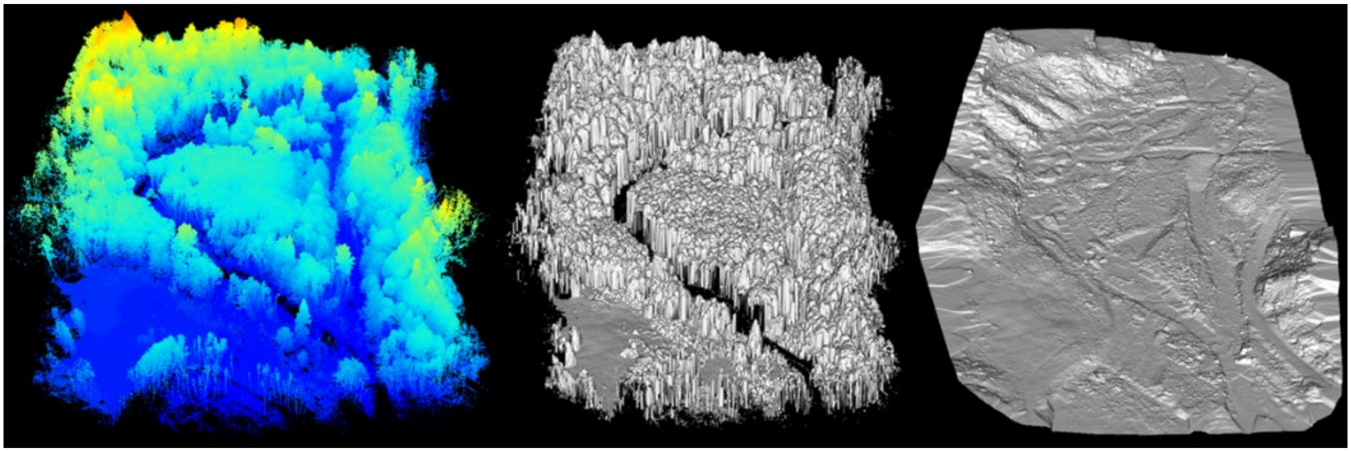
USING REMOTE SENSING AND OTHER TECHNIQUES TO ASSESS AND MONITOR LARGE FLOODPLAIN AND RIPARIAN RESTORATION PROJECTS



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Created: June 15, 2020

Suggested citation: Roni, P., C. Clark, K. Ross, R. Camp, M. Krall, J. Hall, and R. Brown. 2020. Using remote sensing and other techniques to assess and monitor large floodplain and riparian restoration projects. Recreation and Conservation Office, Olympia, Washington.

EXECUTIVE SUMMARY

The Washington State 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. In addition, 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 was contracted by the Recreation and Conservation Office to work with the SRFB Monitoring Panel to develop a monitoring and evaluation plan for large floodplain and riparian projects that leverages the latest remote sensing techniques coupled with field data. To achieve this, we first worked closely with Monitoring Panel to refine the objectives and questions to be answered by the evaluation program. Objectives identified were that the monitoring program should focus on results at the project level, focus on physical and riparian response, and produce results within 5 to 10 years; that annual costs not exceed $250,000 to $300,000; and that the program avoids 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 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?

Next, we identified key response metrics to answer these questions and reviewed the latest remote sensing and monitoring methods to determine the best methods for measuring these metrics. For most questions and metrics, the ideal protocols use a combination of LiDAR (Light Detection and Ranging) to capture topography and bathymetry and riparian conditions across sites coupled with field data collection to validate estimates from LiDAR and calculate metrics that require field-based methods. Based on recently published guidance, lessons from other regional monitoring programs, and the questions and objectives describe, we identified a before-after (BA) design as the most appropriate method to monitor physical response. The lack of adequate remote sensing data—green-LiDAR coupled with required field data—for existing projects largely precludes the use of previously completed projects or a post-treatment design to answer the monitoring questions defined. Therefore, a subset of large floodplain and or riparian projects proposed to begin construction in 2021, 2022 or 2023 will be selected for monitoring.

Projects will be stratified by the eight recovery regions, which will allow the recovery regions to provide input on site selection. This is possible because the level of inference is at the project scale and the study does not require a random sample. This design allows for both the evaluation of individual projects (project-level inference) as well as a roll up and analysis of all projects collectively. Site selection will be done as part of study implementation and a list of candidate projects should be sent to recovery regions as soon as possible. In addition to when the restoration will begin (2021, 2022 or 2023) and be completed, key criteria for site selection include that: a project is 1 km or greater in length, no other habitat management actions will be implemented other than restoration in the foreseeable future, and an adequate buffer of 20 times bankfull width exists at upstream and downstream boundaries of project footprint. The number of sites that can be sampled is limited largely by the cost of acquiring topography and bathymetry (LiDAR), which we estimate will limit sampling to 6-10 sites total, with monitoring at half of the sites initiated in 2020 and the other in 2021. The sampling schedule for sites will be a combination of flow-based and periodic, with sites to be sampled one year before restoration, immediately after restoration is completed (year 0, as built), and at 3, 5, and 10 years after restoration. However, if, for example, in year 1 or 2 after restoration, a 2-year (bankfull) or higher flow event occurs, monitoring will be initiated sooner (year 1 or 2 rather than 3).

Metrics, site layout, methods, and protocols for remote sensing and field data collection necessary to answer the questions are described. Methods were informed by two recent pilot studies to examine remote sensing techniques for evaluating small (<1 km of mainstem) and large (1 to 8 km of mainstem) floodplain projects, a recent extensive literature review, and, methods recently developed for monitoring riparian projects in the Columbia River Basin. Data collection will occur in late summer for field data and after leaf-off for remote sensing (LiDAR). Because of the size of the sites and that the corresponding response should be large (>25% change), data analysis at the individual sites (projects) will focus on graphical summaries and statistical summaries before and after restoration and through time. Evaluation of the efficacy of restoration design for floodplain projects will use a combination of hydraulic modeling and habitat suitability modeling coupled with geomorphic analyses (e.g., geomorphic unit tool, DEM of differences). In contrast, combined analysis across projects will use mixed-effects ANOVA or similar approach. Other monitoring programs have been challenged with data management and reporting, and we outline a detailed plan for both in order to ensure timely reporting of results to inform restoration projects and programs and to adaptively manage the monitoring program. Potential challenges for a study like this are largely related to implementation such as site selection, consistent data, or attempting to monitor additional metrics without adequate funding. However, these can be overcome by following the methods and recommendations provided in the study plan based on pilot studies and lessons learned from other large monitoring and evaluation programs. Finally, we outlined complementary studies such as monitoring changes in water temperature or flow using data loggers that would enhance this monitoring and evaluation program and could be implemented by partners or if additional funding were available.

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List of Acronyms

ADCP	Acoustic Doppler Current Profiler
AEM	Action Effectiveness Monitoring
BA	Before-After
BACI	Before-After Control-Impact
BFW	Bankfull Width
BOS	Bottom of Site
BPA	Bonneville Power Administration
CHaMP	Columbia Habitat Monitoring Program
DEM	Digital Elevation Model
DNR	Department of Natural Resources
DoD	DEM of Difference
DSM	Digital Surface Model
eDNA	Environmental DNA
EPT	Extensive Post-Treatment
ESU	Evolutionary Significant Unit
FLIR	Forward-Looking Infrared
GPS	Global Positioning System
GUT	Geomorphic Unit Tool
HSC	Habitat Suitability Curve
HSI	Habitat Suitability Index
GSRO	Governor's Salmon Recovery Office
IMW	Intensively Monitored Watershed
IPT	Intensive Post-Treatment

ISEMP	Integrated Status and Effectiveness Monitoring Program
LiDAR	Light Detection and Ranging
LW	Large Wood
mBA	Multiple Before-After
mBACI	Multiple Before-After Control-Impact
MQI	Morphological Quality Index
NAIP	National Agriculture Imagery Program
PE	Project Effectiveness
PCSRF	Pacific Coastal Salmon Recovery Fund
RCO	Recreation and Conservation Office
RTK	Real-Time Kinematic
SfM	Structure from Motion
SRFB	Salmon Recovery Funding Board
TOS	Top of Site
WUA	Weighted Usable Area

1.0 INTRODUCTION AND BACKGROUND

The Washington State legislature created the Governor's Salmon Recovery Office (GSRO) to provide a statewide salmon recovery plan and the Salmon Recovery Funding Board (SRFB) to distribute funds earmarked for salmon habitat restoration and protection. Since 2000, the SRFB has invested more than 1 billion dollars in salmon recovery and habitat restoration efforts (GSRO 2018). Federal and state funding agencies needed a way to evaluate and document success of these restoration actions. To meet this need, in 2002, the SRFB provided criteria for the monitoring and evaluation of salmon recovery in their Washington Comprehensive Monitoring Strategy and Action Plan for Watershed Health and Salmon Recovery (MOC 2002). The monitoring strategy aimed to identify monitoring efforts and priority needs and also described the need for statewide project monitoring coordination and a succinct monitoring strategy. In 2004, Washington State established a reach-scale effectiveness monitoring program (Project Effectiveness Monitoring or PE) to assess the response of stream habitat and localized salmon populations to salmon habitat restoration efforts.

The SRFB PE Monitoring Program included monitoring and evaluation discrete categories including fish passage, instream habitat, riparian planting, livestock exclusion, constrained channel, spawning gravel, diversion screening, estuary restoration, and habitat protection. Final data collection was completed in 2018 and a final report was completed in 2019 and detailed findings to date and recommendations for future monitoring. While PE monitoring demonstrated that fish passage projects were successful at increasing juvenile fish numbers (fish passage) and livestock exclusion and instream habitat projects at improving habitat conditions, the results for floodplain and riparian projects were largely inconclusive due to many implementation, procedural, and data management problems seen in other large monitoring programs (e.g., proper site selection, lack of stratification, timing of data collection, data analysis, protocol changes, and data management; Reid 2001; Roni et al. 2018; Rosgen et al. 2018), not the least of which was the sheer difficulty in maintaining a large network (30 or more) of treatment and control sites over more than a decade (Roni et al. 2019b). The final PE report provided detailed recommendations on how to overcome these in the future and recommendations on which project categories needed additional monitoring. Based on results from PE and other large completed and ongoing monitoring programs (e.g., Roni et al. 2015a; Clark et al. 2019, 2020), instream habitat and barrier removal did not warrant additional effectiveness monitoring. In contrast, the final report recommend that additional monitoring was needed for floodplain restoration, riparian restoration, and possibly estuarine and nearshore restoration projects.

In addition, the final report emphasized the need to evaluate large projects as most effectiveness monitoring has focused on small projects that range in size from a few hundred meters to a kilometer.

Other large monitoring programs provide similar lessons on the most appropriate methods for future programmatic evaluation of restoration projects. The Columbia Habitat Monitoring Program (CHaMP), Integrated Status and Effectiveness Monitoring Program (ISEMP), Intensively Monitored Watershed (IMW) Program, and the Action Effectiveness Monitoring (AEM) Program have faced challenges, particularly with implementation and data management (Roni et al. 2015b; Bennett et al. 2016; Rosgen et al. 2018). Results from these programs similarly noted the need for improved implementation of monitoring as well as suggestions for improved protocols for monitoring the effectiveness of floodplain restoration utilizing before-after or before-after control-impact monitoring designs. In addition, recent papers reviewing the methods for programmatically evaluating projects implemented under a large restoration programs like the SRFB, as well as guidance for monitoring river restoration projects across the European Union, have provided additional guidance and improved methods for evaluating floodplain and riparian restoration projects in particular (Friberg et al. 2016; Roni et al. 2018; Weber et al. 2018). These reports collectively provide guidance to overcome challenges in implementation and improved design and protocols for evaluating restoration projects to overcome challenges seen in PE and other effectiveness monitoring programs developed more than a decade ago. Based in part on the results of SRFB PE monitoring and the lessons from other monitoring and evaluation studies, the SRFB Monitoring Panel, with input from the different recovery regions, that evaluation of effectiveness should focus on large (greater than 1 km) floodplain and riparian restoration projects.

Rapid advances in remote sensing and other techniques have provided improved methods to map and monitor physical and biological responses to river, floodplain, and riparian restoration projects (Belletti et al. 2015; Rinaldi et al. 2017; Roni et al. 2019a). Compared to 2003, when the SRFB PE Program was designed and implemented, a suite of remote sensing and analytical approaches have become available or improved that have revolutionized the methods and scale at which one can monitor physical and biological responses to habitat restoration projects. For example, light detection and ranging (LiDAR), satellite imagery, high-resolution aerial photography, multi-spectral imagery, and structure from motion photography (SfM) allow for mapping of the entire floodplain. Similarly, the use of drones or unmanned aircraft with photography, LiDAR, or other instrumentation can be used to map sites in cases where using fixed wing aircraft are too expensive (Tompalski et al. 2017; Roni et al. 2019a). Forward looking infrared (FLIR) can be used with a fixed-wing aircraft to map water-surface temperatures across many kilometers of stream (Handcock et al. 2012). We recently reviewed remote sensing techniques to determine their applicability in monitoring floodplain and riparian restoration projects. Green, sometimes called bathymetric, LiDAR can be used to calculate many of the key metrics used to monitor both changes in riparian vegetation and physical habitat due to restoration (Table 1).

Table 1. Crosswalk between common metrics used to evaluate success of floodplain and riparian restoration projects and which remote sensing techniques can accurately collect data to calculate these metrics. Y = yes, N = no, M = maybe depending on level of resolution, accuracy needed, or site conditions. Not included are radar and other types of LiDAR (e.g., oblique, ground-based). FLIR = forward looking infrared. It should be noted that remote sensing techniques often still require some minimum level of field data collection for validation and supplemental data to calculate of monitoring parameters and metrics.

Parameter/metric	LiDAR (Green or w/ bathymetric survey)	LiDAR (near-infrared)	SfM	Multispectral imagery	Aerial photography	Satellite imagery	FLIR
Channel morphology	Y	Y	Y	N	M	M	N
Channel pattern	Y	Y	Y	N	M	M	N
Bathymetry	Y	N	N	N	N	N	N
Topography	Y	M	Y	N	N	N	N
Habitat units	Y	M	M	M	M	N	N
Habitat diversity	Y	M	M	M	M	N	N
Floodplain inundation	Y	Y	M	N	N	N	N
Floodplain area	Y	Y	Y	N	N	N	N
Area altered	Y	Y	Y	M	M	M	N
Channel migration zone/Active channel	Y	Y	M	N	N	N	N
Side channel no., length, & area	Y	Y	M	M	M	M	N
Pond/wetland number & area	Y	Y	M	M	M	M	N
Sediment deposition & storage	Y	N	M	N	N	N	N
Large wood	Y	Y	Y	Y	Y	M	N
Surface temperature	N	N	N	N	N	N	Y[2]
HSI (Habitat suitability index)	Y	N	M	N	N	N	N
Riparian shade	Y	Y	M	N	N	N	N
Riparian composition	M[1]	M[1]	M	Y	M	N	N
Riparian stem density	M	M	M	N	N	N	N
Plant survival	N	N	N	M	N	N	N
Growth	Y	Y	M	N	N	N	N
Area vegetation extent by class	Y	Y	N	N	N	N	N
Bank stability	Y	Y	M	N	N	N	N
Organic inputs (leaf litter)	Y[3]	Y[3]	N	N	N	N	N

[1] Difficult under heavy canopy

[2] Snapshot in time, should be coupled with field data (temperature loggers) to get daily and seasonal trends

[3] If done at both leaf on and leaf-off.

Similarly, there are also several newer approaches for biological monitoring such as environmental DNA (eDNA), advances in biotelemetry techniques, and genetic mark-recapture (parentage-based tagging; Roni et al. 2019a; Steele et al. 2019). Environmental DNA can be used for looking at species presence and absence in floodplain habitat but cannot be used to estimate population abundance (see review in Roni et al. 2019a). Advances in biotelemetry (e.g., PIT, radio, and acoustic tags) allow monitoring of both juvenile and adult fish movements and survival among floodplain habitats. Tissue samples from a subset of juveniles and adults can use genetic parentage assignment to estimate population size and thus potentially take the place of traditional mark-recapture methods.[1] These advances in physical and biological monitoring highlight the need for any future SRFB monitoring and evaluation program of habitat restoration to utilize the latest advances in remote sensing and other monitoring methods. Recognizing these advances in remote sensing and new methodologies in recent years, the SRFB Monitoring Panel also determined that future monitoring and evaluation of floodplain and riparian projects should utilize remote sensing techniques and focus on changes in physical habitat and riparian vegetation.

As directed by the SRFB and Monitoring Panel, we developed the following study plan to monitor and evaluate large floodplain and riparian projects throughout Washington State using the latest remote sensing and other techniques. Developing a rigorous programmatic monitoring and evaluation program requires several key steps to ensure the monitoring meets its objectives and is properly implemented and completed (Figure 1). We address each of these steps in the monitoring plan. We first discuss goals, questions, and assumptions before discussing the monitoring design and parameters and metrics. We then discuss site selection, data management, projected costs and schedule, and reporting and implementation. We close with challenges and next steps.

This monitoring plan was developed with oversight and guidance from the SRFB Monitoring Panel. This included multiple conference calls and meetings to define the goals and scope of the monitoring plan, the key questions, and potential metrics. This document was developed for the Recreation and Conservation Office (RCO), SRFB, SRFB Monitoring Panel, Council of Regions, and its partners.

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[1] Additional detail advances in biological monitoring methods can be found in Roni et al. (2019a) and Steele et al. (2019).

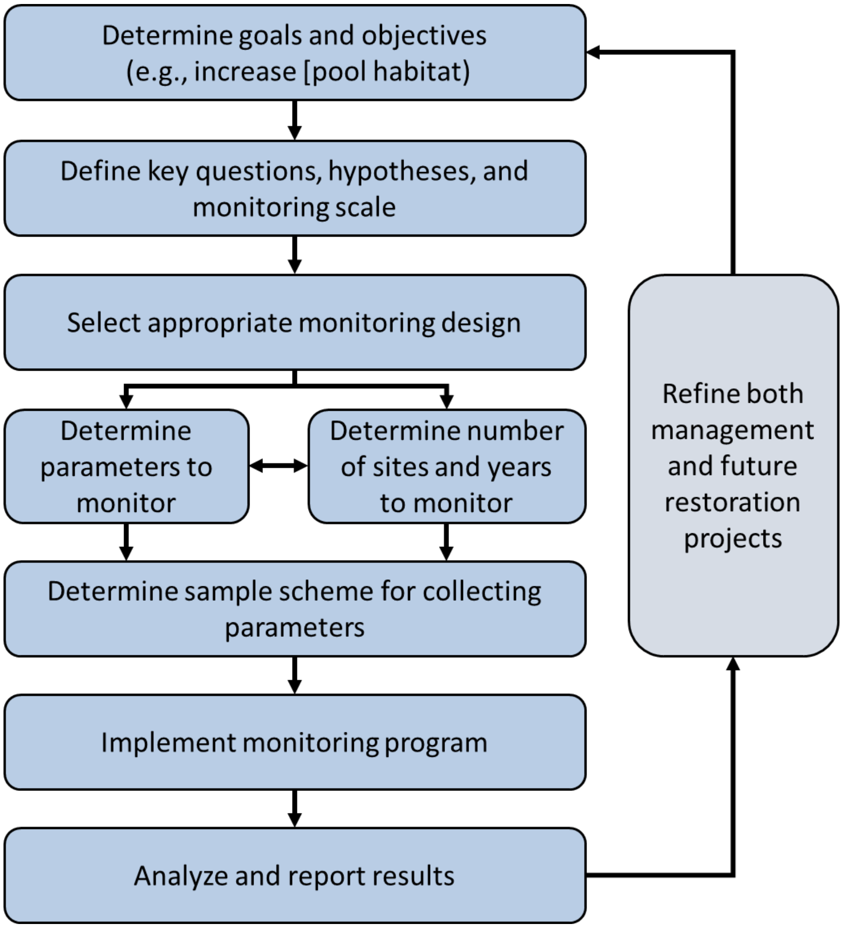

Figure 1. Steps for designing a successful monitoring program to evaluate restoration success (modified from Roni et al. 2005, 2013).

2.0 GOALS, QUESTIONS, AND ASSUMPTIONS

Setting the goals and objectives of a monitoring program (study) and defining key monitoring questions as well as assumptions is a critical step in developing a successful monitoring program (Roni et al. 2005; Weber et al. 2018). The goals and objectives of the restoration and monitoring help inform the questions or hypotheses the monitoring program will answer. These in-turn drive the development of the entire monitoring program. The initial goals and questions for this monitoring program were determined by the SRFB Monitoring Panel. To refine and clarify these, we met with the Monitoring Panel to clarify the goals and objectives of the program as well as any additional side boards. Based on these discussions, the following goals and objectives were defined.

Overall Monitoring Goal – The goal of the program is to evaluate the effectiveness of large (> 1 km in main channel length) floodplain and riparian restoration projects using the latest remote sensing techniques.

