newhalem Powerhouse and extends down to the NPS Newhalem Visitor Center bridge and does not contain any side channels or off-channel habitat.

Reach 2B

Reach 2B spans from the NPS Newhalem Visitor Center bridge down to the County Line Ponds and contains ten side channels (Table 5.3-1, Figures 5.3-1 and 5.3-2). The largest side channel is the Thornton Side Channel at PRM 90.7, which has several inlets that converge into a single large side channel and an additional perennial side channel branching off at PRM 90.25. Three side channels in Reach 2B have been enhanced as part of prior mitigation actions—Agg Ponds, County Line Ponds, and Park Slough. The Agg Ponds and County Line Ponds are two former aggregate mining sites. At both sites side channels were excavated to create aquatic habitat and connect ponds formed in the mining pits to the river. At the County Line The Skagit River has eroded through portions of the County Line Ponds creating additional side channels and connections from two ponds to the river. Park Slough is a blind side channel constructed for Chum spawning in the 1990s. The excavated channels in the Agg Ponds and Park Slough are groundwater fed and provide rearing habitat due to cold water, slow water, and cover from large wood and overhanging vegetation, but spawning functionality in Park Slough has been reduced due to siltation and exacerbated by beaver dams that trap silt deposits. This is supported by the field observations of the Park Slough substrate in the summer of 2021 where extensive silt was observed throughout the slough. Since Park Slough was constructed as a spawning channel and presumably had spawning gravels placed when it was created in the 1990s, the extensive coverage of silt is an indication of

loss of spawning habitat functionality in that area. Additional characterization of beaver activity at the Project's off-channel sites is provided in the TR-09 Beaver Habitat Assessment (City Light 2023h).

Table 5.3-1. Summary of side channels in Reach 2B. Inlet and outlet mainstem connectivity reported as annual flow exceedance probability.

Side Ch ID	Side Channel Name	Approx. Area (ft^2)	Type	Inlet Mainstem Connectivity[3] and Dominant Substrate	Outlet Connectivity[3] and Dominant Substrate	Skagit R. Discharge During Survey[2] (cfs)
92.8-L	Unnamed	195,809	Side Channel	November 2020 /Coarse Gravel	10%/Sand and Fines	2,980
91.7-L	Unnamed	7,649	Side Channel	Inactive/Vegetated	90%/Sand and Fines	3,060
91.7-R	Unnamed	45,421	Side Channel	40%/Cobble	20%/Cobble	3,740
91.4-L	Park Slough[1]	71,098	Constructed Channel	Blind/Subsurface	80%/Coarse Gravel	3,060
91-R-1	Agg Ponds	174,429	Constructed Channel	Blind/Subsurface	>99.9%/Sand and Fines	3,710
91-R-2	Agg Ponds[1]	1,061,099	Constructed Ponds	Blind/Coarse Gravel	60%/Coarse Gravel	3,710
90.7-L	Thornton Side Channel	392,807	Side Channel	>99.9%/Cobble	>99.9%/Coarse Gravel	3,030
90.5-R	Unnamed	24,327	Side Channel	Blind/Subsurface	30%/Coarse Gravel	3,710
90.25-L	Unnamed	114,505	Side Channel	98%/Coarse Gravel	80%/Coarse Gravel	3,030
90.1-R	Unnamed	25,677	Side Channel	98%/Coarse Gravel	80%/Cobble	3,030
89.5-R-1	County Line Ponds	106,327	Side Channel	80%/Cobble	>99.9%/Coarse Gravel	2,900
89.5-R-2	County Line Ponds[1]	294,522	Constructed Pond	60%/Cobble	60%/Coarse Gravel	2,900
89.5-R-3	County Line Ponds[1]	64,010	Side Channel	60%/Fine Gravel	99.9%/Coarse Gravel	2,900
89.5-R-4	County Line Ponds[1]	387,949	Constructed Channel	5%/Sand and Fines	60%/Sand and Fines	2,900
89.5-R-5	County Line Ponds[1]	29,251	Constructed Pond	Blind/Subsurface	10%/Sand and Fines	2,900

1 Feature fed by groundwater or non-mainstem hydrology, connection to mainstem may be more frequent than modeled.

2 Discharge at USGS Skagit Rivet at Marblemount gage (12181000).

3 Annual flow exceedance probability is the percentage of the year discharge is high enough to engage the channel inlet or outlet based on analysis of flow records from USGS stream gages. November 2020 flood discharge was 12,200 cfs at the USGS Skagit River at Newhalem gage (12178000) and 25,300 cfs at Marblemount (USGS gage 12181000), approximating the historical (regulated) 2-year recurrence interval flood at both gages.

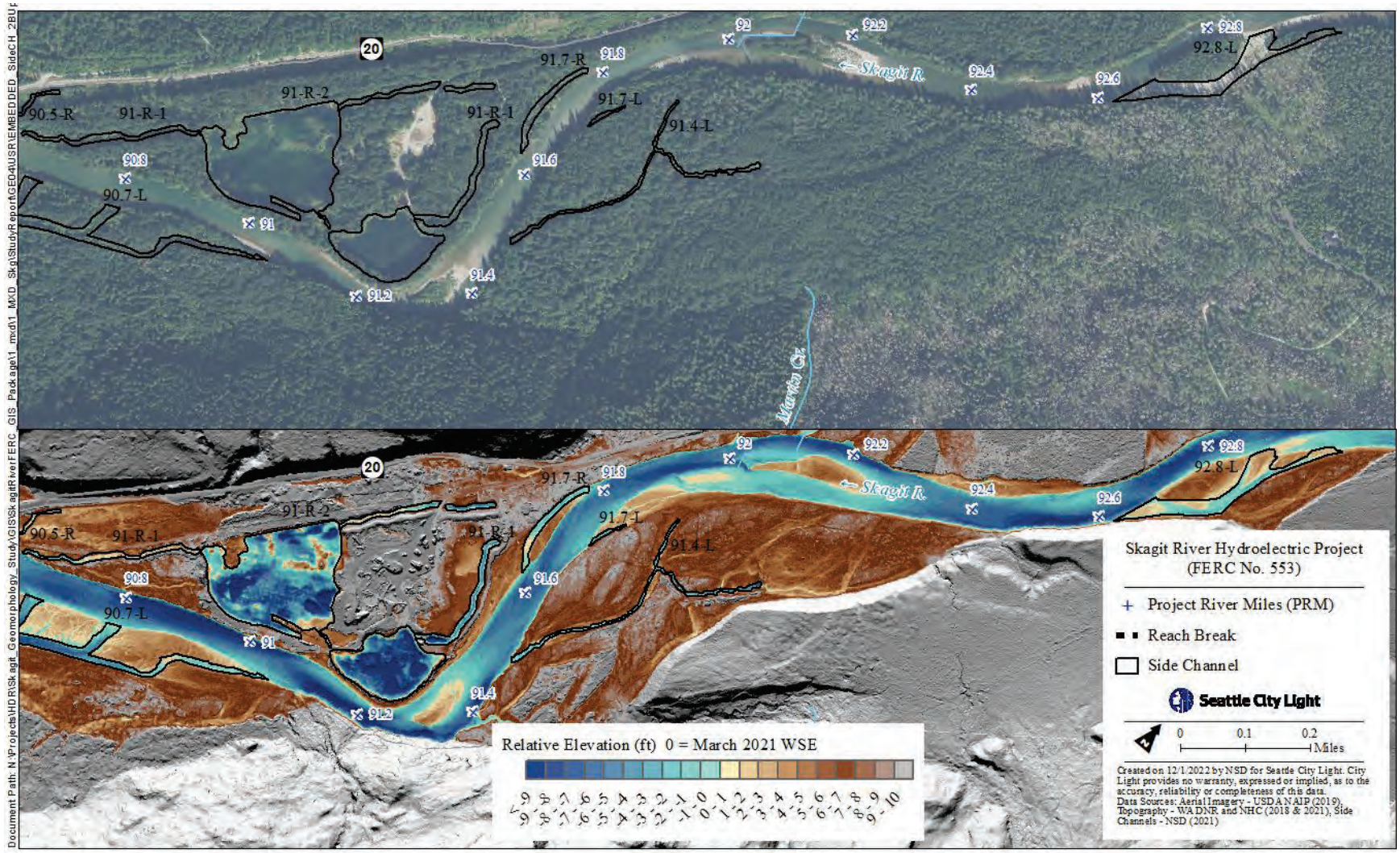


Figure 5.3-1. Map of Reach 2B upper side channels.

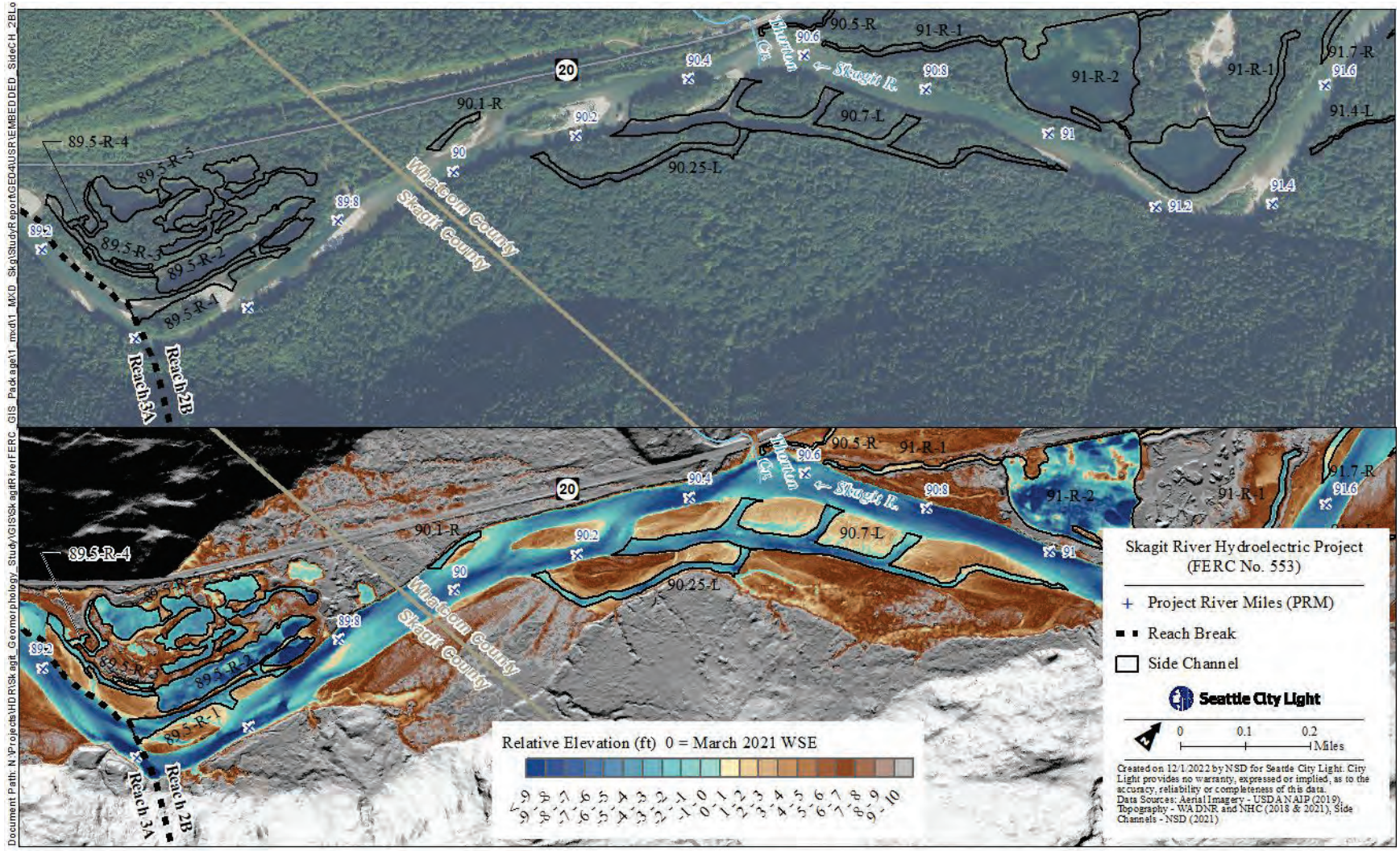


Figure 5.3-2. Map of Reach 2B lower side channels.

Reach 3A

Reach 3A is naturally confined with a narrow floodplain where the river steepens and begins to enter a long series of rapids. Only three side channels are present in Reach 3A (Table 5.3-2 and Figure 5.3-3). The first side channel at PRM 88.8 is seasonal and backwaters from the river at a 20 percent exceedance flow. The second side channel at PRM 88.7 intersects the valley hillslope indicating a groundwater and hillslope fed channel. The channel likely contains water year round, and is connected the majority of the year (60 percent exceedance). Both side channels have inactive vegetated inlets. The third side channel at PRM 88.2 is a marginally connected channel at the mouth of Damnation Creek. The inlet and outlet of the channel are inactive, except at flows above the 1-year flow recurrence, but it does contain perennially ponded area in the middle of the feature.

Table 5.3-2. Summary of side channels in Reach 3A. Inlet and outlet mainstem connectivity reported as annual flow exceedance probability.

Side Ch ID	Side Channel Name	Approx. Area (ft^2)	Type	Inlet Mainstem Connectivity[3] and Dominant Substrate	Outlet Mainstem Connectivity[3] and Dominant Substrate	Skagit R. Discharge During Survey[2] (cfs)
88.8-R	Unnamed	3,518	Side Channel	Inactive/Vegetated	20%/Sand and Fines	2,530
88.7-L[1]	Unnamed	52,254	Side Channel	Inactive/Vegetated	60%/Coarse Gravel	2,930
88.2-R	Unnamed	64,054	Side Channel	Nov 2020/Sand and Fines	Nov 2020/Vegetated	64,054

1 Feature fed by groundwater or non-mainstem hydrology, connection to mainstem may be more frequent than modeled.

2 Discharge at USGS Skagit River at Marblemount gage (12181000).

3 Annual flow exceedance probability is the percentage of the year discharge is high enough to engage the channel inlet or outlet based on analysis of flow records from USGS stream gages. November 2020 flood discharge was 12,200 cfs at the USGS Skagit River at Newhalem gage (12178000), equal to approximately 1.5-year flow at the Newhalem gage and 2.5-year flow at the Marblemount gage (12181000).

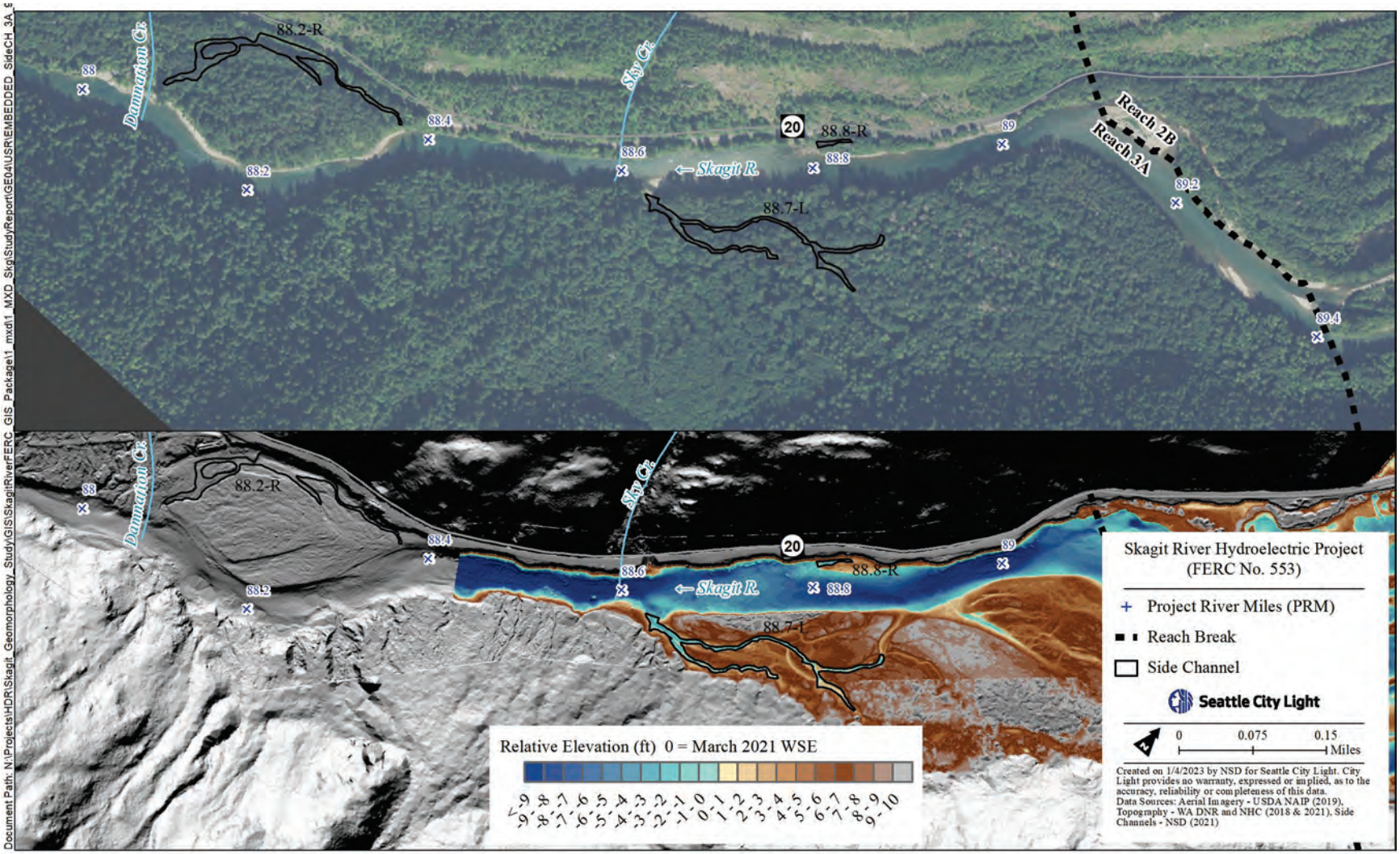


Figure 5.3-3. Map of Reach 3A side channels.

Reach 4

The river is confined to a narrow steep valley with several sections of rapids through Reach 4 and contains only 3 small side channels all near the downstream end of the reach (Table 5.3-3 and Figure 5.3-4). The side channel at PRM 84.5 contains spawning gravel throughout, was less than 0.5 ft deep during the August 2021 survey, and both the inlet and outlet are connected for a majority of the year (60 percent exceedance). The channel at PRM 85.5 has a vegetated inlet and backwaters at the outlet at the 30 percent exceedance flow. The third side channel at PRM 85.3 is mostly inactive and has mature woody shrubs growing within the channel. Only a small area of the outlet connects to the river at the 10 percent exceedance.

Table 5.3-3. Summary of side channels in Reach 4. Inlet and outlet mainstem connectivity reported as annual flow exceedance probability.

Side Ch ID	Side Channel Name	Approx. Area (ft^2)	Type	Inlet Mainstem Connectivity[2] and Dominant Substrate	Outlet Mainstem Connectivity[2] and Dominant Substrate	Skagit R. Discharge During Survey[1] (cfs)
85.5-R	Unnamed	17,085	Side Channel	November 2020 /Vegetated	30%/Sand and Fines	2,530
85.3-L	Unnamed	13,608	Side Channel	Inactive/Vegetated	10%/Vegetated	3,510
84.5-L	Unnamed	14,553	Side Channel	60%/Coarse Gravel	60%/Coarse Gravel	3,510

1 Discharge at USGS Skagit River at Marblemount gage (12181000).

2 Annual flow exceedance probability is the percentage of the year discharge is high enough to engage the channel inlet or outlet based on analysis of flow records from USGS stream gages. November 2020 flood discharge was 12,200 cfs at the USGS Skagit Rivet at Newhalem gage (12178000), equal to approximately 1.5-year flow at the Newhalem gage and 2.5-year flow at the Marblemount gage.

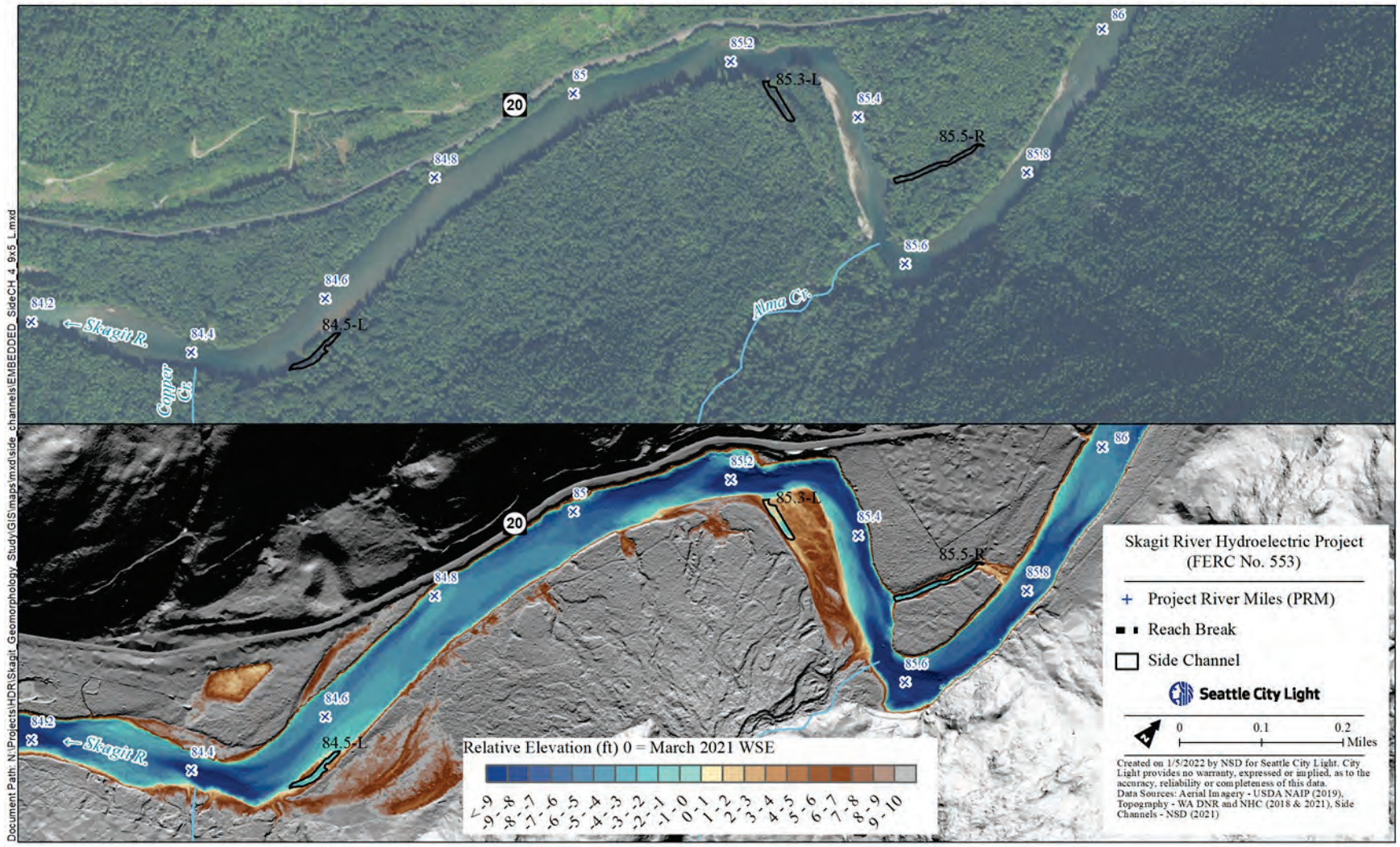


Figure 5.3-4. Map of Reach 4 side channels.

Reach 3B

Reach 3B is a short reach that begins just upstream of Bacon Creek and contains two side channels and one off-channel area (Table 5.3-4 and Figure 5.3-5). The valley and floodplain begin to widen compared to Reach 4, but the river is still confined to a relatively narrow floodplain. The two side channels at PRM 82.8 and 82.5 are flow through and provide spawning and rearing habitat due to spawning sized gravels found in both channels, and rearing habitat elements of pools, slow water, and cover provided by large wood. Both side channels are connected for a majority of the year. The off-channel area at PRM 82.9 is a pond connected to the Skagit River via an outlet connected at the 40 percent exceedance. The inlet is less active and vegetated, only connecting at the 5 percent exceedance. The pond contains aquatic vegetation and large wood, providing rearing habitat when connected to the river (Figure 5.3-6).

Table 5.3-4. Summary of side channels in Reach 3B. Inlet and outlet mainstem connectivity reported as annual flow exceedance probability.

Side Ch ID	Side Channel Name	Approx. Area (ft^2)	Type	Inlet Mainstem Connectivity[2] and Dominant Substrate	Outlet Mainstem Connectivity[2] and Dominant Substrate	Skagit R. Discharge During Survey[1] (cfs)
82.9-L	Unnamed	117,001	Off-Channel	5%/Vegetated	40%/Sand and Fines	3,510
82.8-R	Moses Slough	136,231	Side Channel	40%/Cobble	80%/Sand and Fines	3,880
82.5-L	Unnamed	61,202	Side Channel	80%/Coarse Gravel	98%/Coarse Gravel	3,510

1 Discharge at USGS Skagit River at Marblemount gage (12181000).

2 Annual flow exceedance probability is the percentage of the year discharge is high enough to engage the channel inlet or outlet based on analysis of flow records from USGS stream gages. November 2020 flood discharge was 12,200 cfs at the Skagit River at Newhalem gage (12178000), equal to approximately 1.5-year flow at the Newhalem gage and 2.5-year flow at the Marblemount gage.

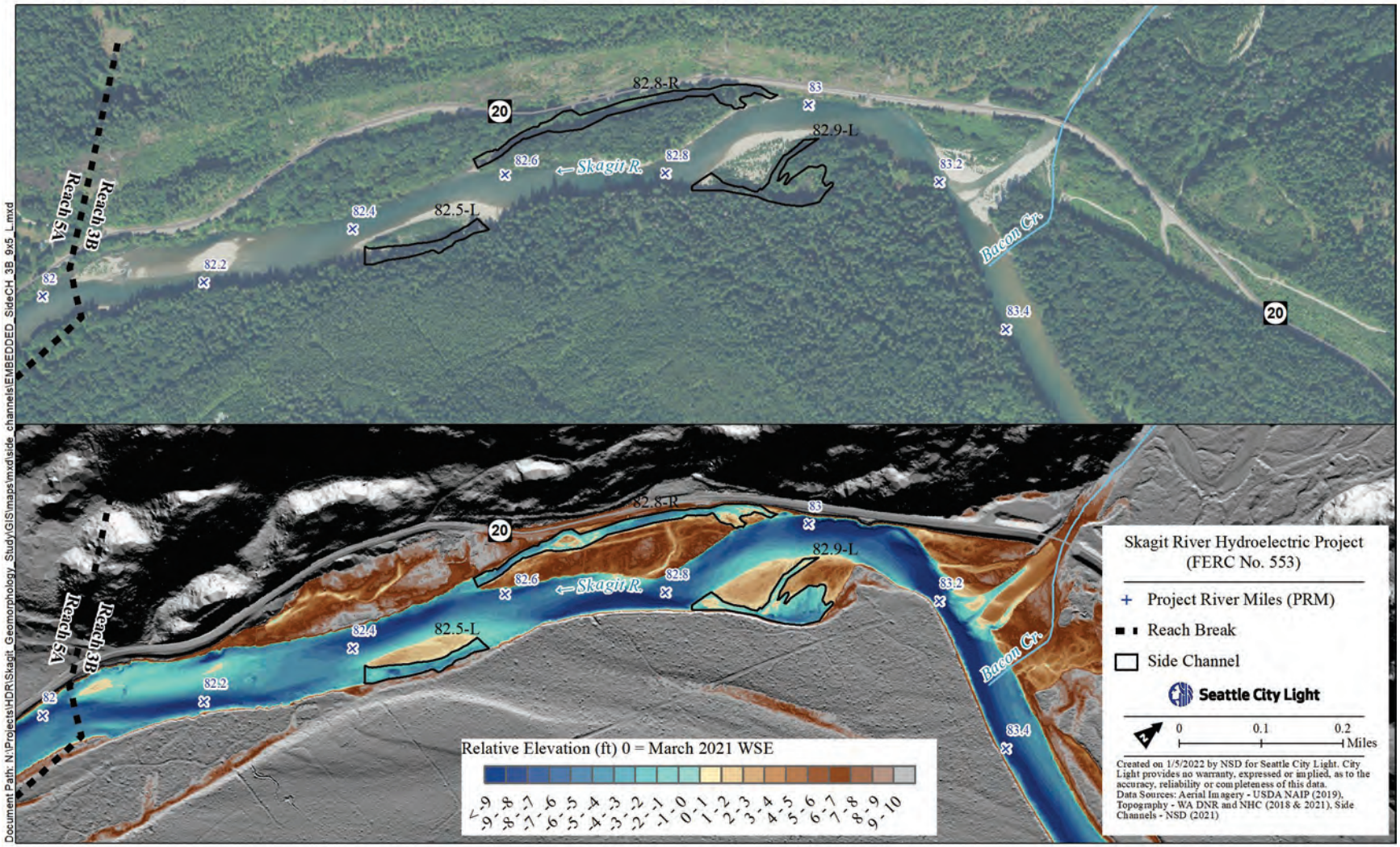


Figure 5.3-5. Map of Reach 3B side channels.



Figure 5.3-6. Off-channel pond in side channel PRM 82.9-L.

Reach 5A

Reach 5A begins upstream of Diobsud Creek and extends down to the Cascade Rockport Road Bridge. Within Reach 5A, the valley becomes wider, but the river channel is straight with a narrow active floodplain and contains three side channels (Figure 5.3-7). Two side channels are connected for 80 percent or more of the year and the third is mostly inactive channel with an outlet only connected at the 10 percent exceedance. (Table 5.3-5). The side channel at PRM 81.4, known as Diobsud Slough, is a backwater pool connected at the 98 percent exceedance with a beaver ponded wetland above the backwater, but the inlet is inactive and vegetated. The side channel at PRM 80, known as Taylor Side Channel, is an excavated Chum Salmon spawning channel created in the 1990s. Taylor Side Channel is groundwater fed and provides rearing habitat due to cold water, slow water, and cover from large wood and overhanging vegetation, but spawning functionality has been reduced due to siltation and beaver colonization.

Table 5.3-5. Summary of side channels in Reach 5A. Inlet and outlet mainstem connectivity reported as annual flow exceedance probability.

Side Ch ID	Side Channel Name	Approx. Area (ft^2)	Type	Inlet Mainstem Connectivity[3] and Dominant Substrate	Outlet Mainstem Connectivity[3] and Dominant Substrate	Skagit R. Discharge During Survey[1] (cfs)
81.4-R	Diobsud Slough	73,138	Side Channel	November 2020/Vegetated	98%/Sand and Fines	3,510
80.6-R	Unnamed	32,741	Side Channel	Inactive/Vegetated	10%/Vegetated	3,510
80-L[1]	Taylor Side Channel	171,393	Constructed Channel	Blind/Subsurface	80%/Fine Gravel	2,690

1 Feature fed by groundwater or non-mainstem hydrology, connection to mainstem may be more frequent than modeled.

2 Discharge at the USGS Skagit River at Marblemount gage (12181000).

3 Annual flow exceedance probability is the percentage of the year discharge is high enough to engage the channel inlet or outlet based on analysis of flow records from USGS stream gages. November 2020 flood discharge was 12,200 cfs at the USGS Skagit River at Newhalem gage (12178000), equal to approximately 1.5-year flow at the Newhalem gage and 2.5-year flow at the Marblemount gage.

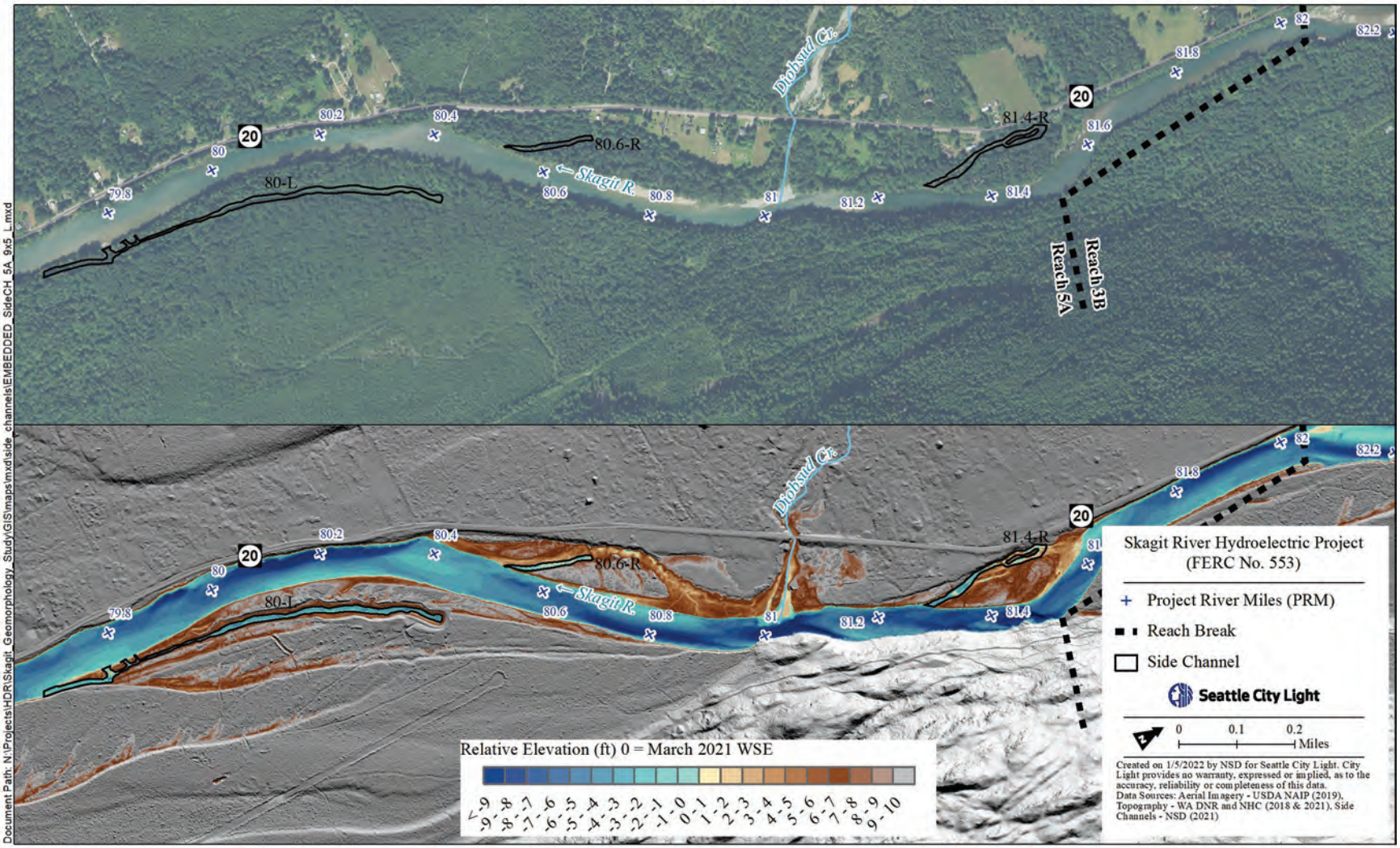


Figure 5.3-7. Map of Reach 5A side channels.

Reach 5B

Reach 5B begins at the Cascade Rockport Rd Bridge and continues down to PRM 74.8 and contains eight side channels and one off-channel area (Table 5.3-6, Figures 5.3-8 and 5.3-9). The upstream most and largest side channels are the Cascade River Distributary Channels at PRM 78.3, which contain several channels with similar characteristics—numerous log jams, pools, and spawning gravels. Marblemount Slough at PRM 78.1 is another large perennial channel and has plane bed morphology and few pieces of large wood. Marblemount Slough shares an inlet, which connects at the 60 percent exceedance, with Pressentin Side Channel. Pressentin Side Channel (77.7-R) is a relict side channel that was reconnected in 2021 with an outlet also connected at the 60 percent exceedance, so it is less connected than Marblemount Slough. The remaining perennial channels are two-plane bed channels devoid of large wood at PRM 76.6 and 77.6, and a channel at PRM 74.6 which used to be a flow-through channel but has become mostly inactive aside from a backwater pool and shallow wetland formed by a beaver dam.

The other channels in Reach 5B consist of Marblegate Slough, Clarks Cabin Side Channel, an unnamed channel at PRM 74.6, and an off-channel wetland at PRM 75. Marblegate Slough at PRM 77 contains two wide, long pools near the outlet that connect to the river at the 20 percent exceedance flow and an inlet that is vegetated and connects above the typical annual flow. Clarks Cabin Side Channel was not visited due to private property access. It has an inactive inlet and an outlet connected at the 80 percent exceedance. The off-channel feature at PRM 75 is a mainstem oxbow forming a depressional wetland that connects to the mainstem via a narrow outlet a majority of the year (60 percent exceedance flow).

Table 5.3-6. Summary of side channels in Reach 5B. Inlet and outlet mainstem connectivity reported as annual flow exceedance probability.

Side Ch ID	Side Channel Name	Approx. Area (ft^2)	Type	Inlet Mainstem Connectivity[4] and Dominant Substrate	Outlet Mainstem Connectivity[4] and Dominant Substrate	Skagit R. Discharge During Survey[1] (cfs)
78.3-L	Cascade River Distributary Channels	317,281	Side Channel	>99.9%/Variable: Cobble to Sand and Fines	>99.9%/Coarse Gravel and Cobble	3,620
78.1-R	Marblemount Slough	150,142	Side Channel	60%/Coarse Gravel	>99.9%/Sand and Fines	2.930
77.7-R	Pressentin Side Channel[2]	137,552	Side Channel	60%/Coarse Gravel	60%/Sand and Fines	Not visited in Aug 2021
77.6-L	Unnamed	233,803	Side Channel	80%/Coarse Gravel	>99.9%/Cobble	3,530
77-L	Marblegate Slough	106,661	Side Channel	November 2020 flood discharge/Vegetated	20%/Sand and Fines	3,530
76.6-R	Unnamed	54,413	Side Channel	>99.9%/Cobble	>99.9%/Cobble	3,510
75.5-R	Clarks Cabin Side Channel[3]	30,985	Side Channel	Inactive/Vegetated	80%	Not visited in Aug 2021
75-L	Unnamed	638,386	Off Channel	Inactive/Vegetated	60%	Not visited in Aug 2021
74.6-R	Unnamed	27,857	Side Channel	5%/Vegetated	>99.9%/Fine Gravel	3,510

1 Discharge at the USGS Skagit River at Marblemount gage (12181000).
2 Constructed in 2021, but not finished until after August 2021 survey. Inlet connection shared with Marblemount Slough.
3 No substrate data available. Not visited during August 2021 survey due to private land access.
4 Annual flow exceedance probability is the percentage of the year discharge is high enough to engage the channel inlet or outlet based on analysis of flow records from USGS stream gages. November 2020 flood discharge was 12,200 cfs at the USGS Skagit River at Newhalem gage (12178000), equal to approximately 1.5-year flow at the Newhalem gage and 2.5-year flow at the Marblemount gage.

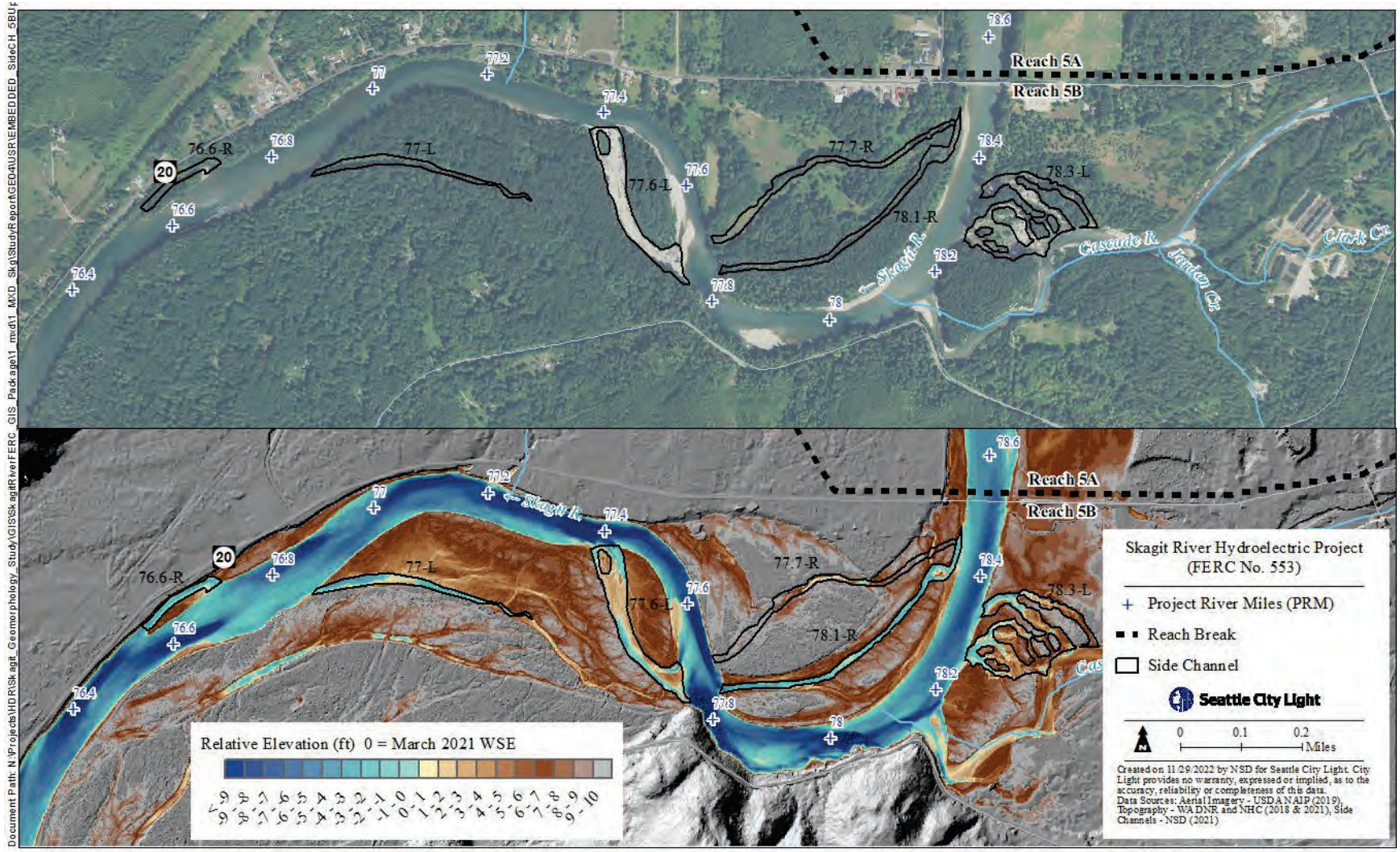


Figure 5.3-8. Map of upper Reach 5B side channels.

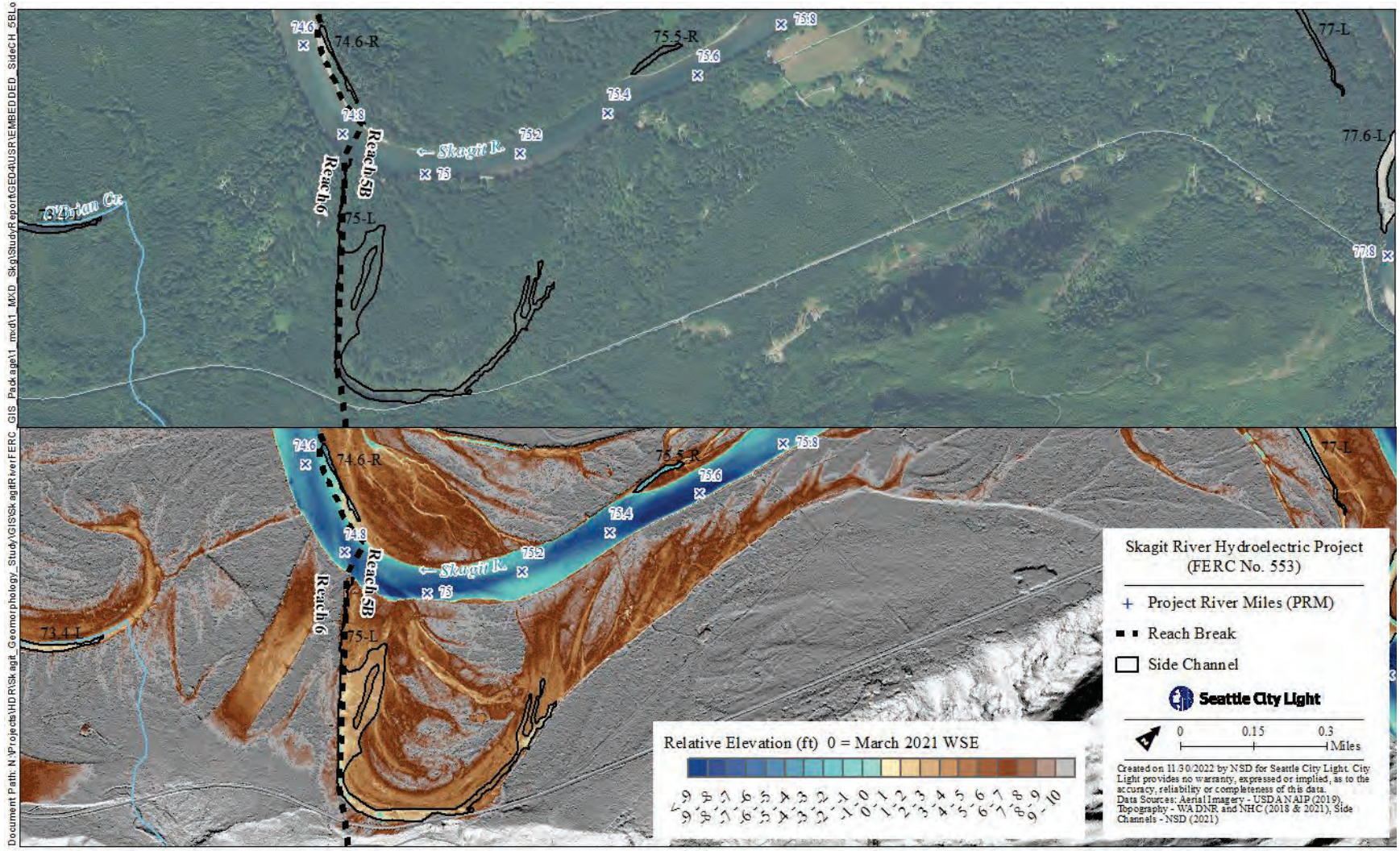


Figure 5.3-9. Map of lower Reach 5B side channels.

Reach 6

Reach 6 begins at PRM 74.8 and continues down to PRM 68.1, just upstream of the SR 530 bridge. It contains 18 side channels, 11 off-channel areas, and two constructed channels and ponds, more than double the number of any other reach (Table 5.3-7, Figures 5.3-10 and 5.3-12). Powerline Pond at PRM 73.9 and Illabot Chum Channel at PRM 73.6 are both excavated Chum spawning channels created in the 1990's that currently function as off-channel areas. Similar to the other spawning channels both have reduced spawning functionality due to siltation but provide rearing habitat via protected channels with cover from large wood, overhanging vegetation, and aquatic vegetation. Powerline Pond has more extensive siltation and minimal spawning habitat.

Connecting the Illabot Chum Channel to the Skagit River is the Illabot Side Channel Complex at PRM 73.6. The Illabot Side Channel Complex is a series of side channels and an off-channel wetland occupying former Skagit River flow-through channels. In present day, the complex is fed by Illabot Creek and subsurface flow and contains a network of channels with large wood and log jams, pools, and vegetation cover that provide rearing and spawning habitat. Across the river, at PRM 73.2, is Buller's Side Channel, also a relict flow-through channel that presently contains a large beaver ponded off-channel area at the upstream end and a side channel connecting to the Skagit River at the downstream end.

The other off-channel features in Reach 6 include Hoopers Slough at PRM 72.3, Washington Eddy at PRM 69.6, a smaller unnamed feature at PRM 68.6 and four off-channel areas in the Barnaby sub-reach (Figure 5.3-12). Barnaby Outlet is an off-channel wetland that historically was connected to two large oxbow wetlands—Barnaby Slough and Harrison Pond. Both Barnaby and Harrison were disconnected from the Skagit River by dikes used to build now derelict fish rearing ponds in the 1960's. Barnaby Slough was recently reconnected to the Barnaby Outlet, adjacent Lucas Slough, and the Skagit River by a restoration project completed in 2021.

Other larger side channels in Reach 6 include Timber Dolo Side Channel at PRM 71.9, Lucas Slough at PRM 69.9, an unnamed side channel at PRM 69.4, Johnson Side Channel at PRM 68.5, and Rockport Side Channel at PRM 68.3.

Table 5.3-7. Summary of side channels in Reach 6. Inlet and outlet mainstem connectivity reported as annual flow exceedance probability.

Side Ch ID	Side Channel Name	Approx. Area (ft^2)	Type	Inlet Mainstem Connectivity[6] and Dominant Substrate	Outlet Mainstem Connectivity[6] and Dominant Substrate	Skagit R. Discharge During Survey[2] (cfs)
73.9-L	Powerline Pond	75,082	Constructed Pond and Channel	Blind/Subsurface	40%/Sand and Fines	3,510
73.6-L	Illabot Chum Channel	146,704	Constructed Channel	Blind/Subsurface	10%/Sand and Fines	2,460
73.4-L	O'Brian Cr Wetland	359,333	Off-Channel	Tributary Flow/Cobble	40/Sand and Fines	Not visited in Aug 2021
73.2-R-1	Buller's Side Channel	67,826	Side Channel	40%/Sand and Fines	99.9%/Fine Gravel	3,420

Side Ch ID	Side Channel Name	Approx. Area (ft^2)	Type	Inlet Mainstem Connectivity[6] and Dominant Substrate	Outlet Mainstem Connectivity[6] and Dominant Substrate	Skagit R. Discharge During Survey[2] (cfs)
73.2-R-2	Buller's Side Channel[1]	192,057	Off-Channel	10%/Cobble	40%/Sand and Fines	3,420
73-L	Unnamed	47,749	Side Channel	10%/Vegetated	40%/Vegetated	4,060
72.8-L-1	Illabot Creek Outlet	748,846	Side Channel	>99.9%/Variable	>99.9%/Coarse Gravel	2,820
72.8-L-2	Illabot Side Channel Complex	411,281	Side Channel	98%/Coarse Gravel	>99.9%/Coarse Gravel	2,820
72.8-L-3	Illabot Side Channel Complex	556,270	Off-Channel	Tributary Flow/Sand and Fines	>99.9%/Sand and Fines	2,820
72.8-L-4	Illabot Side Channel Complex[1]	112,812	Side Channel	90%/Coarse Gravel	10%/Sand and Fines	2,820
72.8-L-5	Illabot Side Channel Complex	34,842	Side Channel	60%/Coarse Gravel	20%/Coarse Gravel	2,820
72.8-L-6	Illabot Side Channel Complex	24,582	Side Channel	Inactive/Vegetated	90%/Sand and Fines	2,820
72.5-R	Unnamed	84,585	Side Channel	20%/Vegetated	80%/Sand and Fines	3,510
72.3-R-1	Hoopers Slough	85,853	Off-Channel	Inactive/Vegetated	>99.9%/Sand and Fines	4,303
72.3-R-2	Hoopers Slough	48,974	Off-Channel	Inactive/Vegetated	10%/Sand and Fines	4,303
72.2-L	Unnamed	51,615	Side Channel	60%/Sand and Fines	60%/Sand and Fines	4,060
71.9-R	Timber Dolo Side Channel	274,451	Side Channel	>99.9%/Cobble	>99.9%/Coarse Gravel	3,710
71.5-R	Unnamed	20,258	Side Channel	November 2020/Vegetated	30%/Sand and Fines	3,970
71.4-R	Unnamed	20,989	Side Channel	60%/Cobble	80%/Coarse Gravel	3,970
71.2-L	Unnamed	38,534	Side Channel	5%/Vegetated	60%/Sand and Fines	4,030
70.8-R	Barr Creek Side Channel	38,407	Side Channel	40%/Coarse Gravel	98%/Coarse Gravel	3,360
70.6-L	Harrison Slough[3]	1,866,361	Off-Channel	Inactive/Vegetated	See Note 3/Sand and Fines	1,866,361
70.4-L	Barnaby Slough[4]	1,802,041	Off-Channel	Inactive/Vegetated	November 2020 /Sand and Fines	3,880

Side Ch ID	Side Channel Name	Approx. Area (ft^2)	Type	Inlet Mainstem Connectivity[6] and Dominant Substrate	Outlet Mainstem Connectivity[6] and Dominant Substrate	Skagit R. Discharge During Survey[2] (cfs)
70.2-L	Barnaby Outlet[1]	330,823	Off-Channel	November 2020 /Vegetated	90%/Sand and Fines	3,880
70-L	Unnamed	32,428	Side Channel	90%/Sand and Fines	>99.9%/Sand and Fines	3,850
69.9-L	Lucas Slough[5]	378,905	Side Channel	See note 5/Sand and Fines	>99.9/Sand and Fines	2,460
69.7-R	Unnamed	54,277	Side Channel	80/Coarse Gravel	98%/Sand and Fines	3,450
69.6-R	Washington Eddy[1]	763,744	Off-Channel	Inactive/Vegetated	99.5%/Sand and Fines	2,820
69.5-L	Unnamed	66,621	Side Channel	>99.9%/Coarse Gravel	90%/Sand and Fines	3,340
69.4-L	Unnamed (larger channel)	242,320	Side Channel	>99.9%/Coarse Gravel	>99.9%/Not visible due to deep water	2,460
69-L	False Lucas Slough	875,027	Off-Channel	Inactive/Vegetated	20%/Sand and Fines	Not visited in August 2021
68.6-R	Unnamed	117,740	Off-Channel	November 2020/Vegetated	99.5%/Sand and Fines	3,140
68.5-R	Johnson Side Channel	196,038	Side Channel	>99.9%/Coarse Gravel	>99.9%/Sand and Fines	3,450
68.3-R	Rockport Side Channel	179,901	Side Channel	>99.9%/Cobble	>99.9%/Cobble	4,300
68.2-R	Unnamed	10,631	Side Channel	5%/Sand and Fines	10%/Sand and Fines	4,300

1 Feature fed by groundwater or non-mainstem hydrology, connection to mainstem may be more frequent than modeled.
2 Discharge at the USGS Skagit River at Marblemount gage (12181000).
3 Harrison Slough outlet is controlled by a relict weir and fish ladder. No direct connection to river.
4 Fed by groundwater, so connection lower than modeled. Outlet also reconnected to river via restoration project in 2021, not reflected in terrain or hydraulic model.
5 Inlet of Lucas Slough is fed by Barnaby Slough, not mainstem Skagit River.
6 Annual flow exceedance probability is the percentage of the year discharge is high enough to engage the channel inlet or outlet based on analysis of flow records from USGS stream gages. November 2020 flood discharge was 12,200 cfs at the USGS Skagit River at Newhalem gage (12178000), equal to approximately 1.5-year flow at the Newhalem gage and 2.5-year flow at the Marblemount gage.

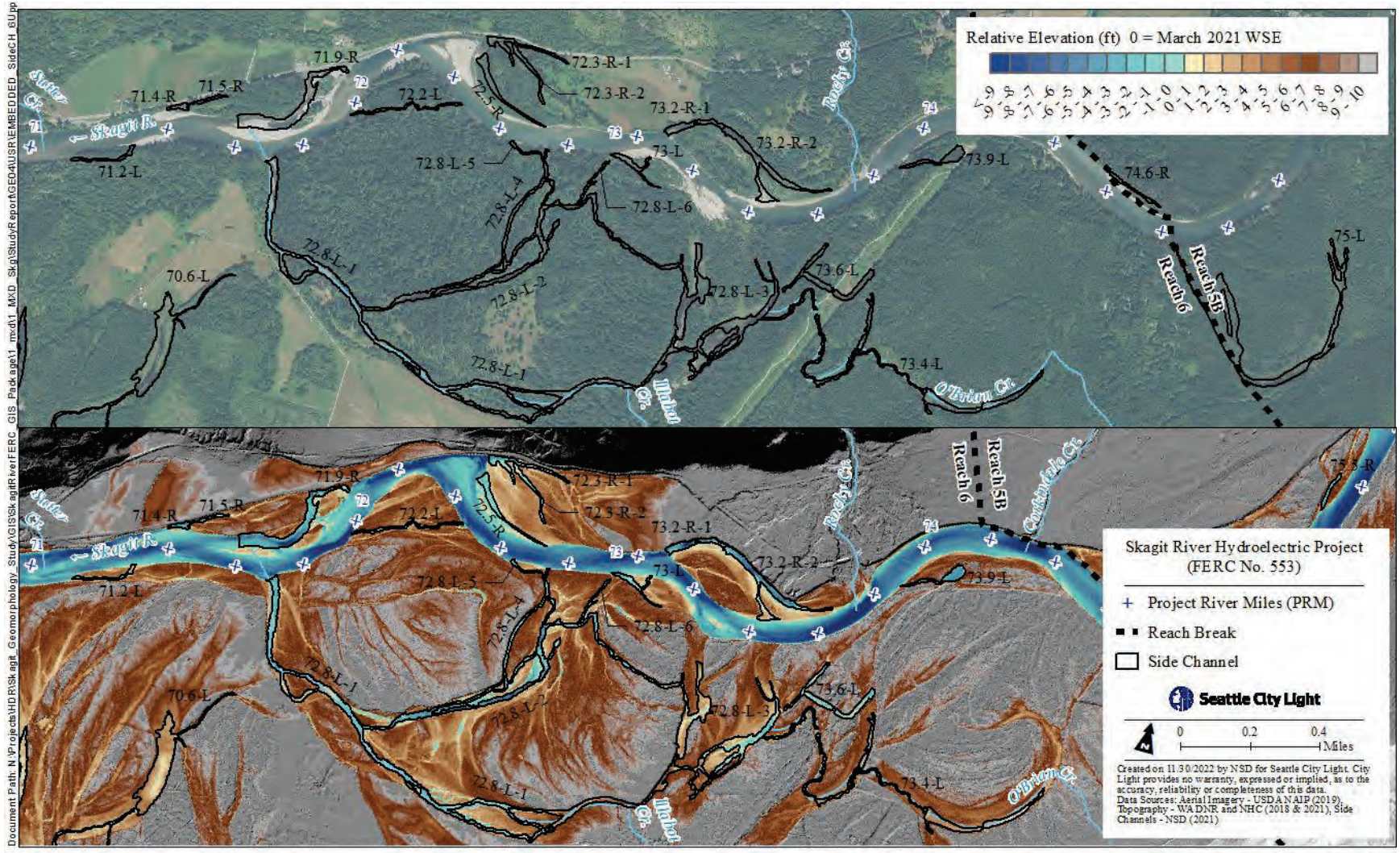


Figure 5.3-10. Map of Upper Reach 6 side channels with labels for Illabot Side Channel Complex channels.

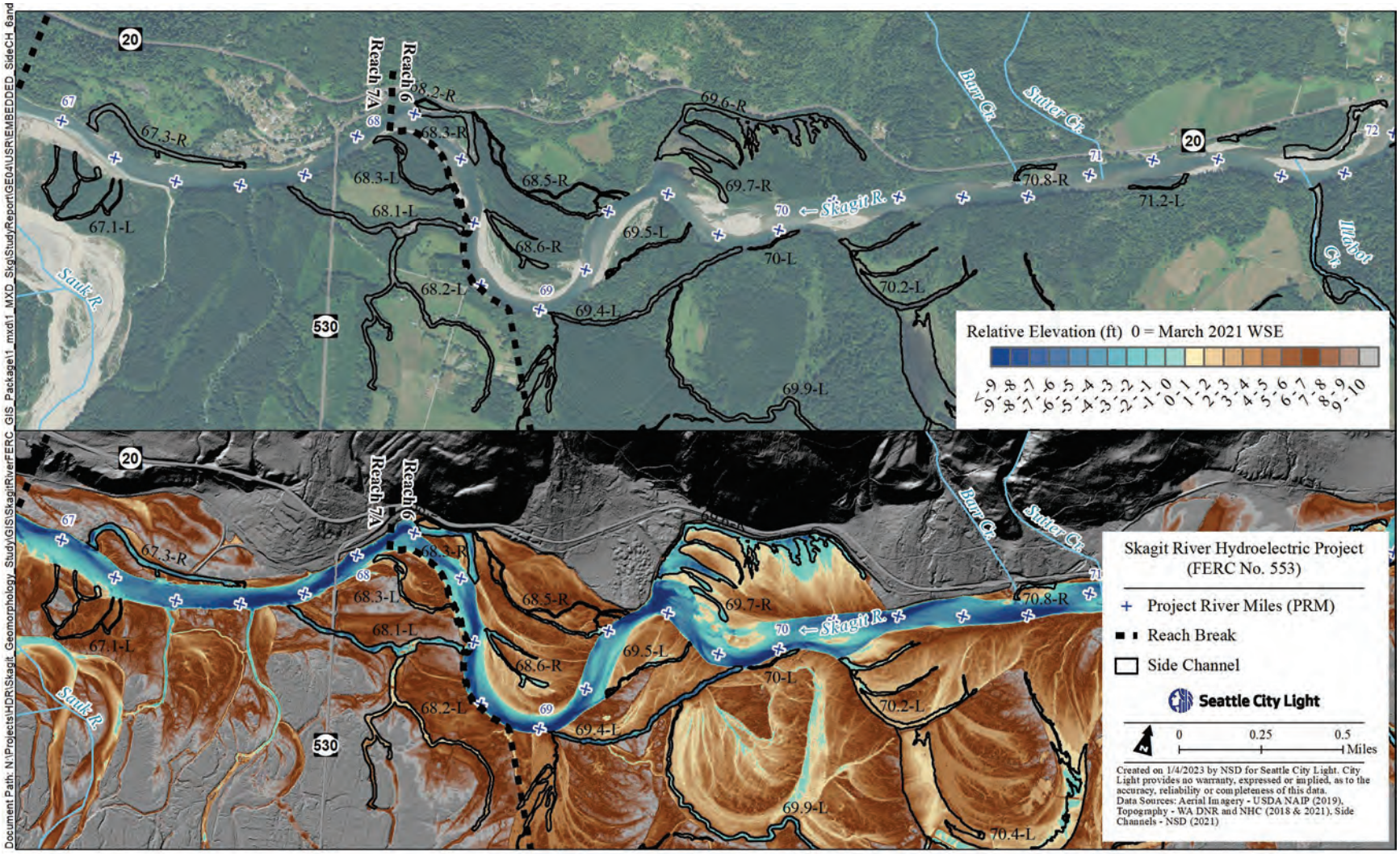


Figure 5.3-11. Map of side channels in Lower Reach 6 and Reach 7A.

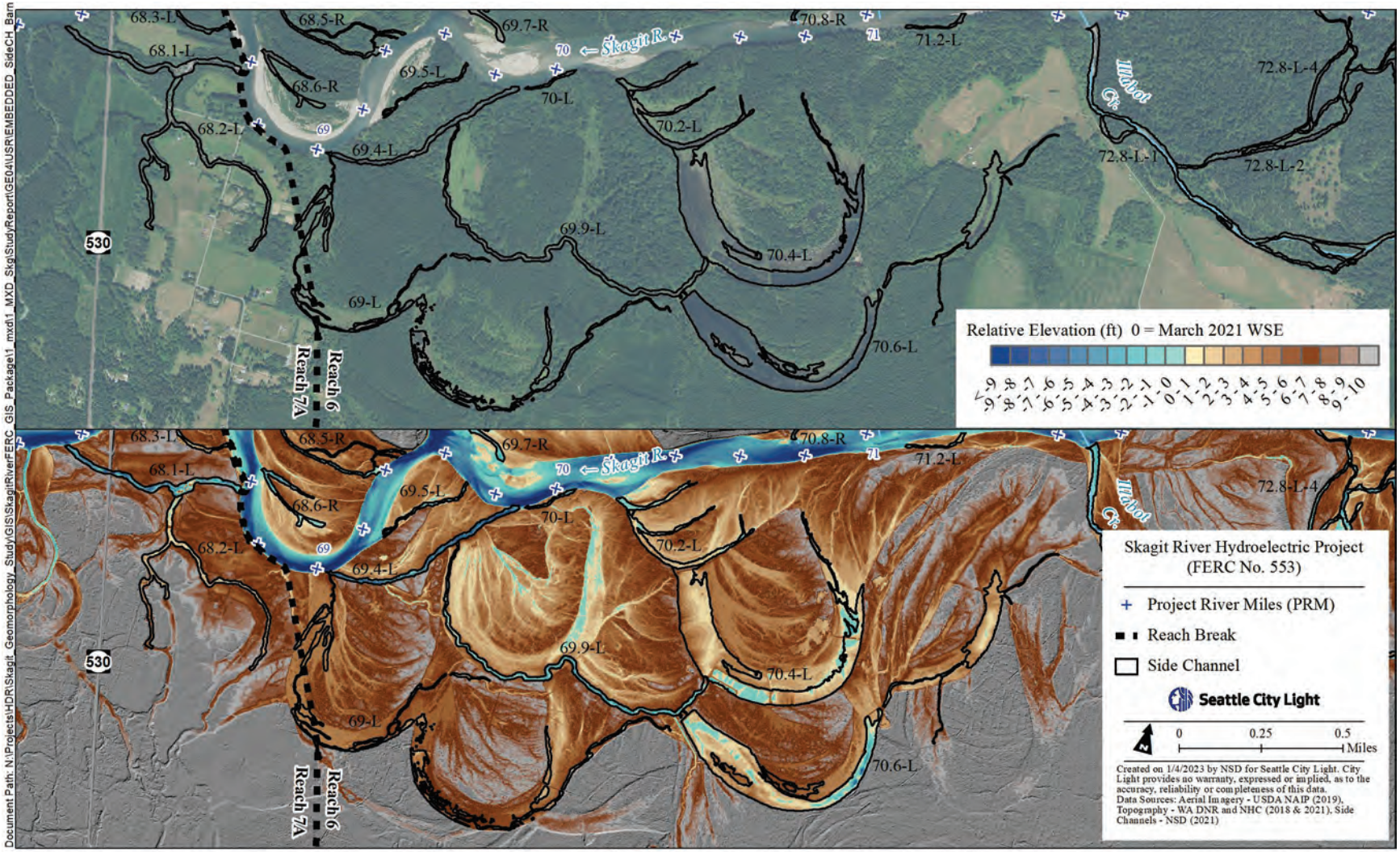


Figure 5.3-12. Map of side channels in the Barnaby area.

Reach 7A

Reach 7A begins just upstream of the SR 530 bridge and extends down to the confluence with the Sauk River and contains five side channels (Table 5.3-8 and Figure 5.3-11). Boh's Slough at PRM 68.1 is a perennial channel and flows under SR 530. Boh's Slough is mainly slower water habitat, glide, and pools, and contains channel spanning log jams and large wood pieces providing rearing habitat. Conversely, the other perennial side channel, Howard Miller Side Channel, is a plane bed channel generally devoid of fish cover and contains less wood, aside from a log jam at the outlet that forms a pool with the mainstem Skagit River.

Table 5.3-8. Summary of side channels in Reach 7A. Inlet and outlet mainstem connectivity reported as annual flow exceedance probability.

Side Ch ID	Side Channel Name	Approx. Area (ft^2)	Type	Inlet Mainstem Connectivity[2] and Dominant Substrate	Outlet Mainstem Connectivity[2] and Dominant Substrate	Skagit R. Discharge During Survey[1] (cfs)
68.3-L	Unnamed	107,445	Side Channel	Dry/Sand and Fines	Dry/Sand and Fines	4,300
68.2-L	Martin Slough	410,229	Side Channel	Inactive/Sand and Fines	10%/Vegetated	Not visited in August 2021
68.1-L	Boh's Slough	282,833	Side Channel	>99.9%/Cobble	>99.9%/Sand and Fines	3,170
67.3-R	Howard Miller Side Channel	258,689	Side Channel	98%/Cobble	>99.9%/Fine Gravel	4,300
67.1-L	Sauk Waterfall	180,561	Side Channel	40%/Sand and Fines	40%/Sand and Fines	3,360

1 Discharge at the USGS Skagit River at Marblemount gage (12181000).

2 Annual flow exceedance probability is the percentage of the year discharge is high enough to engage the channel inlet or outlet based on analysis of flow records from USGS stream gages. November 2020 flood discharge was 12,200 cfs at the USGS Skagit River at Newhalem gage (12178000), equal to approximately 1.5-year flow at the Newhalem gage and 2.5-year flow at the Marblemount gage.

5.3.2 Summary of Side Channel and Off-Channel Mainstem Connectivity

Connectivity was assessed by the connection of side channel and off-channel inlets and outlets to the mainstem Skagit River. Inlet and outlet connectivity for each feature was plotted by PRM and presented in Figure 5.3-13 and 5.3-14. Connectivity for each feature is also summarized by reach in Table 5.3-9 and 5.3-10. In general, channel outlets are connected more frequently than inlets across all reaches. Inlets for many features are not engaged at annual flows. In Reach 2B, two side channels, the Agg Ponds and County Line Ponds were split into multiple subsections for assessment of mainstem connectivity, leading to 15 inlets and outlets assessed for connectivity. One inlet is perennial and four outlets are perennial. Five inlets and seven outlets are connected a majority of the year, as indicated by connection at the 60 percent exceedance. Eight inlets are connected between 5-40 percent exceedance, and six are not connected. All outlets are connected at the 5 percent exceedance or more frequently.

Reach 3A contains three side channels. Inlets for the side channels are not well connected. Two inlets are not connected, and the third is only connected at the November 2020 flow. Side channel outlets in Reach 3A are more connected, with one channel connected a majority of the year (60 percent exceedance), one connected at 30 percent exceedance, and one channel only connected at the November 2020 flow.

Reach 4 contains three side channels. One inlet is connected at 60 percent exceedance, one at November 2020 flows, and one is not connected. Outlets are more connected, with one connected at 60 percent exceedance, and two connected between 5-40 percent exceedance.

Reach 3B contains two side channels and one off-channel feature, and all inlets and outlets are connected annually. One inlet is connected for a majority of the year and two are connected between 5-40 percent exceedance. Two outlets are connected for a majority of the year and one is connected between 5-40 percent exceedance.

Reach 5A contains three side channels. No inlets are connected annually, and only one inlet is connected at the November 2020 flow. Two outlets are connected a majority of the year, and the third is connected at 10 percent exceedance flow.

Reach 5B contains eight side channels and one off-channel feature. Two channels also have perennial inlets, three inlets connected a majority of the year, one inlet connected at 10 percent exceedance, one inlet connected at the November 2020 flow, and one is not connected. Five channels have perennial outlets, three are connected a majority of the year, and one is connected at 20 percent exceedance flow.

In Reach 6, two features were split into subareas. Illabot Creek Side Channel Complex was split into six subareas, and Hooper's Slough was split into two subareas, resulting in 35 inlets and outlets evaluated for connectivity. For inlets, six have perennial connectivity (greater than 99.9 percent exceedance), seven are connected for a majority of the year (60-98 percent exceedance), seven are connected between 5-40 percent exceedance, one connects at the November 2020 flow, and 12 are inactive. For outlets, 12 have perennial connectivity, 11 are connected a majority of the year, ten are connected between 5-40 percent exceedance, one is connected at the November 2020 flow, and one is not connected.

Reach 7 contains five side channels. One inlet has perennial connectivity, one is connected a majority of the year, two are connected between 5-40 percent exceedance, and one inlet is inactive. Two outlets have perennial connectivity, one connected a majority of the year, and two outlets connected between 5-40 percent exceedance flows.

Additional results supporting evaluation of side channel and off-channel connectivity are presented in the technical memorandum documenting floodplain data loggers installed in 2021-2022 (Attachment U).

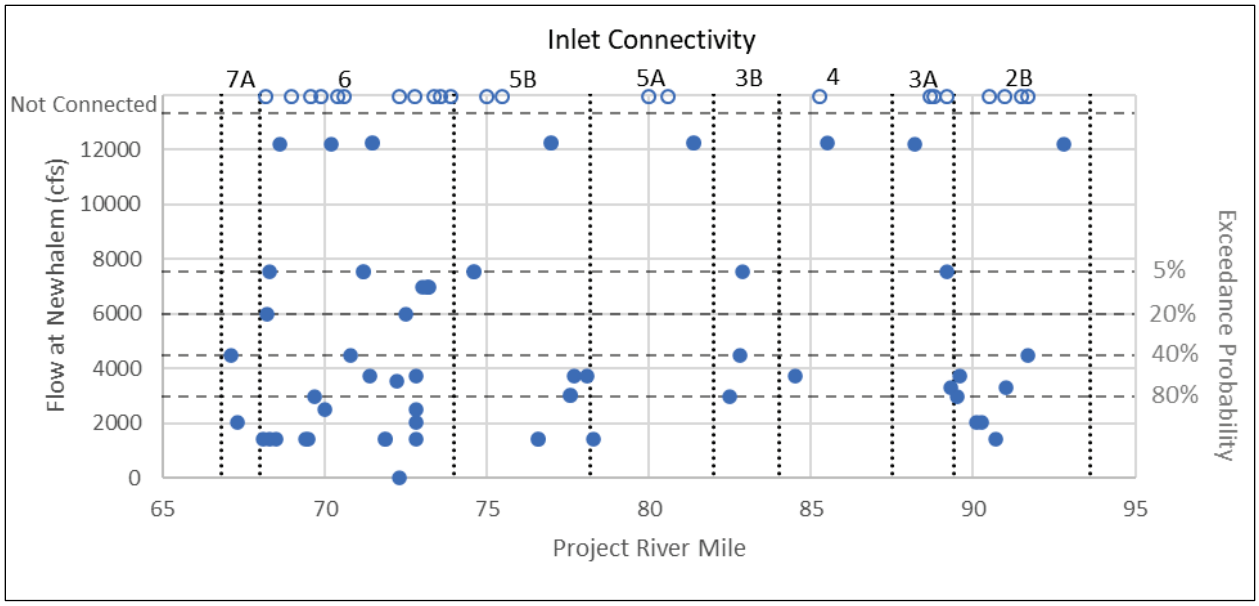


Figure 5.3-13. **Side channel and off-channel inlet mainstem connectivity. Geomorphic reaches labeled at top of plot. Exceedance probabilities are based on annual flow exceedances. Connectivity assessed by hydraulic modeling performed under the FA-02 Instream Flow Model Development Study. Some inlet locations are close enough in proximity to overlap in figure. Hollow points represent not connected inlets.**

Table 5.3-9. **Number of side channel and off-channel inlets connected to the mainstem by annual exceedance probability.**

Reach	NC[1]	Nov 2020	5%	10%	20%	40%	60%	80%	90%	98%	99.5%	>99.9%	Total
2B	6	1	1	0	0	1	2	1	0	2	0	1	15
3A	2	1	0	0	0	0	0	0	0	0	0	0	3
4	1	1	0	0	0	0	1	0	0	0	0	0	3
3B	0	0	1	0	0	1	0	1	0	0	0	0	3
5A	2	1	0	0	0	0	0	0	0	0	0	0	3
5B	2	1	1	0	0	0	2	1	0	0	0	2	9
6	12	3	2	3	1	1	3	1	2	1	0	6	35
7A	1	0	0	0	1	1	0	0	0	1	0	1	5
Total	**26**	**8**	**5**	**3**	**2**	**4**	**8**	**4**	**2**	**4**	**0**	**10**	**76**

1 NC = not connected. Connectivity assessed by hydraulic modeling performed under the FA-02 Instream Flow Model Development Study (City Light 2023a).

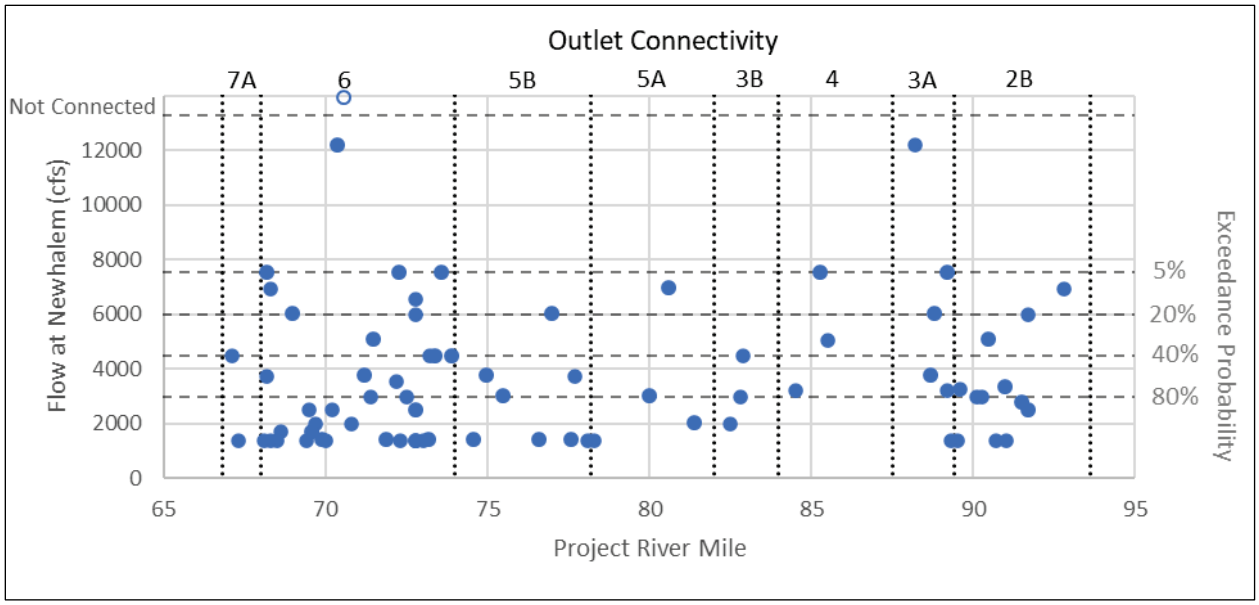


Figure 5.3-14. **Side channel and off-channel outlet mainstem connectivity. Geomorphic reaches labeled at top of plot. Exceedance probabilities are based on annual flow exceedances. Connectivity assessed by hydraulic modeling performed under the FA-02 Instream Flow Model Development Study (City Light 2023a). Some outlet locations in close proximity overlap in figure. Hollow points represent not connected outlets.**

Table 5.3-10. **Number of side channel and off-channel outlets connected to the mainstem by annual exceedance probability.**

Reach	NC[1]	Nov 2020	5%	10%	20%	30%	40%	60%	80%	90%	98%	99.5 %	> 99.9 %	Total
2B	0	0	0	2	1	1	0	3	3	1	0	0	4	15
3A	0	1	0	0	1	0	0	1	0	0	0	0	0	3
4	0	0	0	1	0	1	0	1	0	0	0	0	0	3
3B	0	0	0	0	0	0	1	0	1	0	1	0	0	3
5A	0	0	0	1	0	0	0	0	1	0	1	0	0	3
5B	0	0	0	0	1	0	0	2	1	0	0	0	5	9
6	1	1	0	4	2	1	3	2	2	3	2	2	12	35
7A	0	0	0	1	0	0	1	1	0	0	0	0	2	5
Total	**1**	**2**	**0**	**9**	**5**	**3**	**5**	**10**	**8**	**4**	**4**	**2**	**23**	**76**

1 NC = not connected. Connectivity assessed by hydraulic modeling performed under the FA-02 Instream Flow Model Development Study (City Light 2023a).

5.3.3 Time Series Analysis of Side Channel and Off-Channel Habitat

Results of the time series analysis of side channel and off-channel habitat indicate that the majority of the study area has been stable through time in terms of quality, area, and length of side channels with the exception Reach 2B which has slightly increased and Reaches 3A and 5A which have slightly decreased. Most of the side channel length is in Reach 6, which has had some adjustments across the time series with increases from 1964 to 1978 but has remained relatively stable, returning to close to its 1944 value in 2019 (Figure 5.3-15). The area of side channel and off-channel habitat has increased in some reaches with Reaches 6 and 2B having the largest increases and Reach 5B having a smaller increase over the initial area available in 1944 (Figure 5.3-16). Tables 5.3-9 through 5.3-15 include the data across reaches for each metric.

Visualizations of the data in Table 5.3-9 through Table 5.3-15 are available in Attachment E. Table 5.3-9 and Figure 5.3-15 illustrate that the total length of side channels is dominated by Reach 6, with Reaches 2B, 5B, and 7A also contributing moderate amounts. For changes of greater than 20 percent of side channel length between photo sets, the study team investigated further. Between 1944 and 1964, three reaches changed by more than 20 percent. In Reach 3A, complexity and length were lost in the northern half of the reach in the side channel complex on the left bank. In Reach 3B, a small side channel in the southern portion of the reach was lost. In Reach 5A, two flow-through channels in the northern half on the right bank became blind side channels. Between 1963-64 and 1978, Reach 3A had a loss of side channel length in the center of the reach, while Reach 3B had a small gain in side channel length in the center feature. In Reach 7A, there is a transition from braid to side channel and an increase in complexity of side channels on the left bank.

From the 1990s to the 2000s, some constructed channels were implemented, but those are not included in the natural channel length estimates since the study team was focused on natural formation and degradation of side channel habitat per the direction in the RSP (City Light 2021). Initial construction of Park Slough by the National Park Service occurred before 1990 but the exact date is unclear. Constructed channels and ponds were specifically designed to provide spawning or rearing habitat (specific channels had varying objectives; e.g. Illabot spawning channel vs. Taylor rearing channel), or for other management purposes (e.g., Agg Ponds), but their development is not helpful in determining overall trends in gain and loss of natural side channel and off-channel habitat. Separate tables and figures at the end of this section will summarize the constructed channels. During this period in Reach 4, there is a very small change in channel length, but the overall length of the channel is small, so the percentage change is exaggerated. In Reach 5A, there are flow-through channels in the reach that transition into blind channels as they become less connected to the mainstem. In Reach 7A, the increase seen in 1964 is largely lost. Between 1998 and 2006, a small new channel emerges in Reach 4, and Reach 2B shows a substantial increase in side channel length.

From 2007 through 2019, a new channel formed in Reach 3B on the right bank in the center of the reach, and in Reach 4, there was a loss of side channels from flow through to blind channels and a loss of a connector side channel in the center of the reach. Reach 4 has a low number of total side channel miles so the percent change is exaggerated. Reach 2B also has a small shift of side channel length from side channel to braid. There was a notable increase in length for 2006-2007 in Reach 6, but this may be an artifact of the timing of the aerial photograph collection, as discussed in

Section 4.3.2 of this study report. Figure 5.3-16 shows a slight decrease in side channel length in Reach 5B over time from 1944 through 1998 and then a slight increase in 2006 and a larger increase in 2019. Regardless of these changes, it is clear that Reaches 6, 5B, 2B, and 7 have the greatest capacity for side channel formation and maintenance, while Reaches 5A and 3A have shown negative trends over multiple years and may be losing connectivity via transitioning from flow through to blind channels or loss of channel connection entirely.

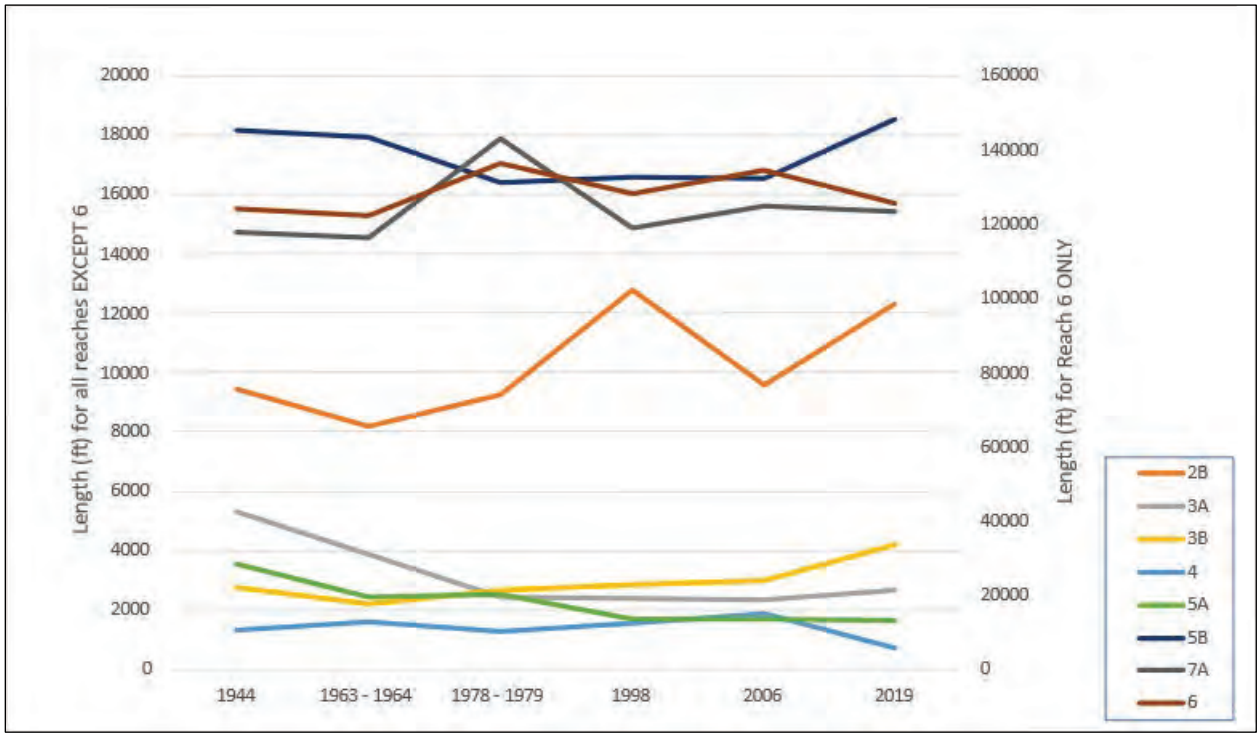


Figure 5.3-15. Length of side channels by reach across time series. Length of constructed channels is not included. Reach 6 length is displayed in the left axis due to the large difference in reach lengths.

Table 5.3-11. Length and percent change of side channels across time series (ft).[1]

Reach	1944 (ft)	1963 – 1964 (ft)	Percent Change (1964-1944) (%)	1978 – 1979 (ft)	Percent Change (1979-1964) (%)	1998 (ft)	Percent Change (1998-1979) (%)	2006 – 2007 (ft)	Percent Change (2007-1988) (%)	2019 (ft)	Percent Change (2019-2007) (%)
2A	0	0	0	0	0	0	0	0	0	0	0
2B	9,442	8,184	-15	9,232	11	12,797	28	9,593	-33	12,318	22
3A	5,287	3,894	-36	2,420	-40	2,384	-2	2,349	-1	2,651	11
4	1,332	1,588	16	1,296	-18	1,555	17	1,899	18	736	-158
3B	2,747	2,190	-25	2,665	22	2,836	6	2,983	5	4,195	29
5A	3,537	2,437	-45	2,530	-3	1,687	-50	1,682	0	1,637	-3
5B	18,167	17,917	-1	16,389	-8	16,565	1	16,553	0	18,543	11
6	124,028	122,195	-2	136,238	12	128,235	-6	134,362	5	125,633	-7
7A	14,744	14,557	-1	17,867	24	14,849	-20	15,608	5	15,417	-1
Total	**179,283**	**172,963**	-4	**188,637**	12	**180,908**	-4	**185,028**	2	**181,129**	-2

1 Does not include constructed channels based on the purpose of tracking processes that degrade or increase side channel habitat, per the RSP (City Light 2021).

Table 5.3-12. Areas of side channel and off-channel habitat across time series (ft^2).

Reach	1944	1963 - 1964	1978 - 1979	1998	2006 – 2007	2019
2A	0	0	0	2,594	0	0
2B	580,934	648,400	625,167	677,030	660,505	950,408
3A	200,575	123,998	49,846	51,626	50,386	53,908
3B	252,784	164,238	155,331	99,869	205,131	259,451
4	67,560	60,691	59,776	17,630	56,410	27,404
5A	91,637	73,680	76,784	54,778	54,542	71,810
5B	734,309	1,138,916	766,776	608,396	694,357	969,734
6	7,858,765	9,430,038	9,911,749	9,236,160	11,435,931	11,656,994
7A	769,934	709,354	1,443,289	936,455	776,941	756,758
	10,556,499	**12,349,315**	**13,088,718**	**11,684,538**	**13,934,203**	**14,746,467**

Overall, the total area of side channel and off-channel habitat have increased since 1944. During the same period the mainstem channel length has decreased while mainstem channel area has increased. The largest increase in main channel area has occurred between 1978 and 2019. Although an area of side channel and off-channel habitat has appeared to increase between 1944 and 2019, there are many areas that have become more vegetated and are less connected in 2019 vs. in 1944 as shown in the example in Figure 5.3-16. Study results identified a large proportion of side channels with connectivity limited by development of vegetated bars at the upstream channel junction that were observed to be more common in recent decades compared to aerial imagery from the 1940s and 1960s. Figure 5.3-16 shows an example of deposition and vegetation encroachment at the side channel entrance upstream of Diobsud Creek near PRM 81.4 (Reach 5A). The 1915 USGS map depicts a flow split around an island. The 1944 imagery shows a wider channel with more exposed gravel substrate. The 2022 LiDAR and imagery show how the side channel entrance is currently obstructed with a vegetated bar. Connectivity between the main channel and side channel is limited to high flow events that overtop the bar and hydraulic model results estimate the threshold for connectivity as about a 1- to 2-yr recurrence interval flow in the current regulated flow regime (Table 5.3-5).

The area of side channel habitat is largely dominated by Reach 6 (over 11 million square ft) (Figure 5.3-17). The next two largest reaches are Reaches 2B and 5B (over 950,000 square ft) with a smaller contribution from Reach 7A (more than 750,000 square ft). Within Reach 6, the area of side channel habitat increased substantially between 1944 and 1963 and again in 2006 with most of the gains occurring in the width of the Barnaby Reach channels and Illabot Slough channels. Reviewing the times series, we noted that the wetted area of these habitats increased substantially as they were affected by infrastructure installed in that area. There was a slight loss between 1979 and 1998 and a slight gain between 2006 and 2019. Reach 5B follows a somewhat similar, but more volatile pattern of change, with a strong increase in 1963 followed by a steep reduction through the 1970s to 1998, and then another increasing pattern through 2006 and 2019. Reach 2B also increased from 1944 to 1963, but then decreased in the 1970s, and increased again in 1998. A slight decrease occurred in Reach 2B in 2006, and then a large increase between 2006 and 2019.

Between 2006 and 2019, there is a side channel connection made between the mainstem and the County Line Ponds that added significantly to the available area in Reach 2B, as well as other small contractions and expansions in habitat. Reach 7A showed drastic growth in 1978-79 but by 2019 was back at the baseline level from 1944. In the 1978-79 time series, there was a connection and expansion of side channels just upstream from Rockport on river right that diminishes by the next time series.

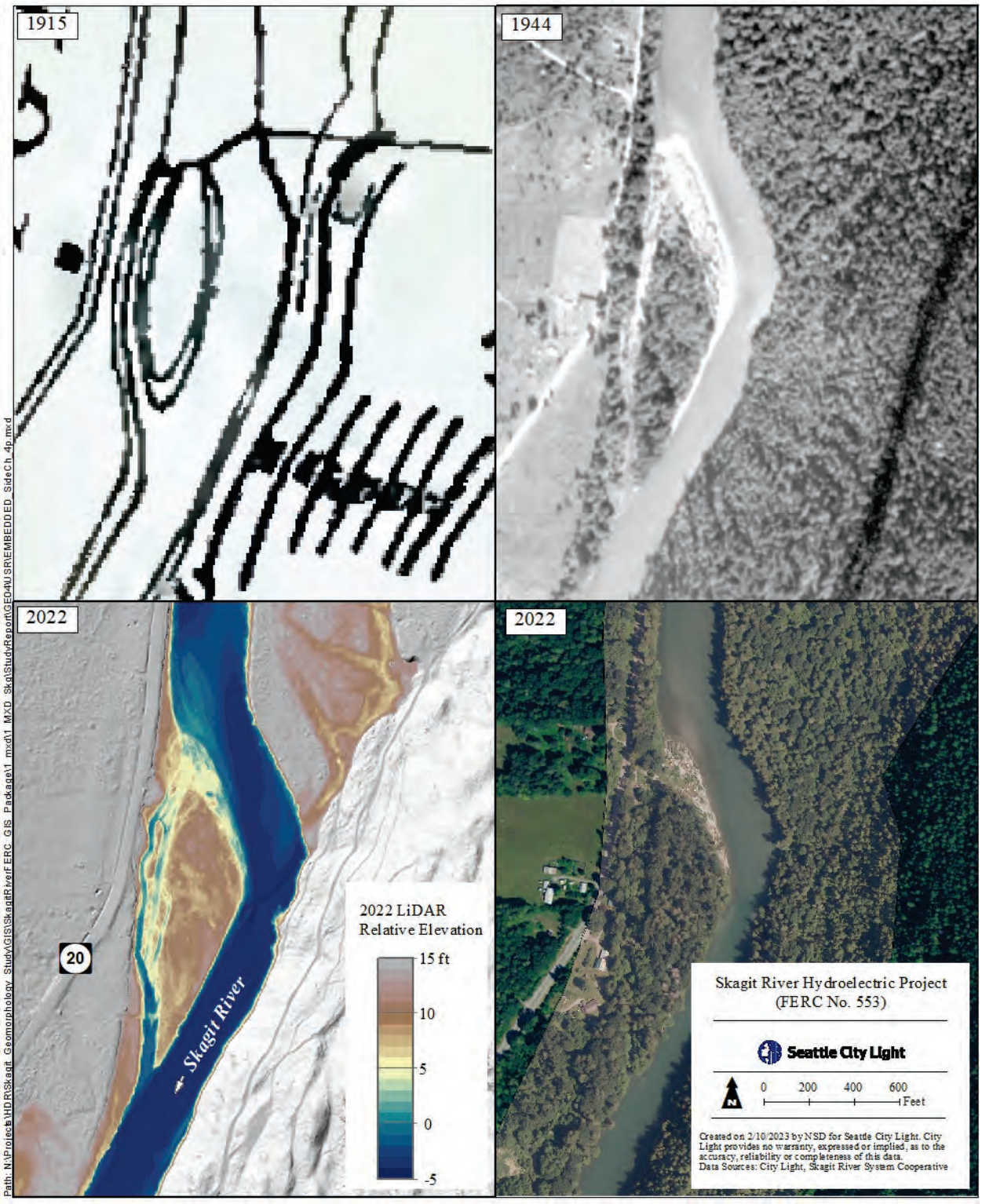


Figure 5.3-16. Historic changes at the side channel location upstream of Diobsud Creek near PRM 81.4 shows an example of decreased side channel connectivity over time with development of a vegetated bar at the side channel entrance.

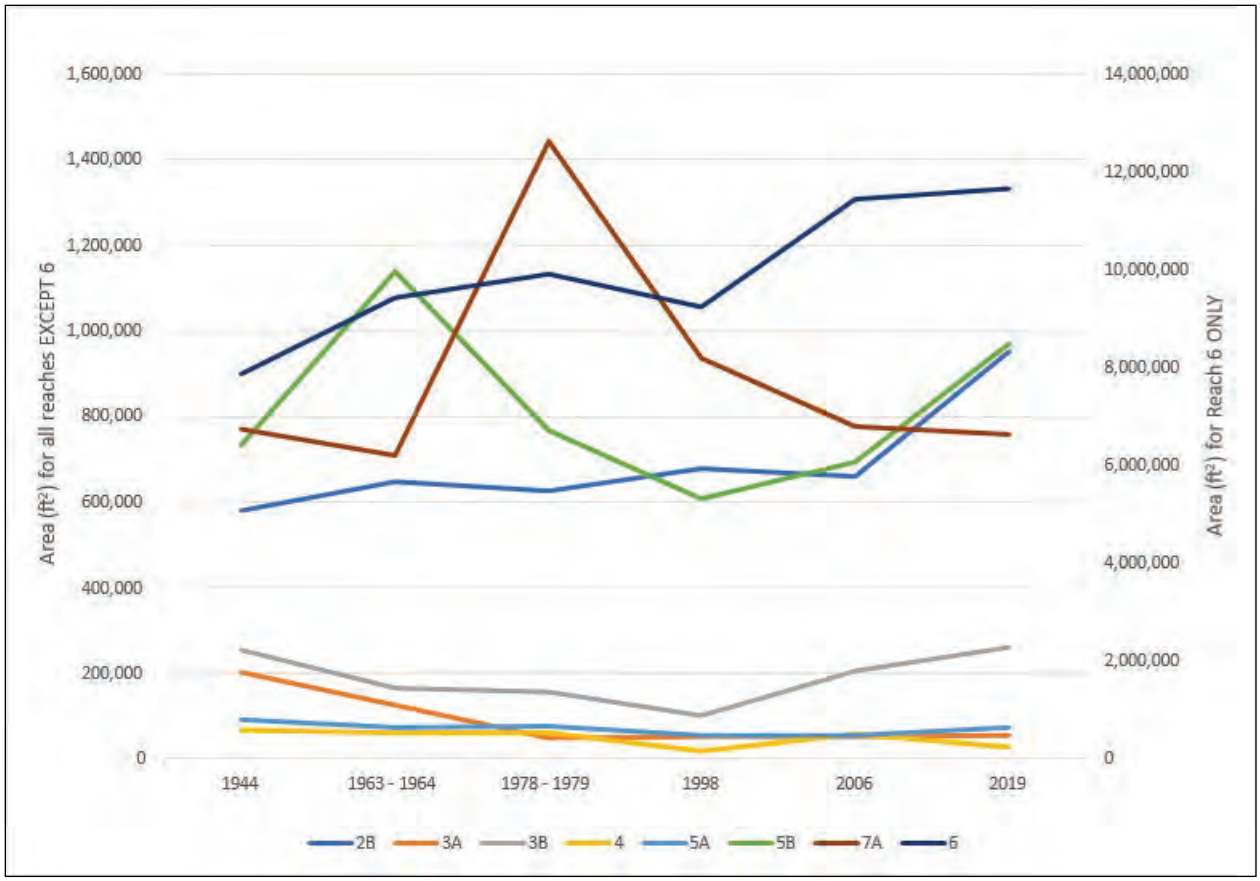


Figure 5.3-17. Area of side channels by reach across time series. Constructed channels are not included. Reach 6 length is displayed in the left axis due to the large difference in reach lengths.

The braid ratio is a measure of how the length of multiple channels in the mainstem compares to the centerline length of the mainstem channel (Table 5.3-13). The upper Skagit River is largely a single thread channel with few braids. The majority of the channel length in all reaches is single thread with some reaches (2A, 3B, 5A, 5B, and 7A) having a ratio equal to zero in several years. In general, Reach 6 maintains the highest braid ratio, but the ratio decreases to a minimum of 0.132 in 1998 and then increases back to the 1944 level by 2019.

Table 5.3-13. Braid ratio across time series. Length of constructed channels is not included.

Reach	1944	1963 - 1964	1978 - 1979	1998	2006 - 2007	2019
2A	0.000	0.000	0.000	0.000	0.000	0.000
2B	0.054	0.104	0.296	0.280	0.245	0.141
3A	0.062	0.086	0.170	0.174	0.193	0.178
4	0.092	0.074	0.007	0.005	0.003	0.010
3B	0.069	0.000	0.000	0.000	0.233	0.131
5A	0.042	0.000	0.000	0.000	0.014	0.068
5B	0.121	0.046	0.126	0.000	0.000	0.000
6	0.428	0.327	0.313	0.132	0.319	0.465
7A	0.243	0.214	0.000	0.000	0.095	0.000

Similarly, the ratio of side channel length to mainstem length (Table 5.3-14) is relatively stable through time in most reaches, but changes are observed in Reaches 6 and 7A. In Reach 6, the highest ratios are seen in 1978-79 and 2006-07, with 2019 roughly equal to the ratio in 1944. For Reach 7A, the highest ratios are also found in 1978-79 and 2006-07, but the 2019 value ends up slightly higher than 1944.

Table 5.3-14. Ratio of the length of side channel to the length of mainstem across time series; (does not include constructed channels).

Reach	1944	1963 - 1964	1978 - 1979	1998	2006 - 2007	2019
2A	0.00	0.00	0.00	0.00	0.00	0.00
2B	0.45	0.39	0.43	0.60	0.45	0.58
3A	0.53	0.40	0.24	0.25	0.24	0.27
4	0.07	0.09	0.07	0.08	0.10	0.04
3B	0.27	0.22	0.26	0.28	0.29	0.41
5A	0.19	0.13	0.14	0.09	0.09	0.09
5B	0.93	0.94	0.85	0.86	0.86	0.97
6	3.51	3.44	3.83	3.74	3.91	3.57
7A	2.19	2.19	2.67	2.22	2.34	2.33

Braid node density is a correlative value to braid ratio (Table 5.3-15). Reach 6 shows a steady decrease to 1998 and then an increase up to 2019. Reach 2B shows an opposite pattern with a steady increase to 1998 and 2006 and then a decrease in 2019.

Table 5.3-15. Braid node density across time series (nodes/mile). Length of constructed channels is not included.

Reach	1944	1963 - 1964	1978 - 1979	1998	2006 - 2007	2019
2A	0.00	0.00	0.00	0.00	0.00	0.00
2B	0.50	0.75	1.74	2.46	2.47	0.99
3A	0.53	1.08	2.06	1.63	1.61	1.60
4	0.86	0.87	0.29	0.29	0.29	0.29
3B	1.02	0.00	0.00	0.00	1.56	1.56
5A	0.58	0.00	0.00	0.00	0.29	0.87
5B	1.08	0.56	0.55	0.00	0.00	0.00
6	3.29	2.52	2.08	0.77	1.67	2.10
7A	0.78	0.79	0.00	0.00	1.58	0.00

The side channel node density is related to the relative length of side channel to main channel, but with a less direct relationship than that between Braid Node Density and Braid Ratio, as side channels in the Skagit are longer than many braids in the main channel (Table 5.3-16). The side channel node density in Reach 6, 7A, 5B, and 2B show varying patterns with change between each time step and no discernable patterns.

Table 5.3-16. Side channel node density across time series (nodes/mile). Length of constructed channels is not included.

Reach	1944	1963 - 1964	1978 - 1979	1998	2006 - 2007	2019
2A	0.00	2.76	0.00	0.00	0.00	0.00
2B	2.25	1.61	2.98	3.20	2.72	3.71
3A	2.65	1.05	0.52	0.54	1.07	1.60
4	0.86	0.58	0.86	0.86	1.43	0.57
3B	1.53	0.87	1.56	1.56	1.56	2.60
5A	1.73	2.23	0.87	0.58	0.58	0.58
5B	2.43	4.75	2.20	2.75	2.48	2.76
6	4.63	3.96	5.34	4.76	4.86	4.35
7A	3.13	2.76	3.95	4.74	4.74	4.78

The RCI (Brown 2002) integrates the sinuosity (or relative meander pattern) with the number of joins or junctions in the channel to summarize channel complexity. As shown in Table 5.3-17 and Figure 5.3-18, Reach 6 has the highest levels of complexity and the greatest amount of change over the time series. Reach 6 has the greatest amount of aquatic habitat, so the magnitude of the increase in the RCI may be magnified by the reach size, as well as be an artifact of differences in remote sensing data quality. Reach 2B shows an increase, Reach 5B shows a decrease, and Reach 7B shows a slight increase, with all other reaches remaining relatively constant.

Table 5.3-17. River Complexity Index across time series (Brown 2002). Length of constructed channels is not included.

Reach	1944	1963 - 1964	1978 - 1979	1998	2006 - 2007	2019
2A	1.13	1.14	1.14	1.14	1.13	1.14
2B	16.23	19.36	28.29	34.09	27.36	27.31
3A	11.81	9.30	9.70	8.06	9.32	10.54
4	8.02	7.86	5.69	5.70	7.98	4.56
3B	6.66	3.24	4.35	4.35	8.73	9.82
5A	9.35	4.15	4.15	4.15	4.15	6.23
5B	24.57	16.34	16.51	15.26	15.25	20.29
6	127.67	135.86	164.33	114.80	131.75	141.80
7A	12.64	13.54	15.67	10.44	16.72	16.57

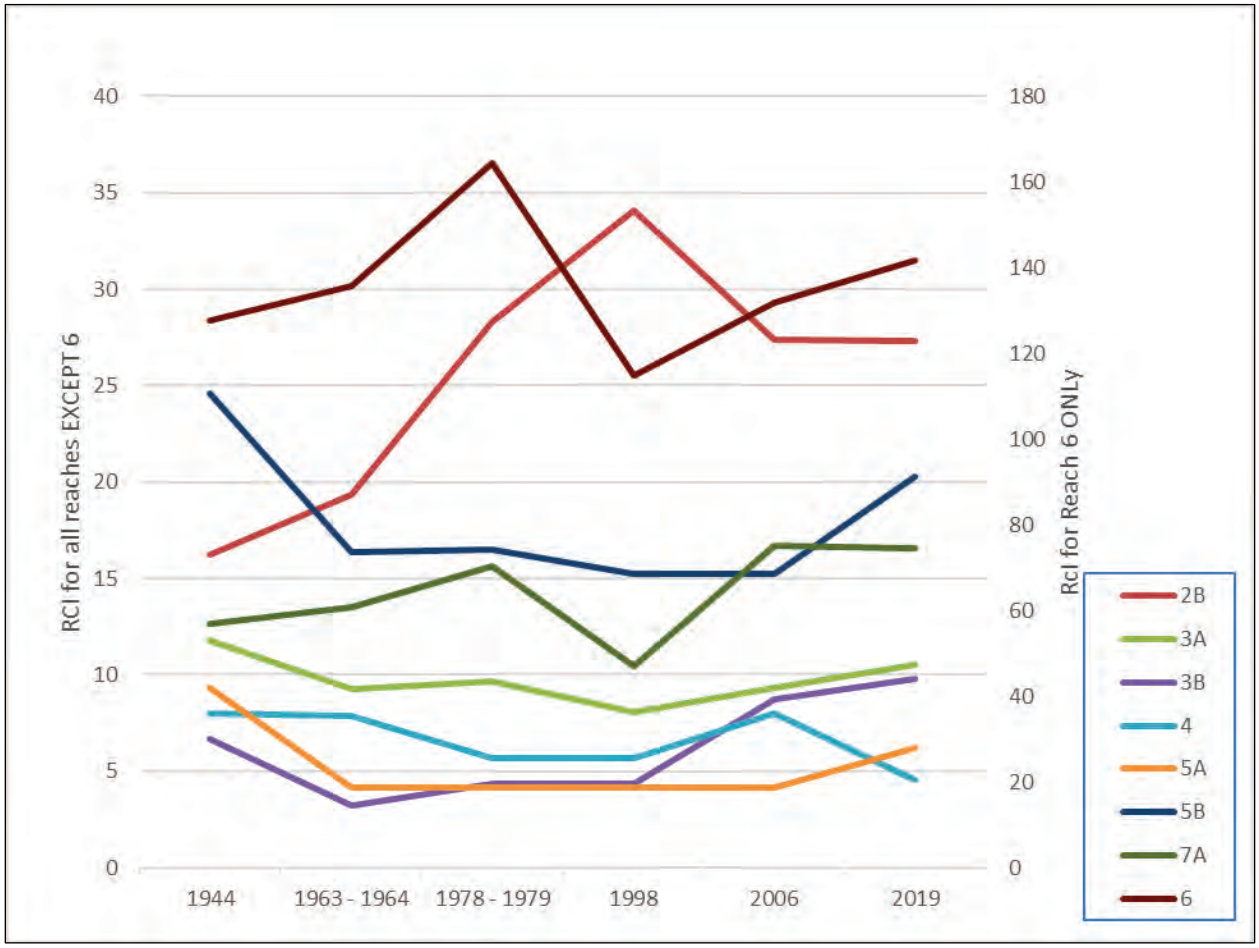


Figure 5.3-18. River Complexity Index across time series. Length of constructed channels is not included. Reach 6 length is displayed in the left axis due to the large difference in reach lengths.

Constructed side channels, although not included in the analysis above are an important component of the restoration efforts that have occurred on the upper Skagit River, some in direct alignment with the provisions of the current FERC license. Tables 5.3-18 and 5.3-19 show the length and area of constructed channels by reach and year. Reach 2B includes the construction of Park Slough, the Agg Ponds and County Line Ponds. Reach 5A includes Taylor Slough and Reach 6 includes Illabot Spawning Channel and Powerline Channel. These data were digitized from aerial photographs through the time series so minor changes in length and area are due to differences in what could be seen in the photograph.

Table 5.3-18. Areas of constructed side channel and off-channel habitat across time series (ft^2).

Reach	1944	1963 – 1964	1978 – 1979	1998	2006 – 2007	2019
2A	-	-	-	-	-	-
2B	-	1,920,920	1,839,642	1,967,586	2,114,632	2,172,789
3A	-	-	-	-	-	-
4	-	-	-	-	-	-
3B	-	-	-	-	-	-
5A	-	-	-	251,096	246,441	194,392
5B	-	-	-	-	-	-
6	-	-	-	31,517	128,594	168,476
7A	-	-	-	-	-	-
Total	-	1,920,920	1,839,642	2,250,198	2,489,668	2,535,657

Table 5.3-19. Length of constructed side channel and off-channel habitat across time series (ft).

Reach	1944	1963 - 1964	1978 - 1979	1998	2006 - 2007	2019
2A	-	-	-	-	-	-
2B	-	12,302	12,803	18,693	18,649	18,763
3A	-	-	-	-	-	-
4	-	-	-	-	-	-
3B	-	-	-	-	-	-
5A	-	-	-	3,871	3,860	4,079
5B	-	-	-	-	-	-
6	-	-	-	1,093	3,838	3,779
7A	-	-	-	-	-	-
Total	-	12,302	12,803	23,657	26,348	26,621

Construction of side channel and off channel habitat has contributed considerably to the area across the time series. The total area of constructed channel was equivalent to between 15.5 and 19.3 percent of the total natural side channel and off-channel habitat area between 1963 and 2019. In terms of length, constructed channels were equivalent to adding another 6.8 to 14.7 percent of side channel and off-channel habitat length since 1963. If we added in constructed side channels into the complexity metric of RCI, it would have a moderate effect on Reaches 2B and 5A, but very little effect on Reach 6 based on the number of existing junctions in each reach.

5.4 Substrate/Sediment

5.4.1 Grain Size Distributions

Sediment at the bar-head locations sampled in this Geomorphology Study is predominantly composed of cobble and gravel, with moderate spatial variability at the reach scale. Surface pebble count results (Figure 5.4-1) indicate D_{50} values of typically 64 to 91 mm and D_{84} values generally toward the upper range of 91 to 128 mm upstream of Finney Creek. Two targeted sample sites (PRM 76.6 and 92.6) were notably coarser than typical conditions along the river. The PRM 76.6 site was an anomalously coarse riffle added to the sampling plan during fieldwork that represents a local grade controlling feature for the Skagit River that was sampled to understand stability of that particular feature rather than general bed mobility conditions. The PRM 92.6 sample was from the head of a point bar just downstream of a rapid included in the original sampling plan. In summer 2021, this feature had some soil development beginning between cobbles, moss establishing on large cobble to small boulder sized particles, and heavy periphyton growth; observations in summer 2022 indicated the bar had been mobilized during the November 2021 flood. The surface grain size distribution coarsens slightly from upstream to downstream at the Bacon Creek confluence (PRM 83), fines to a local minimum above the Cascade River confluence (PRM 78), increases below the Cascade River, and is higher through the remainder of Reach 5. The grain sizes generally fine from upstream to downstream across Reach 6, suggesting that lower channel gradients above the Sauk River confluence (PRM 67) may be inducing a limitation on sediment transport competence of the cobble-sized material. The grain sizes fine between the Sauk River and Jackman Creek, then coarsen slightly between Jackman Creek and Finney Creek. A downstream fining trend begins downstream of Finney Creek. The downstream fining trend becomes stronger around PRM 35; between PRM 35 and PRM 20, typical D_{50} values are between 22.6 and 45 mm and D_{84} values are between 45 and 64 mm. PRM 35 marks the upstream end of the Ross Island reach and the depositional zone encompassing the final 15-20 miles upstream of the gravel-sand transition. The gravel-sand transition is located downstream of all pebble counts; field observations through PRM 14.5 revealed sand becoming dominant on bars around PRM 15.5-15.0, with fine gravel still present down to PRM 14.5.

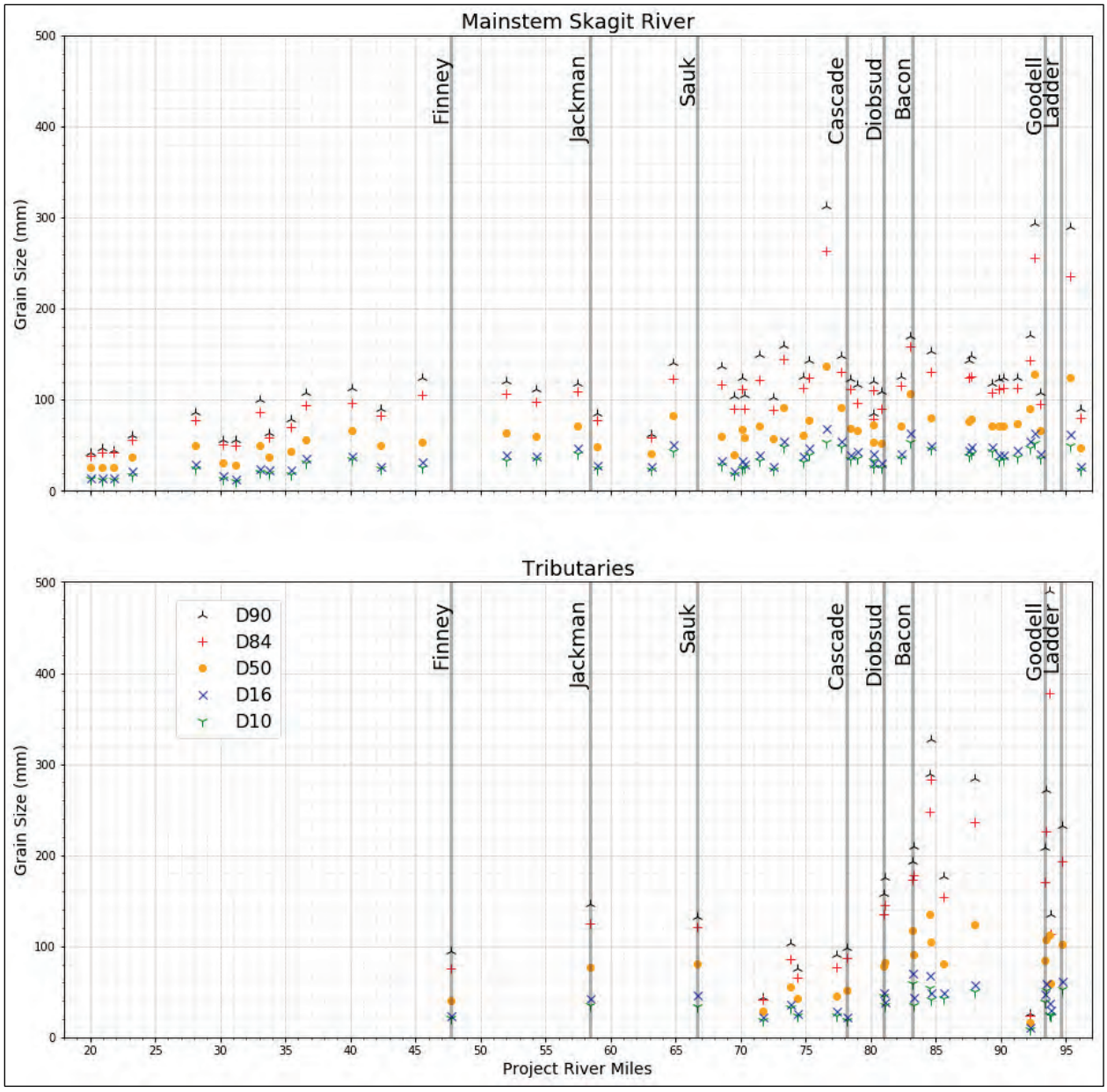


Figure 5.4-1. Summary grain size statistics for all surface pebble count samples.

The grain size distribution of the subsurface material is dominated by gravel-sized material and generally follows the same spatial patterns as the surface material (Figure 5.4-2). The subsurface material only mildly fines in the downstream direction until approximately PRM 35. Downstream fining increases downstream of PRM 35, as in the surface grain size results. Upstream of Bacon Creek (PRM 83), the D_{50} has an average nearly at the 45 mm class size. From Bacon Creek to the Cascade River (PRM 78), the D_{50} decreases to an average of approximately the 32 mm class size. There is a notable increase in grain size below the Cascade River, despite the relatively smaller size fractions sampled upstream on the Cascade River. Downstream from the Cascade River, the D_{50} continues to decrease to the downstream end of Reach 5. Reach 6, above the Sauk River, has relatively low subsurface grain sizes, with D_{50} values between about 7 and 41 mm. As in the

surface grain size results, subsurface grain size fines between the Sauk River and Jackman Creek, then coarsens between Jackman and Finney Creeks. There is a downstream fining trend downstream of Finney Creek. Downstream of PRM 35, subsurface D_{50} values are between 8 and 21 mm and D_{84} values are between 29 and 66 mm.

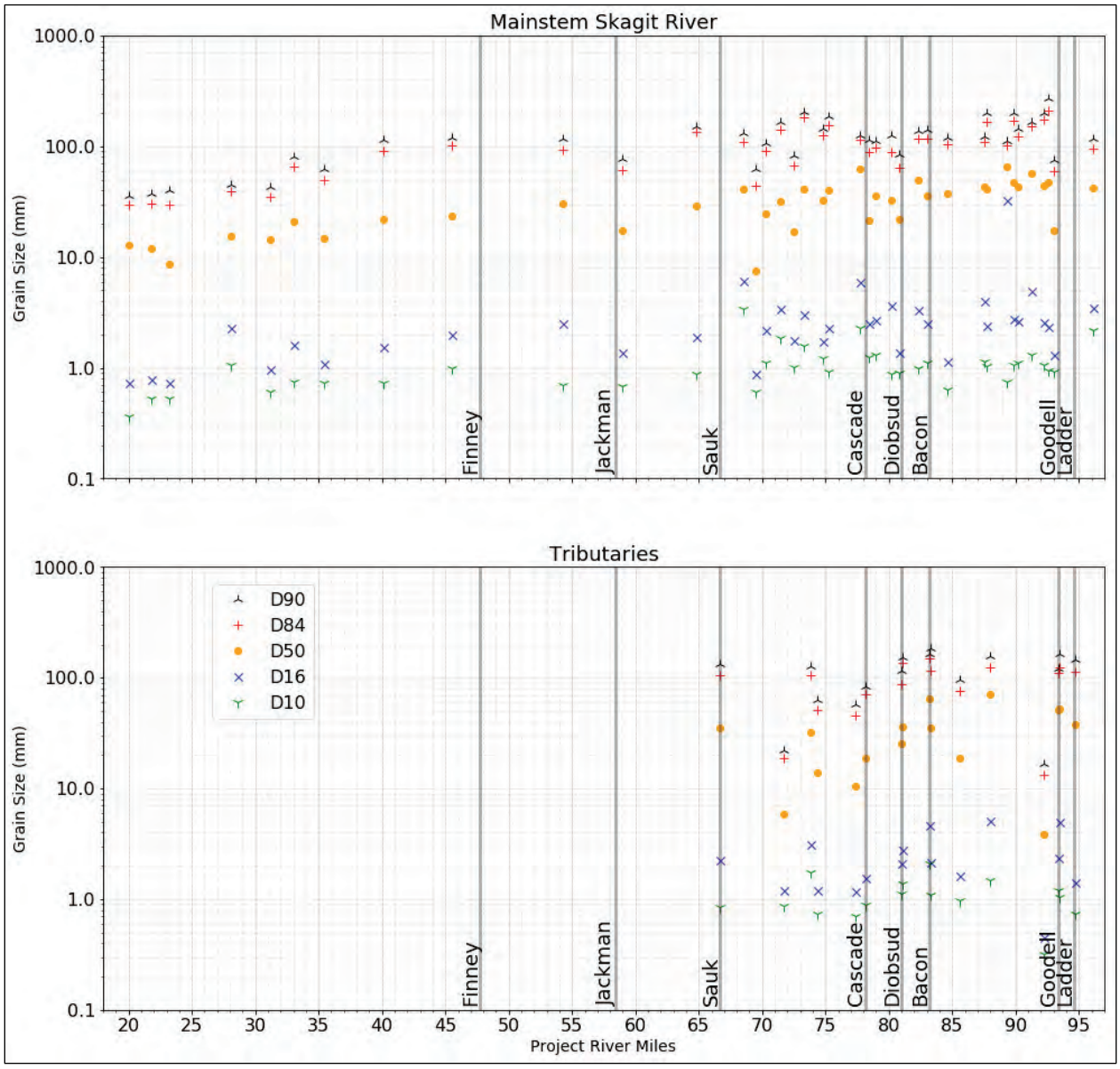


Figure 5.4-2. Summary grain size statistics for all subsurface bulk sediment samples.

