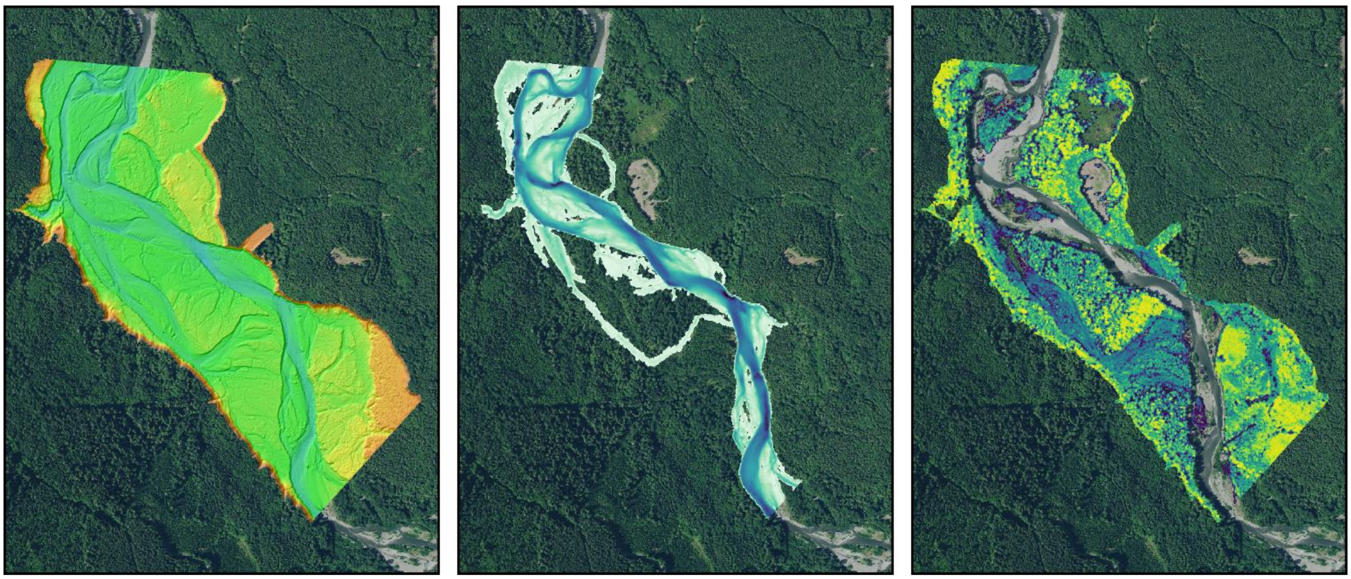
REMOTE SENSING PILOT PROJECT:
EVALUATING THE EFFECTIVENESS OF LARGE FLOODPLAIN AND RIPARIAN RESTORATION PROJECTS USING REMOTE SENSING



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RCO Project 21-1328

March 31, 2023

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EXECUTIVE SUMMARY

Previous restoration effectiveness monitoring programs administered by the Salmon Recovery Funding Board (SRFB) and the Bonneville Power Administration have emphasized the need for better evaluation of large floodplain and riparian restoration projects. Moreover, recent technological advances have made it possible to monitor large restoration projects efficiently using remote sensing. The SRFB Monitoring Panel oversaw the development of a Study Plan to evaluate large floodplain and riparian restoration projects using remote sensing. Prior to implementing the plan, the Monitoring Panel recommended a pilot study on a limited number of sites to test, refine, and confirm the feasibility of the approach and methods in the Study Plan. This report documents the results of the pilot study. We worked closely with the SRFB Monitoring Panel to select sites that met specific criteria (e.g., project length, availability of pre-project LiDAR). Four sites were selected, two in western Washington and two in eastern Washington, which include Countyline (White River), Fobes (South Fork Nooksack River), Tucannon Project Area 3 (PA-3, Tucannon River), and Middle Entiat (Entiat River). The Countyline and Tucannon PA-3 sites represent completed projects where before and after LiDAR data were available, but not all the supplemental field data. The Fobes site is a new project where we were able to collect pre-project data and construction will be completed in 2023. We were able to map and calculate all but a handful of floodplain and riparian metrics on Countyline and Tucannon PA-3 with LiDAR and other remotely sensed data, coupled with hydraulic modeling. For the Fobes site, we were able to collect supplemental field data and calculate all metrics outlined in the Study Plan. The results of the Middle Entiat project, which is funded through Chelan County, are detailed in a separate report. Examination of the Countyline project, which was assessed before and 5 years after restoration (levee set back, large wood placement, side channel construction), showed increases in key floodplain, habitat, and habitat suitability metrics by 50 to several hundred percent, in some cases. For example, side channel metrics increased from 267% to 967% 5 years after restoration. Changes at the Tucannon PA-3 project, which was a wood placement project, were more modest, but we were still able to map and calculate all metrics and measure change before and after restoration. Based on data from these three sites as well as more detailed analysis on the Middle Entiat, the pilot study demonstrated that key monitoring metrics can be calculated at a finer resolution than field surveys using primarily remotely sensed data. Our analysis further demonstrates that, with a few minor modifications, the methods in the Study Plan are an appropriate, efficient, and cost-effective approach for monitoring changes before and after restoration for floodplain and riparian projects. The timing and quality of LiDAR acquisition are also important factors for calculating metrics.

There are a few metrics or methods that will continue to benefit from supplemental field data to validate estimates from remote sensing including bathymetry, large wood on the floodplain, riparian species, and instream fish-habitat classification. In addition, most pilot site projects had qualitative design criteria and we provide a suggested design matrix with specific design targets that would facilitate quantitative evaluation of engineering designs and help inform future projects. We provide the following recommendations based on the results of the pilot study:

- The quality and timing of green LiDAR collection are important for ensuring accuracy and consistency of metrics calculations before and after restoration.
- Supplemental bathymetric and fish-habitat field data collection will be needed at some sites due to depth, turbidity or large wood jams that may prevent accurate mapping of bathymetry with green LiDAR.
- The intensity of the riparian field survey proposed in the Study Plan can be reduced because some metrics can be mapped with LiDAR, but riparian field surveys are still needed for some riparian metrics.
- Large wood can be enumerated using remote sensing techniques, but mapping floodplain wood during riparian surveys should be used to correct remotely sensed wood counts.
- The collection of site-specific habitat preference data for key fish species and life stages could be used to improve HSI mapping at various flows.
- As-built surveys and evaluation of design criteria for each site would benefit from consistent design criteria and matrix across projects.
- In addition to standard reporting, a brief two page project report card should be developed for each project evaluated to quickly convey results and lessons learned to a broader audience.
- The methods in the Study Plan can be used on completed projects if appropriate data are available, but the pilot study demonstrated variability in data quality across project sponsors and years. Thus, ideally selection of new sites should focus on projects that are not yet implemented or will be implemented in 2023 or beyond to allow collection of data of consistent quality before and after restoration.
- Finally, while the methods are most efficient at large projects covering more than one or two kilometers, they could be used on smaller projects, though it may not be as efficient or cost-effective.

ACKNOWLEDGEMENTS

This study was made possible with funding from the Salmon Recovery Funding Board (SRFB) administered through the Washington Recreation and Conservation Office (RCO) (RCO Project 21-1328). Specifically, we thank Keith Dublanica (RCO) and the members of the SRFB Monitoring Panel including: Bob Bilby, Pete Bisson, Ken Currens, Leska Fore, Tracy Hillman, Stacy Polkowske, Jeanette Smith, and Micah Wait. We thank the project sponsors who provided us with data and site access including: Alex Lincoln (King County Department of Natural Resources and Parks), Chris Brummer (King County Department of Natural Resources and Parks), Alex Levell (Lummi Nation), Kris Buelow (Snake River Salmon Recover Board), and Kris Fischer (Confederated Tribes of the Umatilla Indian Reservation). Additionally, we thank Melinda Carr and Pryclynn Kubatka-Campbell (Cramer Fish Sciences) for assisting with field work, Tyler Rockhill (Cramer Fish Sciences) for assisting with field work and providing hydraulic modeling advice, and Meghan Camp (Cramer Fish Sciences) for reviewing and editing the document.

BACKGROUND

The Salmon Recovery Funding Board (SFRB) has invested more than 1 billion dollars in salmon recovery and habitat restoration efforts since 2000. While previous efforts to evaluate the efficacy of SRFB-funded habitat restoration actions have provided some useful information on the effectiveness of instream structures, large wood placement, and barrier removal, they have provided limited information on two of the most important and common habitat restoration actions—floodplain and riparian planting projects. Other monitoring programs and recently published studies have emphasized the need to evaluate large restoration projects that cover several kilometers of stream. Moreover, recent technological advances have made it possible to monitor large restoration projects efficiently using remote sensing. Cramer Fish Sciences (CFS) was contracted by the Recreation and Conservation Office (RCO) to work with the SRFB Monitoring Panel to develop a Study Plan to monitor and evaluate large floodplain and riparian projects using remote sensing techniques coupled with limited field data (Roni et al. 2020b). To achieve this, we first worked closely with the Monitoring Panel to refine the objectives and questions to be answered by the Study Plan. The Monitoring Panel determined that the Study Plan should focus on monitoring project-level physical and riparian response, produce results within 5 to 10 years, and should avoid implementation issues seen in some other regional monitoring programs. Monitoring questions to be answered by the study include:

1. What is the floodplain area in the reach before and after restoration and what is the extent and frequency of floodplain inundation at different flow levels over time?
2. Based on the underlying geomorphic processes and the outcomes expected at the site and reach, did the active channel zone change as predicted and did the project meet its geomorphic design objectives?
3. What is the effect of restoration on channel and floodplain morphology and complexity, seasonal and perennial side channel metrics (length, area, ratio), and the morphological quality index (MQI) in the reach, and how does it change over time?
4. What is the number and diversity of habitat types (i.e., pools, riffles, glides, etc.) within the main channel and side channels at different flows (low, bankfull) in the reach and how much do they change over time?
5. What is the abundance and distribution of large wood in the active channel, wetted channel, and on the floodplain within the reach and how do they change over time? What proportion of the wood is actively interacting with the channel?

6. Based on difference of digital elevation models (DEMs) of the reach before and after restoration, what is the areal extent and distribution of sediment erosion and deposition (storage) on the floodplain and how much do they change over time?
7. Based on modeled depths and velocities, what is the area of suitable habitat for juvenile (low, bankfull, flood flows) and spawning adult Chinook *Oncorhynchus tshawytscha*, steelhead *O. mykiss*, coho *O. kisutch*, or other target salmonid species and how has it changed before and after restoration?
8. What is the riparian vegetation areal extent by vegetation class (e.g., grasses, forbs, shrubs, trees, etc.), species composition, and density and how much do they change over time?
9. Has riparian/floodplain restoration led to restored riparian function including shade, bank stabilization, and organic matter following riparian restoration?

Given the challenges encountered by previous large habitat monitoring programs and the relatively new methods and analytical approaches proposed, the Study Plan recommended that a pilot study be conducted on a handful of sites. At the March 3, 2021 meeting, SRFB, a governing body within RCO, approved the investment of Pacific Coastal Salmon Recovery Funds for a pilot study to utilize remote sensing and other innovative survey techniques to assess the effectiveness of floodplain-scale and riparian restoration. This geographically limited model will serve as a "proof-of-concept," demonstrating the use of remote sensing of large river system reaches as a cost-effective alternative or supplement to traditional ground-based survey methods. If this pilot study is determined to be successful and satisfies the SRFB's needs, RCO may proceed with a larger, more comprehensive investigation of salmon habitat restoration effectiveness using remote sensing at other locations in Washington.

The Floodplain Scale Remote Sensing Pilot Project (Pilot Project) was initiated in August of 2021 to select sites and test the methods developed by CFS to evaluate large floodplain and riparian restoration projects (Roni et al. 2020; RCO Project 19-1757[1]). Initially, it was determined that two sites would be selected in western Washington and one site in eastern Washington to serve as a pilot study to test, refine, and confirm the feasibility of the approach and methods in the Study Plan (Roni et al. 2020b). The following report provides a summary of the results of the Pilot Project including site selection,

[1] Henceforth referred to as "the Study Plan."

analysis and collection of data, and recommendations for future monitoring. The pilot study focuses on using remote sensing techniques to evaluate physical conditions, riparian habitat, and fish habitat suitability and was not designed to evaluate fish population response to restoration.

SITE SELECTION

The selection of pilot sites was overseen by the RCO SRFB Monitoring Panel. The RCO and the Monitoring Panel worked with recovery boards and lead entities in Washington State to develop a list of large floodplain and riparian restoration projects to be considered for the pilot study. To be considered, projects had to focus on floodplain and riparian restoration, cover more than 1 km of main channel length, and have pre-project green LiDAR[2]. A list of potential sites was initially provided by the Monitoring Panel. We screened the initial list to determine suitable sites and then contacted restoration project sponsors to confirm details of the restoration, data available, timing, as well as site access. The Study Plan initially called for selecting new projects so consistent pre-project data could be collected. However, after discussion with the Monitoring Panel, it was determined that it would be worthwhile to include at least one completed project with pre- and post-restoration green LiDAR available to provide results sooner and demonstrate which metrics could be obtained from remote sensing alone.

Working closely with the Monitoring Panel, we selected two sites in western Washington: the Countyline Project on the White River in King County, and the Upper/Lower Fobes Project on the South Fork Nooksack River in Skagit County (Figure 1). The Countyline Project, completed in 2017, represents a completed project that has some pre-project data available, including green LiDAR, while Upper/Lower Fobes is a new project with the first construction phase completed in 2022 (Lower Fobes) and the second phase (Upper Fobes) planned for 2023 (Table 1).

In eastern Washington, the Middle Entiat Project was selected by the Monitoring Panel to serve as the pilot site for eastern Washington. The Middle Entiat Project represents a floodplain project completed in 2019 with pre-project monitoring data collected in 2018 using the same protocols as the Pilot Project[3]

[2] Green LiDAR is also referred to topo-bathymetric LiDAR as it maps both topography and the river bathymetry. In contrast, near-infrared LiDAR which only maps the topography and water surface.

[3] Pre-project monitoring in the Middle Entiat was conducted by CFS as an initial pilot study to test a variety of protocols for monitoring large floodplain projects.

(Table 1). The results of the Middle Entiat project, which is funded through Chelan County, are detailed in a separate report. A second completed eastern Washington site (Tucannon River PA-3) which had green LiDAR available before and after restoration as well as the needed hydraulic modeling outputs – was added in fall of 2022 when additional funding became available. The Tucannon PA-3 project was completed in 2017 with post-project data available in 2020 (Table 1).

Table 1. Summary of sites selected for the floodplain scale remote sensing pilot project. The results of the Middle Entiat project are reported in a separate report. LW = large wood. ELJ = engineered logjams

Project Details	Countyline – White River	Upper/Lower Fobes – South Fork Nooksack	Middle Entiat – Entiat River	PA-3 – Tucannon River
Approximate Length (km)	2.2	1.15/1.16 (Upper/Lower)	8.7	2.6
Year restored	2017	2022/2023	2019/2020	2014/2018
Restoration techniques	Levee removal/setback, LW, ELJs, riparian planting	LW, ELJs, riparian planting, pilot channels	Large wood, ELJs, constructed side channels, riparian planting	LW
Pre-project data collection	2011/2016 (LiDAR/ Bathymetry)	2017/2021 (LiDAR/ Bathymetry)	2018	2017
As-built data collection	NA	2022/2023	2019	NA
Post-project data collection	2022	TBD	2022	2020
Post-project monitoring trigger[4]	Time	Flow or time	Flow and time	Flow and time

[4] As described in the Study Plan, post project monitoring is triggered after either 1) a channel forming flow or 2) three or more years post-restoration has passed.

Figure 1. Map of the pilot study sites in western and eastern Washington. The Middle Entiat Project is being monitored under a contract with the Chelan County Department of Natural Resources and the findings are provided in a separate report.

METHODS

The Study Plan provides detailed information on the metrics and how each were calculated (Table 2, Table 3) We provide a summary here but refer the reader to (Roni et al. 2020b) for details. The Study Plan calls for a simple before-after design with data collection before restoration (ideally < 2 years before) and after restoration, with as-built surveys occurring the year restoration is completed to document design elements. The schedule for the pilot sites is provided in Table 1.

Table 2. List of monitoring questions and parameters or metrics to be measured or calculated to answer these questions for floodplain and riparian restoration sites. R = remote sensing, F = field data. From Roni et al. (2020b).

Question	Parameter/metric and data collection methods (R or F)
(1) What is the floodplain area before and after restoration and what is the extent and frequency of floodplain inundation at different flow levels over time?	Floodplain area (R, F), floodplain inundation index (R, F), area altered (R)
(2) Based on the underlying geomorphic processes and the outcomes expected at the site and reach, did the active channel zone (Beechie et al. 2017; Stefankiv et al. 2019) change as predicted and did the project meet its geomorphic design objectives?	Active channel zone, geomorphic unit tool (GUT) (R, F)
(3) What is the effect of restoration on channel and floodplain morphology and complexity (RCI [Brown 2002]), seasonal and perennial side channel metrics (length, area, ratio [Beechie et al. 2017]), and the morphological quality index (MQI [Rinaldi et al. 2013]) in the reach, and how does it change over time?	Side channel number, length, and area (R, F), pond/wetland number and area (R), sinuosity, bankfull width and depth, side channel ratio, RCI, MQI (R, F)
(4) What is the number and diversity of habitat types (i.e., pools, riffles, glides, etc.) within the main channel and side channels at different flows (low and bankfull) and how much do they change over time?	Shannon diversity index, habitat metrics (pool area, percentage,) (low flow R, bankfull R)
(5) What is the abundance and distribution of large wood in the active channel, wetted channel, and on the floodplain, and how do they change over time? What proportion of the wood is actively interacting with the channel?	Large wood (R)
(6) Based on difference of DEMs of the reach before and after restoration, what is the areal extent and distribution of sediment erosion and deposition (storage) on the floodplain and how much do they change over time?	Sediment deposition and storage, difference in DEM (R)
(7) Based on modeled depths and velocities, what is the area of suitable habitat for juvenile (low, bankfull, flood flows) and spawning adult Chinook *Oncorhynchus tshawytscha*, steelhead *O. mykiss*, coho *O. kisutch*, or other target salmonid species and how has it changed before and after restoration?	Amount of suitable habitat, weighted usable area (WUA based on habitat suitability index [HSI] model) (R, F)
(8) What is the riparian vegetation areal extent by vegetation class (e.g., grasses, forbs, shrubs, trees, etc.), species composition, and density and how much do they change over time?	Areal vegetation extent by class (R, F), riparian composition, richness, diversity, and density (R, F)
(9) Has riparian/floodplain restoration led to restored riparian function including shade, bank stabilization, and organic matter following riparian restoration?	Bank stability (F), shade (R, F), organic inputs (R), large wood (R)

Table 3. Floodplain and riparian metrics needed to answer monitoring questions, the flow or spatial extent at which each metric is calculated (LF = low flow wetted width, BF = bankfull width, FP = floodprone width, NA = not applicable), and a description of methods. All metrics except the light penetrating index and bankfull width to depth ratio are expected to increase following restoration. A decrease in the light penetrating index represents an increase in shade. Depending on the conditions before restoration, an increase or decrease in bankfull width to depth ratio could represent an improvement or degradation of channel conditions.

Metric	Flow/ Extent	Description
Floodplain geomorphology		
Floodplain area	FP	Floodprone area, which is determined using two times the average maximum bankfull depth.
Floodplain inundation index	FP	Floodprone area divided by the mainstem wetted centerline length.
Area altered		Delineate the project footprint from aerial imagery immediately after restoration. Use implementation documents as a guide as well.
Active channel zone[5]	BF	Delineate the active channel based on historical aerial imagery and LiDAR.
Pond/wetland number and area	LF	Delineate the isolated habitats at low flow using LiDAR and aerial imagery to count number and calculate total area.
Side channels		
Side channel number, length, area	LF, BF	Sum of the count, length, and area of all side channels at the wetted and bankfull flows.
Side channel nodes and node density	LF, BF	Count and density of junctions between side channels and the main channel or other side channels at bankfull (Stefankiv et al. 2019).
Side channel ratio	LF, BF	Ratio of the sum of the side channel lengths divided by the mainstem centerline length at bankfull (Beechie et al. 2017).
Channel morphology and instream habitat		
Sinuosity	LF	Divide the thalweg line length by the straight-line distance between the start and end points (i.e., top of site and bottom of site) of the thalweg (Rosgen 1994, 1996).
RCI (River complexity index)	BF	RCI = (S*(1 + J) / (reach length))*100, where S = sinuosity, J = # of side channel bankfull junctions, reach length = mainstem centerline length (Brown 2002).
Bankfull width to depth ratio	BF	For each bankfull transect, divide the bankfull width by the maximum bankfull depth and average this ratio across transects within a reach (Rosgen 1996).
MQI (Morphological quality index	NA	Extensive calculation using field data: confinement, sinuosity, anastomosing index, braiding index, mean bed slope, mean channel width, dominant bed sediment, and others (Rinaldi et al. 2013; Rinaldi et al. 2017).
Pool area and percentage	LF	Sum of pool habitat area, total pool area divided by total wetted area.
Residual pool depth	LF	Maximum pool depth minus the pool tail crest in pool habitats, averaged across a reach for pools that the thalweg runs through (Lisle 1987).
Shannon diversity index of habitat units	LF	Shannon diversity index (H) of the channel units in the mainstem and side channels with habitat units delineated (Shannon 1948).
Habitat Suitability Index (HSI)	LF	Sum of weighted usable area (WUA) and normalized WUA by species and life stage based on hydraulic and HSI modeling.

[5] This is similar to the channel migration zone, but there is not widespread agreement on delineating the CMZ and for this reason NOAA status and trends and other programs are monitoring the active channel zone rather than the CMZ (Beechie et al. 2017; Hall et al. 2019; Stefankiv et al. 2019).

Braiding parameter	BF	Sum of all channel lengths (mainstem and side channels) divided by the mainstem length (Friend and Sinha 1993).
Large wood and sediment storage		
Large wood	NA	Count of jams and individual pieces from aerial imagery or LiDAR (Roni et al. 2020a, Jarron et al. 2021; Kuiper et al 2022).
Sediment deposition and storage	NA	Create a DEM of Difference (DoD) for the years of interest and calculate the areas of deposition and storage.
Riparian		
Riparian, richness, density, diversity	NA	Richness – count of unique species across all transects. Density – count of individual species across all transects, divided by the aggregated area of all transects. Diversity – Shannon's diversity index using species abundance data (Shannon 1948).
Areal extent of riparian vegetation	NA	Ratio of LiDAR returns in different height bands representing vegetation classes to ground points multiplied by the cell area (Akay et al. 2012).
Bank stability	NA	Measure of length of eroding bank
Light penetration index	LF	Ratio of LiDAR ground returns to total returns. Can be interpreted as an indicator of riparian shade potential (Bode et al. 2014).
Organic inputs	LF	Volume of canopy that overhangs the active channel (Laslier et al. 2019).

Floodplain metrics: geomorphology, habitat, large wood, and sediment

To quantify changes in geomorphology, habitat, large wood, and sediment at each site, we used a combination of existing pre-project data and remote sensing techniques. Although the general methodology for our analysis was largely consistent across sites, idiosyncrasies in the available pre- and post-project data, project designs, or geographic contexts (e.g., heavily urbanized versus minimally disturbed watersheds) necessitated modification in some cases. Site-specific methodological details are discussed in greater detail under the individual site subheadings.

We used standard open-source geoprocessing tools implemented within geographic information systems software (QGIS Development Team 2022) to quantify changes in floodplain geomorphology. Floodplain physical metrics (Table 3) were largely obtained from bare earth DEMs. Digital elevation models for all sites were generated from LiDAR point clouds and/or supplemental bathymetric survey data and were provided by project sponsors. The bare earth DEMs were used as inputs into hydraulic models run at predetermined flows representing a low flow and a 2-year flood recurrence interval. A 2-year flood recurrence interval was used because it typically constitutes a "bankfull" flow (Williams 1978; Leopold 1994; Castro and Jackson 2001). In some cases (e.g., Fobes and Countyline), supplemental bathymetric surveys were available and combined with the LiDAR point cloud data to map the channel bed topography more accurately. Where possible, we relied on project sponsors to provide hydraulic model outputs at specified flows. Countyline did not have pre-project model outputs readily available; therefore, we developed our own hydraulic model (for details, see Hydraulic Modeling and Habitat Suitability Index Calculation). The resulting depth, velocity, and water surface extent rasters served as the foundations from which channel and floodplain geomorphological characteristics could be digitized and measured. In addition, we calculated the MQI score for each site, a high-level indicator of geomorphic functionality, artificiality, and channel adjustments (Rinaldi et al. 2013).

Instream habitat and large wood data from field surveys were supplied by some project sponsors and, where appropriate, we provide these along with our estimates from remote sensing. For projects where the habitat surveys were not available or available data were not compatible with our methods, we developed a habitat classification method using a series of algorithms to estimate meso-habitat units (pools, riffles, and glides) from the thalweg elevation profile alone. Our habitat classification methodology uses a three-step process that first identifies pools by interpolating points between troughs in the thalweg profile meeting a minimum residual pool depth criterion. The remaining sections are then broken into segments of consistent gradient and used as inputs to a random forest model to predict the riffles from glides. We used data from extensive habitat and long-profile data on more than 100 sites across 60 wadable streams in the Columbia Basin to develop and train the random forest model (Clark et al. 2019, 2020). Thalweg long profiles were extracted from the DEMs by running a flow accumulation algorithm and identifying the longest continuous flowlines within both the main channel and in the side channel. We are currently preparing formal descriptions and a critical evaluation of the habitat classification methodology with the intent to publish our results. Off channel and backwater habitats were also classified based on connection to mainstem and low water velocity. In addition, we also mapped and quantified finer-scale geomorphic units (Tier 3) using the geomorphic unit tool (GUT), which uses different a theoretical approach to classify geomorphic units based on 2-D topography (Bangen et al. 2017).

We estimated large wood abundance directly from the LiDAR point clouds. We used height-filtering criteria to remove the canopy, low shrubs, and grasses (Joyce et al. 2019; Jarron et al. 2021). We then filtered for only those points with intensity values in the 70th percentile or higher (Kuiper et al. 2022). Large wood is typically identifiable in a LiDAR point cloud as high-intensity linear segments (Figure 2). These linear segments can be extracted in vector format using linear feature extraction algorithms provided in the ‘lidR’ package (Roussel et al. 2020). To further separate true large features from small branches and artifacts in the LiDAR, we discarded linear features less than 3 m long. Large wood within the low flow, bankfull, and floodprone areas were summed and the number of large wood pieces per 100 m calculated. Jams were counted from aerial imagery within the visible portion of the active channel.

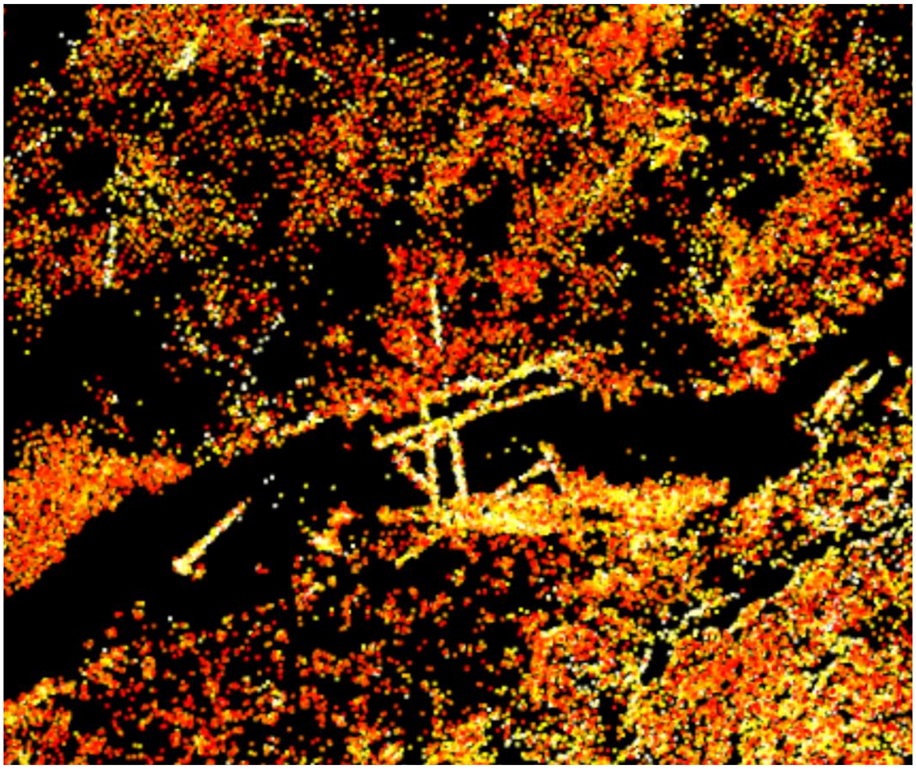


Figure 2. Example of a height filtered point cloud (0.3 m ≤ Z ≤ 1 m) from Tucannon PA-3 in 2017, colored by intensity. Large wood is identifiable as high intensity (brighter colors) linear segments.

