AMENDMENT TO BRADLEY LAKE HYDROELECTRIC PROJECT
(FERC No. 8221),
BRADLEY LAKE EXPANSION PROJECT

Geomorphology and Sediment Transport Study Report

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January 2026

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ACRONYMS AND ABBREVIATIONS

2D	two-dimensional
A	
AEA	Alaska Energy Authority
B	
BLVD	Bradley Lake Vertical Datum
Bradley Lake Project	Bradley Lake Hydroelectric Project (FERC No. 8221)
C	
cfs	cubic feet per second
D	
DSP	Draft Study Plan
E	
EFMR	East Fork Martin River
F	
FERC	Federal Energy Regulatory Commission
ft	foot/feet
G	
GIS	Geographic Information Systems
GPS	global positioning system
H	
HEC-RAS	Hydrologic Engineering Center's River Analysis System
I	
ICD	Initial Consultation Document
L	
LiDAR	light detection and ranging

M

mm	millimeter(s)

N

NIR	near-infrared

O

OCH	off-channel habitat

P

PM&E	Protection, Mitigation, and Enhancement
PRM	Project River Mile
Project	Bradley Lake Expansion Project

R

RM	River Mile

W

WFMR	West Fork Martin River

1.0 INTRODUCTION

1.1 Background

The Alaska Energy Authority (AEA), Licensee and owner of the 120-megawatt Bradley Lake Hydroelectric Project (Bradley Lake Project; Federal Energy Regulatory Commission [FERC] No. 8221), is pursuing a FERC license amendment. The purpose of the proposed amendment is to gain authorization to divert seasonal meltwater coming from Dixon Glacier at the headwaters of the Martin River to Bradley Lake and to raise the Bradley Dam to increase Bradley Lake storage capacity and power production. The Bradley Lake Project is located on the Bradley River in the Kenai Peninsula Borough northeast of the town of Homer in Southcentral Alaska (Figure 1-1).

AEA filed an Initial Consultation Document (ICD) (AEA 2022a) with FERC on April 27, 2022. The ICD describes existing facilities and current Bradley Lake Project operations; characterizes the affected environment; and describes two proposed project alternatives for producing energy from Dixon Glacier meltwater. Following the ICD filing, AEA hosted Joint Agency and Public Meetings in Homer, Alaska, on June 14, 2022, to discuss the ICD and receive stakeholder input. In November 2022, AEA filed a Draft Study Plan (DSP) (AEA 2022b) with FERC, based on the two alternatives, outlining 10 studies, including the *Hydraulic Modeling, Geomorphology, and Aquatic Habitat Connectivity Evaluation*. Stakeholders filed comments to the DSP in December 2022. AEA briefly paused the FERC amendment process while it conducted additional feasibility studies and narrowed down the proposed project alternatives.

Based on further investigations, AEA decided to move forward with the proposed alternative diverting Dixon Glacier meltwater to Bradley Lake (Bradley Lake Expansion Project or Project). The proposed Project would include construction of: a diversion dam near the toe of the Dixon Glacier; an approximately 4.6-mile-long diversion tunnel bored through the mountain extending from Dixon Glacier to Bradley Lake, diverting water from the Martin River basin to Bradley Lake; approximately 1 mile of new, 16-foot-wide, gravel-surfaced access road from the existing Upper Battle Creek diversion access road to the outlet of the proposed diversion tunnel (all referred to as the Dixon Diversion); and modification of the existing Bradley Lake Dam to raise the maximum normal pool elevation currently at Elevation (El.) 1,180 feet (referenced to the Bradley Lake Vertical

Datum [BLVD]) by 16 feet to El. 1,196 feet (referred to as the Bradley Lake Pool Raise). The entire proposed Project is located on state-owned land.

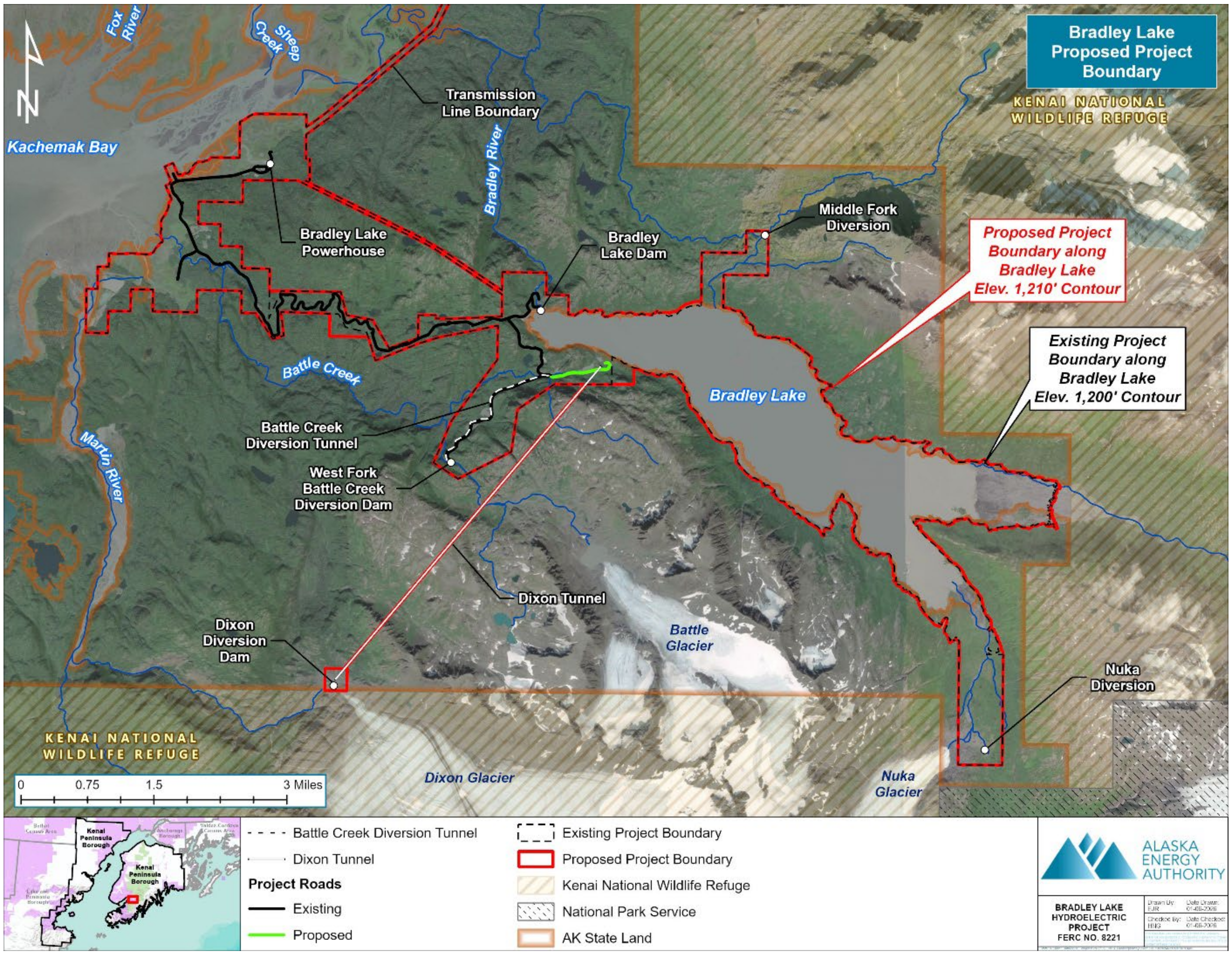


Figure 1-1 Location of the proposed Bradley Lake Expansion at the Bradley Lake Hydroelectric Project (FERC No. 8221) near Kachemak Bay, Alaska.

AEA re-initiated the amendment process in 2024 by hosting public meetings in March and April 2024 to review the selected Project alternative, stakeholder comments to the DSP, and AEA's proposed modifications to the DSP. Meeting summaries are posted to AEA's Bradley Lake Expansion Project website: https://www.akenergyauthority.org/What-We-Do/Railbelt-Energy/Bradley-Lake-Hydroelectric-Project/Bradley-Lake-Expansion-Project.

AEA implemented geomorphology investigations in 2023, 2024, and 2025. An initial report on the 2023 geomorphology observations was developed in early 2024 (Watershed GeoDynamics 2024), and an updated report was prepared in January 2025 (Watershed

GeoDynamics 2025). This report compiles all the information and analyses completed for the Geomorphology and Sediment Transport Analysis component of the *Hydraulic Modeling, Geomorphology, and Aquatic Habitat Connectivity Evaluation* through 2025 and completes the tasks to fulfill the goals and objectives of the study.

1.2 Modifications from the Draft Study Plan

One modification was made to the DSP (AEA 2022b) for the geomorphology and sediment transport evaluation. The following task was added:

- Install timelapse cameras that show changes in braided channel reaches and correlate the timing of channel changes observed with flow at the time to help determine flow levels that initiate channel change/bedload transport.

2.0 GEOMORPHOLOGY STUDY GOALS AND OBJECTIVES

The East Fork Martin River (EFMR) flows from the Dixon Glacier through a high-gradient canyon to the confluence with the West Fork Martin River (WFMR), where it forms the Martin River, which flows about 5 miles through a lower gradient, very dynamic glacial outwash plain to Kachemak Bay. The Dixon Glacier supplies a large amount of sediment to the river and includes material from boulder to clay size. This material is transported through the EFMR canyon reach and then deposited in the Martin River outwash plain as the valley widens and water velocity drops, forming a braided river pattern. Braided rivers are indicative of watersheds that produce more sediment than the available river flow can carry. AEA proposes to divert water from the terminus of the Dixon Glacier into Bradley Lake and allow gravel and larger particles to continue into the Martin River. To understand the potential effects of the proposed Dixon Diversion on the Martin River, it is important to understand the geomorphic history of the Martin River valley and how past changes in sediment/water loading have affected the valley. This report relies on historical aerial photographs (1950-2024), field observations and substrate sampling, timelapse camera footage of river changes in response to flows (2023, 2024, and 2025), and hydraulic model analysis to provide an understanding of past river valley changes and tools to analyze potential future changes. This information, combined with the fisheries, hydraulic, hydrologic, and riparian study results, allows AEA to evaluate potential effects on aquatic and riparian ecosystems in the Martin River valley.

The geomorphology and sediment transport analysis outlined in DSP Section 4.5 (AEA 2022b) analyzed available historical aerial photographs and light detection and ranging (LiDAR) data as well as collected information on substrate size and analyzed potential future sediment transport and accumulation trends based on output from the two-dimensional (2D) hydraulic model using the U.S. Army Corps of Engineers Hydrologic Engineering Center’s River Analysis System (HEC-RAS) software. The geomorphology and sediment transport analysis includes eight tasks listed below (with report sections for each task in parentheses):

- Segment the Martin River into geomorphic analysis reaches based on confinement, degree of braiding, and gradient (Section 5.1.1).
- Delineate past changes to Martin River, adjacent forest community growth/destruction patterns (resulting from channel migration), and stream/pond

connectivity through time using historic aerial photographs (1984 through present are available, possibly older series as well; Section 5.1.3).

- Map the degree of channel braiding in each reach of the Martin River through time to determine past changes to braiding patterns in each geomorphic reach. This step will help to determine expected future variability in braiding patterns (Section 5.1.3.2).
- Compare LiDAR and any other topographic datasets to estimate average annual volume of coarse-grained sediment provided to the river (combined Martin River and EFMR) from the Dixon Glacier based on aggradation volumes (Section 5.5).
- Collect pebble count data and sub-surface samples during low flow conditions in each geomorphic reach (Section 5.3).
- Install timelapse cameras showing changes in braided channel reaches and correlate the timing of channel changes observed with the flow on that day to help determine flow levels that initiate channel change/bedload transport (Section 5.4).
- Analyze sediment transport and deposition potential along the Martin River based on the 2D hydraulic model output under current/proposed flow regime(s) (Section 5.6).
- Compare sediment input and sediment transport potential to estimate future deposition rates and locations (Section 5.6).
- Coordinate with team members assessing riparian and aquatic habitat conditions and connectivity to help develop a multi-disciplinary analysis of the effects of changes in flow regimes (Section 5.7).

3.0 STUDY AREA

The study area consists of the Martin River watershed from its mouth to the EFMR and WFMR confluence and extends up the WFMR to the Red Lake outlet and up the EFMR to the toe of Dixon Glacier (Figure 3-1).

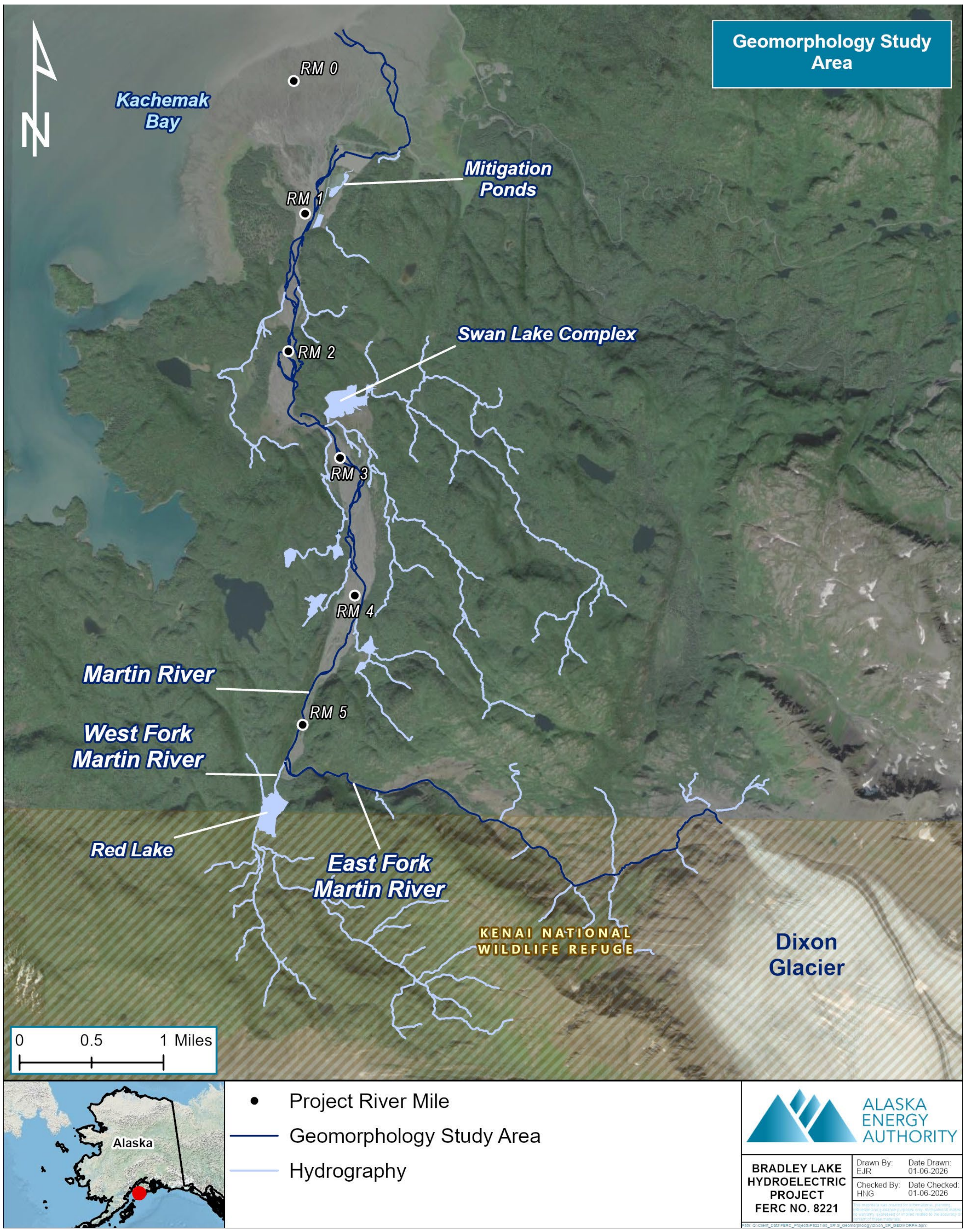


Figure 3-1 Martin River geomorphology and sediment transport study area.

4.0 METHODS

The methods used to meet the study objectives and complete the eight tasks of the geomorphic and sediment transport analysis are described below.

4.1 Geomorphic Reach Mapping and Channel Change Mapping from Historical Aerial Photographs

Geomorphic reach mapping of the Martin River current/recent conditions and analysis of the Martin River changes through time were made based on available LiDAR and aerial photography datasets (Table 4-1). Aerial photographs that did not have positioning data were geo-rectified within ArcGIS Pro using landmarks. Note that there are errors inherent in georectification of older aerial photographs due to lens distortion around the edges of the photographs; positioning on these older images is not precise but is sufficient for the purposes of the analysis of overall channel changes through time.

Table 4-1 Available LiDAR and aerial photography.

Product	Acquisition Date
Near-infrared (NIR)-LiDAR and digital imagery[a]	5/2024
NIR-LiDAR[b]	10/13/2022
4 band digital imagery[b]	7/28/2022
Sentinel 2 satellite imagery (various dates)[c]	2017-2023
Aerial imagery (05915 series)[d]	9/3/1996
Aerial imagery (58200 series)[d]	8/2/1982
Aerial imagery (63640 series)[d]	7/16/1977
Aerial imagery (4KACH series)[d]	9/6/1964
Aerial imagery (BM064 series)[d]	5/25/1951 and 8/15/1952
Aerial imagery (BM 0375 series)[d]	8/6/1950

[a] NV5 Global, Inc. (2024).
[b] NV5 Global, Inc. (2023).
[c] Satellite imagery obtained from Copernicus Brower https://dataspace.copernicus.eu/
[d] Imagery obtained from the U.S. Geological Survey Earth Explorer website https://earthexplorer.usgs.gov/

4.1.1 Recent/Current Geomorphic Reach Delineation and Valley Mapping

The Martin River valley was delineated into geomorphic reaches and map units based on confinement, channel/off-channel connectivity, and vegetation characteristics visible using the 2022 LiDAR and aerial photography (Table 4-1; NV5 Global, Inc. 2023) and updated in 2024 using the 2024 LiDAR and aerial photography (Table 4-1; NV5 Global, Inc. 2024). The valley was defined as the relatively flat valley bottom areas within the steeper side slopes. Mapping extended from the mouth of the Martin River to approximately 0.5 miles upstream of the EFMR canyon (approximately EFMR Project River Mile [PRM] 0.5) and from the mouth of the WFMR to just upstream of Red Lake. The initial 2023 mapping was field checked during the May 2023 field visits (see Section 4.2) and adjusted as needed based on field observations. The 2024 updates were checked during 2024 field visits. Channel changes were visually observed during field visits in 2025, and 2025 changes are discussed in the results sections, but no changes were made to maps.

4.1.2 Mapping Past Changes to Martin River Valley and Degree of Braiding

Mapping of Martin River channel conditions was completed in ArcMap Pro by digitizing active channel area within the Martin River valley using the 1950 through 2024 historical aerial and satellite imagery (Table 4-1) and noting changes to channel conditions and active channel extent through time. Note that the 1964 aerial image coverage was not complete—no aerial photographs were found for the river upstream from PRM 3.6.

Wetted channel lines were digitized using the 2022 aerial images. While the number of wetted channels depends on the flow in the river, the digitized channel lines provide an indication of the relative amount of braiding. The braiding index (total channel length/main channel length) was calculated using the 2022 digitized channels for each geomorphic reach.

The position of the terminus of the Dixon Glacier was also digitized on each set of aerial photographs. A Geographic Information Systems (GIS) coverage of glacial extent mapped by Giffen et al. (2007) was obtained to supplement terminus position mapping. The relative position of the main (northern) terminus (e.g., distance from 1950s terminus) was measured for each image.

4.1.3 LiDAR Aggradation/Degradation Analysis

The 2022 and 2024 LiDAR data were used in ArcMap Pro to determine topographic changes in the Martin River valley by subtracting the 2022 LiDAR elevation from the 2024 LiDAR elevation at each grid cell. The resulting grid was summed for the different geomorphic units in the river valley to determine net aggradation or degradation from 2022-2024. Because the 2024 LiDAR included bathymetric data (e.g., the surface of the ground beneath the water in rivers and ponds), a correction was applied to the 2024-2022 net volume difference to account for the volume of water in the Martin River based on the volume of water per linear foot of channel in the upper, confined reaches of the river where there was little net change between 2022-2024. This volume/linear foot was assumed to be consistent along the valley, a realistic assumption based on the minor amount of tributary inflow along the valley.

A rough estimate of long-term riverbed aggradation in the delta was made comparing the as-built drawings of the right bank levee and the three borrow pit/mitigation ponds located near the mouth of the Martin River with the 2022 and 2024 LiDAR data. The drawings showed up to 5 feet of freeboard (top of levee vs. riverbed) at levee construction, and water depths of up to 20 feet in the mitigation ponds.

No other/historical LiDAR or detailed topographic data were found for the Martin River valley to calculate aggradation or degradation volumes; aerial photographs and field observations of aggradation and degradation patterns were used to assess general aggradation and degradation trends through time.

4.2 Field Visits

Field visits to the Martin River in 2023 were conducted on May 16, May 22-24, and November 2. Field visits were conducted in 2024 on April 18, April 27-29, May 7, August 21, and October 30. In 2025, field visits were made on May 1, July 29, October 3, and November 5.

The following tasks were completed during the visits:

4.2.1 May 16, 2023

- Installed three timelapse cameras set to photograph braided areas of the Martin River valley (see Section 4.4 for details).

4.2.2 May 22-24, 2023

- Collected video footage of the Martin River and EFMR from tidewater to Dixon Glacier.
- Collected surficial Wolman pebble count data (100 clasts each) at 15 locations along the Martin River from Geomorphic Reaches 2 through 9.
- Made general geomorphic observations and performed field checking of mapped Geomorphic Unit breaks and off-channel connectivity corridors.

4.2.3 November 2, 2023

- Collected photographs of the new delta forming in the mitigation ponds and the new Martin River mouth from a helicopter.
- Surveyed elevations along the new delta and took global positioning system (GPS) points to outline the extent of delta deposits in mitigation ponds.
- Took GPS points to preliminarily outline the lateral extent of the erosion/headcutting in the Martin River valley upstream from the levee breach point.
- Took the pebble count at a representative bar in the Martin River at the levee breach location.
- Collected video of the Martin River and EFMR from the Martin River mouth to Dixon Glacier to compare with the May 2023 video.

4.2.4 April 18, 2024

- Installed eight timelapse cameras set to photograph braided and off-channel areas of the Martin River valley (see Section 4.4 for details).
- Collected video of the Martin River from the mouth to EFMR/WFMR confluence area.

4.2.5 April 27-29, May 7, 2024

- Collected a total of 21 surficial Wolman pebble count data (100+ clasts each) along the Martin River, including 13 in-river pebble counts to assist with determining Manning's *n* value for hydraulic modeling.
- Collected sub-surface substrate samples at eight locations along the Martin River.

4.2.6 August 21, 2024

- Made general observations of channel changes following the August 7, 2024 high flow event.
- Collected video of the Martin River from the mouth to EFMR/WFMR confluence area.
- Changed batteries and micro-SD cards in six timelapse cameras (Camera GE-05 was retrieved because the tree it was installed in had fallen and no other suitable mounting locations were available due to channel changes; Camera GE-01 was not accessible due to high flow conditions).

4.2.7 October 30, 2024

- Retrieved seven remaining timelapse cameras.
- Made general observations of channel changes since the site visit on August 21, 2024.
- Collected video of the Martin River from the mouth to EFMR/WFMR confluence area.

4.2.8 May 1, 2025

- Installed eight timelapse cameras set to photograph either primary braided areas, the mouth of the river, or tributary/off-channel/main river connection.
- Collected video/photos of the river mouth to EFMR/WFMR confluence.

4.2.9 July 29, 2025

- Changed batteries and micro-SD cards in the eight timelapse cameras.

4.2.10 October 3, 2025

- Visited the proposed Martin River intake site, completed the pebble count, and measured 10 largest mobile particles; took photographs and videos.
- Collected video/photos of the river mouth to EFMR/WFMR confluence.
- Flew along margins of Bradley Lake to observe and photograph shoreline erosion.

4.2.11 November 5, 2025

- Removed timelapse cameras and took video of the channel.

4.3 Pebble Counts and Sub-surface Sampling

4.3.1 Pebble Counts

In 2023, Wolman pebble counts (100 clasts) were collected at 14 bar locations along the Martin River and one location in the WFMR to characterize substrate size in Geomorphic Reaches along the river on May 22-24 and at one location on the new delta fan on November 2 (Figure 4-1).

In 2024, a total of 21 Wolman pebble counts (100+ clasts each) were collected in the Martin River watershed (19 along the Martin River, one along the EFMR, and one along the WFMR) to characterize either substrate at river bars within the high flow channel in locations indicative of bedload transport, or substrate across the width of the low flow channel to aid in developing appropriate Manning's *n* values for the 2D hydraulic model.

At eight of the river bar pebble count locations, concurrent sub-surface samples were taken in 2024 to aid in bedload transport analysis as described in Section 4.5 (green dots in Figure 4-1).

In 2025, one pebble count was made on a mid-channel bar within the proposed diversion pool near the toe of the Dixon Glacier to provide information on the expected grain size of mobile particles in the area under current conditions. The median diameter of the 10 largest mobile particles (showing signs of imbrication/recent transport) at the site were also measured.

The Martin River is a braided river downstream from Geomorphic Reach 9; river bar pebble count locations were selected at the head of river bars in non-braided reaches and at the head of anabranch bars in braided reaches (after Guerit et al. 2014). A mid-channel bar just downstream of the levee breach was sampled during the November site visit. At each river bar location, 100 clasts were selected using a random-walk method in an area covering approximately 100 square feet (the random walk covered the representative geomorphic facies at each location). For instream sample locations, traverses across the estimated "bankfull" width were made, with one clast measured each step across the channel until at least 100 clasts were measured. If fewer than 100 clasts were measured on one pass across the river, a second entire pass was made to ensure the entire width of the channel was represented in each pass.

For all pebble counts, each clast was passed through a gravelometer, and the size range was recorded (e.g., 2-4 millimeters, 4-8 millimeters, 8-16 millimeters). Particles smaller than 2 millimeters were not counted in any of the locations due to the abundance of interstitial fine material, a lag deposit of fines in many locations, and the desire to capture variations in the coarser bedload-sized material along the river.

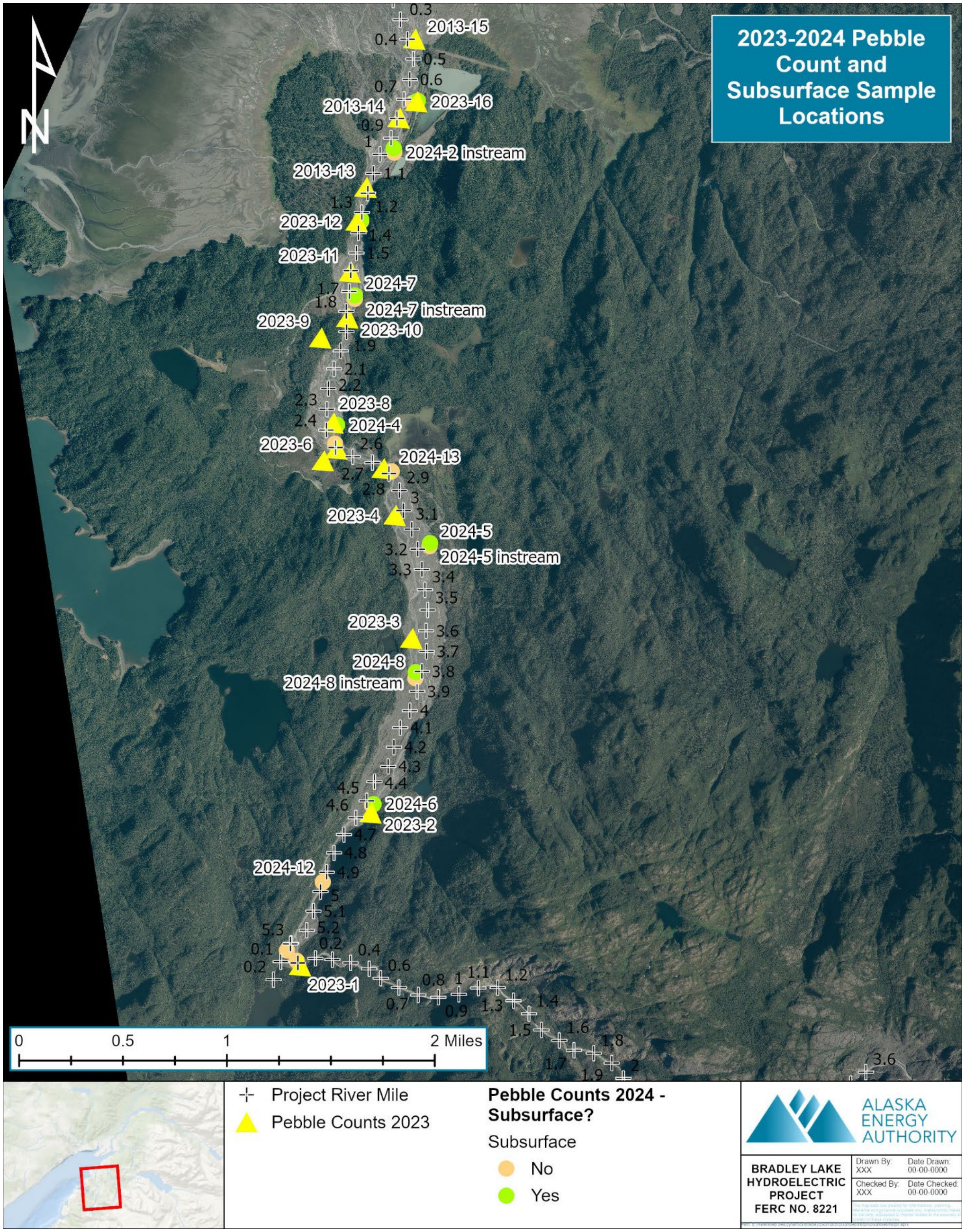


Figure 4-1 Martin River 2023 and 2024 pebble count and sub-surface sample locations.