Similar to the pebble count and subsurface results, the grain size distributions from the hybrid approach, produced following the approach of Rice and Haschenburger (2004), show little variation across most of the study reach, with a slight downstream fining trend until below Finney Creek, where downstream fining becomes stronger (Figure 5.4-3). An increase in grain size is noted directly below the Bacon Creek and Cascade River tributaries. Upstream from Bacon Creek, the D_{50} has an average of approximately 33 mm. From Bacon Creek to the Cascade River (PRM

78), the D_{50} only slightly decreases to an average of approximately 32 mm. Downstream from the Cascade River, the D_{50} has an average of 24 mm and drops from 62 mm to 18 mm from below the Cascade River to below the Sauk River. Grain sizes between the Sauk River and Finney Creek are similar to those between the Cascade and Sauk rivers. Downstream of PRM 35, hybrid D_{50} values are between 8 and 22 mm and D_{84} values are between 28 and 68 mm.

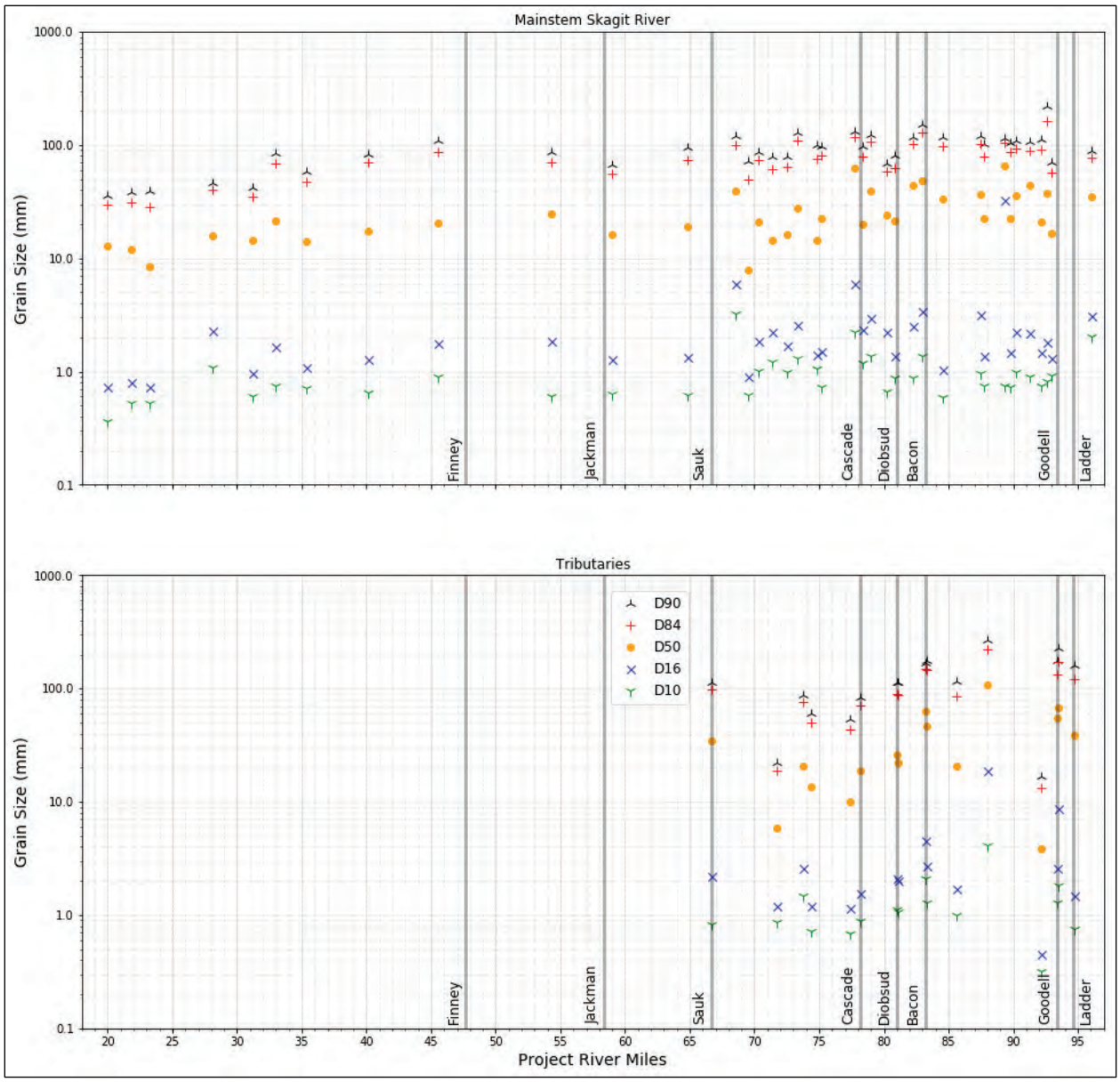


Figure 5.4-3. Summary grain size statistics for all hybrid bulk sediment samples.

The selective removal of fine sediment through the process of winnowing results in bed-armoring, whereby the surface substrate is coarser than the subsurface substrate. Bed-armoring has important implications for understanding and predicting sediment transport rates, and inherently the geomorphology of rivers. Using the ratio of the D_{50} from the surface pebble counts to the D_{50} from the bulk subsurface samples, a relative sense of armoring shows that the surface layer in much of

the study area is typically about 1.5 to 3 times as coarse as the subsurface (Figure 5.4-4), with the lowest armor ratios occurring between Goodell Creek and Cascade River. The observed armor ratio values are typical for moderate-to high-sediment-supply rivers in western North America. One dataset (Pfeiffer et al. 2017) including 26 locations in the mountain west and 12 sites along the west coast shows typical armor ratios of 3.3 ± 2.7 (± 1σ) and a clear inverse relation between relative sediment supply and armor ratio. Selecting only for the subset of 12 higher-sediment-supply west-coast rivers shows typical armor ratios of 1.7 ± 0.7.

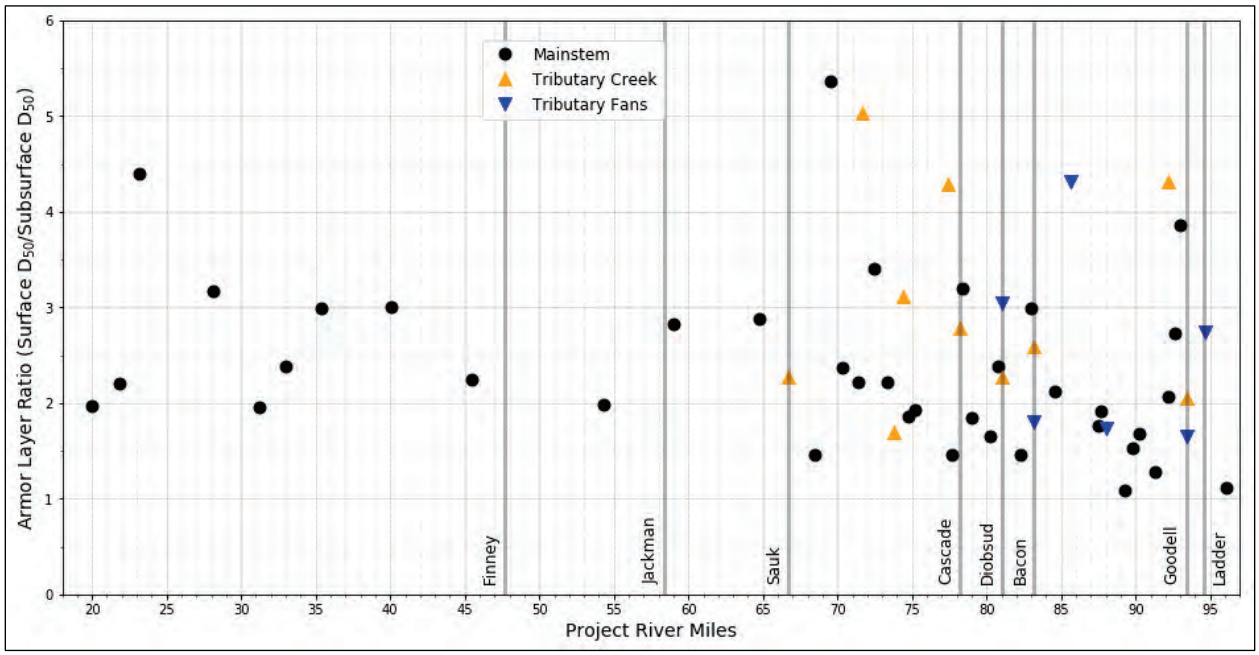


Figure 5.4-4. Armor layer ratio, as defined by the surface D_{50}/subsurface D_{50}.

High concentrations of fine sediment in redds can affect egg-to-fry survival. Evaluation of fine sediment infiltration into redds was not a part of this study, but fine sediment concentrations in bulk samples can provide some information about fine sediment in the characteristic riverbed material. Because redd construction evacuates fines from the gravel, these are likely higher than fine sediment concentrations within redds. Figure 5.4-5 shows histograms of the percentage of fine sediment below a size threshold of 0.85 and 4.8 mm (values commonly used to evaluate fine sediment impacts on incubating redds Jensen et al. 2009). These results show that fine sediment concentrations smaller than both 0.85 and 4.8 mm are lower upstream of the Sauk River confluence compared to downstream of the confluence ($t(20)=3.8$, $p<0.01$ and $t(26)=2.5$, $p<0.01$, respectively). In the primary study area, both the mean concentration of sediment finer than 0.85 (9 percent) and majority of samples (65 percent) were below the 10 percent threshold where sediment of this size begins to substantially affect egg to fry survival (Jensen et al 2009). Similarly, both the mean concentration (24 percent) and majority of samples (58 percent) were below the 25 to 30 percent threshold where sediment of this size begins to substantially affect egg to fry survival (Jensen et al 2009).

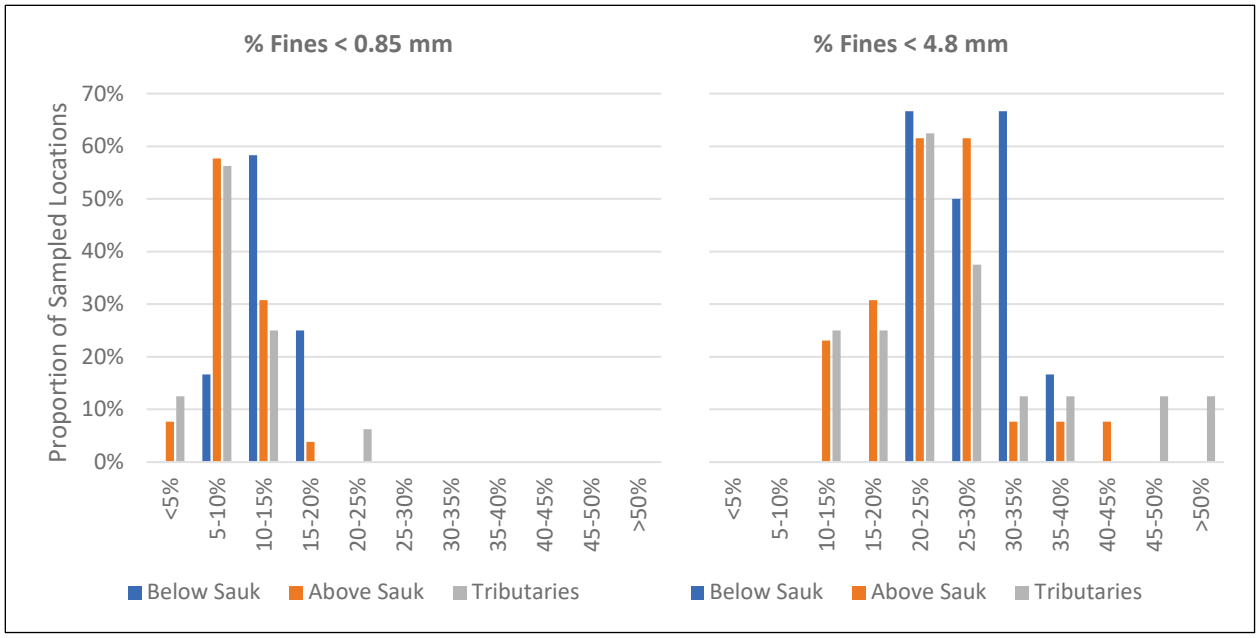


Figure 5.4-5. Histograms of fine sediment concentrations in hybrid bulk sediment samples.

5.4.2 Relationship Between Pebble Counts and Facies Mapping

Comparison of the initial estimates of D_{84} and D_{50} from the interpretation of facies codes (Table 4.4-3) against pebble count data described in Section 5.1 showed both that the facies codes provide a strong indication of the grainsize distribution of the surficial material and that calibration of the initial interpretation of the grainsize meaning of the facies codes was needed in order to use this mapping as a quantitative prediction of the grainsize distribution of bed material. Comparison of the initial D_{84} and D_{50} grainsize quantile estimates to pebble count results of those same grainsize quantiles was completed by developing linear regressions relating each grainsize quantile. In both cases, the regressions show a very strong significant effect between the initial quantile grainsize estimate and pebble count quantile grainsize measurement), but the prediction was much better for D_{84} ($F[1, 35] = 61.05$, $p = <0.0001$, $R^2 = 0.64$ than for D_{50} [($F[1, 35] = 18.07$, $p = .0001$, $R^2 = 0.34$]). There was a visible bias in the predicted D_{84} as compared to the measured D_{84} when viewed as a function of substrate code (Figure 5.4-6). The initial interpretation of facies codes overpredicted D_{84} for substrate mapped as cobble or boulder dominated (code 6, 7, and 8), but under-predicted if dominant substrate was mapped as coarse gravel or finer (code 6 and below). To correct for bias in the visual estimate of the D_{84}, a correction was applied to the data using the regression of the predicted to measured D_{84} (Figure 5.4-7). The D_{50} and D_{90} were then estimated using the average ratio of D_{84}/D_{50} and D_{90}/D_{84} from the 2021 pebble counts to provide an estimate that is informed by the measured pebble count data. The standard error of the estimate of D_{84} was 39 mm. Extrapolating to the D_{50}, the estimated typical error magnitude of the comparison between predicted and measured D_{50} was 26 mm.

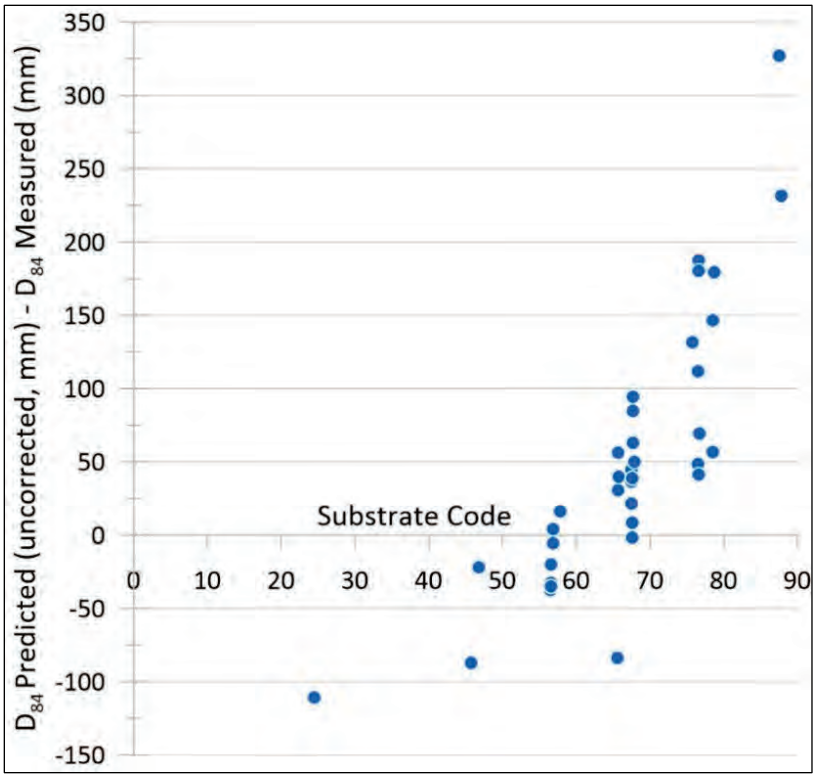


Figure 5.4-6. Comparison of the uncorrected residuals to the mapped substrate code.

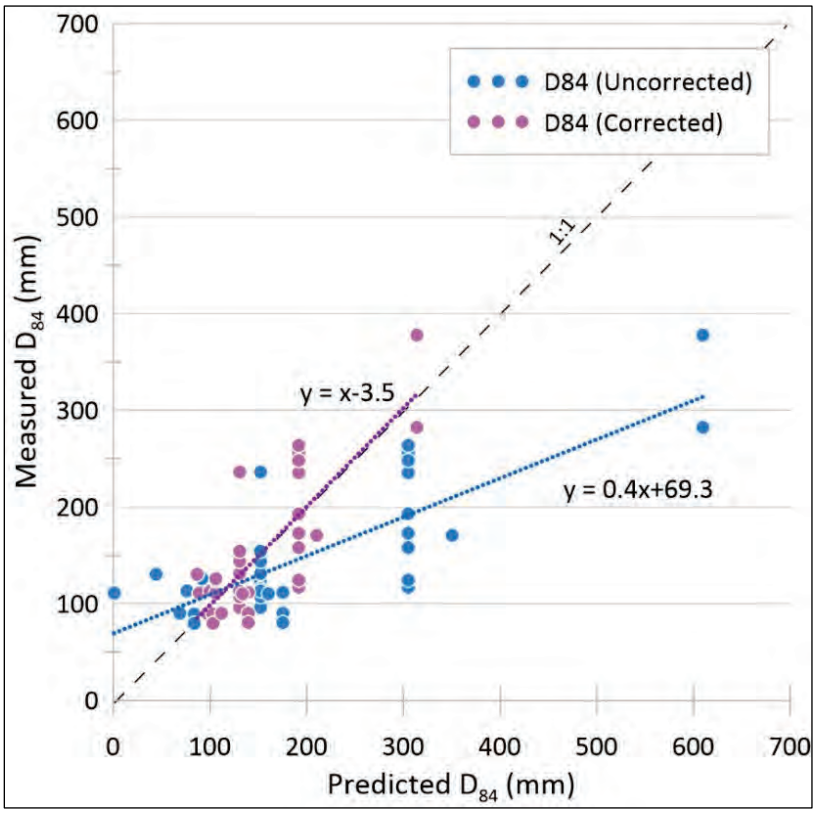


Figure 5.4-7. Comparison of the corrected and uncorrected D_{84}.

The predicted values extracted from the substrate mapping exercise provide the best available estimate of the grainsize distribution of the river bed material for local characterization in places where no pebble count data are available, but the results are bound to several limitations which should be considered during their application in predictive analyses. For one, the mapping exercise did not use pebble counts or other methods to calibrate or check their visual estimates, leaving the calibration of the results to rely on the 35 data points collected by a separate team in 2021. In addition, there are several locations with large discrepancies between what was mapped and what was observed in the pebble count data. For example, at Scour Monitor Array RC 89.9, the facies mapping team categorized the substrate as 24.5 (dominant substrate is sand), while the statistics from the pebble count estimate a D_{50} of 72 mm and D_{84} of 111 mm with minimal sand observed. In addition, the boulder dominated reaches in the river can vary from small boulders (256 mm) to very large boulders (greater than 630 mm), but the simplified substrate codes do not provide the necessary detail to differentiate this range. Therefore, the predicted D_{84} of reaches with observed large boulders, such as the boulder garden near PRM 93.0, is smaller than the true value. It is suggested that error propagation of the uncertainties in D_{84} and the D_{50} be calculated when applying the facies mapping interpretations ($\delta(D_{84}) = \pm$ 39mm, $\delta(D_{50}) = \pm$ 26mm), such as to predict variables like dimensional or non-dimensional shear stress.

5.4.3 Comparison of 2021 and 2022 Grainsize Distributions

Overall, the analysis of repeat grainsize distributions from pebble counts collected between 2021 and 2022 revealed fining in the fine tails (D_{16} and D_{10}) of the distributions, no change in mean grainsize, and in select cases, coarsening of the D_{90} and D_{84} (Figure 5.4-8). The magnitude of fining is greater than the magnitude of coarsening. No change was detected in the subsurface bulk sample comparison between 2021 and 2022. T-tests revealed where in the distribution, change occurred and Quantile – Quantile plots along with calculated change from the mean quantile values showed the direction of change (i.e., coarsening or fining). P-values for statistically significant results ranged from 0.047 to 0.024. Post hoc power from the t-tests was inversely proportional to p-value (i.e., the lowest p-values had the greatest power and the highest p-values had the least power). This analysis identified and compared 34 repeat pebble counts—8 of these included repeat bulk samples. Of the 34 repeat pebble counts, 10 are included in the tributary subset, and 24 are mainstem Skagit River sites. Overall, these results indicate that the surface grainsize distribution became slightly more broadly graded as a result of the November 2021 flood, but that no change occurred in the mean size. This is consistent with previously observed surface armor layer responses to high flows in flume environments (Wilcock 2005).

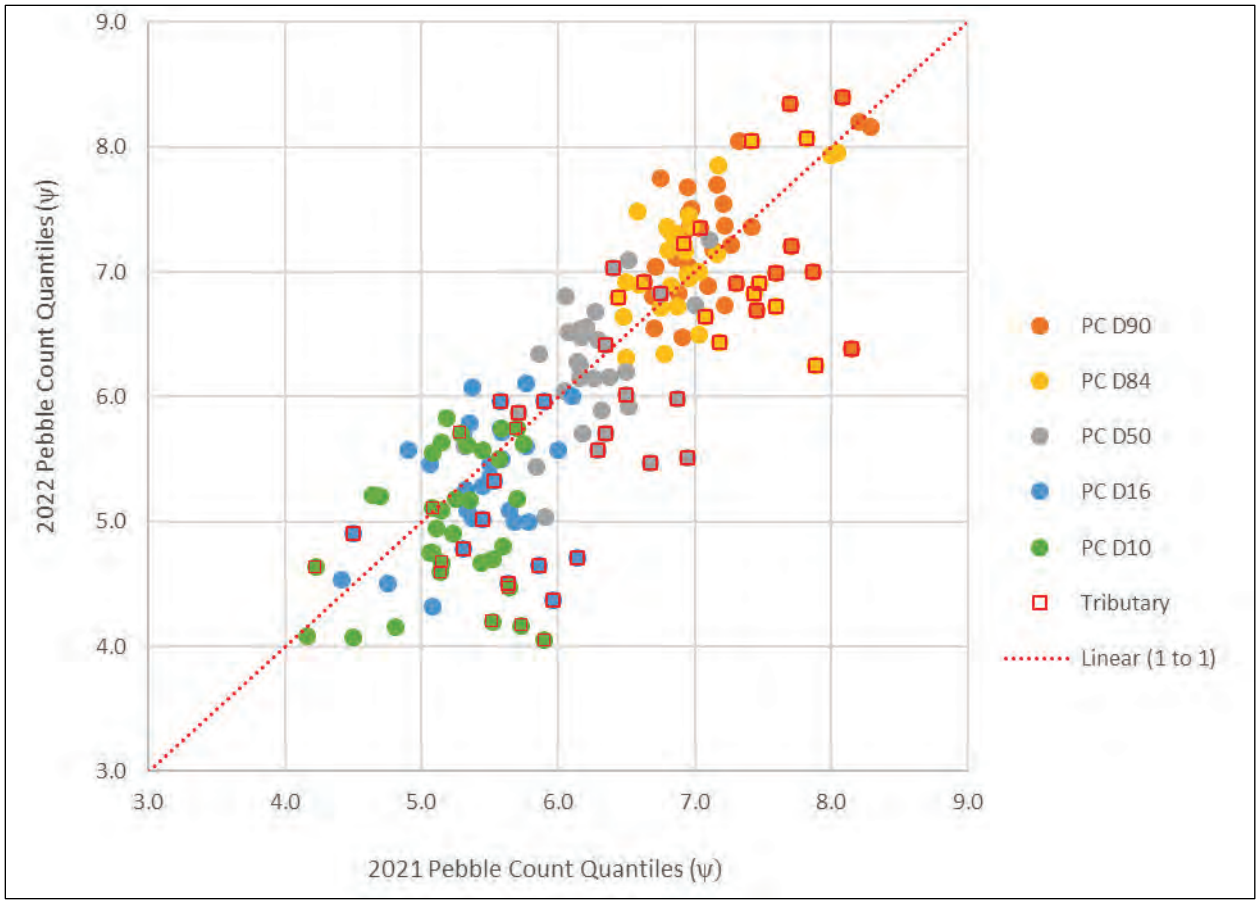


Figure 5.4-8. **Quantile – Quantile plot for all repeat pebble count sites. Data from tributary sites are highlighted by red boxes. The red 1 to 1 line represents the hypothetical relationship between two perfectly equal distributions. Data points to the right of the 1 to 1 line indicate that the quantile was finer in 2022 than in 2021, while data to the left indicate it was coarser.**

5.4.4 Lithology Patterns

The results of tracking lithology in pebble counts are shown in Figure 5.4-9. The results show longitudinal changes in mainstem bed material lithologies, as well as the lithologic composition of tributary bed material inputs. These data provide information about the relative contributions of various tributaries to mainstem bed material; contributions from long-term storage reservoirs such as bank material; and the accuracy of relative bed material flux estimates.

Different lithologies act as tracers for different parts of the Skagit basin and/or specific tributaries (Figure 4.4-4). For example, the mainstem from the Gorge bypass reach to Reach 2B (approximately PRM 96-90) consists almost entirely of Crystalline Core rocks: banded gneiss (Gb), orthogneiss (Go), and granodiorite (GD). The upstream-most tributaries—Ladder, Newhalem, and Goodell creeks—also contribute entirely Crystalline Core rocks. Moving downstream, the Skagit River mainstem picks up additional lithologies including greenschist (SG) from additional tributaries including Bacon and Diobsud creeks. Vesicular volcanics (Vs) and

other Quaternary volcanics (V), derived from Glacier Peak, can be seen entering the Skagit River via the Sauk River.

Bed material lithologies become more heterogeneous farther downstream, particularly downstream of the Sauk River, for several reasons. First, the Sauk and Cascade rivers contribute a wide variety of lithologies sourced from large basins. Second, Western Group bedrock adjacent to some of the tributaries in the lower basin—approximately at and downstream of Jackman Creek—consists of heterogeneous mélange units, in which a single mapped unit can contain many lithologies. Finally, the Cordilleran Ice Sheet deposited thick layers of glacial drift in the lower valley, introducing lithologies from outside the Skagit basin (Riedel et al., 2022). Much of Finney Creek's basin is eroded into glacial deposits, and as a result, the lithology of its bed material is varied. As a result of these factors, the proportion of unidentified lithologies (X) increases in the downstream direction.

Several Eastern Group lithologies are distinctive tracers to the basin upstream of Ross, Diablo, and Gorge dams. Cherty conglomerate (Cc) and Panther Creek conglomerate (Cp) are exclusively derived from the upper basin upstream of the dams, and a distinctive metasedimentary unit (Ms) is derived almost exclusively from the upper basin. The supply of these lithologies to the study area was cut off by regulation. The presence of these units in mainstem pebble counts is interpreted to result from bank erosion, where pre-regulation channel deposits are eroded and incorporated into modern bedload. A pebble count taken from an eroding bank at PRM 88.2 is interpreted to represent pre-regulation bed material at that location, and therefore, the distribution of lithologies that would be contributed to the Skagit River by bank erosion. The bank pebble count at PRM 88.2 contains 17 percent upper basin lithologies. In contrast, the pebble counts for several miles below the Gorge (at PRM 96-91) contain 2 percent or less of upper basin lithologies, and consist almost entirely of Crystalline Core lithologies. Currently, this bed material is contributed primarily from Ladder, Newhalem, and Goodell creeks.

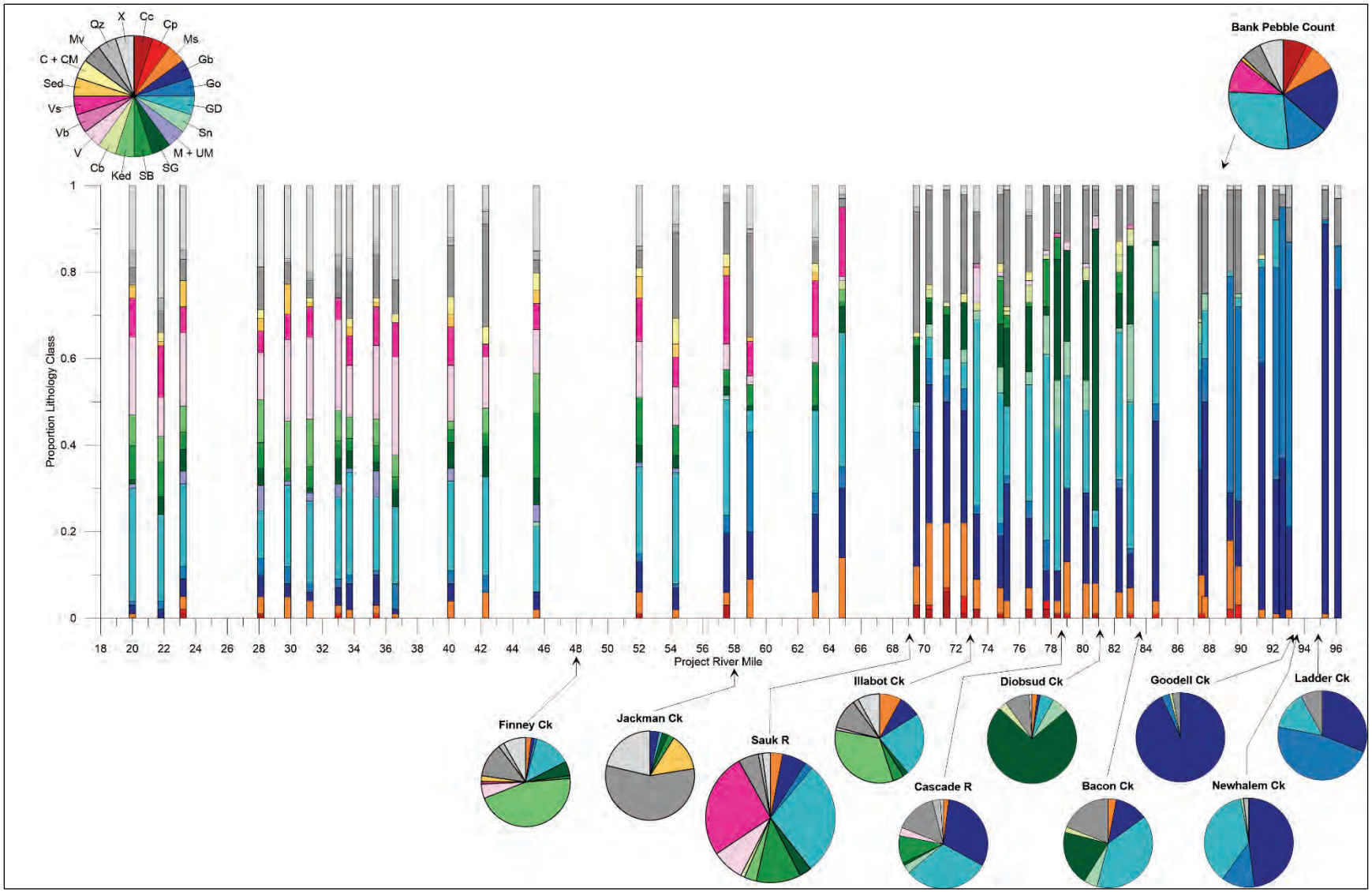


Figure 5.4-9. Observed lithology composition of sediment in Skagit River and select tributaries.

Downstream of PRM 90, the proportion of upper basin lithologies in the pebble counts increases. This trend is interpreted to reflect contributions from long-term storage reservoirs, primarily through bank erosion; the distribution shown in the bank pebble count is mixed into the mainstem distributions, resulting in a higher percentage of upper basin lithologies. The proportion of upper basin lithologies is higher in reaches with greater bank erosion, particularly the County Line and Barnaby reaches (2B and 6, approximately PRM 91-89 and 74-68).

The relative concentrations of tracer lithologies between mainstem and tributary or long-term storage reservoir distributions can be used to check sediment budget estimates. These mixing calculations perform well for many tracer lithologies with distinctive source areas, providing strong support for the accuracy of the bed material sediment budget in Section 5.5.5. Given an upstream Skagit lithology distribution, a tributary lithology distribution, and the ratio of bedload flux between the Skagit River and the tributary, the expected downstream Skagit River lithology distribution can be predicted. These calculations provide a check on the estimates of relative bedload fluxes.

The bank material lithology distribution can be used to evaluate the relative contribution of bank erosion to the sediment budget. See Section 5.5.5 for a detailed discussion of tracer calculations as a check on the bed material sediment budget.

Downstream lithology and grainsize trends were compared in order to check for lithology-dependent weathering that could affect the overall lithology trends. Abrasion during transport and weathering on bars can reduce clast size in more-erodible lithologies. (Pfeiffer et al., 2022) However, more-erodible lithologies (such as vesicular volcanics or Napeequa Schist) did not show more rapid downstream fining than the general population of grainsizes. For each pebble count, the D_{50} of each lithology represented by more than five grains was compared to the overall D_{50} of the pebble count. Downstream trends in overall and lithology-specific D_{50} values were then compared. No trends indicating accelerated fining of specific lithologies were found.

5.5 Sediment Transport

Three largely independent approaches to estimate sediment transport rates are available for the Skagit River, each of which provides unique information on the relation between sediment transport and channel morphodynamics. These are the empirical observations of sediment mobility from the scour monitoring program during the winter 2021-2022 flood season (which included the relatively large flood of November 2021), observations of changes in sediment storage between topobathymetric LiDAR datasets (2017 and 2018 versus 2022) and development of existing conditions mobile bed sediment transport models. The following sections are structured to assemble these various pieces of information into a synoptic view of sediment transport in the river with a focus on understanding the relation between sediment mobility and channel morphodynamics. Section 5.5.1 and Section 5.5.2 report empirical observations of sediment mobility in the Skagit River in the study area derived from the scour monitoring program and particle tracing program, respectively; these results are combined in Section 5.5.3 to produce a morphologic estimate of sediment flux in the Skagit River in the study area. Section 5.5.1 also reports a detailed analysis of redd scour risk derived from the scour monitoring program. Section 5.4 reports results of the fine sediment yield analysis, which—through application of a relation between fine sediment yield and bedload yield—provides a key input to the morphologic sediment

budget (Section 5.5.5) for the river. Section 5.5.6 describes key lessons learned related to the core questions for the sediment transport modeling program (Table 5.5-1) over the course of the existing conditions model development. The developed models will be applied by running alternative hydrologic and/or sediment supply scenarios in the process of PME development to further answer these core questions and other similar questions related to management of sediment-transporting discharges and sediment supply to the river.

5.5.1 Scour Monitoring Program Results

Results of the scour monitoring program can be used both to evaluate the active layer thickness in the channel and to evaluate redd scour risk. This section starts by reporting observations at the locations scour monitors were installed (Section 5.5.1.1), continues with extrapolation from those observation locations to an analysis of reach-average active layer thickness, which is a key input to the morphologic sediment flux estimate (Section 5.5.1.2), and concludes with evaluation of redd scour risk (Section 5.5.1.3).

5.5.1.1 Observations at Locations of Scour Monitors

This section reports results of observations from scour monitoring arrays indicating the depth and timing of bed mobilization through the 2019-2020, 2020-2021, and 2021-2022 winter seasons. Peak flows in winter 2019-2020 and 2020-2021 were modest (approximately the historical regulated 2-year peak flow), while 2021-2022 included a significant flood (2 to 3 times greater than the historical regulated 2-year peak flow).

Observations through summer 2021, which focused exclusively on spawning locations, suggest that very little bed mobility had occurred between the time of installation (2019 and 2020) and time of observation. Most of those locations showed no scour; most observations showing any scour indicated mobilization less than the thickness of the armor layer, and a maximum observed scour depth of 6.8 inches. Of the ten 2019-2020 monitoring arrays, possible scour of at least one of the four golf ball scour monitors was observed at eight arrays (Table 5.5-1). Scour was detected by observing an increase in the total number of balls floating in the scour chains compared to the previous monitoring year, with a scour depth of 1.7 inches for each floating ball added to the depth of the top ball at the time of installation. Observed scour was greatest at the 2019 Sites 1 and 2 with observed scour on three chains at each site and a maximum observed scour of ten inches. Given the proximity of these sites to frequently utilized spawning habitat, it is unknown whether these golf ball releases occurred due to scour on the bed or redd development.

For the 2020-2021 accelerometers, 8 top accelerometers registered tilting of over 15 degrees at spawning arrays, and all 8 instances correlate to low discharge in peak spawning season (September). The sites with presumed spawning activity include Site 1, Site 3, ABSS1 and ABSS3. Therefore, any scour that did occur due to high flows did not penetrate to the depth of the top accelerometer (usually at or just below the armor layer).

Table 5.5-1. Summary of 2020-2021 scour monitoring results.

Site[1]	Chains with floating balls (out of 2) in 2020	Chains with floating balls (out of 4) in 2021	Name of monitors[2]	Depth of scour indicated (in) 2019-2020	Depth of scour indicated (in) 2020-2021
BMM1		2	GBB		5.1
			GBC		4.7
BMM4		1	GBD		1.7
BMM6		0			<1.7
BMM7		1	GBD		5.7
Site 1 (2019)	1	3	GB1	1.7	3.4
			GB2	<0.4	6.8
			GBA	NA	6.9
Site 2 (2019)	1	3	GB4	4.7	10
			GBA	NA	3.4
			GBB	NA	1.7
Site 3 (2019)	1	3	GBA	NA	4.4
			GB5	<4	7.1
			GB6	1.7	<1.7
ABSS1		0			<1.7 to <5.5
ABSS2		0			<3 to <5
ABSS3		2	GBA		6.4

1 Site names reflect location and time of installation. 'Site' prefixes were installed in 2019, BMM were installed in 2020 Below Marblemount, ABSS were installed in 2020 upstream of (above) Shovel Spur; these are all located at spawning areas.

2 See Attachment B for maps illustrating locations of individual scour monitoring devices.

In contrast, observations from the 2021-2022 monitoring season suggest widespread bed mobility did occur during the November 2021 flood. Observations in 2021 included observations at spawning locations and observations at riffle crest and tributary fan locations where shear stress and bed mobility were generally greater than at the spawning locations. As outlined in Table 5.5-2, of the 18 Skagit mainstem scour array sites, 12 sites detected scour at all four top accelerometers, and 8 sites detected scour to at least the depth of all four bottom accelerometers. Both fan arrays, Goodell Creek Fan and Bacon Creek Fan, were completely scoured away, as were all the scour monitors installed at Riffle Crest Site 93.0. Riffle crest arrays experienced a greater frequency and depth of scour than the spawning scour arrays. For the riffle crest arrays, there was a 75 percent rate of scour to the top monitor and 63 percent rate of scour to the bottom accelerometer. Spawning sites had a similar but slightly lower rate of scour to the top accelerometer, at 66 percent, but only 33 percent of bottom accelerometers recorded scour. A total of 16 accelerometers recorded redd activity in the months of September and October at both spawning and riffle crest sites. The maximum recorded bed elevation change from 2021 to 2022 was 2.9 ft of aggradation (BMM4), and the maximum observed scour was -2 ft (RC 93.0), and an average bed elevation change of -

0.1 ft at the scour monitors. For a complete record of redd activity, bed elevation changes, minimum observed scour depths and grainsize information, see Attachment B.

For each monitor that experienced partial or complete scour, sediment transported from upstream partially filled the scoured bed. This post-scour fill, estimated as the difference between the post-flood bed elevation (measured in summer 2022) and the minimum scour depth elevation (derived from the scour monitors as explained in Section 4.5.2.1), provides an estimate of the instantaneous active layer thickness (sensu Church and Haschenburger [2017] and equivalent to the aggregate of the mobile layer and exchange layer of Cui [2007]) at each monitor. Several outliers in the observations include Spawning Site BMM4 and RC 93.0, where substantial net fill and scour (respectively) occurred. At BMM4, over 2.5 ft of sediment deposited on the scour array. Only one accelerometer was recovered due to the digging depth, but the accelerometer pair (ACC A in Table 5.5.2) did register scour to the depth of at least the first accelerometer, resulting in an event active layer thickness of over 3 ft, which is presumably much thicker than the actual instantaneous active layer (See table in Attachment B for active layer thickness). In contrast, all of the scour monitors at RC Site 93.0 were scoured away, providing only a bare minimum scour depth estimate (depth from the original bed surface to the anchor), which may bias the results.

Table 5.5-2. Summary of 2021-2022 scour monitoring observations.

Sites	Category	Reach	%Scour Top ACC	%Scour Btm ACC	ACC A MSD (ft)	ACC B MSD (ft)	ACC C MSD (ft)	ACC D MSD (ft)	GBA MSD (ft)	GBB MSD (ft)	GBC MSD (ft)	GBD MSD (ft)
BMM6	Spwn	7a	100	100	0.33	0.33	0.92	1.08	NA	NA	1.00	NA
RC 70.1	RC	6	100	100	1.38	1.21	1.13	1.25	1.02	2.29	NA	NA
BMM4	Spwn	6	100	0	0.67	NA	NA	NA	NA	NA	NA	NA
BMM1	Spwn	6	NA	0	Error*	Error*	Error*	Error*				0.72
RC 75.2	RC	5b	0	0					0.64	0.56		0.56
Site 3 (2019)	Spwn	5b	67	0		0.42			0.00	0.62		0.47
BMM7	Spwn	5b	100	100	1.17	1.17	1.25	1.08	0.80	0.80	1.37	1.23
Site 1 (2019)	Spwn	5a	0	0					0.52	0.52		
RC 79.0	RC	5a	50	0	0.46		0.46		0.52	0.91	0.66	
RC 82.3	RC	3a	100	100	1.25	1.00	1.00	1.75	1.75	1.58	1.75	2.00
Site 2 (2019)	Spwn	3a	25	0			0.42			0.64	0.43	0.58
Bacon Ck Fan	Fan	3a	100	100	1.42	1.42	1.42	1.42	2.25	2.25	2.25	2.25
ABSS3	Spwn	3b	0	0							0.57	
RC 89.9	RC	2b	100	75	0.54	1.13	1.00	1.04	1.02	1.17	0.52	1.12
ABSS2	Spwn	2b	100	100	1.04	1.21	1.04	1.42	0.74	1.31	1.45	1.31
ABSS1	Spwn	2b	100	0	0.67		0.63	0.58	0.84	0.98	0.42	0.70
RC 93.0	RC	2b	100	100	1.75	1.75	1.75	1.75	2.21	2.13	2.46	2.38
Goodell Fan	Fan	2b	100	100	1.42	1.42	1.42	1.42	2.42	2.42	2.42	2.42
Cascade R RC	Trib	NA	100	25	1.17	0.58	0.58	0.50			0.33	0.67
Bacon Ck RC	Trib	NA	75	75		1.42	1.42	1.42	2.17	2.17	2.17	2.17

1 Site names reflect location and time of installation. 'Site' prefixes were installed in 2019, BMM were installed in 2020 Below Marblemount, ABSS were installed in 2020 upstream of (above) Shovel Spur; these are all located at spawning areas. Riffle Crest (RC) and Fan sites were all installed in 2021.
2 Error* refers to download errors (no data) and NA refers to monitors that could not be recovered.
3 MSD = Minimum Scour Depth (Observed).

5.5.1.2 Nondimensional Scour Analysis and Active Layer Thickness

Following the recommendations of Brenna et al. (2019) and Wilcock and McArdell (1997), predictive models of minimum scour depth and active layer thickness were developed using the regression relationships between the measured sour depth and measured active layer thickness with the modelled τ^*_{max} from the 2-D Upper Skagit Hydraulic Model (City Light 2023a) simulation results of the November 2021 flood. To remain consistent with the terminology of Section 4.5.3, the minimum scour depth will be referred to as $d_{s(scour)}$ and the minimum active layer thickness, or event-scale scour and fill, will be referred to as $d_{s(event)}$. The τ^*_{max} was calculated using the D_{50} of the Wolman pebble count measured at each scour array. Before using τ^*_{max}, the $\tau^*_{instantaneous}$ (τ_* calculated at recorded time of scour) was tested as a predictor, but it did not have a strong relation with scour depth or active layer thickness. For those monitors without observable scour, either not recorded or unknown, a minimum predicted scour depth was estimated using either the measured D_{50} for $\tau^*_{max} > 0.045$, or the predicted mobile D_{50} for calculated $\tau^*_{max} < 0.045$. See Attachment B for a table of τ (instantaneous), τ^*, minimum scour depth and minimum active layer thickness. Results from tributary fan arrays were excluded from the analysis, where scour was attributed to incomparable processes including bank erosion or channel widening. Minimum scour depth and minimum active layer thickness were normalized by the D_{90} in the relations to remain consistent with the results of other studies. A normalization to the D_{90} is used as a scaling factor because it approximates the thickness of the armor layer.

To remain consistent with the results of Brenna et al. (2019) and Wilcock and McArdell (1997), the best-fit power-law relation was chosen to relate dimensionless shear stress (τ^*) to normalized scour depth ($d_{s(scour)}/D_{90}$). The resulting regression indicated that there is a strong relation between τ^* and $d_{s(scour)}/D_{90}$ ($F(1, 110) = 102.25$, $p << 0.001$, $R^2 = 0.48$, $R^2_{adj} = 0.48$). The resulting relation of normalized minimum scour depth

$$\frac{d_{s(scour)}}{D_{90}} = 170\,{\tau^*_{max}}^{1.73}$$

aligns closely with the regression relation derived by the flume experiments of Wilcock and McArdell (1997), which plots within the 95 percent confidence bounds of the predicted values (Figure 5.5-1). The standard error of the estimate of non-dimensional scour depth is 0.67. Results from Brenna et al. (2019) plot higher for τ^* values of 0.1-0.12 but that study lacked data for τ_* larger than 0.12. It should be noted that bias may be present in the data for τ^* greater than 0.1 of this Geomorphology Study. These data points originate from Riffle Crest Site 93.0, where the minimum scour depth is defined as the anchor depth of the scoured monitors, but may in fact be deeper. Therefore, direct comparison of the regression equation coefficients between studies is not appropriate given the uncertainty in observed $d_{s(scour)}$ for τ^* greater than 0.1.

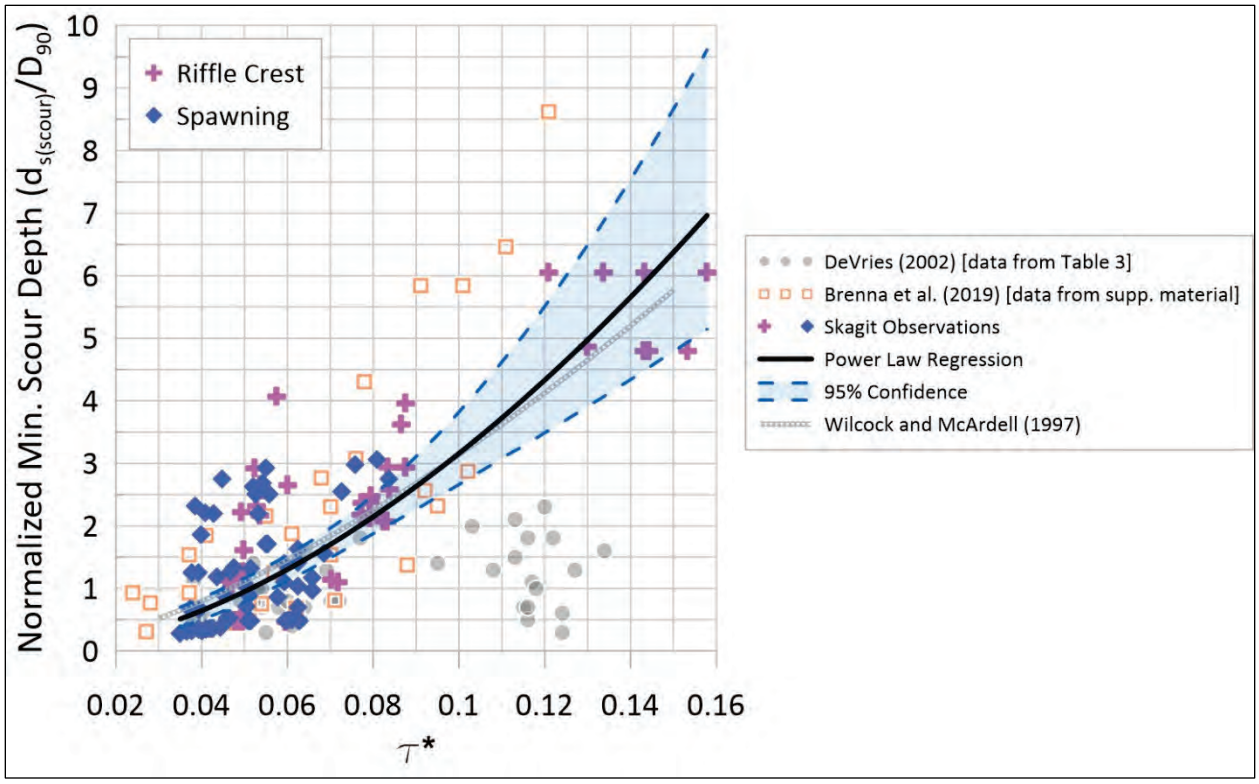


Figure 5.5-1. Comparison of normalized scour depth as a function of τ* for the results of Geomorphology Study as well as DeVries (2000), Brenna et al., (2019), and Wilcock and McArdell (1997).

Unlike nondimensional scour depth, the nondimensional active layer thickness ($d_{s(event)}$) did not have a strong relationship with τ^*_{max} (Figure 5.5-2). The active layer relation for the observations on the Skagit is similar to the results of DeVries (2000), which also show a weak relation between the event active layer thickness (defined by DeVries (2000) as the "bedload disturbance depth") and τ*. Instead, DeVries (2000) suggests two boundary relations be used instead: an initiation of motion at τ* of 0.035 and an upper-bound active layer thickness of $2D_{90}$, stating that only incipient motion, not local scour depth, is a function of bed shear stress unless under catastrophic conditions. The upper bound of the event active layer thickness for the results of this study do plot higher, at $3D_{90}$, but imply a similar initiation of motion at τ* of 0.035 to 0.04. Information on the flood recurrences observed in the DeVries (2000) monitoring period were not included in the study results, but it is reasonable to assume that a relatively large recurrence flood like the November 2021 event did not occur, which may explain the thicker active layer observed in the 2021-2022 monitoring period in which local areas of higher shear stress occurred.

For the purposes of this study, active layer thickness is predicted using the nondimensional $d_{s(scour)}$ regression relation for event active layer thickness below $2D_{90}$. Larger values resulting from higher localized shear stress, as observed in the November 2021 flood, result in net scour and fill that is detected in the morphological flux calculations and are therefore, accounted for already.

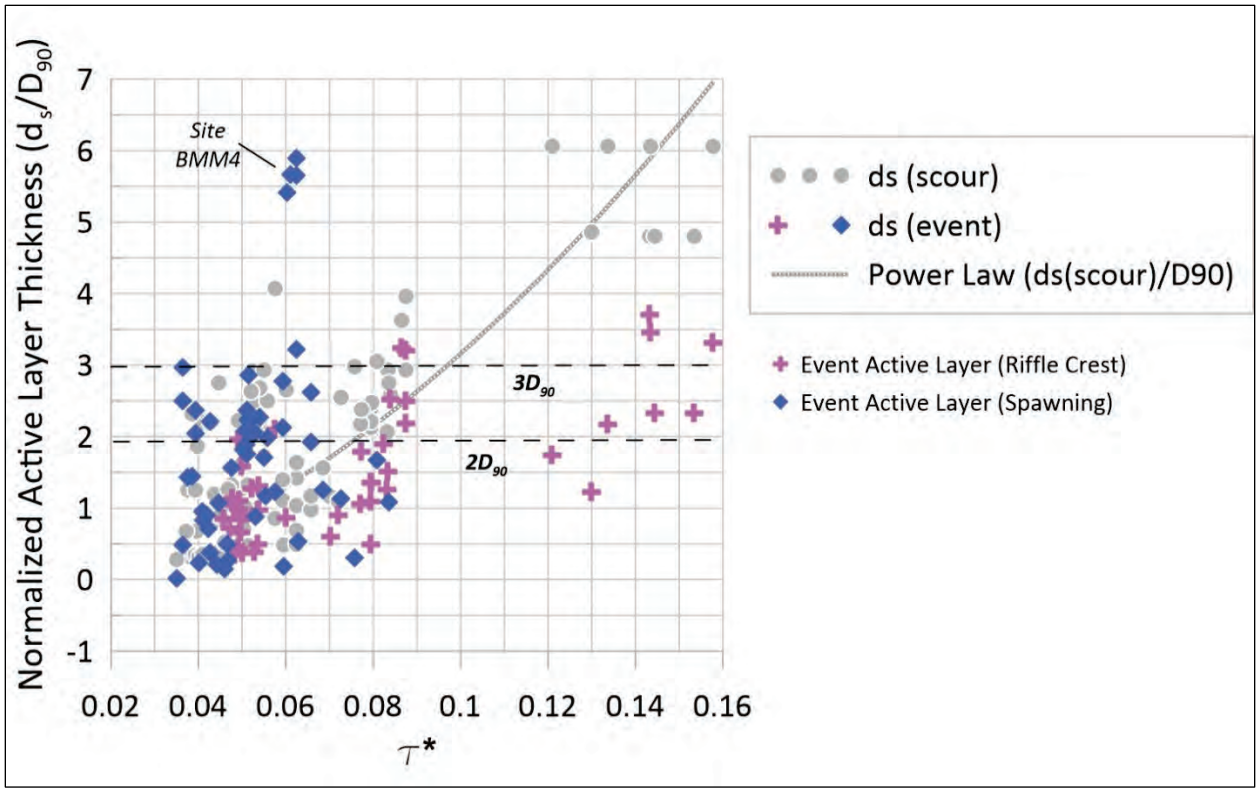


Figure 5.5-2. Comparison of normalized scour depth ($d_{s(scour)}$) and event active layer thickness ($d_{s(event)}$) with horizontal lines drawn for event active layer upper bounds of $2D_{90}$ (DeVries 2000) and $3D_{90}$. Site BMM4 experienced substantial deposition, resulting in a high event active layer thickness even though little scour occurred.

5.5.1.3 Scour at Redd Locations and Burial of Redds

Although there is a clear relation between dimensionless shear stress τ* and scour depth (Sections 5.5.1.1 and 5.5.1.2), there is also meaningful scatter around the mean result. A probabilistic model using logistic regressions was therefore built as a tool to better assess redd scour risk. Each of the logistic regressions were statistically significant (Table 5.5-3). The models explained between 27 and 36 percent of the variance. The percentage of cases correctly classified increased with increasing threshold depth from 72 percent for the top-of-pocket threshold to 97 percent for the 20-inch, bottom-of-Chinook Salmon-redd-pocket threshold. (Refer to Table 4.5-4 for species associated with each threshold depth.) The results of the assessment (Figure 5.5-3) show that the probability of initiating scour to the top of redd pocket depth increases rapidly from less than 10 percent for a value of τ*=0.02 to 50 percent at τ* = 0.05 and to 90 percent at τ* = 0.074. Complete egg loss, however, requires considerably higher dimensionless shear stress, with only 10 percent of sites expected to scour to the bottom of pocket depth for most considered species (14 inches) at τ* = 0.05; at τ* = 0.063, 50 percent of redd sites experience complete egg loss; and 90 percent of redd sites experience complete egg loss at τ* = 0.088.

Table 5.5-3. Summary of binary logistic regression results for scour exceeding each threshold depth as a function of local τ*.

Threshold Depth (d_s)	X2 (1, N=112)	p	Nagelkerke R^2	% Cases Correctly Classified
5.9 in	35.4	<<0.001	0.27	72
10 in	44.2	<<0.001	0.33	76
14 in	42.6	<<0.001	0.32	82
20 in	50.6	<<0.001	0.36	97

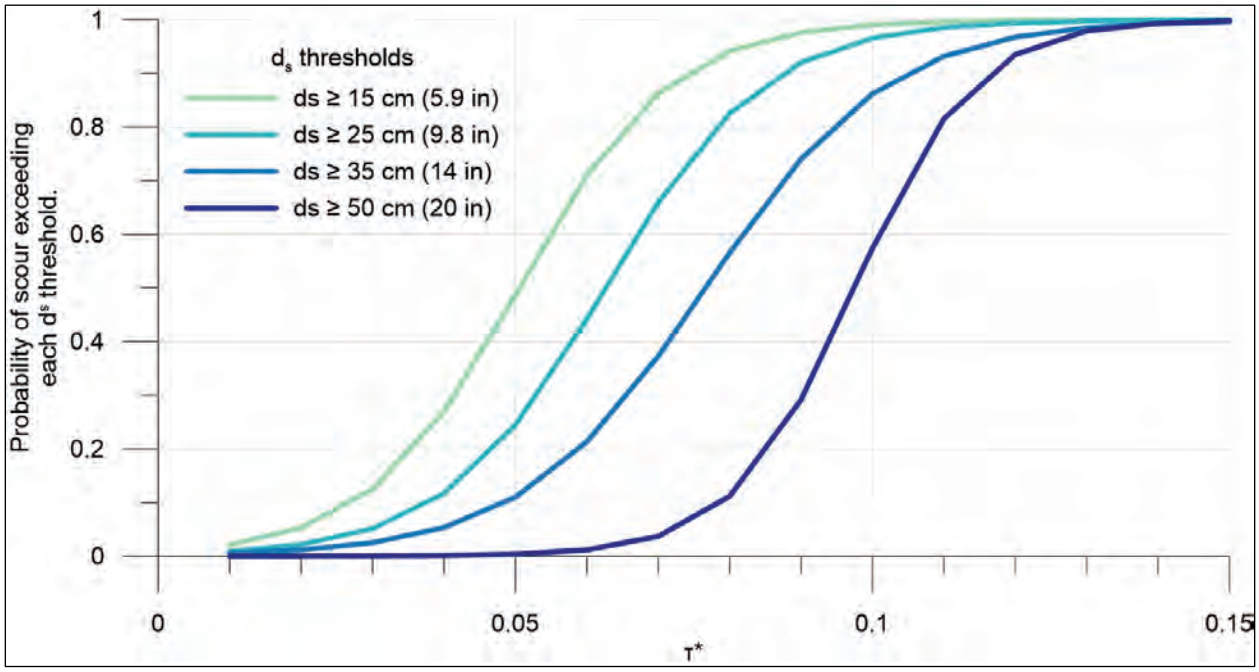


Figure 5.5-3. Probability of exceeding redd scour thresholds as a function of local τ*.

Redd scour risk is a key factor in determining both effective and safe process flows for the Skagit River. To assess the potential risk of scour with increasing flows, the logistic regression equations were applied to map the local probability of scour using 2-D hydraulic model results and facies mapping information for a range of flows from 10,000 through 70,000 cfs. Spatial applications of the probabilistic model allow managers to assess the likelihood of scour at known redd locations. For flows between 10,000 and 70,000 cfs, sections of the Skagit River within the study area with a 50 percent or greater probability of exceeding a threshold (15, 35, and 50 cm) are mapped and presented in Attachment V. In order to compare to known redd locations, surveyed redd locations from 2017-2018 and 2021-2022, City Light boat surveys are overlain for Chinook Salmon, Chum Salmon, and steelhead (Lowery 2022).

It is important to note that the dataset of known redds is biased towards Chum and Chinook salmon redds built in shallow environments (those at greatest risk of dewatering) and is not a complete dataset. Shear stress is a function of depth and so this may result in a bias towards inclusion of lower-scour-risk redds for these species in this mapping, but no more complete mapping of redd locations in the Skagit River within the study area is available. In contrast, the surveyed steelhead points are representative of both shallow and deep redd locations. One additional item to consider when evaluating these maps is that the 2-D hydraulic model was calibrated using bathymetry and LiDAR collected between 2017 and 2020, thus the model results are presented on this older topographic surface. Due to channel migration during the November 2021 flood, some 2017-2018 redds in reaches with active lateral channel migration, such as the Barnaby Reach, no longer exist, while several 2021-2022 points were surveyed in recently eroded areas that appear to be on dry land in the maps.

In general, the risk of scour exceeding 15 centimeters increases throughout the river at a discharge of 30,000 cfs or greater, but the majority of the available surveyed redds are in shallower and lower shear stress environments where predicted scour does not exceed 15 centimeters. By 50,000 cfs, a small portion of the surveyed redds begin falling within the 50 percent probability of exceeding scour to a depth of 15 cm. In particular, the Chinook redds located in shallow environments between Marblemount and Bacon Creek appear to be at the greatest risk of exceeding scour at or greater than 35 centimeters depth for flows of 50,000 cfs or more. Scour risk is generally more widespread upstream of Shovel Spur for higher flows, placing the surveyed steelhead redds adjacent to the most scour-prone areas. The highest concentration of surveyed redd points is located downstream of Marblemount in the Barnaby reach. Spatial correlations in this reach should be made with caution due to channel shifts that occurred in November 2021.

In these more laterally active reaches, where redds are often located along the margins of accreting bars, deep burial of redds may pose a meaningful risk to redd survival. Most literature discussing redd burial focuses on effects of fine sediment infiltration limiting oxygenation and permeability of the redds, which has been shown to alter the timing and size of emerging alevin and decrease the relative fitness of the fry (Chapman, 1988; Lisle 1989). The effects of fine infiltration on embryos to fry are well known, with egg-to-fry survival dropping rapidly as the percentage of fine sediment smaller than 0.85 mm increased above a threshold of about 10 percent and more moderate impacts to egg-to-fry survival occurring as the percentage of fine sediment smaller than 4.8 mm increased above a threshold of about 25 to 30 percent (Jensen et al., 2009). As described in Section 5.4.1, fine sediment concentrations in bed material samples from the Skagit River in the primary study area are generally below these thresholds. However, little information is available in the literature to define how the depth of aggraded sediment above redds affects the survival of embryos and emerging alevin. In a 2003 study of White River Chinook redds in the upper Puyallup watershed, an entombment threshold of 10 centimeters was chosen to predict fry survival, listing the rationale that 10 cm increases the vertical distance of emerging Chinook alevin/fry by 66 percent (Schuette-Hames and Adams, 2003). This tolerance level of 10 cm has not been verified in the literature. A primary example of probable entombment is at scour array BMM4, where over 3 ft of aggradation occurred (Figure 5.5-4). Other potential scenarios of redd entombment include migrating point bars, as well as localized aggradation downstream of tributary or bank erosion sediment pulses.



Figure 5.5-4. Example of probable redd entombment at scour array BMM4, where over 3 ft of aggradation occurred, composed of a widely graded mix of sand to boulders.

While the results of this analysis can provide useful insight into scour likelihood across the model domain, there are limitations on the application of these results. The primary constraint on spatially mapping the logistic functions is the uncertainty in the calculated τ^*. As previously mentioned, the shear stress values were modeled using terrain that is now outdated due to channel migration, and therefore, does not capture the full extent of existing 2022 channel bed. Additionally, the D_{50} grainsize used in the calculations comes from interpretation of the facies mapping dataset, the accuracy of which is evaluated in Section 5.4.2.

Analysis of the likelihood of scour exceedance at critical spawning depths can be extrapolated on the species level if a complete dataset of surveyed redd locations exists. Because census data on locations of steelhead redds are available, it is possible to explicitly evaluate the expected frequency of redd scour as a function of the probability of scour calculated from τ^* and the frequency distribution of τ^* at observed steelhead redd locations. Using the 2017-2018 and 2021-2022 surveyed steelhead data, scour was assessed at the reach scale for scour depth exceedance of 15 cm (top of egg pocket) and 25 cm (middle of egg pocket). The main input variable, τ^*, was calculated using the D_{50} of the mapped facies and modeled shear stress from the 2-D steady state

hydraulic model results. While the maps in Attachment V show the median probability of exceeding a particular scour threshold, they do not describe the full probability distribution. To do this, further statistical analyses are required to understand reach scale redd population dynamics. To do this, the proportion of redds exceeding the particular threshold scour depth was calculated and compared across reaches by using the normalized discharge of the modelled steady state flows (Q = 10,000-70,000 cfs). So that the different reaches could be compared to each other, the flows were then normalized to the existing 2-year daily recurrence interval discharge of each reach (calculated from water year 1988-2020 record; NHC 2023). To understand the differences in the reach comparisons, reach-level cumulative probability was calculated across the range of calculated τ^*. The distribution of surveyed steelhead redd locations is not uniform, so reaches with fewer than 10 surveyed redd locations were excluded from the analysis (Table 5.5-4).

Table 5.5-4. Reach sample size of steelhead case study.

Reach	2a	2b	3a	4	3b	5a	5b	6	7a
Sample Size (N)	NA	20	NA	NA	NA	35	11	140	28

The results show that, for the range of evaluated discharges, scour risk at steelhead redds is low. About ¼ or fewer of observed redd locations would be expected to scour to the top of redd pockets, and less than 15 percent to the middle of the redd pocket. Proportionally, a smaller fraction of redds exceeded the 15-cm scour threshold in Reach 7 for the range of discharges than in the other reaches (Figure 5.5-5). Meanwhile, the slopes of curves for Reaches 6, 5A, 5B, and 2B are all similar, with between 15 and 30 percent of redds exceeding the 15-cm threshold for the highest discharge (70,000 cfs). The slopes diverge slightly at the 25-cm threshold, but Reach 7 remains the least affected by redd scour in comparison. To investigate these differences further, cumulative probability was calculated to compare the odds at a given discharge with respect to τ^* that redd scour will occur at the full range of τ^* (Figure 5.5-6). The cumulative probability is the lowest for Reach 7 because τ^* did not exceed 0.0375 for any of the redd locations. The highest cumulative probability is in Reach 2B, where a larger proportion of redds in the reach population fall into a critical range of τ^* (0.045 to 0.065) compared to other reaches.

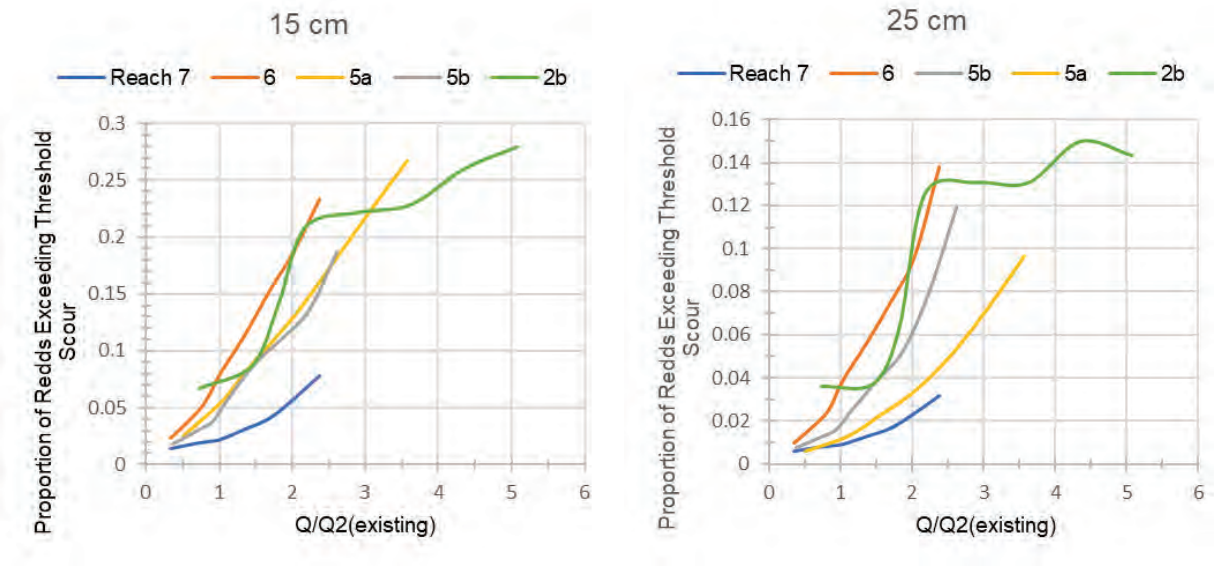


Figure 5.5-5. Proportion of redds exceeding 15- and 25-cm threshold scour between 10,000 and 70,000 cfs, plotted as normalized discharge ($Q/Q_{2\text{-year daily '88-'20}}$).

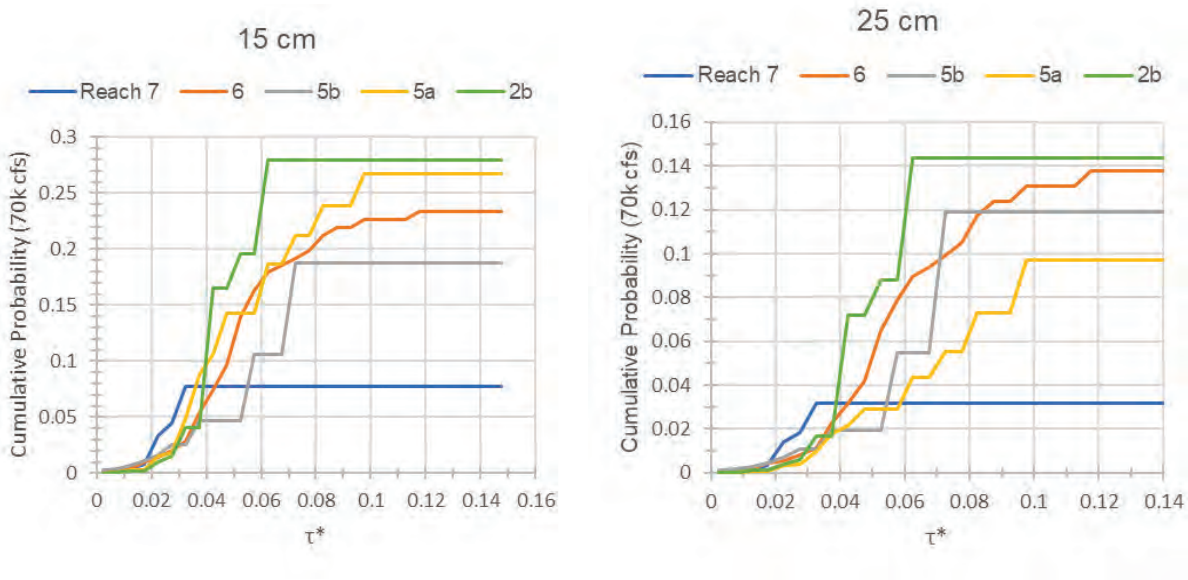


Figure 5.5-6. Cumulative probabilities of exceeding 15- and 25-cm threshold scour at 70,000 cfs for the study reaches.

5.5.2 Particle Tracing and Virtual Velocity

Both detection and non-detection of the deployed tracer particles provide information on the bed mobility conditions that occurred during the period between deployment and recovery of the particles. The recovery statistics are summarized in Table 5.5-5. A total of 93 of the 552 deployed particles (17 percent) were recovered, of which two particles were discarded from the analysis because they returned an unusable particle serial number likely caused by corruption of the RFID signal during field conditions. Five additional particles were determined to have either not been mobilized, or to have registered low displacement lengths (on the order of a few ft). To the best of

the study team's knowledge, the Skagit River is the largest river where RFID particle tracing has been employed. Given the resulting limitations of search depth and very large search area, the study was primarily focused on understanding the patterns of bed mobilization from the deployment locations, and so having enough recovery to calculate displacement distances represents substantial and valuable added information. Because it was possible to search the deployment locations very carefully, the study team interprets non-detection of a deployed particle to indicate that it mobilized away from the deployment location. Therefore, the study team interprets that more than 99 percent of the deployed particles were mobilized at some point during the winter of 2021-22. Of the five non-mobilized particles, three were in the 64-91 mm size class, one in the 94-128 mm size class and one in the 180-256 mm size class. The lack of mobilization of these particles is attributed to these particles having assumed locally stable positions within the Bacon Creek fan.

The calculation of displacement distances is intended to inform understanding of how far particles moved once they were mobilized. Therefore, the five particles that did not mobilize were excluded from the particle displacement analysis. The displacement analysis also excluded 10 additional particles deployed at the upstream Bacon Creek site, which were recovered upstream of its outlet into the Skagit River. The displacement of these particles was driven by flood flows on Bacon Creek with different magnitude and timing than those on the Skagit River. In addition, it is likely that the displacements of these particles were influenced by the backwater effects from the Skagit River, and are therefore deemed to not be representative of transport processes on the Skagit River. Because the flood peak on Bacon Creek preceded that on the Skagit River, the study team interprets that the particles that moved into the Skagit River had similar mobility to those from the Bacon Creek fan deployment site. To this end, the displacements of any recovered particles originally deployed at the upstream Bacon Creek site and recovered on the Skagit River were corrected by reducing the determined displacement length by the distance of the deployment site from the creek outlet. This allowed for considering only the portion of the displacement length that these particles traveled while in the Skagit River. The displacement analysis considered a total of 76 particles.

Table 5.5-5. Number and recovery rate of the tracer particles.

	Size Fraction (mm)								
Deployment Site	**45-64**	**64-91**	**91-128**	**128-180**	**180-256**	**256-360**	**360-512**	**512-712**	**Total**
Bacon Creek Downstream (Fan)	1 (8%)	1 (4%)	3 (15%)	2 (9%)	1 (17%)	0	0	0	8 (9%)
Bacon Creek Upstream	5 (22%)	4 (17%)	4 (25%)	4 (24%)	4 (33%)	0	0	0	21 (22%)
PRM 89.8	2 (6%)	1 (3%)	7 (29%)	1 (14%)	2 (50%)	0	0	0	13 (14%)
Goodell Creek	3 (16%)	3 (11%)	3 (18%)	1 (10%)	0	0	0	0	10 (11%)
Newhalem Creek	4 (13%)	7 (24%)	4 (19%)	4 (25%)	0	0	2 (40%)	1 (50%)	22 (22%)
Ladder Creek	2 (9%)	1 (4%)	3 (19%)	3 (25%)	0	2 (40%)	1 (33%)	0	12 (13%)
Total	17 (12%)	17 (11%)	24 (22%)	15 (23%)	7 (1%)	2 (8%)	3 (37%)	1 (50%)	86 (16%)

The recovery results summarized in Table 5.5-6 allow useful inferences on the tracer particle transport patterns when viewed in conjunction with the search intensity results summarized in Table 5.5-6. Near Bacon Creek, a search of 49 percent of the total area with both the pontoon and wand readers yielded 9 percent and 22 percent of the particles deployed at these two sites with a combined recovery rate of about 16 percent. For the PRM 89.8 deployment site, a 36 percent search intensity yielded about 14 percent of all particles deployed, whereas a 22 percent search intensity at the Goodell, Newhalem, and Ladder Creek areas yielded recovery of about 11 percent, 22 percent, and 13 percent of the deployed particles at each site respectively and a combined recovery rate of about 16 percent. At all deployment sites, the lowest recovery rates occur for the smallest tracer particles deployed (45-64 mm diameter). The lower recovery rate for this size class is likely due to the higher likelihood that these smaller, more mobile particles traveled downstream of the searched areas. It is also less likely for these smaller particles to deposit at the deeper portions of the main channel with higher stresses, which were outside the detection capability of the pontoon reader. The results therefore suggest that the recovered particles in the 45-64 mm size class are underrepresented.

Table 5.5-6. Search intensity results.

Search Area	Pontoon Reader		Wand Reader	
	Area (ac)	Relative Coverage (%)	Area (ac)	Relative Coverage
Bacon Creek	9.8	35%	3.7	13%
PRM 89.8	5.5	29%	1.2	6%
Goodell, Newhalem and Ladder Creeks	16	17%	5.4	6%

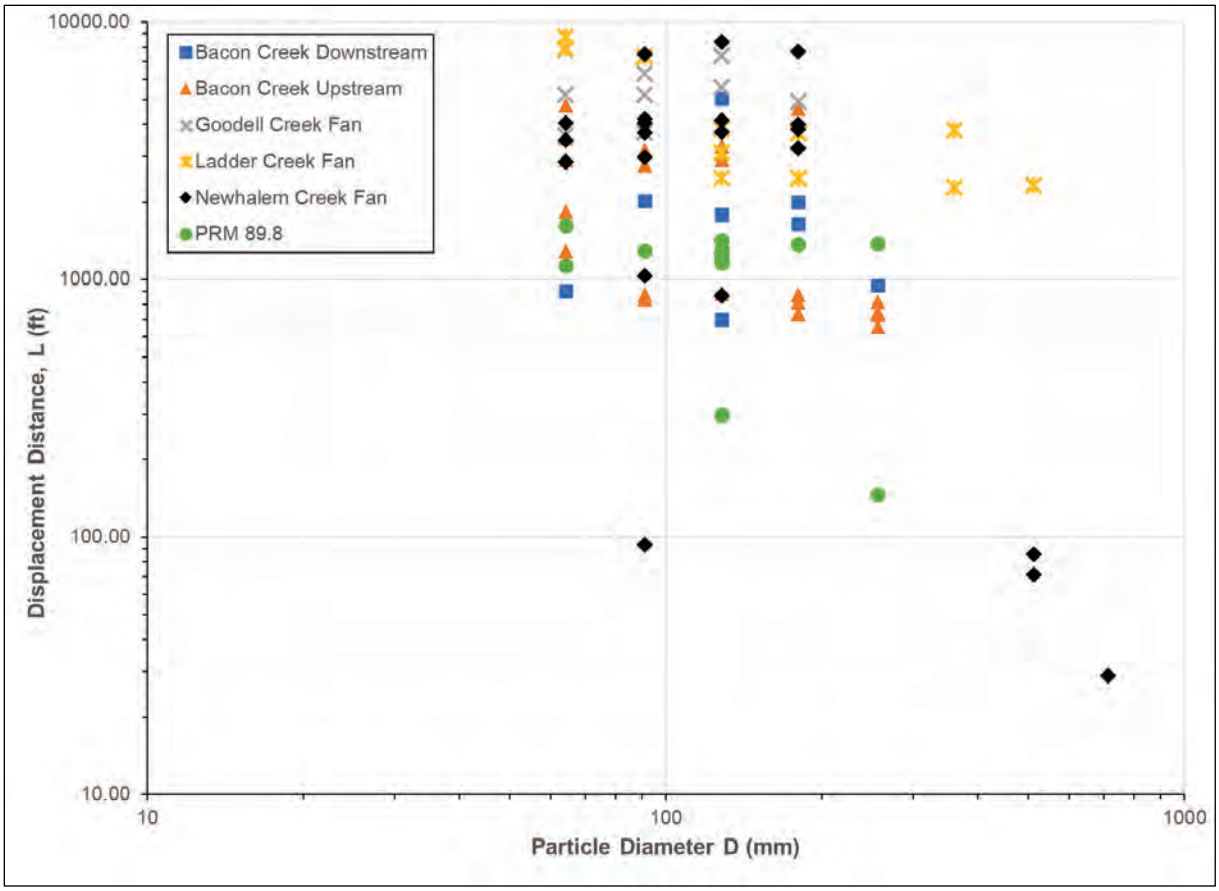


Figure 5.5-7. Estimated displacement lengths for the recovered tagged particles.

The results in Figure 5.5-7 show that the detected displacements of the tagged particles deployed in the upstream and downstream Bacon Creek sites and near PRM 89.8 are generally lower than those deployed at the Goodell, Newhalem, and Ladder Creek sites. The displacements are thus combined into two groups, namely those corresponding to the particles deployed at the Bacon Creek upstream, downstream and PRM 89.8 sites, and those deployed at the Goodell, Newhalem and Ladder Creek sites. The mean displacements(L) of the particles for each size class for these two groups are illustrated in Figure 5.5-8; the error bars on this figure represent one standard deviation about the mean. The results in Figure 5.5-8 show that the mean displacements of the particles deployed in the Goodell, Newhalem, and Ladder Creek sites exhibit strong size selectivity with the mean displacement decreasing with increasing particle size. On the contrary, the mean displacements for the particles deployed at the Bacon Creek and PRM 89.8 sites show minimal sensitivity to particle size, for particle sizes less than 180 mm, in contrast to the trend for the particles deployed at the Goodell, Newhalem, and Ladder Creek sites. This result is attributed to the limited search area downstream of the Bacon Creek and PRM 89.8 deployment sites, which the study team interprets introduced an artificial upper threshold in the displacement distance of the smaller particles and caused an underestimation of the displacement distance of these particles. The study team, therefore, interprets that the displacement trend of the particles deployed at the Bacon Creek and PRM 89.8 sites does not accurately represent the particle transport conditions on the Skagit River, which are more accurately depicted by the displacement trends of the particles deployed at the Goodell, Newhalem and Ladder Creek sites.

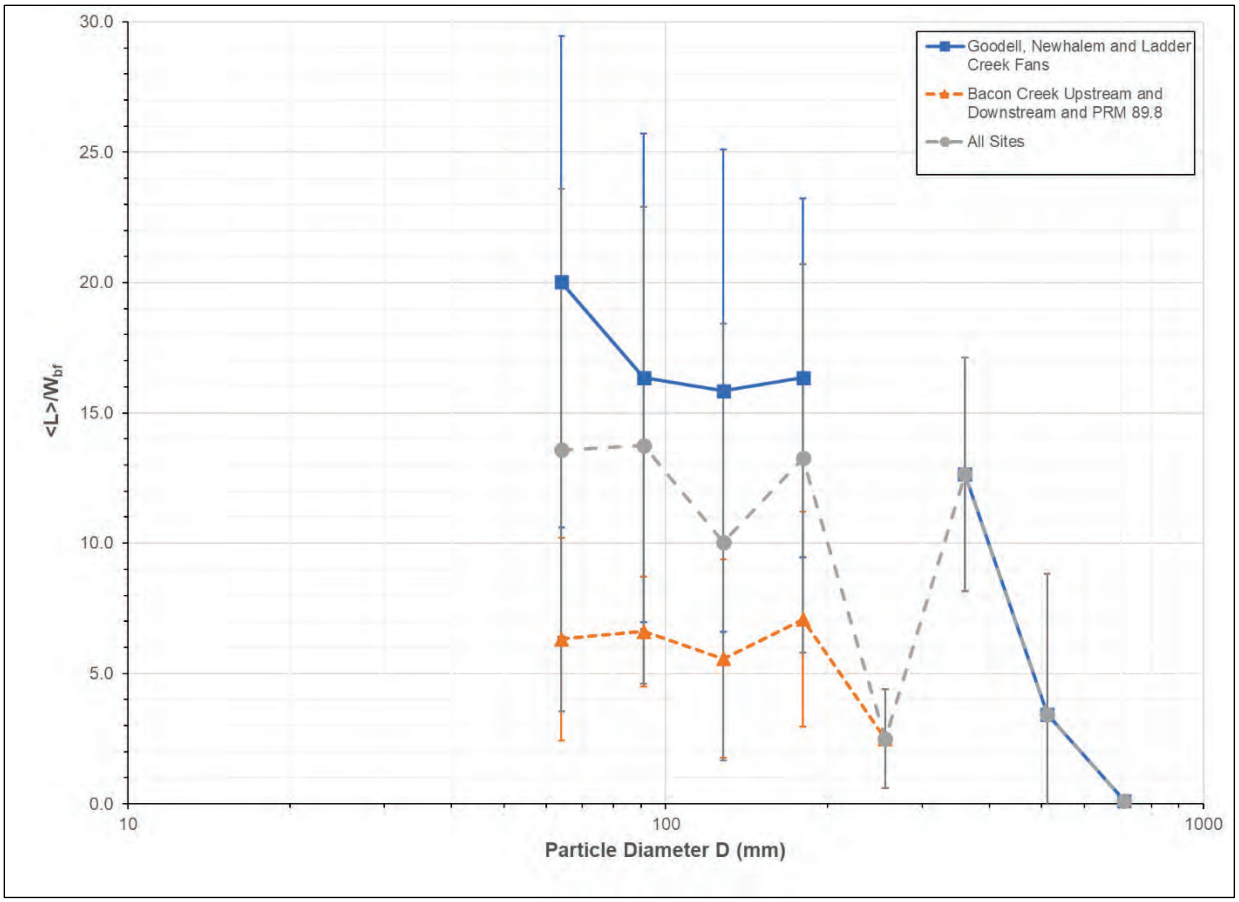


Figure 5.5-8. Mean displacements of the recovered particles normalized with the corresponding bankfull width, W_{bf} and grouped by deployment site. The error bars represent one standard deviation.

Only particles larger than 45 mm were included in the particle displacement analysis, but 2-45 mm gravel represents an important portion (40 to 50 percent) of morphologically significant bed material (Section 5.4.1). In order to estimate the mean displacement distance of the bed material for morphologic flux calculations, it must be understood how the observed displacement distances related to expected displacement distances for this smaller material. To do this, the displacement distance of the recovered particles is cast in the framework of Church and Hassan (1992), who measured relative particle displacement as a function of relative particle size in Figure 5.5-9. In this figure, the gray solid line represents the predictions of the relationship developed by Church and Hassan (1992). The majority of the observed Skagit River tracer particle displacements in Figure 5.5-9 are above the predictions of this relation, which is due to this relation using particle displacements generated by near-bankfull flow conditions. In contrast, particle displacements in the Skagit River dataset are anticipated to be mostly influenced by higher than bankfull flows that occurred during the November 2021 flood. This event is anticipated to have mobilized a larger portion of the bed material sizes, thereby reducing the influence of particle size on particle displacement and creating less size-selective transport conditions.

To predict displacement distances for the finer material, a regression curve utilizing the same functional relation with Church and Hassan (1992) was developed utilizing least squares

regression. The displacements of the smallest, 64 mm size particles at all sites and of the larger tracer particles from the Bacon Creek and PRM 89.8 sites were excluded from the regression analysis. The resulting equation is $L_n = 2.025(1\text{-}\log D_n)^{1.172}$.

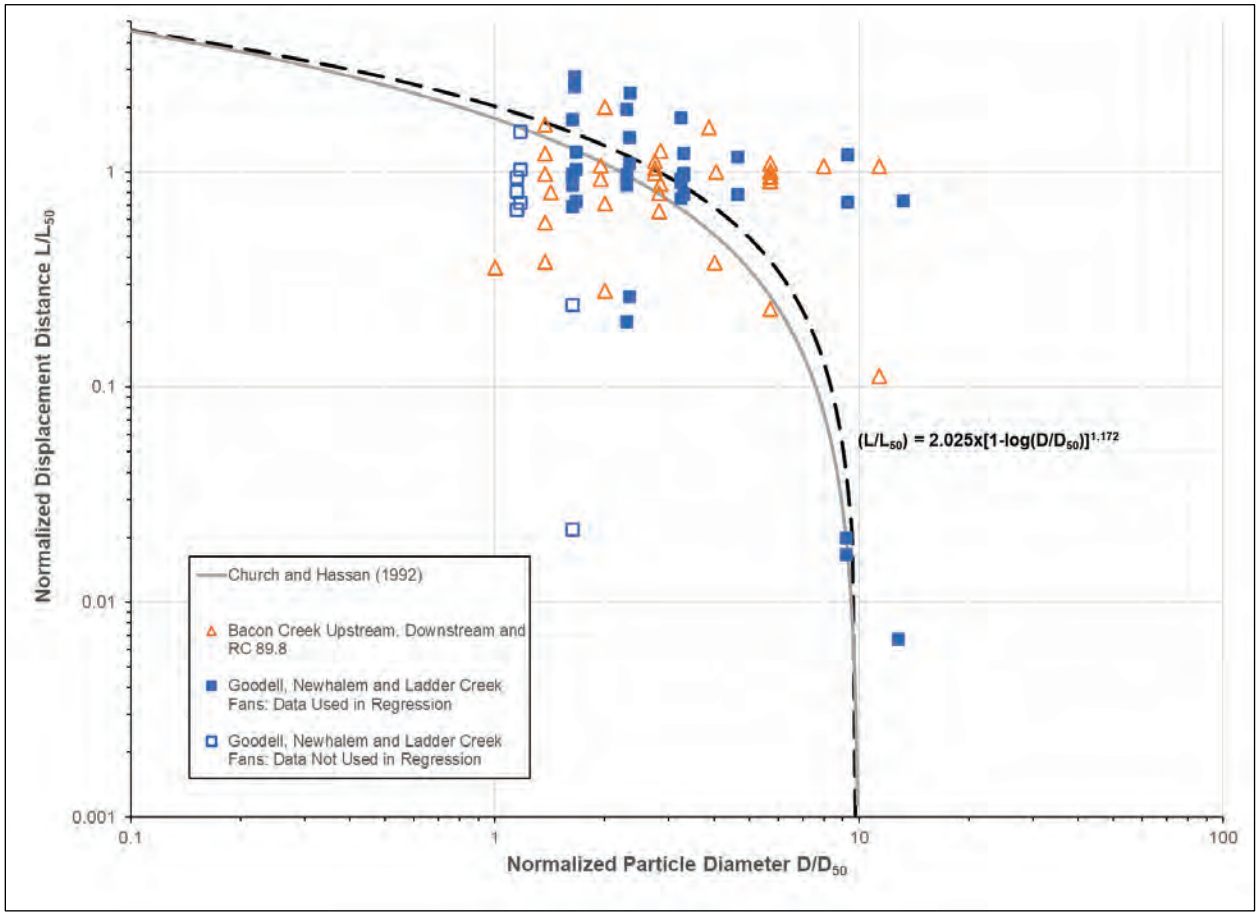


Figure 5.5-9. Displacements of the recovered particles according to the Church and Hassan (1992) framework and comparison with their predictive relation.

Assuming the curve developed in Figure 5.5-9 adequately describes the anticipated average displacement of particles between 2 and 91 mm, the mean displacement length for all particle size fractions on the Skagit River coarser than about 2 mm can be estimated. This was achieved by weighted averaging of the displacement length predictions utilizing the proportion of each particle size fraction in the bedload sediment mixture as the weights. The subsurface grain size distributions collected at PRM 91.3 and PRM 82.3 were assumed to be comparable to the bedload grain size distributions at those areas of the Skagit River and provided the averaging weight coefficients. The weighted average particle displacements for all particles coarser than 2 mm at these two locations were estimated to be approximately 7,530 ft (sites near Newhalem) and 5,960 ft (Bacon Creek and PRM 89.8 sites) during winter 2021-22.

Results of particle tracing on the Skagit River during winter 2021-22 provide strong support for Beechie's (2001) approach to estimating virtual velocity by bankfull width, in which Beechie found that particles move approximately 20 times the bankfull width. The observations reported above show that particles near Newhalem moved approximately 25 bankfull widths and that

particles from the Bacon Creek sites moved approximately 18 bankfull widths during the relatively large and protracted high flows that occurred during the monitoring season. Based on the close agreement between these observations and Beechie's (2001) regression-based prediction, Beechie's width-based regression was recomputed including these two additional data points to provide an approach to estimating virtual velocities at locations along the Skagit River. This new regression shows a very strong relation ($F(1, 13) = 134$, $p << .001$, $R^2 = 0.91$, $R^2_{adj} = 0.90$) between bankfull width (W_{bf}) and virtual velocity (v_b) and takes the form

$$v_b = 15 + 20.8W_{bf}$$

It is not statistically distinguishable from Beechie's relation. Upper- and lower-bound virtual velocity values were calculated as the upper-and lower-bound confidence intervals for the new regression. Figure 5.5-10 illustrates the relation of the revised and original regressions and calculated uncertainty bounds.

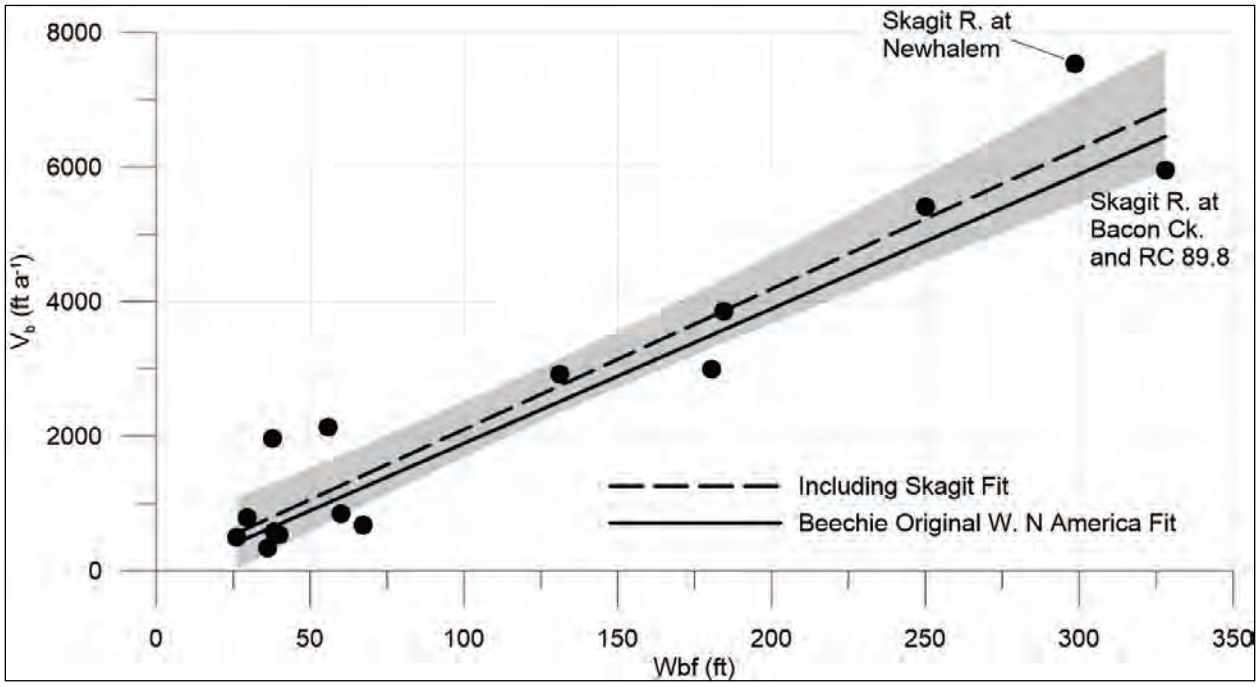


Figure 5.5-10. Relation between bankfull width and virtual velocity including Beechie's (2001) West Coast dataset and observations from the Skagit River. The shaded region indicates the confidence interval for the new regression including Skagit River observations.

5.5.3 Morphologic Bedload Flux Estimates

The morphologic bedload flux estimates average annual bedload transport rates in the Skagit River by integrating observations of change in average cross section shape (net scour and fill) that occurred over the period between topobathymetric LiDAR datasets; estimates of the event active layer thickness; and estimates of the typical distance particles move when they are mobilized (event displacement distance). Results of the analyses to produce each of those key inputs are reported elsewhere in this document (Sections 5.1.2, 5.5.1, and 5.5.2), and Section 4.5.3 describes the integration method. Results of the integration are summarized in Table 5.5-7.

Table 5.5-7. Morphologic sediment flux analysis summary.

Analysis Segment ID	Geomorphic Reach	Period	w_{bf} (yd)	a_m (yd^3/yd/period)	$d_{s\ (composite)}$ (ft/period)	a_s (yd^2/period)	v_b (yd a^{-1})	Q_{bo} (yd^3 a^{-1}) Lower Bound	Q_{bo} (yd^3 a^{-1}) Best Estimate	Q_{bo} (yd^3 a^{-1}) Upper Bound
2	2A	2018-22	75	6.8	2.4 ± 1.3	60 ± 46	1,565 ± 444	10,000	26,000	51,000
3	2B		80	10	2.4 ± 1.3	64 ± 50	1,669 ± 439	12,000	31,000	59,000
4	2B		100	12	1.4 ± 0.3	46 ± 27	2,085 ± 425	21,000	30,000	42,000
5	2B		100	9.2	1.4 ± 0.3	46 ± 27	2,085 ± 425	20,000	29,000	40,000
6	2B		100	17	1.4 ± 0.3	46 ± 27	2,085 ± 425	23,000	33,000	45,000
7	3A		100	3.1	0.8 ± 0.2	25 ± 17	2,085 ± 425	9,000	15,000	23,000
8	3A		100	10	0.8 ± 0.2	25 ± 17	2,085 ± 425	12,000	19,000	28,000
9	4		100	4.8	1.2 ± 0.3	41 ± 25	2,085 ± 425	15,000	24,000	35,000
10	4		100	5.6	1.2 ± 0.3	41 ± 25	2,085 ± 425	16,000	24,000	36,000
11	3B		125	20	0.9 ± 0.3	38 ± 26	2,605 ± 421	24,000	38,000	55,000
12	5a		110	12	1 ± 0.2	38 ± 23	2,293 ± 422	19,000	28,000	40,000
13	5a		110	5.5	1 ± 0.2	38 ± 23	2,293 ± 422	17,000	25,000	36,000
14	5B	2017-22	105	15	1.4 ± 0.3	48 ± 30	2,189 ± 423	19,000	28,000	39,000
15	5B		150	12	1.4 ± 0.3	68 ± 42	3,125 ± 432	35,000	50,000	69,000
16	6		150	46	1.5 ± 0.3	77 ± 46	3,125 ± 432	60,000	77,000	98,000
17	6		200	85	1.5 ± 0.3	103 ± 61	4,165 ± 497	126,000	157,000	194,000
18	6		200	30	1.5 ± 0.3	103 ± 61	4,165 ± 497	85,000	111,000	142,000
19	6		150	96	1.5 ± 0.3	77 ± 46	3,125 ± 432	87,000	108,000	134,000

Derivation of each term in the morphologic flux estimate is described in Section 4.5.3. W_{bf} is the bankfull channel width, a_m is the directly observable morphologic sediment flux calculated from the reach-average cross-sectional area of scour and fill, d_s is the event active layer thickness, a_s is the cross sectional area of the active layer (calculated as the multiple of W_{bf} and ds), v_b is the virtual velocity calculated as described in section 5.5.2, and Qbo is the bedload sediment flux calculated as $v_b(a_m + a_s)$.

5.5.4 Fine Sediment Yield Analysis

The three dams in the Skagit Project interrupt downstream delivery of most of the sediment yield for suspended and wash load and all of the bedload from the 1,172 mi^2 basin area above Gorge Dam. In addition to this, the Baker River hydroelectric project captures sediment yield from another substantial portion of the Skagit basin. Assessment of the effect of the Skagit Project then needs to consider both individual and cumulative contributions.

As described in Section 4.5.4 and Attachment R, the selected regression model predicts specific sediment yield from mean annual precipitation, relief represented using Steepness Index, and basin geology represented with three parameters: bedrock ratio, the area of unconsolidated sediment, and the area of glaciated stratovolcano. Applying the selected model to the upper Skagit River basin gives a best estimate of the specific yield of 473 ± 393 tons mi^2 a^{-1} (± values reported here are for the 90 percent prediction interval for average annual yield). This is lower than yields measured from portions of the basin below the dams (Figure 4.5-15), largely because of lower precipitation, lower relief, and a lack of glaciated stratovolcano influence.

The contributing basin area is 1,172 mi^2, hence the resulting total estimated suspended yield is 672,000 ± 559,000 tons a^{-1}.[(2)] Calculations for the contributing area to each reservoir indicate that 34 percent of this total yield is contributed to Ross Lake, 48 percent to Diablo Lake, and 18 percent to Gorge Lake. Combining these values with the trap efficiency estimates described in Section 4.5.4 (specifically the values for a mixture of sand, silt and clay) to each waterbody, then, gives an estimate of the total quantity of fine sediment actually intercepted by the reservoirs, which comes to 460,000 ± 386,000 tons a^{-1}. The best available estimate of the sediment yield intercepted in the Baker River system is 300,000 ± 100,000 tons a^{-1} (R2 Resource Consultants (2004) in Riedel et al., 2022). Adding these values together with the measured historical sediment yield at Mount Vernon (2.7 million tons a^{-1}) less the volume of suspended sediment estimated to bypass the reservoirs in the current condition (215,000 tons a^{-1}) suggests that, in the absence of suspended sediment discontinuity introduced by upstream dams, 3.5 ± 0.4 million tons a^{-1} of suspended sediment would be delivered to the estuary. In the absence of only the Baker Project, it was estimated that 3.3 ± 0.3 million tons a^{-1} of suspended sediment would be delivered to the estuary. Put another way, the best estimate is that the Skagit Project presently reduces suspended sediment supply to the estuary by 15 percent relative to a reference condition with no dams in the basin with a confidence interval of 3 percent to 27 percent (15 percent ± 12 percent). Relative to a reference condition with only the Baker Project Dams present, it was estimated the Skagit Project reduces suspended sediment supply by an estimated value of 17 percent ± 13 percent.

5.5.5 Calibration Period Bed Material Sediment Budget

The best estimate morphologic sediment budget for calibration period of 2018-2022 (upstream of Marblemount) and 2017-2022 (downstream of Marblemount) was calculated by combining the "best estimate average annual" Q_{bit} values from Table 4.5-4 with the measured change in storage values for the channel along the Skagit River from the comparison of 2017/18 and 2022 topobathymetric data (described in Sections 4.1.4 and 5.1.2) and propagating the calculation from upstream to downstream using the observed change in storage values. The resulting flux diagram

[2] Rounding to the appropriate number of significant digits results in a slightly different value than the simple arithmetic result of the operation.

(Figure 5.5-11) shows that the main inputs upstream of Marblemount were tributaries and that much (70 percent) of the incoming load was deposited within the channel. Between Marblemount and the Sauk River, the dominant source of sediment to the channel was bank erosion, which was not quite balanced by deposition of sediment within the channel, leading to an upstream-to-downstream increase in flux with minimal tributary inputs. Combining the Q_{bo} estimate for the Skagit River just above the confluence with the Sauk and Q_{bi} estimate for the Sauk suggests that about 40 percent of the gravel-cobble load downstream of the confluence is derived from the Sauk River.

Comparison of the best estimate sediment budget Q_{bo} values with those determined by the morphologic sediment flux estimate approach (Figure 5.5-12) shows that the two methods closely agree. They show very similar patterns in both absolute magnitude and along-channel trends in Q_{bo}. The one exception occurs between the Cascade River confluence and the Barnaby Reach, where the morphologic flux estimate is much lower than the mass-conserving sediment budget. This results from the combination of relatively low τ^*–resulting in low active layer thickness—and very limited morphologically detectable flux in this reach. One interpretation may be that the relatively fine bed material sediment feed from the Cascade River acts as overpassing bedload in this reach, with transport dominated by a partial mobility condition and/or virtual velocities much longer than those for the large cobble sediment delivered from the mainstem Skagit upstream of the Cascade River confluence. The other interpretation would be that the assumed contribution of sediment from the Cascade River in the morphologic sediment budget is too high.

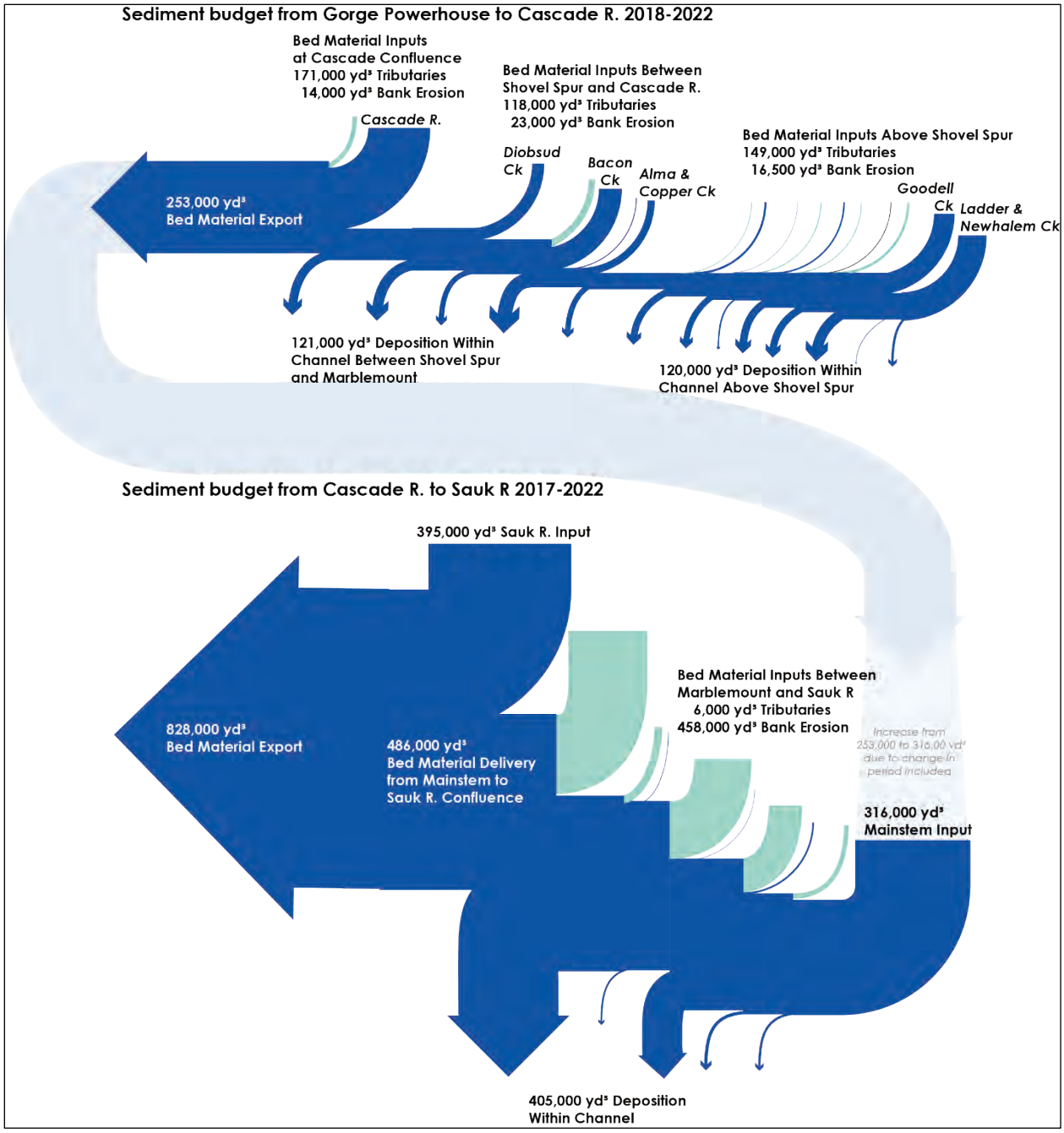


Figure 5.5-11. **Flux diagram for best estimate morphologic cobble-gravel sediment budget for the Skagit River. Lighter-shaded green arrows indicate bank erosion inputs (ΔS_b) and blue arrows indicate tributary (Q_{bi_t}) and mainstem (Q_{bi_c}) inputs.**

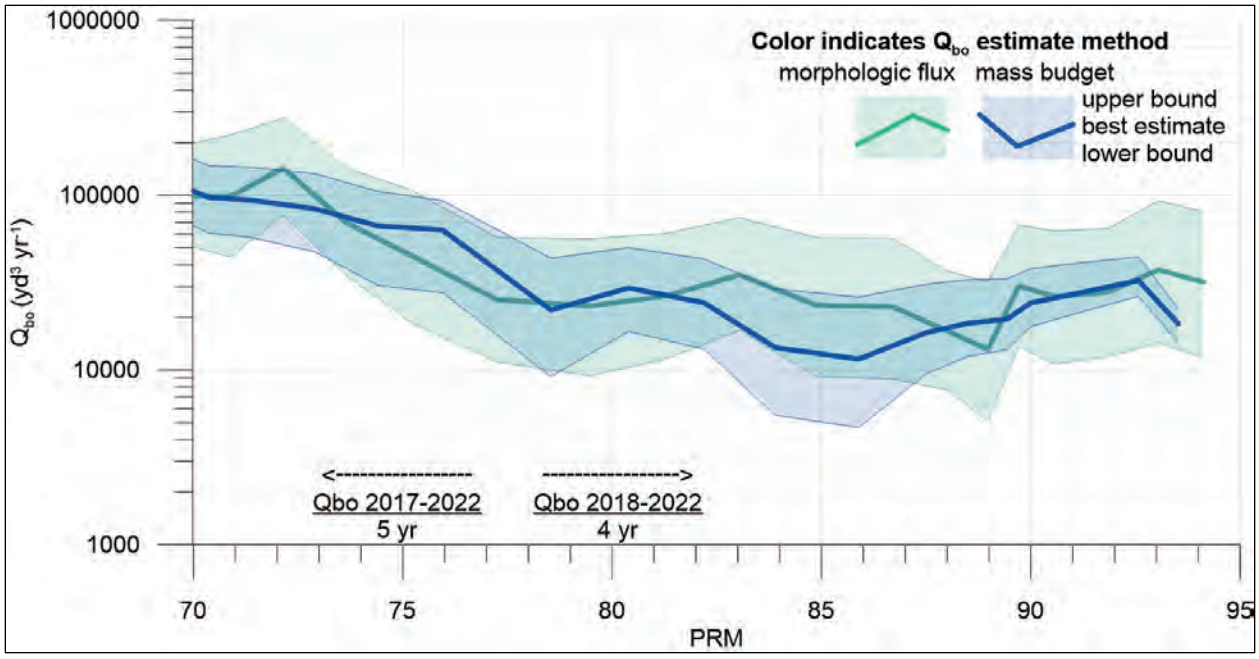


Figure 5.5-12. Comparison of Q_{bo} from traditional mass conservation sediment budget approach (best estimate value) and morphologic flux estimate approach.

The relative concentrations of tracer lithologies between different links in the system and the channel downstream (Section 5.4.4) can also be used to check the sediment budget estimates. If the relative magnitudes of any two Q_{bi} values are correct, then mixing of tracer lithologies observed in the input sediment links in the ratio of those Q_{bi} values should produce the observed concentrations of those lithologies in the channel downstream.

Greenschist is dominantly contributed to the Skagit River by Bacon and Diobsud creeks. The concentration of this material in tributaries and the Skagit River channel can be used to estimate sediment supply ratios between different Q_{bi} links. Mixing calculations give an exact match (24 percent greenschist) in the predicted concentration produced by combining the best estimate sediment budget fluxes and observed greenschist concentrations for the Skagit River above Bacon Creek, Bacon Creek, and Diobsud Creek, compared against the average value in the Skagit River channel between the Diobsud Creek confluence and Cascade River.

Greenschist can also be used as a tracer to compare relative contributions of the Skagit River above the Cascade River confluence and the Cascade River, although some greenschist-like material (field coded as greenschist but probably actually ultramafic) transported by the Cascade River, which could introduce more field identification errors of greenschist in the Skagit River downstream of this source. In this case, the best estimate fluxes suggest an expected greenschist concentration of 9 percent compared to an observed average concentration of 11 percent between PRM 74 and the Cascade confluence. Because of the relatively low concentration, the 2 percent difference has high leverage relative to the relative fluxes. To reproduce the observed value, contributions of 45 percent of the Q_b from the Skagit and 55 percent from the Cascade would be needed, compared to best estimate values of 35 percent and 65 percent. It is not known whether the discrepancy results from an underestimate of the Skagit load or an overestimate of the Cascade load (or some combination thereof). In the most extreme case (assuming it is entirely overestimate

of the Cascade load), correction to produce the observed ratio would require a 33 percent reduction in the best estimate of the Cascade River load, which is well within the identified uncertainty bounds.

The concentration of lithologies that clearly came from the Eastern Group indicate recruitment of sediment into the channel from long-term storage reservoirs (likely mostly bank erosion). One bank toe pebble count was completed at PRM 88.2 to characterize the concentration of these particles in the long-term storage reservoir between Newhalem and Shovel Spur. This showed about 20 percent lithologies belonging to the Eastern Group. This concentration can be compared to observed concentrations in the channel of typically between 5 to 10 percent between that sample and PRM 74, suggesting that bank erosion inputs may contribute 25 percent or more of the material moving down the channel. The concentration of Eastern Group tracer lithologies increases abruptly at PRM 73, which corresponds to a zone of known major bank erosion input. The concentration of Eastern Group lithology in bank material was not measured in this area. A priori, it is expected it would to be less than observed upstream (because there are other important sediment sources from tributaries mixing with the upstream load). The concentration in the channel, however, increases to the same as observed in the upstream bank pebble count sample, suggesting that nearly 100 percent of the load moving downstream towards the confluence with the Sauk River has come from eroding banks, with material transported from upstream moving into and mixing with the long-term storage reservoir. This conclusion is consistent with the calculated large magnitude of the cross-channel sediment flux (the ΔS_c and ΔS_b terms) compared to the down-channel sediment flux (Q_{bo}) in this area.

A third tracer is the concentration of vesicular volcanic rocks (Vs) that are only associated with the Sauk River (which dominantly come from the Suiattle River, as documented by Pfeiffer et al., 2022), which are observed in the Sauk River and in the Skagit River downstream of the confluence. Based on the best estimate fluxes and the observed concentration of this material in the Sauk River (26 percent), the expected concentration in the Skagit downstream of the confluence would be 11 percent. The actual observed concentration between the Sauk River and Jackman Creek was 12 percent. In the same area, the expected concentration of other volcanic rocks (V) is predicted to be 3.5 percent, and the actual value from pebble counts is 3 percent. These results provide very strong support for the best estimate sediment budget relative ratios of Skagit River and Sauk River bed material contributions.

5.5.6 Sediment Transport Modeling

5.5.6.1 Channel Width and Planform Sensitivity to Variability in Channel Forming Discharge and Sediment Supply

The UBCRM and MAST 1-D models were used to investigate channel width sensitivity to change in channel forming discharge. UBCRM was also used to investigate sensitivity in preferred number of channels: the probability of a given channel forming discharge resulting in a single-thread planform, or resulting in an anastomosing planform with a stable multi-channel pattern. Results show a trend of channel widening in response to higher channel forming discharge, with greater sensitivity in response reaches and reaches upstream of the Sauk River. Further, UBCRM results show channel pattern sensitivity to channel forming discharge in response reaches, where higher channel forming discharge leads to a greater preference for multiple channels, but not in transport reaches.

Both UBCRM and MAST 1-D relied on historical regulated and naturalized daily discharge data (NHC 2023). MAST 1-D used daily discharge time series from 1988-2022 for historical regulated hydrology and 1988-2020 for naturalized hydrology. (For consistency, results presented here are from 1988-2020 for both conditions and end before the November 2021 flood.) UBCRM used daily discharge flood quantiles calculated from the historical regulated and naturalized time series for the period of water years 1988-2020. See NHC (2023) for details on the development of the hydrology time series and discharge flood quantiles.

The UBCRM calibration described in Section 4.5.1.1 was used as a starting point from which to explore the changes in width and planform expected if the river were to equilibrate to various channel-forming flows. Two main scenarios were investigated. A scenario in which the channel equilibrates to the historical regulated 2-year discharge represented a possible path of response to regulated hydrology, a baseline trajectory lacking larger process flows. This scenario implies that the current channel geometry is a legacy of larger, pre-regulation channel forming discharges similar to the calibration discharges described in Section 4.5.1.1, and that the river is currently on a gradual trajectory of narrowing. A second scenario, in which the channel equilibrates to the naturalized 10-year discharge, represents a trajectory in which the channel is shaped by larger process flows. These two scenarios are meant to illustrate the directions of change under these two possible hydrologic trends, as well as the relative sensitivity of the different reaches. The assumption of full channel equilibration to the naturalized 10-year discharge depends on the duration of such an event. A long enough duration to allow full channel equilibration is not likely, and so these results indicate an upper bound of plausible channel adjustment rather than an expected outcome.

UBCRM results showing channel width trends under these two change trajectories are shown in Figure 5.5-13. Equilibration to a lower channel forming discharge is expected to cause channel narrowing of 20 to 40 percent, with the greatest narrowing in the reaches upstream of the Sauk River. Equilibration to a higher formative discharge is expected to cause channel widening of 30 to 60 percent in most reaches, with a stronger effect in the reaches upstream of the Sauk River. Greater widening (60-90 percent) is expected in response reaches where the channel pattern shifts from a single channel to a multi-thread anastomosing pattern.

UBCRM results showing trends in channel pattern under these two change trajectories are shown in Figure 5.5-14. The percentages of various numbers of channels shown here are derived from an uncertainty analysis in which channel forming discharge, D_{50}, D_{84}, critical dimensionless shear stress of the bank toe, and bank strength were each varied by 10 to 20 percent. These are calculated based on Monte Carlo sampling of variability in the principal controlling parameters, and so percentages of particular numbers of channels can be thought of either as a probability at any given location or as an expected spatial percent within a reach.

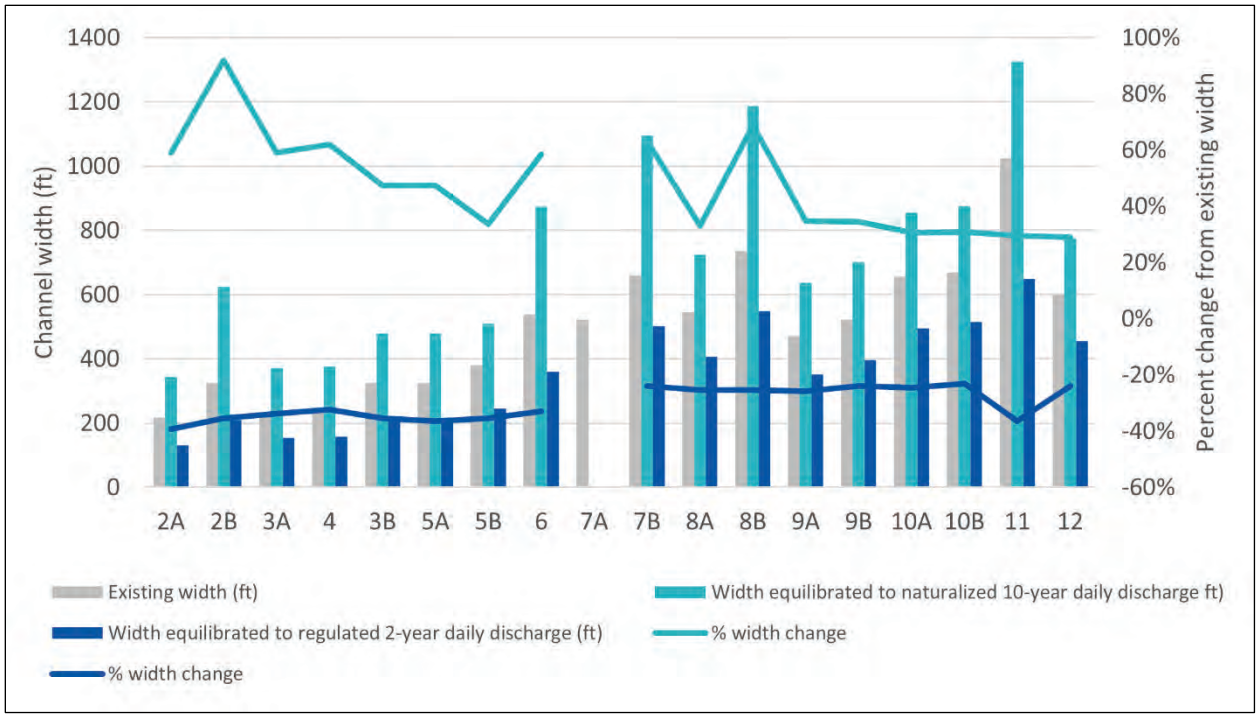


Figure 5.5-13. Results from UBCRM modeling showing width sensitivity to potential changes in formative discharge. Dark blue shows narrowing potential with equilibration to historical regulated 2-year daily discharge. Teal shows widening potential with equilibration to naturalized 10-year daily discharge.