Changes in sediment deposition and storage were evaluated by calculating the DEM of differences for each project site where before and after data were available. Areas of sediment aggradation and degradation can be mapped and quantified simply by subtracting the DEMs and identifying negative and positive changes in elevation. We defined areas of sediment aggradation/degradation based on a minimum elevation change threshold of ±0.5 m.

Methods for the calculation of each metric are listed in Table 3 and described in more detail in the original study proposal (Roni et al. 2020b) and in their respective citations. We also calculated side channel node density and the braiding parameter, which were not in the original Study Plan, but being used by project sponsors at Countyline and the Tucannon for other projects. Side channel node density is the sum of junctions between side channels, the main channel, and other side channels, divided by the site length (Stefankiv et al. 2019). Side channel node density is calculated at bankfull, unless indicated otherwise. The braiding parameter (BP) is a measure of channel complexity and is calculated as $BP = \frac{L_t}{L_m}$, where L_t is the sum of the lengths of all channels (mainstem and side channels) and L_m is the length of the mainstem (Friend and Sinha 1993). The braiding parameter has a range from 1 to ∞, such that a braiding parameter of 1 describes a single thread channel. The braiding parameter is also calculated at bankfull, unless indicated otherwise.

Hydraulic modeling and habitat suitability index

Hydraulic modeling

Depth and velocity rasters from hydraulic models built for each project site provided the basis for floodplain metric calculations and habitat suitability index modeling. We used low flow and bankfull flow (approximately a 2-year flood recurrence interval) modeled depth and velocity rasters provided by project sponsors or from our hydraulic model (Countyline). Site-specific flow conditions used to represent low flow and approximate bankfull conditions are presented in Table 4.

Table 4. Flow conditions used to generate depth and velocity from a hydraulic model for each site.

Flow (cfs)	White River – Countyline	South Fork Nooksack – Upper/Lower Fobes	Tucannon – PA-3
Low flow	500	250	45
2-year flow	6,907	10,332	738

Habitat suitability index

We modeled habitat suitability using depth and velocity preference curves for spawning and juvenile Chinook salmon and juvenile steelhead at all project sites. Habitat suitability index (HSI) values for depth and velocity were combined using the geometric mean to calculate a final HSI value. Exact HSI values vary slightly depending on the specific depth and velocity preference curves used. We used depth and velocity preference curves for Pacific Northwest streams presented in Maret et al. (2006) for juvenile Chinook, Kurko (1977) for spawning Chinook, and in Raleigh et al. (1984) for juvenile steelhead. Habitat suitability index values range from 0 (unsuitable) to 1 (most suitable). For each HSI raster, we calculated weighted usable area (WUA), WUA > 0.5, the geometric mean HSI value (equivalent to the normalized WUA), and the 50th and 90th percentile values. Methodological details for HSI calculations can be found in the Study Plan (Roni et al. 2020b).

Riparian metrics

Calculation of riparian monitoring metrics for all project sites required access to the raw LiDAR point cloud data, which were provided by project sponsors. The LiDAR point clouds were height normalized and clipped to the project study areas prior to any calculations. To ensure consistency in the riparian metric calculations across projects, we also reclassified the ground points using the cloth simulation filter algorithm (Zhang et al. 2016). Details for each of the riparian metrics we calculated (areal extent of vegetation by class, volume of overhanging canopy, and shade) are described individually in the following sections. Processing of the LiDAR point clouds and riparian metric calculations were performed in R using the 'lidR' package (R Core Team 2020; Roussel et al. 2020).

Areal extent of riparian vegetation by height class

We based our methods for calculating the areal extent of vegetation by class on methods described in Akay et al. (2012). LiDAR first returns that were not already classified as ground points within height ranges of interest were filtered and used to coarsely represent vegetation classes—less than 1 m for grasses and shrubs, between 1 and 5 m for mid-story vegetation, and greater than 5 m for trees. We then compared the number of points in each range of interest to the total number of points within grid cells of a predetermined size over the entire study area to obtain the proportion of each cell covered by vegetation in each respective height class. Finally, we computed the area of all cells weighted by the proportion of vegetation coverage to obtain the areal extent of vegetation by height class.

Volume of overhanging canopy (organic inputs)

Volume of overhanging canopy was calculated from a canopy height model, following the examples in Laslier et al. (2019). We segmented individual tree crowns using the Silva et al. (2016) segmentation algorithm. We then created convex hulls from the segmented LiDAR point cloud to obtain a 2D overhead representation of the canopy and calculated the area of the individual tree crowns. Volume of canopy overhanging the channel was then estimated by multiplying tree area by height and taking the intersection of the overhead canopy polygon with the channel boundary such that only trees directly overhanging the wetted channel were included in the calculation.

Shade

We calculated the light penetration index (LPI) as a proxy for riparian shade. Commonly used to quantify canopy openness in forestry applications, LPI can be interpreted as an index of the probability that a random ray of sunlight will penetrate to the forest floor in a given area (Bode et al. 2014). We computed LPI by comparing the number of first returns that were classified as ground points to the total number of points returned within grid cells of a pre-determined size over the entire study area. We took the resulting raster surface, clipped it to the wetted extent, and calculated the mean LPI such that final calculation reflects only the shaded cells within the wetted channel extent. Because the LPI measures light penetration, the lower the value the higher riparian shade.

Project specifics

The same general methods described in the preceding sections were applied to the analysis of all sites. However, specific details for each project analysis varied depending on data quality and availability. Therefore, we report project specific details here.

White River – Countyline

The White River and its tributaries provide important habitat for several species of Pacific salmonids, including Endangered Species Act (ESA) listed native spring run Chinook salmon. The heavily modified White River at Countyline, running through the city of Pacific, WA, experiences significant sedimentation, leading to reduced channel capacity and increased flood risk to nearby properties and infrastructure. The Countyline project, completed in fall 2017, was a levee setback and floodplain reconnection project (2.19 km stream length) designed to improve channel capacity, reduce future flood risk, and create new side and off-channel habitat to benefit native salmon (Figure 3).

King County, the project sponsor, provided a pre-project 1 m resolution DEM (2011) merged with a bathymetric survey (2016), which we used as the pre-project surface for hydraulic modeling. Post-project green LiDAR was collected in April 2022 using dual Riegl sensors in the green and near-infrared wavelengths at an average pulse density of 12 pulses/m^2 (NV5 2022). Preliminary inspection of the LiDAR suggested poor penetration to the riverbed in some areas. To fill gaps in the LiDAR, we conducted a supplemental bathymetric field survey in fall 2022. Field survey data were then merged with the LiDAR and reprocessed with the cloth simulation filter algorithm (Zhang et al. 2016) to produce new ground points. The reprocessed ground points were then used to create a new 1 m resolution DEM.

Habitat surveys provided by King County focused on edge habitat and did not cover the entire project area. Therefore, we used the habitat classification method to map and quantify instream fish-habitat units. We enumerated large wood abundance using the LiDAR data and the method described in the preceding section. King County surveyed large wood at Countyline in 2017 with a field survey supplemented with counts from digital ortho-imagery collected during leaf-off. However, King County was not able to conduct a large wood survey and ortho-imagery collection in 2022 because of sustained high-flows. Therefore, we estimated large wood for both the pre-project and post-project LiDAR years using the LiDAR point cloud filtering method.

Figure 3. Pre- (2011) and post-project (2022) aerial imagery of the Countyline project reach.

Hydraulic modeling

Depth and velocity rasters were not available for Countyline; therefore, we constructed a hydraulic model using HEC-RAS (v 6.0.0). We built a 2-D unsteady flow model using St. Venant shallow-water equations to simulate surface flow. The model uses triangular mesh computational surfaces generated from the pre- and post-project DEMs. The pre-project mesh contains 413,221 cells, ranging in size from 2 ft^2 to 4,922 ft^2. Likewise, the post-project computational mesh was comprised of 375,834 cells, again ranging from 2 ft^2 to 4,922 ft^2. The modeled boundary conditions and Manning's n roughness values were the same as reported in the original project assessment and hydraulic modeling report (Herrera Environmental Consultants Inc. 2012).

The original 2-year flow used in the Countyline restoration design documents and hydraulic assessment was 9,692 cfs (Herrera Environmental Consultants Inc. 2012, 2021). Preliminary evaluation of the project site and hydraulic model outputs indicated that the 2-year flow of 9,692 cfs would inundate nearly the entire project area and was incongruous with the calculation of floodplain metrics. In addition, flow at this site is regulated at Mud Mountain Dam, and the levee to the east and flood protection barriers to the west artificially confine the river. Therefore, in consultation with the project sponsor, we conducted a flood frequency analysis and computed an updated 2-year flow (6,907 cfs) based on gage data at the R Street bridge, which we then used to calculate bankfull metrics (Rockhill et al. 2022). Although the updated 2-year flow was 40% less than the flow reported in the project design reports, the hydraulic model output still showed nearly the entire floodplain between the levee and the flood protection barriers along the project reach. Therefore, we calculated most metrics at low flow for the Countyline site, including side channel metrics and river complexity index.

Supplemental bathymetric survey and post-project LiDAR concerns

Initial inspection of the post-project LiDAR at Countyline (collected in April 2022) had indicated good penetration in all except for a few relatively deep areas, mostly in the mainstem and in the excavated side channel (Figure 4). We conducted a supplemental bathymetric survey in September and October of 2022 to fill in the voids in the LiDAR. However, upon combining our bathymetric survey data with the LiDAR data, it was evident that the 2022 LiDAR had failed to penetrate to the river bottom over a much larger portion of the channel than indicated in the LiDAR report (NV5 2022). Although the White River is actively aggrading, the elevation difference between the pre-project and the post-project bathymetry (~ 1-1.5 m) in some places suggested measurement error in the post-project LiDAR. Unfortunately, we were unable to resurvey the bathymetry for the entire project reach given time and budget constraints. Consequently, some of the post-project monitoring metrics such as aggradation and degradation and residual pool depth for Countyline were affected and should be interpreted accordingly.

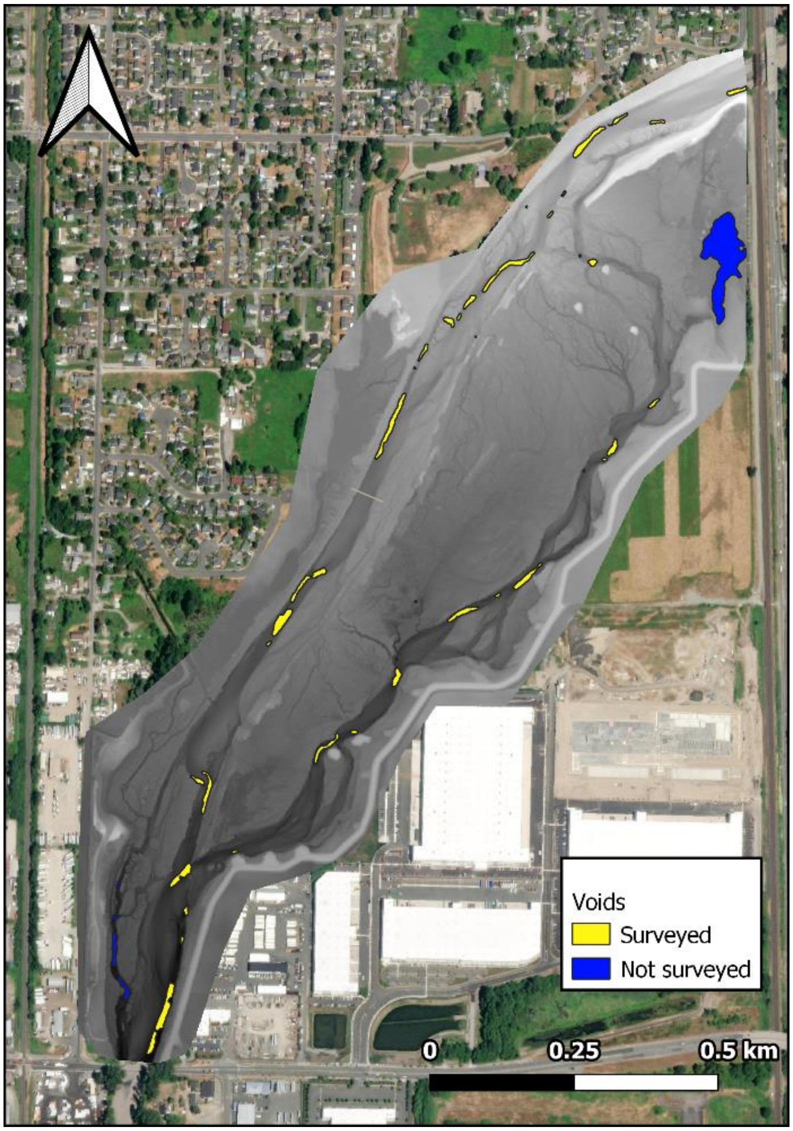


Figure 4. Preliminary DEM for the Countyline project created from the 2022 LiDAR with voids outlined.

South Fork Nooksack River – Upper/Lower Fobes

The Upper/Lower Fobes salmon habitat restoration project covers 2.31 km of the South Fork Nooksack. Commercial forestry is a major presence in the watershed and dominates local land use (Figure 5). Legacy timber harvest and road construction impacts have impaired habitat-forming processes, leading to degraded habitat conditions for threatened salmonids (Brown and Maudlin 2007). Restoration began at Lower Fobes 2022 and will continue at Upper Fobes in 2023. The project includes installation of 36 engineered logjams (ELJs), three channel-spanning ELJs, and 11 acres of riparian planting designed to restore geomorphic and habitat-forming processes (Washington State Recreation and Conservation Office 2022). The project goal is to restore early Chinook salmon spawning, holding, and rearing habitat in the South Fork Nooksack and promote self-sustaining Chinook salmon runs at harvestable levels

(Washington State Recreation and Conservation Office 2022). Post-project data collection is not anticipated until adequate high flows occur or time (3 years) passes (bankfull or higher flow event of at least 24 hours or 2026).

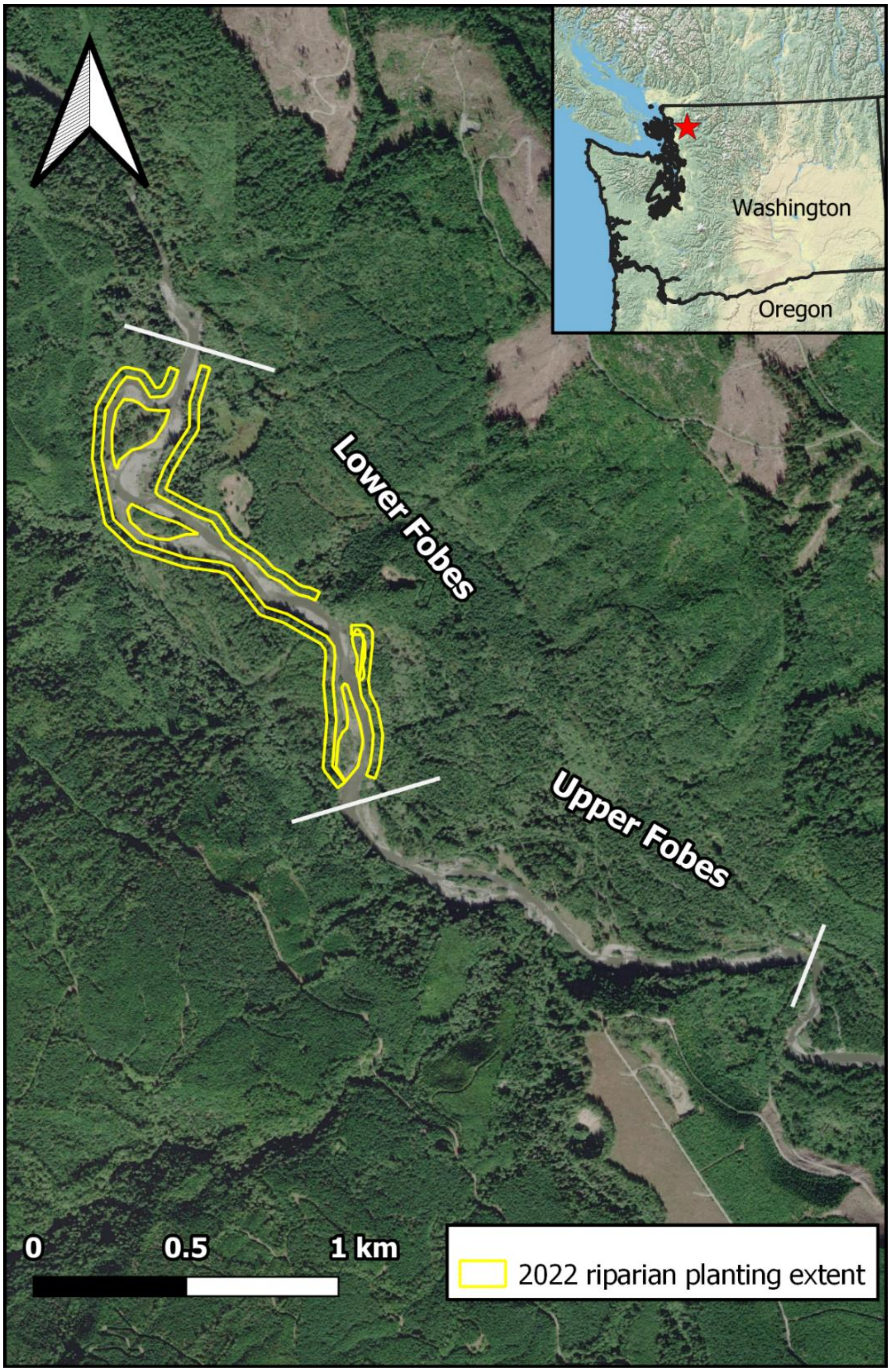


Figure 5. The Upper and Lower Fobes project reach boundaries (white lines) on the South Fork Nooksack River and areas planted in 2022Project construction at Lower Fobes was completed in 2022 and will continue at Upper Fobes in 2023.

Pre-project LiDAR was collected in 2017, followed by a supplemental bathymetric survey in 2021, which were composited and used to generate a 1 m resolution DEM, provided by the project sponsor (Lummi Nation). In addition, the Lummi Nation provided an instream habitat survey which was conducted in 2021 using methods consistent with our Study Plan (Pleus et al. 1999). Thus, we used the Lummi habitat data to map and quantify instream habitat metrics (Brown and Maudlin 2007). Large wood abundance was estimated using the LiDAR point cloud filtering method described in the preceding sections.

As only pre-project data has been collected at Upper/Lower Fobes thus far, no sediment change analysis was conducted (DEM of difference). However, we created a detrended DEM from the pre-project (2017) surface, which we display in the results section to provide a qualitative benchmark of the pre-project geomorphology. Detrending a DEM removes the downstream decreasing elevation trend from the model, accentuating finer details on the bare earth surface.

Upper/Lower Fobes as-built survey

An as-built survey was conducted shortly after construction of Upper Fobes to update the pre-project DEM and support evaluation of the effectiveness of key design elements over time. The as-built survey was conducted jointly by the Lummi Nation, Natural Systems Design (NSD), and CFS in August 2022. Topographic data was collected in the field using real-time kinematic (RTK) positioning on and around installed structures and on modified or disturbed terrain. In addition, Lummi Nation and NSD collected drone imagery of the project site and provided a digital surface model (DSM) created with structure from motion. Elevations from the DSM were used to supplement the RTK survey points. For each project design element, a triangular irregular network was interpolated from the RTK points and sampled elevations from the DSM, which were mosaicked (digitally stitched together) with the pre-project DEM to create a continuous surface representing the as-built topo-bathymetry (Figure 6).

Information on pieces of wood, structure height above streambed, anchoring, piles, percent buried, percent above streambed, percent above bankfull, and small wood filler was collected for all wood structures (Table 5). Each structure was also photographed from multiple angles and the characteristics listed in Table 5 were recorded.

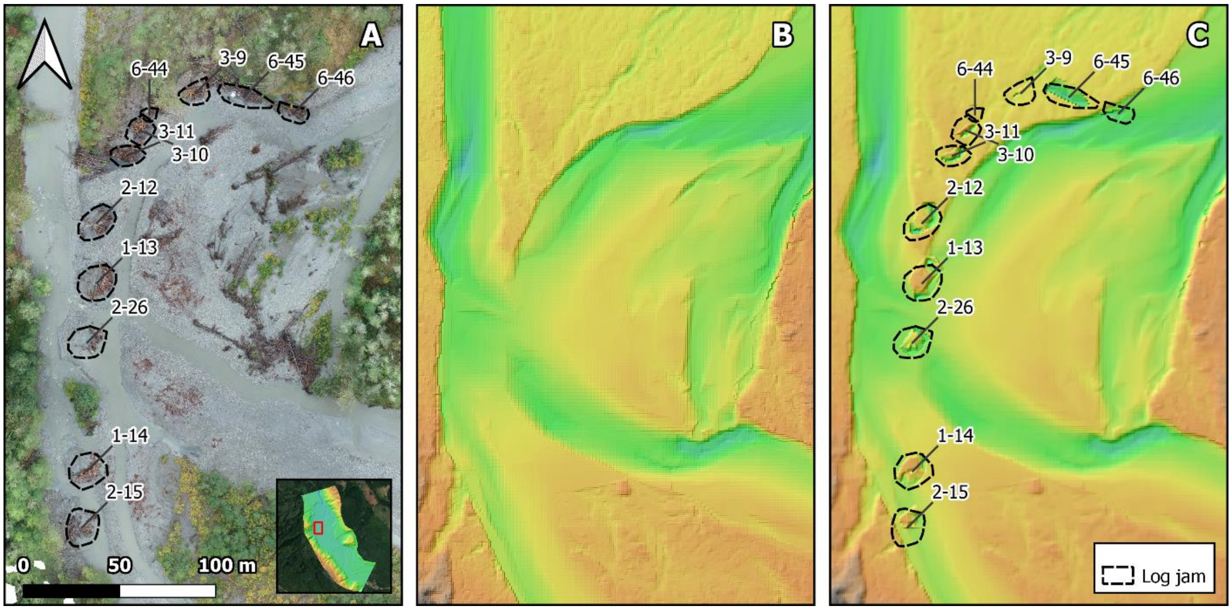


Figure 6. Example displaying how constructed log jams (A) were mosaicked with the pre-project LiDAR surface (B) to create an as-built DEM with project design elements included (C).

Table 5. As-built data collected at large wood structures at Upper Fobes. Similar data will need to be collected at Lower Fobes when construction is completed in 2023.

Characteristic	Definition
Large wood count	Number of qualifying pieces within structure as-built (40 cm diameter by 6 m).
Small wood filler used?	Was small wood/slash (does not qualify as large wood) used to fill in structure (e.g., racking)?
Structure height above streambed	Height of the structure above the streambed. Measurements are taken at the height of the bulk or majority of the structure material (not max height).
Anchoring mechanisms	Mechanisms used to anchor the wood or structure in place (e.g., pins, bolts, rock collar, cable, etc.).
Number of piles	Number of wood piles used to anchor wood and structure in place.
Percent buried	Percent of the whole structure that was buried into the streambed or channel margins (imagine looking at the structure from an aerial view, rough estimate).
Proportion of structure in contact with streambed	Percent of all structure materials in direct contact with the streambed, excluding piles. (e.g., logs directly on the channel substrate).
Proportion of structure below bankfull	Percent of the whole structure that is located below bankfull elevation (e.g., the ordinary high-water mark) (the full volume of the structure, look for visible bankfull cues).
GPS location	Latitude, longitude, elevation, and accuracy at structure location.

Riparian field survey

The purpose of the riparian field survey was to evaluate the pre-restoration riparian condition at the Upper/Lower Fobes reach on the South Fork Nooksack River. Specifically, our goals were to provide validation data for remotely sensed metrics and to characterize riparian metrics that cannot be derived from the remote sensing, including species richness and diversity, and understory cover and composition. Additionally, we aimed to test methods that could be used in post-project monitoring to evaluate change over time.

Surveys at the Upper/Lower Fobes reach were performed prior to construction, beginning at Lower Fobes, on July 7th and 25th 2022 and were completed at Upper Fobes on July 25th and August 17th. The Lummi Nation indicated planting would occur within a 30-m buffer of the active channel, so we targeted our surveys within that extent.

Site layout

We delineated 22 2-m wide transects, equally spaced at 200-m intervals throughout the Upper/Lower Fobes site (Figure 7; Merrit et al. 2017). Transects were placed at a 90-degree angle to the stream, measured using a compass at the active channel, and extended from the active channel to the edge of the planting project boundary, resulting in a minimum transect length of 17 m and maximum length of 130 m. We originally selected 30 m as the minimum transect length to cover the planting buffer width, provide adequate data to validate the LiDAR, and to be consistent with the forest practices riparian management zone buffer widths (Bigley and Deisenhofer 2006; Sweeney and Newbold 2014). However, at six transects we encountered side and tributary channels or changes in valley elevation before reaching 30 m from the active channel and those transects were terminated at that point. Additionally, transects were extended beyond 30 m if the transect angle was such that the planting boundary was not reached in the 30 m length.

For each belt transect, a tape was strung down the middle allowing delineation of a 1 m wide sampling area on either side of the tape. We originally planned to record transect coordinates using an RTK GPS, but dense canopy cover over most transects limited the accuracy of the RTK. Therefore, we used a Bad Elf GPS which provided sufficient accuracy (up to 1 m under open canopy, but typically between 3 and 5 m; Runkle 2016). We recorded the GPS coordinates of the transect start location at the active channel, the transect bearing, and the transect length in meters. Additionally, rebar benchmarks or flagging were placed at the start of transects to assist with relocation and sampling in subsequent sample years.

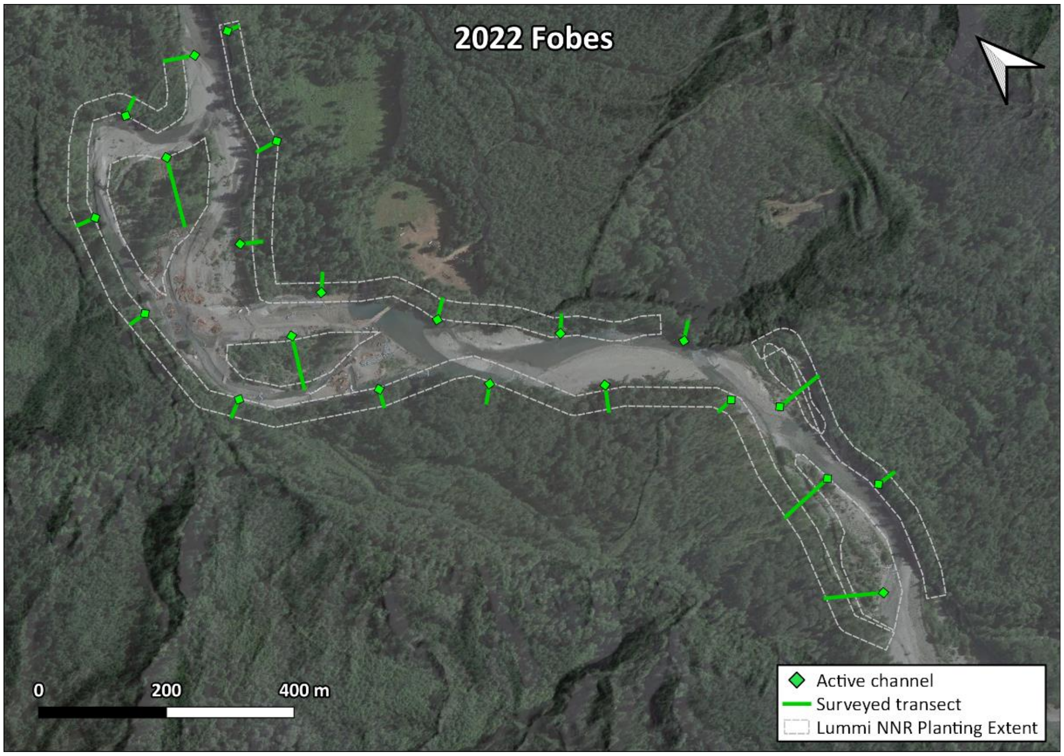


Figure 7. Site layout for the riparian field surveys at Upper/Lower Fobes. Transects were spaced 200 meters apart perpendicular to flow, started at the edge of the active channel, and extended 30 m into the riparian treatment zone (plantings).