4.3.2 Sub-surface Sampling

In 2024, sub-armor samples were taken at eight locations in conjunction with the 2024 pebble counts (Figure 4-1). For sub-surface samples, the surficial (armor) layer was scraped away to one median grain size depth over an approximately 25-40 square foot area. The sub-surface material was removed using a pickaxe and shovel and loaded into 5-gallon buckets. Each bucket was weighed and then sieved through a 32-millimeter sieve in the field. Clasts larger than 32 millimeters were separated into size classes (e.g., 32-45 millimeters, 45-64 millimeters, 64-90 millimeters, 90-128 millimeters) on a tarp. Total sample size varied depending upon the weight of the largest particle, with the 1 percent sample mass criterion of Church et al. (1987) being the goal sample size. If the largest class was extremely heavy (for example, the largest particle in sample 2024-6 was 16.9 kilograms, which would have required a total sample size of 1,690 kilograms), Church et al.'s 2-5 percent criterion was used.

When the entire sample was field sieved, the clasts in each grain size were weighed and recorded on the data sheet. The remainder of the sample (finer than 32 millimeters) was weighed and then split with approximately 15-20 kilograms packed and labeled to bring back for laboratory sieving. Laboratory sieving of the finer fraction sub-samples was conducted by Alaska Testlab in Anchorage, Alaska. Samples were dried and sieved through a series of sieves (32 millimeters, 16 millimeters, 8 millimeters, 4 millimeters, 2 millimeters, 1 millimeter, 0.065 millimeter), and the weight of sample retained on each sieve was recorded, along with the remaining fine fraction. The weights retained reported by the lab were multiplied by the ratio of total finer than 32-millimeter field weight/split weight and combined with the field weights of each particle size class to produce a complete particle size distribution for each sub-armor sample.

4.4 Timelapse Cameras

Timelapse cameras were deployed at three locations with a view of braided areas along the Martin River to record braid/sediment transport timing during 2023 (Cameras GE-01 through GE-03 on Figure 4-2). In 2024, a total of eight timelapse cameras were deployed (Figure 4-2, Photo 4-1 through Photo 4-8). The 2024 deployment included locations with braided channels as well as locations with views of off-channel habitat (OCH) and one location looking up the EFMR canyon. In 2025, eight timelapse cameras were again deployed, with six locations the same as in 2023-2024 and a few new locations to provide information on locations of interest to fisheries staff (Figure 4-3, Photo 4-9 and Photo 4-10).

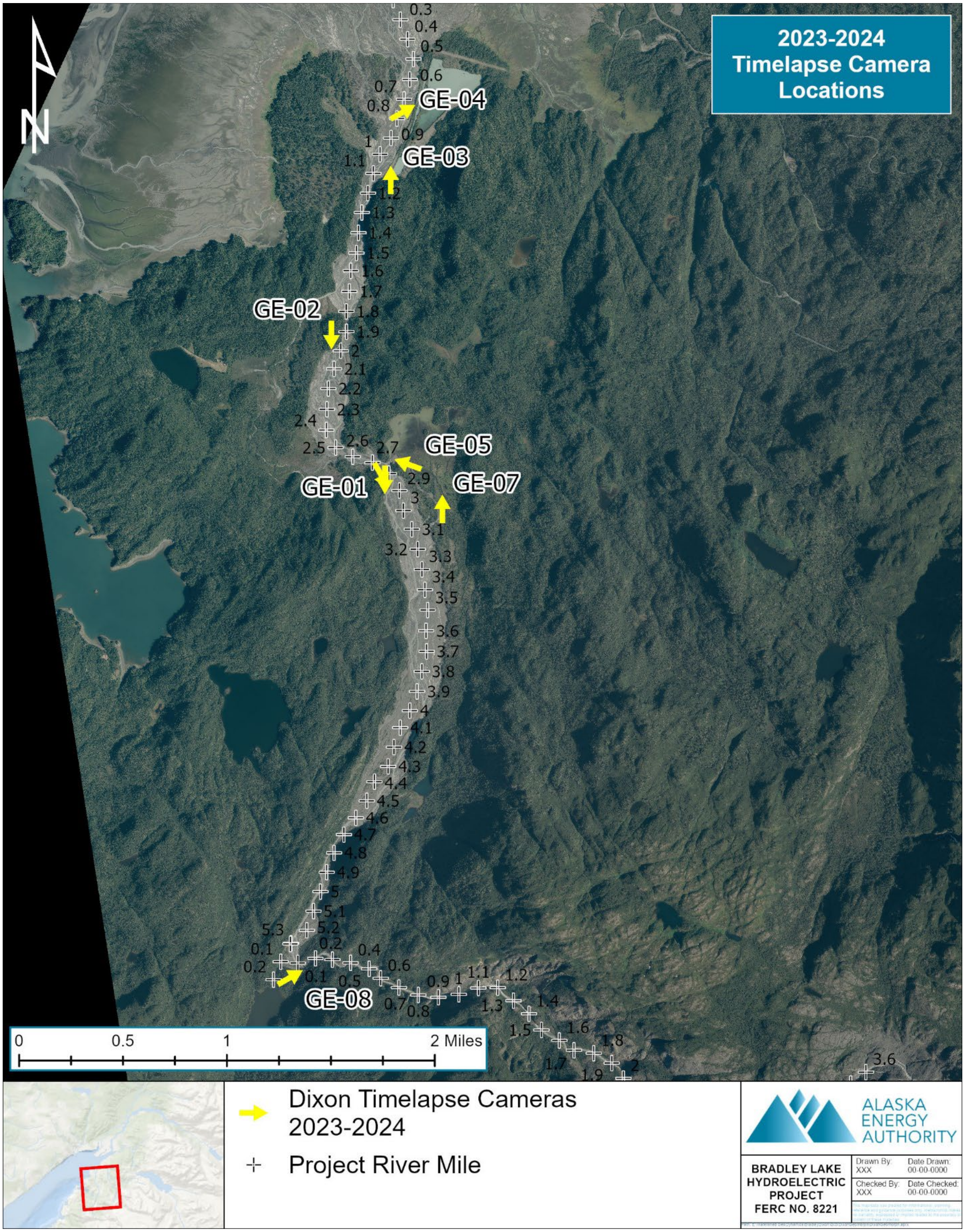
The cameras were Brinno TLC 202 timelapse cameras in waterproof housing (with 1-gram desiccant pack) with a mounting bracket. Each bracket was screwed to a 12-inch-long piece of 1-inch-by-6-inch wooden board. The boards were attached to an appropriately sized tree by two tie-down straps. Cameras were set to take one photo per day at approximately noon in 2023 and three photos per day at 7 a.m., 1 p.m., and 7 p.m. in 2024.

In 2023, cameras were installed on May 16, serviced (fresh batteries and micro-SD cards) on August 24, and removed on October 19.

In 2024, cameras were installed on April 18. Cameras GE-02, GE-03, GE-04, GE-06, GE-07, and GE-08 were serviced on August 21, 2024, and Camera GE-05 was removed on that day due to channel changes that made the location infeasible. Camera GE-01 was not serviced in August due to channel changes that made the location unreachable under the flow conditions that day. All remaining cameras were removed on October 30, 2024.

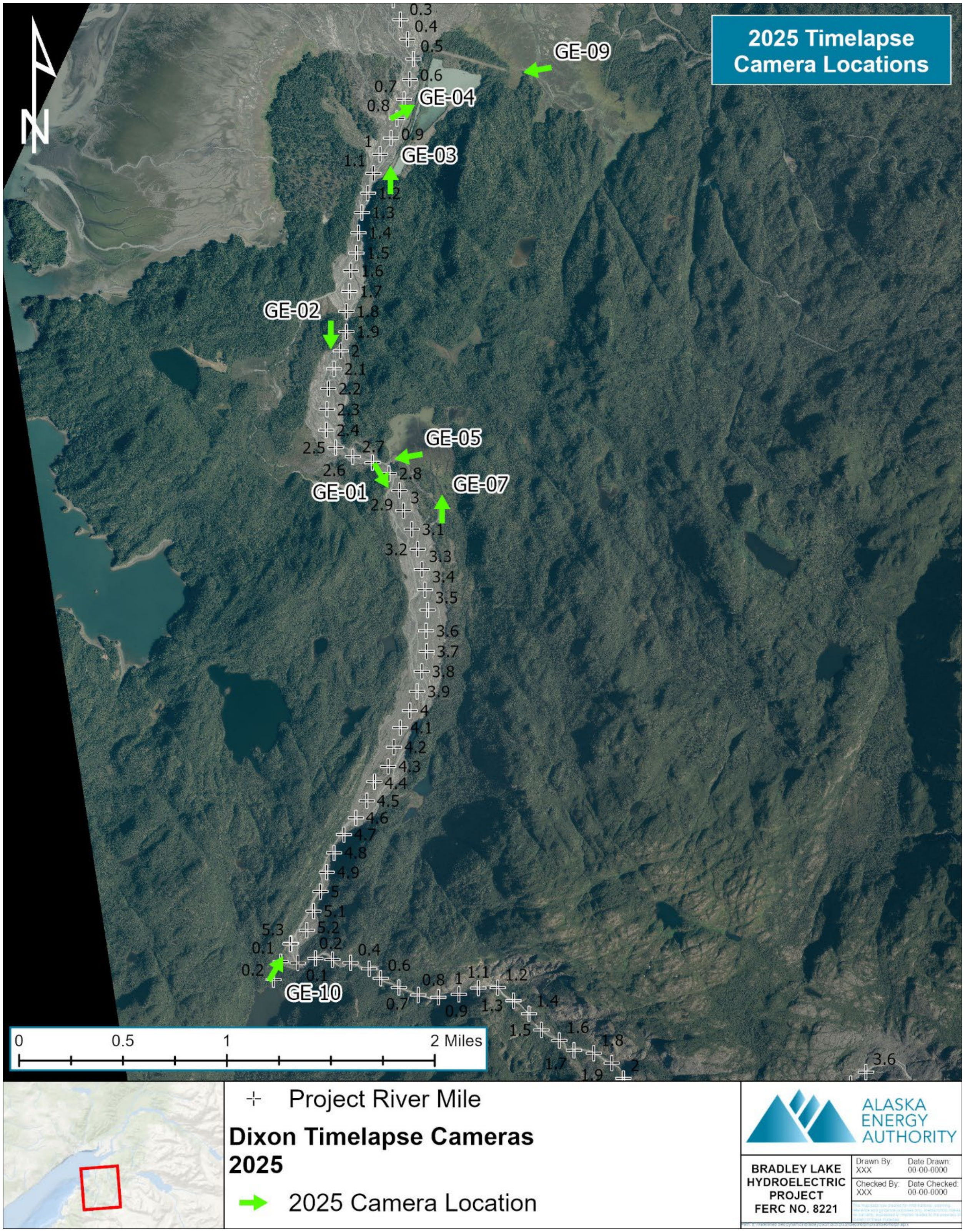
In 2025, cameras were installed on May 1 and serviced on July 29. All cameras were removed on November 5, 2025.

The footage from each camera was viewed to determine dates when channel change occurred. Movement of braided river channels occurs when bedload transport takes place (Middleton et al. 2019). The dates with channel change were noted for each camera and correlated with gage height and/or flow measured at the U.S. Geological Survey (USGS) gage (USGS Gage No. 15238951 EFMR at mouth near Homer, Alaska) and the RM 1.9 constriction gage (DOWL 2024, 2025).



Note: Arrows show direction camera pointed.

Figure 4-2 Martin River 2023 and 2024 timelapse camera locations.



Note: Arrows show direction camera pointed.

Figure 4-3 Martin River 2025 timelapse camera locations.

Photo 4-1 Martin River timelapse Camera GE-01 view looking upstream, May 16, 2023 (top), and April 18, 2024 (bottom).

Photo 4-2 Martin River timelapse Camera GE-02 view looking upstream, May 16, 2023 (top), and April 18, 2024 (bottom).

Photo 4-3 Martin River timelapse Camera GE-03 view looking downstream, May 16, 2023 (top), and April 18, 2024 (bottom).

Photo 4-4 Martin River timelapse Camera GE-04 view looking downstream, April 18, 2024.

Photo 4-5 Martin River timelapse Camera GE-05 view looking downstream, April 18, 2024.

Photo 4-6 Martin River timelapse Camera GE-06 view looking upstream, April 18, 2024.

Photo 4-7 Martin River timelapse Camera GE-07 view looking downstream, April 18, 2024.

Photo 4-8 Martin River timelapse Camera GE-08 view looking upstream, April 18, 2024.

Photo 4-9 Martin River timelapse Camera GE-09 view looking upstream, May 1, 2025.

Photo 4-10 Martin River timelapse Camera GE-10 view looking downstream, May 1, 2025.

4.5 Sediment Transport and Deposition Patterns under Current and Potential Future Flow Regimes

Bedload transport in gravel-bedded rivers occurs when river flows are high enough to mobilize the armor (coarser, surficial) layer on the riverbed. Bedload transport is a function of shear stress acting on the gravel/cobble particles on the riverbed, and it can be calculated based on river depth and velocity.

4.5.1 Sediment Transport Analysis Using Two-dimensional Hydraulic Model Output

The 2D hydraulic model (Kleinschmidt Associates 2025) was used to estimate river depth and velocity under five different peak flow scenarios. The model was run with the following flows:

- EFMR: 1,000 cubic feet per second (cfs), 2,000 cfs, 3,000 cfs, 4,000 cfs, 5,000 cfs
- WFMR: 10 cfs for all scenarios
- Mid-reach inflows: 1 cfs
- Other tributaries: 0 cfs

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

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

where:
D_{crit} = critical diameter (millimeters)
V = velocity (feet per second)
d = depth (feet)

The critical diameter was computed in ArcGIS Pro and used to produce maps showing critical diameter under the five flow scenarios. These maps were compared to surficial grain size data (pebble counts) collected during the field visits.

4.5.2 Comparison of Future Sediment Input and Transport Potential

The 45-year (1979-2024) synthetic flow record for the EFMR developed by DOWL (2025) was used to calculate flows into the EFMR with operation of the proposed Dixon diversion dam and tunnel that would convey water from the EFMR to Bradley Lake. These data, along with timelapse camera and critical diameter from the 2D HEC-RAS models of the Martin River prepared by Kleinschmidt Associates and of the EFMR in the vicinity of the proposed diversion/intake prepared by DOWL, were used to estimate frequency of bedload transport under existing and with-diversion conditions.

4.6 Synthesis of Hydraulic, Geomorphic, Riparian, and Aquatic Analyses: Potential Pathways of Change in River Valley Characteristics, Riparian Habitat, and Aquatic Habitat/Connectivity

Synthesis of hydraulic, geomorphic, riparian, and aquatic resource effects of proposed changes to Martin River flow regimes was completed via meetings and field visits among fisheries, riparian, hydraulic, and geomorphic study leads.

5.0 RESULTS

5.1 Geomorphic Reach Mapping and Channel Change Mapping from Historical Aerial Photographs

Delineation of geomorphic reaches along the Martin River helps differentiate parts of the river with different gradient and confinement characteristics that often correlate with varying responses of the channel to changes in water or sediment supply. Geomorphic mapping units are similar, but instead of linear features, the map units are areas of the river valley that have similar past geomorphic activity. For example, unvegetated alluvial areas indicate recent fluvial reworking, while areas with vegetation of a similar height or age indicate the length of time since the river was active in those areas. The following sections describe geomorphic reaches and geomorphic map units based on recent conditions using the 2022 and 2024 aerial photographs, LiDAR, and field observations. Changes to geomorphic reaches downstream from PRM 1.9 resulted from the August 2023 levee breach.

5.1.1 Geomorphic Reaches of the Martin River

Twelve different geomorphic reaches were delineated along the Martin River and EFMR from tidewater to the Dixon Glacier in both 2022 and 2024 (Table 5-1, Figure 5-1, Figure 5-3). Reaches that are constricted/confined by bedrock or steep valley walls generally have one or two channels; unconfined areas generally have multiple channels (Figure 5-2). The number of wetted channels in each unconfined reach varies depending on flow conditions; at higher flows, more channels are wetted, while at lower flows, only one or two channels may be wetted. Note that Geomorphic Reach 8, while unconfined by valley walls, was subdivided into two distinct sub-reaches: a downstream unconfined sub-reach with multiple channels and an upstream sub-reach that is currently confined by a high terrace. The upstream reach (8b) is currently incising into past deposits to create the confining terrace; this section of the river was not confined to a single channel on historical aerial photographs (see discussion in Section 5.1.3).

In 2022, average channel gradients in the geomorphic reaches were relatively consistent (0.6 to 0.8 percent) between the delta (Geomorphic Reach 1) and Geomorphic Reach 7 except for the slightly steeper Geomorphic Reach 5 constriction. Channel gradients gradually increased in the upstream direction from Geomorphic Reach 7 (0.8 percent) through Geomorphic Reach 9 (1.5 percent). The EFMR canyon (Geomorphic Reach 10) had an average gradient of 6.7 percent, with gradient increasing closer to the Dixon Glacier. Channel changes at the mouth of the Martin River in response to the August 2023 levee breach resulted in slight changes in channel gradient in Geomorphic Units 3 and 4.

Table 5-1 2022 and 2024 geomorphic reach characteristics.

Geo-morphic Reach No.	Reach Characteristics	2022 Length (ft)	2022 Average Gradient	2022 Braid Index	2024 Length (ft)	2024 Average Gradient
0	Tidewater	n/a	n/a	n/a	n/a	n/a
1	Delta	2,530	0.7%	4.0	3,145	0.7%
2	Levee	3,458	0.7%	10.6	2,447	0.7%
3	Constriction	1,365	0.6%	3.8	1,365	0.9%
4	Unconfined, left bank off-channel enters	2,114	0.8%	2.8	2,114	0.8%
5	Constriction	283	1.1%	1.6	283	0.7%
6	Unconfined; left bank off-channel area at upstream end	3,400	0.8%	6.2	3,400	0.8%
7	Moderately confined; right bank side channel enters	1,537	0.8%	6.0	1,537	0.8%
8a	Unconfined, multiple channels	5,536	1.2%	4.9	5,536	1.2%
8b	Unconfined single channel (constrained by high terrace)	3,820	1.2%	2.6	3,820	1.2%
9	Moderately confined single thread Red Lake outflow (WFMR) near upper end of reach	4,238	1.5%	1.1	4,238	1.5%
10	EFMR Canyon	19,671	6.7%	1	19,671	6.7%
11	Glacier	33,256	9.8%	n/a	33,256	9.8%

Figure 5-1 Martin River 2022 geomorphic reaches.

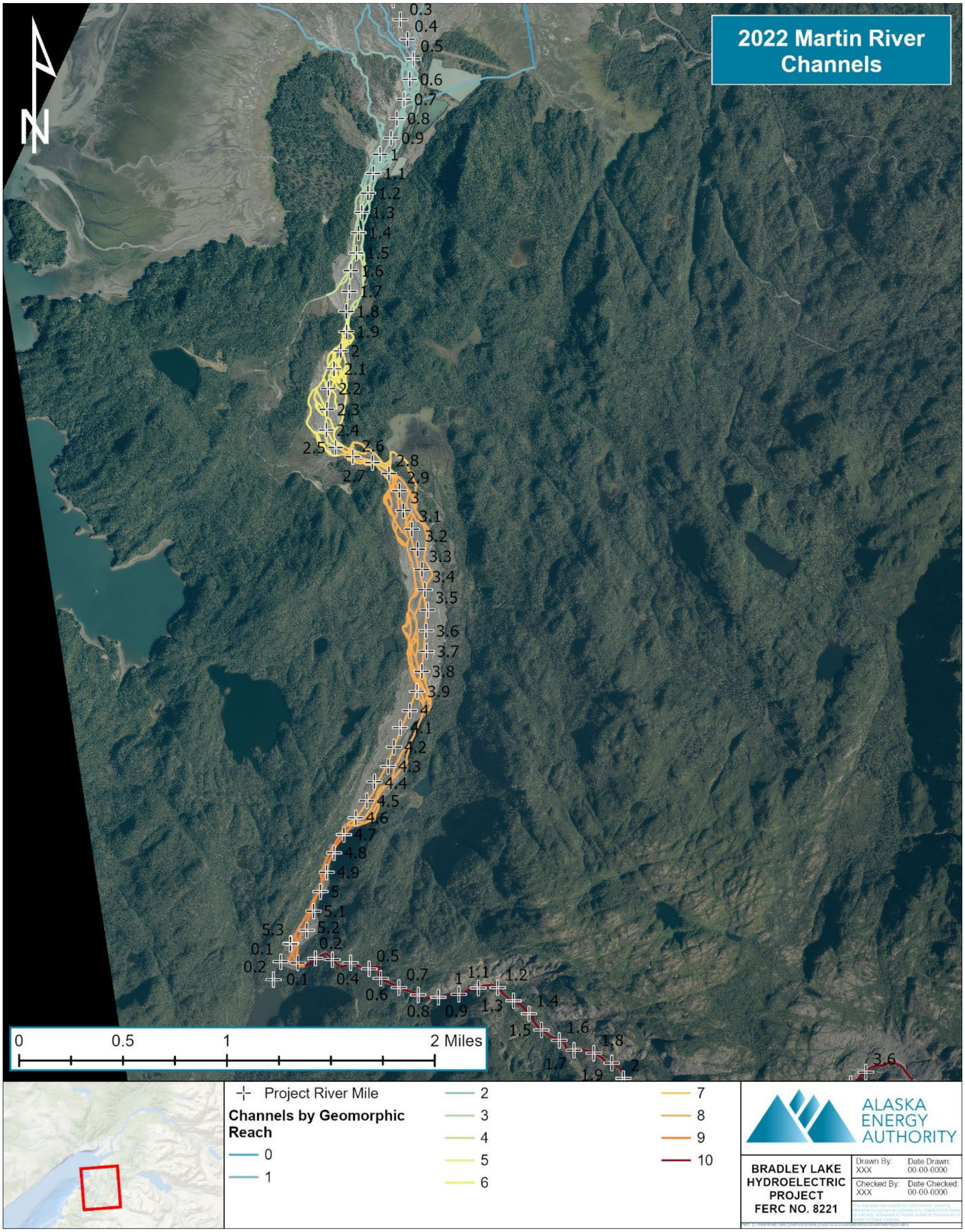


Figure 5-2 Martin River 2022 channels by geomorphic reach.

Figure 5-3 Martin River 2024 geomorphic reaches.

5.1.2 Geomorphic Units in the Martin River Valley

The Martin River valley is relatively flat bottomed with steep bedrock sidewalls as a result of the braided glacial river that has filled the valley with alluvial material. As the river fills one area of the valley bottom, the active channel moves into a different location in the valley bottom, and the previously active area re-vegetates. The valley bottom was delineated into geomorphic units based on 2022 dominant geomorphic process or, in the case of forested valley bottom areas, vegetation height that is indicative of the length of time since the area was part of the active channel (Table 5-2 and Figure 5-4). Geomorphic Units were added to the river valley on the east side of the levee based on the 2024 aerial photographs and LiDAR data based on conditions at the time of the aerial photographs (May 2024). Note that the river continues to evolve east of the levee breach, as discussed in Section 5.1.3.3.

The active channel Geomorphic Unit dominates the Martin River valley, with unvegetated alluvial deposits and an active braid plain up to 1,000 feet wide in unconfined areas of the valley.

At least five off-channel areas or tributaries and connecting channels (corridors) occur between PRM 1.5 and the WFMR confluence. All the off-channel/tributary areas except the left bank lakes at PRM 3.4 show evidence of current or recent (past 50 years) activity from the mainstem river channel in the form of alluvial deposits or turbid water during high flow conditions.

There are three large, forested areas that have small active mainstem channels, primarily high flow channels: the left bank area at the mouth of the river that is part of the Martin River delta, and large areas on the right and left bank between PRM 2 and PRM 3 that connect to off-channel areas. Based on field observations, the river valley has recently been actively aggrading in the active channel adjacent to these locations, which has resulted in fresh alluvium and small high flow channels through the forested areas.

Much of the remaining valley is in various stages of revegetation following past fluvial activity. Tree height and species are indicators of how recently these areas have been active and can provide insights into how frequently the Martin River re-occupies portions of the valley. Revegetation generally starts with forbs, alder, and cottonwood. Spruce regeneration follows. Cottonwood grows tall quickly; spruce grows more slowly.

Table 5-2 2022 and 2024 geomorphic units in the Martin River valley.

Geomorphic Unit Name	Characteristics	2022 Area (acres)	2024 Area (acres)
Tidelands	Areas that are primarily tidal in nature.	33	33
Active channel (2022)	Unvegetated (or very sparsely vegetated) alluvial areas indicative of relatively recent fluvial action.	605	623
Off-channel habitat (OCH) or tributaries	Ponds or wetlands that are connected to the active channel area but do not currently show signs of recent mainstem re-working (some off-channel areas receive high flows from the Martin River, some areas are only connected by channels flowing out of the OCH and maintain relatively low turbidity water). Includes WFMR/Red Lake.	80	98
Off-channel/ tributary connectivity corridor	Small channels that connect off-channel/tributary habitat with the main channel.	4	4
Forested with small active high flow channels	Primarily forested area that contains one or multiple Martin River channels; these channels are wetted primarily under high flow conditions.	395	406
Vegetated (to 5 feet high)	Vegetated valley bottom with shrubs/trees up to 5 feet high.	33	33
Vegetated (to 10 feet high)	Vegetated valley bottom with shrubs/trees up to 10 feet high.	4	6
Vegetated (to 15 feet high)	Vegetated valley bottom with shrubs/trees up to 15 feet high.	16	16
Vegetated (to 20 feet high)	Vegetated valley bottom with shrubs/trees up to 20 feet high.	18	18
Vegetated (to 30 feet high)	Vegetated valley bottom with shrubs/trees up to 30 feet high.	2	2
Vegetated (to 40 feet high)	Vegetated valley bottom with shrubs/trees up to 40 feet high.	37	37
Vegetated (to 50 feet high)	Vegetated valley bottom with shrubs/trees up to 50 feet high.	55	55

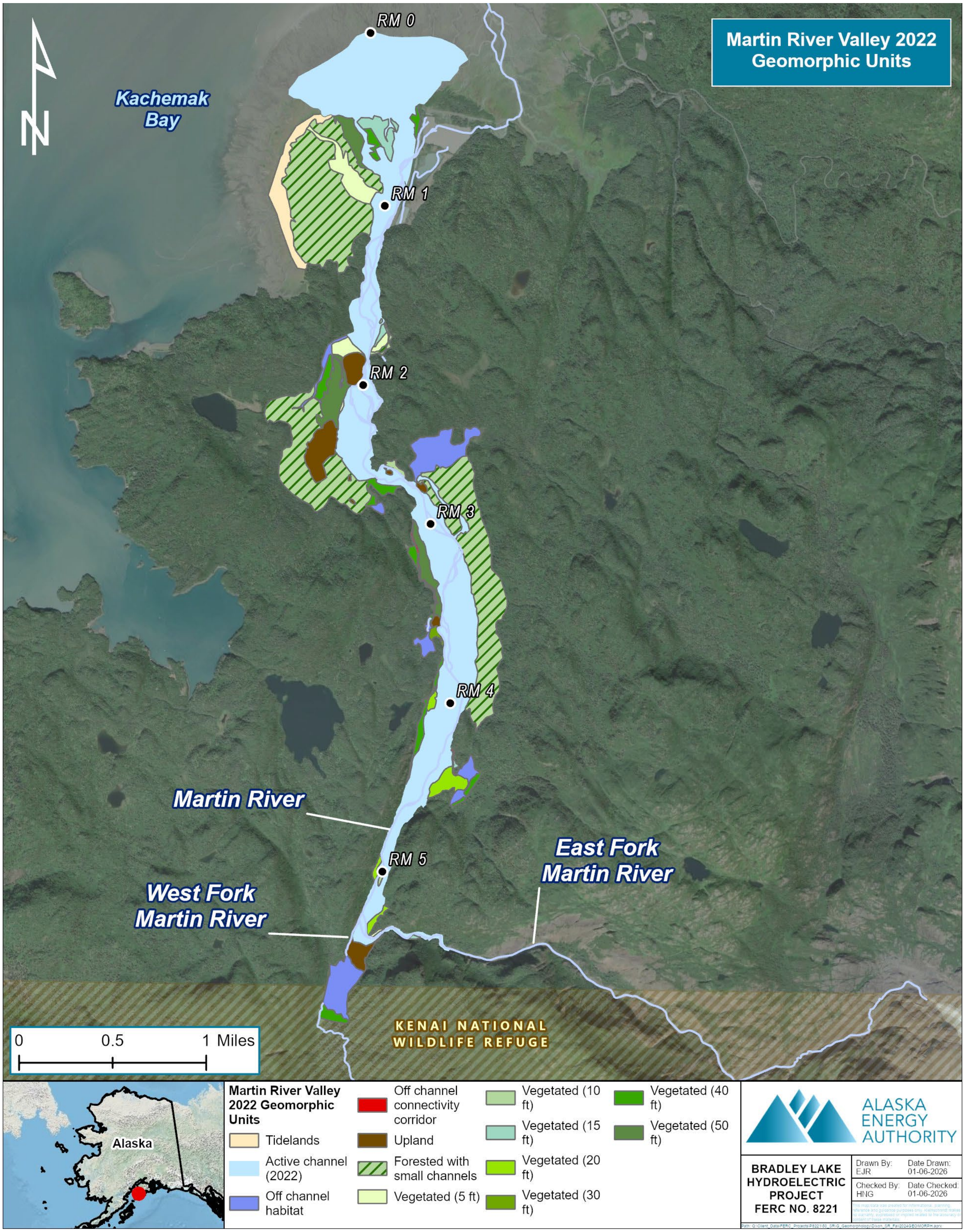


Figure 5-4 2022 Martin River valley geomorphic units.