Channel pattern results differ between transport reaches (in which sediment tends to be transported through rather than being exchanged between channel and floodplain, resulting in lower channel migration rates) and response reaches (in which sediment deposition is more common and channel migration rates are higher). UBCRM channel pattern results indicate that equilibration to a lower channel forming discharge will lead to channel simplification in response reaches, including the County Line, Barnaby, Van Horn, and Ross Island reaches (2B, 6, 8B, and 11). In contrast, equilibration to larger process flows is expected to lead to increased complexity and an increased preference for an anastomosing channel pattern in response reaches. Transport reaches including 2A, 3A through 5B, 9A and 9B remain single-thread in all simulations. Reaches 10A and 10B, upstream of the Ross Island reach, are single-thread in the calibration, but develop a 15 to 20 percent chance of having multiple channels with equilibration to the naturalized 10-year discharge. The pattern of sensitivity to channel forming discharge also indicates areas where other measures, such as addition of stable wood features, may be effective to promote formation of a multi-thread channel morphology. Areas close to the threshold for bifurcation (or trifurcation) may be preferential areas to focus addition of apex- and island head jam type features to the river to promote formation or maintenance of multiple channels.

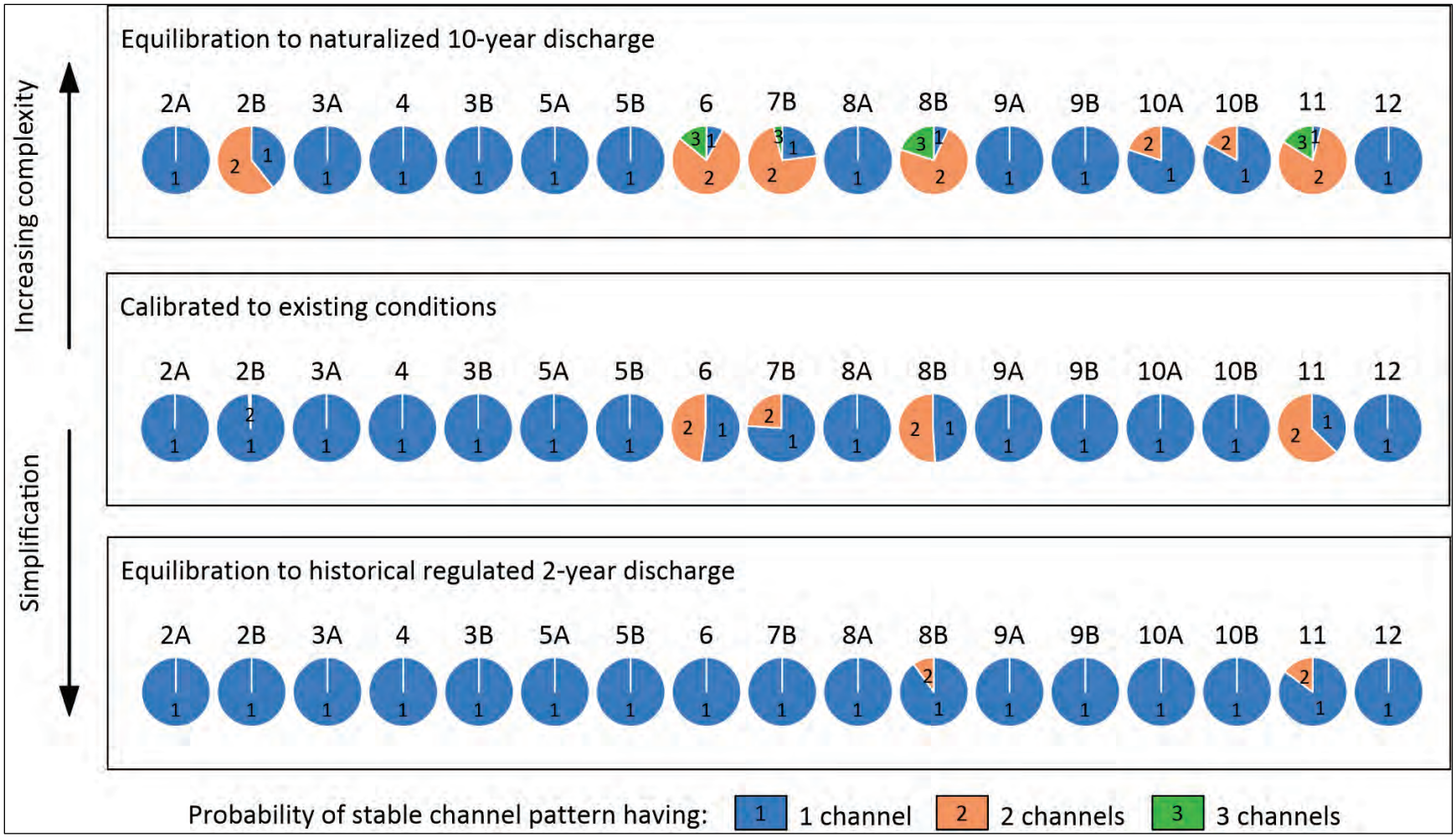


Figure 5.5-14. **Results from UBCRM modeling showing channel planform sensitivity to potential changes in formative discharge. Middle row shows probabilities of particular numbers of channels based on an uncertainty analysis of the calibrated model. Top row shows potential for increased channel complexity with equilibration to naturalized 10-year discharge. Bottom row shows channel simplification potential with equilibration to historical regulated 2-year discharge.**

UBCRM does not model sediment supply explicitly, but it can be represented by changing the D_{50} of the bed surface and making the assumption that an increased sediment supply would lead to less bed armoring and therefore, a finer surface layer. Results from sensitivity analyses, in which D_{50} is varied by 20 percent, generally show minimal width sensitivity to sediment supply. Figure 5.5-15 shows width sensitivity to D_{50} in several response reaches. However, these results likely represent a minimum sensitivity, because any possible feedbacks between sediment deposition and bank erosion are not addressed by the model.

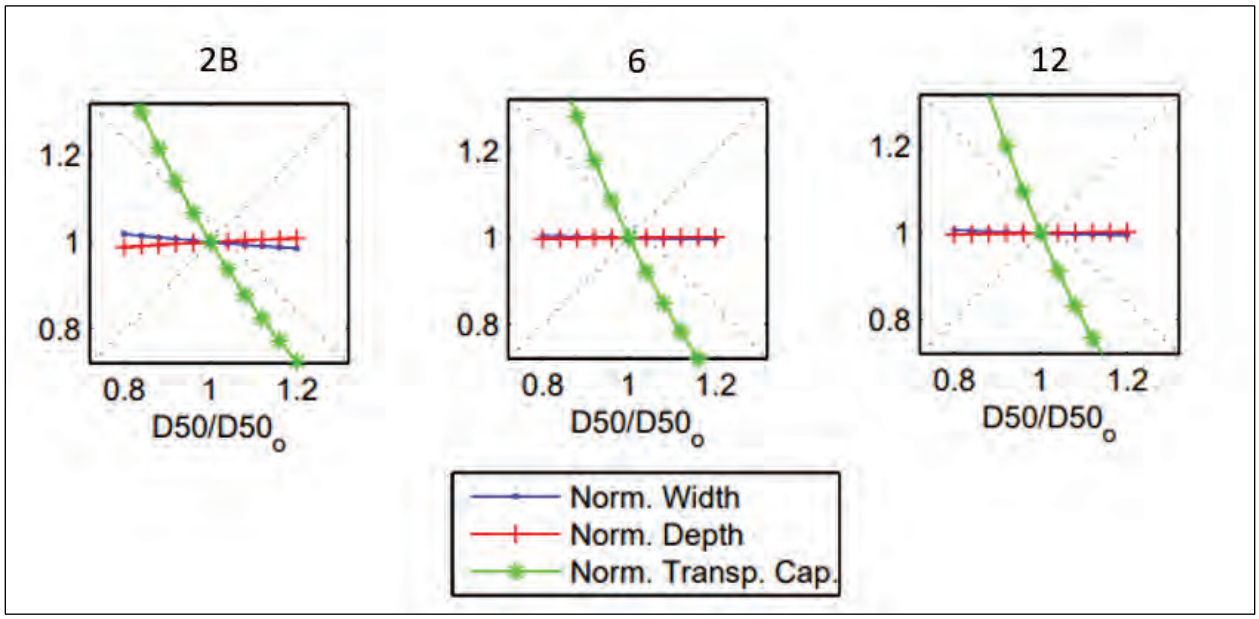


Figure 5.5-15. Results from UBCRM sensitivity analysis showing width, depth, and bedload transport capacity sensitivity to D_{50} in several response reaches.

In contrast to the UBCRM framework, which assumes full channel equilibration to a user-specified channel forming discharge, MAST 1-D calculates both rates of channel widening through bank erosion and channel narrowing through vegetation colonization of bar surfaces as functions of the discharge time series. MAST 1-D was used to evaluate changes in width in response to a time series of 1988-2020 historical regulated daily discharge vs. naturalized daily discharge. In the MAST 1-D simulations, channel width adjusts rapidly at the beginning of the simulation as the model spins up and then, over a period of approximately 10 to 15 years, converges towards a dynamic steady state in which narrowing between flood events balances widening during floods. Dynamic steady-state widths can then be used to assess width differences between regulated and naturalized hydrology, as can the widening rate or cumulative widening during the post-spin-up part of the model run. Of these two related parameters, the dynamic steady-state width is affected by the assumed rate of channel narrowing though bar revegetation, while the widening rate is not.

Figure 5.5-16 illustrates cumulative widening and narrowing over the 1988-2020 model runs and Figure 5.5-17 shows the resulting along-channel trends in width. Dynamic steady-state width differences between regulated and naturalized hydrology are generally limited to a few percent of channel width, and are greatest in the Barnaby Reach (6), immediately upstream of the Sauk River (7A), and in the reach upstream of Marblemount (5A). The naturalized hydrology MAST 1-D runs also result in increased overall widening rates relative to the existing hydrology runs. The

differences in widening are most pronounced between the Cascade and Sauk rivers. Like UBCRM, MAST 1-D shows that width and widening rate sensitivity to flow regulation is overall most pronounced upstream from the confluence with the Sauk River, where the relative hydrologic impact of flow management is greatest. MAST 1-D shows very little influence of flow regulation on width between Baker River and the Ross Island reach (11, downstream of approximately PRM 35).

Steady-state widths in MAST 1-D tend to be narrower than existing channel widths, due to the competition of widening and narrowing processes over time, and the existing conditions UBCRM calibration required use of relatively infrequent flows compared to typical recurrence intervals for channel forming "bankfull" flows in the Pacific Northwest (Castro and Jackson 2001). One hypothesis that may explain this pattern is that flow regulation may have affected channel narrowing in a way not captured by either model. Channel narrowing happens mainly through vegetation colonizing bars during the summer, when discharge is low, bars are exposed, and vegetation is growing. As flow regulation has increased summer low flows, bars that might otherwise have become vegetated may remain submerged (or they may be exposed for less time each year), suppressing germination and vegetation establishment rates. Because MAST 1-D does not model specific bar geometry and holds the narrowing parameter constant between regulated and naturalized runs, any possible differences in narrowing between these conditions would not be captured.

MAST 1-D and UBCRM both show some degree of channel width sensitivity to bank strength (described in detail in Attachment O and Attachment Q). These results show the potential for reducing bank strength in targeted reaches as a management tool. Particularly in reaches farther downstream, where introducing large, low-recurrence-interval process flows may be less feasible, reducing bank strength by removing bank armoring could be a way to allow channel widening and even encourage formation or maintenance of an anastomosing channel pattern. The calibrated MAST 1-D model can be used to investigate the effects of this approach on channel width and bank sediment inputs to the channel.

UBCRM and MAST 1-D results show similar directions but different magnitudes of channel width change in response to a change in channel forming discharge, due to differences between the conceptual frameworks of the two models. UBCRM outputs channel geometry assuming full equilibration to particular channel forming flows, which in this study were selected from 24-hour average flows. UBCRM does not address the time needed to make these channel adjustments, however. A 24-hour-duration flow may not be long enough to actually cause the amount of widening needed to change from the existing channel width to new equilibrium channel width, particularly for scenarios indicating high percentages of widening. Therefore, absolute values of width and planform change from UBCRM results are likely the high end of probable change. As such, UBCRM results represent change directions and relative magnitudes between hydrologic scenarios and geomorphic reaches of the river. MAST 1-D tends to show more moderate magnitudes of change than UBCRM. In addition to widening in response to large flows, MAST 1-D incorporates channel narrowing through bar revegetation between the large flows in a time series, although it does not currently incorporate possible narrowing process differences between regulated and naturalized hydrology. MAST 1-D also incorporates possible feedbacks between bank erosion, sediment load, and channel profile change, which UBCRM does not address.

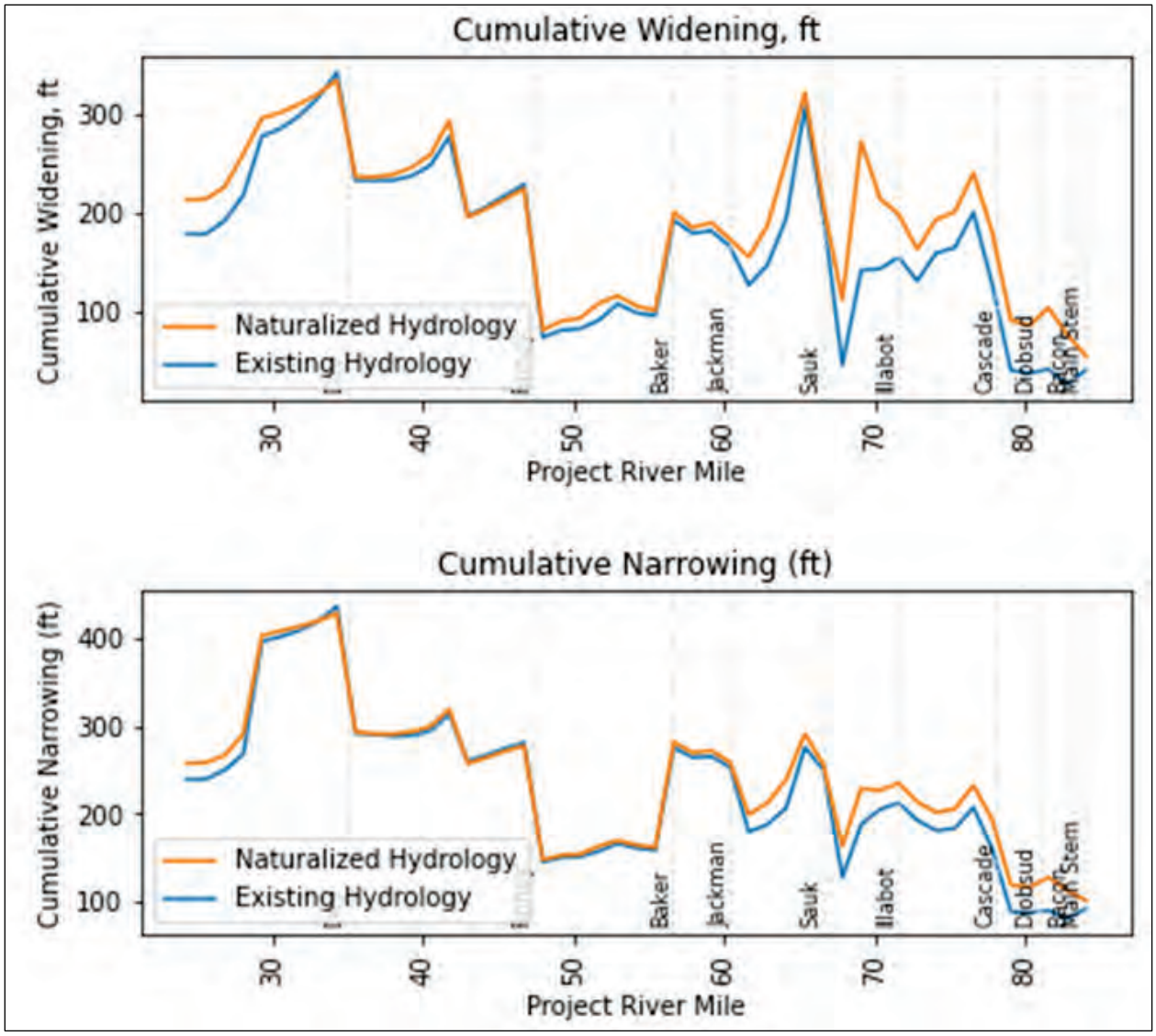


Figure 5.5-16. **Results from MAST 1-D showing cumulative widening and narrowing over the course of the simulations (1988-2020).**

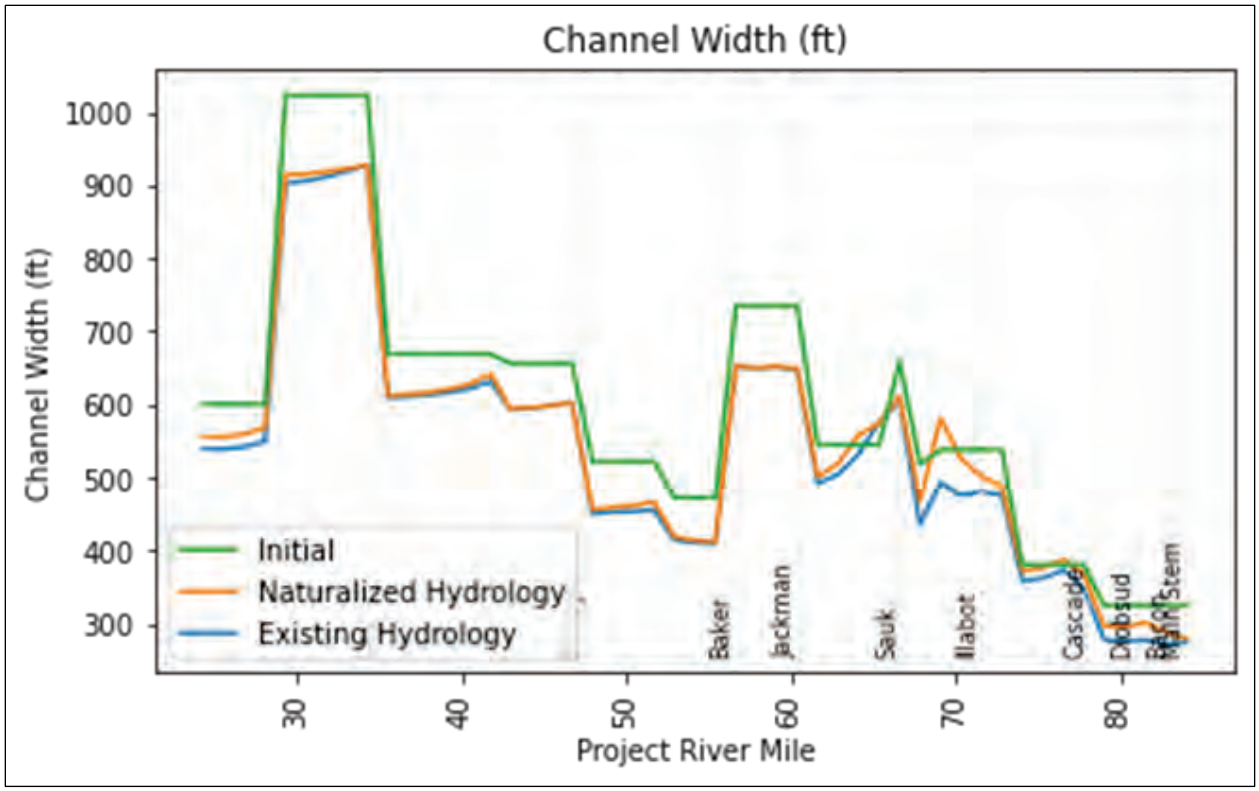


Figure 5.5-17. Results from MAST 1-D modeling showing along-channel trends in width at the beginning and end of the simulations.

5.5.6.2 Channel Profile Sensitivity to Variability in Bed Material Input and Discharge

The 1-D HEC-RAS model is available to evaluate expected changes in the channel profile (areas of localized aggradation and/or degradation) in response to different inputs of water and/or sediment. Full evaluation of these responses will require definition and implementation of a series of scenarios varying water and sediment inputs. Nonetheless, some sensitivity testing and calibration results for the existing conditions model development work provide information useful for understanding expected channel profile sensitivity to variability in bed material input.

Average annual bed changes computed by the 1-D HEC-RAS mobile bed model using historical daily flows from Water Years (WYs) 1978-2022 are shown in Figure 5.5-18. The model indicates overall aggradational trends between approximately PRMs 66-74 and between PRMs 87-91, with relatively insignificant bed changes in the other reaches. Further, calibration runs for the 1-D HEC-RAS model successfully reproduced spatial patterns and magnitudes of aggradation observed in the comparison of LiDAR data from 2017/18 and 2022 (Section 5.1.2), as described in Attachment P. The aggradational reaches predicted by the model generally coincide with the sediment storage areas observed on the Skagit River (as indicated by the presence of in-channel bars and islands), while the relatively stable model reaches coincide with the sediment throughput areas observed on the Skagit River (as indicated by the lack of significant in-channel sediment deposits).

A sensitivity test run was conducted for WYs 1978-2022 with the tributary sediment inflows excluded from the 1-D HEC-RAS model. The computed bed changes with no tributary sediment inflows are included in Figure 5.5-18. The sensitivity test results show an overall degradational

trend along the modeled reach, especially between PRMs 65- 82. The results computed with the 1-D HEC-RAS mobile bed model suggest that sediment inflows from the tributaries play a morphologically significant role in shaping the Skagit River channel and that there is approximate balance between the incoming sediment loads and available energy (provided by flood discharge) to transport that sediment downstream.

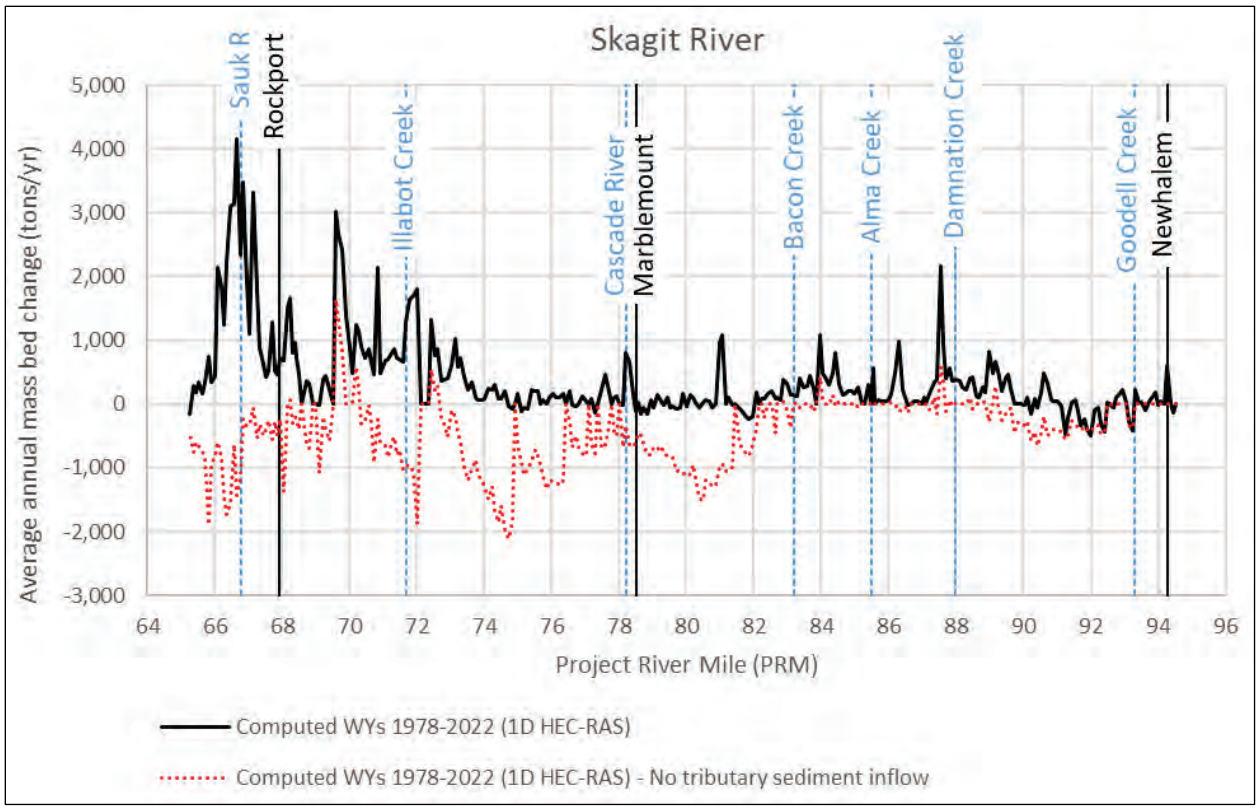


Figure 5.5-18. Computed average annual bed change (1-D HEC-RAS long-term simulations).

Existing conditions model development has not evaluated alternative discharge scenarios. However, the observed sensitivity of the channel to changes in modeled sediment supply suggests that the profile may also be sensitive to changes in sediment-transporting energy resulting from different flood flows. Future model applications may consider individual and coincident variability in the incoming sediment load and flood discharge regime in the river to complete an analysis of channel sensitivity to variability in bed material input and discharge.

5.5.6.3 Channel Grainsize Distribution Sensitivity to Variability in Sediment Supply and Flow Regime

Channel profile changes are closely related to variability in the surface grain size distribution, and so long-term changes in bed surface median sizes computed by the 1-D HEC-RAS mobile bed model using historical daily flows from WYs 1978-2022 are shown in Figure 5.5-19. The simulations started with the bed material data collected by NHC in 2021 (Section 5.4.1). The model indicates overall fining of the surface material by the end of the simulation period, most of which is associated with sediment deposition reaches.

A sensitivity test run was conducted for WYs 1978-2022 with the tributary sediment inflows excluded from the 1-D HEC-RAS model. The computed changes in bed surface median sizes with no tributary sediment inflows are included in Figure 5.5-19. The sensitivity test results show moderate coarsening of the bed surface at the end of the simulations (particularly downstream of PRM 82), which is related to armoring associated with the computed channel degradation without tributary sediment inflows.

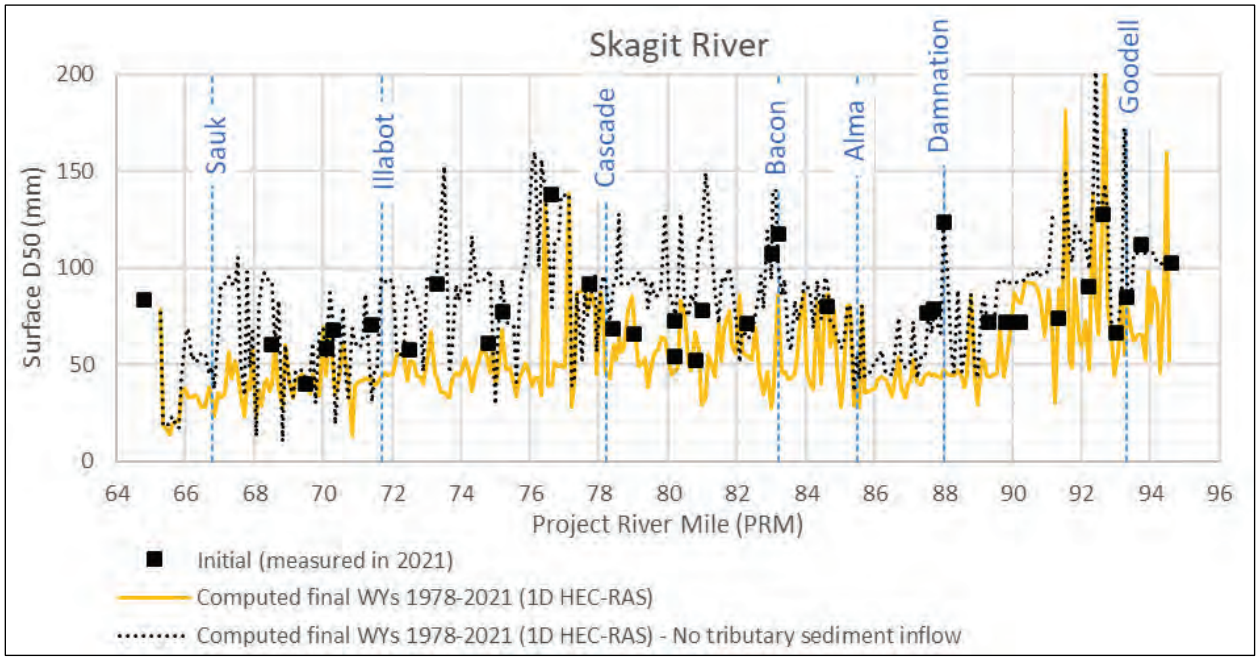


Figure 5.5-19. Computed initial and final surface bed material median sizes (1-D HEC-RAS long-term simulations).

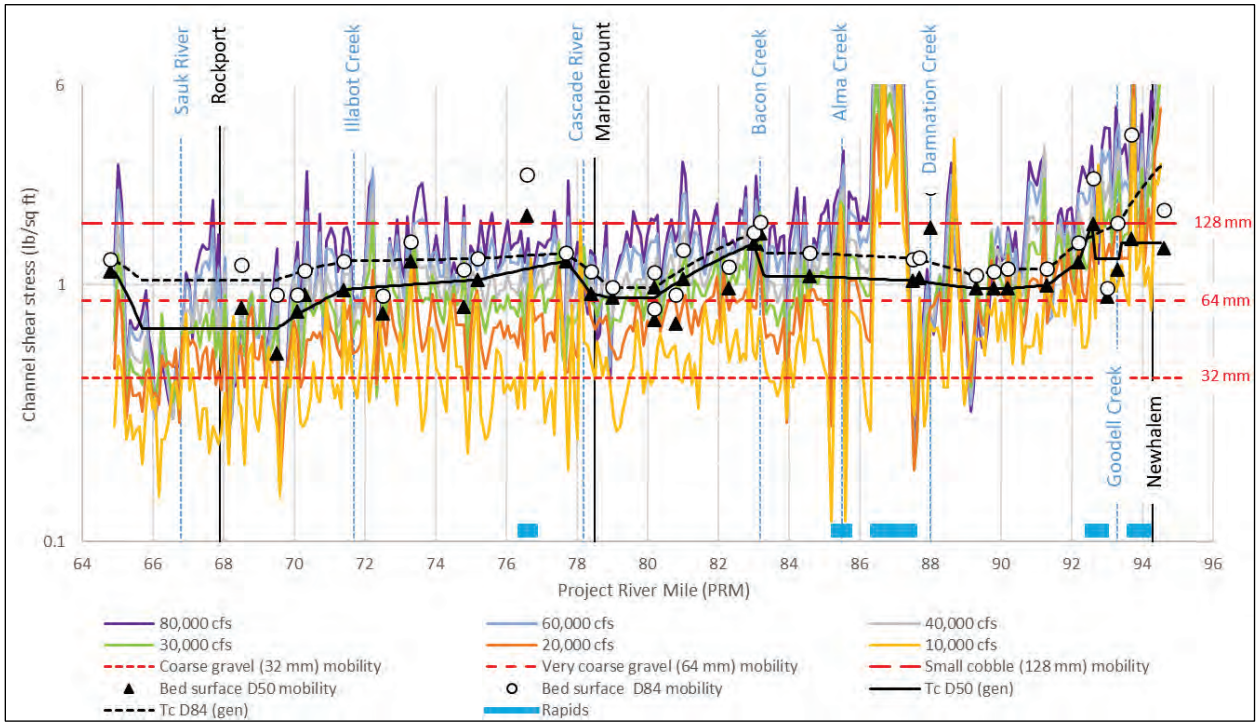
As with the evaluation of profile sensitivity, the existing conditions model development has not evaluated alternative discharge scenarios and their impact on bed material grain sizes. However, the observed sensitivity of the surface grain size distribution to changes in modeled sediment supply suggests that grain size may also be sensitive to changes in sediment-transporting energy resulting from different flood flows. Future model applications during implementation planning or via adaptive management should consider individual and coincident variability in the incoming sediment load and flood discharge regime in the river to complete this analysis of grain size sensitivity to variability in bed material input and discharge.

5.5.6.4 Thresholds of Sediment Mobilization

Reach Average

The threshold for initiation of sediment mobilization is important as it controls sorting of the bed material, interactions of scour with large wood features, and the frequency and severity of bed disturbance. Figure 5.5-20 shows channel shear stress profiles computed by the 1-D HEC-RAS model for a range of steady-state flows and critical shear stresses for mobilization of the surface bed material at the sampling locations. Also shown on the figure are generalized shear stress profiles which eliminate abnormally coarse samples and approximate reach-average bed surface composition. The critical shear stresses were calculated assuming the critical dimensionless shear

stress τ_c^*=0.04 for the D_{50} grain size and selected reference sizes (32 mm, 64 mm, and 128 mm), and τ_c^*=0.03 for the D_{84} grain size (to account for relative overexposure of coarse particles in mixed-size sediment). The results suggest that initial mobilization of the bed in most areas can be expected at flows between about 20,000 cfs and 30,000 cfs. This estimate of the bed mobilization threshold flow closely agrees with the values of approximately 20,000 cfs based on the recent USGS bedload measurement (Scott Anderson, pers. comm 2022) at Marblemount in 2022 and 22,000 cfs based on the observed movement of a gravel bar at PRM 70 (from historical aerial imagery spanning the period between 2009 and 2019).



Very high shear stresses in rapids (e.g. shovel spur between RM 86 and 88) show how alluvial bed material transported into these reaches is readily flushed through. The actual bed in these reaches includes much larger non-alluvial material that resists mobilization by the very high shear stresses that are present.

Figure 5.5-20. Comparison of computed channel shear stress with critical shear stress for bed mobility (1-D HEC-RAS steady-state simulations).

To provide more specific results at the reach scale, the average ratio between the observed shear stress and shear stress required to mobilize the D_{50} (median grainsize) and the D_{84} (84th percentile grainsize, mobilization of which is required to appreciably modify the topography of the bed, called the mobility ratio, was computed from the data shown in Figure 5.5-20. Results are shown in Figure 5.5-21 and Table 5.5-8. A mobility ratio value of 1 typically indicates initiation of motion, and values below this, indicate very low particle mobility. Mobility ratio values greater than about 2 indicate full particle mobility (Lisle et al. 2000). These results show discharges of about 1.5 times the current 2-year daily recurrence interval flow (calculated for water year 1988-2020, NHC 2023) for each reach are required to mobilize the D_{50}, with a range of one (reaches 2A and 2B) to three (reaches 3A and 3B). Substantially higher normalized discharges are required to mobilize the D_{84}, with a typical value of about two times the historical regulated 2-year daily recurrence interval flow and a range of 1.5 to 3 times that flow. Because grain size and shear stress

are spatially heterogeneous in ways that highly impact sediment mobility (Ferguson 2003), some areas of the channel will mobilize at discharges substantially lower than those indicated in this analysis and other areas may require much higher discharges to mobilize.

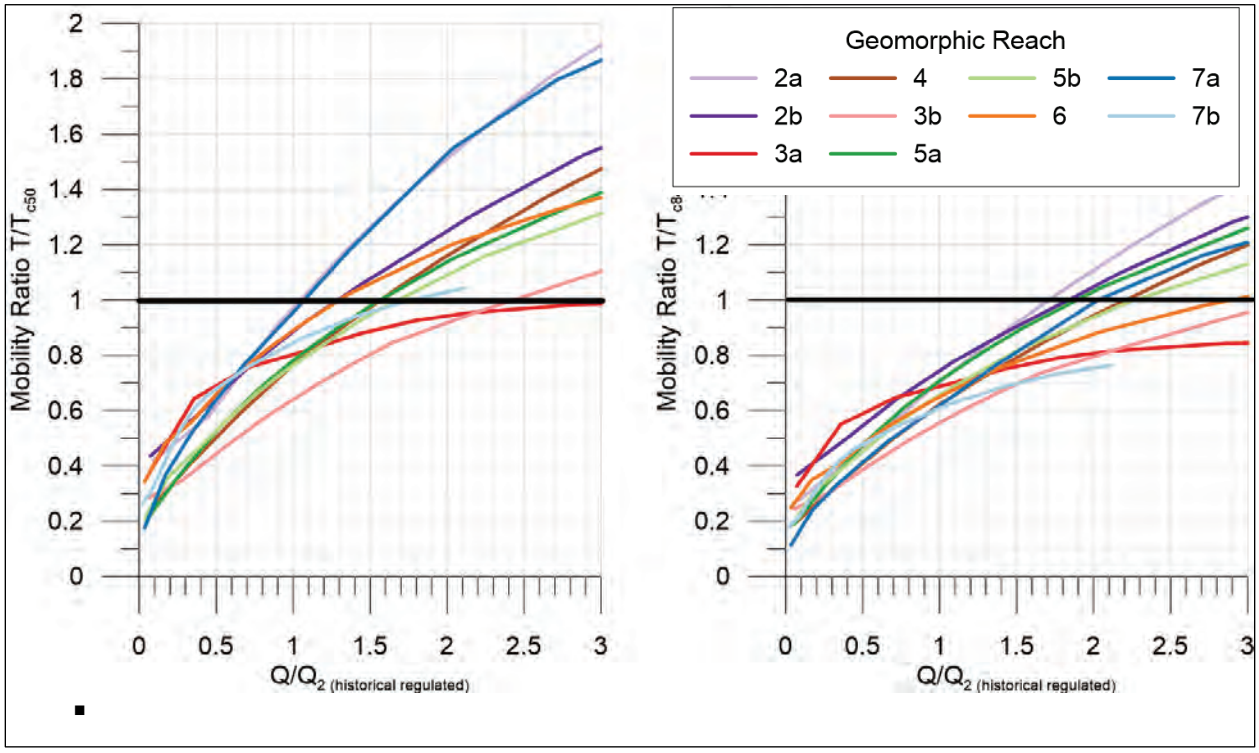


Figure 5.5-21. **Mobility ratios relative to normalized discharge for D_{50} (left) and D_{84} (right) in each geomorphic reach. Discharge values are shown as a ratio to the historical regulated daily 2-year recurrence interval discharge (water year 1988-20) for each reach.**

Table 5.5-8. **Summary of discharges for modeled reach average incipient mobility ($\tau/\tau c=1$) of D_{50} and D_{84}.**

Reach	D_{50}		D_{84}	
	Discharge (cfs)	Q/Q_2 (daily '88-'20)	Discharge (cfs)	Q/Q_2 (daily '88-'20)
2A	12,000	1.0	19,000	1.7
2B	18,000	1.3	25,000	1.8
3A	56,000	4.0	145,000	10
4	24,000	1.6	33,000	2.2
3B	44,000	2.4	60,000	3.3
5A	31,000	1.6	37,000	1.97
5B	45,000	1.7	61,000	2.3
6	38,000	1.3	85,000	2.9
7A	32,000	1.1	60,000	2.0
7B	100,000	1.8	271,000	4.8

Localized Features

As of the time of submittal of this document, 2-D mobile bed simulations are not yet available to evaluate sediment mobility at localized features. However, results of the scour monitoring program (Section 5.5.1 and particularly layers used in the redd scour (Section 5.5.1.3) analysis) can be used to evaluate discharge thresholds for mobilization of the bed under the existing conditions. Preliminary assessment of these results shows they are sensitive to the D_{50} values interpreted from the facies mapping. Local direct observation of the D_{50} at any given feature of interest may be needed to confidently predict the threshold of sediment erosion or deposition at that location.

5.6 Large Wood Inventory

5.6.1 Spatial Distribution of Large Wood and Log Jams

Table 5.6-1 includes a summary of all large wood pieces and jams identified on aerial photographs from 1979-2022 (a span of 43 years) and in the field in 2021. Due to limitations in accessibility at the time of survey, the 2021 field survey included 27.0 of the 30.4 miles of the primary study area. The field survey was not conducted in the Shovel Spur rapids area between PRM 86.7 and PRM 87.6 (0.9 miles length) and the Gorge bypass reach (geomorphic reach 1; 2.5 miles length). In the May 2021 aerial, there were two pieces of large wood identified in the Shovel Spur rapids reach. In aerials between 2009 and 2022, there were one to five pieces of large wood identified in this area. Additionally, due to limitations on safe accessibility and for efficiency, the Gorge bypass reach was inventoried using high resolution drone imagery from July 2021 collected for the FA-05 Bypass Instream Flow Model Development Study (City Light 2023c).

Due to limitations in high resolution remote sensing data available, 1998 includes 11.8 miles, and 1979 includes 11.0 miles of the primary study area. The lesser number of pieces and jams identified prior to 2018 is likely due to the lower resolution of remote sensing imaging available.

A much higher quantity of large wood was inventoried in the August 2021 field survey relative to wood inventoried from aerial photography, likely due to access to large wood that was hidden under canopy cover in the aerial imagery. This difference is especially pronounced when inventorying individual large wood pieces in side channels from aerial photos. The challenge of canopy cover and low resolution in aerial photos makes it difficult to determine with certainty whether there were fewer large wood pieces and log jams historically, or if the trend of large wood loading and log jams increasing in the Skagit River since 1979 reflects a difference in methods and available data. The observed trend appears accurate, but differences in historical image resolution may have made the observed trend more pronounced than it actually is. Throughout the aerial photographs, there was consistently more large wood and log jams identified in reaches 5B and 6.

Table 5.6-1. Individual large wood and log jams inventory in primary project area from 1979 to 2022.

Year	Miles Surveyed in Primary Project Area	Individual Large Wood Pieces[4]	Log Jams	Individual Large Wood Pieces Per Mile in Primary Project Area[4]	Log Jams Per Mile in Primary Project Area
1979[1]	11.0	65	17	6	1.5
1998[1]	11.8	27	14	2	1.2
2009[2]	27.9	90	46	3	1.6
2011[2]	27.9	99	61	4	2.2
2018/2019[2]	30.4	357	114	12	3.8
2021[1]	27.9	209	65	7	2.3
2021[3]	29.5	1714	81	58	2.7
2022[1]	30.4	311	104	10	3.4

1 Aerial photographs.
2 Digital imagery.
3 Field for 27.0 miles and Drone Imagery for 2.5 miles.
4 Individual large wood pieces in aerial photographs and digital imagery could not be detected under bank and side channel canopy cover, resulting in fewer inventoried large wood pieces.

Table 5.6-2 includes the total number of pieces of large wood inventoried individually and in jams for mainstem, tributaries, and side channels during the field inventory in August 2021. The total pieces of large wood in individual pieces and jams in the side channel was 40 percent of the total individual pieces and jams inventoried. The total number of individual side channel pieces was 50 percent of the total individual pieces. Attachment I includes maps with all log jams, individual large wood, and tallied large wood, as well as large wood identified in July 2021 drone imagery in Geomorphic Reach 1. Log jams were estimated in the field as either 10-49 pieces, 50-99 pieces, or 100 plus pieces. A wood count value of 30, 75, and 100 pieces was assigned to each of these estimated log jams, respectively. Piece count defaulted to their exact value for log jams that were counted precisely in the field. This includes all log jams that were made of 5-9 pieces, as well as some larger log jams.

Table 5.6-2. Total number of pieces of large wood inventoried individually and in jams during field work in August 2021 and July 2021 drone imagery.

Type	Mainstem Pieces	Mainstem Pieces Per Surveyed Mile	Tributary Pieces (500 ft surveyed)	Tributaries Pieces Per Surveyed Mile	Side Channel Pieces	Side Channels Pieces Per Surveyed Mile	Total Pieces
Individual	791[1]	28	63	33	858	25	1,714
In Jam	1,530[2]	55	136	72	836	30	2,500
Total	**2,321**	**83**	**199**	**105**	**1,694**	**55**	4,214

1 Geomorphic Reach 1 pieces of large wood are based on July 2021 drone imagery.
2 Log jam wood counts are estimated with wood count values of 30, 75, and 100 pieces based on approximate size.

Table 5.6-3 includes the total number of large wood individual pieces distributed along the primary study area by geomorphic reach channel type. Details about geomorphic reaches are presented in Section 4.0 of this study report.

Table 5.6-3. Total number of individual pieces of large wood inventoried during field work in August 2021 and July 2021 drone imagery by geomorphic reach and channel type.

Geomorphic Reach	Mainstem			Tributary			Side Channel			Total Individual Pieces
	Total Pieces	Total Length	Pieces Per Mile	Total Pieces	Total Length	Pieces Per Mile	Total Pieces	Total Length	Pieces Per Mile	
1[1]	131	2.5	52	0	0.0	N/A	0	0.0	N/A	131
2A	43	1.2	36	8	0.3	27	0	0.0	N/A	51
2B	237	4.1	58	9	0.3	30	117	3.1	37	363
3A	23	1.9	12	33	0.2	165	1	0.5	2	57
4	48	3.5	14	5	0.2	25	4	0.1	40	57
3B	225	2.0	113	8	0.3	27	3	0.8	4	236
5A	72	3.5	21	41	0.2	205	37	1.2	31	150
5B	178	3.7	48	43	0.2	215	606	3.9	155	827
6	1,156	6.7	173	52	0.9	58	700	22.8	31	1,908
7A	188	1.3	145	0	0.0	N/A	226	1.4	161	414
7B[2]	20	0.3	67	0	0.0	N/A	0	0.0	N/A	20
Total	**2,321**	**30.7**	**737**	**199**	**2.6**	**751**	**1,694**	**33.8**	**461**	**4,214**

1 Geomorphic Reach 1 individual pieces of large wood is based on July 2021 drone imagery.

Individual large wood pieces were distributed by dimensions and rootwad presence within the mainstem, tributaries, and side channels as follows.

5.6.1.1 Mainstem

Table 5.6-4 includes the length and diameter of individual pieces within the mainstem Skagit River. The majority of pieces counted in the mainstem were 25-49 ft long with a dbh of 1-1.9 ft. Table 5.6-5 includes the inventory of individual large wood pieces with and without rootwads present within the mainstem Skagit River.

Table 5.6-4. Diameter and length of individual pieces within the mainstem Skagit River.

Length (ft)	Diameter at Breast Height (ft)								Total	
	1-1.9		2-2.9		3-3.9		4.0-6.0			
25-49	308		42		12		2		**364**	**46%**
50-74	193		72		10		4		**279**	**35%**
75-99	26		66		15		4		**111**	**14%**
100 plus	8		11		7		11		**37**	**5%**
Total	**535**	**68%**	**191**	**24%**	**44**	**6%**	**21**	**3%**	**791**	

Table 5.6-5. Diameter and rootwad presence of individual large wood pieces within the mainstem Skagit River.

Rootwad Presence	Diameter at Breast Height (ft)								Total	
	1.0-1.9		2.0-2.9		3.0-3.9		4.0-6.0			
Rootwad	230	43%	118	62%	37	84%	19	90%	**404**	51%
No Rootwad	305	57%	73	38%	7	16%	2	10%	**387**	49%
Total	**535**		**191**		**44**		**21**		**791**	

5.6.1.2 Tributaries

Table 5.6-6 includes the length and diameter of individual pieces within the 20 tributaries. The greatest number of pieces counted in the tributaries were 25-49 ft long with a dbh of 1-1.9 ft. Table 5.6-7 includes the inventory of large wood pieces with and without rootwads present within the tributaries.

Table 5.6-6. Diameter and length of individual large wood pieces within tributaries.

Length (ft)	Diameter at Breast Height (ft)								Total	
	1.0-1.9		2.0-2.9		3.0-3.9		4.0-6.0			
25-49	18		9		1		2		**30**	**48%**
50-74	16		7		0		0		**23**	**37%**
75-99	2		4		2		1		**9**	**14%**
100 plus	0		0		1		0		**1**	**2%**
Total	**36**	**57%**	**20**	**32%**	**4**	**6%**	**3**	**5%**	**63**	

Table 5.6-7. Rootwad presence of individual large wood pieces within tributaries.

Rootwad Presence	Diameter at Breast Height (ft)								Total	
	1.0-1.9		2.0-2.9		3.0-3.9		4.0-6.0			
Rootwad	6	17%	9	45%	2	50%	0	0%	**17**	**27%**
No Rootwad	30	83%	11	55%	2	50%	3	100%	**46**	**73%**
Total	**36**		**20**		**4**		**3**		**63**	

5.6.1.3 Side Channels

Table 5.6-8 includes the length and diameter of individual pieces within the side channels. The majority of pieces counted in side channels were 25-49 ft long with a dbh of 1-1.9 ft. Table 5.6-9 includes the inventory of large wood pieces with and without rootwads present within the side channels.

Table 5.6-8. Diameter and length of individual large wood pieces within side channels.

Length (ft)	Diameter at Breast Height (ft)								Total	
	1.0-1.9		2.0-2.9		3.0-3.9		4.0-6.0			
25-49	475		93		12		5		**585**	**68%**
50-74	157		53		6		0		**216**	**25%**
75-99	19		33		0		1		**53**	**6%**
100 plus	0		2		0		2		**4**	**0%**
Total	**651**	**76%**	**181**	**21%**	**18**	**2%**	**8**	**1%**	**858**	

Table 5.6-9. Rootwad presence of individual pieces within side channels.

Rootwad Presence	Diameter at Breast Height (ft)								Total	
	1.0-1.9		2.0-2.9		3.0-3.9		4.0-6.0			
Rootwad	188	29%	80	44%	10	56%	5	63%	**283**	**33%**
No Rootwad	463	71%	101	56%	8	44%	3	38%	**575**	**67%**
Total	**651**		**181**		**18**		**8**		**858**	

5.6.2 Log Jam Persistence

Log jams were marked as either present, not present, or unknown for each year for which high-resolution aerial imagery was available, in addition to the field inventory completed in 2021. Log jams were then tracked at specific locations in the river through time to determine the minimum length of time historically inventoried log jams persisted. Additionally, log jam types were identified in aerials and in the field, when feasible.

Table 5.6-10 includes the distribution of total years of time that individual log jams persisted from 1979 to 2022 within the mainstem, side channels, and one-quarter mile up tributaries. The log jams listed as present for one year include 60 log jams that were first identified in June 2022 aerial photography. The majority of these log jams likely formed in the October or November 2021 high flow events. There was a total of 112 log jams that persisted 4 or fewer years, 32 log jams that persisted 10 to 13 years, 2 log jams that persisted 24 years, and 4 log jams that persisted for a minimum of 43 years.

Table 5.6-10. Log jam persistence and percentage of small, medium, and large jams from 1979 to 2022.

Years Present	Total Jams	Percentage Small Jams (5 to 49 pieces)	Percentage Medium Jams (50 to 99 pieces)	Percentage Large Jams (100+ pieces)
1 to 2	87	66%	30%	5%
3 to 9	25	56%	28%	16%
10 to 23	32	50%	25%	25%
24 to 42	2	50%	0%	50%
≥ 43	4	25%	50%	25%

Inventoried historical log jams that were present in the August 2021 field inventory, May 2021 imagery, and June 2022 imagery were examined for recent changes in size. Changes were described as either growing, decaying, stable, variable, or unknown. Aerial imagery was used to ascertain recent trends in change of log jams. Log jams that did not display a continuous trend in growth, decay, or stability were defined as variable. Log jams that were surveyed only in August 2021 were defined as having an unknown change (Table 5.6-11).

Table 5.6-11. Historical change of log jams seen in 2021 survey, 2021 imagery, and 2022 imagery.

Growing	Decaying	Stable	Variable	Unknown	Log Jams
73[1]	12	35	22	8	150

1 42 marked as growing are jams that appeared in 2022.

The majority of log jams identified in the jam persistence analysis were bar top, side channel and meander jams. Overall, there were much less apex and submerged jams identified. Bar apex and submerged jams were more likely to persist for 24 or more years than other jam types. Table 5.6-12 includes a summary of log jam locations and their associated period of persistence (Table 5.6-12).

Table 5.6-12. Log jam persistence and location of jams from 1979 to 2022.

Years Present	Meander	Bar Top	Bar Apex	Side Channel	Submerged
1 to 2	23	35	2	26	1
3 to 9	8	7	4	6	0
10 to 23	3	10	2	13	4
24 to 42	0	0	0	0	2
≥ 43	1	1	1	1	0

5.6.3 Log Jam Pools

Main channel pools were identified using the aquatic habitat units and relative elevation model discussed in section 4.2 of this study report. These pools were categorized by the primary and secondary conditions forcing scour. The conditions that were examined are as follows; alluvial-meander forced, bedrock forced, confluence forced, dolosse forced, riprap forced, wood forced, and other. Dolosse are energy-dissipating concrete blocks shaped as jacks and used to reduce erosion. Table 5.6-13 presents the distribution of categorized primary pool scour conditions by geomorphic reach. This analysis does not include many small mainstem pools that were observed in the field by the large wood team and did not meet the criteria to be categorized as an individual pool for the aquatic habitat unit study.

Table 5.6-13. Categorized primary pool scour conditions distributed by geomorphic reach.

Geomorphic Reach	Alluvial-Meander	Bedrock	Confluence	Riprap/ Dolosse	Wood	Other
1	0	16	0	1	0	0
2A	0	2	0	1	1	0
2B	9	1	1	1	2	0
3A	3	2	2	0	0	0
4	2	0	1	0	1	0
3B	3	1	1	0	0	2
5A	1	1	1	0	0	0
5B	6	2	0	0	0	0
6	12	0	0	5	4	6
7A	0	0	0	0	1	1
7B	0	0	0	0	0	0
All	**36**	**25**	**6**	**8**	**9**	**9**

5.6.4 Distribution by Habitat Units

Each individual piece of large wood and log jam inventoried during the August 2021 field inventory was spatially associated using GIS with channel units delineated from 2019 aerial photographs.

These channel units are defined as follows:

- Forested Island;
- Vegetated Bar;
- Main Channel Bar;
- Main Channel Wet; and
- Side Channel.

Large wood that was associated with wet channel units, “Main Channel Wet” or “Side Channel,” were spatially associated with aquatic habitat units in addition to the channel units. More information on the aquatic habitat units can be found in Section 4.2 of this study report. Wood that was inventoried in August 2021, but did not spatially correlate with a delineated channel unit or aquatic habitat unit, were defined as “unknown” and excluded from this analysis. This instance occurred primarily in blind side channels that were surveyed entirely in August of 2021 based on pre-field REM data but were later excluded from the “Side Channel” classification. Additionally, the unknown habitat unit was associated with the wood pieces inventoried in the Gorge bypass Geomorphic Reach 1 because channel units were not delineated in this reach. Total habitat unit area is smaller in Table 5.6-14 than in Section 5.2 of this study report. This is due to the large wood survey covering less area than the habitat unit survey.

Table 5.6-14. Large wood individual pieces and density associated with aquatic habitat units.

Habitat Unit		Total Surveyed Area (acres)	Individual Large Wood Pieces	Individual Large Wood Density[1]
Wet	Side Channel	63.9	1,127	17.6
	Tributary	40.8	611	15.0
	Backwater	11.1	56	5.0
	Pool	91.7	235	2.6
	Riffle	122.1	161	1.3
	Rapid	25.7	26	1.0
	Glide	678.6	646	1.0
	Off-Channel	159.8	113	0.7
	Run	77.5	53	0.7
Dry	Bar	31.3	406	13.0
	Vegetated Bar	N/A	281	N/A
	Forested Island	N/A	132	N/A
Unknown		N/A	367	N/A
Total		**1,302.6**	**4,214**	**N/A**

1 wood density = pieces per surveyed acre.

5.6.5 Large Wood Inventory Detailed Areas

A more detailed large wood inventory was conducted in 10 half-mile areas as described in Section 4.6 of this study report. The distribution of various attributes collected within these detailed areas are as follows.

Tree species was collected for 274 individual large wood pieces within detailed areas (Table 5.6-15). When species was unable to be determined, the study team classified large wood as either a conifer or deciduous, when possible. If a large wood piece could not be determined to be either a conifer or a deciduous species, the study team classified the large wood piece species as "Unknown."

Table 5.6-15. Distribution of tree species of large wood pieces inventoried within detailed areas.

Species	Large Wood Pieces	Percentage of Large Wood Pieces
Alder *(Alnus rubra)*	79	29%
Cottonwood *(Populus trichocarpa)*	68	25%
Cedar *(Thuja plicata)*	58	21%
Maple *(Acer macrophyllum)*	17	6%
Fir *(Pseudotsuga menziesii)*	12	4%
Hemlock *(Tsuga heterophylla*)	2	1%
Conifer	12	4%
Deciduous	2	1%
Unknown	24	9%
Total	**274**	**100%**

Decay class was collected for individual large wood pieces within detailed areas. Their distribution is presented in Table 5.6-16. Decay class is defined as either 1 (fresh), 2 (intermediate), or 3 (rotten). Class 1 refers to wood that is very firm and often has bark and limbs. Class 2 refers to wood that is firm and often has some bark and limbs. Class 3 refers to wood that is softer and has no or very little bark and limbs. Large wood pieces that were not readily accessible were classified as "Unknown."

Table 5.6-16. Distribution of decay class of large wood pieces inventoried within detailed areas.

Decay Class	Large Wood Pieces	Percentage of Large Wood Pieces
1	95	35%
2	119	43%
3	39	14%
Unknown	21	8%
Total	**274**	**100%**

Residual pool depth was measured when present for individual large wood pieces within detailed areas that were not a part of a log jam, a total of 211 large wood pieces. There were 63 pieces identified in log jams that are not part of the next three tables. Residual pool depths associated with individual large wood pieces not located in log jams are presented in Table 5.6-17.

Table 5.6-17. Residual pool depths associated with individual large wood pieces not located in log jams within detailed areas.

Residual Pool Depth (ft)	Large Wood Pieces	Percentage of Large Wood Pieces
8-12	6	28%
4-7.9	13	
1-3.9	25	
Present but not measured	16	
No Pool	151	72%
Total	**211**	**100%**

1 An additional 63 pieces were identified in log jams and not included in this table.

Individual large wood pieces that were inventoried in detailed areas contain attributes associated to rootwad diameter and associated pool depth. In Table 5.6-18, the correlation between rootwad presence and pool presence is summarized for individual large wood pieces that are not in log jams that were inventoried in detailed areas.

Table 5.6-18. Rootwad presence associated with pool presence for individual large wood pieces inventoried in detailed areas.

Rootwad Presence	Large Wood Pieces with Pool[1]		Large Wood Pieces without Pool[1]	
Rootwad Present	47	78%	94	62%
No Rootwad	13	22%	57	38%
Total	**60**		**151**	

1 An additional 63 pieces were identified in log jams and not included in this table.

Individual large wood pieces found in detailed areas that have a rootwad but are not in log jams were binned by their respective rootwad diameters. They were then associated with whether a pool was present in Table 5.6-19.

Table 5.6-19. Rootwad diameter associated with pool presence for individual large wood pieces inventoried in detailed areas.

Rootwad Diameter (ft)	Large Wood Pieces with Pool[1]		Large Wood Pieces without Pool[1]	
2 to 3.9	5	8%	20	13%
4 to 9.9	37	62%	65	43%
10 to 25	18	30%	8	5%
Not Measured	0	0%	58	38%
Total	**60**		**151**	

1 An additional 63 pieces were identified in log jams and not included in this table.

5.6.6 Distribution by Geomorphic Reaches

As shown in Section 3.0 of this study report, the primary study area was split into 7 geomorphic reaches; several of these geomorphic reaches were then divided into subreaches for a total of 11 geomorphic reaches and subreaches. Results relating to wood distribution in each subsequent geomorphic reach and subreach that was field inventoried are summarized below and in Attachment J.

5.6.6.1 Reach 1

Large wood in Reach 1 consisted primarily of large wood pieces stranded on large boulders above the wetted channel (Figure 5.6-1). Only one large log jam existed in Reach 1. This log jam was present on the right bank on the outside of a sharp left meander running adjacent to highway 20. The log jam is surrounded by large boulders with a diameter of 15 ft or greater. Reach 1 contained a total of 131 large wood pieces, 31 of which are individual large wood pieces. One piece of large wood with a rootwad diameter of 7.5 ft was identified. Table 5.6-20 includes a summary of the large wood count in the mainstem and log jams within Geomorphic Reach 1.

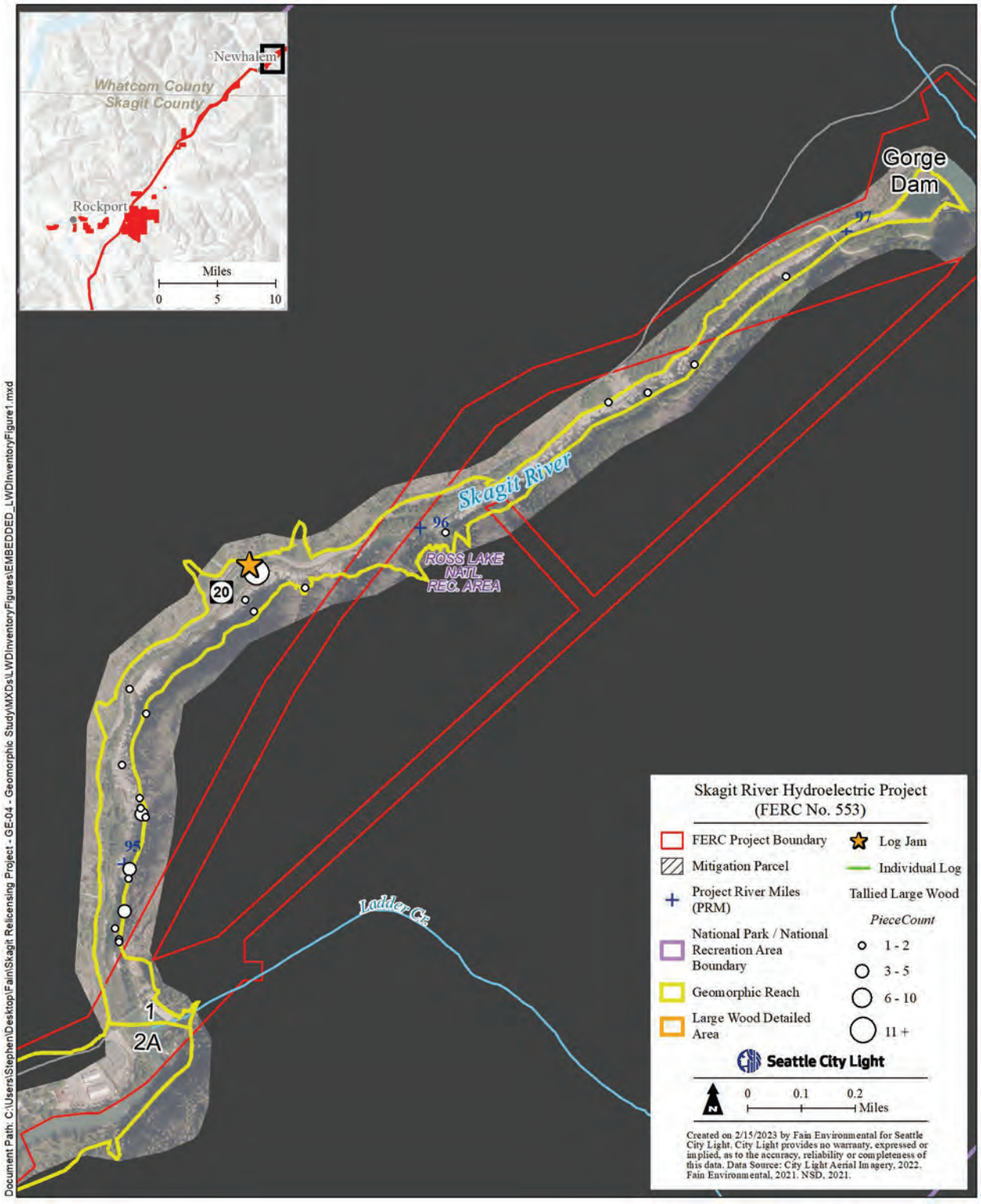


Figure 5.6-1. Large wood July 2021 drone imagery inventory for Reach 1.

Table 5.6-20. Large wood count, rootwad count, and rootwad percentage for Geomorphic Reach 1.

Location	Large Wood Count	Rootwad Count	Percentage with Rootwad
Mainstem	31	1	3%
In Log Jams	100	N/A	N/A
Total Count	**131**	**1**	**1%**

5.6.6.2 Reach 2A

Large wood in Reach 2A has more pieces on the left bank then the right bank where it functions primarily as cover for aquatic habitat during high flows (Figure 5.6-2). In this reach, the study team did not see wood forming pools or wood forming mid-channel bars. The total amount of large wood located in this reach was 52 large wood pieces. Of the 41 individual large wood pieces measured in this reach, nine pieces had rootwads. The rootwads ranged in diameter from 3-10 ft. Table 5.6-21 includes a summary of the large wood and rootwad count in mainstem, tributaries, and log jams within Geomorphic Reach 2A. In this reach, there were two small log jams located in the mainstem Skagit River (Figure 5.6-3).

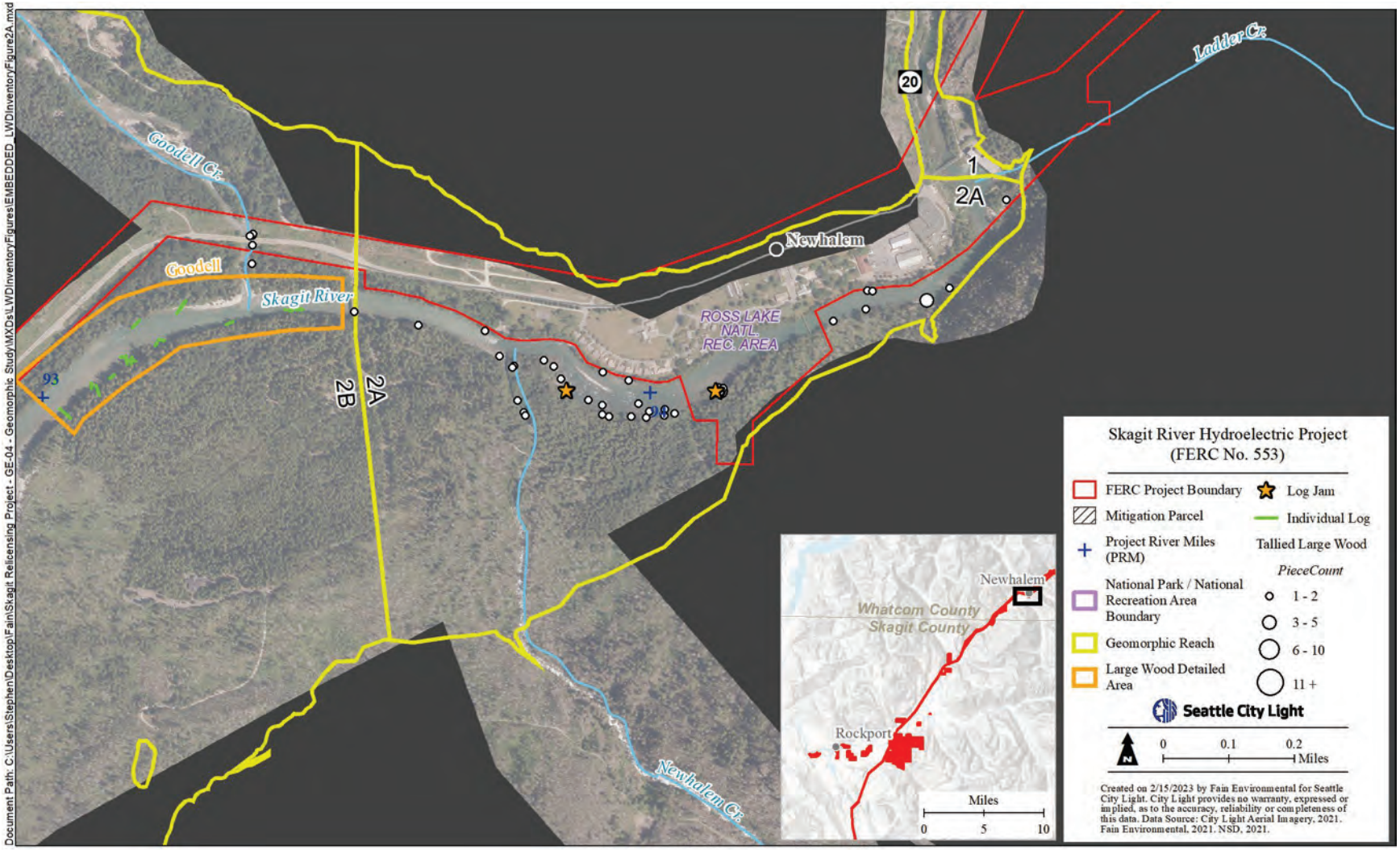


Figure 5.6-2. Large wood August 2021 field inventory for Reach 2A.

Table 5.6-21. Large wood count, rootwad count, and rootwad percentage for Geomorphic Reach 2A.

Location	Large Wood Count	Rootwad Count	Percentage with Rootwad
Mainstem	33	7	21%
Ladder Creek	1	0	0%
Newhalem Creek	7	2	29%
In Log Jams	10	N/A	N/A
Total Count	**51**	**9**	18%



Figure 5.6-3. Small log jam located on left bank at PRM 93.9. Photo taken August 20, 2021.

5.6.6.3 Reach 2B

There were 363 total large wood pieces in Reach 2B, 234 of which were individual large wood pieces (Figures 5.6-4 and 5.6-5). Of these individual large wood pieces, 96 of them had rootwads ranging in diameter from 3-20 ft. A summary of the large wood count, rootwad count, and percentage with rootwad by location for Geomorphic Reach 2B is shown in Table 5.6-22. There were nine small log jams in the mainstem and one small log jam in side channels in the August 2021 inventory. Example photos of an individual large wood piece and a log jam that are located in this reach can be seen in Figures 5.6-6 and 5.6-7.

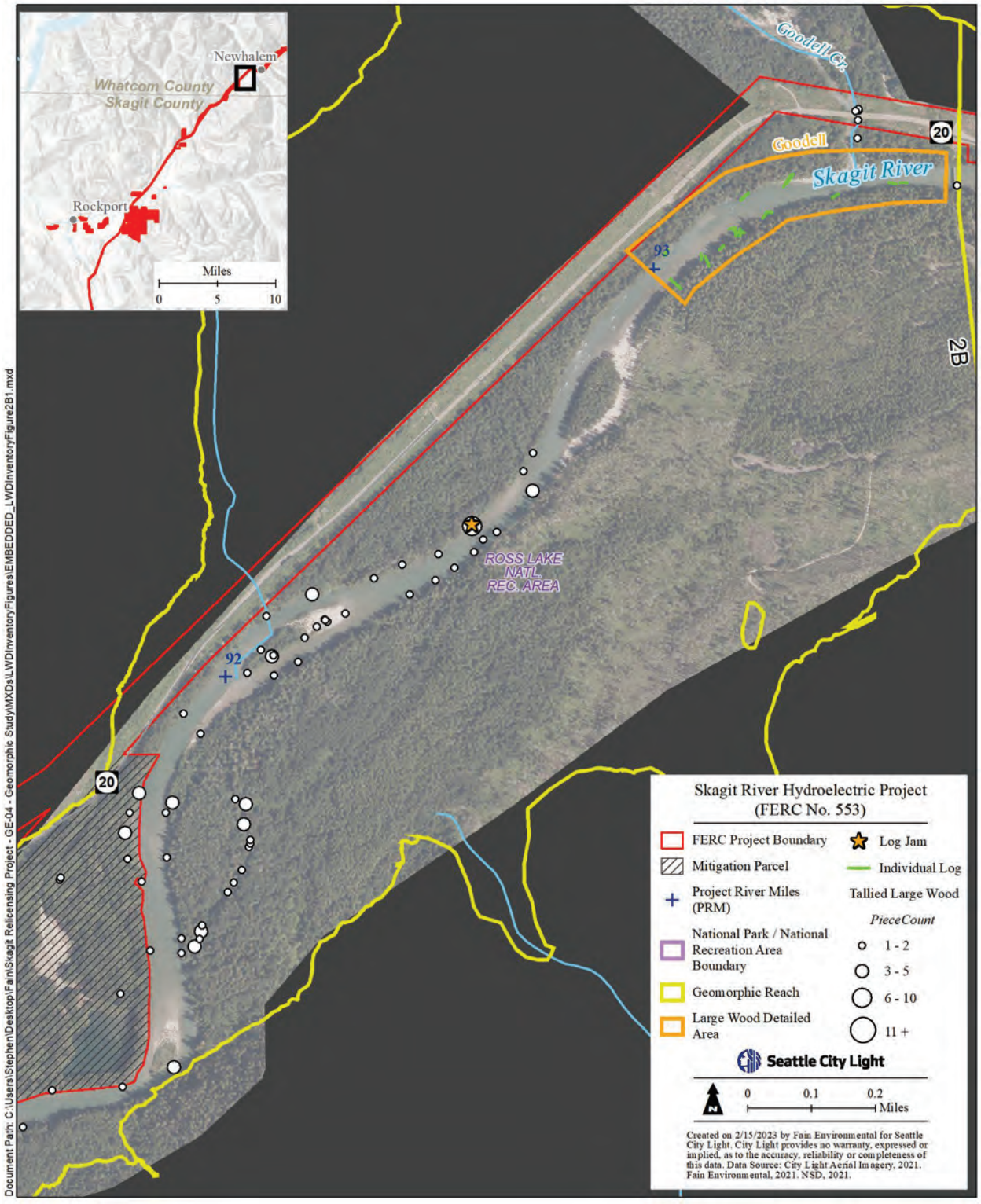


Figure 5.6-4. Large wood August 2021 field inventory for upper section of Reach 2B.

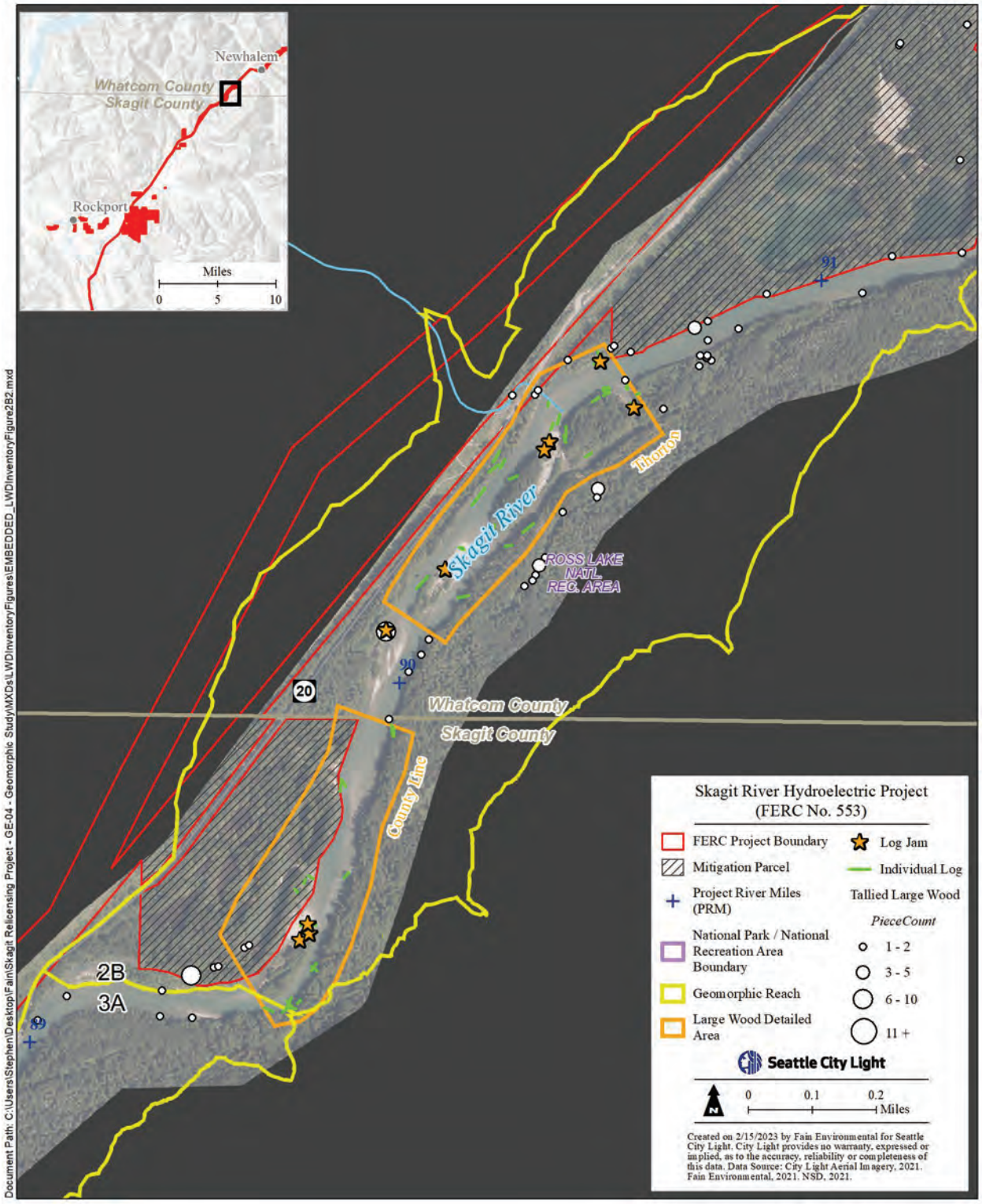


Figure 5.6-5. Large wood August 2021 field inventory for lower section of Reach 2B.

Table 5.6-22. Large wood count, rootwad count, and rootwad percentage for Geomorphic Reach 2B.

Location	Wood Count	Rootwad Count	Percentage with Rootwad
Mainstem	128	57	45%
Goodell Creek	6	0	0%
Thornton Creek	3	2	67%
Side Channels	97	37	38%
In Log Jams	129	N/A	N/A
Total	**363**	**96**	**26%**



Figure 5.6-6. A large wood cedar piece (Tag ID 54) with a 6-ft dbh, 20-ft rootwad, and 70-ft length located at PRM 90.5 looking upstream. Piece forms a pool at rootwad. Photo taken on October 19, 2021.



Figure 5.6-7. Log jam on gravel bar at PRM 89.6. The key piece is an 11-ft rootwad, 67-ft long, 3-ft dbh cottonwood piece that is seen to the right racking a large cedar piece. Flow is from left to right. Photo Taken on August 18, 2021.

5.6.6.4 Reach 3A

Reach 3A is a naturally confined reach with a narrow floodplain and a small amount of large wood pieces (Figure 5.6-8). In August 2021, the study team identified 57 pieces in this reach. A summary of the large wood count, rootwad count, and rootwad count for Geomorphic Reach 3A is shown in Table 5.6-23. In this reach, the study team did not see individual pieces or log jams that formed pools.

Table 5.6-23. Large wood count, rootwad count, and rootwad percentage for Geomorphic Reach 3A.

Location	Wood Count	Rootwad Count	Percentage with Rootwad
Mainstem	23	6	26%
Sky Creek	1	1	100%
Damnation Creek	13	8	62%
Side Channels	1	0	0%
In Log Jams	19	N/A	N/A
Total	**57**	**15**	**26%**

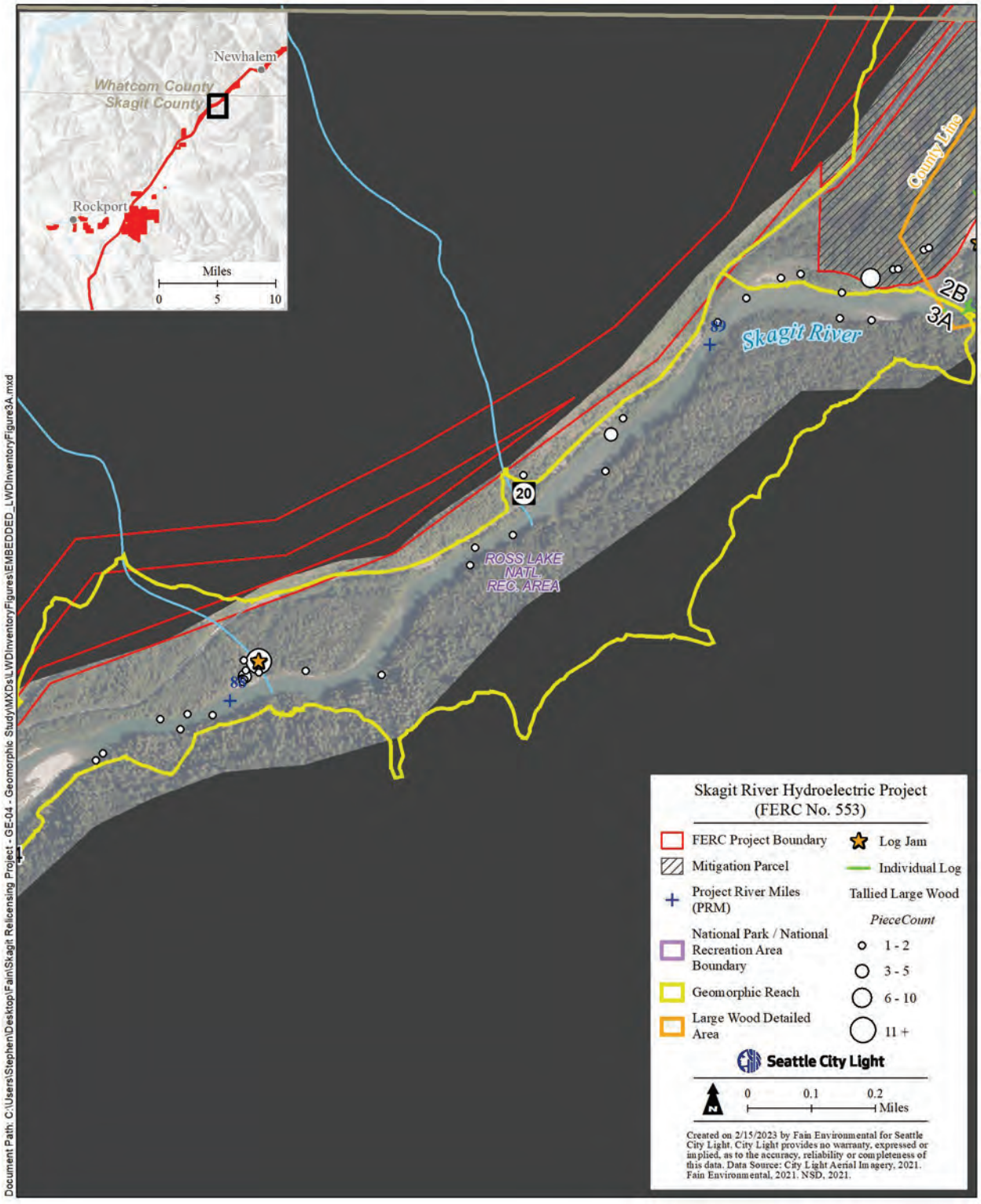


Figure 5.6-8. Large wood August 2021 field inventory for Reach 3A.

5.6.6.5 Reach 4

Geomorphic Reach 4 is approximately 3.5 miles long. Reach 4 is located between Reach 3A and 3B and is referred to as the "landslide zone." Table 5.6-24 presents a large wood count, rootwad count, and percentage by location for Geomorphic Reach 4. There was one log jam present in a side channel. Figures 5.6-9 and 5.6-10 includes the large wood field inventory from August 2021. There were approximately 57 pieces of wood counted in this reach. Intact rootwads were present for 23 of these pieces. In August 2021, the upper mile of this reach, PRM 86.5 to 87.5, was not inventoried because it was inaccessible to jet boats. An example photo of a large wood piece inventoried in this reach is seen in Figure 5.6-11.

Table 5.6-24. Large wood count, rootwad count, and rootwad percentage for Geomorphic Reach 4.

Location	Wood Count	Rootwad Count	Percentage with Rootwad
Mainstem	38	17	45%
Alma Creek	3	1	33%
Copper Creek	2	2	100%
Side Channels	4	3	75%
In Log Jams	10	N/A	N/A
Total	**57**	**23**	**40%**

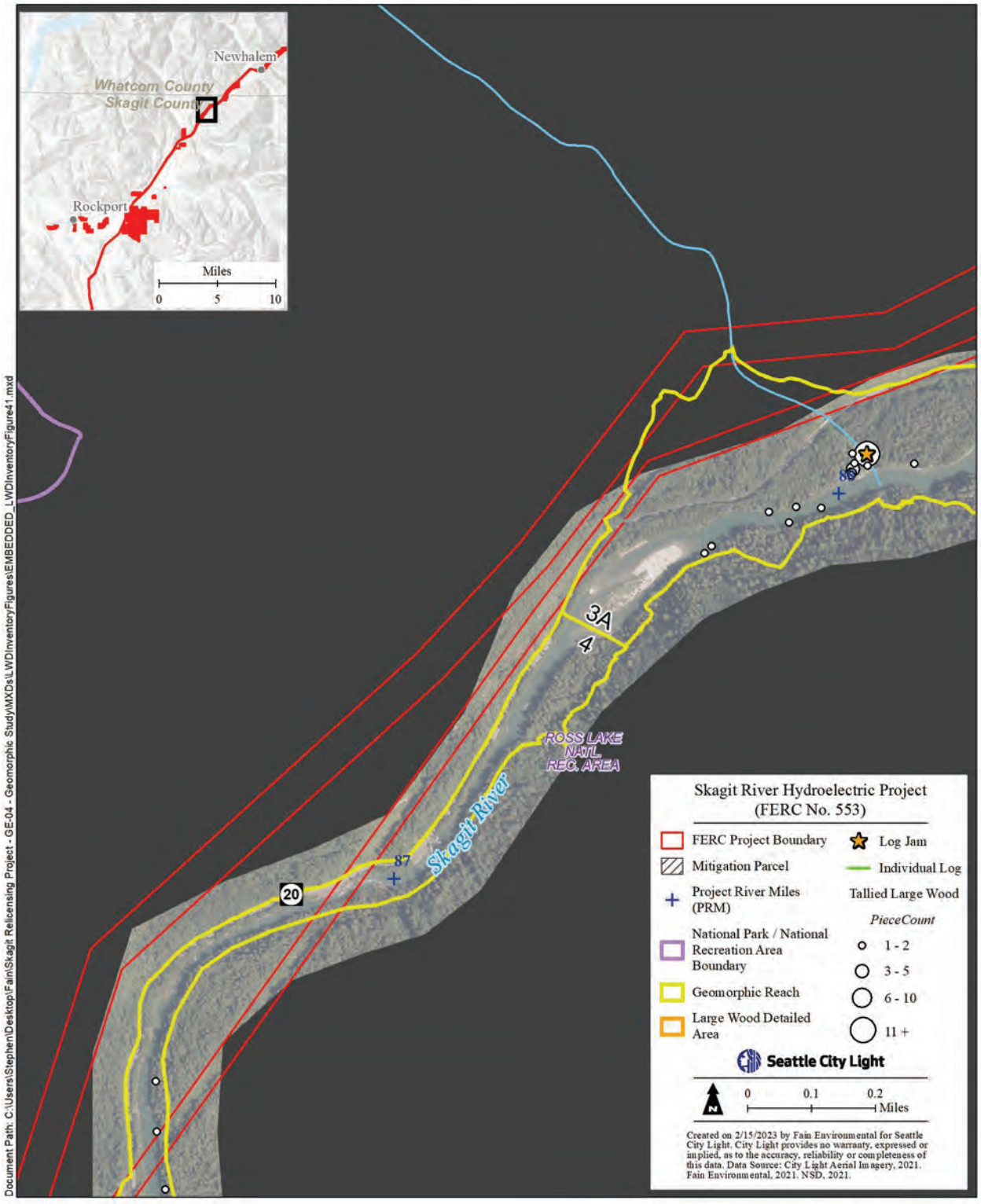


Figure 5.6-9. Large wood August 2021 field inventory for upper section of Reach 4.

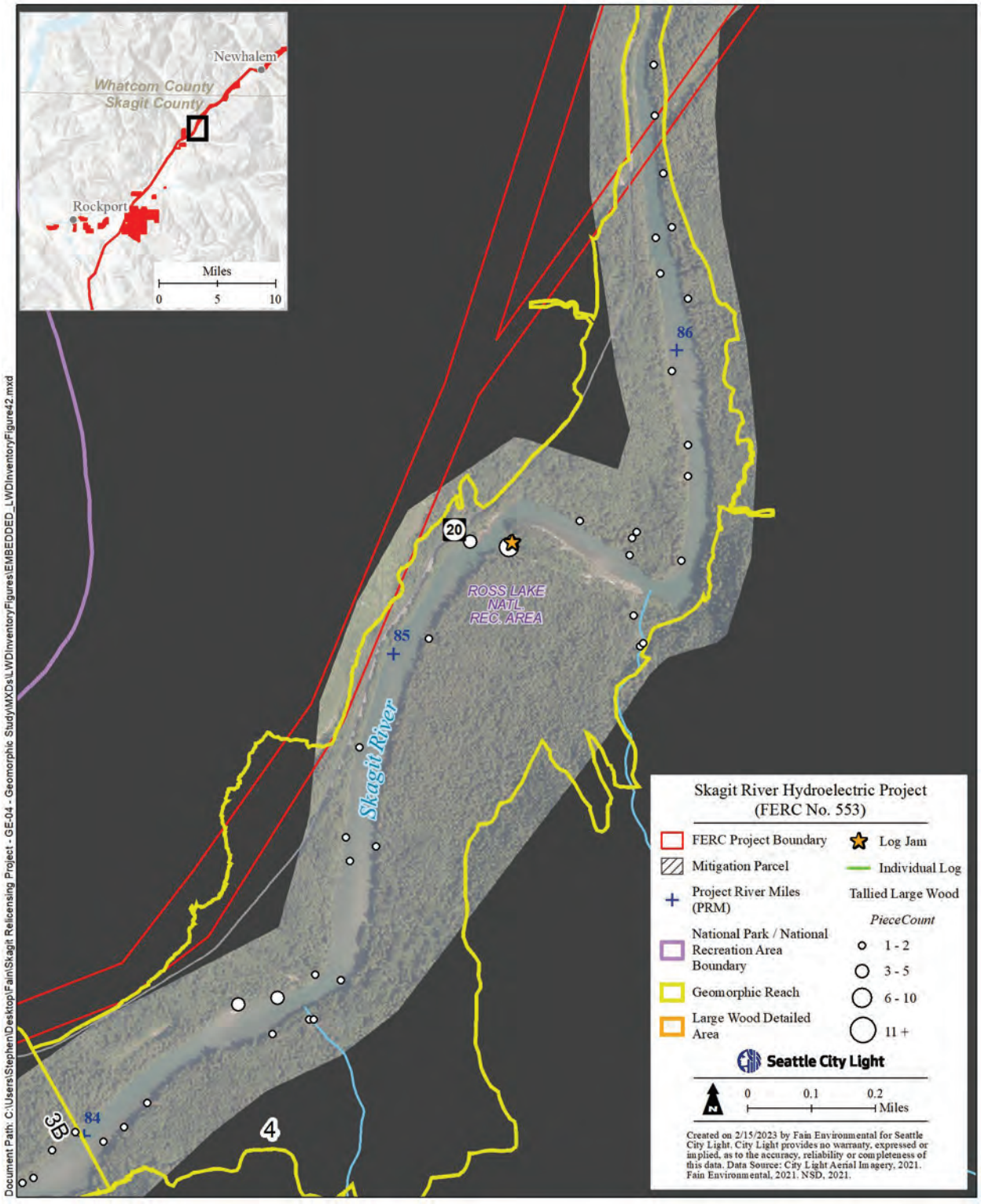


Figure 5.6-10. Large wood August 2021 field inventory for lower section of Reach 4.



Figure 5.6-11. A large wood cedar piece (Tag ID 109) located at PRM 86.1 with a 12 ft diameter rootwad, a 5 ft dbh, and a 100 ft length. Looking downstream. Photo taken on October 19, 2021.

5.6.6.6 Reach 3B

Geomorphic Reach 3B is approximately 1.9 miles long. Table 5.6-25 presents a summary of the large wood inventory for Geomorphic Reach 3B (Figure 5.6-12). There was a total of approximately 236 pieces, with 71 rootwads counted in this reach (Table 5.6-25). Five of the small log jams were located in the mainstem and one was located in a side channel (Figures 5.6-13 and 5.6-14).

Table 5.6-25. Large wood count, rootwad count, and rootwad percentage for Geomorphic Reach 3B.

Location	Wood Count	Rootwad Count	Percentage with Rootwad
Mainstem	102	63	62%
Bacon Creek	8	6	75%
Side Channels	3	2	67%
In Log Jams	123	N/A	N/A
Total	**236**	**71**	**30%**

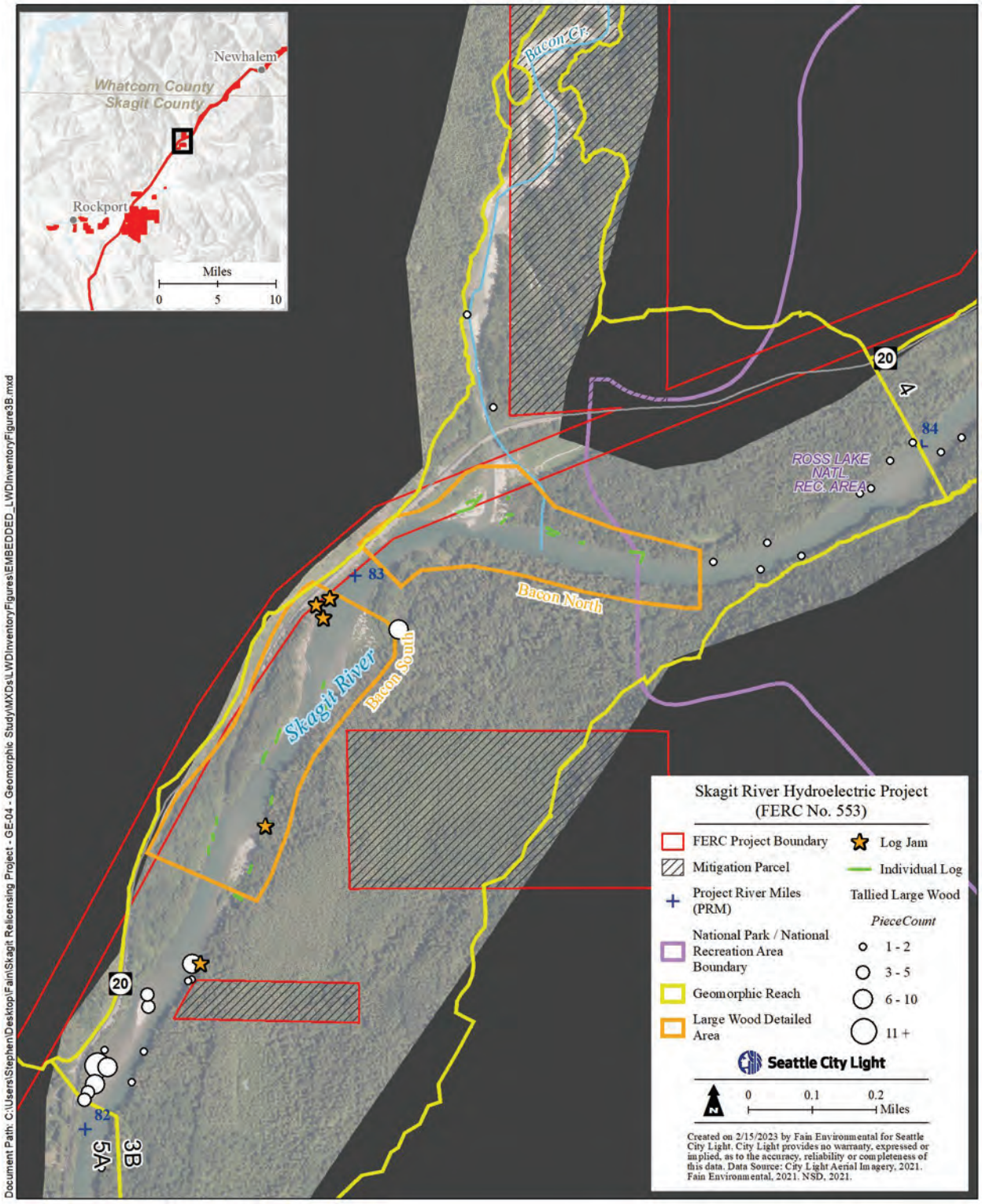


Figure 5.6-12. Large wood count, rootwad count, and percentage by location for Geomorphic Reach 3B.



Figure 5.6-13. **Side channel inlet log jam located on left bank at PRM 82.6. Photo taken August 4, 2021.**



Figure 5.6-14. **Bar apex jam on right bank at PRM 82.9. Jam forms pool with 8 ft residual pool depth at left side of photo. Flow is from left to right. Photo taken August 4, 2021.**

5.6.6.7 Reach 5A

There were 150 total pieces of large wood in Reach 5A of which 100 were individual pieces (Figures 5.6-15 and 5.6-16). Of these individual pieces, 38 of them have rootwads ranging in diameter from 2-10 ft. Table 5.6-26 presents a summary of the large wood count, rootwad count, and rootwad percentage for Geomorphic Reach 5A. This reach is relatively straight compared to the rest of the primary study area. One small log jam is located on the mainstem and one on Diobsud Creek (Figures 5.6-17 and 5.6-18).

Table 5.6-26. Large wood count, rootwad count, and rootwad percentage for Geomorphic Reach 5A.

Location	Wood Count	Rootwad Count	Percentage with Rootwad
Mainstem	52	23	44%
Diobsud Creek	11	8	73%
Side Channels	37	7	19%
In Log Jams	50	N/A	N/A
Total	**150**	**38**	**25%**

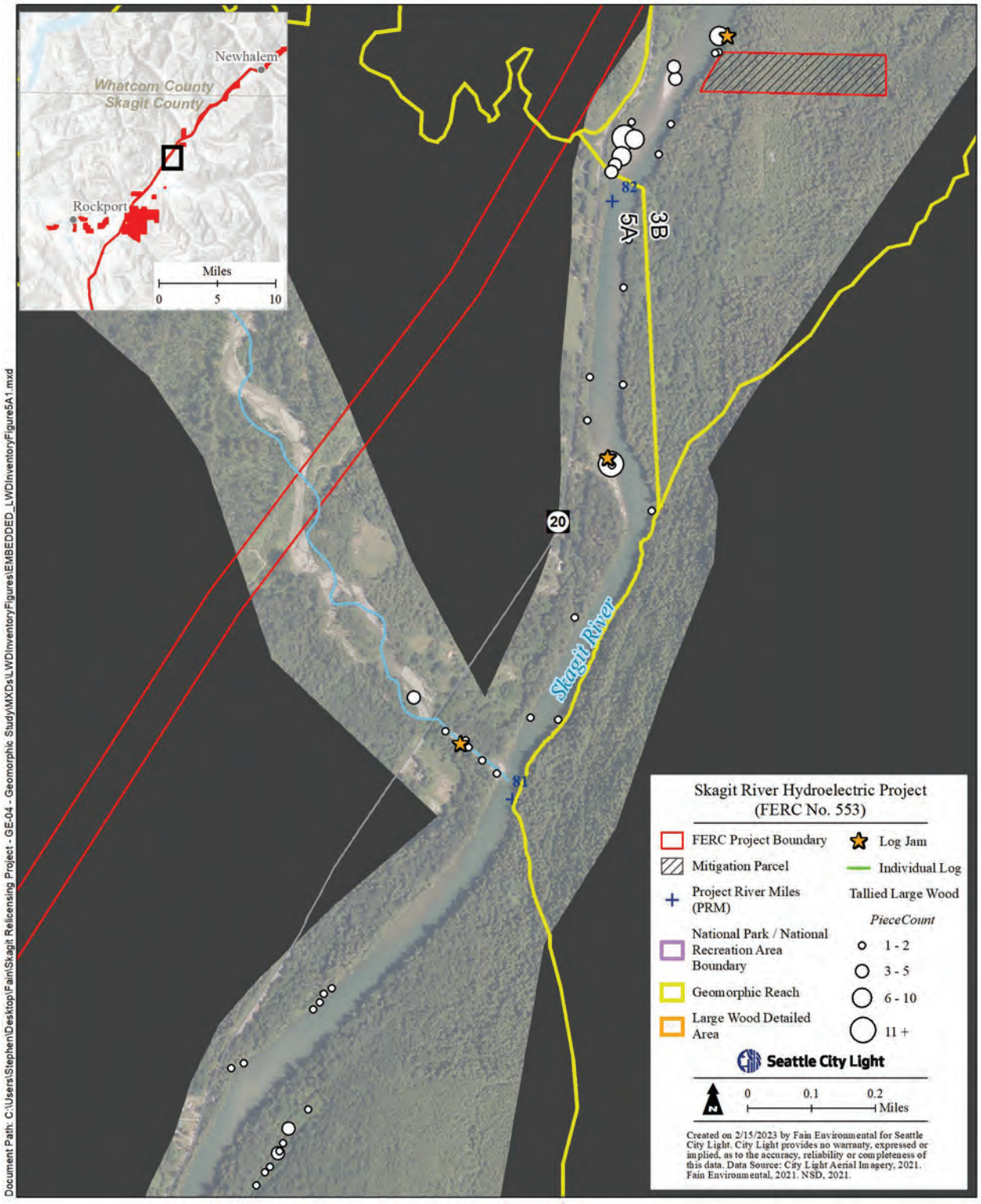


Figure 5.6-15. Large wood August 2021 field inventory for upper section of Reach 5A.

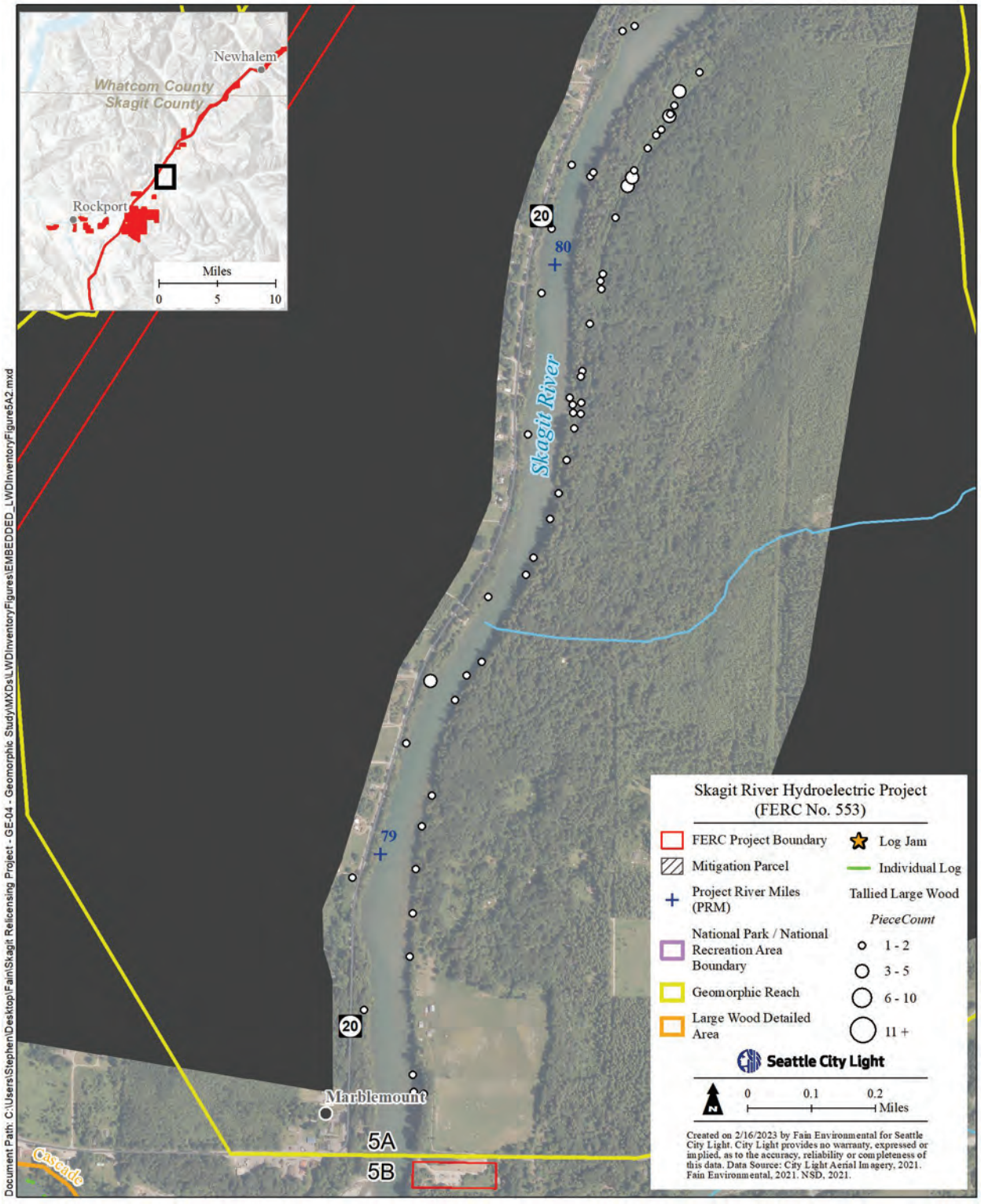


Figure 5.6-16. Large wood August 2021 field inventory for lower section of Reach 5A.



Figure 5.6-17. Bar apex log jam located at PRM 81.6 on right bank. Looking from left bank to right bank, flow is from right to left. Photo taken August 4, 2021.



Figure 5.6-18. Bar apex jam located in Diobsud Creek forming a pool with a residual depth of 2-ft Large wood Tag ID 82 is racked onto this jam. Photo taken looking downstream on August 25, 2021. Between PRM 80.6 and 81.0, there are no pieces of large wood in the mainstem of the channel.

5.6.6.8 Reach 5B

There were 827 total pieces of large wood inventoried in Reach 5B, of which 171 were individual pieces (Table 5.6-27; Figures 5.6-19 and 5.6-20). Of these individual pieces, 81 of them have rootwads ranging in diameter from 1.5-30 ft (Table 5.6-27). The majority of the large wood in Reach 5B is in the Cascade River side channels, as well as in a side channel located at PRM 77.7. Much of this wood is forming pools and functions as cover for aquatic habitat (Figure 5.6-21).

Downstream of the side channel located at PRM 77.7, there is less large wood than upstream and the large wood that is present is primarily bank side pieces that function as cover but do not form pools for aquatic habitat. One large log jam was located in the mainstem (Figure 5.6-22). One small log jam was located in the Cascade River. The Cascade River Distributary side channels included 11 small log jams and one large jam. In the other side channels in this reach, there was a total of eight small and one medium-size jam.

Table 5.6-27. Large wood count, rootwad count, and percentage with rootwad by location for Geomorphic Reach 5B.

Location	Wood Count	Rootwad Count	Percentage with Rootwad
Mainstem	71	25	35%
Cascade River	13	4	31%
Side Channels	87	52	60%
In Log Jams	656	N/A	N/A
Total	**827**	**81**	**10%**

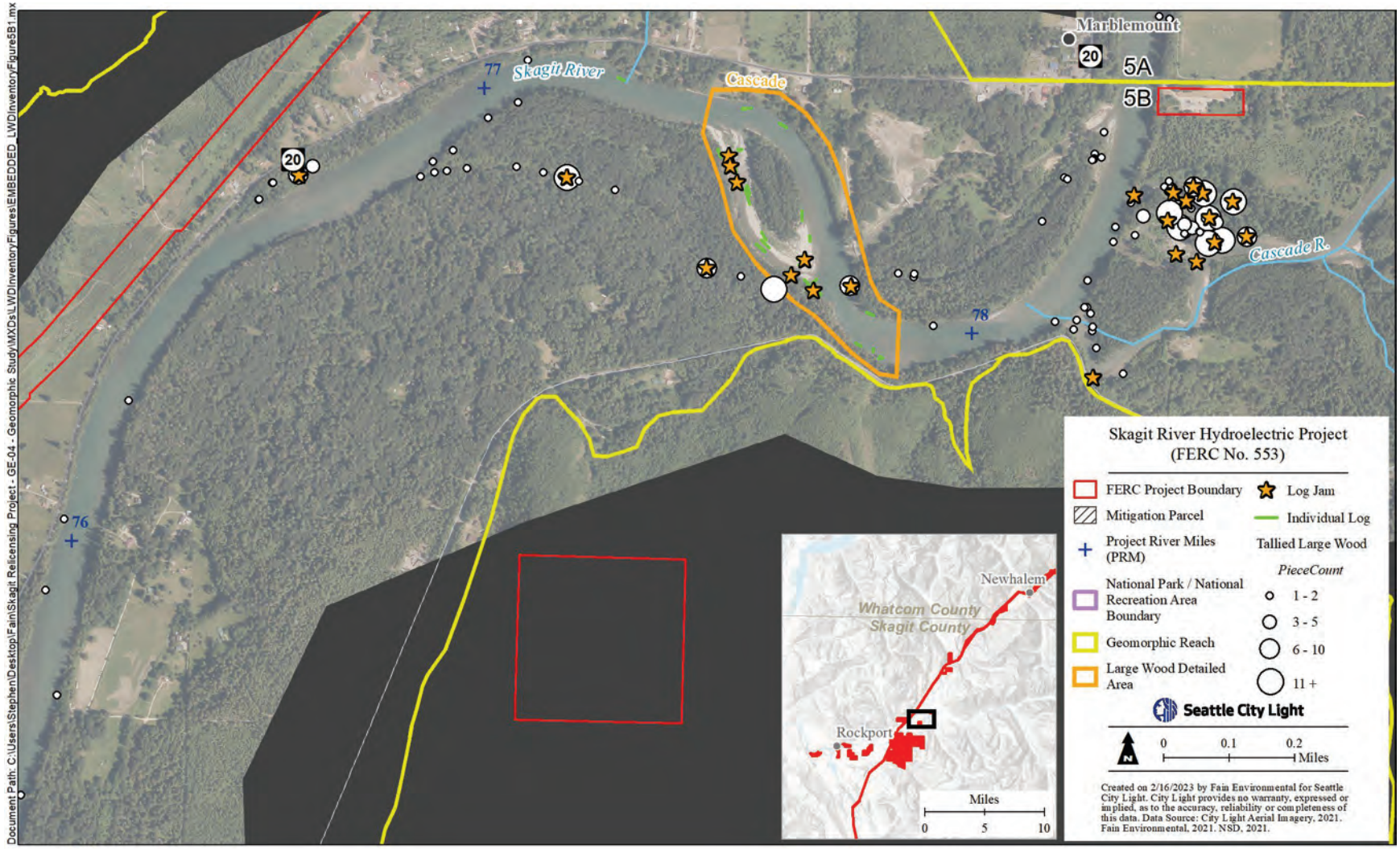


Figure 5.6-19. Large wood August 2021 field inventory for upper section of Reach 5B.

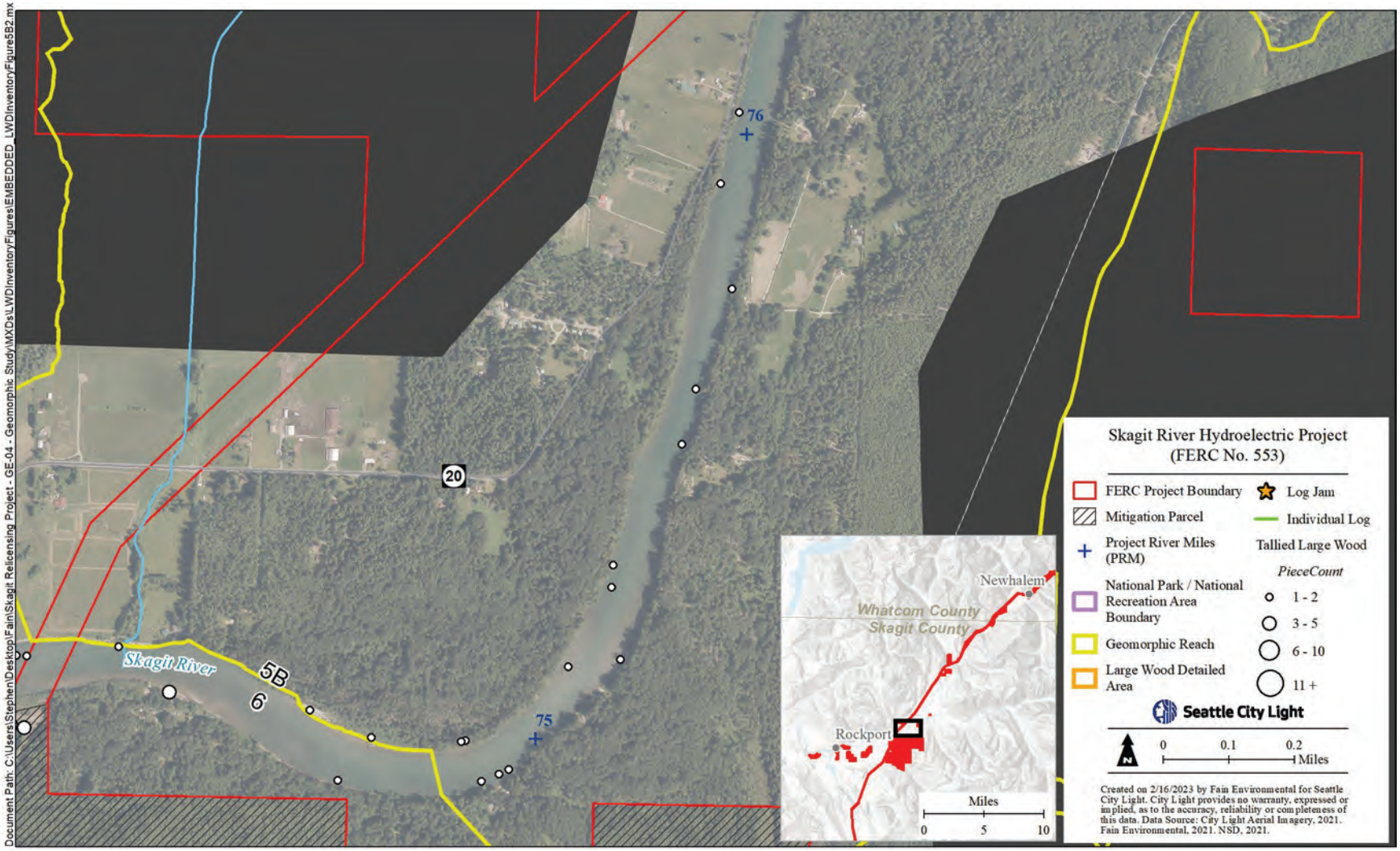


Figure 5.6-20. Large wood August 2021 field inventory for lower section of Reach 5B.



Figure 5.6-21. **Individual large wood piece oriented parallel to flow with its rootwad upstream and forming a residual pool, located in PRM 77.7 ephemeral side channel (Tag ID 36). Flow is from right to left (looking upstream). Photo taken August 4, 2021.**



Figure 5.6-22. **Bar apex jam located at PRM 77.7 on left side of Skagit River, flow is from left to right. Large wood Tag ID 32 and 33 are racked on this jam. Tag ID 32 is a 115-ft long, 5-ft-dbh, 16-ft-rootwad cedar piece. Tag ID 33 is an 80-ft long, 3-ft-dbh, 10-ft-rootwad cedar piece. Photo taken August 4, 2021.**

5.6.6.9 Reach 6

Geomorphic Reach 6 contained 1,908 total pieces of large wood of which 742 were individual pieces. Of these individual pieces, 278 had rootwads (Table 5.6-28; Figures 5.6-23 through 5.6-25). This reach contained the most pieces of large wood in the primary study area. It also contained the most side channels and log jams. In the mainstem, there were eight small log jams, four medium log jams, and two large jams (Figures 5.6-26 through 5.6-28). Rocky Creek and Illabot Creek both had one small log jam (Figure 5.6-29). In the side channels, there were eleven small log jams.

This reach is characterized by a complex channel morphology and significant channel change over time. According to the historical aerial inventory, this reach has had a high concentration of large wood dating back to 1979.

Table 5.6-28. Large wood count, rootwad count, and rootwad percentage for Geomorphic Reach 6.

Location	Wood Count	Rootwad Count	Percentage with Rootwad
Mainstem	228	148	65%
Corkindale Creek	0	0	--
Rocky Creek	10	6	60%
Illabot Creek	0	0	--
Sutter Creek	0	0	--
Barr Creek	0	0	--
Side Channels	533	130	24%
In Log Jams	1137	N/A	N/A
Total	**1908**	**278**	**15%**

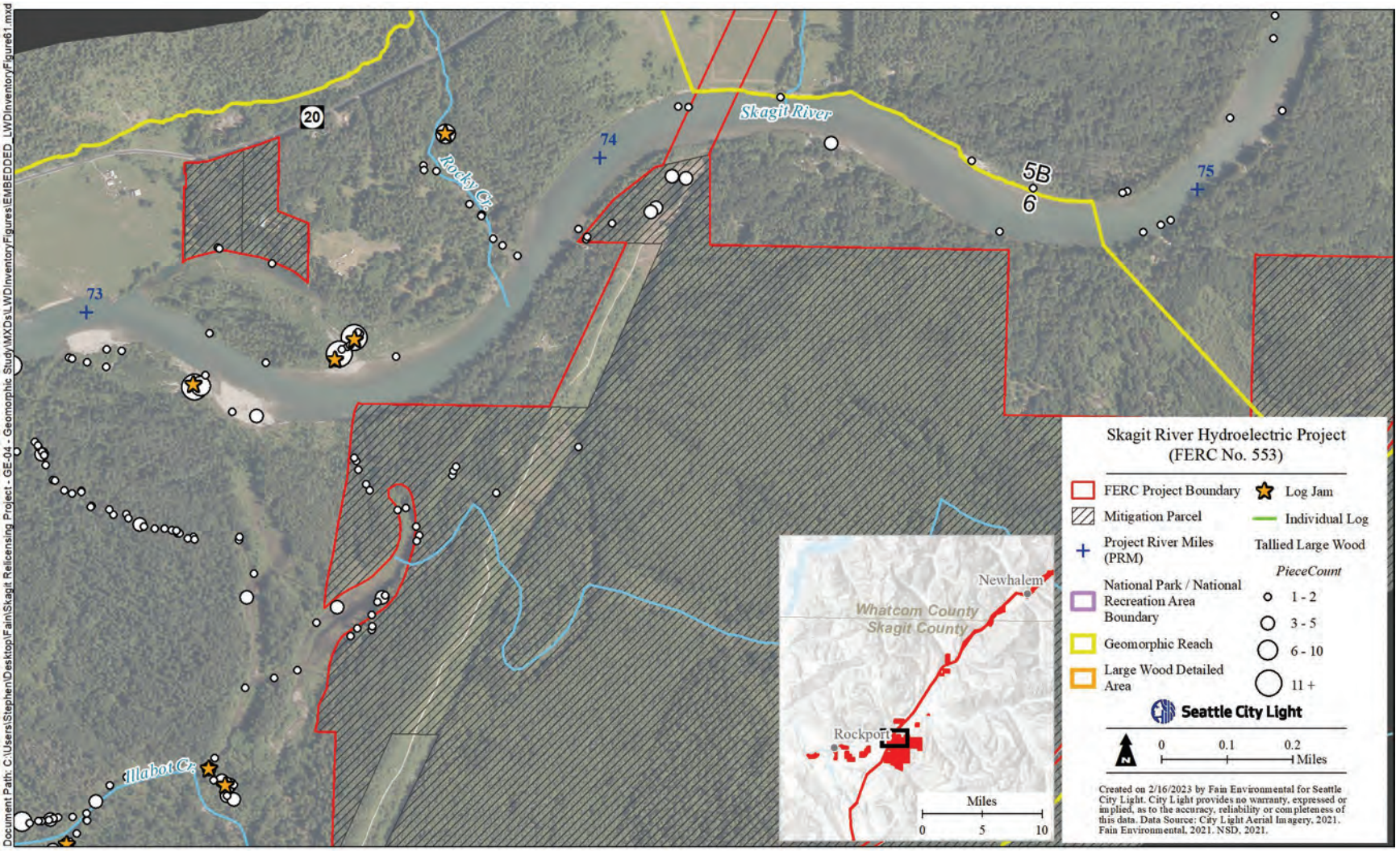


Figure 5.6-23. Large wood August 2021 field inventory for upper section of Reach 6.

