Extensive Riparian Status and Trends Monitoring Project, Scoping Document

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Cooperative Monitoring Evaluation & Research

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Washington State

Cooperative Monitoring, Evaluation, and Research Committee (CMER)

Report

Extensive Riparian Status and Trends Monitoring Project

Scoping Document

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Washington State Forest Practices Adaptive Management Program

The Washington Forest Practices Board (FPB) has adopted an adaptive management program in concurrence with the Forests & Fish Report (FFR) and subsequent legislation. The purpose of this program is to:

> Provide science-based recommendations and technical information to assist the board in determining if and when it is necessary or advisable to adjust rules and guidance for aquatic resources to achieve resource goals and objectives. (Forest Practices Rules, WAC 222-12-045)

To provide the science needed to support adaptive management, the FPB made the Cooperative Monitoring, Evaluation and Research Committee (CMER) a participant in the program. The FPB empowered CMER to conduct research, effectiveness monitoring, and validation monitoring in accordance with guidelines recommended in the FFR.

Proprietary Statement

Full Reference

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Glossary of Terms

ALS: Airborne Laser Scanning – Infrared lidar collected from an airplane. See below for a definition of lidar. Used to measure and model forest and terrain features.

AMP: Adaptive Management Program – A program created to provide science-based recommendations and technical information to assist the Forest Practices Board in determining if and when it is necessary or advisable to adjust rules and guidance.

BAS: Best Available Science – The most reliable and relevant scientific information available for decision-making.

CMER: Cooperative Monitoring, Evaluation, and Research Committee – A committee to conduct necessary business and scientific discussions associated with planning, design, and implementation of research and monitoring projects to meet Forest Practices Adaptive Management Program goals.

DAP: Digital Aerial Photogrammetry – A technique for generating spatial data and maps using aerial photographs.

DEM: Digital Elevation Model – A 3D representation of a terrain's surface.

DFC: Desired Future Condition – Target conditions for ecosystems or habitats as defined by management goals.

eDNA: Environmental DNA – Genetic material collected from environmental samples (e.g., water, soil) used to detect and monitor organisms.

EPA: Environmental Protection Agency – U.S. federal agency responsible for environmental protection.

F/N: Fish-bearing (Type F) and non-fish-bearing (Type N) streams – Designations for streams based on their ability to support fish populations.

FFR: FFR lands – Refers to lands subject to the 2001 Forests & Fish forest practices rules. Some state and private forestlands are subject to their own habitat conservation plan with provisions for different riparian or other forest management rules.

FPA: Forest Practices Application – an application required in Washington State for landowners to receive a permit to conduct activities on forestlands related to growing, harvesting, or processing timber.

FPHCP: Forest Practices Habitat Conservation Plan – A framework to conserve habitat while allowing forest practices.

GIS: Geographic Information System – A system for capturing, storing, and analyzing spatial and geographic data.

GRTS: Generalized Random Tessellation Stratified sampling – A method for spatially balanced random sampling.

HUC: Hydrologic Unit Code – A watershed identified by the nationwide hierarchical coding system for watersheds and sub-watersheds in the United States. A HUC8 indicates a large watershed on the order of hundreds of thousands of acres that is designated with an 8-digit code; these are closely aligned with Washington's Watershed Resource Inventory Areas (WRIAs). HUC12watersheds are typically on the order of tens of thousands of acres and require 12 digits to identify them. These are generally 4^{th} to 6^{th}-order basins (median = 5^{th} order) and are somewhat smaller than the Watershed Administrative Units (WAUs) for which Watershed Analyses were conducted. A HUC8 consists of a collection of HUC12s (see Figure 2).

Hydrography – The measurement and mapping of surface and subsurface water systems, including rivers, lakes, and streams.

Lidar: Light Detection and Ranging – A remote sensing method for measuring distances and creating high-resolution maps of terrain or structures using scanning infrared lasers. **Other wavelengths can be used for other purposes.*

LW: Large Wood – Refers to large wood in streams recruited from either riparian or upslope sources and contributing to stream habitat-forming processes.

Model – A simplified representation of real-world processes, often mathematical or computational, used for analysis and prediction in scientific research.

NAIP: National Agriculture Imagery Program – A program that provides aerial imagery for monitoring agricultural and environmental conditions.

qPCR: Quantitative Polymerase Chain Reaction – a laboratory technique used to quantify the amount of DNA or RNA in a sample.

Riparian Areas –Areas of transitional terrestrial environments bordering streams, lakes, ponds, tidewaters and other bodies of water. They include banks, beaches and associated organic and inorganic constituents; floodplains; areas of high water table associated with plants which require saturated soils during all or pan of the year; plus an area of direct influence which shapes the physical structure of the aquatic environment and influences the quality of fish and wildlife habitat by contributing organic debris, shade and buffering action.

RMZ: Riparian Management Zone – defined zones (areas) adjacent to rivers and streams in which activities related to forest management and timber harvest are regulated under the Washington Forest Practices Act. The various zone definitions are meant to encompass the riparian areas based on differing stream and land factors.

RSAG: Riparian Scientific Advisory Group – A group advising on scientific aspects of riparian management and monitoring.

Sample Frame– Sampling Frame is a physical representation of the target population. It consists of sample units that are potential members of the sample. Sample Frames almost always are not exact representations of the target population. Sample Frame may not include some target population elements: Undercoverage and/or may contain non-target elements, e.g., mis-identified sample units: Overcoverage.

Sample Unit– The element of the target population that will be sampled.

SSN: Spatial Stream Network – A model for predicting stream temperatures based on spatiotemporal characteristics within a stream network.

Target Population– The ecological resource about which estimates are needed.

TFW: Timber, Fish, and Wildlife Policy Committee – A policy committee focused on forest practices and their environmental impacts.

UAV: Unmanned Aerial Vehicle – Also known as drones, used for collecting remote sensing data.

WADNR: Washington State Department of Natural Resources – Agency managing natural resources in Washington State.

Context

Project Description

Extensive monitoring programs evaluate the current status of key watershed resources and habitat condition indicators across FP HCP lands, and document trends in these indicators over time as the forest practices prescriptions are applied across the landscape. Extensive monitoring provides a statewide, landscape-scale assessment of the effectiveness of forest practices rules to attain specific performance targets on FP HCP lands. Extensive monitoring is designed to provide report-card-type measures of rule effectiveness (i.e., to what extent are FP HCP performance targets and resource condition objectives being achieved on a landscape scale over time). These measures can then be used to determine the degree to which progress is meeting expectations (CMER Work Plan). This definition of extensive monitoring is consistent with the landscape scale component of effectiveness monitoring called for in Appendix N of the FPHCP (Schedule L-1).

The purpose of the Extensive Riparian Status and Trends Monitoring Project (Extensive Monitoring Project) is to (1) document the current status of key watershed resources and habitat conditions (stream shade, stream temperature, and stream riparian stand large wood supply potential) across Washington State lands managed under the Forest Practices Habitat Conservation Plan “FPHCP lands” (2) evaluate trends in conditions over time as Forest Practices prescriptions are applied, and (3) assess whether condition trends are moving toward meeting resource objectives and performance targets at the landscape scale. This scoping document presents the potential alternatives to conduct the Extensive Monitoring Project across Washington State and critical questions it is meant to address.

This document includes a review of the state of the art of landscape-scale environmental monitoring strategies and current methods for measuring and reporting riparian characteristics and stream temperature at recommended temporal and spatial scales in the appended “Best Available Science” (BAS) document. The BAS document includes details on contemporary approaches and techniques to provide an understanding of the relationship between riparian management and aquatic resources and includes reviews of direct sampling, stream temperature modeling, and measuring riparian stand characteristics via remote sensing. The scoping relies on that information to present alternative strategies for addressing the critical questions and our recommendation of the best alternative for this program.

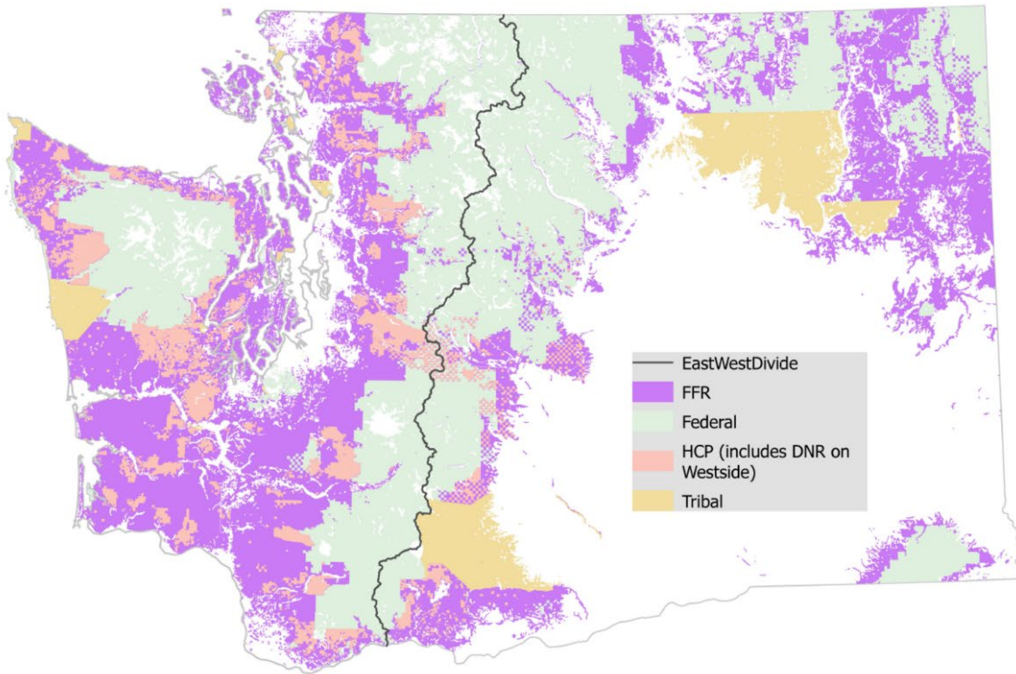


***Figure 1**. Map showing forestlands with various ownership types. Lands subject to the FPHCP include those denoted as "FFR" and "HCP" (Vaugeois 2005).*

Forest Practices Rules

The Washington Administrative Code for timber harvesting ((WAC) 222-30) defines regulations for the removal of timber from forestlands and requirements for vegetation that must be retained for resource protection. Specifically, WAC 222-30-021 and WAC 222-30-022 define buffer rules for the Riparian Management Zones (RMZ) and Wetland Management Zones (WMZ). These rules reflect and apply to lands covered by the Forest Practices Habitat Conservation Plan (FPHCP lands). FPHCP lands are all non-Federal and non-tribal forestlands that are not subject to another habitat conservation plan (HCP). Of particular note, the DNR lands in Eastern Washington are included as FPHCP lands but Western Washington DNR HCP lands are not because the DNR State Lands HCP has specified different riparian rules for Western Washington.

Links to Adaptive Management

Extensive monitoring is described in the CMER Work Plan as an evaluation of the current status of key watershed resources and habitat condition indicators across FPHCP lands and trends as forest practice prescriptions are applied across the landscape. Extensive monitoring is intended to measure rule effectiveness on a landscape scale (i.e., to what extent are FPHCP [Schedule L-1] performance targets and resource condition objectives being achieved on a landscape scale over time) (CMER 2023). The Extensive Monitoring Project is one of four projects in the Type F Riparian Prescriptions and the Type N Riparian Rule Group sections of the CMER Work Plan. In response to the adoption of the forest practice rules derived from the Forests & Fish Report (FFR) , Benkert et al. (2002) provided an integrated monitoring program to support the science part of adaptive management. Extensive Monitoring can also identify where on the landscape resource objectives are not being met over time, which in turn can inform and guide follow up intensive-scale studies.

Background

The current CMER Work Plan lists multiple landscape-scale extensive monitoring projects, including studies to track recoverable and restorable fish habitat, assess coastal tailed frog occupancy, , assess the status of fish passages, and most significantly for the scoping of this project, assess the frequency distribution of water temperatures, shade levels, riparian vegetation types, large wood, and channel measurements along Type F and Type N streams. CMER began an extensive monitoring program in 2007 (Ehinger 2007-2013) (Table 1). TFW Policy decided not to pursue the trends monitoring component due to high costs and the advent of emerging technologies. The extensive monitoring studies following Ehinger (2007-2013) focused on pilot studies to inform TFW Policy's decision-making process on how (methods and costs) or whether to proceed with extensive monitoring.

Table 1. *List of Previous Related CMER Studies.*

Project Title	Year Completed
The Suitability of Aerial Photography for Riparian Buffer Monitoring Study	2007
Extensive Riparian Status & Trend Monitoring Program- Draft Study Plan: Including Westside and Eastside Projects	2007
Eastern Washington Riparian Assessment Project - Riparian Conditions on Type F Streams	2007-2008
Extensive Riparian and Stream Temperature – First-Round Sampling	2008-2009
Development of Protocol for Monitoring Riparian Vegetation and Trends Using Remote Sensing	2009
The Extensive Riparian Status and Trends Monitoring – Temperature, Type F/N Eastside Project Report	2013
The Feasibility of Applying Remote Sensing to a Riparian Stand Conditions Assessment Literature Review	2015
The Extensive Riparian Vegetation Monitoring - Remote Sensing Pilot Study	2017
The Extensive Riparian Vegetation Monitoring Implementation Pilot Study	2018
The Extensive Riparian Status and Trends Monitoring – Temperature, Type F/N Westside Project Report	2019
The Extensive Riparian Vegetation Monitoring Model Transferability Testing Study	2020

CMER collected stream and air temperature in 2007, 2008 and 2009 on FFR lands in a pair of studies as part of the aforementioned Type F/N Stream and Air Temperature Extensive Monitoring Project. Both studies, one for each side of the state, resulted in two CMER-approved final reports. In the eastside study, air and stream temperature data were collected at 50 sites. Though the project successfully detected differences in regional stream temperature distributions between 2007 and 2008 (due to higher summer air temperatures in 2007), long term monitoring was not continued past 2008 due to implementation difficulties, particularly gaining permission to collect data from streams located on small forestland owner properties (Ehinger 2013; WA Dept Ecology 2019). Those reports also noted that due to lack of upstream data and controls, particularly in watersheds with mixed land uses (e.g. agriculture and forestry), causes of the observed temperatures could not be determined.