5.1.3 Historical Aerial Photograph Mapping of the Martin River Valley

An overview of historical aerial photographs from 1950 through the present (see Table 4-1) yielded the following observations, which are examined in greater detail in the following sections:

- The Dixon Glacier has been progressively retreating since the 1952 aerials (and likely since the late 1800s Little Ice Age Maximum). There were large areas of unvegetated and unconsolidated deposits in the EFMR valley that were eroding in the 1952 photos.
- The Martin River downstream from the EFMR canyon has been active across much of the valley, with the active channel occupying different parts of the valley, off-channel areas, and river delta through the years.
- The Martin River has been aggrading differently in the various reaches of the channel through time (e.g., aggradation rates are not necessarily constant throughout the river in space or time).
- The general characteristics of geomorphic reaches (e.g., single or multi-channel) have been relatively constant since 1950 except for Geomorphic Reach 8b, which was a multi-channel reach prior to at least 1996. This suggests downcutting in Geomorphic Reach 8b that created the constraining terrace occurred after 1996.
- The Martin River aggraded enough to overtop and erode the right bank levee at the former borrow pit/mitigation ponds near the mouth of the river in 2023. The river has been adjusting to this change by building a delta into the former borrow pit/mitigation ponds.

5.1.3.1 Glacial Extent and Sediment Sources

The Martin River is a braided river, indicating that the sediment supply to the river far exceeds the ability of the river to transport the sediment load. To understand past and potential future changes to the river valley and channel form, it is important to evaluate sediment source areas and changes to sediment loading through time. Timescales important for river geomorphology and sediment transport are over centuries and decades as well as annual variations. The Dixon Glacier and Martin River watershed are the sediment source areas of the Martin River.

While there are no studies of the Dixon Glacier itself, research on the nearby Grewingk Glacier has shown that following the late Pleistocene glacial maximum, Kenai Peninsula glaciers began retreating during a warming period around 11,000 years ago (Wiles and Calkin 1990; Reger et al. 2008; LaBrecque and Kaufmann 2016). Following multiple readvances and retreats in the early Holocene, the glaciers appear to have retreated to near their present positions by approximately 600 CE. The Little Ice Age saw advance of the Kenai Peninsula glaciers, with the Grewingk Glacier advancing 2-3 miles from its present terminus between about 1400-1850 CE, followed by retreat from the late 1800s to present.

Aerial photograph analysis of the primary eastern terminus of the Dixon Glacier shows it has been receding, with a retreat of 7,622 feet (1.4 miles) between 1952 and 2022 (average 109 feet/year; Figure 5-5 and Figure 5-6). The 1952-2022 retreat rates have not been steady, but this could be influenced by the topography of the canyon at the toe of the glacier; there are several very steep and constrained waterfall areas that result in differential ice thicknesses and toe widths (narrow tongue vs. wider terminus) that affect retreat rates.

The smaller, western lobe of the glacier has also been retreating; when the western terminus retreats above the current topographic divide between the eastern and western lobes, there will be no flow into the Martin River from the western lobe outlet stream. Instead, all flow from the Dixon Glacier will come from the outlet stream emanating from the eastern lobe.

If it is assumed that this average retreat rate can be applied to the retreat of the Dixon Glacier since the Little Ice Age Maximum (late 1800s), it would put the terminus of the Dixon Glacier approximately 3 miles downvalley from the present terminus. This is consistent with the Little Ice Age Maximum advance of the Grewingk Glacier.

Using the 3-mile downvalley estimate as a starting point, the 2022 LiDAR data were evaluated for topographic evidence of the Little Ice Age Maximum of the Dixon Glacier, either moraines or erosional features consistent with glacial activity. A prominent series of moraine features was observed trending north of the present Dixon Glacier that connected to distinct erosional features in the Martin River canyon and moraines and erosional features in the upper Red Lake valley. This estimated position of the Dixon Glacier at the Little Ice Age Maximum is shown in Figure 5-5 as a dashed black line and a dashed blue line on Figure 5-6.

The importance of this Little Ice Age Maximum is the resulting source of sediment to the Martin River, as discussed below.

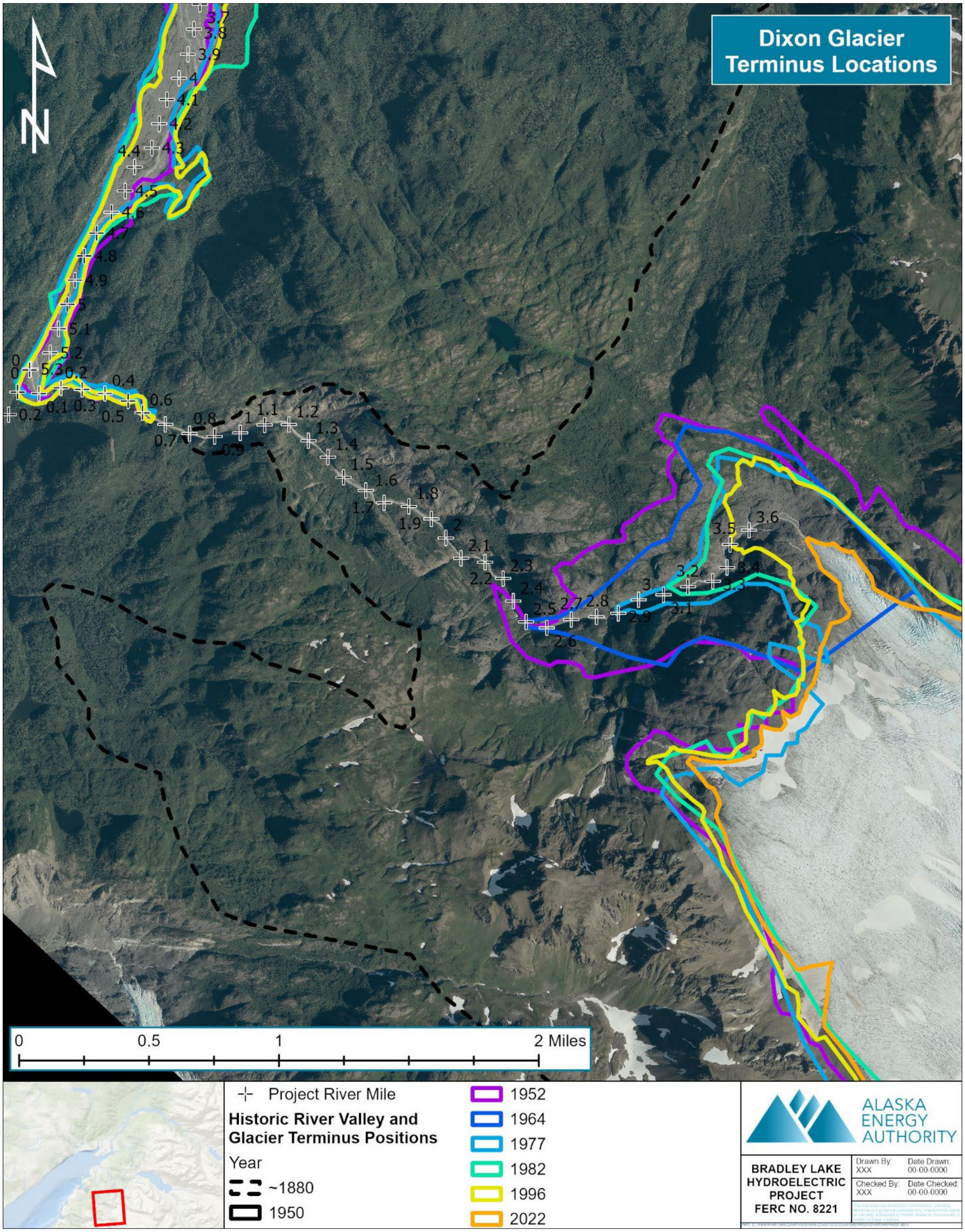


Figure 5-5 Dixon Glacier terminus positions Little Ice Age Maximum (approximately 1880) through 2022.

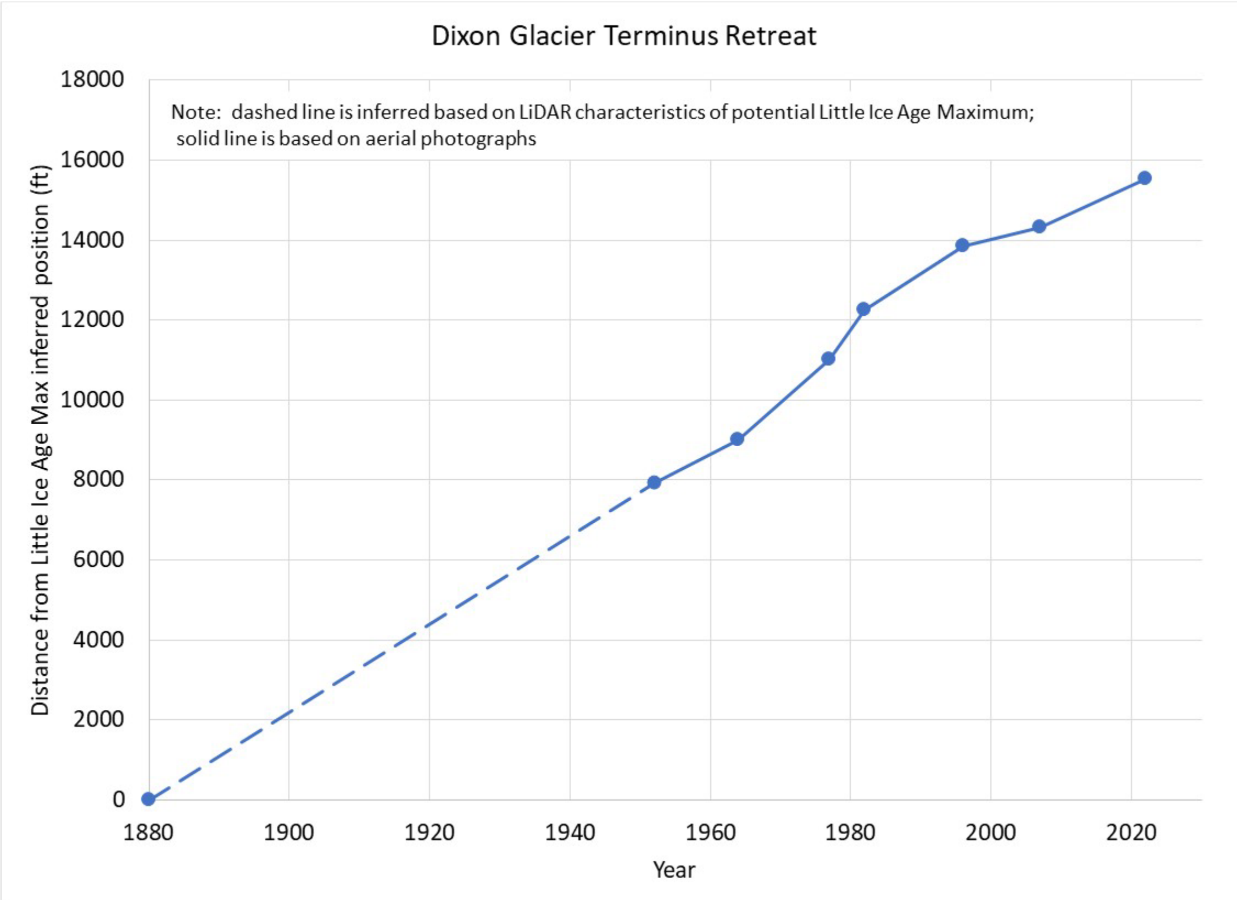


Figure 5-6 Dixon Glacier terminus retreat, late 1800s to 2022.

5.1.3.1.1 Martin River Sediment Sources

Sediment sources to the Martin River include the Dixon Glacier outflow, tributary streams, and landslides/erosion of erodible slopes along the river corridor. The Dixon Glacier currently is the largest source of sediment to the Martin River watershed. Tributary streams are small, and many have lakes that capture upstream sediment. The current stream valley is bounded by competent bedrock in most areas and has no obvious large areas of landslides. However, areas of erodible material upstream of the Little Ice Age maximum do appear to have been a substantial source of sediment in the past as discussed below.

5.1.3.1.1.1 Dixon Glacier

There are no direct measurements of sediment output from the Dixon Glacier. Measurements of basal erosion on other Alaskan glaciers range from 10 to 100 millimeters per year (Hallet et al. 1996). If it is assumed that over the long term, sediment output from the 19-square-mile Dixon Glacier is constant and falls within these basal erosion rates, average total sediment output (fine-grained suspended load plus coarser-grained bedload) could range from 610,000 to 6,100,000 cubic yards per year. Actual sediment supply has been and will continue to be episodic based on the volume of glacial melt and the sub-glacial meltwater environment, with more sediment supply expected in later summer/fall than earlier in the summer as the glacier warms through the melt season and becomes less firmly attached to the bed (Engel et al. 2024). The sub-glacial environment and plumbing of alpine glaciers is complex, and observations of the recently de-glaciated areas of the Dixon Glacier suggest that pockets of till exist between areas of scraped and polished bedrock. As these pockets are encountered by sub-glacial meltwater or uncovered as the glacier retreats, they could provide episodic large sources of sediment to the Martin River.

Again, there are no data from the Dixon Glacier to provide guidance for partitioning the total sediment output into fine-grained (suspended load) and coarse-grained sediment (bedload). Data from other glacier systems is sparce and suggest that underlying bedrock characteristics such as hardness and composition affect the ratio, but total sediment load in other glacial systems ranges from 5 to 50 percent bedload (coarse sand to boulder) with the remainder suspended load (fine sand, silt, clay). Increased sediment discharge during glacier retreat has been suggested by Delaney and Adhikari (2020), so sediment yields from the Dixon Glacier outflow will likely remain similar to yields since the Little Ice Age Maximum. Observations of till just downstream from the current terminus of the Dixon Glacier in October 2025 are likely representative of the mix of material supplied from the glacier. A particle size distribution was not made on the till, but it appears to be typical of alpine till, with an unconsolidated sandy matrix and a mix of larger gravel/cobble/boulder particles within the matrix. The material is loose and easily erodible by rain, streams, or raveling (Photo 5-1).

Photo 5-1 Till deposits at the terminus of the Dixon Glacier, October 3, 2025.

5.1.3.1.1.2 Other Sources of Sediment

In addition to sediment supply from Dixon Glacier outflow, sediment is supplied to the Martin River from the rest of the watershed. There are no large tributaries that supply sediment to the river (most sediment from the WFMR valley is trapped in Red Lake), and no large landslides or other major sources of sediment were observed in the mainstem Martin River valley. However, there is evidence of large sediment sources within the footprint of the Little Ice Age Maximum of the Dixon Glacier in the EFMR valley.

The 1952 and 1964 aerial imagery shows large areas of unvegetated sediment between EFMR PRM 0.9 and PRM 2.2 in the EFMR valley with gullies and landslide scars and a wide, sediment-rich river in what is now the canyon (Figure 5-7). The 2022 LiDAR data further corroborate this interpretation of abundant sediment yield from unconsolidated, formerly sub-glacial sediment deposits between EFMR PRM 0.9 and PRM 2.2. A large left bank, 3,500-square-foot landslide scar is also evident in the LiDAR data between EFMR PRM 0.6 and PRM 0.7; this landslide has a 250-foot-high headscarp. These features are still eroding on the 1964 aerial imagery, and then at least partially vegetated on the next available aerial image (1977, Figure 5-8), and the river is a narrower, single-thread channel, similar to conditions in the EFMR today (Figure 5-9). These images suggest that between the Little Ice Age Maximum and the mid 1900s, a large amount of sediment was supplied to the Martin River from erosion of unconsolidated sediment in the EFMR valley. Based on the glacial retreat rate shown in Figure 5-6, it is likely that this sediment source area was exposed to maximum erosion (following glacial retreat and prior to revegetation) between about 1920 and 1965. The volume of sediment supplied from this source is difficult to calculate exactly because the pre-erosion topography is not known but based on elevational differences in the landslide and surrounding areas and in the sub-glacial deposit areas; up to 12 million cubic yards of material could have been supplied to the Martin River over the 45-year period. This value will be compared to estimated aggradation volumes in the Martin River valley in subsequent sections.

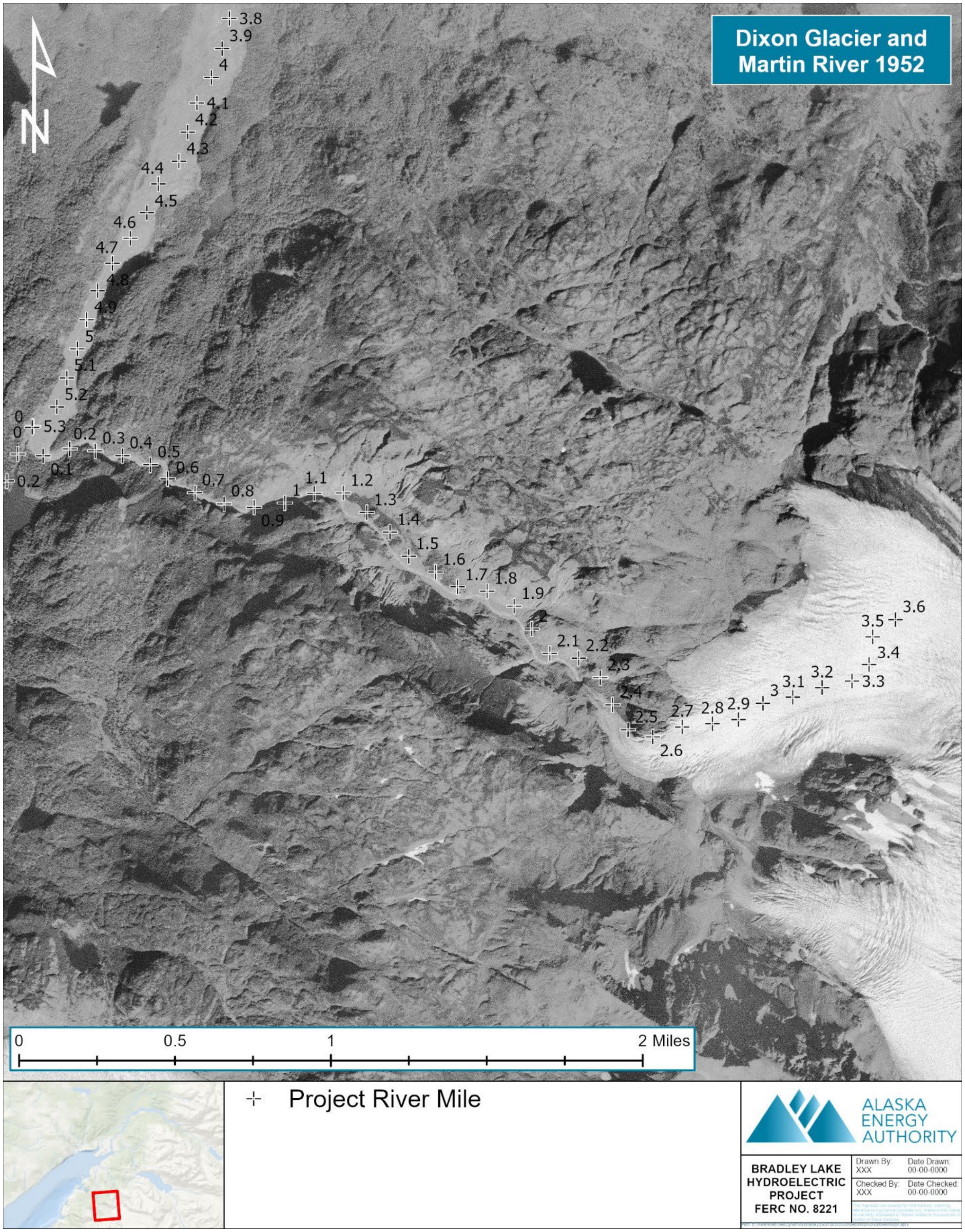


Figure 5-7 Dixon Glacier, East Fork Martin River, and upper Martin River 1952.

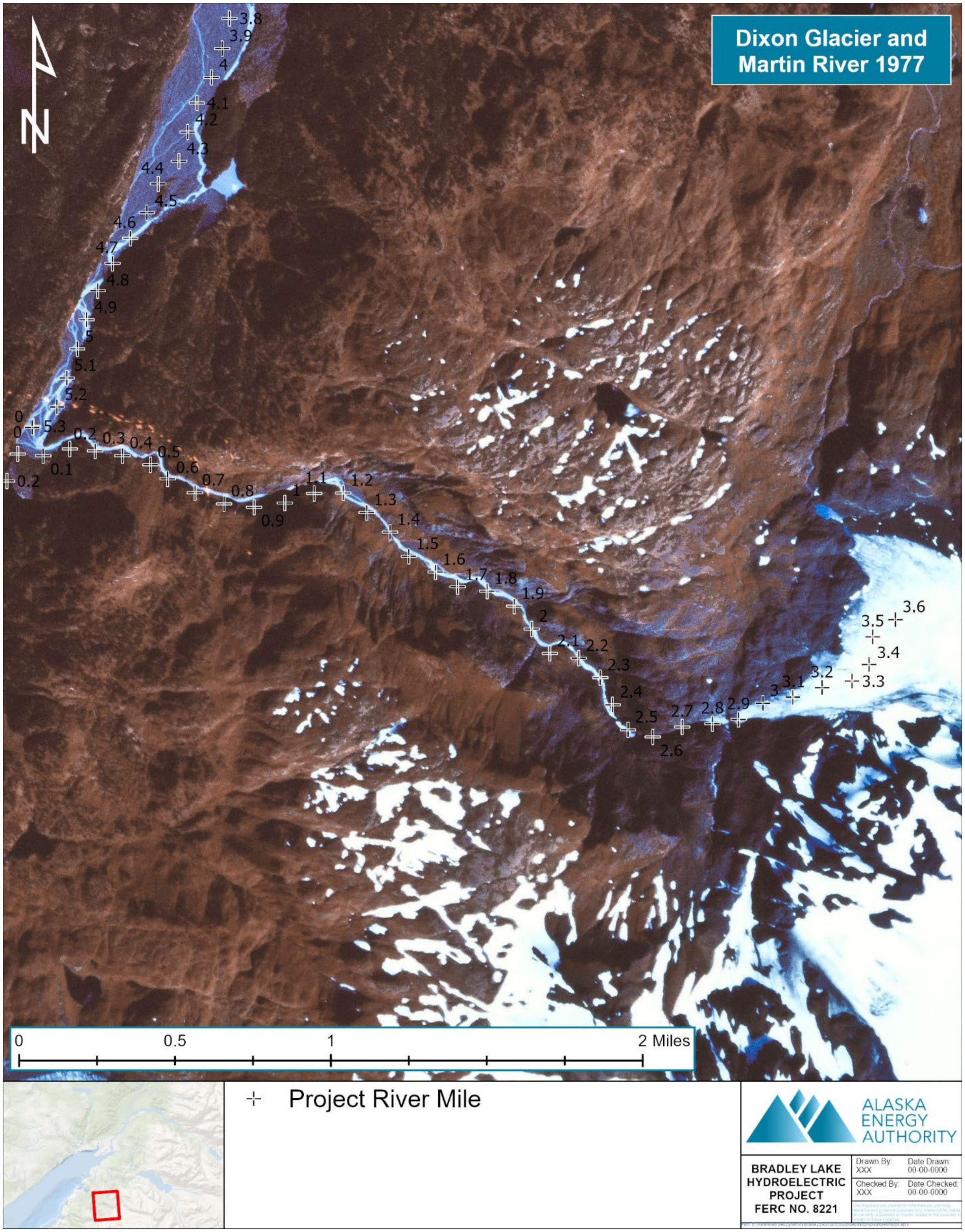


Figure 5-8 Dixon Glacier, East Fork Martin River, and Martin River 1977.

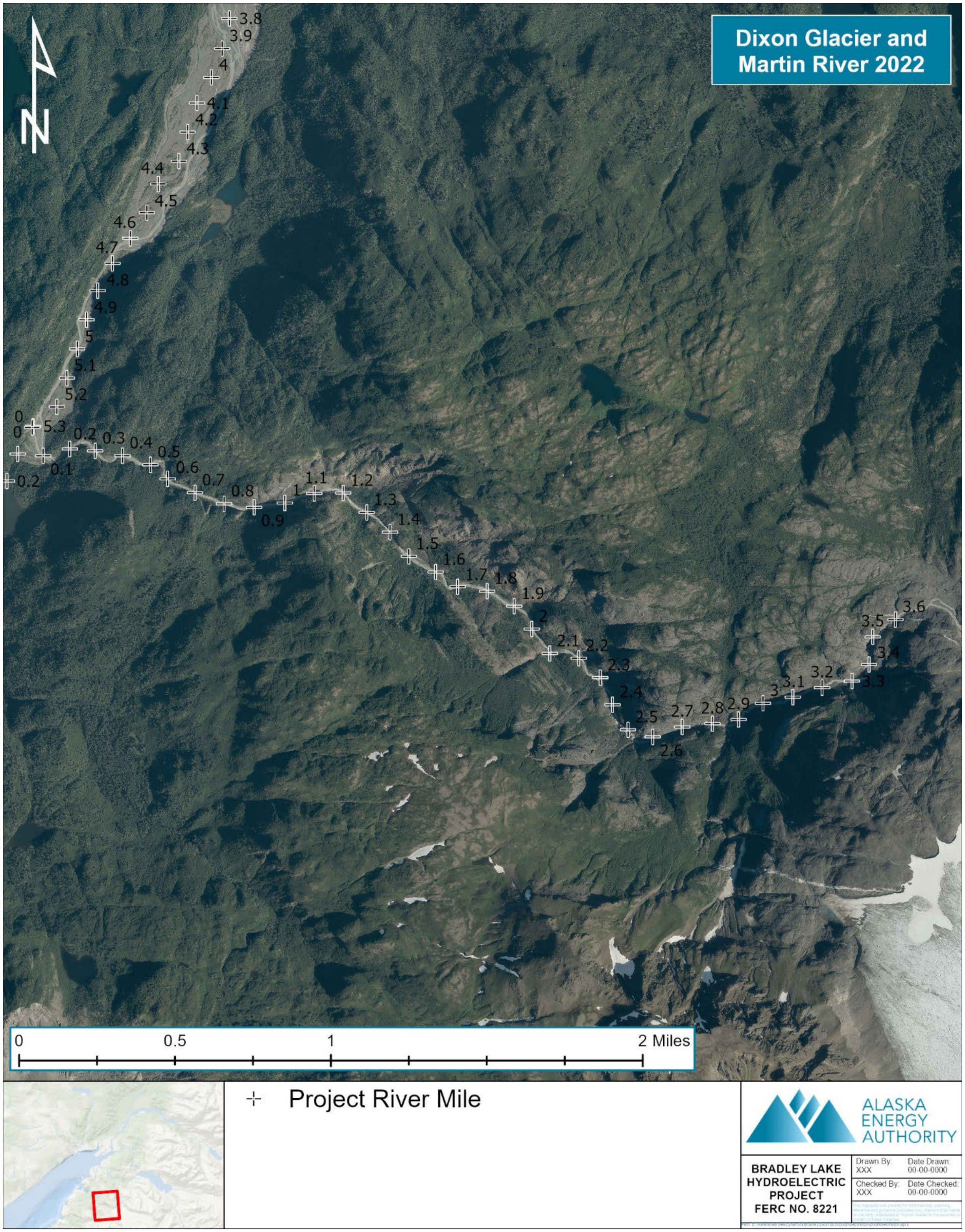


Figure 5-9 Dixon Glacier, East Fork Martin River, and upper Martin River 2022.