Vegetation surveys

At each transect, all woody shrubs and trees were counted and identified to species, except willows and roses, which were identified to genus (*Salix* spp. and *Rosa* spp., respectively). We measured the height class of the first ten woody plants encountered followed by every 20th; heights for all others were visually estimated. Height classes were binned as low (<1 m), mid-story (1–5 m), and canopy (>5 m) (Harris 2005). Additionally, the location of each woody plant along the transect was recorded if it was within the first meter of the transect and then within 3 m interval bins for the remaining transect length (e.g., 0–1 m, 1–3 m, 3–6 m, etc.). Surveys were intended to capture the pre-restoration condition; however, some restoration and planting had occurred at the site in 2010; therefore, if we encountered a planted woody species, identified by the presence of planting markers (e.g., planting tube, fence, tarp, tree marker), we recorded the type of marker present, the height, the location along the transect, and whether the planting was living or dead. Additionally, these methods could be utilized post-restoration to identify species present as the result of planting. If patchy and clumped vegetation in the 0-1 or 1-5 m height class was difficult to enumerate, such as Himalayan blackberry *Rubus armeniacus*, salmonberry *R. spectabilis*, and common snowberry *Symphoricarpos albus*, we recorded the continuous length of transect covered and estimated the number of individuals within the first meter to estimate total abundance (Harris 2005). Due to the complexities in identifying forbs and grasses, they were assigned to a single category (forbs and grasses), and the continuous length they occupied along the transect was recorded.

Vegetation cover was also assessed in the three different height classes (low vegetation (<1 m), mid-story vegetation (1–5 m), and canopy (>5 m)) following the line-intercept method (Elzinga et al. 2001; Merrit et al. 2017). The length of the transect centerline that was covered by each height class was measured by recording the point along the tape where the woody plant cover of a given height class began and ended. Native and invasive cover were recorded separately. The length of the centerline with no cover, by either woody or forb and grass vegetation, was also recorded as bare earth cover.

While riparian shade was calculated from remote sensing, some field data was useful to validate these estimates. Therefore, canopy cover (i.e., shading) was measured using a convex spherical densiometer. The densiometer was taped so there was a “V” at the bottom with 17 grid intersections visible (Mulvey et al. 1992). Densiometer readings were collected at the wetted edge of a stream and at the active channel boundary. At these locations, four readings were recorded, facing downstream, upstream, toward the center of the channel, and away from the main channel. The densiometer was held level 1 m above the water surface. The number of grid intersections covered by a tree, leaf, branch, or other vegetative shade providing feature was recorded (0–17).

Tucannon River – Project Area 3

The upper Tucannon River provides spawning and rearing habitat for federally listed salmonids, including Snake River summer steelhead, spring and fall Chinook, and bull trout *Salvelinus confluentus*. The Confederated Tribes of the Umatilla Indian Reservation (CTUIR) leads a habitat restoration program in the Tucannon River watershed intended to improve instream habitat and floodplain connectivity, primarily through large woody debris supplementation and side channel excavation (Tetra Tech 2014). Restoration at Tucannon PA-3 began in 2014 with the construction of 42 large wood structures over approximately 2 km of stream (PA-3.2; Figure 8). Rapid habitat survey results for the 2014-2018 monitoring period showed >900% increase in large wood volume, 89% increase in pool frequency, 162% increase in pool area, and 44% increase in side channels (Foltz and Buelow 2018). Adaptive management action was recommended in 2017 to maintain and improve stream conditions. Tucannon PA-3.2 was retreated with wood in 2018, including an additional area 0.6 km upstream (PA-3.1; Figure 8). In spring 2020, the Tucannon River experienced a greater than approximately 25-year flow (U. S. Geological Survey 2016), qualifying this site for inclusion in this study under our flow -

based criteria (Roni et al. 2020b). Our analysis focuses on measuring changes in floodplain and riparian metrics between 2017 and 2020 as a result of the 2018 restoration work. Unfortunately, LiDAR and hydraulic modeling data were not available prior to 2017 to examine changed due to the original treatment in 2014.

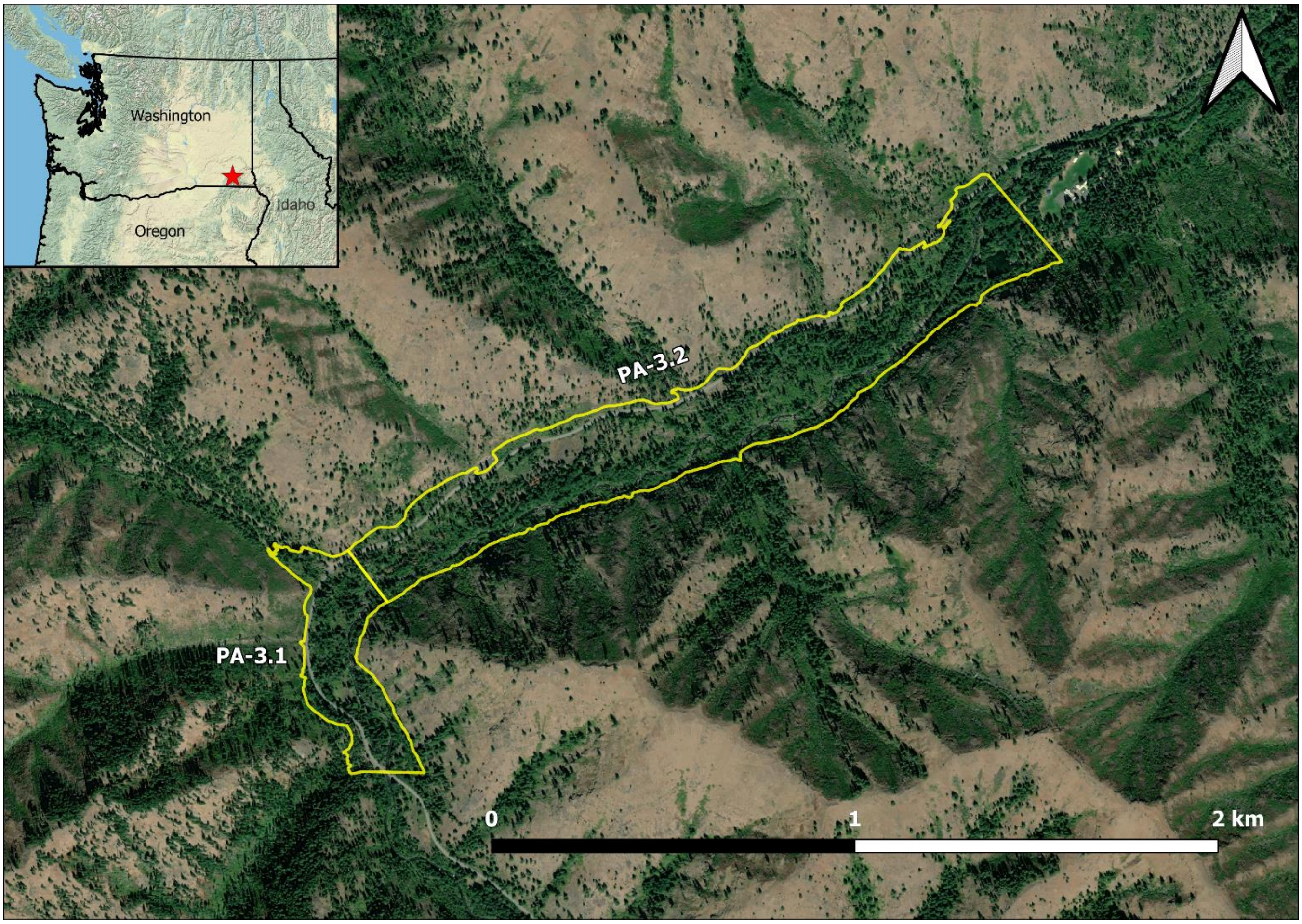


Figure 8. Tucannon PA-3 project boundary including sub-project areas PA-3.1 and 3.2.

Topo-bathymetric LiDAR was collected from a fixed-wing aircraft using a Riegl VQ-880-G laser scanner at an average density of 12 pts/m^2 in 2017 and again at 8 pts/m^2 in November 2020 following a 25-year flood event which occurred in the spring of 2020 (QSI 2018; NV5 2021). The project sponsor provided the raw LiDAR point cloud, which we used to generate 0.5 m resolution DEMs.

Large wood and pool survey data were provided by the project sponsor. Pre-project large wood and pool surveys were conducted in 2014 and 2018, and a post-project survey was conducted in 2020. However, the pool habitat surveys conducted by the project sponsor did not include all pool metrics originally included in the Study Plan; therefore, we also classified and characterized pools using previously described habitat classification method we developed. We present project sponsor large wood survey estimates alongside LiDAR derived estimates.

RESULTS

Results for each of the three project sites are presented separately.

Countyline

Geomorphology and habitat

The floodplain area and floodplain inundation index at Countyline increased by 16% and 14%, respectively (Table 6). The area altered (calculated at low flow) was 17.79 ha. Hydraulic modeling shows that the 2-year flow (6,907 cfs) would almost completely inundate the floodplain between the left bank levee and the right bank flood protection barriers (Figure 9).

Table 6. Summary of floodplain area and floodplain inundation metrics for Countyline.

Metric	Pre-project	Post-project	Percent Change
Question 1: What is the floodplain area before and after restoration and what is the extent and frequency of floodplain inundation at different flow levels over time?			
Floodplain area (ha)	58	67	+16%
Floodplain to bankfull area ratio	1.45	1.27	-12%
Floodplain inundation index	0.26	0.31	+14%

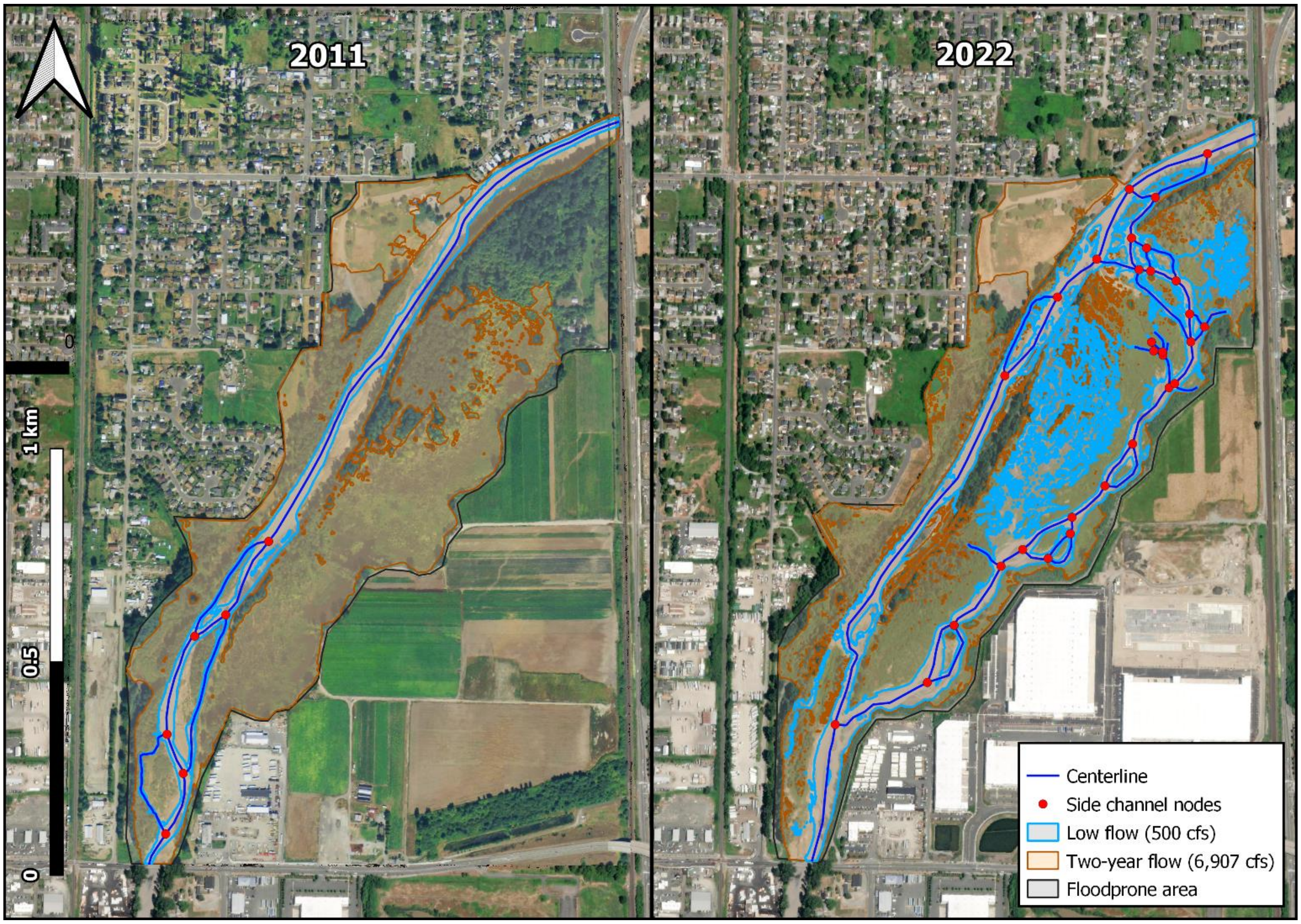


Figure 9. Comparison of the water surface extents at low flow and a 2-year flow at Countyline in 2011 and 2022. Side channel nodes are the junctions between the main channel and each side channel entrance. Base maps are 2011 (pre-project) and 2021 (post-project) NAIP imagery.

Fourteen out of fifteen metrics relating to the effect of restoration on channel and floodplain morphology increased between 2011 and 2022 (Table 7). Side channel metrics (e.g., length, area, ratio, node density, RCI) increased by 267 to 967%. The MQI, a multi-metric index of overall quality, showed moderate improvement (25%), in part because the site is constrained by setback levees. Depths in the main channel of the White River at Countyline decreased (Figure 10); however, it was evident that the LiDAR in 2022 likely did not penetrate through to the mainstem river bottom over much of the project area. Therefore, metrics relying on accurate estimates of channel depth, namely the bankfull width to depth ratio, residual pool depth, and sediment aggradation/degradation are probably biased.

Table 7. Summary of channel and floodplain morphology metrics for Countyline.

Metric	Pre-project	Post-project	Percent Change
Question 3: What is the effect of restoration on channel and floodplain morphology and complexity (RCI [Brown 2002]), seasonal and perennial side channel metrics (length, area, ratio [Beechie et al. 2017]), and the morphological quality index (MQI [Rinaldi et al. 2013]) in the reach, and how does it change over time?			
Sinuosity	1.53	1.51	-1%
Wetted area (ha)	7	23	+228%
Wetted width (m)	23.15	54.24	+134%
Bankfull area (ha)	58	71	+22%
Bankfull width (m)	281	341	+22%
Bankfull width to depth ratio	111.91	134.50[6]	+20%
Wetted side channel count	3	11	+267%
Wetted side channel nodes (density)	6 (2.74)	30 (13.70)	+400%
Wetted side channel length (km)	0.98	4.03	+311%
Wetted side channel area (ha)	0.70	7.63	+967%
Side channel ratio	0.45	1.89	+324%
Isolated ponds/wetlands	2	7	+250%
River Complexity Index (RCI)	0.49	2.14	+337%
Braiding parameter	1.45	2.84	+96%
Morphological Quality Index (MQI)	0.51	0.64	+25%

Instream habitat composition at Countyline in both 2011 and 2022 was largely dominated by glides and pools, with the total length of pool habitat increasing in 2022 (Table 8; Figure 11). The habitat classification method we developed indicated a 71% increase in pool length, a 166% increase in glide length, and a 23% decrease in riffle length.

[6] Poor LiDAR penetration at Countyline in 2022 may have resulted in artificially shallow depth estimates.

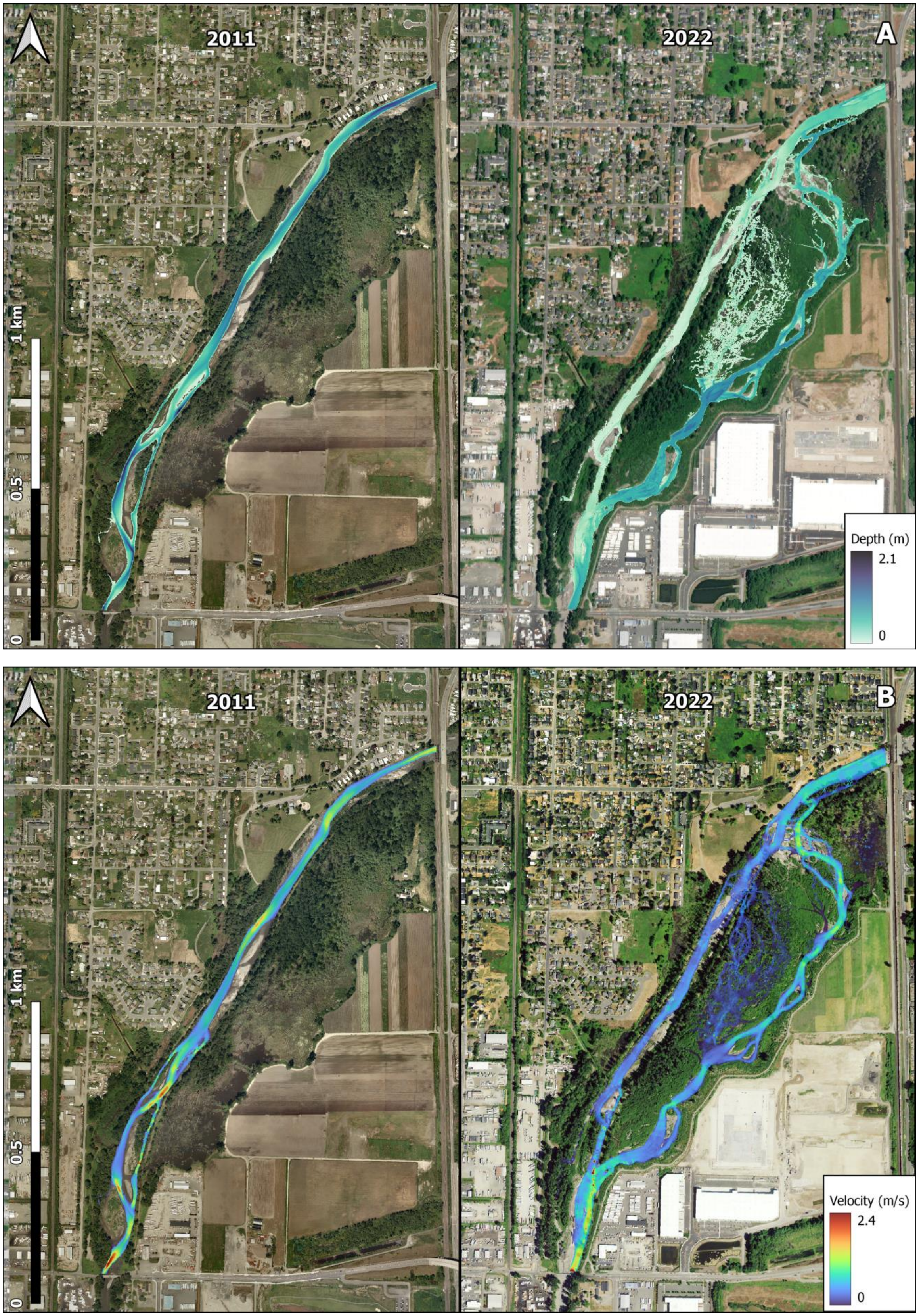


Figure 10. Modeled depths (A) and velocities (B) for Countyline at low flow (500 cfs). Base maps are 2011 (pre-project) and 2021 (post-project) NAIP imagery.

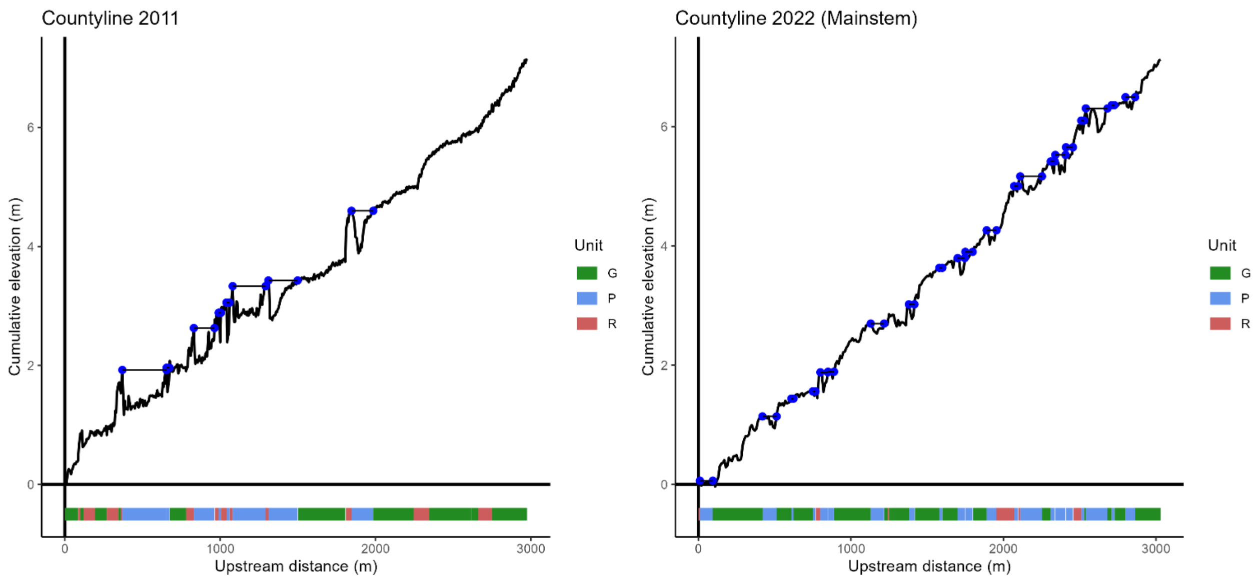


Figure 11. Thalweg long profile and results from habitat classification for Countyline (mainstem only). Habitat unit type definitions are as follows: G = Glide, P = Pool, R = Riffle.

Most of the additional glide length (56%) and the additional pool length (34%) in 2022 was in the large side channel (Figure 12). Within the main channel alone, pool length increased by 13%, glide length increased by 16%, whereas riffle length decreased by 58%. Similarly, the pool-riffle ratio increased nearly threefold following restoration. The Shannon diversity index of habitat units decreased slightly following restoration from 1.08 to 1.0.

Table 8. Summary of pool metrics and habitat diversity for Countyline. Habitat units and associated metrics were derived from the thalweg long profile.

Metric	Pre-project	Post-project	Percent Change
Question 4: What is the number and diversity of habitat types (i.e., pools, riffles, glides, etc.) within the main channel, and side channels at different flows (low and bankfull), and how much do they change over time?			
Shannon Diversity Index (habitat units)	1.08	1.00	-8%
Percent pool area	40%	68%	+70%
Number of pools	8	27	+238%
Pool to Riffle ratio	0.67	3.00	+347%
Residual pool depth	2.03	0.60[7]	-74%

[7] Poor LiDAR penetration at Countyline in 2022 may have resulted in artificially shallow depth estimates.

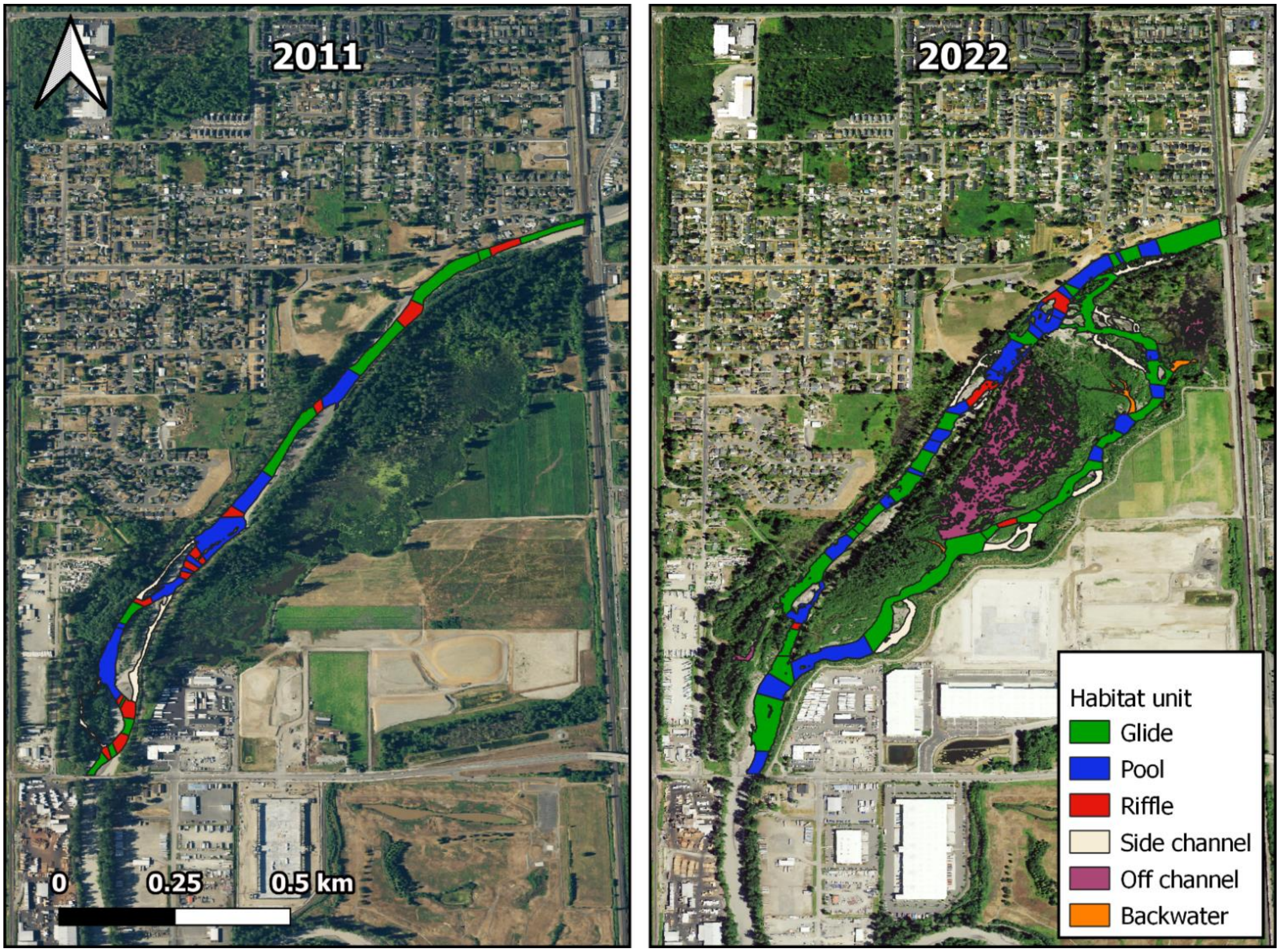


Figure 12. Low flow (500 cfs) fish habitat units classified using the thalweg long profile and aerial imagery. Pool, riffle, and glide unit boundaries were identified from the thalweg long profile, while side channels, off channels, and backwaters were mapped in GIS based on the hydraulic model output and aerial imagery. Base maps are 2011 (pre-project) and 2021 (post-project) NAIP imagery.