In the westside study, air and stream temperature data were collected in 2008 and 2009 at 61 Type F/S streams and 54 Type Np streams. The westside study had similar implementation difficulties as the eastside study, and given concerns about bias and data reliability, the final report was primarily limited to reporting descriptive statistics, including average stream and air temperatures and channel configuration information. As a result of these implementation issues, TFW Policy guided CMER to postpone extensive monitoring for stream temperature and focus on determining if and how remote sensing technologies might address stream and riparian extensive monitoring critical questions.

In 2006 CMER tested the utility of high-resolution aerial photographs taken from a helicopter to quantify riparian buffer conditions. This work was in response to concerns about cost and time constraints associated with collecting riparian stand data using field crews. It was anticipated that the methods tested and developed in this effort could eventually be used in a range of CMER riparian monitoring studies, including extensive monitoring. CMER never adopted these methods, though the contractor working on the project concluded that large-scale aerial custom photography could meet riparian assessment needs if combined with other remote sensing (e.g., lidar) to accurately locate streams (Grotefendt 2007).

In 2015 CMER worked with the University of Washington Precision Forestry Cooperative (PFC) to complete a literature synthesis that compared the cost and value of readily available remote sensing tools to quantify 13 riparian forest metrics (Moskal and Cooke 2015). This literature synthesis was followed by a pilot field study in the Mashel Watershed in 2017 that focused on a field evaluation of several remote sensing datasets, including red lidar, National Agriculture Imagery Program (NAIP) imagery, and World View 3 (satellite) imagery to quantify a range of riparian forest metrics. A 2018 follow-up study evaluated the feasibility of expanding proposed methods and models to other regions across Washington (Moskal and Cooke 2018). The transferability of these models and methods was tested and evaluated in the Olympic Experimental State Forest (OESF) in 2019 (Cooke and Devine 2020). The authors concluded the transfer of these models should be done with caution.

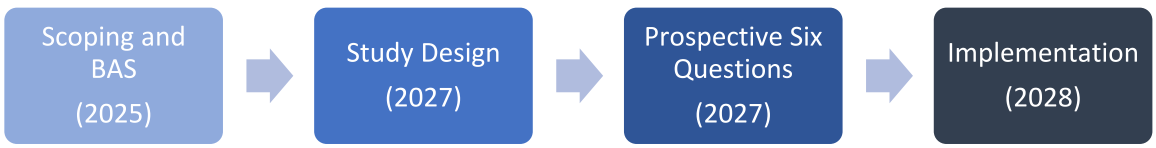
After the completion of the studies evaluating remote sensing from 2015 through 2020, and considering previous work, CMER sought input from TFW Policy to provide clarification on research questions prior to initiating additional extensive monitoring projects. Notably, CMER held a series of workshops where they informed TFW Policy of other extensive monitoring being conducted in Washington on State and private forest lands and that while remote sensing technologies can be used to quantify riparian forest conditions, the current technology cannot directly measure stream temperatures, especially in small streams under closed forest canopies. In 2021, TFW Policy accepted the Extensive Monitoring Workgroup recommendation that "a strategy be developed to inform the direction of this component [extensive monitoring] of the CMER research and monitoring program." Subsequently, in 2022, TFW Policy requested, "CMER develop an Extensive Monitoring (EM) proposal for stream temperature and riparian stand conditions."

CMER assigned the project to RSAG and RSAG developed a memo for TFW Policy that sought to "…seek clarity on the questions posed by Policy, outline some of the extensive monitoring options and to provide critical background documents that are relevant to initiating a meaningful iterative conversation between RSAG/CMER and Policy." This memo and the associated materials were the basis of an initial joint workshop between RSAG, CMER, and TFW Policy. A subsequent memo was developed by RSAG, and second joint workshop was convened with similar goals in early 2023.

Culminating the iterative conversations, TFW Policy directed CMER to "*develop options for a monitoring program to help determine how stream temperature and riparian functions have changed or are changing in association with the application of the forest practice rules.*" (TFW Policy Committee Minutes, March 2, 2023).

Timeline

Study design development is projected to begin in the latter half of 2025 and conclude in 2027, with the development of the prospective answers to CMER six questions thereafter also in 2027. A preliminary timeline is presented below.



Resource Objectives and Performance Targets

The Extensive Monitoring Project will inventory riparian stand and stream temperature conditions across the FPHCP lands. These data will be used to evaluate the degree to which riparian conditions are meeting overall performance goals described in the Schedule L-1, including DFC. Repeat sampling will provide information on trends in the metrics over time.

Problem Statement

The Forests & Fish Agreement (further adopted within the Forest Practices Habitat Conservation Plan: FPHCP) is intended to maintain riparian and aquatic resources for the protection of fish and other riparian-dependent species on over nine million acres of state and private forest lands in the State of Washington. There is uncertainty surrounding how well resource objectives of the FPHCP are met across the full extent of forestlands subject to the Forest Practices Rules. Implementation of the Extensive Monitoring Project will reduce uncertainties surrounding the status and trends of aquatic conditions, riparian forest structure and functions that support desired habitat conditions for the species identified in the FPHCP on lands managed under the current Forest Practices Rules.

Purpose Statement

The purpose of the Extensive Riparian Status and Trends Monitoring Project is to (1) document the current status of the key watershed resources of stream shade, stream temperature, and riparian stand large wood supply potential (FPHCP Appendix N (Schedule L-1), 2005) across Washington State lands managed under the FPHCP, (2) evaluate trends in conditions over time as Forest Practices prescriptions are applied, and (3) assess whether condition trends are moving towards meeting Schedule L-1 resource objectives and performance targets at the landscape scale.

Objectives

- Measure and evaluate current stream temperature, stream shade level, and riparian stand structure across forestlands covered under the FPHCP (Figure 1).
- Measure and evaluate how stream temperature, stream shade level, and riparian stand structure are changing over time.

Critical Questions

- **CQ 1.A** What is the distribution of stream temperatures in streams with perennial flow across watersheds on FPHCP lands?
- **CQ 1.B** How is the distribution of stream temperatures in streams with perennial flow across watersheds on FPHCP lands changing over space and time?
- **CQ 2.A** What is the riparian stand composition (e.g., hardwood, conifer, shrub) and characteristics (e.g., height, basal area, cover) along all streams on FPHCP lands?
- **CQ 2.B** How is the distribution of riparian stand composition and characteristics along all streams changing on FPHCP lands over space and time?
- **CQ 3.A** What is the riparian stand potential to provide shade and large wood ecological functions on FPHCP lands?
- **CQ 3.B** How is the distribution of riparian stand potential to provide shade and large wood ecological functions changing on FPHCP lands over time and space?

Target Population, Sample Frame, and Sample Unit

Target Population[7]

The target population is the ecological resource about which estimates are needed. The target population for assessing the riparian condition includes 200-ft wide riparian areas on each side of the bankfull edge associated with all streams, rivers, and lakes on FPHCP lands. The target population for assessing stream temperature includes all stream reaches on FPHCP lands that have a high probability of continuous flow throughout the summer; including applicable Np streams[8]. Another CMER study, the Water Temperature and Amphibian Use in Type Np Waters with Discontinuous Surface Flow in Western Washington Project, is currently in development to investigate discontinuous flow and water temperature in first-order streams. Findings from that study will extend the understanding of stream temperatures farther up the channel network in future extensive monitoring sampling events.

Summer stream temperatures are an important concern under Clean Water Act requirements. Continuous surface flow throughout the summer season is necessary to monitor summer stream temperatures. Therefore, the target population will include those portions of streams where water temperature can be reliably monitored throughout the summer. Past CMER studies have demonstrated that in small, and especially high-gradient, stream channels, the surface flow is spatially discontinuous during the summer low-flow period. For example, the CMER extensive monitoring efforts were unable to identify a sufficient number of sites for monitoring in Eastern Washington and lost a high proportion

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[7] Terminology and definitions for describing the study population are adopted from the definitions published by EPA (Aquatic Resource Monitoring | Health and Environmental Effects | Research & Development | US EPA).

[8] “Type Np Water means all segments of natural waters within the bankfull width of defined channels that are perennial nonfish habitat streams. Perennial streams are flowing waters that do not go dry any time of a year of normal rainfall and include the intermittent dry portions of the perennial channel below the uppermost point of perennial flow.” (WAC 222-16-21-030/031)

of data from Type N sites in the Western Washington sample through the sampling season due to the lack of summer surface water presence (Ehinger 2013; WA Dept of Ecology 2019). The upper extent of the stream monitoring network will be determined during study design by an analysis of basin characteristics (i.e., geology, precipitation, topography, basin area) that are known predictors of perennial surface flow (e.g., Miller et al. 2015). Stream temperature at the uppermost point of our monitoring will reflect the cumulative impacts of anthropogenic and natural influences on the basin upstream of this point.

Sample Unit and Frame

The sample unit is the element of the sample population that will be sampled (e.g., 100m stream reaches; HUC12watershed). The sample frame is the collection of sample units from the target population. Although the target population is the same for all alternatives in each of the two study topics, some alternatives entail hierarchical levels of sampling and, therefore, differing sample units and sample frames associated with the different hierarchical levels. Sample frames and units relevant to each hierarchical level are described in each alternative description.

Summary of Best Available Science

A complete version of the BAS can be found in Appendix A.

The Best Available Science review focuses on the state of the science of different methodologies and tools for collecting and estimating riparian stand conditions and stream temperatures across a large landscape like Washington state. There have been recent technological advancements in remote sensing and stream temperature modeling techniques. The review examines the reliability and utility of Airborne Laser Scanning (ALS), Digital Aerial Photogrammetry (DAP), and Satellite Imagery. These technologies differ in spatial resolution, cost, and temporal scale. Certain technologies may be more well suited for measuring certain riparian characteristics than others.

Stream temperature models like Spatial Stream Network (SSN) models and Generalized Additive Models (GAMs) are currently being used and refined in the PNW and can generate an array of stream temperature metrics relevant to biological resources. Direct measurements of stream temperature are an important input necessary for both of these models.

Remote sensing technologies and stream temperature models continue to advance, evolve, and change. What works, and is available, today may be outdated or unavailable for future sampling events. So continual evaluation of remote sensing technologies and stream temperature monitoring and modeling should remain a part of the extensive monitoring program moving forward.

Data Requirements

Exact data requirements necessary for the successful implementation of the Extensive Monitoring Project will depend on the alternatives and add-ons selected by TFW Policy. A brief description of data generally relevant to the core Project is summarized in this section.

1. **Hydrographic Datasets**

Successful monitoring of stream and riparian forest conditions on FPHCP lands across the state requires knowledge of where the streams and riparian zones of interest are and, to some degree, their characteristics. The current state forest practices rules are based around the DNR's "wchydro" and "wbhydro" GIS layers for water courses and water bodies. Stream lengths and other summary data in this and other CMER work are based on that hydrography. Work is underway to create a more accurate statewide hydrography based on a digital terrain model derived from high-resolution lidar data. The DNR will have an interim layer available for internal use on forestlands in 2025, which will be used initially for this project. An official USGS statewide hydrography (3DHP) may be available in 2028 or earlier. Subsequent extensive monitoring work would be transitioned to the 3DHP hydrography when available.

2. **Stream Temperature Data:**
    - **Direct Measurements:** Continuous and spot measurements of stream temperatures using loggers and manual readings at selected sample locations in streams with perennial flow.
    - **Remote Sensing Data:** Satellite imagery, Airborne Laser Scanning (ALS), and Digital Aerial Photogrammetry (DAP) will be used to map and predict stream temperature across FPHCP lands through modeling.
    - **External Data:** Use of existing temperature data from federal, state, and local agencies to enhance modeling accuracy and cost-effectiveness.
3. **Riparian Stand Data:**
    - **Vegetative Characteristics:** Collection of data on riparian stand composition, density, and structure using ground-based surveys and remote sensing methods like ALS and Sentinel-2 Satellite Imagery.
    - **Stand Functions:** Measurement of riparian functions, such as shade and large wood (LW) potential, through both direct field assessments and remote sensing-derived models.
    - **Topographical Data:** High-resolution topographic data from remote sensing technologies to understand the influence of landscape features on riparian and aquatic conditions.
4. **Sampling and Spatial Data:**
    - **Sample Units and Frames:** Clearly defined sample units (e.g., 100m stream reaches) and sample frames (e.g., HUC12watersheds) for random and focused sampling efforts.
    - **Geographic Information Systems (GIS) Layers:** Development of GIS layers to delineate lands under FPHCP, including specific areas for riparian and temperature monitoring.
    - **Disturbance Data:** Records of disturbances such as timber harvests, weather events, fires, and land developments to account for their impacts on stream temperatures and riparian conditions.
5. **Modeling Inputs:**
    - **Stream Network Models:** Parameters for models like the Spatial Stream Network (SSN) and Generalized Additive Models (GAMs), including flow data, canopy cover, and stream morphology.
    - **Validation Data:** Ground-truthing data from field surveys to validate and refine remote sensing and modeled estimates.
    - **Weather/Climate Data:** Available meteorological records.