Specific objectives and guidance provided by the Monitoring Panel included:

- Evaluate floodplain and riparian projects with the assumption that most floodplain restoration projects have a riparian planting component
- If there are suitable number of large riparian-only projects (1 km or longer in length), consider including them as part of the monitoring program
- Focus on large projects(> 1 km)—phased projects should be considered one project
- Event-driven monitoring rather than time driven (after so many high flow events rather than strictly 3, 5, 7 years post treatment)
- Focus on remote sensing and monitoring protocols that will give us response at a large (broad) scale
- Focus on physical monitoring with understanding that if there is some efficient way to do biological monitoring it would be described as an option
- Time frame – initial results in 5 to 10 years (sooner if possible), with idea that this would be set up for monitoring long term (20+ years) response
- To ensure the full impact of restoration, consider monitoring additional habitat immediately upstream and downstream of project footprint
- Level of inference is the individual project and site (area influenced by project)
- Evaluate effectiveness of previously completed projects if possible and new projects if necessary
- If possible, include sites where previous data/monitoring has occurred to leverage previous data/efforts
- Cost of monitoring needs to be within modest PE monitoring budget (presumably $250,000 to $300,000 per year)
- Ensure program does not face same implementation challenges as IMW program (e.g., funding, delays in restoration, coordination, dependence on many partners for data collection)

Defining the questions for an effectiveness monitoring program can be a difficult task as different parties are interested in different questions. For example, managers and policy makers who distribute funds are often interested in broad-scale questions about whether specific types of projects are effective at improving habitat or increasing abundance, while practitioners are often more interested in not only what types of projects are most effective, but why a specific project was or was not successful or why a specific design worked or did not achieve desired physical objectives (Table 2). Traditionally, effectiveness monitoring programs have focused only on broad questions about effectiveness and provide general design guidance. For example, studies examining the effectiveness of large wood (LW) placement have shown that the projects that have the most pool forming wood or increase pool habitat the most lead to the largest increases in juvenile salmonids (Roni and Quinn 2001; Roni et al. 2015a; Clark et al. 2019), but stopped short of evaluating design of specific projects.

Table 2. Cross walk of major monitoring questions often posed about effectiveness of restoration projects, the scale the response is measured at, the scale of inference (scale results can be applied to), whether the monitoring focuses on an individual project, or multiple projects, or all projects in a program, and which parties are typically interested in a specific questions. Traditionally, effectiveness monitoring has provided general guidance on projects design, which is often the main focus of practitioners, while funders and managers have been focused on broader questions of effectiveness.

Questions	Scale of measurement	Scale of inference	Monitoring of individual or multiple projects	Interested parties (in order of importance)
Watershed Scale				
What is effect of a specific project on watershed conditions or a salmon population?	Watershed	Watershed	Individual project	Managers/funders
What is effect of a suite of projects on watershed conditions or a salmon population?	Watershed	Watershed	All projects	Managers, funders, practitioner
Segment or Reach-scale				
What is the effect of projects on fish and habitat in a valley segment? (multiple reaches)	Valley segment	Valley segment	All projects in segment	Funders, practitioners
What is effect of a specific project on habitat and fish in project reach?	Reach or project	Reach, project	Individual project	Funders, Practitioners
What is effect of a project type on habitat or fish at a reach-scale?	Reach	Program/region	All or sub-sample of a specific project type	Managers, funders
Project Level Monitoring				
How effective was design of a specific project?	Project, meso and micro-habitat	Project	Individual project	Practitioner, funder
What is optimal design for different project types under different conditions?	Project, meso and micro-habitat	Program, project	All or sub-sample of projects	Practitioner, funder

Based on input from both managers and practitioners and guidance provided by the Monitoring Panel, an additional goal is to provide feedback on project designs. Thus, in addition to the questions on reach-scale effectiveness, enough detailed information should be collected to evaluate the design of the project. This will meet the objectives of reach-scale monitoring, but the inference will be at the project scale.

The Monitoring Panel also provided and initial list of monitoring questions that they had developed with input from the Council of Regions and others. We refined these questions based on guidance above and added additional questions to help evaluate project design. The monitoring program is designed to answer the following questions[2]:

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 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?

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[2] An additional twelfth question related to remote sensed monitoring of water temperature was proposed, but moved as an optional or complementary study.

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?

2.1 Scale

Based on the questions and the objectives of the monitoring program, both the scale of monitoring and the scale of inference become clear. First, because the goal is to look at broad-scale response relying primarily on remote sensing, the actual monitoring will occur at the reach or valley segment scale[3]. The scale of inference refers to the at which conclusions can be accurately drawn. Rather than using the monitoring data to draw conclusions regarding all possible floodplain or riparian restoration projects in a region (i.e., project or restoration type inference), this monitoring is designed to draw conclusions about individual projects. Thus, the level of inference is at the restoration project level, which may cover an entire reach or valley segment. This is with the understanding that these projects can be analyzed collectively to provide guidance to other similar projects being implemented throughout the region.

The above questions are designed to provide detailed evaluation of selected projects. Less detailed or specific questions utilizing existing data and completed projects could also be answered. These would be designed to answer very general questions about effectiveness of specific project types such as: does floodplain restoration lead to increased side channel length or does vegetation cover increase following riparian restoration? These would not provide information about the effectiveness of a specific project but would provide broader-scale information on overall effectiveness of floodplain or riparian projects and the overall SRFB program. Because this less rigorous monitoring would not meet original goals and questions defined by SRFB and Monitoring Panel, we discuss this in section 8.2 Related or Complimentary Studies.

In addition, to the guidance provided by the Monitoring Panel, we made the following assumptions. First, we assume that physical response for floodplain restoration projects will begin to occur within three to five years following restoration, while riparian restoration (planting) may take more than 10 years to see a response. We also assume that any new projects selected will be implemented within 1 to 2 years of the

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[3] We follow the definitions of Gurnell et al. (2015) were a reach is geomorphically similar section of stream ranging from 0.1 to 10 km in length and a valley segment is a section of river subject to similar valley-scale influences ranging from 10 to 100 km.

initiation of the monitoring program. This is to ensure that the program does not become too protracted. We also assume that broad climatic factors will not change dramatically before and after restoration, or if they do, we can account for these by looking at aerial imagery for other nearby stream reaches. Finally, we assume that the study should be designed to evaluate the suite of floodplain restoration techniques used to restore connectivity of the main channel with the floodplain. These include but are not limited to levee removal or set back, removal of bank armoring removal, Stage 0 restoration, channel remeandering, side-channel reconnection and construction, and large wood placement[4].

3.0 MONITORING DESIGN

There are a handful of different experimental designs used to evaluate restoration projects, each with strengths and weaknesses. Common designs used to evaluate restoration projects include before-after (BA), before-after control-impact (BACI), multiple-BA (mBA) or multiple-BACI (mBACI), extensive post-treatment (EPT), and intensive post-treatment (IPT; Hicks et al. 1991; Downes et al. 2002; Roni et al. 2005, 2013). The first four designs (BA, BACI, mBACI, mBA) require data collection before and after restoration and each has strengths and weaknesses (Table 3). For evaluating a restoration program like the SRFB Program, these designs have been applied using different approaches that are suited for different scales and time frames (Table 3).

Table 3. Summary of the strengths and weaknesses of different programmatic monitoring and evaluation approaches. For the first four strengths, Yes or No indicates if an approach can address this question. Level of inference is whether one can apply results across a program or only to an individual project or both. Hybrid design includes a combination of experimental designs including before-after (BA), multiple before-after control-impact (BACI), extensive post-treatment (EPT), or others. Table is adapted from a recent review of approaches for monitoring and evaluating a restoration program (Roni et al. 2018). IMW = intensively monitored watershed.

Strength	Case study	Meta-analysis	Multiple BA or BACI	EPT	IMW	Hybrid
Can examine interannual variation in response?	Yes	Yes	Yes	No	Yes	Yes
Provides info on why some project are more effective than others?	No	Yes	Yes	Yes	No	Yes
Results are broadly applicable?	No	Yes/No	Yes	Yes	No	Yes
Requires standardized data collection?	No	No	Yes	Yes	Yes	Yes
Length of monitoring (years)	10+	10+	5+	1-3	15+	3+
Cost (low, medium, or high)	L	M	H	M	H	M
Level (scale) of inference	Project & Program	Project & Program	Project & Program	Program	Program	Program
Monitoring designs	BA, BACI	BA, BACI, EPT	BA or BACI	EPT	BA or BACI	Various

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[4] Only when large wood is placed with goal of reconnecting floodplain or side channels.

Almost all of the 12 monitoring questions defined above require before and after monitoring. Moreover, based on the scale of the monitoring (reach or segment > 1 km), scale of inference (project), the focus on physical monitoring, and the difficulty in finding suitable control reaches for larger floodplain projects, this indicates that paired control or reference reaches are unlikely to exist and not necessary.

Another factor to consider in the design is characteristics of the restoration projects themselves. Any type of post-treatment design will require a large population of projects to choose from as typically one-third or less of all projects will have suitable control reaches (Roni et al. 2013). Moreover, before and after monitoring of past projects will require locating completed projects where the necessary data have been collected. To examine this, we queried all completed, active, and proposed projects in the PRISM database that had floodplain and riparian elements and treated more than 0.9 kilometers of stream[5]. Because there are not no specific work elements in PRISM for floodplain or riparian projects, we used a multi-step process to identify appropriate worksites (restoration sites). First, we worked with the RCO to query the PRISM database for project types that included restoration (i.e., Acquisition & Restoration, Acquisition & Restoration & Development, Planning & Restoration, Planning & Restoration & Acquisition, and Restoration). This was further limited to the Salmonid Habitat Restoration and Acquisition project category and two sub-categories: Instream Habitat and Riparian Habitat. We then selected for work types related to floodplain (channel reconfiguration and connectivity) or riparian restoration (riparian plantings, invasive plant removal, and/or other riparian project types). Projects that solely focused on invasive plant removal, while important, are not the focus of this monitoring program. We then filtered these worksites, which represent unique on the ground restoration sites (projects) for those that were greater than 0.9 km (Table 4).

There were 74 projects with floodplain components that reported treating more than approximately 1 km (Table 5). These projects (work sites) ranged in size from approximately 1 km to more than 4 kms, with an average length of approximately 2 km (Figure 2). Of these floodplain projects, 51 also contained riparian restoration treatments, demonstrating that most floodplain projects incorporate riparian planting or other riparian treatments. However, when we examined the Washington Department of Natural Resources (DNR) LiDAR Portal to see how many of these projects had readily available LiDAR, only 22 of the 74 large projects(~30%) had LiDAR before the restoration occurred, and only three (4%) had green LiDAR. It is likely that not all LiDAR datasets available have been reported in the DNR LiDAR Portal,

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[5] The estimates of length or area treated reported in PRISM are approximate, so we used 0.9 km to make sure we captured any projects that might have underestimated length treated.

but this analysis indicates that few if any existing projects will have adequate pre-project data. There were also 242 riparian restoration only worksites that reported treating more than approximately 1 km.

Table 4. Entries from the Pacific Coastal Salmon Recovery Fund (PCSRF) data dictionary and headings used to select relevant categories, sub-categories, and metrics for identifying worksites in the PRISM database. PRISM uses the PCSRF data dictionary to track project, work type, work type metrics for each worksite (unique restoration site).

Category	Sub-category	Data field ID	Work type	Work type metrics	ID #	Data field format and metrics
C. Salmonid Habitat Restoration and Acquisition	C.4 Instream Habitat	C.4.c	Channel reconfiguration and connectivity	Changes in channel morphology, sinuosity or connectivity to off-channel habitat, wetlands or floodplains. This includes instream pools added/created; removal of instream sediment; meanders added; former channel bed restored; removal or alteration of levees or berms (including setback levees) to connect floodplain; and, creation of off-channel habitat consisting of side channels, backwater areas, alcoves, oxbows, ponds, or side-pools.	C.4.c.3	# miles (to nearest 0.01 mile) of stream treated.
					C.4.c.4	# miles (to nearest 0.01 mile) of off-channel stream created
	C.5 Riparian Habitat	C.5.b	Total riparian area treated	Total length of streambank riparian area treated and amount of riparian area treated or managed. Report the actual length of streambank riparian area treated, adding lengths of treatment on both sides of stream if treatment was on both streambanks.	C.5.b.1	# miles (to nearest 0.01 miles) of streambank treated.
		C.5.c	Riparian planting	Riparian planting or native plant establishment.	C.5.c.4	# miles (to nearest 0.01 mile) of streambank treated.
		C.5.k	Unspecified or other riparian habitat project	Unspecified or other riparian habitat project (not included in C.5.c to j.).	C.5.k.2	# miles (to nearest 0.01 mile) of streambank treated.

Table 5. Results of query of the Recreation and Conservation Office (RCO) PRISM database for completed, current, and proposed restoration projects in Washington State that have a floodplain component and were 1 kilometer or larger. We used a length of 0.9 kilometer rather than 1 km realizing that project sponsors often estimate the total length treated. We also examined how many of these had riparian metrics and riparian treatments that also spawned more than 1 km. We then queried the DNR LiDAR portal to see the number of projects where LiDAR data was readily available and how many of those sites had green (bathymetric) LiDAR. Metrics search in PRISM were c.4.c.4 miles of stream treated for channel reconfiguration and connectivity and c.4.c.4 miles of off-channel stream created.

	Floodplain metric	Floodplain metric + any riparian metric	Floodplain metric + riparian metric ≥0.9 km
Total projects	282	174	64
Projects with ≥0.9 km floodplain metric	74	51	38
Projects with any LiDAR	66	46	36
Projects with LiDAR from 2010+	64	44	35
Projects Green LiDAR from 2010+	5	2	1
Projects with LiDAR from 2010+ and before implementation	22	16	13
Projects with Green LiDAR from 2010+ and before implementation	3	1	1

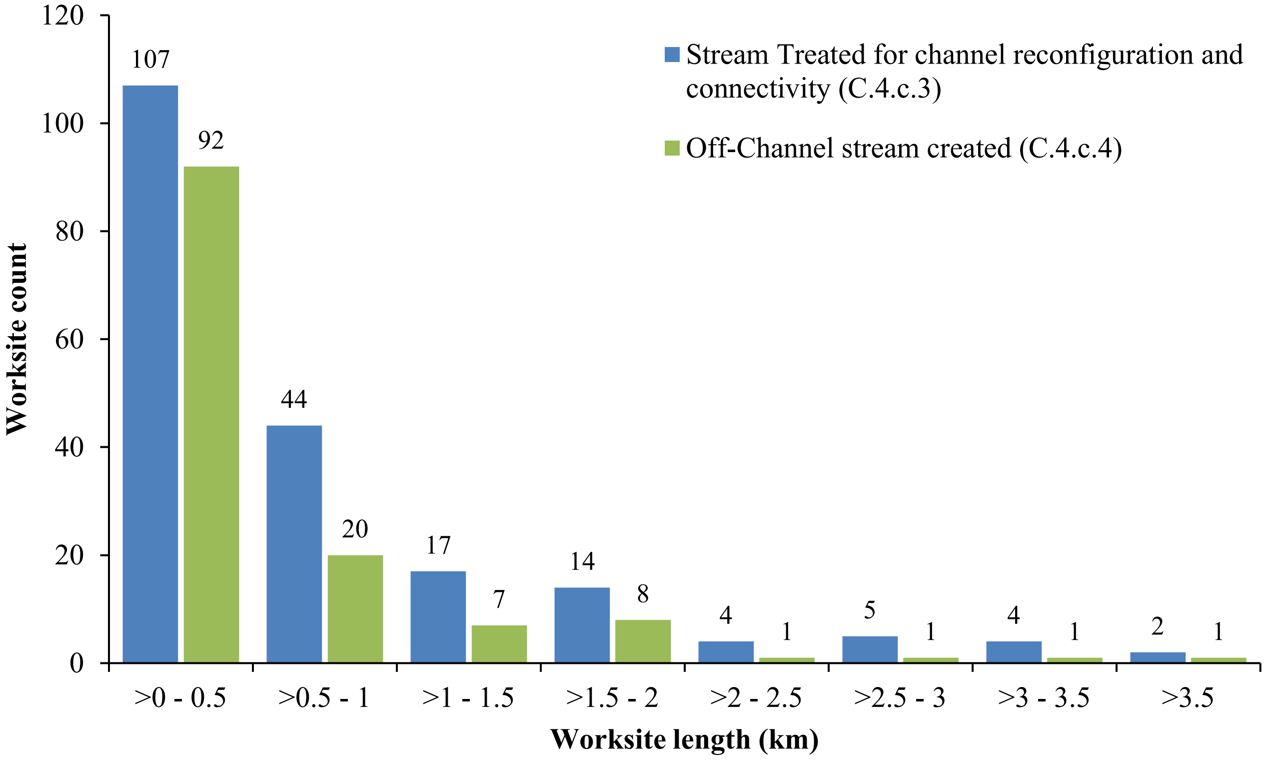

Figure 2. Frequency of projects (worksites) that reported floodplain treatments that were more than 1 kilometer in length. The two primary work elements related to floodplain restoration in the PRISM database were C.4.c3 and C.4.c.4). It was not possible to determine “phased projects” based on data available so some sites may be much longer but may have been phased over multiple years and projects.

This analysis indicates that a post-treatment design or a before-after design using previously completed projects will be very difficult because only a few projects have the required pre-project data LiDAR data. Moreover, it is unlikely any of these have the necessary field data that will need to be collected at the time of LiDAR acquisition. Therefore, we recommend a simple before-after design to evaluate floodplain and riparian restoration projects.

3.1 Spatial and Temporal Replication

The next step in designing an effectiveness monitoring program is typically to estimate the number of sites and number of years that need to be monitored. However, given that the proposed monitoring program focuses on project level results, large projects, and the availability of potentially costly techniques (LiDAR), a rigorous power or sample size estimation is neither necessary nor particularly useful. We will discuss in the cost section specifics of estimating the cost of monitoring, but green LiDAR alone will likely cost in excess of $30,000 per site. We recommend sampling as many sites as is possible given funding, ideally at least one per recovery region (8) but a minimum of a half a dozen projects. If large riparian projects are to be monitored as a separate category, a similar sample size should be monitored.

Defining the temporal replication is more straightforward and needs to consider the required pre-project data, how long it will take to implement project, and how long before a response is detected. Given the lower inter-annual variability, large size of projects, and the expected improvements in habitat, one year of pre-project data is adequate for physical habitat metrics. In contrast, fish or other biota may require many years of pre-project monitoring because of their high interannual variability (Minns et al. 1996; Ham and Pearsons 2000; Roni et al. 2013). To address questions about whether a project is meeting design objectives, an "as-built" survey completed within a few months of the completion of restoration and before any high flow events is needed along with a planting plan and "as-planted" map for riparian projects. Post-treatment monitoring for floodplain projects would ideally be flow-based and initially occur after one or more channel forming flows (bankfull or approximately 1.5- to 2-year recurrence interval; Williams 1978; Leopold 1994; Castro and Jackson 2001) and following large flow events (5-, 10-year recurrence interval). However, this can make planning and implementing monitoring difficult as it will require waiting until late spring each year to determine which projects will be sampled. In addition, depending upon the goals and techniques used for a floodplain restoration project, the response time could be anywhere from a few years to more than a decade to see the full response of the channel or aggradation and degradation. Response of riparian restoration is less flow dependent, though riparian planting and treatments can take on the order of several decades to see full vegetation response. Another factor to consider are the goals and assumptions of the project. In this case, the SRFB would like to see responses within 5 to 10 years, with the idea that these sites will likely be monitored for many years beyond that. Based on these factors we developed a pre- and post-treatment monitoring schedule that considers all these factors and uses a combination of event based and periodic monitoring (Table 6).

Table 6. General sampling schedule for floodplain sites based on necessary sampling one year before restoration, after restoration is completed, and post-treatment monitoring based on either flow or time passed since restoration. If no bankfull flow event occurs within first three years, monitoring should occur in year 3, should a bankfull event occur in year 1 or year 2, year 3 monitoring should be bumped up to year 1 or 2 and then not repeated again until year 5. Sites that have riparian restoration only are not as dependent on flow could be monitored at regular intervals.

	-1 (pre)	0 (as-built)	1	2	3	4	5	6	7	8	9	10	15	20
Regular intervals	X	X			X		X					X	X	X
If event occurs in year 1+	X	X	X				X					X	X	X
If event occurs in year 2+	X	X		X			X					X	X	X

An additional temporal component is the season of sampling. Much of the remote sensing and field data collection will occur during low flow and during late fall because it is the optimum period to obtain data and map the topography and bathymetry. To examine seasonal aspects of changes in floodplain habitat, many metrics will be calculated at different flows that represent different seasons (e.g., base flow [summer low flow], bankfull flow, spring-snowmelt). We describe these seasonal or flow-based aspects for appropriate metrics in Section 4.0 Parameters, Metrics, and Protocols.

3.2 Stratification

Washington State is composed of eight salmon recovery regions which roughly coincide with EPA Level III ecoregions and ESA evolutionarily significant units (ESU) for salmon and steelhead populations (Figure 3). Given the differences in salmonid species, climate, geology as well as the fact that different groups oversee restoration in each region, we recommend stratifying projects by recovery region, ideally with a minimum of one project monitored in each recovery region. This will also allow different recovery regions to assist with selection of projects for monitoring.