The GUT analysis, which maps fine-scale geomorphic units within the bankfull channel rather than fish habitat, also showed a large increase in pool habitat from 0.39 ha in 2011 to 2.87 ha in 2022 (Table 9). The GUT analysis of finer scale geomorphic units also showed an increase in glide-run habitat and slight decrease riffle area (Figure 13).

Table 9. Tier 3 geomorphic units summary for Countyline, calculated from the geomorphic unit tool (GUT) output.

	Area (ha)			Count		
	2011	2022	Percent change	2011	2022	Percent change
Bank	0.01	1.01	10,000%	31	425	1271%
Barface	0	0.01	NA	0	13	NA
Margin Attached Bar	1.36	3.98	193%	305	324	6%
Mid-channel Bar	0.35	1.74	397%	22	211	859%
Pocket Pool	0	0.01	NA	0	267	NA
Pool	0.39	2.87	636%	224	379	69%
Rapid	0	0.01	NA	0	1	NA
Riffle	0.09	0.08	-11%	7	7	0%
Transition	0.39	2.38	510%	57	5168	8967%
Glide-Run	4.49	11.83	163%	157	193	23%
Total	7.09	22.87	223%	803	6988	770%

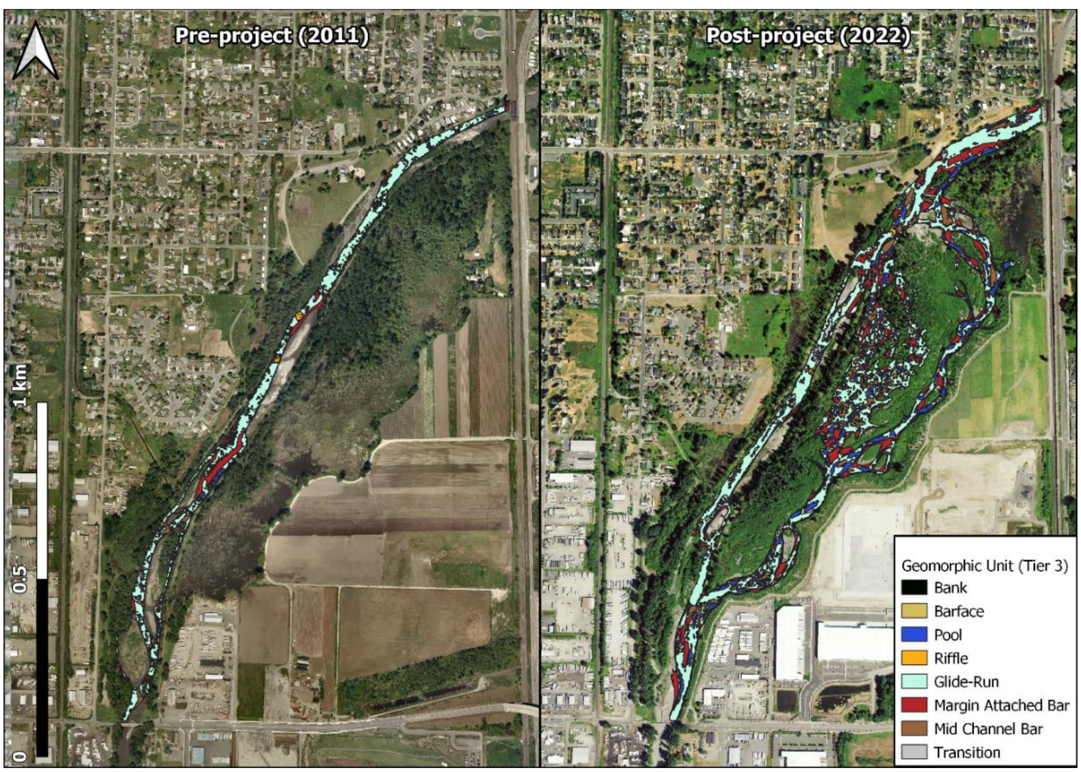


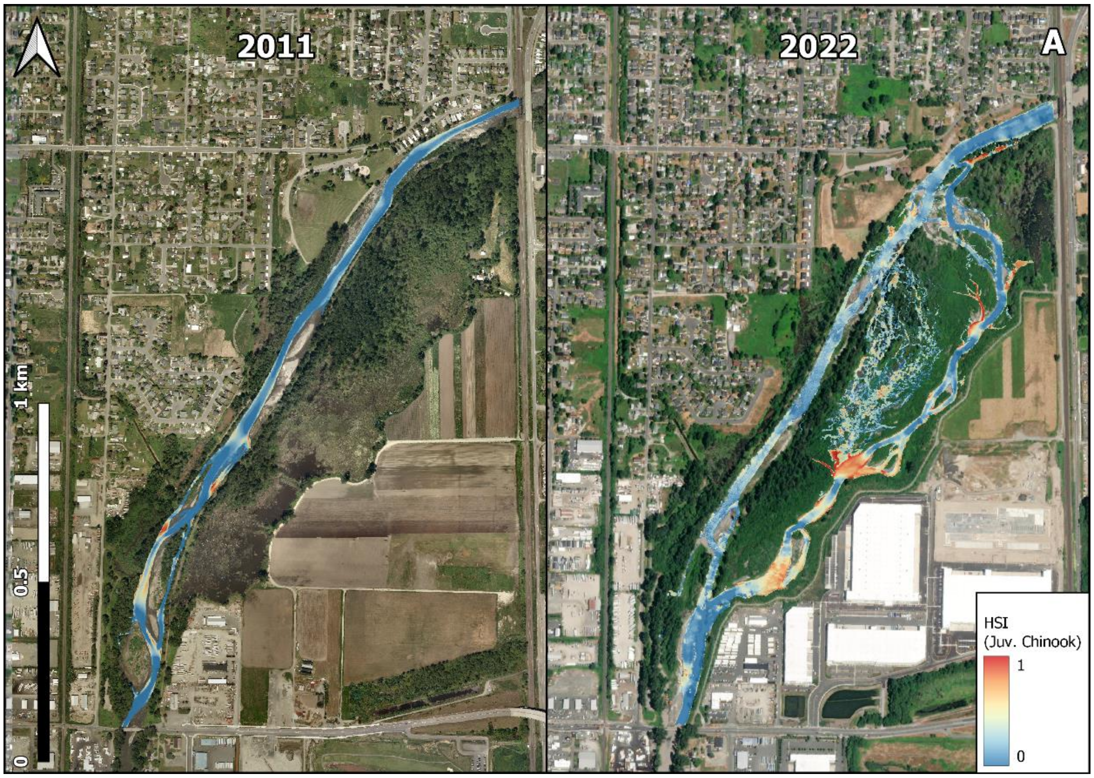
Figure 13. Tier 3 geomorphic units at Countyline at low flow (500 cfs), delineated using the Geomorphic Unit Tool (GUT). Base maps are 2011 (pre-project) and 2021 (post-project) NAIP imagery.

HSI

The total weighted usable area (WUA) at base flow increased for all species and life stages following restoration with the largest increases in juvenile Chinook and steelhead (465 and 353%, respectively). The geometric mean HSI value for juvenile Chinook salmon and steelhead both increased at Countyline between 2011 and 2022 at a base flow of 500 cfs (Table 10). Mean HSI decreased from 0.38 to 0.19 for spawning Chinook at base flow, with most of the high-quality spawning habitat shifting from the main channel to the side channel (Figure 14). The mean HSI values, total WUA, and WUA >0.5 decreased slightly for both juvenile Chinook (Figure 14) and steelhead (Figure 15) before and after restoration at a two-year flow, primarily due to the increase in velocity caused by the side channel, but also because the project remains constrained between two set-back levees.

Table 10. Geometric means, 50th and 90th percentiles, and amount of weighted usable area (WUA) of the habitat suitability index by species and life stage at Countyline at low flow(500 cfs).

Species and Life Stage	Year	Geometric Mean	50th percentile	90th percentile	WUA (ha)	WUA HSI >0.5
Juvenile Chinook	2011	0.13	0.04	0.40	0.92	0.28
	2022	0.25	0.20	0.61	5.20	0.22
Spawning Chinook	2011	0.38	0.38	0.82	2.71	1.75
	2022	0.19	0.09	0.55	4.00	1.79
Juvenile Steelhead	2011	0.24	0.19	0.50	1.69	0.46
	2022	0.37	0.50	0.69	7.65	3.29



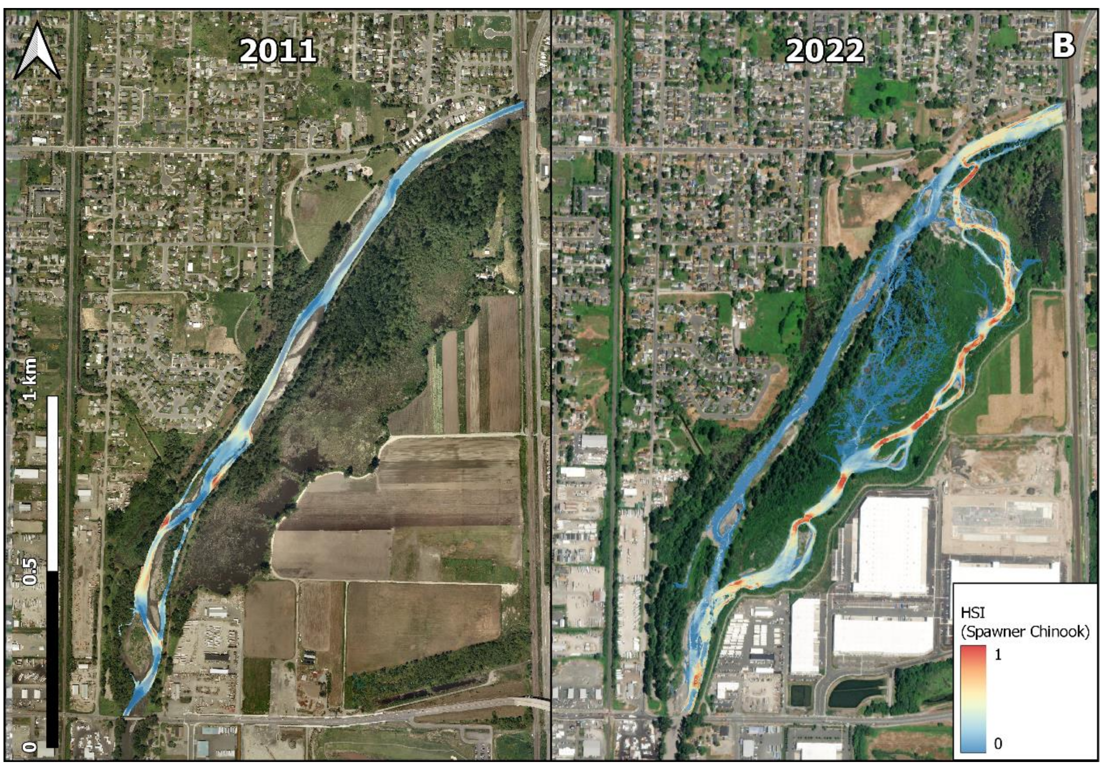


Figure 14. Habitat suitability index results for Countyline at low flow (500 cfs) for juvenile Chinook(A) and, spawning Chinook (B). Base maps are 2011 (pre-project) and 2021 (post-project) NAIP imagery.

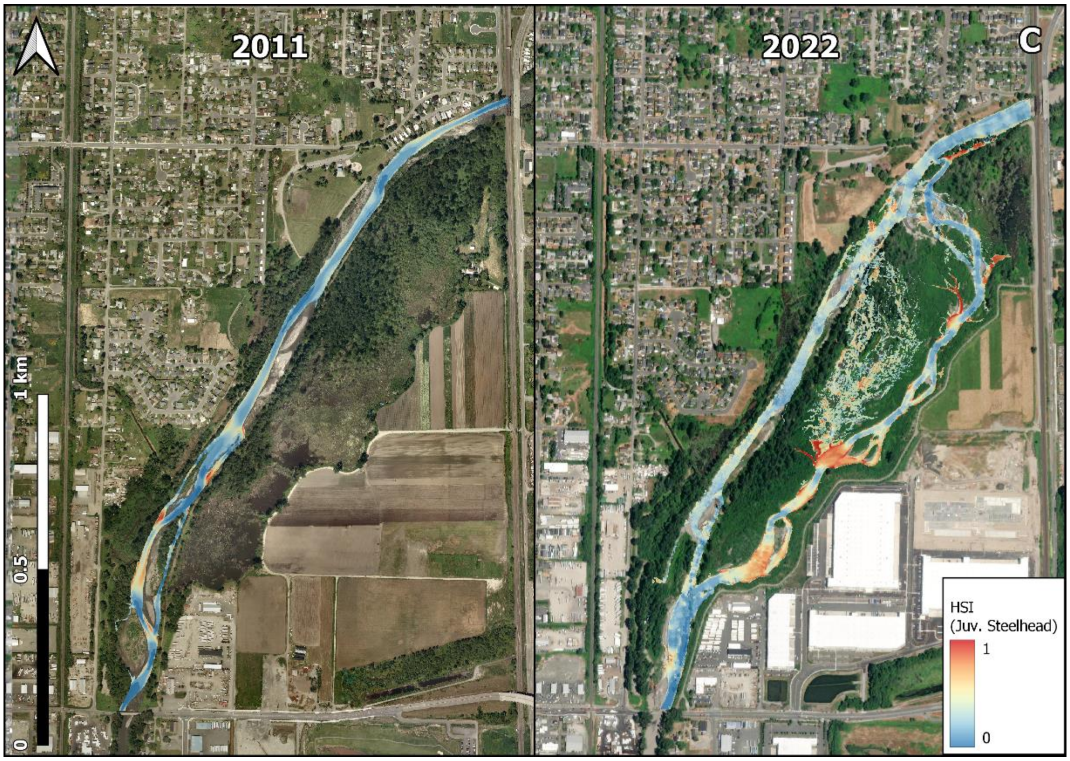


Figure 15. Habitat suitability index results for Countyline at low flow (500 cfs) for juvenile steelhead. Base maps are 2011 (pre-project) and 2021 (post-project) NAIP imagery.

Large wood and sediment

Quantitative comparisons for large wood were made using metrics generated from the LiDAR/aerial imagery analysis; however, we also present results from the pre-project survey conducted by King County for comparison. Cumulative counts of individual large wood pieces increased from 2,405 to 4,730 piece between 2011 to 2022 with the total count of wood in the wetted channel increasing by more than 1000% (Table 11). The total count of jams increased from 9 to 38. The dramatic increase in large wood is not surprising given that large wood placement and construction of log jams was part of the restoration.

Table 11. Summary of large wood abundance and frequency at Countyline. Data from 2017 are from a field survey conducted by King County prior to project completion. The percent change is derived from the 2011 and 2022 LiDAR data.

Metric	Pre-project (King County)	Pre-project (CFS)	Post-project (CFS)	Percent Change
Question 5: What is the abundance and distribution of large wood in the active channel, wetted channel, and on the floodplain, and how do they change over time? What proportion of the wood is actively interacting with the channel?				
Year	2017	2011	2022	
Data source(s)	Field survey; aerial imagery	LiDAR; aerial imagery	LiDAR; aerial imagery	
Large wood pieces (wetted)	167	63	874	+1,287%
Large wood pieces (bankfull)	1,465	1,530	2,528	+65%
Large wood pieces (floodplain)	202	812	1,328	+64%
Cumulative count (pieces)	1,834	2,405	4,730	+95%
Count of jams	33	9	28	+311%
Large wood frequency (pieces; #/100 m)	74.52	109.82	155.34	+41%
Large wood frequency (jams; #/100 m)	1.51	0.41	1.28	+211%

The DEM of difference (2011 – 2022) at Countyline indicated that 81% of the project area (68.48 ha) has aggraded, for an estimated total sediment volume of 462,993 m^3 (Figure 16). Concurrently, 16% of the project area (13.86 ha) has degraded, or 55,830 m^3 of sediment. Thus, total aggradation at the site was 407,163 m^3 of sediment. However, poor LiDAR penetration in 2022 may have resulted in biased estimates of aggradation and degradation in deepest areas of the channel.

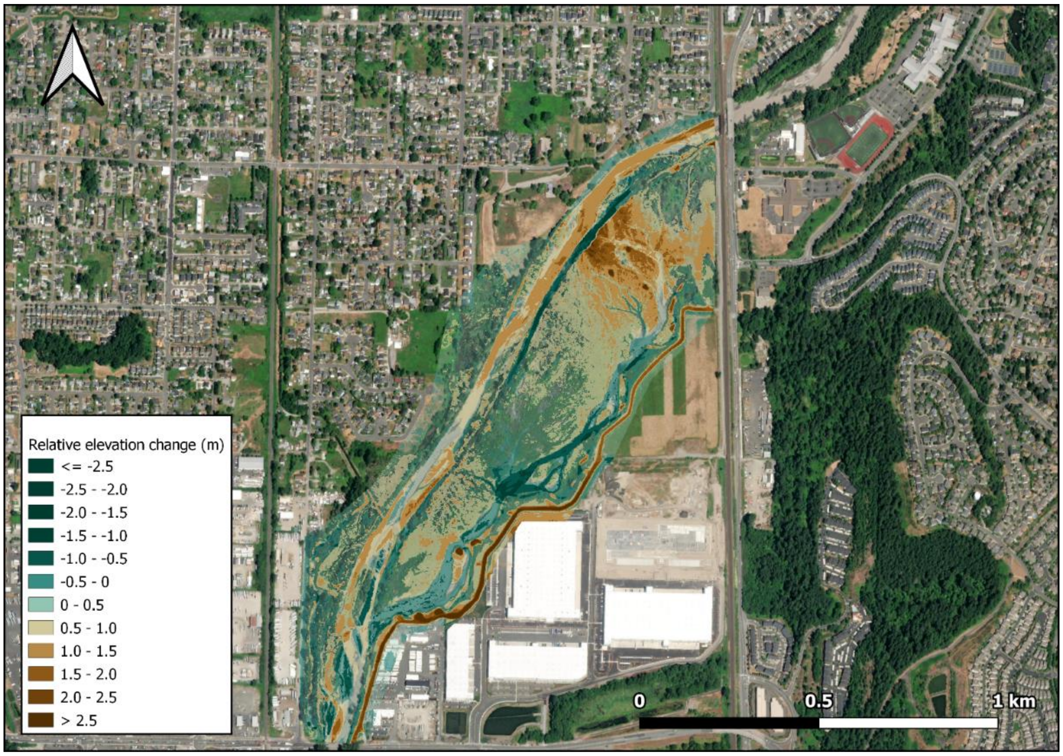


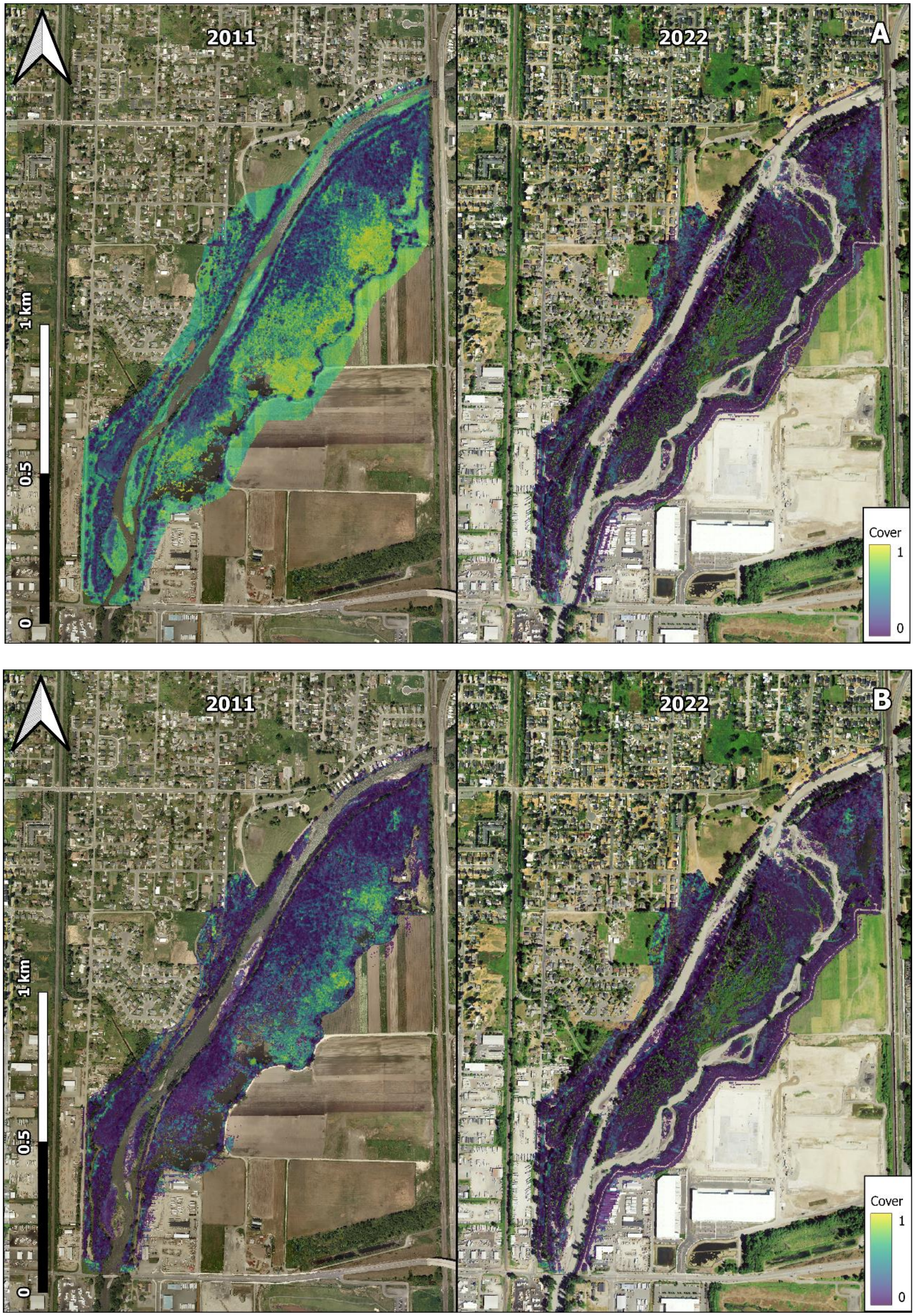
Figure 16. Relative elevation change at Countyline from 2011 to 2022 based on topo-bathymetric LiDAR.

Riparian

The areal extent of low (<1 m) and mid-story (1 – 5 m) vegetation decreased from the pre- to post-project periods from 37 to 5 ha and 10 to 4 ha, respectively, while the areal extent of canopy (>5 m) increased from 25 to 32 ha or more than 25% (Table 12). This appears largely due to increased tree cover as areal coverage maps based on LiDAR data show that the Countyline project was dominated by low vegetation in 2011, but trees were the dominant vegetation class in 2022 (Figure 17). Much of this is presumably due to the rapid growth of many of the planted trees.

Table 12. Summary of the areal extent of riparian vegetation by class at Countyline.

Metric	Pre-project	Post-project	Percent Change
What is the riparian vegetation areal extent by vegetation class (e.g., grasses, forbs, shrubs, trees, etc.), species composition, and density and how much do they change over time?			
Areal extent of low vegetation (ha)	37	5	-86%
Areal extent of mid-story vegetation (ha)	10	4	-60%
Areal extent of canopy (ha)	25	32	+28%


2011
2022
A
1 km
0.5
0
Cover
1
0
2011
2022
B
1 km
0.5
0
Cover
1
0

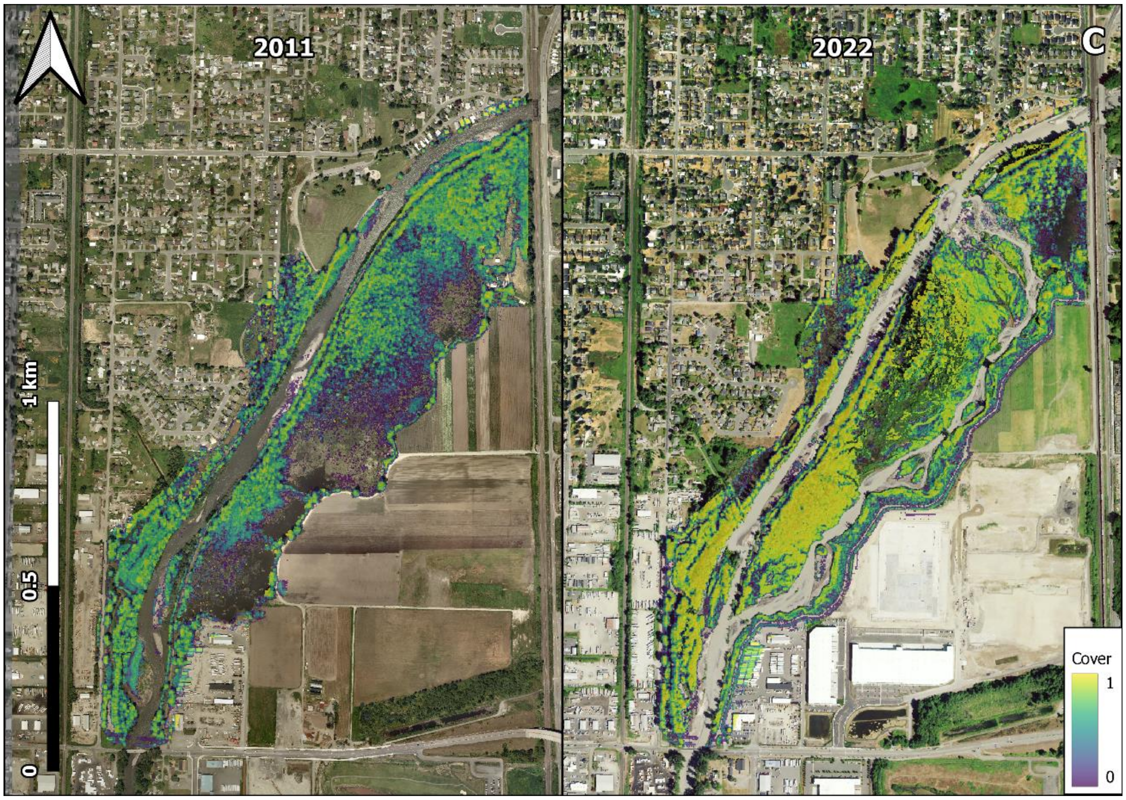


Figure 17. Areal extent of low vegetation (A; LiDAR returns < 1 m), mid-story vegetation (B; LiDAR returns ≥ 1 m and ≤ 5 m), and canopy (C; LiDAR returns > 5 m) at Countyline. Colors in each cell represent the proportion of the cell area covered by vegetation in each height class.

The mean LPI over the wetted channel decreased by 10% from 2011 to 2022, indicating an increase in riparian shade. The estimated volume of organic inputs also increased by more than 200% concomitant with the increase in the areal extent of canopy coverage (Table 13). The change in the spatial distribution of LPI before and after project implementation is shown in Figure 17.

Table 13. Summary of riparian function metrics at Countyline derived from LiDAR data.