Alternatives Analysis

Stream Temperature Alternatives

Overview of Alternatives

There are 5 Stream Temperature Alternatives being considered:

1. **Spatially balanced reach-level samples randomly selected from all FFR streams** - Repeat the first-round extensive monitoring study conducted in 2008-2009.
2. **Focused sampling using randomly located sample sites within selected sub-watersheds (HUC12s) within FPHCP lands**
3. **Focused sampling within selected watersheds to generate stream temperature models -** Sample locations within the watershed would be selected based on stream network properties to optimize construction of multivariate, spatial stream network models that predict stream temperature regimes.]
4. **Develop stream temperature models statewide -** Collaborate in efforts to develop a set of stream temperature models to predict temperature metrics of interest across the state; clip out area of FPHCP lands to summarize data for population of interest.
5. **Combine alternatives 3 & 4**

The alternative approaches to implement the Extensive Monitoring Project range from a simple random sample over the area of interest to focused monitoring of stream temperature and riparian conditions sampling within selected representative watersheds to landscape-level modeling efforts that could be applied across all FPHCP lands. The alternatives currently assume watersheds for focused study are currently proposed to be HUC12s (see Figure 2). HUC12watersheds are typically on the order of tens of thousands of acres and are generally 4th to 6th-order basins (median = 5th order). They are somewhat smaller than the Watershed Administrative Units (WAUs) for which Watershed Analyses were conducted. The optimal basin size for this program will be assessed during the Study Design phase.

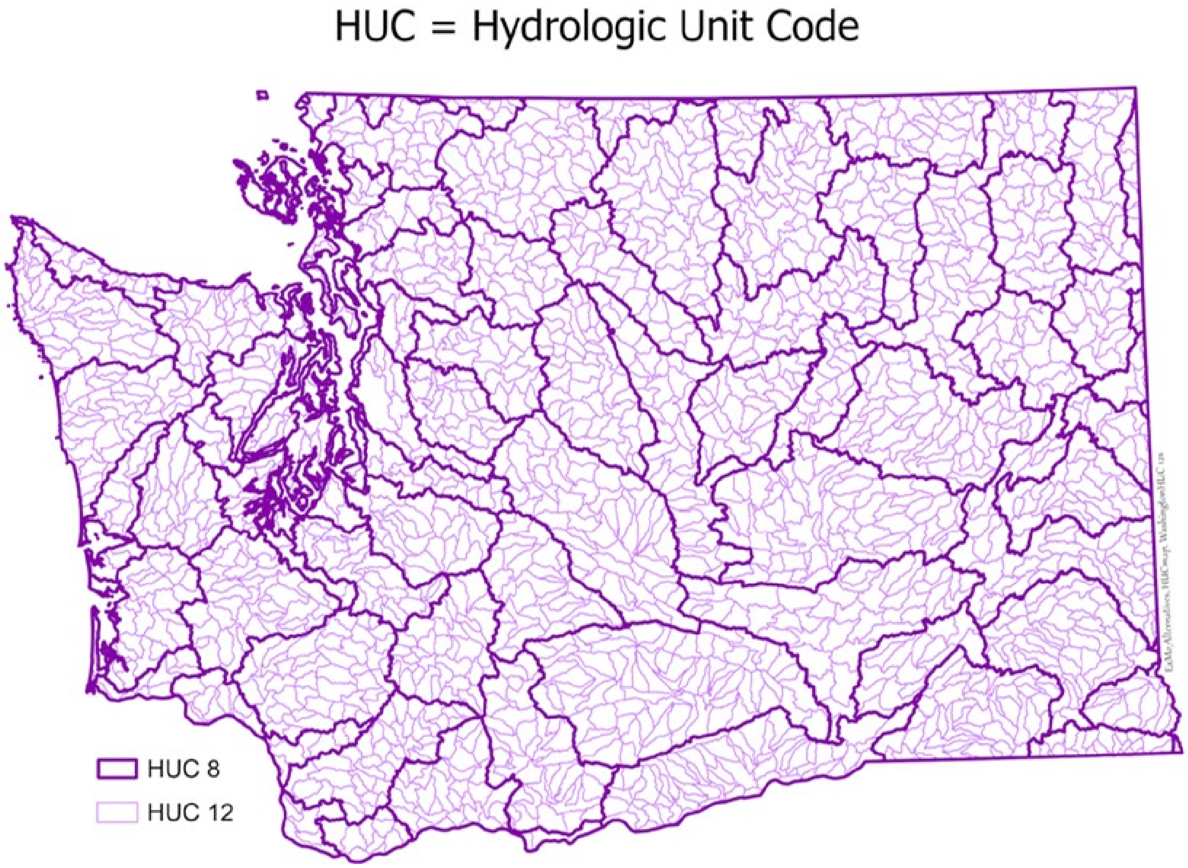

Figure 2. *Watersheds of Washington, delineated at the HUC8 (hundreds of thousands of acres) and HUC12(tens of thousands of acres) levels.HUC8s are generally aligned with but not always identical to Watershed Resource Inventory Areas (WRIAs). HUC12s are somewhat smaller than Watershed Administrative Units (WAUs). Mapping data from US EPA.*

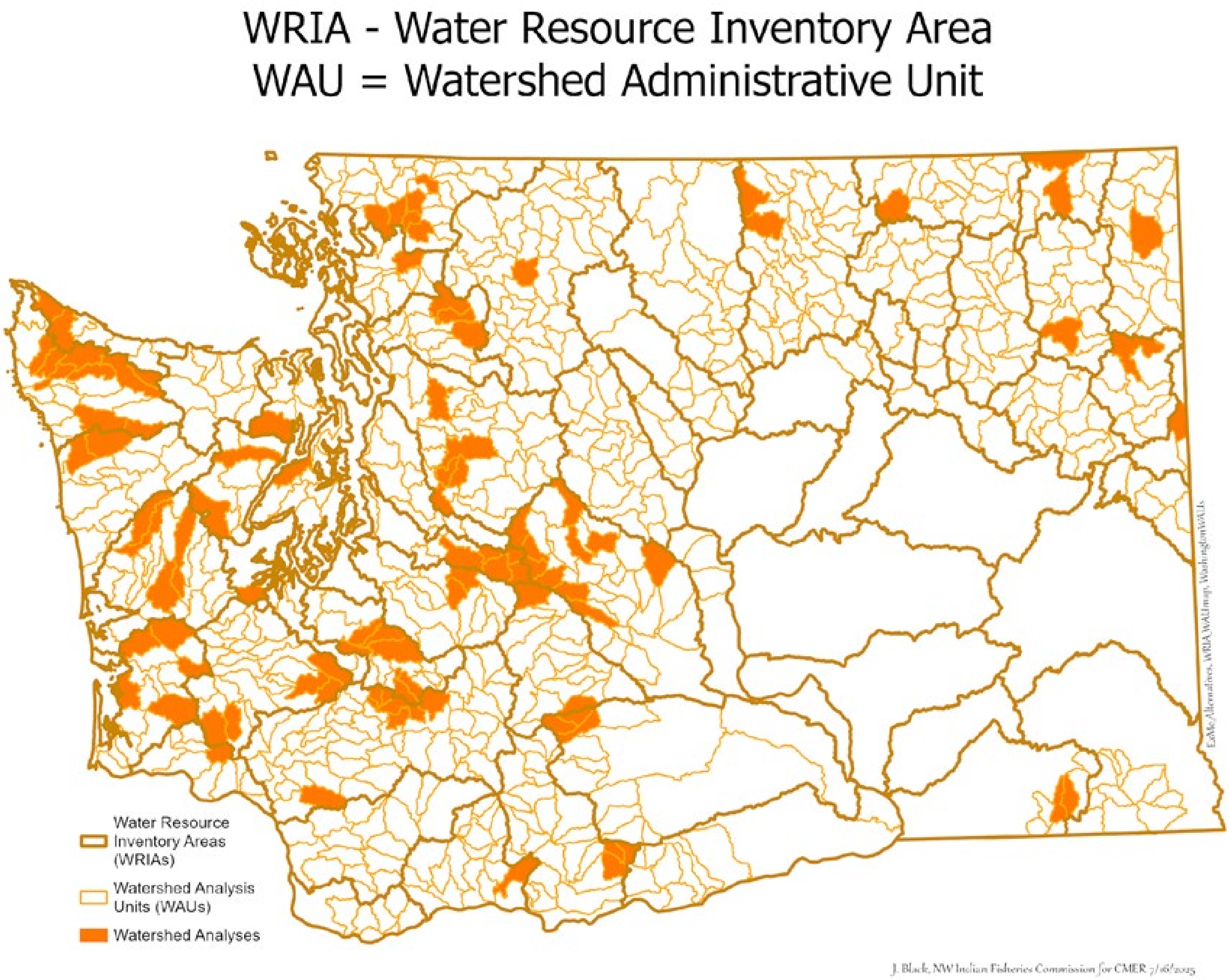

Figure 3. *Washington State's WRIAs and WAUs for comparison with* HUC8*s and HUC12s. WAUs having Watershed Analyses from the 1990s are indicated by solid orange polygons.*

One or more of the five alternatives for assessing riparian conditions, described separately in a latter section, will be paired with the chosen stream temperature monitoring design. The ground-based riparian sampling method(s) would be conducted at sample locations that are consistent with those of the selected stream temperature monitoring alternative(s). Elements of the riparian condition data will be included as variables in stream temperature models in addition to being summarized for riparian condition reporting and monitoring.

It is not feasible to collect continuous stream temperature data throughout the entire target population; empirical temperature data are needed, and modeling is necessary to extrapolate or interpolate to unsampled reaches. Accordingly, inference is used and must rely on the assumption that the distribution of data from measured locations is similar to the distribution of values in unsampled locations. However, when applying generalities, context is important and we must consider that stream temperatures are affected by physical characteristics such as lithology, size, precipitation, and aspect and by disturbances such as timber harvest, fire, land development, and other pulse disturbances that are not evenly distributed. Current modeling techniques are able to use local proximal information to predict stream temperature in non-sampled stream reaches based upon physical properties and locations and intensity of disturbances rather than relying on the simple assumption that the distributions of stream temperatures and other characteristics of interest on unsampled reaches mimics the distributions within the sampled reaches. Newly developed modeling techniques specific to stream networks such as those described in the BAS section, combined with advances in remote sensing and interpretation of physical features such as riparian canopy and channel valley confinement across large areas, provide the opportunity to generate stream temperature distribution information for the entirety of streams on FPHCP-covered lands based upon local conditions. Such models can account for non-uniform management and disturbances across the landscape and allow more accurate assessment and reporting of stream temperatures across the statewide FPHCP landscape. These issues are additionally addressed in Alternatives 2, 3, and 5 by grouping watersheds by physical and land use features and focusing work in this program within watersheds that are strongly dominated by FPHCP lands.

Developing watershed-scale spatial stream models, such as Spatial Stream Network (SSN) models, appropriate to regions of the state that contain significant proportions of forest lands managed under the FPHCP might be a viable method for this project. Using existing data as much as possible would also help augment specific data needs. The Washington Coast SSN model described in the BAS (Winkowski 2023; Appendix A) relied on coarser covariate data than are now available as both input and for prediction. Using updated lidar-based terrain and stream data as well as other high-resolution riparian and land use data from more recent aerial imagery would improve newly developed models. Cooperating with other entities , such as the Washington Department of Fish and Wildlife and Coast Salmon Foundation, in developing these models could also be beneficial for this project.

Details of Alternatives

In this section, we describe each alternative more fully and conclude with a table of comparison for several areas of consideration with each alternative.

Stream Temperature Alternative 1: Spatially balanced reach-level samples randomly selected from all FFR streams

Approach: Repeat the first-round extensive monitoring study conducted in 2008-2009. Use the survey and study design principles from the previous project (Ehinger et al. 2007). That effort used the Washington State Master Sample to select sample points across all FPHCP lands, which was generated using a Generalized Random Tessellation Stratified (GRTS) sampling scheme. That sample is a spatially balanced approach and has the objective of matching the spatial densities of the sample units with the density of stream reaches in the sample frame.

First-Round (2008-09) Extensive Monitoring Locations

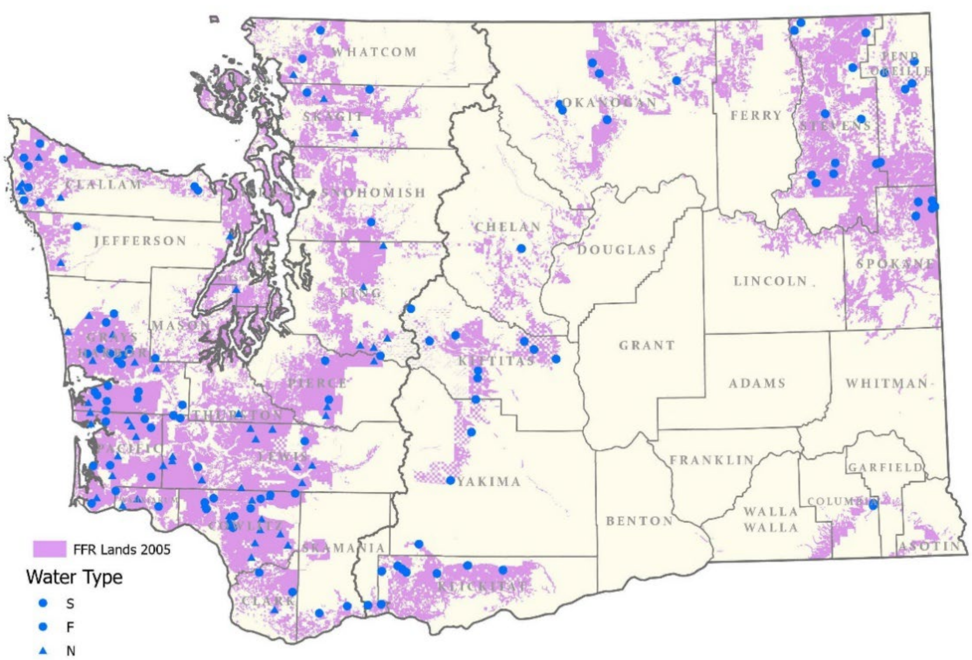

Figure 4. *CMER extensive monitoring locations in 2008-2009 sampling effort.*

Target population, sample frame, and sample: The target population under this alternative is the same as the study population of interest and would consist of all stream segments on FPHCP lands in Washington that meet the minimum threshold characteristics noted above, and their associated riparian zones. The sample frame would consist of points on streams developed through the selected method, such as the GRTS sample points generated for the first round of extensive monitoring. The sample frame would be stratified by Eastern and Western Washington and by stream type. Sample points would be geographically distributed randomly in selected locations within the sample frame (please see example provided by Figure 4).