5.1.3.2 Martin River Channel and Valley Evolution

As discussed in previous sections, the Martin River is a braided river with a high sediment load from the current Dixon Glacier outflow as well as large episodic inputs of sediment from erosion of past glacial deposits in the EFMR watershed. It is hypothesized that these large episodic sediment inputs occurred between approximately 1920 through the mid-1960s following retreat of the Dixon Glacier after the Little Ice Age Maximum. Based on field and aerial photograph observations, it appears that this large sediment input has been progressively moving downstream over the past century. Researchers in gravel bed rivers have suggested that large episodic sediment inputs (sediment "slugs") diffuse as they move downstream, with finer grained sediment moving more rapidly and coarser grained sediment more slowly (Beechie 2001; Cui et al. 2003; James 2010; Nelson and Dubé 2016). Typical response time for rivers to return to pre-slug conditions is decades to centuries depending upon the side of the sediment slug and specific river dynamics.

Field observations of indicators of rapid aggradation in the Martin River valley include large buried trees in growth position in the middle of the Martin River valley, particularly in Geomorphic Reaches 8a and 8b (between PRM 3 and PRM 4.5; see Photo 5-2) and near the mouth of the river, which suggest periods of rapid aggradation in the past. The buried trees near PRM 4.4 are particularly interesting because they show: (a) a mature forest existed in the middle of the Martin River valley in the past; (b) there was relatively rapid aggradation of at least 7-8 feet that buried the trees and protected the stumps from erosion; and (c) subsequent incision of a similar amount exposed them. Field observations of river valley margins in 2023 and 2024 also showed indicators of aggradation, with valley-margin vegetation buried in recent gravel resulting in tree death, new channels into the left bank off-channel areas at PRM 2.5 and PRM 1.2, and overtopping of the right bank levee near the mouth of the river in late 2023 (see Section 5.1.3.3 for detailed discussion of the August 2023 levee breach).

Photo 5-2 Buried trees in growth position near Martin River PRM 4.4, photo taken looking upstream, May 22, 2023.

Observations of channel and valley evolution from the 1950s to present aerial photography further corroborate the field evidence of valley aggradation progressing downstream.

Off-Channel Habitat at PRM 4.2 right bank (OCH4.2R): The 1952 aerial photographs show that the Martin River was not connected to the OCH4.2R pond, with a band of relatively mature forest between the active (unvegetated) valley area and the pond (Figure 5-10). By 1977, the river had aggraded and shifted toward the OCH, depositing sediment in a fan that reached the OCH4.2R pond and split it into two ponds, killed part of the forest band, and allowed turbid mainstem water into the ponds. The 1982 aerial photographs show further development of the fan, no evidence of the former forested band, and a shift of the main channel back toward the middle of the valley.

Interestingly, this forest band is in the same location as the exposed stumps shown in Photo 5-2, suggesting that at least 7-8 feet of aggradation occurred between 1952-1982. The 1996-2022 aerial photographs show that the main channel no longer connected to the OCH4.2R ponds, and riparian vegetation was beginning to grow on the former fan. By

2022, the river had incised and is likely still a few feet above the pre-1952 elevation forest in this area based on the buried tree stump elevations.

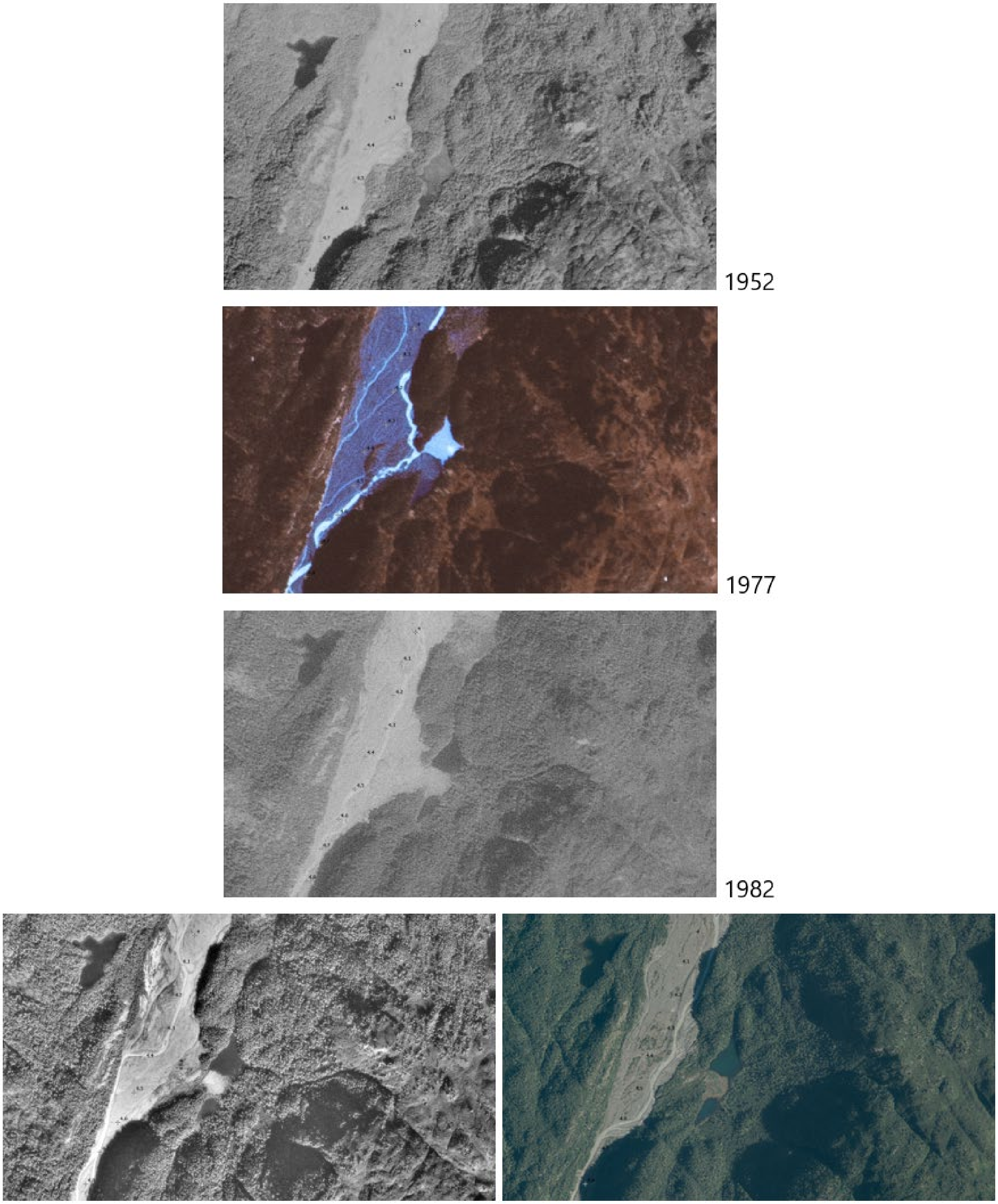


Figure 5-10 Evolution of Martin River OCH4.2R area.

Unconfined Geomorphic Reaches 8a (PRM 2.85-PRM 3.9) and 6 (PRM 1.9-PRM2.55): In unconfined valley areas, changes in the active valley width (unvegetated valley width) through time can indicate changes in sediment deposition rates. Increases in sediment deposition (aggradation) can correspond with a valley widening response as sediment encroaches upon vegetation on valley margins. Conversely, decreases in active valley width can correspond to decreases in deposition rates or downcutting as vegetation can become re-established. Measurements of active valley width in Geomorphic Reach 8a show that active valley width increased through the mid-1980s, then decreased through 2022 (Figure 5-11). The next unconfined geomorphic reach downstream (Geomorphic Reach 6) shows an increase in active valley width since the late 1970s through present (Figure 5-12).

The aerial photograph analysis, combined with field observations, suggests that the large sediment input that is inferred to have come from the EFMR valley between 1920 and 1964 has been progressively working downstream, with deposition around PRM 4.3 in the 1970-1980 period (followed by channel incision in this area), deposition in the PRM 2.8-PRM 3.9 area through the mid-1980s, and deposition in the PRM 1.9-PRM 2.5 area from the 1980-1990 period through present. Assuming an average of 5 feet of aggradation in the active channel geomorphic units downstream from the EFMR/WFMR confluence in the last 100 years, a total of 4.6 million cubic yards of sediment is estimated to have accumulated in the valley over the last century. The accumulated material includes boulder, cobble, gravel, and sand-sized particles; most of the finer sediment (silt/clay; glacial flour) would have been transported as suspended load through the Martin River into Kachemak Bay. The 4.6 million cubic yards of accumulation is a reasonable estimate when compared to the estimated 12 million cubic yards of sediment input from the EFMR valley and 610,000-6,10,000 cubic yards per year of sediment input from the Dixon Glacier (likely 80 percent to 95 percent of the sediment produced from the Dixon Glacier would be silt and clay). The sediment input estimates include both coarse- and fine-grained sediment; most of the fine-grained sediment would have been transported through the river without being deposited.

The following section discusses aggradation at the mouth of the river and changes that have taken place since the 2023 levee breach.

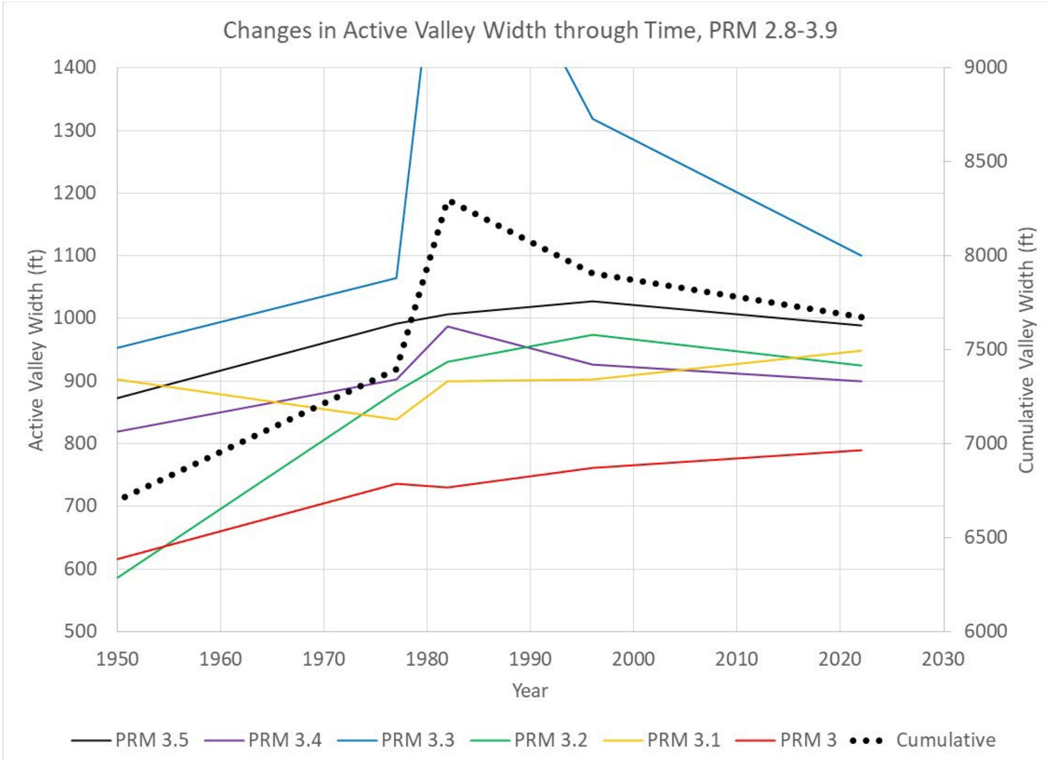


Figure 5-11 Changes in active valley width, Martin River PRM 2.8-PRM 3.9.

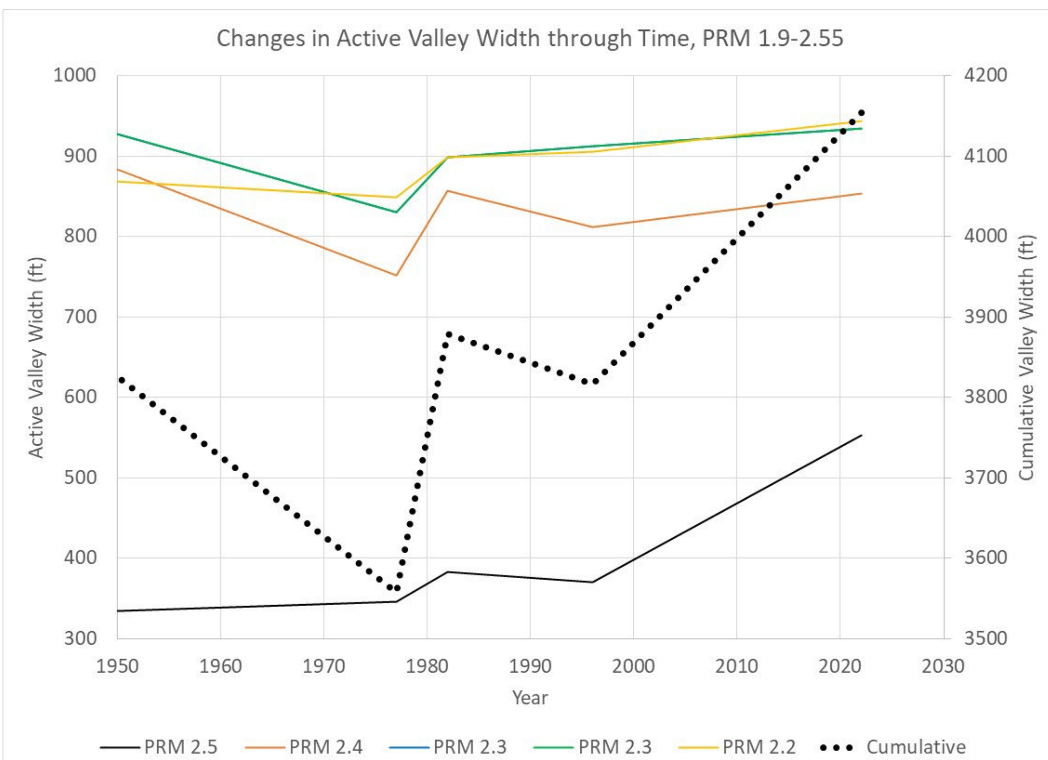


Figure 5-12 Changes in active valley width, Martin River PRM 1.9-PRM 2.55.

5.1.3.3 Evolution of the Martin River Following the August 2023 Levee Breach

The mouth of the Martin River has built a large, arcuate delta into Kachemak Bay. Prior to construction of a constraining, right-bank levee in the 1980s, the river position across the delta shifted as sediment was deposited and the delta aggraded. Construction of the right bank levee constrained the river and deposition areas to west of the levee.

The right bank levee was constructed to separate the river from borrow pits that were dug to supply material during construction of the Bradley Lake Hydroelectric Project in the 1980s. The levee spanned the east side of the Martin River delta from the airstrip at approximately PRM 0.4 to a bedrock constriction near PRM 1.1. The borrow pits were rehabilitated for fish spawning and rearing ponds in 1991 by AEA. As-built drawings of the borrow pits/levee (dated March 12, 1992) show the top of the levee was approximately 5 feet higher than the river at the breach location at time of construction, and borrow pits were dug 15 to 35 feet deep (Figure 5-13 and Figure 5-14). The levee was constructed with riprap armoring on the river side but filled and topped with native material. It was anticipated that the Martin River would aggrade and eventually breach the levee based on assessments at the time (Parry and Seaman 1994).

As anticipated, the Martin River aggraded following construction of the levee. During reconnaissance site visits at high flow levels in 2022, a minor amount of flow from the river was overtopping the levee in the vicinity of the middle of the three ponds (approximately PRM 0.2), the location where levee breaching occurred in 2023. The right bank levee was overtopped and breached by the river at the beginning of August 2023 (Figure 5-15). Based on satellite imagery from July and August 2023, the breach occurred between July 31 and August 2, 2023. It is hypothesized that the levee overtopped, and river flow over the top and back side of the levee was forceful enough to erode the fill on the back side of the levee, leading to eventual undercutting of the protective riprap on the river side of the levee and breaching of the levee (Photo 5-3). Pieces of riprap were observed in the newly cut channel downstream from the breach location. Assuming 5 feet of aggradation in the 32 years between construction and overtopping yields an average aggradation rate of 0.16 feet per year.

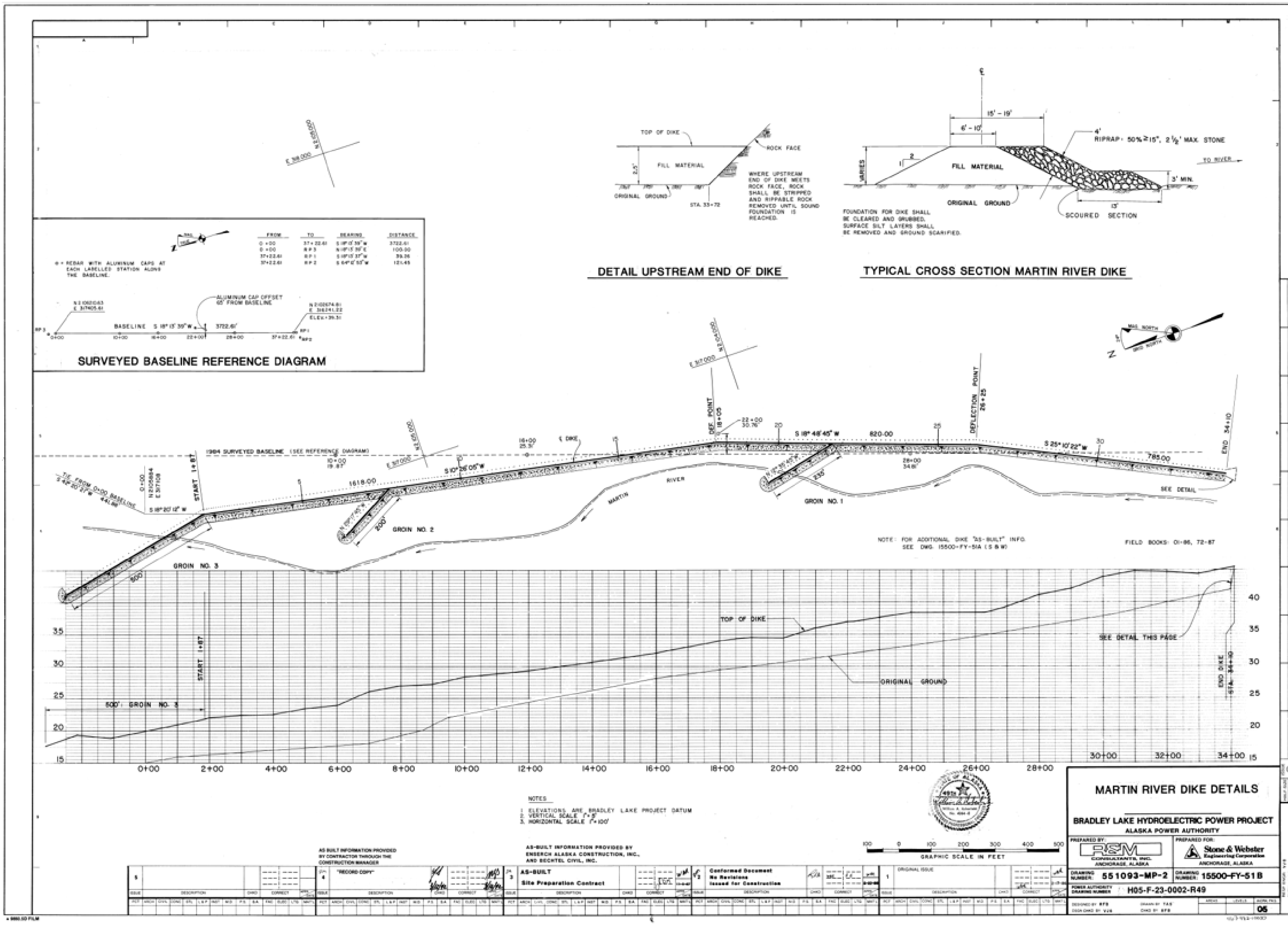


Figure 5-13 As-built drawing of Martin River levee.

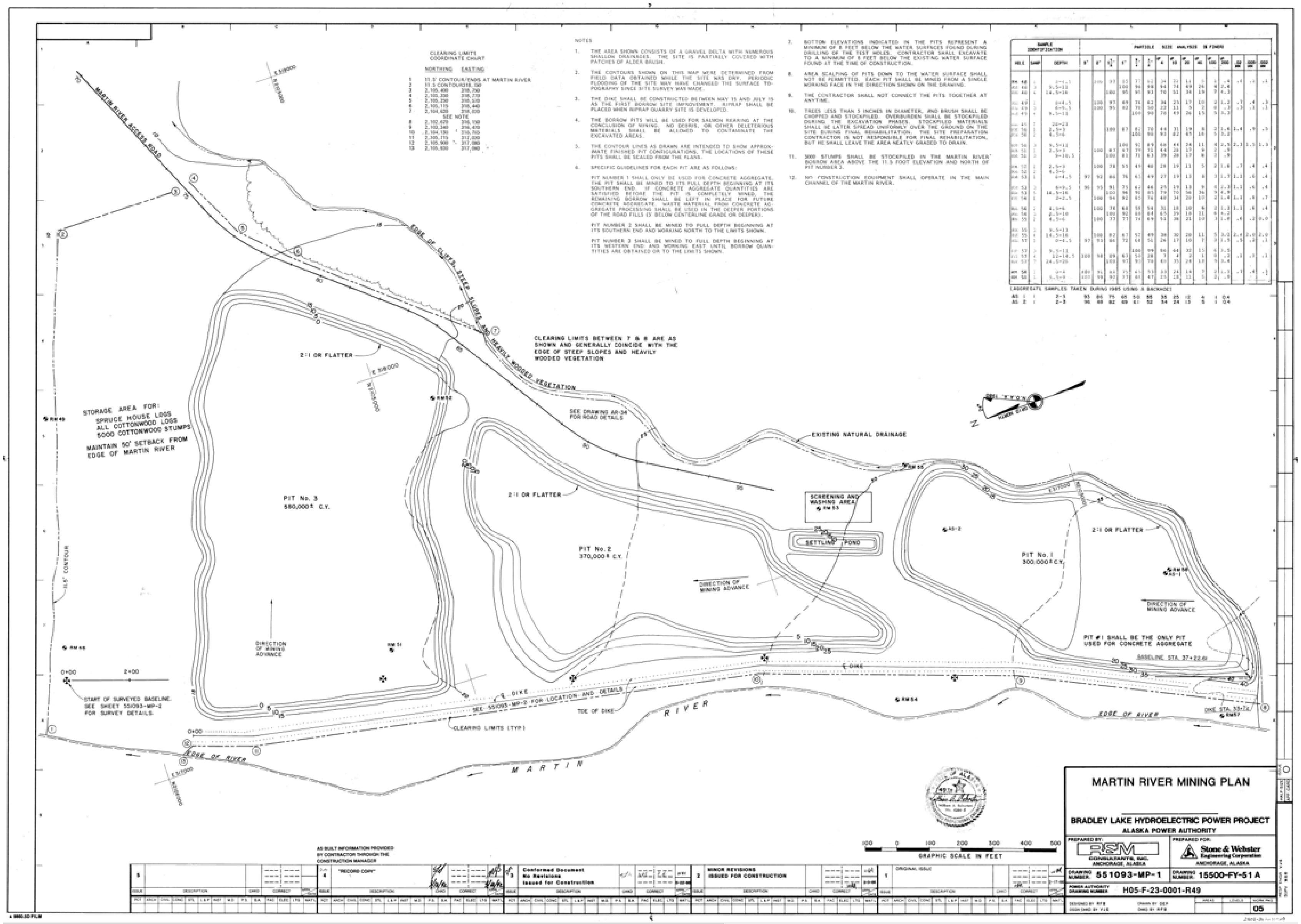


Figure 5-14 As-built drawing of Martin River mining plan (ponds).

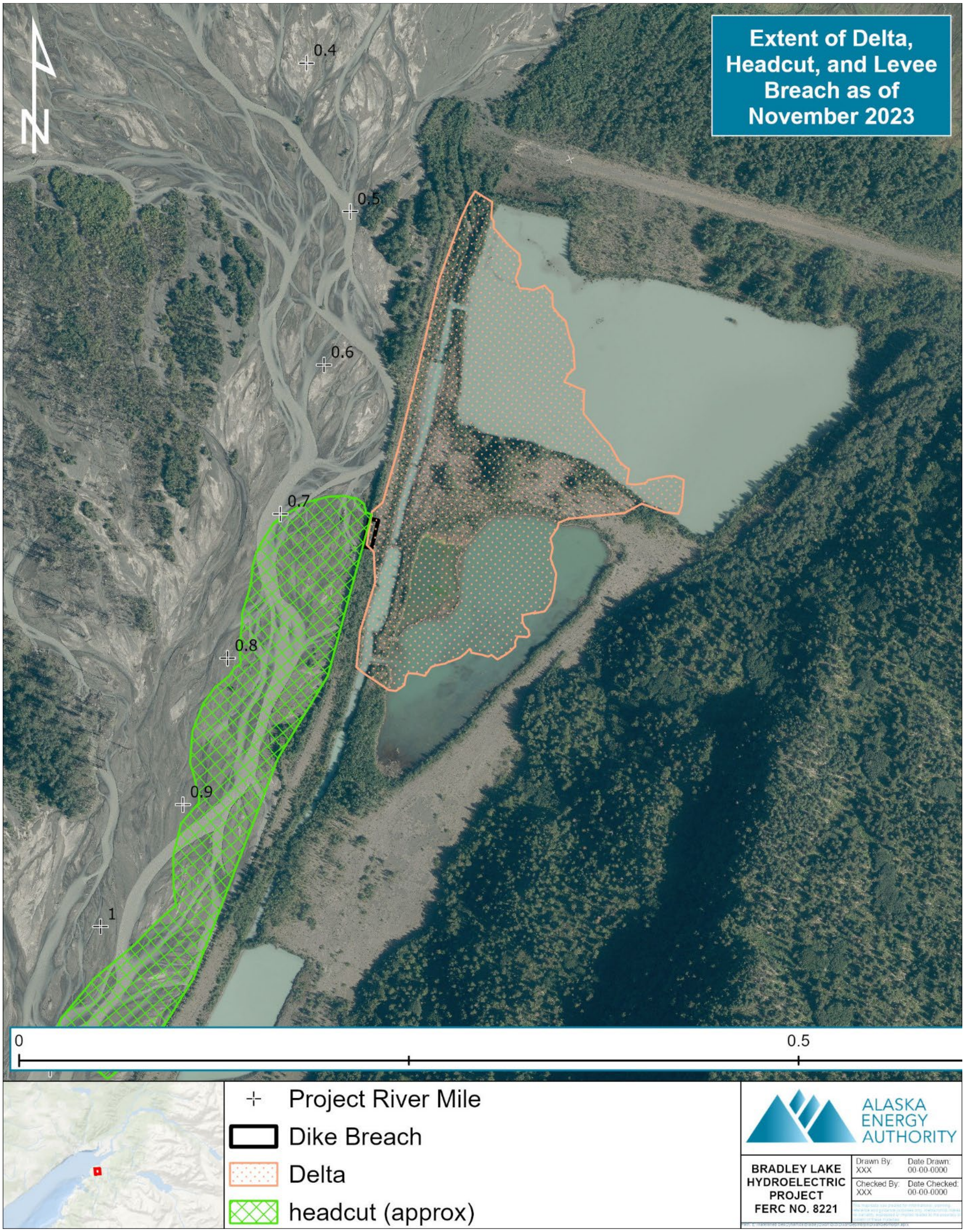


Figure 5-15 Extent of new delta, headcut, and levee breach location near the mouth of the Martin River, November 2023.

Photo 5-3 Cross section of levee at breach location, November 2, 2023.

Since August 2, 2023, all flow from the Martin River flows through the levee breach, into the mitigation ponds, and out a low point at the northeast corner of the largest (northern) pond into Kachemak Bay (Photo 5-4, Photo 5-5, and Photo 5-6). The river has been building a delta into the ponds, with up to 15- to 35-foot-deep accumulations in some areas (as of November 2023) assuming the northern-most ponds were originally dug 15 to 35 feet below grade as shown on the as-built drawings. As of November 2023, the delta covered approximately 19.5 acres. Coho Salmon (*Oncorhynchus kisutch*) adults were observed in the ponds and just upstream of the levee breach during the November 2023 site visit, indicating that they were able to utilize and traverse the new river channel. In November 2023, the bottom of the channel was approximately 10-12 feet below the top of the levee at the breach location. Upstream from the levee breach, the river has been eroding and headcutting as it adjusts to the new base level.