Metric	Pre-project	Post-project	Percent Change
Question 9: Has riparian/floodplain restoration led to restored riparian function including shade, bank stabilization, and organic matter following riparian restoration?			
Light penetration index (LPI)	0.91	0.82	-10%
Organic inputs (m^3)	194,664	614,897	+216%

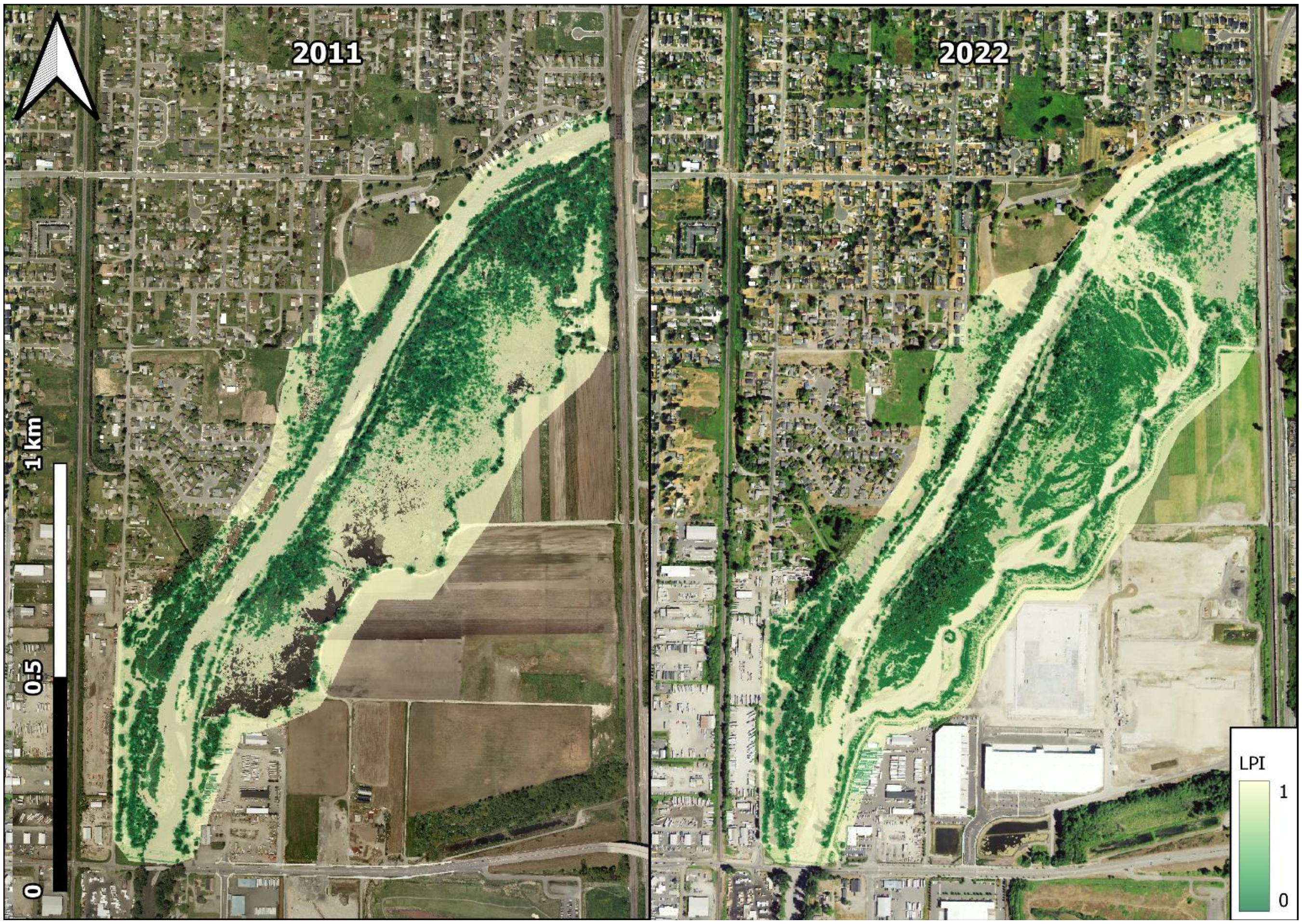


Figure 18. Light penetration index (LPI) proportion of first returns in each cell that are ground points) at Countyline.

Design objectives

The Countyline basis of design report lists three major project goals, each with three to four objectives (Herrera Environmental Consultants Inc. 2014). Most of the measurable objectives relevant to this study addresses Goal 1, which relates to riverine process restoration and salmonid rearing habitat enhancement (Table 14). One additional relevant objective (Objective 2.2) addresses Goal 2, related to flood storage capacity. The remaining objectives are related to flood hazard protection and infrastructure; therefore, we do not report them here. We did not have an as-built survey for the Countyline project which would allow us to evaluate specific design elements. However, we cross walked these objectives with the metrics we calculated before and after restoration to determine whether the project is meeting its design objectives. Based on our analysis and metrics we calculated, it appears the project is meeting all of its riverine process and fish habitat objectives (Table 14). For example, using the various side channel metrics we calculated (e.g., number, length, and RCI) it is clear that the project has met Objective 1.2 “Encourage the formation of off-channel rearing habitat (pool complexes and side-channels), through installation and future natural recruitment of large wood, that will promote the return of the complexity, diversity, and morphology found in an unconstrained floodplain.”

Table 14. List of relevant goals and objectives listed in the Countyline basis of design report (Herrera et al. 2014), monitoring metrics we used to evaluate objectives, and whether the objective was met based on our analysis of pre- and post-data.

Goal and Objectives	Monitoring metric(s)	Objective met?
Goal 1: Restore riverine processes and functions to the lower White River and its floodplain within the project area (inside the proposed levees) in order to enhance salmonid rearing habitat, in particular for spring and fall Chinook, coho, and steelhead.		
Objective 1.1: Allow natural channel movement within the project area by removing and setting back the existing levee along the left bank.	Floodplain area, floodplain to bankfull area ratio, altered area	Yes
Objective 1.2: Encourage the formation of off-channel rearing habitat (pool complexes and side-channels), through installation and future natural recruitment of large wood, which will promote the return of the complexity, diversity, and morphology found in an unconstrained floodplain.	Side channel number, length, area, node density, and ratio, RCI, large wood, pool area/percentage	Yes
Objective 1.3: Provide off-channel flood refuge for salmonids by allowing a more natural frequency of inundation of the floodplain complex during flood events within the project boundaries.	Floodplain inundation index	Yes
Objective 1.4: Protect existing mature riparian buffer areas and restore a corridor of mature riparian vegetation within the project boundaries to provide, shoreline and stream channel shading, invertebrate prey supply, and large wood recruitment.	Areal extent of riparian vegetation classes, light penetration index, large wood	Yes
Goal 2: Prevent an increase in flood and geomorphic hazards outside of the project area from this restoration project and, if possible, reduce existing hazards.		
Objective 2.2: Increase flood storage along the length of the project, which will also have a net benefit on flood elevations in the immediate vicinity of the project, particularly the right bank.[8]	Floodplain area	Yes

[8] While floodplain area increased post-project, hydraulic model simulations still show significant inundation up to the flood protection barriers on the right bank though observations by King County staff indicate that it was predicted to become worse without the project. Thus, the project has likely reduced risk of overtopping right-bank flood protection barriers (Figure 9).

Upper/Lower Fobes

Geomorphology and habitat

Pre-project (2017) floodplain area, floodplain to bankfull ratio and floodplain inundation index were 58 ha, 2.41, and 0.42 respectively (Table 15). Prior to project construction in summer 2022, there were three low flow side channels at Upper/Lower Fobes, two of which were backwater channels, and two side channels at bankfull (Figure 19).

Table 15. Summary of floodplain area and floodplain inundation metrics for Upper/Lower Fobes.

Metric	Pre-project	Post-project	Percent Change
Question 1: What is the floodplain area before and after restoration and what is the extent and frequency of floodplain inundation at different flow levels over time?			
Floodplain area (ha)	58	TBD	TBD
Floodplain to bankfull area ratio	2.41	TBD	TBD
Floodplain inundation index	0.42	TBD	TBD

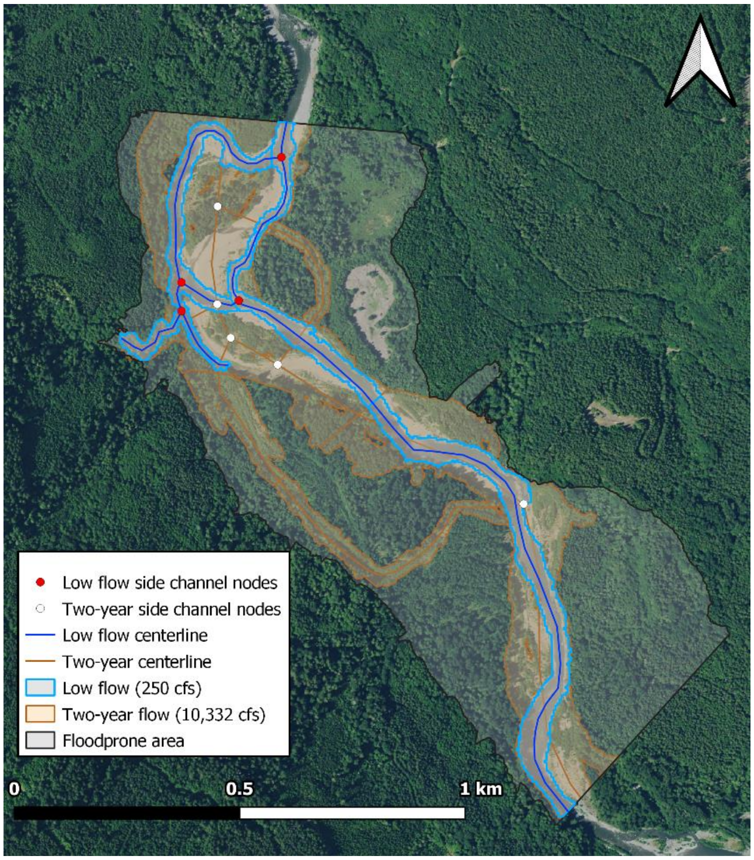


Figure 19. Comparison of the water surface extents at low flow, a 2-year flow, and the floodprone area at Upper/Lower Fobes in 2021 (pre-project). Side channel nodes are the junctions between the main channel and each side channel entrance. The base map is 2021 NAIP imagery.

Pre-project sinuosity was 1.36 with a bankfull width of 41 m and a river complexity index of 0.35 which reflects the low number of active side channels. A complete list of pre-project monitoring floodplain and channel morphology metrics are displayed in Table 16. Depth and velocity profiles and maps are displayed in Figure 20. All these metrics are expected to improve following project implementation and adequate flow events.

Table 16. Summary of channel and floodplain morphology metrics for Upper/Lower Fobes.

Metric	Pre-project	Post-project	Percent Change
Question 3: What is the effect of restoration on channel and floodplain morphology and complexity (RCI [Brown 2002]), seasonal and perennial side channel metrics (length, area, ratio [Beechie et al. 2017]), and the morphological quality index (MQI [Rinaldi et al. 2013]) in the reach, and how does it change over time?			
Sinuosity	1.36	TBD	TBD
Wetted area (ha)	11	TBD	TBD
Wetted width (m)	37.05	TBD	TBD
Bankfull area (ha)	41	TBD	TBD
Bankfull width (m)	212.08	TBD	TBD
Bankfull width to depth ratio	11.41	TBD	TBD
Wetted side channel count	3	TBD	TBD
Wetted side channel nodes	4	TBD	TBD
Wetted side channel length (km)	0.77	TBD	TBD
Wetted side channel area (ha)	1.60	TBD	TBD
Side channel ratio	0.94	TBD	TBD
Isolated ponds/wetlands	0	TBD	TBD
River Complexity Index (RCI)	0.35	TBD	TBD
Braiding parameter	1.78	TBD	TBD
Morphological Quality Index (MQI)	0.95	TBD	TBD

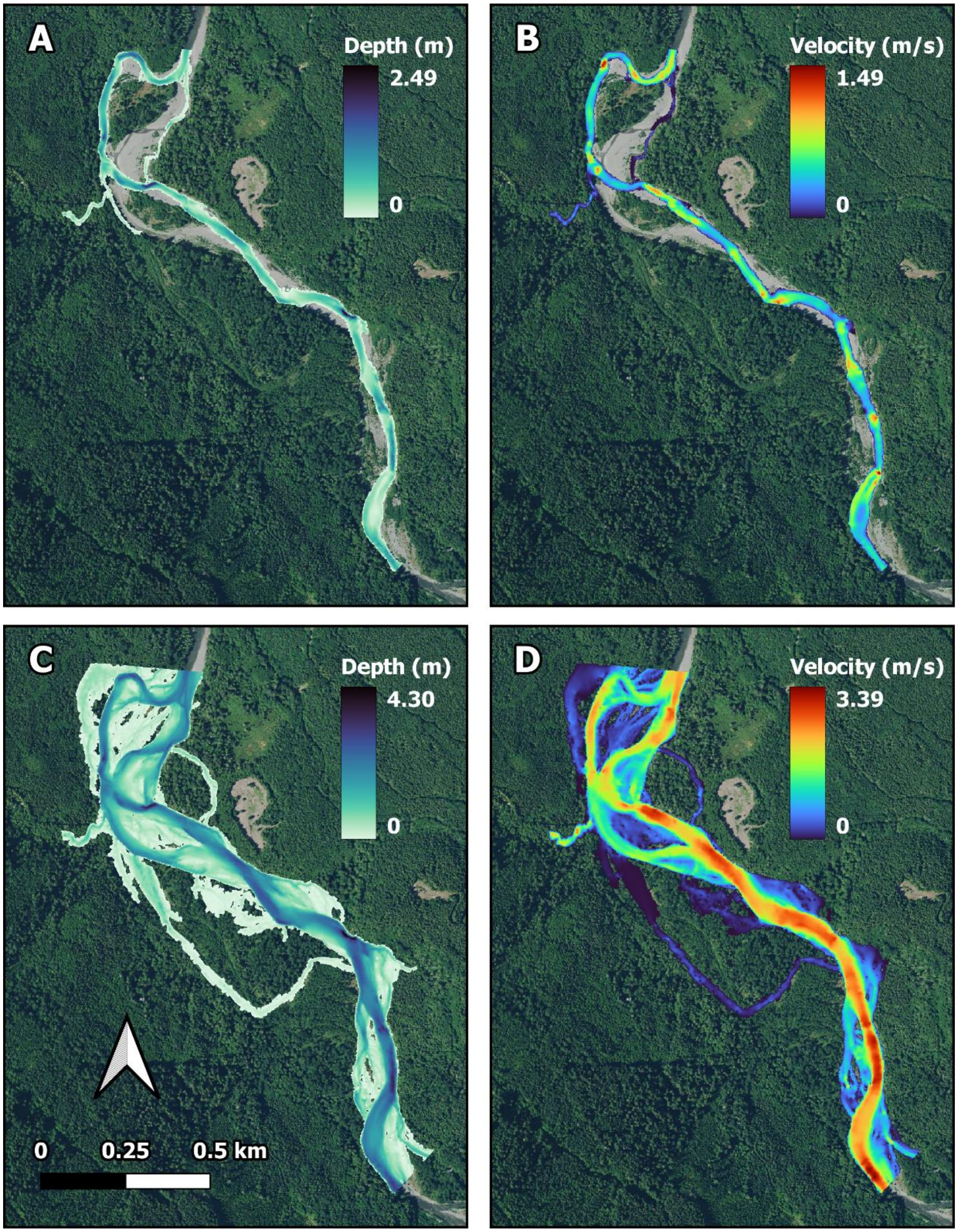


Figure 20. Depth and velocity for the Upper/Lower Fobes project site on the South Fork Nooksack River. Panels A and B show the low flow scenario (250 cfs) and panels C and D show the 2-year flow scenario (10,332 cfs).

Prior to restoration there were 18 pools with 38% of the habitat length classified as pools (Table 17 Figure 21). Similar to the field habitat survey, the GUT analysis, which covers the bankfull channel, showed that the reach was dominated by fast water geomorphic channel units, with the largest percent of bankfull channel area (26%) being classified as rapids (Figure 22; Table 18).

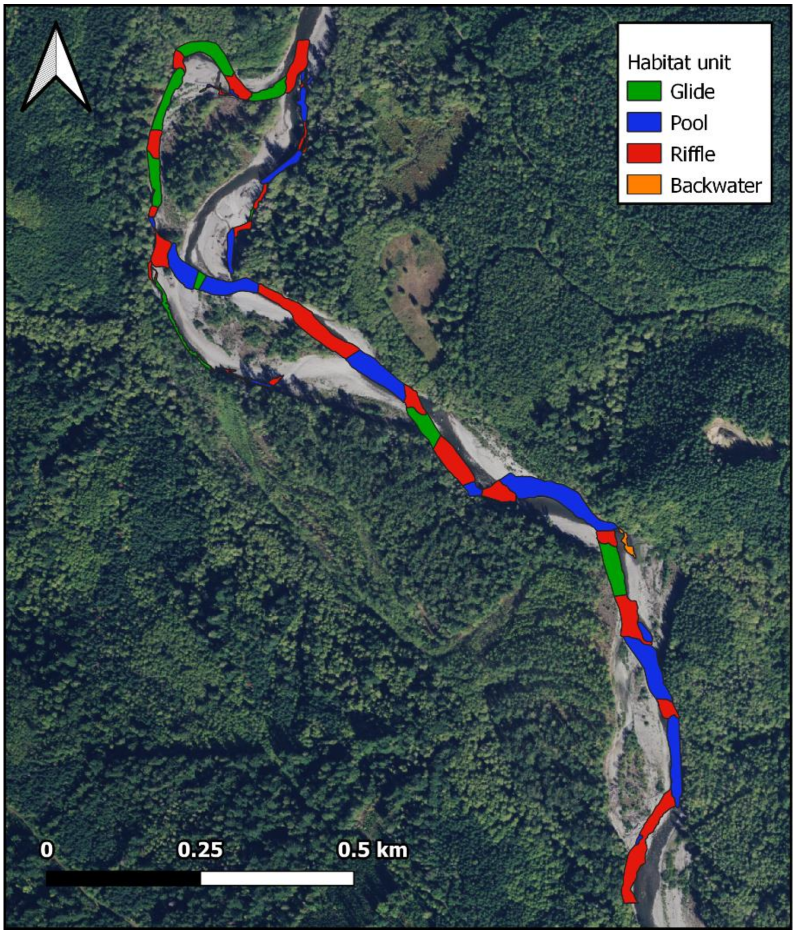


Figure 21. Fish habitat units at Upper/Lower Fobes from a 2021 field survey (data provided by Lummi Nation). The base map is 2021 (pre-project) NAIP imagery.

Table 17. Summary of pool metrics and habitat diversity for Upper/Lower Fobes. Post-project and percent change will be calculated after project completion and post-project monitoring.

Metric	Pre-project	Post-project	Percent Change
Question 4: What is the number and diversity of habitat types (i.e., pools, riffles, glides, etc.) within the main channel, and side channels at different flows (low and bankfull), and how much do they change over time?			
Shannon Diversity Index (habitat units)	1.12	TBD	TBD
Percent pool area	38%	TBD	TBD
Number of pools	18	TBD	TBD
Pool to Riffle ratio	0.78	TBD	TBD
Residual pool depth	2.7	TBD	TBD

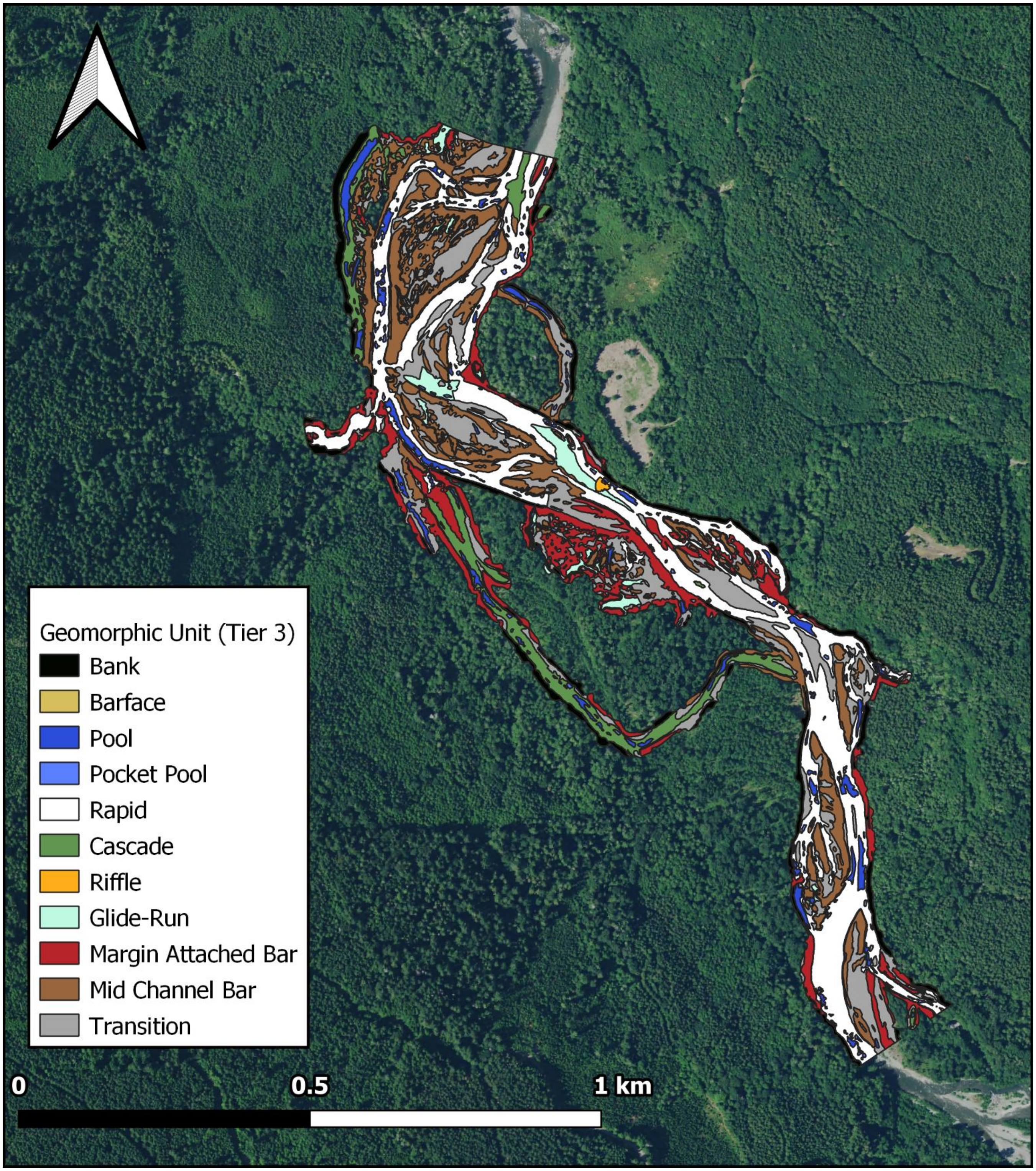


Figure 22. Tier 3 geomorphic units at Upper/Lower Fobes, delineated using the modeled 2-year water surface extent, 2021 bathymetry, and the Geomorphic Unit Tool (GUT)). The base map is 2021 (pre-project) NAIP imagery.

Table 18. Tier 3 geomorphic units summary for Upper/Lower Fobes calculated from the geomorphic unit tool (GUT) output. The percent of the total bankfull area is given in parentheses. Post-project and percent change will be calculated after project completion and post-project monitoring.

Unit Type	Area (ha)		Count	
	Pre-project	Post-project	Pre-project	Post-project
Bank	2.66	TBD	68	TBD
Barface	0.01	TBD	7	TBD
Cascade	2.55	TBD	12	TBD
Glide-Run	1.05	TBD	17	TBD
Margin Attached Bar	5.22	TBD	44	TBD
Mid-channel Bar	8.17	TBD	120	TBD
Pocket Pool	0.47	TBD	171	TBD
Pool	1.49	TBD	56	TBD
Rapid	11.04	TBD	2	TBD
Riffle	0.04	TBD	1	TBD
Transition	9.62	TBD	784	TBD
Total	42.32	TBD	1282	TBD

HSI

The total WUA (WUA >0.5) at low flow (250 cfs) was 3.64 (1.37) ha, 5.62 (2.29) ha, and 3.72 (1.27) ha for juvenile Chinook, spawning Chinook, and juvenile steelhead, respectively (Figure 23). The geometric mean (50^{th} – 90^{th} percentiles) HSI values at base flow were 0.22 (0.16 – 0.54) for juvenile Chinook, 0.23 (0.18 – 0.53) for spawning Chinook, and 0.34 (0.31 – 0.63) for juvenile steelhead.

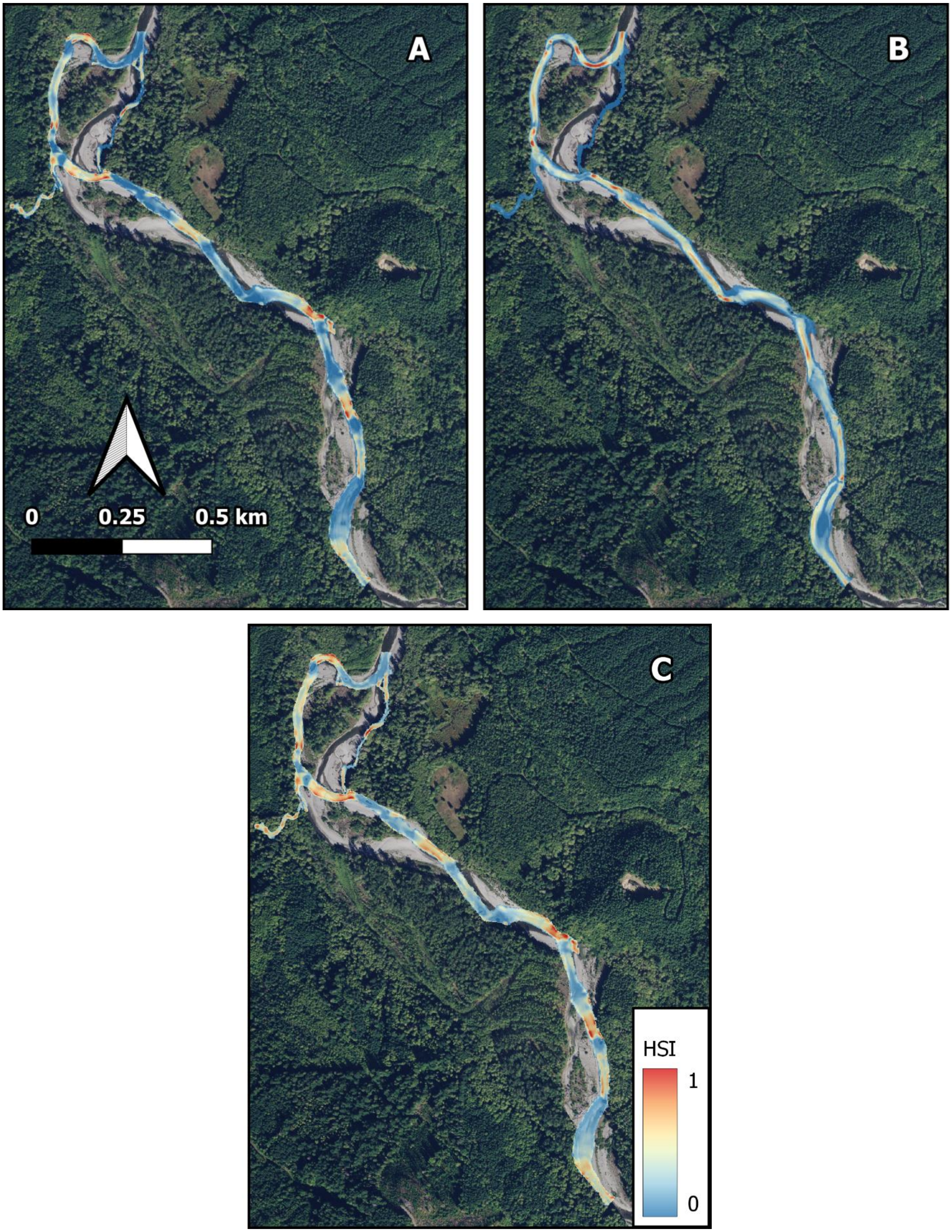


Figure 23. Habitat suitability index at low flow (250 cfs) at Upper/Lower Fobes for juvenile Chinook (A), spawning Chinook (B), and juvenile steelhead (C). The base map is 2021 (pre-project) NAIP imagery.