3.3 Site Selection

The method of how sites will be selected for the study is a key component of the monitoring design. The actual selection of sites is typically done as part of the implementation phase. Because the program focuses on evaluation of projects funded by the SRFB, an initial population of projects can be drawn from the PRISM database. As noted previously, currently there are 74 worksites that include floodplain metrics that cover approximately 1 km or longer, though many of these are completed projects, and only 17 of these are projects that have not been completed (Table 7). However, this likely does not include all projects that are planned in the next few years and some recovery regions have more projects than others. It also assumes that data in PRISM are accurate. Therefore, the list of projects should be shared with the Recovery Regions prior to implementation so that they can confirm that these projects meet the following criteria:

- Main objective of project is floodplain restoration (or riparian restoration for riparian projects)
- Restoration treatments cover greater than 1 km of mainstem channel
- The year the project will start construction
- Landowner(s) willing to allow access for next 10 years
- There is access to area immediately upstream and downstream of project (20 times bankfull width) to allow monitoring/surveys to include areas outside of project footprint potentially influences by restoration (not necessary for riparian only projects)

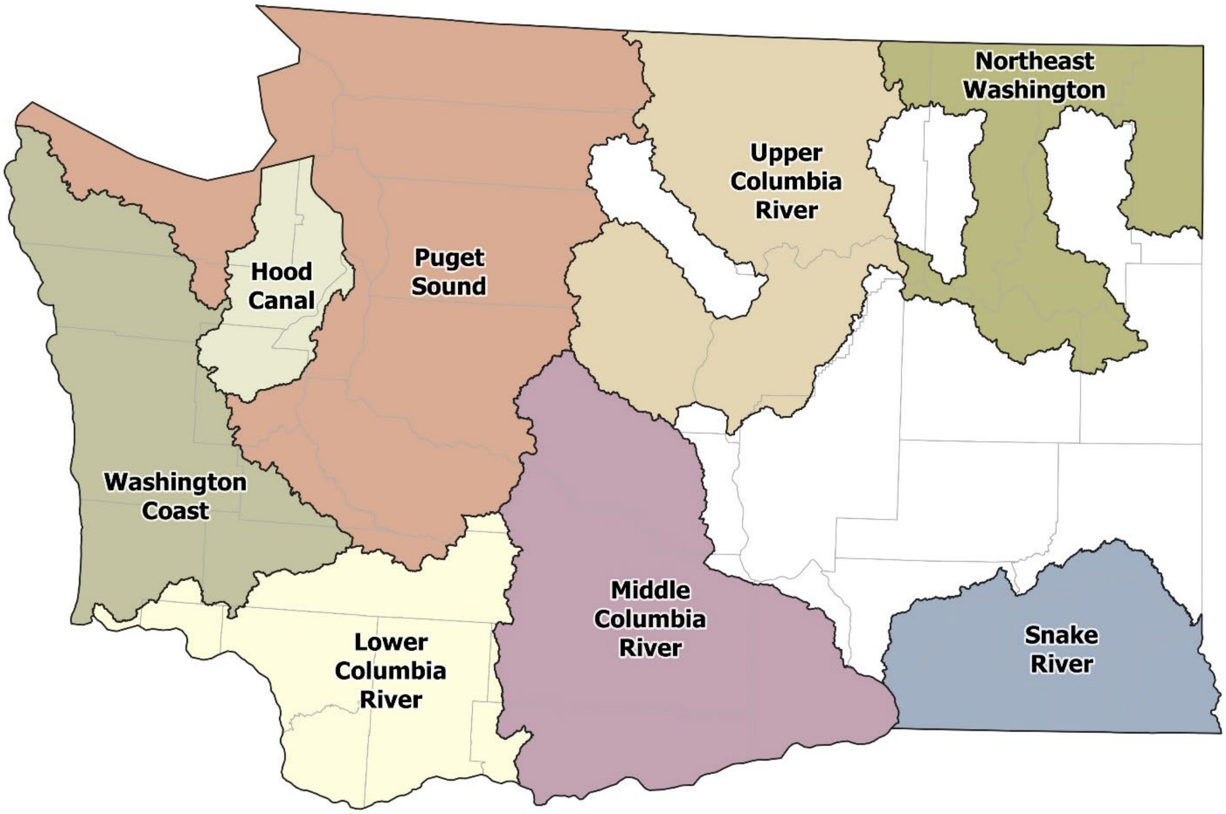

Figure 3. Map of eight Washington State salmon recovery regions.

Based on the revised list of sites from the recovery regions, the contractor implementing the monitoring program will select sites for long-term monitoring. To expedite this process, an initial list of projects that met the above criteria was drawn from the RCO PRISM database in March 2020 and shared with the recovery regions. Based on the above criteria they provided updates to the list of potential projects drawn (Table 7). Field visits are needed to confirm the sites meet the criteria and are appropriate including in the study. If there are more than one or two sites that meet the criteria, either sites can be selected randomly, or the recovery regions could be allowed to identify which site or sites would be most useful[6]. The latter could be beneficial in ensuring that the recovery regions and lead entities are supportive of sites selected. Additional criteria to consider during final site selection include whether there is an existing stream gauge, the site is freshwater (no tidal influence), and that the restoration will be implemented within 1 to three years.

Table 7. Initial list of worksites in PRISM with floodplain component (C.4.c.3 or C.4.c.4) greater than approximately 1 km (0.9 km) that are proposed or expected to be completed in 2020 and beyond including: recovery region, PRISM project name and worksite name, expected year of completion (end year), latitude, and longitude. It is likely that other projects exist that are not in PRISM or that length metrics were not accurate. This list was vetted and updated by recovery regions in May of 2020. A list of projects that are completed can be found in Appendix A.

Recovery Region	Project Number	Project Name	End Year	Latitude	Longitude
Coast	18-2125, 20-1130	M Hoquiam Tidal Restoration	2022	47.02499727	-123.9124202
Coast	18-2005	Hoh River Master Plan	2023?	47.81015025	-124.0368253
Coast	18-2156, 20-1200	Lower Quillayute River Restoration	2023	47.91298219	-124.6102664
Hood Canal	16-1372	Lower Dungeness Floodplain Restoration	2021	48.142678	-123.1301
Hood Canal	18-1300	Dungeness River Floodplain Restoration	?	48.142745	-123.1287
Lower Columbia River	16-1519	Elochoman Stream Restoration Cothren	2021	46.228453	-123.364
Lower Columbia River	16-1520	Skamokawa Stream Restoration Project McClellan	2020	46.315347	-123.4549
Lower Columbia River	17-1025	Elkinton Property Stream Restoration	2021	46.2215	-123.3423
Lower Columbia River	17-1030	Johnston Wilson Creek Restoration	2022	46.296752	-123.3952
Middle Columbia River	20-1320	Little Naches Longmire Levee Breach	2022?	47.02170128	-121.14598790
Middle Columbia River	20-1390	West/Middle Fork Teanaway Instream Wood Design	?	47.25723123	-120.89930225
Middle Columbia River	20-1202	Kachess River Restoration Project	?	47.41118576	-121.23710588
Middle Columbia River	20-1393	Nile Creek Restoration	?	46.84717714	-121.00670908
Puget Sound	16-1651	Hansen Creek Reach 5 Restoration	2022	48.515343	-122.2007
Puget Sound	18-1258	Riverbend Floodplain Restoration Construction	2023	47.464215	-122.1119
Snake River	N/A	PA27/28.1 Add Function & Complexity: Phase II	2024	46.451849	-117.798617
Snake River	19-1495	Tucannon PA 13 Habitat Enhancement	2023	46.317065	-117.663022

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[6] Assuming funds are available to monitor more than one site.

Recovery Region	Project Number	Project Name	End Year	Latitude	Longitude
Snake River	19-1496	North Touchet Restoration RM 1.3-2.0	2023	46.292213	-117.932596
Snake River	20-1050	North Touchet Phase 3 Restoration (RM 2.0-2.7)	2024	46.287674	-117.921389
Snake River	N/A	PA 44 Floodplain Connectivity and Channel Reconfiguration	2023	46.532842	-118.148666
Snake River	N/A	Cummins Creek Delta Channel Complexity	2024	46.332857	-117.673382

The exact schedule for monitoring of sites would need to be developed after site selection and need to consider when the project will be implemented. We propose that projects be selected where construction will begin in either 2021, 2022, or 2023[7] so that data collection can be staggered to allow a stable budget for the project through time and spread monitoring costs across years. This schedule could be adjusted depending on when the study begins, but we caution against including sites over several years as this has led to the problems with other programs evaluating restoration projects using a mBA or BACI design (Roni et al. 2018, 2020a). Another factor that will need to be considered is the time it takes to complete restoration; it is likely that some projects will take more than a year for restoration to be completed. This will influence the monitoring schedule.

4.0 PARAMETERS, METRICS, AND PROTOCOLS

To determine the methods and protocols for monitoring, we first defined the parameters and metrics needed to answer the monitoring questions (Table 8). The questions were designed in such a way that, when possible, they state clearly the response metric. For example, to answer the first question related to changes in floodplain inundation at different flows, we need to calculate floodplain area and floodplain inundation. As demonstrated in Table 8, monitoring of physical parameters for floodplains consists of metrics that summarize and evaluate channel and floodplain morphology, meso-habitats, large wood, sediment storage, and flow. Monitoring of riparian areas consists of metrics that summarize and evaluate changes in vegetation cover, species composition, bank stability, organic matter inputs, and shade.

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[7] At the time of writing of this study plan, it was assumed that pre-project data collection would begin in 2020 and that projects would be selected that would begin construction in 2021 or 2022. If the start of study is delayed until 2021, then projects that will begin construction in 2022 and 2023 may need to be selected.

Table 8. 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.

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 la. 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, diversity , habitat metrics (pool area, percentage,) (low flow F, 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)

Determining the appropriate monitoring protocol requires defining how each metric is calculated, the data that will need to be collected to calculate those metrics, and the method(s) needed to collect those data (Table 9). While a handful (6) of these metrics are calculated using solely data obtained from remote sensing, the majority require at least some data from field surveys; with the most common data need being bankfull width measurements for floodplain projects. While there are methods for determining bankfull width without direct field measurements, they are often subjective (i.e., rely on expert opinion; CHaMP River Bathymetry Toolkit, CHaMP 2016), rely on assumptions about bank morphology that cannot be guaranteed across many study sites or regions (reliance on bank inflection points; De Rosa et al. 2019, Fryirs et al. 2019), or are designed for broad-scale assessments (Beechie and Imaki 2014), and provide relatively coarse measures of bankfull width that are not ideal for monitoring at a site or reach scale.

Table 9. Floodplain and riparian metrics needed to answer monitoring questions and methods for calculating each. References provided where appropriate.

Metric	Calculation
Floodplain area	Floodprone area, which is determined using 2 times the average maximum bankfull depth
Floodplain inundation index	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[8]	Delineate the active channel based on historical aerial imagery and LiDAR.
Side channel number, length, area, and ratio	Sum of the side channel wetted centerline lengths and areas Sum of the side channel bankfull centerline lengths areas Sum of all the side channel bankfull centerline lengths divided by the mainstem bankfull centerline length (Beechie et al. 2017)
Pond/wetland number and area	Delineate the isolated habitats at low flow using LiDAR and aerial imagery to count number and calculate total area
Residual pool depth	Maximum pool depth minus the pool tail crest in pool habitats, averaged across a reach for pools that the thalweg runs through (Lisle 1987)
Sinuosity	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; Jones et al. 2015)
RCI (River complexity index)	RCI = (S*(1 + J) / (reach length))*100, where S = sinuosity, J = # of side channel bankfull junctions, reach length = mainstem wetted centerline length (Brown 2002)
Bankfull width to depth ratio	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	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, 2017)
Pool area and percentage	Sum of pool habitat area, total pool area divided by total wetted area
Shannon diversity index of habitat units	Shannon diversity index (H) of the channel units in the mainstem and side channels with habitat units delineated (Shannon 1948)
Large wood	Count of jams and individual pieces from aerial imagery or LiDAR ((Richardson and Moskal 2016Beechie et al. 2017; Roni et al. 2020b)
Sediment deposition and storage	Create a DEM of Difference (DoD) for the years of interest and calculate the areas of deposition and storage
Habitat Suitability Index (HSI)	Sum of weighted usable area (WUA) and normalized WUA by species and life stage based on hydraulic and HSI modeling
Riparian composition and density, richness, density, diversity	Ratio of number of lidar returns in understory height band to number in ground band. Similar for overstory (R, F) (Akay et al. 2012) Richness – count of unique species across all transects (F) Density – count of individual species across all transects, divided by the aggregated area of all transects (F) Diversity – Shannon's diversity index using species abundance data (Shannon 1948)
Bank stability	Measure of length of eroding bank (F)
Shading	Total insolation hours. Calculate using the GRASS r.Sun modules (R, F) (Greenberg et al. 2012)
Organic inputs	Volume of canopy that overhangs the active channel (R) (Laslier et al. 2019)

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[8] 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).

Based on the requirements in Table 9, surveys are required to collect data on topography and bathymetry, habitat and channel characteristics, substrate, flow, and riparian condition. We first describe the basic methods for laying out the survey extent and then summarize the remote sensing or field methods for each of these survey types below.

Site Layout

Site layout consists of delineating the top and bottom mainstem channel boundaries, which define the longitudinal extent of the site. For floodplain restoration sites, the upstream and downstream boundaries of the site should be delineated based on the proposed restoration plans and then an additional length upstream and downstream of 20 times the average bankfull width of the reach will be measured to mark the top and bottom of the survey. The additional length above and below the project is needed to quantify any changes in habitat due to the restoration that might occur immediately upstream or downstream of the project footprint[9]. Care should be taken to ensure the survey boundaries do not bisect a channel unit (e.g., do not split a pool unit with the boundary). All site visits following the initial survey will reoccupy the site boundaries (i.e., boundary locations to not change even if a channel unit is bisected during subsequent visits). The lateral survey extent for floodplain projects will include all of the floodplain. The procedure for delineating survey extent for riparian only projects will include marking the upstream and downstream ends of the riparian treatment as additional length upstream and downstream of the project is not needed.

4.1 Topography and Bathymetry

Collecting the topography of the floodplain and the active channel are essential for data collection and calculating the metrics to answer monitoring questions about floodplain restoration projects being monitored. Our review of the latest remote sensing techniques and our pilot study on floodplain monitoring methods (CFS 2019, 2020), demonstrated that the optimal method for this is green (or bathymetric) LiDAR. The near-infrared (red) LiDAR, which is the most frequently acquired data for mapping topography, does not penetrate the water surface and thus cannot be used to map bathymetry. Bathymetric (green) LiDAR can be used to map below the water surface. However, the depth that the green laser can penetrate into the water to measure subsurface topography depends on water clarity, turbulence, and streambed reflectance (i.e., needs high clarity, low turbulence, and a reflective bottom), as well as the type of sensor used. Green LiDAR has been shown to be powerful enough to measure river bathymetry on medium to large rivers with depths of three or four meters (Campana et al. 2014; Roni et al. 2020b; Figure

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[9] Twenty-times bankfull width represents the length of a stream needed to characterize geomorphology and habitat in a reach (Harrelson et al .1994; Rosgen 1994, 1996).

4). Most green LiDAR sensors can measure depth of 1.5 to 2.5 Secchi depths depending on water clarity and bed reflectance (Quadros 2013; Pratomo et al. 2019). Thus, green LiDAR cannot effectively map bathymetry if the channel is too deep or turbid, or there where there are high levels of surface turbulence. Acquiring green LiDAR, which currently needs to be flown with a fixed-winged aircraft[10], can be costly (>$30,000 for 3–8 km^2 or >$40,000 for 8–20 km^2) and still requires some field data collection. For floodplain projects that cover less than approximately 4 kilometers of main channel length, it is currently more cost effective to fly red LiDAR with a drone to obtain topography (<$5,000 for a site covering 4 km of mainstem or 8 km^2) and collect bathymetric data with using a field survey with a real-time kinematic (RTK) global positioning system (GPS). In addition, as we describe in the channel and habitat survey section, even green LiDAR will require some field data collection for validating the LiDAR and for collecting habitat data necessary for many metrics. Based on this and current costs, we propose that green LiDAR is flown only at sites greater than 4 km and where turbidity or depth is not an issue, and red LiDAR using a drone is flown on smaller sites and coupled with an RTK survey of bathymetry. The optimal methodological approach will in part be based on the site and the cost-tradeoffs of the different approaches, which may change over time. Given that the current information suggests most floodplain projects are less than 4 km, the drone-based red LiDAR is likely most appropriate for most sites. For sites that include only riparian restoration, red LiDAR is adequate and can be flown with either a drone or fixed winged aircraft (red LiDAR is less costly than green LiDAR).

Table 10. Table of methods for collecting topographic or bathymetric data for floodplain projects. Within limit of green LiDAR

Site Size	Water depth, clarity, turbidity, turbulence	Method
Main channel length < 4 km	Any	Red LiDAR with RTK Survey
Main channel length > 4 km	Within limits of green LiDAR	Green LiDAR
Main channel length > 4 km	Exceeds limits of green LiDAR	Red LiDAR and RTK GPS or ADCP

Given that LiDAR sensors continue to improve, it is important that LiDAR data collected are consistent and compatible. Therefore, LiDAR acquisitions should be of sufficient quality to support creation of digital elevation and surface models at half meter resolution (0.5 m^2 pixels) with a goal of at least 5-15 ground returns per meter (Thomas et al. 2017). LiDAR should be flown during low flow and leaf-off conditions to ensure adequate ground returns to facilitate accurate DEM models. This ideally would occur

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[10] Several vendors are working to develop a green LiDAR sensor that is small and light enough to be flown with a drone, but there are many technological challenges to this and none have been perfected or accurate to date are on the market as of the writing of this report. If perfected, they will likely be far more expensive than a near infrared LiDAR sensor for a drone which currently cost $60K to $100K or more.

in October before any high flow events. In addition to the DEM for topography, a digital surface model (DSM), and the point clouds from LiDAR are necessary for monitoring riparian conditions at both floodplain and riparian restoration sites. For sites that green LiDAR is not appropriate, potential methods for a mapping channel bathymetry are described below.

4.2 Channel and Habitat Survey

The approach for the channel and habitat survey will differ in intensity based on whether green LiDAR or red LiDAR is obtained. We first describe the approach assuming green LiDAR is acquired, we then describe additional bathymetric data needed if red LiDAR is collected. While green LiDAR allows for creation of a DEM and collection of detailed topographic and bathymetric data at a level not possible historically, it has not completely eliminated the need for field data. Supplemental field data is needed to calculate many floodplain metrics, ground truth elevations calculated from the LiDAR DEM, and collect data needed for hydraulic modeling and Habitat Suitability Index (HSI) calculations. To obtain the supplemental data, a field survey using an RTK GPS and a tablet with survey forms will be used to collect habitat unit boundaries, bankfull points, and side channel data. The bankfull points are needed to assist with delineating a bankfull polygon to calculate bankfull width and depth, which can be done in part from the DEM.

While some geomorphic units can be calculated in the bankfull channel using the geomorphic unit tool (GUT; Bangen et al. 2017), these do not coincide with meso-habitats types that are indicators of fish-habitat quality (Roni et al. 2020b). Thus, characterization of habitat units at base flow (summer low-flow) will be conducted in the mainstem and flowing side channels as part of field surveys to accurately quantify fish habitats. Habitat units will be numbered and classified as pool, riffle, rapid, cascade, glide, or backwater (Hawkins et al. 1993), and recorded on a tablet with unit number and unit type. All habitat units within a reach will be delineated at the wetted edge in addition to across the bottom and top of the habitat units. These data will be used with the DEM to delineate the wetted edge and wetted area of each habitat unit at the surveyed flow. If a bar is present, additional habitat unit points (wetted edge) should be collected so the bar can be delineated in post-processing. In-channel habitat unit points should be collected for habitat units with complex boundaries (i.e., boundaries not perpendicular to channel orientation) for better delineating in post-processing. The top and bottom of all wetted or dry side channels will be delineated. For wetted side channels, where channel units greater than 10 m^2 can be delineated, then habitat units will be surveyed using the same procedures as described above for the main channel. Any other water features that are not connected to the mainstem will be delineated and classified as off channel habitats.

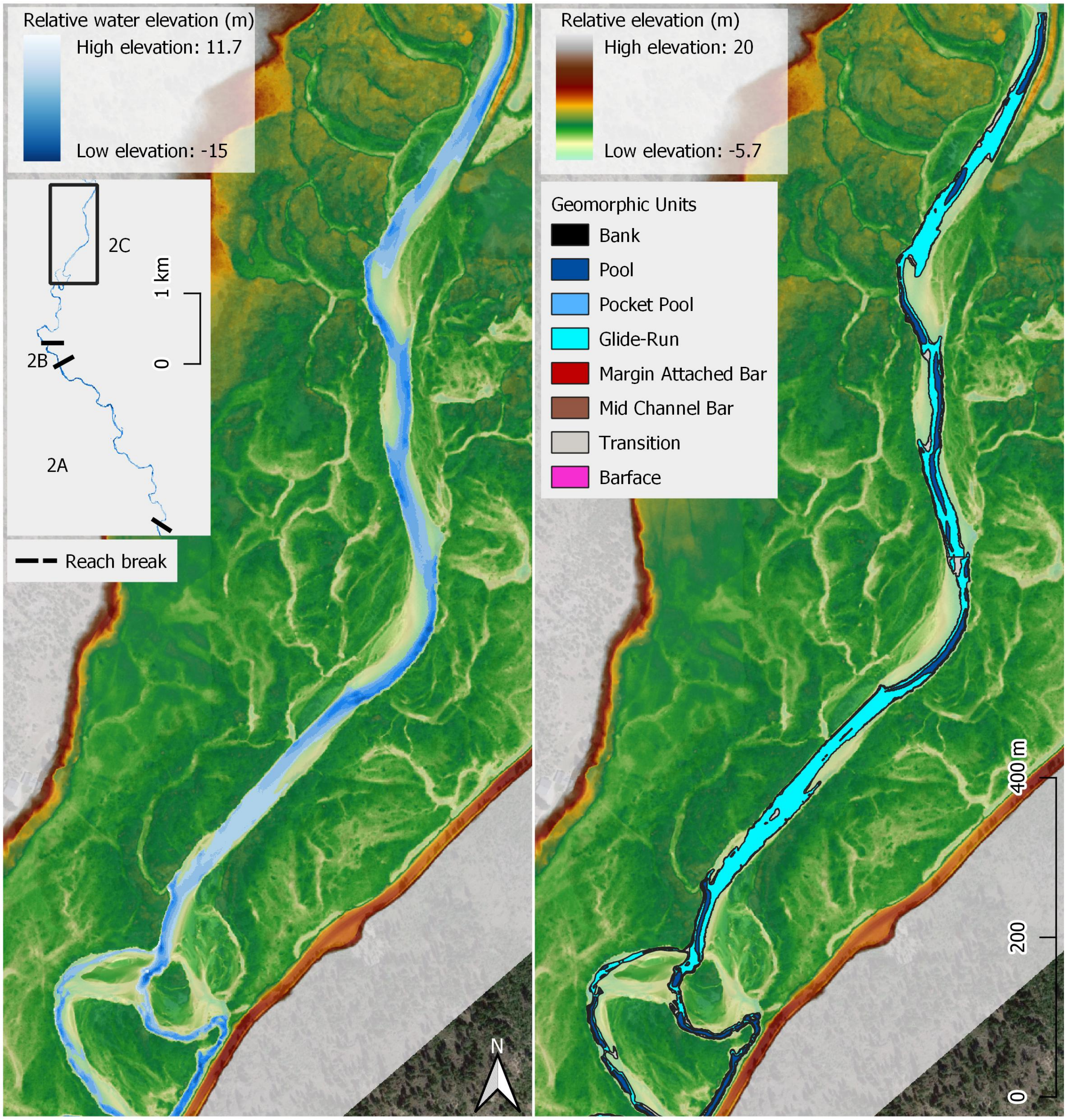

Figure 4. Example of topography and bathymetry from green LiDAR flown before restoration on Entiat River (from Roni et al. 2020b).