Photo 5-4 Extent of deposition in mitigation ponds; new Martin River outlet to tidewater (top right), November 2, 2023.

Photo 5-5 New outlet of Martin River looking upstream from tidewater to the northeast corner of the lowermost mitigation pond, November 2, 2023.

Photo 5-6 Mid-channel bar just downstream from levee breach (pebble count 2023-16 location), looking downstream, November 2, 2023.

Aerial imagery and LiDAR data were acquired in May 2024 and showed the extent of the delta building at the mouth of the Martin River compared to 2022 conditions as well as the headcutting upstream from the breach location (Figure 5-16 and Figure 5-17). The difference between the 2024 and 2022 LiDAR data is shown in Figure 5-18 with aggradation in red and erosion in green. Note that the former mitigation ponds are shown as erosion (blue/green); this is because the 2024 LiDAR captured the elevation of the bottom of the ponds, and the 2022 LiDAR captured the surface elevation of the ponds—the difference shown is water depth in the ponds.

Field observations during May through October 2024 showed that the delta continued to aggrade into the former mitigation ponds. The high flow in August 2024 accelerated this delta building as well as headcutting upstream of the levee breach. Additional erosion of the northern levee edge occurred and was captured on the timelapse cameras (see images in Section 5.4 and Appendix A). It was estimated that the levee breach increased from 100 feet wide to approximately 200 feet wide during the high flow event.

As of the end of October 2024, the river had filled both northern mitigation ponds with sediment and had cut a wider channel through both the levee and the eastern pond/river outlet (Photo 5-7). There was evidence of multiple channels flowing across the airfield under high flow conditions throughout 2025 field observations, with gravel transport out into the tidelands at the new river mouth (Photo 5-7).

Photo 5-7 Martin River mouth looking downstream from levee breach, October 30, 2024 (left), and July 29, 2025 (right).

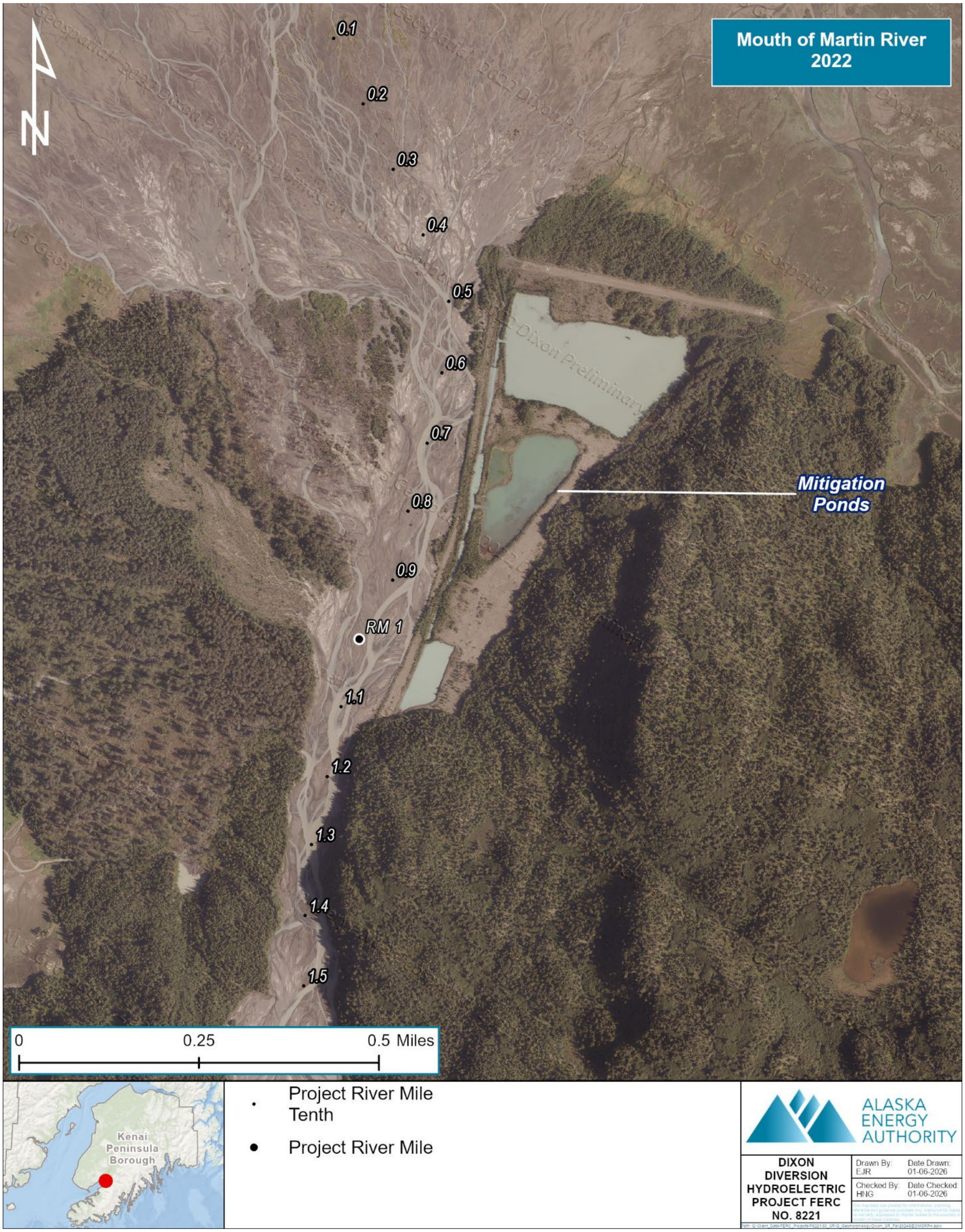


Figure 5-16 Mouth of the Martin River, 2022.

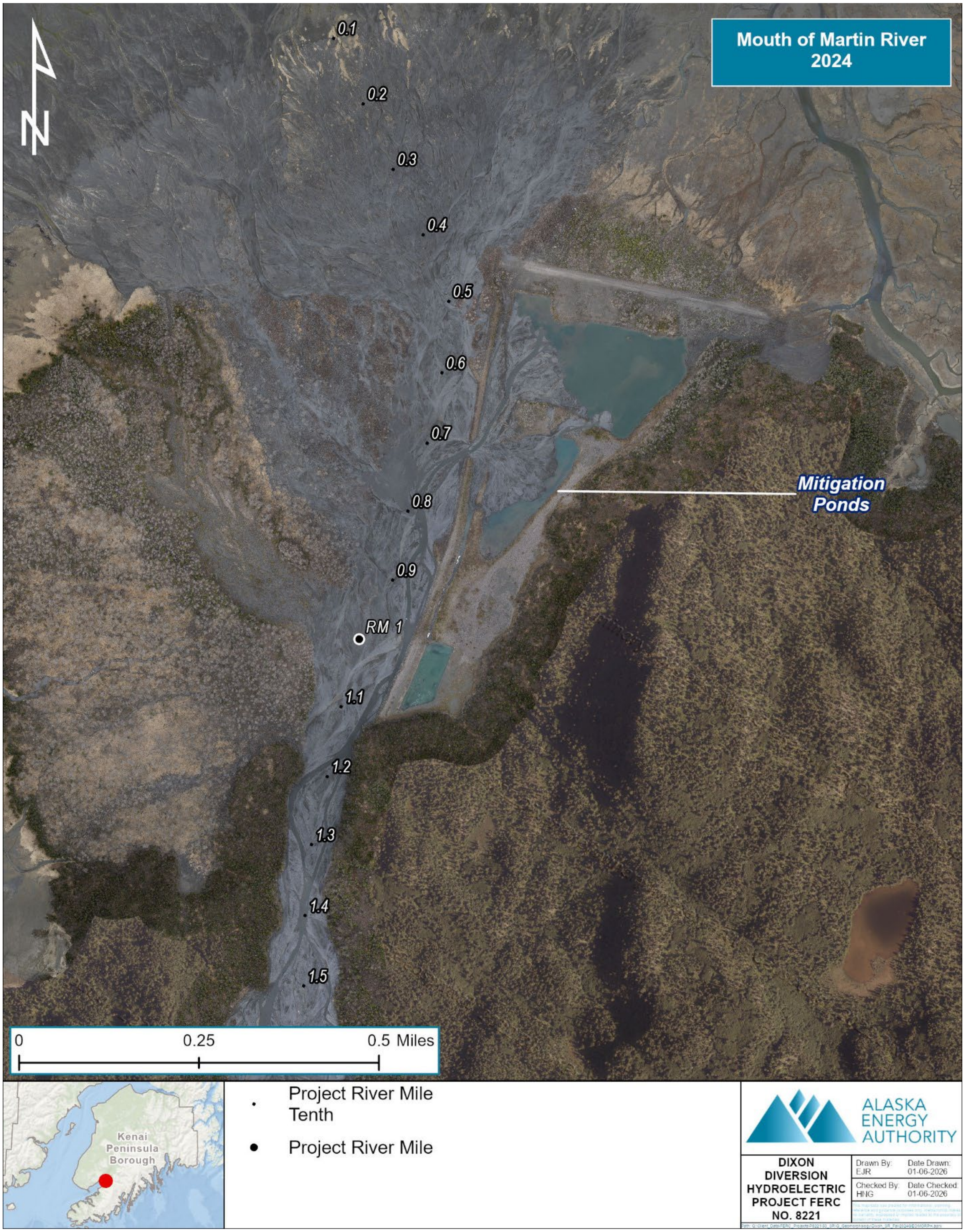


Figure 5-17 Mouth of the Martin River, 2024.

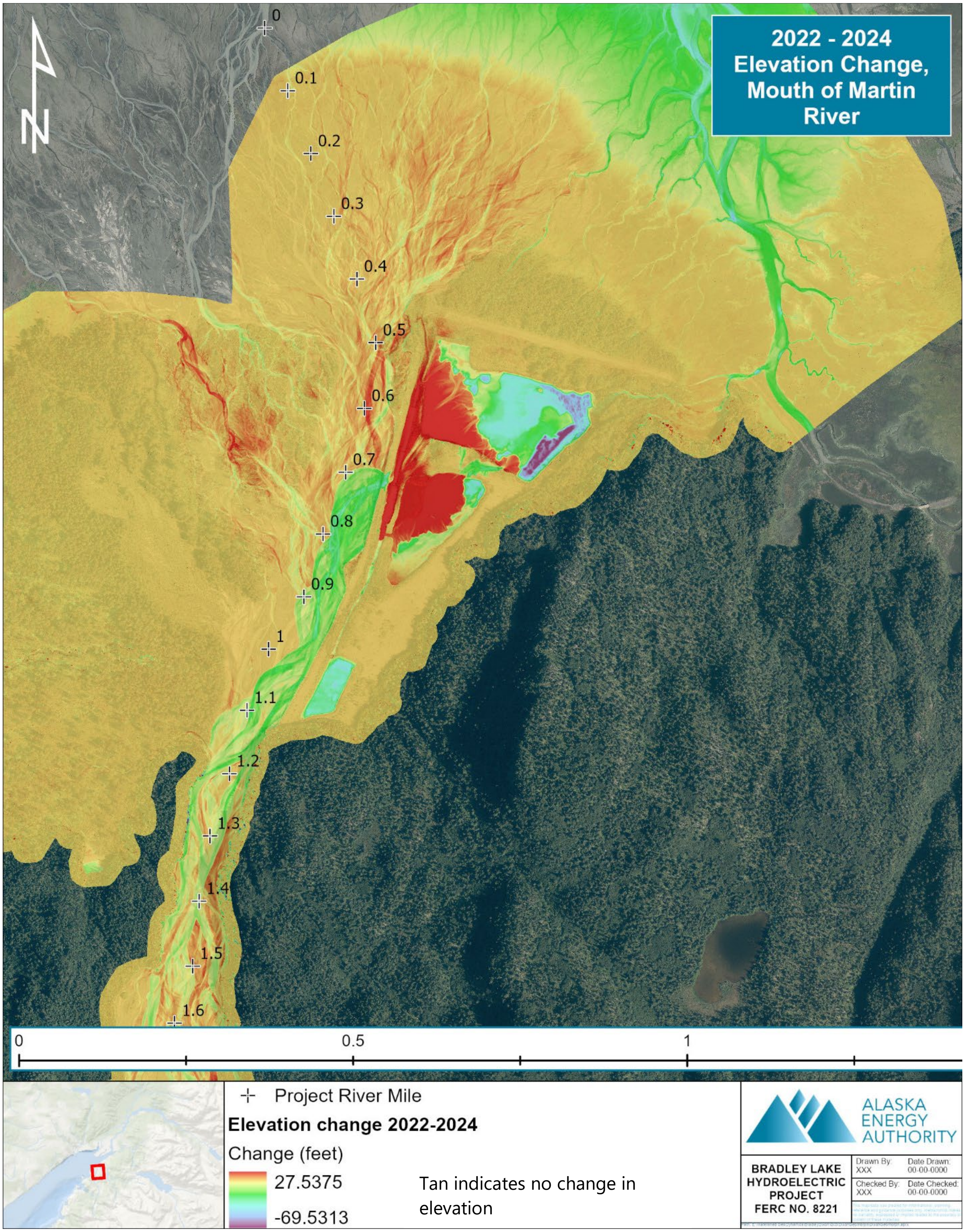


Figure 5-18 Elevation changes at the mouth of the Martin River, 2022-2024.

5.2 Field Visit Observations

5.2.1 May 16, 2023

- Main channel flow was low/clear. Substrate in most of main channel (from tidewater to EFMR canyon) was cobble/gravel dominated and generally coarsened upstream. Substrate suitable for spawning fish was observed in most main channel areas.
- Changes to channel locations (braids) have occurred since aerial photographs (July 28, 2022) and LiDAR data (October 13, 2022) were collected in some areas, indicating river flows in the time between aerials/LiDAR and LiDAR/freeze-up were high enough to transport bedload material.

5.2.2 May 22-24, 2023

- There was evidence of very high sediment loading from Dixon Glacier (or glacial deposits) to the Martin River. The entire Martin River valley mapped as "active channel 2022" in Geomorphic Reaches 2 through 8a is aggrading as evidenced by sediment deposition along all active channel Geomorphic Unit margins covering tree trunks, resulting in dying vegetation. Old, buried trees (in grown position) were observed throughout valley. There was fresh gravel/cobble deposition into vegetated areas on left bank in Geomorphic Reaches 6 and 2 (likely during previous autumn, with only a few scattered leaves on surface from last autumn's leaf fall).
- Past deposition in Geomorphic Reach 8b (lightly vegetated bars) is currently incising; there are 5- to 6-foot incision depths to top of banks, uncovering buried cottonwood stumps in the middle of the channel.
- The outlet of left bank off-channel open water area in Geomorphic Reach 8a was checked via helicopter—this will be adjusted in GIS/map.
- Main channel flow has shifted to the right bank side channel at the downstream end of Geomorphic Reach 8a; deposition of small to medium gravel in the channel is controlling the water level in the large off-channel open water area on right bank.
- Deposition in the Martin River valley/fan has blocked the outlet to the former spawning channel/mitigation pond drainage near the mouth of the river. The ponds currently drain to the east toward the Battle Creek estuary over a shallow lip. This likely affects fish passage into/out of ponds.
- Gravel deposition in Martin River fan extends out to tidewater, and the boundary between river and tidewater can be delineated based on color change on aerials (light gray gravel to organic sand).

5.2.3 November 2, 2023

- Main channel flow was low/fairly clear.
- The Martin River eroded an approximately 100-foot-wide section of the existing levee; likely mechanism was aggradation on the river side of the levee, overtopping of levee during high flows, and erosion of the pond-side (unprotected) portions of the levee, which then undercut riprap protection on the river side of the levee. Depth of erosion from top of dike to bottom of channel on November 2, 2023, was approximately 10-12 feet (based on estimated water depth in channel). Observations of levee cut showed riprap blanket on river side, smaller fill material on pond side.
- There were extensive gravel, sand, and cobble deposits in middle and lower pond areas (deposits cover 19.5 acres).
- There was extensive headcut upstream from the dike breach (total extent of headcut not delineated). The width of headcut was up to 350 feet.

5.2.4 April 18, 2024

- Main channel flow was fairly high and slightly turbid from rains and associated snowmelt. The river was about 1 foot higher than the previous day based on the USGS gage at the EFMR/WFMR confluence. Turbidity was tan/brown color, indicating surface runoff rather than glacial melt.

5.2.5 April 27-29 and May 7, 2024

- Main channel flow was low and clear, allowing pebble counts to be taken within the wetted channel of the Martin River.
- Incidental wildlife observations (tracks and scat or animals): black bear, brown bear with cub, moose, wolf, coyote, river otter, bald eagles.

5.2.6 August 21, 2024

- The high flow event on August 7, 2024, resulted in major river channel changes in the Martin River.
- Mainstem flows had been extremely high and turbid throughout the river and appeared to result in overall channel incision in many areas based on observations (no elevation measurements were made).
- The high mainstem flows resulted in incursion of turbid mainstem water into all off-channel ponds and channels during the high flow event; all off-channel ponds (including Red Lake) were still very turbid during the August 21 field visit even

though mainstem flow was no longer entering the ponds (except for PRM 2.8R pond).

- Mainstem flow at the exit of the canyon (EFMR/WFMR confluence) had been extremely high and overflowed into the WFMR and backwatered into Red Lake. The EFMR is now split into two channels at this location. One high water mark GPS point was taken.
- The OCH4.2R pond was very turbid and had evidence of past inflow and sediment deposition from the mainstem.
- On August 21, turbid mainstem flow (via side channels) was flowing into the large off-channel right bank PRM 2.8 pond (Swan Lake). Turbid mainstem water was seen accessing the OCH2.8R channels near approximately PRM 3.1 and PRM 3.6 (see video). The pond was extremely turbid, and much smaller in size than previously observed. It is hypothesized that deposition of fines on the south side of the pond where the tributary channels enter as well as incision in the mainstem that appears to have dropped the hydraulic control of the pond outlet approximately 1-2 feet has resulted in a smaller pond area. A pair of swans was still using the pond, and a large moose was observed.
- Incision of the mainstem channel was observed in many locations where we were on the ground, including near PRM 2.8, PRM 1.9 (downstream from the constriction), and near and upstream from the levee breach.
- The river had eroded approximately 100 additional feet of levee on the north side of the breach and totally filled in the two downstream mitigation ponds (the upstream pond was not filled).
- The river through the ponds appears to be a relatively consistent gradient (no large drops).
- The new river outlet from the ponds has widened and looks like an established single channel (formerly was multiple channels through the trees).
- The airstrip was covered with additional fine sediment.
- It appeared that at some point during the high flow event, at least a small amount of flow went down the former delta.
- Several videos and still photos of the river were taken and are available on the project SharePoint site.
- Incidental wildlife observed: one large moose, a pair of swans, and other waterflows near/in Swan Lake; one set of recent very large brown bear tracks near PRM 2.8, many older black bear tracks along the river in many locations; many coyote and river otter tracks in most locations.

5.2.7 October 30, 2024

- All mainstem and tributary flows were low and clear.
- There was approximately 6 inches of snow on the ground; air temperature was cold in the morning (mid 20s degrees Fahrenheit), and there was ice forming on ponds and locations where streamflow was low.
- Continued incision of the mainstem channel was observed downstream of the constriction.
- The new delta downstream from the levee breach continues to aggrade. Channels have formed across the old airstrip and flow to saltwater.
- Incidental wildlife observed: waterfowl in OCH4.2R pond; one set of recent very large brown bear tracks in the snow that went from the OCH4.2R water quality site downstream to at least PRM 2.8, coyote and river otter tracks in locations downstream from PRM 3; eagles at the constriction; large salmonid in WFMR near water quality site.

5.2.8 May 1, 2025

- Water was low and clear.
- There was continued aggradation downstream of the levee breach.
- Incidental wildlife observed: fresh moose, otter, and coyote sign (tracks/scat), no fresh bear signs.

5.2.9 July 29, 2025

- Mainstem flow was high and turbid.

5.2.10 October 3, 2025

- All mainstem and tributary flows were low, and the Martin River was fairly clear.
- Dixon Diversion area: recently deglaciated, measured grain size on mid-channel bar and largest particles mobile to help with sizing diversion gate/sediment management. There were goat tracks on river bars.
- Bradley Lake shorelines: many areas of bedrock (not erodible); several large slides in colluvium/glacial deposits; smaller areas of bank erosion as well. The head of the lake has little bank erosion; low gradient shorelines are well vegetated.

5.2.11 November 5, 2025

- All mainstem and tributary flows were low, and the Martin River was clear.

- There was continued aggradation downstream of the levee breach; there is delta/gravel deposition extending out below sea level, and the channel has developed across the former airstrip.

5.3 Pebble Counts and Sub-surface Sampling

River substrate provides habitat for fish and aquatic organisms and channel roughness that influences hydraulic conditions. Gravel- and cobble-bedded rivers exhibit a coarser armor layer that forms as finer grained material (generally sand and fine gravel) are selectively removed following bedload transport events. The sub-armor layer is representative of the mix of material that moves during bedload transport events; the surficial armor layer represents the substrate that influences aquatic habitat and hydraulics. Both surficial pebble counts and sub-surface sediment samples were taken along the Martin River in 2023 and 2024 to help characterize aquatic substrate and provide information for hydraulic modeling and sediment transport calculations (Figure 4-1 above shows locations of sample sites). Grain size distribution data for the surficial pebble counts are shown in Table 5-3 through Table 5-5, Figure 5-19, and Figure 5-20. Grain size distribution data for the sub-surface samples are shown in Table 5-6, Figure 5-21, and Figure 5-22.

Surficial grain size generally decreased in a downstream direction, with the median (D_{50}) grain size ranging from 231 millimeters at the EFMR canyon outlet to 17 millimeters in the delta near sea level. Substrate is primarily gravel and cobble downstream from PRM 4 with cobble, gravel, and boulder upstream from PRM 4.

Sub-surface material is remarkably uniform along the sampled areas of the river, from PRM 0.7 to PRM 3.8, with the median (D_{50}) grain size ranging from 17-20 millimeters and being primarily gravel-sized with some sand and cobble.

The grain size data suggest that the majority of boulder and the largest cobble material that are transported down the EFMR canyon are deposited close to the mouth of the canyon, upstream of approximately PRM 4.5. Downstream of approximately PRM 4.5, bedload material (e.g., sub-surface material) is relatively uniform, but surficial substrate continues to fine in a downstream direction to approximately PRM 2.5 and is fairly uniform downstream of PRM 2.5.

In 2025, one pebble count was made at a mid-channel bar within the proposed intake/diversion pool area, as well as a measurement of the largest particles that were recently mobile, to document the size of particles that would be supplied to the intake area from the Dixon Glacier. The median (D_{50}) particle size for the pebble count sample was 192 millimeters, with 37 percent boulder, 39 percent cobble, and 24 percent sand-size particles. The median diameter of the 10 largest mobile particles was 720-1,024 millimeters.

Table 5-3 Martin River 2023 river bar pebble count summary statistics.

Sample No.	2023-1	2023-2	2023-3	2023-4	2023-5	2023-6	2023-7	2023-8	2023-9	2023-10	2023-11	2023-12	2023-13	2023-14	2023-15	2023-16
PRM	EFMR 0.2	4.55	3.65	3.00	2.75	2.50	2.50	2.35	1.95	1.85	1.60	1.35	1.18	0.80	0.40	0.7
Geomorphic Reach	9/10	8b	8a	8a	7	Side Channel	6/7	6	Side Channel	5	4	3	3	2	1	New Delta at Levee Breach
Grain Size (mm)																
D_{16}	86	64	34	31	50	13	25	17	13	23	9	14	8	11	8	11
Median – D_{50}	231	119	68	55	84	27	49	30	23	43	18	25	16	20	17	33
D_{84}	481	250	132	87	143	50	83	47	51	75	40	51	43	36	31	64
D_{90}	542	299	156	100	160	56	90	54	64	84	47	67	55	43	40	74
Percent in Grain Size Category																
Sand	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	2%
Gravel	10%	16%	46%	65%	31%	97%	65%	98%	90%	75%	96%	88%	94%	96%	98%	82%
Cobble	44%	69%	54%	35%	69%	3%	35%	2%	10%	25%	4%	12%	6%	4%	2%	16%
Boulder	47%	15%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Table 5-4 Martin River 2024 river bar pebble count summary statistics.

Sample No.	2024-1	2024-2	2024-3	2024-4	2024-5	2024-6	2024-7	2024-8
PRM	0.70	1.00	1.25	2.45	3.15	4.50	1.70	3.80
Geomorphic Reach	2 – levee breach	2	3	5	8a	8b	4	8a
Grain Size (mm)								
D_{16}	14	19	18	19	20	30	15	21
Median – D_{50}	31	41	35	41	44	69	35	42
D_{84}	60	61	70	74	74	124	72	79
D_{90}	71	69	80	83	83	197	80	87
Percent in Grain Size Category								
Sand	0%	0%	0%	0%	0%	0%	0%	0%
Gravel	87%	88%	80%	77%	76%	45%	78%	72%
Cobble	13%	12%	20%	23%	24%	48%	22%	28%
Boulder	0%	0%	0%	0%	0%	7%	0%	0%

Table 5-5 Martin River 2024 instream pebble count summary statistics.

Sample No.	2024-1	2024-2	2024-3	2024-5	2024-6	2024-7	2024-8	2024-10	2024-11	2024-12	2024-13	2024-14	2024-15
PRM	0.70	1.00	1.25	3.15	4.50	1.70	3.80	EFMR 0.15	WFMR 0.05	5	2.8	2.8 side channel	2.5
Geomorphic Reach	2 – levee breach	2	3	8a	8b	4	8a	9	WFMR	9	6	6	5
Grain Size (mm)													
D_{16}	23	14	28	20	24	16	15	19	40	53	19	9	34
Median – D_{50}	46	32	66	65	73	46	41	97	96	144	43	16	68
D_{84}	87	55	102	118	166	87	91	342	194	397	89	37	114
D_{90}	100	67	113	132	221	99	111	422	272	461	107	43	125
Percent in Grain Size Category													
Sand	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Gravel	80%	98%	58%	60%	49%	71%	73%	37%	28%	19%	67%	100%	46%
Cobble	39%	12%	64%	60%	56%	37%	28%	43%	61%	49%	33%	0%	54%
Boulder	0%	0%	0%	1%	8%	0%	3%	20%	11%	32%	1%	0%	0%

Table 5-6 Martin River 2024 sub-surface sample summary statistics.

Sample No.	2024-1	2024-2	2024-3	2024-4	2024-5	2024-6	2024-7	2024-8
PRM	0.70	1.00	1.25	2.45	3.15	4.50	1.70	3.80
Geomorphic Reach	2 – levee breach	2	3	5	8a	8b	4	8a
Grain Size (mm)								
D_{16}	2	3	3	1	2	2	2	2
Median – D_{50}	18	19	19	18	18	20	19	17
D_{84}	59	64	55	56	58	104	74	44
D_{90}	78	81	70	72	86	142	98	61
Percent in Grain Size Category								
Sand	16%	12%	12%	28%	16%	12%	12%	16%
Gravel	69%	72%	76%	59%	70%	63%	68%	75%
Cobble	15%	16%	12%	13%	15%	23%	20%	9%
Boulder	0%	0%	0%	0%	0%	2%	0%	0%

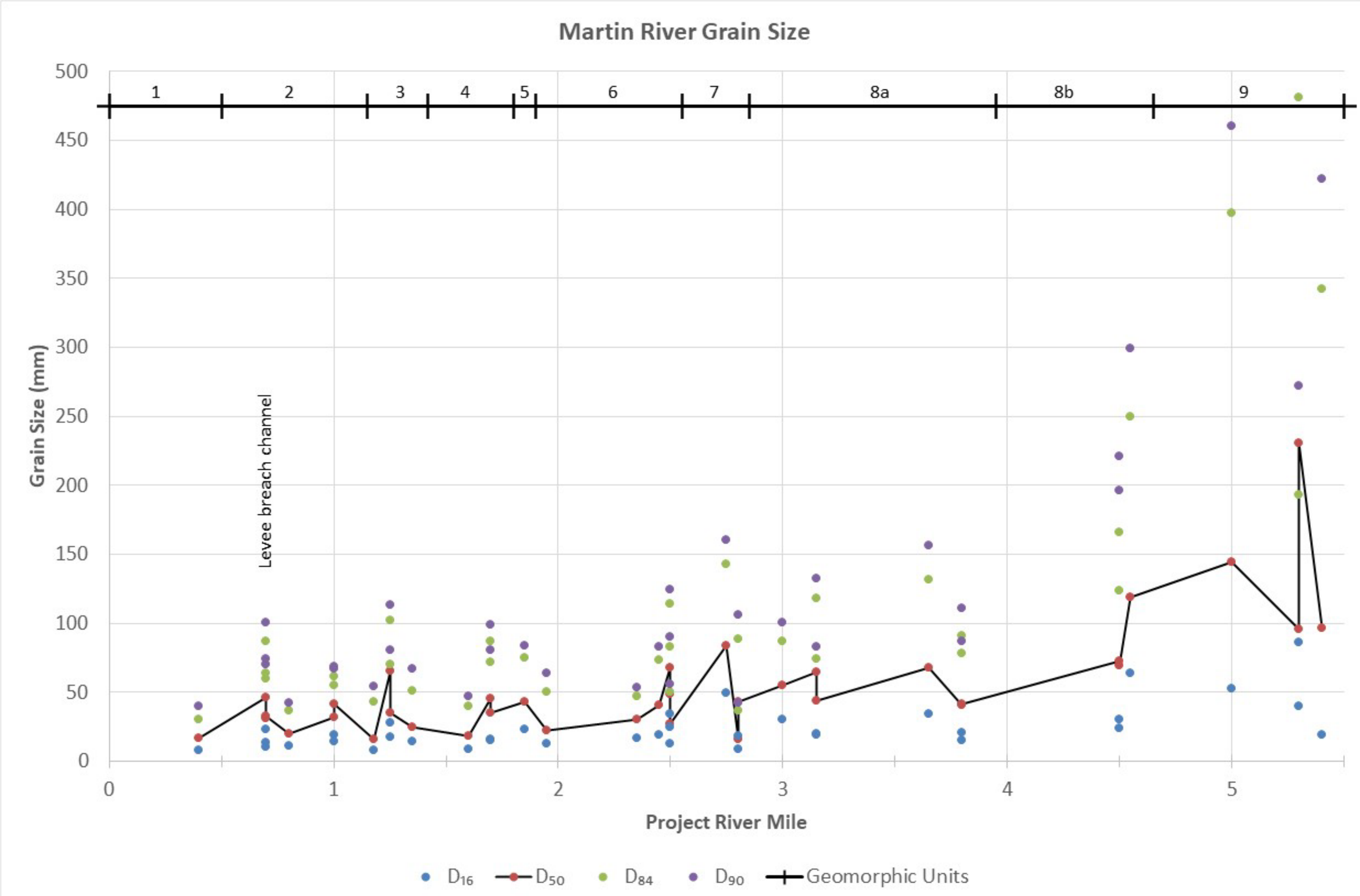


Figure 5-19 Martin River longitudinal variations in surficial grain size.