Statistical inference: Random sampling scheme would permit statistical inference across the entire sample frame within each stratum.

Sample unit: Stream reaches thirty times as long as the bankfull width (as in 2008-09 effort).

Results. Results are specific to each sampling year and would summarize stream temperature metrics (e.g., 7-day average, mean, maximum, median etc.) by spatial strata (e.g., east versus west side, ecoregion, other regions to be defined) and by stream size (e.g., by stream order, stream base).

Resampling for Long-Term Trend Analysis. A rotating panel sampling design is commonly employed where subsets of the randomly-selected sample sites are remeasured at various time intervals to develop a trends analysis and would be planned for this alternative.

Strengths. This is a well-established method that has been successfully applied to landscape-level stream monitoring programs and was the design suggested by the Monitoring Design Team (Benkert et al. 2002) and utilized during the first-round of extensive monitoring in 2008-09 (Ehinger 2013; WA Dept of Ecology 2019). This alternative would provide a statistical inference across the entirety of FPHCP lands, assuming valid sample sites can be obtained for all strata within FPHCP lands.

Data collection and analyses are straightforward and well-established.

Weaknesses. Expensive, and as previous implementation in 2008 demonstrated, issues of access to many landowner properties is difficult and affects inference of findings. Only provides ability to answer general status questions.

Results do not account for the influence of either local or upstream watershed conditions; observed temperatures don't necessarily have any correlation to forest management. Relies on the assumption that the sampled sites adequately represent the range of conditions in forest streams on FPHCP lands across the state while providing no ability for us to test that assumption. It also provides little data to weight the results from each site according to the local conditions when making inferences to conditions across the landscape. Therefore, this alternative has high uncertainty surrounding the inferences about conditions on the entirety of FPHCP lands.

Requires physical access to sites. Sampling entails large travel effort for a given number of sampling points. Access to private property and coordination with a large number of landowners would be needed. The 2008-2009 extensive monitoring first-round effort found that:

- For both Type F/S and Type Np waters, small forest landowners were much less likely to participate than industrial forestland owners. As a result, a proportion of the land base was not sampled. However, there was no evidence this introduced substantive bias into the study. There were errors in the sampling frame that resulted in misclassification of some sampling sites (i.e., wrong water type or incorrect land use). These errors were relatively minor and expected when applying a regulatory definition to GIS-derived stream layers.
- Some [Westside] Type Np streams had too little water in the summer to submerge data loggers. The previous effort was unable to obtain a reasonable sample of valid Type N streams in Eastern Washington due to lack of summer surface water flow. "Given the difficulties noted above, the estimated scope of inference was 70% and 68% of the original sample frame for Type F/S and Type Np streams, respectively, and this study is the only unbiased estimate available for commercial forestlands." (Ehinger 2019)

Cost: $$$$$[9]. Field component would consist of installing temperature sensors across the state, in random locations that make installation, monitoring, and maintenance costs higher in relation to other alternatives listed in this document. Analysis costs would be minimal, but value would also be minimal.

[9] The estimated cost of each alternative is in relative terms with “$$$$$” indicating a relatively high cost, “$” indicating a relatively low cost, and a range between. Actual costs will vary depending on a wide-range of factors including data availability/costs, agency coordination/collaboration, personnel costs, etc.

Stream Temperature Alternative 2: Focused watershed sampling using randomly-located sample sites within selected sub-watersheds within FPHCP lands

Approach. This alternative is to implement a random selection of sites as in Alternative 1 above but to confine our monitoring efforts each year to sets of representative sub-watersheds (HUC12s) that contain high percentages of FPHCP lands.

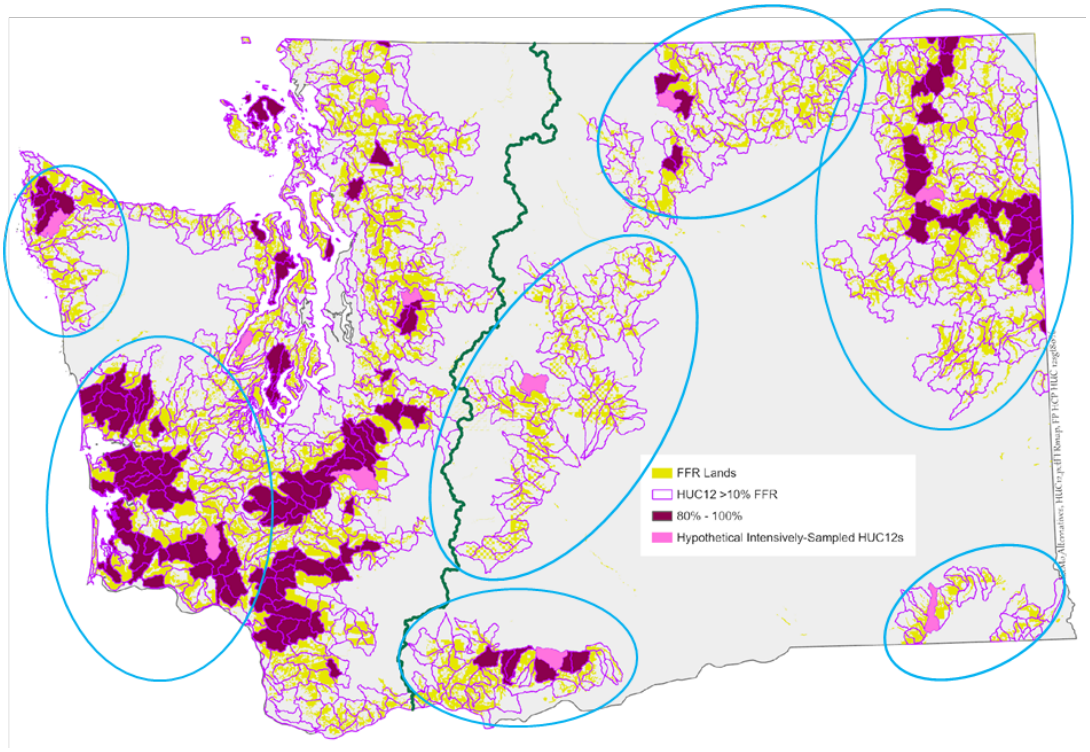

Figure 5. *Sub-watershed level Hydrologic Units (HUC12) incorporating at least 10% potential FPHCP-covered forestland (yellow). HUC12s containing at least 80% FPHCP lands are colored deep purple. The map also shows a hypothetical selection of those (in pink) to be intensively sampled in one sample event (year). 80% is used here as an example "high proportion" of FPHCP lands. The actual percentage to be used would be decided in the study design phase.*

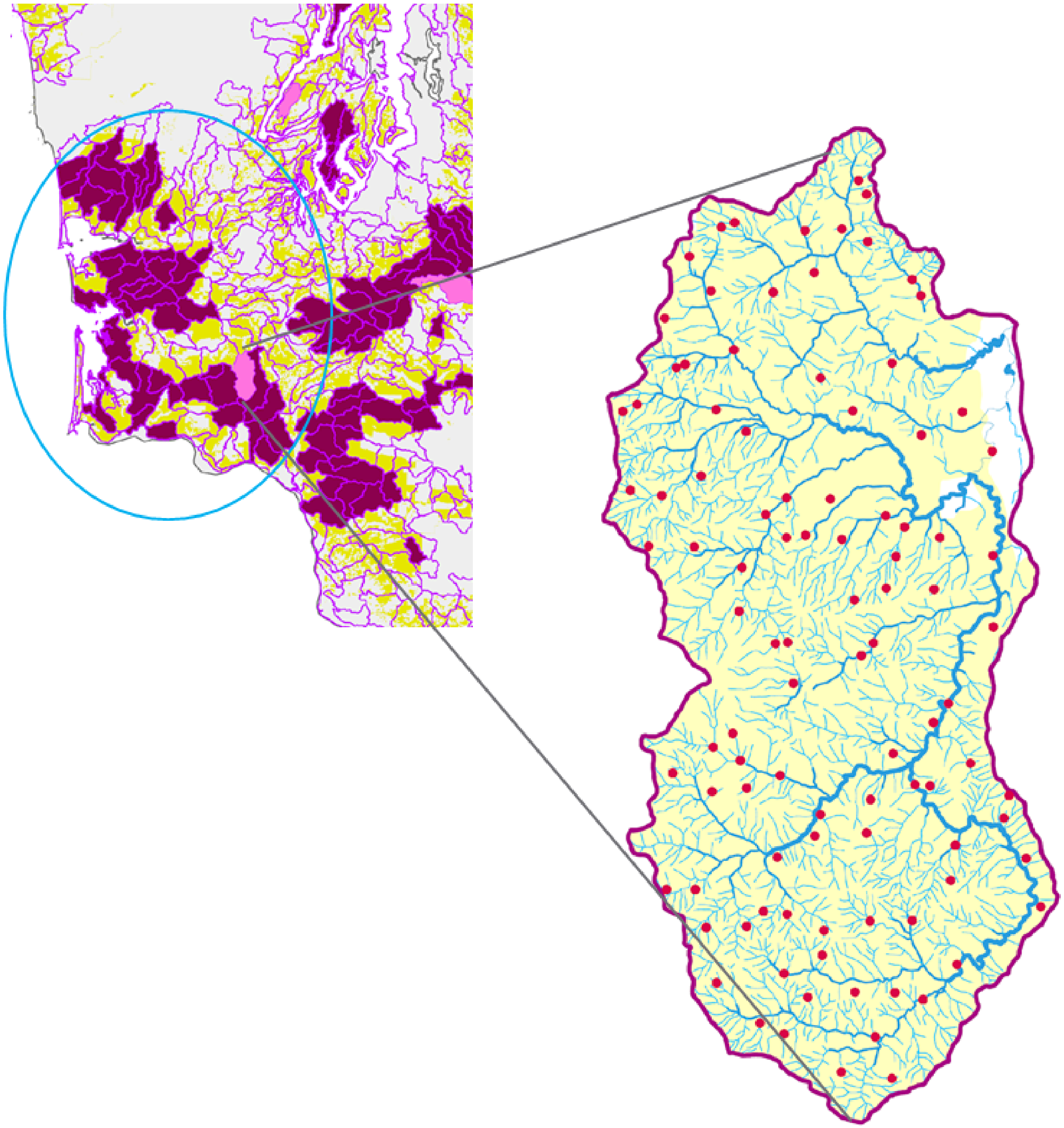

Figure 6. *Example of a focus sub-watershed from one grouping with randomly-selected sampling locations indicated by red dots.*

Target population and sample frame. This option requires two levels of consideration of sample population and sample frame. The first level relates to selecting the focus watersheds to be investigated and the second relates to sampling within those watersheds. The **t**arget population of watersheds would be all the HUC12s in Washington that consist of a minimum percentage (e.g., 10%) FPHCP lands. The sample frame would be the subset of those HUC12s that consist of a high proportion (to be determined but proposed to be 80 or 90%) of FPHCP lands. This criterion reduces the potential confounding effects non-FFR management practices may have on the response of stream temperatures.

The HUC12target population would be grouped by identifying similar HUCs using multivariate techniques such as cluster analysis or analysis of similarity (ANOSIM; Clarke 1993) to determine similarity / dissimilarity measures based on climatic and basin characteristics such as lithology, size, precipitation, and aspect (e.g., Bax 2008). We expect that differentiation by east and west sides of the state would occur in the similarity analyses. HUCs to be sampled would be selected from those exceeding the minimum specified percentage of FPHCP land within each group. The size of the HUC12sample would be determined based on the results of the multivariate analyses and budget constraints.

The second level of sampling occurs within each selected HUC12. The target population within each HUC would be all streams on FPHCP land within the HUC. The sample frame and sample would be randomly-selected stream points and reaches as Alternative 1 but confined to the selected HUC12s.

Sample unit: HUC12s would be the first level of sample unit in that results found within a HUC12would be inferred to the related HUC12s; within HUC12, the sampling units would be randomly selected 100m stream reaches (as in the 2008-09 effort)

Statistical Inference. The findings from the sampled watersheds would be representative within each HUC12and assumed to be inferential to the forestland streams in the non-sampled watersheds within the group associated with each sampled watershed.

Results. Results are specific to each sampling year and would summarize stream temperature metrics (e.g., 7-day average, mean, maxim, median etc.) and temperature distribution metrics by sub-basin cluster and by stream size (e.g., by stream order, stream base).

Resampling for Long-Term Trend Analysis. The set of HUC12s having a high proportion of FPHCP lands would be resampled through time. The determination of what constitutes a “high” proportion of FPHCP land would be determined during the study design phase. Repeat sampling of a given watershed would draw new sample locations for every repeat sampling. Deliberate inclusion of some locations within the watersheds would serve as controls (i.e., were reasonably mature and did not experience harvest in the interval) could be part of the study design to provide a basis to speak to climatic effects among sampling years.

Strengths. Focus on watersheds with high percentage of FPHCP lands reduces confounding effects of non-forestry land uses and allows more in-depth analyses and reporting. Provides a high level of confidence in inference to streams within the monitored watersheds due to higher concentration of sample points than if the points were distributed across the entire FPHCP land area (as in Alternative 1). This higher concentration could allow associations to be made between land conditions and measured stream temperatures. No modeling efforts are required for this alternative, simplifying analysis and reporting and reducing the likelihood of stakeholders questioning results

Weaknesses. Requires an additional level of similarity assumptions than Alternative 1 because the results from the selected focus watersheds are inferred to represent the other watersheds in the similarity group. However, there would be lower confidence in inference of results to unsampled watersheds, because the sample locations are not selected randomly across the entire cluster of watersheds.

Cost. $$$[10]. Reduced travel expenses compared to Alt. 1 as samples are within a limited number of watersheds.