Bankfull and wetted edge points will be collected using the RTK at 50 m intervals depending on site length beginning at the bottom of survey extent (BOS) and continuing upstream along both stream margins to the top of the survey extent (TOS). In addition, wetted edge points outside the survey extent will be collected to assist with detrending the entire DEM (CFS 2019). Four wetted edge points should be collected on each bank and extending approximately 30 meters up- and downstream, for a total of 16 wetted edge points outside the site survey extent (8 upstream of TOS and 8 downstream of BOS).

Data on substrate will be collected to assist with hydraulic and HSI modeling. The dominant (≥50%) and sub-dominant (<50%) substrate classes will be visually estimated within each habitat unit. Substrate will be assigned to categories of fines (<0.06 mm), sand (0.06–2 mm), gravel (2–64 mm), cobble (64–256 mm), small boulder (256–1,024 mm), large boulder (1,024–4,096 mm), bedrock (>4096 mm), or hardpan/clay.

Similarly, bank armoring, erosion, and riparian condition along the main channel are needed for calculating the Morphological Quality Index (MQI) and will be collected as part of the habitat and channel survey. The length (m) of eroding bank and length (m) of armored bank within each habitat unit will be visually estimated. In addition, any significant substrate embeddedness and bed armoring will be noted for each habitat unit as ‘yes’ or ‘no’, as well as the presence of a bed stability structure. Finally, any evidence of riparian vegetation removal within a habitat unit and along the banks will be noted as ‘yes’ or ‘no’. Detailed riparian surveys to monitor riparian response are described below.

If red LiDAR is collected rather than green LiDAR, in addition to the above data, a bathymetric survey needs to be conducted while collecting habitat data so that a point cloud of the bathymetry can be created and meshed with the topography collected with red LiDAR. This will include using an RTK to conduct a longitudinal survey of the mainstem channel thalweg coupled with channel cross sections, and supplemental data points as necessary to capture inflections in bathymetry. The longitudinal thalweg profile involves surveying the streambed elevation where the greatest stream depth and flow coincide (the thalweg), yielding a two-dimensional longitudinal profile of streambed elevation (Mossop and Bradford 2006). Significant inflections (>30 cm) of streambed elevations at the channel thalweg are recorded by collecting X, Y, and Z point data with the RTK rover. Based on our pilot study (CFS 2019), we recommend point spacing should not be greater than 1 to 1.5 bankfull widths (BFW) or 10 meters, whichever is greater. Typically, 40 or more locations along the thalweg will be measured to adequately capture topographic changes every 100 m. At each measured point water depth and elevation will be recorded. Cross-section profiles (i.e., transects) will be collected using the RTK at 50 m intervals beginning at the bottom of site and continuing upstream. The transect cross section should start at the bankfull edge and continue perpendicular to the direction of flow until the traverse has ended at the opposing riverbank bankfull edge. As the transect is traversed, any significant inflection points encountered will be captured using the transect point types as necessary. Required points to capture along a cross section include bankfull, wetted edge, and toe of slope. The number of points collected between the two wetted edge points will depend on the variation in bed topography. A streambed with little to no variation between these points will result in just a couple points being collected. Conversely, an undulating stream bed will require several points across the stream bed. Additionally, additional points can be collected between transects when the point is needed to better map the channel bathymetry.

Large Wood

Large wood jams and individual pieces within the bankfull channel and side channels will be identified using aerial imagery. Imagery sources may range from the most current National Agriculture Imagery Program (NAIP) imagery, Google Satellite imagery, or imagery collected during site visits (e.g., during LiDAR flight). The imagery used needs to be collected at base flow to be consistent with topographic, bathymetric, and fish-habitat data collection. Jams and pieces will be enumerated within the site boundaries. Minimum discernable size will depend on the resolution of the imagery. Previous studies have reported a minimum diameter of 0.25 m and length of 2 m when using NAIP imagery (Roni et al. 2020b). In general, this method does not allow for exact counts of wood contribution for larger jams therefore large wood will be classified as small jams (3-4 pieces), large jams (>5 pieces) or individual pieces (1 or 2 pieces). Jams and pieces will be attributed as wet or dry based on having any visible contact with the water surface. All jams that encompass an area of > 50m^2 will be delineated in GIS to calculate the total area of LW jams (e.g., Beechie et al. 2017; Figure 5). It is important that LW enumeration is done with aerial imagery from approximately base-flow. To ensure this, aerial imagery should also be collected during LiDAR flights. The acquired LiDAR can be used to enumerate in-channel wood obscured in aerial imagery by overhanging vegetation as well as on the floodplain (Richardson and Moskal 2016).

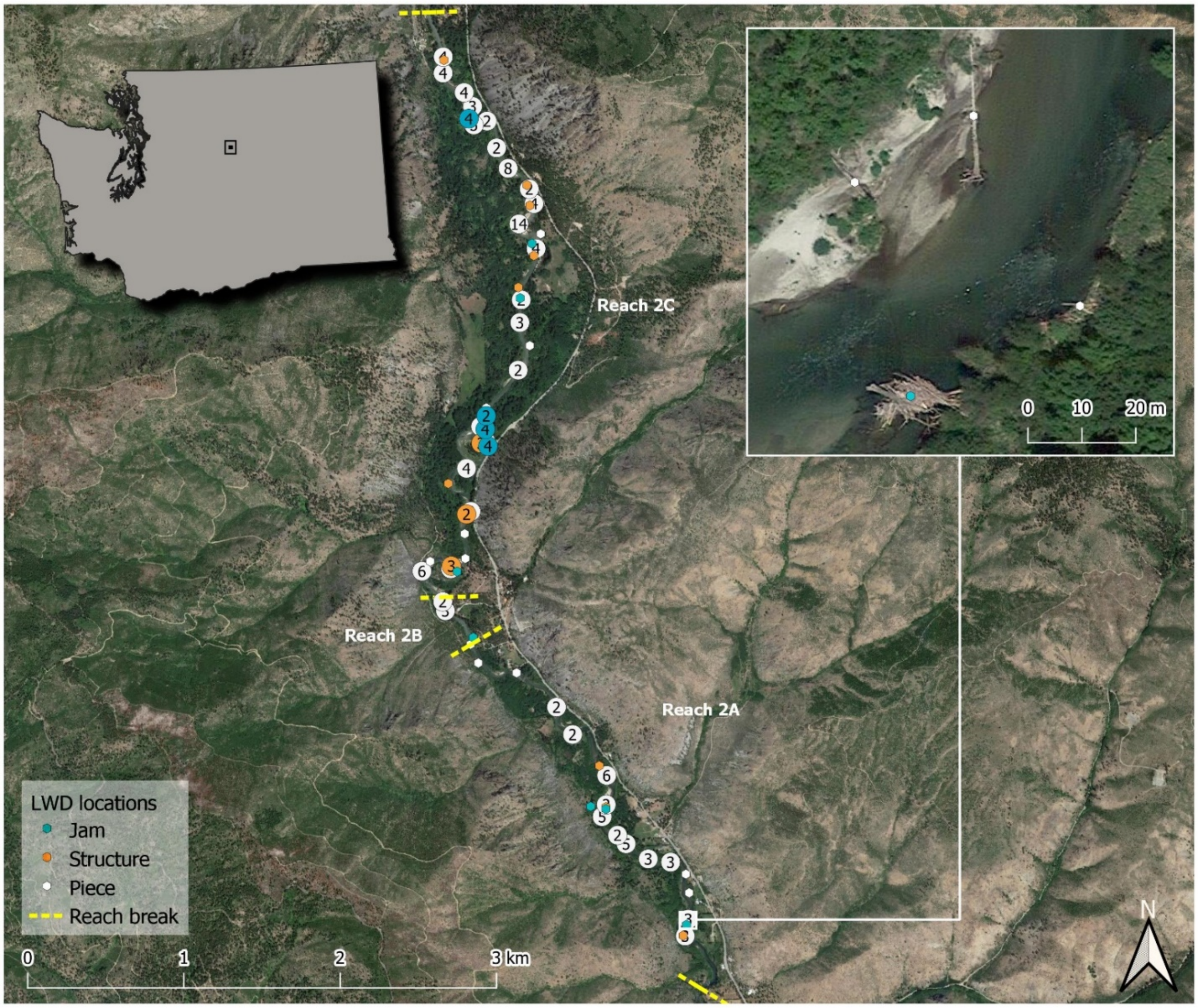

Figure 5. Example of results of LW survey using aerial imagery. Locations of natural large woody debris in the Middle Entiat River were identified using aerial imagery and classified as pieces (<3), small jams (3-4), or large jams (≥5) based on the number of contributing pieces of wood in each complex. Numbers indicate clusters of the same wood jam categories. Imagery was flown on July 1, 2017 at a mean flow of 1,025 cfs (29 cms). From Roni et al. (2020b).

Flow

Flow measurements are needed for the habitat and channel survey and to build the hydraulic model for HSI modeling. Flow will be taken at the top and bottom of each study site. Flow will be recorded at each site using a calibrated water velocity meter to the nearest 0.01 ft/s after delineating reach and channel unit boundaries. A measuring tape will be strung perpendicular to the stream channel from river left to river right and the measuring tape readings on both banks will be recorded. Total wetted width will be measured and recorded and a minimum of 20 equally spaced flow points will be collected across the channel. If water depth is 2.5 feet or less, velocity will be measured at 0.6 times total depth. If water depth exceeds

2.5 feet velocity will be measured at 0.2- and 0.8-times total depth and averaged to obtain one velocity reading for that station (Harrelson et al. 1994). Distance from the bank, the tape measure reading, and water depth will be recorded at each flow measurement.

4.3 HSI Modeling

A 2D hydraulic model will be developed using HEC-RAS (or similar 2D hydraulic modeling software) using the topobathymetry and selected data from the channel and habitat survey (Brunner 2016). Regardless of the methods used to collect and compile the topography and bathymetry, the final topobathymetric surface will include the entire floodplain and channel within the survey extent. The final topobathymetric surface will be the base surface for the hydraulic model and used to create a computational mesh covering as much of the valley bottom as possible. The river geometry including the channel centerline, banks, junctions, flow paths, and downstream and upstream boundaries will be created based on the topography.

The model will then be parameterized using data collected during the channel and habitat survey. Roughness values for the channel, banks, and floodplain will be informed by the dominant substrate of each habitat unit and estimated based on a range of typical values (Arcement and Schneider 1989; Yochum et al. 2014). The topographic mesh cell size will be set to 0.5–1 m, depending on quality of the topobathymetry. Steady flow model runs will be prepared for discharges that match biologically and geomorphically significant levels and seasonal timing. The model run for base flows will be based on the discharge measured during the field surveys. Discharges for the 2- (bankfull), 5-, and 10-year flow recurrence intervals will be estimated using local gauge data or based on regional regressions. Discharges for biologically significant model runs will be determined by site depending on the periodicity of present species and at a minimum will cover mean discharge during rearing and spawning life stages. For example, if a site contains only steelhead, there would be a minimum of five steady flow model runs (base, snowmelt, 2-, 5-, and 10-year flows) that would adequately cover summer and winter juvenile rearing and adult spawning (Figure 6).

The hydraulic model will contain values for water depth and velocity for each run and provides the basis for calculating the HSI. Habitat suitability curves (HSC) available in the literature express the preferences for water depth and velocity by species and life stage on a unitless scale of 0 (not suitable) to 1 (most suitable; Figure 6). Unless site-specific HSCs have been developed, the HSCs reported in Beecher et al. (2016) or Maret et al. (2006) will be used. A suitability index for water depth and velocity will be calculated separately for ever raster cell in the hydraulic model results. Then, depth and velocity suitability will be combined using the geometric mean, resulting in a final HSI value for every raster cell. As an option, substrate preferences may be added to this workflow if an appropriate HSC exists for the species and life stage in question. This process will be repeated for each steady flow model run.

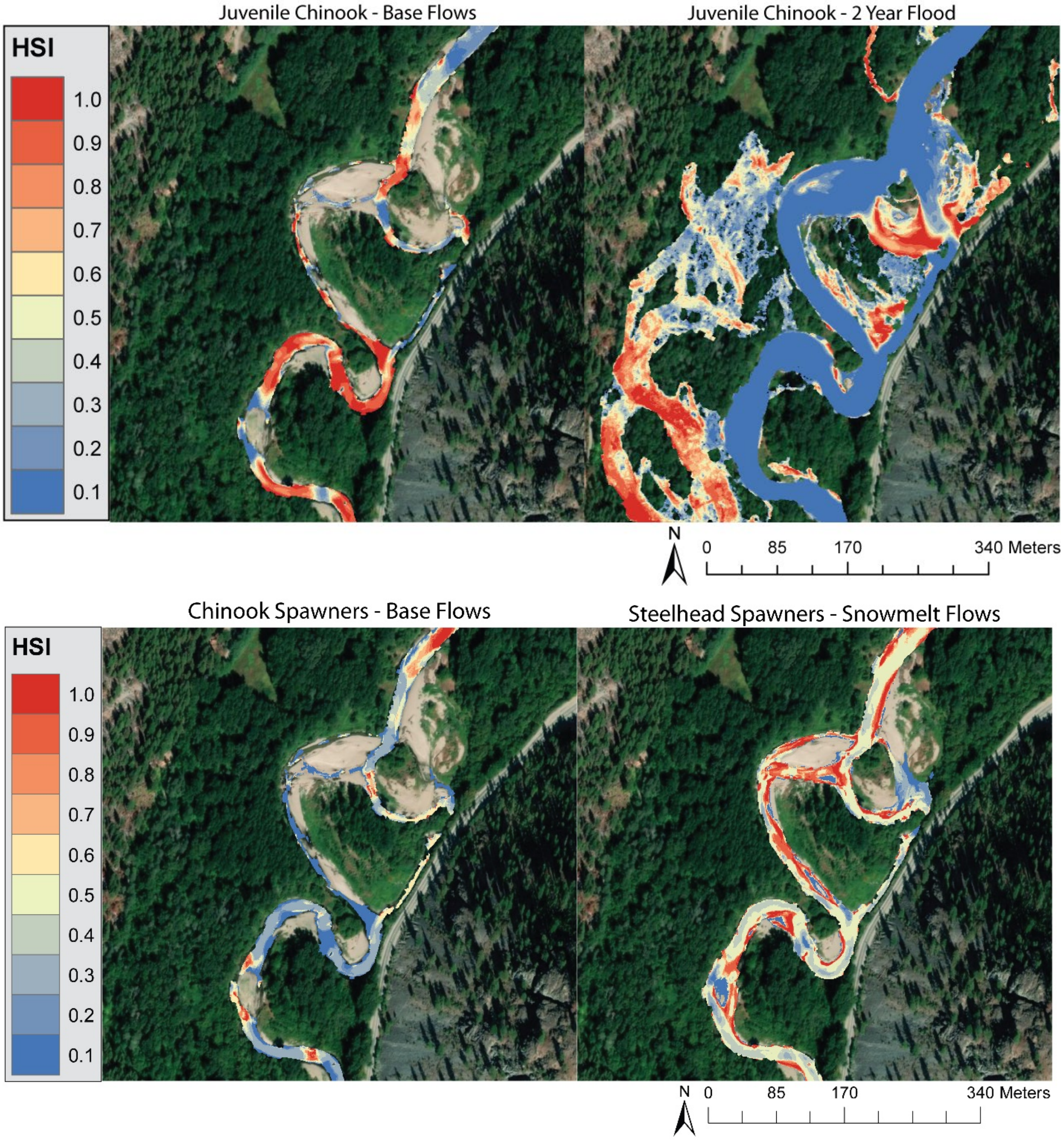

Figure 6. Example of HSI outputs and maps for different flows, species, and life stages for the Entiat River before restoration (Roni et al. 2020b).

Habitat suitability index results will be summarized graphically as histograms and maps to visualize the distribution of HSI values among each site and modeled discharge. To summarize HSI at the reach scale, weighted usable area (WUA) will be calculated as the sum of the product of HSI and cell area (Equation 1). WUA represents the amount of habitat that is available to a species during a given discharge (Kondolf et al. 2000; Hong et al. 2018). Normalized WUA (nWUA) is helpful to facilitate interpretation and compare discharges, reaches, subsequent surveys, and is calculated as WUA divided by the total area evaluated (Equation 2). nWUA represents the proportional area that contains suitable habitat during a given discharge.

Equation 1. Calculation for weighted usable area (WUA).

$$WUA = \sum (HSI \ \times cell\ area)$$

Equation 2. Calculation for normalized weighted usable area (nWUA).

$$nWUA = \frac{\sum (HSI \ \times cell\ area)}{total\ area}$$

4.4 Riparian Survey

The types of data required to monitor riparian projects are heavily influenced by the questions being investigated. Monitoring riparian response to floodplain or riparian restoration requires a combination of remotely sensed data (LiDAR data products) and field data to both validate and verify remotely sensed estimates and to measure parameters necessary to calculate metrics that cannot be estimated from remotely sensed platforms (e.g., understory species composition). The point cloud associated with LiDAR data can be classified and analyzed to create several data products to calculate monitoring metrics such as canopy models, understory layers, and shade models, but does not eliminate the need for high quality field data to answer the key monitoring questions for this monitoring program. The canopy height model can be used to monitor tree growth and could be used to model future LW recruitment. In addition to topographic data (DEM) that will be obtained from the LiDAR, a DSM, as well as the point cloud itself (Figure 7) will be analyzed to help generate many of the riparian monitoring metrics. In general, most LiDAR vendors provide a classified point cloud along with a DEM and DSM, but these products should be considered required from the contractor or vendor for this study. Below we describe riparian field methods including initial site layout, which are based on and consistent with the recent U.S. Forest Service riparian monitoring guidance (Merritt et al. 2017), and those recently developed to monitor riparian projects as part of Bonneville Power Administration's (BPA) Action Effectiveness Monitoring (AEM) Program (Roni et al. 2020a).

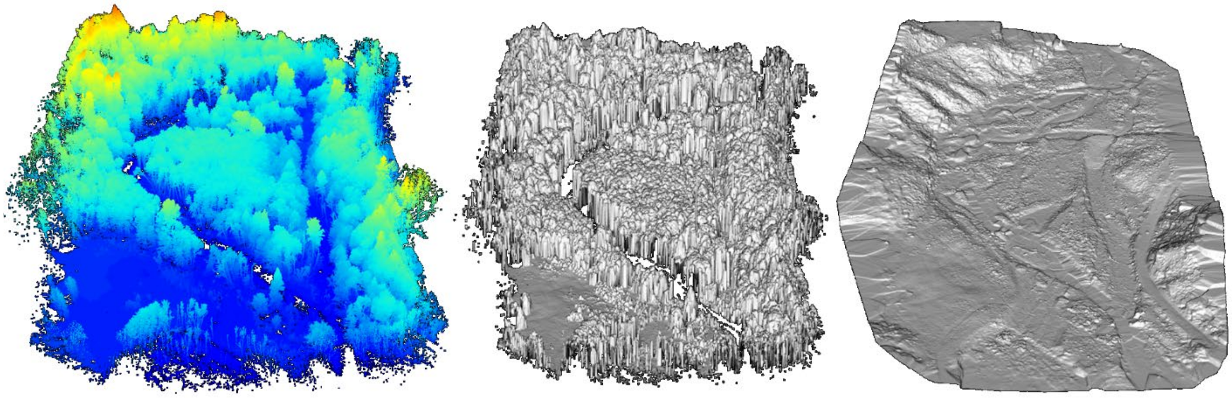

Figure 7. Example of point cloud (left) and digital surface model (DSM; middle) and digital elevation model (DEM) right from drone-based LiDAR flown on Morse Creek Washington in fall of 2019.

Riparian Site Layout and Survey Methods

The purpose of this survey is to (1) identify species, (2) provide validation data for remotely sensed metrics, and (3) record conditions relating to planting projects, such as evidence of browsing, or if planting protections are still functional (tree tubes, fencing). While we described delineation of the upstream and downstream location of site boundaries, additional detail on site layout for riparian monitoring is described in the following. Field sampling of riparian conditions at floodplain restoration sites or at floodplain and riparian only restoration sites will be done using a transect approach (Merritt et al. 2017). The sampling layout along a site consists of equally spaced, 2-m wide transects every 100 meters that extend from the active channel zone to the edge of the planting project or 30 m, whichever is greater, and are 90 degrees perpendicular to the stream channel at the location of each transect (Figure 8). Thirty meters was chosen as the extent of the transect in part because it is validation for the LiDAR and necessary for plant species and diversity data, but also because many riparian plantings do not extend beyond this point, it represents the extent of the riparian management zone for forest practices, and beyond 30 meters we are relying on the remote sensing. A meter tape will be strung down the middle of each transect allowing delineation of a 1 m-wide sampling area on each side of the meter tape. Sampling transects every 100 m will result in a minimum of 10 transects for a 1 km site. Additional transects can be added if the equally spaced transects do not cover the riparian treatment areas. The exact GPS coordinates of the transects will be recorded and benchmarks placed in the field to assist with relocated and sampling the exact same transects each year.