Large wood and sediment

There were a total of 1123 pieces of large wood pre-project (2017) and 12 jams, with the majority of the large wood being on the floodplain and 171 pieces being in the wetted channel (Table 19).

Table 19. Summary of large wood abundance and frequency at Upper/Lower Fobes. Post-project and percent change will be calculated after project completion and post-project monitoring.

Metric	Pre-project	Post-project	Percent Change[9]
Question 5: What is the abundance and distribution of large wood in the active channel, wetted channel, and on the floodplain, and how do they change over time? What proportion of the wood is actively interacting with the channel?			
Large wood pieces (wetted)	171	TBD	TBD
Large wood pieces (bankfull)	316	TBD	TBD
Large wood pieces (floodplain)	636	TBD	TBD
Cumulative count (pieces)	1123	TBD	TBD
Count of jams	12	TBD	TBD
Large wood frequency (pieces; #/100 m)	58.28	TBD	TBD
Large wood frequency (jams; #/100 m)	0.62	TBD	TBD

Aggradation and degradation after post-project data are collected (Date TBD). Therefore, there are no sediment change results to report. However, Figure 24 shows the detrended DEM derived from the 2017 LiDAR, which provides a snapshot overview of the geomorphic qualities of the reach and will function as the frame of reference in the eventual sediment change analysis.

[9] Percent change was calculated from the LiDAR derived numbers.

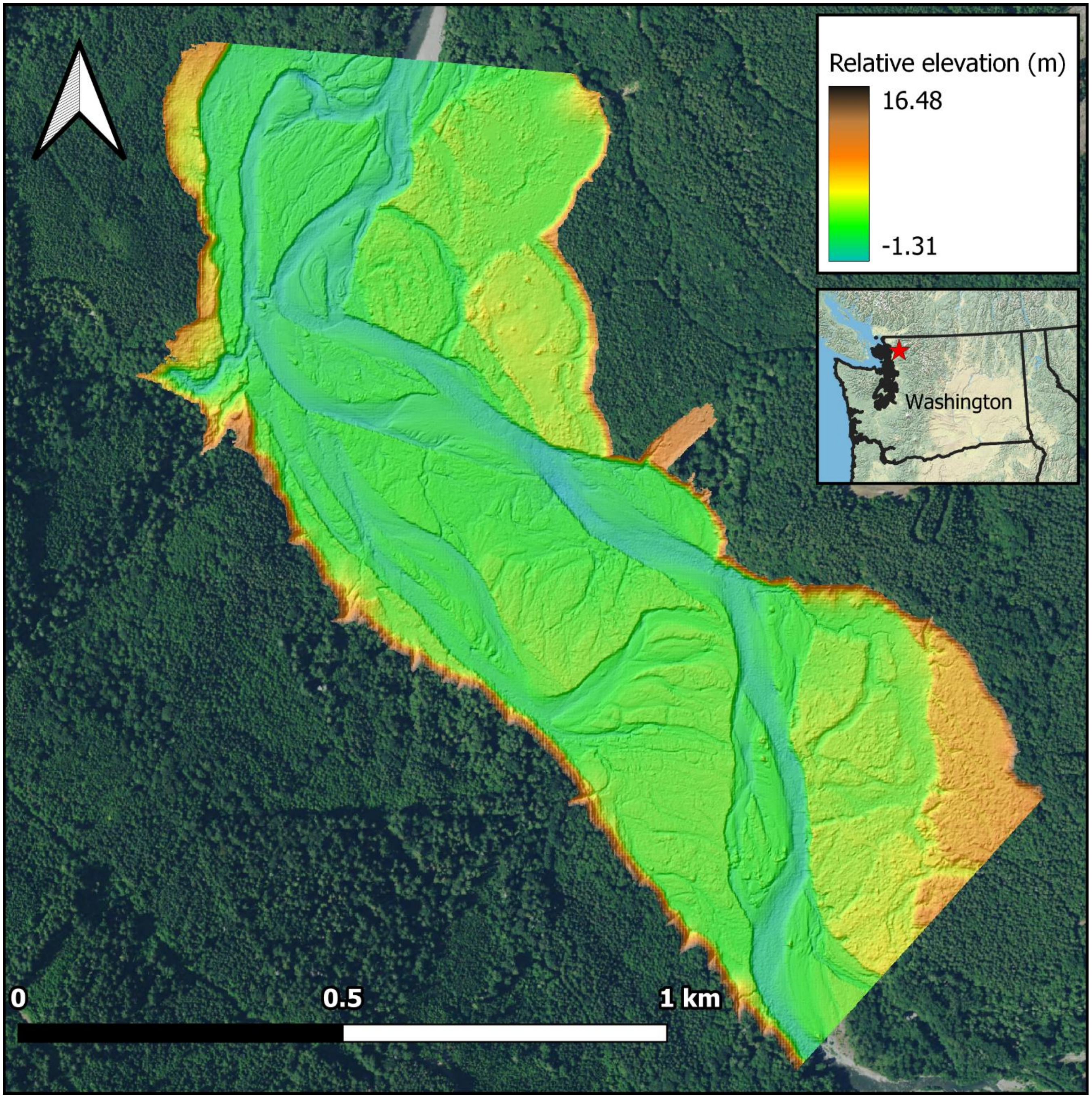


Figure 24. The detrended pre-project (2017) DEM at Upper/Lower Fobes clipped to the floodprone elevation contour.

Riparian

Riparian vegetation extent at Upper/Lower Fobes was greatest for the canopy and low vegetation height classes which covered 50% and 42% of the floodplain area, respectively, with the remaining 8% belonged to the mid-story vegetation class (Table 20; Figure 25). The riparian field survey identified 29 unique species. Himalayan blackberry was the most common in the low vegetation category (<1 m), *Salix* spp. was the most common mid-story (1-5 m) species, and red alder *Alnus rubra* was the most common canopy (>5 m) species (Figure 26). Native species comprised 71% of species, while invasive species made up 29% of species sampled. Invasive species prevalence was highest in the low vegetation (<1 m) category at 94%. Six percent of shrub species were classified as invasive and no invasive tree species were identified.

Table 20. Summary of the areal extent, richness, and diversity of riparian vegetation at Upper/Lower Fobes. Post-project and percent change will be calculated after project completion and post-project monitoring.

Metric	Pre-project	Post-project	Percent Change
What is the riparian vegetation areal extent by vegetation class (e.g., grasses, forbs, shrubs, trees, etc.), species composition, and density and how much do they change over time?			
Areal extent of low vegetation (ha)	9	TBD	TBD
Areal extent of mid-story vegetation (ha)	6	TBD	TBD
Areal extent of canopy (ha)	39	TBD	TBD
Species richness	29	TBD	TBD
Shannon diversity index	1.99	TBD	TBD

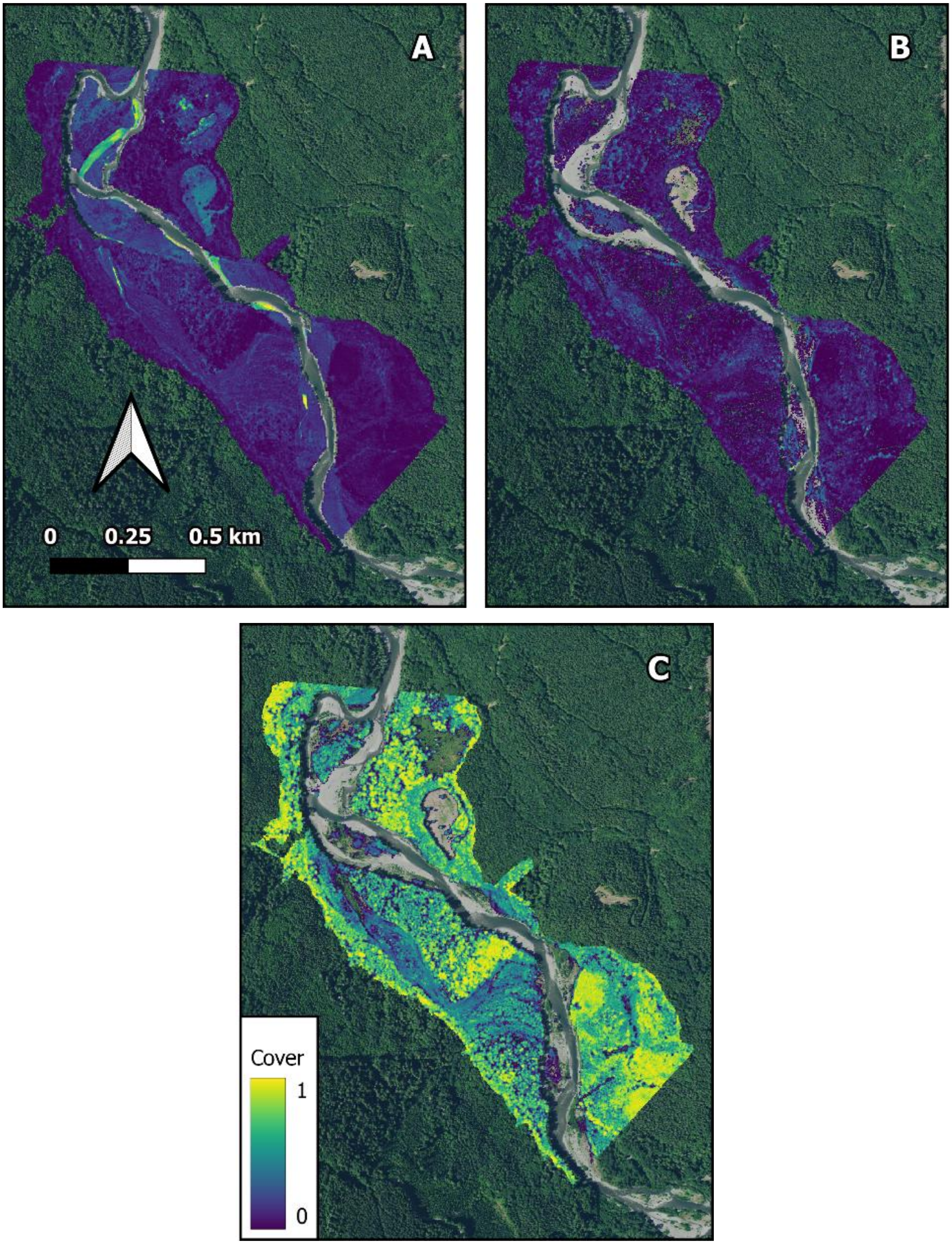


Figure 25. Areal extent of low vegetation (A; LiDAR returns <1 m), mid-story vegetation (B; LiDAR returns ≥ 1 m and ≤ 5 m), and canopy (C; LiDAR returns > 5 m) at Upper/Lower Fobes. Colors in each cell represent the proportion of the cell area covered by vegetation in each height class.

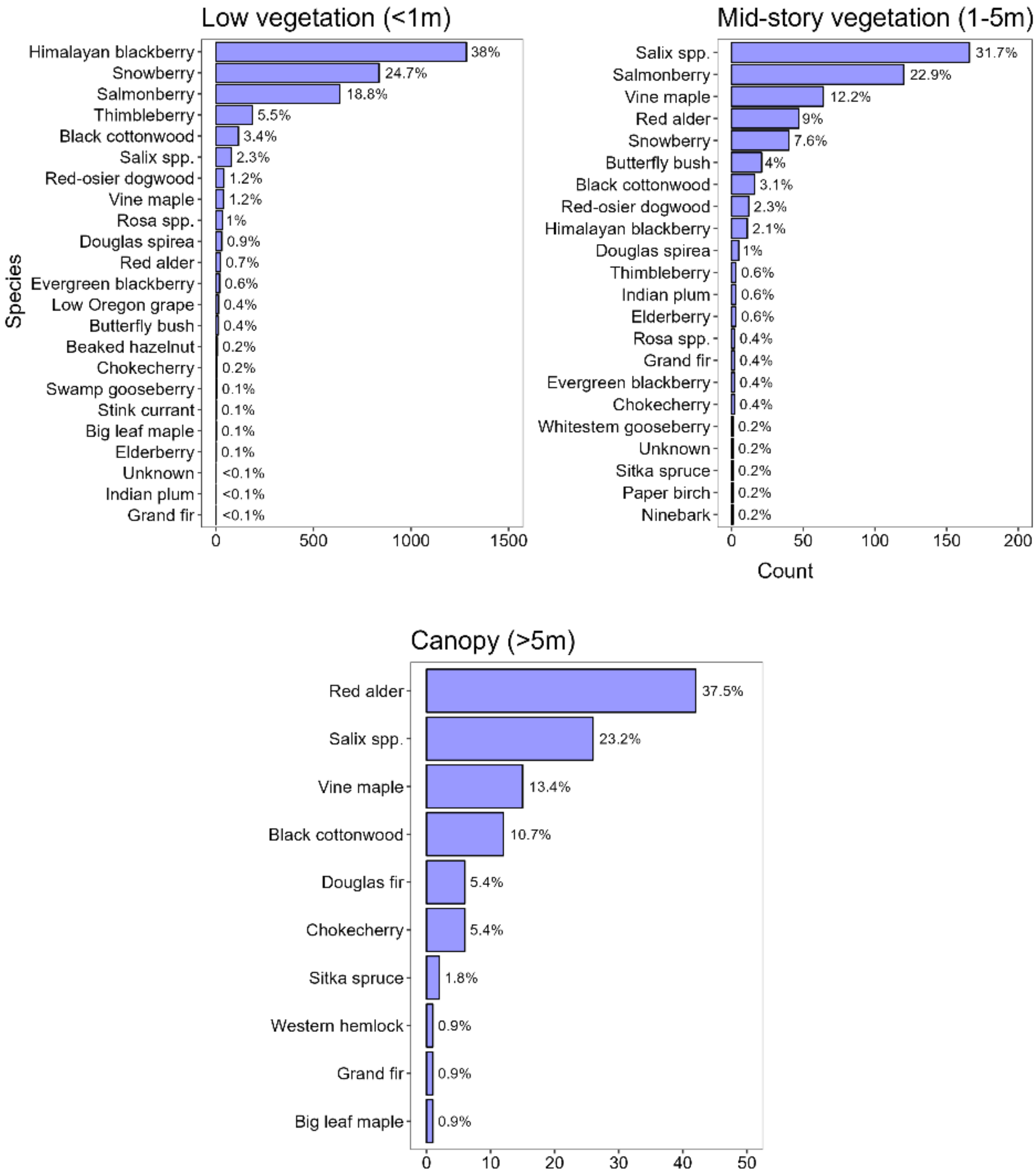


Figure 26. Count frequency plots of riparian vegetation species by height category encountered during the riparian field surveys (July/August 2022) at Upper/Lower Fobes.

The LPI indicated that Upper/Lower Fobes is highly shaded; however, it was evident in the LPI raster that the LiDAR did not penetrate to the thalweg (hence, the bathymetry survey conducted by NSD in 2016) (Figure 27). As such, the LPI value displayed in Table 21 may be biased low.

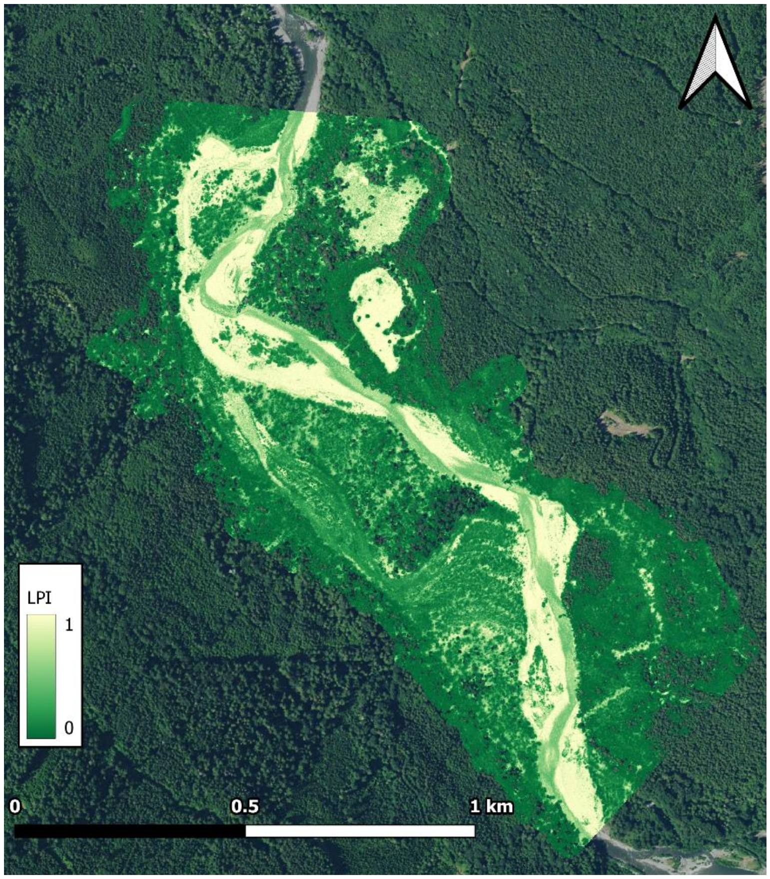


Figure 27. Light penetration index (LPI) proportion of first returns in each cell that are ground points) at Upper/Lower Fobes.

Table 21. Summary of riparian function metrics at Upper/Lower Fobes. Post-project and percent change will be calculated after project completion and post-project monitoring.

Metric	Pre-project	Post-project	Percent Change
Question 9: Has riparian/floodplain restoration led to restored riparian function including shade, bank stabilization, and organic matter following riparian restoration?			
Light penetration index (LPI)	0.57	TBD	TBD
Organic inputs (m^3)	1,190,592	TBD	TBD

Design objectives

The goal of the Upper/Lower Fobes habitat restoration project is to restore early Chinook spawning, rearing, and holding habitat by addressing limiting factors such as temperature, habitat diversity, and key habitat quantity (Washington State Recreation and Conservation Office 2022). In addition, the project is intended to encourage specific physical and biological outcomes and we extracted specific outcomes from the available documentation (Table 22). Upon completion of post-project monitoring, we will evaluate change in the relevant metrics and determine whether the anticipated outcomes were achieved.

Table 22. List of anticipated outcomes of the Upper/Lower Fobes restoration project and metric/analysis that will be used to assess those outcomes. Anticipated outcomes are paraphrased from the project webpage on the Salmon Recovery Funding Board website (Washington State Recreation and Conservation Office 2022).

Anticipated Outcome	Metric/Analysis
Combat incision and aggrade the channel.	DEM of difference
Encourage split flows and anabranching channel form.	RCI, MQI, side channel ratio, side channel nodes
Increase side channel habitat and floodplain connectivity.	Side channel count, side channel ratio, side channel area, floodplain area, floodplain inundation index
Create thermal refugia and low flow pool habitat.	Light penetration index, pool count, pool area, percent pool area
Promote forested island development.	Areal extent of mid-story and canopy vegetation on islands

Tucannon PA-3

Geomorphology and habitat

Floodplain area and the floodplain inundation index at Tucannon PA-3 both increased by 29% following the 2018 restoration (Table 23). The total area altered by the project (calculated at a 2-year flow [738 cfs]) was 11.36 ha. The spatial extent of the wetted, bankfull, and floodprone areas increased following restoration as displayed in Figure 28.

Table 23. Summary of floodplain area and floodplain inundation metrics for Tucannon PA-3.

Metric	Pre-project	Post-project	Percent Change
Question 1: What is the floodplain area before and after restoration and what is the extent and frequency of floodplain inundation at different flow levels over time?			
Floodplain area (ha)	24	31	+29%
Floodplain to bankfull area ratio	3.94	5.15	+31%
Floodplain inundation index	0.09	0.12	+29%

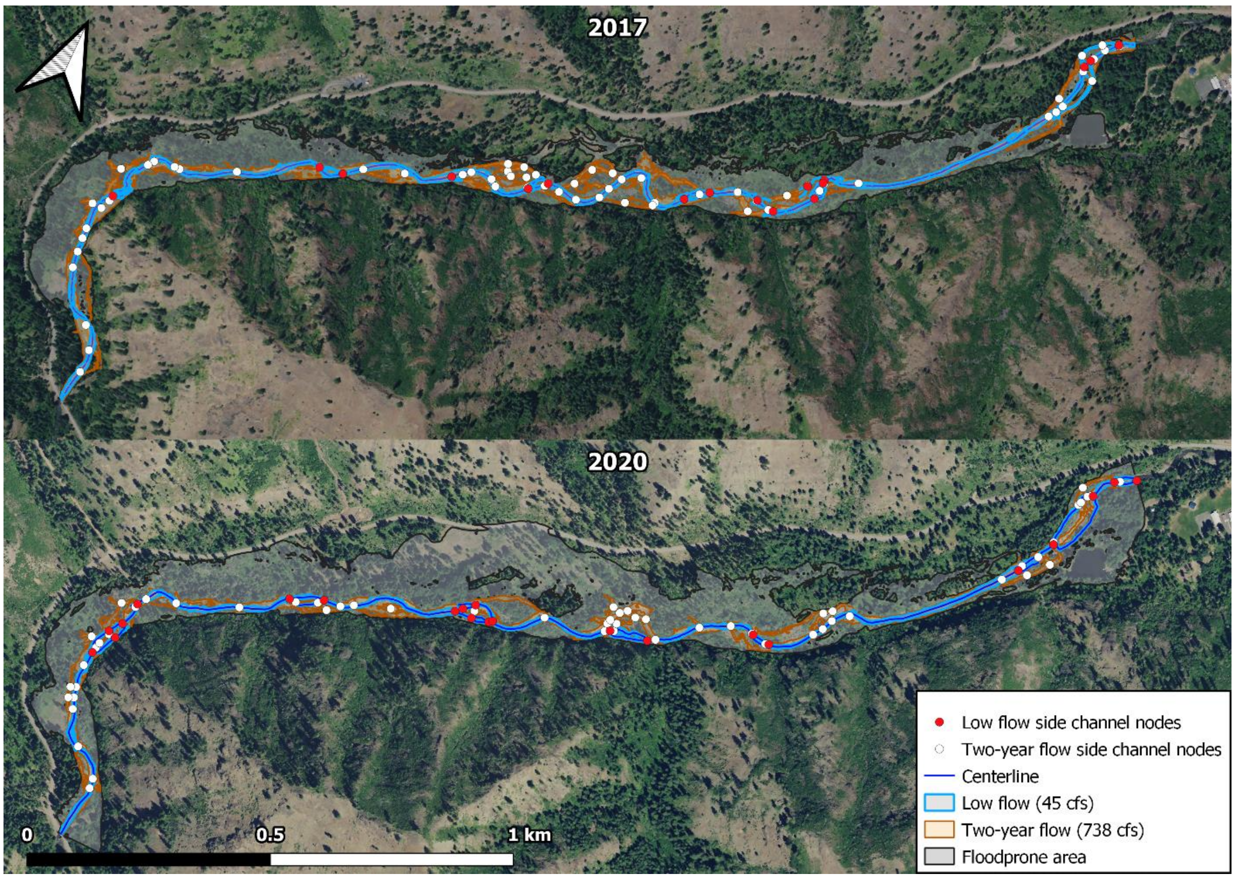


Figure 28. Comparison of the water surface extents at low flow, a 2-year flow, and the floodprone area at Tucannon PA-3 in 2017 (pre-project) and 2020 (post-project). Side channel nodes are the junctions between the main channel and each side channel entrance. Base maps are 2017 and 2020 NAIP imagery.

Bankfull area, sinuosity, and MQI increased slightly following restoration in 2018, though many other metrics decreased (Table 24). Figure 29 shows an example of the change in depth and velocity along a 600 m stretch of Tucannon PA-3.

Table 24. Summary of channel and floodplain morphology metrics for Tucannon PA-3.

Metric	Pre-project	Post-project	Percent Change
Question 3: What is the effect of restoration on channel and floodplain morphology and complexity (RCI [Brown 2002]), seasonal and perennial side channel metrics (length, area, ratio [Beechie et al. 2017]), and the morphological quality index (MQI [Rinaldi et al. 2013]) in the reach, and how does it change over time?			
Sinuosity	1.23	1.30	+6%
Wetted area (ha)	2.59	2.42	-6%
Wetted width (m)	7.71	7.24	-6%
Bankfull area (ha)	6.18	6.28	+2%
Bankfull width (m)	25.27	22.26	-12%
Bankfull width to depth ratio	8.67	7.3	-16%
Bankfull side channel count	22	19	-14%
Bankfull side channel nodes	64	59	-8%
Bankfull side channel length (km)	2.98	2.49	-16%
Bankfull side channel area (ha)	1.38	1.17	-15%
Side channel ratio	1.04	0.95	-9%
Isolated ponds/wetlands	1	1	No change
River Complexity Index (RCI)	3.03	2.96	-2%
Braiding parameter	1.26	1.29	+3%
Morphological Quality Index (MQI)	0.92	0.93	+1%

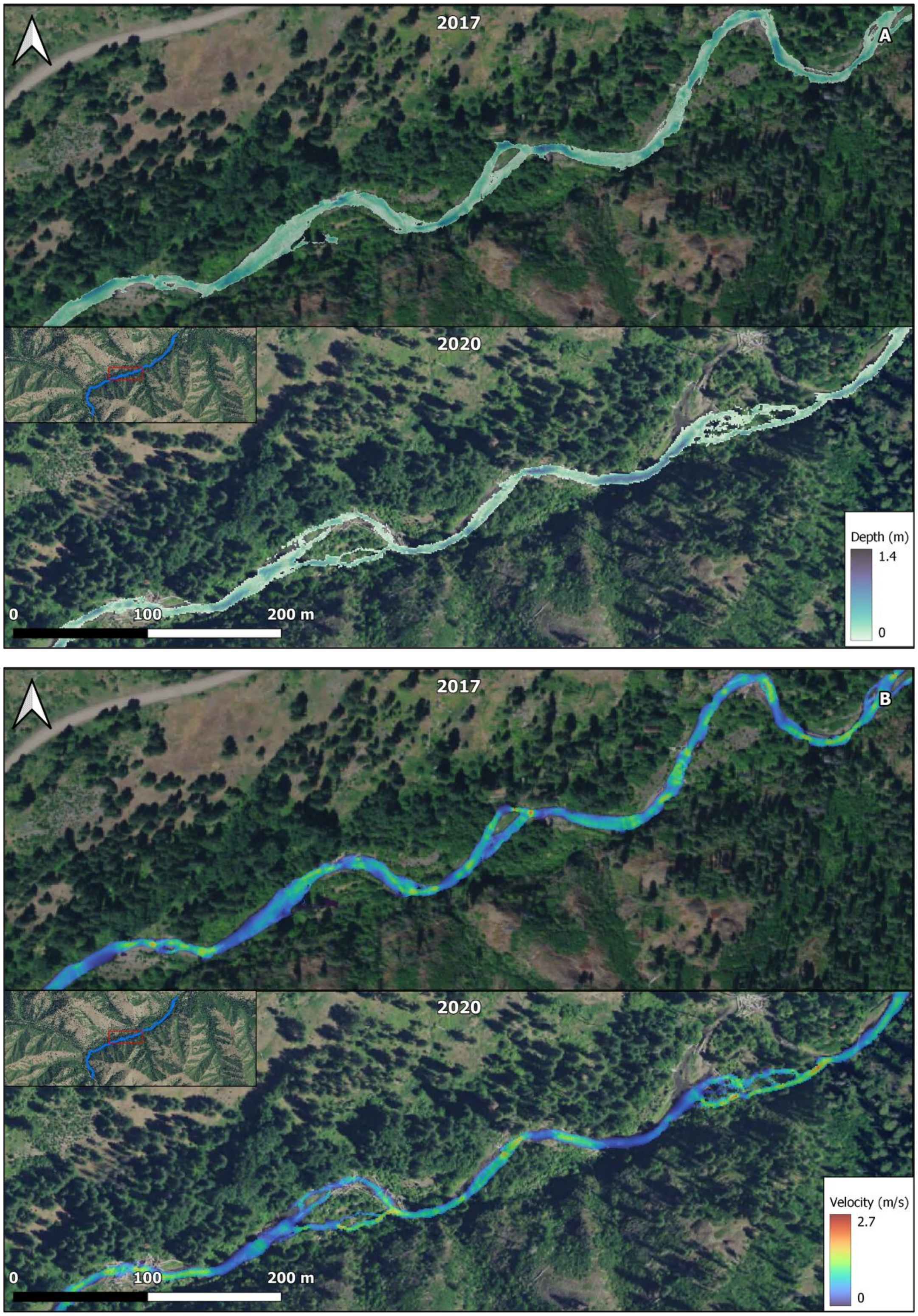


Figure 29. Modeled depths (A) and velocities (B) at a section of Tucannon PA-3 at low flow (45 cfs). Base maps are 2017 (pre-project) and 2020 (post-project) NAIP imagery.