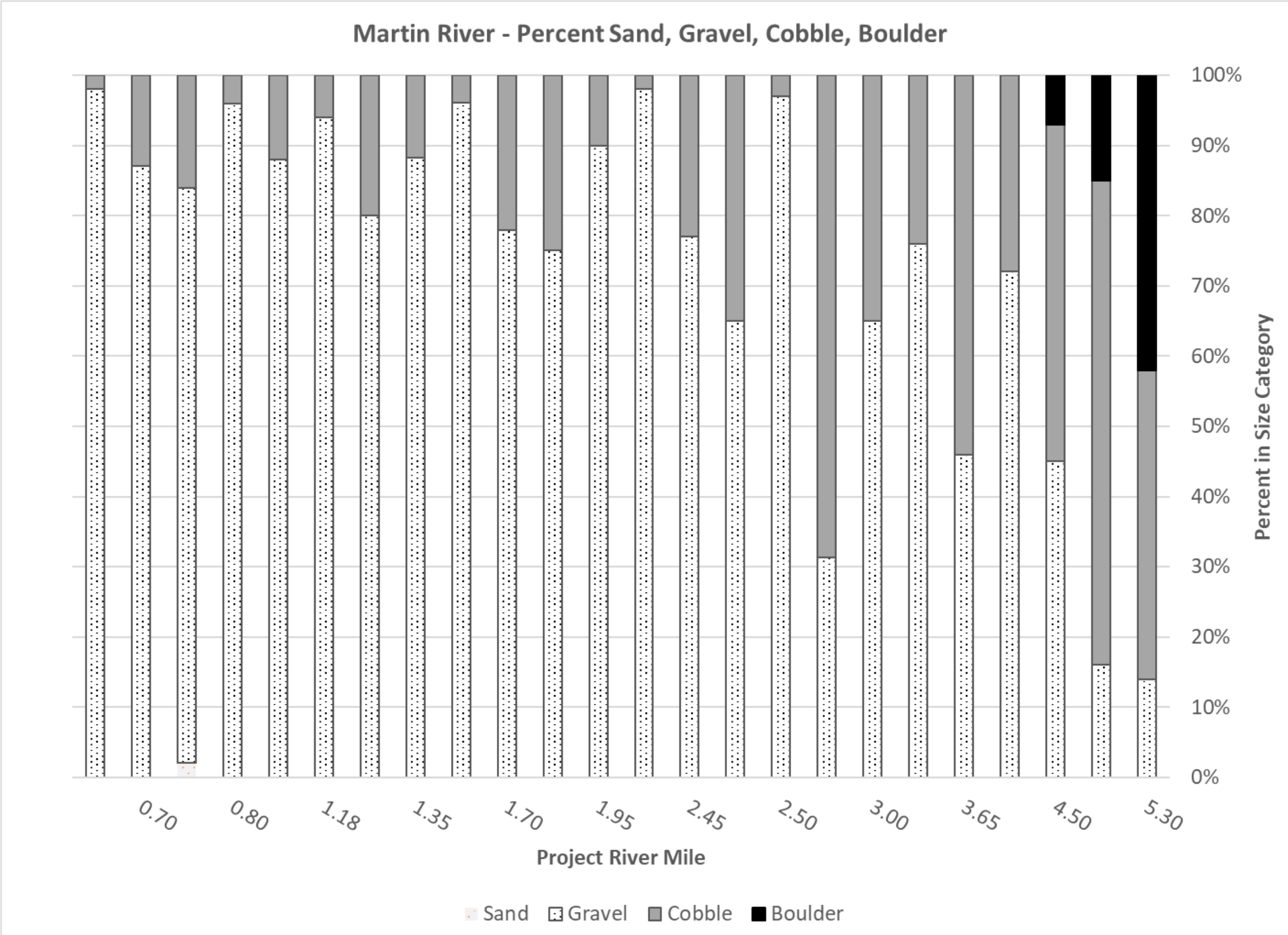


Figure 5-20 Martin River percent sand, gravel, cobble, and boulder in surficial pebble counts.

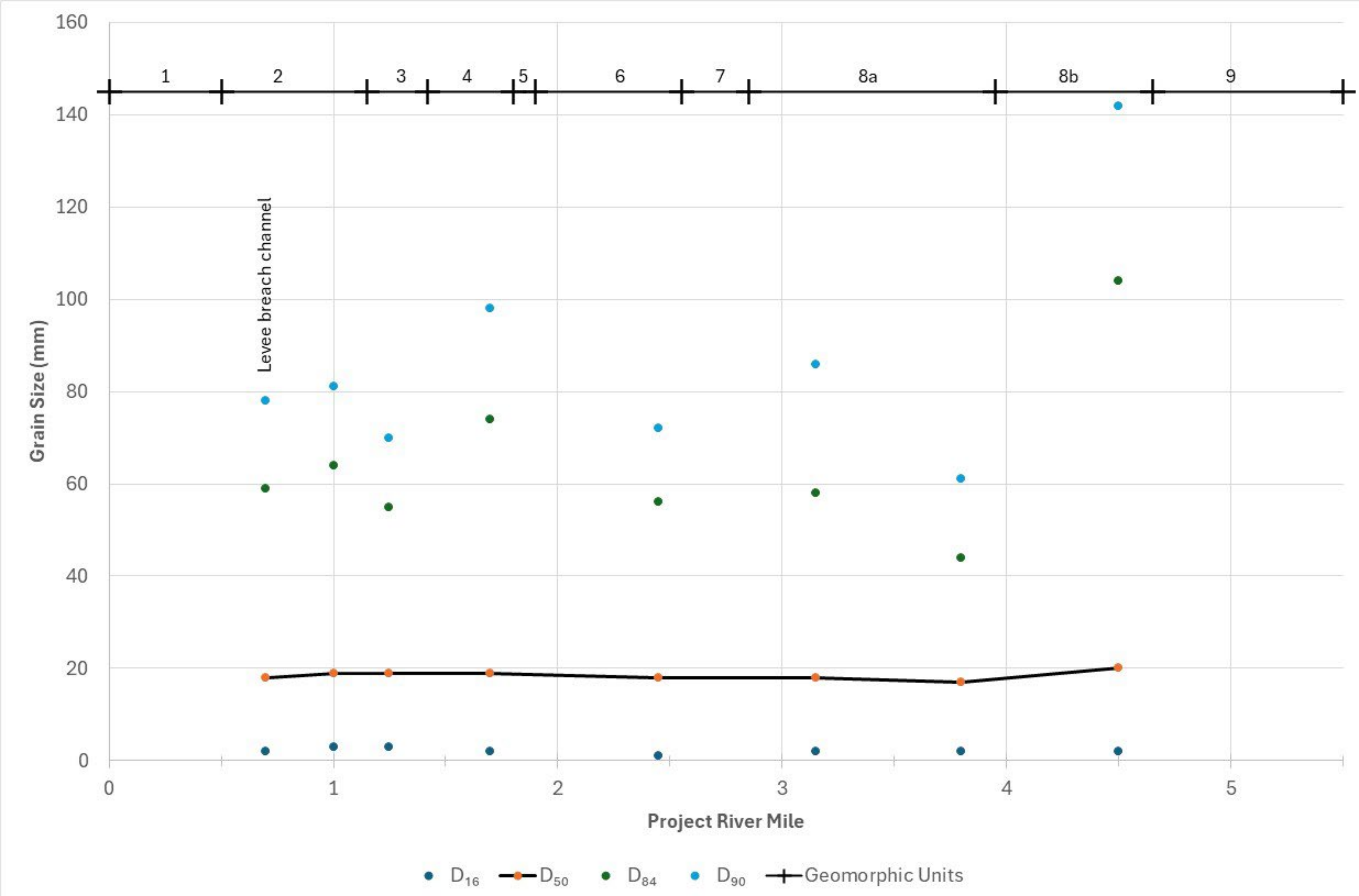


Figure 5-21 Martin River longitudinal variations in sub-surface sample grain size.

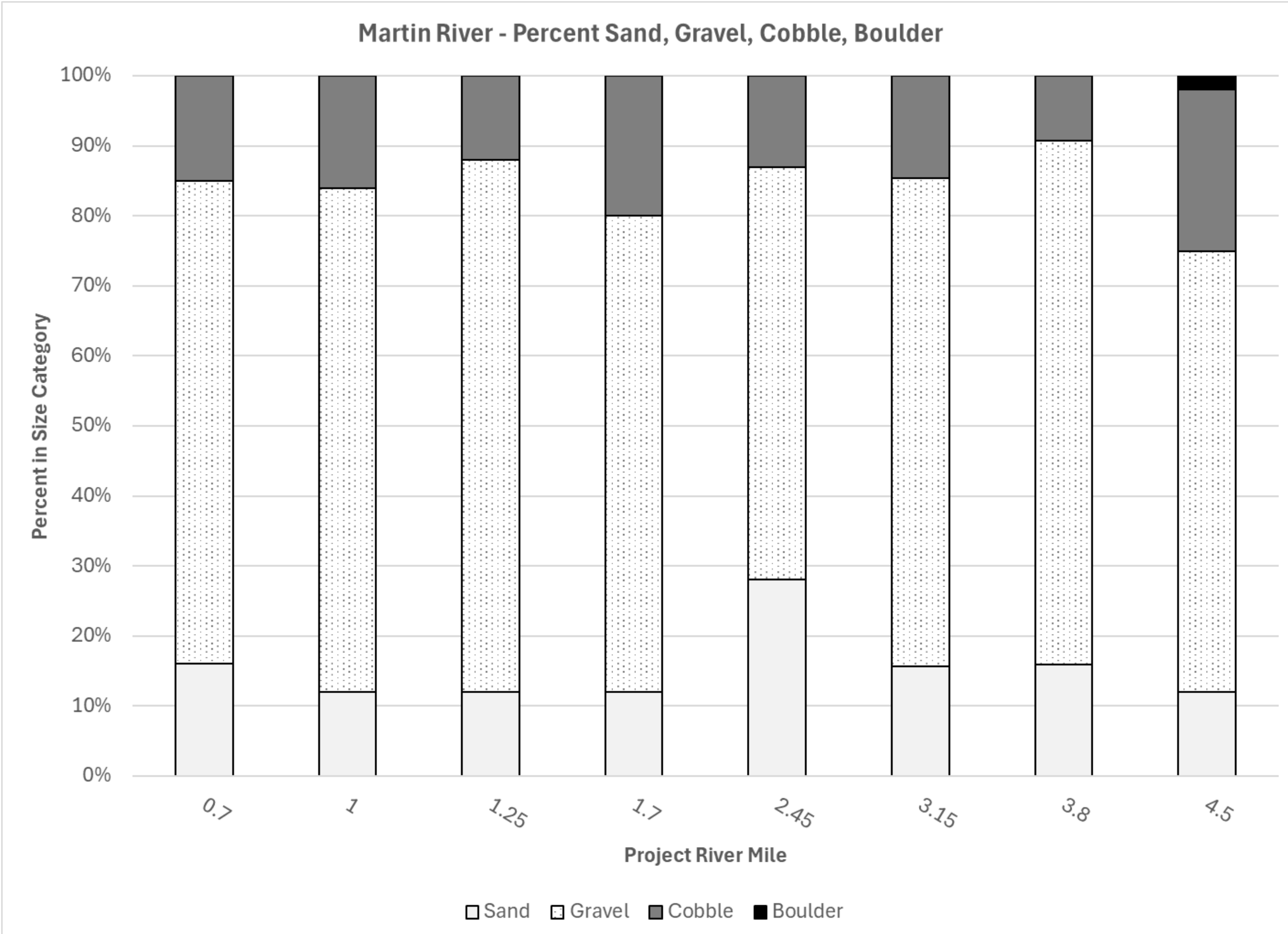


Figure 5-22 Martin River percent sand, gravel, cobble, and boulder in sub-surface samples.

5.4 Timelapse Camera Analysis

Timelapse camera images from the cameras that were deployed along braided sections of the Martin River showed change during six to eight high flow events in 2023, one to six high flow events in 2024, and two to eight high flow events in 2025 depending upon camera location (Table 5-7 through Table 5-9, Figure 5-23 through Figure 5-25). Channel changes (e.g., shifts in channel locations) in braided river systems occur when flows are high enough to transport bedload sediment (Middleton et al. 2019).

Table 5-7 2023 dates with channel change on timelapse camera footage.

Date	USGS Gage No. 15238951 Stage (ft) PROVISIONAL	USGS Gage No. 15238951 flow (cfs) ESTIMATED	Camera Designation		
			GE-01 (PRM 2.8)	GE-02 (PRM 2)	GE-03 (PRM 1.1)
6/24/2023	6.30	1,184	X	X	
6/25/2023	6.44	1,457	X	X	
6/26/2023	6.27	1,148		X	X
6/27/2023	6.28	1,164		X	
6/28/2023	6.20	1,027		X	
7/3/2023	6.34	1,184			X
7/6/2023	6.30	1,185		X	X
7/7/2023	6.36	1,309		X	
7/16/2023	6.64	1,943			X
7/17/2023	6.45	1,486			X
7/22/2023	6.22	1,058		X	
7/28/2023	6.44	1,452			X
7/29/2023	6.49	1,562	X	X	
7/30/2023	6.18	994		X	
8/6/2023	6.52	1,645		X	X
8/7/2023	6.70	2,108	X	X	
8/12/2023	6.61	1,844			X
8/14/2023	6.39	1,352	X		
8/21/2023	5.91	655			X
8/25/2023	6.62	1,875	X	X	
8/27/2023	6.72	2,154			X
8/29/2023	6.86	2,598		X	X
8/31/2023	6.70	2,100		X	X
9/16/2023	6.27	1,146		X	X

Table 5-8 2024 dates with channel change on timelapse camera footage.

Date	USGS Gage No. 15238951 Stage (ft) PROVISIONAL	Flow at Constriction (PRM 1.9, cfs)	Camera Designation					
			GE-01 (PRM 2.8)	GE-02 (PRM 2)	GE-03 (PRM 1.1)	GE-04 (PRM 0.7)	GE-05 (PRM 2.7)	GE-08 (EFMR PRM 0.15)
7/12/2024	6.8	1,369	X	n/a	X	X	X	
8/7/2024	10.2	3,162-5,500	X	X	X	X	X	X
8/12/2024	6.9	1,130				X	n/a	
8/18/2024	7.2	1,352			X	X	n/a	
9/5/2024	7.6	1,280	X	X	X	X	n/a	
9/13/2024	7.0	1,337		X	X	X	n/a	

Notes: - n/a indicates camera was not deployed or not functioning on these dates.

- Channel change at Camera GE-08 may have occurred on other dates, but the single channel was full all summer, and changes could not be discerned.
- Cameras GE-06 and GE-07 were deployed in side channels/tributaries for aquatic habitat study purposes and are not included in this table.
- The peak flow on August 7, 2024, is unknown since all gage locations were damaged; this represents the likely range of the peak discharge.

Table 5-9 2025 dates with channel change on timelapse camera footage.

Date	USGS Gage No. 15238951 Stage (ft) PROVISIONAL	Flow at Constriction (PRM 1.9, cfs)	Camera Designation				
			GE-01 (PRM 2.8)	GE-02 (PRM 2)	GE-03 (PRM 1.1)	GE-04 (PRM 0.7)	GE-05 (PRM 2.7)
7/8-7/9	6.5	570			X	X	
8/9-8/10	6.5	900-1,030			X		
8/10	6.5	900			X	X	
8/27	6.5	1,700			X		
8/28	7.0	2,600	X	X	X	X	X
9/2	6.2	1,800			X		
9/4	6.2	1,400				X	X
9/7	6.2	1,300				X	
9/8	6.3	1,150			X		
9/9-9/10	6.3	1,500	X	X	X	X	X

In 2023, the upstream-most camera (GE-01) showed the least amount of channel change; this may have been due to the camera location that primarily showed a secondary, left bank channel that had less flow than the main channel (Photo 4-1 above). The GE-02 and GE-03 cameras both showed frequent channel changes (during at least eight different high flow events) during the 2023 flow season, consistent with braided glacial river dynamics. In addition, images from the GE-03 camera (Photo 4-3 above) showed channel incision, bank erosion, and resulting base level changes on August through October images following the downstream right bank levee breach.

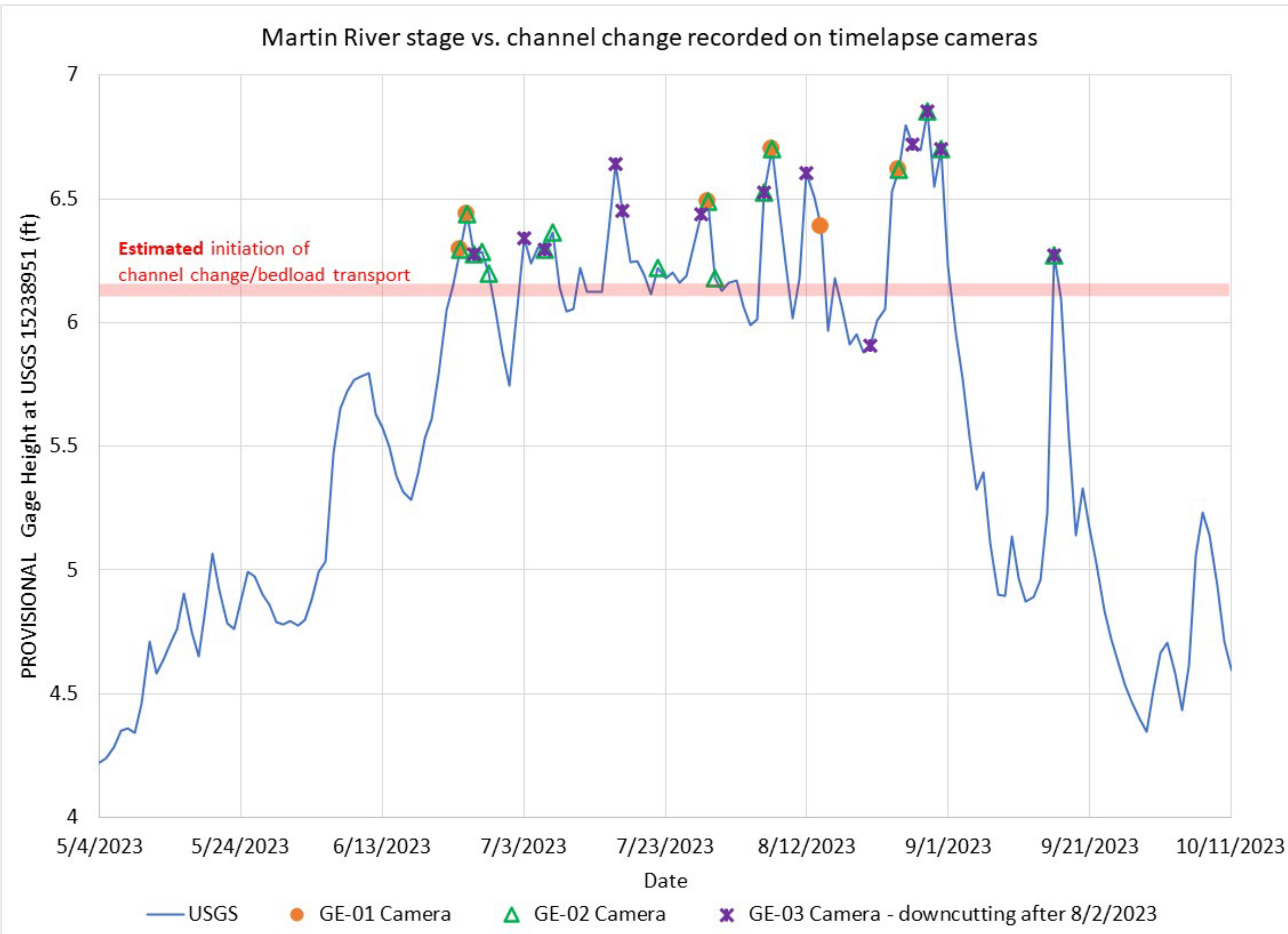


Figure 5-23 Martin River stage versus channel change, 2023.

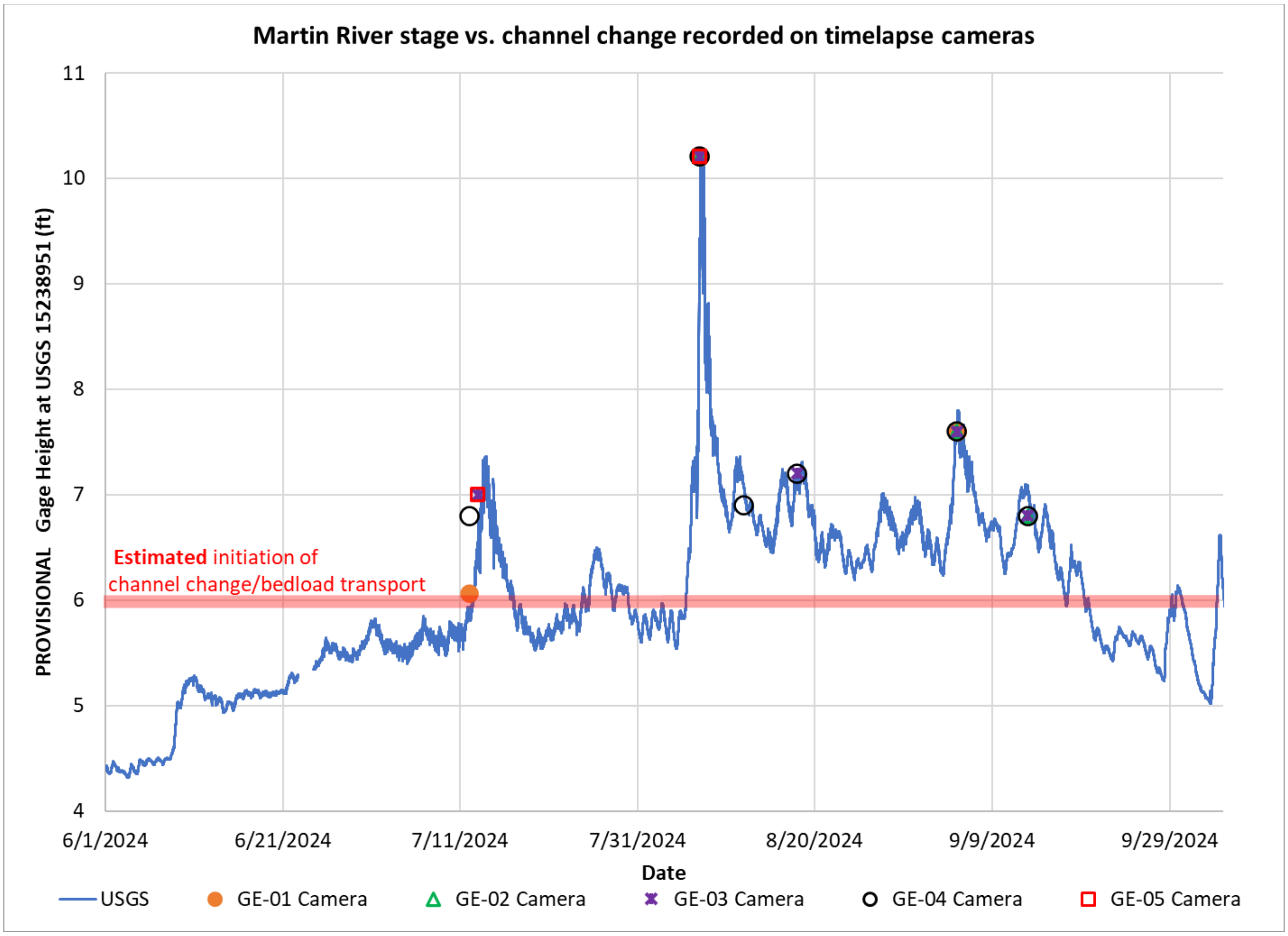


Figure 5-24 Martin River stage versus channel change, 2024.

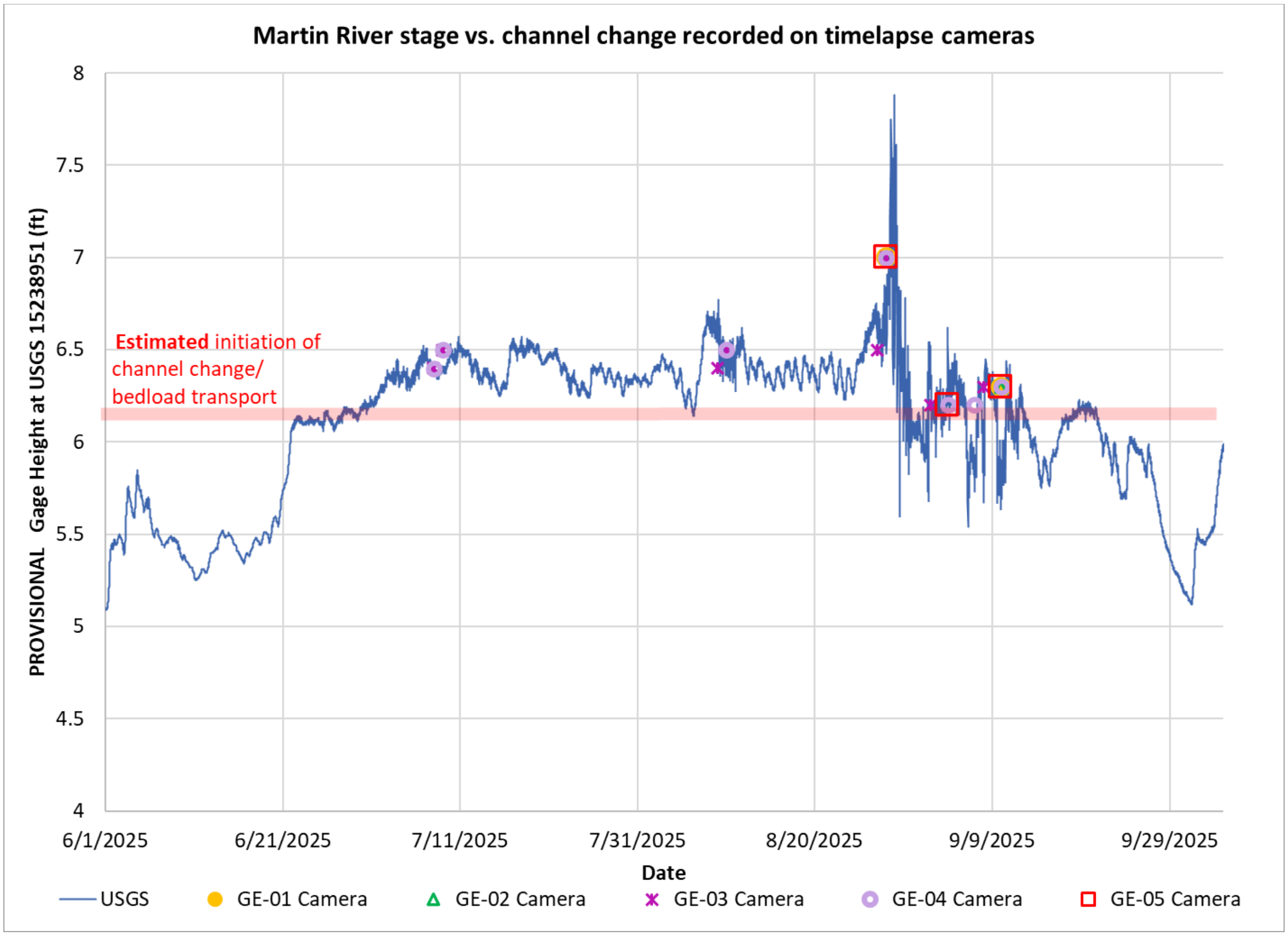


Figure 5-25 Martin River stage versus channel change, 2025.