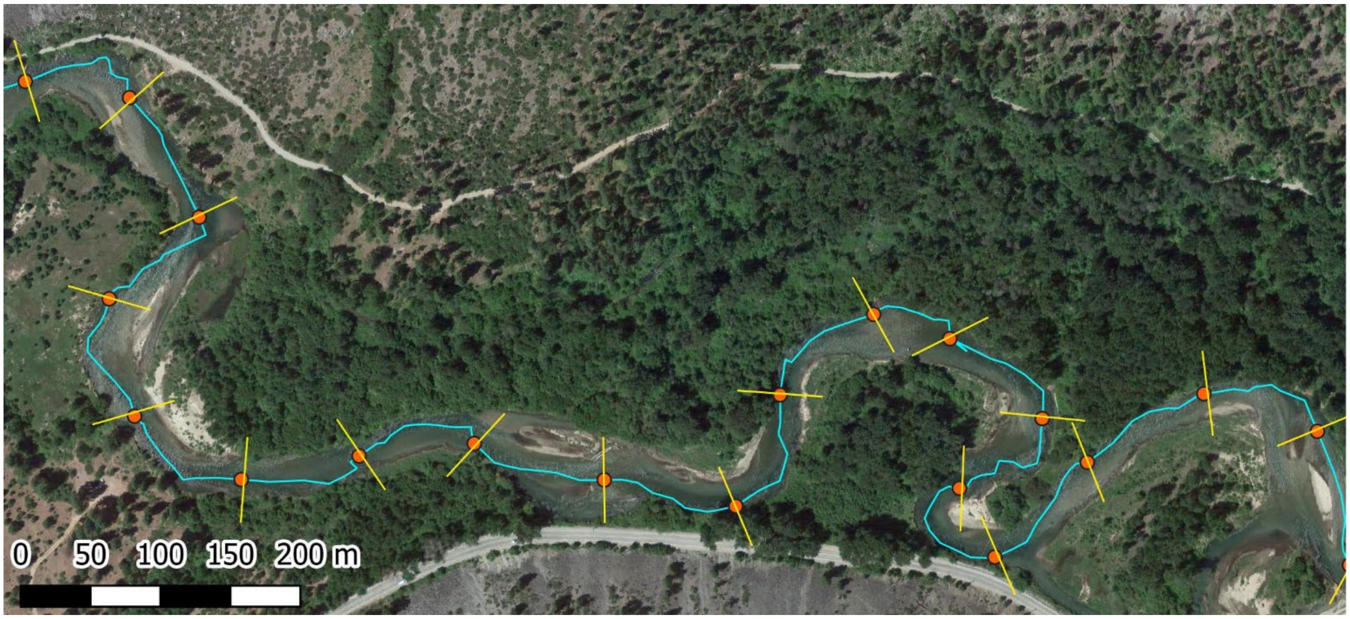

Figure 8. Example of site layout for riparian field surveys of a 2-kilometer long site (floodplain or riparian restoration) project. Transects will be spaced 100 meters apart perpendicular to the flow and start at the edge of active channel and extend 30 m into the riparian treatment zone (plantings). Additional transects can be added if riparian treatments as part of floodplain restoration are not continuous and not intersected by 100 m transects and, the same number of transects are surveyed before and after restoration at each site.

At each transect, all woody species (shrubs and trees) will be identified down to species except for willows, which will be denoted as *Salix* spp. The location along the transect and the height of each woody plant specimen encountered will be recorded. Due to the complexities in identifying forbs and grasses, they will be assigned to a single category (forbs and grasses), and the continuous length they occupy along the meter tape will be recorded. Additional data on individual woody plant species will be collected as follows: bud browse (y/n), beaver damage (y/n), living or dead, and evidence of planting (e.g., planting tube, fence, tree marker).

Vegetation cover will be assessed in three different height categories using a line transect (meter tape located in the middle of the transect) following the line-intercept method (Elzinga et al. 2001). Cover estimates are calculated along the transect by noting where along the tape the canopy of an individual plant begins and ends. Plant height categories include herbaceous (<1 m), shrub (1–5 m), and tree (>5 m). The length of the center line represented by bare earth will also be measured. Bare earth, logs, rocks, etc. must occupy more than 30 cm to be counted in the bare earth category.

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

Multiple site characteristics will also be recorded during surveys for further analysis to elucidate why some plantings within and among projects are more successful than others. These characteristics include: (1) whether a planting plan was drafted and followed, (2) if ongoing maintenance has been taking place at the site (e.g., watering, soil augmentation), (3) the distance of the riparian restoration plot (site) from the active channel edge, and (4) the elevation from the stream bed surface to the floodplain or riparian planting site height (taken at the project midpoint). Additionally, for floodplain projects, the bankfull depth and incision (from floodplain monitoring) will be measured.

Areal Vegetation Extent by Class

Areal extent of vegetation classes will be based on the methods developed by Akay et al (2012). LiDAR returns between a min and max height (shrub height) will enumerated and compared to the number of ground returns. More understory coverage will intercept more pulses, increasing the returns in the height band, and decreasing the number of ground returns, so this serves a relatively direct proxy for understory cover. A similar method will be used for measuring the overstory areal extent. Predicting the extent of the herbaceous layer is more difficult and will depend on site characteristics. Comparisons of LiDAR derived estimates to field based surveys will allow the LIDAR estimates to be calibrated and validated. Calculating this metric requires the point cloud and DEM data from LiDAR coupled with binned understory data and other field data to calibrate the LiDAR data.

Riparian Composition and Density

Riparian composition and density can only be reliably calculated using the field survey data. Species richness will be calculated as the sum of identified unique species, while density will be estimated by species counts divided by area of transects. Diversity will be calculated using Shannon’s diversity index (Shannon 1948) and averaged across all transects. Additionally, there is potential to extrapolate values to unsampled areas using LiDAR data and machine learning techniques (Singh et al 2015).

Bank Stability

Coarse measures of bank stability and erosion can be done with remote sensing but can be unreliable under heavy riparian cover or can be too coarse for reach-scale monitoring (Longoni et al. 2016; Billah 2018). Therefore, to assess bank stability, field crews will measure and record the length of unstable banks at each transect (see section 4.2 Channel and Habitat Survey above).

Shade

Riparian shade will be measured using the DEM and DSM to measure vegetation height based on methods of Greenberg et al. (2012) and requires understory canopy height estimates from riparian transects. LiDAR data is used to create surface models, and then 100 m stream buffers are analyzed to estimate solar insulation using the r.Sun model (Hofierka and Suri 2002) incorporated into the GRASS geospatial software environment (GRASS Development Team 2017), which incorporates time of day, time of year, and atmospheric turbidity, and can model both clear sky and overcast conditions (Greenberg et al. 2012). Comparisons to bare earth model-based results can describe the impact and effect of riparian vegetation along the waterbody. The GRASS insolation workflow describes methods to estimate surface albedo and Linke atmospheric turbidity coefficients (Linke 1922), which are both required to run simulations.

Organic Inputs

Organic matter inputs will be estimated based on volume of canopy that overhangs the active channel (Laslier et al. 2019). This can be directly estimated from LiDAR point cloud returns. Although this methodology is consistent, it is a low-end estimate for organic input as it does not consider input from locations adjacent to the active channel, and both gravity and wind are ignored. More accurate input could be obtained from remote sensing if LiDAR was flown both on leaf-on and leaf-off, but we assumed that would be too costly so the method we proposed is based on LiDAR flown at leaf-off only. We caution that due to the many nuances and complexities of measuring organic inputs, a separate study is warranted if these questions are of critical importance.

5.0 DATA MANAGEMENT AND ANALYSIS

5.1 Types of Data Generated

All collected data and data products for metric generation will range widely in file size based on the data and the size and complexity of the site. Altogether, total file size *per site per visit* will likely exceed 10 GB with all the data collections and data products combined (Table 11). Once all spatial data and shapefiles are created and finalized for a site, they should be stored in one spatial database per site for consistency and to decrease file size. Due to the large file size, it is imperative that the computers and/or hard drives storing the data have the appropriate storage space and computing capacity. Planning for the total amount of data will require estimates of total sites, size of site (sq. km) and the total number of visits in the monitoring plan.

Table 11. File types and the range of their overall file size for floodplain projects for one site visit.

File type	General file size
Point cloud (LAS file)	0.5 to 6.5 GB
DEMs	5 to 16 MB
Aerial imagery	1.5 to 4 GB
RTK data exports	3 to 10 MB
RTK point data	2 to 6 MB
Shapefiles (e.g., polygons, linework)	2 to 8 MB
Riparian field surveys	< 2 MB

5.2 Data Management, Storage, and Backup

Prior to any data acquisition, it is important to create a data management structure that is clear and organized (Figure 9). All folder and file names should be descriptive of a site name or number as well as the year of survey (e.g., Cle Elum_2020, Cle Elum_2020_wetted-polygon). Folder and file structure with a similar naming system and files with the same column headings across all monitored sites and years will allow for easier automation in metric generation. Once a data management structure is finalized, it is important to have a system in place that provides the site name, reach, and year monitored for all sites in one file location.

For best data management practices, all data should be backed up in multiple locations on a regular basis.

Figure 9. Example of folder structure for data storage. This is not the exact folder structure that needs to be used but is an example of one possible layout.

- 🗁 Site Name
  - 🗁 Year
    - 🗁 Collected Data
      - 🗁 Topography
      - 🗁 Bathymetry
      - 🗁 Auxiliary
        - 🗁 RTK Data
        - 🗁 Field Data
    - 🗁 Data Products
    - 🗁 Metrics

Any collected auxiliary data—both RTK and field data—should go through a thorough quality assurance and quality control workflow. Visually inspect data to identify any erroneous measurements that may need further consideration. Auxiliary data needs to be exported and stored each day to eliminate data loss in the case of any malfunctioning equipment.

Finally, for improved cost efficiency, executable scripts should be developed for automated metric generation using the data products. The metric calculations described in Table 9 should be used when developing any scripts for metric generation. As metrics are calculated, they should be exported and stored in one file that will be used in data summarization and analysis. In addition, data analysis and summarization scripts should be developed for improved cost efficiency and consistency across years (see Section 7.0 for reporting).

5.3 Data Analysis

5.3.1 Project Level Analysis

Because the focus of the monitoring design is at the project level, analyses will include evaluating the difference in metric values before and after restoration (see Table 6 yearly schedule). The change in each metric will be quantified and relativized (i.e., percent change) to help determine the effectiveness of projects. Some metrics will likely see immediate changes due to restoration treatments (e.g., large wood, side channel area), while some changes may take several years before a change can be seen or detected (e.g., increased shading from riparian planting), and still others will depend on a large disturbance event taking place before changes can be detected (e.g., changes in sinuosity post flood).

Changes will be reported and analyzed both in tabular form, as well as diagrams and figures that demonstrate changes over time as more data points are collected (Table 12). Metrics with continuous spatial representation (e.g., topography, bathymetry, solar insolation, cover class) derived from remote sensing will be displayed analogously to a DEM of Difference (DoD), where a new surface layer is created that represents the difference in metrics at that site (Figure 10). Compared to aggregated metrics (e.g., total insolation, aggradation, degradation), this provides a more granular summary of changes, highlights spatial patterns, and can help to understand the extent of effects. For example, the aggregated metric of average insolation hours (energy/m^2) may show a decrease, which implies additional shading, but the surface of differences will show where the changes in solar insolation are occurring. Similarly, See 7.0 Reporting and Implementation for more information on table and figure reporting recommendations.

Table 12. Example of tabular presentation of six floodplain restoration sites monitored before and after restoration. These sites were approximately 0.5 km in length and are being monitored as part of BPA's AEM Program but provide a simple example of tabular summaries for a subset of floodplain monitoring metrics. RCI =river complexity index, LW = large wood. Yr -1 = before restoration, Yr +1 or Yr +3 year of post-restoration monitoring.

Site name	Year	Pool:riffle ratio	Slow water (%)	Residual pool depth (m)	Habitat Diversity (H)	RCI	LW
Hartsock	Yr -1	1.33	40	0.26	1.31	0.44	15.2
	Yr +1	0.86	40	0.32	1.24	1.62	73.8
Touchet	Yr -1	0.25	46	0.18	0.96	0.64	0.5
	Yr +3	0.60	39	0.29	1.08	0.65	15.4
Southern Cross	Yr -1	0.40	48	0.29	1.03	0.40	0.7
	Yr +3	1.00	72	0.62	1.10	0.40	110.9
Tucannon	Yr -1	1.00	31	0.58	1.37	3.22	75.3
	Yr +3	1.6	42	0.42	1.51	2.61	143.5
Pine	Yr -1	2.33	77	0.50	1.03	1.34	26.2
	Yr +3	2.33	82	0.53	1.23	1.41	203.7
Caribou	Yr -1	1.60	78	0.53	0.88	0.63	0.8
	Yr +1	2.67	90	0.65	1.16	1.25	31.1

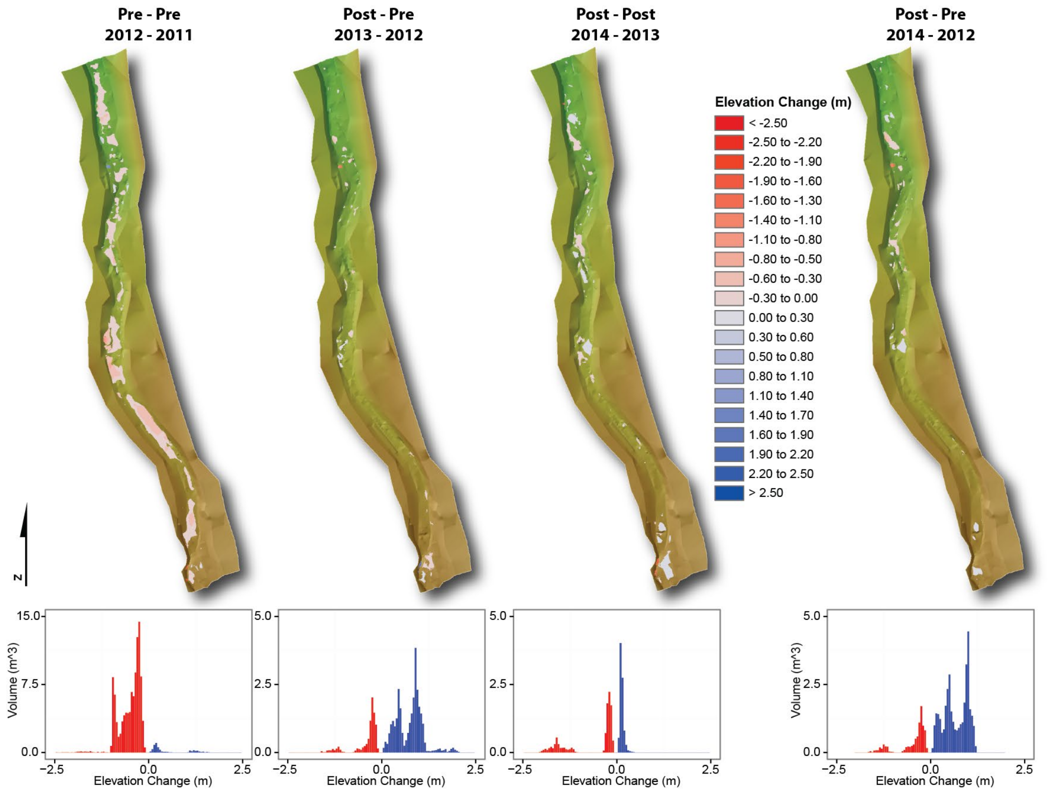

Figure 10. Example of DEM of Difference (DoD) at different points in time before and after restoration showing aggradation and degradation.

Evaluating whether a project meets its design objectives is not as straightforward as traditional monitoring analysis, and requires detailed information on the project design, goals, and objectives as well as detailed "as-built" survey data. Previous programmatic effectiveness monitoring programs were designed to provide general recommendations on project design (e.g., most successful projects more pool forming wood; Roni and Quinn 2001; Roni et al. 2018; Clark et al. 2019). Fortunately, for the proposed study, the pre-project topographic and bathymetric data and hydraulic and HSI models, combined with information from the aggradation and degradation and outputs from the GUT can be used to understand why certain actions (e.g., logjams, side channels, levee removal, meanders) did or did not result in the desired changes in scour, deposition, and habitat formation (Figure 11). This information can be used to provide detailed information on restoration design not previously examined in SRFB PE monitoring, and one of the main reasons that "as-built" surveys are needed once restoration has been is completed.

5.3.2 Combined Analysis

While sites will not be selected entirely randomly, they will be stratified by recovery region and representative of projects occurring in the region. Therefore, a combined analysis can be conducted to examine the overall response of large floodplain and riparian projects sampled as long as it is understood that drawing inference to all other floodplain or riparian projects in the region is not appropriate. A mixed-effects model will be used to collectively analyze floodplain and LW projects sampled (Downes et al. 2002; Schwarz 2015). Other approaches (Bayesian, repeated-measures, boosted regression trees) are also potential methods for analyzing the data that will be considered, but the mixed-effects model is considered the most robust method for analyzing data collected using BACI and BA designs (Downes et al. 2002; Schwarz 2015). Mixed-effects models are also being used to evaluate floodplain projects under BPA's AEM Program. Sample size can influence the ability to detect changes, but evaluation of smaller floodplain projects (<1 km in length) have shown differences due to restoration with a sample size of only six sites, assuming responses are relatively large (>50% change). Simple graphical summaries will also be provided to demonstrate differences among projects (Figure 12).

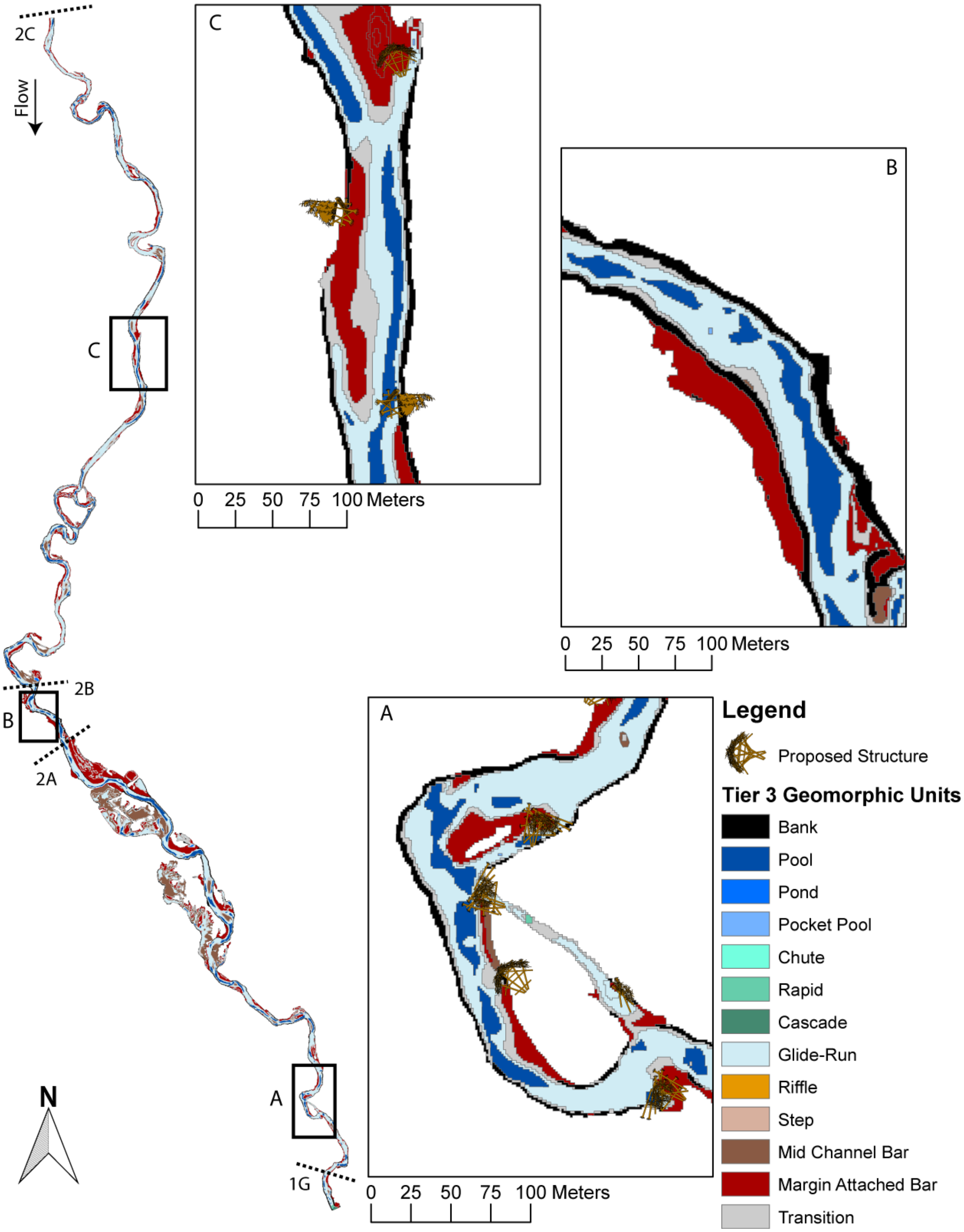

Figure 11. Example of output from GUT at bankfull stage and proposed structures for a large (~8 km) restoration project underway on Entiat River (Roni et al. 2020b).