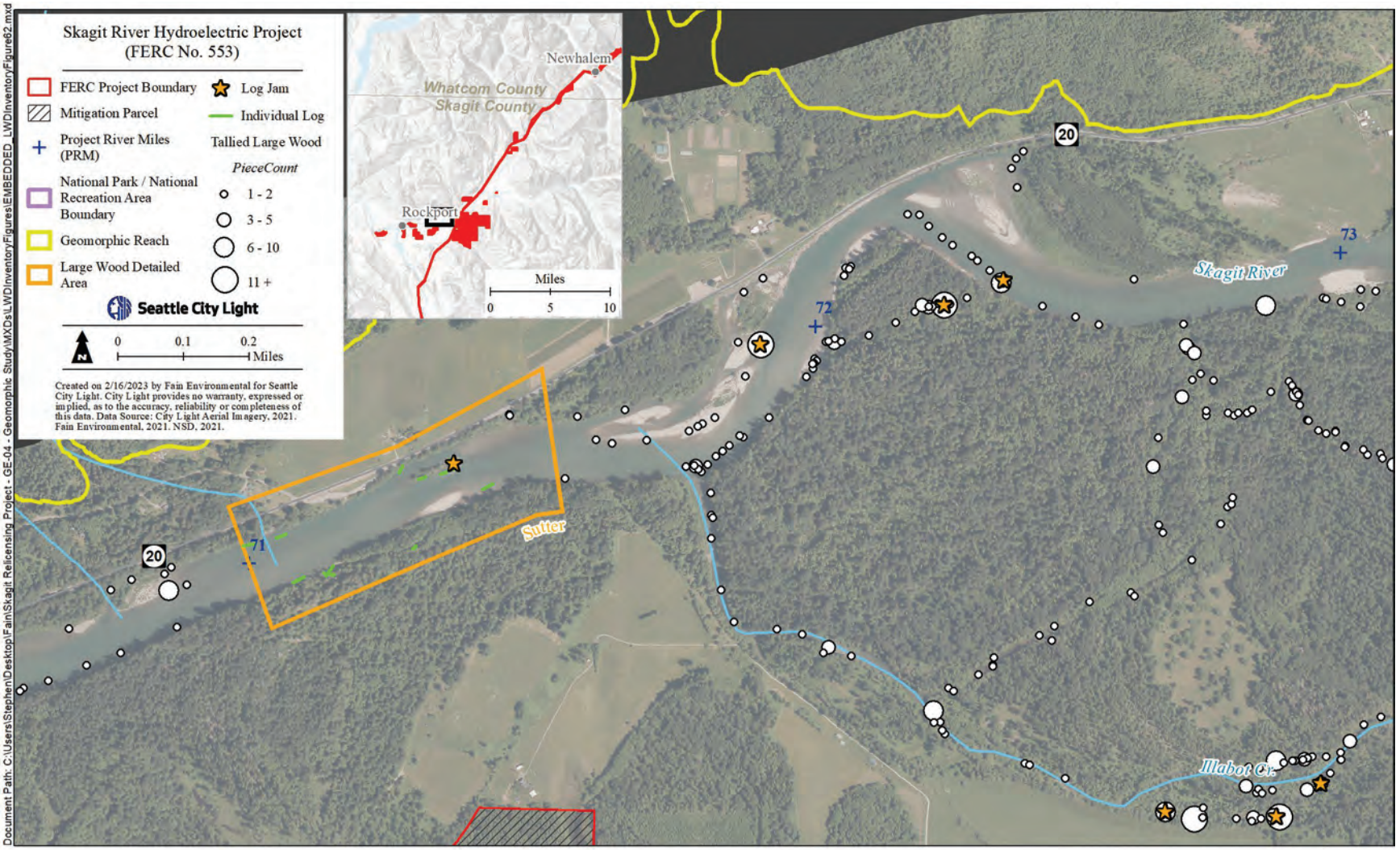


Figure 5.6-24. Large wood August 2021 field inventory for middle section of Reach 6.

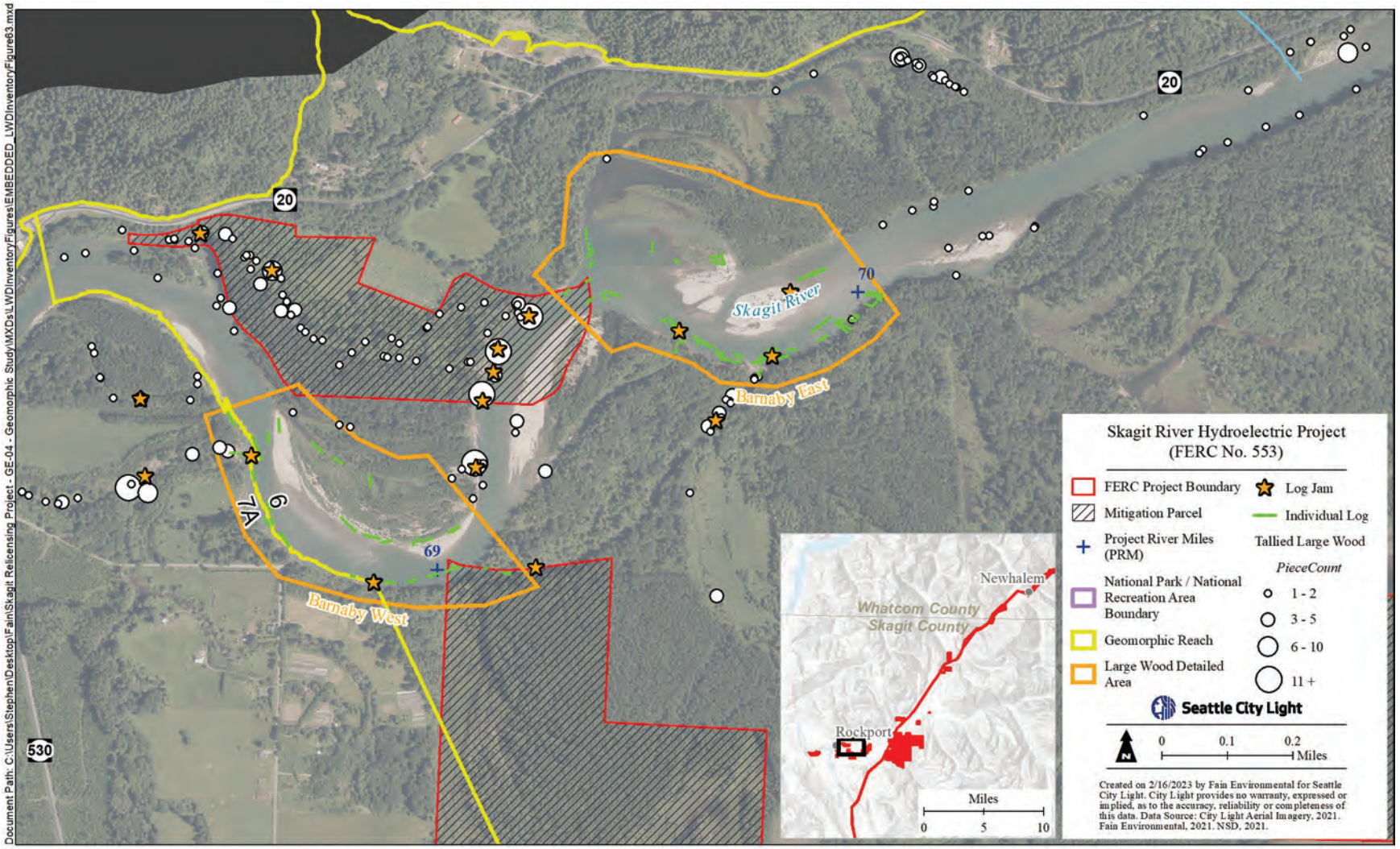


Figure 5.6-25. Large wood August 2021 field inventory for lower section of Reach 6.



Figure 5.6-26. **Looking downstream at PRM 72.1. Right arrow is dolosse revetment structure along roadside bank, center arrow is dolosse apex jam, and left arrow is natural apex jam at PRM 72.0. Large wood Tag ID 65 is in the central dolosse apex jam. Large wood Tag ID 67 is in the natural apex jam on the left. Photo is taken August 5, 2021.**



Figure 5.6-27. **Large apex jam that has persisted for 42 years at head of forested island at PRM 71.4, looking downstream. Forested island contains two large wood pieces on the left side that are tagged (Tag ID 16 and 17). Photo taken August 5, 2021.**



Figure 5.6-28. Bar apex inlet jam at entrance to Boh's Slough side channel located at PRM 68.6 on river left. Flow is from left to right. Inlet jam contains tagged large wood pieces 159 and 160. Photo taken August 3, 2021.



Figure 5.6-29. Log jam located on Illabot Creek just upstream of confluence with Illabot side channel complex. Photo is looking upstream taken on August 26, 2021.

5.6.6.10 Reach 7A

Table 5.6-29 presents the wood count, rootwad count, and percentage with rootwad by location for Geomorphic Reach 7A. Figure 5.6-30 includes Reach 7A and 7B. The study team identified approximately 414 pieces in Reach 7A of which 90 had rootwads (Table 5.6-29). There were six log jams in the mainstem and three jams in the side channel (Figure 5.6-31). Six of the nine log jams were forming pools.

Table 5.6-29. Large wood count, rootwad count, and rootwad percentage for Geomorphic Reach 7A.

Location	Wood Count	Rootwad Count	Percentage with Rootwad
Mainstem	63	32	51%
Side Channels	110	58	53%
In Log Jams	241	N/A	N/A
Total	**414**	**90**	**22%**

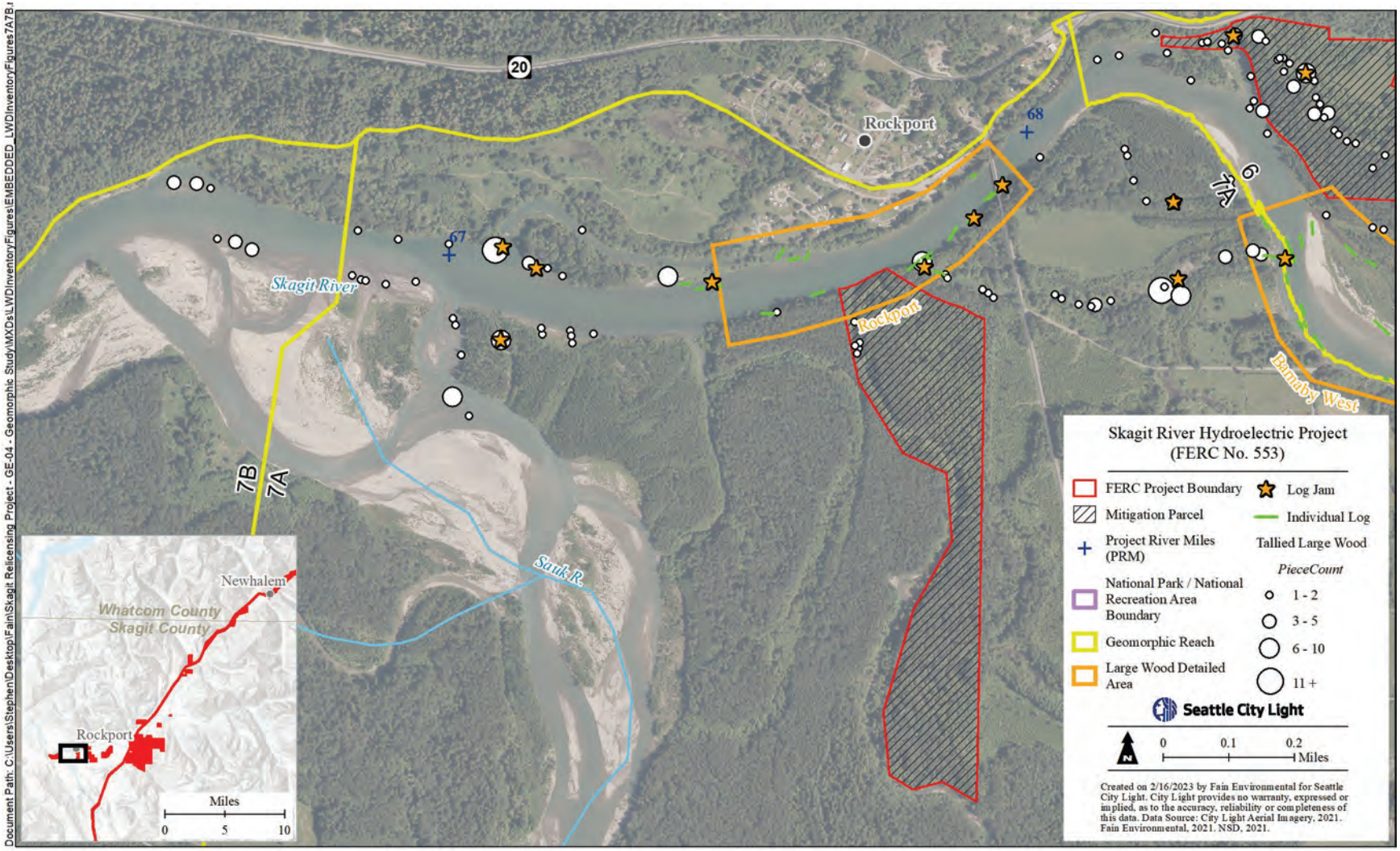


Figure 5.6-30. Large wood August 2021 field inventory for Reach 7A and 7B.



Figure 5.6-31. Medium log jam located in Boh's Slough between PRM 67.6 and 68.6. Photo is looking upstream and was taken on August 10, 2021.

5.6.6.11 Reach 7B

Fieldwork for LWD inventory only included approximately 0.3 miles of the upstream area in Reach 7B. Figure 5.6-30 includes Reach 7A and 7B. Historical LWD inventory using aerial photos (1979-2019) was not completed in reach 7B because it is downstream of the primary study area. The total number of pieces counted in August 2021 was 20 of which four had rootwads. Four large wood pieces in Reach 7B at PRM 66.6 are presented in Figure 5.6-32.



Figure 5.6-32. Four large wood pieces in Reach 7B at PRM 66.6 on river right. Flow is from right to left. Photo taken August 5, 2021.

5.6.7 Stability of Large Wood between April 2018 and June 2022

Stability of individual large wood pieces based on aerial photography between April 2018 and June 2022 is presented in Table 5.6-30. The large wood stability from April 2018 to May 2021 was approximately 35 percent. During this time, the highest flow at Marblemount gage was 31,300 cfs. The large wood stability between May 2021 and August 2021 was 57 percent. During this time, the highest flow at Marblemount gage was 18,500 cfs. The large wood stability between August 2021 and June 2022 was 4 percent. This time period included high flow event on the Skagit River on November 15-16, 2021, with a peak at Marblemount of 63,400 cfs. The peak stream flow at the Newhalem and Marblemount gages were between a 2- and 10-yr recurrence interval. The large wood stability between individual large wood pieces identified in May 2021 and June 2022 aerials was 13 percent.

Table 5.6-30 Summary of large wood stability between April 2018 and June 2022.

Time Period	USGS Skagit River at Marblemount gage (12181000)		Unstable Large Wood Pieces		Stable Large Wood Pieces		Total Pieces
	Highest Flow (cfs)	Date of Highest Flow	Number of Pieces	Percentage	Number of Pieces	Percentage	
April 2018 - May 2021[1]	31,300	2/1/2020	231	65%	126	35%	357
May 2021 - August 2021[2]	18,500	6/30/2021	36	43%	48	57%	84
August 2021[2] - June 2022	63,400	11/15/2021	262	96%	12	4%	274
May 2021 - June 2022	63,400	11/15/2021	187	87%	27	13%	214

1 April 2018 to May 2021 used 5-ft buffer around 2018 and 2019 imagery to detect pieces still present in 2021.
2 August 2021 includes only the 5 miles of detailed inventory areas.

The next sections focus on stability analysis from May 2021 to August 2021; and August 2021 to June 2022. The analysis included an examination of aerial photos from May 2021 and June 2022, as well as the detailed area field inventory collected in August 2021.

5.6.7.1 Stability of Large Wood between May 2021 to August 2021

Stability between May 2021 and August 2021 was compared to mean length, diameter, rootwad diameter, and total volume of each piece of large wood (Table 5.6-31). On average, stable pieces had a greater length, diameter, rootwad diameter, and volume.

Table 5.6-31 Summary of large wood stability between May 2021 to Aug 2021.

Attribute	Mean Stable Piece	Number of Stable Pieces	Mean Unstable Piece	Number of Unstable Pieces	Total Number of Pieces
Length	68 ft	48	64 ft	36	84
Diameter	2.4 ft	48	2.0 ft	36	84
Rootwad Diameter	6.9 ft	48	3.4 ft	36	84
Volume	2139 cu ft	48	525 cu ft	36	84

Length

There were 48 stable pieces with a mean length of approximately 68 ft and 84 unstable pieces with a mean length of approximately 64 ft., On average, the 48 stable pieces were 4 ft longer than the 84 unstable pieces.

The group containing large wood between 75 and 100 ft in length had the highest percentage of stable large wood, at 64.3 percent stable. The lowest percentage of stable large wood was between 50 and 75 ft in length, at 40 percent stable.

Diameter

There were 48 pieces with a mean diameter of approximately 2.4 ft and 84 unstable pieces with a mean diameter of approximately 2.0 ft. On average, the 48 stable pieces had a 0.4 ft larger diameter than the 84 unstable pieces The group containing large wood with a diameter at breast height (dbh) between 4 and 5 ft had the highest percentage of stable large wood, at 100 percent stable. There were only three pieces in this group. The second highest percentage included large wood with a dbh between 3 and 4 ft, at 70 percent stable. The lowest percentage of stable large wood had a dbh between 1 and 2 ft, at 49 percent stable.

Rootwad Diameter

There were 48 stable pieces with a mean rootwad diameter of approximately 6.9 ft and 84 unstable pieces with a mean rootwad diameter of approximately 3.4 ft. On average, the 48 stable pieces had a 3.5 ft larger rootwad diameter than the 84 unstable pieces.

The group containing large wood with a rootwad diameter greater than 15 ft had the highest percentage of stable large wood, at 100 percent stable. There were 7 pieces in this group. The second highest percentage included large wood with a rootwad diameter between 10 and 15 ft, at 79 percent stable. The lowest percentage of stable large wood had a rootwad diameter between 1 and 3 ft, at 46.2 percent stable.

Volume

There were 48 pieces with a mean volume of approximately 2139 cu ft and 84 unstable pieces with a mean volume of approximately 525 cu ft. On average, the 48 stable pieces had a 1614 cu ft greater volume than the 84 unstable pieces.

The group containing large wood with a volume greater than 2000 cu ft had the highest percentage of stable pieces, at 86 percent stable (Figure 5.6-33). The second highest percentage included large wood with a volume between 1000 and 2000 cubic ft, at 80 percent stable (Figure 5.6-33). The lowest percentage of stable large wood had a volume between 100 and 200 cu ft, at 27 percent stable (Figure 5.6-33).

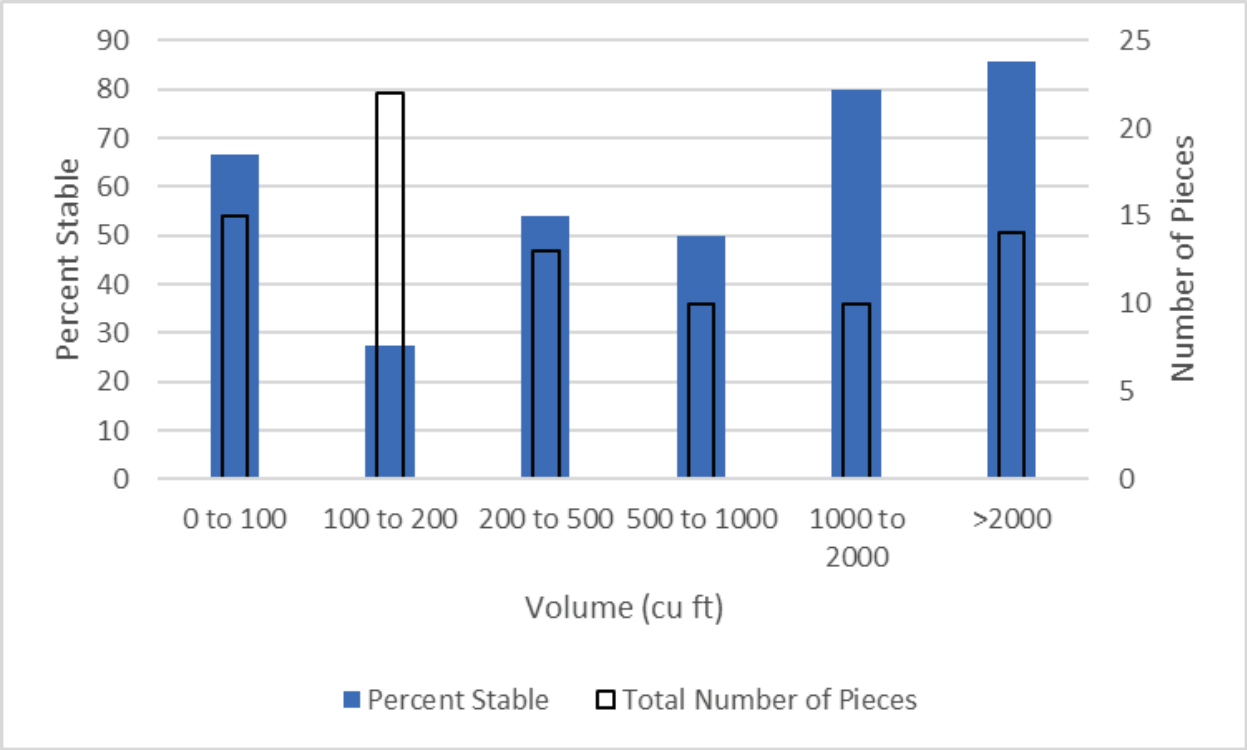


Figure 5.6-33. Percent of stable large wood pieces versus piece volume from May 2021 to August 2021. Stability of Large Wood between August 2021 to June 2022

5.6.7.2 Stability of Large Wood between August 2021 to June 2022

Stability between August 2021 and June 2022 was compared to mean length, diameter, rootwad diameter, and total volume of each piece of large wood. The overall stability was 4 percent during this time period. On average, stable pieces had a greater length, diameter, rootwad diameter, and volume. (Table 5.6-32).

Table 5.6.32. Summary of large wood stability from Aug 2021 to June 2022.

Attribute	Mean Stable Piece	Number of Stable Pieces	Mean Unstable Piece	Number of Unstable Pieces	Total Number of Pieces
Length	74 ft	12	61 ft	262	274
Diameter	2.6 ft	12	2.0 ft	262	274
Rootwad Diameter	8.2 ft	12	4.8 ft	262	274
Volume	2867 cu ft	12	871 cu ft	262	274

Length

There were 12 stable pieces with a mean length of approximately 74 ft and 262 unstable pieces with a mean length of approximately 61 ft. On average, the 12 stable pieces were 13 ft longer than the 262 unstable pieces.

The group containing large wood between 125 and 150 ft in length had the highest percentage of stable large wood, at 25 percent stable. The lowest percentage of stable large wood were between 25 and 50 ft in length, at 1.8 percent stable, followed closely by those that were between 50 and 75 ft in length, at 5.7 percent stable.

Diameter

There were 12 stable pieces with a mean diameter of approximately 2.6 ft and 262 unstable pieces with a mean diameter of approximately 2.0 ft. On average, the 12 stable pieces had a 0.6 ft larger diameter than the 262 unstable pieces.

The group containing large wood with diameter at breast height (dbh) between 3 and 4 ft had the highest percentage of stable large wood, at 17.4 percent stable. The second highest percentage included large wood with a dbh between 2 and 3 ft, at 10 percent stable. The lowest percentage of stable large wood had a dbh between 4 and 5 ft, at 0 percent stable.

Rootwad Diameter

There were 12 stable pieces with a mean rootwad diameter of approximately 8.2 ft and 274 unstable pieces with a mean rootwad diameter of approximately 4.8 ft. On average, the 12 stable pieces had a 3.4 ft larger rootwad diameter than the 262 unstable pieces. The group containing large wood with a rootwad diameter estimated at greater than 15 ft had the highest percentage of stable large wood, at 22.2 percent stable. The second highest percentage included large wood with a rootwad diameter between 10 and 15 ft, at 6.7 percent stable. The lowest percentage of stable large wood had a rootwad diameter between 6 and 10 ft, at 2.4 percent stable.

Volume

There were 12 stable pieces with a mean volume of approximately 2867 cu ft and 273 unstable pieces with a mean volume of approximately 871 cu ft. On average, the 12 stable pieces had a 1996 cu ft greater volume than the 262 unstable pieces.

The groups containing large wood with a volume between 500 and 1000 cubic ft, and greater than 2000 cubic ft had the highest percentages of stable large wood, both at 12.5 percent stable. The second highest percentage included large wood with a volume greater than 2,000 cubic ft, at 3.5 percent stable. The lowest percentage of stable large wood had a volume between 100 and 200, and 1000 to 2000 cubic ft, at 0 percent stable. (Figure 5.6-34).

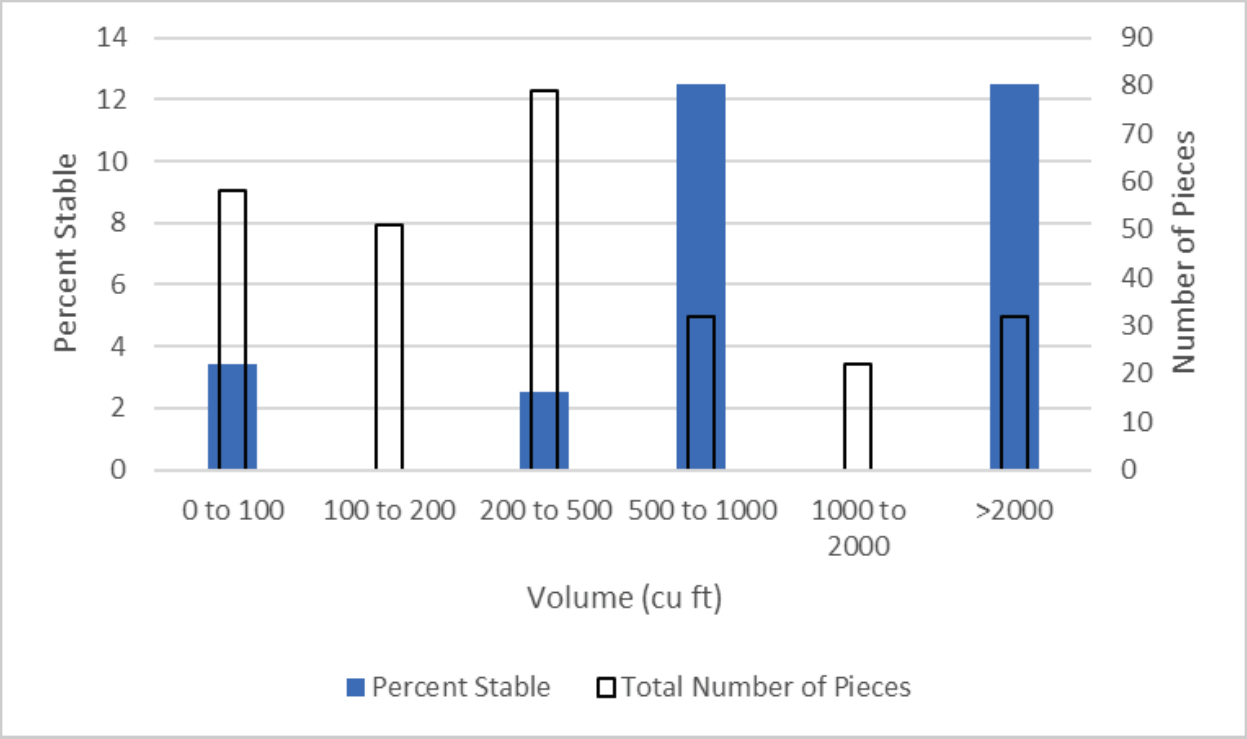


Figure 5.6-34 Percent of stable large wood pieces versus volume of large wood pieces from August 2021 to June 2022.

5.7 Large Wood Transport

Large wood tracking, transport, and augmentation was analyzed in combination with the Upper Skagit Hydraulic Model results from the FA-02 Instream Flow Model Development Study (City Light 2023a). The tracking provided results to understand thresholds for motion of pieces by size and river discharge, transport distance, relationship between rootwads and mobility, jam stability, and potential recruitment areas.

5.7.1 Large Wood Tracking

Between October 13, 2021, and March 31, 2022, the study team installed radio tags and metal tags on 198 pieces of wood (Table 5.7-1). These tags were placed on large wood in the mainstem, tributaries, and side channels. A detailed table and map location of pieces of tagged wood is shown in Attachment K. Of these 198 pieces, 36 pieces were tagged and released into the mainstem river on December 9, 2021. Most wood that is stored at the Agg pond site accumulated at Ross Lake Dam and was removed under the current license's wood management protocols. These pieces are cut to 13 ft or less because of the difficulties involved with transporting wood around hairpin turns on the haul road below Ross Dam. A summary of the pieces that have been tagged by geomorphic reach is shown in Table 5.7-1. The wood being stored at the Agg Pond site was released into the mainstem river on December 9, 2021.

Table 5.7-1. Number of large wood pieces tagged between October 13, 2021 and March 31, 2022 by geomorphic reach.

Geomorphic Reach	Tagged Large Wood Pieces
2A	3
2B	63[1]
3A	3
4	8
3B	21
5A	17
5B	30
6	47
7A	6
7B	0
Total	198

1 Piece count includes 28 Ross Lake logs and 8 Agg Pond locally recruited logs.

The study team monitored and tracked large wood that has been tagged after flows greater than 15,000 cfs at the USGS Skagit River at Marblemount gage (12181000). The first peak of this magnitude during the study period occurred on October 28 to 29, 2021. (Table 5.7.2, Figure 5.7-1).

Table 5.7-2. Peak flows in the Skagit River, Sauk River, Bacon Creek, Newhalem Creek, and Cascade River on October 28-29, 2021.

Location	USGS Gage	Peak Flow (cfs)	Date and Time
Skagit River at Newhalem	12178000	10,200	10/28/2021, 7:15pm
Newhalem Creek	12178100	2,650	10/28/2021, 8:30pm
Bacon Creek	12179900	4,640	10/28/2021, 8:45pm
Skagit River at Marblemount	12181000	29,100	10/28/2021, 9:45pm
Cascade River at Marblemount	12182500	9,170	10/28/2021, 11:30pm
Sauk River at Sauk	12189500	52,900	10/29/2021, 3:00am

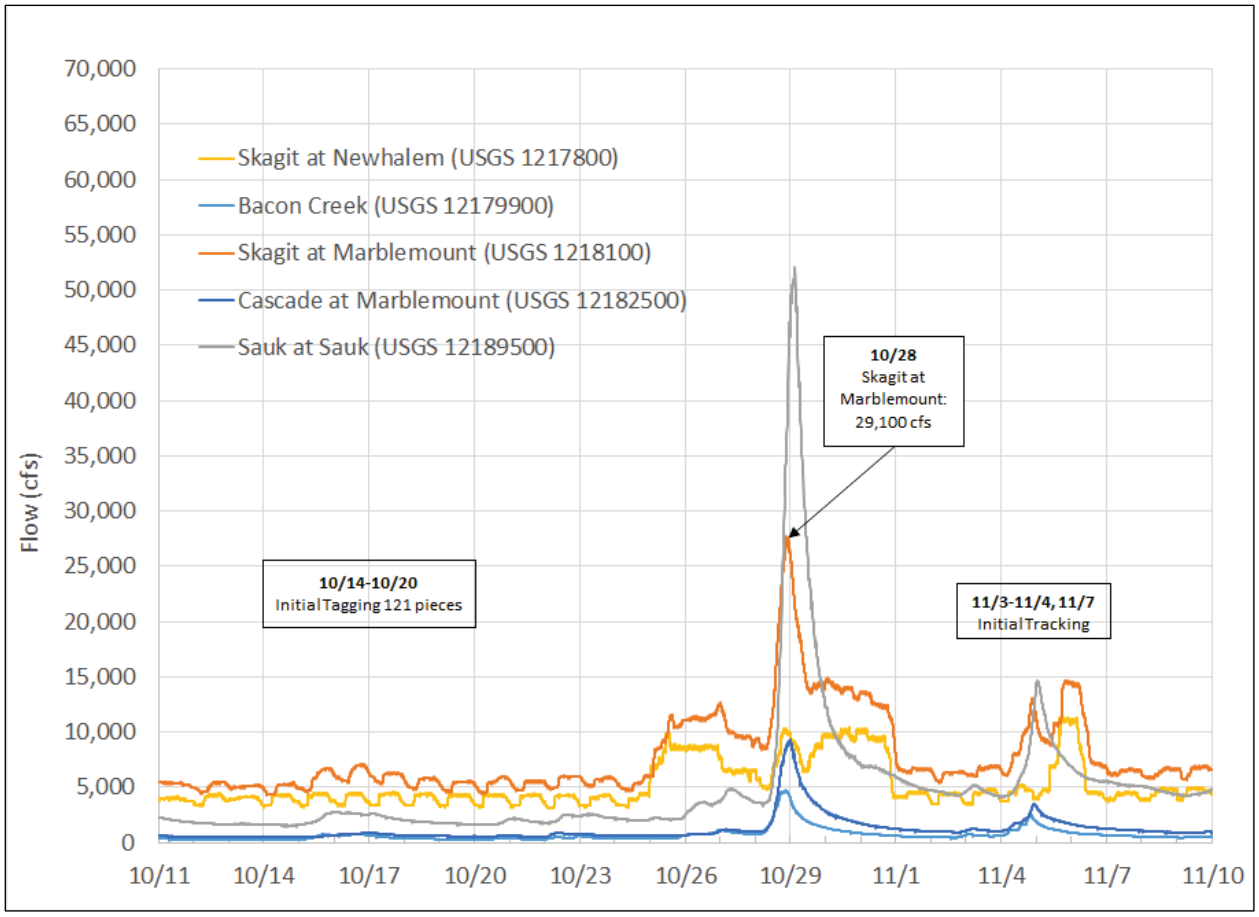


Figure 5.7-1. October 28-29, 2021 large flow event in the Skagit River, Sauk River, Bacon Creek, and Skagit River.

The study team completed tracking efforts related to this flow event in the primary study area on November 3, 4, and 11, 2021. Additionally, the team tracked wood downstream of the study area in some locations along the lower Skagit River from the shoreline between Concrete and Sedro Wooley on November 7 and 25, 2021. During the initial tracking efforts, after the October large flow event, 39 of the 121 pieces that had been tagged up to that date had moved at least 100 ft. At least five of the pieces of large wood moved 10-60 miles and were transported downstream of the Sauk River, outside of the primary study area.

From November 12 to 16, 2021, there were two large flow events in the Skagit River, Sauk River, and tributaries (Figure 5.7-2). The peak flows during these flow events are shown in Table 5.7-3.

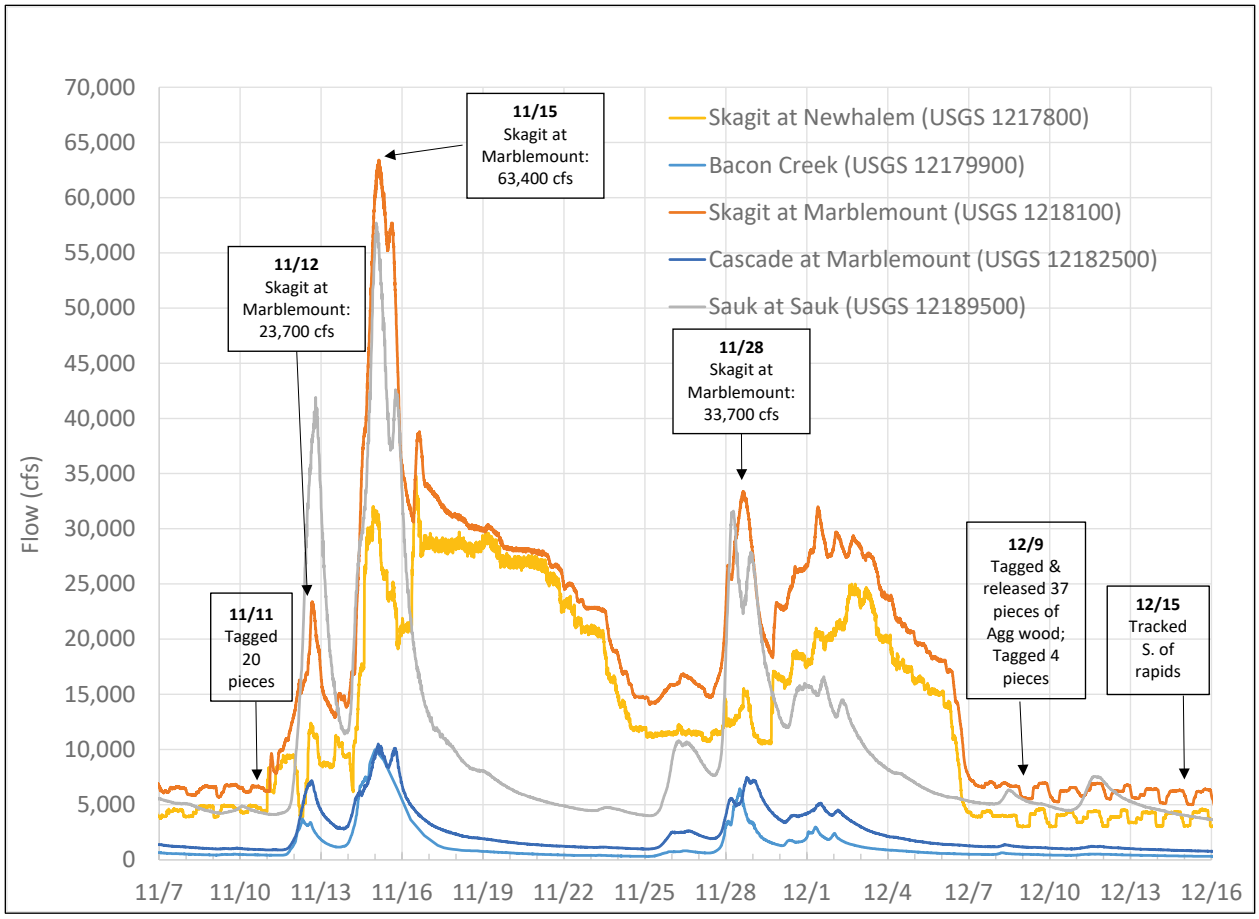


Figure 5.7-2. November large flow events in the Skagit River, Sauk River, Bacon Creek, and Cascade River.

Table 5.7-3. Peak flows in the Skagit River, Sauk River, Bacon Creek, Newhalem Creek, and Cascade River on November 15-16 2021.

Location	USGS Gage	Peak Flow (cfs)	Date and Time
Skagit River at Newhalem	12178000	33,700	11/16/2021, 12:35pm
Newhalem Creek	12178100	5,110	11/15/2021, 12:30am
Bacon Creek[1]	12179900	8,980[1]	11/15/2021, 12:00am
Skagit River at Marblemount	12181000	63,400	11/15/2021, 3:20am
Cascade River at Marblemount	12182500	10,500	11/15/2021, 3:00am
Sauk River at Sauk	12189500	57,800	11/15/2021, 1:15am

1 Peak flow at the Bacon Creek gage was estimated by USGS because the gage was not working from November 14, 2021 at 7pm, until November 18, 2021 at 12:30pm.

Tracking after the November 2021 flood occurred in the primary study area downstream of the rapids at PRM 86.5 on December 15, 2021. Two low magnitude peak flow events occurred on January 12 and March 1, 2022 (Figure 5.7-3; Table 5.7-4, Table 5.7-5). Tracking in the study area upstream of the rapids at PRM 86.5 did not occur until March 11, 2022, due to accessibility in the upper reach being disrupted by the November 12 to December 6, 2021, high flow events.

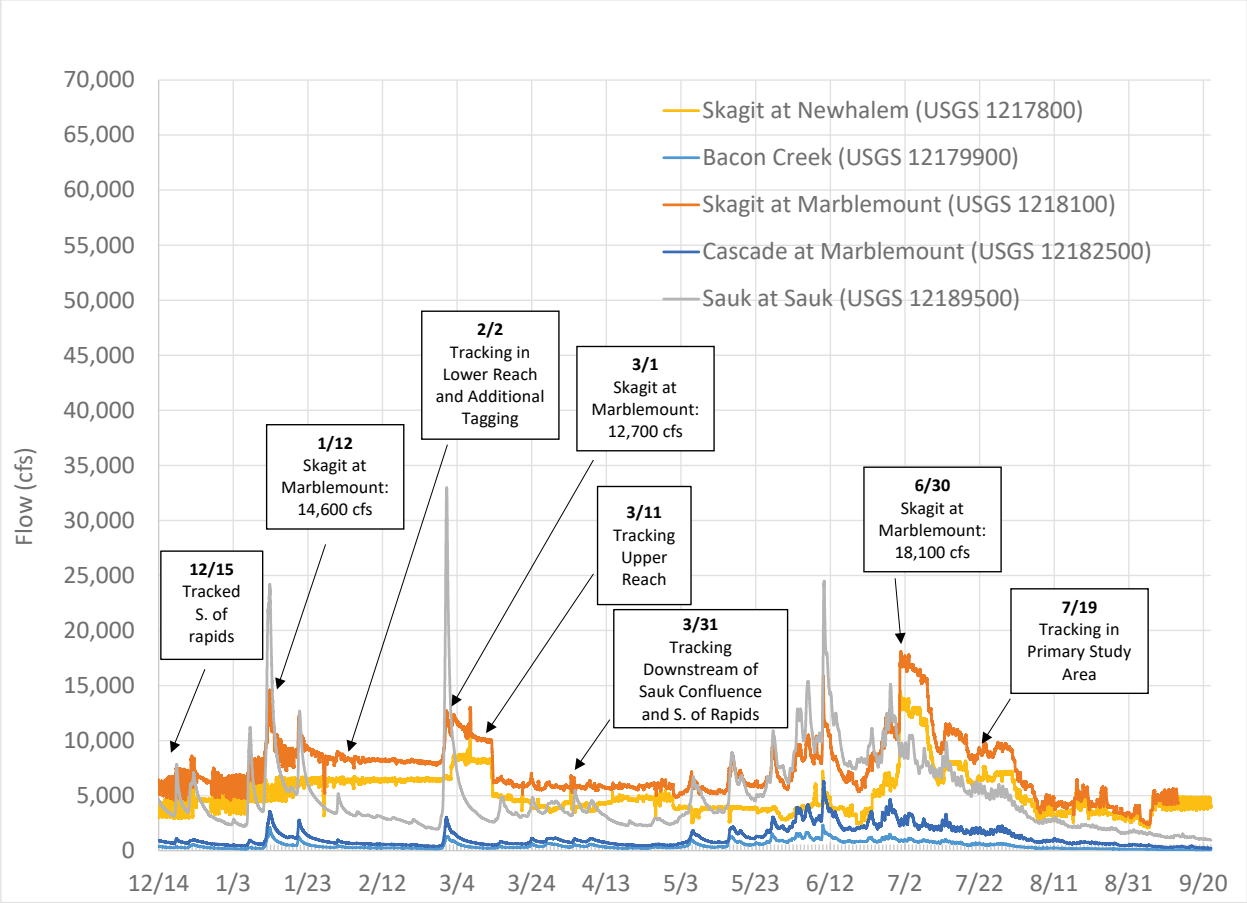


Figure 5.7-3. December 2021 to September 2022 high flow events and tracking efforts in the Skagit River primary study area.

Table 5.7-4. Peak flows in the Skagit River mainstem, Sauk River, Bacon Creek, Newhalem Creek and Cascade River on January 12, 2022.

Location	USGS Gage	Peak Flow (cfs)	Date and Time
Skagit River at Newhalem	12178000	6,040	1/12/2022, 4:45am
Newhalem Creek	12178100	1,480	1/12/2022, 6:00pm
Bacon Creek	12179900	2,130	1/12/2022, 6:00pm
Skagit River at Marblemount	12181000	14,600	1/12/2022, 7:05pm
Cascade River at Marblemount	12182500	3,570	1/12/2022, 7:00pm
Sauk River at Sauk	12189500	24,200	1/12/2022, 7:00pm

Table 5.7-5. Peak flows in the Skagit River mainstem, Sauk River, Bacon Creek, Newhalem Creek and Cascade River on March 1, 2022.

Location	USGS Gage	Peak Flow (cfs)	Date and Time
Skagit River at Newhalem	12178000	6,860	3/1/2022, 1:20am
Newhalem Creek	12178100	1,120	3/1/2022, 3:45am
Bacon Creek	12179900	1,300	3/1/2022, 4:15am
Skagit River at Marblemount	12181000	12,700	3/1/2022, 3:30am
Cascade River at Marblemount	12182500	3,040	3/1/2022, 3:15am
Sauk River at Sauk	12189500	33,000	3/1/2022, 4:45am

On March 31, 2022, tracking efforts were expanded downstream of the primary study area from the Sauk confluence to the Skagit River delta to try to locate pieces that had moved out of the primary study area, as well as within the primary study area downstream of the rapids at PRM 86.5. A high magnitude flow release event occurred on June 30, 2022, and created a high discharge event in the Skagit River mainstem (Table 5.7-6 and Figure 5.7-3). The final round of tracking in the primary study area both upstream and downstream of the rapids occurred on July 19, 2022.

Table 5.7-6. Peak flows in the Skagit River mainstem, Sauk River, Bacon Creek, Newhalem Creek and Cascade River on June 30, 2022.

Location	USGS Gage	Peak Flow (cfs)	Date and Time
Skagit River at Newhalem	12178000	14,500	6/30/2022, 7:05pm
Newhalem Creek	12178100	693	6/30/2022, 11:30pm
Bacon Creek	12179900	994	6/30/2022, 10:00pm
Skagit River at Marblemount	12181000	18,100	6/30/2022, 9:45pm
Cascade River at Marblemount	12182500	2,920	6/30/2022, 12:15am
Sauk River at Sauk	12189500	10,300	6/30/2022, 12:15am

Large wood scanning efforts resulted in a recovery rate between 39 and 100 percent of pieces where movement was detected between scanning periods (Table 5.7-7). The March 29 to March 31, 2022, scanning effort included the Skagit River mainstem downstream of the Sauk River confluence to the Puget Sound. This scanning effort recovered 25 pieces downstream of the Sauk River confluence. These pieces moved from the primary study area into the region downstream of the Sauk River confluence sometime between the initial deployment of the tagged large wood pieces and the March 29 to March 31, 2022 scanning effort.

Table 5.7-7. Tagged large wood piece recovery rate of pieces where movement was detected.

Scanning Period	Total Recovered Pieces where Movement was Detected		Total Pieces Where Movement was Detected	
	Number of Pieces	Percentage	Number of Pieces	Percentage
11/3/21 - 11/13/21	12	39%	31	100%
12/14/21 - 12/20/21	33	54%	61	100%
2/2/22	10	100%	10	100%
3/29/22 - 3/31/22[1]	34	83%	41	100%
7/18/22	18	51%	35	100%
All Scanning Periods	**107**	**60%**	**178**	**100%**

1 Scanning was conducted downstream of the Sauk confluence. Pieces whose movement was detected, but not recovered in previous scanning efforts, were recovered in this scanning effort.

5.7.2 Large Wood Transport

Large wood transport results are discussed in the following two subsections. The large wood transport analysis was completed using the results of the large wood tracking study. The Upper Skagit Hydraulic Model was utilized for additional analysis of the large wood transport.

5.7.2.1 Large Wood Transport Analysis

Large wood transport analysis was informed by the results of the large wood tracking effort. A summary of large wood pieces that remained stable as opposed to those that were mobile for one or more instance during the study period, between October 2021 and July 2022, is included in Table 5.7-8. This table also discerns the difference in mobility between natural large wood pieces and wood pieces placed in the water from the Aggregate Pond site.

Table 5.7-8. Natural large wood and Aggregate Pond wood mobility during large wood tracking study period, between October 2021 and July 2022.

Mobility	Natural Large Wood		Aggregate Pond Wood	
	Number of Pieces	Percentage	Number of Pieces	Percentage
Mobile	107	66%	36	100%
Stable	55	34%	0	0%
Total	**162**	**100%**	**36**	**100%**

Large wood tracking results were associated to flood events that occurred over the course of the tracking study period. Individual large wood piece movement or stability was associated to the highest magnitude flow recorded at the USGS Skagit River at Marblemount gage (12181000) between a pieces known location recorded from tracking efforts. The study team examined three flood events that occurred over the course of the tracking effort. These are the flood events that occurred on October 28-29, 2021, November 15-16, 2021, and January 12, 2022. The large wood transport results of these three high flow events are reported in summary in Table 5.7-9 and detail in Attachment L.

Table 5.7-9. Large wood transport results of pieces that moved and remained stable in high flow events between October 2021 and June 2022.

High Flow Event Dates	Large Wood Pieces that Moved		Large Wood Pieces that Remained Stable		Total Pieces Scanned
October 28-29, 2021	36	31%	80	69%	116
November 15-16, 2022	74	63%	43	37%	117
January 12, 2022	11	14%	65	86%	76
March 1, 2022	8	10%	74	90%	82
June 30, 2022	35	21%	134	79%	169

Large wood transport characteristics of the October 28-29, 2021, storm are reported in Table 5.7-10 and Table 5.7-11. Table 5.7-10 describes the characteristics of where large wood pieces moved from, as well as where large wood pieces remained stable. Table 5.7-11 describes where pieces that moved ultimately deposited. In the following tables 5.7-10 through 5.7-15 the term "undetermined" is used. This term describes the scenario in which a large wood piece location was determined approximately but not precisely using the radio tag scanning device described in 4.7.1. "Undetermined" large wood pieces also describe a scenario when a large wood piece was not found at all in the primary study area but was confirmed to move. Movement was confirmed when a piece could not be found at its last known precise location. Due to this, a characteristic location in the channel could not be confidently prescribed to these pieces and their locations were considered "undetermined."

Table 5.7-10. Large wood pieces that moved from or remained stable in locations within the Skagit River primary study area during the October 28-29, 2021 storm.

Initial Location	Number of Pieces that Moved	Number of Pieces that Remained Stable	Percentage of Pieces that Moved	Percentage of Pieces that Remained Stable
On Bank	10	41	20%	80%
Point Bar	7	2	78%	22%
Mid Channel Bar	6	8	43%	57%
Racked in Log Jam	5	12	29%	71%
Wetted Channel	5	12	29%	71%
Lateral Bar	3	5	38%	63%
All Locations	**36**	**80**	**31%**	**69%**

Table 5.7-11. Deposition location of large wood pieces that moved during the October 28-29, 2021 storm.

Deposition Location	Number of Pieces that Deposited	Percentage of Pieces that Deposited
On Bank	0	0%
Point Bar	4	11%
Mid Channel Bar	1	3%
Racked in Log Jam	9	25%
Wetted Channel	1	3%
Lateral Bar	0	0%
Undetermined	21	58%
All Locations	**36**	**100%**

Large wood transport characteristics of the November 15-16, 2021 storm are reported in Table 5.7-12 and Table 5.7-13. Table 5.7-12 describes the characteristics of where large wood pieces moved from as well as where large wood pieces remained stable. Table 5.7-13 describes where pieces that moved ultimately deposited.

Table 5.7-12. Large wood pieces that moved from or remained stable in locations within the Skagit River primary study area during the November 15-16, 2021 storm.

Initial Location	Number of Pieces that Moved	Number of Pieces that Remained Stable	Percentage of Pieces that Moved	Percentage of Pieces that Remained Stable
On Bank	29	19	60%	40%
Point Bar	9	5	64%	36%
Mid Channel Bar	7	1	88%	13%
Racked in Log Jam	17	6	74%	26%
Wetted Channel	9	9	50%	50%
Lateral Bar	3	2	60%	40%
Undetermined	0	1	0%	100%
All Locations	**74**	**43**	**63%**	**37%**

Table 5.7-13. Deposition location of large wood pieces that moved during the November 15-16, 2021 storm.

Deposition Location	Number of Pieces that Deposited	Percentage of Pieces that Deposited
On Bank	7	9%
Point Bar	1	1%
Mid Channel Bar	2	3%
Racked in Log Jam	13	18%
Wetted Channel	1	1%
Lateral Bar	0	0%
Undetermined	50	68%
All Locations	**74**	**100%**

Large wood transport characteristics of the January 12, 2022 storm are reported in Table 5.7-14 and Table 5.7-15. Table 5.7-14 describes the characteristics of where large wood pieces moved from as well as where large wood pieces remained stable. Table 5.7-15 describes where pieces that moved ultimately deposited.

Table 5.7-14. Large wood pieces that moved from or remained stable in locations within the Skagit River primary study area during the January 12, 2022 storm.

Initial Location	Number of Pieces that Moved	Number of Pieces that Remained Stable	Percentage of Pieces that Moved	Percentage of Pieces that Remained Stable
On Bank	0	20	0%	100%
Point Bar	0	4	0%	100%
Mid Channel Bar	0	0	N/A	N/A
Racked in Log Jam	0	14	0%	100%
Wetted Channel	0	6	0%	100%
Lateral Bar	0	4	0%	100%
Undetermined	11	17	39%	61%
All Locations	**11**	**65**	**14%**	**86%**

Table 5.7-15. Deposition location of large wood pieces that moved during the January 12, 2022 storm.

Deposition Location	Number of Pieces that Deposited	Percentage of Pieces that Deposited
On Bank	0	0%
Point Bar	0	0%
Mid Channel Bar	0	0%
Racked in Log Jam	0	0%
Wetted Channel	0	0%
Lateral Bar	0	0%
Undetermined	11	100%
All Locations	**11**	**100%**

Similar to the January 2022 large wood transport characteristics, large wood pieces that moved during the March 1, 2022 and June 30, 2022 high flow events included only large wood movement data with undetermined deposition locations. This was due to field logistics requiring both scanning efforts to be quick scans that did not gather precise deposition location data for large wood pieces that moved. For this reason, tables similar to 5.7-12 through 5.7-15 are not reported for either of these events. Results of the total portion of large wood pieces that moved during all five of these events is reported in Table 5.7-9.

Large wood transport results were associated to the geomorphic reaches being used for analysis in this report. Large wood transport results were used to inform which geomorphic reach displayed characteristics of a large wood accumulation zone and which geomorphic reaches displayed characteristics of a large wood transport zone. For this report, a large wood accumulation zone is defined as an area where mobile large wood in the Geomorphology Study stabilized a higher percentage of the time when transporting through a reach. A large wood transport zone is defined as an area where mobile large wood in the Geomorphology Study stabilized a lower percentage of the time when transporting through a reach. To clarify these definitions are informed by the results of the large wood transport data alone with no association to channel complexity or other channel characteristics. For this analysis, tagged Agg Pond wood pieces were not examined as they do not reflect naturally recruited mobile large wood in the Skagit River. As described previously, Agg Pond wood pieces, which are transported to the site from Ross Lake did not all meet the size criteria the study team has defined for “large wood.” Also, they are not recruited through natural tributary or bank recruitment processes. Tables describing the result of the large wood accumulation zone study are included below (Table 5.7-16, Table 5.7-17).

Table 5.7-16. Reach-scale large wood accumulation data of natural mobile large wood that was tagged, displayed as a number of pieces.

Geomorphic Reach	Initially Tagged in the Reach	Initially Tagged, then Left the Reach	Initially Tagged and Stayed in the Reach	Moved into the Reach	Moved into the Reach and Stayed	Moved into the Reach, Stayed, and then Left	Moved through the Reach
2A	3	3	0	0	0	0	0
2B	27	16	11	3	1	0	2
3A	3	0	3	18	0	0	18
4	8	5	3	18	1	0	17
3B	21	11	10	22	1	0	21
5A	17	11	6	32	2	0	30
5B	30	17	13	41	1	1	39
6	47	32	15	57	19	10	28
7A	6	4	2	70	0	1	69
7B	0	0	0	74	1	1	72

Table 5.7-17. Reach-scale large wood accumulation data of natural mobile large wood that was tagged, displayed as a percentage.

Geomorphic Reach	Initially Tagged, then Left the Reach	Initially Tagged and Stayed in the Reach	Moved into the Reach and Stayed	Moved into the Reach, Stayed, and then Left	Moved through the Reach
2A	100%	0%	n/a	n/a	n/a
2B	59%	41%	33%	0%	67%
3A	0%	100%	0%	0%	100%
4	63%	38%	6%	0%	94%
3B	52%	48%	5%	0%	95%
5A	65%	35%	6%	0%	94%
5B	57%	43%	2%	2%	95%
6	68%	32%	33%	18%	49%
7A	67%	33%	0%	1%	99%
7B	n/a	n/a	1%	1%	97%

5.7.2.2 Large Wood Transport Analysis with Hydraulic Model Results

Large wood transport results were analyzed using Upper Skagit Hydraulic Model output runs that are representative of the October 28-29, 2021, and November 15-16, 2021 high flow events (Table 5.7-2 and 5.7-3). A total of six possible transport scenario locations were examined between the October and November flood event. These are the initial and final locations for pieces that moved and the location where pieces remained stable. These three transport scenarios were examined for

each flood event for a total of six transport scenarios being analyzed. Initial examination of large wood mobility using the Upper Skagit Hydraulic Model was completed using the output of depth values in the primary study area compared with the geometry of large wood pieces tracked in the large wood tracking study. The ratio between the rootwad diameter of a large wood piece and the depth that piece was exposed to was examined. The ratio between each large wood pieces depth that it was exposed to according to the hydraulic model and the diameter of the pieces rootwad was calculated. This average ratio of every piece was then calculated for each possible scenario being examined. If flow depth relative to rootwad diameter is the primary driver of large wood piece mobility, there would be a higher ratio for unstable pieces compared with the ratio calculated for stable pieces. This analysis did not find any significant correlation between average rootwad diameter and average depth for any of the scenarios being examined.

The study team completed more detailed analysis of wood mobility in relation to outputs from the Upper Skagit Hydraulic Model. This was completed as depth outputs and rootwad diameter alone do not appear to predict the fate of large wood piece mobility. Using the conceptual wood transport model described in Section 4.7 and the Upper Skagit Hydraulic Model output runs, the fate of tagged wood was predicted and then compared to what was observed in the field. The conceptual model accounted for drag forces on the rootwad, buoyancy force on the piece, gravitation force on the piece, and frictional force from the bed depending on the depth and velocity values for each location. Buoyancy force was determined by the volume of the tree that was submerged and the density of the large wood piece. Submerged volume was calculated based on the depth of flow at the site and the length, dbh, and rootwad diameter of the piece. Submerged volume was calculated assuming the piece was lying at an angle due to the protruding rootwad being on a flat surface. Large wood piece density was assigned based on the standardized dry wood density of each individual tree species type (Engineering Toolbox 2004). For large wood pieces, whose species was categorized as “Other,” a density of 30 pounds per cubic foot was assigned. For this analysis, the pieces are assumed to be laying on the bed, not entrenched, and parallel to flow with the rootwad upstream. If a rootwad was not present, then the piece was assumed to be parallel to flow.

Only 61 of the 198 tagged large wood pieces were analyzed using this method. The exact location of these 61 pieces were recorded for both the October 28, 2021, and November 15, 2021 flood events in the field. This meant that the GPS location of these large wood pieces had a precision equal to the precision of the GPS recording their location (plus or minus approximately 15 ft). The predicted outcomes of these 61 pieces based on the hydraulic model output runs are presented in Attachment N. Large wood density in this analysis was assumed to be a dry density for each piece. It is likely that many pieces in this analysis had a density greater than this as these pieces are often exposed to submerged conditions. The study team completed the analysis reported in Attachment N using density values that are 25 and 50 percent greater than dry density. These results yielded no significant changes than what is reported with the calculated density in Attachment N.

Large wood movement outcomes predicted using the large wood movement model assumed that all large wood pieces were oriented parallel to flow, with their rootwad upstream, and lying on the bed of the channel for every scenario that a large wood piece was in for both the October 28, 2021, event and November 15, 2021 event. Table 5.7-18 reports on the percentage of scenarios that large wood pieces examined in this analysis were in this assumed position.

Table 5.7-18. Large wood predicted outcome scenarios and their assumed[1] vs. actual position in the mainstem of the Skagit River.

Large Wood Predicted Outcome Scenarios	Number of Scenarios	Percentage of Scenarios
Scenarios In Assumed Position	45	33%
Scenarios Not in Assumed Position	91	66%
All Scenarios	**137**	**100%**

1 The assumed position is lying on the bed, not entrenched, and parallel to flow with the rootwad upstream. If a rootwad was not present, then the piece was assumed to be parallel to flow.

Predicted large wood movement outcomes were further subdivided by whether they were oriented in the assumed position in the channel, as well as if the outcome that was predicted by the large wood movement model matched what was expected, based on what occurred in the field (Table 5.7-19).

Table 5.7-19. Large wood predicted outcome scenarios and their assumed[1] vs. actual position in the mainstem of the Skagit River compared with whether their outcome was expected or unexpected.

Large Wood Predicted Outcome Position	Expected Outcome		Unexpected Outcome	
	Number	Percentage	Number	Percentage
Assumed Position	25	46%	19	23%
Not in Assumed Position	29	54%	62	77%
All Scenarios	**54**	**100%**	**81**	**100%**

1 The assumed position is lying on the bed, not entrenched, and parallel to flow with the rootwad upstream. If a rootwad was not present, then the piece was assumed to be parallel to flow.

Predicted large wood movement outcomes were examined in further detail following the same format as Table 5.7-19, but while subdividing the table based on the type of scenario that was observed in the field. These include large wood pieces that were observed in the field to be stable during a flood event and pieces that were observed in the field to be unstable during a flood event. Table 5.7-20 reports on pieces that were observed to be stable during a flood event.

Table 5.7-20. Large wood predicted outcome scenarios and their assumed vs. actual position in the channel compared with whether their outcome was stable.

Large Wood Predicted Outcome Position	Expected Stable Outcome		Unexpected Stable Outcome	
	Number	Percentage	Number	Percentage
Assumed Position	10	63%	17	25%
Not in Assumed Position	6	38%	51	75%
All Scenarios	**16**	**100%**	**68**	**100%**

1 The assumed position is lying on the bed, not entrenched, and parallel to flow with the rootwad upstream. If a rootwad was not present, then the piece was assumed to be parallel to flow.

5.7.3 Large Wood Recruitment

Large wood recruitment from the past and future was calculated using satellite imagery of the mainstem Skagit River and its tributaries. The upstream end of the primary study area begins by the town of Newhalem and the downstream end terminates at the Sauk River. The tributary channel migration zones were mapped for Cascade River, Bacon Creek, Diobsud Creek, and Goodell Creek from their mouth to where it appeared that lateral migration was nonexistent. For these tributaries, 2019 imagery was used when 2021 imagery was not available. The length of each tributary's mapped channel migration zone is noted below the respective tables. Attachment M includes maps of channel migration zones determined for these tributaries.

The number of trees greater than 11 inches (0.92 ft) dbh recruited per year in the primary study area of the mainstem Skagit River between 1998 and 2006 was approximately 605. Between 2006 and 2019, approximately 433 trees with a dbh greater than 11 inches were recruited each year. Using the historical migration rates and projecting those rates at every transect showed that there is potential for 399 trees to be recruited each year between 2019 and 2039 (Table 5.7-22).

The number of trees greater than 31 inches (2.6 ft) dbh recruited each year between 1998 and 2006 in the primary study area of the mainstem Skagit River was approximately 21 trees. Between 2006 and 2019, approximately 15 trees with a dbh greater than 31 inches were recruited each year. Using the historical migration rates calculated for each transect, the future recruitment potential is approximately 15 trees with a dbh greater than 31 inches per year between 2019 and 2039 (Table 5.7-21).

Table 5.7-21. Skagit River recruitment of trees greater than 0.92 ft (11 in) and 2.6 ft (31 in) dbh from Newhalem to Sauk River.

Beginning Date	Ending Date	Number of Years	Number of trees greater than 0.92 ft dbh	Number of trees greater than 2.6 ft dbh	Number of trees greater than 0.92 ft dbh per year	Number of Trees greater than 2.6 ft dbh per year
1998	2006	8	4841	168	605	21
2006	2019	13	5624	195	433	15
2019	2039	20	7986	302	399	15

Future large wood recruitment potential within each geomorphic reach is displayed below in Table 5.7-22. This data represents expected recruitment in the mainstem primary study area from 2019 to 2039. Reach 1 historical channel migration was not mapped. Approximately 93 percent of the predicted recruitment would occur in Geomorphic Reach 6 for trees with greater than 11- and 31-inch dbh.

Table 5.7-22. Skagit River future recruitment of trees greater than 0.92 ft (11 in) and 2.6 ft (31 in) dbh from 2019 to 2039 split by geomorphic reach.

Geomorphic Reach	Number of trees greater than 0.92 ft dbh	Number of trees greater than 2.6 ft dbh	Number of trees greater than 0.92 ft dbh per year	Number of Trees greater than 2.6 ft dbh per year
1	N/A	N/A	N/A	N/A
2A	0	0	0	0
2B	38	1	2	0
3A	0	0	0	0
4	0	0	0	0
3B	140	7	7	0
5A	0	0	0	0
5B	98	13	5	1
6	7454	270	373	14
7A	193	7	10	0
7B	63	5	3	0
All	**7986**	**303**	**399**	**15**

The analysis of Cascade River recruitment of trees was performed from the confluence with the Skagit River to 17.2 miles upstream. The number of trees greater than 11 inches dbh recruited per year in the Cascade River, between 1998 and 2006, was approximately 1299. Between 2006 and 2019, approximately 340 trees with a dbh greater than 11 inches were recruited each year. Using the historical migration rates and projecting those rates at every transect showed that there is potential for 284 trees to be recruited each year between 2019 and 2039 (Table 5.7-24).

The number of trees greater than 31 inches dbh recruited each year, between 1998 and 2006 in the mainstem, was approximately 43. Between 2006 and 2021, approximately 11 trees with a dbh greater than 31 inches were recruited each year. Using the historical migration rates calculated for each transect, the future recruitment potential is approximately 20 trees with a dbh greater than 31 inches each year between 2021 and 2039 (Table 5.7-23). 2019 imagery was substituted where 2021 imagery was not available.

Table 5.7-23. Recruitment of trees greater than 0.92 ft (11 in) and 2.6 ft (31 in) dbh in the lower 17.2 miles of Cascade River.

Beginning Date	Ending Date	Number of Years	Number of trees greater than 0.92 ft dbh	Number of trees greater than 2.6 ft dbh	Number of trees greater than 0.92 ft dbh per year	Number of Trees greater than 2.6 ft dbh per year
1998	2006	8	10389	343	1299	43
2006	2021	15	5099	168	340	11
2021	2039	18	5120	355	284	20

The analysis of Bacon Creek recruitment of trees was performed from the confluence with the Skagit River to 7.1 miles upstream. The number of trees greater than 11 inches dbh recruited per year in Bacon Creek, between 1998 and 2006, was approximately 797. Between 2006 and 2019, approximately 148 trees with a dbh greater than 11 inches were recruited each year. Using the historical migration rates and projecting those rates at every transect showed that there is potential for approximately 134 trees to be recruited each year between 2019 and 2039 (Table 5.7-25).

The number of trees greater than 31 inches dbh recruited each year between 1998 and 2006 in the mainstem was approximately 27 trees. Between 2006 and 2021, approximately 4 trees with a dbh greater than 31 inches were recruited each year. Using the historical migration rates calculated for each transect, the future recruitment potential is approximately 9 trees with a dbh greater than 31 inches each year between 2021 and 2039 (Table 5.7-24). 2019 imagery was substituted where 2021 imagery was not available.

Table 5.7-24. Recruitment of trees greater than 0.92 ft (11 in) and 2.6 ft (31 in) dbh in the lower 7.1 miles of Bacon Creek.

Beginning Date	Ending Date	Number of Years	Number of trees greater than 0.92 ft dbh	Number of trees greater than 2.6 ft dbh	Number of trees greater than 0.92 ft dbh per year	Number of Trees greater than 2.6 ft dbh per year
1998	2006	8	6376	220	797	27
2006	2021	15	1922	51	148	4
2021	2039	18	2685	174	134	9

The analysis of Diobsud Creek recruitment of trees was performed from the confluence with the Skagit River to 1.9 miles upstream. The number of trees greater than 11 inches dbh recruited per year in Diobsud Creek, between 1998 and 2006, was approximately 172. Between 2006 and 2019, approximately 52 trees with a dbh greater than 11 inches were recruited each year. Using the historical migration rates and projecting those rates at every transect showed that there is potential for 40 trees to be recruited each year between 2019 and 2039 (Table 5.7-26).

The number of trees greater than 31 inches dbh recruited each year, between 1998 and 2006 in the mainstem, was approximately 6. Between 2006 and 2021, approximately 2 trees with a dbh greater than 31 inches were recruited each year. Using the historical migration rates calculated for each transect, the future recruitment potential is approximately 2 trees with a dbh greater than 31 inches each year between 2021 and 2039 (Table 5.7-25). 2019 imagery was substituted where 2021 imagery was not available.

Table 5.7-25. Recruitment of trees greater than 0.92 ft (11 in) and 2.6 ft (31 in) dbh in the lower 1.9 miles of Diobsud Creek.

Beginning Date	Ending Date	Number of Years	Number of trees greater than 0.92 ft dbh	Number of trees greater than 2.6 ft dbh	Number of trees greater than 0.92 ft dbh per year	Number of Trees greater than 2.6 ft dbh per year
1998	2006	8	1380	48	172	6
2006	2021	15	773	26	52	2
2021	2039	18	726	39	40	2

Note: Diobsud Creek from Skagit to 1.9 miles upstream. 2019 imagery was substituted where 2021 imagery was not available.

The analysis of Goodell Creek recruitment of trees was performed from the confluence with the Skagit River to 6.9 miles upstream. The number of trees greater than 11 inches dbh recruited per year in Goodell Creek, between 1998 and 2006, was approximately 1123. Between 2006 and 2019, approximately 99 trees with a dbh greater than 11 inches were recruited each year. Using the historical migration rates and projecting those rates at every transect showed that there is potential for 241 trees to be recruited each year between 2019 and 2039 (Table 5.7-27).

The number of trees greater than 31 inches dbh recruited each year, between 1998 and 2006 in the mainstem, was approximately 39. Between 2006 and 2021, approximately 3 trees with a dbh greater than 31 inches were recruited each year. Using the historical migration rates calculated for each transect, the future recruitment potential is approximately 14 trees with a dbh greater than 31 inches each year between 2019 and 2039 (Table 5.7-26).

Table 5.7-26. Recruitment of trees greater than 0.92 ft (11 in) and 2.6 ft (31 in) dbh in the lower 6.9 miles of Goodell Creek.

Beginning Date	Ending Date	Number of Years	Number of trees greater than 0.92 ft dbh	Number of trees greater than 2.6 ft dbh	Number of trees greater than 0.92 ft dbh per year	Number of Trees greater than 2.6 ft dbh per year
1998	2006	8	8986	310	1123	39
2006	2019	13	1286	39	99	3
2019	2039	20	4579	280	229	14

5.8 Process Flows

Study results from preceding sections of this report were integrated with findings derived from the IHA analysis of unregulated flow conditions. Results of the process flow investigation includes evaluation of:

- Flows that mobilize river bar deposits;
- Flows that mobilize deposits at tributary mouths;
- Flows that erode river banks and contribute to channel migration
- Flows that instigate side channel development/maintenance; and
- Flows that hydraulically connect side channel and off-channel habitat.

5.8.1 Naturalized (Unregulated) Flow Regime

Results derived from the IHA analysis characterize the naturalized hydrologic regime for unregulated flow conditions and evaluate the magnitude of hydrologic alteration under existing (regulated) conditions. A technical memorandum describing the data, methods, and results of the IHA analysis is included as Attachment T. Table 5.8-1 summarizes the flow thresholds derived from the unregulated flow series in IHA for gaging station locations at Newhalem, Marblemount, and Concrete. Note that IHA software analyzes the time series of daily average flows and that peak flow statistics used to define the unregulated 2-year and 10-year recurrence interval flows are

reported as daily values. As such, IHA flow statistics are expected to be lower than flood frequency statistics developed for instantaneous peak flows for an equivalent recurrence interval.

Key findings documenting changes in the magnitude, duration, frequency, and timing of EFCs are summarized for each gaging station in Table 5.8-2, Table 5.8-3, and Table 5.8-4. The annual maximum flood series for unregulated and regulated flows are plotted in Figure 5.8-1 along with estimates of the unregulated 2-year and 10-year recurrence interval flows. There were no events exceeding the unregulated 10-year recurrence interval flow threshold during the study period. The frequency of flow events classified as small floods (peak flow greater than the 2-year recurrence interval flow in the unregulated flow series) decreased at all sites and the timing of small floods shifted earlier in the year due to storage of spring/summer snowmelt runoff.

IHA parameters representing high flow pulses (flushing flows) under regulated conditions showed relatively little change in frequency compared to unregulated conditions. The mean magnitude of high flow pulses decreased at all sites and was most altered at Newhalem (22 percent decrease in magnitude). The duration of events exceeding the threshold for high flow pulses increased at Newhalem and decreased at Marblemount and Concrete. The seasonal timing of high flow pulses is distributed throughout the year. IHA model results show a slight shift in timing towards earlier in the year (-14 days) at Newhalem, no substantial change (+1 day) at Marblemount, and a slight shift (+11 days) towards later in the year at Concrete.

Table 5.8-1. Flow thresholds derived from the unregulated daily flow series in IHA.

	Daily Flow in the Skagit River (cfs)		
	At Newhalem	**At Marblemount**	**At Concrete**
Extreme Low Flow Threshold (90% daily exceedance)	1,530	2,050	5,840
Low Flow Threshold (50% daily exceedance)	3,190	4,440	12,280
High Flow Threshold (25% daily exceedance)	5,730	7,860	19,100
Small Flood Minimum Peak Flow (2-year recurrence interval[1])	23,600	32,430	63,800
Large Flood Minimum Peak Flow (10-year recurrence interval[1])	48,300	66,300	152,400

1 Flood frequency statistics calculated as daily recurrence intervals based on the time series of unregulated daily flows for WY 1989-2020.

Table 5.8-2. Changes in EFC parameters at Newhalem.

	Unregulated	**Regulated**	**Change**
Extreme Low Flow			
Frequency (events/yr)	11	0	-100%
Mean Duration (days)	3.0	N/A	N/A
Mean Timing	December 2	N/A	N/A
High Flow Pulse			
Mean High Flow Peak (cfs)	9,360	7,330	-22%
Frequency (events/yr)	9.2	8.9	-3%
Mean Duration (days)	7.7	10	+32%
Mean High Flow Timing	March 18	March 4	-14 days
Small Floods			
Mean Small Flood Peak (cfs)	30,250	28,180	-7%
Frequency (events/yr)	0.56	0.13	-78%
Mean Duration (days)	37	29	-22%
Mean Small Flood Timing	June 13	November 12	152 days
Large Floods			
Mean Large Flood Peak (cfs)	52,270	N/A	N/A
Frequency (events/yr)	0.09	0	-100%
Mean Duration (days)	22	N/A	N/A
Mean Large Flood Timing	November 10	N/A	N/A

Table 5-8.3. Changes in EFC parameters at Marblemount.

	Unregulated	Regulated	Change
Extreme Low Flow			
Frequency (events/yr)	9.6	0.4	-96%
Mean Duration (days)	3.7	2.7	-27%
Mean Ex. Low Timing	November 1	September 26	-36 days
High Flow Pulse			
Mean High Flow Peak (cfs)	13,350	10,650	-20%
Frequency (events/yr)	11	12	+15%
Mean Duration (days)	7.7	5.2	-32%
Mean High Flow Timing	February 26	February 27	+1 day
Small Floods			
Mean Small Flood Peak (cfs)	43,280	42,760	-1%
Frequency (events/yr)	0.59	0.16	-74%
Mean Duration (days)	21	28	+36%
Mean Small Flood Timing	January 24	November 13	-73 days
Large Floods			
Mean Large Flood Peak (cfs)	76,640	N/A	N/A
Frequency (events/yr)	0.09	0	-100%
Mean Duration (days)	26	N/A	N/A
Mean Large Flood Timing	November 10	N/A	N/A

Table 5.8-4. Changes in EFC parameters at Concrete.

	Unregulated	Regulated	Change
Extreme Low Flow			
Frequency (events/yr)	7.8	3.0	-62%
Mean Duration (days)	5.2	5.1	-2%
Mean Ex. Low Timing	August 3	September 17	+45 days
High Flow Pulse			
Mean High Flow Peak (cfs)	29,560	28,150	-5%
Frequency (events/yr)	11	11	0%
Mean Duration (days)	6.8	6.2	-9%
Mean High Flow Timing	February 17	February 28	+11 days
Small Floods			
Mean Small Flood Peak (cfs)	85,830	91,770	+7%
Frequency (events/yr)	0.81	0.53	-35%
Mean Duration (days)	15	23	+49%
Mean Small Flood Timing	December 11	November 20	-21 days
Large Floods			
Mean Large Flood Peak (cfs)	161,700	N/A	N/A
Frequency (events/yr)	0.09	0	-100%
Mean Duration (days)	27	N/A	N/A
Mean Large Flood Timing	November 11	N/A	N/A

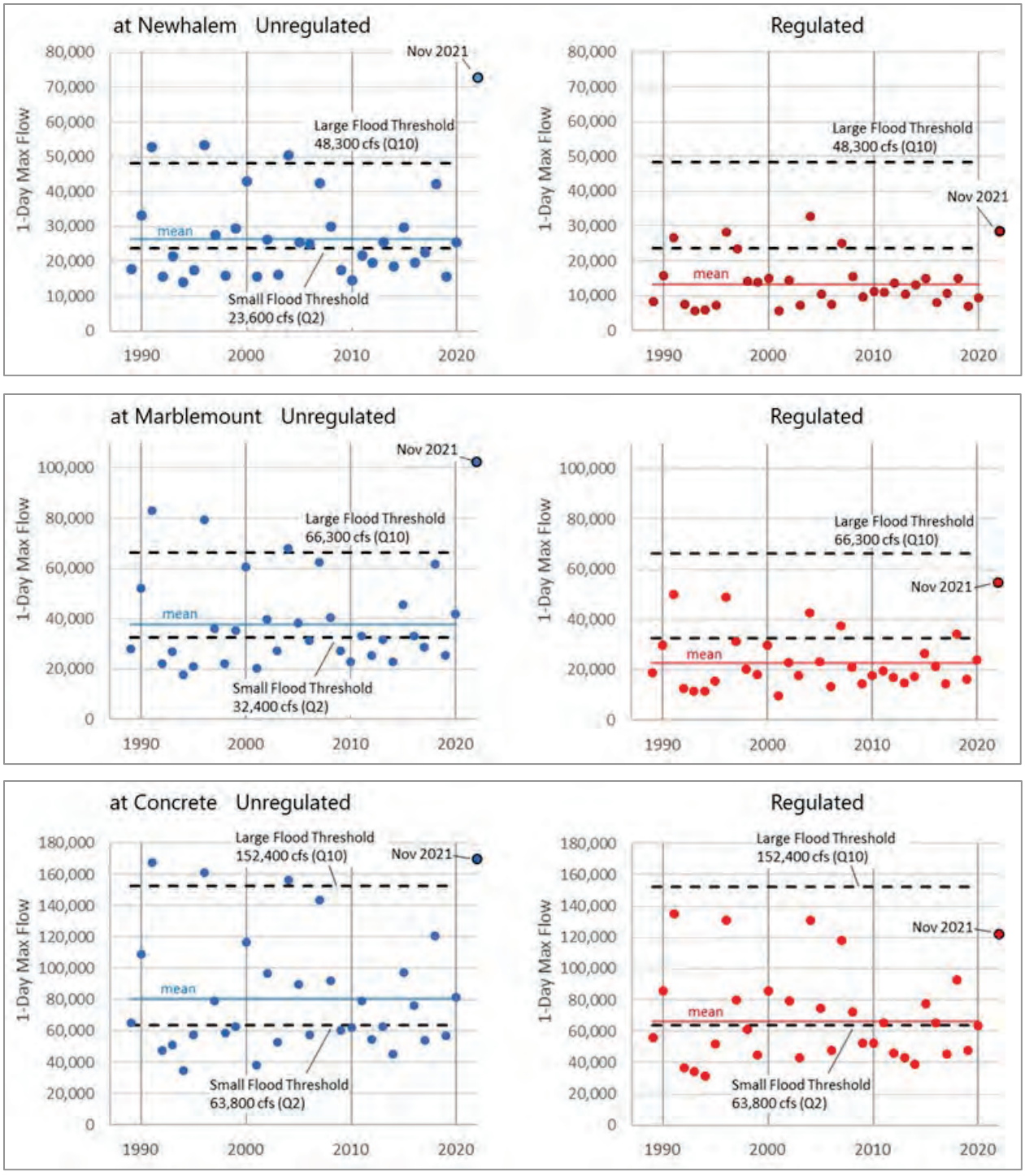


Figure 5.8-1. **Time series plots of annual maximum flow for the unregulated and regulated flow series relative to the thresholds of small and large floods represented by the 2-year (Q2) and 10-year (Q10) recurrence intervals, respectively. November 2021 was not included in IHA analysis but shown for reference.**

5.8.2 Sediment Mobilizing Flows

Results derived from the sediment transport analysis in Section 5.5 provide input to the characterization of flows that mobilize river bar deposits in the study area. Section 5.5.6.4 describes the reach average threshold for initiation of sediment mobilization estimated from shear stress profiles in the 1-D HEC RAS Model as a range between 20,000 and 30,000 cfs for most of the study area. Field observations from the scour monitoring program described in Section 5.5.1.1 similarly showed little to no scour occurred at most locations during years represented by only modest flood flows. For example, scour during winter of 2020 (instantaneous peak flow of 31,300 cfs at Marblemount) did not penetrate the depth of the top accelerometer at most sites. As such, the unregulated 2-year flow estimated in IHA (daily average flow of 23,600 cfs at Newhalem; 32,400 cfs at Marblemount) could be a reasonable threshold for use in estimating flows that mobilize river bar deposits and sediments at tributary mouths. Results from the scour monitoring following a larger flood in November 2021 revealed scour at nearly 50 percent of scour monitoring locations and scour depth suggests that flows of this magnitude have a meaningful, but not catastrophic, impact on egg-to-fry-survival. Additional results anticipated from future work utilizing 2-D mobile bed simulations will refine the evaluation of sediment mobility at localized features.

5.8.3 Channel Migration

Flows that erode river banks, recruit large wood, and contribute to channel migration were relatively infrequent for most of the study area over the period of historical aerial imagery evaluated in Section 5.1. River banks observed in the study area are generally composed of gravel and cobble-sized sediments. As such, the threshold for initiation of bank erosion and channel migration is expected to be similar or greater than the threshold for initial sediment mobilization described above (20,000 to 30,000 cfs). Even in Reach 6 where modest rates of channel migration occurred through bend migration over the historical period, comparison of 2019 aerial imagery with subsequent imagery and field observations from August 2021 revealed that little to no bank erosion occurred at flows up to 31,300 cfs at Marblemount. In contrast, observed flows during November 2017 (instantaneous peak flow of 17,400 cfs at Newhalem; 44,100 cfs at Marblemount) eroded river banks on the outside of meander bends in Reach 6 but caused little to no erosion in reaches upstream. During the recent flood in November 2021 (instantaneous peak flow of 34,800 cfs at Newhalem; 63,400 cfs at Marblemount) only small, localized areas of bank erosion were observed upstream of Marblemount. As such, flows exceeding 30,000 to 40,000 cfs appear to be the lower limit of flows that contribute to bank erosion, wood recruitment, and channel migration processes in the study area. These results are generally in agreement with analysis of channel-forming flows developed from UBCRM in Section 5.5.6.1. The magnitude of channel changes and rate of channel migration under future process flow scenarios would be determined by the duration of flows exceeding this threshold over time or geomorphic work equivalence.

5.8.4 Side Channel Development/Maintenance

Side channels and off-channel habitat in the Skagit River are primarily formed through channel migration and avulsion. Much of the side channel and off-channel habitat inventoried as part of the aquatic habitat characterization (Sections 5.2 and 5.3) is located within channel features that were formed as a result of channel migration and bend cutoff processes. Additional side channel habitats have formed in areas of localized channel widening. In the absence of disturbance

resulting from channel migration, side channels are prone to sedimentation that lead to decreased connectivity over time. These observations are supported by findings derived from the UBCRM modeling discussed in Section 5.5.6.1 that predict a simplification of channel pattern with reductions in channel forming flows.

6.0 DISCUSSION AND FINDINGS

The Geomorphology Study has met the goals and objectives stated in the RSP and presented in Section 2.0 of this study report. The study characterizes the current condition of aquatic habitat and evaluates how Project-related changes in peak flows and sediment affect geomorphic processes. Study results use aerial photographs, LiDAR, and field data to characterize channel migration patterns, distribution of aquatic habitat, substrate, sediment delivery, and large wood. Results are documented at the reach scale highlighting variability between geomorphic reaches distinguished by differences in geology, valley width, channel slope, sinuosity, and large breaks in contributing basin area at select tributary confluences.

Project operations and flood risk management have altered both the bedload sediment supply and the frequency of sediment-mobilizing flows in the Skagit River downstream of Gorge Dam. Study results suggest there have been approximately proportional reductions in both sediment supply and transport capacity downstream of Newhalem resulting in little change to the bed elevation profile over the period of flow regulation. Bed material is predominantly composed of cobble and gravel and bed armor ratios in the Skagit River through the study area are typical for large gravel-bedded rivers, further suggesting approximately equivalent reductions in both sediment supply and transport capacity. The spatial pattern of armor ratios shows lowest armor ratios (least armoring) in areas just below Goodell Creek, suggesting that any imbalance between sediment supply and transport capacity likely reflects a greater reduction in sediment transport capacity than sediment supply.

The frequency of peak flows that erode river banks and contribute to channel migration processes has been reduced and these effects are exacerbated by localized areas of bank armoring. Study reaches between Newhalem and Marblemount have low rates of channel migration and tributaries are currently the dominant source of the bedload sediment supply. More moderate rates of channel migration were documented in the river segment between Rocky Creek and the Sauk River which is characterized by a meandering channel pattern and bank erosion is the dominant source of bedload sediment in this reach.

Historical impacts to wood dynamics in the Skagit River began prior to Project operations by direct removal of wood from the channel and clearing of riparian forests as a part of logging and navigation activities. Historical impacts have reduced current abundance of wood in Puget Sound rivers by one to two orders of magnitude compared to conditions before European settlement (Collins et al. 2002). Wood is an important control on geomorphic processes such as formation of pools and development of side channel features (Abbe and Montgomery 1996; 2003). Few trees remain that are sufficient in size to function as key pieces that initiate stable log jams when recruited to the channel. In the absence of key pieces and stable log jams, moderate and small sized wood is transported downstream. Project operations trap wood in reservoirs upstream of the study area; however, this impact is more important to the transport of smaller wood than large wood as any key pieces would have been likely to either form stable jams near the source of recruitment or break apart during transport through the Skagit Gorge upstream of Newhalem. Wood recruitment is further limited by the reduced rates of channel migration caused by reduced peak flows and bank armoring. Large tributary channels are the primary source of wood inputs to study reaches upstream of Rocky Creek. Any wood mobilized by tributary channel flows is unlikely to function as a key piece in the mainstem channel. Additionally, wood pieces artificially input at the aggregate

pond site upstream of Rocky Creek were shown to be highly mobile and too small to function as key pieces. Bar top jams were the most abundant type of wood jam inventoried in the study and this type of jam is relatively unstable and has little effect on channel morphology. Mobile wood deposited as racked wood in log jams more often than any other possible configuration in the channel.

Geomorphic Reach 6 has the highest concentration of log jams and individual wood pieces both presently and historically. Reach 6 has had a higher concentration of log jams because it is more complex and has higher channel migration rates than any other reach. Historic aerial analysis shows that log jam density varies greatly by geomorphic reach in the study area but has not varied greatly over time. Additionally, historic aerial analysis shows that log jams that are most likely to persist for a significant period are composed of 100 pieces or more. Study results suggest that large wood augmentation would most effectively address historical impacts to wood recruitment processes by emphasizing addition of large snags and/or stable engineered log jams to increase retention of smaller wood inputs currently supplied from tributary sources and localized bank erosion.

Observed geomorphic changes and modeling results suggest the Skagit River is slowly adjusting to changes in the flow and sediment regimes along a modest trajectory of channel narrowing and simplification. The reduction in channel width translates to a reduced tendency for the channel to sustain a multi-thread (anabranching) pattern and study results suggest the channel sensitivity to changes in peak flows is greater than the sensitivity to changes in sediment supply. Sedimentation at side channel junctions combined with reduced frequency and duration of peak flows have contributed to a gradual decline in side channel connectivity, that, in the absence of future disturbance, may be expected to reduce abundance of side channel features.

Formation of new side channel features has occurred in select areas of the floodplain through development of forested islands within depositional zones of the channel (e.g., Thornton Side Channel complex in Reach 2B) or by downstream translation of meander bends (e.g. Washington Eddy in Reach 6). There is greater potential for creation of additional side channel habitats in geomorphic reaches where channel migration processes are sustained. In the absence of flows with sufficient power to drive channel migration processes and restoration interventions, declines in side channel connectivity will likely outpace formation of new habitats.

Observations from the November 2021 flood provide information to describe the anticipated channel response to process flow releases in the Skagit River. Peak flow releases during November 2021 were slightly less than the naturalized (unregulated) 5-year recurrence interval flow at Newhalem and between the naturalized 5-year and 10-year recurrence interval flows at Marblemount. The event caused localized bank erosion in reaches upstream of Rocky Creek and more extensive bend scour along the outside of meanders in Reach 6. Sediment was mobilized and redistributed within the channel and the net response was depositional in all reaches downstream of Newhalem to Rocky Creek. Segments of Reach 6 between Rocky Creek and the Sauk River had a net export of sediment due to large volumes of sediment mobilized by bank erosion. No new side channels formed in response to the 2021 flood. Side channels that intersect the main channel along eroding banks on the outside of meander bends widened or became better connected in response to mobilization of sediment from side channel junctions. Side channels that split from the main channel in other locations generally responded with net deposition of sediment at side channel

junctions resulting in decreased connectivity. Bed scour was detected at nearly 50 percent of scour monitoring locations and scour depth suggests that flows of this magnitude have a meaningful, but not catastrophic, impact on egg-to-fry-survival. Further discussion of study results follows below, organized by study element.

6.1 Geomorphic Change

The analysis of geomorphic change utilized a combination of aerial photographs, LiDAR, and field observation to characterize the baseline channel configuration and channel migration patterns. Rates of bank erosion and channel migration processes have been moderated by reductions in peak flows due to Project operations and flood risk management. The active channel area has decreased in width by an average of 8 percent since 1944. No changes in sinuosity were observed in the series of historical imagery.

Channel patterns in reaches between Newhalem and Rocky Creek (Reach 2A-5B) have been generally static with little to no bank erosion occurring over the period of historical imagery and reach average migration rates between 0 and 0.4 ft/yr. The absence of bank erosion and channel migration processes in these segments limits potential for wood recruitment to the channel and is a constraint on formation of new side channels and off-channel habitat.

Downstream of Rocky Creek to the Sauk River (Reach 6), bank erosion has occurred at a relatively low rate (4.1 ft/yr) along the outside of meander bends. Prior to the period of flow regulation, two large amplitude meanders formed bend cutoffs in the early 1900s that reduced channel sinuosity in Reach 6. The cutoffs contributed to areas of channel incision upstream of the abandoned meanders at Barnaby Slough and Illabot Creek. Channel migration processes during large flood events have resulted in formation of new side channel habitat in select areas of Reach 6 over recent decades. Hydromodifications such as bank armoring limit channel migration processes along portions of the study area.

Results from an investigation of vertical channel changes at USGS gaging stations at Newhalem and Marblemount revealed that the channel bed has been generally stable at both locations over the period of record with a relatively small increase in channel bed elevation (+0.6 ft) since the 1980s. Analysis of longitudinal profiles derived from historical data sources yielded inconclusive results given a large range of uncertainty with elevation data from 1915 and 1947 topographic maps. Comparison of channel cross-sections collected in 1975 with recent topobathymetric LiDAR data revealed a net increase in bed elevation suggesting aggradation of between 1 and 3 feet in reaches between Marblemount and the Sauk River.

Analysis of geomorphic change between LiDAR datasets collected in 2017/2018 and new LiDAR acquired by City Light in 2022 was used to calculate sediment inputs from bank erosion and map patterns of deposition and erosion in response to recent flood events in 2017 and 2021. Bank erosion rates were low in most segments between Newhalem and Rocky Creek (Reach 2A-5B). Deposition within the channel and on bars resulted in a net accumulation of sediment suggesting that the sediment supplied from tributary channels exceeded the sediment transport capacity provided by flows in the Skagit River. The thalweg elevation increased in all reaches upstream of the Sauk River with an average aggradation of 0.3 ft. More extensive areas of bank erosion were noted in Reach 6 such that the volume of sediment contributed from bank erosion exceeded the net volume of changes in the river bed and bars resulting in a net export of sediment from subreach

areas between Rocky Creek and Barnaby Slough. Results of the geomorphic change analysis were used in calibration of sediment transport analyses described in Section 5.5.5.

The findings derived from the analysis of geomorphic change, combined with field observations and results from sediment transport analyses presented in Section 5.5, suggest that the Skagit River is undergoing a period of relatively slow geomorphic adjustments in response to the reduced sediment supply and regulation of peak flows. Historical floodplain surfaces that formed through channel migration process under the natural (unregulated) flow regime are less connected and only rarely inundate during large floods. Study results suggest that there has not been systemic channel incision in response to Project operations. Rather, floodplain connectivity appears to be limited by the reduced frequency of peak flows. In dynamic channel segments of Reach 6, new floodplain surfaces, side channels, and off-channel habitats have formed as a result of recent channel migration processes. Floodplain areas formed under the regulated flow regime tend to be lower in elevation relative to the adjacent terraces formed during periods of higher flows.

Channel segments that lack sufficient stream power to erode river banks, or are constrained by hydromodifications that limit channel migration such as bank armoring, are in a period of arrested channel evolution. Over time, these channels are becoming slowly narrower and sediment deposition is affecting hydrologic connectivity to side channel features. Observation of the channel response to peak flows observed in November 2021 suggest that flows of that magnitude or greater are needed in channel segments between Newhalem and Marblemount to initiate bank erosion, recruit large woody material from the floodplain, and form new side channel and off-channel habitats through channel migration processes.

6.2 Aquatic Habitat

Aquatic habitat in the study area has been mapped and summarized in Section 5.0 of this study report. Metrics for Reaches 1 through 7A have been calculated and are available for review. Additional data and information from the FA-02 Instream Flow Model Development Study (City Light 2023a) was used to provide further detail on the amount and quality of habitat within the study area. Hydraulic modeling results for the 80 percent annual exceedance flow were used to calculate pool depth and quantity of edge habitat, and substrate and cover mapping were used to evaluate sediment size by reach, the amount of fish cover in pools and edge habitat. A detailed presentation of summary aquatic habitat metrics (Table 4.2-3) is presented in Section 5.2.1 and includes comparison of habitat metrics across reaches such as size and diversity of habitat types, pool quantities and amounts, woody debris and channel size and bank characteristics.

Aquatic habitat characteristics are affected by geomorphic setting and position in the watershed and varied across reaches. The most common channel unit classification by area across all reaches was glide habitat which, in general, increased in the downstream direction. Reaches 2B and 6 have the largest proportion of off-channel and side channel habitat, while Reaches 7A and 6 have the highest amounts of slow water habitat due to lower gradients, unconfined floodplains and more flow in these reaches. Mean pool depth and pool frequency were fairly consistent across all reaches, while the deepest pools were found in Reaches 1, 5A and 5B.

In terms of large wood, reaches lower in the study area (5B, 6, and 7A) had the highest number of pieces, a high number of log jams (as compared to other reaches), and the highest jam density in the study area. As reaches that are farther downstream in the study area, with more unconfined

floodplains the accumulation of wood in these reaches was expected. Pieces of large wood forming pools showed a similar basic pattern with Reaches 5B and 6 showing the highest relative number of pieces, however, Reach 3B has the highest density of pool-forming pieces by length.

Cover and substrate data were extracted from the FA-02 Instream Flow Model Development Study and reflect conditions for both rearing and spawning habitat availability and quality (City Light 2023a). Percent cover varied from 4 to 30 across reaches with most areas in the high teens to low twenties. This level of cover is somewhat low for ideal rearing habitat but is affected by the large width of the Skagit River, where the center of the channel is not shaded by terrestrial vegetation (Hyatt 2022). Reaches 3A, 5B and 4 had the largest proportion of edge habitat with cover which is likely to be used by juvenile salmon for rearing. Substrate also varied across reaches, but was dominated by gravels, cobbles and boulders. Spawning gravels appropriate for Chinook and chum were the most common with Reaches 4 and 5A having the highest proportion for Chinook and Reaches 6, 7A and 3B having the highest proportion for chum.

Habitat along the banks of the river was characterized by the percent of the length with hydromodifications and the percent of the length with active erosion. Hydromodifications were most common along the right side of the river, while active erosion was mostly observed in Reaches 6 and 7A. Hydromodifications on the left side of the river range from 0 to 6 percent. On the right bank, Reaches 3A, 4 and 3B have modifications along 21 to 37 percent of the bank length, many of which are associated with protection of State Route 20. These modifications lead to a "shadowing" or disconnection of side-channel and off-channel habitat as the river becomes more confined within its existing channel with little chance to migrate. Additional information on aquatic habitat can be found in FA-02 Instream Flow Model Development Study as part of the Upper Skagit Habitat Model.

6.2.1 Tributary Passability Analysis

According to the Statewide Washington Integrated Fish Distribution (SWIFD 2021), all five species of Pacific salmon and steelhead exist throughout the mainstem Skagit River at each of the studied tributary mouths. As chum are the least athletic jumpers and burst swimmers (Reiser et al. 2006) and least able to swim up steepening grades (WDFW 2019), fish passability was primarily evaluated in terms of chum athleticism.

No fish passage issues were found based on water depth alone that appeared isolated to tributary mouths or caused by aggradation of the alluvial fan. While three dry channel beds were found, conditions at the tributary mouth were consistent throughout the surveyed reach and not isolated to the confluence or alluvial fan. As dry channel beds alone do not constitute a fish passage barrier, since flow depths fluctuate seasonally (WDFW 2019; Reiser, et al. 2006), these were not considered barriers, even though at the time of the survey, fish could not access the tributaries.

Common regulatory practice in Washington evaluates fish passability based on stream gradient, channel width, and hydraulic drops (WDFW 2019). Regarding stream gradient and width, impassable conditions must be sustained for 525 linear ft to be considered a barrier (WDFW 2019). While this is the generally accepted guidance, it should be noted that this is purposefully conservative, so as not to preclude fish presence in a given area, and is not intended to state a particular species is necessarily able to pass freely, which is influenced by additional factors such as boulder size, flow velocity, constriction, proximity to natal streams of particular populations

(Reiser et al. 2006; WDFW 2019) and even individual athleticism (Meixler et al. 2009). While chum only utilize grades below 3 percent, they are able to pass through grades up to 5 percent freely and may pass even higher grades if the reach length is less than 525 linear ft (WDFW 2019).

Three streams had average gradients over 5 percent. The streams did not have natural fish passage barriers due to waterfalls: Alma Creek, Copper Creek, and Damnation Creek. Alma Creek most consistently had grades of 3-4 percent, with one 60-ft section that had a sustained gradient of 17 percent. According to WDFW fish passage criteria, this is not a barrier to chum. Copper Creek had fairly sustained gradients of approximately 6 percent, which appeared to continue past the surveyed reach and may preclude chum from this tributary; however, it is not steep enough to preclude the other salmonid species, which can swim freely in grades lower than 7 percent, and are able to pass grades up to 12 percent (WDFW 2019). Damnation Creek had consistent grades of approximately 4.2 percent, with a reach break of 8.3 percent for 57 linear ft, which is not considered a barrier due to grade (WDFW 2019).

In terms of hydraulic drops, fish passage barriers were found on Ladder Creek and Sky Creek within the surveyed reaches. Both tributaries have natural waterfalls with heights over 12.1 ft between pools of depths equal to or greater than fish body length, which is the minimum depth necessary for a fish to orient and prepare for a leap (Reiser et al. 2006; WDFW 2019).

While Goodell Creek could not be surveyed due to inaccessibility of the river as a result of deep, swift waters, and erosive banks. the mouth and area beneath the bridge were visually inspected. It was determined that fish passability, based on the above criteria, was not an issue in this tributary due to both sufficient water depth and low gradient channel bed.

6.3 Side Channels and Off-Channel Habitat

6.3.1 Current Side Channel and Off-Channel Habitat

The current conditions of side channels and off-channel habitats of the Skagit River were evaluated using remote sensing data and field observations. In total, 67 side channel and off-channel features were evaluated: 53 side channels and 14 off-channel features. Side and off-channel habitats were evaluated for connectivity with the Skagit River and inlet and outlet condition, as well as the presence of habitat features, such as large wood, fish cover, and spawning gravels. A detailed narrative describing each feature is available in Attachment H.

Side channel and off-channel habitat varies substantially by geomorphic reach. Generally, the greatest amount of side and off-channel habitats are found in the furthest downstream portions of the study area below the Cascade River, where the valley width is wider and the floodplain and geomorphology are more dynamic. The majority of side and off-channel habitat is found in three reaches. Reach 6 contains the greatest amount of side channel and off-channel habitat, followed by Reach 5B and Reach 2B. Other reaches contain relatively low amounts of side and off-channel habitat.

Analysis of the connectivity of side channel and off-channel areas shows outlets are connected more frequently than inlets. Only 37 percent of inlets are connected a majority of the year while 67 percent of outlets are connected a majority of the year as measured by connection at the 60 percent annual flow exceedance. Inlets are also much more frequently inactive with 45 percent of

inlets not connected at 5 percent annual exceedance flow compared to 4 percent of outlets not connected at 5 percent exceedance. The lack of inlet connection is a contributing factor to the loss and degradation of side channel and off-channel areas over time. During flood events, areas with only outlets connected become inundated via backwatering from the mainstem river, and suspended sediment is deposited. Deposition over time will reduce area and volume in features where inlets are not connected to provide flushing flows to transport fine sediment and periodic channel maintenance flows to erode encroaching vegetation. The side channel at PRM 74.6 is an example of a side channel filling in over time. The side channel was once a flow through feature with an active inlet and outlet, but the inlet became inactive and currently the channel only functions as a small backwater at the outlet. Deposition of fine sediment will also reduce spawning habitat, which has been observed within the constructed spawning channels such as Taylor Side Channel, Powerline Pond, and Illabot Spawning Channel.

6.3.2 Time Series Analysis of Side channel and Off-Channel Habitat

Time series data are useful for detecting changes in habitat conditions. Since side channel and off-channel habitat are, by nature, generally transitory within the dynamics of river processes, using a time series of images or remote sensing data can provide a record of the trajectories of side channel and off-channel habitat formation and degradation in specific areas, reaches, and throughout the study area. Aerial images used in mapping geomorphic change for the period 1944-2019 were used to summarize the changes in side channel and off-channel habitats (Attachment E). Metrics for each time step were calculated to summarize status and trends of floodplain habitat through time. Results are presented in Section 5.3.3 of this study report.

Trends in side channel and off-channel areas were evaluated by comparisons to the hydrograph during that period between aerial images to evaluate the relationship between changes in amount and characteristics of side and off-channel habitat and changes in the flow regime through time. The length and area of side channels detected using the aerial photos did not change substantially between 1944 and 2019. Analysis of the maximum flows at Marblemount from the existing data in Section 4.1, (Figure 4.1-2) shows that the maximum flow levels increase in 1998 and then are somewhat lower in 2006 and 2019. As noted in Section 5.1, large sections of Reach 6 have aggraded in the mainstem channel while the lower portion of Reach 2 (Reach 2B) has degraded in elevation. These findings are an indication that the sediment transport processes (which affect side channel connectivity) may be different in the two reaches, resulting in different patterns in the time series metrics.

Other analysis of time series data included evaluation of focus areas identified as having changed substantially through time, contributing to substantial changes in length or area of side channel habitat across the time series These data identified some of the conditions that may result in loss or degradation of side channel and off-channel habitat through time. Other factors in the primary study area that influence side channel and off-channel habitat connectivity include sediment transport, flow levels and velocities, influences from large wood, hydromodifications, erosion, and land use impacts. Although the length and area of side channels detected using the aerial photos did not change substantially between 1944 and 2019, several areas became more vegetated and are likely less connected than they have been in the past. In addition, it should be noted that the earliest aerial photos used in the analysis were taken in 1944, following construction of the Project and substantial changes in the valley as compared to natural flow levels. As shown in Riedel (2020),

additional relict channels exist on the landscape, some of which may have been connected prior to the Project construction. Since the earliest photo set is after construction of the Project, the area and length of side channel and off-channel habitat may be an underestimate.

Finally, constructed side channel lengths and areas are presented by reach. These were intentionally kept out of the analysis of the natural gain and loss of side channels so as not to introduce error into that assessment of natural changes. This information indicates that constructed side channels provide an added 6.7 to 14.7 percent of the total length of natural channels and 14 to 19.2 percent of the total area of natural side and off-channel habitat across the time series.

6.4 Substrate/Sediment

A total of 54 bulk samples to characterize the subsurface material and 72 lithology-specific pebble counts to characterize the armor layer were collected from locations distributed along the river and distal reaches of tributaries (Figures 4.4-2 and 4.4-3).

Results of the grainsize analysis of the sediment samples are described in Section 5.4.1 of this study report. Sediment at the bar-head locations sampled in this study is predominantly composed of cobble and gravel, with moderate spatial variability at the reach-scale. Surface pebble count results from upstream of the Sauk River (Figure 5.4-1) indicate D_{50} values typically of 64 to 91 mm and D_{84} values generally toward the upper range of 91 to 128 mm. The grainsize distribution of the subsurface material is dominated by gravel-sized material, with characteristic D_{50} values ranging from 20 to 50 mm. A strong downstream fining trend only begins at approximately PRM 35, at the upstream end of the Ross Island reach. Between PRM 35 and the downstream end of sediment sampling at PRM 20, surface D_{50} values were typically 22 to 45 mm and D_{84} values were typically 45 to 64 mm. The D_{50} of subsurface material downstream of PRM 35 was about 8 to 22 mm.

Bed-armoring has important implications for understanding and predicting sediment transport rates, and inherently the geomorphology of rivers. The selective removal of fine sediment through the process of winnowing results in bed-armoring, whereby the surface substrate is coarser than the subsurface substrate. Using the ratio of the D50 from the surface pebble counts to the D50 from the bulk subsurface samples, a relative sense of armoring shows that much of the study reach is about twice as coarse in the surface as it is in the subsurface. These values are typical for moderate- to high-sediment-supply rivers in western North America. Further, because armor ratio reflects the relationship between the relative supply to and the sediment transport capacity of the channel (Dietrich et al. 1989; Wilcock 2005; Hassan et al. 2006; Pitlick et al. 2008; Mueller and Pitlick 2013; Pfeiffer et al. 2017), the spatial pattern observed in Skagit River armor ratios, where armor ratios generally increase in the downstream direction, suggests that sediment transport capacity has been reduced by the Project more than sediment supply in the proximal reaches to Newhalem.

6.5 Sediment Transport

Observations of river bed material (Sections 5.4 and 6.4), geomorphic changes (Section 5.1.2) and bed mobility (Sections 5.5.1 and 5.5.2) during the November 2021 flood, morphologic flux estimates (Section 5.5.3), development of a morphologic sediment budget (Section 5.5.5), and lessons learned during development of the suite of four sediment transport models (Section 5.5.6)

paint a coherent picture of the relation between the Skagit Project, sediment transport, and channel morphodynamics in the Skagit River downstream of the Project. Key findings follow:

(1) The Project has reduced bedload sediment supply to the Skagit River below the Newhalem Powerhouse. Ladder, Newhalem, and Goodell provide a large input of sediment below the Project that is roughly equivalent to the bedload sediment supply blocked by the Project. Therefore, the best available estimate is that below the Goodell Creek confluence sediment supply has been reduced by approximately 50 percent. Sediment recruitment from tributaries and bank erosion downstream of this monotonically decreases the relative influence with increasing distance downstream.

(2) The Project has reduced the duration and magnitude of peak flows appreciably (Section 5.8). This has two important effects:

   (a) Sediment transport capacity is a nonlinear function of discharge, such that high, infrequent flows dominate the total transport in the river. The reduction in peak flows in favor of longer durations of moderate flows therefore reduces the available sediment transporting energy in the river. Thus, the sediment transport capacity is reduced.

   (b) The reduction in peak flows also reduces the expected channel widths. In sedimentation zones of the river (Reaches 2B, parts of 3A, part of 5A, 6, and 7 in the primary study area, along with the Reaches 8B and 11 downstream of the Sauk River confluence), this translates into a reduced tendency for the channel to sustain a multi-thread planform that may provide greater rearing habitat availability than the dominant single-thread planform. Channel sensitivity to the changes in channel forming peak discharges is much greater than to changes in the bed material sediment supply.

(3) The combined impact of findings (1) and (2a) on river bed levels (expected aggradation or degradation response) is indeterminant, a priori, because they are on opposing sides of the Lane (1954) balance:

$$Q_s d \propto Q_w S,$$

where Q_s is the quantity of bedload sediment, d is the size of that sediment, Q_w is the discharge, and S is the slope of the stream (which governs aggradation and degradation relative to a particular downstream base level control). Finding 1 specifies a reduction in Q_s, while finding 2a specifies a reduction in Q_w. Examples exist both of degradation following upstream regulation (Kondolf 1997; Grams et al. 2007; Singer 2010; Draut et al. 2011; Ma et al. 2012) and of aggradation following upstream regulation (Bakker et al. 2018, Collins et al. 2019), with the outcome depending on the ratio of change to Q_s and Q_w.

The bed material sediment budget for the calibration period (2018-2022, Section 5.5.5) and calibration exercises for the 1-D HEC-RAS mobile bed model (Section 5.5.6.2) both show that period resulted in net aggradation between Newhalem and Shovel Spur, and longer-term (multi-decadal) indications of historical bed elevations show relatively little change (Sections 5.1 and 6.1), except for a localized area of pronounced degradation in the

upstream portion of Reach 4 affected by backwater dynamics as the river enters the Shovel Spur Rapids. These same lines of evidence indicate that the bed is slightly aggradational to stable from Shovel Spur downstream to the Barnaby Reach, where it is aggrading. Given the abundant sediment supply at Newhalem from Goodell, Newhalem, and Ladder Creeks, and armor ratio patterns (Section 5.4.1 and Section 6.4), these data suggest there have been approximately proportional reductions in the sediment supply (Q_s) and discharge-related sediment transporting energy (Q_w) in the river proximal to Newhalem. Given fully alluvial channel boundaries and aggradational conditions in the Barnaby Reach, the study team interprets that changes in downstream sediment transport and sediment transporting energy have been approximately proportional, with the reduction in sediment transport to the Sauk River confluence occurring primarily because of the reduction in flow energy, not reduced bed material supply at Newhalem.

(4) Local tributary and bank erosion inputs are both large terms in the overall sediment budget compared to the down-channel sediment flux (Section 5.5.5), suggesting there is low along-channel connectivity of bedload sediment transport resulting in large reach-to-reach variability in bedload sediment transport rates, findings supported by morphologic sediment flux calculations (Section 5.5.3), particle tracer observations (Section 5.5.2) and preliminary results of the 1-D HEC-RAS Sediment transport model (Section 5.5.6). Given the low along-channel connectivity in bedload sediment transport and the characteristic diffusive nature of sediment waves in gravel-cobble rivers (Nicholas et al. 1995; Lisle et al. 2001; Cui et al. 2003; Cui et al. 2005), detectable effects of any plausible gravel augmentation would be expected to be relatively localized.

(5) The combination of findings 2b, 3, and 4 can be used to develop a framework for evaluating the potential benefits and implications of sediment augmentation. Under the existing conditions flow regime, sediment augmentation near Newhalem would be expected to provide material that could accelerate channel narrowing planform responses to the reduced discharge and the rate of aggradation. Given the indeterminate value, sediment augmentation may not be the best use of resources under the existing flow regime. However, the potential of implementing a channel-forming process flow regime would increase sediment transporting energy in the river, which may tilt the Lane balance from a generally stable condition toward degradation. While aggradation rather than degradation was observed upstream of reach 6 in the geomorphic change analysis using LiDAR pre and post November 2021 flood, implementation of higher-energy and more frequent process flows could lead to degradation. As such, sediment augmentation should be modeled and considered as a complementary measure available to maintain dynamic equilibrium.

(6) Utilization of the 1-D HEC-RAS sediment transport model to evaluate scenarios covering a range of plausible process flow regimes and sediment supply regimes to determine the expected channel profile impacts of various combinations would be an advisable first step. Following such an evaluation, a sediment augmentation pilot program may be appropriate to implement in conjunction with experimental process flow releases in consideration of potential implications to channel complexity and habitat quality, hydrologic connectivity between the main channel and side channels and the floodplain at various flows, spawning and redd protection, flood risk management, and other resource concerns.

The November 2021 flood provided a natural experiment during the implementation of this study, giving detailed information on channel response to process-flow-magnitude discharges. The daily peak flow at the Newhalem gage was about midway between naturalized 2- and 10-yr daily (water year 1988-2020 period of record) recurrence interval discharges. Between Goodell Creek and the Sauk River Confluence peak flows were slightly less than the naturalized 10-yr recurrence interval flow (NHC 2023). This event:

- Effectively mobilized large volumes of sediment from tributary creek fans (Sections 5.1.1, 5.1.2 and 5.5.1) (except for Alma Creek, where the fan is comprised dominantly of boulder-dominated deposits).
- Caused slight bed aggradation through most of the study area.
- Caused only localized bank erosion (Sections 5.1.1 and 5.1.2), except downstream of Marblemount. Nonetheless, some of the localized erosion resulted in disruptive damage to infrastructure.
- Resulted in 48 percent of scour monitors at redd locations exceeding 15 cm of scour (initiation of egg loss), 26 percent exceeding 25 cm (middle of redd pocket for most salmon species), and 15 percent exceeding 35 cm (complete egg loss for most species). No redd scours indicated a scour depth exceeding 50 cm of scour (complete egg loss for Chinook). Assuming the redd scour monitor locations are representative of the distribution of redd sites in the river, this likely represents a meaningful but not catastrophic impact on egg-to-fry survival. Comparison of escapement and outmigration abundance data for species incubating at the time of the 2021 flood may provide another useful reference point for understanding the importance of this effect.

A final key finding relevant to consideration of process flows is the threshold for mobilization of the bed material. At the reach-average scale, flow magnitudes ranging from approximately 1.25 to 2.5 times the historical regulated 2-yr daily recurrence interval discharge are required to mobilize the D_{50} and flows between about 1.75 and 3 times the existing conditions 2-yr daily recurrence interval flow are required to mobilize the D_{84}. Between Goodell Creek and Bacon Creek, the ratio of the naturalized 2-yr daily recurrence interval discharge to the historical regulated 2-yr daily discharge is 1.9, between Bacon Creek and the Cascade River it is about 1.7, and between the Cascade River and the Sauk River it is about 1.5. Ratios of the naturalized 10-yr daily recurrence interval to the historical regulated 2-yr daily recurrence interval follow a similar pattern, decreasing from 3.7 below Goodell Creek to 2.8 below the Cascade River. This finding suggests that discharges in the range of the 2- to 10-year recurrence interval daily naturalized flows are needed for channel forming and maintaining flows. These flows help sustain a multi thread channel planform, maintain connectivity of side channels, drive bank erosion to recruit large wood, all supporting creation and maintenance of rearing habitat for juvenile salmonids. The river is currently actively managed to protect salmon spawning and egg-to-fry survival, protect salmon fry, protect steelhead spawning and egg-to-fry survival, protect steelhead fry, and facilitate fry outmigration. Implementation of process flows intended to increase channel complexity benefiting rearing habitat may have impacts on these other values.

Refinement of this understanding is expected following implementation of process flow scenario evaluations using the suite of sediment transport models.

6.6 Large Wood Inventory

The large wood historical and field inventory study indicate important findings about large wood and log jams in the primary study area.

- Based on 1979 to 2022 aerials and the field inventory, the log jam density varied from 1.5 to 3.8 per mile and varied substantially by reach.
- The majority of jams that were formed in the last two years are bar top jams. These are the least stable jam type.
- Large jams (100 plus pieces) are more likely to persist over longer periods than small (10-50 pieces) or medium (51-99 pieces) jams.
- In the 2021 field inventory, 40 percent of the large wood in jams and individual pieces were located in side channels.
- Reach 6 has historically and currently contains a higher concentration of log jams and individual large wood pieces than the other reaches in the primary study area. This is due to Reach 6 having a high river channel complexity metric and high channel migration rates.
- Approximately 59 percent of large wood pieces were in log jams found within the mainstem, and side channels.
- The majority of large wood, approximately 65 percent, was found in Reach 5B and 6.
- Presence of rootwads generally increased in a downstream direction.
- Cascade River and Diobsud Creek have significantly more large wood accumulation near the Skagit confluence than other tributaries.
- Most large wood individual pieces in the mainstem primary study area are bar top wood that only interacts with the wetted channel at high flows.
- Large wood with a greater dbh is more likely to have an attached rootwad.
- Large wood with a greater diameter rootwad is more likely to form a pool.
- During the 35-month long period between April 2018 and May 2021, more pieces remained stable than the 13-month period from May 2021 to June 2022.
- Between April 2018 and May 2021, approximately 35 percent of large wood pieces remained stable and 75 percent of pieces between 100 and 125 ft remained stable. During this period, the highest flow event reached 31,300 cfs at the USGS Skagit River at Marblemount gage (12181000).
- Between May 2021 and June 2022, approximately 13 percent of individual large wood pieces remained stable. During this period, the highest flow event reached 63,400 cfs at the USGS Skagit River at Marblemount gage (12181000).

The results of a historical large wood inventory from 1979 to 2022 are presented in Section 5.6 of this study report. The resolution of historical imagery increased over time. The higher resolution potentially amplifies the increasing trend of individual large wood pieces. The actual magnitude of large wood per mile in the primary study area could be similar in each year. Alternatively, aerial inventory of log jams is potentially a more reliable remote sensing technique than individual large

wood piece inventory as log jams are much larger features. Results from this analysis show that despite the potential variation in large wood and log jam magnitude, the spatial distribution of large wood and log jams in the mainstem of the primary study area, has remained similar on a geomorphic reach scale since 1979. Large wood and log jams have retained a higher concentration in Reach 6 than the rest of the primary study area. This is due to Reach 6 having a significantly higher river channel complexity metric in all periods dating back to 1944 than any other reach (Table 5.3-15). As discussed in section 6.7.2, river channel complexity is a driver of wood accumulation.