In 2024, there were fewer observed instances of channel change at the timelapse cameras, likely due to the flow hydrograph that stayed relatively high from the large peak flow in early August through mid-September, making it difficult to discern channel change due to water covering the river bars. However, channel change was observed during one to six different high flow events at the various cameras (Table 5-8).

In 2025, Cameras GE-01 and GE-02, covering two of the wide braided sections on the Martin River, showed channel change twice during the year at flows of 1,500-2,600 cfs. Cameras GE-03 and GE-04 showed channel change more frequently and at flows as low as 600-900 cfs, likely because these two cameras are located near the mouth of the river and are still responding to the 2023 levee breach that lowered the base level of the river in this area. As a result, the bed is headcutting and more mobile than upstream areas. Camera GE-05 is located in the side channel of the Martin River at the outlet of Swan Lake and responded similarly to the Cameras GE-01 and GE-02.

The provisional USGS gage heights (USGS Gage No. 15238951) were compared for each date that had channel change in 2023, 2024, and 2025 and showed that in general, flow events corresponding to gage heights above about 6 feet resulted in channel change (Figure 5-23 and Figure 5-24). Based on rating curves for the constriction gage near Martin River PRM 1.9 on the dates when channel change was noted in 2023 and 2024, it appears that a flow of approximately 1,000-1,300 cfs is needed to mobilize bedload and induce channel change in the braided areas of the Martin River. Higher flow is needed to mobilize sediment in the lower end of the EFMR canyon due to the large boulders on the bed; channel change was observed following an estimated flow of approximately 3,000-5,500 cfs, but there are not enough instances of flows between 2,000 and 4,200 cfs to discern the threshold for bedload movement in the lower canyon.

The peak flow event on August 7, 2024, resulted in major changes in the Martin River channel. The peak gage height and flow are estimated due to equipment issues during the large peak, but flow was estimated by DOWL to be 3,162 cfs at the gage at the PRM 1.9 constriction; due to the mobile bed at this location, actual flow is not known. DOWL has reported that the flow on this date using a synthetic record based on the Upper Bradley River near Nuka Glacier (USGS Gage No. 15238990) would be approximately 5,500 cfs. The flow was large enough to completely fill the canyon at the mouth of the EFMR (Camera GE-08) and spanned much of the valley at other camera locations, and it was likely much larger than 5,000 cfs based on water depths under peak flows modeled with the 2D HEC-RAS model (see Section 5.5). Representative before, during, and/or after photos of the flood are included in Appendix A.

5.5 Sediment Transport and Deposition Patterns

A discussion of sediment deposition and erosion patterns in the Martin River through time is also included in Section 5.1.3 above. This section describes and quantifies deposition and erosion locations and volumes between the October 2022 and May 2024 LiDAR data acquisition dates, essentially quantifying the net volume of sediment erosion, transport, and deposition during 2023.

Elevation changes between the 2022 and 2024 LiDAR data in the Martin River valley are shown on Figure 5-26 and Figure 5-27. Areas of aggradation (deposition) appear in red tones on the figures, and areas of degradation (erosion) appear in green tones. Yellow tones indicate little topographic change. Note that the 2022 LiDAR elevation data show the top water surface of rivers and ponds, whereas the 2024 LiDAR data include bathymetric data and shows the bottom of rivers and ponds. Therefore, river channels and ponds appear in green/blue/purple colors indicating water depth rather than erosion.

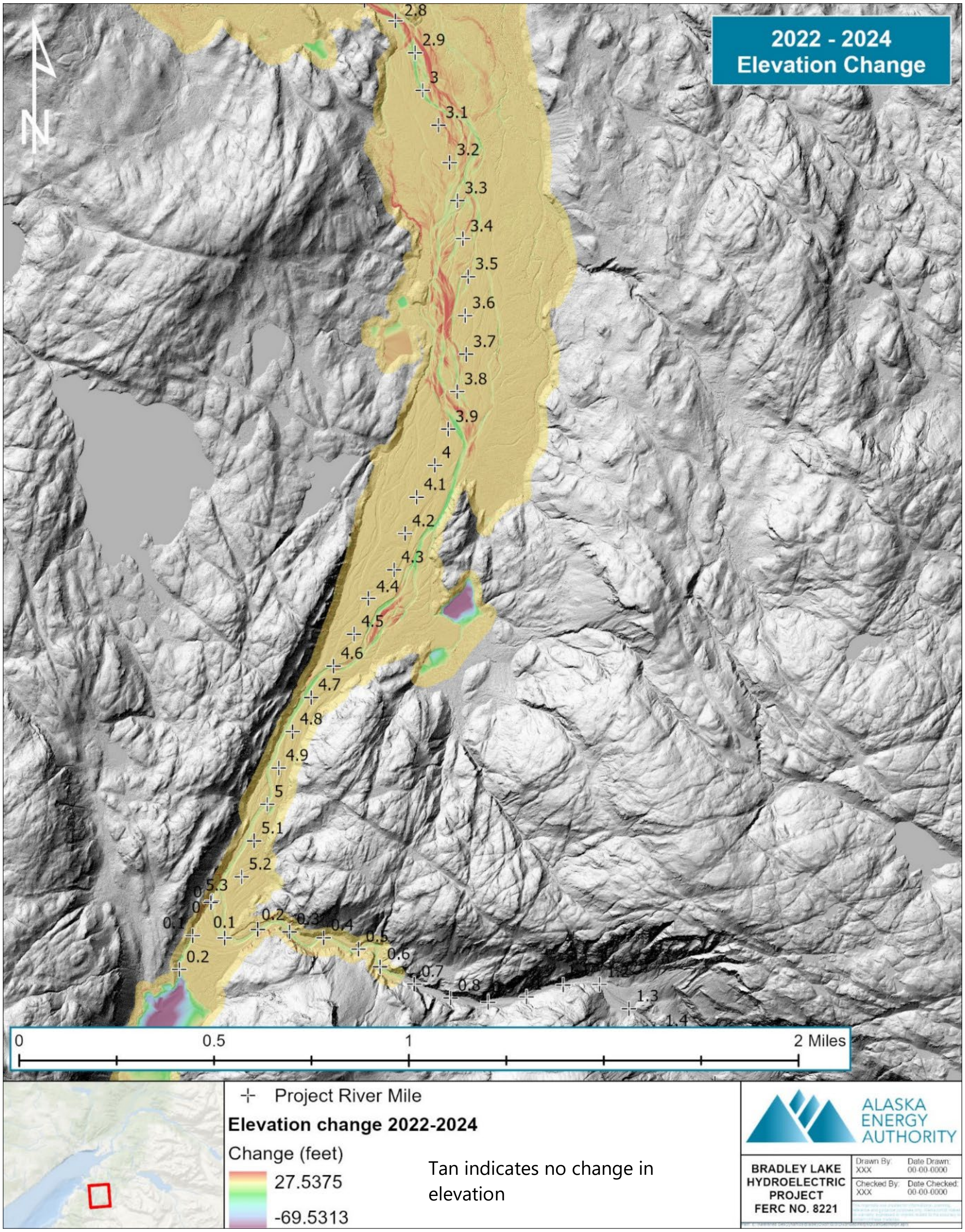


Figure 5-26 Martin River upper valley elevation changes, 2022 to 2024.

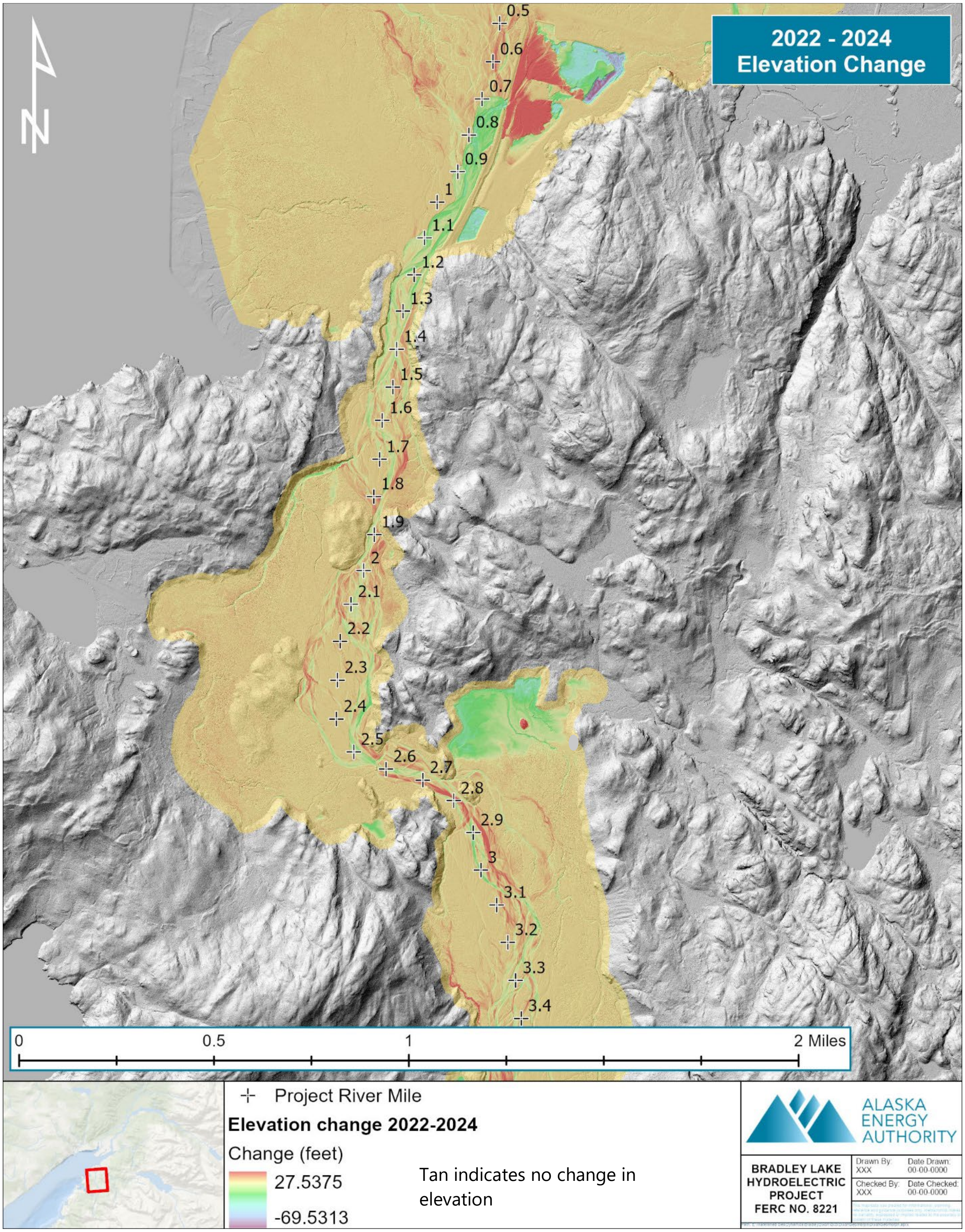


Figure 5-27 Martin River lower valley elevation changes, 2022 to 2024.

The 2022-2024 comparison shows little change upstream from PRM 4.5, discrete areas of deposition and erosion representing migration of the braided river channels between PRM 2.5 and PRM 4.5, and more diffuse erosion and deposition between PRM 1.2 and PRM 2.5. Downstream from PRM 1.2, the net channel incision resulting from the drop in base level following the August 2023 right bank levee breach is shown, along with deposition in the former delta area near PRM 0.5-PRM 0.7 that presumably occurred prior to the levee breach, and deposition in two lobes in the former lower and middle mitigation ponds east of the levee breach.

The 2024-2022 net change in topography in the Martin River active channel/valley was summed by geomorphic unit to show trends in sediment deposition or erosion along the river valley (Figure 5-28). The net change shows a small amount of net erosion in the upper, confined areas of the river (Geomorphic Units 8b and 9; upstream from PRM 3.9), net deposition as the valley widens and the river spreads out in Geomorphic Unit 8a, minor net changes through PRM 1.4, channel erosion in response to the headcut upstream from the levee breach in Geomorphic Units 2 and 3, and a large amount of deposition in the new delta that built into the former mitigation ponds. Note also that there was net deposition in the former delta area (labeled "old delta" on the figure) between the October 2022 LiDAR acquisition and the early August 2023 levee breach; an average of 0.12 feet of aggradation is spread across the entire old delta area. This rate is consistent with the long-term estimate of 0.16 feet per year of aggradation in the delta area as discussed in Section 5.1.3.2.

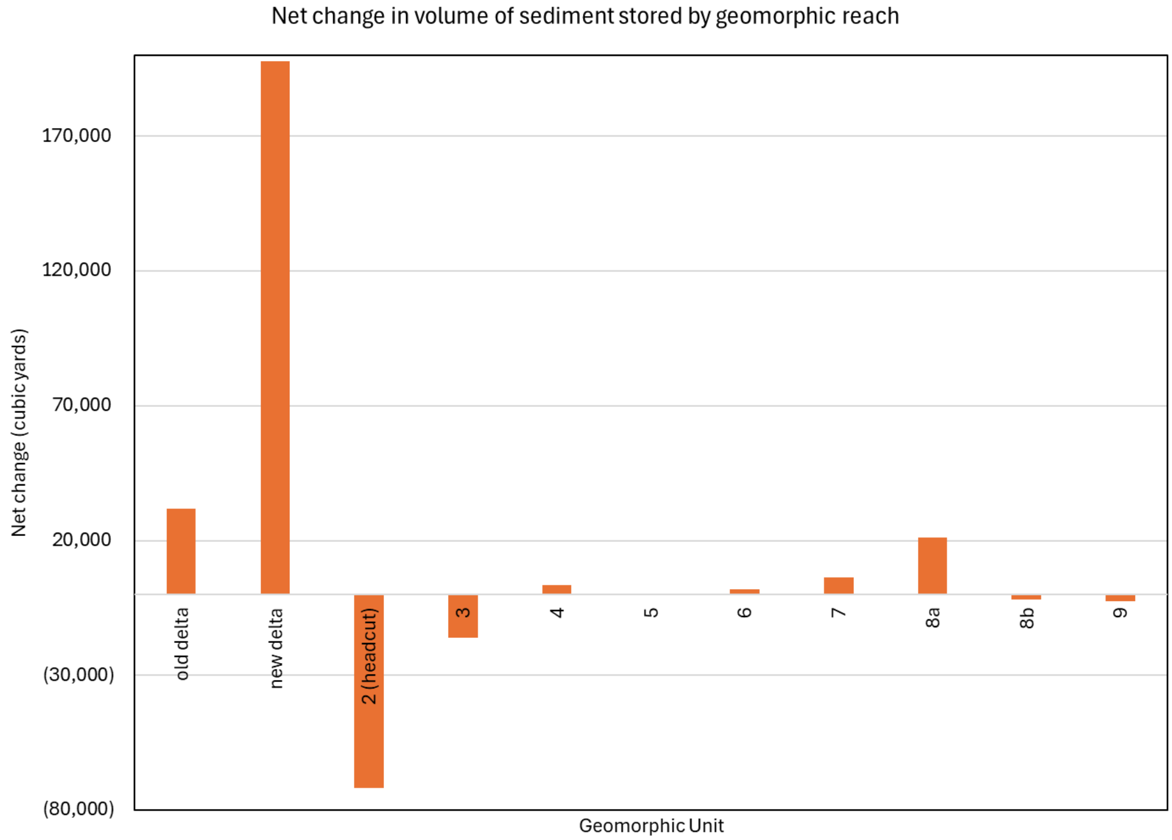


Figure 5-28 Net change in volume of sediment stored in the Martin River active channel/valley by geomorphic reach, October 2022-May 2024.

5.6 Sediment Transport Analysis using Two-dimensional Hydraulic Model Output

The output from the 2D HEC-RAS hydraulic model representative of May 2024 topographic conditions was used to predict the critical grain diameter, e.g., the size of particles that could be entrained by flows of 1,000-5,000 cfs. These predicted grain sizes indicate the diameter of particles that could theoretically be eroded from the bed of the river at each model cell location under the modeled flow.

Examples of the critical grain diameter analysis for the upper Martin River near the EFMR and WFMR confluence for 1,000 and 5,000 cfs are shown in Figure 5-29 and Figure 5-30, and for the mouth of the Martin River in Figure 5-31 and Figure 5-32. As expected, critical grain diameter in confined and higher gradient areas is larger (cobble to boulder-sized) in the upper river areas than in downstream, unconfined areas. Areas where the model predicts smaller critical grain diameter downstream from areas of larger critical grain diameter, indicative of areas where deposition could be expected, are similar to those areas where deposition occurred in the 2022-2024 LiDAR data comparison (Figure 5-26 and Figure 5-27 in previous section).

The predicted critical grain diameter under the 1,000 cfs modeled flow was compared with the median (D_{50}) substrate size collected along the river in May 2024, the same timeframe as the 2D hydraulic model topography was collected (see pebble count data in Section 5.3). In almost all locations, the substrate D_{50} was similar to the predicted critical grain size, further validating the predictive ability of the 2D model analysis.

The 2D model analysis was used in 2025 to help determine changes to sediment transport patterns under potential future flow regimes.

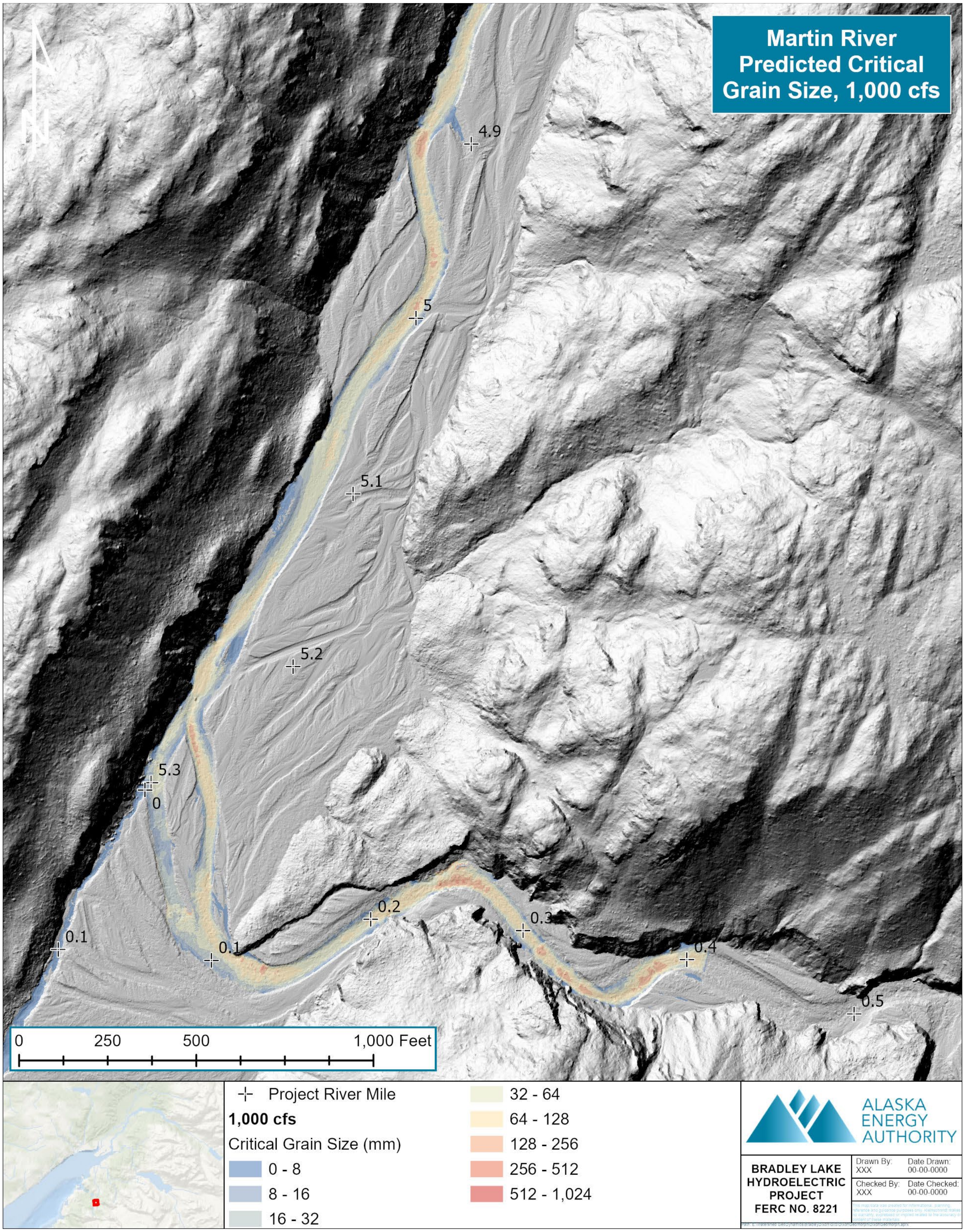


Figure 5-29 Critical grain diameter, 1,000 cfs, upper Martin River.

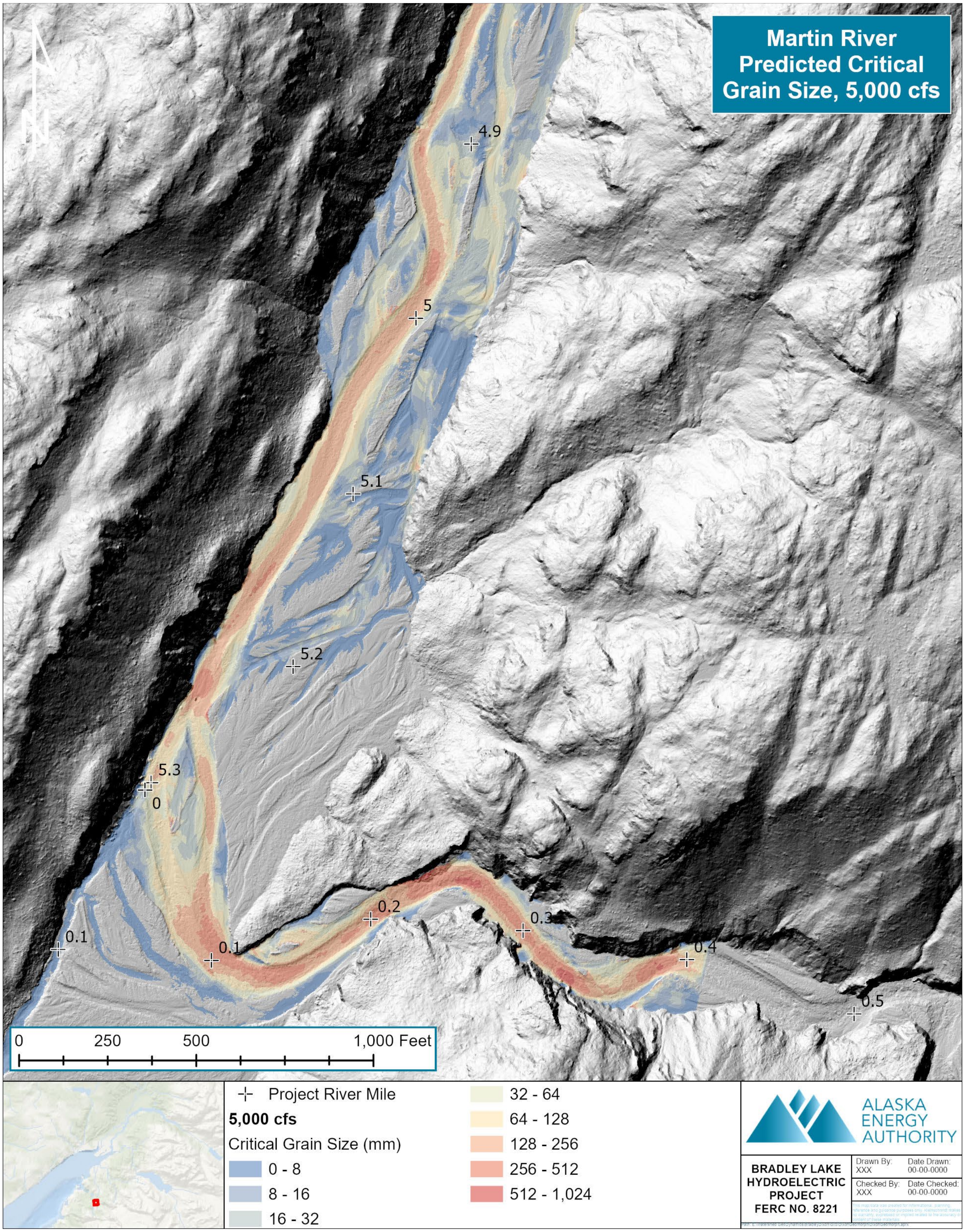


Figure 5-30 Critical grain diameter, 5,000 cfs, upper Martin River.

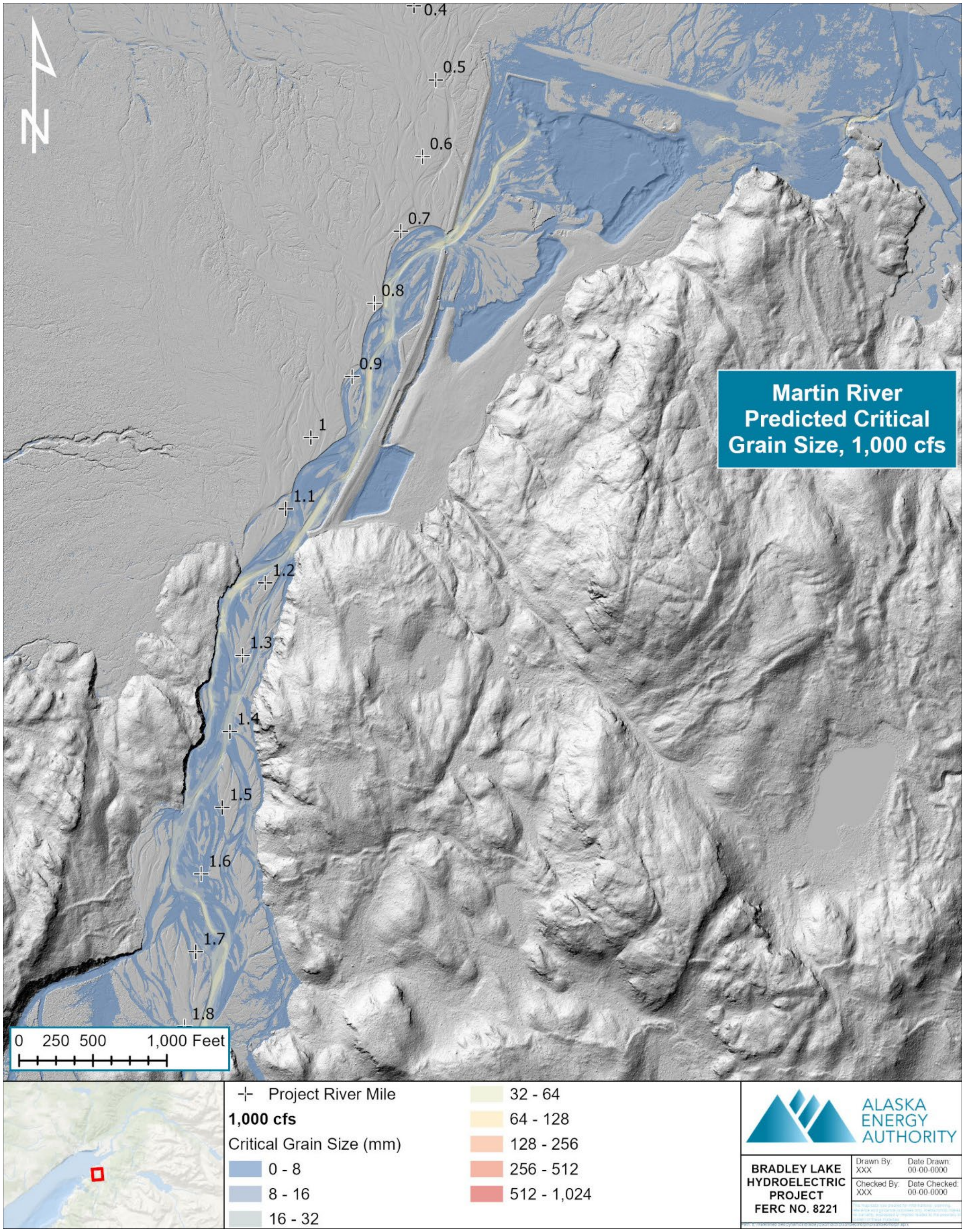


Figure 5-31 Critical grain diameter, 1,000 cfs, mouth of Martin River.