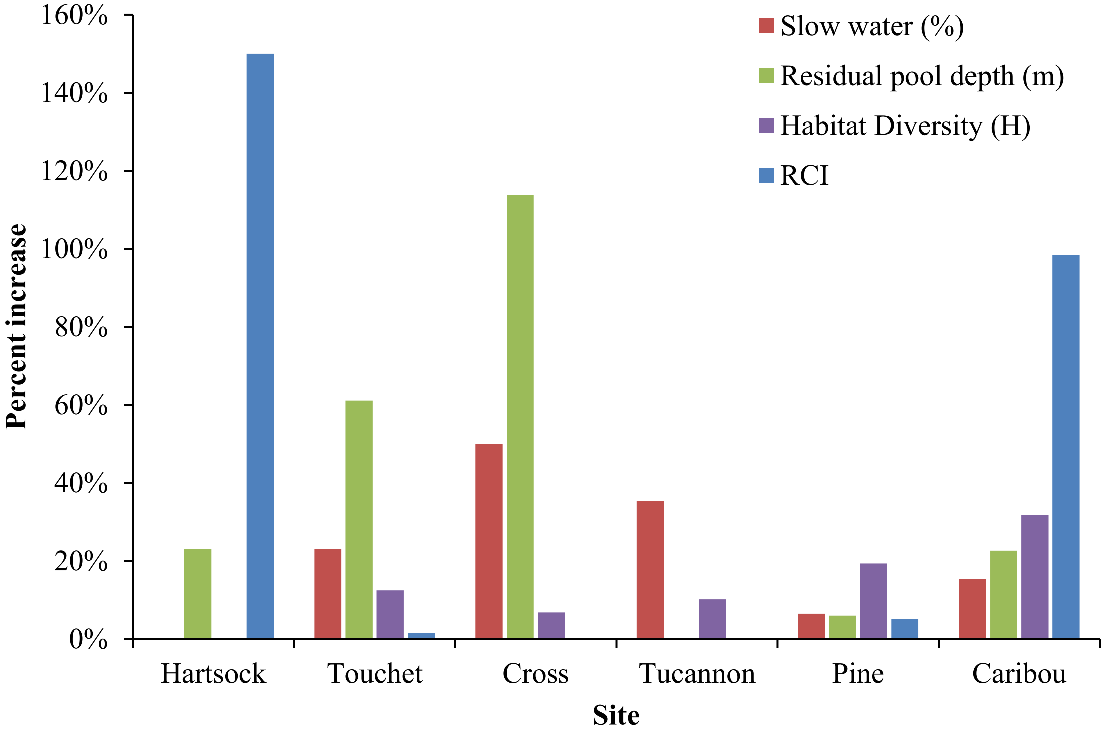

Figure 12. Example of simple graphical presentation of change of a sub-set of monitoring metrics for six floodplain restoration projects before and after restoration.

6.0 APPROXIMATE COSTS

While costs for data analysis and reporting are not trivial, the costs of the proposed monitoring program are largely driven by three key components: the cost of acquiring LiDAR, the cost of field data for floodplain metrics, and the cost of riparian surveys. These three components are largely driven by the number, size, and complexity of sites, making accurate costs estimates before study sites have been identified challenging. Based on our experience with pilot studies (CFS 2019; Roni et al. 2020b), our experience monitoring other riparian and floodplain projects in the last two years, and estimates of green LiDAR acquisition from the Department of Natural Resource's LiDAR vendor, we estimated the approximate costs for data acquisition for different sized sites. These estimates are for planning purposes and actual costs will depend upon site selected, contractor staffing costs, and other factors and may be slightly higher or lower. Given that the average mainstem length of floodplain restoration treatment for large restoration worksites in PRISM was 2 kilometers, with most worksites ranging from 1 to 4 kilometers (Figure 2), we estimate the cost for sites in this size range (Table 13). Given that acquiring green LiDAR will cost about $35,000 (range $30-40,000) for sites of up to 8 km in mainstem length, it will likely be more cost-effective to acquire data for sites shorter than 4 km using drone-based red LiDAR and a field survey for bathymetry. Total costs for acquiring floodplain data with this approach will be about $17,750 per kilometer. Riparian surveys will cost approximately $4,500 per kilometer.

Table 13. Approximate cost of acquisition LiDAR and necessary field data for monitoring floodplain restoration projects. Field surveys for riparian projects would only require riparian component and red LiDAR, which could be acquired with either drone or fixed wing aircraft.

	Length of Site Surveyed			
	1 km	**2 km**	**3 km**	**4 km**
Green LiDAR (fixed wing aircraft)	$35,000	$35,000	$35,000	$35,000
Field data	$3,600	$7,200	$10,800	$14,400
Total	*$38,600*	*$42,200*	*$45,800*	*$49,400*
Red LiDAR (drone)	$6,200	$6,200	$6,200	$6,200
Bathymetry and field data	$11,550	$23,100	$34,650	$46,200
Total	*$17,750*	*$29,300*	*$40,850*	*$52,400*
Riparian	$4,450	$8,900	$13,350	$17,800

Costs for analysis and reporting are likely similar regardless of length of sites surveyed, and while we did not estimate them, based on our experience with other monitoring programs allocating $25,000 or more a year each for analysis and reporting is not unexpected. Nor is $15,000 for coordination and study management unreasonable; though in the first year of the study, it may be nearly double that to do initial site selection. In addition, the initial development and validation of hydraulic models at multiple flows could cost $5,000 to $10,000 per site, though updating the models with a new surface from post-treatment surveys should cost substantially less (<~$1,000). If one assumes that most floodplain sites will be 2 km in length and data collection will begin at four sites 2020 and four in 2021, for a total of one site per recovery region (8 sites), data collection alone will $152,800 a year at least for the first two years. Including riparian only projects in the study would increase costs, but field data collection is much less expensive, and since they do not require bathymetry, red LiDAR might be available from DNR or other partners. If not, red LiDAR can be collected relatively inexpensively ($6,200 per a site) using a drone.

It is likely that there could be some costs savings as time goes on but given many studies or monitoring programs evaluating restoration have been underfunded, it is wise to not assume this will occur. These estimates are for planning purposes and highlight the decisions that need to be made in terms of site selection (e.g., size, number, and type) and in potentially refining or prioritizing the study questions (e.g., are all questions relevant).

7.0 REPORTING AND IMPLEMENTATION

While most attention on developing a monitoring program is placed on design, methods, protocols, and even costs, the lack of proper reporting has plagued many large monitoring programs (Reid 2001; Roni et al. 2015b, 2018, 2019b; Bennett et al. 2016; Rosgen et al. 2018). Restoration often fails because data are not regularly anayzed and reported (Kershner 1997). Previous monitoring programs like SRFB PE, CHaMP, the IMW monitoring program, and ISEMP have all suffered from lack of standardized scientific reporting. Thus, annual reporting is critical for effectiveness monitoring to ensure timely anaysis of data, identify errors in data collection and analysis, adpatively manage results, facilitate review of the monitoring program, and perhaps most importantly, dissimenate information to partners and interested party for adaptive management and collaborative learning (Weber et al. 2018). To meet these requirements, we outline the key components that should be reported on an annual basis for the effectiveness monitoring report:

Executive Summary
Acknowledgements
1.0 Introduction
  1.1 Background
  1.2 History
  1.3 Goals and Objectives
  1.4 Monitoring Questions
2.0 Methods
  2.1 Design and Replication
  2.2 Metrics
  2.3 Data Collection
    2.3.1 Remote sensed data
    2.3.2 Field data
    2.3.3 Data management
  2.4 Data Analysis
    2.4.1 Individual project level
      2.4.1.1 Graphical analysis
      2.4.1.2 Statistical analysis
      2.4.1.3 Additional modeling

- 2.4.2 Across Projects
  - 2.4.2.1 Graphical analysis
  - 2.4.2.2 Statistical analysis
  - 2.4.2.3 Additional modeling
- 3.0 Results
  - 3.1 Floodplain
    - 3.1.1 Project level
    - 3.1.2 Across projects
  - 3.2 Riparian
    - 3.2.1 Project level
    - 3.2.2 Across projects
- 4.0 Discussion and Management Recommendations
  - 4.1 Project Level
  - 4.2 Across Projects
  - 4.3 Current Year Results Compared to Previous Year
  - 4.4 Recommendations for Next Year of Monitoring
  - 4.5 Management Recommendations Based on Current Results
- 5.0 References
- Appendix A: Floodplain Projects – Summary data tables by project and year for all metrics
- Appendix B: Riparian Projects – Summary data tables by project and year for all metrics

A critical component will be to ensure that all data are summarized and reported for all metrics and, if not provided in body of results, are provided in summary data tables in appendices. Moreover, each annual report should build off the previous one so that it includes not just the current year's data, but all previous years. This will allow the Monitoring Panel, partners, and others to examine see the data and conduct an independent evaluation or analysis of the data quality and findings. It will also allow restoration practitioners to readily locate and obtain data on their project and use it for their own purposes. An example of a summary data table and caption for multiple projects from the SRFB PE final report is provided in Table 14. Given the number of metrics, this could mean fairly lengthy appendices in the later years of the project, but it ensures all data are reported and readily available.

Table 14. Bank erosion (%) in the treatment and control reach for all sampling years for livestock exclusion projects. Missing values were not measured in that year of sampling for a particular site.

Site ID	Site name	Reach	Year 0	Year 1	Year 3	Year 5	Year 10
02-1498	SRFB: Abernathy	Treatment	2	3	4	7	0
		Control	2	0	3	13	0
04-1655	SRFB: Hoy Riparian	Treatment	100	100	96	4	0
		Control	70	90	83	0	0
04-1698	SRFB: Vance	Treatment	70	0	0	0	0
		Control	40	0	0	11	0
05-1447	SRFB: Indian Creek-Yates	Treatment	10	2	0	0	0
		Control	0	0	0	0	0
05-1547	SRFB: Rauth Coweeman	Treatment	33	21	7	30	19
		Control	1	2	5	12	18
205-060a	OWEB: Bottle	Treatment	11	1	3	5	12
		Control	7	2	12	15	31
205-060b	OWEB: NF Clark	Treatment	39	0	2	9	0
		Control	37	5	8	32	0
206-072	OWEB: Greys	Treatment	13	35	5	0	---
		Control	63	64	7	8	---
206-095	OWEB: Jordan	Treatment	95	0	6	12	12
		Control	100	100	27	47	59
206-283a	OWEB: Johnson	Treatment	80	75	26	12	39
		Control	4	77	4	12	20
206-283b	OWEB: Noble	Treatment	50	11	1	---	---
		Control	0	28	21	---	---
206-357	OWEB: NF Malheur	Treatment	71	42	37	7	29
		Control	59	34	45	12	26

With the focus on project level inference for interpreting results, simple straightfoward graphics will be an important part of the reports. Graphical interpretation of effectiveness monitoring using the BA or mBA monitoring designs often lend itself well to graphical or tabular analysis and are often more easily understood by a broader audience (Conquest et al. 1994; Kershner 1997). For example, quantifying the number and area of side channels and wetted area can be easily presented before and after restoration in a simple table, but maps and graphics can more clearly demonstrte these differences (Figure 13).

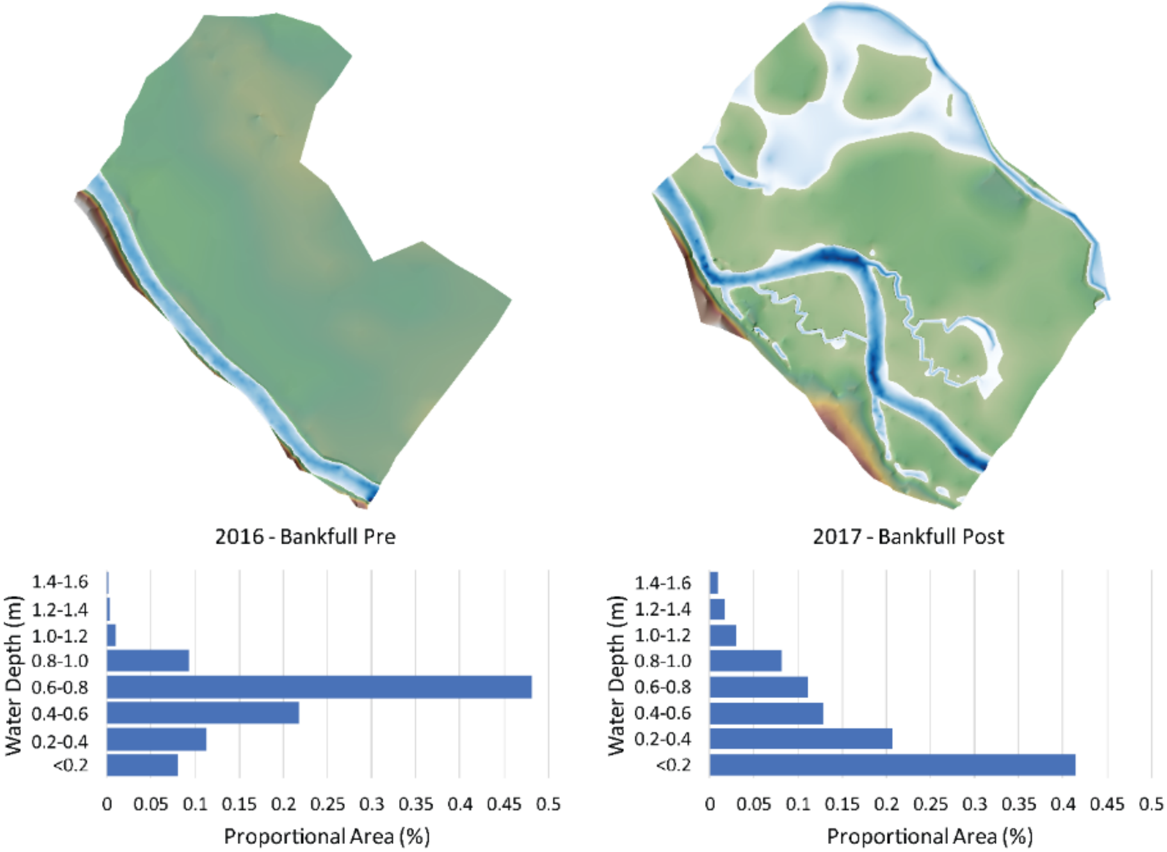

Figure 13. Example of a topographic survey output showing side channels and water depth distribution at bankfull flow before and after floodplain restoration for Catherine Creek, Oregon.

7.1 Annual Reporting Schedule

There should be an annual reporting schedule based on when (what year) data need to be collected within year. Based on the timing of data acquisition, both remote sensing and auxiliary field data, which should occur in late summer or early fall, we recommend the approximate annual schedule for the study including draft and final reporting in Table 15.

Table 15. Proposed annual schedule including period for data collection and dates for draft and final report.

Task	Time Frame
Planning for data collection	April to July
Data collection	Aug to October
Data processing	October to November
Data analysis and writing	November to January
Draft Annual Report	March
SRFB/Monitoring Panel review	April
Final Annual Report	May

In addition to annual reporting, sharing and communicating results to funders, partners, and stakeholders is key to maintaining interest and ultimately the success of long-term ecological monitoring programs (Lindenmayer and Likens 2018). Thus, it will be important to present the results and share the finding of the study annually to SRFB at regional meetings and workshops. Ideally, this would occur at scientific meetings that occur annually or biennially in the region including River Restoration Northwest, Upper Columbia Science Conference, Salmon Recovery Conference, and other conference as well as meetings and workshops of the SRFB and different recovery regions.

8.0 CHALLENGES, COMPLIMENTARY STUDIES, AND NEXT STEPS

8.1 Potential Challenges to Implementing the Monitoring

Many factors other than goals, questions, design, and protocols can reduce the utility of long-term monitoring (>5 years) programs (Lindenmayer and Likens 2018). Below we discuss potential challenges that the proposed study evaluating large floodplain and riparian preojcts might face over the long-term and how these can be avoided or overcome. We see a number of potential challenges that fall into two major categories: (1) implementation (e.g., site identification, controlling other management activities, relying on others for data collection), and (2) technological challenges (e.g. technological changes, improvements in analytical methods, limitations of remote sensing). We describe these challenges below and how they can be addressed or overcome should they arise.

8.1.1 Potential Challenges in Implementation

Potential challenges in implementing an evaluation and effectiveness study or monitoring program include site identification, controlling other mangaement activities, and broad-scale climate changes. Site identification is an important part of any effectiveness monitoring program. Given the amount of floodplain and riparian restoration occurring in Washington State every year, it is assumed that an adequate number of large projects will be scheduled for implementation in 2021 to 2023, so that all pre-project data can be collected in that period. This depends in part on identifying two or more suitable sites in each recovery region by summer 2021 and potentially more importantly, that these projects will all be completed on schedule within one to two years of pre-project monitoring. Delays in the start or completion of the restoration (the treatment) at study sites, will protract the study, which happened with the IMW monitoring programs, and is a problem seen in large programmatic effectiveness monitoring using an MBACI or BA design (Bennett et al. 2016; Roni et al. 2018; Roni et al. 2019b). This challenge can be addressed in three potential ways. First, if the duration of the study is not a concern, then initiation of monitoring at the site can be delayed with the understanding that the change in timing may lead to shifting in costs for monitoring of that project into other years. Second, given that the main level of inference of the study is at the project level, a site that has unforseen delays in restoration timing or other implementation issues after monitoring has begun could be dropped, though it would reduce the sample size for analysis across projects. Third, one could include extra sites with the idea that some sites might eventually be dropped due to issues with implemenation or other management activities compromising the site.

A common challenge faced by any long-term field study is confounding effects of additional restoration measures, maintenance, or other management acitivities following initial restoration implementation. The first two might simply be additional treatments or maintenance that are deemed necessary to improve habitat at the site. For example, it is not uncommon for watering and maintenance to occur at riparian planting sites for three or more years after initial treatment. These restoration measures are expected for riparian planting, but larger efforts such as additional addition of large wood or channel construction could "reset the clock" on the time since restoration. The monitoring would still continue at the site, but the post-restoration monitoring schedule might need to be adjusted. Additional management interventions, such as bank armoring or other infrastructure would need to be treated on a case to base basis. If they impact a large portion or the site or trajectory of the site, the site may need to be dropped (i.e., monitoring discontinued). However, if they impact only a small portion of the site, the monitoring can continue.

Another potential challenge could be large-scale changes occuring at a scale much broader than the reach where the monitoring is occuring, such as a large flood that causes signficant changes in floodplain conditions throughout a watershed or broad-scale changes in climate that influence flow and temperature throughout a region. Two main approaches can be used to address these concerns. For floodplain projects, the reach monitored will include monitoring an additional length upstream and downstream of the project footprint (area to be restored) of 20 times bankfull to examine if restoration-induced channel changes are transmitted beyond the site. This may give some insight into changes occurring elsewhere in the watershed. These areas could be expanded so that they encompass a larger area upstream and downstream not likely to be influenced by the restoration. More importantly, while intensive monitoring of channel changes will occur at the sites, examination of coarser-resolution remote sensing (aerial or satellite imagery) data several kilometers above and below the restoration site will alllow us to quickly determine if similar broad-scale changes are occuring in other parts of the basin.

Finally, relying on data collection or acquisition from partners can be problematic and increases the need for extensive coordination. First, given the history with field data collection by multiple partners for SRFB PE, IMWs, and CHaMP/ISEMP programs (Rosgen et al. 2018; Bennett et al. 2016; Krall et al. 2019), all field data collected should be overseen by one group or contractor. All remote sensing data collection should be done or coordinated by the contractor leading the study. However, if partners are scheduling flights that are intended to acquire LiDAR to be used in this study, it will be necessary for the contractor leading this study to ensure the data is collected on or by specfic dates and under the specifications required. Moreover, if the data is not collected by that date, the contractor needs to go collect the data using a drone or schedule another flight with the green LiDAR vendor.

8.1.2 Potential Technological Challenges

Another category of challenges involves technological issues including changes in technology over time or challenges in data acquisition (e.g., LiDAR, data collected by partners). The quality, accuracy, and resolution of LiDAR has improved from it's initial use. It is likely that in the next decade we will see improvements in quality, accuracy, and resolution of the LiDAR sensors and processing algorithms. However, given that current collection allows for submeter pixel resolution (often ~3 to 5 cm), it is unlikely that near-future improvements to LiDAR resolution will change our recommendations for calculating many of the proposed metrics. Moreover, taking higher resolution data and resampling it to reduce it to be consistent with lower resolution data is statistically possible and well supported.

While there may be some improvements in technology and resolution, a key change likely to occur is improvements in processing and analytical techniques (Tomsett and Leyland 2019). Our review of remote sensing techinques found few new methods in recent years, with most papers focusing on new and novel ways to procsses or analyze the data. Rather than a challenge, however, these innovations are likely to reduce the time and cost of processing the data. For example, new methods for examining riparian metrics from LiDAR are constantly appearing in the published literature. In addition, while most remote sensing relys on ground control points and surveys to confirm and refine mapping and estimates of parameters (Tomsett and Layland 2019), it is likely that these new innovations in analysis will reduce the intensity of field data that needs to be collected, further reducing costs or allowing the monitoring budget to stay stable across years, despite potential inflation.

The reliance on remote sensing when possible in this study may lead to some limitations in resolution or accuraccy of data collected. For example, LW volume and counts will be based on aerial imagery, which may undercount total volume of large wood in areas of heavy canopy or LW that is under the water surface, though LIDAR data can also be used ot help characterize and enumerate LW (e.g., Abalharth et al. 2015; Richardson and Moskal 2016). In addition, if this is a large concern, some field data could be collected to corroborate or supplement LW estimated from remote sensing. However, it should be noted that the questions around wood focus mostly on LW accumulations (jams) in the active channel and causing changes in the floodplain, which should be visible with remote sensing. If it appears that vegetation or water are obscuring a large portion of LW at one or more sits, aerial analysis will be supplemented with LiDAR to characterize LW (Richardson and Moskal 2016), but this will need to be done consistently a site before and after restoration.

The majority of floodplain restoration projects occur on rivers where either green LiDAR or an RTK survey can acquire bathymetry. However, it is possible that some sites will be too deep for either approach. In those cases, an an Acoustic Doppler Current Profiler (ADCP) mounted on a raft or drone (remote control boat) can be used to map the bathymetry (CFS 2020; Tomsett and Leyland 2019). This is widely used by the Bureau of Reclamation (Sixta 2019) and others for mapping bathymetry in large-rivers and likely similar in cost to an RTK survey.