[10] The estimated cost of each alternative is in relative terms with "$$$$$" indicating a relatively high cost, "$" indicating a relatively low cost, and a range between. Actual costs will vary depending on a wide-range of factors including data availability/costs, agency coordination/collaboration, personnel costs, etc.

Stream Temperature Alternative 3: Focused sampling within selected watersheds, located to optimize the generation of stream temperature models

Approach. Develop stream temperature models within each of several intensively-sampled-watersheds selected as described in Alternative 2. Sampling locations within the watersheds would be placed to optimize construction of stream temperature models based on stream network properties.

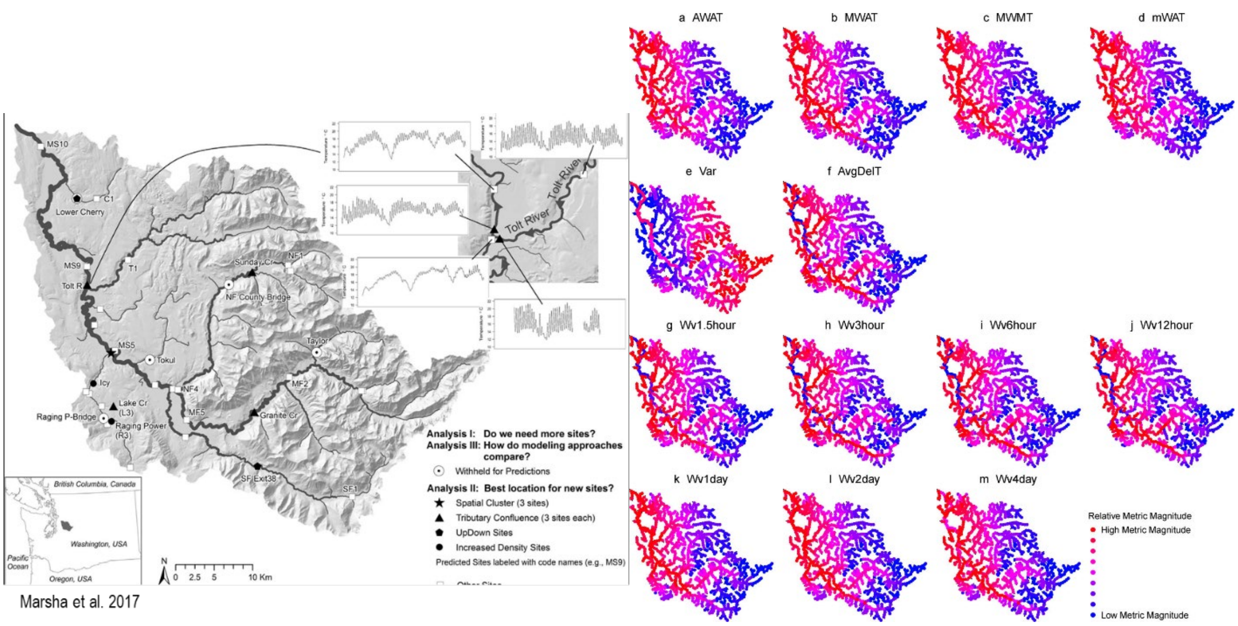

Figure 7. *A) shows an example of stream temperature sampling locations designed to maximize accuracy of SSN stream temperature models in the Snoqualmie Watershed. B) illustrates results from that model for various temperature metrics (Steele et al. 2016).*

Target Population and Sample Frame. This option requires the same two levels of consideration of target population and sample frame as Alternative 2 and would use the same similarity analysis as described previously to select watersheds for focused sampling. The first level relates to selecting the focus watersheds to be investigated and the second relates to sampling within those watersheds. The target population of watersheds would be all the HUC12s in Washington that consist of a minimum percentage (e.g., 10%) FPHCP lands. The sample frame would be the subset of those HUC12s that consist of a high proportion (to be determined but proposed to be 80 or 90%) of FPHCP lands. This criterion reduces the potential confounding effects non-FFR management practices may have on the response of stream temperatures. The HUC12target population would be grouped by identifying similar HUCs using multivariate techniques such as cluster analysis or analysis of similarity (ANOSIM; Clarke 1993) to determine similarity / dissimilarity measures based on climatic and basin characteristics (e.g., Bax 2008). We expect that differentiation by east and west sides of the state would occur in the similarity analyses. HUCs to be sampled would be selected from those exceeding the minimum specified percentage of FPHCP land within each group. The size of the HUC12sample would be determined based on the results of the multivariate analyses and budget constraints.

The second level of sampling occurs within each selected HUC12. The target population within each HUC would be all streams on FPHCP land within the HUC. Under this alternative, monitoring locations within the sampled watersheds would be strategically located to capture the variability in the longitudinal profile and network relationships among stream branches and thereby optimize model performance (Marsha et al. 2018; Som et al. 2014; Pearse et al. 2020).

Statistical Inference. The findings from the sampled watersheds would be assumed to be inferential to the forestland streams in the non-sampled watersheds in the group defined by the multivariate analysis.

Results. These data would be used in an SSN (Marsha et al. 2018; Ver Hoef and Peterson 2010) or other stream network water temperature model. The results would be expressed as longitudinal profiles by stream temperature metric (e.g., mean summer 7-day maximum) along with the riparian conditions. Basin-wide summary statistics would be generated by temporal or spatial strata. Tables that show the proportion of stream reach lengths in different criteria categories (e.g., Table 2) would also be reported.

Table 2. *Example of reporting tables for stream or riparian criteria findings on FPHCP lands . (Schedule L-1 metrics and targets are currently [2025] being reviewed under a separate effort.)*

HUC 12 Intensive	WQ Standards	Schedule L-1 Target	FPHCP Lands Modeled	WQ Standards	Schedule L-1 Target
% Stream length meeting criteria	XX%	XX%	% Stream length meeting criteria	XX%	XX%
% Stream length not meeting criteria	YY%	YY%	% Stream length not meeting criteria	YY%	YY%

Resampling for Long-Term Trend Analysis. The set of high-FPHCP-land watersheds would be resampled through time. Repeat sampling of a given watershed would use the same sampling locations of the previous survey.

Strengths. Focus on watersheds dominated by FPHCP lands removes the confounding effects of other land uses on stream temperatures. Longitudinal profiles of all stream temperatures patterns within the focus watersheds will be able to show both the temporal and spatial patterns based on actual measures and interpolated results between measured sites. This alternative would allow for possibility of estimating stream temperature profiles in the past or future based on past and hypothetical future climatic and watershed conditions.

Weaknesses. Requires an additional level of similarity assumptions than Alternative 1 because the results from the selected focus watersheds are inferred to represent the other watersheds in the similarity group. Stream network modeling is data and computationally intensive.

Cost. $$$[11]. Reduced travel expenses compared to Alt. 1 as the samples are within the same watershed.

[11] The estimated cost of each alternative is in relative terms with "$$$$$" indicating a relatively high cost, "$" indicating a relatively low cost, and a range between. Actual costs will vary depending on a wide-range of factors including data availability/costs, agency coordination/collaboration, personnel costs, etc.

Stream Temperature Alternative 4: Develop regional stream temperature models for entire state with collaborators

Approach. Collaborate in efforts to develop a set of stream temperature models to predict temperature metrics of interest across the state; clip area of FPHCP lands to summarize data for population of interest. As described in the BAS section, several geographic-based numerical simulation models specific to streams and watersheds have been developed in recent years to demonstrate concepts and allow for broad-scale projections. Landscape-level stream modeling approaches include the Spatial Stream Network (SSN) technique developed by a consortium from the EPA and the USFS Intermountain and Pacific Northwest Research Stations as well as General Additive Models (GAM) such as was developed by Siegel et al. (2019). In this approach, we would work with ongoing efforts by NOAA to develop current and more refined Spatial Stream Network (SSN) or General Additive Model (GAM) models using newly-available covariate data sources, existing available stream temperature (and covariate) data, and augmented by data we collect specifically on FFR target lands (https://www.fisheries.noaa.gov/west-coast/climate/stream-temperature-monitoring-and-modeling-pacific-northwest). This would be analogous to the 2021 effort by the WDFW and the Coastal Watershed Assessment project (Figure 9; Adams and Zimmerman 2023; Winkowski 2023). Additionally, Department of Ecology expects to develop SSN models for some watersheds as they conduct TMDL analyses, which could also be part of this effort. Models would be validated using available or subsequently-collected ground-based measurements not used in model development.

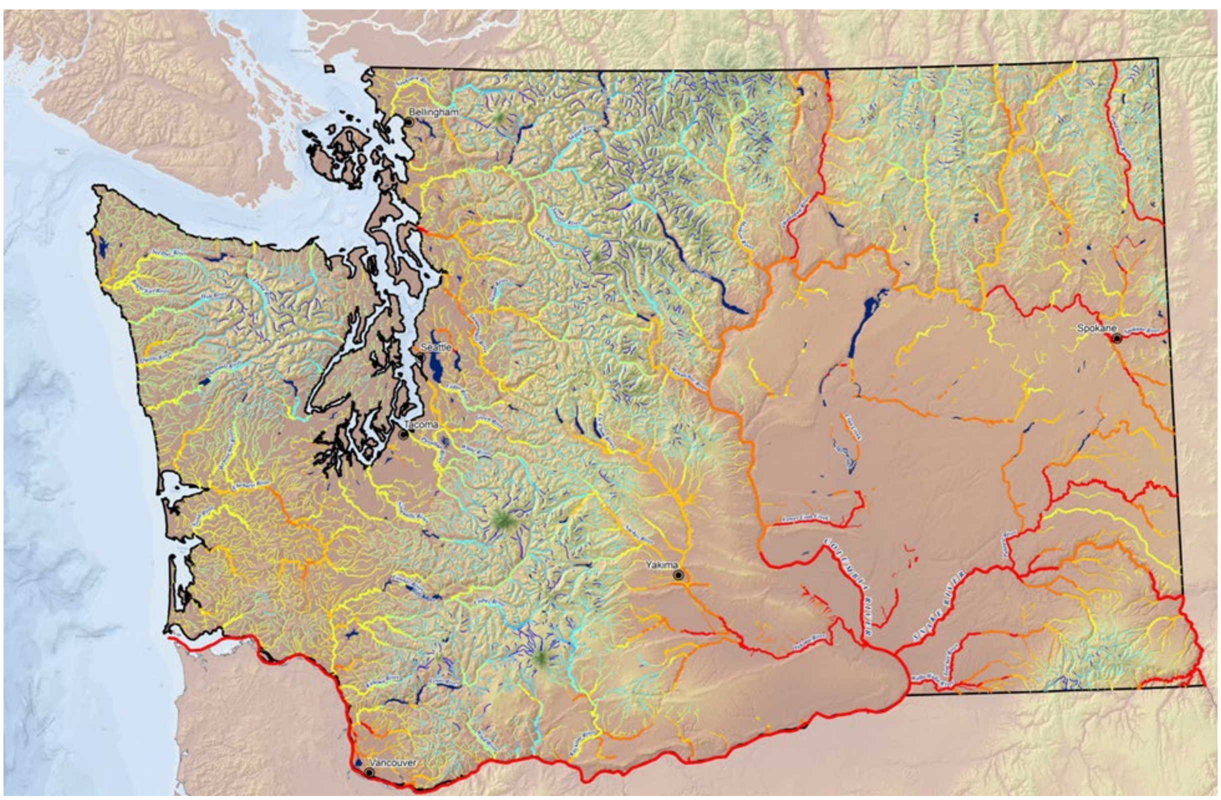

Figure 8. *Mean August stream temperatures for Washington predicted by the NorWeST model based on compiled in-stream temperature data through 2014. Rocky Mountain Research Station, US Forest Service https://www.fs.usda.gov/rm/boise/AWAE/projects/NorWeST/images/ThermalscapeWesternUS_StreamTemperaturesFinal.jpg.*

Sample Frame. The sample frame for the purposes of this study would consist of fish bearing streams on forested lands in Washington. The sample population would consist of all stream segments on forested lands in Washington across all ownerships and could be stratified by Eastern and Western Washington and by the regions of each model. Due to the occurrence of many small streams outside the geomorphic limitations described in the Target Population section, Type N streams would not comprehensively be included in the stream temperature modeling.

Sampling Method. Collect stream temperature data in areas of specific interest for the purposes of this program as input for development of the cooperative models. Sampling locations would be determined in cooperation with co-modelers (e.g., NOAA, WA Dept. Of Ecology, WDFW, landowners, etc.) to optimize model accuracies and fill in gaps in conditions or locations of interest to the FP AMP.

Statistical Inference. The modeled stream temperatures would encompass all stream reaches in watersheds containing forestlands and as such, would include those located on FPHCP lands. Both geographic and stream type inference would be model-specific.

Results. The modeled stream temperature data across the landscape could be delivered as maps that display stream temperature metrics displayed via color coding or show sections of stream that are meeting/not meeting specific standards or criteria. The maps will have corresponding tables that show the proportion of stream reach lengths in different categories as in Alternative 3, Table 2.

Resampling for Long-Term Trend Analysis. Models can be updated over time with more recent stream temperature data and covariate data.

Strengths. The modeling efforts offer the ability to infer conditions on streams not directly sampled and reduces the need for fieldwork that is time consuming and can be costly. Leverages efforts (and budget) from multiple entities and reduces replication of efforts.

Weaknesses. While efforts appear to be very useful in modeling most fish habitat, the efforts to date have not been able to create effective models of small, high-gradient streams typical of the Type N stream population. Therefore, we would be less confident in any modeling of high gradient streams. Threats to Federal agencies and potentially to funding of cooperative efforts could be a risk.

Cost. $$$[12]**.**

[12] The estimated cost of each alternative is in relative terms with "$$$$$" indicating a relatively high cost, "$" indicating a relatively low cost, and a range between. Actual costs will vary depending on a wide-range of factors including data availability/costs, agency coordination/collaboration, personnel costs, etc.