Instream habitat composition at Tucannon PA-3 in 2017 based on our habitat classification methodology and the thalweg long profile was 83% riffle, 15% glide, and 2% pool. In 2020, instream habitat composition was 80% riffle, 19% glide, and <1% pool. Residual pool depth increased and the percentage of pool area increased from 16% to 19% (a 19% increase), The habitat classification method showed a reduction pools. By contrast, the field survey of pool habitat conducted by SNSRB found an increase in the total number of pools between 2017 and 2020 from 36 to 39 (Table 25). The GUT analysis of finer geomorphic units also suggested a decline in pool area though it is highly dependent on the quality of the bathymetric data (Table 26). A closer examination of the LiDAR data indicated that the green LiDAR did not map pools obscured by large wood. Therefore, the estimates of habitat and GUT metrics from the LiDAR data underestimated pools and other deep-water habitats and the field count of pools provided by the Snake River Salmon Recovery Board are likely more accurate.

Table 25. Summary of pool metrics and habitat diversity for Tucannon PA-3. SRSRB = Snake River Salmon Recovery Board. CFS = Cramer Fish Sciences. Number of pools (CFS) represent pools determined by the LiDAR derived thalweg profile and our habitat classification method, while the SRSRB data are based on a field survey of pools.

Metric	Pre-project	Post-project	Percent Change
Question 4: What is the number and diversity of habitat types (i.e., pools, riffles, glides, etc.) within the main channel, and side channels at different flows (low and bankfull), and how much do they change over time?			
Shannon Diversity Index (habitat units)	0.90	0.73	-19%
Percent pool area	16%	19%	+19%
Number of pools (CFS)	6	1	-83%
Number of pools (SRSRB)	36	39	+8%
Pool to Riffle ratio	0.20	0.03	-85%
Residual pool depth	0.16	0.82	+413%

Table 26. Tier 3 geomorphic units summary for Tucannon PA-3 calculated from the geomorphic unit tool (GUT) output before (pre-project, 2017) and after 2018 restoration (post-project: 2020). The percent of the total bankfull area is given in parentheses.

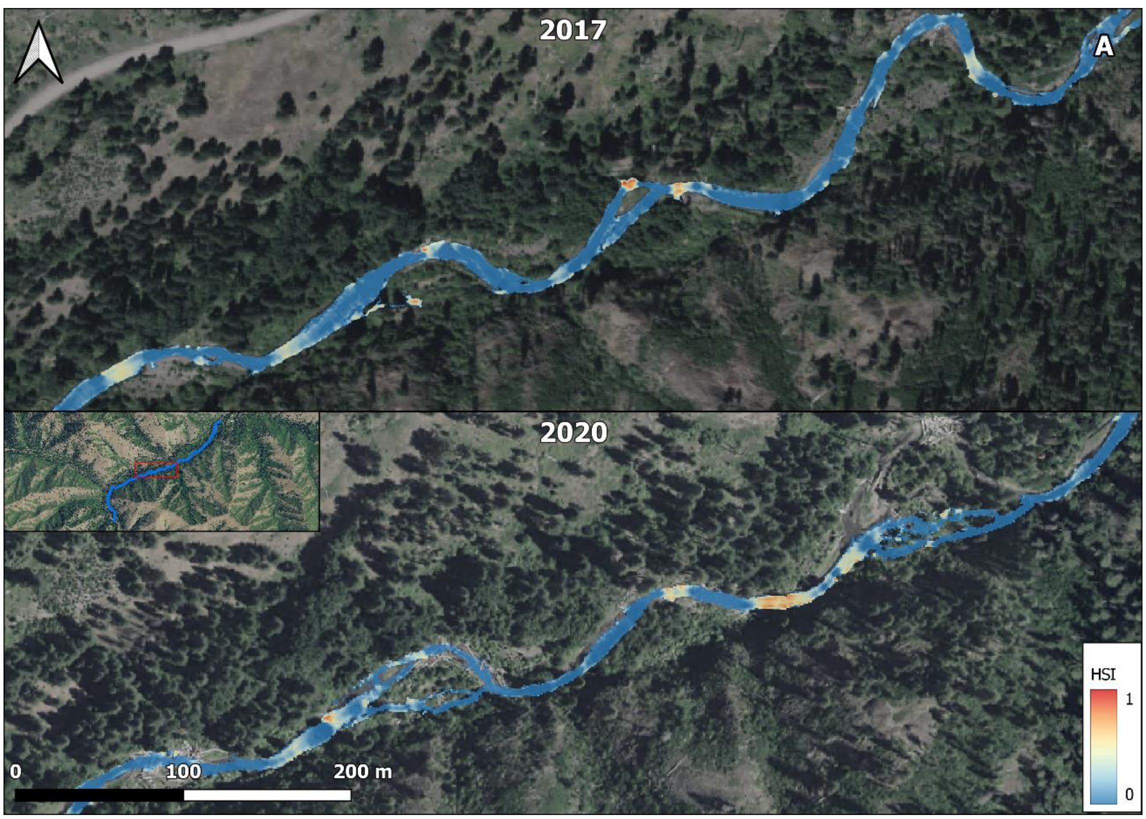
Unit Type	Area (ha)			Count		
	Pre-project	Post-project	Percent change	Pre-project	Post-project	Percent change
Bank	0.18	0.18	0%	283	291	3%
Barface	0.03	0.04	33%	145	158	9%
Cascade	0.01	0.79	7800%	2	173	8550%
Glide-Run	1.64	0.39	-76%	293	81	-72%
Margin Attached Bar	1.12	1.12	0%	497	512	3%
Mid-channel Bar	0.65	0.71	9%	198	188	-5%
Pocket Pool	0.06	0.09	50%	162	268	65%
Pool	0.79	0.59	-25%	229	201	-12%
Rapid	0.1	0.55	450%	41	125	205%
Riffle	0.03	0.01	-67%	7	3	-57%
Transition	1.68	1.8	7%	2348	2,148	-9%
Total	1.68	1.81	8%	803	6988	770%

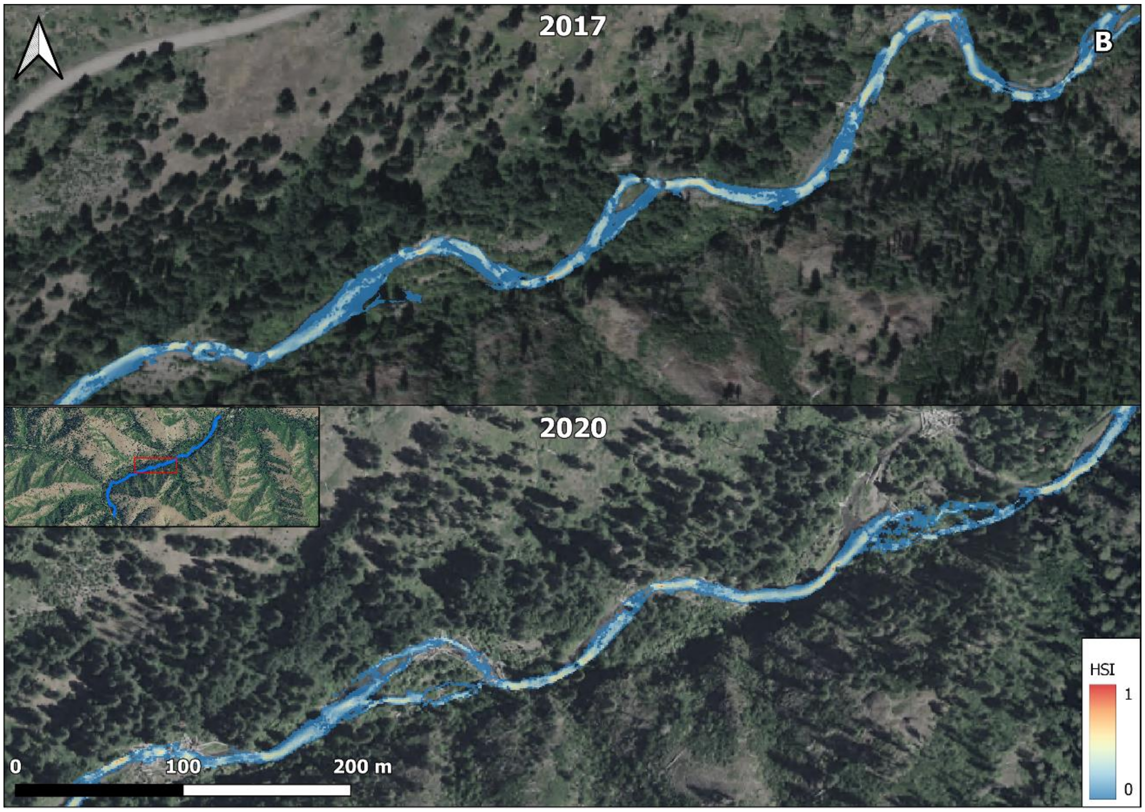
HSI

The geometric mean HSI value increased slightly at Tucannon PA-3 for all species at base flow (Table 27). The WUA at low flow (45 cfs) increased between 2017 and 2020 by 10% for juvenile Chinook, 4% for spawning Chinook, and 0.6% for juvenile steelhead Table 27; Figure 30). The WUA with high HSI values (>0.5) increased by 65%, 39%, and 140% for juvenile Chinook, steelhead, and Chinook spawning, respectively. The geometric mean, which approximates the total proportion of the reach that is suitable habitat, suggests that less than 10% of the habitat was suitable for juvenile Chinook in 2017 or 2020, while 17 or 18% is suitable for juvenile steelhead at low flows.

Table 27. Geometric mean HSI value, 50th and 90th percentiles, and amount of weighted usable area (WUA) of the habitat suitability index by species and life stage at Tucannon PA-3 at low and 2-year flow.

Species and Life Stage	Year	Geometric Mean	50^{th} percentile	90^{th} percentile	WUA (ha)	WUA HSI >0.5
Low flow (45 cfs)						
Juvenile Chinook	2017	0.08	0.00	0.27	2.17	0.34
	2020	0.09	0.00	0.31	2.39	0.56
Spawning Chinook	2017	0.11	0.05	0.32	3.22	0.10
	2020	0.13	0.06	0.35	3.35	0.24
Juvenile Steelhead	2017	0.17	0.12	0.39	4.76	0.75
	2020	0.18	0.12	0.42	4.79	1.04





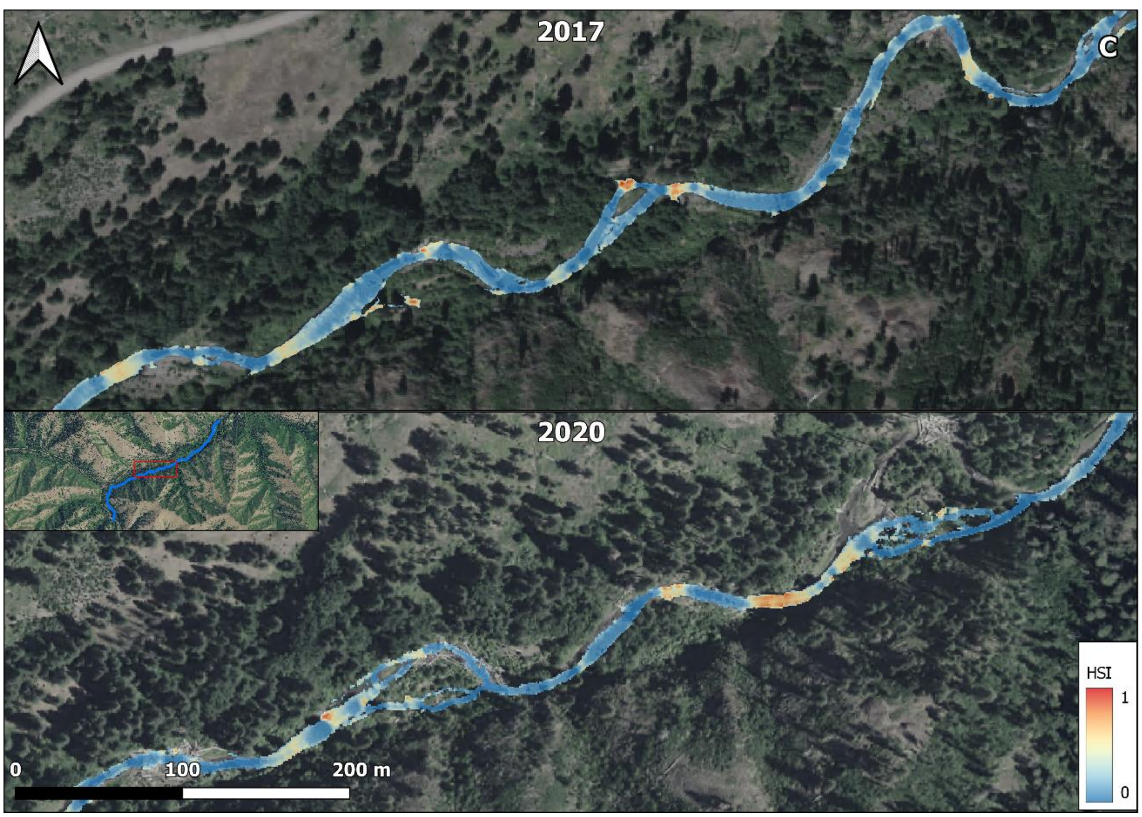


Figure 30. Habitat suitability index results for Tucannon PA-3 at low flow (45 cfs) for juvenile Chinook (A), spawning Chinook (B), and juvenile steelhead (C). Base maps are 2017 (pre-project) and 2021 (post-project) NAIP imagery.

Large wood and sediment

Large wood in the wetted channel increased from 56 to 595 pieces (116%) following restoration, with a slight decrease in wood in the bankfull channel (-7%), and considerable increase in the floodplain (45%) (Table 28). Because large wood placement was the main restoration technique these results are expected, and longer-term monitoring is needed to track wood transport in and out of the reach.

Table 28. Large wood metrics for Tucannon PA-3 estimated from LiDAR and aerial imagery. SRSRB = Snake River Salmon Recovery Board.

Metric	Pre-project (SRSRB)	Post-project (SRSRB)	Pre-project (CFS)	Post-project (CFS)	Percent Change
Question 5: What is the abundance and distribution of large wood in the active channel, wetted channel, and on the floodplain, and how do they change over time? What proportion of the wood is actively interacting with the channel?					
Year	2014	2020	2017	2020	
Data source(s)	Field survey	Field survey	LiDAR; aerial imagery	LiDAR; aerial imagery	
Large wood pieces (wetted)	56	595	38	82	+116%
Large wood pieces (bankfull)	74	441	151	140	-7%
Large wood pieces (floodplain)	142	1098	471	685	+45%
Cumulative count (pieces)	130	1036	189	222	+17%
Count of jams	32	39	15	41	+173%
Large wood frequency (pieces; #/100 m)	5.40	41.75	17.91	26.05	+673%
Large wood frequency (jams; #/100 m)	1.22	1.48	0.57	1.56	+21%

Tucannon PA-3 aggraded by an estimated sediment volume of 31,250 m^3 (Figure 31). The DEM of difference (2017 – 2021) at Tucannon PA-3 indicated that 56% of the project area (33.4 ha) has aggraded, for an estimated total sediment volume of 48,607 m^3. Concurrently, 12% of the project area (6.86 ha) has degraded, or 17,357 m^3 of sediment. The remaining 32% of the project area (19.2 ha) was stable (exhibiting no change in elevation difference). The spatial distribution of the relative elevation change is shown in Figure 31.

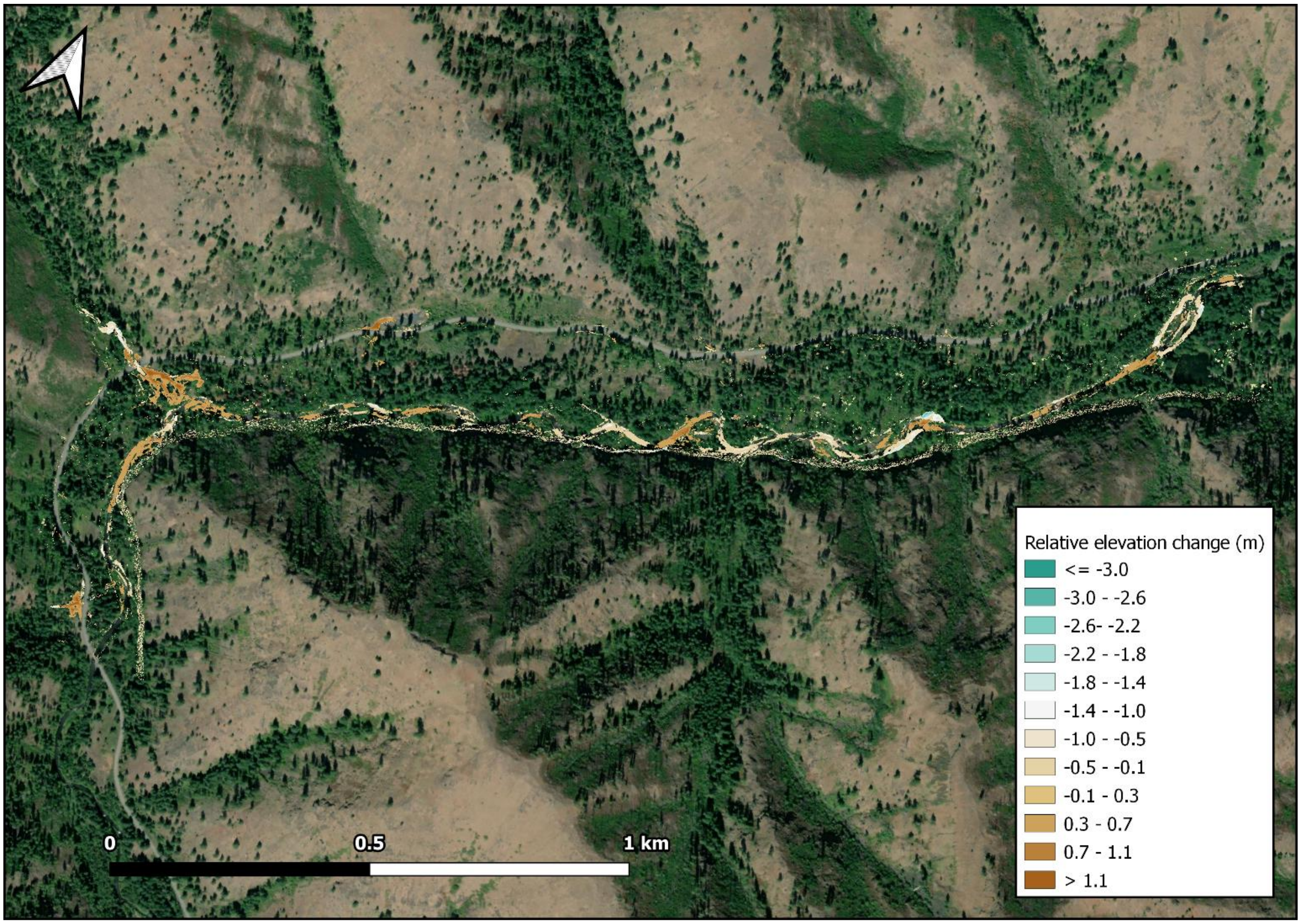


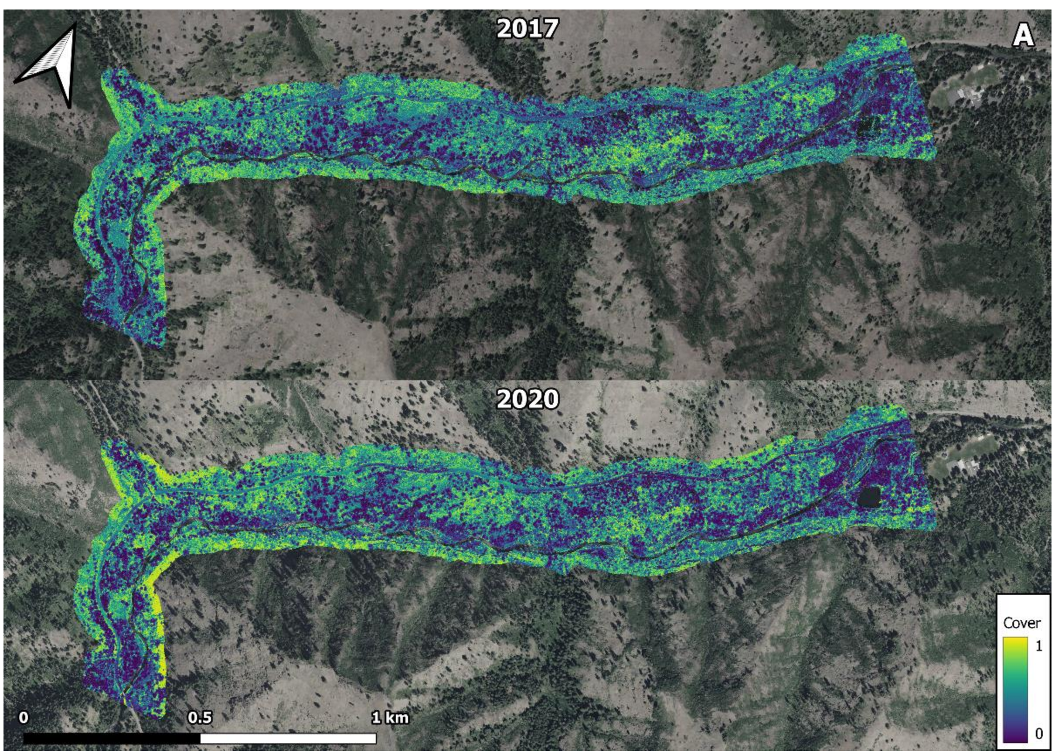
Figure 31. Relative elevation change at Tucannon PA-3 from 2017 to 2020 based on topo-bathymetric LiDAR.

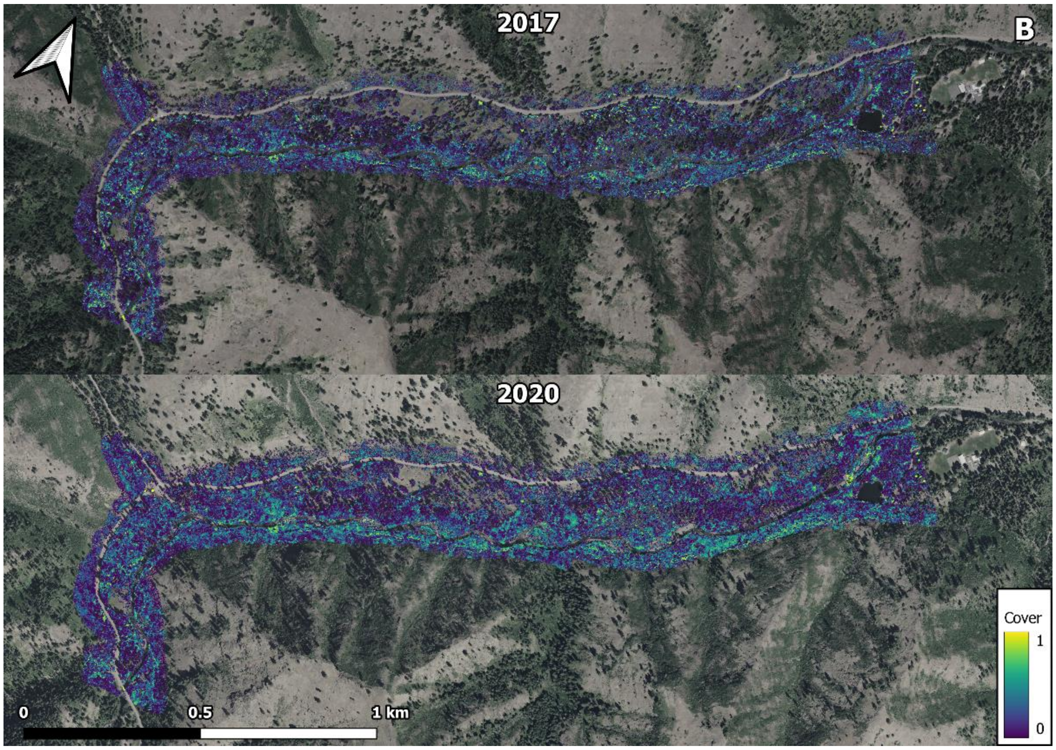
Riparian

The areal extent of riparian vegetation increased at Tucannon PA-3 from 2017 to 2020 across all size classes, with the largest increases occurring the low and mid-story vegetation (Table 29). For example, mid-story vegetation increased from 2.88 ha to 3.94 ha, a 37% increase. Low vegetation covered most of the project area in both years, while mid-story comprised the second largest height category (Figure 32).

Table 29. Summary table of the areal extent of riparian vegetation by class at Tucannon PA-3.

Metric	Pre-project	Post-project	Percent Change
What is the riparian vegetation areal extent by vegetation class (e.g., grasses, forbs, shrubs, trees, etc.), species composition, and density and how much do they change over time?			
Areal extent of low vegetation (ha)	2.88	3.94	+37%
Areal extent of mid-story vegetation (ha)	0.79	1.15	+46%
Areal extent of canopy (ha)	1.64	1.69	+3%





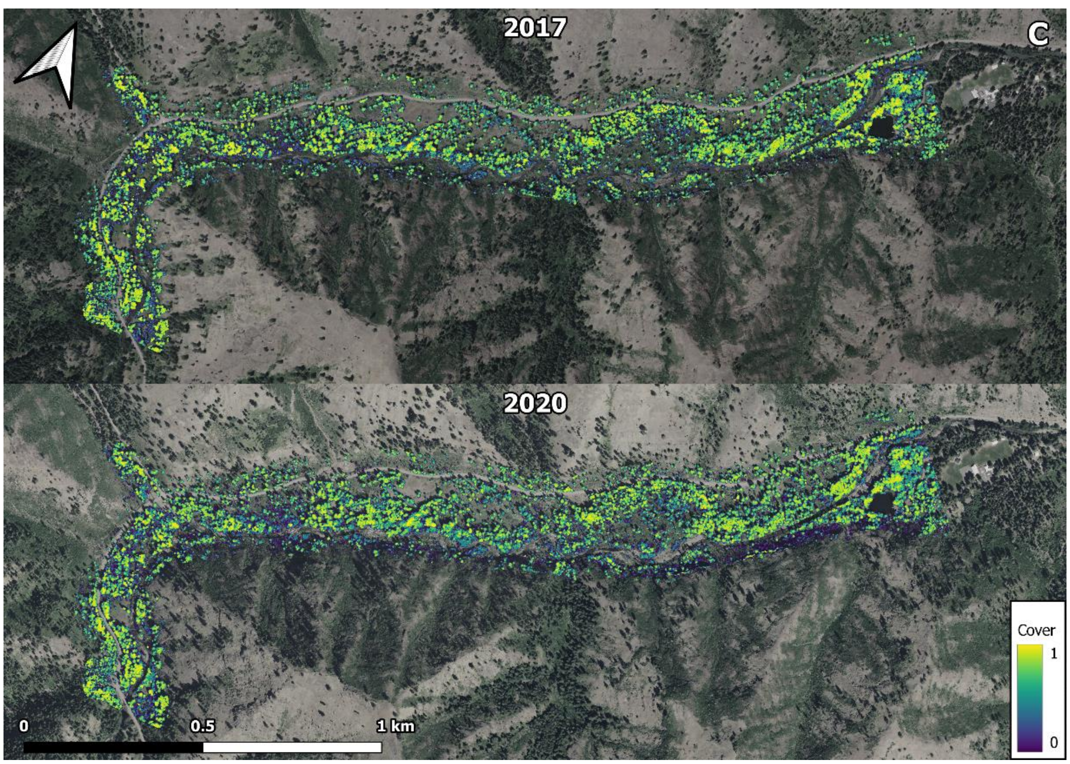


Figure 32. Areal extent of low vegetation (A; LiDAR returns < 1 m), mid-story vegetation (B; LiDAR returns ≥ 1 m and ≤ 5 m), and canopy (C; LiDAR returns > 5 m) at Tucannon PA-3. Colors in each cell represent the proportion of the cell area covered by vegetation in each height class.