8.2 Related or Complimentary Studies

There are a handful of complimentary studies or data collection that could be done that would enhance the proposed study. This study was designed to meet the goals and questions defined by the SRFB and its partners to detect large changes (>25%) in physical habitat and riparian conditions at large floodplain and riparian restoration projects. Because of the need for high quality and consistent remotely sensed and field data to calculate metrics and answer these questions before and after restoration at each and every project being monitoring, it is difficult, if not impossible to use previously collected data or monitor previously completed projects. However, there are two related approaches that could be used to evaluate projects using completed projects. These include evaluating completed projects using an EPT design, sometimes called a control-impact design, or reducing the number of metrics to just those that can be evaluated with existing LiDAR data to evaluate historical projects before and after restoration.

The EPT design—which samples paired treatment and control reaches at many sites well after restoration has occurred—has been widely used to evaluate the effectiveness of historical restoration action in both the U.S. and Europe (e.g., Roni and Quinn 2001; Louhi et al. 2011; Hering et al. 2015; Poppe et al. 2016; Roni et al. 2018). As noted in Table 3, this design is meant to answer questions about the effectiveness of different project types for managers and provides limited information on individual projects.

For floodplain projects, the question would be:

1) Have previously completed large-floodplain restoration projects lead to improvements in key physical and biological metrics (e.g., floodplain area and inundation, channel migration, side channel area, habitat diversity, HSI)?

Thus, it could be done by modifying methodologies described in this document. There are approximately 175 existing floodplain projects to choose from based on the data in the RCO PRISM database as of January 2020. This design requires locating a suitable control, which even for projects that are less than 1 km in length can be challenging. For example, our efforts have suggested that one-third or less of all projects examined for inclusion in this design have a suitable control (Roni et al. 2018). This will prove much more challenging for large projects (> 1 km), though it is likely that at least 15 to 20 sites can be located from the available sites in PRISM. This design is not recommended for riparian projects both due to the difficulty in finding suitable controls, but also because, often, poor records exist for the extent and location or riparian projects (Roni et al. 2020a). This EPT monitoring design will provide some general project and engineering design guidance, but really describes the average response of all projects and will provide limited information on efficacy of different project or engineering designs. The original recommendations from the PE Final Report (Roni et al. 2019b), were in fact to couple a BA study at a small number (6 to 10) new floodplain projects, coupled with an EPT study evaluating previously completed restoration projects. Bonneville Power Administration is using this approach to monitor floodplain restoration projects in the interior Columbia River Basin, though on floodplain project that are less than 1 km in length, as part of the AEM Program.

Another companion or alternative study would be to reduce the list of metrics in Table 9 that can be calculated without auxiliary field data and with just red LiDAR (topography, but not bathymetry) and conduct a simple mBA design to evaluate previously completed projects using existing data or some new or existing data. This would limit the study to just a handful of metrics and allow one to evaluate previously completed projects that have pre-project LiDAR data. Moreover, post-project data could be collected and then projects that are not yet completed could also be included. This would leverage existing data but provide an examination of only a subset of metrics. Without the auxiliary field data, bathymetric data, and the ‘as-built surveys’, it would be difficult to provide specific recommendations on restoration design to project sponsors. Similar to the EPT approach, this approach would provide answers to broad questions about physical changes and changes in riparian cover before and after restoration for a limited set of metrics that are often of most interest to managers (Table 2).

If one wanted to look at past projects that had existing green LiDAR and other remote sensing techniques, 13 of the 29 metrics could be calculated with only remote sensing data (Table 16). If one were to use coarser, less reliable methods that have not been proven effective for monitoring change, potentially 20 of the metrics could be calculated from remote sensing. The major change in methods would be using professional judgement to estimate bankfull width from a DEM derived from LiDAR and using the GUT to estimate geomorphic units, which is not a reliable indicator of amount of fish habitat (Roni et al. 2020b). There would likely not be the required data to do hydraulic and HSI modeling. It should be noted that few sites have green LiDAR and there have been advances in green LiDAR sensors in recent years, and the quality of older green LiDAR may not be accurate. More importantly, the coarser level of resolution when utilizing purely remote sensing for metrics that require information on bankfull width, depth, and elevation will reduce the ability to detect changes in key floodplain metrics before and after restoration.

Table 16. Floodplain and riparian metrics that can be calculated with only remote sensing (green LiDAR)using proposed protocols and those that could be calculated with remote sensing using coarser less quantitative methods than proposed. * = approximate BFW from DEM (professional opinion), ** = based on Geomorphic Unit Tool (GUT) at bankfull depth, *** = forward looking infrared (FLIR). Y = yes can be reliably measured with remote sensing, Blank = cannot be reliably estimated with remote sensing.

Metric	Current methods	Less accurate or unproven methods
Floodplain area		Y*
Floodplain inundation index		Y*
Area altered	Y	Y
Active channel zone	Y	Y*
Side channel number	Y	Y
Side channel length	Y	Y
Side channel area		Y*
Pond/wetland number	Y	Y
Pond/wetland area	Y	Y
Residual pool depth	Y	Y
Sinuosity	Y	Y*
Side channel ratio	Y	Y
River complexity index		
Bankfull width to depth ratio		Y*
Morphological Quality Index (MQI)		
Pool/riffle ratio		Y**
Slow water (%)		Y**
Pool area		Y**

Metric	Current methods	Less accurate or unproven methods
Pool frequency	Y	Y
Shannon diversity index of habitat units		Y**
Large wood	Y	Y
Sediment deposition and storage	Y	Y
Habitat suitability (HSI)		
Aerial vegetation extent		
Riparian composition (richness, diversity)		
Bank stability		Y
Shading	Y*	Y
Organic inputs	Y	Y
Water temperature		Y***

Restoration of floodplains can lead to changes in water temperature where there is significant change in hyporheic or groundwater exchange (Beechie et al. 2013), and an original question posed by the monitoring panel was:

> What is the spatial distribution of water temperatures in summer and winter, and how much do they change over time?

While there are remote sensing methods like FLIR, which have been used to map surface temperatures across an entire river or valley segment and to identify thermal refuges (Torgersen et al. 2001; Handcock et al. 2012; Dugdale 2016; Dugdale et al. 2019), FLIR methods create a snapshot in time and would need to be repeated seasonally. To compare these thermal maps before and after restoration would require sampling a much broader extent upstream and downstream of the restoration project to ensure any differences seen before and after restoration could be attributed to the actual restoration. FLIR is best suited for monitoring changes before and after restoration at reach-scale when coupled with placement of continuous data loggers throughout a study reach. Ideally, FLIR would be used to map a reach and identify locations for deployment of continuous data loggers at a study site so that seasonal and diurnal changes in temperature before and after restoration could be examined.

Moreover, floodplain restoration includes a variety of treatments and not all projects lead to physical changes that will produce changes in water temperature and exchange with hyporheic or groundwater. So, it is likely that a substantial investment in both remote sensing and field data (temperature loggers) would need to be made, with the understanding that some sites will show little or no change in temperature. Therefore, we recommend temperature monitoring as an optional study component that could be added at sites where substantial temperature changes or refugia are goals of the floodplain restoration. For example, some floodplain projects include remeandering a straightened channel, which may have limited effects on temperature, while others, like Stage 0 restoration projects (Power et al. 2018), potentially create dramatic changes in hyporheic exchange and thus water temperatures. Given the site specificity of this approach and need for periodic downloading of data loggers, it might be a well-suited monitoring component for local partners.

Because of the focus on physical monitoring other than the riparian monitoring, we did not propose other biological monitoring. We see two potential biological components that could be conducted by partners or as companion studies. First, while eDNA is not to the point where it can be used to accurately estimate abundance, it can be used to look for fish presence and absence in different habitats (Ficetola et al. 2008; Thomsen and Willerslev 2015; see Roni et al. 2019a for a review). As was done on a large restoration project in the Entiat River, samples could be collected in different side channels and other floodplain habitats in winter or multiple seasons to examine species presence and diversity in different seasons. This would, of course, be limited to examining broad changes in species presence and habitat use before and after restoration.

Finally, there are obvious additional data collection that could be added to refine the proposed methods or provide more detailed responses (e.g., site specific flow monitoring, leaf-off and leaf-on LiDAR flights, snorkel surveys or other fish monitoring). Estimating bankfull flow, width, and hydraulic modeling could be enhanced by placing pressure transducers at the top and bottom of each site and conducting periodic flow measures to create site specific bankfull and other flow statistics. Estimates of riparian shade and organic matter inputs would be enhanced by flying red LiDAR both during summer (leaf-on) and early fall (leaf-off). These and other components would improve the precision and possibly the accuracy of metrics monitored, but could substantially increase the cost and reliance on field methods. As with some of other complimentary previously discussed, these types of data collection that could be funded or taken on by partners.

8.3 Next Steps

In this study plan, we have outlined all of the key components of a robust study to evaluate the effectiveness of large floodplain and riparian restoration projects. Apart from selecting a contractor to implement this plan, there are several steps to implement the program. These include but are not limited to:

1. Site selection
    a. Reach out to recovery regions to get list of projects
    b. Do preliminary site selection based on response from recovery regions
    c. Visit sites and meet with recovery regions and project sponsors
    d. Delineate site boundaries
        i. Restoration footprint
        ii. Additional length above and below project (20x BFW)
2. Develop a draft field manual
    a. Update MQI
3. Work out sampling schedule and time frame for sites
    a. Annual and 10-year schedule
4. Based on sites selected and footprint, determine best approach for acquiring LiDAR at each site
    a. For any sites requiring green-LiDAR begin coordinating with DNR and LiDAR vendor
5. Begin collecting pre-project data for sites scheduled for construction in 2021

The most important and pressing of these is site selection, which should be done as part of the study implementation and by the team doing the monitoring. An additional consideration would be drafting a field manual including data. A draft field manual is recommended to train field staff for collection of both remote sensing and field data. This could be drafted and revised and finalized after the first year of data collection. It might also be beneficial to have the field manual detail any post-processing steps needed to calculate metrics from data collected. This should include modifying MQI for use in rivers across Washington State. This multi-metric index of floodplain morphology was developed for use in European rivers, and tested on some sites in Washington and Oregon, some minor regional modifications are still needed for adaptation of use at sites throughout the Pacific Northwest.

9.0 REFERENCES

Abalharth, M., M. A. Hassan, B. Klinkenberg, V. Leung, and R. McCleary. 2015. Using LiDAR to characterize logjams in lowland rivers. Geomorphology 246:531-541.

Akay, A. E., M. G. Wing, and J. Sessions. 2012. Estimating structural properties of riparian forests with airborne lidar data. International Journal of Remote Sensing 33:7010-7023.

Arcement, G., and V. Schneider. 1989. Guide for selecting Manning's Roughness Coefficients for natural channels and flood plains. United States Geological Survey, Water Supply Paper 2339.

Bangen, S.G., N. Kramer, J. M. Wheaton, and N. Bouwes. 2017. The GUTs of the Geomorphic Unit Tool: what is under the hood. EP31D-1901. American Geophysical Union Fall Meeting, New Orleans, Louisiana. doi:10.13140/RG.2.2.31118.66884.

Beecher, H., B. Caldwell, and J. Pacheco. 2016. Instream flow study guidelines: technical and habitat suitability issues including fish preference curves. 04-11-007. Washington Department of Fish and Wildlife, Washington Department of Ecology, Olympia.

Beechie, T., and H. Imaki. 2014. Predicting natural channel patterns based on landscape and geomorphic controls in the Columbia River basin, USA. Water Resources Research 50(1):39-57.

Beechie, T., Imaki, H., Greene, J., Wade, A., Wu, H., Pess, G., Roni, P., Kimball, J., Stanford, J. Kiffney, P., Mantua, N. 2013. Restoring salmon habitat for a changing climate. River Research and Applications 29:1535-1467.

Beechie, T. J., O. Stefankiv, B. Timpane-Padgham, J. E. Hall, G. R. Pess, and M. L. M. Rowse, K. Fresh, and M. J. Ford. 2017. Monitoring salmon habitat status and trends in Puget Sound: development of sample designs, monitoring metrics, and sampling protocols for large river, floodplain, delta, and nearshore environments. National Oceanic and Atmospheric Administration, Seattle, Washington.

Belletti, B., M. Rinaldi, A. D. Buijse, A. M. Gurnall, and E. Mosselman. 2015. A review of assessment methods for river hydromorphology. Environmental Earth Sciences 73:2079-2100.

Bennett, S., G. Pess, N. Bouwes, P. Roni, R. E. Bilby, S. Gallagher, J. Ruzycki, T. Buehrens, K. Krueger, W. Ehinger, J. Anderson, C. Jordan, B. Bowersox, and C. Greene. 2016. Progress and challenges of testing the effectiveness of stream restoration in the Pacific Northwest using Intensively Monitored Watersheds. Fisheries 41(2):92-103.

Billah, M. 2018. Mapping and monitoring erosion-accretion in an alluvial river using satellite imagery: the riverbank changes of the Padma River in Bangladesh. Quaestiones Geographicae 37(3):87-95.

Brown, A. G. 2002. Learning from the past: palaeohydrology and palaeoecology. Freshwater Biology 47:817-829.

Brunner, G. W. 2016. HEC-RAS River Analysis System User's Manual, Version 5.0. U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis, California.

Campana, D., E. Marchese, J. I. Theule, and F. Comiti. 2014. Channel degradation and restoration of an Alpine river and related morphological changes. Geomorphology 221:230-241.Castro, J. M., and P. L. Jackson 2001. Bankfull discharge and recurrence intervals and regional hydraulic geometry relationships: patterns in the Pacific Northwest, USA. Journal of the American Resources Association 37:1249-1262.

Castro, J. M. and P. L. Jackson. 2001. Bankfull discharge recurrence intervals and regional hydraulic geometry relationships: patterns in the Pacific Northwest, USA. Journal of the American Water Resources Association, 37: 1249-1262.

CFS (Cramer Fish Sciences). 2019. Floodplain restoration monitoring: 2019 pilot study to evaluate new methods and metrics for monitoring project effectiveness. Report prepared by Cramer Fish Sciences for Recreation and Conservation Office and Bonneville Power Administration.

CFS (Cramer Fish Sciences). 2020. Review of remote sensing and emerging technologies for use in evaluating floodplain and riparian projects. Memo to Keith Dublanica and Recreation and Conservation Office dated February 10, 2020. 20pp.

CHaMP (Columbia Habitat Monitoring Program). 2016. Scientific protocol for salmonid habitat surveys within the Columbia Habitat Monitoring Program. Protocol prepared by CHaMP for the Bonneville Power Administration, Portland, Oregon.

Clark, C., P. Roni, and S. Burgess. 2019. Response of juvenile salmonids to large wood placement in Columbia River tributaries. Hydrobiologia 842:173-190.

Clark, C., P. Roni, J. Keeton, and G. Pess. 2020. Evaluation of the removal of impassable barriers on anadromous salmon and steelhead in the Columbia River Basin. Fisheries Ecology and Management 27:102-110.

Conquest, L. L., S. C. Ralph, and R. J. Naiman. 1994. Implementation of large-scale stream monitoring efforts: sampling design and data analysis issues. Pages 69-90 *in* S. L. Loeb, and A. Spacie, editors. Biological monitoring of aquatic systems. Lewis Publishers, Boca Raton, Florida.

De Rosa, P. A. Fredduzzi, and C. Cencetti. 2019. A GIS-based tool for automatic bankfull detection from airborne high resolution DEM. ISPRS International Journal of Geo-Information 8:480-496. doi:10.3390/ijgi8110480.

Dugdale, S. J. 2016. A practitioner's guide to thermal infrared remote sensing of rivers and streams: recent advances, precautions and considerations. Wiley Interdisciplinary Reviews: Water 3:251-268.

Dugdale, S. J., C. A. Kelleher, I. A. Malcolm, S. Caldwell, and D. M. Hannah. 2019. Assessing the potential of drone-based thermal infrared imagery for quantifying river temperature heterogeneity. Hydrological Processes 33:1152-1163.

Downes, B. J., L. A. Barmuta, P. G. Fairweather, D. P. Faith, M. J. Keough, P. S. Lake, B. D. Mapstone, and G. P. Quinn. 2002. Monitoring ecological impacts: concepts and practice in flowing waters. Cambridge University Press, New York.

Elzinga, C. L., D. Salzer, J. R. Gibbs, and J. W. Willowghly. 2001. Monitoring plant and animal populations. A handbook for field biologists. Bureau of Land Management Technical Document 1730-1, Denver, Colorado.

Ficetola, G. F., C. Miaud, F. Pompanon, and P. Taberlet. 2008. Species detection using environmental DNA from water samples. Biology Letters 4:423-425.

Friberg, N., N. V. Angelopoulos, A. D. Biujse, I. G. Cowx, J. Kail, T. F. Moe, H. Moir, M. T. O’Hare, P. F. M. Verdonschot, and C. Wolter. 2016. Effective river restoration in the 21st century: from trial and error to novel evidence-based approaches. Pages 535–611 *in* A. J. Dumbrell, R. L. Kordas, and G. Woodward, editors. Advances in ecological research, Volume 55. Elsevier, London, UK.

Fryirs, K. A., J. M. Wheaton, S. Bizzi, R. Williams, and G. J. Brierley. 2019. To plug-in or not to plug-in? Geomorphic analysis of rivers using the River Styles Framework in an era of big data acquisition and automation. Wiley Interdisciplinary Reviews: Water 6(5):e1372.

GRASS Development Team. 2017. Geographic Resources Analysis Support System (GRASS) Software, Version 7.2. Open Source Geospatial Foundation. Electronic document: http://grass.osgeo.org.

Greenberg, J. A., E. L. Hestir, D. Riano, G. J. Scheer, and S. L. Ustin. 2012. Using LiDAR data analysis to estimate changes in insolation under large-scale riparian deforestation. Journal of the American Water Resources Association 48:939-948.

GSRO (Governor's Salmon Recovery Office). 2018. 2018 State of salmon in watersheds: governor's update. Available at URL: https://stateofsalmon.wa.gov/exec-summary/.

Gurnell, A. M., M. Rinaldi, B. Belletti, S. Bizzi, B. Blamauer, G. Braca, A. D. Buijse, M. Bussettini, B. Camenen, F. Comiti, L. Demarchi, D. Garcia de Jalon, M. González del Tánago, R. C. Grabowski, I. Gunn, H. Habersack, D. Hendriks, A. J. Henshaw, M. Klösch, B. Lastoria, A. Latapie, P. Marcinkowski, V. Martínez-Fernández, E. Mosselman, J. O. Mountford, L. Nardi, T. Okruszko, M. T. O'Hare, M. Palma, C. Percopo, N. Surian, W. van de Bund, C. Weissteiner, and L. Ziliani. 2015. A multi-scale hierarchical framework for developing understanding of river behaviour to support river management. Aquatic Sciences 78(1):1-16.

Hall, J., K. Ross., D. Arterburn, M. Krall, S. Burgess, and P. Roni. 2019. Chinook salmon progress report: A summary of Chinook salmon habitat Common Indicators. Report to the Puget Sound Partnership, Tacoma, Washington.

Ham, K. D., and T. N. Pearsons. 2000. Can reduced salmonid population abundance be detected in time to limit management impacts? Canadian Journal of Fisheries and Aquatic Sciences 57(1):17-24.

Handcock, R. N., C. E. Torgersen, K. A. Cherkauer, A. R. Gillespie, T. Klement, R. N. Faux, and J. Tan. 2012. Thermal infrared remote sensing of water temperature in riverine landscapes. Pages 85–113 *in* P. E. Carbonneau and H. Piégay, editors. Fluvial remote sensing for science and management. Wiley-Blackwell, Chichester, UK.

Harrelson, C. C., C. L. Rawlins, and J. P. Potyondy. 1994. Stream channel reference sites: an illustrated guide to field technique. Gen. Tech. Rep. RM-245. U.S. Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

Hawkins, C. P., J. L. Kershner, P. A. Bisson, M. D. Bryant, L. M. Decker, S. V. Gregory, D. A. McCullough, C. K. Overton, G. H. Reeves, R. J. Steedman, and M. K. Young. 1993. A hierarchical approach to classifying stream habitat features. Fisheries 18(6):3-12.

Hering, D., J. Aroviita, A. Battrup-Pedersen, K. Brabec, T. Buijse, F. Ecke, N. Friberg, M. Gielczewski, K. Januschke, J. Köhler, B. Kupilas, A. Lorenz, S. Muhar, A. Paillex, M. Poppe, T. Schmidt, S. Schmutz, J. Vermaat, P. F. M. Verdonschot, R. C. M. Verdonschot, C. Wolter, and J. Kail. 2015. Contrasting the roles of section length and instream habitat enhancement for river restoration success: a field study of 20 European restoration projects. Journal of Applied Ecology 52:1518-1527.

Hicks, B. J., J. D. Hall, P. A. Bisson, and J. R. Sedell. 1991. Responses of salmonids to habitat changes. Pages 483–518 *in* W. R. Meehan, editor. Influences of forest and rangeland management on salmonid fishes and their habitats. American Fisheries Society Special Publication 19, Bethesda, Maryland.

Hofierka, J., and M. Suri. 2002. The solar radiation model for open source GIS: implementation and applications. International GRASS Users Conference, Trento, Italy.

Hong, I., J. S. Kim, K. H. Kim, H. S. Shin, and H. S. Jeon. 2018. Analysis of physical habitat change for target fish induced by extended floodplain. Journal of Coastal Research 85:86-90.

Kershner, J. L. 1997. Monitoring and adaptive management. Pages 116-131 *in* J. E. Williams, C. A. Wood, and M. P. Dombeck, editors. Watershed restoration: principles and practices. American Fisheries Society, Bethesda, Maryland.

Kondolf, G. M., E. W. Larsen, and J. G. Williams. 2000. Measuring and modeling the hydraulic environment for assessing instream flows. North American Journal of Fisheries Management 20(1):1016-1028.

Krall, M., C. Clark, P. Roni, and K. Ross. 2019. Lessons learned from long-term effectiveness monitoring of instream habitat projects. North American Journal of Fisheries Management 39:1395-1411.