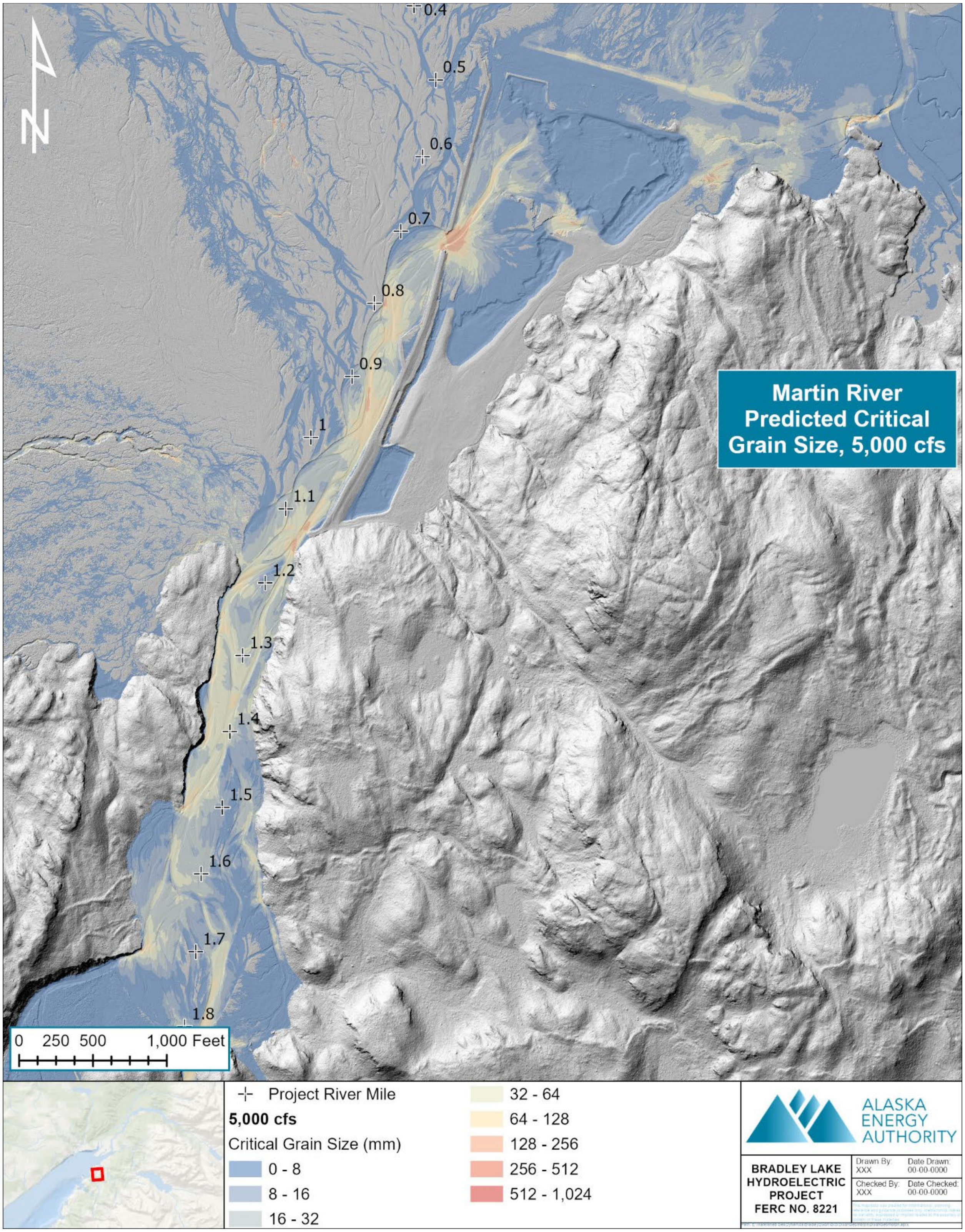


Figure 5-32 Critical grain diameter, 5,000 cfs, mouth of Martin River.

5.7 Potential Changes to Martin River Geomorphology with Proposed Dixon Diversion

5.7.1 Changes to Martin River Sediment Transport under Proposed Future Flow Regimes

The proposed Dixon Diversion intake and tunnel would be constructed at approximately PRM 3.8 in the EFMR just downstream from the current terminus of the Dixon Glacier. The diversion dam is still under design but is anticipated to be approximately 25 feet tall and equipped with two gates to flush accumulated sediment on a periodic basis. A forebay area would act as a stilling basin for the intake, currently estimated to include a storage capacity of approximately 5 acre-feet (7,000-8,000 cubic yards) at El. 1,275 feet. The diversion tunnel is currently anticipated to have a capacity of 1,650 cfs and convey water from the EFMR to Bradley Lake. A minimum instream flow and flushing flow regime will be established in consultation with resource agencies. For initial analysis of potential changes to flows and sediment transport potential in the Martin River downstream from the diversion, a minimum instream flow of 100 cfs in the Martin River was assumed. This would result in all flows over 100 cfs and up to tunnel capacity (1,650 cfs) being directed into the tunnel to Bradley Lake and no longer flowing down the Martin River.

5.7.1.1 Changes to Sediment Input

Coarse-grained sediment emanating from the Dixon Glacier would accumulate in the diversion intake pool as water velocities drop. On behalf of AEA, DOWL is developing a 2D hydraulic model of the diversion pool to estimate velocities and grain size of sediment trapped; for analysis purposes it is assumed that all sediment larger than fine gravel would be deposited in the intake pool, forming a delta that progrades into the pool and decreases pool capacity. Finer grained sediment (silt, clay, fine sand) would remain in suspension through the intake diversion pool and be conveyed down the tunnel to Bradley Lake (except for suspended sediment in the 100 cfs minimum instream flow that would continue down the Martin River). It is possible that coarse sand may also accumulate in the diversion pool at some times, depending upon flows and remaining pool capacity. Assuming an average annual input of 30,000 cubic yards per year of gravel/cobble/boulder material from the Dixon Glacier, the intake pool would need to be flushed of sediment on at least an annual basis. As noted in 5.1.3.1.1.1, coarse-grained sediment supply from alpine glaciers is episodic; it is possible that the pool may not accumulate enough sediment to require flushing in each year, or if multiple large influxes of sediment occur the pool may need to be flushed more than once a year. It is assumed for analysis purposes that annual flushing of sediment would take place during flows of at least 500 cfs to provide velocities necessary to flush cobble-sized material from the intake pool.

As a result of Project operations, it is anticipated that the total volume of coarse-grained sediment supplied to the Martin River would be similar to current conditions, but the timing of sediment supply would be altered. Coarse-grained sediment would be stored within the intake pool and flushed periodically into the Martin River. Finer grained sediment (silt, clay, fine sand) supply to the Martin River would be greatly reduced as that material would travel with the diverted flow into Bradley Lake.

5.7.1.2 Changes to Flow and Bedload Transport Potential

Martin River flow and bedload transport potential would change as a result of Project operations. Proposed operations currently include a 100-cfs minimum instream flow release (or inflow if less than 100 cfs) into the EFMR and diverting flow above 100 cfs, up to 1,650 cfs, into the diversion tunnel to Bradley Lake. This would reduce flow and bedload transport capacity in the Martin River.

Using a 45-year (1979-2024) synthetic flow record for the EFMR developed by DOWL (2025), and assuming a flow of 1,000 cfs is required to mobilize the bed in the Martin River downstream from the EFMR/WFMR confluence, the average number of days per year with bedload transport was calculated for historical and with-diversion conditions. This initial analysis assumes no flushing flow regime both for comparison purposes and to help determine the frequency and magnitude of flushing flows needed.

Figure 5-33 shows historical synthetic flows (blue line), the Martin River 1,000 cfs threshold for bedload transport (yellow line), the maximum tunnel capacity of 1,650 cfs (orange line), and the combined bedload transport and tunnel capacity threshold of 2,650 cfs (brown line). Under historical conditions, bedload transport in the Martin River is estimated to have occurred at flows above 1,000 cfs (flows above yellow line). Under with-diversion conditions, bedload transport could occur when flows are above the brown line, an average frequency of 0.9 days per year compared to 25 days per year under historical conditions. As shown in Figure 5-33, bedload transport is episodic, with some years having frequent bedload transport and a few with little or no bedload transport under historical conditions.

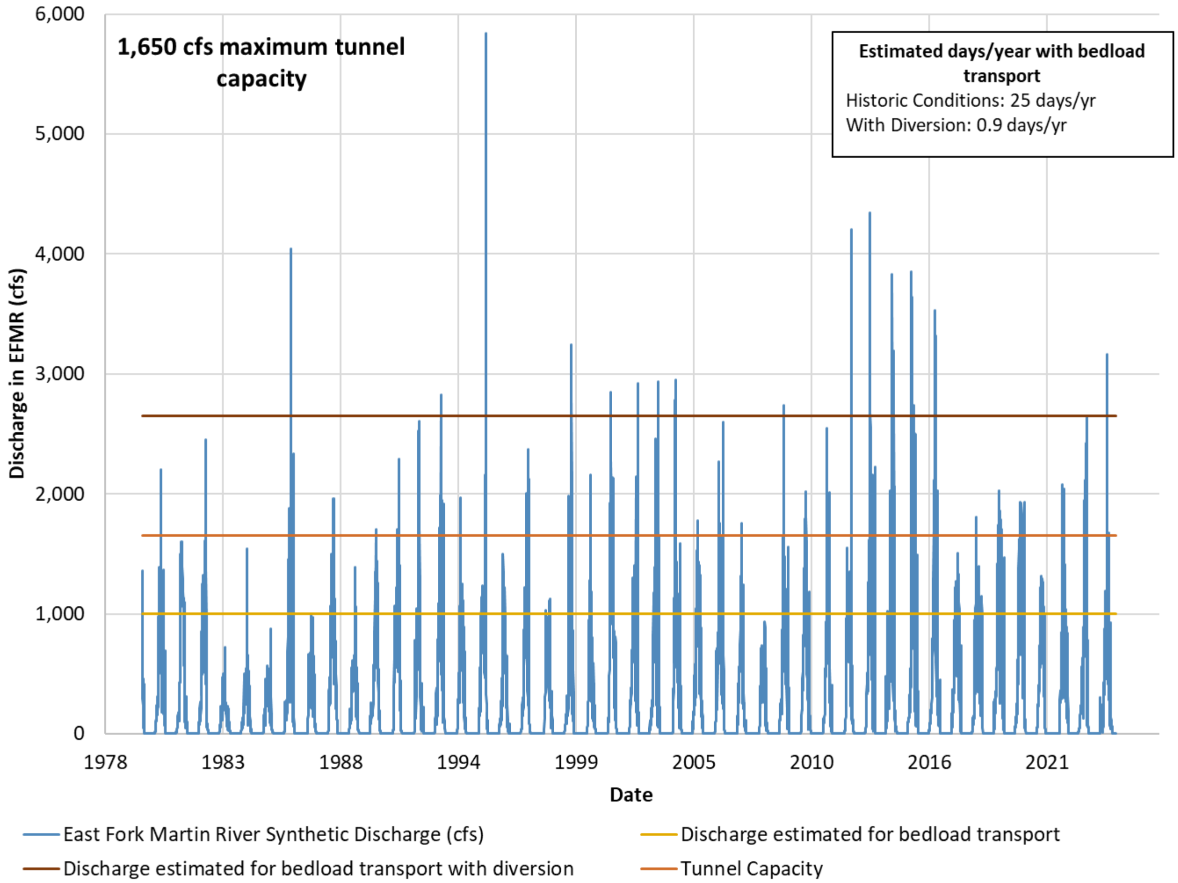


Figure 5-33 Potential changes in Martin River flow and sediment transport capacity.

The net effect of decreased flow in the EFMR and mainstem Martin River and episodic input of coarse-grained sediment from the EFMR during sediment flushing procedures will depend upon the magnitude and timing of flows and sediment flushes.

Currently proposed sediment flushing procedures are to flush sediment on an as-needed basis when sediment deposits appear to be accumulating in the diversion pool to an extent that may affect Project operations (e.g., sediment appears to be depositing close to the forebay/intake tunnel). Since sediment input from the Dixon Glacier is episodic, for analysis purposes it is assumed that a sediment flush would occur under a flow of 500 to 1,000 cfs when approximately 7,000 cubic yards of boulder/cobble/gravel have accumulated in the diversion pool. Proposed sediment flush operations are to quickly drop one or more of the gates for 1 hour, then raise the gate(s) and visually assess the success of the flush. Based on 2D hydraulic modeling, flow of 500 cfs would flush most cobble and finer material through the diversion pool, and flow of 1,000 cfs would flush all cobble (but not boulder-sized material).

Based on visual observations of existing bed material in the EFMR canyon, it is anticipated that most of the flushed material would be transported through the canyon (average 6.7 percent gradient). Based on 2D hydraulic modeling, larger material (cobble/boulders) would likely be deposited near the EFMR/WFMR confluence under a sediment flush flow of 500 cfs but would be transported farther downstream to approximately PRM 3.5-PRM 4.5 under a flow of 1,000 cfs. Note that the 1-hour duration of the proposed sediment flush flow may not allow adequate time for coarser material to be transported all the way downstream to PRM 3.5-PRM 5; the hydraulic model does not provide information on bedload movement speed.

Using the information in Figure 5-33, the currently proposed new flow regime for the Martin River under with diversion conditions is shown in Figure 5-34. If sediment is deposited in the upper reaches of the Martin River following a sediment flush, it may remain there for several years because no bedload transport in the Martin River would be anticipated for many years. In addition, based on observations in the Martin River during fall time periods, fine- to medium-gravel accumulations may occur within the river channel on the waning limbs of peak flow events, and finer sediment deposition may occur in side channels or areas of slow-moving water. To help this material move through the river system, a flushing flow regime of 1,000 cfs for 12 hours 3 times in a 10-year period has been proposed as part of Protection, Mitigation, and Enhancement (PM&E) measures. This level of flushing flow may occur naturally, but if not, flow releases from the diversion dam would be used to provide the recommended sediment movement. Furthermore, due to uncertainty around the exact amount and timing of sediment flushes and exact flows to transport bed material through the Martin River, monitoring sediment accumulations and grain size in the Martin River has been proposed as part of PM&Es to assess the actual effects of the proposed flow regime and the ability to maintain a passage corridor for aquatic species to tributary and OCH.

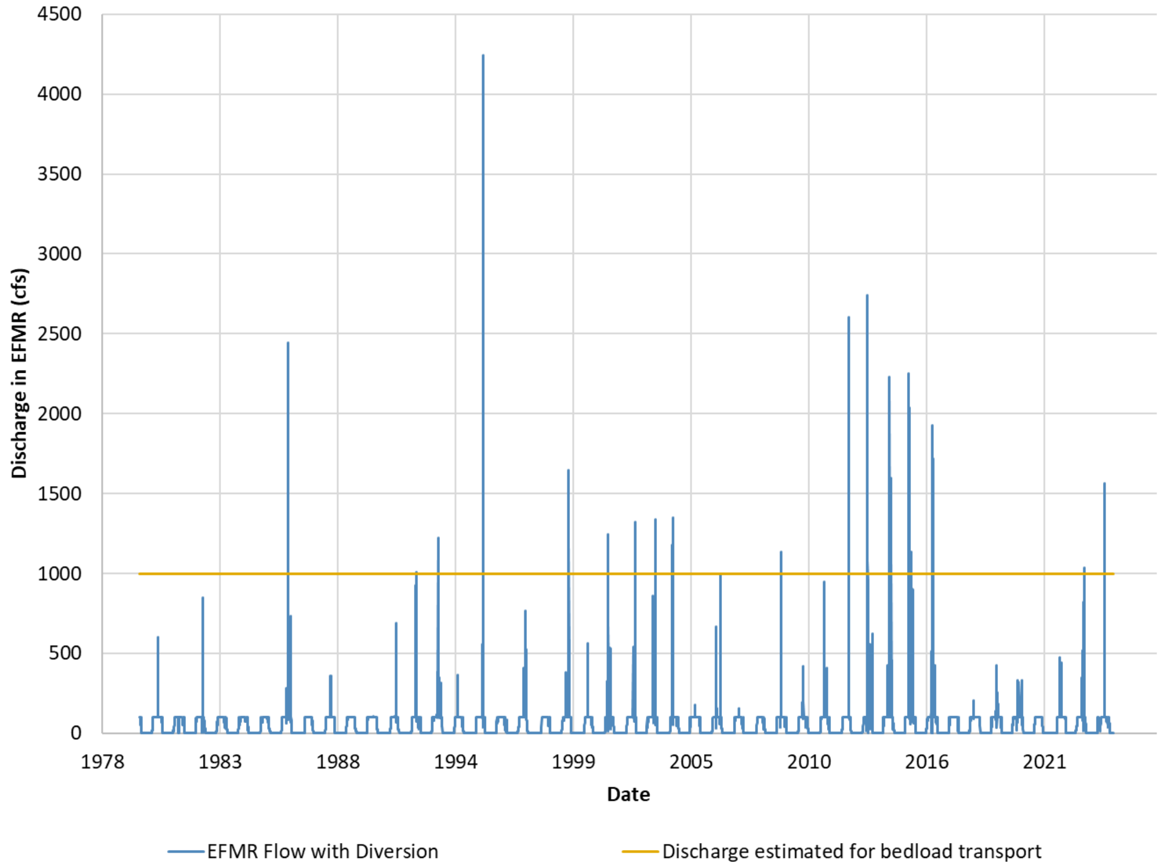


Figure 5-34 EFMR flow with proposed Project operations.

5.7.2 Synthesis of Hydraulic, Geomorphic, Riparian, and Aquatic Analyses

Evolution of the Martin River channel with operation of the proposed diversion structure will result in changes to and interactions among hydraulic, geomorphic, riparian, and aquatic resources.

Studies of hydropower developments on other alpine glacial river systems have shown that reduction in flows and sediment input and transport resulting from dam construction have reduced braiding, with rivers tending toward fewer or a single channel morphology (Liu et al. 2025; Comiti et al. 2011; Piégay et al. 2006). Comiti et al. (2011) studied the long-term effects of watershed development, including dam operation, urbanization, timber harvest, and gravel mining on a large, braided river in the Italian Alps over a 200-year span. They found that the braided sections of the river narrowed and transitioned to a meandering/wandering morphology. Bed incision was particularly triggered by gravel mining, followed by colonization of riparian forests in the former active braid plain.

Following cessation of gravel mining, incision has ceased and large floods are causing island erosion and channel change. Goss (2021) analyzed changes in several proglacial rivers and found that a decrease in discharge decreased braiding complexity. Piégay et al. (2006) discussed changes in braided rivers, from expansion with increased flow and/or sediment inputs (similar to the evolution of the Martin River valley since the Little Ice Age) to contraction with decreased flow and/or sediment supply. Under contraction, braided rivers move to a condition with fewer braids and colonization of formerly active valley bottoms with riparian vegetation.

Operation of the Dixon Diversion will greatly reduce flow and the total volume of fine-grained sediment transported into the Martin River (Figure 5-33 and Figure 5-34), but Project operation will not substantially reduce the volume of coarse-grained gravel and larger particles that currently make up the bed of the Martin River. It is most likely that the Martin River will evolve into a single-channel system, but it is possible that the occasional large peak flows that will still occur, coupled with the transport of coarse-grained sediment through the EFMR canyon, will result in reaches with multiple or braided characteristics, particularly following an extreme flow event. Project-related factors will combine with existing conditions as the river evolves. The continued decrease in coarse sediment input following revegetation of the Little Ice Age sediment sources (see Section 5.1.3.1) and the lowered base level and headcutting resulting from breaching of the levee near the mouth of the river will result in continued channel incision. The incision will continue to work downstream from the EFMR/WFMR confluence and upstream from the mouth of the river. While change toward a single channel system is the most likely scenario of future channel evolution, there is some uncertainty around exactly how the channel will evolve given there may be changes to the frequency of large peak flows and sediment input from the Dixon Glacier as the glacier recedes.

Both the Bradley River downstream from Bradley Lake and Battle Creek, a tributary just east of the Martin River where water has been diverted into Bradley Lake in a similar manner as the proposed Dixon Diversion, were considered as potential analogue sites for how the Martin River may respond to proposed changes in flow. However, both the Bradley River and Battle Creek flow through confined, high gradient bedrock valleys between the point of diversion and Kachemak Bay, so they are not suitable for comparison with the unconfined reaches of the Martin River. Instead, recent changes to the upper Martin River between PRM 3.9 and PRM 5.3 after the Little Ice Age sediment pulse passed through this area may be a better analogue. As shown in Figure 5-10, this area aggraded in the late 1900s and had a braided pattern, but it has incised into primarily a single-channel system since the early 2000s (Figure 5-26). Riparian vegetation (alder/willow/cottonwood and *Dryas*) is starting to colonize areas of the braid plain because it is no longer subject to frequent inundation or braided channel movement (Photo 5-8). Alder is also colonizing the banks of old side channels in this area, again because the channels are more stable (Photo 5-9).

Photo 5-8 Revegetation on the Martin River braid plain, PRM 4.2, July 31, 2025.

Photo 5-9 Alder growth along edges of old side channel on the Martin River braid plain, PRM 4.1, July 31, 2025.

It is likely that, similar to the PRM 3.8-PRM 5.5 area, the future reduced flows in the Martin River will result in a more stable channel configuration throughout the rest of the river and allow riparian vegetation to become established along the channel margins. Root strength associated with the vegetation will help to stabilize the streambanks and further reduce channel planform movement. The most common riparian shrubs along the side channels in the Martin River are alder (*Alnus viridis* ssp. *sinuata*), willows (*Salix alaxensis, S. sitchensis*), cottonwood (*Populus trichocarpa*), and the dwarf shrub (*Dryas drummondii*); along with a diversity of disturbance-tolerant forb and graminoid species adapted to river bars, these will likely be the first plants to colonize the streambanks. The current active channel area in the Martin River valley is characterized by a wide, sparsely vegetated cobble/gravel braid plain. This area will also begin to be colonized by riparian vegetation. Challenges to plant growth on the braid plain include the extremely well-drained substrate and lack of fine-grained material, organics, and nutrients.

The channel changes will also result in changes for fish and other aquatic species in the Martin River. The reduction of flow and increase in mainstem water temperatures, channel stability, and riparian vegetation are likely to increase both the quality and quantity of habitat for use by both juvenile and adult salmonids. In its current state, the mainstem Martin River serves primarily as a migration corridor due to suboptimal temperatures, few pools, and high velocities, with virtually all salmonid rearing and spawning habitat in the watershed confined to off-channel, tributary areas.

As demonstrated by field observations, tributaries and OCH connections with the mainstem of the Martin River have persisted through the 2023-2025 study seasons despite major main channel changes, extreme flood events, and incision resulting from breaching of the levee near the mouth of the river. Detailed hydraulic modeling of the Martin River in 2024 demonstrated that connectivity between the mainstem and OCHs were maintained at EFMR flows as low as 100 cfs. It appears that flow from the tributaries and off-channel areas has been sufficient to maintain surface water connectivity across the braid plain even when the main channel migrates away from the off-channel areas. This conclusion is supported by observations of spawning or juvenile Dolly Varden Trout (*Salvelinus malma*), Coho Salmon, and Sockeye Salmon (*O. nerka*) in representative off-channel features throughout the study period regardless of main channel changes.

It is likely that the new mainstem flow regime will result in a more stable main channel and that connectivity with off-channel areas will be maintained. However, as this connectivity is crucial to provide passage for adult and juvenile fish to OCH areas, it is recommended that monitoring connectivity be part of the proposed Project protection, mitigation, and enhancement measures.

6.0 SUMMARY

The Martin River is a braided glacial river with a very high sediment load. Channel gradient is relatively consistent from the mouth to the EFMR canyon, with a slight increase in gradient upstream from PRM 2.5. Substrate is primarily gravel and cobble downstream from PRM 4 with cobble, gravel, and boulder upstream from PRM 4 and in the moderately confined Geomorphic Reach 7.

The Martin River has been actively aggrading. The braided channels migrate, and bedload transport occurs multiple times per flow season (June through August), particularly in unconfined reaches. Current OCH areas were part of the active channel in the past and could be part of the active channel in the future as the river migrates across the valley bottom. It is estimated that bedload transport downstream from the EFMR/WFMR confluence occurs when flows reach approximately 1,000-1,300 cfs. Bedload transport is episodic, with some years having frequent bedload transport and a few with little or no bedload transport under historical conditions.

Aerial photograph analysis suggests that a large episodic input of sediment occurred from the early to mid-1900s following retreat of the Dixon Glacier Little Ice Age Maximum. This resulted in a sediment "slug" that has been moving and diffusing down the Martin River valley. As the sediment slug has moved down the valley, 5-7 feet of aggradation has occurred across the entire valley, followed by slow channel incision. It is anticipated that the sediment slug will continue to move through the lower valley for the next few decades before the river reaches a quasi-equilibrium with future sediment supply primarily coming from the Dixon Glacier.

In addition to the aggradation and subsequent incision caused by the sediment slug, the levee breach near the mouth of the river in August 2023 will continue to affect channel dynamics as the river adjusts to the new base level. The levee breach resulted in aggradation in the right bank mitigation ponds as a delta builds into the ponds and headcutting upstream of the breach location as the river adjusts to the new channel configuration. Channel adjustment related to the breach will continue for years to decades until a new, more stable base level is reached.

Operation of the proposed Dixon Diversion will greatly reduce flow and the total volume of fine-grained sediment transported into the Martin River but will not substantially reduce the volume of coarse-grained gravel and larger particles that currently make up the bed of the Martin River. Under with-diversion conditions, bedload transport would occur an average of 0.9 days per year compared to 25 days per year under historical conditions. Currently proposed Project operation includes a plan to periodically flush sediment from the intake pool on an as-needed basis (likely annually, but possibly every few years to several times per year depending upon actual sediment supply). It is anticipated that most of the flushed sediment would be transported through the canyon, and larger material (cobble/boulders) would be deposited near the EFMR/WFMR confluence under a flow of 500 cfs during the sediment flush but would be transported farther downstream to approximately PRM 3.5-PRM 4.5 if the flow was at or above 1,000 cfs. It is possible that, in the absence of a flushing flow regime, gravel/cobble may accumulate within the mainstem Martin River and fine sediment may accumulate in any side channel or still water environments.

Under proposed Project operations, it is anticipated that the Martin River will evolve into a single channel system with a more stable channel configuration that will allow riparian vegetation to become established along the channel margins. Root strength associated with the vegetation will help to stabilize streambanks and further reduce channel movement. A more stable main channel location will likely also allow connectivity with off-channel areas to stabilize. It is possible that the occasional large peak flows that will still occur, coupled with the flushing of coarse-grained sediment through the EFMR canyon, will result in reaches with multiple or braided characteristics, particularly following an extreme flow event.

While change toward a single channel system is the most likely scenario of future channel evolution, there is some uncertainty around exactly how the channel will evolve. Monitoring of channel and substrate changes, along with a flushing flow regime, is recommended to include as part of the Project operational and monitoring plans.

7.0 STUDY STATUS AND SCHEDULE

This report summarizes geomorphic and sediment transport data collection and analyses completed in 2023, 2024, and 2025 for the proposed Bradley Lake Expansion Project. This report completes all objectives of the Geomorphology and Sediment Transport Analysis component of the *Hydraulic Modeling, Geomorphology, and Aquatic Habitat Connectivity Evaluation* of the DSP. The study is complete.

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Appendix A

Representative Timelapse Camera Images of August 7, 2024 Peak Flow

Camera views before, during, and/or after peak flow event
(Note that the date/time stamp is shown on each photo)

Photo A-1 Camera GE-08, mouth of EFMR canyon looking upstream, before peak flow event.

Photo A-2 Camera GE-08, mouth of EFMR canyon, looking upstream, during peak flow event.

Photo A-3 Camera GE-08, mouth of EFMR canyon, looking upstream, after peak flow event.

Photo A-4 Camera GE-01, PRM 2.9, looking upstream, before peak flow event.

Photo A-5 Camera GE-01, PRM 2.9, looking upstream, during peak flow event.

Photo A-6 Camera GE-05, PRM 2.75 right bank side channel, looking downstream, before peak flow event.

Photo A-7 Camera GE-05, PRM 2.75 right bank side channel, looking downstream, during peak flow event.

Photo A-8 Camera GE-04, PRM 2, looking downstream, before peak flow event.

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Photo A-9 Camera GE-04, PRM 2, looking downstream, View 1 during peak flow event.

Photo A-10 Camera GE-04, PRM 2, looking downstream, View 2 during peak flow event.

Photo A-11 Camera GE-04, PRM 2, looking downstream, after peak flow event.