The mean LPI over the wetted channel decreased from 0.71 to 0.62 or 13% from 2017 to 2020, indicating an increase in riparian shade, corroborated by an increase in organic inputs (Table 30). Figure 33 shows the change in the spatial distribution of LPI before and after project implementation.

Table 30. Summary of riparian function metrics at Tucannon PA-3.

Metric	Pre-project	Post-project	Percent Change
Question 9: Has riparian/floodplain restoration led to restored riparian function including shade, bank stabilization, and organic matter following riparian restoration?			
Light penetration index (LPI)	0.71	0.62	-13%
Organic inputs (m^3)	25,604	40,499	+58%

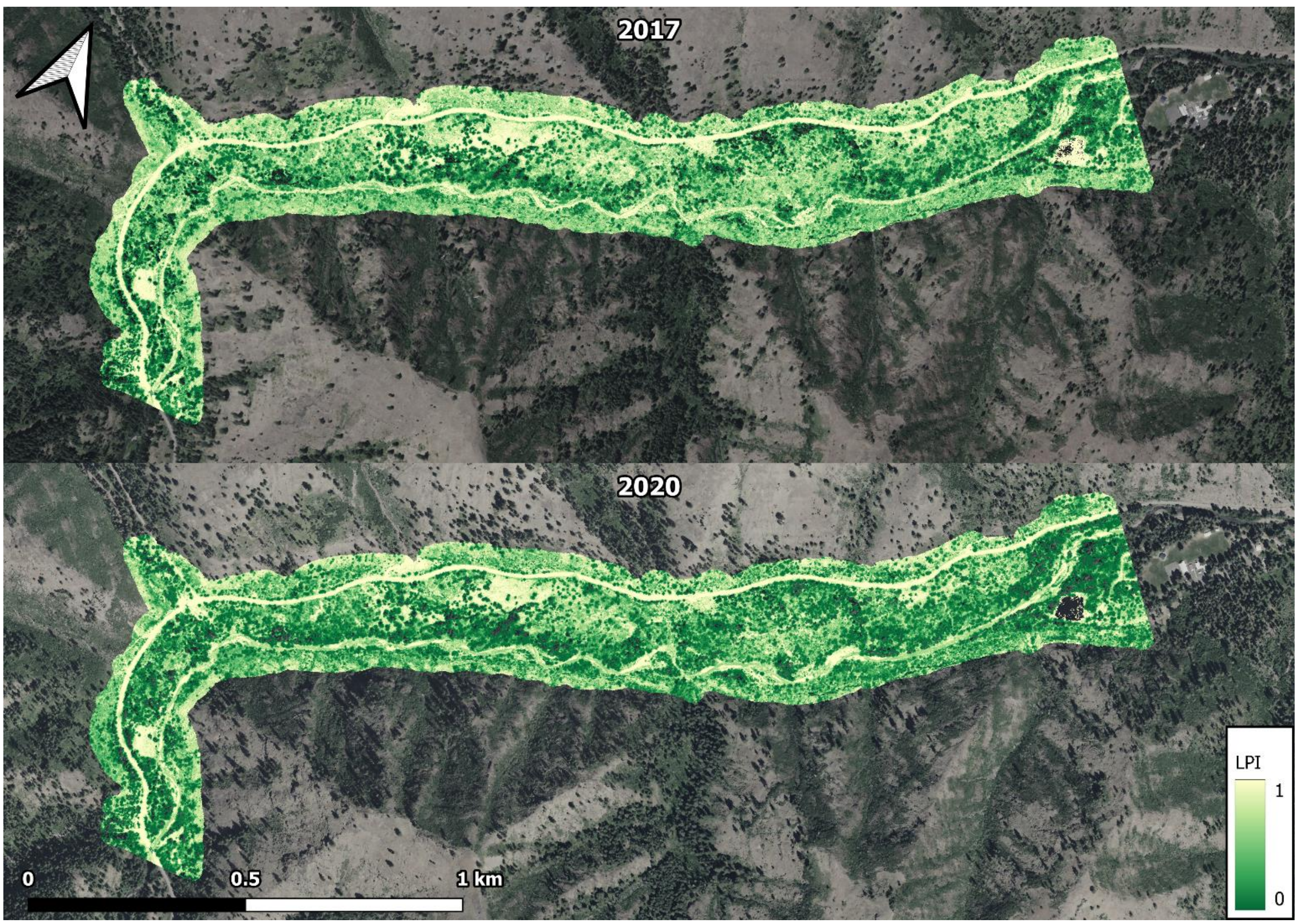


Figure 33. Light penetration index (LPI) proportion of first returns in each cell that are ground points) at Tucannon PA-3.

Design objectives

The restoration goals set for Tucannon PA-3 in the project design documents included two general goals, which were to increase LW to promote habitat complexity and improve stream channel form and function (CTUIR, unpublished data). The second major goal was to increase floodplain connectivity. The stated goals and objectives lacked detailed quantitative targets in most cases (Table 31). We did not have an as-built survey for the Tucannon project which would have allowed us to evaluate specific design elements in more detail. Regardless, we were able to assess whether the general design objectives were met to date based on our above analysis and by assigning key metrics to each objective. The objective for large wood (Objective 1.1) has been met. It is less clear for pool counts and habitat diversity (Objective 2.1) because of some issues with the bathymetric LiDAR data. The other objectives have been partially met with clear increases in some of the metrics, but not in others (Table 31). While there was a 25-year flow in the spring of 2020, the data we had was only two years after treatment (2018). Thus, additional changes have likely occurred and will occur in the future, which may warrant additional data collection and analysis. As noted previously, our analysis does not examine changes for the 2014 restoration work, but only those changes for restoration work that occurred in 2018.

Table 31. List of relevant goals and objectives listed in the Tucannon PA-3 as-built design documents (CTUIR, unpublished data), monitoring metrics used to evaluate objectives, and whether the objective was fully met (Yes), partially met (Partial), or uncertain (Uncertain). LW = large wood.

Goals and Objectives	Monitoring Metric(s)	Objective Met?
Goal 1: Increase LW for habitat complexity and to improve stream channel form and function		
Objective 1.1: Increase LW densities to > 2/bankfull width.	Large wood counts, large wood frequency	Yes
Goal 2: Increase proper floodplain structure/connectivity through supplemental wood placements		
Objective 2.1: Force pools and hydraulic variability in plane-bed sections through wood placement.	Pool counts, habitat diversity	Uncertain
Objective 2.1: Decrease instream velocities, provide additional hydraulic complexity in deep incised sections, and promote a more complex channel.	Percent pool area, RCI	Partial
Objective 2.3: Restore habitat function, improve channel structure and complexity, promote floodplain connectivity, and reactivate historic side-channels.	HSI, braiding parameter, RCI, floodprone area, floodprone inundation index, side channel metrics.	Partial

Objective 2.4: Support retention of additional LW and induce aggradation of the bed over-time increasing floodplain connection, easing channel confinement, and promoting channel migration within the reconnected floodplain area during high flows.	Sediment aggradation/degradation, channel confinement, channel migration	Partial

DISCUSSION AND RECOMMENDATIONS

The results of this pilot study demonstrated that most of the floodplain monitoring metrics we proposed to calculate in the Study Plan can be obtained with remote sensing. For example, on the Countyline and Tucannon PA-3 projects, which were previously completed, all metrics were calculated with remote sensing, except those that currently require field data (i.e., riparian species richness and diversity). Out of 29 metrics outlined in the original Study Plan, 25 could be quantified using LiDAR, hydraulic modeling, and aerial imagery. Some metrics, including riparian species richness and diversity, will likely continue to require field surveys to obtain. Moreover, the resolution (typically ≥ 10 measurements per m^2) and spatial coverage of LiDAR (virtually the entire project area) offers clear advantages over field surveys for quantifying geomorphic, floodplain, and riparian conditions. While many floodplain and channel morphology metrics can be obtained with remote sensing, other metrics will benefit from limited field data to validate and refine calculations from remotely sensed data. These include fish-habitat, large wood, HSI modeling, and riparian species composition. Based on the pilot study, we also provide recommendations for LiDAR acquisition, as-built surveys, and site selection. Responses to questions posed by the monitoring panel in the original RFQQ are provided in Appendix 1.

Fish habitat

The Study Plan called for conducting fish-habitat surveys before and after restoration. Fish habitat unit surveys were requested from each of the project sponsors; however, only one project (Upper/Lower Fobes) had complete fish-habitat survey data similar to that outlined in the Study Plan. Classifying habitat units in small streams from thalweg field surveys is a well-known, replicable method (Mossop and Bradford 2006; Clark et al. 2019). Therefore, we developed a fish-habitat classification method that uses a series of algorithms to detect instream fish habitat units from the longitudinal profile of a DEM derived thalweg down the mainstem and side-channels. Our algorithms appear to accurately classify pools based on the shape of the longitudinal profile and a residual pool depth criterion. However, additional data and fine tuning to the algorithms are required to improve its ability to distinguish glides from riffles. Most notably, data from larger rivers are needed. Issues with the quality of the LiDAR, discussed below, can also limit the utility.

Large wood

Enumerating large wood using only remotely sensed data worked well on the Entiat River (Roni et al. 2020a) but presented challenges at other sites. The protocol in the Study Plan called for using aerial imagery, which is suitable for counting and measuring wood in the active channel or at sites with comparatively open tree canopy, such as some areas in eastern Washington. However, it is difficult to map wood from aerial imagery on the floodplain, particularly under dense canopy typical in western Washington and some areas of eastern Washington. Furthermore, high quality aerial imagery is not universally available at all sites for all years. For example, the National Agriculture Imagery Program (NAIP) collects 1 m^2 resolution imagery across the United States. Even at 1 m^2 resolution, the ability to accurately identify large wood, even under open canopy, can be hampered. Furthermore, imagery is collected on a 3-year cycle, meaning that pre- and post-project imagery may not always be available for the appropriate monitoring years.

To address these challenges, we tested a method that combines LiDAR and aerial imagery to detect and count large wood at each pilot site. While we successfully used methods described in Joyce et al. (2019) and Kuiper et al. (2022), we did not explicitly validate our wood counts against field observations. However, the ability for LiDAR to detect and count large wood is dependent on pulse density (i.e., the quality of the LiDAR) (Magnusson et al. 2007; Joyce et al. 2019). Pulse density is defined by the number of pulses emitted per unit area, as measured by the footprint spacing along scanning lines (Gatziolis and Andersen 2008). Distinct from the return density, which can vary depending on the target being scanned (e.g., canopy can result in a single pulse generating multiple returns), pulse density is the only consistent measure of LiDAR quality (Gatziolis and Andersen 2008). Pulse density can be affected by laser scanner specifications and choices made during the LiDAR acquisition. Increasing altitude or flight speed to save costs, for example, can result in a lower pulse density (Magnusson et al. 2007). For reference, the USGS 3D Elevation Program, a national repository for high quality LiDAR data, sets minimum standards for inclusion at ≥ 2 pulses/m^2 (Heidemann 2012). Low pulse densities can limit the ability to distinguish true large wood features from low brush and understory. Joyce et al. (2019) tested the ability of LiDAR to detect known large wood pieces in forest plots using high density ($\geq$24 pulses/m^2) LiDAR and successfully detected 23% of the large wood present; however, detection probability plateaued at 16 pulses/m^2. In a similar study, Jarron et al. (2021) successfully detected 64%

of measured large wood in circular forest plots from LiDAR (10 pulses/m^2 average pulse density). While most of the LiDAR used in our study exceeded 16 pulses/m^2, the pre-project pulse density at the Countyline reach was 1.2 pulses/m^2. Pre- and post-project LiDAR should be of similar quality to make valid comparisons; therefore, LiDAR derived pre-project floodplain wood counts at Countyline should be viewed with caution.

Given the challenges with using LiDAR to enumerate large wood, it may be more appropriate to view LiDAR derived large wood counts as an index of abundance rather than a true number. Nonetheless, LiDAR still provides some advantages over other methods, most notably is the ability to detect large wood instream and under canopy. Further, if the pre- and post-project LiDAR are of similar and acceptable quality, valid comparisons can still be made to assess the direction and magnitude of change. Supplemental field surveys, potentially done concomitantly with riparian vegetation surveys, could help validate and correct LiDAR counts. Wood counts could be incorporated into the riparian surveys as a method for validating remotely sensed estimates of large wood. Regardless, wood placement was a key design component in all projects we evaluated for this study; therefore, it should be expected that large wood counts will increase in the immediate years following restoration. Long-term monitoring of wood (>10 years) and its function (interaction with active channel) is ultimately required to determine success for wood loading projects.

Riparian surveys

We performed riparian surveys on the South Fork Nooksack in the summer of 2022, prior to restoration of the Lower Fobes site, with the primary goal of validating the remote sensing-derived riparian metrics and identifying species composition. We collected species and cover data to test and refine methods. After analyzing and processing these data along with the remote sensing data, we have several recommendations for future data collection efforts. The Study Plan aimed to evaluate the impact of floodplain restoration on the total area of riparian vegetation, species composition, density, and function. We demonstrated that vegetation area and height can be derived from the LiDAR, with field surveys being used primarily for validation and to calculate species richness and diversity.

Given the goals of the riparian monitoring in the Study Plan and our observations at pilot sites, we recommend some modifications to the riparian monitoring protocol. Rather than one transect every hundred meters, which would have resulted in more than 20 transects on both sides of the river at the Upper/Lower Fobes site, we recommend delineating ten equally spaced transects, with equal transect lengths determined by the planting extent, throughout the project area. Within each 2 m belt transect, we recommend identifying the woody species present, estimating the dominant species, and evaluating the percent of transect covered by the three height classes of native and invasive vegetation. By streamlining field surveys to only collect data needed to validate LiDAR and identify species present, we can meet the goals of the study and subsequently allow for more time to perform in-depth analyses or additional monitoring visits. As noted in the large wood section, one addition to the protocol would be to enumerate large wood in each transect to use in validation of wood counts from LiDAR and aerial imagery. In addition, while bank stability was one of the riparian metrics, it was not available at Countyline or Tucannon PA-3. It is likely not an appropriate metric at most floodplain restoration sites as they are often promoting erosion deposition and channel migration. Thus, the inclusion of bank stability as a metric is likely only appropriate at sites with a history of agriculture or grazing.

Habitat suitability

The modeling of habitat suitability provides an index of the amount of suitable habitat for a given species and life-stage and is a useful tool for both designing and evaluating restoration. While HSI is correlated with fish abundance, it is not a direct measure (Gallagher and Gard 1999; Boavida et al. 2013; Railsback et al. 2017; Wheaton at al. 2018; Roni et al. *in press*). Furthermore, HSI results are both sensitive to, and carry forward, the assumptions of the hydraulic model and the habitat suitability curves used as inputs. Methods continue to be developed to improve hydraulic model representation of the channel and channel roughness (large wood), but most HSI modeling continues to use habitat preferences curves developed in other streams many decades ago. The selection of the preference curves in the HSI modeling process can influence the HSI values and amount of suitable habitat (Railsback 2017; Roni et al. In press). For our HSI modeling we used depth and velocity preference curves Maret et al. (2006) and Raleigh et al. (1984), which are some of the more commonly used curves. Ideally, one collects river-specific habitat preference data and develops sites specific criteria curves for HSI modeling, though it is rarely done. Thus, a simple recommendation to improve HSI modeling would be to collect site-specific depth and velocity preference data for species of interest and develop habitat suitability curves specific to each river or site. This would likely require a rather limited field effort to observe fish and collect depth, velocity, and other data at each site. Data could also be collected at a couple of key flows and seasons to improve the accuracy of HSI values; this has rarely been done (existing preference curves are not flow specific), but would require a larger field effort.

LiDAR acquisition

It is important that green LiDAR be collected under ideal conditions (Countyline case in point), otherwise many floodplain monitoring metrics will be biased or inaccurate. The ideal time for green LiDAR data collection is just after leaf-off and before any fall rains (western Washington). However, collecting LiDAR during leaf-off will underestimate the amount of canopy cover, shade, and organic inputs. The post-project LiDAR for Countyline was collected in April when flows were above 1500 cfs. Because the White River is glacially fed, winter and spring represent periods of potential high-water clarity and low flow, while summer flows are high and extremely turbid. However, it appears that slight turbidity during the 2022 LiDAR acquisition may have resulted in poor penetration through the water column. We also saw issues with LiDAR on the Tucannon where the LiDAR did not penetrate logjams and thus did not accurately map bathymetry and pools in areas with channel spanning logjams.

In general, LiDAR contractors do not collect bathymetric validation data in water deeper than 90 cm and while their models may appear accurate, additional ground truthing is often needed. The LiDAR report for the Countyline project had indicated good penetration in all but a few very deep locations, so our field survey focused on those areas. However, our field survey data suggested that the LiDAR based DEM was inaccurate for much of the deep (>1.5 m areas of the channel). Green LiDAR can accurately map the bathymetry in medium to large sized rivers with clear water at low flow and we have seen this on other larger rivers such as the Entiat and Bogachiel. However, for large and deep rivers with persistently high turbidity, a more exhaustive supplemental bathymetric field survey should be conducted. One option would be to continue to use field surveys to classify fish habitat data while collecting additional bathymetric data simultaneously to fill in any potential holes in the LiDAR data due to depth, turbidity, or logjams that cover entire channel in smaller channels.

As-built surveys

We did not have as-built surfaces for either Countyline or Tucannon PA-3. Moreover, the design criteria in the basis of design reports for these two projects was general and lacked specific targets Thus, we recommend that project sponsors define the expected change in key metrics (low, medium, or high) for each restoration project prior to or during the project implementation phase. This will ensure that specific design elements can be properly evaluated to determine if restoration targets were met and will provide guidance on future project designs (Table 32). Requesting that sponsors provide a list of specific project design criteria would support consistency among projects and allow for the development of a concise “report card” for each project. A one to two page report card could be prepared to quickly convey project results and successes and lessons learned to project sponsors, managers, and other interested parties. There are detailed design criteria for the Middle Entiat project and we will provide additional recommendations for as-built surveys in that report. We worked closely with the Lummi Tribe to collect as-built survey data for the Upper/Lower Fobes project, which was largely successful. However, it is important that as-built survey protocols are consistent among projects. Further, while many contracts for restoration projects require as-built design sheets, they do not provide the level of detail needed for monitoring. Therefore, the as-built surveys should be collected as part of the monitoring program, rather than relying on the sponsor or their contractor to collect the data.

Table 32. Example of setting project targets for monitoring metrics that will help coordinate goal setting at the design phase and allow evaluation of those targets during monitoring. L = < 25% change, M = 25% to 50% change, H = > 50% change. All metrics, except riparian metrics, are assumed to change within 3 to 5 years or following channel-forming high flow events (≥ 2-year flow for more than 24 hours). Riparian metrics may take 5 to 10 years or more. Monitoring questions were outlined in Table 2.

Metric (Monitoring question number)	Expected Change
Floodplain area (1)	M
Floodplain inundation index (1)	M
Area altered (1)	M
Active channel zone (2)	H
GUT (2)	H
Side channel metrics (3)	H
Pond/wetland area (3)	L
Sinuosity (3)	L
Bankfull width and depth (3)	M
RCI (3)	H
MQI (3)	M
Pool area, ratio, percentage (4)	H
Shannon diversity index (4)	H
Large wood metrics (5)	H
Sediment deposition and storage (6)	M
DEM of difference (6)	H
WUA spawning (7)	M
WUA rearing (7)	H
Areal vegetation extent by class (8)	M
Riparian composition, richness, diversity, and density (8)	M
Bank stability (9)	L
Shade (Light Penetration Index) (9)	H
Organic inputs (9)	M

Site selection

We worked closely with the Monitoring Panel to select pilot sites. The criteria we considered included: year of implementation; availability of pre-project green LiDAR, DEM, and hydraulic model; project size (> 1 km of mainstem), and landowner access or willingness. These are still key considerations in site selection. Based on our experience with the pilot project, we have several recommendations for selection of future sites. First, as far as the size of projects, one kilometer of mainstem channel length is sufficient, assuming that the entire length or project area is restored. If only parts of a reach are restored, which is fairly common, a mainstem length closer to two kilometers would be appropriate to justify the cost of acquiring the remotely sensed data. However, it should be noted that the methods detailed in this report can be used on almost any size project, including projects only a few hundred meters in length. Smaller projects may not warrant using a fixed winged aircraft to collect green LiDAR and it might be more cost effective to use a drone-based near-infrared LiDAR for small sites with a supplemental field survey to obtain bathymetry. The Study Plan provides a summary of cost trade-offs between drone based near infrared LiDAR and fixed wing green LiDAR acquisition and at what site size each is warranted (Roni et al. 2020b). Most drone-based LiDAR sensors emit on the near-infrared spectrum, which does not penetrate water. This may change in the next five years as it is likely that reliable and economical green LiDAR sensors that can be deployed with a drone will become available. Another consideration is the width of the project and floodplain. Again, almost any size project can be evaluated with remote sensing techniques, but projects with narrow floodplains or very small streams will show limited change in side channels and floodplain area.

Second, the original Study Plan calls for selection of yet to be implemented floodplain and riparian projects, with data collection before and after restoration and an abbreviated as built survey. We included two completed projects that had green LiDAR available. While we were able to calculate most metrics for these sites, considerable time was spent acquiring existing data including the LiDAR data, hydraulic model outputs, and other information. It would be easier to select sites that are scheduled for restoration so that we could work with project sponsors to acquire the necessary pre-project data, design documents, and goals. Further, by being involved throughout the entire project timeline, we could provide guidance and ensure collection of pre-project and as-built data will be suitable for addressing restoration goals. If additional completed projects are included in the program, allocating time for additional coordination and data summarization will be beneficial.

Moreover, many projects are using wood placement to improve instream conditions and reconnect the main channel with the floodplain. Thus, there is the potential for projects that are primarily wood placement and instream habitat projects to be classified as floodplain restoration projects when, in fact, there may be little actual effect on floodplain monitoring metrics. Confirming that a wood placement project is truly designed to restore the floodplain should occur during the site selection process.

Highly modified stream reaches (e.g., Countyline) presented some challenges for quantifying classic floodplain monitoring metrics. We relied on hydraulic models to simulate a bankfull flow and assumed a 2-year flood recurrence interval would represent bankfull flow. However, hydraulic modeling suggested that a 2-year flow at Countyline would overtop the banks and inundate most of the available floodplain. As such, many classic monitoring metrics (e.g., side channel metrics) could not be calculated at bankfull flow at the Countyline project. However, it should be noted this was not an issue on any of the other pilot sites, and unique to highly modified sites or sites with set-back levees. If additional sites with highly modified floodplains and hydrology are selected in the future, developing a consistent approach for selecting appropriate flows to calculate key floodplain metrics would be beneficial

SUMMARY

The pilot study demonstrated that, with minor modifications, the Study Plan metrics can be accurately calculated with remotely sensed data and limited field data. Moreover, the proposed metrics can be used to monitor and evaluate changes in floodplain, geomorphology, habitat, riparian, and fish-habitat conditions and suitability due to restoration. We provide the following recommendations based on the results of the pilot study:

- The quality and timing of green LiDAR collection are important for accurate and consistent calculation of metrics before and after restoration.
- Supplemental field data collection of bathymetric and fish-habitat data will be needed at some sites due to depth, turbidity or large wood jams that may prevent accurate mapping of bathymetry with green LiDAR.
- The intensity of the riparian field survey proposed in the Study Plan can be reduced because some metrics can be mapped with LiDAR, but riparian field surveys are still needed for some riparian metrics.
- Large wood can be enumerated using remote sensing techniques, but mapping floodplain wood during riparian surveys should be used to correct remotely sensed wood counts.

- The collection of site-specific habitat preference data for key fish species and life stages could be used to improve HSI mapping at various flows.
- As-built surveys and evaluation of design criteria for each site would benefit from consistent design criteria and matrix across projects.
- In addition to standard reporting, a brief two-page project report card should be developed for each project evaluated to quickly convey results and lessons learned to a broad audience.
- The methods in the Study Plan can be used on completed projects if appropriate data are available, but the pilot study demonstrated variability in data quality across project sponsors and years. Thus, ideally selection of new sites should focus on projects that are not yet implemented or will be implemented in 2023 or beyond to allow collection of data of consistent quality before and after restoration.
- Finally, while the methods are most efficient at large projects covering more than one or two kilometers, they could be used on smaller projects, though it may not be as efficient or cost-effective.

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APPENDIX 1: RESPONSES TO RFQQ QUESTIONS

RFQQ Questions:

Did these techniques detect changes in habitat, as predicted?

The techniques were able to detect changes in habitat, floodplain, geomorphic, and riparian conditions. This is most apparent at Countyline where a levee and engineered logjams were placed, but also at Tucannon PA-3, which focused on large wood placement. As noted previously field validation is still needed for a handful of metrics and to collect supplemental bathymetric data where LiDAR has difficulty mapping the stream bottom.

Did the focus on large-scale floodplain restoration efforts, whose actions aimed at reconnecting rivers with natural floodplains, improve off-channel spawning and rearing habitats and restore native riparian plant communities?

It is clear that the large floodplain projects, such as Countyline, improved spawning and rearing habitat, as is demonstrated by the change in fish habitat, geomorphic units, and more importantly, habitat suitability as demonstrated by HSI modelling.

What are the advantages to and/or limitations of using remote sensing to measure restoration-related habitat changes in floodplains following flood events? Can remote sensing provide a scientifically supported evaluation of restoration-related habitat changes in floodplains following flood events?

Remote sensing, specifically LiDAR, offers clear advantages for assessing floodplain restoration projects because it can rapidly map the entire floodplain with high degrees of precision and accuracy, provided a minimum pulse density threshold is met during acquisition (typically $\geq$ 8 pulses/m^2). However, for some metrics (e.g., large wood), a pulse density $\geq$ 10 pulses/m^2 would be ideal which is typical for current LiDAR but lacking for some older LiDAR data. Such level of spatial resolution is not possible with traditional field survey methods. Moreover, some supplemental field surveys are needed to ground truth green LiDAR particularly at sites with deep or turbid water (County Line) or dense large wood (Tucannon). As with any data collection method, LiDAR and aerial imagery are snapshots in time. Currently, the Study Plan outlines data collection either 3 years post-project or following any channel-forming flow ($\geq$ 2-year flow). However, the methods we tested are scientifically robust and can be repeated after any high flow event, assuming updated topo-bathymetric data are collected.

How effective are the associated riparian improvements and verification of stream topographic profiles?

Currently, we only have extensive post-project riparian planting data for the Countyline site. It is evident from LiDAR analysis that planting has increased canopy cover in the 5 years after planting, particularly for taller shrubs and trees. Understory and shrubs decreased, in part because the river is reworking a large former isolated wetland, causing extensive aggradation following removal of the levee. Changes in topography were also evident from the LiDAR at all sites (Pre-project and as-built data only at Upper/Lower Fobes).

How well did other techniques that use fixed-wing or remote-controlled drone devices perform (i.e., thermal imaging, high resolution photography)? Should they also be evaluated?

Because of the size of the sites in question, fixed-winged aircraft was used to collect LiDAR. We know that drone-based near-infrared LiDAR coupled with a field bathymetric survey may be cost effective for smaller sites (sites covering less than 1 km of stream or 100 ha). We used satellite and 1 m resolution NAIP imagery to help identify large wood; however, higher resolution drone imagery would help improve in-channel large wood estimation and on the floodplain under open or semi-open canopy. Satellite or high-resolution imagery can be used to map vegetation types, condition, and some species, but cannot provide height, light penetration (shade), and other riparian metrics. We did not have or collect thermal imagery at any of the sites, but it is first necessary to determine if any specific questions or metrics require thermal imagery.