Most individual large wood pieces located in side channels could not be inventoried using aerial images due to canopy cover unless they were located in the Cascade River distributary side channels. As a result, conclusions on the variation of large wood loading in side channels from 1979 to 2022 cannot be made. The results of the August 2021 field inventory show that 40 percent of large wood is in side channels. In addition to a high channel complexity, Reach 6 has had a significantly greater length of side channels than any other reach in all periods dating back to 1944 (Table 5.3-9). Based on this metric, Reach 6 likely contained a large quantity of large wood in side channels in all time periods.

The majority of log jams identified in the jam persistence analysis were bar top, side channel, and meander jams. As expected, the percentage of jams identified as small and medium decreased with increasing number of years present, and the percent of persistent large jams increased with total number of years present. This suggests that large jams are more likely to persist over longer periods than small or medium jams. Historical analysis of large wood and log jams within geomorphic reaches has shown that large wood and log jams are most prevalent, but distribution changes most commonly within Reach 5B and Reach 6. These changes are often linked to channel migration. In other reaches, where less channel migration is occurring, large wood and log jams often accumulate in the same location over time.

Large wood pieces in the gorge bypass reach contain the lowest percentage of pieces with an attached rootwad, 3 percent, in the mainstem primary study area. The number of pieces with attached rootwads then increases downstream to a percentage of pieces in the mainstem between 21 and 65 percent. Large wood pieces in the gorge bypass reach are often old due to periods of minimal flow and transport. Moving downstream more pieces that are within the channel are locally sourced from natural recruitment processes resulting in a higher percentage of large wood pieces with an attached rootwad.

The large wood field inventory completed in tributaries show that Cascade River and Diobsud Creek had the highest abundance of large wood and log jams near their confluences with the Skagit River. These tributaries are larger, have more meanders, and recruitment than many of the other ones. This is followed by Bacon Creek, Goodell Creek, Rocky Creek, Damnation Creek, and Illabot Creek. Tributaries showing less wood recruitment are typically characterized by narrow, channelized reaches with few bars and meanders. The mouths of these low recruitment tributaries are usually narrow and do not feature the large bars found in larger creeks. The remaining tributaries had a small amount of large wood to no large wood within the area surveyed.

Reaches containing more side channels are characterized by more meander bends and channel junctions than those single threaded channel reaches with few side channels. This channel

morphology promotes more opportunities for mobile wood to move outside the thalweg and deposit on to banks and log jams where depth is comparably lower. This is because bends and flow splits create a thalweg with many changes in velocity vectors compared to a straight single threaded channel. It was observed that reaches with many side channels have more large wood than reaches with few or no side channels. It was also observed that reaches with many side channels tend to accumulate more mobile wood. Approximately 45 percent of side channel inlets are not connected at 5 percent annual exceedance flows as opposed to 4 percent of side channel outlets (Section 5.3.2). This is important to wood loading as wood transport into side channels only occurs during high flow events through side channel inlets, not outlets. Side channel wood loading could increase if more side inlets were to become connected at higher flows.

In the mainstem, large wood pieces had a density of 1 piece per acre in the wetted channel and a density of 13 pieces per acre on dry bars. This observation shows that a significant portion of large wood in the mainstem is bar top wood that does not interact with the wetted channel during low flows.

Large wood characteristics gathered in the field inventory show that large wood pieces that have a greater dbh are more likely to have a rootwad attached. This was seen in the mainstem and side channels. The inventory also showed that pool forming large wood is more often associated with large wood that has a rootwad attached. Additionally, this study found that large wood with a larger diameter rootwad is more likely to form a pool than large wood with a smaller diameter rootwad. Large wood with a 2-to-3.9-ft diameter rootwad formed a pool 17 percent of the time whereas large wood with a 10-to-25-ft rootwad formed a pool 64 percent of the time. The potential geomorphic importance of an individual large wood piece may be directly related to its size and shape (Schuett-Ames et al 1999).

Some additional characteristics gathered about large wood in the study teams' field inventory included decay class and species. Approximately 85 percent, of the large wood has a decay class of either 1 or 2, least or intermediate. This suggests a short residence time for large wood pieces, which is in line with other studies. In a study on the Queets River on Washington's Olympic Peninsula, 80 percent of pieces inventoried had a residence time of less than 50 years (Hyatt and Naiman 2001). Additionally, 73 percent of large wood inventoried was either a cedar, cottonwood, or alder tree species.

Analysis of large wood stability between May 2021 and June 2022 was completed using aerial photographs and field data. Additionally, stability was calculated with aerials between April 2018 and May 2021 and between May 2021 and June 2022. The maximum high flow event during the May 2021 to June 2022 period was approximately twice the magnitude of discharge than the April 2018 to May 2021 period.

To see how large wood acts during average flow regimes, the study team looked at wood stability between April 2018 and May 2021. The highest flow in this period was 31,300 cfs at the USGS Skagit River at Marblemount gage (12181000), similar to October 2021 event of 29,100 cfs. Between April 2018 and May 2021, the overall large wood stability was approximately 35 percent and 75 percent of pieces between 100 and 125 ft remained stable. This means that length could be the greatest single factor in stability during average conditions.

To create a comparison that showed only the effect that fall and winter flows had on stability, the field inventory done in August 2021 was compared to the large wood identified in the June 2022 imagery. The field inventory consisted of 10 half-mile detailed areas that were dispersed through the study area and concentrated in areas with more large wood. To create a direct comparison between the field inventory and imagery, the data collected from the imagery was clipped to the detailed areas used in the field inventory. Another assessment was done using only imagery from 2021 and 2022. Using only imagery reduces error introduced by comparing a higher resolution, ground-level inventory to relatively low-resolution imagery captured from above. It is likely that many pieces that could be seen from a boat were obscured by foliage in the imagery. This method captured the November 2021 flood measured at 63,400 cfs at the USGS Skagit River at Marblemount gage (12181000) but did not show pieces that may have moved into place and become stable in spring floods. In the main Geomorphology Study period, from May 2021 to June 2022, data from May 2021, August 2021, and June 2022 was available. Because there was no large wood count recorded in early November, the study team could not capture the effect that the 29,100 cfs October flow on the Skagit River at Marblemount had on stability. The highest flow between 2018 and 2021 on the Skagit River at Marblemount was 31,300 cfs. This is similar to the magnitude of the October 2021 event. The stability from April 2018 to May 2021 time period was 35 percent. The overall May 2021 to June 2022 time period stability was 13 percent.

Statistics were not calculated for stability between periods of greater than 10 months because there is a lot of uncertainty around which specific event caused the large wood pieces to move. The overall percentage stable wood is useful in relationship to the largest flow during a particular time period.

Between May 2021 and August 2021, 57 percent of the large wood remained stable. During this period, a flood event on June 29, 2021, was measured at 29,400 cfs. Between August 2021 and June 2022, 4 percent of the large wood remained stable. The largest flow was 63,400 cfs and there were a number of other events that were higher than on an average year. With only 12 stable large wood pieces identified, it is difficult to say with certainty which attributes had the greatest effect on stability, but 17.4 percent of pieces with a dbh between 3 and 4 ft were stable, and 22.2 percent of pieces with a rootwad diameter greater than 15 ft were stable. These numbers suggest that dbh and rootwad diameter have an effect on large wood stability.

There are multiple factors that may be contributing to a low percentage of stable wood. The flows experienced in this period are much greater than average, flushing out more large wood than an average flood season might. Another factor is the method used to track stability. As previously mentioned, analyzing wood stability through imagery only tells part of the story. The wood that is likely more stable may be deposited against banks hidden under foliage, and only the wood not obscured by foliage was captured. The only way to get a realistic representation of wood stability is to do a field inventory year after year. However, the study team determined that a far higher percentage of wood remains stable during average flow years than it does during higher than average flow years. Based on this study, there was no single factor that consistently had a greater effect on stability.

6.7 Large Wood Transport

The large wood transport study indicates important findings about transport dynamics of large wood and log jams in the primary study area.

- Wood pieces input at the Aggregate Pond site are all mobile at both low and high flows.
- Log jams are generally stable but when flows surpass their stability threshold, a high number of large wood pieces sourced from log jams enter the channel as mobile wood.
- Most mobile large wood pieces that remain in the primary study area deposit as racked wood in log jams.
- Reach 6, the most complex reach with the greatest number of jams, retains a significantly higher portion of mobile large wood than any other geomorphic reach.
- Most large wood being recruited in the mainstem is within Reach 6. As a result, upstream of Reach 6, large wood recruitment will be primarily from tributary input.
- Large wood predicted to be recruited into the mainstem has a smaller dbh on average than trees that have been inventoried in the mainstem channel. This is likely because small dbh trees with no rootwad are being selectively transported more often than large trees with a rootwad attached. This observation provides evidence that large wood pieces with a greater dbh have a higher likelihood of remaining stable in the channel.
- It is predicted that between 2019 and 2039, an average of 399 large wood pieces with a diameter greater than 11 inches (0.92 ft) will be recruited in the mainstem primary study area each year. It should be noted that during years of higher or lower than average peak flows, large wood recruitment may vary substantially from the mean.

The following subsections discuss in detail the results of the large wood tracking method used in this study, the conclusions drawn from analysis of large wood transport and recruitment, and suggestions for effective large wood augmentation methods in the primary study area.

6.7.1 Large Wood Tracking

Between October 13, 2021, and March 31, 2022, the study team installed radio tags and metal tags on 198 pieces of wood, 37 of which were generally smaller pieces transported down from Ross Lake and released to the channel at the Agg Pond site on December 9, 2021. (Table 5.7-1). Several important findings were indicated from this analysis.

Large wood tracking efforts resulted in a recovery rate for each scanning period between 39 and 100 percent of pieces that mobilized prior to a scanning period, on average across all scanning periods, 60 percent of pieces that mobilized were recovered (Table 5.7-6). A significant scanning period to note was the March 29 to 31, 2022 scanning effort that recovered 84 percent of the 41 large wood pieces that mobilized prior to this scanning period. This effort differs from other scanning periods because it was conducted within the entire primary study area, as well as downstream of the Sauk confluence to Puget Sound. Downstream of the primary study area, 25 large wood pieces that were mobilized but not recovered in earlier scanning efforts were recovered. One large wood piece was found on the coast in Similk Bay, 10 miles away from where the Skagit River meets Puget Sound. The recovery rate of the scanning efforts was high enough to provide

valuable wood movement data for the Geomorphology study although a significant percentage, 40 percent, of mobile pieces were not recovered during scanning efforts. These pieces may have floated downstream of the study area or were captured in side channels that brought them out of range of the scanning device. This possibility is not limited to small pieces of tagged large wood, as one of the largest tagged pieces, a 6-ft diameter, 100-ft long, and 20-ft diameter rootwad cedar (Tag ID 54) was found downstream of the primary study area in the March 29 to 31, 2022 scanning effort.

Results of large wood tracking effort culminated in an effort that reliably tracked the movement of large wood pieces throughout the Skagit River. The data were used to inform an analysis of the large wood transport dynamics in the primary study area.

6.7.2 Large Wood Transport

Large wood transport study results indicate several important findings about large wood transport dynamics in the primary study area.

Large wood transport results show that a significant portion, 66 percent, of large wood pieces that were tracked became mobile at one or more instances during the large wood tracking study (Table 5.7-8). Results also show that an even greater portion, 100 percent, of Agg Pond pieces became mobile during the large wood tracking study (Table 5.7-8). This result is more dramatic considering that Agg Pond wood was released into the mainstem of the Skagit River on December 9, 2021. This is after the two highest magnitude flow events occurred. This analysis shows that large wood in the primary study area is generally very mobile. Agg pond wood being significantly smaller than natural large wood tagged in the large wood tracking study is even more mobile.

Additionally, characteristics of where pieces were stable during flood events varied by the magnitude of the flood event. The October 28, 2021 flood event resulted in the two most unstable positions in the channel being a point bar and a mid-channel bar where 78 percent and 43 percent respectively of pieces were not stable. During this flood event, 29 percent of racked wood pieces in log jams remained stable (Table 5.7-2). During the November 15-16, 2021 flood event, which was a much higher magnitude than the October 28-29, 2021 flood event, the two most unstable positions in the channel were mid-channel bars and racked large wood pieces. At these locations, 88 percent of mid-channel bar pieces were unstable and 74 percent of racked pieces were unstable. At point bars, 64 percent of large wood pieces were unstable (Table 5.7-12). This observation provides insight that racked large wood in the primary study area is significantly more stable during flood events that are equal to or less than the magnitude of discharge that was observed in the October 28-29, 2021 flood event when compared with flood events that are of equal or greater magnitude than what was observed in the November 15-16, 2021 flood event. Racked wood pieces likely do not become mobile until a flow discharge threshold is exceeded that destabilizes the log jam they are a part of. Once this is reached, racked logs that make up the log jam can become mobile in the channel. Considering that 64 percent of large wood pieces in the mainstem are found within log jams, the discharge where average log jams in the primary study area become unstable, will correspond with a sudden increase in the number of mobilized large wood pieces once that average discharge is exceeded (Table 5.6-2). This data also shows that bar top wood is considerably less stable during flood events of any magnitude than large wood found in other positions within the active channel.

Most mobile large wood deposits as racked wood in log jams in the primary study area. During the October 28-29, 2021 flood event, 60 percent of known large wood piece deposition locations were large wood pieces deposited as racked wood in log jams (Table 5.7-3). Also, during the November 15, 2021 storm, 54 percent of known large wood piece deposition locations were large wood pieces deposited as racked wood in log jams (Table 5.7-5). The reported percentage of wood depositing as racked wood is also likely an underestimate. This is because many deposited large wood pieces that were classified as "undetermined" were suspected to have deposited in log jams. Gaining access to pieces that were suspected to be in log jams was more difficult than any other characteristic deposition location in the primary study area. If the study team could access all of these suspected racked pieces, the percentage of mobile large wood confirmed to be depositing in log jams, would be higher.

Large wood transport results were analyzed at a geomorphic reach scale. The results of this analysis can be seen in Table 5.7-8 and Table 5.7-9. The study team examined reaches where mobile large wood accumulated and reaches where mobile large wood did not appear to accumulate. Results of this analysis show that mobile large wood has a much higher likelihood of accumulating in Reach 6 than any other geomorphic reach in the primary study area. Reach 6 had the highest percentage, 51 percent, of mobile large wood pieces that entered the reach and either deposited for the remaining entirety of the large wood tracking study or deposited for a period long enough to be captured by the following large wood tracking effort. The geomorphic reach that showed the second highest percentage of mobile pieces that deposited in the reach for a detectable period are Reaches 4 and 5A. In these reaches, 6 percent of mobile pieces deposited for a detectable period. Reach 2B had a significant percentage of mobile pieces deposit for a detectable period, although due to the low sample size of 3 mobile large wood pieces moving into the reach, this result was considered too imprecise to be considered. The results of this analysis show that Reach 6 has a significantly higher probability of retaining mobile large wood than any other geomorphic reach in the primary study area.

Reach 6 has the highest probability of retaining mobile large wood because it contains the most log jams and largest log jams in the mainstem of any geomorphic reach in the primary study area. There are 14 total log jams in the mainstem within Reach 6, four of which are medium sized containing an estimated 50 to 100 pieces and two of which are large with an estimated 100 or more pieces. Discussed previously, the study team observed that most mobile large wood will deposit as racked wood in existing log jams within the primary study area. From this observation it is concluded that a high number of log jams will result in a high deposition probability of mobile wood. This trend is what is observed in Reach 6. In all other reaches there are significantly less log jams and the log jams that do exist are smaller. Across the entire mainstem primary study area only four large log jams existed during the August 2021 field inventory. Of these four large jams, one was Reach 1 and did not interact with any tagged large wood. Another large jam was in Reach 5B, this jam disappeared after the November high flow event. The remaining two large jams remained stable in Reach 6 throughout the duration of the transport study. Only four medium sized log jams were inventoried in the mainstem primary study area during the August 2021 field inventory. All four of these medium sized jams were in Reach 6. A diminished presence of large log jams is characteristic of reaches where mobile large wood transported through without stabilizing. Another factor driving mobile wood accumulation in Reach 6 is channel complexity. This reach had a reported channel complexity metric of 141.80 in 2019 (Table 5.3-15). The second highest 2019 complexity metric in the primary study area was Reach 2B with a value of 27.31

(Table 5.3-15). Channel complexity is a metric of sinuosity and the number of junctions in a channel. A sinuous channel with many braids and junctions will promote wood transport into side channels and flow splits. Often these splits will have smaller channel widths and bed surface depths than where a mobile piece may be transporting from. This will cause mobile wood to have a higher likelihood of depositing. Reach 6 having a much greater channel complexity than any other reach is capturing more mobile wood because of this process.

6.7.3 Large Wood Recruitment

Large wood recruitment study results indicate several important findings about large wood transport dynamics in the primary study area.

Future large wood recruitment potential in the mainstem primary study area is distributed disproportionally. Approximately 93 percent of trees with a dbh greater than 11 inches (0.92 ft), as well as 93 percent of trees with a dbh greater than 31 inches (2.6 ft), are predicted to be recruited within Reach 6 (Table 5.7-22). Most trees that are recruited between 2019 and 2039 will have no possibility of interacting with much of the primary study area. The primary source of large wood recruitment to the primary study area upstream of Reach 6 will be from tributary input.

There are 399 large wood pieces expected to be recruited each year into the mainstem primary study area between 2019 and 2039. Of these only 15 pieces, 4 percent, are expected to be greater than 31 inches in diameter (Table 5.7-21). When comparing what is expected to be contributed to the Skagit River from mainstem bank recruitment to the large wood that is currently present in the mainstem primary study area there is a difference in proportion. The August 2021 field inventory found that 9 percent of trees have a dbh greater than 36 inches in the mainstem primary study area, as opposed to the 4 percent of trees expected to be recruited with a dbh greater than 31 inches (Table 5.6-4, 5.7-21). It is likely that this discrepancy is because trees with a greater dbh have a higher probability of remaining stable during high flow events. Trees with a dbh greater than 31 inches are recruited at a rate of 4 percent of the total trees being recruited. The proportion of these larger trees in the mainstem primary study area increases as smaller trees are selectively transported. The large wood transport study discussed in the previous section found evidence that wood mobility was driven primarily by its location in the channel. This study shows that the number of recruited trees greater than 31 inches dbh increases as a proportion of the total trees in the primary study area relative to what is being recruited. This observation provides evidence that the dbh and likely the associated rootwad diameter of a large wood piece could be a secondary driver of wood mobility.

A potential Project effect that can impact the balance of recruitment and transport is when flows are regulated in the mainstem Skagit River while flows remain unregulated in tributaries. As observed following the November 15-16, 2021 flow event, flows were regulated at a significant discharge for several weeks to allow stored water elevation to decrease over time while tributaries decreased to prior flood event conditions within one or two days. This could have caused a net loss of large wood in the mainstem primary study area as large wood was being transported and recruited in the mainstem while significant input from tributary transport was not occurring.

6.7.4 Large Wood Augmentation

Per the June 9, 2021 Notice, City Light will model to determine locations and methods for wood and sediment augmentation no later than 6 months following completion of the instream flow model. Sediment transport modeling and wood inventory, wood transport analysis and recruitment analyses inform a large wood augmentation strategy as part of an ecosystem approach to habitat restoration, which will include both flow measures and non-flow habitat restoration measures to be described in the FLA. Sediment, flow and wood processes interact to create and sustain a complex mosaic of mainstem, riparian, floodplain, side channel, and off-channel habitats and a healthy ecosystem.

Large wood, and in particular log jams, influence geomorphic process and habitat conditions on both a habitat unit and reach scale. Strategic placement of wood in reaches and sub-reaches with higher potential for maintaining and creating a multi-threated channel may provide the greatest functional uplift. As is evident from the large wood studies, key pieces and log jams will need to be of sufficient size to achieve geomorphic and habitat objectives. Smaller pieces unsecured in jams such as the wood introduced from Ross at the Agg Ponds as part of a pilot are very mobile.

Table 6.7-1 summarizes the relationship between geomorphic processes influenced by wood and aquatic and riparian habitat conditions. The study team observed many natural large wood structures in the primary study area that accomplish the aquatic and riparian habitat functions outlined in Table 6.7-1. Existing log jams that are achieving these desired effects serve as examples of what a successful large wood augmentation measure could accomplish. These observed natural large wood structures in some cases also provide sites where existing effective natural wood structures could be enhanced to provide even greater ecological and geomorphic function.

Table 6.7-1 Aquatic and riparian habitat functions that large wood structures can accomplish.

Aquatic/Riparian Habitat Objective	Process
Complex Cover	Complex wood structures create alcoves for hiding from predators, blocks direct sunlight, and inhibits flow velocity.
Pool formation	Flow is redirected and scours bed.
Mid channel bar/island formation	Inhibits local flow velocity allowing sediment to fall out of transport and deposit.
Floodplain connectivity	Inhibits local flow velocity and raises local water surface elevation.
Side channel connectivity	Inhibits local flow velocity and raises local water surface elevation. Also, protects side channel inlet banks from erosion.
Bank erosion and large wood recruitment	Redirects flow into banks.
Sustaining mid-channel bar/island formations	Protects local banks and inhibits flow velocity behind structure allowing sediment to deposit.
Mobile large wood retention	Creates a porous catchment point where mobile large wood is directed by flow into log jam structures and retained.

Achieving the aquatic and riparian conditions show in Table 6.7-1 to support salmonid life histories, address limiting factors such as rearing habitat, and sustain a dynamic and diverse ecosystem is a primary goal of river restoration. As discussed throughout this report, project and flood control related effects such as reduced peak flows as well as non-project related effects such as hydromodifications and legacy impacts of riparian clearing and wood removal have contributed to channel simplification. Wood augmentation is one of the primary methods in the restoration toolkit for increasing complexity. Wood augmentation techniques include engineered log jams, enhancement of existing jams, key piece stabilization, and riparian tree tipping. Other potential tools to be considered for use in concert with wood augmentation include modifying constructed channels to make them more functional and self-sustaining, removing encroaching vegetation and sediment plugs at side channel inlets, restoring riparian conditions, and augmenting gravel as necessary to maintain dynamic equilibrium of flow and sediment under future process flow scenarios. These non-flow measures would supplement flow tools under evaluation as part of the FLA, which may include pulse flows to increase side channel and off channel connectivity and channel maintenance and channel forming process flows.

Another important consideration is wood recruitment potential. Reaches further upstream (2B and 3A) have less wood recruitment potential, and thus are top candidate areas for wood augmentation. Within these reaches, engineered log jams, secured key pieces and tree tipping could be used to create additional hard points to form and stabilize forested islands and side channels. Locating structures in reaches downstream of major tributary confluences that provide an important source of large wood, would have the additional potential benefit of capturing and retaining mobile wood as racking material.

In some cases, inlets to side channels may be a beneficial location for wood augmentation. Placing structures near the inlets of side-channels that are experiencing sedimentation and vegetation encroachment could help further engage these features. At these locations mechanical removal of vegetation and accumulated sediment along with wood placement and process flows could help move these features on a more rapid trajectory toward re-activation. In addition to these natural features, wood augmentation and excavation of channel inlets could be used to enhance constructed blind channels that are silting in due to lack of flushing flows. HEC RAS 1-D and 2-D models developed as part of this study provide valuable design tools for evaluating risks, benefits, and stability of potential wood augmentation actions during implementation planning.

The study team recommends that wood augmentation be considered in the context of an ecosystem approach to restoration rather than actions focused on a single species or habitat type. Where possible, actions should be considered on a reach scale and remove as many constraints that inhibit channel migration as possible. Elements of a successful strategy should include the following elements:

- Clear objectives and desired outcomes.
- Prioritized and focused for greatest effect.
- Large enough scale for desired effect.
- Address root causes.
- Achieve site potential.

- Designed to be resilient and self-sustaining (rates/cycles of physical, chemical and biological processes).

Several site-specific considerations will need to be addressed prior to any wood augmentation program, such as land ownership and access, flood risk, logistics, viability of wood large enough to initiate logjam formations, and other considerations. Wood augmentation opportunities, along with other habitat enhancement measures, will be further explored in the FLA.

6.8 Process Flows

High flow events are necessary to sustain geomorphic processes that form and maintain aquatic habitat. Results charactering the naturalized (unregulated) flow regime using IHA software as part of this study provide a benchmark to inform development of process flow scenarios. Wald (2009) provides guidance recommending three categories of high flows to support geomorphic processes and habitat values: (1) High flow pulses for fish migration and flushing of fine sediment from the channel; (2) Channel maintenance flows for creating and maintaining aquatic habitat; and (3) Channel forming flows that alter channel patterns and activate floodplain processes. The flow thresholds recommended by Wald (2009) include preserving or providing the natural (unregulated) 2-year recurrence interval peak flow for at least 24 hours duration as channel maintenance flows at intervals of 2 years, and the unregulated 10-year recurrence interval peak flow for at least 24 hours duration as channel forming flows at intervals of 10 years if not provided naturally.

Study results derived from investigations of existing habitat conditions, geomorphic change, wood dynamics, and analysis of sediment transport indicate that high-flow recommendations for provision of channel maintenance flows and channel forming flows using the unregulated 2-year and 10-year recurrence interval peak flow targets may be appropriate goals for development of process flow scenarios for the Skagit River. Flows similar in magnitude to the recommended channel maintenance flows occur under the existing regulated conditions; however, the frequency of channel maintenance flows has decreased by 78 percent at Newhalem and 74 percent at Marblemount. An increased frequency of occurrence for channel maintenance flows will support geomorphic functions that scour the bed, undercut banks, and recruit wood to the channel.

Channel forming flows are larger, less frequent floods that transport significant amounts of bedload sediment, drive channel migration and avulsion, recruit large wood from the floodplain. These higher magnitude events are important to the formation and maintenance of side channels. Use of the naturalized 10-year recurrence interval peak flow as a target for channel forming flows would provide an appropriate disturbance mechanism to sustain these geomorphic functions; however, flow releases of this magnitude are likely constrained by need to balance additional factors including dam safety and the need to manage flood and erosion risk to infrastructure and private property downstream of the Project.

Additional discussion presented in Section 6.5 summarizes key findings on anticipated response to process flows based on observations from the November 2021 flood. For reference, the November 2021 flood was slightly less than the unregulated 10-year recurrence interval flow at the Marblemount gaging station. If process flow releases of similar magnitude or greater are infeasible given existing constraints, then alternate measures could be considered to intervene with Project actions that create similar localized disturbance to mimic geomorphic effects of large floods.

6.9 Status of June 9, 2021 Notice

The June 9, 2021 Notice noted the following items of discussion related to the implementation of this Geomorphology Study. The status of each is summarized in Table 6.9-1.

Table 6.9-1. Status of the Geomorphology Study modifications identified in the June 9, 2021 Notice.

Study Modifications identified in the June 9, 2021 Notice: As Written	Status
City Light will develop a 1-D HEC RAS model for stream flow from the Sauk to the estuary and work with technical experts and LPs to identify robust sampling of mutually agreed to measurement endpoints within reference reaches within major reach segments. City Light will incorporate Jon Riedel's (NPS) work and the full range of hydrology and operations will be modeled.	As described in Section 4.5.1 of the Geomorphology Study report, City Light has implemented a suite of modeling tools to address areas between Gorge Powerhouse and the estuary. The modeling approach and suite of models were defined in consultation with LPs in workshops in July, September, and October 2021. Sediment transport modeling work has identified response reaches where channel morphology and channel floodplain morphology may be relatively sensitive to Project effects.
City Light will convene workshops to address the technical issues such as channel migration, LWD, suspended sediment transport and washload, and off-channel habitat associated with the modeling effort or other additional modeling efforts.	The geographic extent of each modeling tool is described in Section 4.5.1 of the Geomorphology Study report. Tools for application downstream of the Sauk include UBCRM and MAST 1-D, which were extended to the gravel-sand transition at approximately PRM 21. The rationale for using MAST 1-D model in lieu of 1-D HEC-RAS model is explained in Section 7.3 of the Geomorphology Study report.
City Light will modify the study plan to include collaboration with the LPs to look for opportunities to incorporate sediment modeling in reference reaches below the Sauk to the estuary.	Fine sediment delivery to the estuary has been evaluated by combining watershed-scale sediment yield analysis (Section 4.5.3 of the Geomorphology Study report) with evaluation of floodplain-channel sediment exchange using the MAST 1-D model.
Regarding LPs' comments regarding LWD inventory, this is a topic of the lower river synthesis study. To the extent the synthesis study identifies a data gap, City Light will work collaboratively with the LPs to address it (including but not limited to the Watershed Council Middle Skagit River Restoration Plan, aerial photos, etc.).	Results of the Lower River Synthesis Study are provided in the SY-01 Synthesis and Integration of Available Information on Resources in the Lower Skagit River (City Light 2023g).
City Light will provide LPs with its existing inventory of LWD in the three project reservoirs by no later than August 1, 2021 and conduct an annual inventory of inputs during the study period.	Reservoir wood data from 2017 to 2022 is included with this updated study report.
City Light will convene a workshop with the LPs during the fourth quarter of 2021 to collaboratively develop strategies for short-term and long-term management of woody debris in the reservoirs and transport of woody debris to the lower river.	This topic was discussed at the November 2021 Geomorphology Work Group meeting and in early 2022.

Study Modifications identified in the June 9, 2021 Notice: As Written	Status
Action item: LPs will work with City Light within the next 30 days to develop protocol for wood crew to enumerate woody debris coming into reservoir.	City Light provided the data form to LPs and collected additional wood data on Ross Lake in August with right-of-way crews responsible for corralling woody debris. These additional data were included as part of the Geomorphology Study interim report (City Light 2022) and this updated study report.
City Light will convene workgroup meetings to clarify expected capabilities of sediment transport and morpho-dynamic models for predicting changes to channel morphology.	This topic was discussed at the October 2021 Geomorphology Work Group meeting.
City Light will calibrate sediment transport models to at least the 10-year recurrence interval (subject to available data) and calibrate sediment transport model to help predict where sediment would be stored. If necessary, City Light will provide controlled releases to assist in calibrating the model. Such controlled releases will be designed in a manner as to not contribute to downstream property damage or risk to health and human safety.	The sediment transport models have been calibrated to the November 2021 flood, which ranges from approximately a midway between a 2-yr and 10-yr natural flow condition recurrence interval event at the Newhalem Gage to approximately a 10-yr natural flow recurrence interval event at Marblemount. Repeat topobathymetric LiDAR bracketing this flood (2017/18 and 2022) and the empirical bed mobility observations described in Section 4.5.2 of the Geomorphology Study report provide that calibration information.
City Light will model to determine locations and methods for wood and sediment augmentation no later than 6 months following completion of the instream flow model. Based on the results of the modeling, City Light will implement a wood and sediment augmentation pilot program to be developed jointly by City Light and the LPs no later than 2023 (unless City Light and the LPs mutually determine that such a pilot program is unnecessary). City Light and the LPs expect that the augmentation pilot program will include monitoring, including monitoring downstream of the Sauk confluence, and will result in information to inform development of possible PM&E measures in the new license.	As committed to in the RSP, City Light developed a suite of tools (including a 2-D sediment transport model, a 1-D sediment transport model, a UBCRM model, and a MAST1-D model, in addition to the instream flow and operations models developed as part of other studies) to assist in the analysis of potential protection, mitigation, and enhancement (PME) measures. The above information and tools (e.g., models) will be used as part of the license application and PME development process to assess potential flow regimes, gravel, or wood augmentation plans, in consideration of other integrated resource concerns and PMEs, for the new license. In addition to the modeling tools, over 500 sediment particles with RFID tags were deployed in early November 2021, as described in Section 4.5.2 of this study report. These tracers provided information on the size of sediment a river is competent to move and the magnitude of sediment particle displacement between the time of their deployment and recovery over a range of flows (including the November 2021 flood). Additionally, and also as part of this Geomorphology Study, 198 pieces of wood were tagged in the mainstem, tributaries, and side channels, and supplemental wood was tagged and released in the Skagit River, as described in section 4.7 of this study report. Serving as a preliminary pilot augmentation program, the tracking of these tracer particles and large wood not only assisted in the calibration of the sediment transport models, but will also be instrumental to the development of any augmentation program identified in the FLA.

Study Modifications identified in the June 9, 2021 Notice: As Written	Status
	Based on the results of the analysis to be included in the FLA, which will include an integrated analysis of ongoing Project effects and a comprehensive PME package, City Light will work with LPs to determine if additional wood and sediment augmentation pilot efforts are necessary. Any such pilot program would be implemented in coordination with modifications to the existing flow regime and other relevant PMEs as identified in the FLA.
City Light will continue current data collection/tagging of wood that is placed in the river under current programs and will disseminate data from these ongoing programs to the LPs as soon as practicable.	LWD data tagging/tracking field effort of 37 reservoir wood pieces at the Agg pond is described in this study report. All Agg pond pieces moved during low flows.
The results of GE-04 and the other studies will be used to inform sediment and wood augmentation throughout the Skagit River system.	See response above related to wood and sediment augmentation.
City Light will provide LPs information about current data collection/tagging of wood as soon as practicable. The Federal and state resource agencies will consider what information and permitting is needed to implement the augmentation pilot program. City Light will work cooperatively with LPs to ensure timely implementation of the pilot program with all required permits in place.	LWD data tagging/tracking field effort of natural large wood pieces and reservoir wood pieces was performed between October 2021 and July 2022 and is described in this study report. Updates on the wood tagging topic were presented at Geomorphology Work Group meetings in September, and October 2021, November 2022, and in January 2023.
City Light will convene technical workshops with the purpose of expanding the scope, and changing and/or adding proposed tagging/monitoring of tributary sediment deposits to more tributaries, including downstream of Sauk Confluence.	City Light expanded the scope of particle tracing activity to include Ladder Creek, Newhalem Creek, Goodell Creek, one riffle crest near County Line, and Bacon Creek (including tracers on the fan and upstream of the SR 20 bridge). These results are described in Section 5.5.2. In addition, lithology tracer results have been evaluated for tributaries downstream of the Sauk River confluence (Sections 5.4.4 and 5.5.5).
City Light will include continuous stage readers in selected off-channel habitats in the floodplain to validate floodplain connectivity. The location and placement of stage readers will be agreed upon by City Light and the LPs in a future workshop.	20 water level data logger sites were established in the Skagit River floodplain between Newhalem and the Sauk River. Site selection was coordinated with LPs and presented in a series of work sessions. A technical memorandum describing the data logger sites and results compiled for WY 2022 is presented in Attachment U.
Action item: City Light will convene workshops to discuss the influence of groundwater and utility of FLIR on hyporheic exchange and in the selection of study reaches.	The initial workshop on FLIR occurred on October 21, 2021, with ongoing discussions on this topic occurring during subsequent work group meetings in 2022. City Light plans to complete FLIR in 2023, in consultation with LPs.

Study Modifications identified in the June 9, 2021 Notice: As Written	Status
By relying upon focus areas in application of the 2-D transport model and using the instream flood model, City Light will assess floodplain flow conditions including shear stress and scour.	This issue was considered in the list of questions to be addressed by the model suite that has been developed for the Geomorphology Study.
As part of its FERC license application, City Light will integrate the results of GE-04 with the FA-02 hydraulic model and other available information to inform the impacts of process flows on anadromous salmon habitat and population productivities.	Will be addressed in the FLA.
City Light will clarify the study plan to describe metrics available in the IHA software and will apply it to process flows. See Wald, A.R. 2009. Report of investigations in instream flow: High flows for fish and wildlife in Washington. Department of Fish and Wildlife, Olympia.	An overview of IHA methods and results was presented at a work group meeting in October 2022. Additional detail of IHA analysis is provided in Attachment T.
City Light and the LPs will develop in the workshop a suite of metrics to illustrate longitudinal disturbance regimes.	A GE-04/FA-02 workshop and data needs discussion was held on October 12, 2021 and the suite of metrics were developed and informed this study.
City Light will modify the study plan to include flows necessary to inundate habitat features in the validation discharge data set (off-channel).	20 water level data logger sites were established in the Skagit River floodplain between Newhalem and the Sauk River. Site selection was coordinated with LPs and presented in a series of work sessions. A technical memorandum describing the data logger sites and results compiled for WY 2022 is presented in Attachment U. Validation of the logger data to the FA-02 Instream Flow Model Development Study are described in the FA-02 Instream Flow Model Development Study report.
City Light will quantify sediment supply into Ross Reservoir as an annual rate by using the existing DHSVM model and historical contours and bathymetry information.	Available information was reviewed and discussed at Fall 2021 work group meetings with further discussion in Q1 2022. During work group meetings in Fall 2021, DHSVM was determined to not be the preferred tool for this; rather, a regression relation to predict basin-scale fine sediment yield was developed and compared to information on historical bathymetric changes.
This issue [process flows] has been resolved through commitments with respect to integration. That is, as part of its FERC license application, City Light will integrate the results of GE-04 with the FA-02 hydraulic model and other available information to inform the impacts of process flows on anadromous salmon habitat and population productivities.	Integration of results of GE-04 and FA-02 to inform process flows will be described in the FLA.
As part of a Q3/4 workshop, City Light will address the simulation of added sediment, flow, and log jams in the model mesh via scenarios developed in coordination with the LPs. Otherwise, this issue is addressed by topic above and via scenarios implemented in the study plan.	Topic was addressed during Geomorphology Work Group meetings.

Study Modifications identified in the June 9, 2021 Notice: As Written	Status
Issue: Adjust modeling focus areas so they are scaled to channel dimensions (e.g., 10-20x channel width) depending on process to be modeled June 9, 2021 Notice Modification: This issue will be resolved in a workshop.	As described in Section 4.5.1 of the Geomorphology Study report, City Light has applied a suite of modeling tools to address areas below the Sauk confluence. The suite of models was discussed with LPs in workshops in July, September, and October 2021. The length of each model domain has been designed to capture the process of interest and minimize boundary condition effects on those processes.
Issue: Adjust study to characterize sediment supply from the Sauk so that we could assess the potential for bed aggradation in the Skagit at the confluence and the associated changes in dynamics from the upstream reach. June 9, 2021 Notice Modification: Action item: City Light to contact NPS, USIT, and Skagit River System Cooperative to resolve this outstanding issue.	Sediment supply from the Sauk River has been considered as a part of the assessment of tributary sediment inputs for the morphologic sediment budget, 1-D HEC-RAS sediment transport model, and MAST1-D model.
Issue: Link sediment modeling with the development of data on flows. June 9, 2021 Notice Modification: City Light will link sediment modeling with the development of data on flows.	As described in Section 4.5.1, City Light developed a suite of modeling tools that were discussed with LPs in workshops in July, September, and October 2021, November 2022, and in January 2023. Existing conditions and alternative process flow regimes were estimated.
Issue: Explore use of 2-D HEC-RAS model in focus reaches to inform the 1-D model. June 9, 2021 Notice Modification: This issue will be addressed through workshops.	As described in Section 4.5.1, City Light developed a suite of modeling tools that were discussed with LPs in workshops in July, September, and October 2021, November 2022, and in January 2023. It includes six 2-D focus reaches above the Sauk river.
City Light will hold workshop with those who have recent expertise in sediment and/or wood-transport modeling.	NPS geomorphologists and Wes Lauer have participated in Geomorphology Work Group meetings and Wes Lauer has contributed substantially to development of the MAST 1-D model as applied to the Skagit River.
Issue: Need an empirical model to capture dynamic balance between floodplain formation on bars and destruction at eroding banks and avulsions. June 9, 2021 Notice Modification: Action item: City Light to contact NPS, USIT, and Skagit River System Cooperative to resolve this outstanding issue.	As described in Section 4.5.1, City Light developed a suite of modeling tools that were discussed with LPs in workshops in July, September, and October 2021, November 2022, and in January 2023. It includes a MAST 1-D model intended to explicitly evaluate the dynamic balance between floodplain formation on bars and erosion by lateral channel migration.
City Light will map vegetation areas within the bank full from aerial photography and through a period of record.	Vegetated bars and forested islands were mapped from the time series of aerial imagery as described in Section 4.1.1. Evaluation of the potential for future large wood loading from bank erosion has been completed in 2022 (Section 6.1.7 of the Geomorphology Study report).

7.0 VARIANCES FROM FERC-APPROVED STUDY PLAN AND PROPOSED MODIFICATIONS

Variances from the study plan's methodology are described below. All except the last variance were previously described in the GE-04 Skagit River Geomorphology Between Gorge Dam and the Sauk River Study Interim Report (City Light 2022). Notwithstanding these variances, study goals and objectives were met as explained below.

7.1 Variances in Aquatic Habitat

The approach to measurement and analysis of aquatic habitat was largely directed by the FERC-approved study plan with a few additions as described in Section 4.2.2. For the tributary analysis, since the WDFW Fish Passage Manual (WDFW 2019) recommends using multiple metrics, rather than depth, to assess passage barriers, these metrics were collected and used (to the extent feasible) to supplement the assessment of fish passage at tributary mouths. Measurements of depth were still collected for the lowest 500 ft of the tributary consistent with the RSP, but additional information, such as gradient, was also gathered consistent with the WDFW Fish Passage Manual (WDFW 2019). This methodology ensured study goals and objectives were met.

7.2 Bulk Sample Volume and Hybrid Grainsize Classification Method

As described in Section 4.4.3 of this study report, in order to facilitate completion of the planned field program in the available time, the volume of bulk samples was reduced from the standard "maximum practicable" weight of 1,100 pounds suggested by Church et al. (1987) to 440 pounds. In consultation with LPs, the hybrid approach of Rice and Haschenburger (2004) was added to ensure that bulk samples appropriately represent the grainsize distribution of coarse material. This approach better met the study objective to characterize the subsurface grainsize distribution of material along the river because it enabled better spatial coverage of the subsurface bulk grainsize sampling program while ensuring that the grainsize distributions defined by these samples appropriately represent the coarse (cobble and larger) fraction of the grainsize distribution that would have been systematically under-sampled following only the Church et al. (1987) approach.

7.3 Sediment Transport Modeling Program

As described in Section 4.5.1, a modeling program to fulfill the RSP and the June 9, 2021 Notice was developed in collaboration with LPs during a series of workshops held on July 20, July 27, September 28, and November 9, 2021. Conversation at these meetings resulted in the following modifications relative to commitments in the June 9, 2021 Notice for evaluation of sediment transport downstream of the Sauk River.

- Rather than developing a 1-D HEC-RAS hydrodynamic model of this reach, which would not have explicitly simulated sediment transport, the modeling program developed a MAST 1-D model of the reach. The MAST 1-D model provides similar information on reach-scale hydraulic conditions relevant to processes governing channel morphodynamics and sediment transport to what would have been provided by a 1-D HEC-RAS model. It also provides tools to quantify channel planform and profile sensitivity and sensitivity of bedload sediment transport patterns to variable inputs of flow and sediment. Thus, it provides a better tool with

which to evaluate the magnitude and character of the existing flow regime and potential changes on this reach of the river.

- The spatial extent of the sediment transport modeling program was revised to make the boundary of the model spatially consistent with the boundary of the process domain it was developed to simulate. Rather than extending downstream to the estuary, the downstream boundary of the model was at the gravel-to-sand transition near Sedro Woolley where the character of the bed material, hydraulics, and mechanisms of bed material sediment transport fundamentally change relative to all reaches upstream from there to Newhalem. The study objective of understanding project effects on fine sediment delivery to the estuary was evaluated by combining the sediment yield assessment described in Section 4.5.3 with results characterizing bank erosion sources of fine sediment in the MAST 1-D model.

7.4 Large Wood

The study objective of completing "[a]n inventory of the current status of large wood in the Skagit River between Gorge Dam and the Sauk River…" using field methods mentioned in Section 2.6.6 of the RSP was not entirely met via field efforts. This was due to limitations on safe accessibility and efficiency in the Gorge bypass reach. An inventory of large wood was conducted in the Gorge bypass reach using high resolution drone imagery collected in 2021 by the FA-05 Bypass Instream Flow Model Development Study team as opposed to a field study. High resolution drone imagery meets the study objective of completing an inventory of this reach that is similar in precision to a field study.

Also, field inventory of the Shovel Spur rapids reach between PRM 86.7 and PRM 87.6 was not conducted due to safety concerns not allowing access to this reach. An inventory of large wood in the Shovel Spur rapids reach using aerial imagery was conducted using 2021 and 2022 imagery. This modification meets the RSP objective of capturing the current status of large wood in the Skagit River as the large wood historical inventory of this reach shows sparse wood loading. Although there is potential to miss large wood hidden under canopy cover, the quantity of large wood is likely to be negligible and will not impact the objective of capturing the current status of large wood in the Skagit River between the Gorge Dam and the Sauk River.

The proposed study objective of creating an initial inventory of large wood using current (2019) filtered LiDAR cross referenced to concurrent aerial photographs (similar to methods described in Abalharth et al. 2015), mentioned in Section 2.6.6 of the RSP, was not completed because the available 2019 LiDAR data was not a high enough resolution to delineate large wood features. Instead, the study team achieved this objective by delineating large wood features in aerial imagery from 2018 and 2019.

The wood tracking task described in Section 4.7.1 included areas downstream of the primary study area to collect field data on wood accumulation in reaches downstream of the Sauk River to the estuary. This expansion of the study area in response to LP requests improved understanding of the downstream fate of tagged wood that was transported downstream of the primary study area.

7.5 Geomorphic Change

As described in Section 2.6.2 of the RSP, the study estimated sediment inputs from channel migration. The RSP referenced methods previously used by Rothluetner (2017). The methodology used to estimate sediment inputs from bank erosion was modified given acquisition of additional topobathymetric LiDAR data by City Light in 2022. The additional high-resolution LiDAR dataset allowed for direct comparison to topobathymetric LiDAR previously collected in 2017 and 2018, yielding a more precise estimate of sediment inputs from bank erosion.

8.0 REFERENCES

Abalharth, M., M.A. Hassan, B. Klinkenberg, V. Leung, and R. McCleary. 2015. Using LiDAR to characterize log jams in lowland rivers. Geomorphology 246: 531-541.

Abbe, T.B. 2000. Patterns, Mechanics and Geomorphic Effects of Wood Debris Accumulations in a Forest River System. University of Washington. Seattle, Washington.

Abbe, T.B., and Montgomery, D.R. 1996. Large woody debris jams, channel hydraulics, and habitat formation in large rivers. Regulated Rivers: Research and Management 12, 201–221.

Abbe, T.B., and Montgomery, D.R., 2003. Patterns and process of wood debris accumulation in forest channels. Geomorphology 51, 81–107.

Adams, S., 2022. Personal Correspondence, in person conversation October 14, 2022.

Anderson, S.W. 2022. Personal Correspondence, Emails dated September 21, 23, 2022.

Anderson, S. W., Konrad, C. P., Grossman, E. E., and Curran, C. A. 2019. Sediment storage and transport in the Nooksack River basin, northwestern Washington, 2006–15 (2019–5008). USGS Numbered Series. U.S. Geological Survey, Reston, VA. [online] URL: http://pubs.er.usgs.gov/publication/sir20195008. Accessed March 2, 2020.

Bakker, M., Costa, A., Silva, T. A., Stutenbecker, L., Girardclos, S., Loizeau, J. -L., Molnar, P., Schlunegger, F., and Lane, S. N. 2018. Combined Flow Abstraction and Climate Change Impacts on an Aggrading Alpine River. Water Resources Research, 54(1), 223–242.

Bauer, S. B. and T. A. Burton. 1993. Monitoring protocols to evaluate water quality effects of grazing management on western rangeland streams. Environmental Protection Agency (EPA), Region 10. EPA 910/R-93-017, Seattle, Washington.

Beamer, E.R, and R.A. Henderson. 1998. Juvenile salmonid use of natural and hydromodified stream bank habitat in the mainstem Skagit River, Northwest Washington. Prepared for the U.S. Army Corps of Engineers, Seattle District. September 1998.

Beamer, E.R., T. Beechie, B. Perkowski, and J. Klochak. 2000. Application of the Skagit Watershed Council's Strategy. River basin analysis of the Skagit and Samish Basins: Tools for salmon habitat restoration and protection. Skagit Watershed Council. Mount Vernon, Washington. 86 pp.

Beecher, H., Caldwell, B., and Pacheco, J. 2016. Instream Flow Study Guidelines. [Online] URL: https://fortress.wa.gov/ecy/publications/documents/0411007.pdf. Accessed Dec 15, 2022.

Beechie, T.J. 2001. Empirical predictors of annual bed load travel distance, and implications for salmonid habitat restoration and protection. Earth Surface Processes and Landforms 26:9, 1025–1034.

Beechie, T.J., M. Leirmann, E.M. Beamer, and R. Henderson. 2005. Classification of habitat types in a large river and their use by juvenile salmonids. Transactions of the American Fisheries Society 134: 717-719.

Beechie, T.J., O. Stefankiv, B. Timpane-Padgham, J.E. Hall, G.R. Pess, M. RoM. Liermann, K. Fresh, and M.J. Ford. 2017. Monitoring Salmon habitat status and trends in the Puget Sound: Development of sample designs, monitoring metrics, and sampling protocols for large river, floodplain, delta, and nearshore environments. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-137. [Online] URL: https://doi.org/10.7289/V5/TM/-NWFSC-137. Accessed January 5, 2022.

Bisson, P.A., K. Sullivan, and J.L. Nielsen. 1988. Channel hydraulics, habitat use, and body form of juvenile coho salmon, steelhead, and cutthroat trout in streams. Transactions of the American Fisheries Society 117:262-273.

Brenna, A., Surian, N., & Mao, L. 2019. Virtual velocity approach for estimating bed material transport in gravel-bed rivers: Key factors and significance. Water Resources Research, 55, 1651–1674. https://doi.org/10.1029/2018WR023556.

Brown, A.G. 2002. Learning from the past: paleohydrology and paleoecology. Freshwater Biology 47:817-829.

Brune, G. M. 1953. Trap efficiency of reservoirs. Transactions, American Geophysical Union, 34(3), 407. doi:10.1029/TR034i003p00407.

Bunte, K., and S.R. Abt. 2001. Sampling surface and subsurface particle-size distributions in wadable gravel-and cobble-bed streams for analyses in sediment transport, hydraulics, and streambed monitoring. [Online] URL: http://www.treesearch.fs.fed.us/pubs/4580. Accessed December 2016.

Castillo, M., E. Muñoz-Salinas, and L. Ferrari. 2014. Response of a landscape to tectonics using channel steepness indices (ksn) and OSL: A case of study from the Jalisco Block, Western Mexico. Geomorphology 221: 204–214.

Castro, J. M., and Jackson, P. L. 2001. Bankfull Discharge Recurrence Intervals and Regional Hydraulic Geometry Relationships: Patterns in the Pacific Northwest, USA. Journal of the American Water Resources Association, 37(5): 1249–1262.

Chapman, D. W. 1988. Critical review of variables used to define effects of fines in redds of large salmonids. Transactions of the American Fisheries Society, 117(1), 1-21.

Cram, J.M., Torgersen, C.E., Klett, R.S. Klett, G.R. Pess, D. May, T.N. Pearsons, and A.H. Dittman. 2012. Tradeoffs between homing and habitat quality for spawning site selection by hatchery-origin Chinook salmon. Environ Biol Fish 96, 109–122 (2013). https://doi.org/10.1007/s10641-012-0026-1.

Cram, J.M., C.E. Torgersen, R.S. Klett, G.R. Pess, D. May, T.N. Pearsons, and A.H. Dittman. 2017. Spatial variability of Chinook salmon spawning distribution and habitat preferences. Transactions of the American Fisheries Society, 146:2, 206-221, DOI: 10.1080/00028487.2016.1254112.

Church, M. A., D.G. McLean, and J.F. Wolcott. 1987. Riverbed gravels: sampling and analysis. In C.R. Thorne, J.C. Bathurst, and R.D. Hey (Eds.), Sediment Transport in Gravel-bed Rivers (pp. 43–88). John Wiley & Sons Ltd., Chichester, England.

Church, M.A., and O. Slaymaker. 1989. Disequilibrium of Holocene sediment yield in glaciated British Columbia. Nature 337:452–454.

Church, M.A. 2006. Bed Material Transport and the Morphology of Alluvial River Channels. Annual Review of Earth and Planetary Sciences 34:325–354.

Church, M.A., and J.K. Haschenburger. 2017. What is the "active layer"?: THE "ACTIVE LAYER." Water Resources Research 53:5–10.

Church, M. and Hassan, M.A., 1992. Size and distance of travel of unconstrained clasts on a streambed. Water Resources Research, 28(1):299-303.

Cienciala, P., Melendez Bernardo, M., Nelson, A. D., and Haas, A. D. 2020. Sediment yield from a forested mountain basin in inland Pacific Northwest: Rates, partitioning, and sources. Geomorphology, 374.

Cluer, B.D. and C. Thorne. 2013. A stream evolution model integrating habitat and ecosystem benefits. river research and applications. John Wiley & Sons, Ltd. DOI: 10.1002/rra2631.

Collins, B.D. and A.J. Sheikh. 2002. Methods used to map the historical riverine landscape and habitats of the Skagit River. Report to the Skagit River System Cooperative.

Collins, B.D., Montgomery, D.R. and Haas, A.D., 2002. Historical changes in the distribution and functions of large wood in Puget Lowland rivers. Canadian Journal of Fisheries and Aquatic Sciences, 59(1), pp.66-76.

Collins, B.D., S.E. Dickerson-Lange, S. Schanz, and S. Harrington. 2019. Differentiating the effects of logging, river engineering, and hydropower dams on flooding in the Skokomish River, Washington, USA. Geomorphology 332:138–156.

Cui, Y. 2007. The Unified Gravel-Sand (TUGS) Model: Simulating Sediment Transport and Gravel/Sand Grain Size Distributions in Gravel-Bedded Rivers: TUGS MODEL. Water Resources Research, 43:10.

Cui, Y., G. Parker, J. Pizzuto, and T.E. Lisle. 2003. Sediment pulses in mountain rivers: 2. Comparison between experiments and numerical predictions. Water Resources Research 39:1240.

Cui, Y., G. Parker, T.E. Lisle, J.E. Pizzuto, and A.M. Dodd. 2005. More on the evolution of bed material waves in alluvial rivers. Earth Surface Processes and Landforms 30:107–114.

Cui, Y., D. Miller, P. Schiarizza, and L.J. Diakow. 2017. British Columbia digital geology: British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey Open File. [Online] URL: https://www2.gov.bc.ca/gov/content/industry/mineral-exploration-mining/british-columbia-geological-survey/geology/bcdigitalgeology. Accessed September, 2022.

Curran, C.A., E.E. Grossman, M.C., Mastin, and R.L. Huffman. 2016. Sediment load and distribution in the lower Skagit River, Skagit County, Washington. U.S. Geological Survey (USGS) Scientific Investigations Report 2016–5106. Available at: http://dx.doi.org/10.3133/sir20165106.

Czuba, J., C.S. Magirl, C.R. Czuba, E.E. Grossman, C. Curran, A.S. Gendaszek, and R.S. Dinicola. 2011. Sediment load from major rivers into Puget Sound and its adjacent waters: USGS Fact Sheet 2011–3083. [Online] URL:http://pubs.usgs.gov/fs/2011/3083/. Accessed January, 2014).

De Rego, K., J.W. Lauer, B. Eaton, and M. Hassan. 2020. A decadal-scale numerical model for wandering, cobble-bedded rivers subject to disturbance. Earth Surface Processes and Landforms 45:912–927.

DeVries, P. 1997. Riverine salmonid egg burial depths: review of published data and implications for scour studies. Canadian Journal of Fisheries and Aquatic Sciences 54:1685–1698.

DeVries, P. 2000. Scour in low gradient gravel bed streams: patterns, processes, and implications for the survival of salmonid embryos. PhD dissertation. University of Washington.

DeVries, P. 2002. Bedload layer thickness and disturbance depth in gravel bed streams. Journal of Hydraulic Engineering 128:983–991.

Dietrich, W.E., J.W. Kirchner, H. Ikeda, and F. Iseya. 1989. Sediment supply and the development of the coarse surface layer in gravel-bedded rivers. Nature 340:215–217.

Division of Geology. 2010. Digital Geology of Washington State at 1:100,000 Scale version 3.0. 1 :100,000. Washington State Department of Natural Resources Division of Geology and Earth Resources. [Online] URL http://www.dnr.wa.gov/publications/ger_portal_surface_geology_100k.zip. (Accessed 1 April 2013).

Draut, A.E., J.B. Logan, and M.C. Mastin. 2011. Channel evolution on the dammed Elwha River, Washington, USA. Geomorphology 127:71–87.

Eaton, B. 2007. The University of British Columbia Regime Model (UBCRM) - User's manual: Draft. University of British Columbia. Vancouver, BC pp.

Federal Emergency Management Agency (FEMA), 1984. Flood Insurance Study, Skagit County, Washington, Unincorporated Areas, Community Number 530151.

Ferguson, R. I. 2003. The missing dimension: Effects of lateral variation on 1-D calculations of fluvial bedload transport. Geomorphology, 56(1): 1–14.

Ferguson, R.I., Bloomer, D.J., Hoey, T.B. and Werritty, A. 2002. Mobility of river tracer pebbles over different timescales. Water Resources Research, 38(5), pp.3-1.

Forte, A.M., and K.X. Whipple. 2019. Short communication: The Topographic Analysis Kit (TAK) for TopoToolbox. Earth Surface Dynamics 7:87–95.

Gendaszek, A.S., C.S. Magirl, C.R. Czuba, and C.P. Konrad. 2013. The timing of scour and fill in a gravel-bedded river measured with buried accelerometers. Journal of Hydrology 495:186–196.

Grams, P.E., J.C. Schmidt, and D.J. Topping. 2007. The rate and pattern of bed incision and bank adjustment on the Colorado River in Glen Canyon downstream from Glen Canyon Dam, 1956–2000. Geological Society of America Bulletin 119:556–575.

Hartson R. and J. Shannahan. 2015. Inventory and assessment of hydromodified bank structures in the Skagit River Basin: Chinook bearing streams. Submitted to Northwest Indian Fisheries Commission and Environmental Protection Agency (PA-00J322-01).

Haschenburger, J.K., M. Church. 1998. Bed material transport estimated from the virtual velocity of sediment. Earth Surface Processes and Landforms 23:791–808.

Haschenburger, J.K. 1999. A probability model of scour and fill depths in gravel-bed channels. Water Resources Research 35:2857–2869.

Hassan, M.A., R. Egozi, and G. Parker. 2006. Experiments on the effect of hydrograph characteristics on vertical grain sorting in gravel bed rivers: Experiments on the armoring of gravel bed rivers. Water Resources Research 42.

Haugerud, R.A. and R.W. Tabor. 2009. Geologic map of the North Cascade Range, Washington. U.S. Department of the Interior, U.S. Geological Survey (USGS).

Hawkins, C.P., J.L. Kershner, P.A. Bisson, M.D. Bryant, L.M. Decker, S.V. Gregory, D.A. McCullough, G.H. Reeves, R.J. Steedman, and M.K. Young. 1993. A hierarchical approach to classifying stream habitat features. Fisheries 18:6, pp. 3-12.

Herrera Environmental Consultants, 2017. Feasibility Study Report—Goodell Creek Alluvial Fan Restoration Project, Newhalem, Washington: Herrera Environmental Consultants, Seattle, Washington.

Hyatt, T.L., Naiman, R.J., 2001. The residence time of large woody debris in the Queets River, Washington, USA. Ecol. Appl. 11, 191–202, http://dx.doi.org/10.1890/1051-0761(2001)011[0191:TRTOLW]2.0.CO;2.

Hu, X., B. Pan, E. Kirby, Q. Li, H. Geng, and J. Chen. 2010. Spatial differences in rock uplift rates inferred from channel steepness indices along the northern flank of the Qilian Mountain, northeast Tibetan Plateau. Chinese Science Bulletin 55:3205–3214.

James, L.A., 1991. Incision and morphologic evolution of an alluvial channel recovering from hydraulic mining sediment: Geological Society of America Bulletin, v. 103, no. 6, p. 723–736.

Jaeger, K.L., C.A. Curran, S.W. Anderson, S.T. Morris, P.W. Moran, and K.A. Reams. 2017. Suspended sediment, turbidity, and stream water temperature in the Sauk River Basin, Washington, water years 2012–16. U.S. Geological Survey (USGS) Scientific Investigations Report 2017–5113. Available at https://doi.org/10.3133/sir20175113.

Jensen, D. W., Steel, E. A., Fullerton, A. H., & Pess, G. R. 2009. Impact of fine sediment on egg-to-fry survival of Pacific salmon: a meta-analysis of published studies. Reviews in Fisheries Science, 17(3), 348-359.

Juracek, K.E. and F.A. Fitzpatrick. 2009. Geomorphic applications of stream-gage information: River research and applications, v. 25, no. 3, p. 329–347.

Kondolf, G.M. 1997. Profile: hungry water: effects of dams and gravel mining on river channels. Environmental management 21:533–551.

Lane, E.W. 1954. The Importance of Fluvial Morphology in Hydraulic Engineering: Bureau of Reclamation, U.S. Department of the Interior Hydraulic Laboratory Report 372. [Online] URL: http://www.usbr.gov/pmts/hydraulics_lab/pubs/HYD/HYD-372.pdf. Accessed June, 2014.

Lauer, J.W., E. Viparelli, and H. Piégay. 2016. Morphodynamics and sediment tracers in 1-D (MAST-1-D): 1-D sediment transport that includes exchange with an off-channel sediment reservoir. Advances in Water Resources 93:135–149.

Legg, N.T., C. Heimburg, B.D. Collins, and P.L. Olson. 2014. The channel migration toolbox: ArcGIS tools for measuring stream channel migration. State of Washington Department of Ecology.

Lisle, T. E. 1989. Sediment transport and resulting deposition in spawning gravels, north coastal California. Water resources research, 25(6), 1303-1319.

Lisle, T. E., Nelson, J. M., Pitlick, J., Madej, M. A., and Barkett, B. L. 2000. Variability of bed mobility in natural, gravel-bed channels and adjustments to sediment load at local and reach scales. Water Resources Research, 36(12): 3743–3755. Lisle, T.E., Y. Cui, G. Parker, J.E. Pizzuto, and A.M. Dodd. 2001. The dominance of dispersion in the evolution of bed material waves in gravel-bed rivers. Earth Surface Processes and Landforms 26:1409–1420.

Lowery, E., 2022. Personal Correspondence, Emails and Teleconference December 5, 2022.

Ma, Y., H.Q. Huang, G.C. Nanson, Y. Li, and W. Yao. 2012. Channel adjustments in response to the operation of large dams: The upper reach of the lower Yellow River. Geomorphology 147:35–48.

Mathews, R. and Richter, B.D. 2007. Application of the Indicators of hydrologic alteration software in environmental flow setting. Journal of the American Water Resources Association 43(6):1400-1413.

Mao, L., L. Picco, M.A. Lenzi, and N. Surian. 2017. Bed material transport estimate in large gravel-bed rivers using the virtual velocity approach. Earth Surface Processes and Landforms 42:595-611.

McLean, D.G., and M. Church. 1999. Sediment transport along lower Fraser River: 2. Estimates based on the long-term gravel budget. Water Resources Research 35:2549–2559.

McQueen, R., P. Ashmore, N. Goeller. 2022. Bed particle displacements and morphological development in a wandering gravel-bed river. Water Resources Research, 57, https://doi.org/10.1029/2020WR027850

Meixler, Marcia, S., Mark B. Bain, M. Todd Walter, Predicting barrier passage and habitat suitability for migratory fish species, Ecological Modeling, Volume 220, Issue 20, 2009, Pages 2782-2791, ISSN 0304-3800, [Online] URL: https://doi.org/10.1016/j.ecolmodel.2009.07.014. Accessed January 5, 2022.

Milan, D.J. 2013. Virtual velocity of tracers in a gravel-bed river using size-based competence duration, Geomorphology, http://dx.doi.org/10.1016/j.geomorph.2013.05.018

Milhous, R. T. 2001. Specific weight and median size of the bed material of gravel and cobble bed rivers. Seventh Federal Interagency Sedimentation Conference. Reno, NV.

Millar, R., B. Eaton, and M. Church. 2014. UBC Regime Model. [Online] URL: http://blogs.ubc.ca/beaton/working-code. Accessed December 19, 2021.

Milliman, J.D., and J.P. Syvitski. 1992. Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. The Journal of Geology 525–544.

Mueller, E.R., and J. Pitlick. 2013. Sediment supply and channel morphology in mountain river systems: 1. Relative importance of lithology, topography, and climate: Sediment supply and channel morphology 1. Journal of Geophysical Research: Earth Surface 118:2325–2342.

Natural Systems Design (NSD). 2017. Skagit River Large Woody Debris Assessment, Connecting LWD to the 2005 Skagit Chinook Recovery Plan. Report prepared for Skagit Watershed Council. November 13, 2017.

Neill, C.R. 1971. River bed transport related to meander migration rates. Journal of Waterways, Harbors, and Coastal Engineering Division 97:783-786.

Neill, C.R. 1983. Bank erosion vs bedload transport in a gravel river, *in* River Meandering, ASCE. [Online] URL:http://cedb.asce.org/cgi/WWWdisplay.cgi?8400979. Accessed September, 2015.

Northwest Hydraulic Consultants (NHC). 2021. Drone Datasets, Bypass Reach. Dataset collected by Northwest Hydraulic Consultants for Seattle City Light. August 2021.

Northwest Hydraulic Consultants (NHC). 2023. Hydrology Datasets, Newhalem to Mount Vernon. Technical memorandum prepared by Northwest Hydraulic Consultants for Seattle City Light. March 2023.

Nicholas, A.P., P.J. Ashworth, M.J. Kirkby, M.G. Macklin, and T. Murray. 1995. Sediment slugs: large-scale fluctuations in fluvial sediment transport rates and storage volumes. Progress in Physical Geography 19:500–519.

Norton, K.P., L.M. Abbühl, and F. Schlunegger. 2010. Glacial conditioning as an erosional driving force in the Central Alps. Geology 38:655–658.

O'Connor, J.E., J.F. Mangano, S.W. Anderson, J.R. Wallick, K.L. Jones, and M.K. Keith. 2014. Geologic and physiographic controls on bed-material yield, transport, and channel morphology for alluvial and bedrock rivers, western Oregon. Geological Society of America Bulletin 126:3-4, 377-397.

Ouimet, W.B., K.X. Whipple, and D.E. Granger. 2009. Beyond threshold hillslopes: Channel adjustment to base-level fall in tectonically active mountain ranges. Geology 37:579–582.

Paulson, K.M. 1997. Estimating Changes in Sediment Supply Due to Forest Practices: A Sediment Budget Approach Applied to the Skagit River Basin in Northwestern Washington. Master's Thesis. University of Washington, Seattle, Washington.

Pfeiffer, A.M., N.J. Finnegan, & J.K. Willenbring. 2017. Sediment supply controls equilibrium channel geometry in gravel rivers. Proceedings of the National Academy of Sciences 114:13, 3346-3351.

Pfeiffer, A.M., S. Morey, H.M. Karlsson, E.M. Fordham, and D.R. Montgomery. 2022. Survival of the strong and dense: Field evidence for rapid, transport-dependent bed material abrasion of heterogeneous source lithology. Journal of Geophysical Research: Earth Surface, 127:6. https://doi.org/10.1029/2021JF006455.

Pierce, J.L., G.A. Meyer, and A.J. Timothy Jull. 2004. Fire-induced erosion and millennial-scale climate change in northern ponderosa pine forests: Nature 432:87–90.

Pitlick, J., E.R. Mueller, C. Segura, R. Cress, and M. Torizzo. 2008. Relation between flow, surface-layer armoring and sediment transport in gravel-bed rivers. Earth Surface Processes and Landforms 33:1192–1209.

Popov, I.V. 1962a. A sediment balance of river reaches and its use for the characteristics of the channel process. Trudy GGI 94:3–21.

Popov, I.V.. 1962b. A sediment balance of river reaches and its use for the characteristics of the channel process: Trudy GGI, 94:3–21.

PRISM. 2015. 30-yr normal precipitation: Annual; period 1981-2010: PRISM Climate Group, Oregon State University, scale 00000. [Online] URL: http://www.prism.oregonstate.edu/normals/. Accessed August, 2022.

Quantum Spatial, Inc. (QSI). 2017. Skagit Topobathy, Washington, Topobathymetric LiDAR Technical Data Report.

_____. 2018. Upper Skagit, Gorge Lake & Diablo Lake, Washington, Topobathymetric LiDAR & Orthoimagery Technical Data Report.

R2 Resource Consultants. 2004. Hydrology and Geomorphology of the Baker and middle Skagit Rivers: Part 2 of 2: Sediment Transport and Channel Response. Report Prepared for Puget Sound Energy.

Reiser, D.W., C.M. Huang, S. Beck, M. Gagner, and E. Jeanes. 2006. Defining flow windows for upstream passage of adult anadromous salmonids at cascades and falls, Transactions of the American Fisheries Society, 135:3, 668-679, DOI: 10.1577/T05-169.1.

Renard, K.G., J.M. Laflen, G.R. Foster, and D.K. McCool. 2017. The revised universal soil loss equation, in Soil erosion research methods. Routledge, New York, NY. 105–126 pp.

Rice, S., and J. Haschenburger. 2004. A hybrid method for size characterization of coarse subsurface fluvial sediments. Earth Surface Processes and Landforms 29:3, pp. 401–421.

Riedel, J. 1990. Skagit River Project FERC No. 553 Report on Existing Conditions of Reservoir and Streambank Erosion. Report prepared by National Park Service (NPS), Jon Riedel Project Manager. January 1990.

_____. 2007. Late Pleistocene Glacial and Environmental History of Skagit Valley, Washington and British Columbia. Ph.D. thesis, Simon Fraser University, Vancouver, BC.

_____. 2019. Barnaby Slough Restoration Project, Quaternary Geology Report.

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

Riedel, J., S. Sarrantonio, G. Seixas, and J. Chan. 2022. Draft Skagit River Geomorphology Inventory Report: Part II – Middle Skagit Valley from Sauk River to Hamilton. Report to Seattle City Light by the U.S. National Park Service (NPS).

Rothleutner, A.D. 2017. Sediment Budget of the Middle Skagit River, Washington 1937-2015 Reveals Decadal Variations in Sediment Export and Storage. Western Washington University MS Thesis. November 17, 2017.

Schiefer, E., Hassan, M. A., Menounos, B., Pelpola, C. P., and Slaymaker, O. 2010. Interdecadal patterns of total sediment yield from a montane catchment, southern Coast Mountains, British Columbia, Canada. Geomorphology, 118(1–2): 207–212.

Schuett-Hames, D. A. E. Pleus, J. Ward, M. Fox, and J. Light. 1999. TFW Monitoring Program Method Manual for the Large Woody Debris Survey. Prepared for the Washington State Department of Natural Resources under Timber, Fish, and Wildlife Agreement. TFWAM9-99-004. DNR #106.

Schuett-Hames, J. and D. Adams. 2003. Upper White Watershed Spring Chinook Redd, Scour, and Cross-Section Assessments: 1995 – 2001. Washington Department of Ecology Report.

Seattle City Light (City Light). 2020. Pre-Application Document (PAD) for the Skagit River Hydroelectric Project, FERC Project No. 553. April 2020.

_____. 2021. Revised Study Plan (RSP) for the Skagit River Hydroelectric Project, FERC Project No. 553. April 2021.

_____. 2022a. TR-01 Vegetation Mapping Study, Draft Report for the Skagit River Hydroelectric Project, FERC Project No. 553. Prepared by Environmental Science Associates. March 2022.

_____. 2022b. TR-02 Wetland Assessment, Draft Report for the Skagit River Hydroelectric Project, FERC Project No. 553. Prepared by Environmental Science Associates. March 2022.

_____. 2023a. FA-02 Instream Flow Model Development Study Report for the Skagit River Hydroelectric Project, FERC Project No. 553. Prepared by Northwest Hydraulic Consultants, Inc. and HDR Engineering, Inc. March 2023.

_____. 2023b. FA-04 Fish Passage Technical Studies Program Report for the Skagit River Hydroelectric Project, FERC Project No. 553. Prepared by HDR Engineering, Inc. March 2023.

_____. 2023c. FA-05 Skagit River Gorge Bypass Reach Hydraulic and Instream Flow Model Development Study Report for the Skagit River Hydroelectric Project, FERC Project No. 553. Prepared by Northwest Hydraulic Consultants, Inc. and HDR Engineering, Inc. March 2023.

_____. 2023d. GE-02 Erosion and Geologic Hazards at Project Facilities and Transmission Line Right-Of-Way Study Report for the Skagit River Hydroelectric Project, FERC Project No. 553. Prepared by American Forest Management, Inc., Shannon and Wilson, Inc., Terrapin Environmental, and Watershed GeoDynamics. March 2023.

_____. 2023e. GE-03 Sediment Deposition in Reservoirs Affecting Resource Areas of Concern Study Report for the Skagit River Hydroelectric Project, FERC Project No. 553. Prepared by Watershed GeoDynamics. March 2023.

_____. 2023f. OM-01 Operations Model Study Report for the Skagit River Hydroelectric Project, FERC Project No. 553. Prepared by HDR Engineering, Inc. March 2023.

_____. 2023g. SY-01 Integration and Synthesis of Available Information on Resources in the Lower Skagit River Report for the Skagit River Hydroelectric Project, FERC Project No. 553. Prepared by Cramer Fish Sciences, Inc. March 2023.

_____. 2023h. TR-09 Beaver Habitat Assessment Report for the Skagit River Hydroelectric Project, FERC Project No. 553. Prepared by HDR Engineering, Inc. March 2023.

Singer, M.B. 2010. Transient response in longitudinal grain size to reduced gravel supply in a large river. Geophysical Research Letters 37:L18403-L18408.

Skagit River System Cooperative (SRSC). 2019. Digitized geospatial data files for multiple years of imagery on the Skagit River between Sauk River confluence and Marblemount.

Skagit River System Cooperative (SRSC) and Natural Systems Design (NSD). 2019. Hydraulic and Geomorphic Assessment Barnaby Reach of the Skagit River. April 4, 2019.

Slaven, S., Slaven, I., and Anders, A.M., 2014, New Gripping and Binding Device Greatly Improves Preparation of Natural Clasts for RFID Tracking: Journal of Hydraulic Engineering, v. 140, p. 06014017, doi:10.1061/(ASCE)HY.1943-7900.0000943.

Smith, C.J. 2003. Salmon and steelhead habitat limiting factors Water Resource Inventory Areas 3 & 4 Skagit Watershed. Washington State Conservation Commission, Olympia, Washington.

Smith, D. and K. Ramsden. 2006. Illabot Creek Habitat Restoration Feasibility Study. Skagit River System Cooperative. January 17, 2006.

Smith, D., K. Ramsden, and S. Hinton. 2011. Reach Level Analysis for the Middle Skagit River Assessment. Report prepared for the Skagit Watershed Council. July 7, 2011.

Statewide Washington Integrated Fish Distribution (SWIFD). 2021. [Online] URL: https://geo.nwifc.org/swifd/. Accessed in August 2021.

Statistics Kingdom. 2017. Logistic Regression Calculator. [Online] URL:https://www.statskingdom.com/420logistic_regression.html. Accessed December, 2022).

Tabor, R.W. and R.A. Haugerud. 1999. Geology of the North Cascades: a mountain mosaic. The Mountaineers Books. Seattle, WA.

Tunnicliffe, J., M. Church, J.J. Clague, and J.K. Feathers. 2012. Postglacial sediment budget of Chilliwack Valley, British Columbia. Earth Surface Processes and Landforms 37:1243–1262.

Turowski, J.M., D. Rickenmann, and S.J. Dadson. 2010. The partitioning of the total sediment load of a river into suspended load and bedload: a review of empirical data: The partitioning of sediment load. Sedimentology 57:1126–1146.

U.S. Army Corps of Engineers (USACE). 2008. Skagit River Flood Damage Reduction Feasibility Study Skagit River Basin Sediment Budget and Fluvial Geomorphology. Report prepared by the USACE Seattle District. June 2008.

_____. 2013. Hydraulic Technical Documentation. Skagit River Flood Damage Reduction Feasibility Study.

U.S. Geological Survey. 1999. Map Accuracy Standards: U.S. Geological Survey Fact Sheet 171–99, 2 p.

Verstraeten, G., and Poesen, J. 2000. Estimating trap efficiency of small reservoirs and ponds: methods and implications for the assessment of sediment yield. Progress in Physical Geography, 24(2): 219–251.

Vezzoli, G., E. Garzanti, M. Limonta, and G. Radeff. 2020. Focused erosion at the core of the Greater Caucasus: Sediment generation and dispersal from Mt. Elbrus to the Caspian Sea. Earth-Science Reviews 200:10298.

Wald, A.R. 2009. High flow for fish and wildlife in Washington. Report of investigation in instream flow. Washington Department of Fish and Wildlife (WDFW). [Online] URL: https://wdfw.wa.gov/sites/default/files/publications/00578/wdfw00578.pdf. Accessed in February 2022.

Washington Department of Fish and Wildlife (WDFW) and Washington Department of Ecology (Ecology). 2016. Instream Flow Study Guidelines - Technical and Habitat Suitability Issues Including Fish Preference Curves. Updated March 9, 2016. Olympia, WA.

Washington Department of Fish and Wildlife (WDFW). 2019. Fish passage and surface water diversion screening assessment and prioritization manual. Olympia, Washington.

Washington Department of Natural Resources (DNR). 2020. RS-FRIS Version 4.0. Remote-sensing based forest inventory for WA DNR State Trust lands.

Whipple, K.X., C. Wobus, B. Crosby, E. Kirby, and D. Sheehan. 2007. New tools for quantitative geomorphology: Extraction and interpretation of stream profiles from digital topographic data. GSA short course 506:1–26.

Wilcock, P.R., A.F. Barta, C.C. Shea, G.M. Kondolf, W.V.G. Matthews, and J. Pitlick. 1996. Observations of Flow and Sediment Entrainment on a Large Gravel-Bed River. Water Resources Research 32:2897–2909.

Wilcock, P.R., and B.W. McArdell. 1997. A systematic analysis of eight decades of incipient motion studies, with special reference to gravel-bedded rivers. Water Resources Research 33:1993–2029

Wilcock, P.R.. 2005. Persistence of armor layers in gravel-bed streams. Geophysical Research Letters 32:L08402-L08405.

Wolman, M.G. 1954. A method of sampling coarse river-bed materials. Transactions of the American Geophysical Union 35:6, 951–956.

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SKAGIT RIVER GEOMORPHOLOGY BETWEEN GORGE DAM AND THE SAUK RIVER STUDY REPORT

ATTACHMENT A

ANNOTATED BIBLIOGRAPHY OF GEOMORPHOLOGY FROM SAUK RIVER CONFLUENCE TO SKAGIT ESTUARY

SKAGIT RIVER GEOMORPHOLOGY BETWEEN GORGE DAM AND THE SAUK RIVER STUDY REPORT

ATTACHMENT A

ANNOTATED BIBLIOGRAPHY OF GEOMORPHOLOGY FROM SAUK RIVER CONFLUENCE TO SKAGIT ESTUARY

The following attachment provides an annotated bibliography for relevant geomorphic references for the GE-04 Skagit River Geomorphology Between Gorge Dam and the Sauk River Study (Geomorphology Study). A template example, topics and keyword, and data flags are included below. This format is similar to the ones being used in the SY-01 Integration and Synthesis of Available Information on Resources in the Lower Skagit River Study (SY-01 Synthesis Study). The SY-01 Synthesis Study developed an extensive annotated bibliography of aquatic habitat, water quality, and other topics of interest downstream of the Sauk.

Example format for annotated bibliography

Reference	AFS Style Guide for References: https://fisheries.org/wp-content/uploads/2016/01/References.pdf. Use the "References" style in the Home tab to get the style correct for the references section.									
Source Information	***Type***	Source Type	***Status***	Draft/ Final	***Quantitative Data***	Yes/ No	***Spatial Data***	Yes/ No		
Topics and Keywords	***Topic:*** keywords.									
Species and Life Stages	***Species:*** life stages.									
Reaches and Spatial extent	Reaches.									

Summary: Brief description of the study.

Relevant Information: Information specifically relevant to the Geomorphology Study.

Topics and Key Words

A framework of topics and keywords was developed to attribute sources to indicate the type of information provided by each source. These attributes were added to a relational database during screening of identified sources, with attributes being linked to references in the reference database based on a citation ID. The following table provides the current list of topics and keywords used to attribute sources during screening, with a description of each topic and keyword combination for both SY-01 Synthesis Study and the Geomorphology Study.

Table A-1 List of attributes for topics and keywords for sources.

Topic	Keyword	Notes
Geomorphology and Landforms	Change	Changes in geomorphology or processes over time
	History	Geological history and history of formation and processes
	Channel migration	Channel migration, including lateral channel migration, channel migration zones, or active channel zone
	Channel incision	Channel incision
	Sinuosity	Channel sinuosity
	Slope	Channel slope or gradient
	Floodplain	Information on floodplain width or flood prone width

Topic	Keyword	Notes
	Side and off-channels	Abundance, connectivity, diversity of secondary channel habitats including braids, off-channels, and side channels
	Floodplain connectivity	Connectivity to floodplains or floodplain habitats
	Substrate and sediment	Substrate or sediment composition
	Sediment transport and supply	Sediment transport or supply, including landslides and reservoir retention
	Shallow and deep surface processes	Hydrostatic rebound, compaction, subsidence
	Large wood	Large wood abundance, recruitment, transport, retention
	Log jam	Log jam abundance, growing, decay, stable, variable
	Aquatic habitats and landforms	Fluvial geomorphology, or riverine landforms
	Estuarine habitats and landforms	Tidally influenced or estuarine habitats and landforms
	Climate change	Impacts of climate change on geomorphology
	Data gaps	Data gaps are identified
Water Quality and Productivity	Temperature	Temperature, maximum, mean, 7-day averages
	Nutrients	Nitrate, phosphorous, ammonia, nitrite
	Dissolved oxygen	Dissolved oxygen concentration
	pH	pH, alkalinity, acidity
	Bacteria	Fecal coliform or other bacteria
	Contaminants	Heavy metals, hydrocarbons, pesticides
	Turbidity	Turbidity, NTU, secchi
	Salinity	Salinity and conductivity
	Primary productivity	Periphyton or algal abundance
	Secondary productivity	Invertebrate abundance or diversity
	Climate change	Impacts of climate change on water quality
	Data gaps	Data gaps are identified
Modeling Tools	Hydrology	Hydrodynamic, hydrologic or hydraulic models
	Sediment	Sediment models
	Life cycle	Life cycle models
	Bioenergetics	Bioenergetic models or food web models
	Adult returns	Forecasting models for adult returns
	Climate change	Models the predict effects of climate change or predict climate change
	Habitat	Models describing habitat, intrinsic potential
	Connectivity	Habitat connectivity, landscape connectivity
	Data gaps	Data gaps are identified
Land Use and Cover	Land cover	General land cover information
	Forestry	Forestry and logging information, extent, management
	Agriculture	Agriculture land use information, extent
	Commercial	Commercial and industrial land use extent and types

Topic	Keyword	Notes
	Urban	Urban land use information, extent
	Banks and shoreline	Levees/dikes, shoreline hardening, armoring
	Floodplain	Irrigation/diking, wetland losses/conversion
	Climate change	Climate change impacts on land cover
	Data gaps	Data gaps are identified
Fish and Habitat	Habitat, instream flow	Peak flows, flood recurrence intervals, mean flows
	Habitat, riparian	Riparian extent or condition, stand structure, buffers
	Habitat, wetlands	Wetland quantity, quality, or type
	Habitat, beaver	Beaver abundance, distribution, habitat effects, conflicts, BDAs, beaver deceiver
	Habitat, barriers	Fish passage barriers
	Habitat, invasive species	Aquatic or terrestrial invasive species
	Habitat, freshwater	Habitat quantity, quality, or type
	Habitat, estuary	Habitat quantity, quality, or type
	Habitat, pocket estuary	Habitat quantity, quality, or type
	Habitat, nearshore	Habitat quantity, quality, or type
	Habitat, ocean	Habitat quantity, quality, or type
	Habitat, connectivity	Patchiness, landscape connectivity, local connectivity, accessibility
	Habitat, capacity	Capacity of habitat to support fish
	Habitat, limiting factors	Identifies habitat limiting factors
	Habitat, status and trends	Habitat status and trends
	Habitat, restoration	Projects, plans, designs, targets
	Habitat, climate change	Climate change impacts on habitat
	Habitat, data gaps	Data gaps are identified
	Fish, abundance	Abundance estimates for fish
	Fish, diet	Diet composition, foraging behavior, preference
	Fish, condition	Measures of condition, condition factor, lipids, weight
	Fish, density dependence	Measures of density dependent processes or patterns
	Fish, competition	Interspecific or intraspecific competition, territory
	Fish, survival	Survival at different life stages (e.g., egg to fry, smolt to adult), size selective mortality, density dependence
	Fish, growth	Growth estimates from mark recapture, otolith or scales
	Fish, swimming speed	Swimming speeds, travel speeds, movement
	Fish, physiology	Physiological studies
	Fish, rearing	Fish rearing patterns or preferences
	Fish, predation	Predation on fish, avian, marine mammal, fish
	Fish, life history	Life history characterization, description, diversity, resilience
	Fish, age structure	Age structure information
	Fish, size structure	Size structure, length frequency
	Fish, sex structure	Sex structure, ratios
	Fish, periodicity	The timing and duration of life stages
	Fish, status and trends	Population status and trends information, extent, management

Topic	Keyword	Notes
	Fish, hatchery	Hatchery abundance, strategies, interactions
	Fish, harvest	Harvest rates, fisheries, exploitation rates
	Fish, climate change	Climate change impacts on fish (e.g., temperature or periodicity)
	Fish, data gaps	Data gaps are identified
	Monitoring, restoration	Monitoring restoration projects (e.g., response, effectiveness)
	Monitoring, climate change	Monitoring climate change impacts or climate change
	Monitoring, data gaps	Data gaps are identified
	Monitoring, habitat	Habitat status and trends, monitoring
	Monitoring, abundance	Smolt trap, electrofishing, seining, fyking, angling, carcass, redd, or other abundance monitoring methods
	Monitoring, biotelemetry	PIT, radio, acoustic tagging, mark recapture studies
	Monitoring, scale or otoliths	Age analysis, time of entry, residency/transition periods, growth
	Monitoring, genetics	GMR, population assignment, origin
	Monitoring, flow	Flow monitoring

Data Flags

Information and data for target species, life stages, and reaches was also identified for sources using data flags, as well as flags to identify if quantitative data or spatial data are provided by the source. The following table provides a list of the data flags to support identification and classification of sources and data compiled. Note, topics and keywords are attributed with these data flags rather than the sources so that the flags can be associated with specific topics or information. For example, a source with information or data on juvenile Chinook survival from rearing to outmigration can be attributed as Topic = Fish and Habitat; Keyword = Fish, survival; Species = Chinook; Life Stage = rearing to outmigration. This approach allows us to associate specific data types to sources rather than a generic flag that could incorrectly suggest that a source contained survival information for other species or life stages. Note Reach flags may include ranges or combinations of reaches depending on the spatial extent of the study and available data. Geomorphic reach descriptions for mainstem Skagit River were quoted from Riedel et al. (2020).

Table A-2 Proposed data flags to support identification and classification of sources and compiled data.

Field	Values	Description
Species	Chinook	Contains information or data on Chinook Salmon
	Coho	Contains information on Coho Salmon
	Sockeye	Contains information on Sockeye Salmon
	Chum	Contains information on Chum Salmon
	Pink	Contains information on Pink Salmon
	Bull Trout	Contains information on Bull Trout
	Steelhead	Contains information on steelhead
	All	Contains information on all target anadromous species

Field	Values	Description
	NA	Data not associated with target species (used for topics and keywords not related to target species)
Life Stage	Migration	Adult migration, including holding
	Spawning	Adult spawning
	Incubation	Egg incubation in substrate
	Rearing	Juvenile rearing in freshwater habitats
	Outmigration	Juvenile emigration from freshwater habitats
	Estuary rearing and emigration	Juvenile rearing, transition, and emigration through estuary habitats
	Nearshore rearing and emigration	Juvenile rearing in nearshore habitats, including pocket estuaries
	Ocean	Ocean maturation
	Migration – spawning	Adult migration through spawning
	Incubation – rearing	Incubation through rearing
	Incubation – outmigration	Incubation through outmigration
	Rearing - outmigration	Rearing through outmigration
	Outmigration – migration	Juvenile outmigration to adult migration
	Full life cycle	Full life cycle
	NA	Does not contain information on species or life stages
Reach	US R7	Reaches upstream of R7
	Sauk River	Includes Sauk River, tributary to the mainstem Skagit River that confluences at R7.
	R7	R7-Sauk River Alluvial Fan – “Wide alluvial fan that forces Skagit to north side of valley. Influenced by Glacier Peak sediment, some from lahars.” PRM 68-65.
	R8	R8-Sauk Alluvial fan to Baker Mouth – “Steep, narrowed channel because river is incised into 30-50m thick, over-consolidated glacial deposits (till, silt, sand, and gravel).” PRM 65-56.5.
	R9	R9-Baker to Finney Cr. – “Channel incised into glacial and lahar terraces, Baker Hydro influence on sediment, large wood, and channel pattern.” PRM 56.5-49.
	R10	R10-Finney Cr. To Hamilton Moraine – “Sinuosity higher strong right bank ground water influence, extensive lahar terrace.” PRM 49-36.5.
	R11	R11-HM to Sedro-Wooley – “High sinuosity in wide outwash valley wide meander loops. Extensive lahar terrace on right bank.” PRM 36.5-NA.
	R12-13	R12 and R13-SW to Burlington Hill – “River leaves valley and enters Puget Lowland. Start of river levees transition to sand bed.” PRM NA. Downstream extent of tidally influenced habitats.
	R14	R14-Delta (BH to Skagit Bay) – “Puget lowland river constrained by levees on delta, split into two distributary channels, very limited sediment and LWD.” PRM NA. This is the delta extent and range of tidally influenced habitats.

Field	Values	Description
	Skagit Bay	Skagit Bay – Skagit Bay and nearshore shoreline, including neritic and embayment habitats from the Deception Pass outlet in the North to the mouth between Whidbey Island and Camano Island in the South
	Padilla Bay	Padilla Bay – northern outlet of Swinomish Channel that is included in the geomorphic delta boundary for the Skagit River.
Quantitative Data	Yes/No	Indicates whether the source provides quantitative data on the topic and keyword, and/or species and life stage
Spatial Data	Yes/No	Indicates whether the source provides spatial data on the topic and keyword, and/or species and life stage

Additional List of Acronyms and Abbreviations

CMZ	channel migration zone
DHSVM	Distributed Hydrology Soil Vegetation Model
FV-COM	Finite Volume Coastal Ocean Model
GCM	Global Climate Model
PNNL	Pacific Northwest National Laboratory
RCP	Representative Concentration Pathway
Tg	teragram
SSC	suspended sediment concentration
SSL	suspended sediment load
VIC	Variable Infiltration Capacity
VSP	viable salmonid population

Annotated Bibliography

Bandaragoda et al. 2015

Reference	Bandaragoda, C., C. Frans, E. Istanbulluoglu, C. Raymond, and L Wasserman. 2015. Hydrologic Impacts of Climate Change in the Skagit River Basin. Final Report Prepared for Skagit Climate Science Consortium. Available at: http://www.skagitclimatescience.org/wp-content/uploads/2016/04/UW-SC2_SkagitDHSVM-glacierModel_FinalReport_2015.pdf									
Source Information	***Type***	Report	***Status***	Final	***Quantitative Data***	Yes	***Spatial Data***	Yes		
Topics and Keywords	***Geomorphology:*** Climate change, change, aquatic habitats and landforms. ***Modeling Tools:*** Hydrology, climate change. ***Fish and Habitat:*** Habitat, climate change; Fish, climate change.									
Species and Life Stages	None.									
Reaches and Spatial extent	Reach 1-13, Skagit River.									

Summary: This final report includes projections of naturalized streamflow based on a coupled glacio-hydrology model (DHSVM) at Skagit River Hydroelectric Project reservoir locations (Ross, Diablo, Gorge) and at sixteen tributaries using future climate change scenarios. The future streamflow projections are a collaboration between Seattle City Light, Swinomish Indian Tribal community, and the Sauk-Suiattle Indian Tribe administered by the Skagit Climate Consortium (SC2) and the University of Washington (UW). The model domain included the entire Skagit River basin at 150 m (492 ft) digital elevation model (DEM) with nested models of 50 m (164 ft) resolution of selected basins (Thunder Creek and Cascade River) that have major glacier ice cover at their high elevations. The DHSVM model was calibrated using historical meteorological data and observed ice extent between 1960-2010 and corrections were conducted using empirical data, naturalized flows at reservoirs, and observed stream gauges. Future projects were calculated using Global Climate Models (GCMs) 30-year period starting from 2010 to 2099.

The authors highlight the changes applicable to 2050. In glaciated high elevation basins, the current conditions of approximately 100 km^2 (39 square miles) of glacier ice are projected to decrease to less than 50 km^2 (19 square miles) by 2050. Tributary contributions, as measured by the August 90 percent exceedance probability between Newhalem to Marblemount are currently approximately 350 cfs and by 2050 could decrease to approximately 230 cfs (35 percent decrease). The South Fork Sauk River is predicted to decrease by 80 percent, from 14 cfs to 3 cfs for the August 90% streamflow. This represents a significant change in salmon habitat during a critical period.

The Sauk River currently has a bimodal annual hydrograph and is projected to progressively lose the summer peak (from snowmelt) and increase winter peak (from rainfall); by 2099 the Sauk River annual hydrograph is projected to have a single peak consistent with hydrograph timing of rain-dominated systems. The impacts of this shift will be most apparent in the August change where the decrease would be approximately 60%.

The lowest flows are currently 2000 cfs at the Gorge dam and predicted to decrease approximately 500 cfs in each 30-year period, to lower than 500 cfs in August by the end of the century.

Relevant Information: The authors highlight the changes applicable to 2050. In glaciated high elevation basins, the current conditions of approximately 100 km^2 (39 square miles) of glacier ice are projected to decrease to less than 50 km^2 (19 square miles) by 2050. Tributary contributions, as measured by the August 90% exceedance probability between Newhalem to Marblemount are currently approximately 350 cfs and by 2050 could decrease to approximately 230 cfs (35% decrease). The South Fork Sauk River is predicted to decrease by 80%, from 14 cfs to 3 cfs for the August 90% streamflow. This represents a significant change in salmon habitat during a critical period.

The changes predicted throughout the system include less glacial coverage and more of a rain-dominated system throughout the entire basin. The decrease in August flows is concerning for salmon habitat. This underlines the need for climate change to be considered in all future flow and operational scenarios.

Bandaragoda et al. 2020

Reference	Bandaragoda, C., S. Lee, E. Istanbulluoglu, and A. Hamlet. 2020. Hydrology, stream temperature, and sediment impacts of climate change in the Sauk River basin. Prepared by Hydroshare for Sauk-Suiattle Indian Tribe and Skagit Climate Science Consortium. Available at: http://www.hydroshare.org/resource/e5ad2935979647d6af5f1a9f6bdecdea									
Source Information	***Type***	Report	***Status***	Final	***Quantitative Data***	Yes	***Spatial Data***	Yes		
Topics and Keywords	***Geomorphology:*** Climate change, change, aquatic habitats and landforms. ***Modeling Tools:*** Hydrology, climate change. ***Fish and Habitat:*** Habitat, climate change; Fish, climate change. ***Water Quality and Productivity:*** Temperature.									
Species and Life Stages	None.									
Reaches and Spatial extent	Sauk River.									

Summary: The study explored how low streamflows and peak annual flood streamflow in the Sauk Basin and tributaries are projected to respond to climate change using a coupled glacio-hydrology model (Distributed Hydrology Soil Vegetation Model, DHSVM) with highlighted discussions on 20 model output locations. The two climate change models that were used include Representative Concentration Pathways (RCP) 4.5 Ensemble and RCP 8.5 Ensemble. The Sauk River near Sauk is projected to have significantly more increases in winter time (November-January) streamflow and decreases in summer time (July-September) streamflow. The Sauk River currently has a bimodal annual hydrograph, but is projected to lose the summer peak from snowmelt and increase the winter peak from rainfall. By the end of the century the Sauk River annual hydrograph is projected to have a single peak consistent with rain-dominated systems. The impact will be most apparent in the August flow changes as future scenarios consistently give from around 50 percent to 90 percent declines toward the end of the century. High flows and peak events are projects to substantially increase by 2050, with statistically significant peak events (e.g., 100-year flood) expected to increase 20-30 percent for a moderate warming climate change scenario (RCP 4.5) and increase by 40 percent for high warming scenarios (RCP 8.5).

Historic daily maximum temperature during summers were 17.8°C (64.0°F), 19.2°C (66.6°F), and 17.4°C (63.3°F) at the Sauk River above Suiattle, Sauk River near Darrington, and the White

Chuck River, respectively. Daily maximum temperature is projected to increase by 2-3°C for all scenarios and sites. The Sauk River near Darrington shows the largest increase in maximum temperature and the White Chuck River the least.

Mean annual suspended sediment load (SSL) estimates were obtained using historical (1960-2010) and future modeled streamflows in suspended sediment rating curve for lower and middle Sauk locations. Historical SSL was approximately 40% lower than the 5-year mean annual historic yield reported by the USGS study in the Sauk River, when stream streamflow is used directly without monthly bias correction. Monthly bias-corrected streamflow gave historical suspended load approximately 20 percent greater than the 5-year mean reported by USGS. The RCP 4.5 scenario models predict approximately twofold increase by the middle and much higher by end of the century. SSL gets consistently higher in the second half of the century in the worst-case RCP 8.5 scenario of climate change. Bias-corrected streamflow also results in consistent relative increases in SSL in lower Sauk for future climate scenarios. These results are limited by the assumption that sediment supply level does not vary and increases from the pro-glacial areas melting are not considered. Loss of snow and ice cover with climate and resulting exposure of unconsolidated and fine sediments to overland flow would also increase suspended sediment loads in the Sauk River.

Relevant Information: The Sauk River provides a large load of sediment to the Skagit River. The future changes in high flows and peak events will affect the Skagit River in terms of hydrology, temperature, and SSL. This report provides estimates of SSL and temperature that could enter the Skagit River in moderate to high warming climate change scenarios (RCP 4.5 and RCP 8.5). Although approximately 30 miles downstream of the Gorge, the confluence of the Sauk and Skagit River is an important area to understand. Both the Sauk and mainstem Skagit River are predicted to reduce in flow and increase in temperature over the century. This could be problematic to salmon that can be affected adversely by the August reduction in flows and increase in temperature.

Beamer et al. 2010

Reference	Beamer, E., J. Shannahan, K. Wolf, E. Lowery, and D. Pflug. 2010. Freshwater habitat rearing preferences for stream type juvenile Chinook salmon (Oncorhynchus tshawytscha) and steelhead (O. mykiss) in the Skagit River basin: phase 1 study report. Report prepared for Skagit River System Cooperative, La Conner, Washington.									
Source Information	***Type***	Study	***Status***	Final	***Quantitative Data***	Yes	***Spatial Data***	Yes		
Topics and Keywords	***Geomorphology:*** Side and off-channels, large wood, log jam, aquatic habitats and landforms. ***Fish and Habitat:*** Habitat, status and trends; Fish, abundance.									
Species and Life Stages	Chinook-rearing, steelhead-rearing.									
Reaches and Spatial extent	R1-R14, Sauk River.									

Summary: This study was conducted to better understand the decline of Chinook and steelhead salmonoid species in the Skagit River basin. The study's purpose is to identify seasonal and habitat type preferences in the Skagit River basin for these salmonoid species in order to inform restoration efforts. This study is split into two parts. Phase 1 of this study is designed to assess the feasibility of the proposed sampling design. Results from Phase 1 informs Phase 2 which will implement a larger scale effort of this assessment that aims to identify seasonal and habitat type preferences. This document reports on Phase 1 of this study.

This study assembled a habitat database of the Skagit River basin in GIS. This habitat database was organized by a nested scale habitat classification scheme. These classifications began with large scale habitat definitions including “Large mainstem”, “Small mainstems or tributaries”, and “Floodplain channels”. The smaller unit scale definitions included “Pool”, “Riffle”, “Bar”, “Bank”, and more. These delineated habitat units then had representative reaches selected based on factors of space, time of year, and habitat type. These representative reaches were then assessed in the field and pilot level fish observation data was collected. This fish data was then used to conduct a statistical power analysis to inform Phase 2 of this study. The field methods implemented in Phase 1 of this study were then refined based on experience in the field as well as the results of the power analysis conducted to inform the minimum effort required for Phase two of this study.

The results of Phase 1 of this study found detectable differences in fish assemblage abundance for all three factors that were hypothesized to determine fish assemblage abundance. These three factors are space, season, and habitat type. The power analysis conducted in Phase 1 found that in general juvenile Chinook data is the limiting factor in making a robust enough sample size to be statistically significant. Overall, a doubling or tripling of efforts conducted in Phase 1 would be sufficient to create statistically significant results in Phase 2.

Relevant Information This study provides data on the location and distribution of habitat unit types in the Skagit River during 2007. These habitat unit types follow a nested scale habitat definition scheme that begins with channel type and fines down to individual habitat unit types. In addition to habitat unit delineations this study also delineated locations that large log jams were interacting with the low flow channel in 2007. This data will help inform changes in habitat unit type and large wood abundance and distribution that are being reported on in the GE-04 study report.

Beechie et al. 2017

Reference	Beechie, T. J., O. Stefankiv, B. Timpane-Padgham, J. E. Hall, G. R. Pess, M. Rowse, M. Liermann, K. Fresh, and M. J. Ford. 2017. Monitoring Salmon Habitat status and trends in Puget Sound: development of sample designs, monitoring metrics, and sampling protocols for large river, floodplain, delta, and nearshore environments. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-137, Seattle.									
Source Information	***Type***	Report	***Status***	Final	***Quantitative Data***	Yes	***Spatial Data***	Yes		
Topics and Keywords	***Geomorphology and Landforms:*** Aquatic habitats and landforms, Estuarine habitats and landforms. ***Land Use and Cover:*** Land cover, Banks and shoreline, Floodplain. ***Fish and Habitat:*** Habitat, freshwater, Habitat, nearshore, Habitat, status and trends, Monitoring, habitat									
Species and Life Stages	Chinook-rearing, chum-rearing, steelhead-rearing. Chinook-spawning, chum-spawning, steelhead-spawning.									
Reaches and Spatial extent	R1-R14, Sauk River, Skagit bay.									

Summary: This report addresses the first stage of development of a habitat monitoring program for four salmon and steelhead spawning and rearing environments across the Puget Sound: large rivers, floodplains, deltas, and the nearshore. This program will be used to provide data for assessing habitat changes across each environment.

The goals of the first year of this monitoring effort are as follows:

1) To develop a hierarchical sampling design to monitor habitat status and trends.

2) To identify habitat metrics that are cost-effective and related to viable salmonoid population parameters.

3) To develop protocols to measure those metrics.

4) To test the satellite, aerial photography, and field methods for repeatability and reliability.

5) To evaluate habitat status to assess the ability of each metric to detect habitat differences among our chosen land-cover strata.

These efforts will be used to refine the habitat monitoring program to ensure consistency and relevancy so that it may be used reliably in the future.

Results from the first year of monitoring are included in this report. These results include next steps on the refinement of the habitat monitoring program as well as the current status of habitat for the four salmon and steelhead spawning and rearing environments.

Relevant Information This report provides data on the 2017 status of salmon and steelhead habitat across Puget Sound basins which include the Skagit River. Additionally, it provides a guideline for a habitat monitoring program using remote sensing and field-based techniques that has been extensively reviewed and evaluated for improvements on consistency and reliability. This is relevant to City Light as this methodology can be used to inform current aquatic habitat monitoring practices.

Collins et al. 2002

Reference	Collins, B. D., D. R. Montgomery, and A. Haas. 2002. Historical changes in the distribution and functions of large wood in Puget Lowland Rivers. Can. J. Fish Aquatic Science 59:66-76.									
Source Information	***Type***	Study	***Status***	Final	***Quantitative Data***	Yes	***Spatial Data***	Yes		
Topics and Keywords	***Geomorphology:*** Large wood, log jam, change.									
Species and Life Stages	None.									
Reaches and Spatial extent	R13.									

Summary: This study examines the historic change of large wood function and distribution in Puget lowland rivers. The purpose of this study is to examine the statement that the influence of large wood decreases with increasing channel size. The authors of this study hypothesize that historic stream cleaning has greatly decreased the abundance of large wood in Puget lowland rivers and levee construction and riparian forest clearing has diminished the potential for lowland rivers to recruit wood. This combined effect suggests that the current condition of large wood loading in Puget lowland rivers is not representative of their historical condition.

The authors of this study examine this hypothesis by comparing the current condition of large wood distribution and function in reaches across three Puget lowland rivers. Two of these rivers, the Snohomish and Stillaguamish, have been heavily leveed, cleared, and logged. They are meant to represent conditions in a Puget lowland river that has been subject to extensive European

settlement impact. The other river examined, the Nisqually River, contains reaches that have been largely untouched since European settlement. The study reaches in the Nisqually are meant to represent historic conditions of other Puget lowland rivers pre-European settlement. Additionally, the authors examined archival materials of wood distribution and function of these three rivers as well as other Puget lowland rivers, including the Skagit River, to provide insight into their historical condition.

Results from this study show significant differences in wood distribution and function between the Nisqually River and the Snohomish and Stillaguamish Rivers.

Archival materials of the Nisqually River suggest that the study reach is relatively unchanged from its mid-19th century condition. Present day large wood distribution is similar to the size distribution in 1873. Additionally, the present-day anastomosing channel planform in the Nisqually is similar to what is seen in historic aerial photos and historic maps. The historic distribution and function of large wood in the Nisqually is comparable to the historic conditions in the Stillaguamish. The Stillaguamish had comparable wood sizes to the Nisqually, abundant log jams, and an anastomosing channel planform according to archival materials. The Snohomish was dissimilar in that it did not have as much wood as the Nisqually and Stillaguamish. Additionally, it exhibited a single meandering planform as opposed to anatomizing. The authors note that the Snohomish does exist in a broad low-gradient valley created by Pleistocene subglacial runoff as opposed to the post-glacial incision dominated valleys that the Nisqually and Stillaguamish exist in. This could be the cause for the variation in historic conditions of these channels.

There are strong contrasts in wood distribution and function when comparing the Nisqually with the Stillaguamish and Snohomish River current day conditions. The Nisqually has 8 and 21 times more wood than the Snohomish and Stillaguamish, respectively. This difference is accounted for primarily from wood jams in the Nisqually which are much more abundant than in the Snohomish and Stillaguamish. Additionally, large wood was shown to have a greater impact on the overall aquatic habitat in the Nisqually forming 61 percent of pools versus 12 percent and 6 percent in the Stillaguamish and Snohomish respectively. The large wood in the Snohomish and Stillaguamish was also shown to lack long, large-diameter, pieces with rootballs which function in the Nisqually to initiate and stabilize log jams as key pieces.

The authors concluded that the present-day large wood conditions seen in most Puget lowland rivers is not representative of historic conditions. Large wood historically was one to two orders of magnitude more abundant pre-European settlement. This loss of large wood has been driven by human interaction.

Relevant Information This study discusses historic conditions of large wood distribution in the Skagit river and provides comparison of present day and mid-19th century large wood distribution conditions in Puget lowland rivers comparable to the Skagit river. This study cites archival materials that describe a log raft on the Skagit river near Mt. Vernon as “nine meters deep, consisting of from five to eight tiers of logs, which generally ranged from three to eight feet in diameter and existed for at least a century”, this jam was reported to be “large enough to support live trees 0.6 to 1.2 meters in diameter”. This raft jam was greater than 1 kilometer long. Additional archival materials discuss the prevalence of tidal distributary channels that were reportedly characterized by “hundreds of miles of old channels that were choked with wood, filled with sediment, and abandoned”. The study also provides evidence that Puget lowland rivers had one to two orders of magnitude more wood abundance in the mid-19th century.

Curran et al. 2016

Reference	Curran, C. A., E. E. Grossman, M. C., Mastin, and R. L. Huffman. 2016. Sediment load and distribution in the lower Skagit River, Skagit County, Washington. U.S. Geological Survey Scientific Investigations Report 2016–5106. Available at: http://dx.doi.org/10.3133/sir20165106.									
Source Information	***Type***	Report	***Status***	Final	***Quantitative Data***	Yes	***Spatial Data***	Yes		
Topics and Keywords	***Geomorphology:*** Change, sediment transport and supply, substrate or sediment, climate change. ***Modeling Tools:*** Hydrology, sediment.									
Species and Life Stages	None.									
Reaches and Spatial extent	Reach 12 and 13, Skagit Bay.									

Summary: The authors developed and evaluated regression models of sediment transport (sediment-rating curves) by utilizing 175 measurements of suspended-sediment load, made routinely from 1974 to 1993, and sporadically from 2006 to 2009. Five different regression models were evaluated. The five types of models they used were ordinary least squares, polynomial least squares, seasonal, time-interval, and flow-range. The flow-range model had the closest fit between estimated and measured suspended sediment concentrations (SSC). Using this regression model for 75 years of daily discharge (1941-2015), a mean annual suspended-sediment load in the Skagit River of 2.5 teragrams (1 Tg = 1 million metric tons) was estimated. Individual large floods accounted for as much as 40 percent of annual sediment delivery. In 2007, an extremely wet year an annual load of 4.5 Tg was measured from daily suspended-sediment samples collected with an automated sampler. For 2007, the flow-range rating curve overestimated the SSC by 6.7 percent, while the seasonal rating curve underestimated load by 11 percent.

A summer low-flow model showed poor correlation between SSC values estimated from discharge and measured SSC values. The poor correlation indicates that discharge is a poor surrogate for SSC during the summer low-flow period. A comparison of models for three-time intervals revealed an overall increase of 66 percent in the slope of the SSC to discharge relation between 1974-1976 and 2006-2009. The increase suggests changes in sediment supply, channel hydraulics, and/or basin hydrology.

Particle size was an important factor controlling sediment delivery and deposition. The percentage of fines generally increased with increasing discharge during the winter storm season. A continuous turbidity record from the Anacortes Water Treatment Plan from water year 1999-2013 was used as a surrogate for the concentration of fines. The turbidity record confirms that about one-half of the mean annual suspended-sediment load is composed of fines.

Relevant Information: Regression models were developed to relate SSC to discharge, turbidity, and flow distribution the 15-km stretch of lower river. The flow-range model has the closest fit between estimated and measured SSC. All the models have considerable variability and poor correlation during summer low-flow periods. The increase in SSC over time suggests changes in sediment supply, channel, hydraulics, and/or basin hydrology. These relationships can be used to estimate sediment delivery and relative particle-size distribution and inform proposed delta restoration design.

Grossman et al. 2020

Reference	Grossman, E. E., A. W. Stevens, P. Dartnell, D. George, and D. Finlayson. 2020. Sediment export and impacts associated with river delta channelization compound estuary vulnerability to sea-level rise, Skagit River Delta, Washington, USA. Marine Geology 430:106336.									
Source Information	***Type***	Journal	***Status***	Final	***Quantitative Data***	Yes	***Spatial Data***	Yes		
Topics and Keywords	***Geomorphology:*** Change, history, channel migration, channel incision, sinuosity, floodplain, side- and off channels, floodplain connectivity, substrate and sediment, sediment transport and supply, aquatic habitats and landforms, estuarine habitats and landforms, climate change. ***Modeling Tools:*** Hydrology, climate change.									
Species and Life Stages	None.									
Reaches and Spatial extent	Reach 13, Skagit Bay.									

Summary: The study authors used bathymetric change, sediment cores, and modeling to show how an estimated 142 ± 28 M m^3 of sediment, of which 68 percent was sand deposits, accumulated across the Skagit River delta between 1890 and 2014 related to land uses. The amount stored in reservoirs represents approximately 39 percent of the fluvial sand fraction over this time period. However, accumulation of 83 percent of the fluvial sand fraction found near the river mouth make retention in the delta foreset and tide flats effective metrics to evaluate land use impacts on sediment dynamics and ecosystems. A higher ratio of sand retention during the period 1890-1939, coinciding with extensive deforestation, channel dredging, and channelization activities, was found relative to the period 1940-2014, which was characterized by improved forest practices, and sediment management to protect endangered species.

Comparable offshore sand retention over time and higher nearshore retention before 1940 after normalizing for the assumed reduction in sediment runoff associated with improved forest practices, suggests the channelization has continued to influence sediment export at a magnitude equal to the effects of early logging. Adverse impacts of the bypassing sediment regime to natural hazards risk and ecosystem management concerns are discussed. Sediment budget and coastal change analyses provide a framework for evaluating opportunities to achiever great resilience in low-lying deltas worldwide.

Relevant Information:

The amount of sediment estimated in this study is important to the GE-04 study. With changes in dam operations there could be changes propagated downstream. The sediment budget and historical change analyses provide a framework to assess coast responses to sediment delivery and routing to guide vulnerability assessments and resiliency planning.

Hartson and Shannahan 2015

Reference	Hartson, R. and J.P. Shannahan. 2015. Inventory and Assessment of Hydromodified Bank Structures in the Skagit River Basin Chinook Bearing Streams. Final report submitted to Northwest Indian Fisheries Commission and Environmental Protection Agency. Prepared for The Upper Skagit Indian Tribe Natural Resources Division.

Source Information	***Type***	Report	***Status***	Final	***Quantitative Data***	Yes	***Spatial Data***	Yes		
Topics and Keywords	***Land Use and Cover:*** Banks and shoreline.									
Species and Life Stages	None.									
Reaches and Spatial extent	R1-R13, Sauk River.									

Summary: This document reports on a 2015 field inventory of hydromodified banks in the Skagit basin. The inventory's extent encompasses all recorded Chinook salmon bearing channels within the Skagit basin. This 2015 inventory was based on an initial inventory of hydromodified banks conducted in 1998 in the Skagit basin. The 2015 field inventory was conducted using Trimble GPS units and is being stored in a GIS database. In addition to capturing the spatial distribution of hydromodifications the 2015 inventory also defined modification by "hydromodification type", "size class of material", "levee association", "length of structure", "location in channel", and more. Photos were also taken of each hydromodification.

The results of this field inventory will be used to inform and prioritize restoration efforts in the Skagit basin.

Relevant Information: This report provides data on hydromodified banks within the entire Skagit basin. This includes information in the main project area from the Gorge Dam to the Sauk River.

Hood 2007

Reference	Hood, W. G. 2007. Large woody debris influences vegetation zonation in an oligohaline tidal marsh. Estuaries and Coasts, 30(3):441-450.									
Source Information	***Type***	Journal	***Status***	Final	***Quantitative Data***	Yes	***Spatial Data***	Yes		
Topics and Keywords	***Geomorphology:*** Large wood, estuarine habitats and landforms, change, substrate and sediment, sediment transport and supply. ***Water Quality and Productivity:*** Nutrients. ***Fish and Habitat:*** Habitat, estuary.									
Species and Life Stages	None.									
Reaches and Spatial extent	Reach 13, Skagit Bay.									

Summary: This study shows that LWD plays a role in the establishment of shrubs, particularly nitrogen-fixing *Myrica gale* L. (*M. gale;* sweetgale) in the Skagit Delta tidal marshes. LWD, sweetgale, and other shrubs were surveyed along line transects in an oligohaline tidal marsh and in abandoned agricultural land whose dikes failed over 50 years ago and has reverted to marsh. The results show a strong association between LWD and *M. gale*. Sweetgale was very rare on LWD < 30 cm (12 in), more common for LWD between 30-75 cm (12-30 in), and always present on LWD ≥ 75 cm (30 in). The marsh surface was generally 45 cm below mean higher high water (MHHW), suggesting LWD provides a growth platform at an elevation near MHHW and reduces flood stress. The largest and most abundant tree in the marsh averaged only 35.8 cm (14 in), which

suggests LWD recruitment from upstream sources is necessary to sustain sweetgale populations in the geomorphologically dynamic Skagit marsh.

Relevant Information: *M. gale* dependence on estuarine LWD suggests upstream riparian management can affect LWD subsidies to estuaries with potentially cascading effects on estuarine ecology, particularly community structure and nitrogen dynamics. Long-term estuarine habitat management should include upstream riparian zone management to allow LWD recruitment to the estuary to sustain LWD-dependent estuarine ecosystem structures and processes.

Hood 2007b

Reference	Hood, W. G. 2007b. Scaling tidal channel geometry with marsh island area: a tool for habitat restoration, linked to channel formation process. Water Resources Research 43:W03409.									
Source Information	***Type***	Study	***Status***	Final	***Quantitative Data***	Yes	***Spatial Data***	Yes		
Topics and Keywords	***Geomorphology:*** Estuarine habitats and landforms ***Modeling Tools:*** Connectivity									
Species and Life Stages	None.									
Reaches and Spatial extent	Skagit Bay									

Summary: This study proposes an alternative approach to examining tidal channel geometry and evolution to inform marsh restoration. This approach relies on scaling relationships between marsh island surface area and various metrics of the set of tidal channels draining each marsh island. This study was conducted in the Skagit River delta.

Tide channel margins were digitized from aerial photos and used to measure marsh island and tide channel geometries. These geometries were then scaled with each other as a function of marsh island area for 7 tide channel metrics which include total channel length, total channel surface area, tributary count, and more. These scaled relationships were then analyzed for statistical significance. This process was done separately for five different marsh island groups in the Skagit delta, one of which was cut off from sediment inputs by anthropogenic processes in the 1950s.

Results from this analysis showed statistically significant scaling for 6 of 7 metrics. When comparing these scaling relationships between marsh island groups it was observed that slopes remained uniform, but the intercepts varied. The difference in scaling intercept between the marsh island group cut off from sediment inputs and the other marsh island groups was most pronounced.

This new approach to examining tidal marsh systems show promise as seen in the difference in scaling relationships of a sediment starved marsh island group and a sediment connected marsh island group. This difference could be used in identifying marsh restoration sites.

Relevant Information: This study examines an alternative process for examining tide channel geometries and evolution. This study was conducted in and reports on empirical data collected in the Skagit River delta. This data could be used to inform current status of tide channels in the Skagit delta.

Reference	Hood, W. G. 2010. Tidal channel meander formation by depositional rather than erosional processes: examples from the prograding Skagit River delta (Washington, USA). Earth Surface Processes and Landforms 25(3):319-330.									
Source Information	***Type***	Journal	***Status***	Final	***Quantitative Data***	No	***Spatial Data***	Yes		
Topics and Keywords	***Geomorphology:*** estuarine habitats and landforms, change, substrate and sediment, sediment transport and supply, channel migration.									
Species and Life Stages	None.									
Reaches and Spatial extent	Skagit Bay.									

Summary: The author used geographic information system (GIS) analysis of historical aerial photographs of the Skagit Delta marshes. These provide examples of an alternative channel meander forming process in a rapidly prograding river delta. Parallel sequences of marsh ridges and swales indicate locations of historical distributary shoreline levees adjacent to filled former island/mainland gaps. The location of marsh islands within delta distributaries is not random. Islands are disproportionately associated with blind tical channel/distributary confluences. Additionally, blind tidal channel outlet width is positively correlated with the size of the marsh island that forms at the outlet and the time until island fusion occurs within mainland marsh. These observations suggest confluence hydrodynamics favor sandbar/marsh island development. The transition from confluence sandbar to tidal channel meander can take less than 10 years, but usually occurs over several decades. This channel meander formation process is part of a larger scale depositional process of delta progradation that includes distributary elongation, gradient reduction, flow-switching, shallowing, and narrowing

Relevant Information: The Skagit River provides 34-50% of Puget Sound's freshwater and sediment inputs, depending on the season. Distinguishing systems in which depositional version erosional channel-forming processes predominate may provide useful guidance for further refinement of morphodynamic models and for land-use management affecting sediment supply or river discharge to deltaic systems.

Hood 2015

Reference	Hood, W. G. 2015. Geographic variation in Puget Sound tidal channel planform geometry. Geomorphology 230:98-108.									
Source Information	***Type***	Journal	***Status***	Final	***Quantitative Data***	Yes	***Spatial Data***	Yes		
Topics and Keywords	***Geomorphology:*** Large wood, estuarine habitats and landforms, change, substrate and sediment, sediment transport and supply, channel migration, change, aquatic habitat and landforms, sea level rise. ***Fish and Habitat:*** Habitat, estuary.									
Species and Life Stages	None.									
Reaches and	Reach 13, Skagit Bay.									