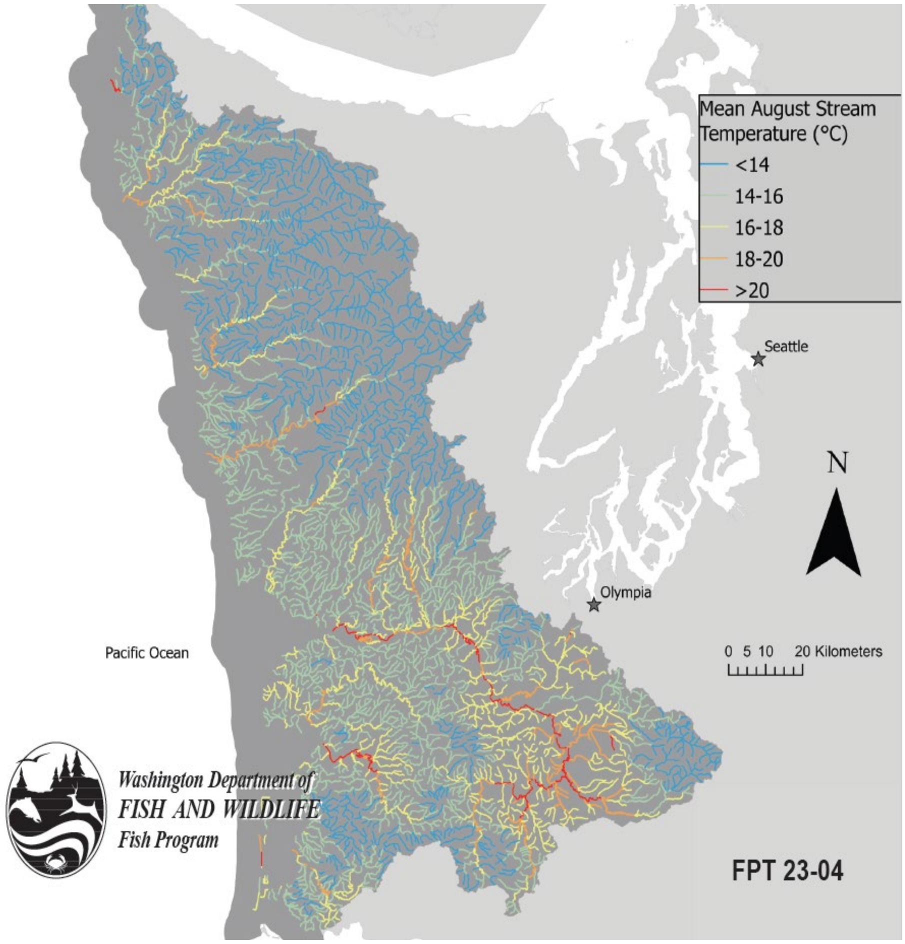

***Figure 9**. Coastal Watershed spatial stream network (SSN) model results for mean August stream temperatures (Winkowski 2023).*

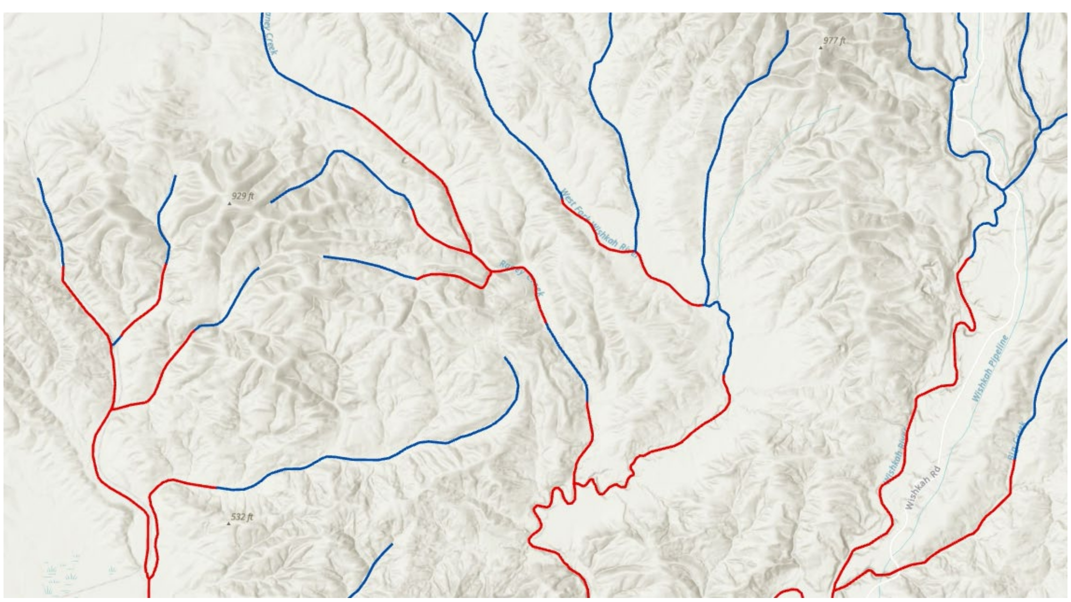

***Figure 10**. Hypothetical map of stream reaches that do (blue) and do not (red) meet any given Forest Practices Criterion.*

Stream Temperature Alternative 5: Combine Alternatives 3 & 4

Approach. Collect data and develop stream temperature models for selected focus watersheds as described in Alternative 3, although perhaps for a smaller number of subbasins/clusters. Report temperature distributions within the focus watersheds. Use the data and model relationships developed in conjunction with other data sources to develop more extensive regional models cooperatively with other entities to predict temperature metrics of interest across the state. As with Alternative 4, clip area of FPHCP lands to summarize data for population of interest from the wider models. Both models would be validated using available ground-based measurements not used in model development. Results from the focused watershed models, which was based on more detailed sampling, would also be compared with those from the broader regional models to corroborate their results and serve as another level of validation.

Sample Frame. All streams on FPHCP lands within sampled HUC12s that are downstream of threshold basin area/gradients as noted in Introduction; All HUC12s containing XX% (to be determined in study design) FPHCP lands; All streams on FPHCP forestlands that meet threshold criteria.

Sampling Method. Sampling stations strategically located to capture the variability within stream longitudinal profiles and to optimize accuracy of regional stream temperature models within focus watersheds, along with any other existing data, to build regional models.

Statistical Inference. The findings from the sampled watersheds would be assumed to be inferential to the forestland streams in the non-sampled watersheds deemed similar from the multivariate analysis described in Alternatives 2 and 3. This will also be combined with the modeled stream temperatures that will cover all FFR streams. Models can be updated over time with new stream temperature data and covariate data. Stream temperature models can also be built using climate prediction data to help infer future conditions.

Results. This alternative would establish temperature metrics along longitudinal stream profiles within selected focus watersheds and create modeled stream temperature maps and generate stream temperature metrics for those and the remainder of Washington watersheds. The maps would have corresponding tables that show the proportion of stream reach lengths in different categories as in Alternative 3, Table 2.

Resampling for Long-Term Trend Analysis. The set of high-FPHCP-land watersheds would be resampled using a rotating panel design. Repeated sampling of a given watershed would use the same sampling location of the previous survey. The models can be updated over time with more recent stream temperature data, including later direct measurements from this study, as well as updated covariate data.

Strengths. Combination of both collected data and modeled data. High confidence in results for focus watersheds combined with modeled results utilizing current covariate data for remainder of FPHCP land, though with lower confidence, reduces need for inference assumptions. Leverages teaming opportunities with other entities in the state for acquisition and development of statewide data sets and models.

Weaknesses. The intensively-sampled focus sub-watersheds do not cover the full spatial extent for gathered data. Modeled temperatures will have associated error that will be taken into consideration.

Cost. $$$$[13]. Combining field and modeled data will likely be a similar cost to other alternatives, but modeling will require personnel with advanced statistical skills and high-power computers.

[13] The estimated cost of each alternative is in relative terms with "$$$$$" indicating a relatively high cost, "$" indicating a relatively low cost, and a range between. Actual costs will vary depending on a wide-range of factors including data availability/costs, agency coordination/collaboration, personnel costs, etc.

Table 3. *Comparison of Stream Temperature Monitoring Alternatives*

Alternative Number	**1**	**2**	**3**	**4**	**5**
Sample Frame	All streams that fall within the bounds of the FFRlands GIS layer	HUC12s with a specified minimum of FPHCP lands	HUC12s with a specified minimum of FPHCP lands	Streams that meet minimum physical criteria on all forested lands in Washington	Streams meeting minimum criteria within sampled HUC12s; All HUC12s containing a high proportion of FPHCP lands
Sampling Method	Spatially balanced reach-level samples randomly selected	Spatially balanced reach-level sites randomly selected within specific HUC12s	Sampling stations strategically located to capture the variability within stream longitudinal profile to optimize stream temperature model accuracy	Develop stream temperature models in cooperation with other agencies/entities; collect data on FPHCP lands as needed to facilitate that effort; clip out results for FPHCP lands	Sampling stations strategically located to capture the variability within stream longitudinal profile & stream temperature models
Anticipated Results	Temperature metrics summarized by strata.	Temperature metrics summarized at HUC12level generated by temporal or spatial strata	Temperature metrics along longitudinal profile within HUC12s	Modeled stream temperature maps and stream temperature metrics summarized for FPHCP streams	Temperature metrics along longitudinal profile within HUC12& Modeled stream temperature maps and generated stream temperature metrics

Alternative Number	1	2	3	4	5
Statistical Inference	All FPHCP streams that meet the threshold criteria for that sample year.	Representative of sampled HUC12and assumed to be inferential to the forestland streams in similar, non-sampled watersheds	Representative of sampled HUC12and assumed to be inferential to the forestland streams in similar, non-sampled watersheds	All streams on FPHCP lands that meet the model threshold criteria	All streams on FPHCP lands that meet the model threshold criteria
Strengths	Well established method	No modeling efforts required	Longitudinal profile of streams based on actual measures and interpolated results between measures; Modeling can allow projections into future conditions	Infer conditions on streams not directly sampled. Modeling can allow projections into future conditions. Leverages existing data and cooperative relationships leverage limited funding.	Combination of both collected data and modeled data allows high confidence within sampled HUCs combined with results for all FPHCP streams, though with somewhat lowered confidence outside sampled HUCs.
Weaknesses	Sample points do not account for spatial context; It can describe a condition, but it does nothing to increase understanding of relationships; other alternatives allow for further analyses in ways this alternative does not; relies on inference of stream temperature conditions across wide	The results of selected watersheds are inferred to represent other watersheds	The results of selected watersheds are inferred to represent other watersheds	The minimal efforts to date have not been able to create effective models of small, high-gradient streams typical of the Type N stream population	Singular HUC being sampled does not cover full spatial extent for gathered data

Alternative Number	1	2	3	4	5
	disparate areas based on limited number of individual point measurements				
Cost	Field work would be relatively expensive, analysis relatively inexpensive, $$$$$	Reduced travel expenses due to sampling in limited areas, $$$	Reduced travel expenses due to sampling in limited areas, $$$	Relatively accessible analysis, $$	Field sampling mixed with analysis, $$$$

Riparian Functions/Conditions Alternatives

Overview of Alternatives

There are 5 Riparian Functions/Conditions Alternatives being considered:

1. **Ground-based Riparian Stand Survey**
2. **Airborne Laser Scanning (ALS)**
3. **WADNR-Remote-Sensing Forest Resource Inventory System (RS-FRIS)**
4. **Sentinel-2 Satellites Imagery**
5. **Integrated Airborne Laser Scanning and Imagery-Based Remote Sensing** (e.g., FRIS or Sentinel-2)

For most riparian metrics, remote sensing models are well-developed for all these methods, and our effort would consist of validating those modeled results in our target riparian populations. There might be a few metrics for which the effort would also include developing or further refining remote sensing interpretation models to meet the specific needs of this monitoring program. Any of these riparian methods could be applied with the same sampling strategy as the selected stream temperature monitoring alternative and would be implemented in a way that supports that work.

Details of Alternatives

The following alternatives are for riparian data collection methods and describe advantages and disadvantages of each method for the buffer characteristics of interest to this program.

Riparian Alternative 1: Ground-based Riparian Stand Survey

Approach. A ground-based inventory of riparian timber stand structure and composition is a reliable and repeatable methodology for estimating riparian forest stand area-based metrics (e.g., density, basal area, mortality), tree-based metrics (e.g, species, DBH, age, total height, live crown height) and lateral distribution relative to the stream channel. Marquardt (2010) examined several survey methods and found that rectangular strip plots perpendicular to channel outperformed several other field inventory methods for estimating tree height, basal area (BA) and density in riparian forest stands of western Oregon. Therefore, rectangular strip plots are recommended for obtaining stand structure and composition data that are needed to address critical questions. Further, the strip plots perpendicular to the channel can detect and quantify the large lateral variability that is common in riparian stands; due in part to previous harvest rules, complex valley morphology and soil wetness (Villarin et al. 2009).

Sampling Method. Conduct a field inventory of riparian stands using rectangular strip plots orientated perpendicular to the channel.

Spatial and Temporal Inference. Spatial inference is dependent on spatially balanced and representative samples from stand types and the range of stand conditions (e.g., age, density, size) that are commonly found on FPHCP lands. Repeated visits to sample plots over time will provide data for assessing change and trends. Spatial inference at sample sites will extend out to 45 m (150 ft) which will encompass the source distances for most riparian functions including the area providing 95 percent of the total instream wood inputs (Reeves et al. 2018). Also, this will encompass the core and inner zones of the most commonly implemented FP rules (Black et al. 2024).

Results. Accurate estimates of area-based and tree-based metrics for sample plots within riparian stands.

Resampling for Long-Term Trend Analysis. Monuments can be installed at sample plots to facilitate repeated measures over time.

Strengths.