Laslier, M., L. Hubert-Moy, and S. Dufour. 2019. Mapping riparian vegetation functions using 3D bispectral LiDAR data. Water 11(3):483.

Leopold, L. B. 1994. A view of the river. Harvard University Press, Cambridge, Massachusetts.

Lindenmayer, D. B., and G. E. Likens. 2018. Effective ecological monitoring – second edition. CSIRO Publishing Clayton South, Victoria, Australia.

Linke, L. 1922. Transmissions-Koeffizient und Trübungsfaktor. Beiträge zur Physik der freien Atmosphäre 10:91-103.

Lisle, T. E. 1987. Using “residual depths” to monitoring pool depths independently of discharge. Note PSW-RN-394. U.S. Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California.

Longoni, L., M. Papini, D. Brambilla, L. Barazzetti, F. Roncoroni, M. Scaioni, and V. V. Ivanov. 2016. Monitoring riverbank erosion in mountain catchments using terrestrial laser scanning. Remote Sensing 8(3):241-263. doi:https://doi.org/10.3390/rs8030241.

Louhi, P., H. Mykrä, R. Paavola, A. Huusko, R. Vehanen, A. Mäki-Petäys, and T. Muotka. 2011. Twenty years of stream restoration in Finland: little response by benthic macroinvertebrate communities. Ecological Applications 21:1950-1961.

Maret, T. R., J. E. Hortness, and D. S. Ott. 2006. Instream flow characterization of upper Salmon River Basin streams, central Idaho, 2005. Report 2006-5230. U.S. Geological Survey Scientific Investigations.

Merritt, D. M., M. E. Manning, and N. Hough-Snee, editors. 2017. The national riparian core protocol: a riparian vegetation monitoring protocol for wadeable streams of the conterminous United States. General Technical Report RMRS-GTR-367. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. Fort Collins, Colorado.

Minns, C. K., J. R. M. Kelso, and R. G. Randall. 1996. Detecting the response of fish to habitat alterations in freshwater ecosystems. Canadian Journal of Fisheries and Aquatic Sciences 53(Supplement 1):403-414.

Mossop, B., and M. J. Bradford. 2006. Using thalweg profiling to assess and monitor juvenile salmon (*Oncorhynchus* spp.) habitat in small streams. Canadian Journal of Fisheries and Aquatic Sciences 63(7):1515-1525.

Richardson, J., and L. Moskal. 2016. An integrated approach for monitoring contemporary and recruitable large woody debris. Remote Sensing 8(9):778.

MOC (Monitoring Oversight Committee). 2002. The Washington comprehensive monitoring strategy and action plan for watershed health and salmon recovery – Volume 1. Available at URL: https://rco.wa.gov/salmon-recovery/monitoring/.

Mulvey, M., L. Caton, and R. Hafele. 1992. Oregon nonpoint source monitoring protocols and stream bioassessments field manual for macroinvertebrates and habitat assessment. Oregon Department of Environmental Quality, Laboratory Monitoring Section, Portland.

Poppe, M., J. Kail, J. Aroviita, M. Stelmaszczyk, M. Giełczewski, and S. Muhar. 2016. Assessing restoration effects on hydromorphology in European mid-sized rivers by key hydromorphological parameters. Hydrobiologia 769:21-40.

Powers, P. D., M. Helstab, and S. L. Niezgoda. 2018. A process-based approach to restoring depositional river valleys to Stage 0, an anastomosing channel network. River Research and Applications 35(1):3-13.

Pratomo, D. G., D. Khomsin, and B. F. E. Putranto. 2019. Analysis of the green light penetration from Airborne LiDAR bathymetry in shallow water area. IOP Conference Series: Earth and Environmental Science 389-398. doi:10.1088/1755-1315/389/1/01200.

Quadros, N. D. 2013. Unlocking the characteristics of bathymetric LiDAR sensors. LiDAR Magazine 3:62-67.

Reid, L. M. 2001. The epidemiology of monitoring. Journal of the American Water Resources Association 37:815-820.

Richardson, J., and L. Moskal. 2016. An integrated approach for monitoring contemporary and recruitable large woody debris. Remote Sensing 8(9):778.

Rinaldi, M., B. Belletti, M. Bussettini, F. Comiti, B. Golfieri, B. Lastoria, E. Marchese, L. Nardi, and N. Surian. 2017. New tools for the hydromorphological assessment and monitoring of European streams. Journal of Environmental Management 202(Part 2):363–378.

Rinaldi, M., N. Surian, F. Comiti, and M. Bussettini. 2013. A method for the assessment and analysis of the hydromorphological condition of Italian streams: The Morphological Quality Index (MQI). Geomorphology 180-181:96-108.

Roni, P., U. Aberg, and C. Weber. 2018. A review of approaches for monitoring the effectiveness of regional river habitat restoration programs. North American Journal of Fisheries Management 38:1170-1186. doi:10.1002/nafm.10222.

Roni, P., T. Beechie, C. Jordan, and G. Pess. 2015b. Basin scale monitoring of river restoration: recommendations from case studies in the Pacific Northwest USA. American Fisheries Society Symposium 78:73-98.

Roni, P., T. Beechie, G. Pess, and K. Hanson. 2015a. Wood placement in river restoration: fact, fiction, and future direction. Canadian Journal of Fisheries and Aquatic Sciences 72:466-478.

Roni, P., C. Clark, R. Camp, and D. Arterburn. 2020b. Middle Entiat restoration monitoring pilot project: baseline monitoring of a large-scale floodplain restoration project. Report to Bonneville Power Administration, Portland, Oregon.

Roni, P., C. Clark, M. Krall, S. Burgess, and K. Ross. 2020a. Bonneville Power Administration Action Effectiveness Monitoring Program – 2019 Annual Report. Project Number 2016-001-00. Report to Bonneville Power Administration, Portland, Oregon.

Roni, P., J. E. Hall, S. M. Drenner, and D. Arterburn. 2019a. Monitoring the effectiveness of floodplain habitat restoration: A review of methods and recommendations for future monitoring. Wiley Interdisciplinary Reviews: Water:e1355.

Roni, P., M. Krall, C. Clark, and K. Ross. 2019b. Salmon Recovery Funding Board reach-scale project effectiveness monitoring program: 2018 Final Report. Report to the Washington Salmon Recovery Funding Board, Recreation and Conservation Office, Olympia. Available at URL: https://rco.wa.gov/documents/monitoring/Project_Effectiveness_Report_CFS-2019-01-07.pdf.

Roni, P., M. C. Liermann, C. Jordan, E. A. Steel. 2005. Steps for designing a monitoring and evaluation program for aquatic restoration. Pages 13–34 *in* P. Roni, editor. Monitoring stream and watershed restoration. American Fisheries Society, Bethesda, Maryland.

Roni, P., M. Liermann, S. Muhar, and S. Schmutz. 2013. Monitoring and evaluation of restoration actions. Pages 254-279 *in* P. Roni and T. Beechie, editors. Stream and watershed restoration: a guide to restoring riverine processes and habitats. Wiley-Blackwell, Chichester, UK.

Roni, P., and T. P. Quinn. 2001. Density and size of juvenile salmonids in response to placement of large woody debris in Western Oregon and Washington streams. Canadian Journal of Fisheries and Aquatic Sciences 58(2):282-292.

Rosgen, D. L. 1994. A classification of natural rivers. Catena 22:169-199.

Rosgen, D. L. 1996. Applied river morphology. 2nd Edition. Wildland Hydrology, Fort Collins, Colorado.

Rosgen, D., B. Rosgen, D. Geenen, R. Pierce, J. Nankervis, R. Kovach, M. Geenen, and A. Taillacq. 2018. A technical review of the Columbia Habitat Monitoring Program's protocol, data quality and implementation. Report to Bonneville Power Administration, Portland Oregon. Wildland Hydrology, Fort Collins, Colorado.

Schwarz, C. J. 2015. Analysis of BACI experiments. Pages 705-804 in C. J. Schwarz. Course notes for beginning and intermediate statistics. Available at URL: http://www.stat.sfu.ca/~cschwarz/CourseNotes.

Shannon, C. E. 1948. A mathematical theory of communication. Bell System Technical Journal 27:379-423, 623-656.

Singh, K. K., A. J. Davis, and R. K. Meentemeyer. 2015. Detecting understory plant invasion in urban forests using LiDAR. International Journal of Applied Earth Observation and Geoinformation 38:267-279.

Sixta, M. 2019. Hydraulics modeling of the Gray and Stormy reaches – 80% Design. Report No. ENV-2019-089. U.S. Bureau of Reclamation, Technical Service Center, Sedimentation and River Hydraulics Group, Denver, Colorado.

Steele C. A., M. Hess, S. Narum, and M. Campbell. 2019. Parentage-based tagging: reviewing the implementation of a new tool for an old problem. Fisheries 44:412-422.

Stefankiv, O., T. J. Beechie, J. E. Hall, G. R. Pess, and B. Timpane-Padgham. 2019. Influences of valley form and land use on large river and floodplain habitats in Puget Sound. River Research and Applications 35:133-145.

Thomas, I. A., P. Jordan, O. Shine, O. Fenton, P. E. Mellander, P. Dunlop, and P. N. C. Murphy. 2017. Defining optimal DEM resolutions and point densities for modelling hydrologically sensitive areas in agricultural catchments dominated by microtopography. International Journal of Applied Earth Observation and Geoinformation 54:38-52.

Thomsen, P. F., and E. Willerslev 2015. Environmental DNA – an emerging tool in conservation for monitoring past and present biodiversity. Biological Conservation 183:4-18.

Tompalski P., N. C. Coops, J. C. White, M. A. Wulder, and A. Yuill. 2017. Characterizing streams and riparian areas with airborne laser scanning data. Remote Sensing of Environment 192:73-86.

Tomsett, C., and J. Leyland. 2019. Remote sensing of river corridors: a review of current trends and future directions. River Research and Applications 35:779-803.

Torgersen, C. E., R. N. Faux, B. A. McIntosh, N. J. Poage, and D. J. Norton. 2001. Airborne thermal remote sensing for water temperature assessment in rivers and streams. Remote Sensing of Environment 76:386-398.Weber, C., U. Åberg, A. D. Buijse, F. M. R. Hughes, B. G. McKie, H. Piégay, P. Roni, S. Vollenweider, and S. Haertel-Borer. 2018. Goals and principles for programmatic river restoration monitoring and evaluation: collaborative learning across multiple projects. Wiley Interdisciplinary Reviews: Water 5(1):e125.

Williams, G. P. 1978. Bank-full discharge of rivers. Water Resources Research 14:1141-1154.

Yochum, S., F. Comiti, E. Wohl, G. David, and L. Mao. 2014. Photographic guidance for selecting flow resistance coefficients in high-gradient channels. General Technical Report RMRS-GTR-323. U.S. Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado.

APPENDICES

Appendix A. Initial List of All Floodplain Worksites in PRISM

Table A-1. Initial list of worksites in PRISM with a floodplain component (C.4.c.3 or C.4.c.4) greater than 1 km (0.9 km) including: recovery region, PRISM project name and worksite name, expected year of completion (end year), latitude, and longitude.

Recovery Region	Project Number	Project Name	Worksite Name	End Year	Latitude	Longitude
Hood Canal	09-1610	Donovan Creek Acquisition and Restoration - 135	Lower Donovan Creek	2013	47.828091	-122.8587
Hood Canal	14-1284	Lower Big Beef Creek Restoration - Construction	Lower Big Beef Creek	2019	47.648787	-122.7834
Hood Canal	15-1053	Dungeness R. RR Reach Floodplain Restoration	Trestle at Railroad Bridge Park	2016	48.085342	-123.148
Hood Canal	16-1372	Lower Dungeness Floodplain Restoration	Towne Road between Schoolhouse and Creamery	2021	48.142678	-123.1301
Hood Canal	18-1300	Dungeness River Floodplain Restoration	Towne Road between Schoolhouse and Creamery	Un-known	48.142745	-123.1287
Lower Columbia River	00-1872	LCRE Grays River Phase II	LCRE Grays Bay/Secret River #1	2005	46.306173	-123.6904
Lower Columbia River	07-1675	Abernathy Habitat Restoration and Riparian Protect	Abernathy Habitat Restoration	2012	46.206039	-123.1535
Lower Columbia River	07-1676	Historic Skamokawa Creek Restoration	Historic Skamokawa Restoration	2014	46.287636	-123.449
Lower Columbia River	07-1692	Lower Dean Creek Restoration	Lower Dean Creek Restoration	2012	45.83104	-122.6398
Lower Columbia River	08-1735	Lower Hamilton Ck Restoration Phase 1 Reach 2	Hamilton Crk Reach 2	2013	45.640291	-121.9777
Lower Columbia River	10-1022	Upper Washougal Restoration III	Upper Washougal Restoration III	2015	45.675903	-122.1375
Lower Columbia River	10-1028	Lower Hamilton Restoration Phase II	Hamilton Creek Mainstem & Spring channel	2015	45.665765	-121.9961
Lower Columbia River	13-1156	Lower Cispus Side Channels Restoration	Lower Cispus Side Channels	2017	46.441871	-121.8453
Lower Columbia River	14-1311	Abernathy Creek Cameron Site	Abernathy Creek Cameron Site	2018	46.196281	-123.1638
Lower Columbia River	14-1335	SFK Toutle@ Johnson Creek Restoration	SF Toutle at Johnson Creek	2018	46.312123	-122.6605
Lower Columbia River	16-1519	Elochoman Stream Restoration Cothren	Elochoman River Cothren	2021	46.228453	-123.364

Recovery Region	Project Number	Project Name	Worksite Name	End Year	Latitude	Longitude
Lower Columbia River	16-1520	Skamokawa Stream Restoration Project McClellan	Skamokawa Stream Restoration Project McClellan	2020	46.315347	-123.4549
Lower Columbia River	17-1025	Elkinton Property Stream Restoration	Elkinton	2021	46.2215	-123.3423
Lower Columbia River	17-1030	Johnston Wilson Creek Restoration	Johnston Wilson Creek	2022	46.296752	-123.3952
Lower Columbia River	17-1115	IMW- Erick Creek In-Stream Habitat Restoration	Erick Creek	2020	46.268115	-123.1759
Middle Columbia River	Aug-48	Upper Wapato Reach Restoration	SS Wildlife Area - Donald Wapato Reach	2013	46.480984	-120.4123
Middle Columbia River	Jul-20	Reecer Creek Floodplain Restoration 2	Reecer Creek Floodplain	2013	46.990942	-120.5719
Middle Columbia River	Jun-41	Cle Elum River Instream Habitat	Cle Elum River Instream Habitat	2010	47.226435	-121.0502
Middle Columbia River	Jun-77	Upper Klickitat R. Enhancement, Phase II	Upper Klickitat River Enhance Phase II	2009	46.318558	-121.2591
Middle Columbia River	07-1725	Upper Klickitat River - Phase 3	Upper Klickitat - Phase 3	2013	46.355505	-121.1945
Middle Columbia River	09-1461	Tepee Creek Restoration - Phase 2 Construction	RM 4.5-5.3	2014	46.172662	-121.0327
Middle Columbia River	10-1742	Upper Klickitat R. Enhancement, Phase IV	Upper Klickitat River	2015	46.458661	-121.3875
Middle Columbia River	10-1765	Eschbach Park Levee Setback & Restoration	Eschbach Park Phase 2	2015	46.679516	-120.6507
Middle Columbia River	11-1428	Klickitat Floodplain Restoration Phase 3	Phase 3	2014	45.887521	-121.1149
Middle Columbia River	12-1317	Yakima River Gap to Gap Habitat Enhancement	Gap to Gap Reach-Terrace Heights to Buch	2016	46.594407	-120.4686
Middle Columbia River	12-1644	Klickitat Floodplain Restoration Phase 4	Haul Road Phase 4	2015	45.864495	-121.0956
Middle Columbia River	13-1314	Cle Elum River Side Channel Restoration Ph 2	Cle Elum River Side-channel Restoration	2015	47.228582	-121.0536
Middle Columbia River	13-1401	Klickitat Floodplain Restoration Phase 5	Phase 5 Project Area	2017	45.859419	-121.0849
Middle Columbia River	14-1860	Klickitat River Floodplain Restoration Phase 6	Phase 6 Project Area	2019	45.92631	-121.1282

Recovery Region	Project Number	Project Name	Worksite Name	End Year	Latitude	Longitude
Middle Columbia River	17-1179	Yakima River Side Channel at Bull Canal Diversion	Irene Rinehart Riverfront Park	2021	46.986579	-120.5702
Middle Columbia River	18-1711	Teanaway Community Forest Floodplain Restoration	Indian Creek Section 16	2022	47.307897	-120.8461
Puget Sound	Jul-08	Lower Ohop Creek Restoration Phase II	Lower Ohop Creek	2011	46.856286	-122.3514
Puget Sound	Aug-56	Lower Tolt River Floodplain Reconnection 08	Tolt River Floodplain Reconnection	2010	47.640339	-121.9267
Puget Sound	Jun-23	Greenwater R. ELJs and Rd Decommission	Greenwater Engineered Log Jams	2010	47.120313	-121.5722
Puget Sound	Jun-50	Chinook Bend Levee Removal 06	Chinook Bend Levee Removal	2012	47.668675	-121.9223
Puget Sound	01-1237	Sherwood Creek Fish Passage	Sherwood Creek Fish Passage Project	2006	47.35052	-122.8914
Puget Sound	01-1307	North Meander Slough Reconnection	North Meander Slough	2006	48.201553	-122.232
Puget Sound	01-1421	Puyallup River Setback Levee	Puyallup River Setback Levee	2007	47.088492	-122.211
Puget Sound	02-1606	Pentland Creek/Smoke Farm Rearing	Pentland Creek at Smoke Farm	2008	48.253555	-122.0572
Puget Sound	04-1338	Lower Newaukum Restoration	Lower Newaukum Restoration	2010	47.284056	-122.0657
Puget Sound	04-1646	Ennis Creek Restoration	Ennis Creek	2007	48.656331	-122.2041
Puget Sound	05-1503	Lower Ohop Creek Restoration, Phase 1	Lower Ohop Restoration	2009	46.846792	-122.3653
Puget Sound	07-1701	Cherry Creek Floodplain Restoration	Cherry Creek Floodplain Restoration	2013	47.761344	-121.9571
Puget Sound	07-1735	Blue Slough Side Channel Reconnection	Blue Slough Side Channel Reconnection	2011	48.281917	-121.7608
Puget Sound	07-1737	NF Stillaguamish ELJs	North Fork Stillaguamish Eng. Log Jam	2012	48.419756	-121.6666
Puget Sound	09-1379	Klein Farm Acquisition and Restoration	Dan and Pamela Klein Farm	2013	48.18337	-122.0807
Puget Sound	10-1852	Howard Miller Steelhead Park Off Channel Enhance	Howard Miller Steelhead Park	2013	48.48295	-121.6075
Puget Sound	10-1863	Calistoga Setback Levee - Construction	Calistoga Setback Levee	2015	47.091214	-122.2156
Puget Sound	13-1144	Lower Ohop Restoration Ph III	Ohop Valley	2017	46.856941	-122.3523
Puget Sound	15-1198	Moga Back Channel Construction	Rt Bank Snohomish River RM 15.7	2019	47.857783	-122.0785
Puget Sound	16-1651	Hansen Creek Reach 5 Restoration	Hansen Creek New Channel	2022	48.515343	-122.2007
Puget Sound	16-1899	Lower Russell Levee Setback & Habitat Restoration	Lower Russell Levee Setback & Habitat Restoration	2021	47.409112	-122.267

Recovery Region	Project Number	Project Name	Worksite Name	End Year	Latitude	Longitude
Puget Sound	18-1258	Riverbend Floodplain Restoration Construction	Riverbend	2023	47.464215	-122.1119
Puget Sound	18-2085	MF - Porter Creek Reach Phase 1	Phase 1	2017	48.805803	-122.1277
Snake River	00-1691	George Creek Instream and Riparian	Hagenah	2005	46.308512	-117.1126
Snake River	09-1596	Tucannon River Off-Set Dike Construction	Tucannon River Off-Set Dike	2014	46.446602	-117.7884
Snake River	12-1641	Project Area 14 LW Restoration	Project Area 14	2015	46.336419	-117.6807
Snake River	13-1391	Tucannon Ranch Habitat Improvement	Tucannon Ranch	2015	46.525134	-118.1411
Snake River	14-1900	PA 24 Floodplain and Channel Complexity	PA 24 Floodplain and Channel Complexity	2018	46.430721	-117.729
Snake River	15-1286	NF Touchet Floodplain & Habitat Rest. RM 3.3-4.3	Phase 1	2020	46.272538	-117.8931
Snake River	15-1323	Tucannon Large Wood & Floodplain Restoration PA6-9	Tucannon Large Wood & Floodplain Restoration PA6-9	2019	46.28287	-117.6565
Snake River	16-2091	Tucannon Complexity & Connectivity (PA-18)	PA-18 WDFW	2020	46.38559	-117.6964
Snake River	17-1267	Bridge to Bridge Restoration Phase 2-	Bridge to Bridge Phase 2	2020	46.052314	-118.57
Snake River	18-2091	Tucannon River Habitat Restoration, PA-32	PA-32	2021	46.483753	-117.9543
Upper Columbia River	Jun-92	Hancock Springs Restoration Project	Hancock Springs Restoration Project	2011	48.534144	-120.3316
Upper Columbia River	18-1762	Middle Entiat Restoration - Area F (RM 16.2-16.7)	Middle Entiat Restoration Projects Area F	2021	47.799903	-120.4029
Washington Coast	00-1892	Elk Creek Restoration Project	Elk Creek Restoration Project	2004	46.705153	-123.7088
Washington Coast	02-1463	Salmon Creek 02	Salmon Creek Restoration	2007	46.410865	-123.6248
Washington Coast	09-1232	Wickett Flood Plain Connection/Barrier Removal	Barrier Removal Site	2011	46.829631	-123.2596