Spatial extent	

Summary: The author performed allometric models to predict the number and size of tidal channels that could develop following salt marsh restoration and channels were digitized. Channel size and complexity were positively related to tidal range and negatively related to wave height in tidal channels throughout Puget Sound. The apparent accretion deficit suggested by larger tidal channel in the South Fork (SF) Skagit delta compared to North Fork (NF) delta is consistent with greater declines in historical salt marsh progradation rates in the SF compare to the NF delta. The results of this study suggest that sediment-challenged salt marshes in Puget Sound are already showing impacts from 20th Century sea level rise.

Relevant Information:

The results of this study suggest restoration of system-scale natural processes through relaxation of anthropogenic constraints on sediment supply could likely change patterns within the affected deltas. Wave environments appear to affect channel geometry. Wave-sheltered areas experience relative sediment deficits, such that some salt marshes in Puget Sound, such as the SF Skagit delta, are suffering sea-level rise impacts.

Hood *No Date*

Reference	Hood, W. G. No date. Distribution of large woody debris in river delta tidal marshes: Preliminary Results. Skagit River System Cooperative.									
Source Information	***Type***	Unpublished	***Status***	Final	***Quantitative Data***	Yes	***Spatial Data***	Yes		
Topics and Keywords	***Geomorphology:*** change, history, channel migration, channel incision, sinuosity, floodplain, floodplain connectivity, substrate and sediment, sediment transport and supply, aquatic habitats and landforms, estuarine habitats and landforms, side- and off-channel habitat.									
Species and Life Stages	None.									
Reaches and Spatial extent	Skagit Bay.									

Summary: The author present examples of how large wood moves in the Skagit River delta. Some of the factors that affect LWD include topography, fetch, elevation, proximity to distributaries and dikes. The marsh island size strongly correlates ($r^2 = 0.90$) with total LWD length and count in the SF Skagit. The tidal channel size affects wood density and size. There is more total wood on the marsh surface than in channels, but channel density is higher. The wood appears to get trapped in tidal channels, especially smaller channels.

Relevant Information: The LWD in the Skagit is affected by topography, fetch, elevation, proximity to distributaries, and dikes. The tidal channel and marsh island size affects wood density and size. This has implications for large wood movement and location.

Jaeger et al. 2017

Reference	Jaeger, K.L., C. A. Curran, S. W. Anderson, S. T. Morris, P.W. Moran, and K. A. Reams. 2017. Suspended sediment, turbidity, and stream water temperature in the Sauk River Basin, Washington, water years 2012–16. U.S. Geological Survey Scientific Investigations Report 2017–5113. Available at https://doi.org/10.3133/sir20175113.

Source Information	***Type***	Report	***Status***	Final	***Quantitative Data***	Yes	***Spatial Data***	Yes		
Topics and Keywords	***Geomorphology:*** Change, history, substrate and sediment, sediment transport and supply. ***Water Quality and Productivity:*** Temperature, turbidity. ***Fish and Habitat:*** Fish, survival.									
Species and Life Stages	Chinook.									
Reaches and Spatial extent	Sauk River.									

Summary: Suspended sediment, turbidity, and water temperature data was collected at two USGS streamgages in the upper and middle reaches of the Sauk River over a 4-year period, October 2011 to September 2015, and at a downstream location in the lower Sauk River for a 5-year period from October 2011 to September 2016. Over the 5-year period, mean annual suspended sediment loads (SSL) at the upper, middle, and lower Sauk River streamgages were 94,200 metric tons (t) (240 t/km^2), 203,000 t (270 t/km^2), and 940,000 t (510 t/km^2), respectively. The median daily SSL for the streamgages was 27 t at Upper Sauk, 34 t at Middle Sauk, and 242 t at Lower Sauk. At the upper, middle, and lower Sauk River streamgages the fine sediment (smaller than 0.0625 mm) was approximately 53 percent, 42 percent, and 34 percent, respectively, of the total SSL.

SSL in the Sauk River Basin exhibited seasonal trends and substantial inter-annual variability. Fall (September to December) SSL, on average, accounted for more than half of the total annual suspended sediment load at the three streamgages (55 percent in upper, 67 percent in middle, and 62 percent in lower. Summer suspended sediment load was the smallest at the upper and middle streamgages (6 and 7 percent, respectively) and was 16 percent at the lower streamgage. The higher suspended sediment load at the lower gage was attributed to a relatively high load associated with late summer glacial melt in the tributary river, the Suiattle River, which joins the Sauk River downstream of the middle streamgage. Sediment availability typically remained high during the first fall storms, which glacial sediment accumulated over the summer was flushed out of the watershed. During five fall floods in fall 2015, 1.5 million metric tons more sediment was transported than would have been expected based on typical relations between sediment load and discharge.

A mass-balance analysis indicates that the Suiattle River accounts for about 80 percent of the total suspended-sediment load in the lower Sauk streamgage. The remaining load was split evenly between the inputs from the Upper Sauk River and White Chuck River Basins (10 percent each). About 60 percent of the SSL from the Suiattle River is estimated to be from the eastern flank of Glacier Peak. Sediment from the eastern flank of Glacier Peak may contribute approximately 50 percent of the sediment load for the entire Sauk River Basin in any given year.

Less than 1 percent of the study period included elevated water temperature and turbidity values that could impair Chinook salmon at various life stages at the Sauk River streamgages. During the study, potential temperature stress to fish in the Sauk River usually occurred during late summer and early fall, compared to periods of concern of turbidity. The study provides an opportunity to effectively determine what the background level might be for this or other regional rivers with regards to Washington state water quality standards.

Relevant Information: The study provides information on sediment load of the Sauk River, which enters the Skagit at the downstream end of the main project area. The Sauk River supplies a large amount of sediment to the Skagit River each year. The authors measured SSL from 2011 to 2016

in the Sauk River and provide a budget that can be used to better understand the SSL contribution from the Sauk River to the Skagit River inter-annually and seasonally.

Lee et al. 2016

Reference	Lee, S-Y, A.F. Hamlet, and E.E. Grossman. 2016. Impacts of Climate Change on Regulated Streamflow, Hydrologic Extremes, Hydropower Production, and Sediment Discharge in the Skagit River Basin. Northwest Science 90(1), 23-43.									
Source Information	***Type***	Report	***Status***	Final	***Quantitative Data***	Yes	***Spatial Data***	Yes		
Topics and Keywords	***Geomorphology:*** Change, sediment transport and supply, climate change. ***Water Quality and Productivity:*** Temperature, turbidity, climate change. ***Modeling Tools:*** Hydrology, climate change. ***Land Use and Cover:*** Banks and shoreline, floodplain. ***Fish and Habitat:*** Habitat – instream flow, estuary, freshwater; Fish – climate change.									
Species and Life Stages	None.									
Reaches and Spatial extent	R1 – R14, Sauk River, Baker River.									

Summary: To assess the hydrologic response of the Skagit River due to climate change an integrated daily-time-step reservoir operations model, SkagitSim, was created to simulate reservoir operation policies for historical flow conditions and projected flow conditions in the 2040s (2030–2059) and 2080s (2070–2099). Results show that climate change will cause substantial seasonal changes in both natural and regulated projected flow conditions. The Skagit River Basin will transition from a mixed rain and snow watershed with dual peaks in the winter and spring to a rain dominated watershed with a single peak in the winter for both natural and regulated flow conditions.

Projected flow conditions were calculated using five different global climate models (GCMs) forced by the A1B greenhouse gas emissions scenario. The Variable Infiltration Capacity (VIC) hydrologic model was implemented at 1/16 latitude and longitude resolution over the Pacific Northwest. The VIC model was used to generate a streamflow time series for this study.

The projected shift in seasonal timing of flow affects the magnitude and timing of hydropower production. Hydropower production will increase in the winter and decrease in the summer. This will be a benefit to the region in the winter but will present challenges in the summer with additional increases in energy demand due to an increase in population and an increase in cooling demand. Additionally, increasing pressure to use reservoir releases of cold water to sustain temperature sensitive fish downstream may present additional challenges.

There will be large changes in the magnitude and timing of sediment load at the Skagit River near Mount Vernon. The peak sediment load in December will increase from a historic average of 0.40 teragrams/month to a projected average of 1.74 teragrams/ month (+ 335%) by the 2080s. The December to February total sediment discharge is projected to increase by 376% for the 2080s. This will benefit the Skagit delta by potentially mitigating the projected loss of marsh and shallow water habitat due to rising sea levels. Although an increase in suspended sediment load may also negatively impact many aquatic species.

The 100-year flood is projected to increase relative to historic baselines for both a natural and regulated scenario in both the 2040s and 2080s. Additionally annual peak flows are projected to increase in magnitude and occur more frequently in the winter season. Alternative flood control operations that increase flood control storage were shown to be not effective in mitigating higher flood risks in future climate change scenarios.

Extreme low flows under regulated conditions are projected to decrease due to an increase in evapotranspiration and a decrease in summer precipitation. Although projected low flows under regulated conditions will still be higher than historic low flows under natural conditions. This suggests that ecosystem impacts from a changing low flow regime may be modest.

Relevant Information: The report provides insight on projected changes in seasonal hydropower generation, flood mitigation, and sediment loading in the Skagit River Basin. Annual hydropower generation will not change significantly based on projected hydrologic conditions but seasonal changes in hydropower production will be significant. By the 2080s hydropower generation in the Skagit basin is projected to increase by 19% in the winter and spring and decrease by 29% in the summer. Annual peak flows as well as 100-year interval flows are projected to increase in magnitude causing an increase in flood risks downstream. An alternative reservoir operation policy that allows for an increase in flood control storage was shown to be ineffective in mitigating flood risks. There is projected to be a dramatic increase in sediment load with the total sediment discharge from December to February at the Skagit River near Mount Vernon increasing by 376%.

Nichols & Ketcheson 2013

Reference	Nichols, R. A., and G. L. Ketcheson. 2013. A two-decade watershed approach to stream restoration log jam design and stream recovery monitoring: Finney Creek, Washington. Journal of the American Water Resources Association 49(6):1367-1384.									
Source Information	***Type***	Report	***Status***	Final	***Quantitative Data***	Yes	***Spatial Data***	Yes	***Project Impacts***	No
Topics and Keywords	***Geomorphology:*** change, history, large wood, substrate and sediment, log jam, data gaps, aquatic habitats and landforms. ***Fish and Habitat:*** Fish, survival.									
Species and Life Stages	Chinook, juvenile, rearing.									
Reaches and Spatial extent	Reach 9-10.									

Summary: This report synthesizes 12 years (1999-2010) of stream restoration log jam design and stream recovery monitoring on Finney Creek, tributary to the Skagit River downstream of the Sauk River. A total of 1881 pieces of large wood were placed in 181 log jams, including 60 floating log ballasted jams, were constructed along 12.2 km (7.6 miles) of the Finney Creek channel. The goal was to alter hydraulic processes that affect aquatic habitat formation along 39 km (24.4 miles) with emphases on 18.5 km (11.5 miles) of lower Finney Creek. Aquatic habitat surveys over a five-year period show an increase in the area of large pools and an increase in residual and maximum pool depth in the lower reach of Finney Creek. Channel cross-sections show a deeper channel at most log jams, better channel definition in the gravel deposits at the head of the log jams, and improved riffle and thalweg development below the log jams. Stream temperature in the upper creek decrease by 1.0 degrees F in the first three years, and 1.1 degrees F in the lowest treated reach over nine

years. Photo points over the restoration time period show that riparian vegetation is recolonizing gravel bars.

Relevant Information: Log jams alter local hydraulics and sediment transport and storage processes that contribute to creation and maintenance of high-quality habitat features. A total of 1881 logs were imported and placed in 181 log jams covering 7.6 miles (12.2 km) of stream. The log jam number density went from 4.2 per mile to 39.3 per mile. In August 2021, the main project area from Gorge Dam to the Sauk River had a density of 2.7 log jams per mile.

NSD 2017

Reference	NSD (Natural Systems Design). 2017. Skagit River large woody debris assessment: connecting LWD to the 2005 Skagit Chinook recovery plan. Report prepared for Skagit Watershed Council, Mount Vernon, Washington.									
Source Information	***Type***	Report	***Status***	Final	***Quantitative Data***	No	***Spatial Data***	No		
Topics and Keywords	***Geomorphology:*** change, history, large wood, substrate and sediment. ***Fish and Habitat:*** Fish, survival.									
Species and Life Stages	Chinook.									
Reaches and Spatial extent	Reach 1-13.									

Summary: This report presents a method for developing a set of descriptive conceptual models that explain how large wood in the Skagit River Basin functions to achieve the goals of the 2005 Skagit Chinook Recovery Plan, as well as a method for a comprehensive assessment of large wood resources across Chinook habitat in the Skagit Basin. The seven limiting factors that influence the presence of large woody debris (LWD) include seeding levels, degraded riparian zones, dam operations, sediment and mass wasting, flooding, high water temperatures, and hydromodification. Throughout the Skagit River Basin, LWD forms key riverine habitat features that have a significant impact on hydraulic processes, geomorphology, and salmonid habitat quality. The depletion of LWD has led to extensive degradation of fish habitats throughout the Skagit Basin and region.

NSD presents a conceptual model for four distinct geomorphic sections of the Skagit River:

1) In narrow, high-gradient, headwater Skagit River reaches individual LWD can span the channel and dominate stream bedform and hydraulics.

2) Wider, intermediate-gradient reaches in the middle of the Skagit River system, LWD no longer spans the channel and is often is lodged on the bank, on bars, or in the channel bed.

3) In low-gradient tributaries, single pieces of wood usually do not span channel, but can form snags in the channel that can cause large LWD jams and obstruct large portions of the channel.

4) In wide, low-gradient Skagit River reaches surrounded by historic floodplain, single pieces of wood can lead to the formation of massive LWD jams that can change the course of the river, block river channels, and induce massive floods. In lower reaches of the Skagit River system, LWD jams and jam-related river features have the highest densities of juvenile Chinook across multiple seasons.

NSD presents a metrics matrix for the seven limiting factors that include processes affected and characteristics to measure to better understand the interaction between limiting factors and LWD. Additionally, the report identifies methods for wood inventory and assessment on large and small rivers. This includes using high resolution LiDAR, Green LIDAR, imagery, field verification, and modeling. The report provides recommended metrics for LWD assessment in the Skagit Basin. This included number of jams, number of key members, number of nodes, river complexity index, volume of wood, and number of pools greater than 1 meter depth by reach.

Relevant Information: The report provides guidelines for a comprehensive assessment of large wood in the Skagit Basin. Many of the recommended metrics were measured by the GE-04 Study Team in August 2021. Additionally, available LiDAR, green LiDAR, and aerial photography was used to identify historic location of jams and individual pieces, when the imagery hade high resolution. The conceptual model for four distinct geomorphic sections provides some patterns and trends that were verified as part of the GE-04 study. The model can be refined based on the additional data collected.

Riedel et al. 2020 – Summarized in SY-01 USR

Riedel et al. TBD – Skagit River geomorphology inventory report: part 2 – Sauk River to Hamilton.

Rothleutner 2017

Reference	Rothleutner, A. D. 2017. Sediment budget of the middle Skagit River, Washington 1937-2015 reveals decadal variations in sediment export and storage. Master's thesis. Western Washington University, Bellingham.									
Source Information	***Type***	Thesis	***Status***	Final	***Quantitative Data***	Yes	***Spatial Data***	Yes		
Topics and Keywords	***Geomorphology:*** change, history, substrate and sediment, sediment transport and supply.									
Species and Life Stages	None.									
Reaches and Spatial extent	Reach 7-12.									

Summary: The thesis includes an evaluation of historical channel meandering since 1937 of the middle reach Skagit River between Rockport and Sedro-Wooley, Washington (Geomorphic Reach 7-12). The active floodplain has periodically been a significant source of sediment to the lower Skagit River and delta. She examined the geomorphic change and potential sediment production of the middle reach to test whether it is a significant source to the lower river. ArcGIS was used to calculate sediment volume produced by bank erosion versus stored in bars, island, and side channels through time. The results show changes in net sediment production through time, between 2006 through 2015, recruitment of floodplain sediment from the middle reach to the active channel produced approximately 27 percent of the annual sediment mean load measured in Mount Vernon. The sediment source was dominated by lateral incision at rates of 3-8 m/yr in several areas of high-relief (3-15 m) banks characterized by unconsolidated deposits. The results help quantify recent channel dynamics, rates of change, and sources of sediment that influence sediment transport and aggradation patterns, that are important to flood risk and salmon habitat.

Channel width consistently decrease through time along the entire mainstem middle Skagit reach. The overall width decreased from an average of 221.2 m in 1937 to 178.8 m in 2015. Channel widths were generally wider in the confined reach. There is an increase in the amount of erosion in comparison to aggradation in the more recent time periods of 2003-2006 and from 2006-2015. There will likely be a much more seasonal pattern of aggradation and erosion in the future. Erosion will likely be much higher during the winter months with periods of higher flow and more precipitation falling as rain.

Between 2006-2015 the mean annual sediment load from the middle reaches was 630,000 Mg. This accounts for approximately 25 percent of the estimated 2,500,000 Mg annual sediment load calculated from sediment rating curves. However, this value is probably an underestimate because most of the changes identified by the 2D Model for Aggradation and Erosion are large scale. Smaller changes are less likely to be captured. The estimated sediment contributions from the Sauk River are 950,000 Mg.

Relevant Information: Between 1937 and 2015, the overall channel width has decreased by approximately 42 m (138 feet) in the middle Skagit. There has been an increase in the amount of erosion in recent years. The mean annual sediment load for the middle reaches between 2006-2015 was approximately 63,000 Mg. This account for approximately 25 percent of the estimated 2,500,000 Mg annual sediment load calculated from sediment rating curves. Climate change and dam operations can potentially change the amount of sediment being discharged. Therefore, this study provides important information that can be used to understand how the sediment load could change in the future.

Seixas and Veldhuisen 2019

Reference	Seixas, G. B., and C. N. Veldhuisen. 2019. Forest practices and regulatory channel migration zones in the Skagit River basin since the forests and fish report. Report prepared for Skagit River System Cooperative, La Conner, Washington.									
Source Information	***Type***	Report	***Status***	Final	***Quantitative Data***	No	***Spatial Data***	Yes		
Topics and Keywords	***Geomorphology:*** Channel migration, Channel incision, Side and off-channels, Floodplain connectivity, log jam. ***Land Use and Cover:*** Forestry.									
Species and Life Stages	None.									
Reaches and Spatial extent	R9-R11, Sauk River.									

Summary: In Washington State, riparian corridors along fish bearing streams are protected from forest practices. Rivers that show potential for channel migration face additional protections. Channel migration zones (CMZs) are recognized areas adjacent to streams and rivers that are deemed susceptible to channel migration within the next 140 years. Land managers are required to begin their riparian buffers at the outer edge of the CMZ. This protects critical riparian processes for future migrating channels such as large wood recruitment and streamside shading. These protections were put into practice in 2001 under the updated Forest Practice Rules document.

This report assesses the implementation of recognized CMZ zones within the Skagit River basin since the 2001 update. Additionally, CMZs within the basin that were missed are included in this

assessment. “Missed” CMZs are sites where channel migration occurred since 2001 or occurred prior to 2001 in aerial photographs that were not analyzed in the original forest practice application. This assessment was done through an analysis of a compiled dataset of aerial photographs, LiDAR derived digital elevation models, and data from forest practice applications.

The results of this assessment found that of the 25 sites that were assessed, 11 sites were recognized as a CMZ and migration occurred, 3 sites were not recognized as a CMZ and migration occurred, 7 sites were not recognized as a CMZ and migration did not occur, and 4 sites were not recognized as a CMZ and migration did not occur. Additionally of the 14 sites that experienced migration only one avulsed and the other 13 migrated due to bank erosion. The authors of this paper propose four possible reasons as to why bank erosion is a more common process than avulsion among study sites. Reason one is that landowners may preferentially avoid avulsion-prone reaches due to easily identifiable risks. Reason two is that the historical removal of large wood may have increased channel incision and disconnected side channels and low-lying floodplains. Reason three, a reduction in sediment supply increased relative incision which again would disconnect side channels and low-lying floodplains. Reason four, it’s possible the authors methods of identifying avulsion prone reaches may have overestimated the number of avulsion-prone reaches.

Several conclusions could be drawn from this estimate. Channel migration occurs most commonly at the outer edges of meander bends and along unconfined channels. Additionally, bank erosion was the most common migration process affecting the sites in the dataset.

Relevant Information: Bank erosion appears to be the most common channel migration processes that occurs at recognized CMZ sites within the Skagit River Basin, avulsion is much less common. There are several geomorphic factors that may have led to this observed condition. 1) riparian logging practices that historically removed old growth trees along channel banks decreased the overall rooting depth of floodplain vegetation and increased the likelihood for undercutting of banks. 2) historic removal of log jams disabled their ability to increase the upstream water surface elevation during floods and thus disconnected side channels and low-lying floodplains. Lastly, a decrease in sediment supply could have increase relative incision of the bed and further disconnected side channels and low-lying floodplains.

This is relevant to GE-04 as the lack of CMZs that experienced avulsion provides evidence that the Skagit River system is being impacted by the historic removal of log jams, harvest of trees from the riparian zone, and a decrease in sediment supply.

Seixas et al. 2020

Reference	Seixas, G. B., C. N. Veldhuisen, and M. Olis. 2020. Wood controls on pool spacing, step characteristics and sediment storage in headwater streams of the northwestern Cascade Mountains. Geomorphology 348:106898.									
Source Information	***Type***	Report	***Status***	Final	***Quantitative Data***	Yes	***Spatial Data***	Yes		
Topics and Keywords	***Geomorphology:*** Large wood, Aquatic habitat and landforms.									
Species and Life Stages	None.									
Reaches and Spatial extent	Headwater streams in Skagit River watershed.									

Summary: This report investigates the relationships between wood, pools, steps, and sediment storage characteristics in northwest Cascade headwater streams. The authors of this paper aim specifically to test three hypotheses.

1) Larger diameter classes of large wood are critical step-keying materials in headwater channels despite narrow channel widths.
2) Wood-keyed steps trap more sediment than clast- and root-keyed steps.
3) The negative relationship between LW frequency and the distance between pools observed elsewhere in large streams extends to headwater streams.

These hypotheses were investigated through a field analysis of 32 sites. These sites spanned a range of channel widths less than 4 meters, covered a range of gradients, were in unlogged and logged forests, and contained either sandstone or phyllite bedrock. Each site was studied across a reach length 30 to 50 times the active channel width. At each site a channel survey was completed which includes a longitudinal profile along with the width of the active channel every 10 meters. Additionally, a wood inventory was completed at every site and all pools exceeding 10 centimeters in height were documented.

The authors classified wood into categories of 2-5, 5-10, 10-20, 20-40, and 40-100 centimeters in diameter. The results of this study showed wood within the 40-100 centimeter (16-39 inches) diameter class has the greatest potential to form key pieces relative to the total piece count associated with step formation in that diameter class. Additionally, the authors note that wood smaller than 10 centimeters (4 inches) diameter plays a significant role in key-step formation within channels that are less than 2 meters (6.6 feet) wide but drops off sharply on wider channels. These findings show that wood in larger size classes are particularly effective at anchoring steps and are critical for step formation in small headwater channels. The observation that smaller wood in channels less than 2 meters wide play a more significant role in key-step formation than in wider channels shows that potential wood function depends on channel size even within a small range of 1- to 4-meter (3.3- to 13.1-feet) width channels.

This report found that wood-keyed steps are significantly more likely to trap sediment than clast- and root-keyed steps. The authors of this report suspect this effect is due to the geometry of most wood pieces having a much larger length compared to their diameter. This increases the likelihood of jamming in between channel banks which thus creates stable structures that accumulates sediment.

This report found that there is a significant correlation between large wood frequency and distance between pools, similar to what has been observed in larger streams. As the frequency of large wood increase the average distance between pools decreases. This emphasizes the importance of large wood in headwater streams to form pools.

Relevant Information: This report gives information on the importance of wood in forming pools, steps, and trapping sediment in small headwater stream in the Cascade region. This is relevant to the project as it provides insight on wood in small width side channels and tributaries. One particularly important finding from this report is that wood smaller than 10 centimeters (4 inches) in diameter plays a significant role in step-pool formation within channels that are less than 2 meters (6.6 ft) wide. This highlights that wood that may not be geomorphically important in the main stem of the Skagit could be geomorphically important in side channels and tributaries.

Smith et al. 2011

Reference	Smith, D., K. Ramsden, and S. Hinton. 2011. Reach level analysis for the middle Skagit River assessment. Report prepared by Skagit River System Cooperative for Skagit Watershed Council, Mount Vernon, Washington.									
Source Information	***Type***	Report	***Status***	Final	***Quantitative Data***	Yes	***Spatial Data***	Yes		
Topics and Keywords	***Geomorphology:*** Change, History, Floodplain, Side- and off-channel, floodplain connectivity, aquatic habitats and landforms, data gaps. ***Land Use and Cover:*** Land cover, Banks and shoreline. ***Fish and Habitat:*** Habitat, freshwater. ***Modeling Tools:*** Hydrologic.									
Species and Life Stages	Chinook, rearing, spawning.									
Reaches and Spatial extent	R8-11.									

Summary: This report identifies priority reaches within the Middle Skagit River, from Sedro-Wooley upstream to the confluence of the Sauk River. A conceptual model for rating reaches included geomorphic potential, existing habitat function, and floodplain impairment. Skagit Watershed Council contracted with Pacific Northwest National Laboratory (PNNL) to develop a three-dimensional hydrodynamic model covering all of the Middle Skagit study area except the Rockport reach. The model was developed with the Finite Volume Coastal Ocean Model (FV-COM) software to estimate water depth, velocity, and shear stress across the channel and floodplain for the 2-year, 5-year, and 25-year flow.

In order to estimate juvenile Chinook capacity for each reach, the surface area for banks and bars was estimated by measuring lengths from aerial photography. The measured length was multiplied by an average width which was based on field measurements. The area of remaining habitat types was measured in GIS. Then assumed fish capacity was calculated for each habitat type. The highest density of juvenile Chinook were found in natural backwater, natural bank, hydromodified backwater, and natural bars. The most fish were found in Skiyou, Ross Island, Savage, and Cockreham reaches (NPS R10-11, Smith Reach 1-4).

The geomorphic potential refers to potential of the channel within the reach to migrate across its floodplain and create or maintain abundant side-channel, off-channel, and complex mainstem edge habitats. The reaches with the least confinement, largest floodplain areas, and widest floodplain widths occur in the downstream end of the study area and include Skiyou, Ross Island, and Cockreham (NPS R11, Smith Reach 1-3). Baker and Aldon (NPS Reach 6 and 8) reaches had the least floodplain inundation and Rockport reach was not measured.

The Cockreham reach has the highest floodplain impairment based on forest conditions, followed by Skiyou, Cape Horn, Ross Island, and Savage. Aldon and Rockport rated the lowest.

The top three reaches for geomorphic potential, Skiyou, Ross Island, and Cockreham were rated high for both restoration and protection actions. Skiyou was rated “Med/High” for protection because current habitat function was rated as medium, and Ross Island was rated “Med/High” for

restoration because floodplain impairment was rated as medium. Savage was also rated "Med/High" for protection because even though it was rated medium for geomorphic function it was rated high for current habitat function.

The report recommends additional modeling, vegetation, habitat, and floodplain impairment data be collected. For specific sites additional data may be useful for understanding project feasibility, field check for existing habitat features, hydrodynamic modeling for individual hydromodifications, photo survey to identify historic channels and migration, and fish modeling of potential new habitat.

Relevant Information The reaches in this study (Smith) roughly match the NPS reaches as follows: NPS R8 (Smith Reach 7,8, and 9), NPS R9 (Smith Reach 5&6), NPS R10 (Smith Reach 3&4), NPS R11 (Smith Reach 1, 2, and 3). The report provides a conceptual model for geomorphic potential, existing habitat function, and floodplain impairment. This can be used to characterize the reaches from Rockport to Sedro Wooley.

Todd et al. 2009

Reference	Todd, S., O. Odum, M. Koschak, and A. McBride. 2009. Quality assurance and methodology for mapping marine shoreline geomorphology. Report by Skagit System Cooperative, La Conner, Washington.									
Source Information	***Type***	Report	***Status***	Final	***Quantitative Data***	No	***Spatial Data***	Yes		
Topics and Keywords	***Geomorphology:*** Estuarine habitats and landforms. ***Land Use and Cover:*** Land cover, Banks and shoreline.									
Species and Life Stages	None.									
Reaches and Spatial extent	Skagit Bay.									

Summary: This report describes the methodology implemented for mapping marine shoreline geomorphology in the Puget Sound region. This work was completed by the Salmon and Steelhead Habitat Inventory and Assessment Program. The first draft of this work used a dataset that composed of DNR (Washington Department of Natural Resources) Geology, 10-meter DEMs, ecology drift cells, and DNR hydrography data. The updated quality assurance version of this work relied on a systematic evaluation of recent aerial photos. The intent of this work was to capture a "present day" shoreline geomorphology dataset that could be compared with a "historic" shoreline geomorphology dataset being developed by Puget Sound Nearshore Ecosystem Restoration Program. This could be used to help identify potential nearshore restoration sites.

Relevant Information This dataset maps "present day" shoreline geomorphology at a high level of precision and accuracy within the Puget Sound region, including the Skagit Bay. This dataset could be helpful to inform potential geomorphic changes that have occurred along the Skagit Bay.

USACE 2008

Reference	USACE (U.S. Army Corps of Engineers). 2008. Skagit River flood damage reduction feasibility study, Skagit River basin, sediment budget and fluvial geomorphology. DRAFT. CENWS-ED-TB-HE 6/11/2008. Report prepared by USACE, Seattle District, Washington.									
Source Information	***Type***	Report	***Status***	Draft	***Quantitative Data***	Yes	***Spatial Data***	Yes		
Topics and Keywords	***Geomorphology:*** change, history, climate change, substrate and sediment, sediment transport and supply, data gaps.									
Species and Life Stages	None.									
Reaches and Spatial extent	Reach 1-14, Skagit Bay.									

Summary: This report includes a description of the Skagit River's sediment budget and fluvial geomorphology. The Skagit River channel is fairly stable with the most migration occurring the middle reach. Channel alignment in the upper basin is predominately controlled by geology and the lower river and estuary are primarily controlled by levees and bank protection, The middle reach has intermittent bank protection and the active migration zone is up to 2 miles wide.

The average annual sediment yield at Mount Vernon is in the range of 0.6 to 2.8 mcy (0.5 to 2.1 Tg). The major sources of sediment are the Cascade and Sauk rivers. Approximately half the basin does not contribute sediment because the sediment is stored in reservoirs. Storms with daily discharges greater than 50,000 cfs are a major factor in sediment production. These large discharge events can cause upper basin land disturbances and produce an estimated 21 percent of the average annual sediment yield.

Upstream of PRM 17, the Skagit River bed is composed of gravel, cobble, and boulders. Downstream of PRM 17, the riverbed and nearshore delta bottom are mainly sand. The 2.8 mcy (2.1 Tg) annual suspended sediment (SSC) yield at Mount Vernon is composed of approximately 50 percent sand, 50 percent silt and clay are transported through the lower river and into Skagit Bay.

Since 1931, there has been a long-term trend of sediment deposition in the channels downstream of Sedro-Wooley. There has been an overall averaged bed elevation increase of approximately 2.25 ft since 1931. The bed upstream of PRM 15.8 appears to be rising slightly faster than the overall average. Sand deposition has also been occurring in the estuary and on the delta.

Relevant Information

The study determines an average annual sediment yield at Mount Vernon of 0.5 to 2.1 Tg. Subsequent studies, such as Curran et al. 2016, have reported higher annual sediment yields (2.5 Tg). There has been a long-term trend of sediment deposition in the channels downstream of Sedro-Wooley. If there was more sediment being transported in the Skagit River, the amount of sediment deposition could increase more in the future.

References

Bandaragoda, C., C. Frans, E. Istanbulluoglu, C. Raymond, and L Wasserman. 2015. Hydrologic Impacts of Climate Change in the Skagit River Basin. Final Report Prepared for Skagit Climate Science Consortium. Available at: http://www.skagitclimatescience.org/wp-content/uploads/2016/04/UW-SC2_SkagitDHSVM-glacierModel_FinalReport_2015.pdf

Bandaragoda, C., S. Lee, E. Istanbulluoglu, and A. Hamlet. 2020. Hydrology, stream temperature, and sediment impacts of climate change in the Sauk River basin. Prepared by Hydroshare for Sauk-Suiattle Indian Tribe and Skagit Climate Science Consortium. Abstract available at: http://www.hydroshare.org/resource/e5ad2935979647d6af5f1a9f6bdecdea

Beamer, E., J. Shannahan, K. Wolf, E. Lowery, and D. Pflug. 2010. Freshwater habitat rearing preferences for stream type juvenile Chinook salmon (Oncorhynchus tshawytscha) and steelhead (O. mykiss) in the Skagit River basin: phase 1 study report. Report prepared for Skagit River System Cooperative, La Conner, Washington.

Beechie, T. J., O. Stefankiv, B. Timpane-Padgham, J. E. Hall, G. R. Pess, M. Rowse, M. Liermann, K. Fresh, and M. J. Ford. 2017. Monitoring Salmon Habitat status and trends in Puget Sound: development of sample designs, monitoring metrics, and sampling protocols for large river, floodplain, delta, and nearshore environments. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-137, Seattle.

Collins, B. D., D. R. Montgomery, and A. Haas. 2002. Historical changes in the distribution and functions of large wood in Puget Lowland Rivers. Can. J. Fish Aquatic Science 59:66-76.

Curran, C. A., E. E. Grossman, M. C., Mastin, and R. L. Huffman. 2016. Sediment load and distribution in the lower Skagit River, Skagit County, Washington. U.S. Geological Survey Scientific Investigations Report 2016–5106. Available at: http://dx.doi.org/10.3133/sir20165106.

Grossman, E. E., A. W. Stevens, P. Dartnell, D. George, and D. Finlayson. 2020. Sediment export and impacts associated with river delta channelization compound estuary vulnerability to sea-level rise, Skagit River Delta, Washington, USA. Marine Geology 430:106336.

Hartson, R. and J.P. Shannahan. 2015. Inventory and Assessment of Hydromodified Bank Structures in the Skagit River Basin Chinook Bearing Streams. Final report submitted to Northwest Indian Fisheries Commission and Environmental Protection Agency. Prepared for The Upper Skagit Indian Tribe Natural Resources Division.

Hood, W. G. 2007a. Large woody debris influences vegetation zonation in an oligohaline tidal marsh. Estuaries and Coasts, 30(3):441-450.

Hood, W. G. 2007b. Scaling tidal channel geometry with marsh island area: a tool for habitat restoration, linked to channel formation process. Water Resources Research 43: W03409.

Hood, W. G. 2010. Tidal channel meander formation by depositional rather than erosional processes: examples from the prograding Skagit River delta (Washington, USA). Earth Surface Processes and Landforms 25(3):319-330.

Hood, W. G. 2015. Geographic variation in Puget Sound tidal channel planform geometry. Geomorphology 230:98-108.

Hood, W. G. No date. Distribution of large woody debris in river delta tidal marshes: implications for habitat restoration.

Jaeger, K.L., C. A. Curran, S. W. Anderson, S. T. Morris, P.W. Moran, and K. A. Reams. 2017. Suspended sediment, turbidity, and stream water temperature in the Sauk River Basin, Washington, water years 2012–16. U.S. Geological Survey Scientific Investigations Report 2017–5113. Available at https://doi.org/10.3133/sir20175113.

Lee, S-Y, A.F. Hamlet, and E.E. Grossman. 2016. Impacts of Climate Change on Regulated Streamflow, Hydrologic Extremes, Hydropower Production, and Sediment Discharge in the Skagit River Basin. Northwest Science 90(1), 23-43.

Nichols, R. A., and G. L. Ketcheson. 2013. A two-decade watershed approach to stream restoration log jam design and stream recovery monitoring: Finney Creek, Washington. Journal of the American Water Resources Association 49(6):1367-1384.

NSD (Natural Systems Design). 2017. Skagit River large woody debris assessment: connecting LWD to the 2005 Skagit Chinook recovery plan. Report prepared for Skagit Watershed Council, Mount Vernon, Washington.

Riedel, J., S. Sarrantonio, K. Ladig, and M. Larrabee. 2020. DRAFT Skagit River geomorphology inventory report: part I – Gorge Dam to Sauk River. Report prepared by the National Park Service for Seattle City Light.

Riedel, J., S. Sarrantonio, K. Ladig, and M. Larrabee. TBD. DRAFT Skagit River geomorphology inventory report: part 2 – Sauk River to Hamilton. Report prepared by the National Park Service for Seattle City Light.

Rothleutner, A. D. 2017. Sediment budget of the middle Skagit River, Washington 1937-2015 reveals decadal variations in sediment export and storage. Master's thesis. Western Washington University, Bellingham.

Seixas, G. B., and C. N. Veldhuisen. 2019. Forest practices and regulatory channel migration zones in the Skagit River basin since the forests and fish report. Report prepared for Skagit River System Cooperative, La Conner, Washington.

Seixas, G. B., C. N. Veldhuisen, and M. Olis. 2019. Wood controls on pool spacing, step characteristics and sediment storage in headwater streams of the northwestern Cascade Mountains. Geomorphology 348:106898.

Smith, D., K. Ramsden, and S. Hinton. 2011. Reach level analysis for the middle Skagit River assessment. Report prepared by Skagit River System Cooperative for Skagit Watershed Council, Mount Vernon, Washington.

Todd, S., O. Odum, M. Koschak, and A. McBride. 2009. Quality assurance and methodology for mapping marine shoreline geomorphology. Report by Skagit System Cooperative, La Conner, Washington.

USACE (U.S. Army Corps of Engineers). 2008. Skagit River flood damage reduction feasibility study, Skagit River basin, sediment budget and fluvial geomorphology. CENWS-ED-TB-HE 6/11/2008. Report prepared by USACE, Seattle District, Washington.

SKAGIT RIVER GEOMORPHOLOGY BETWEEN GORGE DAM AND THE SAUK RIVER STUDY REPORT

ATTACHMENT B

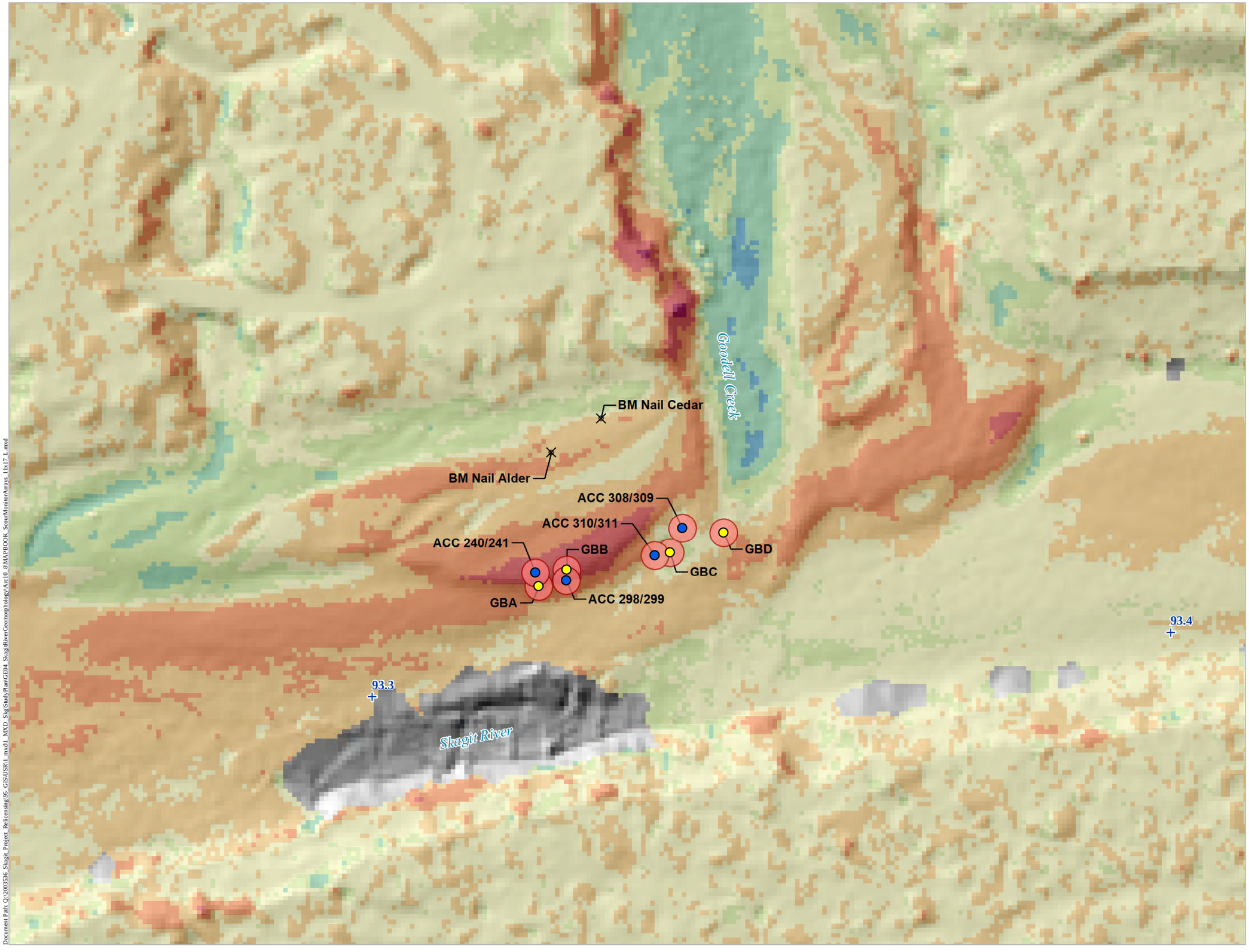
SCOUR MONITOR INSTALLATION MAPBOOK

SKAGIT RIVER GEOMORPHOLOGY BETWEEN GORGE DAM AND THE SAUK RIVER STUDY REPORT

ATTACHMENT B

SCOUR MONITOR INSTALLATION MAPBOOK

GE-04 GEOMORPHOLOGY STUDY
SCOUR MONITORING SITE ID: GOODELL CK FAN



+ Project River Mile (PRM)

Scour Monitors

- Benchmark
- Accelerometer
- Golf Ball
- Small Bead
- Past Accelerometer (2019/2020)

Observed Scour Depth

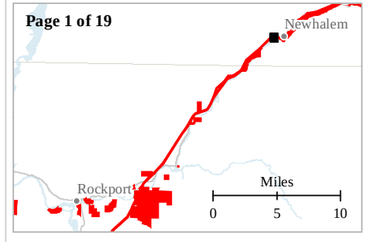
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- 0.4 - 0.8
- 0.9 - 1.5
- 1.6 - 2.5

LiDAR Compare, ft (2017-2022)

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- -9.9 - -5
- -4.9 - -2
- -1.9 - -0.5
- -0.4 - 0.5
- 0.6 - 2
- 2.1 - 5
- 5.1 - 10
- 10+

0 50 100 Feet

N



Seattle City Light

SKAGIT RIVER HYDROELECTRIC PROJECT (FERC NO. 553)

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Data Source: Northwest Hydraulic Consultants (2022)

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GE-04 GEOMORPHOLOGY STUDY
SCOUR MONITORING SITE ID: RC93.0

20

93

Skagit River

ACC 332/333

GBD

GBC

ACC 334/335

ACC 328/329

ACC 330/331

BM Alder

GBB

GBA

92.9

+ Project River Mile (PRM)

Scour Monitors

- Benchmark
- Accelerometer
- Golf Ball
- Small Bead
- Past Accelerometer (2019/2020)

Observed Scour Depth

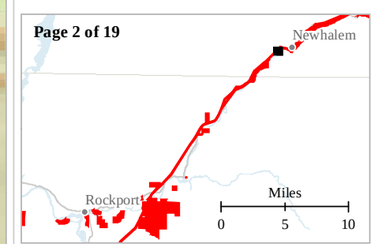
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- 1.6 - 2.5

LiDAR Compare, ft (2017-2022)

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- -9.9 - -5
- -4.9 - -2
- -1.9 - -0.5
- -0.4 - 0.5
- 0.6 - 2
- 2.1 - 5
- 5.1 - 10
- 10+

0 50 100 Feet

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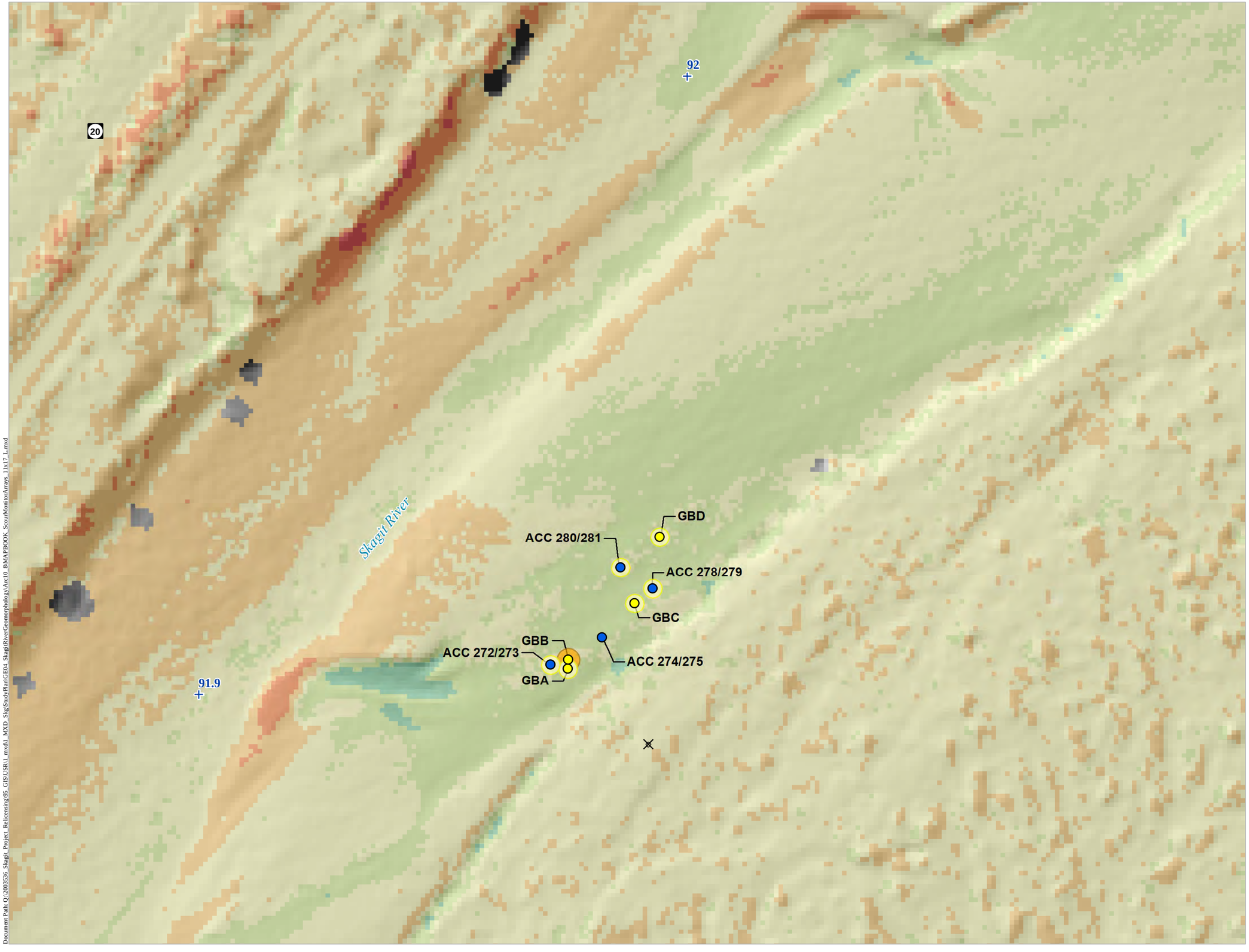


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GE-04 GEOMORPHOLOGY STUDY
SCOUR MONITORING SITE ID: ABSS1

+ Project River Mile (PRM)

Scour Monitors

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- Golf Ball
- Small Bead
- Past Accelerometer (2019/2020)

Observed Scour Depth

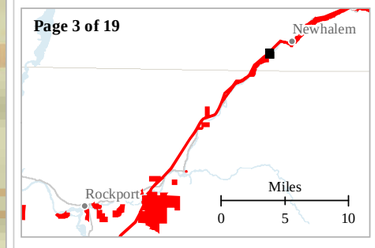
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LiDAR Compare, ft (2017-2022)

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- -9.9 - -5
- -4.9 - -2
- -1.9 - -0.5
- -0.4 - 0.5
- 0.6 - 2
- 2.1 - 5
- 5.1 - 10
- 10+

0 50 100 Feet

N



Seattle City Light

SKAGIT RIVER HYDROELECTRIC PROJECT (FERC NO. 553)

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GE-04 GEOMORPHOLOGY STUDY
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ACC 246/247
ACC 136/137
ACC 130/131
GBA
GBC
GBD
ACC 242/243
GBB
ACC 248/249
ACC 132/133
ACC 244/245
91.2
91.1
Skagit River

+ Project River Mile (PRM)

Scour Monitors

- Benchmark
- Accelerometer
- Golf Ball
- Small Bead
- Past Accelerometer (2019/2020)

Observed Scour Depth

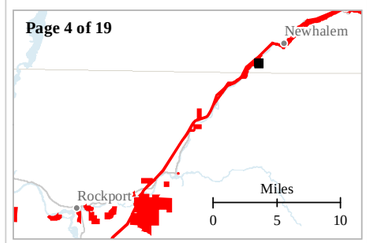
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- 1.6 - 2.5

LiDAR Compare, ft (2017-2022)

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- -9.9 - -5
- -4.9 - -2
- -1.9 - -0.5
- -0.4 - 0.5
- 0.6 - 2
- 2.1 - 5
- 5.1 - 10
- 10+

0 50 100 Feet

N

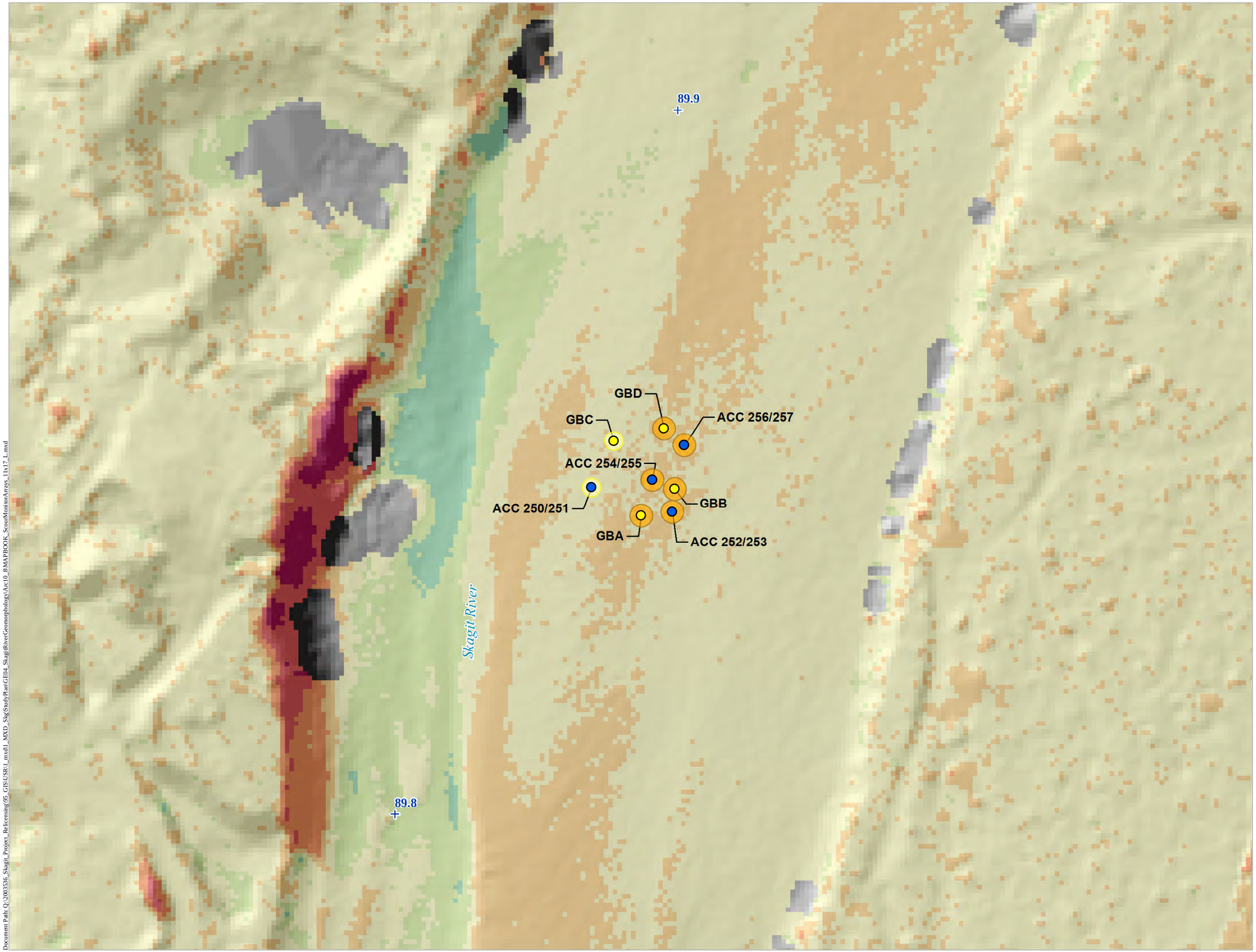


Seattle City Light

SKAGIT RIVER HYDROELECTRIC PROJECT (FERC NO. 553)

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GE-04 GEOMORPHOLOGY STUDY
SCOUR MONITORING SITE ID: RC89.8

+ Project River Mile (PRM)

Scour Monitors

- Benchmark
- Accelerometer
- Golf Ball
- Small Bead
- Past Accelerometer (2019/2020)

Observed Scour Depth

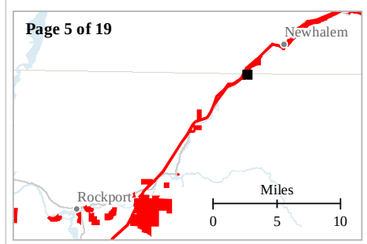
- 0.0 or NA
- 0.4 - 0.8
- 0.9 - 1.5
- 1.6 - 2.5

LiDAR Compare, ft (2017-2022)

- -10+
- -9.9 - -5
- -4.9 - -2
- -1.9 - -0.5
- -0.4 - 0.5
- 0.6 - 2
- 2.1 - 5
- 5.1 - 10
- 10+

0 50 100 Feet

N



Seattle City Light

SKAGIT RIVER HYDROELECTRIC PROJECT (FERC NO. 553)

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Data Source: Northwest Hydraulic Consultants (2022)

Document Path: Q:\2003536_Skagit_Project_Relicensing\05_GIS\USR\1_mxd\1_MXD_SkgStudyPlanGE04_SkagitRiverGeomorphology\Arc10_8\MAPBOOK_ScourMonitorArrays_11x17_L.mxd

GE-04 GEOMORPHOLOGY STUDY
SCOUR MONITORING SITE ID: ABSS3 DOWNSTREAM CLUSTER & ABSS3 UPSTREAM CLUSTER

20

89.1

Skagit River

ACC 306/307
GBD
ACC 304/305
GBC
ACC 172/118

GBB
ACC 168/169
ACC 300/301
ACC 302/303
SB1
ACC 166/167
GBA
SB2

+ Project River Mile (PRM)

Scour Monitors

- Benchmark
- Accelerometer
- Golf Ball
- Small Bead
- Past Accelerometer (2019/2020)

Observed Scour Depth

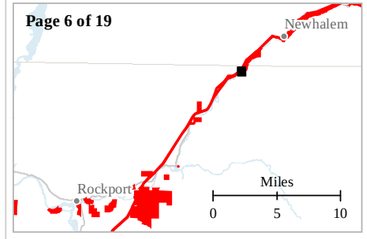
- 0.0 or NA
- 0.4 - 0.8
- 0.9 - 1.5
- 1.6 - 2.5

LiDAR Compare, ft (2017-2022)

- -10+
- -9.9 - -5
- -4.9 - -2
- -1.9 - -0.5
- -0.4 - 0.5
- 0.6 - 2
- 2.1 - 5
- 5.1 - 10
- 10+

0 50 100 Feet

N

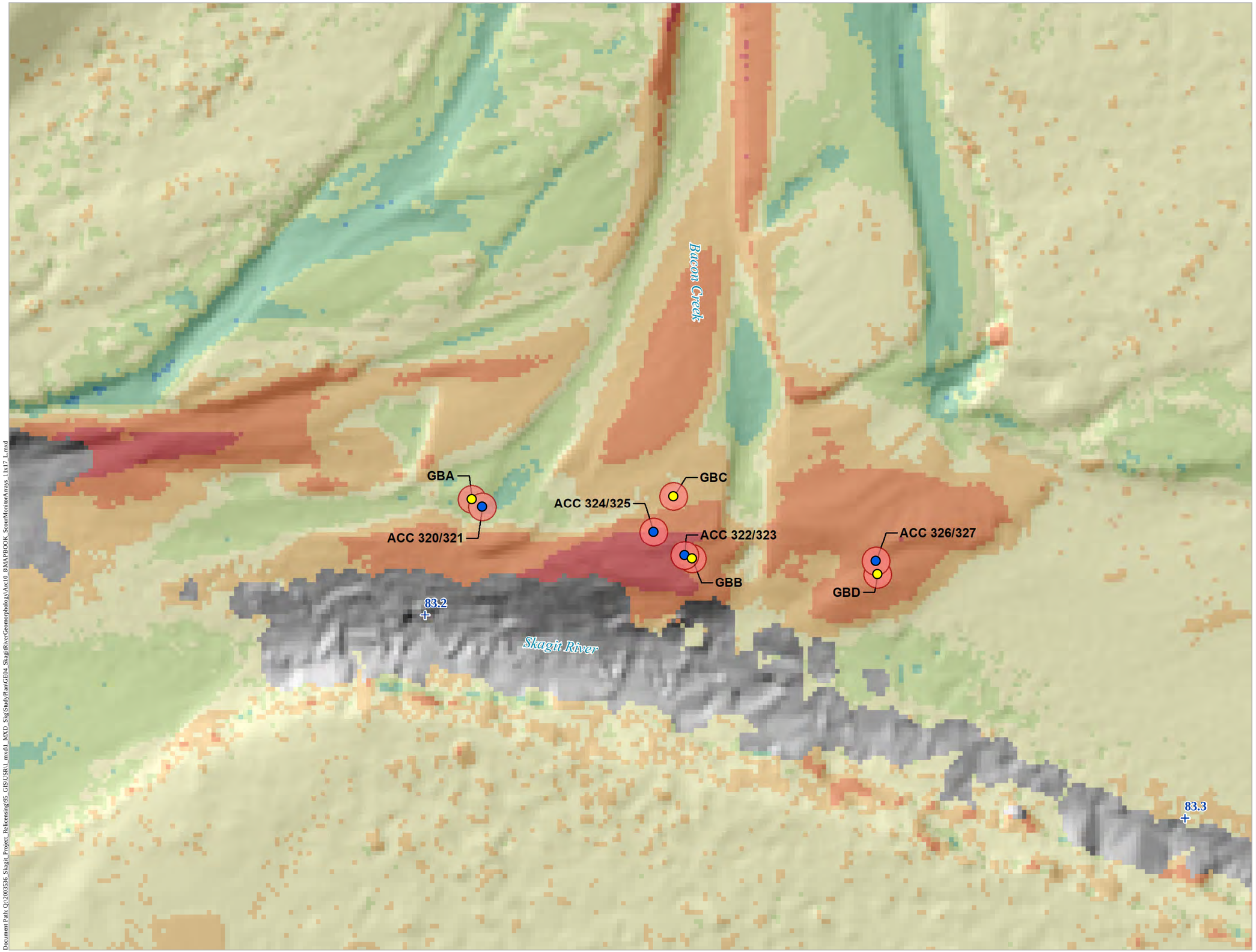


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GE-04 GEOMORPHOLOGY STUDY
SCOUR MONITORING SITE ID: BACON CREEK FAN

+ Project River Mile (PRM)

Scour Monitors

- Benchmark
- Accelerometer
- Golf Ball
- Small Bead
- Past Accelerometer (2019/2020)

Observed Scour Depth

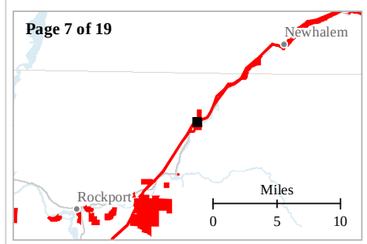
- 0.0 or NA
- 0.4 - 0.8
- 0.9 - 1.5
- 1.6 - 2.5

LiDAR Compare, ft (2017-2022)

- -10+
- -9.9 - -5
- -4.9 - -2
- -1.9 - -0.5
- -0.4 - 0.5
- 0.6 - 2
- 2.1 - 5
- 5.1 - 10
- 10+

0 50 100 Feet

N

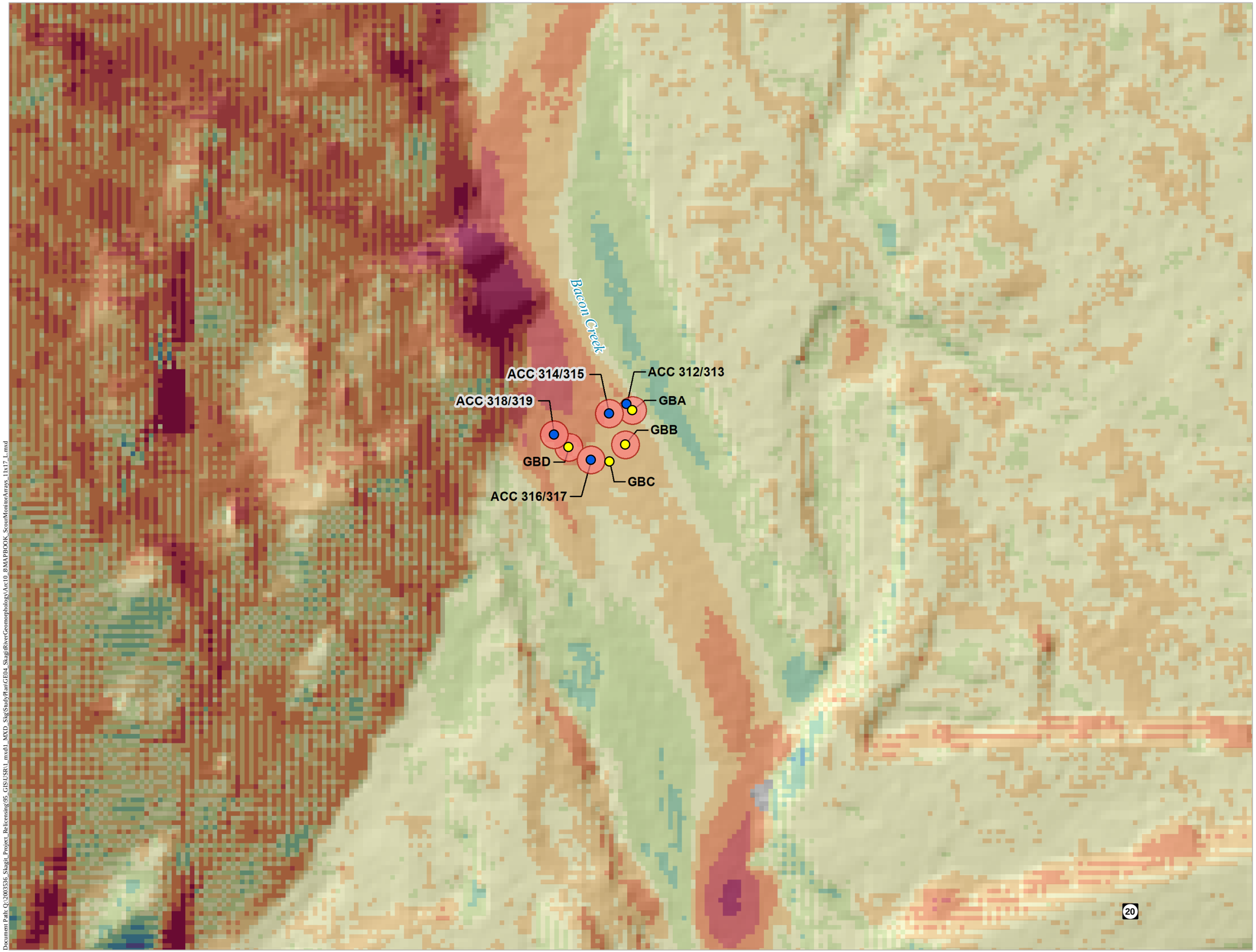


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GE-04 GEOMORPHOLOGY STUDY
SCOUR MONITORING SITE ID: RC BACON CK

+ Project River Mile (PRM)

Scour Monitors

- Benchmark
- Accelerometer
- Golf Ball
- Small Bead
- Past Accelerometer (2019/2020)

Observed Scour Depth

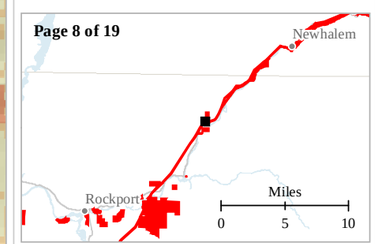
- 0.0 or NA
- 0.4 - 0.8
- 0.9 - 1.5
- 1.6 - 2.5

LiDAR Compare, ft (2017-2022)

- -10+
- -9.9 - -5
- -4.9 - -2
- -1.9 - -0.5
- -0.4 - 0.5
- 0.6 - 2
- 2.1 - 5
- 5.1 - 10
- 10+

0 50 100 Feet

N

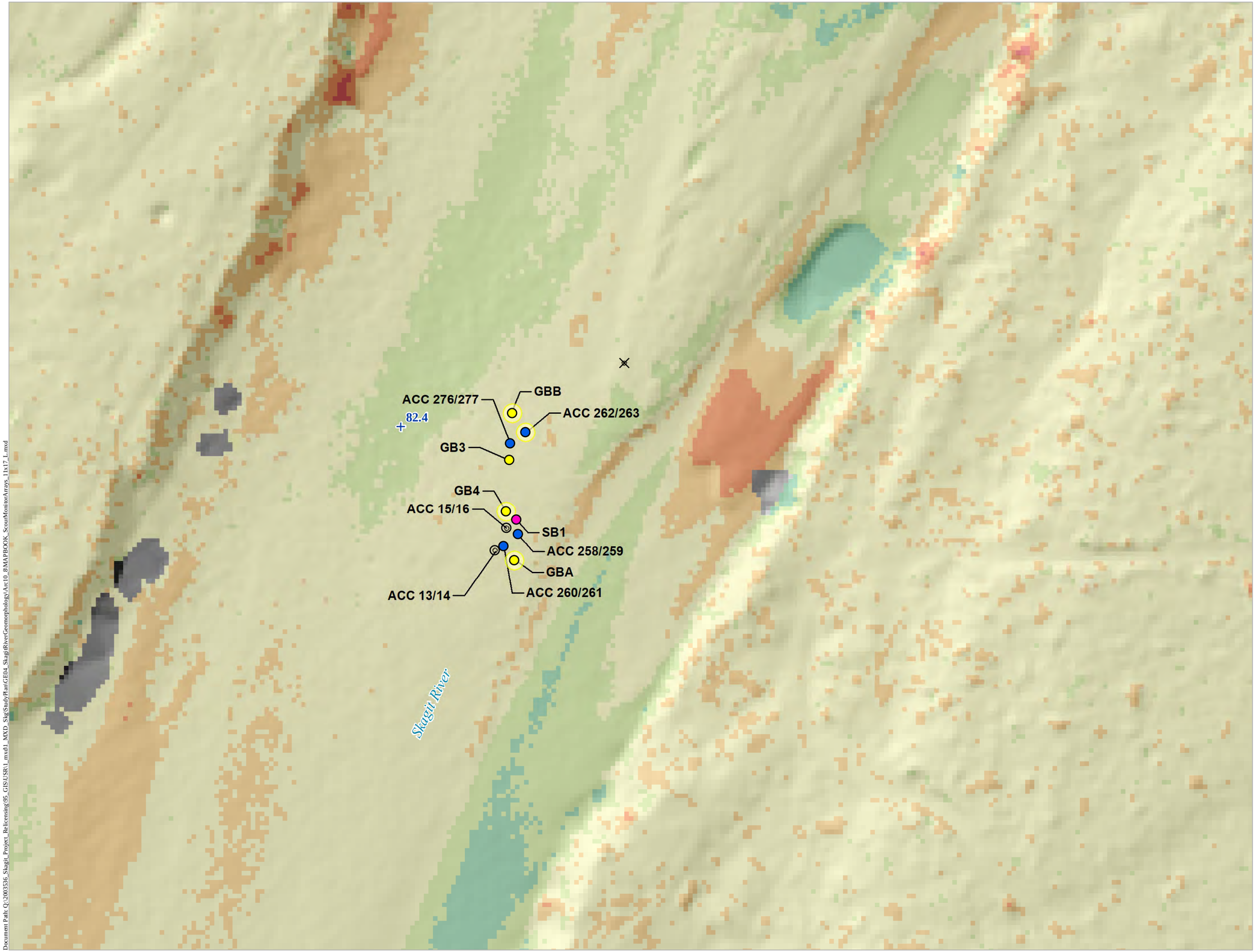


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GE-04 GEOMORPHOLOGY STUDY
SCOUR MONITORING SITE ID: SITE2 (MOSES BAR)

Project River Mile (PRM)

Scour Monitors

- Benchmark
- Accelerometer
- Golf Ball
- Small Bead
- Past Accelerometer (2019/2020)

Observed Scour Depth

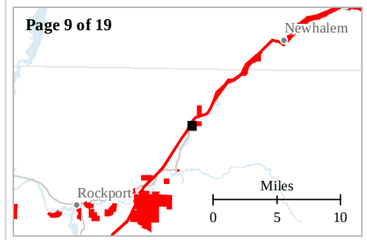
- 0.0 or NA
- 0.4 - 0.8
- 0.9 - 1.5
- 1.6 - 2.5

LiDAR Compare, ft (2017-2022)

- -10+
- -9.9 - -5
- -4.9 - -2
- -1.9 - -0.5
- -0.4 - 0.5
- 0.6 - 2
- 2.1 - 5
- 5.1 - 10
- 10+

0 50 100 Feet

N



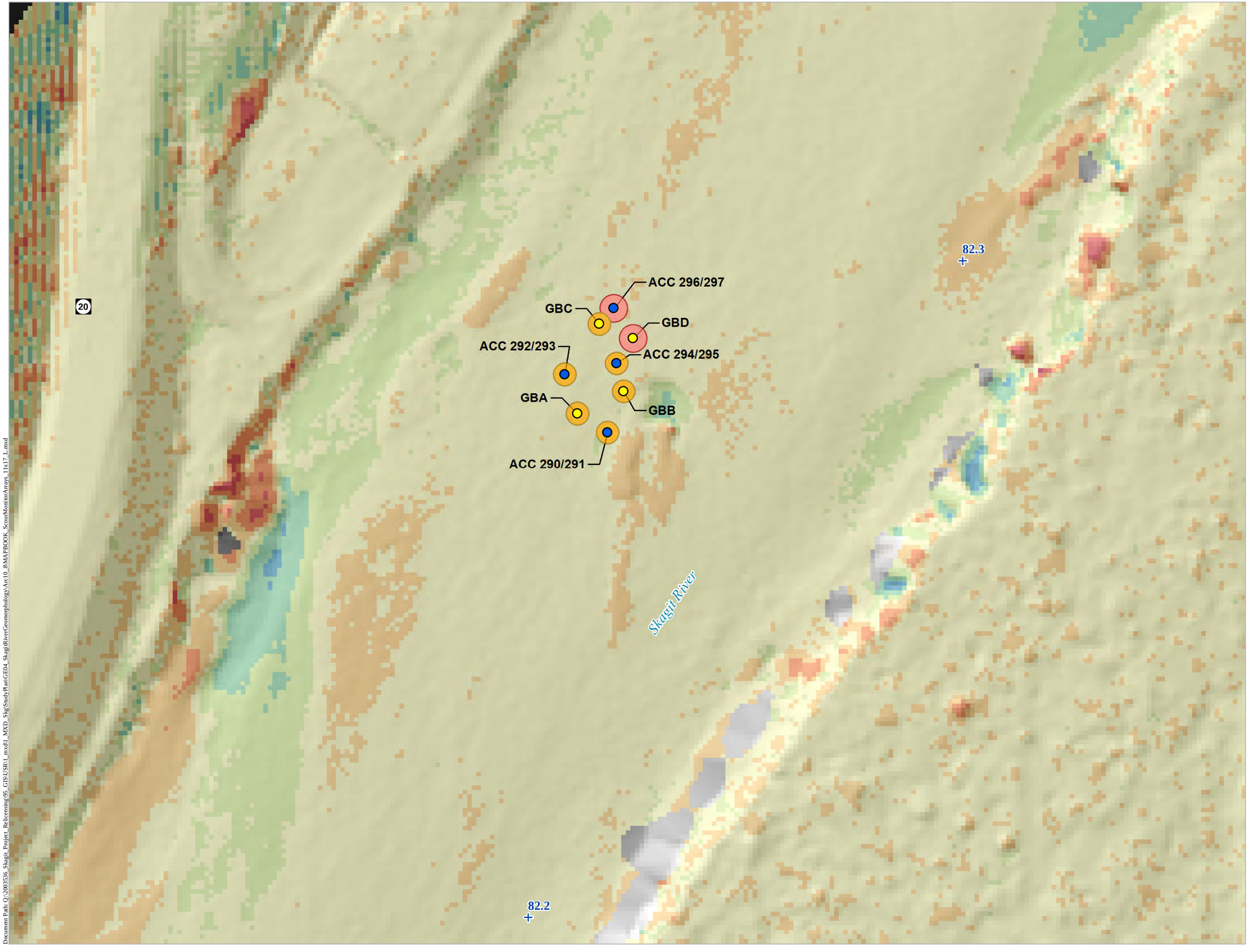
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GE-04 GEOMORPHOLOGY STUDY
SCOUR MONITORING SITE ID: RC82.3



+ Project River Mile (PRM)

Scour Monitors

- Benchmark
- Accelerometer
- Golf Ball
- Small Bead
- Past Accelerometer (2019/2020)

Observed Scour Depth

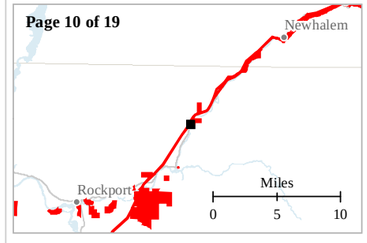
- 0.0 or NA
- 0.4 - 0.8
- 0.9 - 1.5
- 1.6 - 2.5

LiDAR Compare, ft (2017-2022)

- -10+
- -9.9 - -5
- -4.9 - -2
- -1.9 - -0.5
- -0.4 - 0.5
- 0.6 - 2
- 2.1 - 5
- 5.1 - 10
- 10+

0 50 100 Feet

N



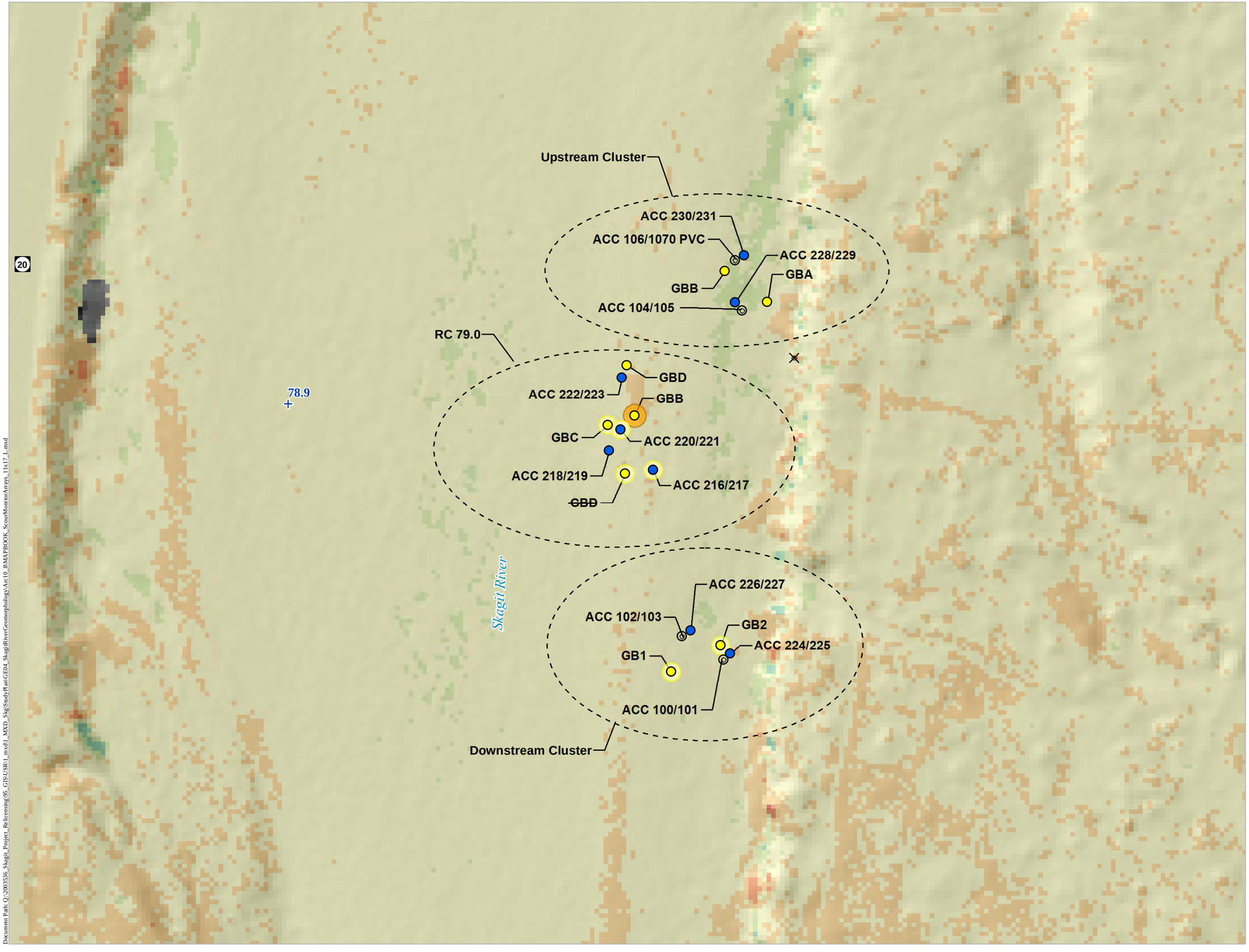
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GE-04 GEOMORPHOLOGY STUDY
SCOUR MONITORING SITE ID: SITE 1 DOWNSTREAM CLUSTER, SITE 1 UPSTREAM CLUSTER & RC79.0



- Project River Mile (PRM)

Scour Monitors

- Benchmark
- Accelerometer
- Golf Ball
- Small Bead
- Past Accelerometer (2019/2020)

Observed Scour Depth

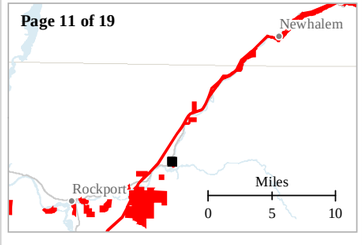
- 0.0 or NA
- 0.4 - 0.8
- 0.9 - 1.5
- 1.6 - 2.5

LiDAR Compare, ft (2017-2022)

- -10+
- -9.9 - -5
- -4.9 - -2
- -1.9 - -0.5
- -0.4 - 0.5
- 0.6 - 2
- 2.1 - 5
- 5.1 - 10
- 10+

0 50 100 Feet

N



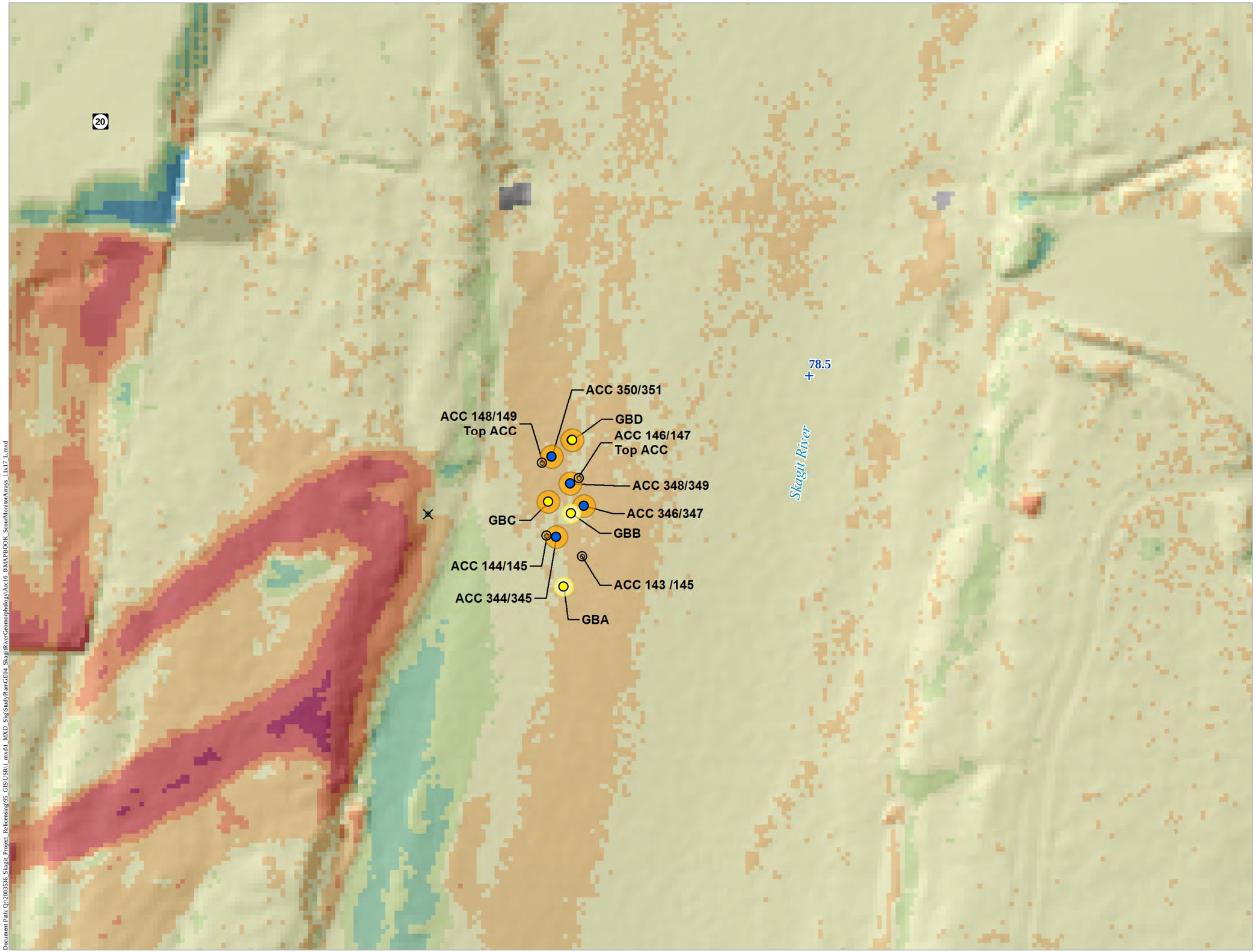
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GE-04 GEOMORPHOLOGY STUDY
SCOUR MONITORING SITE ID: BMM7



+ Project River Mile (PRM)

Scour Monitors

- Benchmark
- Accelerometer
- Golf Ball
- Small Bead
- Past Accelerometer (2019/2020)

Observed Scour Depth

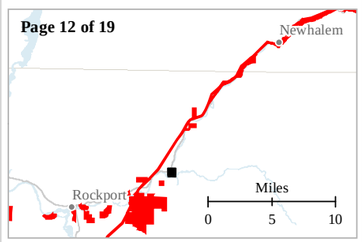
- 0.0 or NA
- 0.4 - 0.8
- 0.9 - 1.5
- 1.6 - 2.5

LiDAR Compare, ft (2017-2022)

- -10+
- -9.9 - -5
- -4.9 - -2
- -1.9 - -0.5
- -0.4 - 0.5
- 0.6 - 2
- 2.1 - 5
- 5.1 - 10
- 10+

0 50 100 Feet

N

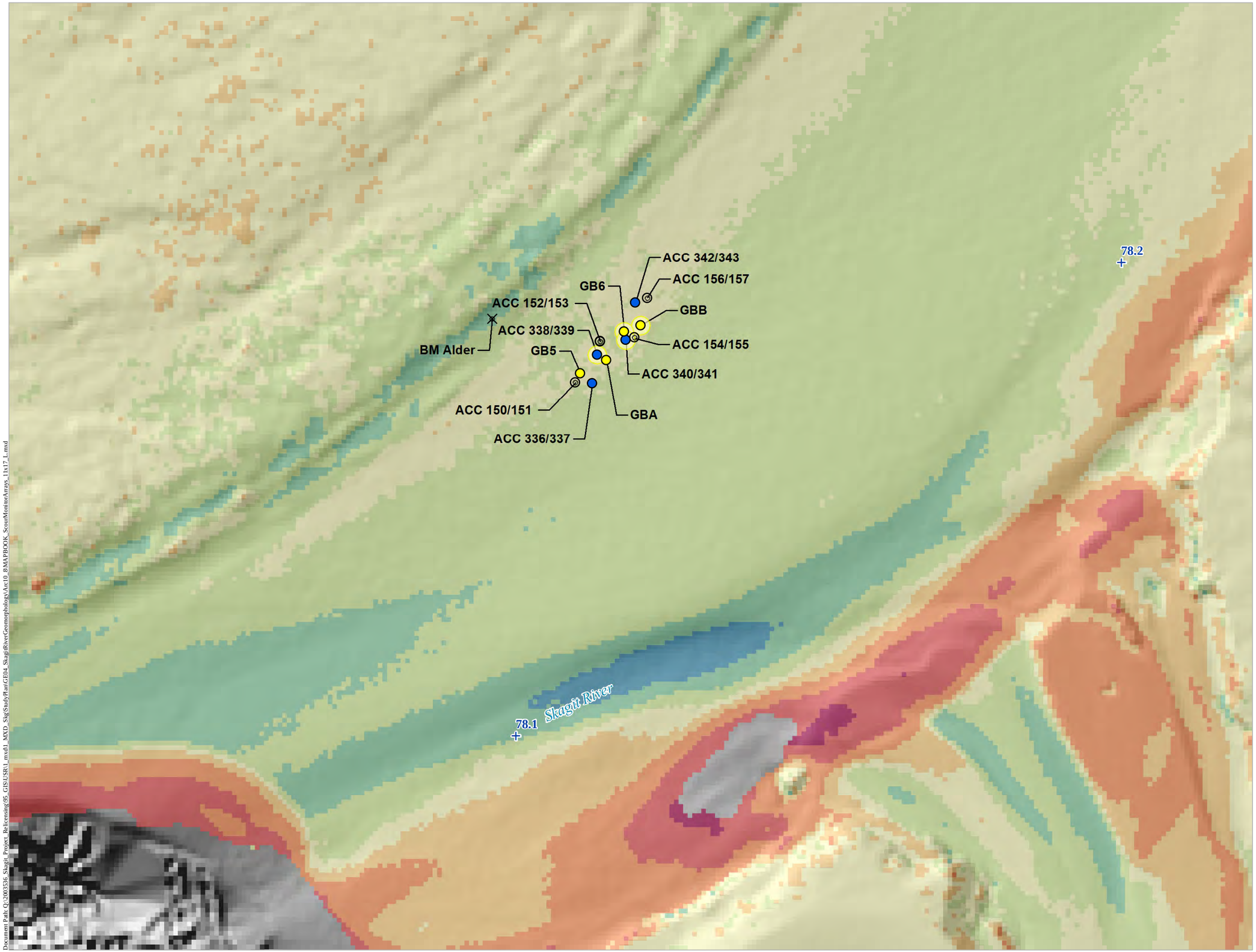


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SKAGIT RIVER HYDROELECTRIC PROJECT (FERC NO. 553)

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GE-04 GEOMORPHOLOGY STUDY
SCOUR MONITORING SITE ID: SITE3

+ Project River Mile (PRM)

Scour Monitors

- Benchmark
- Accelerometer
- Golf Ball
- Small Bead
- Past Accelerometer (2019/2020)

Observed Scour Depth

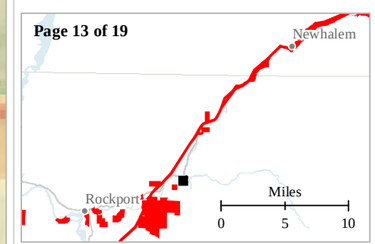
- 0.0 or NA
- 0.4 - 0.8
- 0.9 - 1.5
- 1.6 - 2.5

LiDAR Compare, ft (2017-2022)

- -10+
- -9.9 - -5
- -4.9 - -2
- -1.9 - -0.5
- -0.4 - 0.5
- 0.6 - 2
- 2.1 - 5
- 5.1 - 10
- 10+

0 50 100 Feet

N

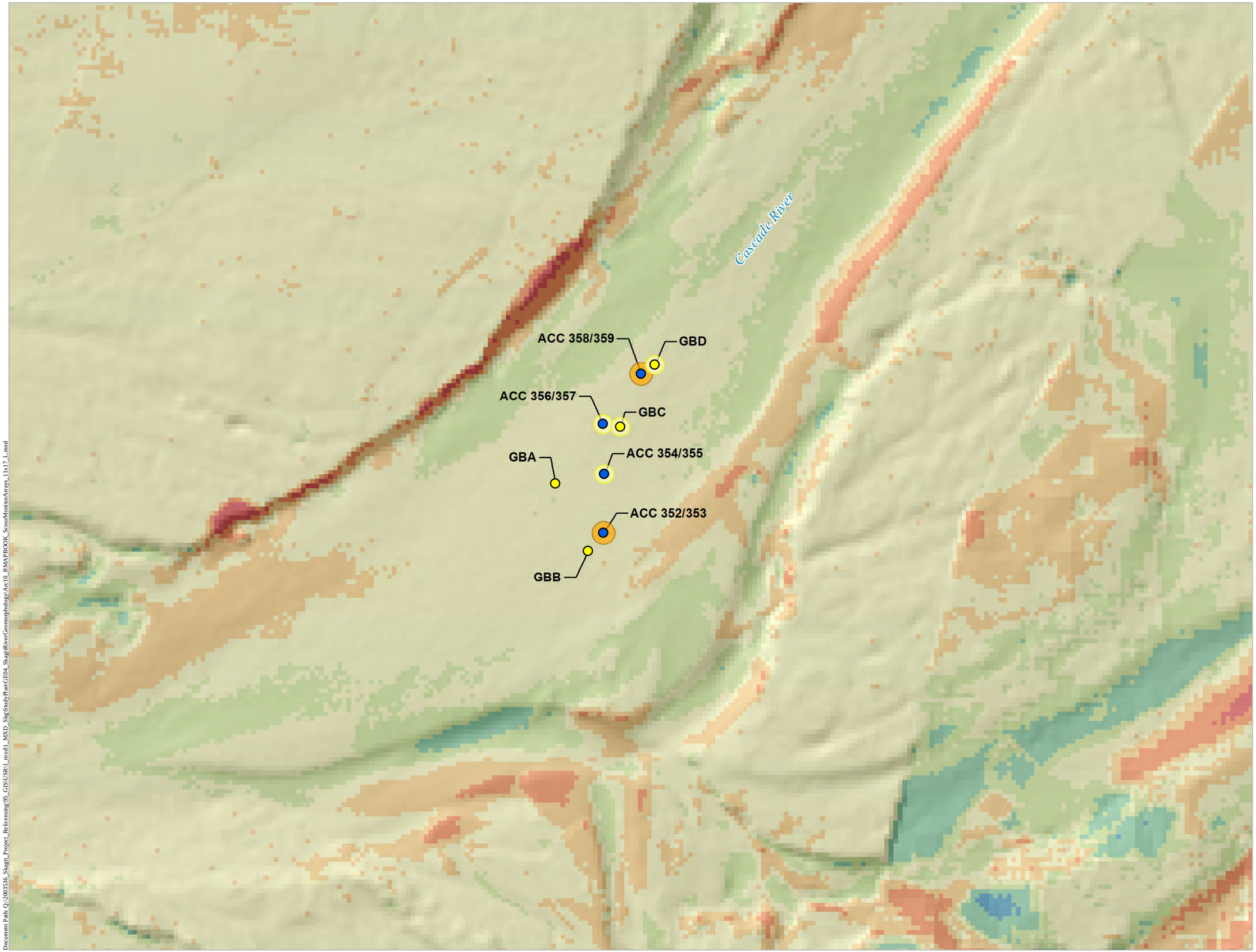


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GE-04 GEOMORPHOLOGY STUDY
SCOUR MONITORING SITE ID: RC CASCADE R.

+ Project River Mile (PRM)

Scour Monitors

- Benchmark
- Accelerometer
- Golf Ball
- Small Bead
- Past Accelerometer (2019/2020)

Observed Scour Depth

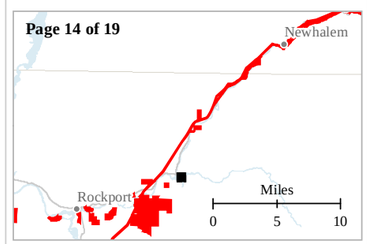
- 0.0 or NA
- 0.4 - 0.8
- 0.9 - 1.5
- 1.6 - 2.5

LiDAR Compare, ft (2017-2022)

- -10+
- -9.9 - -5
- -4.9 - -2
- -1.9 - -0.5
- -0.4 - 0.5
- 0.6 - 2
- 2.1 - 5
- 5.1 - 10
- 10+

0 50 100 Feet

N

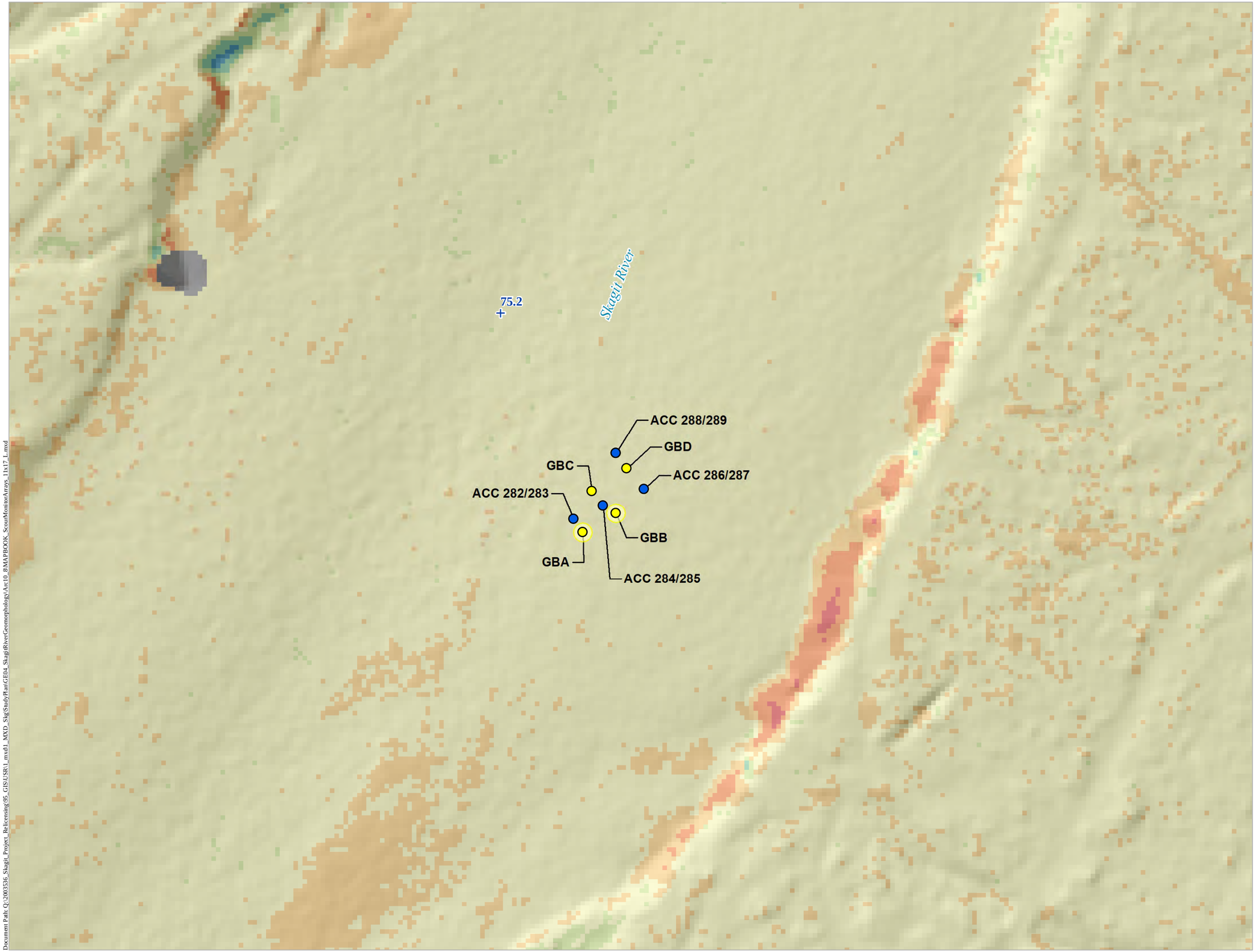


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GE-04 GEOMORPHOLOGY STUDY
SCOUR MONITORING SITE ID: RC75.2

+ Project River Mile (PRM)

Scour Monitors

- Benchmark
- Accelerometer
- Golf Ball
- Small Bead
- Past Accelerometer (2019/2020)

Observed Scour Depth

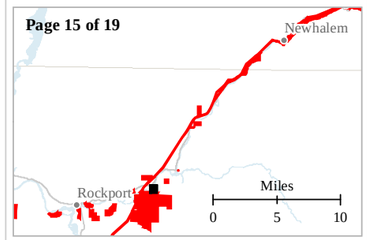
- 0.0 or NA
- 0.4 - 0.8
- 0.9 - 1.5
- 1.6 - 2.5

LiDAR Compare, ft (2017-2022)

- -10+
- -9.9 - -5
- -4.9 - -2
- -1.9 - -0.5
- -0.4 - 0.5
- 0.6 - 2
- 2.1 - 5
- 5.1 - 10
- 10+

0 50 100 Feet

N

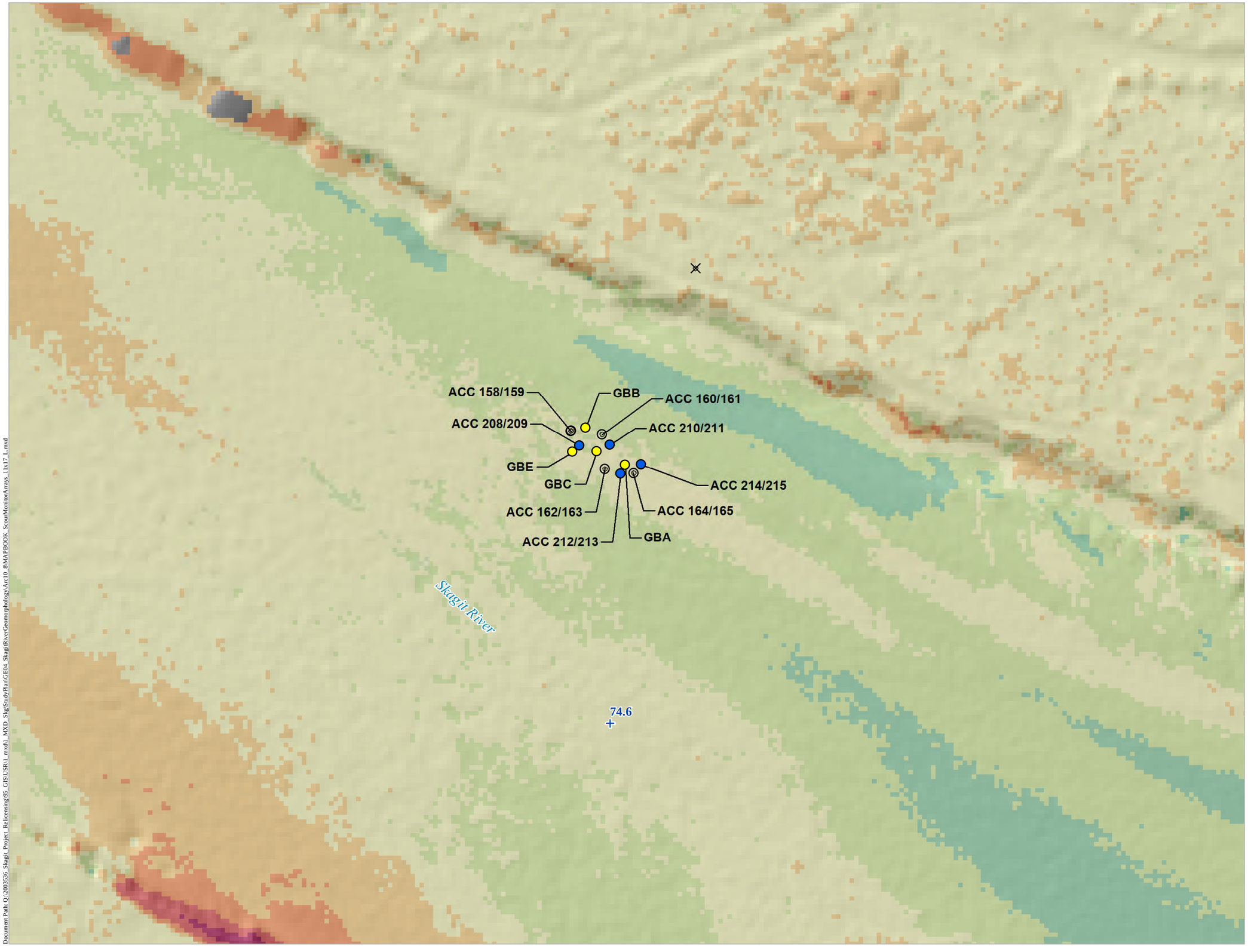


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GE-04 GEOMORPHOLOGY STUDY
SCOUR MONITORING SITE ID: BMM1

+ Project River Mile (PRM)

Scour Monitors

- Benchmark
- Accelerometer
- Golf Ball
- Small Bead
- Past Accelerometer (2019/2020)

Observed Scour Depth

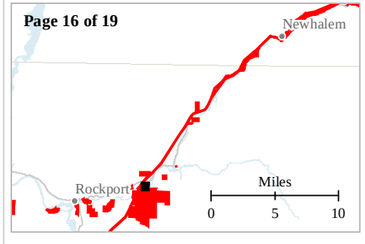
- 0.0 or NA
- 0.4 - 0.8
- 0.9 - 1.5
- 1.6 - 2.5

LiDAR Compare, ft (2017-2022)

- -10+
- -9.9 - -5
- -4.9 - -2
- -1.9 - -0.5
- -0.4 - 0.5
- 0.6 - 2
- 2.1 - 5
- 5.1 - 10
- 10+

0 50 100 Feet

N

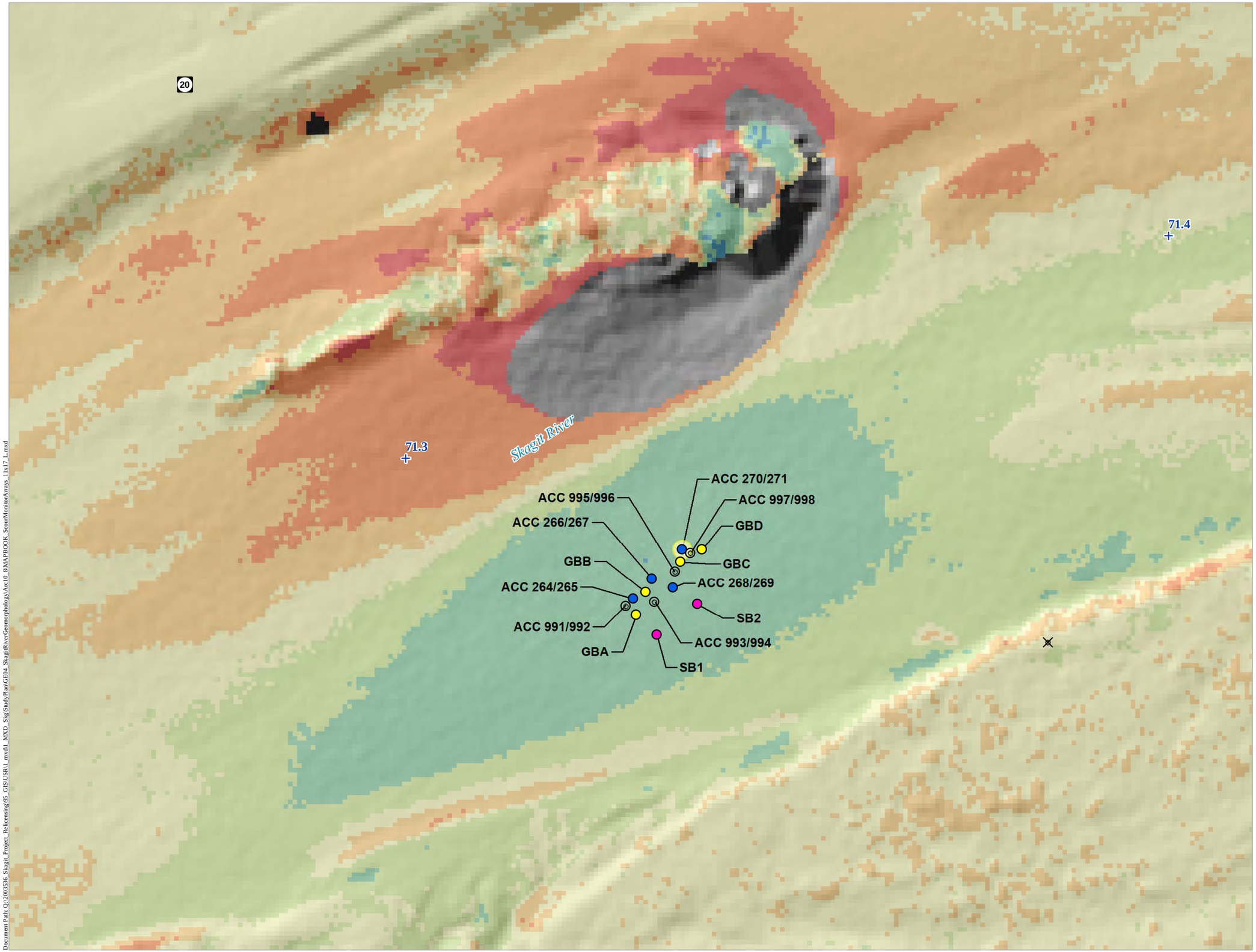


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GE-04 GEOMORPHOLOGY STUDY
SCOUR MONITORING SITE ID: BMM4

+ Project River Mile (PRM)

Scour Monitors

- Benchmark
- Accelerometer
- Golf Ball
- Small Bead
- Past Accelerometer (2019/2020)

Observed Scour Depth

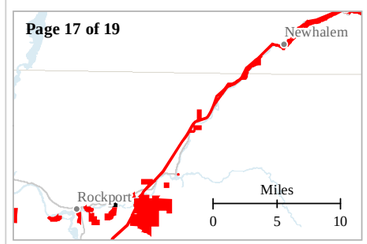
- 0.0 or NA
- 0.4 - 0.8
- 0.9 - 1.5
- 1.6 - 2.5

LiDAR Compare, ft (2017-2022)

- -10+
- -9.9 - -5
- -4.9 - -2
- -1.9 - -0.5
- -0.4 - 0.5
- 0.6 - 2
- 2.1 - 5
- 5.1 - 10
- 10+

0 50 100 Feet

N



Seattle City Light

SKAGIT RIVER HYDROELECTRIC PROJECT (FERC NO. 553)

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Data Source: Northwest Hydraulic Consultants (2022)

Document Path: Q:\2003536_Skagit_Project_Relicensing\05_GIS\USR\1_mxd\1_MXD_Sag\Study\Plan\GE04_SkagitRiverGeomorphology\Arc10_0\MAPBOOK_ScourMonitorArrays_11x17_L.mxd

GE-04 GEOMORPHOLOGY STUDY
SCOUR MONITORING SITE ID: RC70.1

70.1

Skagit River

ACC 206/207

GBD

GBB

ACC 204/205

ACC 200/201

GBC

ACC 202/203

GBA

+ Project River Mile (PRM)

Scour Monitors

- Benchmark
- Accelerometer
- Golf Ball
- Small Bead
- Past Accelerometer (2019/2020)

Observed Scour Depth

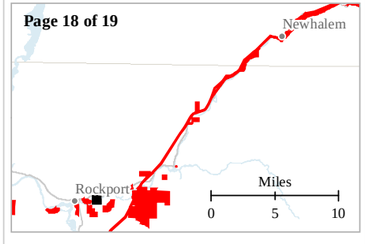
- 0.0 or NA
- 0.4 - 0.8
- 0.9 - 1.5
- 1.6 - 2.5

LiDAR Compare, ft (2017-2022)

- -10+
- -9.9 - -5
- -4.9 - -2
- -1.9 - -0.5
- -0.4 - 0.5
- 0.6 - 2
- 2.1 - 5
- 5.1 - 10
- 10+

0 50 100 Feet

N

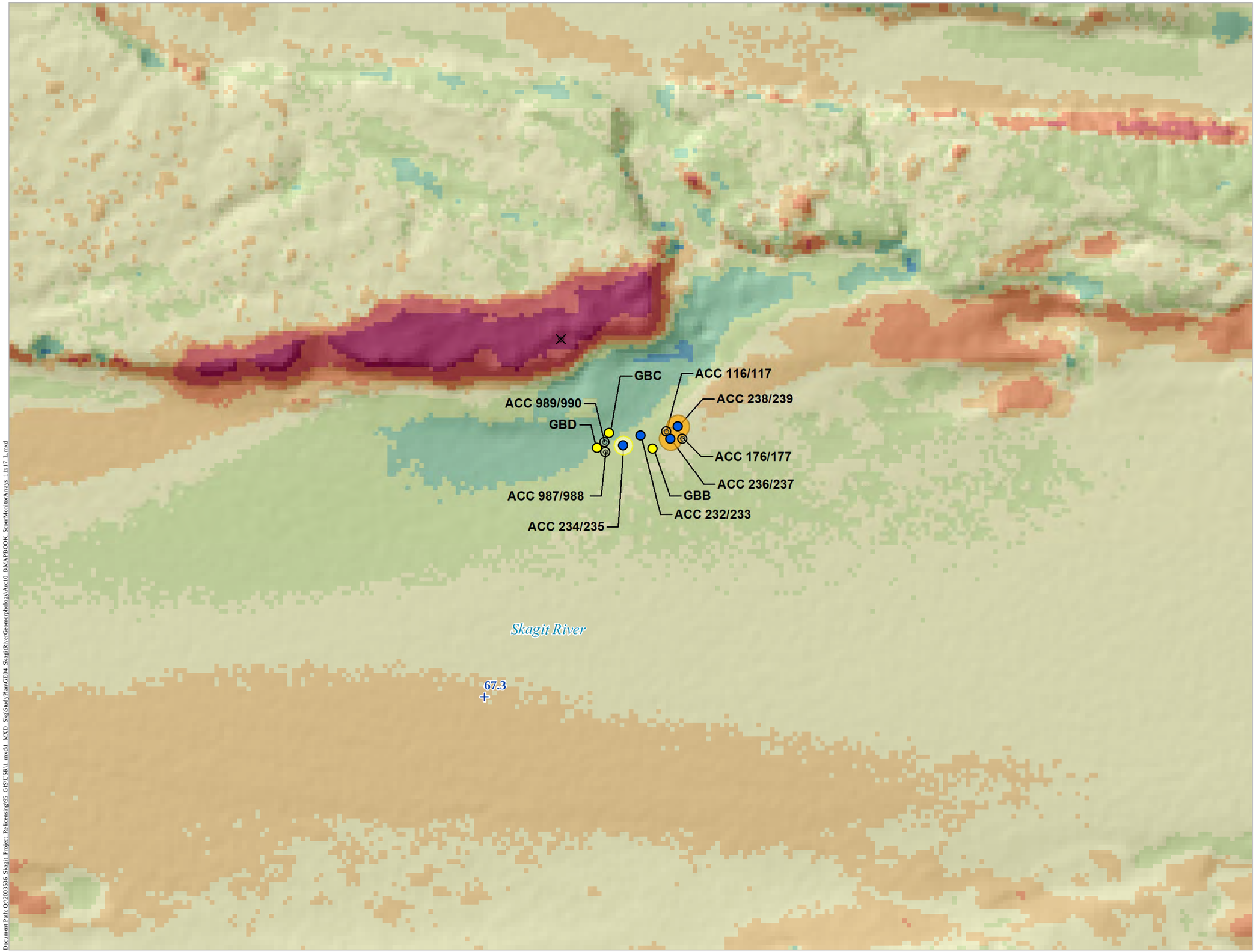


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Document Path: Q:\2003536_Skagit_Project_Relicensing\05_GIS\USR\1_mxd\1_MXD_SkgStudyPlanGF04_SkagitRiverGeomorphology\Arc10_8\MAPBOOK_ScourMonitorArrays_11x17_1.mxd



GE-04 GEOMORPHOLOGY STUDY
SCOUR MONITORING SITE ID: BMM6

+ Project River Mile (PRM)

Scour Monitors

- Benchmark
- Accelerometer
- Golf Ball
- Small Bead
- Past Accelerometer (2019/2020)

Observed Scour Depth

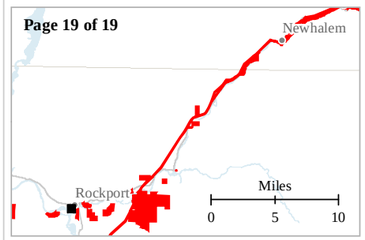
- 0.0 or NA
- 0.4 - 0.8
- 0.9 - 1.5
- 1.6 - 2.5

LiDAR Compare, ft (2017-2022)

- -10+
- -9.9 - -5
- -4.9 - -2
- -1.9 - -0.5
- -0.4 - 0.5
- 0.6 - 2
- 2.1 - 5
- 5.1 - 10
- 10+

0 50 100 Feet

N



Seattle City Light

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Document Path: Q:\2003536_Skagit_Project_Relicensing\05_GIS\USR\1_mxd\1_MXD_SkgStudyPlan\GE04_SkagitRiverGeomorphology\Arc10_8\MAPBOOK_ScourMonitorArrays_11x17_L.mxd

Site	Monitor ID	Category	GE04 Reach	Redd Obs?	Change in Bed Elev. (mm)	Min Obs. Scour Depth (mm)	τ Top ACC (psf)	τ Btm ACC (psf)	τ_{max} (psf)	τ^*_{max}	D_{50} (mm)	D_{84} (mm)	Adj. Min Scour Depth (mm)	Active Layer (mm)
RC 70.1	**ACC 200/201**	**RC**	**6**	0	-235.9	419.1	1.1	0.58	1.18	0.052	67	112	419.1	136
	ACC 202/203	**RC**	**6**	0	-227.8	368.3	0.92	0.83	1.22	0.054	67	112	368.3	94.9
	ACC 204/205	**RC**	**6**	1	-193.5	381	1.09	1.09	1.22	0.054	67	112	381	148.7
	ACC 206/207	**RC**	**6**	0	-256.7	381	1	1.33	1.36	0.06	67	112	381	72.9
	GBA	**RC**	**6**		-240.2	311.8			1.21	0.054	67	112	311.8	23.5
	GBB	**RC**	**6**		-283.3	584.2			1.3	0.057	67	112	584.2	244.2
	GBC	**RC**	**6**		-276.4	331.7			1.19	0.053	67	112	331.7	331.7
	GBD	**RC**	**6**		-67.7				1.35	0.06	67	112	67	81.2
RC 75.2	**ACC 282/283**	**RC**	**5b**	0	99.7				1.28	0.049	77	125	77	119.6
	ACC 284/285	**RC**	**5b**	0	-20.9				1.26	0.048	77	125	77	25.1
	ACC 286/287	**RC**	**5b**	0	104				1.24	0.048	77	125	77	124.8
	ACC 288/289	**RC**	**5b**	0	99.1				1.24	0.048	77	125	77	119
	GBA	**RC**	**5b**		-28.7	195.6			1.25	0.048	77	125	195.6	161.2
	GBB	**RC**	**5b**		-54.1	170.2			1.23	0.047	77	125	170.2	105.2
	GBC	**RC**	**5b**		68.5				1.29	0.05	77	125	77	82.2
	GBD	**RC**	**5b**		-35.1	170.2			1.29	0.05	77	125	170.2	128.1
RC 79.0	**ACC 216/217**	**RC**	**5a**	0	-32.7	139.7	0.83		1	0.046	65	97	139.7	100.5
	ACC 218/219	**RC**	**5a**	0	17.3				1.09	0.05	65	97	65	20.8

Site	Monitor ID	Category	GE04 Reach	Redd Obs?	Change in Bed Elev. (mm)	Min Obs. Scour Depth (mm)	τ Top ACC (psf)	τ Btm ACC (psf)	τ_{max} (psf)	τ^*_{max}	D_{50} (mm)	D_{84} (mm)	Adj. Min Scour Depth (mm)	Active Layer (mm)
	ACC 220/221	**RC**	**5a**	1	-85.8	139.7	0.85		1.08	0.049	65	97	139.7	36.8
	ACC 222/223	**RC**	**5a**	0	-18.7				1.1	0.05	65	97	65	22.5
	GBA	**RC**	**5a**			157.5			1.09	0.05	65	97	157.5	157.5
	GBB	**RC**	**5a**		-33.1	276.9			1.08	0.049	65	97	276.9	237.2
	GBC	**RC**	**5a**		-3.3	200.7			1.09	0.05	65	97	200.7	196.8
	GBD	**RC**	**5a**		57.2				1.08	0.049	65	97	65	68.6
RC 82.3	**ACC 296/297**	**RC**	**3b**	0	-55.1	533.4			2.08	0.087	71	115	533.4	467.2
	ACC 294/295	**RC**	**3b**	0	-25.9	304.8	1.98	1.96	1.98	0.082	71	115	304.8	273.7
	ACC292 /293	**RC**	**3b**	0	-119.2	304.8	1.68	1.88	1.99	0.083	71	115	304.8	161.7
	ACC 290/291	**RC**	**3b**	0	-8.9	381	1.72	1.72	2.01	0.084	71	115	381	370.3
	GBA	**RC**	**3b**		-209	431.8			2	0.083	71	115	431.8	180.9
	GBB	**RC**	**3b**		-63.1	431.8			2.1	0.088	71	115	431.8	356.1
	GBC	**RC**	**3b**		-110.6	431.8			2.1	0.088	71	115	431.8	299.1
	GBD	**RC**	**3b**		-112.2	584.2			2.1	0.088	71	115	584.2	449.6
RC 89.9	**ACC 250/251**	**RC**	**2b**	1	-78	165.1	0.95		1.69	0.07	71	112	165.1	71.6
	ACC 252/253	**RC**	**2b**	1	-147.6	342.9	0.96	1.35	1.9	0.079	71	112	342.9	165.8
	ACC 254/255	**RC**	**2b**	1	-148	304.8	0.94	1.3	1.9	0.079	71	112	304.8	127.3
	ACC 256/257	**RC**	**2b**	1	-245.7	317.5	0.96	1.15	1.9	0.079	71	112	317.5	22.7

Site	Monitor ID	Category	GE04 Reach	Redd Obs?	Change in Bed Elev. (mm)	Min Obs. Scour Depth (mm)	τ Top ACC (psf)	τ Btm ACC (psf)	τ_{max} (psf)	τ^*_{max}	D_{50} (mm)	D_{84} (mm)	Adj. Min Scour Depth (mm)	Active Layer (mm)
	GBA	**RC**	**2b**		-160	312.4			1.85	0.077	71	112	312.4	120.4
	GBB	**RC**	**2b**		-160.7	355.6			1.91	0.08	71	112	355.6	162.7
	GBC	**RC**	**2b**		-28.5	157.5			1.73	0.072	71	112	157.5	123.3
	GBD	**RC**	**2b**		-83.5	340.4			1.85	0.077	71	112	340.4	240.2
RC 93.0	**ACC 328/329**	**RC**	**2b**		-133.7	584.2			3.19	0.143	66	95	584.2	423.8
	ACC 330/331	**RC**	**2b**		-442.6	591.4			2.9	0.13	66	95	591.4	60.3
	ACC 332/333	**RC**	**2b**		-300.4	584.2			3.42	0.153	66	95	584.2	223.8
	ACC 334/335	**RC**	**2b**		-300.1	584.2			3.22	0.144	66	95	584.2	224.1
	GBA	**RC**	**2b**		-524	736.6			2.69	0.121	66	95	736.6	107.8
	GBB	**RC**	**2b**		-471.6	736.6			2.98	0.134	66	95	736.6	170.7
	GBC	**RC**	**2b**		-333.8	736.6			3.52	0.158	66	95	736.6	336
	GBD	**RC**	**2b**		-316.3	736.6			3.2	0.143	66	95	736.6	357.1
BMM6	**ACC 232/233**	**Spawning**	**7a**	1		101.6	0.66		0.8	0.039	60	117	101.6	101.6
	ACC 234/235	**Spawning**	**7a**	1		101.6	0.77		0.76	0.037	60	117	101.6	101.6
	ACC 236/237	**Spawning**	**7a**	1		279.4	0.65	0.77	0.81	0.04	60	117	279.4	279.4
	ACC 238/239	**Spawning**	**7a**	1		330.2	0.73	0.72	0.83	0.041	60	117	330.2	330.2
BMM4	**ACC 270/271**	**Spawning**	**6**	0	641.3	203.2	1.41		1.5	0.062	71	112	203.2	972.8
	ACC 268/269	**Spawning**	**6**		704.4				1.45	0.06	71	112	71	845.3

Site	Monitor ID	Category	GE04 Reach	Redd Obs?	Change in Bed Elev. (mm)	Min Obs. Scour Depth (mm)	τ Top ACC (psf)	τ Btm ACC (psf)	τ_{max} (psf)	τ^*_{max}	D_{50} (mm)	D_{84} (mm)	Adj. Min Scour Depth (mm)	Active Layer (mm)
	ACC 266/267	**Spawning**	**6**		741.1				1.46	0.061	71	112	71	889.3
	ACC 264/265	**Spawning**	**6**		739.9				1.5	0.062	71	112	71	887.9
Site 3	**ACC 342/342**	**Spawning**	**5b**	1	248.7				1.18	0.051	68	111	68	298.4
	ACC 340/341	**Spawning**	**5b**	1	209.7	127	0.83		1.17	0.051	68	111	127	378.7
	ACC 338/339	**Spawning**	**5b**	0	156.7	101.6	1.05		1.16	0.05	68	111	101.6	289.6
	ACC 336/337	**Spawning**	**5b**	0	201.1				1.17	0.051	68	111	68	241.4
	GBA	**Spawning**	**5b**		182.4				1.17	0.051	68	111	68	218.8
	GBB	**Spawning**	**5b**		129.5	188			1.18	0.051	68	111	188	343.4
	GB5	**Spawning**	**5b**		338.4				1.18	0.051	68	111	68	406
	GB6	**Spawning**	**5b**		151.5	144.8			1.16	0.051	68	111	144.8	326.6
BMM7	**ACC 344/345**	**Spawning**	**5b**	0	-62.6	355.6	1.04	1.03	1.21	0.053	68	111	355.6	280.5
	ACC 346/347	**Spawning**	**5b**	0	-73.7	355.6	1.15	1.1	1.28	0.056	68	111	355.6	267.2
	ACC 348/349	**Spawning**	**5b**	0	-57.9	381	1.03	1.23	1.24	0.054	68	111	381	311.5
	ACC 350/351	**Spawning**	**5b**	0	-125	330.2		0.86	0.88	0.038	68	111	330.2	180.1
	GBA	**Spawning**	**5b**		-77.3	243.8			1.27	0.055	68	111	243.8	151.1
	GBB	**Spawning**	**5b**			243.8			1.26	0.055	68	111	243.8	243.8
	GBC	**Spawning**	**5b**		-173.9	416.6			1.26	0.055	68	111	416.6	207.9
	GBD	**Spawning**	**5b**		-89.9	373.4			1.19	0.052	68	111	373.4	265.5

Site	Monitor ID	Category	GE04 Reach	Redd Obs?	Change in Bed Elev. (mm)	Min Obs. Scour Depth (mm)	τ Top ACC (psf)	τ Btm ACC (psf)	τ_{max} (psf)	τ^*_{max}	D_{50} (mm)	D_{84} (mm)	Adj. Min Scour Depth (mm)	Active Layer (mm)
Site 1	ACC 224/225	Spawning	5a	0	20.7				0.8	0.036	65	97	39.5	24.8
	ACC 226/227	Spawning	5a	0	74.1				0.9	0.041	65	97	44.4	88.9
	ACC 228/229	Spawning	5a	0	270.8				0.8	0.036	65	97	39.5	324.9
	ACC 230/231	Spawning	5a	0	328.7				0.8	0.036	65	97	39.5	394.5
	GB1	Spawning	5a		21.7	155.4			0.83	0.038	65	97	155.4	181.5
	GB2	Spawning	5a		138.5	155.4			0.86	0.039	65	97	155.4	321.6
	GBA	Spawning	5a						0.83	0.038	65	97	40.8	0
	GBB	Spawning	5a		211.4				0.86	0.039	65	97	42.6	253.7
Site 2	ACC 258/259	Spawning	3b	1	-43.5				0.84	0.035	71	115	41.4	52.2
	ACC 260/261	Spawning	3b	0	-13.2				0.96	0.04	71	115	47.4	15.9
	ACC 262/263	Spawning	3b	1	54	127	1.37		1.38	0.058	71	115	127	191.8
	ACC 276/277	Spawning	3b	0	7.4				1.51	0.063	71	115	71	8.9
	GB3	Spawning	3b		-42.8				1.43	0.06	71	115	71	51.4
	GB4	Spawning	3b		34.6	195.6			1.14	0.048	71	115	195.6	237.1
	GBA	Spawning	3b			132.1			1.08	0.045	71	115	132.1	132.1
	GBB	Spawning	3b			175.3			1.05	0.044	71	115	175.3	175.3
ABSS3	ACC 300/301	Spawning	3a	0	-2.1				1.12	0.047	71	107	71	2.6
	ACC 302/303	Spawning	3a	0	251.9				1.02	0.043	71	107	50.4	302.3

Site	Monitor ID	Category	GE04 Reach	Redd Obs?	Change in Bed Elev. (mm)	Min Obs. Scour Depth (mm)	τ Top ACC (psf)	τ Btm ACC (psf)	τ_{max} (psf)	τ^*_{max}	D_{50} (mm)	D_{84} (mm)	Adj. Min Scour Depth (mm)	Active Layer (mm)
	ACC 304/305	**Spawning**	**3a**	0	-173.4				1	0.042	71	107	49.5	208.1
	ACC306 /307	**Spawning**	**3a**	0	-147				1.01	0.042	71	107	50	176.4
	GBA	**Spawning**	**3a**		-81.3				1.06	0.044	71	107	52.4	97.5
	GBB	**Spawning**	**3a**		-51				1.1	0.046	71	107	71	61.2
	GBC	**Spawning**	**3a**		-136	172.7			1.12	0.047	71	107	172.7	9.6
	GBD	**Spawning**	**3a**		-161.9				0.99	0.041	71	107	48.6	194.3
ABSS2	**ACC 242/243**	**Spawning**	**2b**	0	-190.4	317.5	0.9	1.15	1.31	0.053	73	113	317.5	89
	ACC 244/245	**Spawning**	**2b**	0	-205.2	368.3	1.62	1.59	1.79	0.073	73	113	368.3	122.1
	ACC 246/247	**Spawning**	**2b**	0	-262.3	317.5	0.83	0.91	1.05	0.043	73	113	317.5	2.7
	ACC 248/249	**Spawning**	**2b**	0	-387.9	431.8			1.87	0.076	73	113	431.8	33.7
	GBA	**Spawning**	**2b**		-44.9	226.1			1.69	0.069	73	113	226.1	172.2
	GBB	**Spawning**	**2b**		-243.5	398.8			1.1	0.045	73	113	398.8	106.6
	GBC	**Spawning**	**2b**		-200.2	442			1.99	0.081	73	113	442	201.7
	GBD	**Spawning**	**2b**		-242	398.8			2.06	0.084	73	113	398.8	108.4
ABSS1	**ACC 272/273**	**Spawning**	**2b**	0	304.8	203.2	1.59		1.8	0.059	90	143	203.2	569
	ACC 274/275	**Spawning**	**2b**	0					1.9	0.063	90	143	90	
	ACC 278/279	**Spawning**	**2b**	1		190.5	1.68		1.9	0.063	90	143	190.5	190.5
	ACC 280/281	**Spawning**	**2b**	1	302.3	177.8	1.9		2	0.066	90	143	177.8	540.5

Site	Monitor ID	Category	GE04 Reach	Redd Obs?	Change in Bed Elev. (mm)	Min Obs. Scour Depth (mm)	τ Top ACC (psf)	τ Btm ACC (psf)	τ_{max} (psf)	τ^*_{max}	D_{50} (mm)	D_{84} (mm)	Adj. Min Scour Depth (mm)	Active Layer (mm)
	GBA	**Spawning**	**2b**		133.9	256.5			1.8	0.059	90	143	256.5	417.2
	GBB	**Spawning**	**2b**		289.8	299.7			1.9	0.063	90	143	299.7	647.5
	GBC	**Spawning**	**2b**			127			1.9	0.063	90	143	127	127
	GBD	**Spawning**	**2b**		138.2	213.4			2	0.066	90	143	213.4	379.1

1 Site names reflect location and time of installation. 'Site' prefixes were installed in 2019, BMM were installed in 2020 Below Marblemount, ABSS were installed in 2020 upstream of (above) Shovel Spur; these are all located at spawning areas. Riffle Crest (RC) and Fan sites were all installed in 2021.