- Accurate measures of stand size and composition metrics (e.g., dbh, crown, species, over- and understory) and by RMZ zones (core, inner, outer). Can include accurate understory inventory.
- Directly measures key riparian ecological functions including stream shade, LW input and potential LW supply by source distance, and surface erosion delivery potential.
- Can provide direct measures of channel physical characteristic (BFW, gradient, substrate size composition) and instream habitat features (wetted width, depth, pools, riffles, LW load) in sample reach adjacent to riparian plots
- Directly measures understory cover/composition and in-grow
- Data directly suitable for assessing DFC status and modeling DFC trajectory

Weaknesses.

- Spatial resolution limited to stand. Therefore, requires large spatial representative sample to characterize variability at reach, basin, and landscape scales.
- Data collection requires access to site.
- Labor intensive sampling may restrict the number of sites sampled which may limit the spatial representativeness of the sample population.
- Long inventory cycle
- Ground-based measures of stand heights and canopy cover can be less accurate than those from aerial methods
- Field measurements are only applicable to sample plots, but data can be used to extrapolate to all similar stand types.

Cost.

- $$$$$[14] - High relative to other approaches because of labor intensive methodology.
- Low economics of scale

[14] The estimated cost of each alternative is in relative terms with “$$$$$” indicating a relatively high cost, “$” indicating a relatively low cost, and a range between. Actual costs will vary depending on a wide-range of factors including data availability/costs, agency coordination/collaboration, personnel costs, etc.

Riparian Alternative 2: Airborne Laser Scanning (ALS)

ALS data are spatially explicit and capable of accurately characterizing riparian stand structure and associated ecological functions (Goodbody et al. 2024).

Approach. Use ALS remote sensing technology to accurately quantify riparian stand structure (e.g., cover, height), composition (e.g., conifer, broadleaf), and spatial distribution at the reach, network, and landscape scales. Incorporate modeling for estimating riparian ecological functions (e.g., shade, large wood supply potential) and potential future conditions (e.g., DFC).

Sample Frame. The sample frame would consist of all riparian areas within FPHCP lands. The sample unit is spatially continuous within the sample frame.

Sampling Method. ALS data from state Lidar Portal would provide the basic data needed to estimate riparian forest metrics at spatial scales (e.g., reach, network, landscape) needed to support temperature modeling and to address critical question. Publicly available inventory models and new model development, if needed, would be used to assess forest metrics for different stand types. Ground plots (e.g. Riparian Option 1) would be used for model development and validation.

Spatial and Temporal Inference. Spatial inference high given:

- potential wall-to-wall coverage of target population across landscape,
- continuous measures of riparian metrics and functions along entire stream network, and
- high resolution of metric estimates for any lateral width band (zone) within riparian stand.

Proposed repeat Lidar by WADNR at 10-yr intervals (spatially rotating survey) will provide data necessary for assessing change and trends.

Results. Accurate estimates of forest metrics for riparian stands along entire stream network within target population.

Resampling for long-term trend analysis. Repeat Lidar surveys expected at approximately 10-yr intervals facilitate long-term trend monitoring.

Strengths.

- Accurate measures/estimates of stand composition and metrics (1-m resolution).
- Eliminates spatial sampling bias because all areas in target sample population can be inventoried (i.e., ground access unnecessary)
- Accurate measures and estimates of riparian functions (stream shade and LW supply potential) by lateral width zones (e.g., 25, 50, 100 ft)
- Data and metrics (e.g., Basal Area) suitable for stand growth modeling and for assessing DFC status
- Reliable methodology for accurate change detection (trends)
- Can match specific sample frame for any stream temperature monitoring alternative.

Weaknesses.

- Complete spatial coverage is not synchronized for a given year or short time period; acquisitions have occurred over a several year period. Therefore, ALS coverages may not be available for all areas within sample population during same year.
- Estimating stand metrics depends on the availability of reliable inventory models (i.e. ground-truth) for different forest types. Therefore, some new models may be needed and some may need up-dating and validation.
- The timing of data collection (leaf-on/off) may influence model outputs depending on metric (e.g., species/composition type).
- Data not suitable of for modeling DFC trajectory
- Surface erosion not measurable under canopy
- Information for understory cover and in-grow has lower certainty

Cost. $$$[15] **-** Relatively low cost pending the availability of public data. If data are needed for specific areas or time periods the acquisition cost for custom flights and data post processing is considerable.

[15] The estimated cost of each alternative is in relative terms with "$$$$$" indicating a relatively high cost, "$" indicating a relatively low cost, and a range between. Actual costs will vary depending on a wide-range of factors including data availability/costs, agency coordination/collaboration, personnel costs, etc.

Riparian Alternative 3: WADNR-Remote-Sensing Forest Resource Inventory System (RS-FRIS)

Approach. Use *RS-FRIS (Version 5)* technology to quantify riparian stand structure (e.g., cover, height), composition (e.g., conifer, broadleaf), and spatial distribution at the reach, network, and landscape scales.

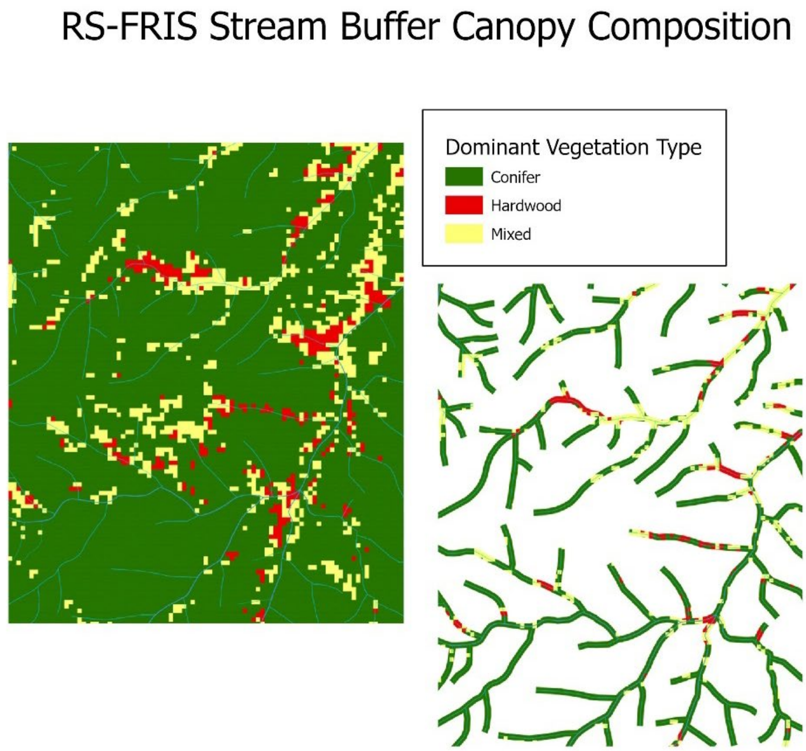

Figure 11*. Example of clipping RS-FRIS data rasters to stream buffers in preparation for riparian characteristic summarization*

Sampling Method. Estimated forest metrics from RS-FRIS would be used to populate riparian stands (e.g., polygon width-bands; 0-50 ft, 50-100 ft, 100-200 ft) within the sample population. Data would be aggregated and summarized at spatial scales (e.g., reach, network, landscape) that are needed to support temperature modeling and to address critical question.

Spatial and Temporal Inference. Spatial inference high given:

- can provide wall-to-wall coverage of target population across landscape
- continuous measures of riparian metrics along entire stream network.

Planned repeat surveys by WADNR at 2-yr intervals provides high temporal frequency data for assessing change and trends.

Results. Estimates of stand-based forest metrics for riparian stands along entire stream network within target population.

Resampling for long-term trend analysis. Repeat surveys planned at 2-yr intervals facilitates long-term trend monitoring.

Strengths.

- Unbiased estimates of stand composition and area-based metrics
- Simple to implement as no additional modeling would be necessary to derive forest metrics
- Relatively high spatial resolution (20-m pixel) well suited for landscape scale assessment
- Good precision at stand level for common area-based forest metrics
- Data and metrics (e.g., Basal Area) suitable for stand growth modeling and for assessing DFC status
- Inventory models maintained and updated by agency (WDNR).
- Ground access unnecessary because the FRIS program has an extensive ground calibration/validation program within it.
- Provides reliable estimates of stand conditions and change detection at basin and larger scales
- Potential to detect forest health

Weaknesses.

- Requires high resolution DEM for accurate delineation of channel network and metric modeling.
- Images with shadows affect modeling, Consequently the accuracy of modeled metrics influenced by canopy density (i.e., accuracy declines with decreasing canopy density, increasing shadows).
- Understory excluded except in low density and wide spaced stands
- Estimates of shade and LW supply potential approximated from predicted metrics (i.e., canopy cover, canopy closure, tree height, QMD, basal area).
- Data not suitable of for modeling DFC trajectory
- Low precision for delineation of lateral variability (e.g., width zones 25, 50, 100 ft) in riparian conditions and detection of small changes across small areas. Limited by 20-m pixel resolution.
- Surface erosion not measurable under canopy.

Cost.

- $[16] - Relatively low cost and cost-effective source of landscape forest metric data
  High economics of scale

[16] The estimated cost of each alternative is in relative terms with "$$$$$" indicating a relatively high cost, "$" indicating a relatively low cost, and a range between. Actual costs will vary depending on a wide-range of factors including data availability/costs, agency coordination/collaboration, personnel costs, etc.

Riparian Alternative 4: Sentinel-2 Satellites Imagery

Approach. Use Sentinel-2 Satellite Imagery to estimate (model) riparian stand structure (e.g., cover, height), composition (e.g., conifer, broadleaf), and spatial distribution at the reach, network, and landscape scales.

Sampling Method. Estimated forest metrics from satellite imagery would be used to populate riparian stands (e.g., polygon width-bands; 0-50 ft, 50-100 ft, 100-200 ft) within the sample population. Data would be aggregated and summarized at spatial scales (e.g., reach, network, landscape) that are needed to support temperature modeling and to address critical question.

Spatial and Temporal Inference. Spatial inference high given:

- can provide wall-to-wall coverage of target population across landscape
- continuous measures of riparian metrics along entire stream network.
- moderate resolution (10-m pixel) facilitates coarse estimates of lateral patterns /distribution of riparian stand characteristics.

Frequent return intervals of satellite (5-days) can provide high temporal frequency data for assessing change and trends. Data starting in 2015 enables past trend analyses including short-and longer-term change detection.

Results. Estimates of area-based forest metrics for riparian stands along entire stream network within target population.

Resampling for long-term trend analysis. Periodic acquisitions of satellite data facilitate long-term trend monitoring.

Strengths.

- Relatively accurate estimates of forest structure, stand composition, species and area-based metrics
- Data and metrics (e.g., Basal Area) suitable for stand growth modeling and for assessing DFC status
- Models publicly available because satellite-based data are commonly used for forest assessment around the world.
- High temporal frequency of data collection facilitates the selection of cloud-free data for any given location
- Ground access unnecessary.
- Potential to detect forest health conditions.

Weaknesses.

- Requires high resolution DEM for accurate delineation of channel network and metric modeling.
- Low precision for delineation of lateral variability (e.g., width zones 25, 50, 100 ft) in riparian conditions and detection of small changes across small areas. Limited by 10-m pixel resolution.
- Images with shadows affect modeling.
- Publicly available models require ground-truthing for different forest types.
- Estimates of shade and LW supply potential approximated.
- Data not suitable of for modeling DFC trajectory
- Surface erosion not measurable under canopy.

- Identifying and detecting lateral variability in riparian conditions is limited by 10-m resolution.

Cost. $[17]**.** No-cost for open-source data. However, cost required for model validation that would include riparian plot surveys (e.g., Option 1).

[17] The estimated cost of each alternative is in relative terms with "$$$$$" indicating a relatively high cost, "$" indicating a relatively low cost, and a range between. Actual costs will vary depending on a wide-range of factors including data availability/costs, agency coordination/collaboration, personnel costs, etc.

Riparian Alternative 5: Combine Alternative 2 with either 3 or 4 (Integrate Airborne Laser Scanning and Imagery based Remote Sensing FRIS or Sentinel-2)

Approach. No single data type can provide spatially accurate high-quality information for all desired attributes and on a schedule suitable for both status and trend monitoring. Therefore, the combination of ALS and Image-based remote sensing data could provide both high spatial accuracy and temporal frequency data collection capabilities.

ALS would be used to establish a baseline assessment of riparian forest stand conditions (e.g., cover, height, composition, structure) and function potential (shade, LW supply); stratified by lateral width zones and aggregated at the reach, network, and landscape scales. Image-based forest metrics would be estimated for a representative sample population (common forest type) during same time frame as ALS data and used in comparative analyses to determine relative utility of image-based data for trend monitoring.

Sampling Method. See Alternatives 2, 3, 4

Spatial and Temporal Inference. See Alternatives 2, 3, 4

Results. See Alternatives 2, 3, 4

Resampling for long-term trend analysis. See Alternatives 2, 3, 4

Strengths. See Alternatives 2, 3, 4.

- Accurate measures of stand size and composition metrics from ALS
- Simple implementation as no additional modeling would be necessary to derive forest metrics from RS-FRIs
- Moderate to high temporal frequency of data collection from RS-FRIS and Satellite, respectively

Weaknesses. See Alternatives 2, 3, 4. Also:

- Because most of Washington State's ALS data are acquired during leaf-off conditions the accuracy of canopy height measurements for deciduous trees reduced. This affects estimates of area-based metrics (e.g., basal area/ac) as well as estimating understory cover. The trade-offs of using leaf-off ALS versus acquiring leaf-on data (cost benefits) will need to be considered. There is uncertainty concerning the future temporal frequency and cost for acquiring FRIS data. Therefore, the cost/benefits of using FRIS versus Sentinel-2 data will need to be evaluated.
- Both image-based data types will require field validation. However, the Sentinel-2 will require the project team to design and implement the field survey plot and associated modeling. Whereas less effort will be needed for validation of FRIS because the DNR has a built-in validation component for FRIS using existing upland forest inventory plots. Additional plots in riparian stands will be needed to supplement validation data.

Cost. $$$[18]**.** See Alternatives 2, 3, 4.