2 Category refers to monitoring site location type, either Fan, "RC" for riffle crest or "Spawning" for preferred spawning areas.

3 Redd Obs? shows monitors with recorded redd activity in the accelerometer data log (1) or zero.

4 Change in Bed Elev. refers to the net change in channel bed elevation from August 2021 to August 2022 (RTK survey grade).

5 Min Obs. Scour Depth is the minimum recorded scour depth registered from an accelerometer disturbance or golf ball chain.

6 τ (Top, Bottom, Max) is either instantaneous modelled shear stress at time of scour (Top, Bottom) or maximum modelled shear stress at the scour monitor location using the calibrated FA02 2D hydraulic model results.

7 D_{50} and D_{84} are calculated from the 2021 pebble count data.

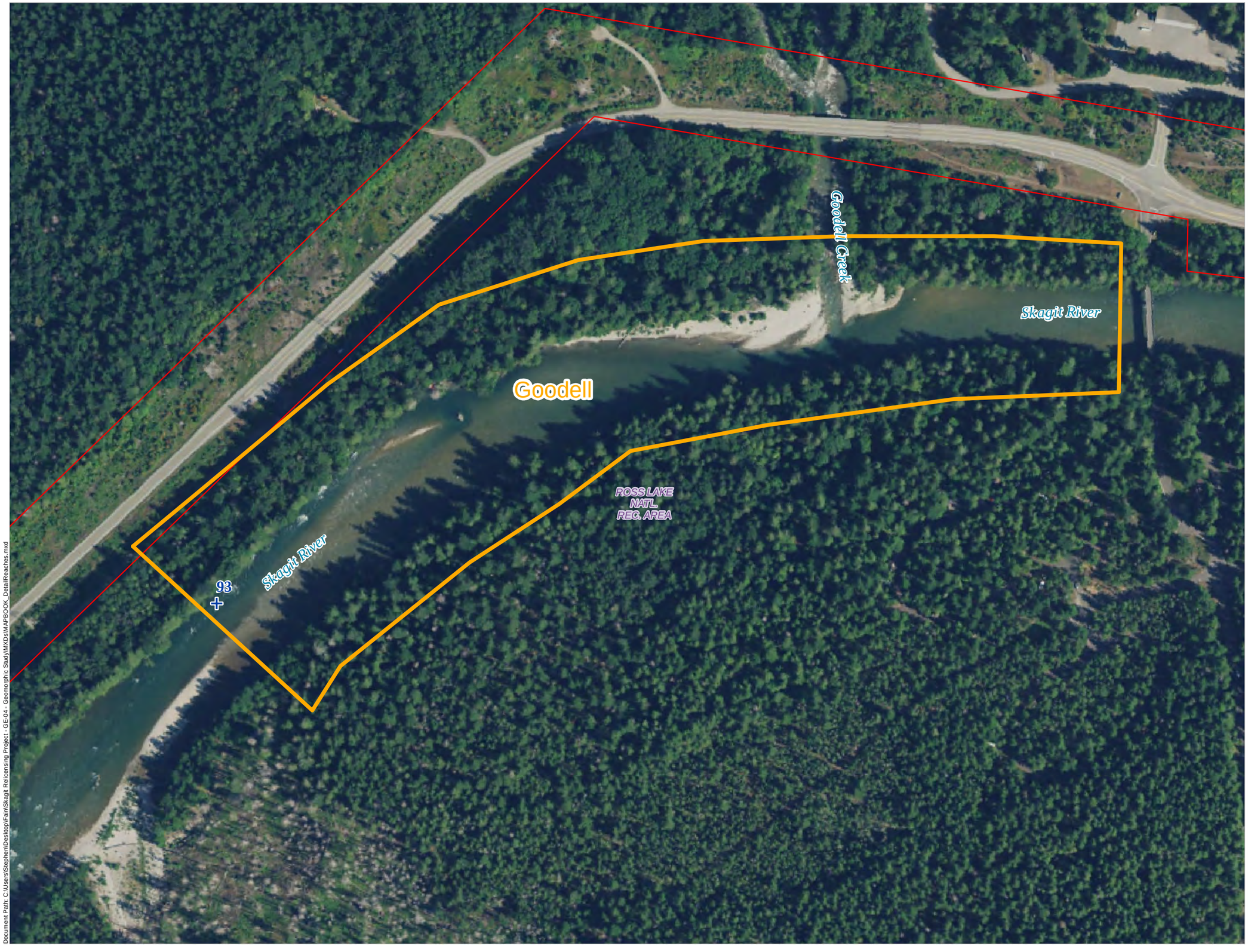
8 Adj Min Scour Depth refers to the scour depth either observed (see 5) or, if no scour was detected or the depth unknown, a minimum predicted sour depth was estimated using either the measured D50 for τ^* max > 0.045, or the predicted mobile D50 for calculated τ^* max < 0.045.

9 Active Layer refers to the thickness of the active layer defined as the event layer scour and fill (if any).

SKAGIT RIVER GEOMORPHOLOGY BETWEEN GORGE DAM AND THE SAUK RIVER STUDY REPORT

ATTACHMENT C

LARGE WOOD INVENTORY DETAILED AREAS MAPBOOK



GE-04 GEOMORPHOLOGY STUDY

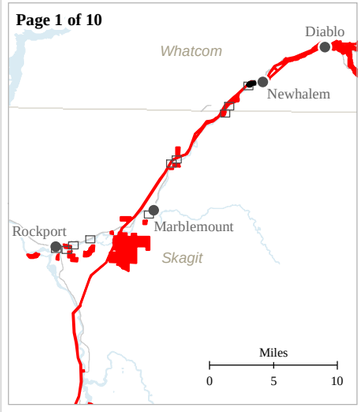
Large Wood Inventory
Detailed Areas - Goodell

- FERC Project Boundary
- Project River Miles (PRM)
- National Park / National Recreation Area Boundary
- Large Wood Detailed Area

N

0 130 260 Feet

Page 1 of 10

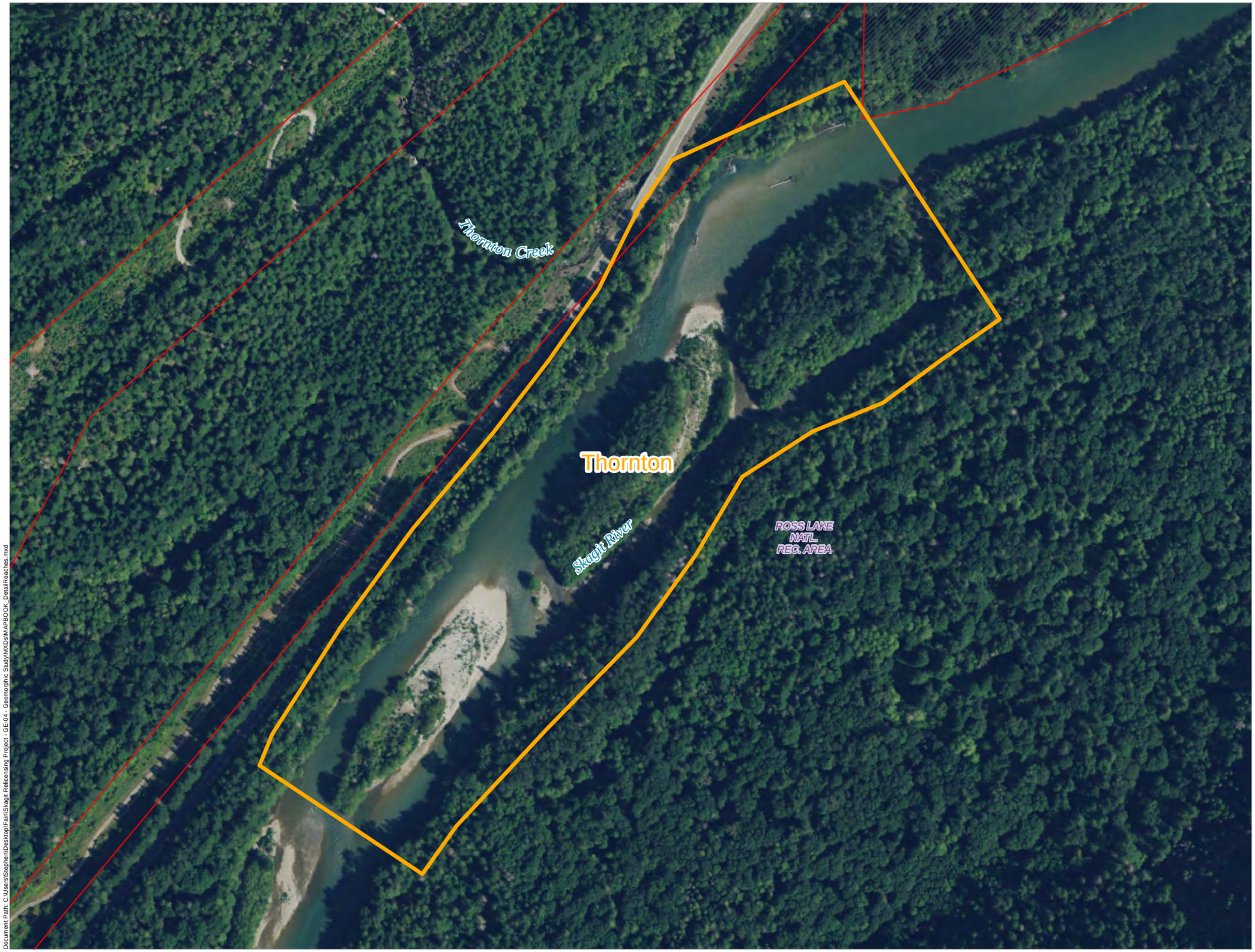


Seattle City Light

SKAGIT RIVER HYDROELECTRIC PROJECT (FERC NO. 553)

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Document Path: C:\Users\StephenIDesktop\Fain\Skagit Relicensing Project - GE-04 - Geomorphic Study\MXDs\MAPBOOK_DetailReaches.mxd



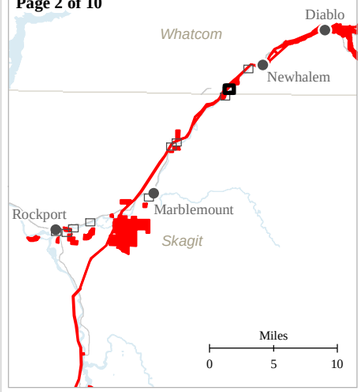
GE-04 GEOMORPHOLOGY STUDY

Large Wood Inventory
Detailed Areas - Thorton

- FERC Project Boundary
- Mitigation Parcel
- National Park / National Recreation Area Boundary
- Large Wood Detailed Area

N

0 150 300 Feet

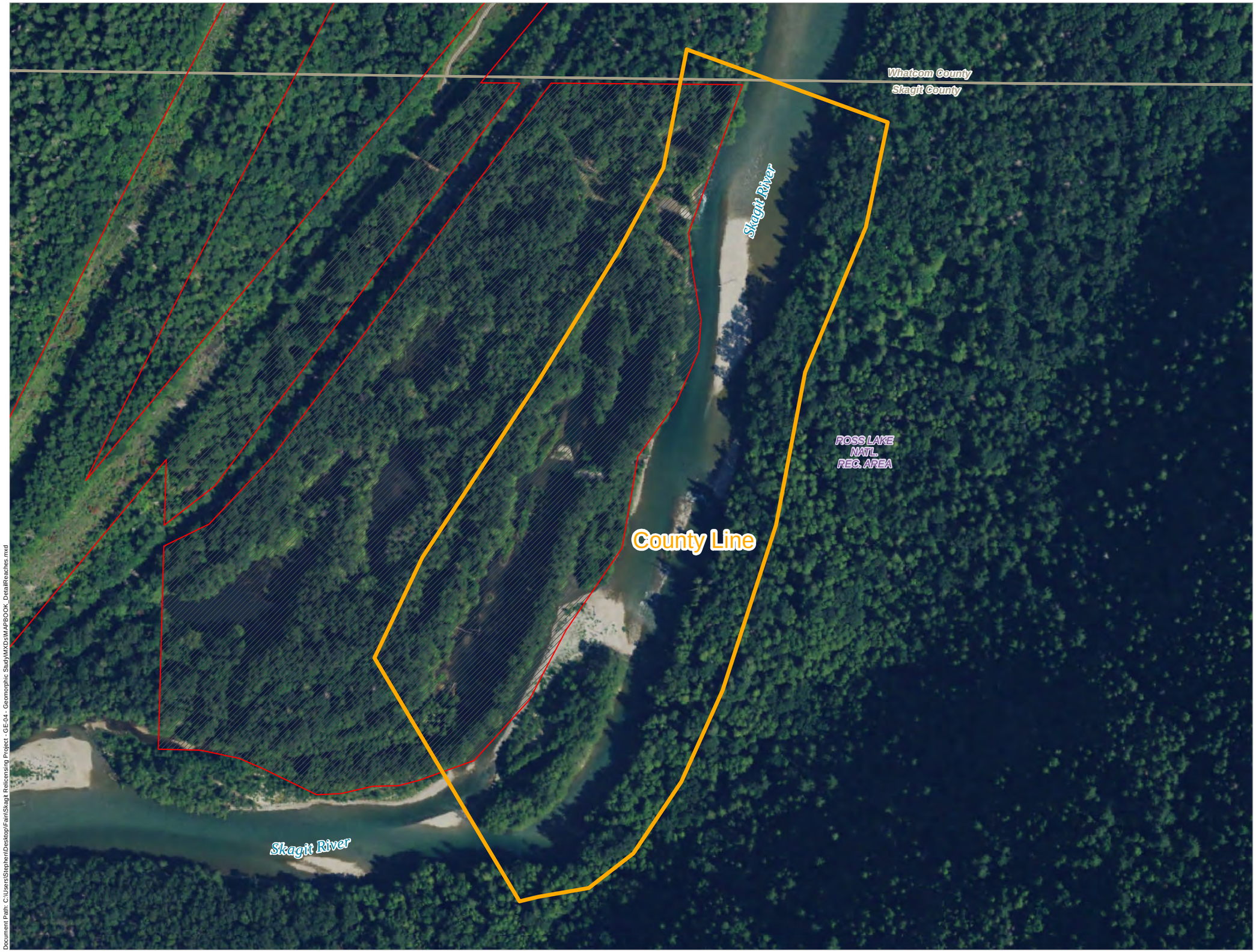


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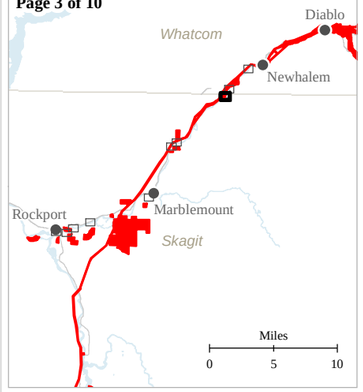
GE-04 GEOMORPHOLOGY STUDY

Large Wood Inventory
Detailed Areas - County Line

- FERC Project Boundary
- Mitigation Parcel
- National Park / National Recreation Area Boundary
- Large Wood Detailed Area

N

0 150 300 Feet

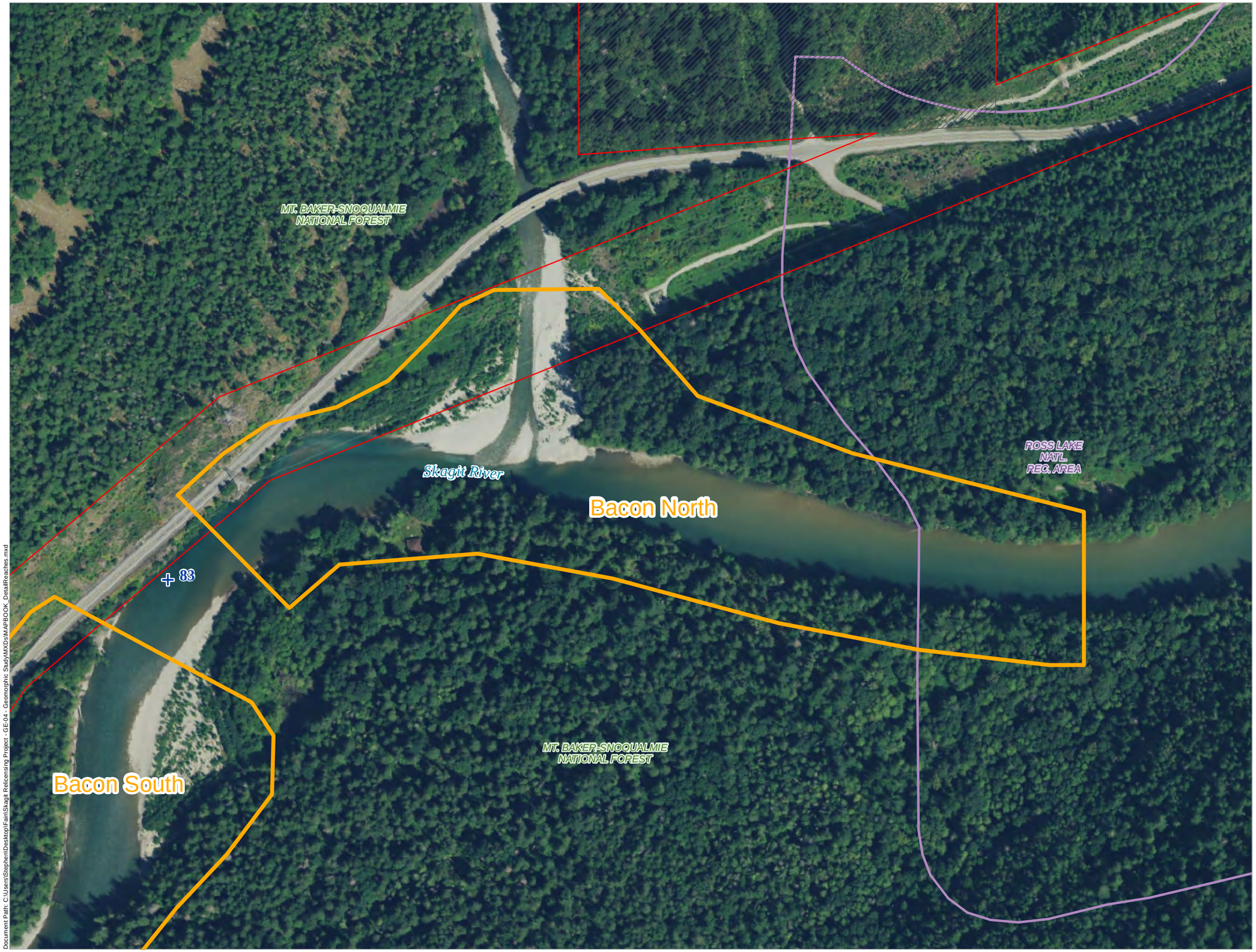


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GE-04 GEOMORPHOLOGY STUDY

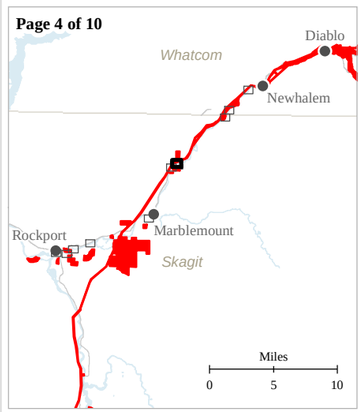
Large Wood Inventory
Detailed Areas - Bacon North

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- National Park / National Recreation Area Boundary
- Large Wood Detailed Area

N

0 150 300 Feet

Page 4 of 10

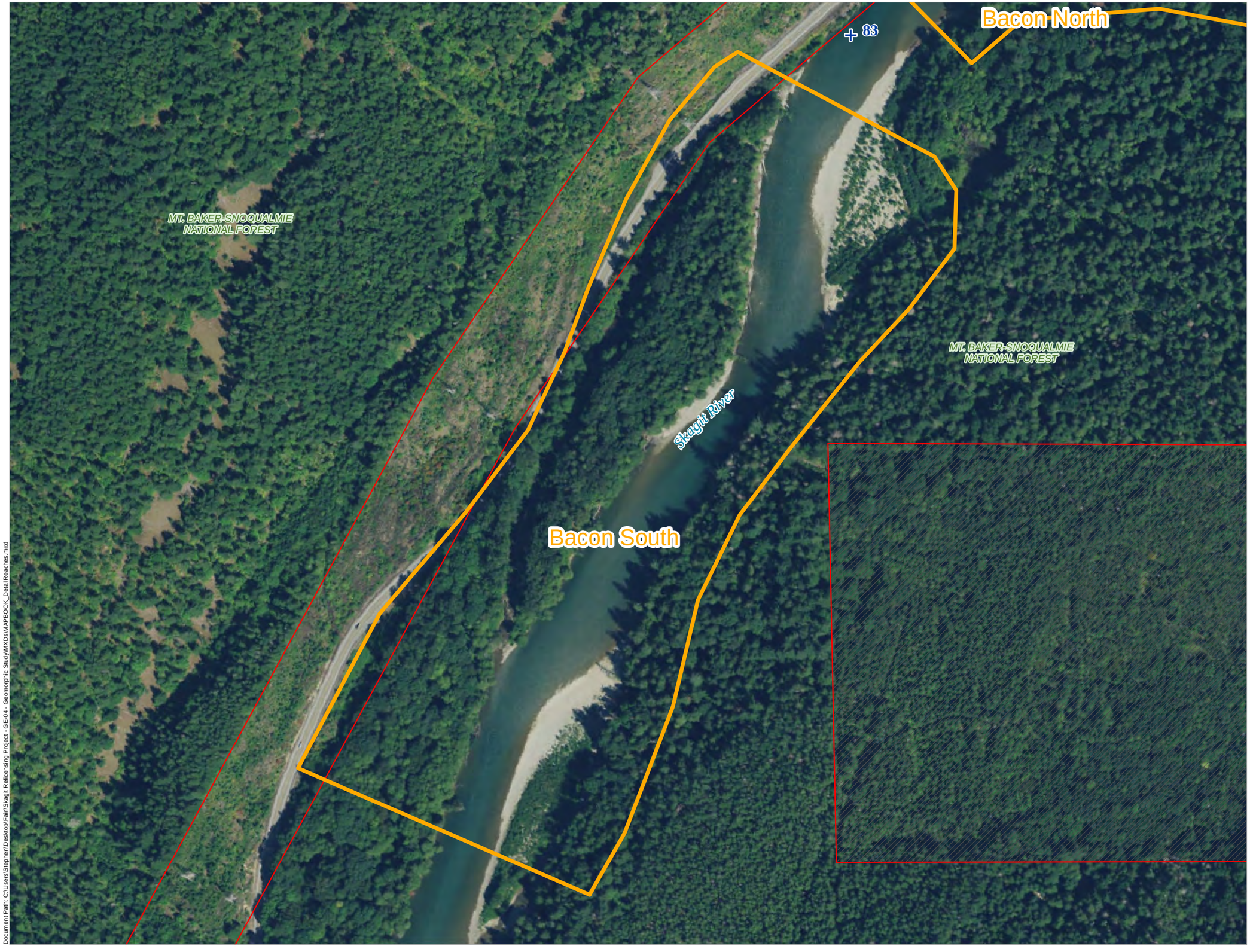


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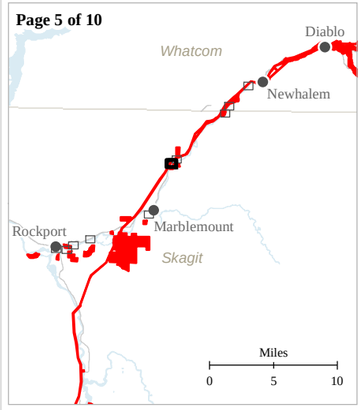
GE-04 GEOMORPHOLOGY STUDY

Large Wood Inventory
Detailed Areas - Bacon South

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Large Wood Detailed Area

N

0 150 300 Feet

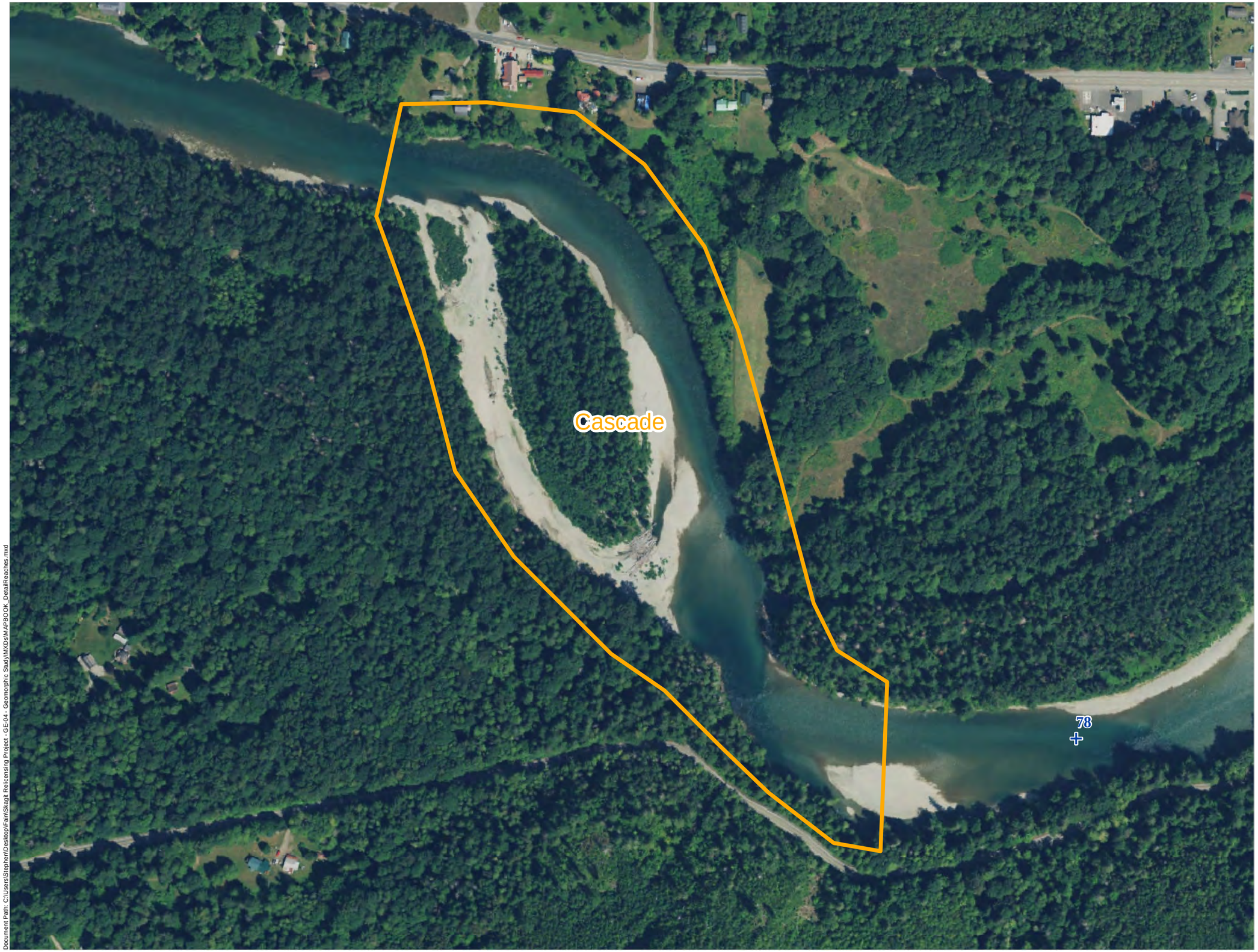


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GE-04 GEOMORPHOLOGY STUDY

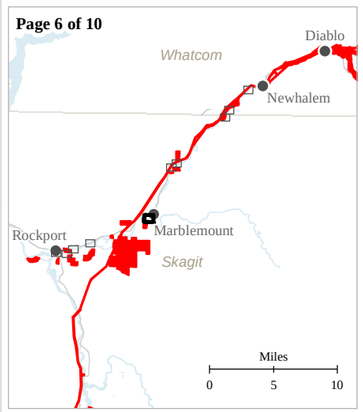
Large Wood Inventory
Detailed Areas - Cascade

+ Project River Miles (PRM)

Large Wood Detailed Area

N

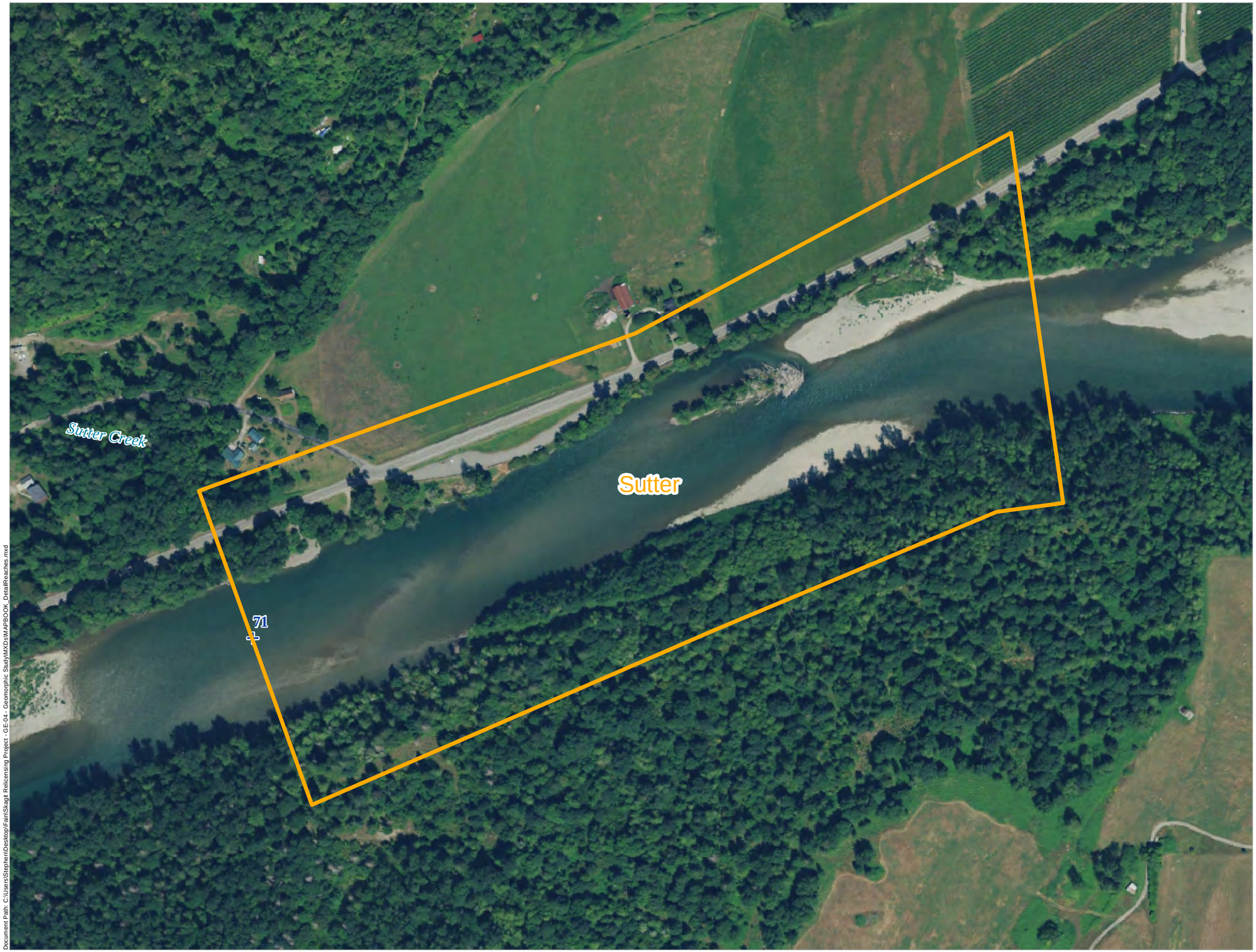
0 150 300 Feet



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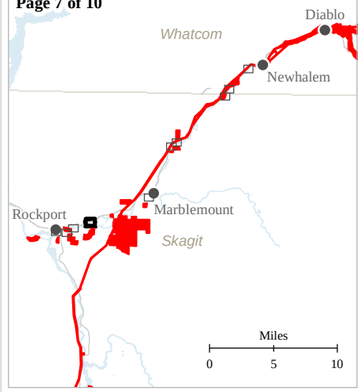
Large Wood Inventory Detailed Areas - Sutter

+ Project River Miles (PRM)

Large Wood Detailed Area

N

0 150 300 Feet



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Barnaby East

70

Document Path: C:\Users\Stephen\Desktop\Fain\Skagit Relicensing Project - GE-04 - Geomorphic Study\MXDs\MAPBOOK_DetailReaches.mxd

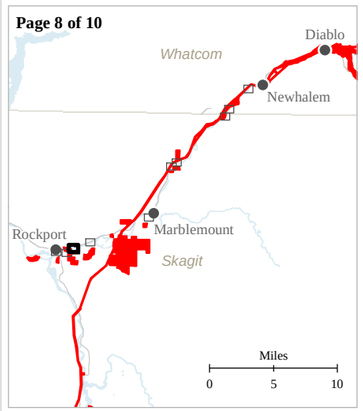
GE-04 GEOMORPHOLOGY STUDY

Large Wood Inventory
Detailed Areas - Barnaby East

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Large Wood Detailed Area

N

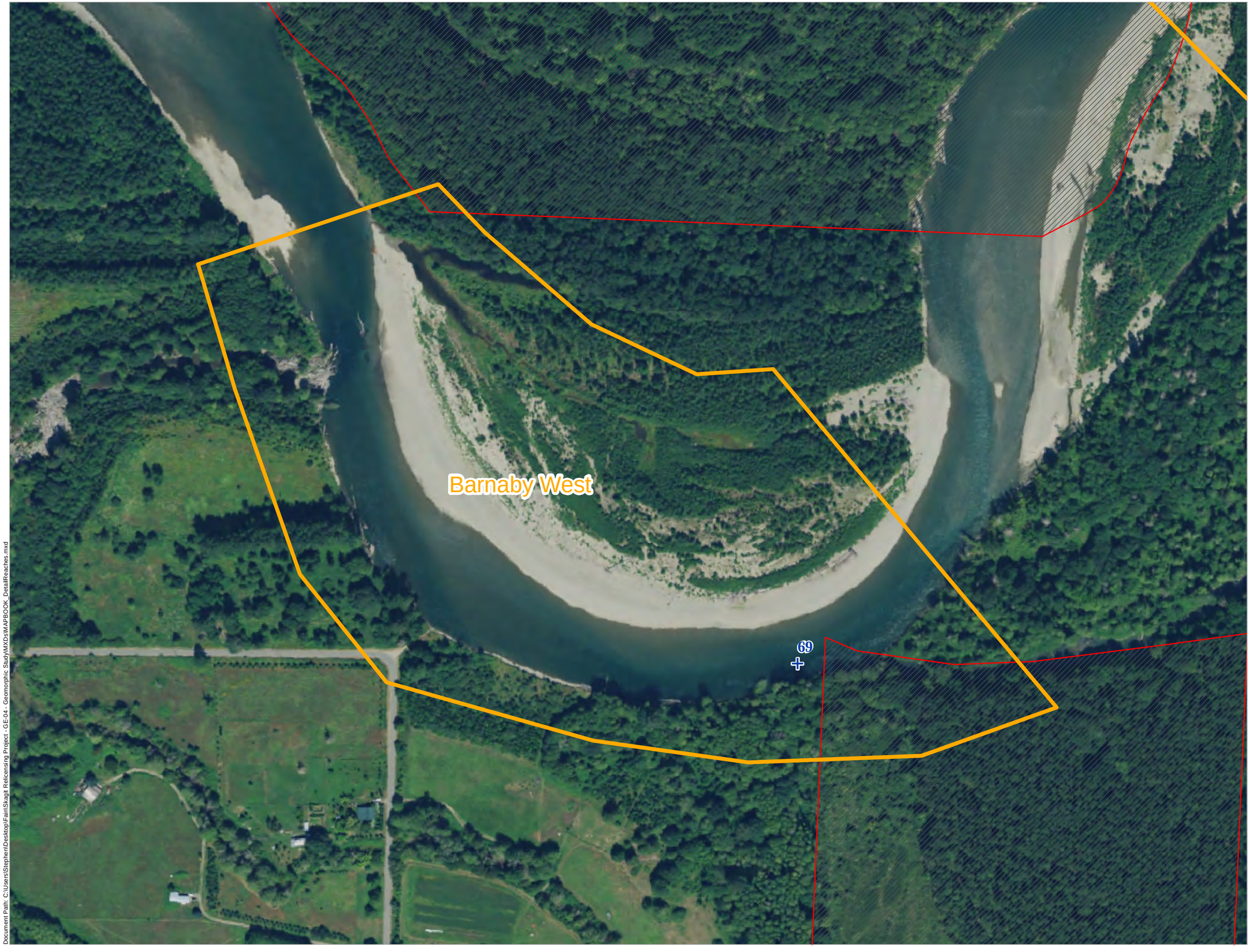
0 150 300 Feet



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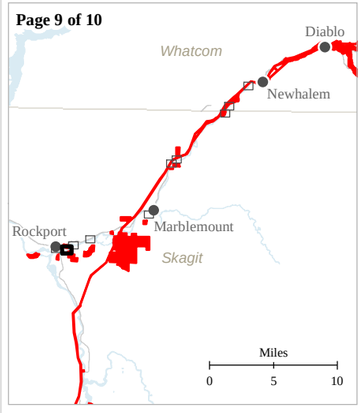
GE-04 GEOMORPHOLOGY STUDY

Large Wood Inventory Detailed Areas - Barnaby West

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Large Wood Detailed Area

N

0 150 300 Feet

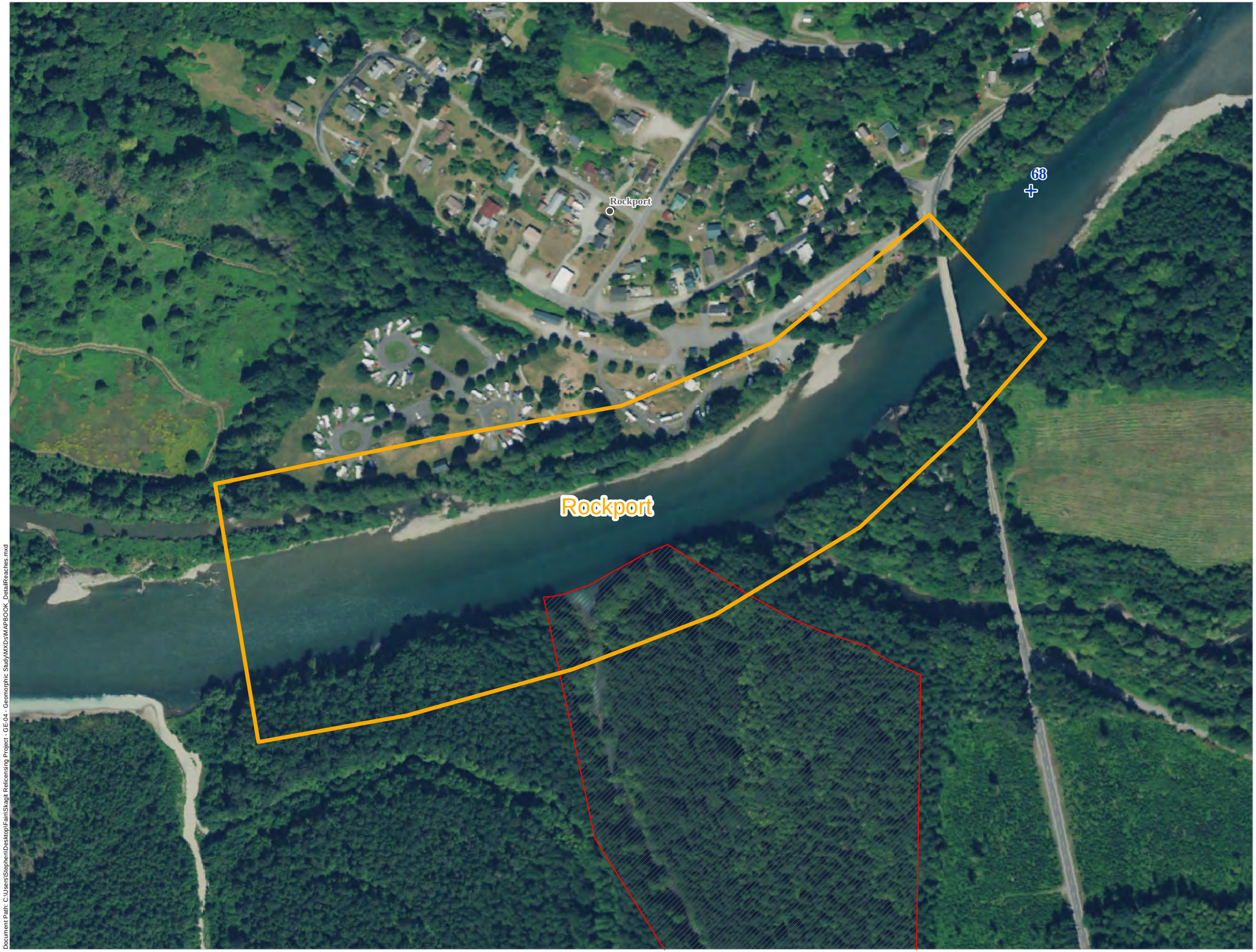


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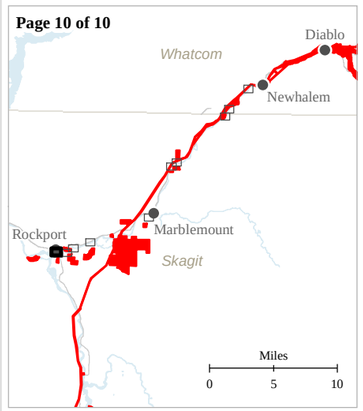


GE-04 GEOMORPHOLOGY STUDY

Large Wood Inventory
Detailed Areas - Rockport

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Large Wood Detailed Area

0 150 300 Feet



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SKAGIT RIVER GEOMORPHOLOGY BETWEEN GORGE DAM AND THE SAUK RIVER STUDY REPORT

ATTACHMENT D

LIDAR REM MAPBOOK

GE-04 GEOMORPHOLOGY STUDY RELATIVE ELEVATION - SHEET 1

- FERC Project Boundary
- Project River Miles (PRM)
- Stream Gage (USGS)
- National Park / National Recreation Area Boundary

Relative Elevation (ft)

15
10
5
0
-5

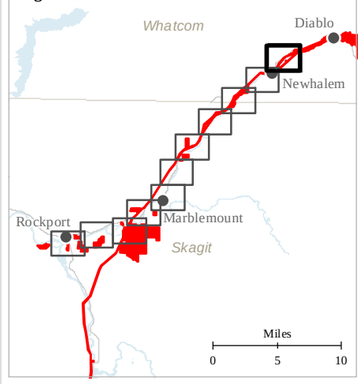
Relative Elevation Map derived from a mosaic of multiple data sources including: 2017 topobathymetric lidar downstream of Marblemount, 2018 topobathymetric lidar upstream of Marblemount; and 2016 lidar covering remaining areas of the valley outside of the map extent for 2018 lidar. Selected void areas filled by NHC survey data.

PRM shown at 0.2-mi intervals

N

0 600 1,200 Feet

Page 1 of 11



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GE-04 GEOMORPHOLOGY STUDY RELATIVE ELEVATION - SHEET 2

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Stream Gage (USGS)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary

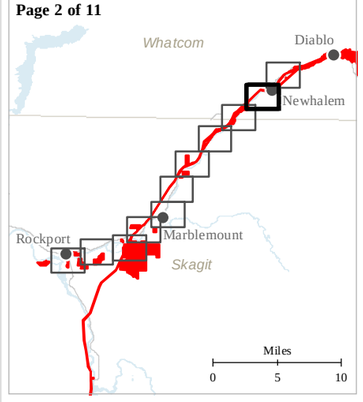
Relative Elevation (ft)

15
10
5
0
-5

Relative Elevation Map derived from a mosaic of multiple data sources including: 2017 topobathymetric lidar downstream of Marblemount, 2018 topobathymetric lidar upstream of Marblemount; and 2016 lidar covering remaining areas of the valley outside of the map extent for 2018 lidar. Selected void areas filled by NHC survey data.

PRM shown at 0.2-mi intervals

0 600 1,200 Feet



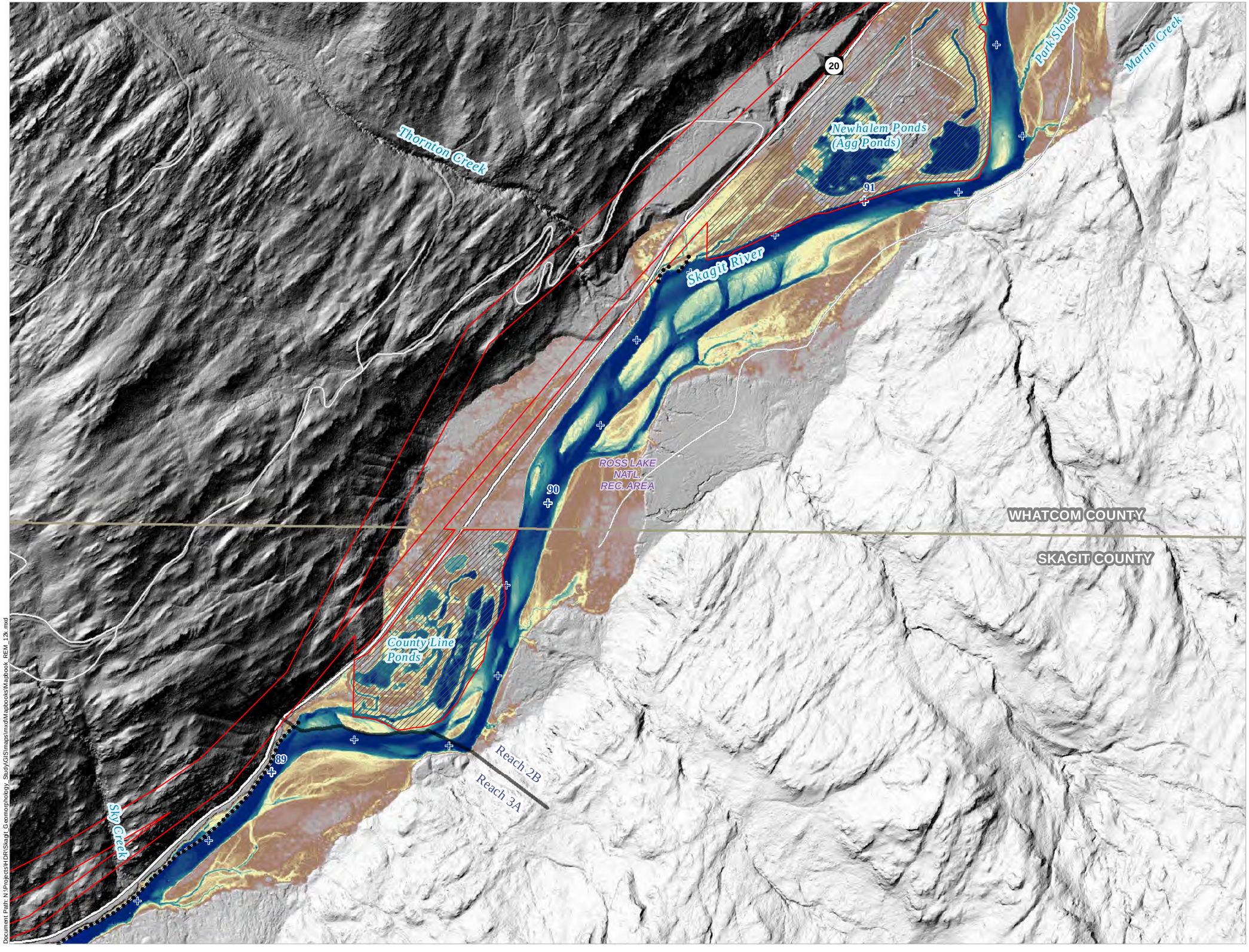
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GE-04 GEOMORPHOLOGY STUDY RELATIVE ELEVATION - SHEET 3



- FERC Project Boundary
- Mitigation Parcel
- \+ Project River Miles (PRM)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary

Relative Elevation (ft)

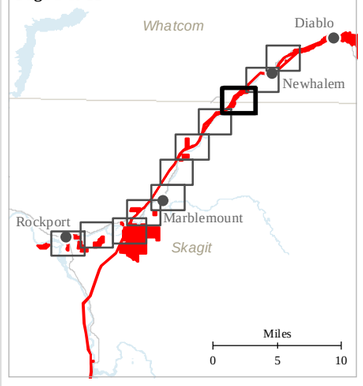
15
10
5
0
-5

Relative Elevation Map derived from a mosaic of multiple data sources including: 2017 topobathymetric lidar downstream of Marblemount, 2018 topobathymetric lidar upstream of Marblemount; and 2016 lidar covering remaining areas of the valley outside of the map extent for 2018 lidar. Selected void areas filled by NHC survey data.

PRM shown at 0.2-mi intervals

N

0 600 1,200 Feet



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GE-04 GEOMORPHOLOGY STUDY RELATIVE ELEVATION - SHEET 4

- FERC Project Boundary
- Project River Miles (PRM)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary

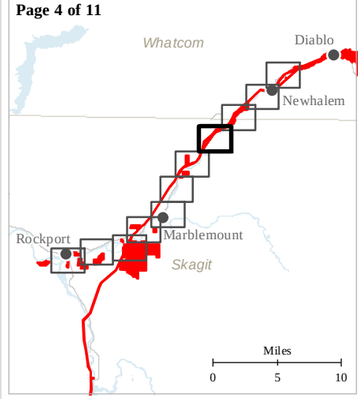
Relative Elevation (ft)

15
10
5
0
-5

Relative Elevation Map derived from a mosaic of multiple data sources including: 2017 topobathymetric lidar downstream of Marblemount, 2018 topobathymetric lidar upstream of Marblemount; and 2016 lidar covering remaining areas of the valley outside of the map extent for 2018 lidar. Selected void areas filled by NHC survey data.

PRM shown at 0.2-mi intervals

0 600 1,200 Feet



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GE-04 GEOMORPHOLOGY STUDY RELATIVE ELEVATION - SHEET 5

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary

Relative Elevation (ft)

15
10
5
0
-5

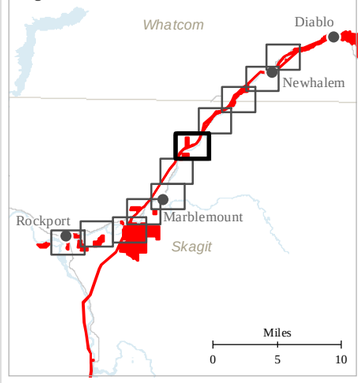
Relative Elevation Map derived from a mosaic of multiple data sources including: 2017 topobathymetric lidar downstream of Marblemount, 2018 topobathymetric lidar upstream of Marblemount; and 2016 lidar covering remaining areas of the valley outside of the map extent for 2018 lidar. Selected void areas filled by NHC survey data.

PRM shown at 0.2-mi intervals

N

0 600 1,200 Feet

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GE-04 GEOMORPHOLOGY STUDY RELATIVE ELEVATION - SHEET 6

MT. BAKER-SNOQUALMIE NATIONAL FOREST

MT. BAKER-SNOQUALMIE NATIONAL FOREST

MT. BAKER-SNOQUALMIE NATIONAL FOREST

82

81

80

20

Reach 3B

Reach 5A

Diobsud Creek

Skagit River

Taylor Spawning Channel

- FERC Project Boundary
- Mitigation Parcel
- \+ Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary

Relative Elevation (ft)

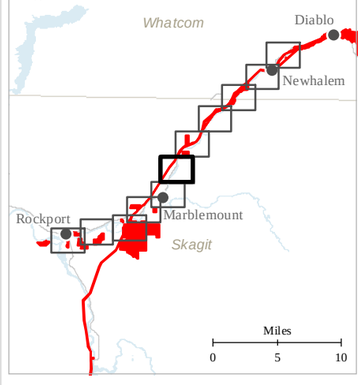
15
10
5
0
-5

Relative Elevation Map derived from a mosaic of multiple data sources including: 2017 topobathymetric lidar downstream of Marblemount, 2018 topobathymetric lidar upstream of Marblemount; and 2016 lidar covering remaining areas of the valley outside of the map extent for 2018 lidar. Selected void areas filled by NHC survey data.

PRM shown at 0.2-mi intervals

N

0 600 1,200 Feet



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GE-04 GEOMORPHOLOGY STUDY RELATIVE ELEVATION - SHEET 7

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Stream Gage (USGS)
- Hydromodified Banks
- Reach Boundary

Relative Elevation (ft)

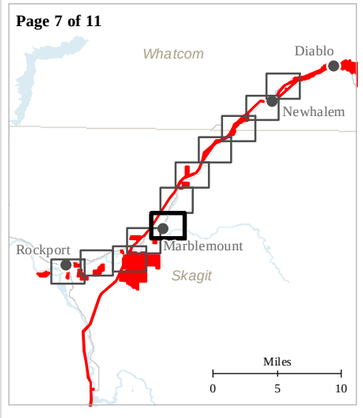
15
10
5
0
-5

Relative Elevation Map derived from a mosaic of multiple data sources including: 2017 topobathymetric lidar downstream of Marblemount, 2018 topobathymetric lidar upstream of Marblemount; and 2016 lidar covering remaining areas of the valley outside of the map extent for 2018 lidar. Selected void areas filled by NHC survey data.

PRM shown at 0.2-mi intervals

N

0 600 1,200 Feet



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MT. BAKER-SNOQUALMIE NATIONAL FOREST
Taylor Creek
Skagit River
20
79
Olson Creek
Ranger Station Rd
MT. BAKER-SNOQUALMIE NATIONAL FOREST
Cascade River Rd
Marblemount
77
20
Reach 5A
Reach 5B
MT. BAKER-SNOQUALMIE NATIONAL FOREST
Cascade River
Marblemount Slough
78
Marblegate Rd

GE-04 GEOMORPHOLOGY STUDY RELATIVE ELEVATION - SHEET 8

MT. BAKER-SNOQUALMIE NATIONAL FOREST

Marblegate Rd

Skagit River

Willow Ln

Rockport - Cascade Rd

Corkindale Creek

Reach 5B

Reach 6

Powerline Spawning Channel

20

74

75

76

77

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary

Relative Elevation (ft)

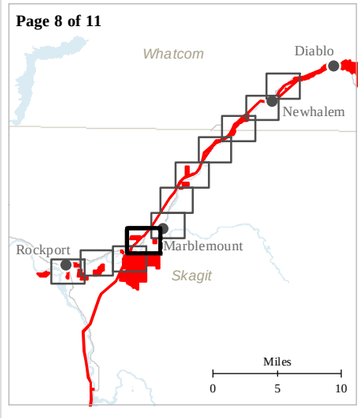
15
10
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0
-5

Relative Elevation Map derived from a mosaic of multiple data sources including: 2017 topobathymetric lidar downstream of Marblemount, 2018 topobathymetric lidar upstream of Marblemount; and 2016 lidar covering remaining areas of the valley outside of the map extent for 2018 lidar. Selected void areas filled by NHC survey data.

PRM shown at 0.2-mi intervals

N

0 600 1,200 Feet



Seattle City Light

SKAGIT RIVER HYDROELECTRIC PROJECT (FERC NO. 553)

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GE-04 GEOMORPHOLOGY STUDY RELATIVE ELEVATION - SHEET 9

MT. BAKER-SNOQUALMIE NATIONAL FOREST

Rocky Creek

20

73

74

75

Skagit River

Powerline Spawning Channel

Illabot Spawning Channel

Reach 6

Reach 5B

Pandora Cir

O'Brian Creek

Rockport - Cascade Rd

Illabot Creek

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary

Relative Elevation (ft)

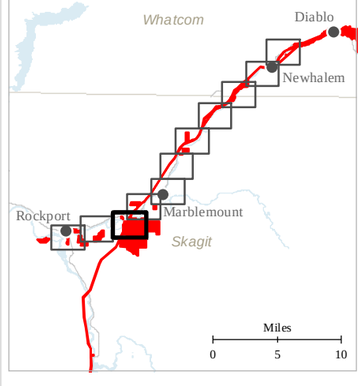
15
10
5
0
-5

Relative Elevation Map derived from a mosaic of multiple data sources including: 2017 topobathymetric lidar downstream of Marblemount, 2018 topobathymetric lidar upstream of Marblemount; and 2016 lidar covering remaining areas of the valley outside of the map extent for 2018 lidar. Selected void areas filled by NHC survey data.

PRM shown at 0.2-mi intervals

N

0 600 1,200 Feet



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GE-04 GEOMORPHOLOGY STUDY RELATIVE ELEVATION - SHEET 10

MT. BAKER-SNOQUALMIE NATIONAL FOREST

Barr Creek

Sutter Creek

Skagit River

Illabot Creek

Barnaby Slough

Harrison Pond

Martin Ranch Rd

20

70

71

72

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Stream Gage (USGS)
- Hydromodified Banks

Relative Elevation (ft)

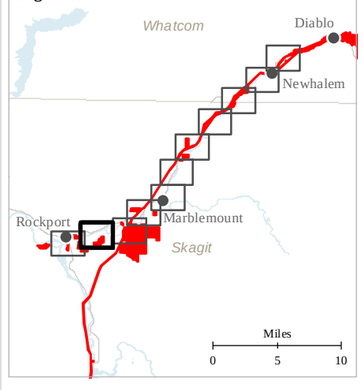
15
10
5
0
-5

Relative Elevation Map derived from a mosaic of multiple data sources including: 2017 topobathymetric lidar downstream of Marblemount, 2018 topobathymetric lidar upstream of Marblemount; and 2016 lidar covering remaining areas of the valley outside of the map extent for 2018 lidar. Selected void areas filled by NHC survey data.

PRM shown at 0.2-mi intervals

N

0 600 1,200 Feet



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GE-04 GEOMORPHOLOGY STUDY RELATIVE ELEVATION - SHEET 11

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary

Relative Elevation (ft)

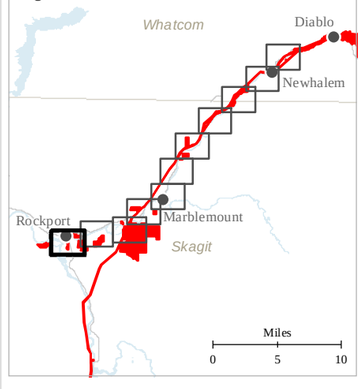
15
10
5
0
-5

Relative Elevation Map derived from a mosaic of multiple data sources including: 2017 topobathymetric lidar downstream of Marblemount, 2018 topobathymetric lidar upstream of Marblemount; and 2016 lidar covering remaining areas of the valley outside of the map extent for 2018 lidar. Selected void areas filled by NHC survey data.

PRM shown at 0.2-mi intervals

N

0 600 1,200 Feet



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SKAGIT RIVER GEOMORPHOLOGY BETWEEN GORGE DAM AND THE SAUK RIVER STUDY REPORT

ATTACHMENT E

HISTORICAL CHANNEL CHANGES MAPBOOK

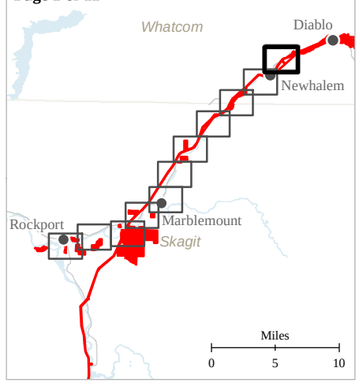
GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1915 MAP* - SHEET 1

+ Project River Miles (PRM)

*1915 topographic maps from USGS mosaiced and overlaid with hillshade derived from composite of 2016-2018 lidar

0 600 1,200 Feet

Page 1 of 11



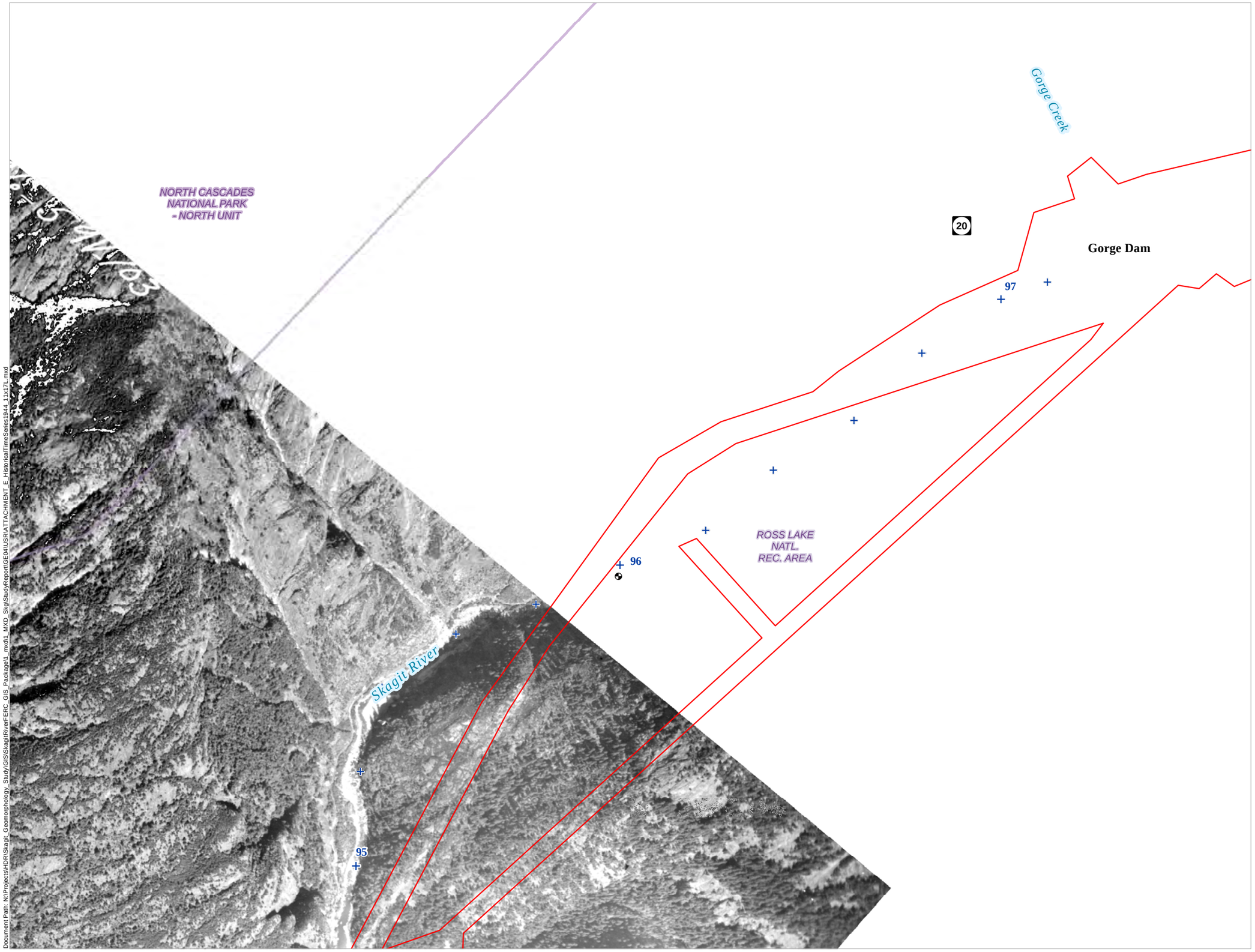
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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1944 - SHEET 1



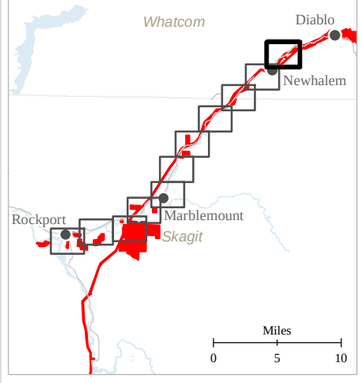
- FERC Project Boundary
- Project River Miles (PRM)
- Stream Gage (USGS)
- National Park / National Recreation Area Boundary

Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet



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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1963/64 - SHEET 1

- FERC Project Boundary
- Project River Miles (PRM)
- Stream Gage (USGS)
- National Park / National Recreation Area Boundary

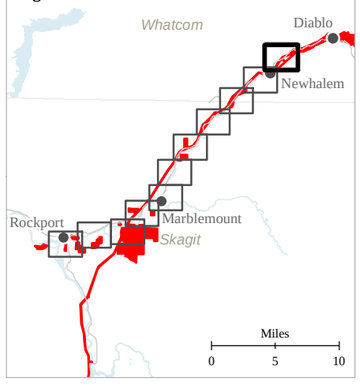
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

Page 1 of 11



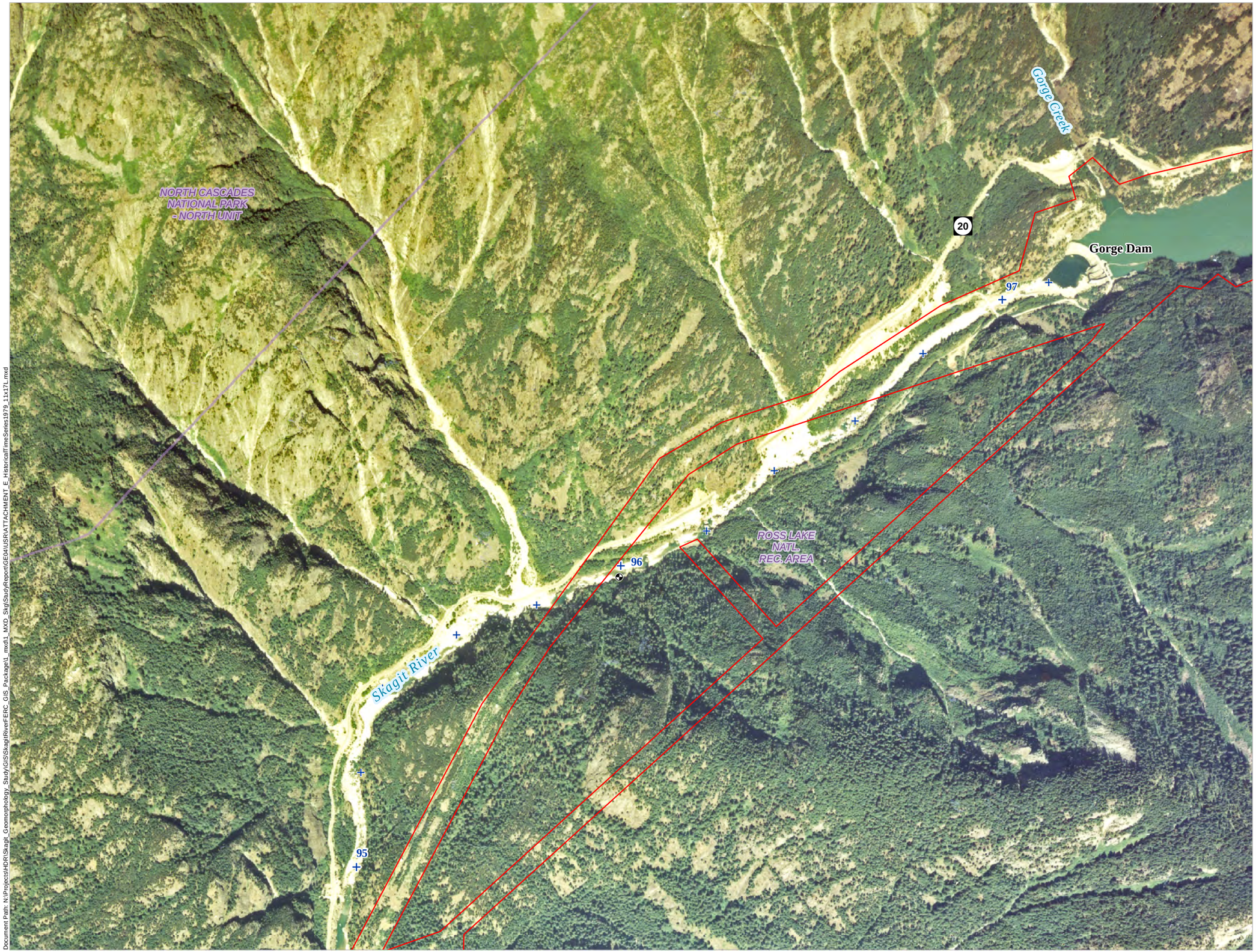
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GE-04 GEOMORPHOLOGY STUDY HISTORICAL TIME SERIES 1978/79 - SHEET 1



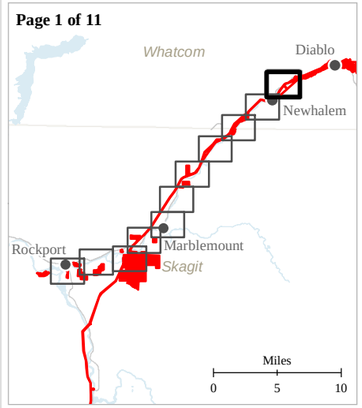
- FERC Project Boundary
- Project River Miles (PRM)
- Stream Gage (USGS)
- National Park / National Recreation Area Boundary

Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

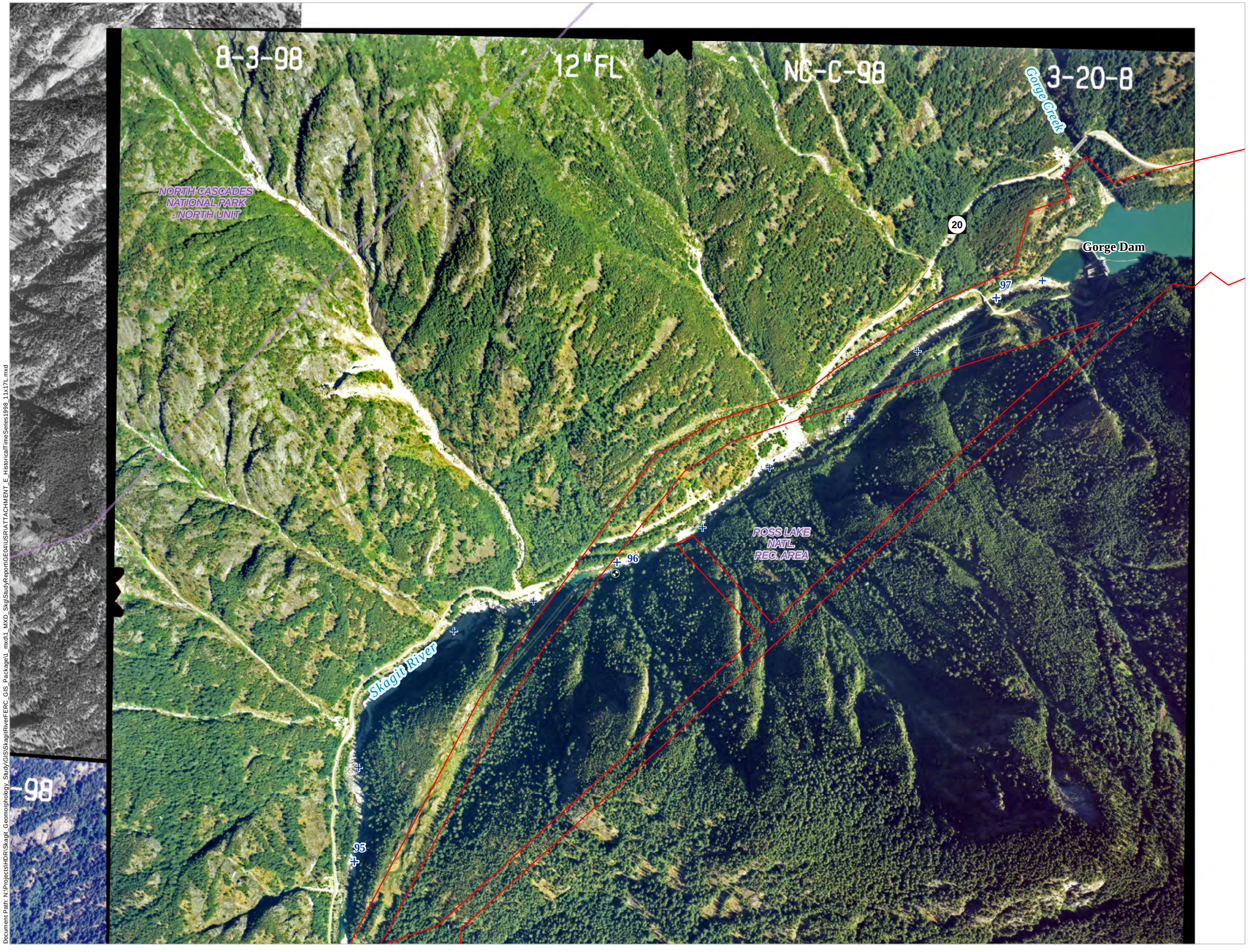


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GE-04 GEOMORPHOLOGY STUDY HISTORICAL TIME SERIES 1998 - SHEET 1

- FERC Project Boundary
- Project River Miles (PRM)
- Stream Gage (USGS)
- National Park / National Recreation Area Boundary

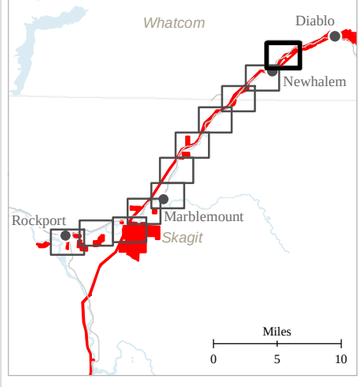
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

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GE-04 GEOMORPHOLOGY STUDY HISTORICAL TIME SERIES 2006 - SHEET 1



- FERC Project Boundary
- Project River Miles (PRM)
- Stream Gage (USGS)
- National Park / National Recreation Area Boundary

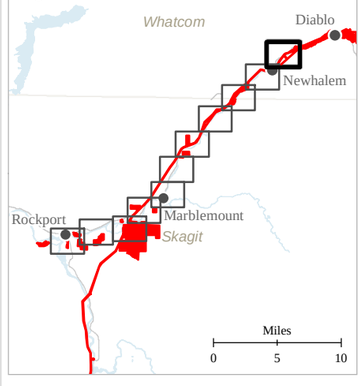
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

Page 1 of 11



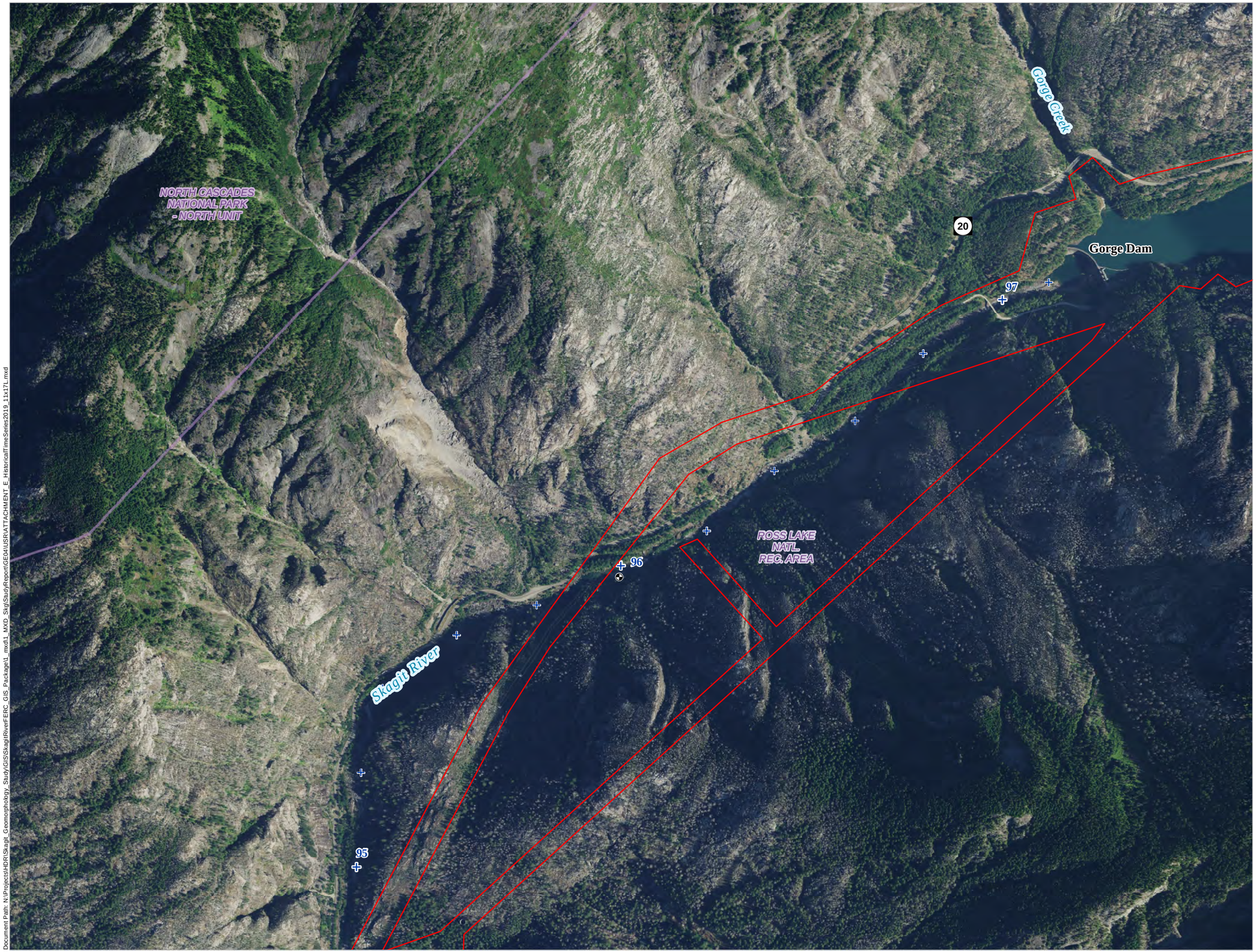
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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
2019 - SHEET 1



- FERC Project Boundary
- Project River Miles (PRM)
- Stream Gage (USGS)
- National Park / National Recreation Area Boundary

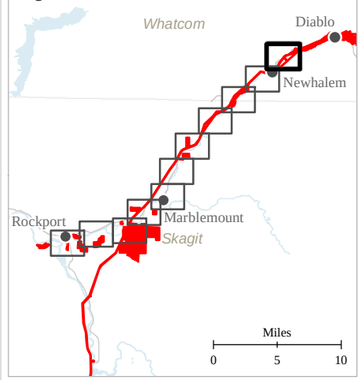
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

Page 1 of 11



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GE-04 GEOMORPHOLOGY STUDY HISTORICAL TIME SERIES 1915 MAP* - SHEET 2

+ Project River Miles (PRM)

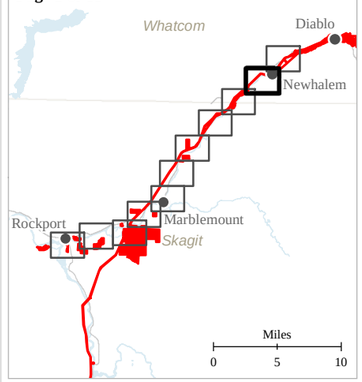
Reach Boundary

*1915 topographic maps from USGS mosaiced and overlaid with hillshade derived from composite of 2016-2018 lidar

N

0 600 1,200 Feet

Page 2 of 11



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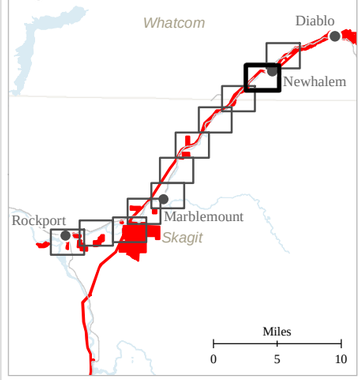
GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1944 - SHEET 2

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Stream Gage (USGS)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary

Channel Type

- Main Channel
- Braid Channel
- Side Channel

0 600 1,200 Feet



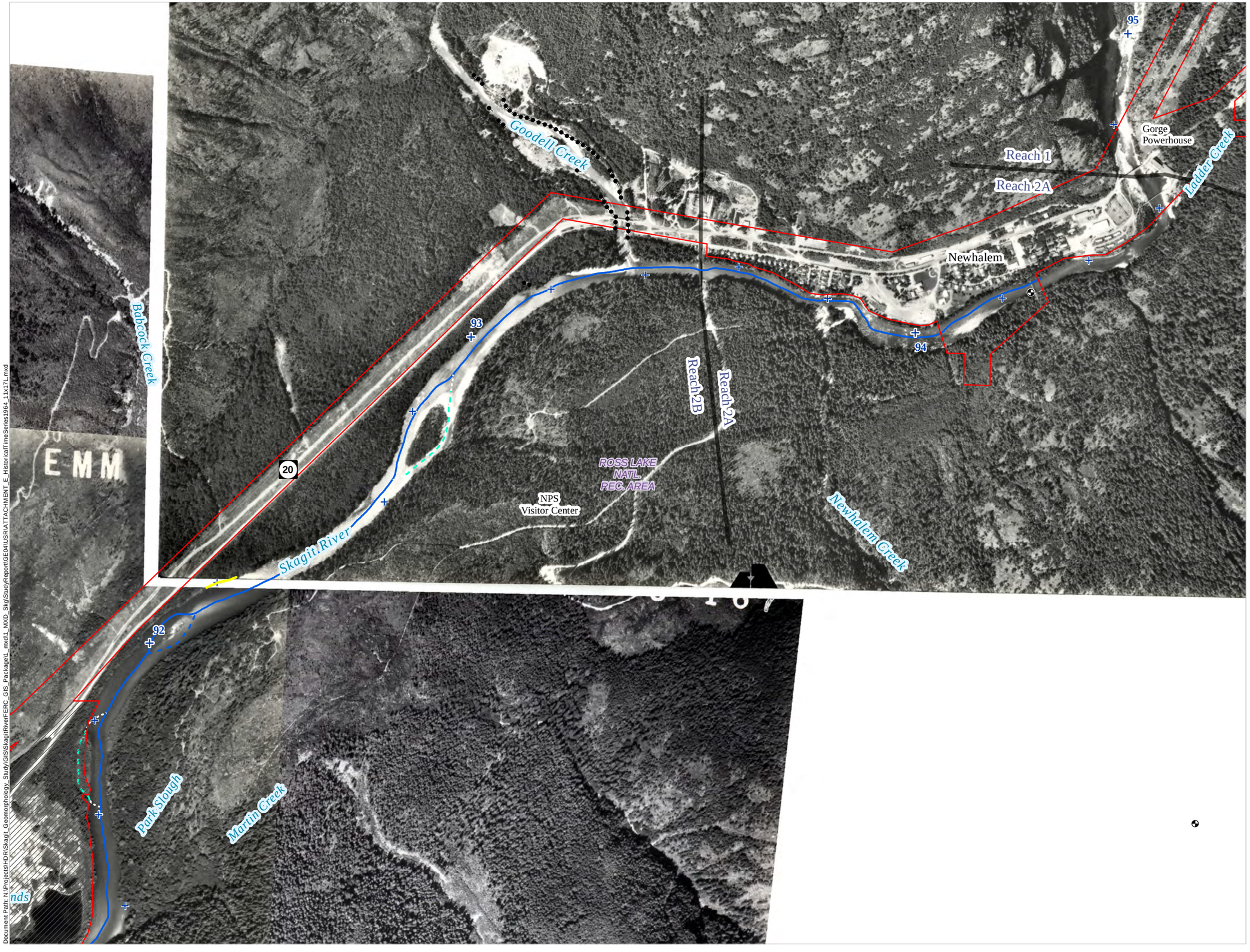
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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1963/64 - SHEET 2



- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Stream Gage (USGS)
- National Park / National Recreation Area Boundary
- Reach Boundary
- Eroding Bank 1944-1964

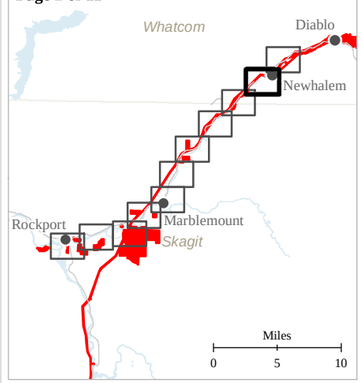
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1978/79 - SHEET 2

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Stream Gage (USGS)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 1964-1979

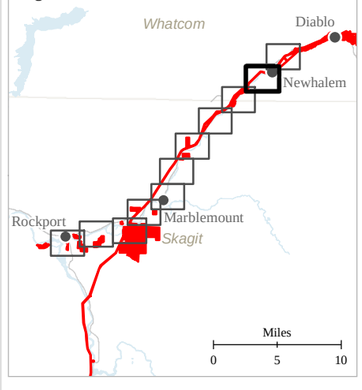
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

Page 2 of 11



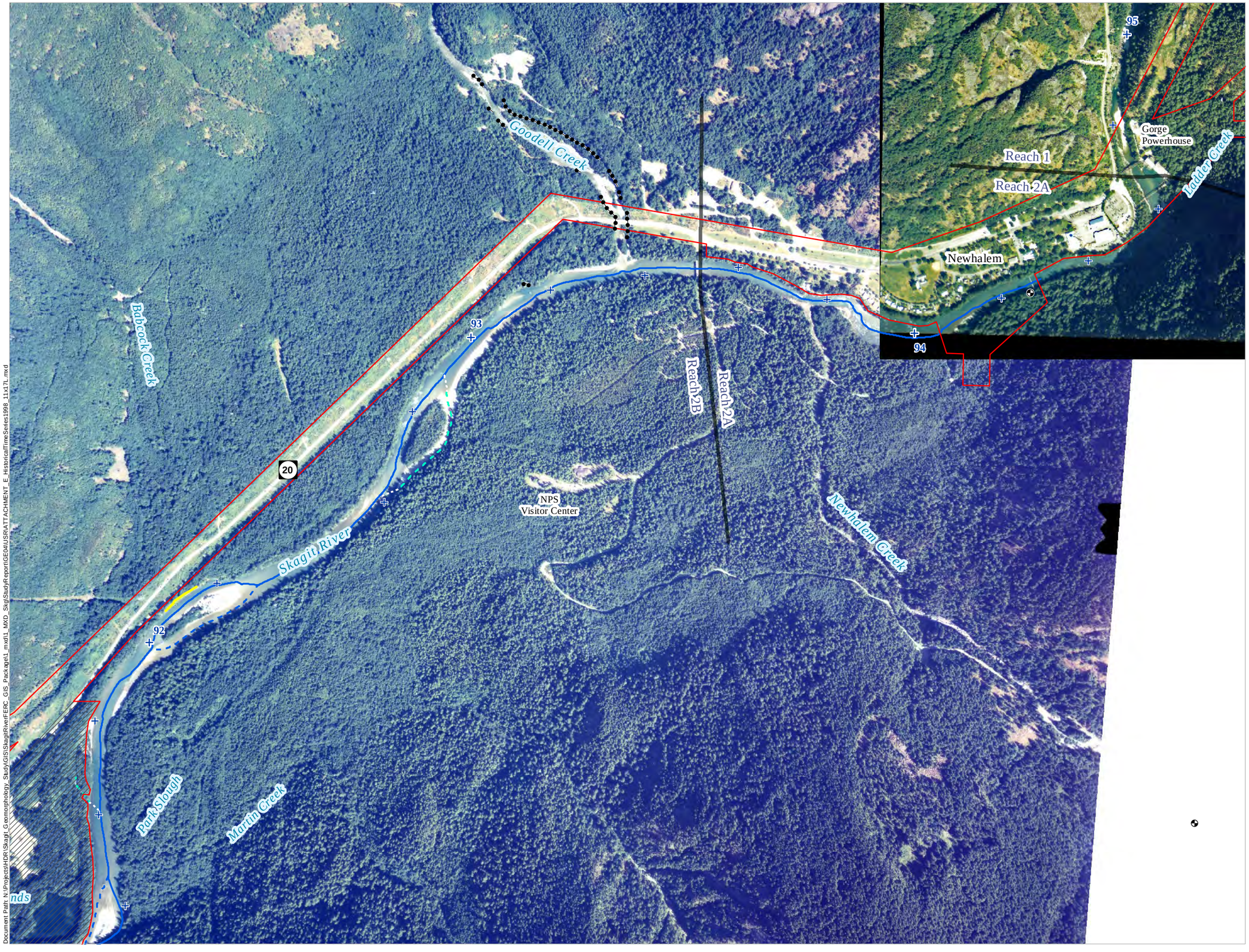
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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1998 - SHEET 2



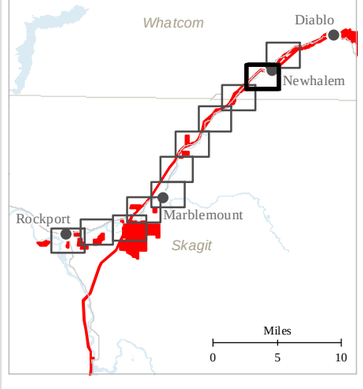
- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Stream Gage (USGS)
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 1979-1998

Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet



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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
2006 - SHEET 2

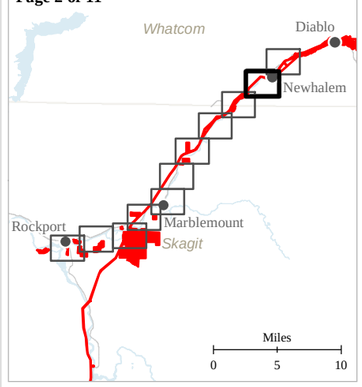
- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Stream Gage (USGS)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 1998-2006

Channel Type

- Main Channel
- Braid Channel
- Side Channel

0 600 1,200 Feet

Page 2 of 11



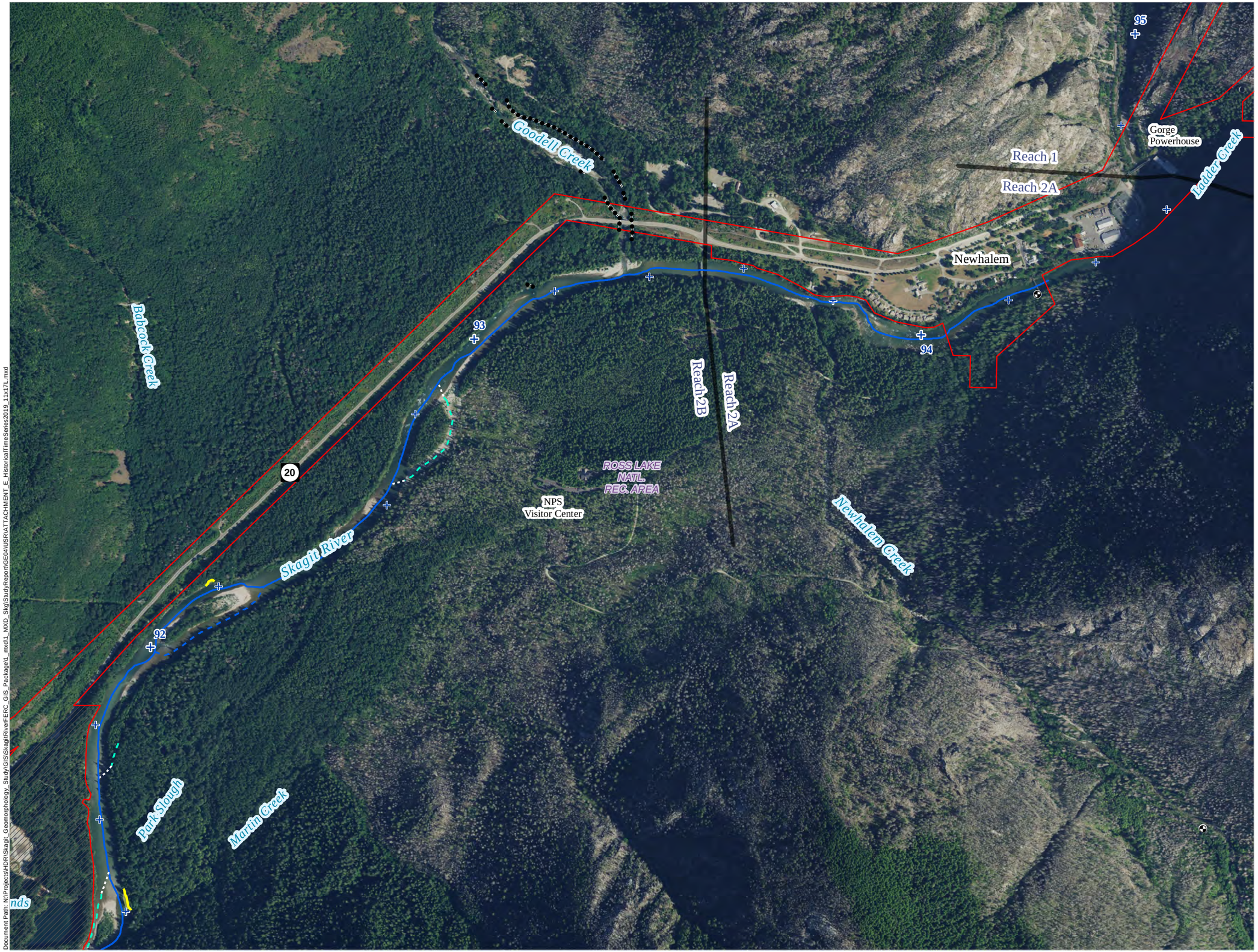
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GE-04 GEOMORPHOLOGY STUDY HISTORICAL TIME SERIES 2019 - SHEET 2

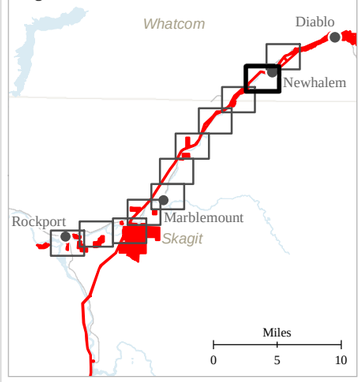


- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Stream Gage (USGS)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 2006-2019

Channel Type

- Main Channel
- Braid Channel
- Side Channel

0 600 1,200 Feet



Seattle City Light

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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL CHANNELS
1944-2019 - SHEET 2

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Stream Gage (USGS)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary

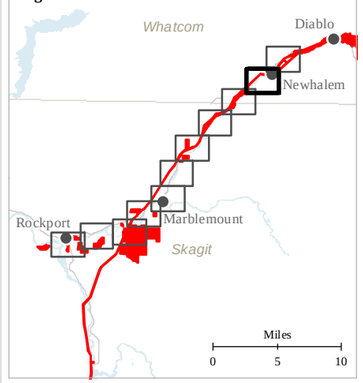
Historic Channels

- 2019
- 2006
- 1998
- 1978/79
- 1963/64
- 1944

N

0 600 1,200 Feet

Page 2 of 11



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Goodell Creek
Babcock Creek
Reach 1
Reach 2A
Reach 2B
Reach 2A
Gorge Powerhouse
Ladder Creek
Newhalem
95
94
93
92
20
ROSS LAKE NATL. REC. AREA
NPS Visitor Center
Newhalem Creek
Skagit River
Park Slough
Martin Creek
nds

GE-04
GEOMORPHOLOGY STUDY
HISTORICAL CHANNEL OCCUPANCY - SHEET 2

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Stream Gage (USGS)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary

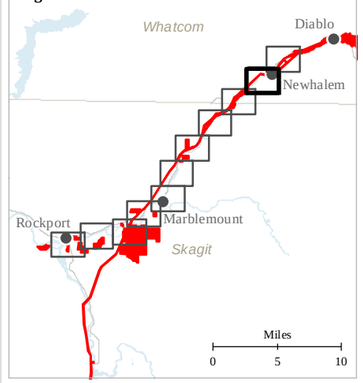
Historic Channel Occupancy
% of time 1944-2019

100%

0%

N

0 600 1,200 Feet



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Goodell Creek
Babcock Creek
Reach 1
Reach 2A
Reach 2B
Gorge Powerhouse
Ladder Creek
Newhalem
95
94
93
92
20
ROSS LAKE NATL. REC. AREA
NPS Visitor Center
Skagit River
Newhalem Creek
Park Slough
Martin Creek
nds

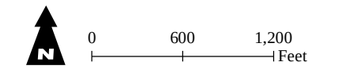
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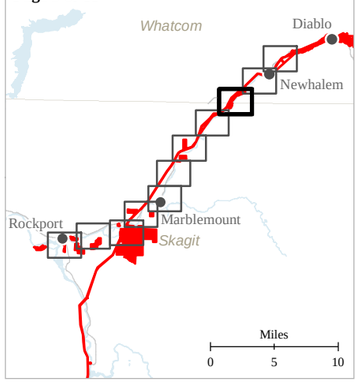
GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1915 MAP* - SHEET 3

+ Project River Miles (PRM)

Reach Boundary

*1915 topographic maps from USGS mosaiced and overlaid with hillshade derived from composite of 2016-2018 lidar





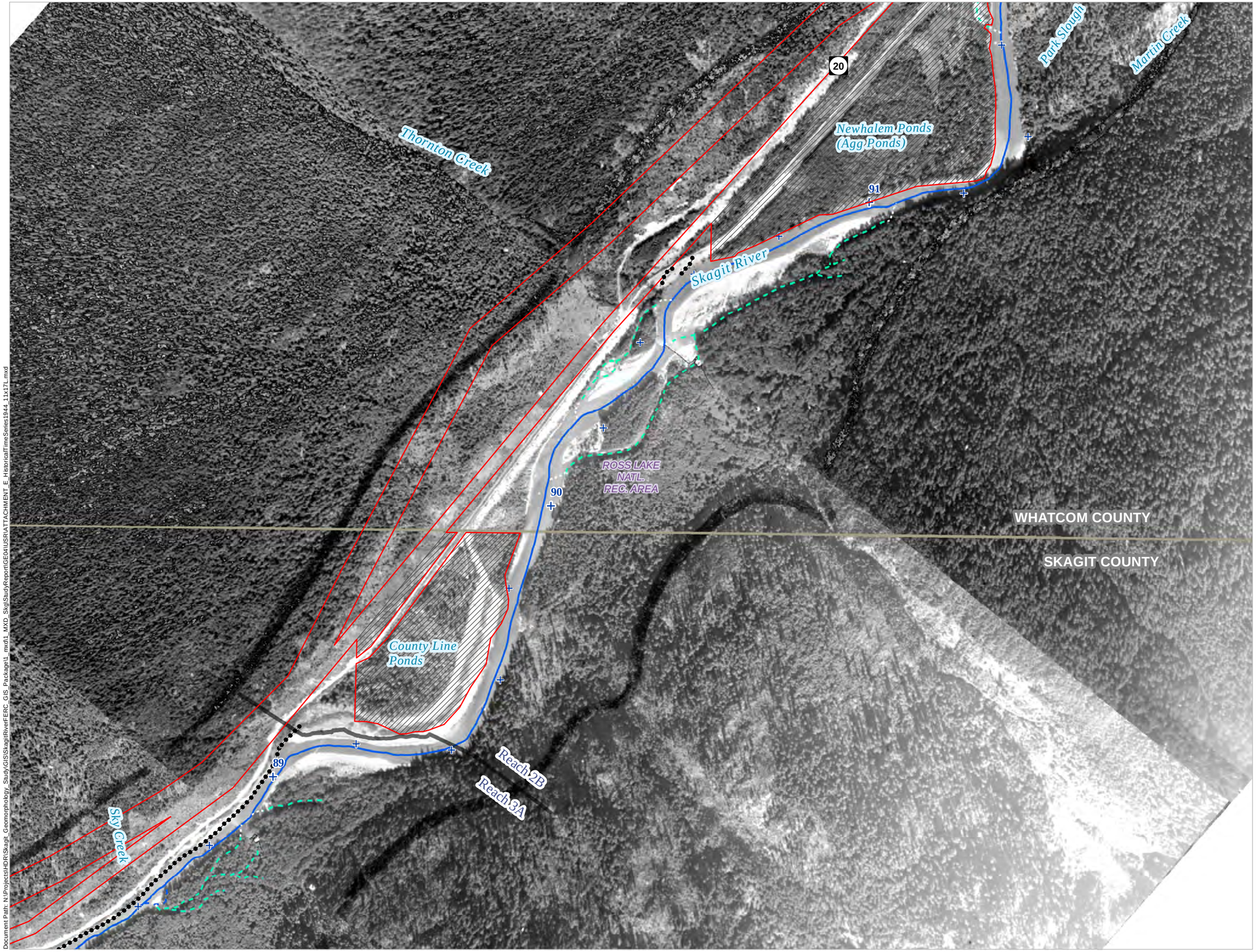
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GE-04 GEOMORPHOLOGY STUDY HISTORICAL TIME SERIES 1944 - SHEET 3



- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary

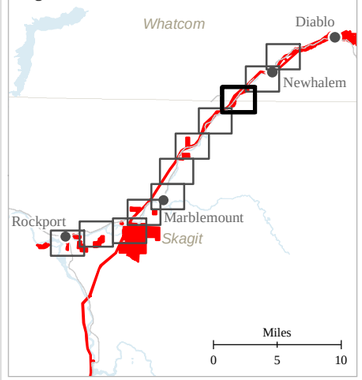
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

Page 3 of 11



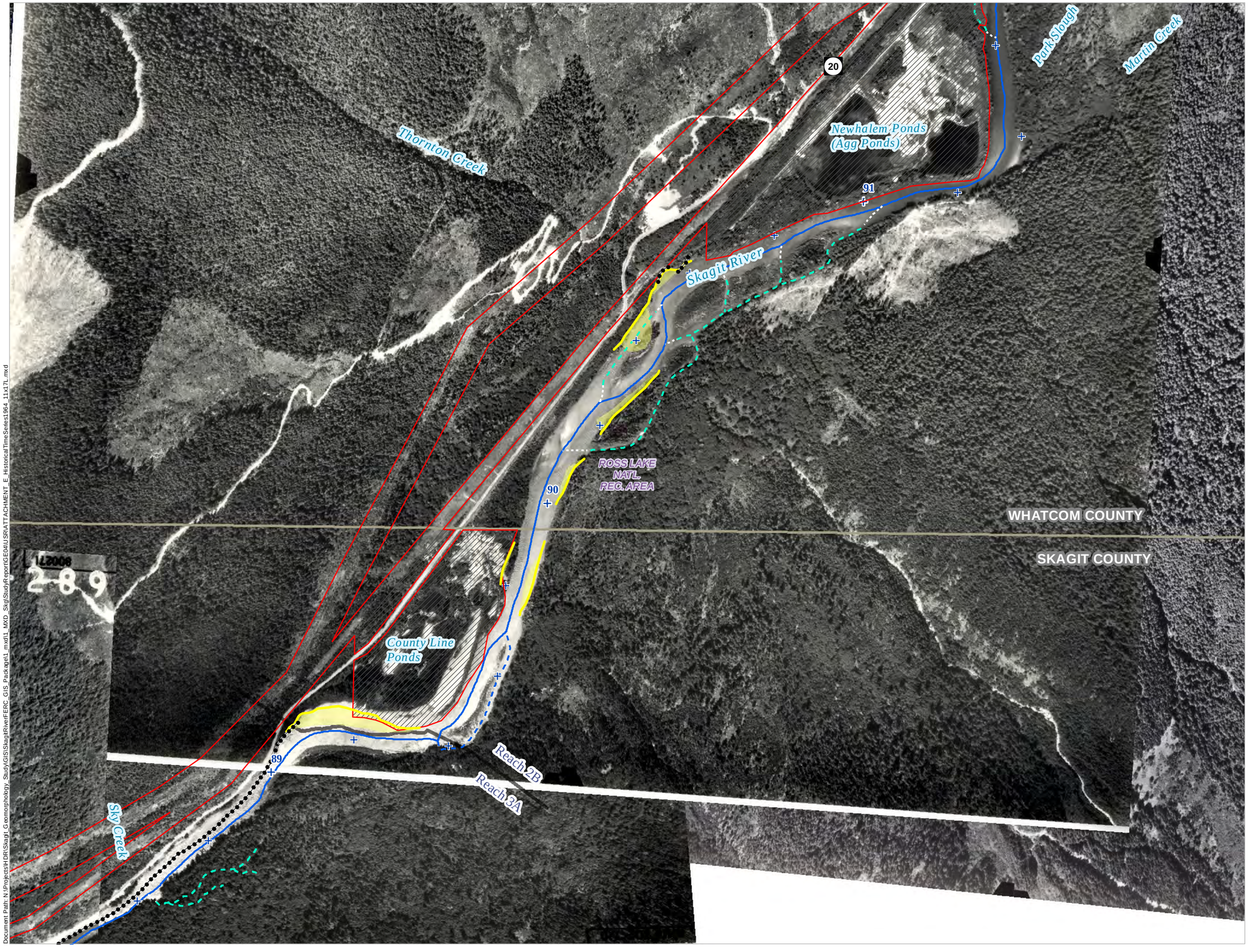
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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1963/64 - SHEET 3



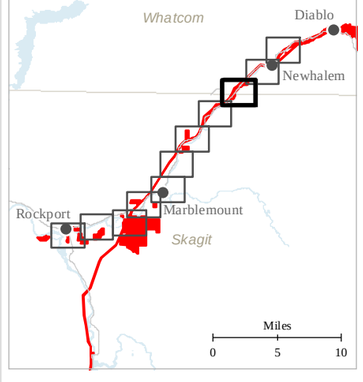
- FERC Project Boundary
- Mitigation Parcel
- \+ Project River Miles (PRM)
- National Park / National Recreation Area Boundary
- Reach Boundary
- Eroding Bank 1944-1964

Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet



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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1978/79 - SHEET 3

Thornton Creek
Newhalem Ponds
(Agg Ponds)
Park Slough
Martin Creek
Skagit River
ROSS LAKE
NATL.
REC. AREA
County Line
Ponds
Reach 2B
Reach 3A
Sky Creek
20
91
90
89
WHATCOM COUNTY
SKAGIT COUNTY

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary

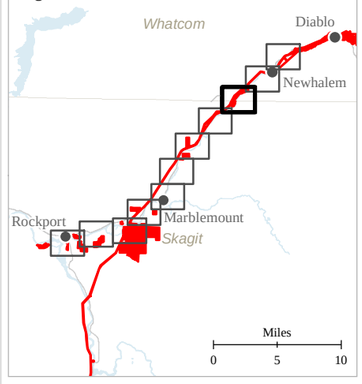
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

Page 3 of 11



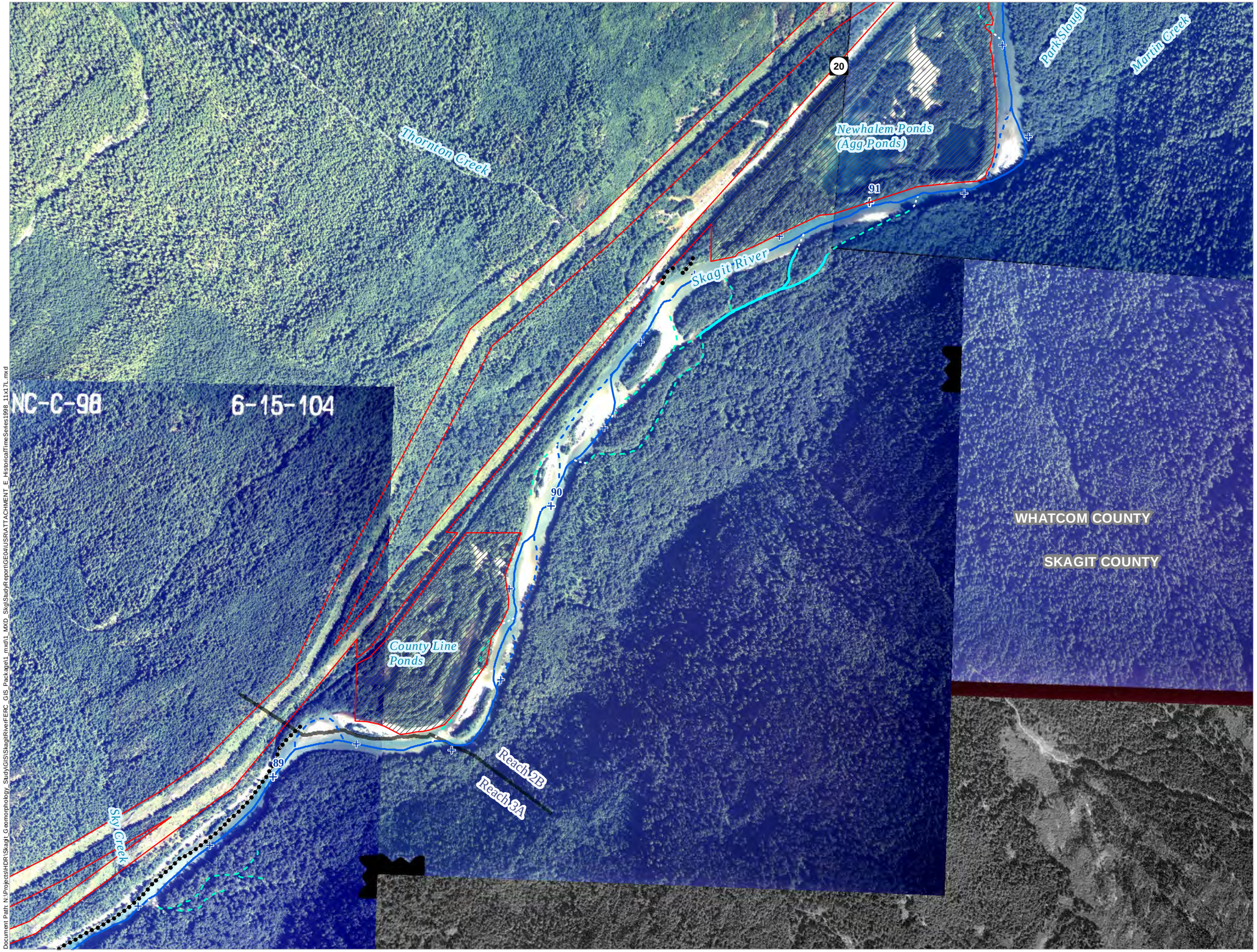
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GE-04 GEOMORPHOLOGY STUDY HISTORICAL TIME SERIES 1998 - SHEET 3



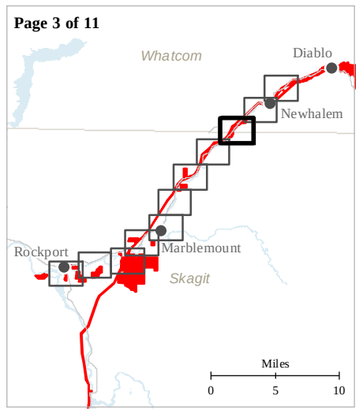
- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary

Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet



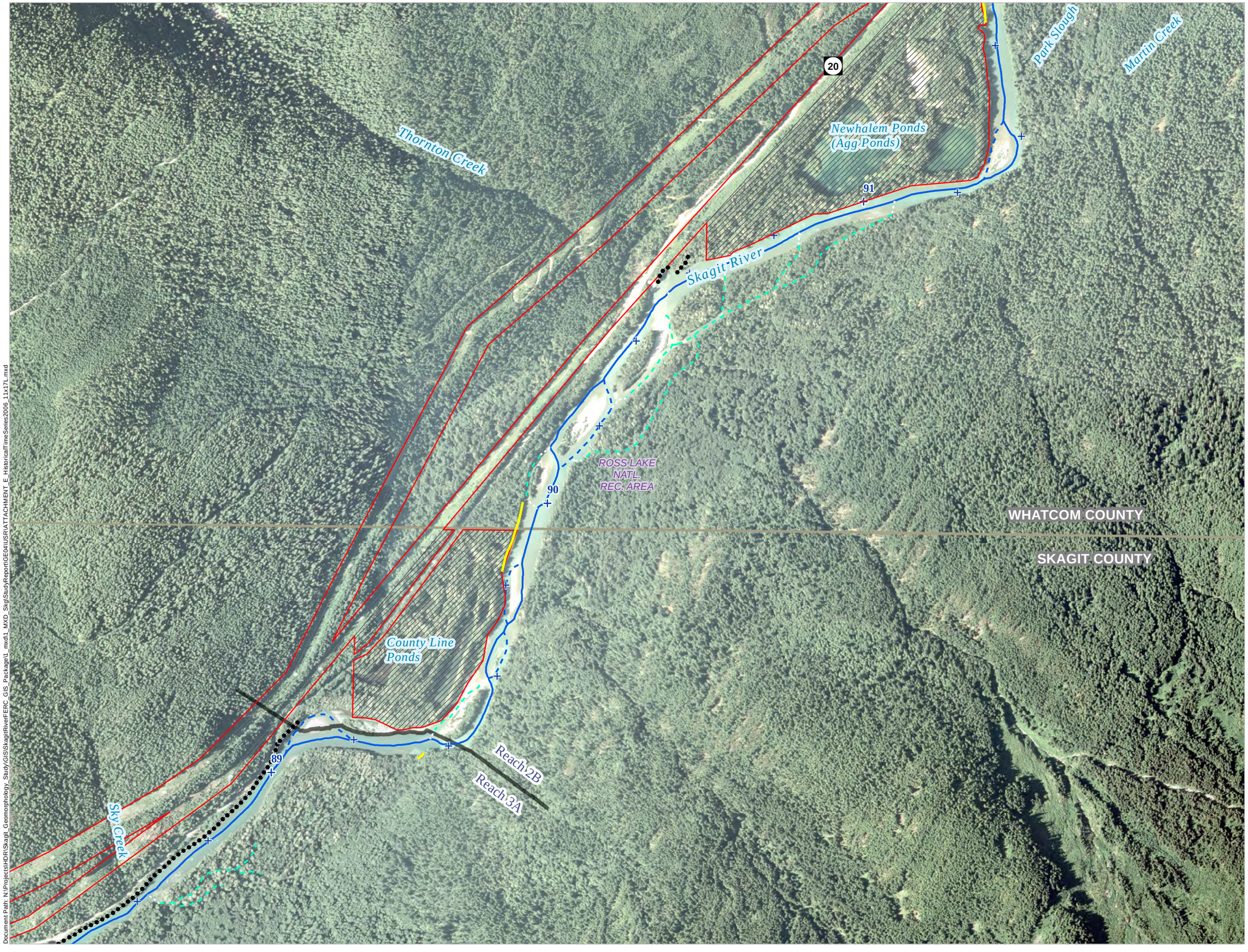
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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
2006 - SHEET 3



- FERC Project Boundary
- Mitigation Parcel
- \+ Project River Miles (PRM)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 1998-2006

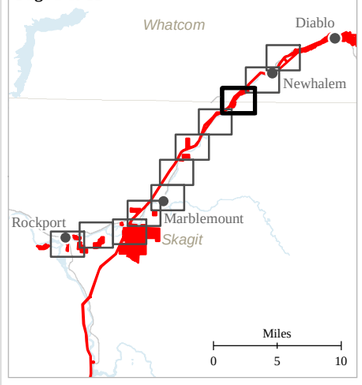
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

Page 3 of 11



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GE-04 GEOMORPHOLOGY STUDY HISTORICAL TIME SERIES 2019 - SHEET 3

Thornton Creek
Newhalem Ponds (Agg Ponds)
Park Slough
Martin Creek
20
91
Skagit River
ROSS LAKE NATL REC. AREA
90
WHATCOM COUNTY
SKAGIT COUNTY
County Line Ponds
89
Reach 2B
Reach 3A
Sky Creek

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 2006-2019

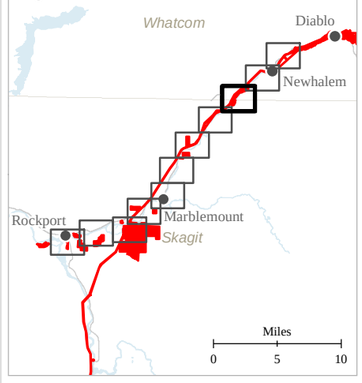
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

Page 3 of 11



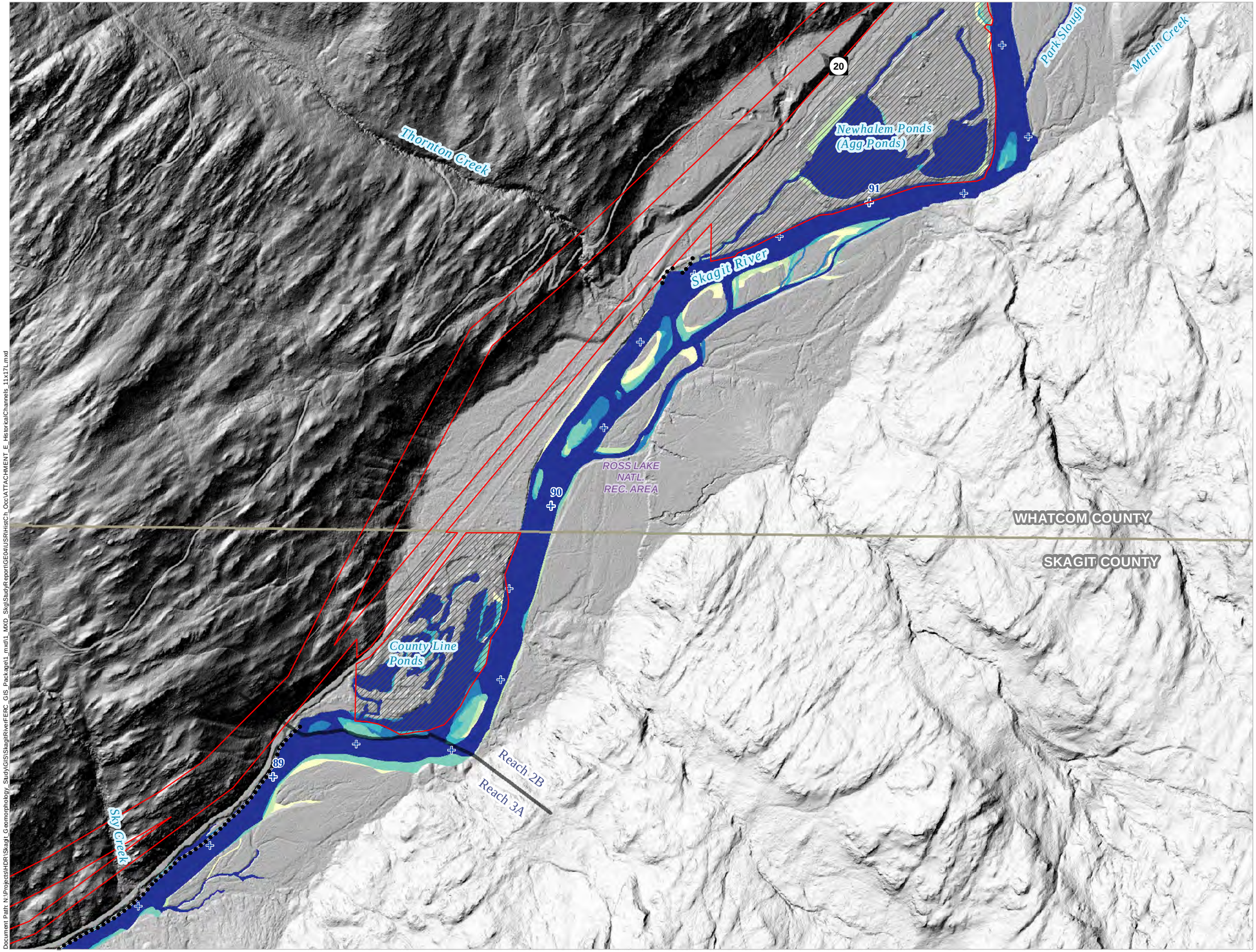
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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL CHANNELS
1944-2019 - SHEET 3



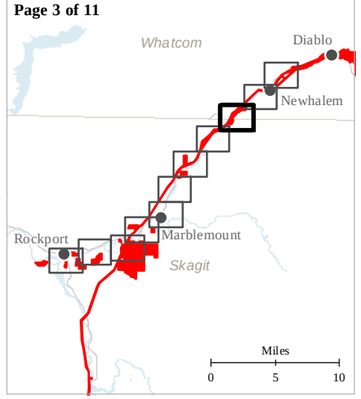
- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary

Historic Channels

- 2019
- 2006
- 1998
- 1978/79
- 1963/64
- 1944

N

0 600 1,200 Feet



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GE-04 GEOMORPHOLOGY STUDY HISTORICAL CHANNEL OCCUPANCY - SHEET 3

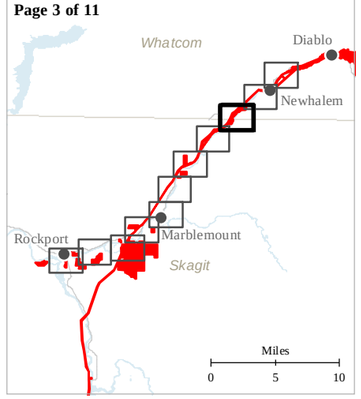
Thornton Creek
Newhalem Ponds (Agg Ponds)
Park Slough
Martin Creek
20
91
Skagit River
ROSS LAKE NATL. REC. AREA
90
WHATCOM COUNTY
SKAGIT COUNTY
County Line Ponds
89
Reach 2B
Reach 3A
Sky Creek

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary

Historic Channel Occupancy
% of time 1944-2019

100%
0%

N
0 600 1,200 Feet



Seattle City Light

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GE-04 GEOMORPHOLOGY STUDY HISTORICAL TIME SERIES 1915 MAP* - SHEET 4

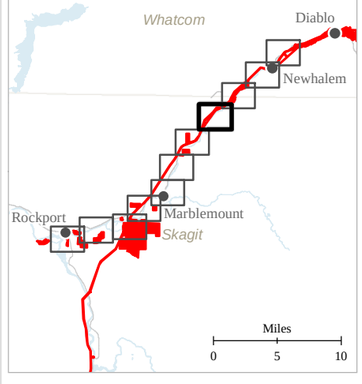
+ Project River Miles (PRM)

Reach Boundary

*1915 topographic maps from USGS mosaiced and overlaid with hillshade derived from composite of 2016-2018 lidar

N

0 600 1,200 Feet



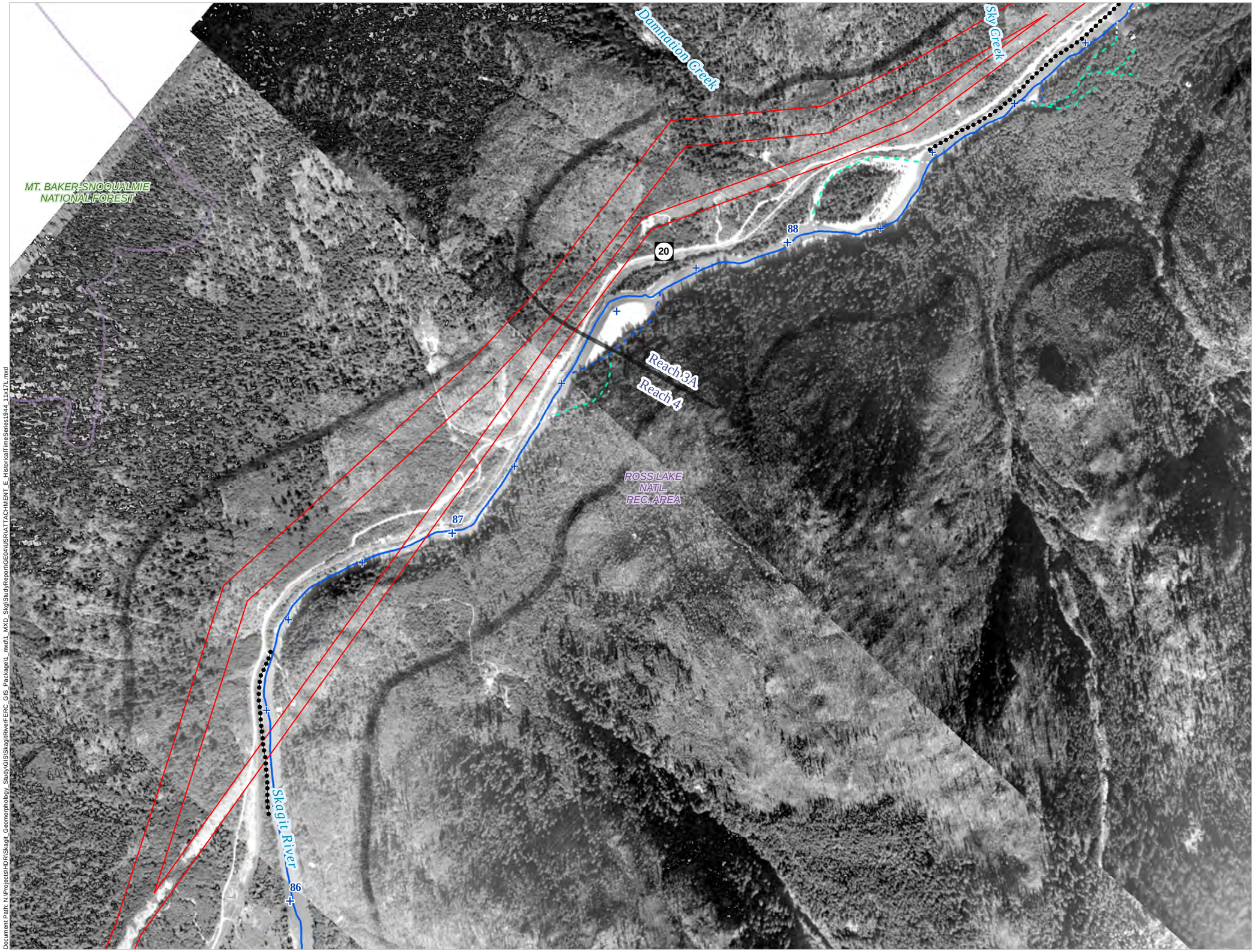
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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1944 - SHEET 4



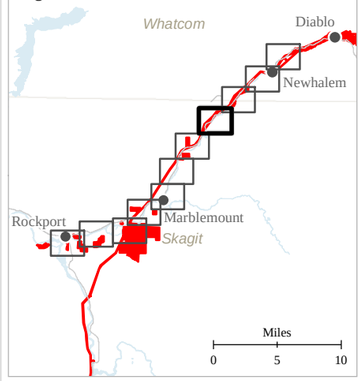
- FERC Project Boundary
- Project River Miles (PRM)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary

Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet



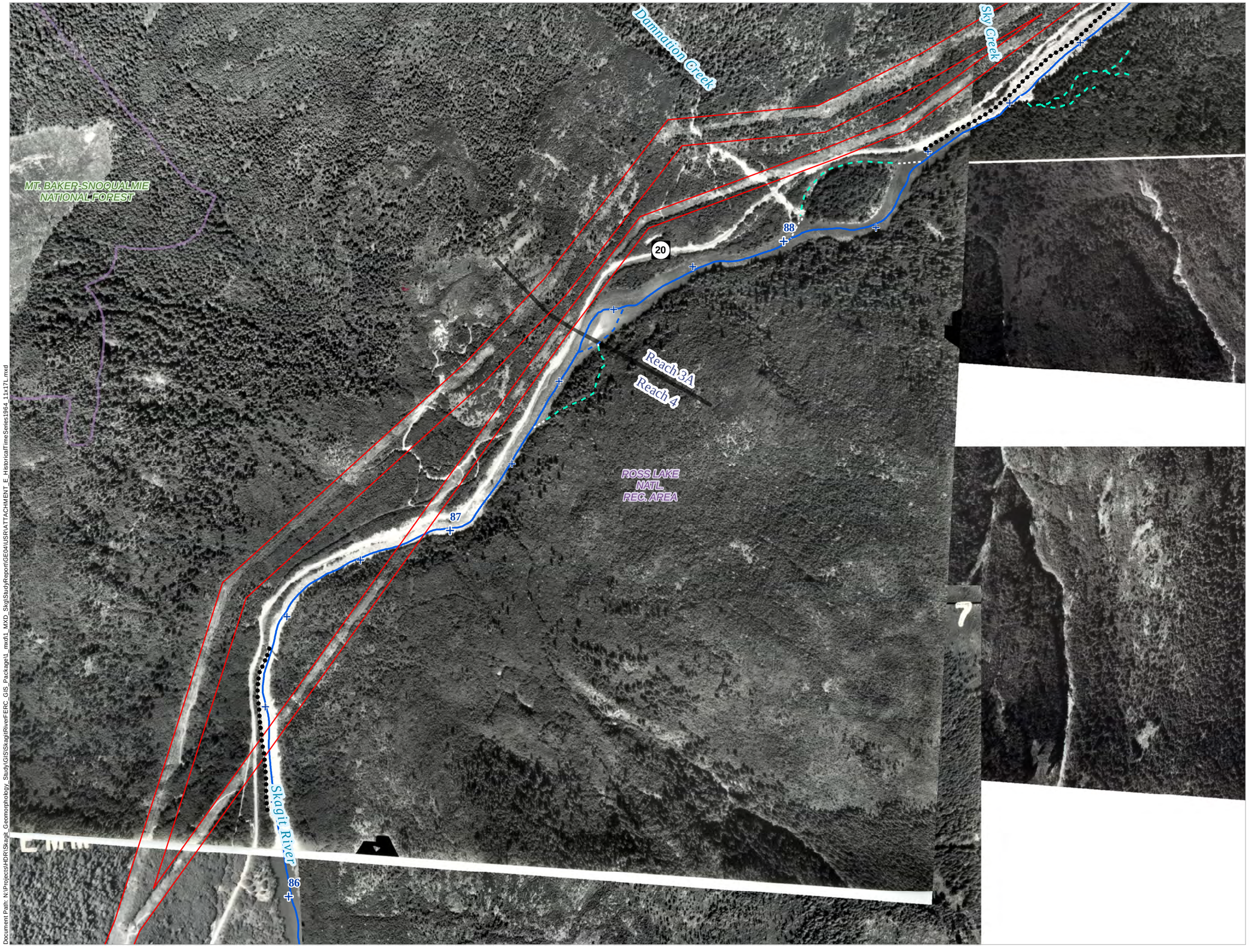
Seattle City Light

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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1963/64 - SHEET 4



- FERC Project Boundary
- Project River Miles (PRM)
- National Park / National Recreation Area Boundary
- Reach Boundary

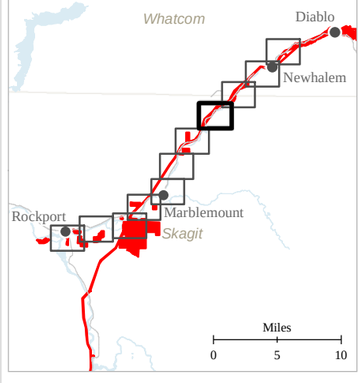
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

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GE-04 GEOMORPHOLOGY STUDY HISTORICAL TIME SERIES 1978/79 - SHEET 4

Damnation Creek

Sky Creek

MT. BAKER-SNOQUALMIE NATIONAL FOREST

ROSS LAKE NATL. REC. AREA

Reach 3A

Reach 4

Skagit River

20

86

87

88

- FERC Project Boundary
- Project River Miles (PRM)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 1964-1979

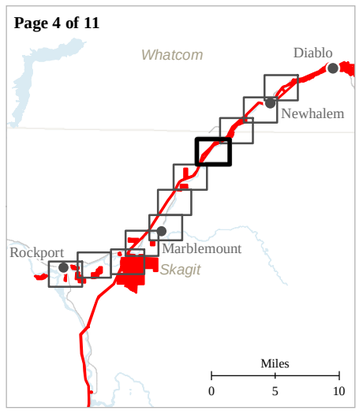
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

Page 4 of 11

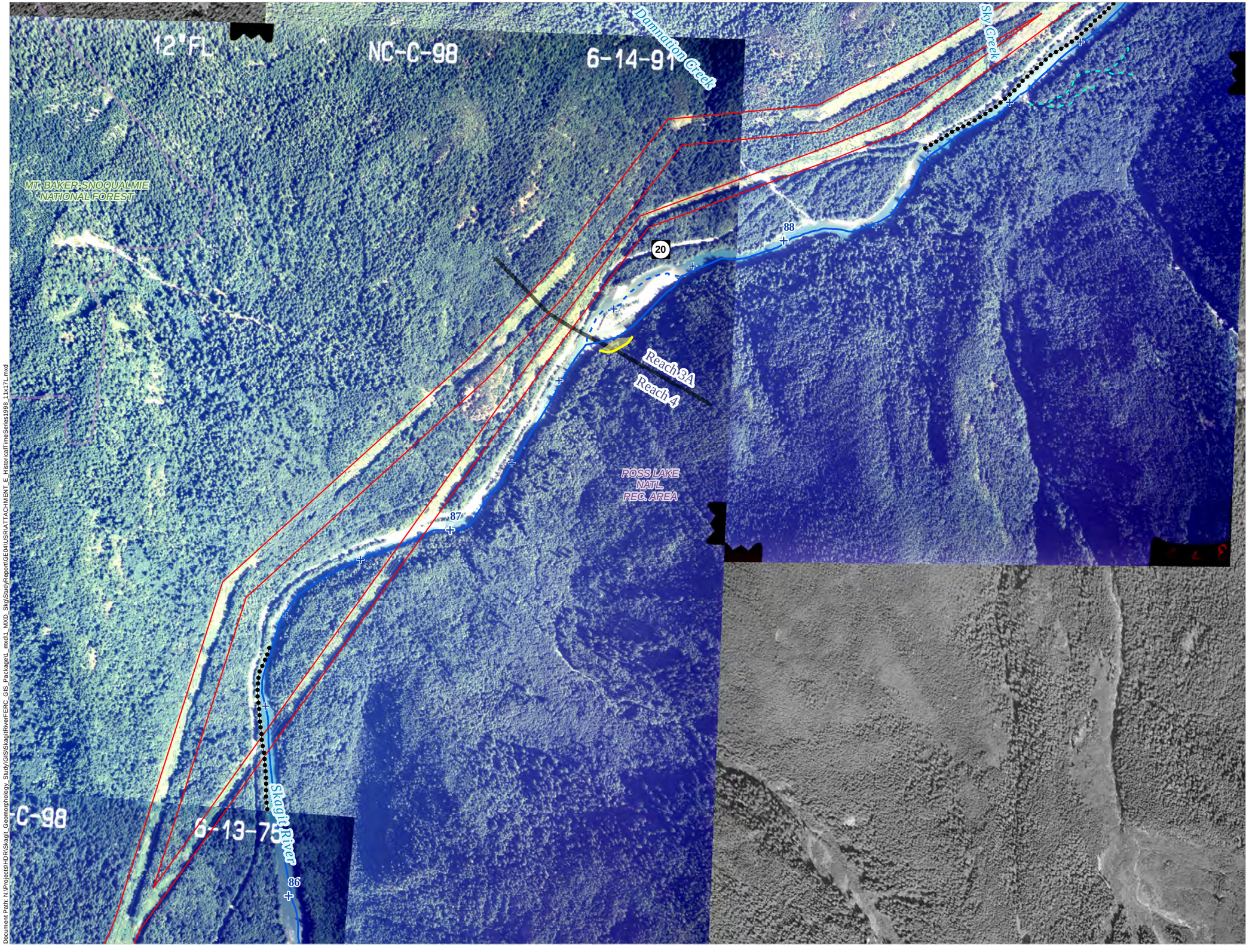


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GE-04 GEOMORPHOLOGY STUDY HISTORICAL TIME SERIES 1998 - SHEET 4

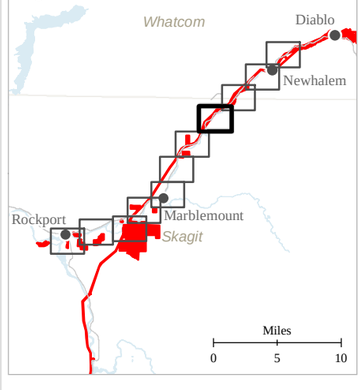
- FERC Project Boundary
- Project River Miles (PRM)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 1979-1998

Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet



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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
2006 - SHEET 4



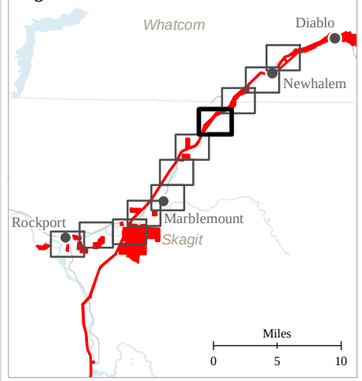
- FERC Project Boundary
- Project River Miles (PRM)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary

Channel Type

- Main Channel
- Braid Channel
- Side Channel

0 600 1,200 Feet

Page 4 of 11



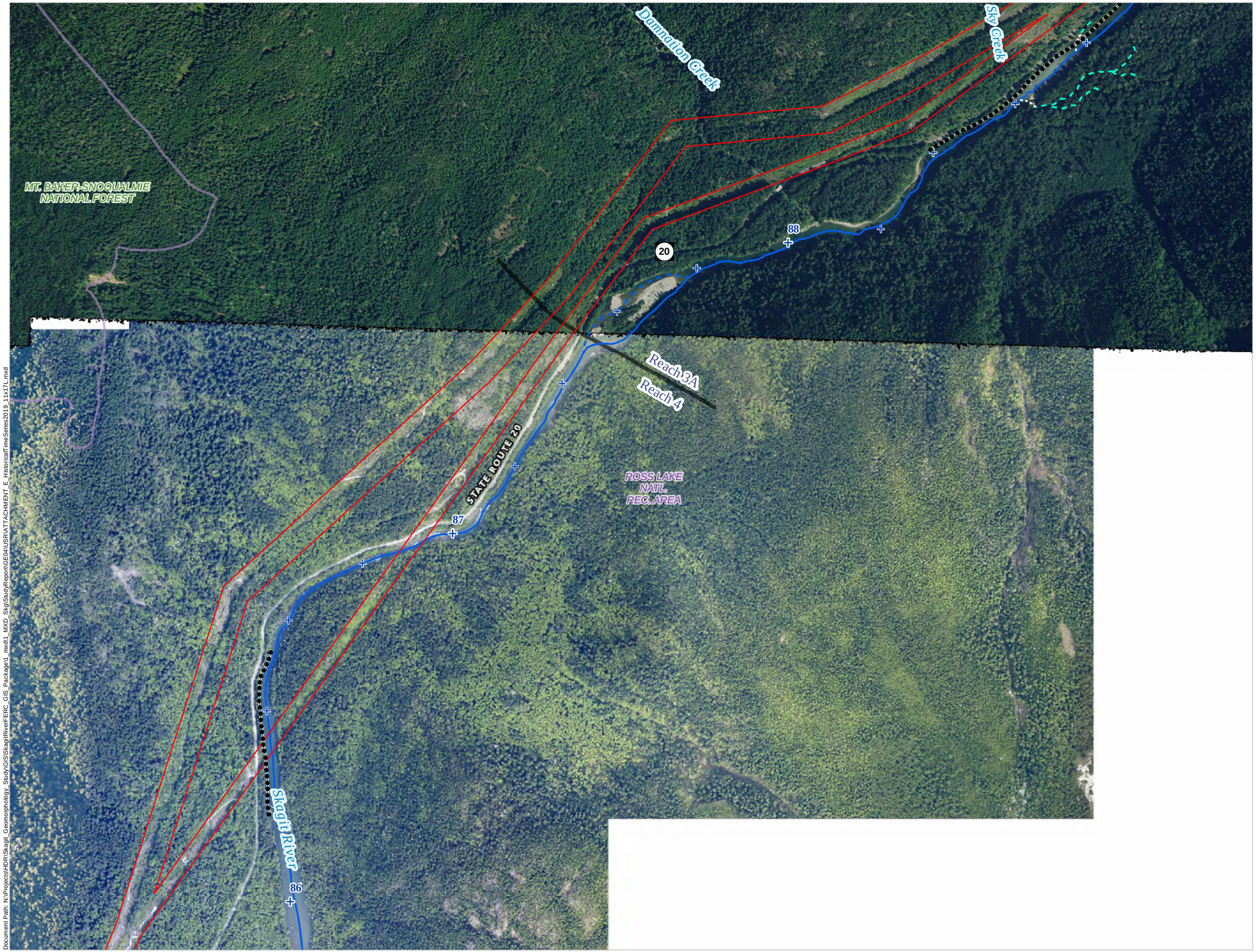
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GE-04 GEOMORPHOLOGY STUDY HISTORICAL TIME SERIES 2019 - SHEET 4



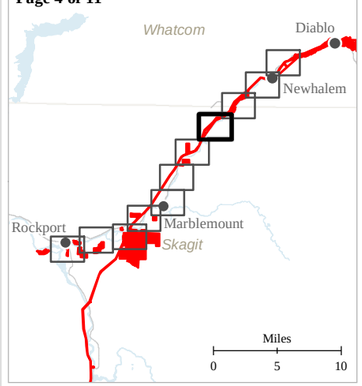
- FERC Project Boundary
- Project River Miles (PRM)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary

Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet



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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL CHANNELS
1944-2019 - SHEET 4

Damnation Creek

Sky Creek

MT. BAKER-SNOQUALMIE NATIONAL FOREST

ROSS LAKE NATL. REC.-AREA

Reach 3A

Reach 4

Skagit River

88

87

86

20

FERC Project Boundary

Project River Miles (PRM)

National Park / National Recreation Area Boundary

Hydromodified Banks

Reach Boundary

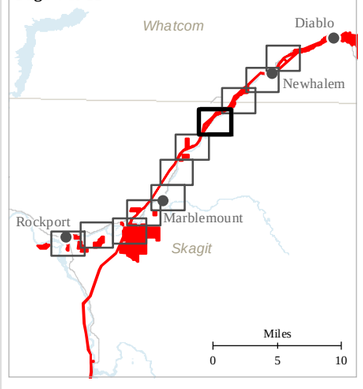
Historic Channels

- 2019
- 2006
- 1998
- 1978/79
- 1963/64
- 1944

N

0 600 1,200 Feet

Page 4 of 11



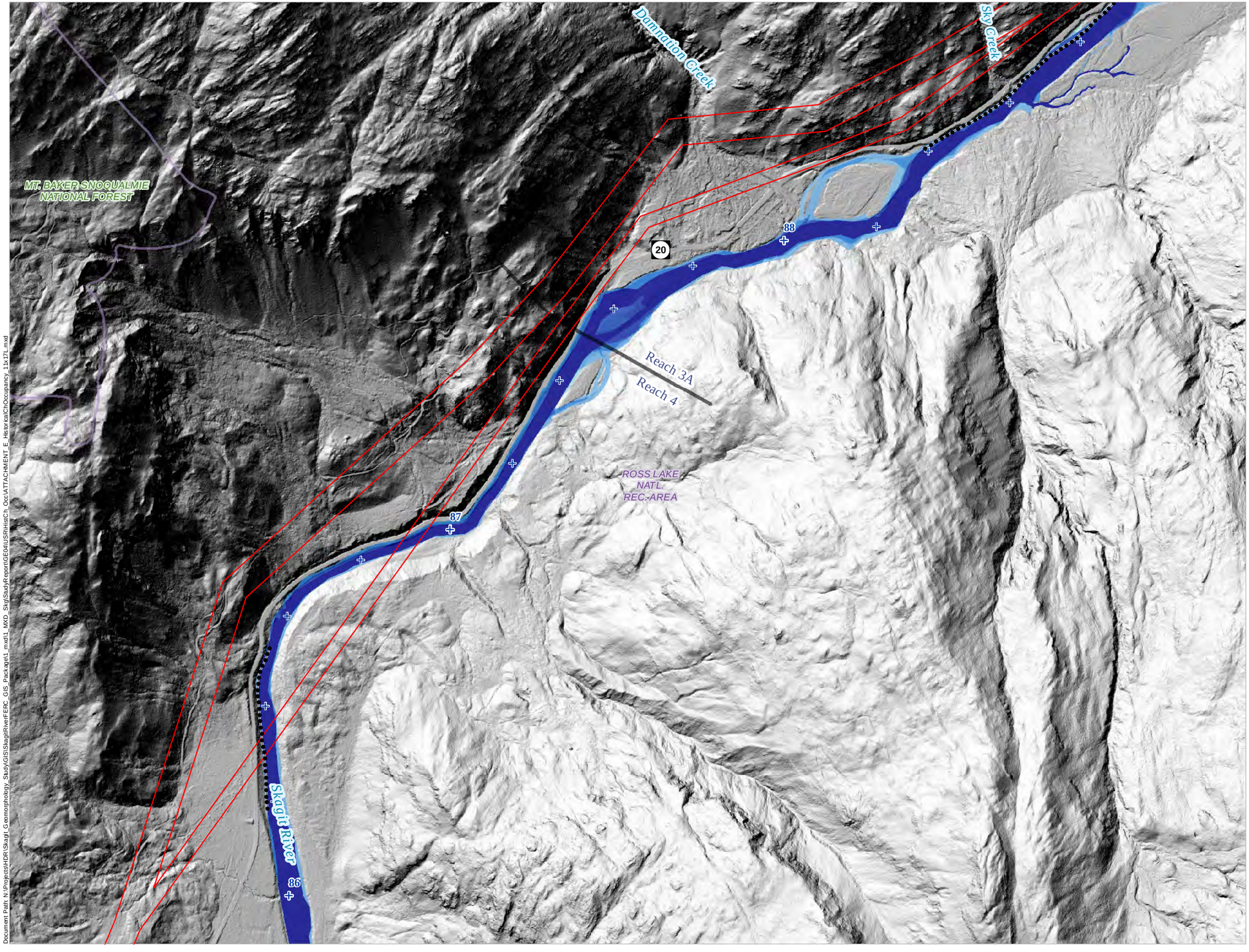
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GE-04 GEOMORPHOLOGY STUDY HISTORICAL CHANNEL OCCUPANCY - SHEET 4



- FERC Project Boundary
- Project River Miles (PRM)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary

Historic Channel Occupancy
% of time 1944-2019

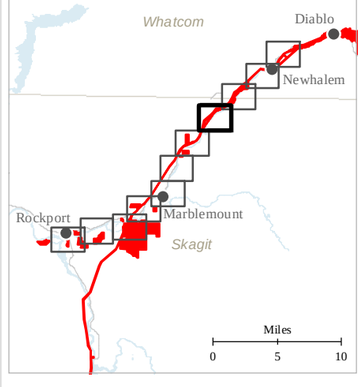
100%

0%

N

0 600 1,200 Feet

Page 4 of 11



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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1915 MAP* - SHEET 5

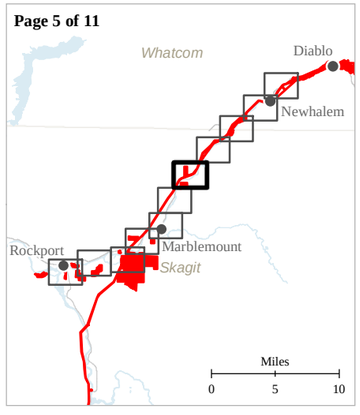
+ Project River Miles (PRM)

Reach Boundary

*1915 topographic maps from USGS mosaiced and overlaid with hillshade derived from composite of 2016-2018 lidar

N

0 600 1,200 Feet



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GE-04 GEOMORPHOLOGY STUDY HISTORICAL TIME SERIES 1944 - SHEET 5

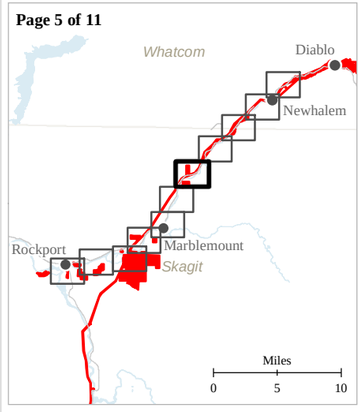
- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary

Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet



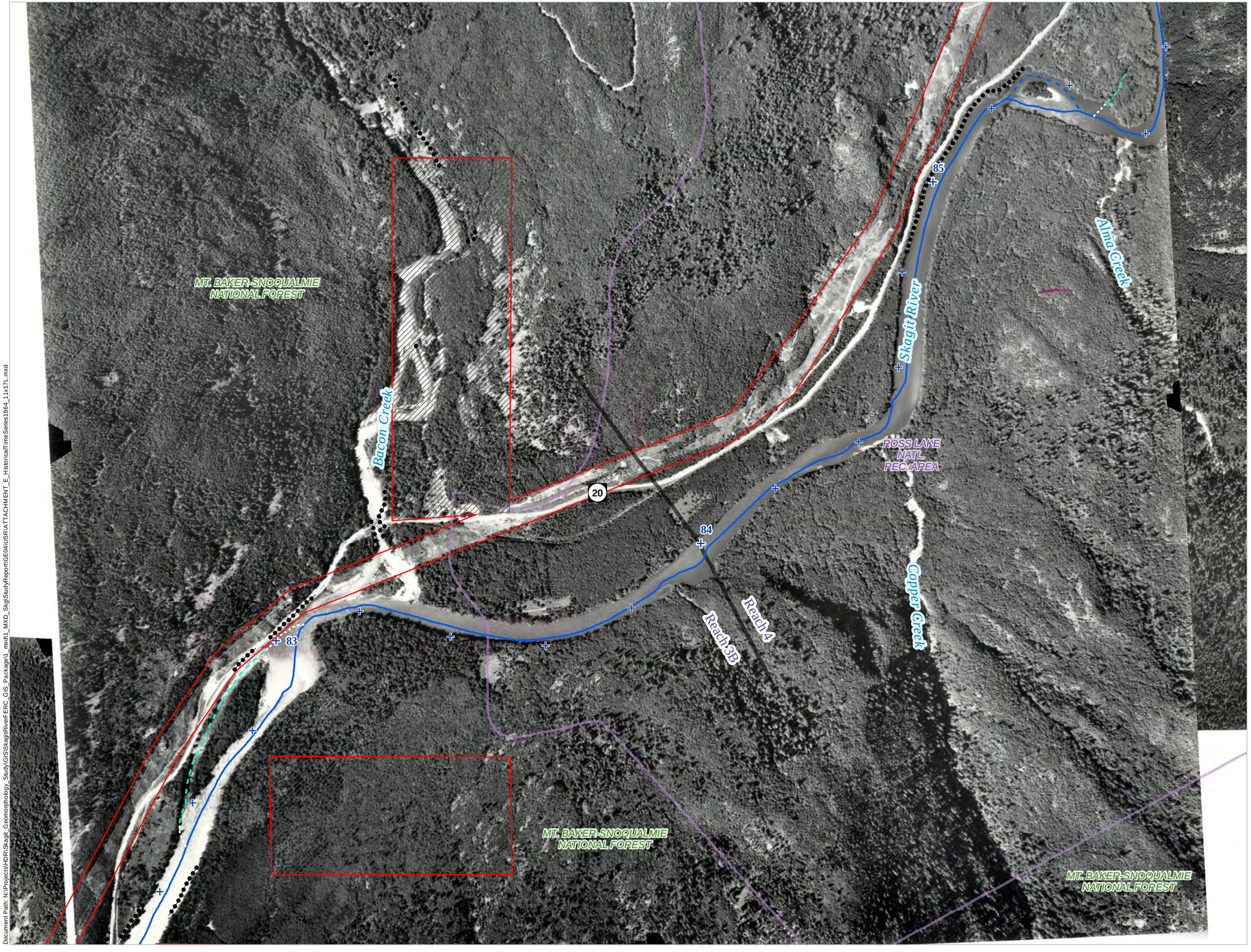
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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1963/64 - SHEET 5



- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- National Park / National Recreation Area Boundary
- Reach Boundary

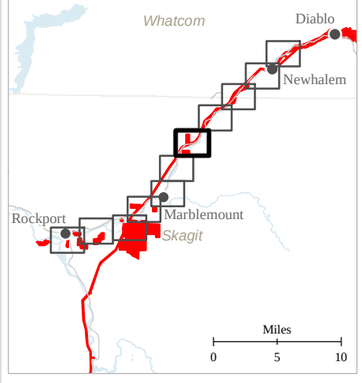
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

Page 5 of 11



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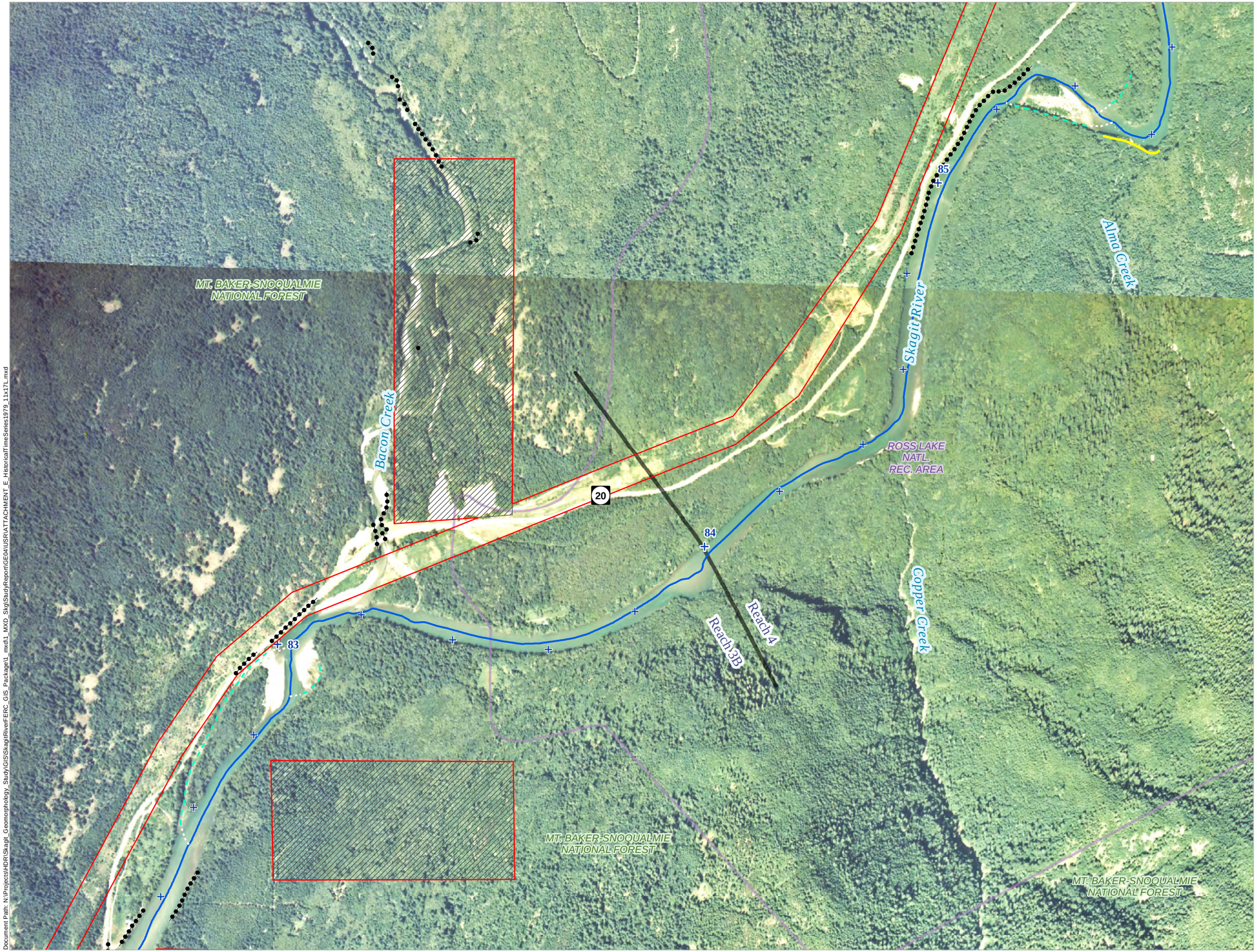
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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1978/79 - SHEET 5

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 1964-1979

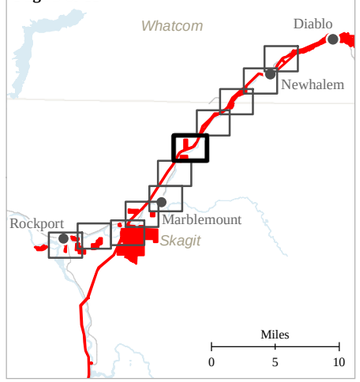
Channel Type

- Main Channel
- Braid Channel
- Side Channel



N

0 600 1,200 Feet



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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1998 - SHEET 5

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 1979-1998

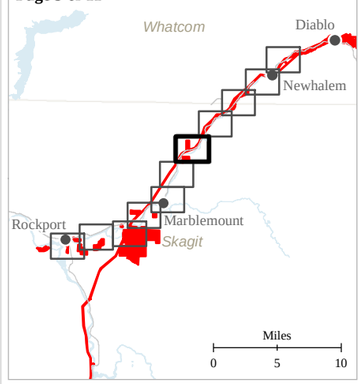
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

Page 5 of 11



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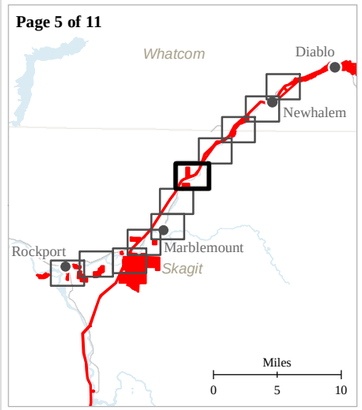
GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
2006 - SHEET 5

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 1998-2006

Channel Type

- Main Channel
- Braid Channel
- Side Channel

0 600 1,200 Feet



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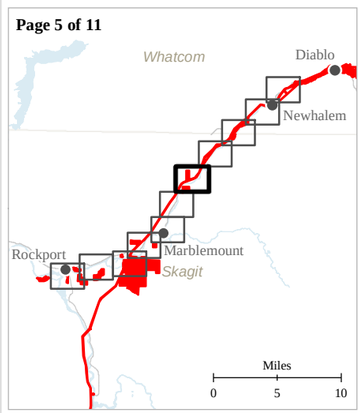
GE-04 GEOMORPHOLOGY STUDY HISTORICAL TIME SERIES 2019 - SHEET 5

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 2006-2019

Channel Type

- Main Channel
- Braid Channel
- Side Channel

0 600 1,200 Feet



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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL CHANNELS
1944-2019 - SHEET 5

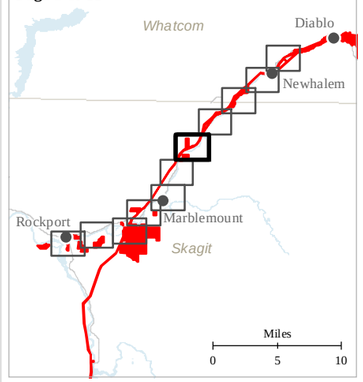
- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary

Historic Channels

- 2019
- 2006
- 1998
- 1978/79
- 1963/64
- 1944

N

0 600 1,200 Feet



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MT. BAKER-SNOQUALMIE NATIONAL FOREST
Bacon Creek
20
84
83
85
Skagit River
Alma Creek
ROSS LAKE NATL. REC. AREA
Reach 3B
Reach 4
Copper Creek
MT. BAKER-SNOQUALMIE NATIONAL FOREST
MT. BAKER-SNOQUALMIE NATIONAL FOREST

GE-04 GEOMORPHOLOGY STUDY HISTORICAL CHANNEL OCCUPANCY - SHEET 5

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- National Park / National Recreation Area Boundary
- Hydromodified Banks
- Reach Boundary

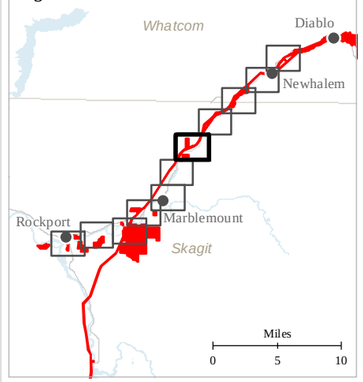
Historic Channel Occupancy
% of time 1944-2019

100%
0%

N

0 600 1,200 Feet

Page 5 of 11



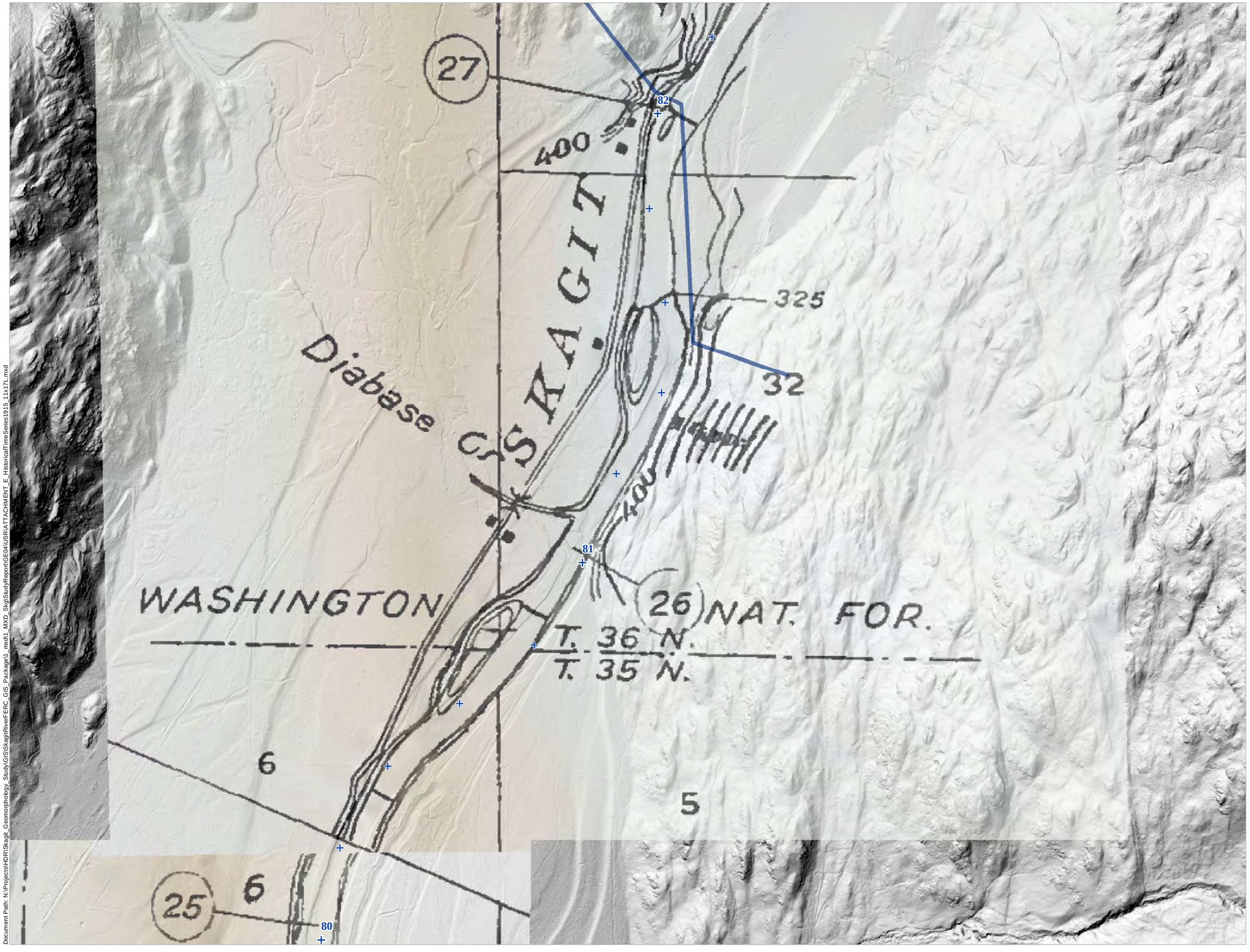
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MT. BAKER-SNOQUALMIE NATIONAL FOREST
Bacon Creek
20
83
84
85
Skagit River
ROSS LAKE NATL. REC. AREA
Alma Creek
Reach 3B
Reach 4
Copper Creek
MT. BAKER-SNOQUALMIE NATIONAL FOREST
MT. BAKER-SNOQUALMIE NATIONAL FOREST



GE-04 GEOMORPHOLOGY STUDY HISTORICAL TIME SERIES 1915 MAP* - SHEET 6

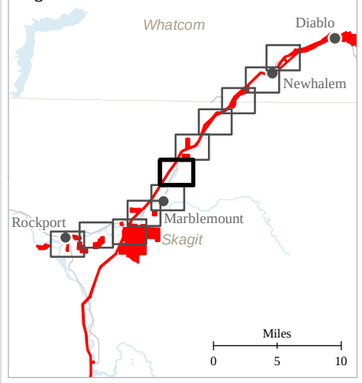
+ Project River Miles (PRM)

Reach Boundary

*1915 topographic maps from USGS mosaiced and overlaid with hillshade derived from composite of 2016-2018 lidar

N

0 600 1,200 Feet



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GE-04 GEOMORPHOLOGY STUDY HISTORICAL TIME SERIES 1944 - SHEET 6

MT. BAKER-SNOQUALMIE NATIONAL FOREST

MT. BAKER-SNOQUALMIE NATIONAL FOREST

MT. BAKER-SNOQUALMIE NATIONAL FOREST

82

Reach 3B

Reach 5A

Diobsud Creek

20

81

Skagit River

Taylor Spawning Channel

80

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary

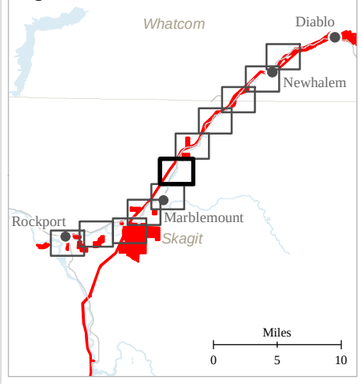
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

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Seattle City Light

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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1963/64 - SHEET 6

MT. BAKER-SNOQUALMIE NATIONAL FOREST

MT. BAKER-SNOQUALMIE NATIONAL FOREST

MT. BAKER-SNOQUALMIE NATIONAL FOREST

82

81

80

20

Reach 3B

Reach 5A

Diobsud Creek

Skagit River

Taylor Spawning Channel

EMM 11-285

800271

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Reach Boundary
- Eroding Bank 1944-1964

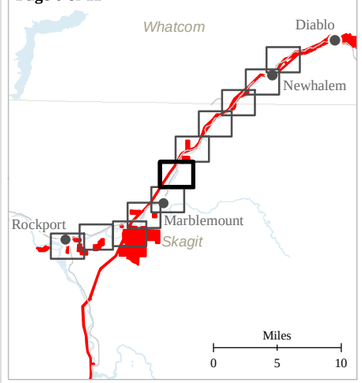
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1978/79 - SHEET 6

MT. BAKER-SNOQUALMIE NATIONAL FOREST

MT. BAKER-SNOQUALMIE NATIONAL FOREST

MT. BAKER-SNOQUALMIE NATIONAL FOREST

82

81

80

20

Reach 3B

Reach 5A

Diobsud Creek

Skagit River

Taylor Spawning Channel

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 1964-1979

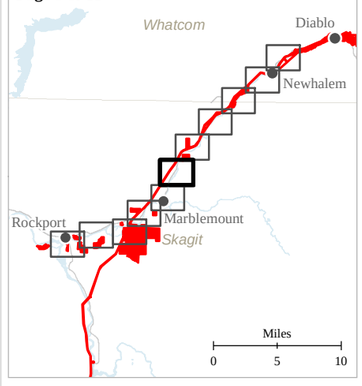
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

Page 6 of 11

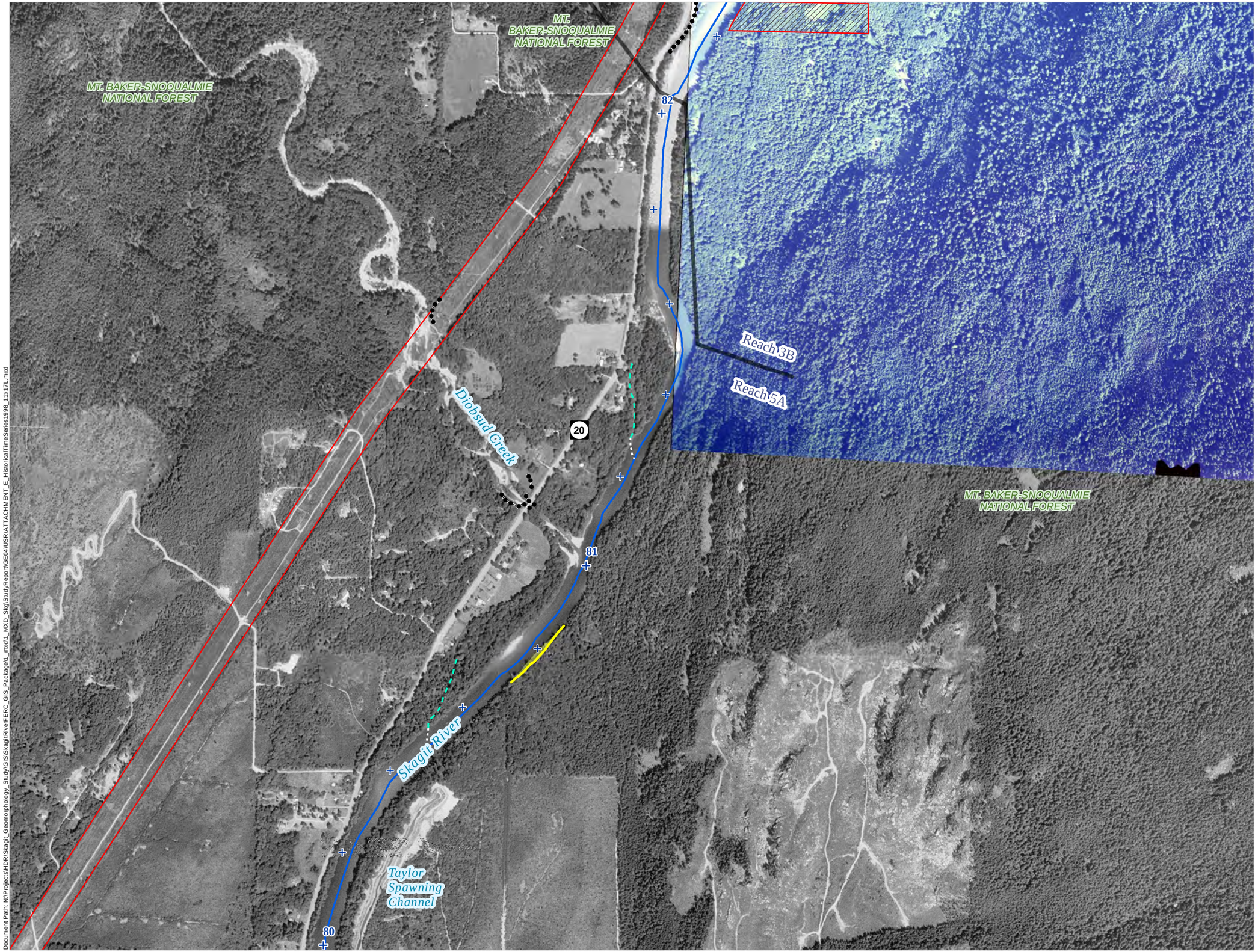


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GE-04 GEOMORPHOLOGY STUDY HISTORICAL TIME SERIES 1998 - SHEET 6

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 1979-1998

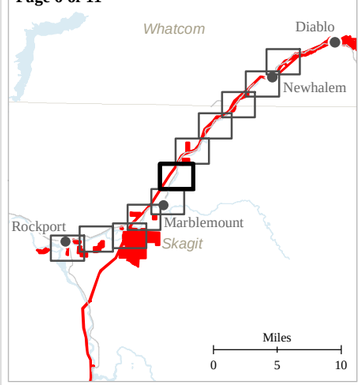
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
2006 - SHEET 6

MT. BAKER-SNOQUALMIE NATIONAL FOREST

MT. BAKER-SNOQUALMIE NATIONAL FOREST

MT. BAKER-SNOQUALMIE NATIONAL FOREST

82

81

80

20

Diobsud Creek

Skagit River

Taylor Spawning Channel

Reach 3B

Reach 5A

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary

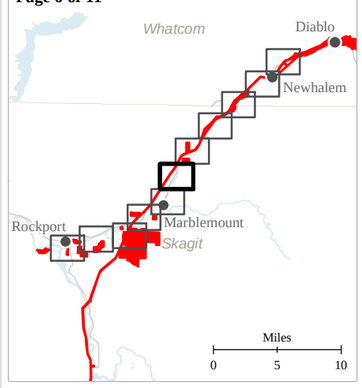
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

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GE-04 GEOMORPHOLOGY STUDY HISTORICAL TIME SERIES 2019 - SHEET 6

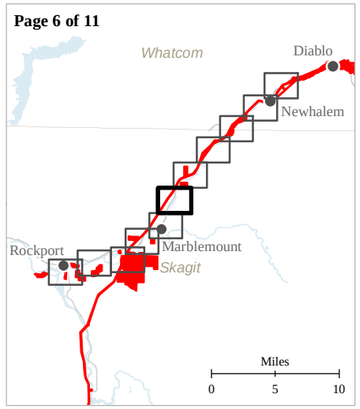
- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary

Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet



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GE-04 GEOMORPHOLOGY STUDY HISTORICAL CHANNELS 1944-2019 - SHEET 6

MT. BAKER-SNOQUALMIE NATIONAL FOREST

MT. BAKER-SNOQUALMIE NATIONAL FOREST

MT. BAKER-SNOQUALMIE NATIONAL FOREST

82

Reach 3B

Reach 5A

Diobsud Creek

20

81

Skagit River

Taylor Spawning Channel

80

- FERC Project Boundary
- Mitigation Parcel
- \+ Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary

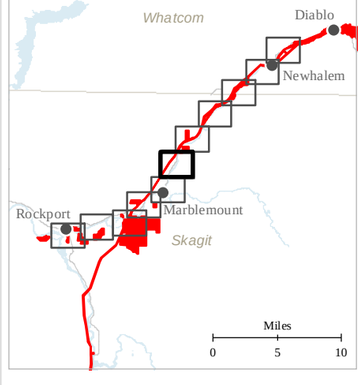
Historic Channels

- 2019
- 2006
- 1998
- 1978/79
- 1963/64
- 1944

N

0 600 1,200 Feet

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GE-04 GEOMORPHOLOGY STUDY HISTORICAL CHANNEL OCCUPANCY - SHEET 6

MT. BAKER-SNOQUALMIE NATIONAL FOREST

MT. BAKER-SNOQUALMIE NATIONAL FOREST

MT. BAKER-SNOQUALMIE NATIONAL FOREST

82

81

80

20

Reach 3B

Reach 5A

Diobsud Creek

Skagit River

Taylor Spawning Channel

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary

Historic Channel Occupancy
% of time 1944-2019

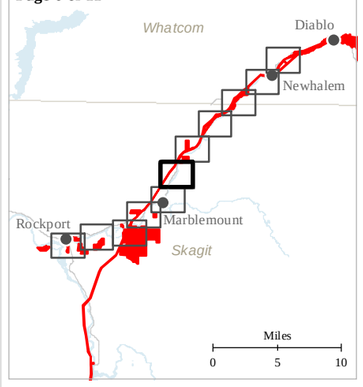
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N

0 600 1,200 Feet

Page 6 of 11

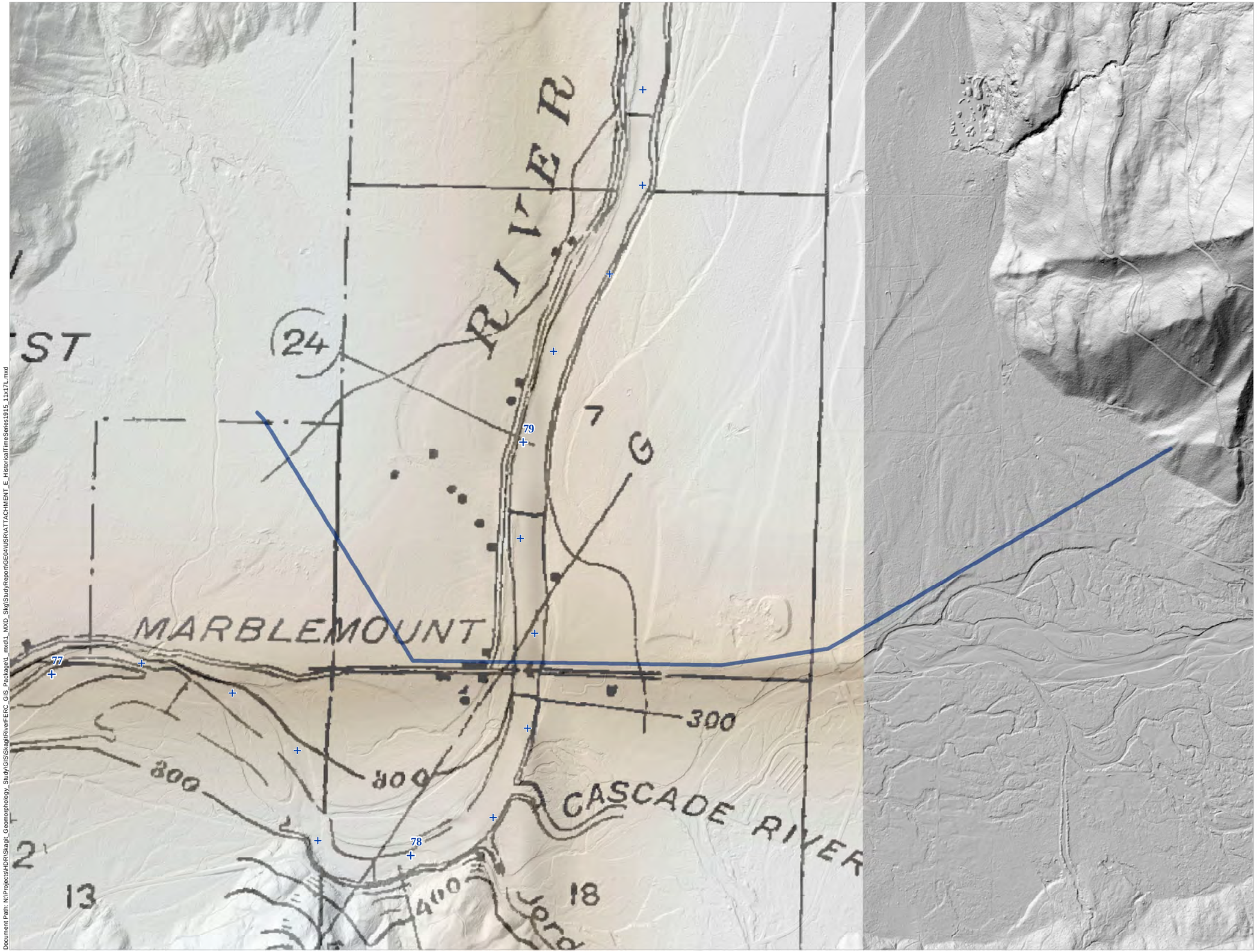


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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1915 MAP* - SHEET 7

+ Project River Miles (PRM)

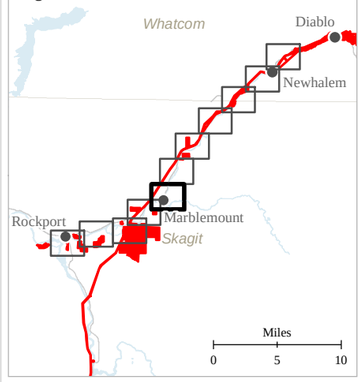
Reach Boundary

*1915 topographic maps from USGS mosaiced and overlaid with hillshade derived from composite of 2016-2018 lidar

N

0 600 1,200 Feet

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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1944 - SHEET 7

- FERC Project Boundary
- Project River Miles (PRM)
- Stream Gage (USGS)
- Hydromodified Banks
- Reach Boundary

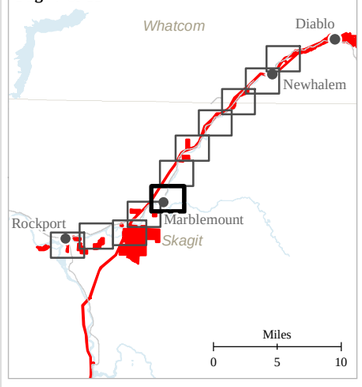
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

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Seattle City Light

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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1963/64 - SHEET 7

- FERC Project Boundary
- Project River Miles (PRM)
- Stream Gage (USGS)
- Reach Boundary
- Eroding Bank 1944-1964

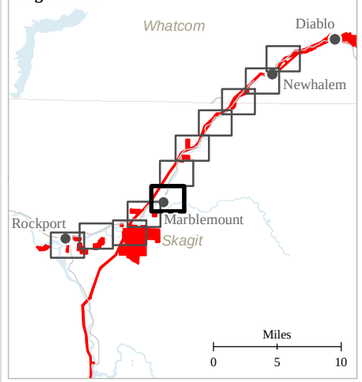
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1978/79 - SHEET 7

MT. BAKER-SNOQUALMIE NATIONAL FOREST

Skagit River

Olson Creek

Ranger Station Rd

Marblemount

Reach 5A

Reach 5B

Marblemount Slough

Marblemount Rd

MT. BAKER-SNOQUALMIE NATIONAL FOREST

Taylor Creek

Cascade River Rd

Cascade River

20

79

77

78

272

- FERC Project Boundary
- Project River Miles (PRM)
- Stream Gage (USGS)
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 1964-1979

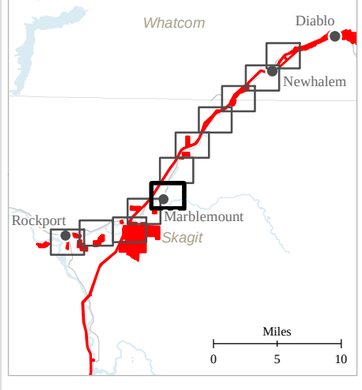
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

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Seattle City Light

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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1998 - SHEET 7

- FERC Project Boundary
- Project River Miles (PRM)
- Stream Gage (USGS)
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 1979-1998

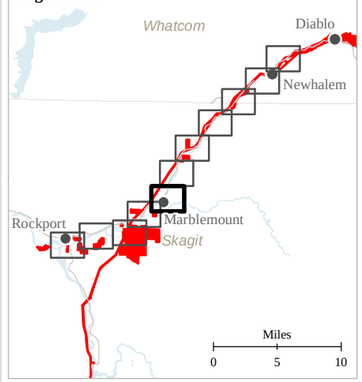
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

Page 7 of 11



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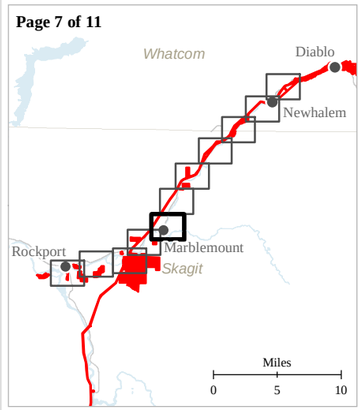
GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
2006 - SHEET 7

- FERC Project Boundary
- Project River Miles (PRM)
- Stream Gage (USGS)
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 1998-2006

Channel Type

- Main Channel
- Braid Channel
- Side Channel

0 600 1,200 Feet



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GE-04 GEOMORPHOLOGY STUDY HISTORICAL TIME SERIES 2019 - SHEET 7

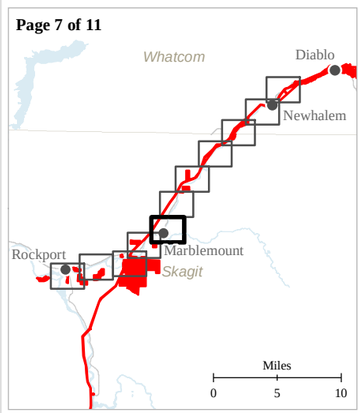
- FERC Project Boundary
- Project River Miles (PRM)
- Stream Gage (USGS)
- Hydromodified Banks
- Reach Boundary

Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet



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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL CHANNELS
1944-2019 - SHEET 7

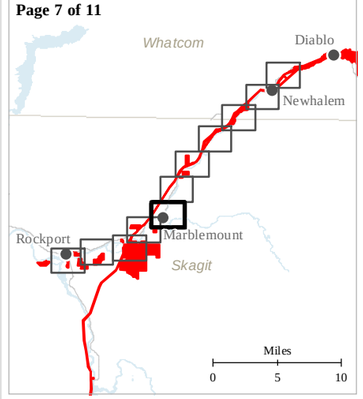
- FERC Project Boundary
- Project River Miles (PRM)
- Stream Gage (USGS)
- Hydromodified Banks
- Reach Boundary

Historic Channels

- 2019
- 2006
- 1998
- 1978/79
- 1963/64
- 1944

N

0 600 1,200 Feet



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MT. BAKER-SNOQUALMIE NATIONAL FOREST
Skagit River
Taylor Creek
20
79
Olson Creek
Ranger Station Rd
Cascade River Rd
Marblemount
Reach 5A
Reach 5B
77
78
Marblemount Slough
Cascade River
Marblegate Rd

GE-04 GEOMORPHOLOGY STUDY HISTORICAL CHANNEL OCCUPANCY - SHEET 7

- FERC Project Boundary
- Project River Miles (PRM)
- Stream Gage (USGS)
- Hydromodified Banks
- Reach Boundary

Historic Channel Occupancy
% of time 1944-2019

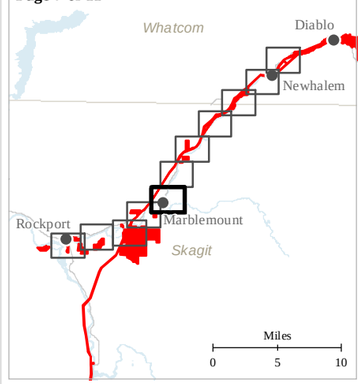
100%

0%

N

0 600 1,200 Feet

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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1915 MAP* - SHEET 8

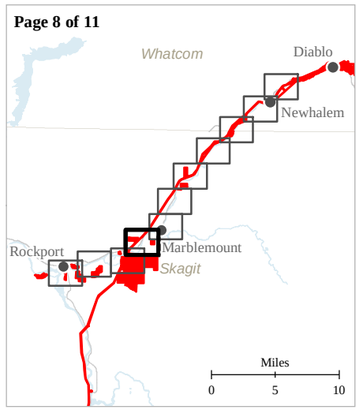
+ Project River Miles (PRM)

Reach Boundary

*1915 topographic maps from USGS mosaiced and overlaid with hillshade derived from composite of 2016-2018 lidar

N

0 600 1,200 Feet



Seattle City Light

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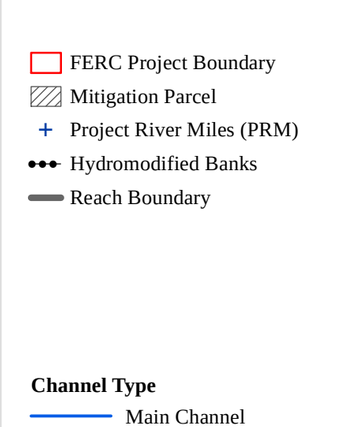
GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1944 - SHEET 8

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary

Channel Type

- Main Channel
- Braid Channel
- Side Channel

0 600 1,200 Feet



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MT. BAKER-SNOQUALMIE NATIONAL FOREST
Corkindale Creek
Reach 5B
Reach 6
Powerline Spawning Channel
Skagit River
Marblegate Rd
Willow Ln
Rockport - Cascade Rd
74
75
76
77
20
04

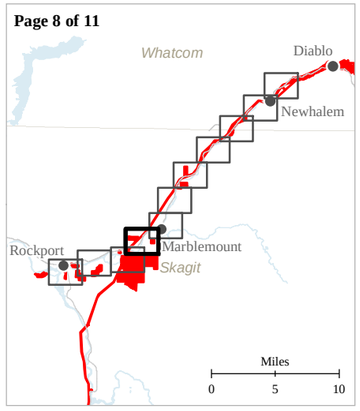
GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1963/64 - SHEET 8

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Reach Boundary
- Eroding Bank 1944-1964

Channel Type

- Main Channel
- Braid Channel
- Side Channel

0 600 1,200 Feet



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GE-04 GEOMORPHOLOGY STUDY HISTORICAL TIME SERIES 1978/79 - SHEET 8

MT. BAKER-SNOQUALMIE NATIONAL FOREST

Marblegate Rd

Skagit River

Willow Ln

Rockport - Cascade Rd

Corkindale Creek

Reach 5B

Reach 6

Powerline Spawning Channel

77

76

75

74

20

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 1964-1979

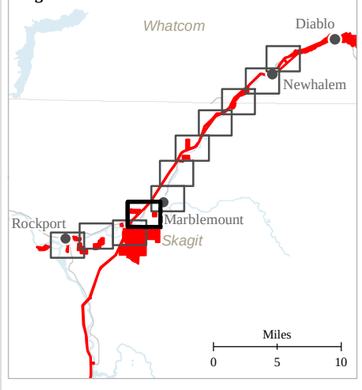
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

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GE-04 GEOMORPHOLOGY STUDY HISTORICAL TIME SERIES 1998 - SHEET 8

MT. BAKER-SNOQUALMIE NATIONAL FOREST

Corkindale Creek

Skagit River

Marblegate Rd

Willow Ln

Rockport-Cascade Rd

Reach 5B

Reach 6

Powerline Spawning Channel

74 75 76 77

20

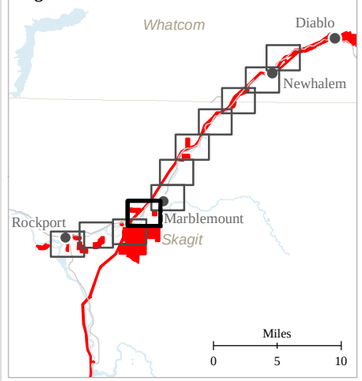
- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 1979-1998

Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet



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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
2006 - SHEET 8

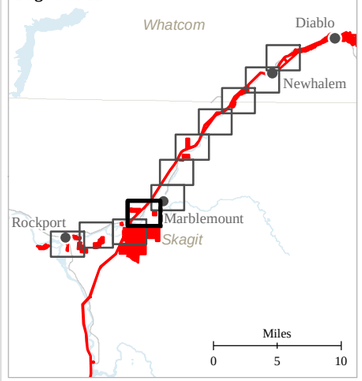
- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 1998-2006

Channel Type

- Main Channel
- Braid Channel
- Side Channel

0 600 1,200 Feet

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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
2019 - SHEET 8

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 2006-2019

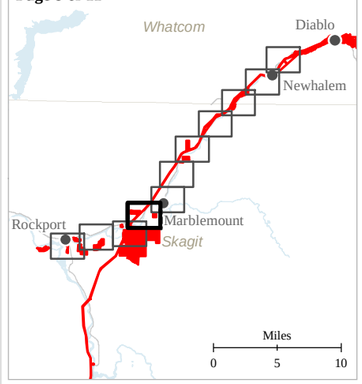
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

Page 8 of 11



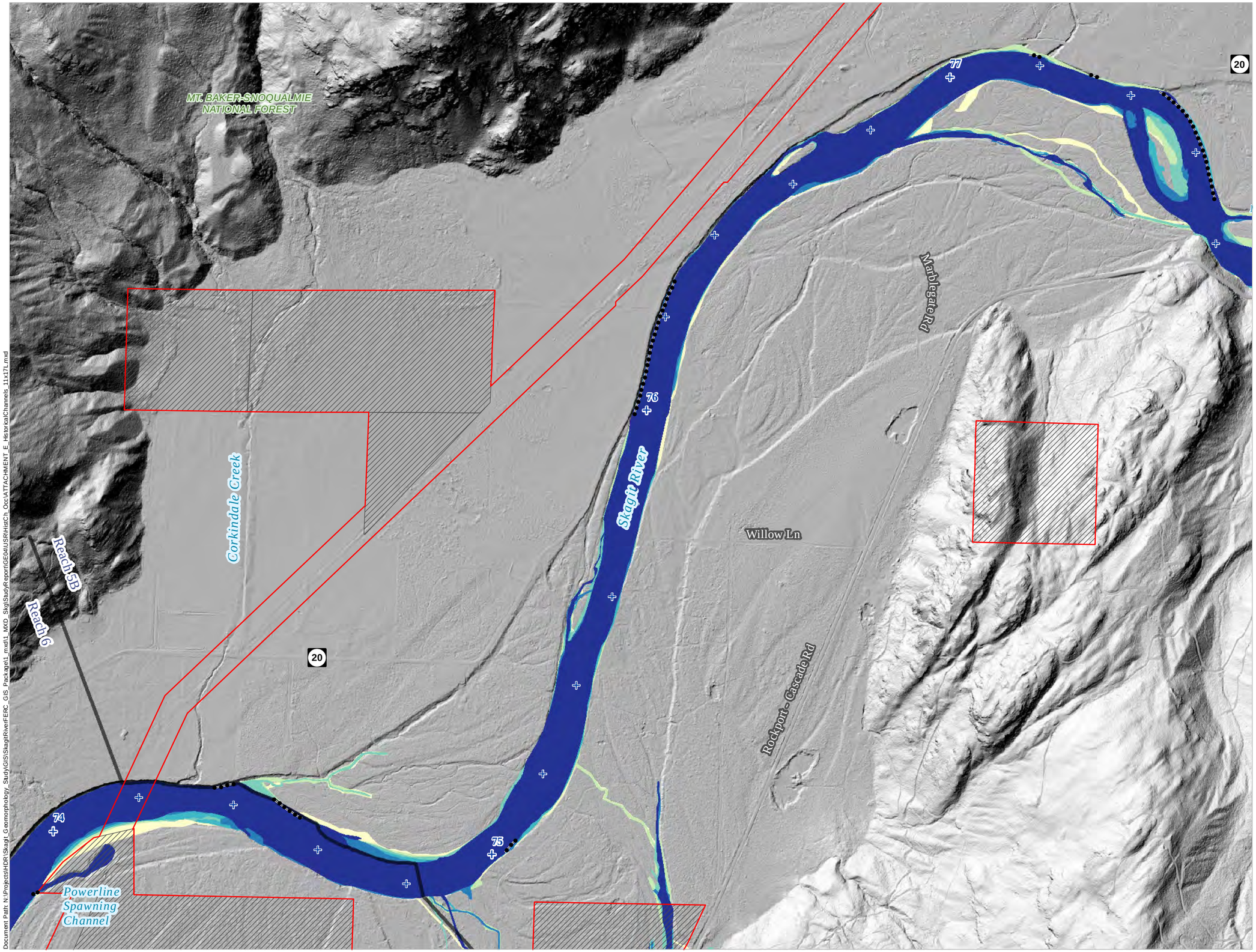
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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL CHANNELS
1944-2019 - SHEET 8



- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary

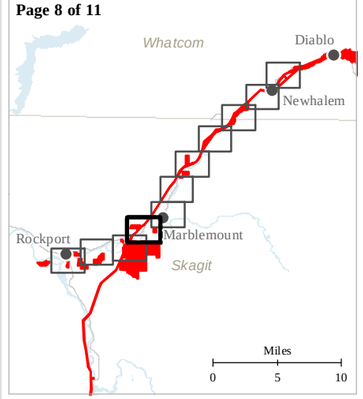
Historic Channels

- 2019
- 2006
- 1998
- 1978/79
- 1963/64
- 1944

N

0 600 1,200 Feet

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GE-04 GEOMORPHOLOGY STUDY HISTORICAL CHANNEL OCCUPANCY - SHEET 8

MT. BAKER-SNOQUALMIE NATIONAL FOREST

Corkindale Creek

Reach 5B

Reach 6

Skagit River

Marblegate Rd

Willow Ln

Rockport-Cascade Rd

Powerline Spawning Channel

20

74

75

76

77

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary

Historic Channel Occupancy
% of time 1944-2019

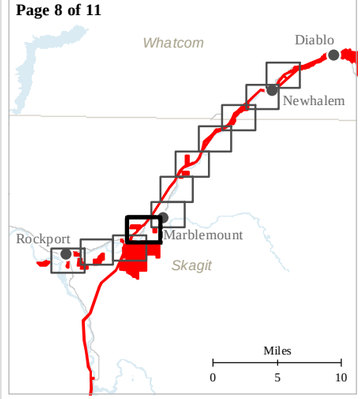
100%

0%

N

0 600 1,200 Feet

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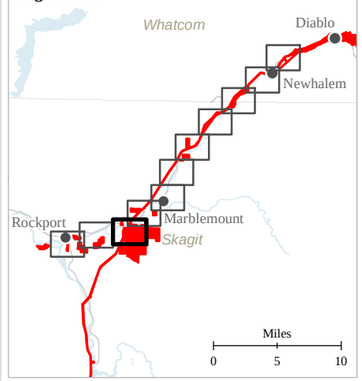
GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1915 MAP* - SHEET 9

+ Project River Miles (PRM)

Reach Boundary

*1915 topographic maps from USGS mosaiced and overlaid with hillshade derived from composite of 2016-2018 lidar

0 600 1,200 Feet



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GE-04 GEOMORPHOLOGY STUDY HISTORICAL TIME SERIES 1944 - SHEET 9

MT. BAKER-SNOQUALMIE NATIONAL FOREST

Rocky Creek

20

74

75

73

Powerline Spawning Channel

Skagit River

Reach 6

Reach 5B

Pandora Cir

Illabot Spawning Channel

O'Brian Creek

Rockport - Cascade Rd

Illabot Creek

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary

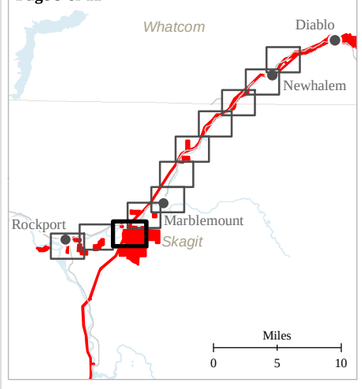
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

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GE-04 GEOMORPHOLOGY STUDY HISTORICAL TIME SERIES 1963/64 - SHEET 9

LINE 20

EMM 2-186

MT. BAKER-SNOQUALMIE NATIONAL FOREST

Rocky Creek

20

74

75

73

Powerline Spawning Channel

Skagit River

Reach 6

Reach 5B

Pandora Cir

Illabot Spawning Channel

O'Brian Creek

Rockport - Cascade Rd

Illabot Creek

- FERC Project Boundary
- Mitigation Parcel
- \+ Project River Miles (PRM)
- Reach Boundary
- Eroding Bank 1944-1964

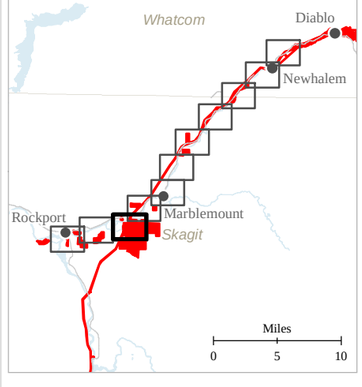
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

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GE-04 GEOMORPHOLOGY STUDY HISTORICAL TIME SERIES 1978/79 - SHEET 9

MT. BAKER-SNOQUALMIE NATIONAL FOREST

Rocky Creek

Powerline Spawning Channel

Skagit River

Illabot Spawning Channel

Reach 6

Reach 5B

Pandora Cir

O'Brian Creek

Rockport - Cascade Rd

Illabot Creek

20

73

74

75

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 1964-1979

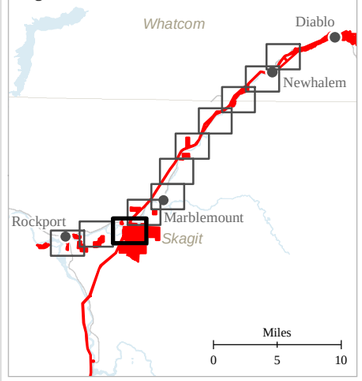
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
2006 - SHEET 9

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 1998-2006

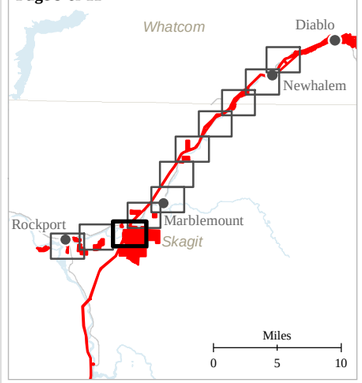
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

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GE-04 GEOMORPHOLOGY STUDY HISTORICAL TIME SERIES 1998 - SHEET 9

MT. BAKER-SNOQUALMIE NATIONAL FOREST

Rocky Creek

20

73

74

75

Skagit River

Powerline Spawning Channel

Illabot Spawning Channel

Reach 6

Reach 5B

Pandora Cir

O'Brian Creek

Rockport - Cascade Rd

Illabot Creek

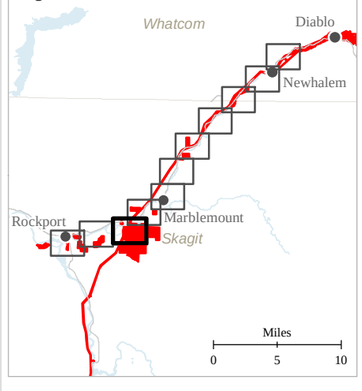
- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 1979-1998

Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet



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GE-04 GEOMORPHOLOGY STUDY HISTORICAL TIME SERIES 2019 - SHEET 9



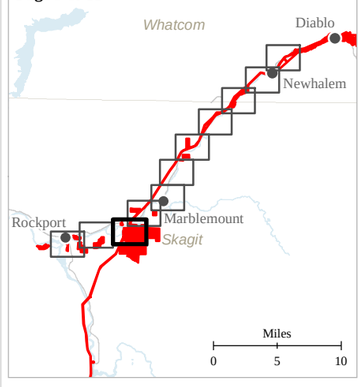
- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 2006-2019

Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet



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GE-04 GEOMORPHOLOGY STUDY HISTORICAL CHANNELS 1944-2019 - SHEET 9

MT. BAKER-SNOQUALMIE NATIONAL FOREST

Rocky Creek

20

73

74

75

Skagit River

Powerline Spawning Channel

Illabot Spawning Channel

Reach 6

Reach 5B

Pandora Cir

O'Brian Creek

Rockport-Cascade Rd

Illabot Creek

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary

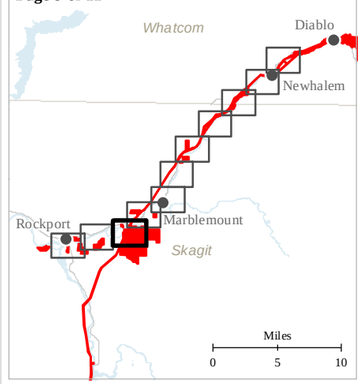
Historic Channels

- 2019
- 2006
- 1998
- 1978/79
- 1963/64
- 1944

N

0 600 1,200 Feet

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GE-04 GEOMORPHOLOGY STUDY HISTORICAL CHANNEL OCCUPANCY - SHEET 9

MT. BAKER-SNOQUALMIE NATIONAL FOREST

Rocky Creek

20

73

74

75

Skagit River

Powerline Spawning Channel

Illabot Spawning Channel

Reach 6

Reach 5B

Pandora Cir

O'Brian Creek

Rockport-Cascade Rd

Illabot Creek

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary

Historic Channel Occupancy
% of time 1944-2019

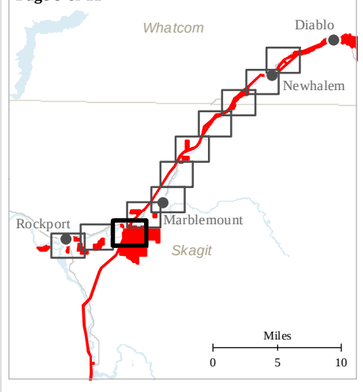
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0%

N

0 600 1,200 Feet

Page 9 of 11



Seattle City Light

SKAGIT RIVER HYDROELECTRIC PROJECT (FERC NO. 553)

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Data Sources: City Light, Upper Skagit Indian Tribe, National Park Service, USDA Forest Service, USGS

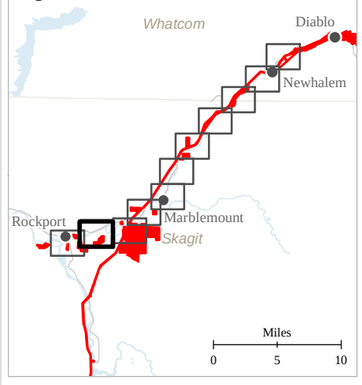
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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1915 MAP* - SHEET 10

+ Project River Miles (PRM)

*1915 topographic maps from USGS mosaiced and overlaid with hillshade derived from composite of 2016-2018 lidar

0 600 1,200 Feet



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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1944 - SHEET 10

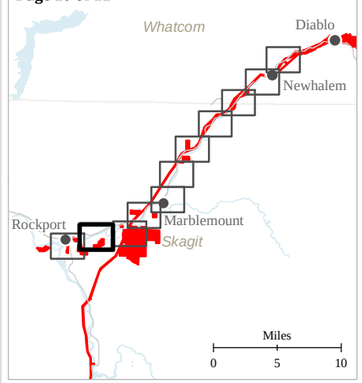
- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Stream Gage (USGS)
- Hydromodified Banks

Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet



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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1963/64 - SHEET 10

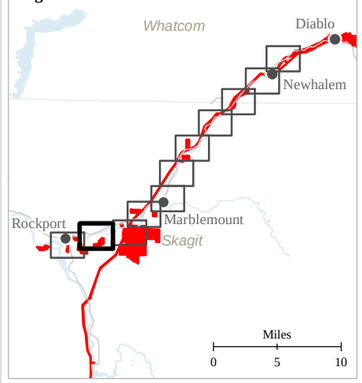
- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Stream Gage (USGS)
- Eroding Bank 1944-1964

Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet



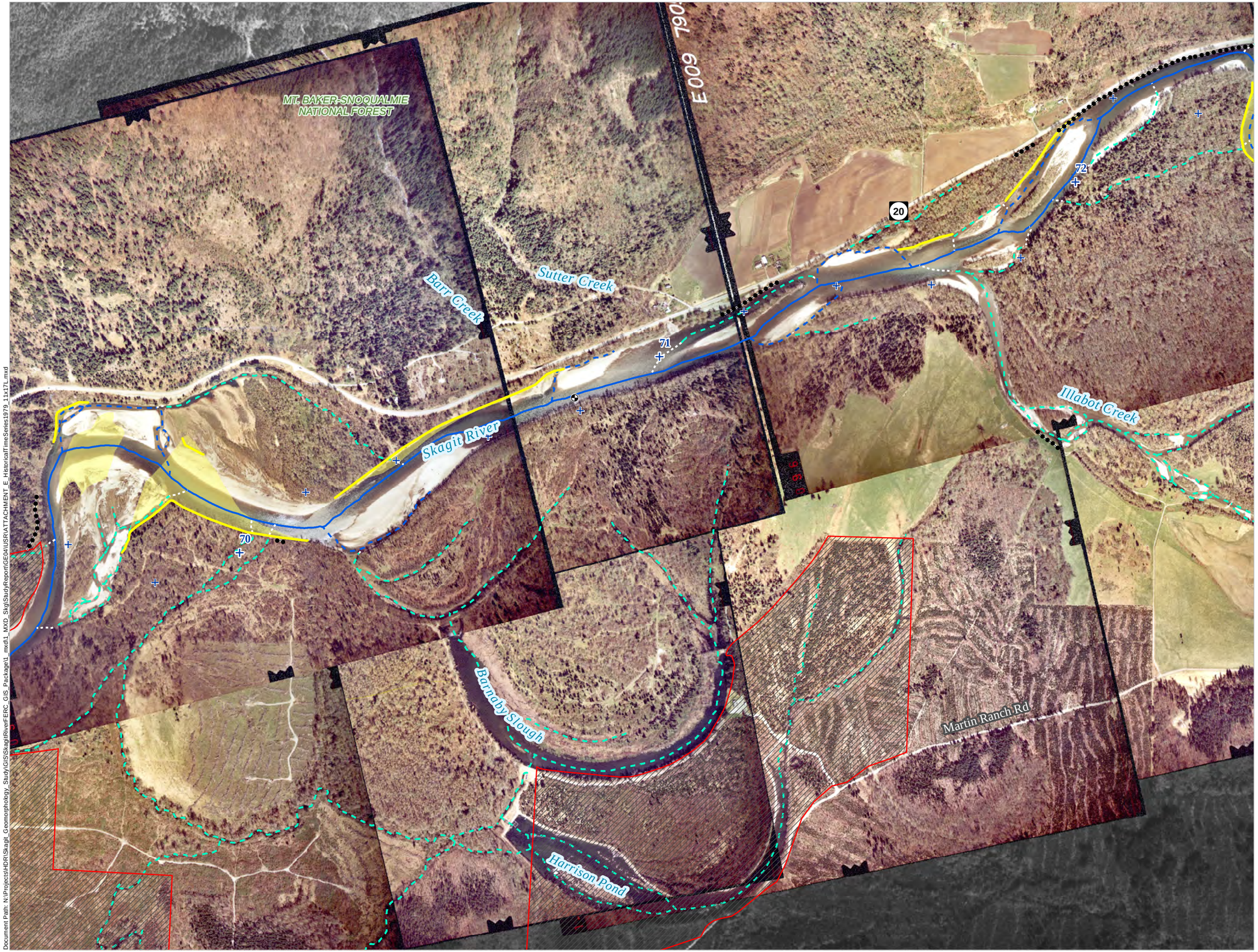
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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1978/79 - SHEET 10



- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Stream Gage (USGS)
- Hydromodified Banks
- Eroding Bank 1964-1979

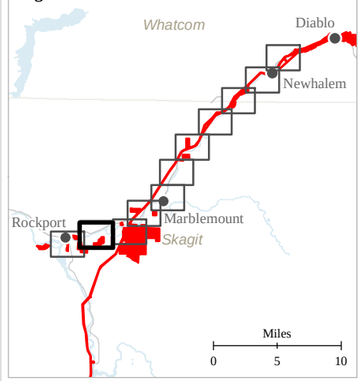
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

Page 10 of 11



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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1998 - SHEET 10

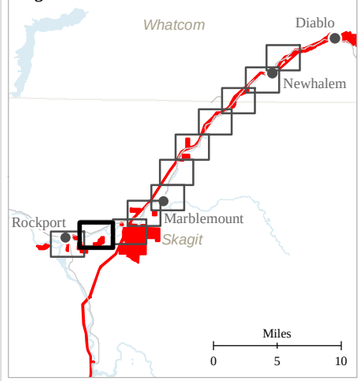
- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Stream Gage (USGS)
- Hydromodified Banks
- Eroding Bank 1979-1998

Channel Type

- Main Channel
- Braid Channel
- Side Channel

0 600 1,200 Feet

Page 10 of 11



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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
2006 - SHEET 10

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Stream Gage (USGS)
- Hydromodified Banks
- Eroding Bank 1998-2006

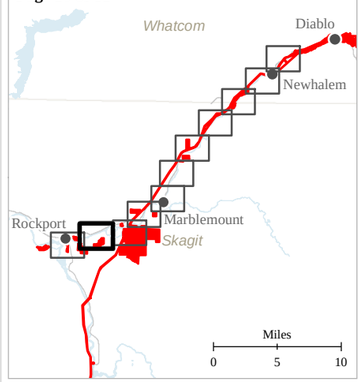
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

Page 10 of 11



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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
2019 - SHEET 10

MT. BAKER-SNOQUALMIE NATIONAL FOREST

Barr Creek

Sutter Creek

Skagit River

Barnaby Slough

Harrison Pond

Martin Ranch Rd

Illabot Creek

20

70

71

72

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Stream Gage (USGS)
- Hydromodified Banks
- Eroding Bank 2006-2019

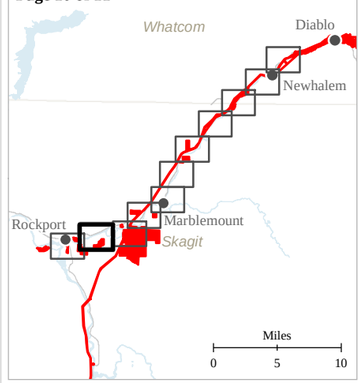
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

Page 10 of 11



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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL CHANNELS
1944-2019 - SHEET 10

MT. BAKER-SNOQUALMIE NATIONAL FOREST

Barr Creek

Sutter Creek

Skagit River

Barnaby Slough

Harrison Pond

Illabot Creek

Martin Ranch Rd

20

70

71

72

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Stream Gage (USGS)
- Hydromodified Banks

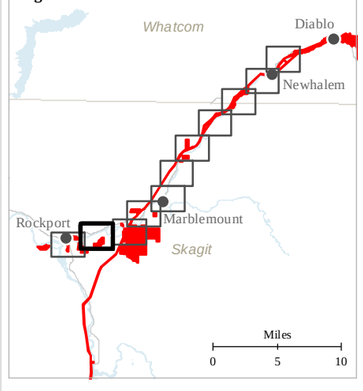
Historic Channels

- 2019
- 2006
- 1998
- 1978/79
- 1963/64
- 1944

N

0 600 1,200 Feet

Page 10 of 11



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GE-04 GEOMORPHOLOGY STUDY HISTORICAL CHANNEL OCCUPANCY - SHEET 10

MT. BAKER-SNOQUALMIE NATIONAL FOREST

Barr Creek

Sutter Creek

Skagit River

Barnaby Slough

Harrison Pond

Illabot Creek

Martin Ranch Rd

20

70

71

72

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Stream Gage (USGS)
- Hydromodified Banks

Historic Channel Occupancy
% of time 1944-2019

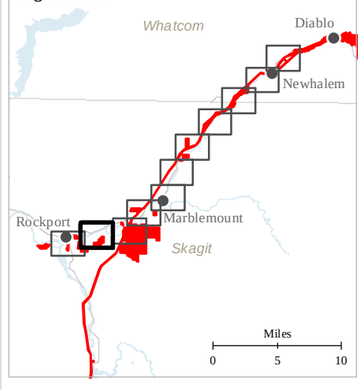
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N

0 600 1,200 Feet

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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1915 MAP* - SHEET 11

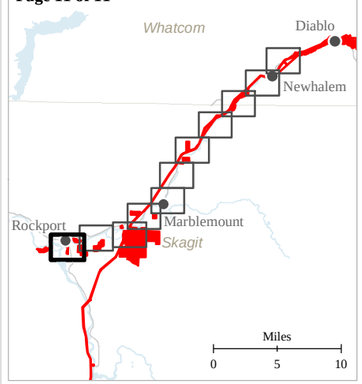
+ Project River Miles (PRM)

Reach Boundary

*1915 topographic maps from USGS mosaiced and overlaid with hillshade derived from composite of 2016-2018 lidar

0 600 1,200 Feet

Page 11 of 11



Seattle City Light

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GE-04 GEOMORPHOLOGY STUDY HISTORICAL TIME SERIES 1944 - SHEET 11

MT. BAKER-SNOQUALMIE NATIONAL FOREST

Reach 7B
Reach 7A
Reach 6
Reach 7A

20

Rockport

67
68
69

Skagit River
Bohs Slough
McLeod Slough
Sauk River

530

Martin Rd

Rockport - Cascade Rd

MT. BAKER-SNOQUALMIE NATIONAL FOREST

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary

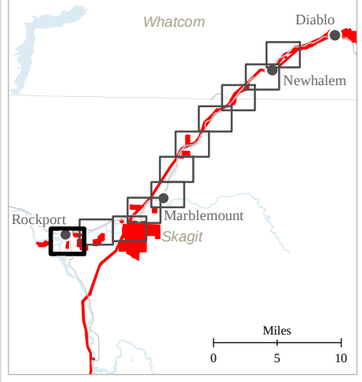
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

Page 11 of 11



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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1963/64 - SHEET 11

MT. BAKER-SNOQUALMIE NATIONAL FOREST

Reach 7B
Reach 7A
Reach 6
Rockport
Skagit River
Bohs Slough
McLeod Slough
Sauk River
Martin Rd
Rockport - Casdcade Rd
MT. BAKER-SNOQUALMIE NATIONAL FOREST
800271
+12,302.91RM
20
530
67
68
69

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Reach Boundary
- Eroding Bank 1944-1964

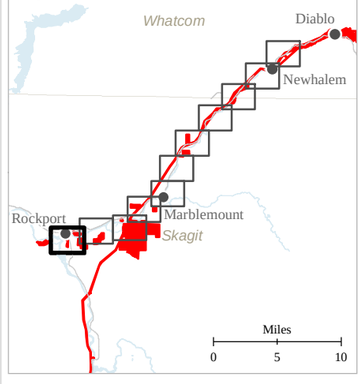
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

Page 11 of 11



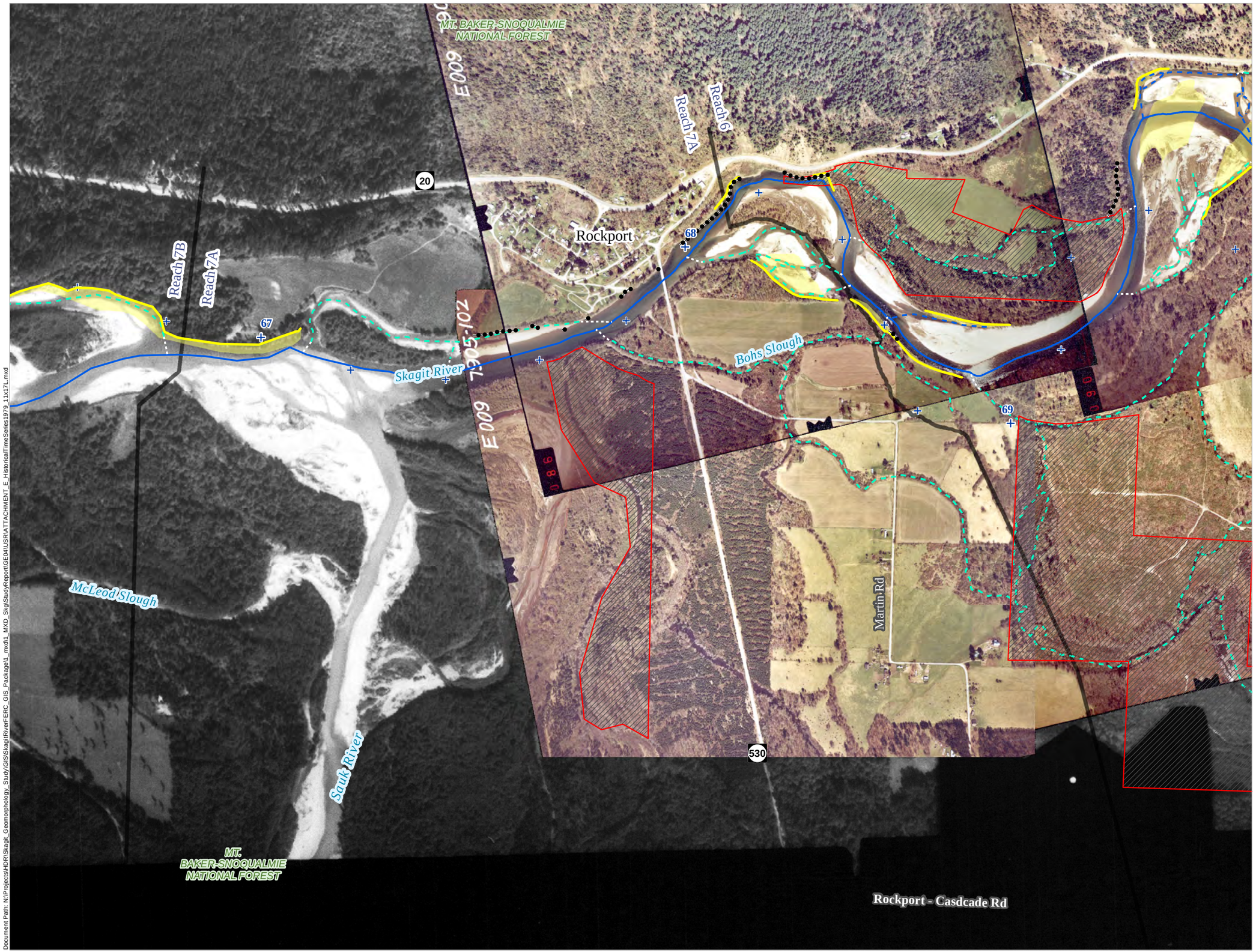
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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1978/79 - SHEET 11



- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 1964-1979

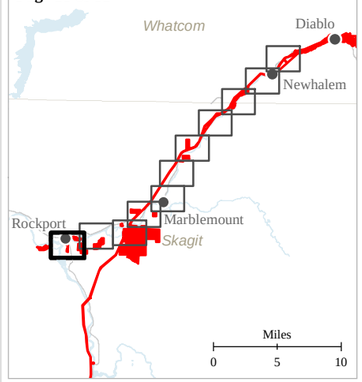
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
1998 - SHEET 11

MT. BAKER-SNOQUALMIE NATIONAL FOREST

Reach 7B
Reach 7A
Reach 7A
Reach 6

20

Rockport

67
68
69

Skagit River
Bohs Slough
McLeod Slough
Sauk River
Martin Rd

530

Rockport - Casdcade Rd

MT. BAKER-SNOQUALMIE NATIONAL FOREST

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 1979-1998

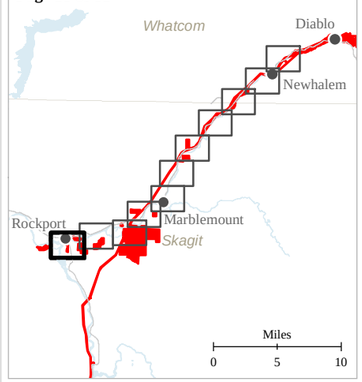
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

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GE-04
GEOMORPHOLOGY STUDY
HISTORICAL TIME SERIES
2006 - SHEET 11

MT. BAKER-SNOQUALMIE NATIONAL FOREST

Reach 7B
Reach 7A
Reach 7A
Reach 6

20

Rockport

68
67
69

Skagit River
Bohs Slough
McLeod Slough
Sauk River

Marlin Rd

530

Rockport - Cascade Rd

MT. BAKER-SNOQUALMIE NATIONAL FOREST

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 1998-2006

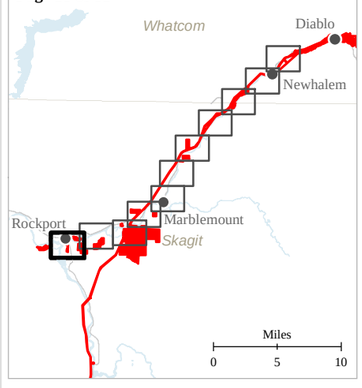
Channel Type

- Main Channel
- Braid Channel
- Side Channel

N

0 600 1,200 Feet

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GE-04 GEOMORPHOLOGY STUDY HISTORICAL TIME SERIES 2019 - SHEET 11

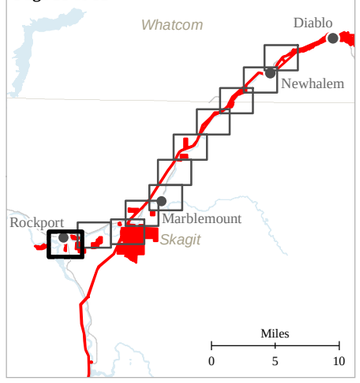
- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary
- Eroding Bank 2006-2019

Channel Type

- Main Channel
- Braid Channel
- Side Channel

0 600 1,200 Feet

Page 11 of 11



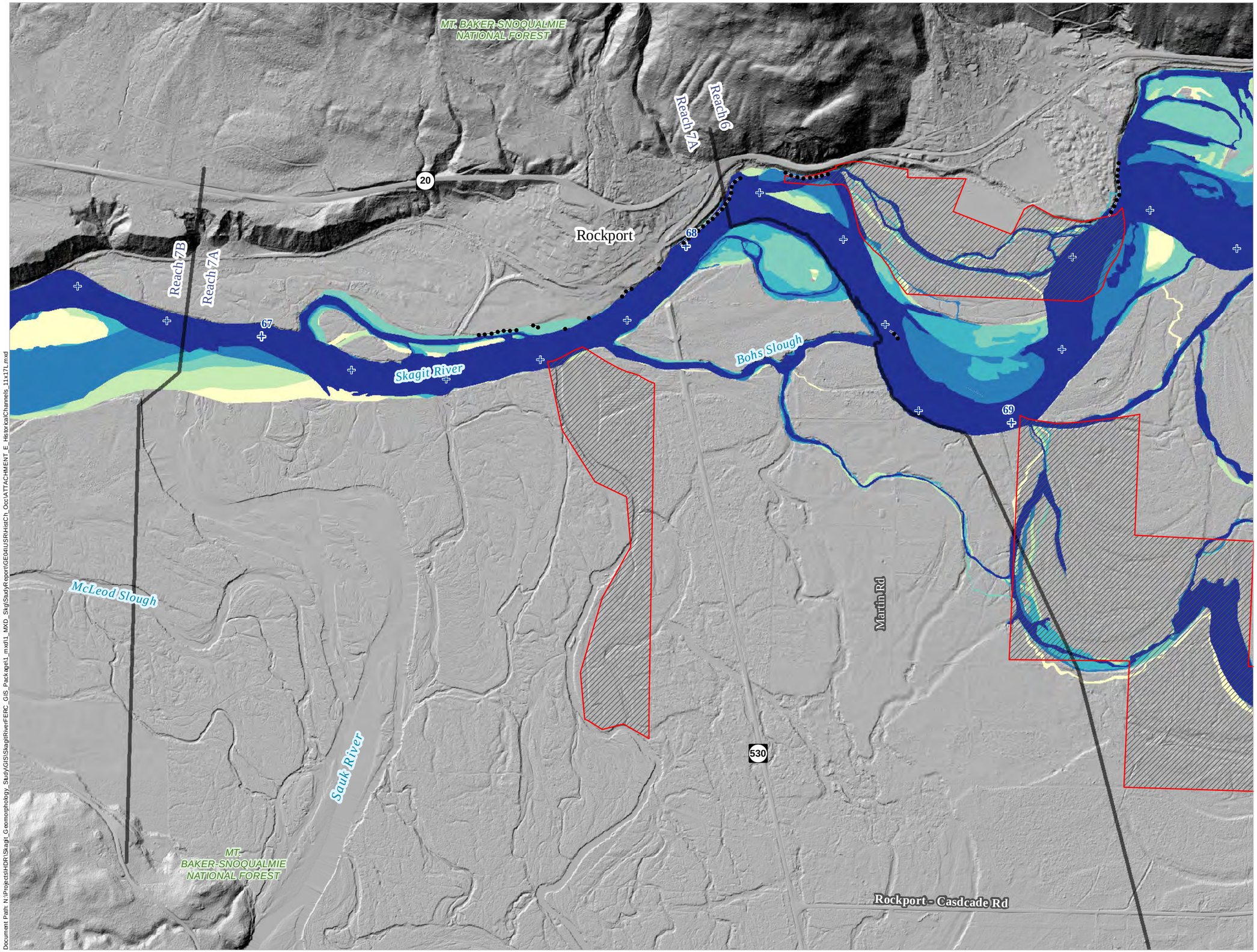
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SKAGIT RIVER HYDROELECTRIC PROJECT (FERC NO. 553)

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City Light provides no warranty, expressed or implied, as to the accuracy, reliability or completeness of this data.
Data Sources: City Light, Upper Skagit Indian Tribe, National Park Service, USDA Forest Service, USGS

Document Path: N:\Projects\HDR\Skagit_Geomorphology_Study\GIS\Skagit\RiverFERC_GIS_Package\s1_mxd\1_MXD_Skgt\StudyReport\GE04\USR\ATTACHMENT_E_HistoricalTimeSeries2019_11x17L.mxd

GE-04 GEOMORPHOLOGY STUDY HISTORICAL CHANNELS 1944-2019 - SHEET 11



FERC Project Boundary
Mitigation Parcel
Project River Miles (PRM)
Hydromodified Banks
Reach Boundary

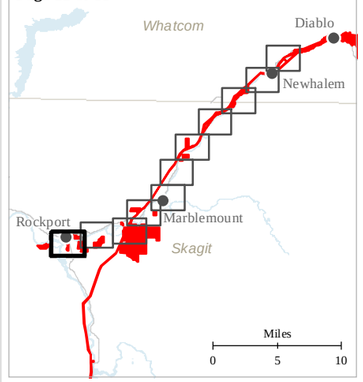
Historic Channels

- 2019
- 2006
- 1998
- 1978/79
- 1963/64
- 1944

N

0 600 1,200 Feet

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GE-04 GEOMORPHOLOGY STUDY HISTORICAL CHANNEL OCCUPANCY - SHEET 11

MT. BAKER-SNOQUALMIE NATIONAL FOREST

Reach 7B
Reach 7A
Reach 7A
Reach 6

20

Rockport

68
67
69

Skagit River
Bohs Slough
McLeod Slough
Sauk River
Martin Rd
530
Rockport - Casdcade Rd

MT. BAKER-SNOQUALMIE NATIONAL FOREST

- FERC Project Boundary
- Mitigation Parcel
- Project River Miles (PRM)
- Hydromodified Banks
- Reach Boundary

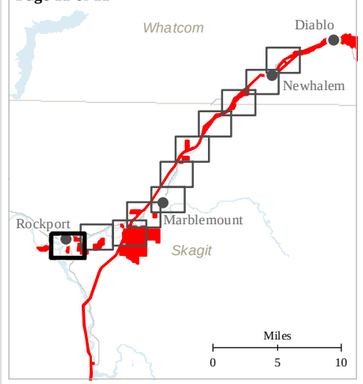
Historic Channel Occupancy
% of time 1944-2019

100%
0%

N

0 600 1,200 Feet

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