[18] The estimated cost of each alternative is in relative terms with "$$$$$" indicating a relatively high cost, "$" indicating a relatively low cost, and a range between. Actual costs will vary depending on a wide-range of factors including data availability/costs, agency coordination/collaboration, personnel costs, etc.

Table 4. *Comparison of Riparian Function/Condition Monitoring Alternatives.*

Alternative Number	**1**	**2**	**3**	**4**	**5**
Sample Frame	All riparian areas within FPHCP lands.	All riparian areas within FPHCP lands.	All riparian areas within FPHCP lands.	All riparian areas within FPHCP lands.	All riparian areas within FPHCP lands.
Sampling Method	Ground-based rectangular strip plots	Airborne Laser Scanning (Lidar)	Digital aerial photogrammetry from NAIP imagery	Multi-band imagery from Sentinel-2 Satellite Imagery	Integrated Airborne Laser Scanning and Imagery based Remote Sensing
Anticipated Results	Accurate estimates of area-based and tree-based metrics for sample plots	Accurate estimates (1-m resolution) of forest metrics for riparian stands along entire stream network within target population.	Relatively accurate estimates (20-m resolution) of forest metrics for riparian stands along entire stream network within target population	Relatively accurate estimates (10-m resolution) of forest metrics for riparian stands along entire stream network within target population	See Alternatives 2, 3, 4
Statistical Inference	All FPHCP lands, depending on spatially balanced and representative sample design	Potential for wall-to-wall coverage of target population	Potential for wall-to-wall coverage of target population	Potential for wall-to-wall coverage of target population	See Alternatives 2, 3, 4
Strengths	Accurate measures of overstory and understory composition by RMZ widths. Can include channel physical characteristics	Accurate and unbiased estimates of forest metrics. Reliable methodology for change detection. High precision for delineation of lateral variability. Ground access unnecessary	Unbiased estimates of forest metrics. Simple to implement. Models maintained by agency (DNR). Ground access unnecessary.	Accurate and unbiased estimates of forest metrics. Models publicly available. Ground access unnecessary. Repeat data collection at 2-week intervals.	See Alternatives 2, 3, 4

Alternative Number	1	2	3	4	5
		Opportunity to team with other entities to acquire statewide data, allowing comparison of FPHCP conditions with those of other ownership and land use types.	Repeat data collection at 2-yr interval	Opportunity to team with other entities to acquire statewide data, allowing comparison of FPHCP conditions with those of other ownership and land use types.	
Weaknesses	Requires large spatial representative sample, Access restricted	ALS coverages may not be available for all areas within sample population during same year. Timing of data collection (leaf-on/off) may influence metric estimates and change detection	Images with shadows affect accuracy of estimates. Requires high resolution DEM for accurate metric modeling. Low precision for delineation of lateral variability in riparian conditions	Images with shadows affect accuracy of estimates. Requires high resolution DEM for accurate metric modeling. Moderate precision for delineation of lateral variability in riparian conditions. Requires model validation	See Alternatives 2, 3, 4
Cost	$$$$$, Relatively high due to labor intensive field work	$$$, Relatively low cost if public data available. If not, relatively high cost for data acquisition. Potential to share costs with other entities/programs in WA	$, Relatively low cost pending data availability from WDNR; might require partial CMER contribution in future	$, Relatively low cost Potential to share costs with other entities/programs in WA	$$$, See Alternatives 2, 3, 4

Potential Add-Ons

Overview of Potential Add-Ons

A memorandum to CMER from the Adaptive Management Program Administrator (AMPA) in April 2022 described a request from TFW Policy to consider the inclusion of add-ons to the scoping of the Extensive Monitoring Project that would be cost-efficient, including a specific request to evaluate stream-associated amphibian presence.

Three add-ons are proposed for consideration.

- **Amphibian Presence**
- **Quantifying the Spatial Extent Riparian Management under FP Rules**
- **Westside Type F Riparian Prescription Effectiveness Project, Follow-Up**

Details of Potential Add-Ons

Add-on 1. Amphibian Presence

An Overall Performance Goal under Schedule L-1 of the Forests & Fish Report (Appendix N of the FPHCP) is to "*Support the long-term viability of other covered species.*" In this context, "*other covered species*" refers to FP-designated stream-associated amphibians, namely, Coastal and Rocky Mountain Tailed Frogs (*Ascaphus truei*, *A. montanus*); Cascade, Columbia and Olympic Torrent Salamanders (*Rhyacotriton cascadae, R. kezeri, R. olympicus*); and Dunn's and Van Dyke's Salamanders (*Plethodon dunni, P. vandykei*). This add-on proposes to obtain eDNA samples in streams already being visited in the Extensive Monitoring Project.

Potential supplemental critical questions

- **S.1.A** What is the spatial distribution of FP-designated stream-associated amphibian occurrence across FPHCP lands? (Status)
- **S.1.B** How does the distribution of FP-designated stream-associated amphibian occurrences across FPHCP lands change over time and space? (Trends)

Purpose: Evaluate the spatial patterns of stream-associated amphibian distribution across FPHCP lands for FP-designated "other covered species," which includes 7 species of amphibians Establish current distributions and evaluate potential changes in those distributions over time.

Objectives: Establish the current spatial distribution of stream associated amphibians across FPHCP lands. Evaluate temporal changes in species distributions across the FPHCP landscape.

Understanding the current spatial distributions of stream-associated amphibian occurrence would provide some information relative to whether the Program is meeting the Overall Performance Goal to "*Support the long-term viability of other covered species"* (Appendix N of the FPHCP). Understanding the distribution and patterns of occupancy across the FPHCP landscape would be valuable to detect status and trends for species of interest. It would also benefit the Program by allowing contextual interpretation of the findings from other FP AMP research and efforts. For example, we know from the Type N Hard Rock Study (McIntyre et al. 2021) that stream-associated amphibian densities, particularly for Coastal Tailed Frog, declined in recently harvested Type N basins. Nonetheless, these species continue to exist throughout western Washington, including in basins that have been managed intensively for timber production for 200+ years, and with some basins having been harvested multiple times and under a complete lack of riparian protection. However, the added context of how those species are distributed across FPHCP lands and whether those distributions are changing over time and space would allow some inference about what this basin-level decline means for amphibian populations at the landscape scale.

The Best Available Science (BAS) review (Appendix A) supports the inclusion of eDNA as an appropriate cost- and time-effective method for inclusion in the Extensive Monitoring Program of the AMP to evaluate stream-associated amphibian presence to establish status and future trends of their spatial distributions. Alternatives, such as visual encounter surveys, offer a commonly utilized alternative to establishing stream amphibian presence, but this approach can be more inconsistent in terms of the effort required to establish occupancy (e.g., if you observe of all target species quickly, it can be cost effective, but if you have to survey longer to determine occupancy for one or more species the effort and cost become more variable). However, the program may may want to consider the complementary use of eDNA with other more traditional sampling approaches (e.g., animal surveys) to maximize obtain the most robust data while maximizing cost and time efficiencies (Beng and Corbett 2020). Most commonly, eDNA is used for detecting aquatic species through the collection and filtering of water samples. eDNA is most effective in establishing occupancy for a species. Options for using eDNA concentrations as a surrogate for abundance or density are also being explored; however, it is not clear when these methods may be validated for use in headwater stream habitats for the amphibian species of interest (note though that a current AMP supported effort is evaluating this in relation to abundance estimates and eDNA samples for study sites included in the Type N Hard Rock Study). The utility and accuracy of eDNA for detecting terrestrial salamanders (i.e., Dunn's and Van Dyke's Salamanders) has not been established and as such the Project Team recommends focusing on in-stream breeding amphibians (e.g., tailed frogs and torrent salamanders) in this proposed effort.

The Project Team recommends qPCR (versus metabarcoding) as the viable option for this effort given the specific species of interest and the added certainty. Since the three torrent salamander species and the two tailed frog species are distributed regionally, the Project Team recommends analyzing each sample for tailed frog (coastal *or* rocky mountain, depending on where the sample was collected), and torrent salamander (Columbia, Cascade *or* Olympic, again, depending on where the sample was collected). There would be opportunity to include giant salamanders (Cope's and/or Coastal; *Dicamptodon copei* and *D. tenebrosus*) if desired, however, these are not FP-designated amphibians. Note though that previous FP AMP efforts (e.g., Type N Hard Rock Study) have included giant salamanders in their evaluation of FP rule effectiveness as another stream-associated amphibian that occurs across much of the FPHCP landscape. Future developments may allow for the use of metabarcoding to detect the focal stream-associated amphibians, which would have the added benefit of being able to simultaneously sample for up to 30 species of interest as a part of eDNA monitoring. The Project Team recommends reevaluating this opportunity regularly to ensure the greatest efficiency and to maximize the utility of any eDNA monitoring effort.

The effort scoped herein assumes obtaining eDNA samples in streams already being visited and in coordination with field sampling designed to evaluate stream temperature and riparian functions/conditions as a part of the broader Extensive Monitoring effort. This would be the most time- and cost-effective approach for this add on. An effort specific to assessing amphibian distributions independently of another field effort would be much more expensive and is beyond the scope of what is proposed herein. However, if eDNA is selected for inclusion in the Extensive Monitoring effort, the Project Team recommends careful evaluation of existing data to carefully address the use of eDNA, especially as related to detection probabilities, and design the most effective sampling approach for the species of interest. Note that the preferred sampling design may integrate traditional amphibian sampling methods at a sub-set of sites to maximize the ability to reliably detect species occupancy and trends.

Budget cannot be fairly evaluated in advance of study design development as the numbers of study sites included in the Extensive Monitoring Project, the numbers of those sites appropriate for or selected for inclusion in the amphibian occupancy evaluation effort, and the number of samples desired for each site have not been established. However, to put the cost of this add-on in context, we have provided some budget estimates across a variable number of sites included (50, 100, 200) and across several options for the number of samples desired for each site (3, 6, 9). Cost for just the laboratory analysis of a single sample/filter for up to five species per sample is currently between $75 and $100 per sample, depending upon the assays used. For purposes of this estimate, we have used $85/sample. Under these assumptions, the cost of this add on could range from approximately $200,000 to $300,000 annually including supplies, cost and personnel time (though subject to change during study design development as details are finalized). Note that the effort to establish the status would likely be greater (desire to include all sites in the sample), whereas subsequent annual sampling could cycle through the sites for sample on a rotational basis (e.g., northwest, northeast, southwest, southeast Washington).

Add-on 2. Quantifying Riparian Management

Potential supplemental critical questions

- **S.2.A** What is the proportion and/or length of streams in FPHCP lands that have been managed under 2001 and later FP Rules? (Status)
- **S.2.B** How is the proportion and/or length of streams in FPHCP lands that have been managed under 2001 and later FP Rules changing over space and time? (Trends)

Purpose: The purpose of the proposed supplemental critical questions is to assess the extent of the application of the 2001 and later Forest Practices rules on streams within FPHCP-designated lands. This add-on would evaluate the current status (proportion and/or length) of streams that have been managed under these rules (Question S.2.A) and investigate spatial and temporal trends in their application (Question S.2.B) starting from about 2003 when the FFR rules were first applied. This information would provide critical insights into the effectiveness and evolution of forest practices in preserving aquatic ecosystems, informing adaptive management strategies and future policy development.

Objectives: Quantify the proportion and/or length of streams in FPHCP-designated lands that have been managed under FPHCP rules, providing a baseline for understanding the current implementation extent. Examine and characterize how the management of streams under FPHCP rules has changed over space and time, identifying patterns of implementation, regional disparities, and temporal shifts in application. Explore associations between management patterns and riparian characteristics patterns across the FPHCP landscape.

Implementation: This effort would require a combination of geospatial analysis, and data modeling. Geospatial data, Forest Practices Application (FPA) records, including land use records and stream delineation maps, could be integrated to calculate the proportion and length of streams under FPHCP management. Temporal trends could be analyzed using historical datasets spanning multiple years, combined with satellite imagery to detect land-use changes and management activity. Statistical techniques, such as regression analysis, could be applied to evaluate trends over time and across geographic regions. Personnel costs involve salaries for GIS specialists, data analysts, and time for stakeholder engagement and reporting. Data acquisition costs include access to satellite imagery, historical land-use records, and, potentially, proprietary datasets. Many of the costs associated with this work would be shared with addressing other project elements.

Add-on 3. Westside Type F Riparian Prescription Effectiveness Project, Follow-Up

Collect riparian data (e.g., remote sensing) at the Westside Type F Exploratory Study units in addition to the sample units required for the Extensive Monitoring Project to fulfill the recommendation from the Westside Type F Exploratory Report Final Six Questions Document, supported by the Project Team, CMER, and AMPA: "Riparian conditions and functions may change beyond the scope of this study (3- 6 years post-harvest), so we recommend adding these sites to the CMER Extensive Monitoring Program currently being scoped by RSAG" (Westside Type F Exploratory Study Findings Report, 2024). Furthermore, the existing ground-based stand inventory/condition data could complement the extensive monitoring and be used to ground-truth remote sensing data models and assessment of trends in riparian conditions and functions.

Potential supplemental critical questions

- **S.3.A** How have the riparian functions/conditions (that are observable using the remote sensing and field methods used in the Extensive Monitoring Project) changed in the Westside Type F Riparian Prescriptions Exploratory Study sites since the exploratory sampling in 2019? (Status)
- **S.3.B** How do the riparian functions/conditions change over time? (Trends)
- **S.3.C** How accurate are the selected remote sensing methods for measuring riparian stand conditions and change?

Purpose: The purpose of this potential add-on would be to monitor Westside Type F Riparian Exploratory study sites for substantial changes to their capacity to provide the key riparian functions of shade, wood recruitment, and sediment filtering. Continued monitoring of these sites was part of the original recommendation not to pursue an experimental study of the existing westside Type F/S riparian rules and instead investigate potential alternative rules that could "test active riparian management to accelerate recovery of DFC, promote large tree growth in riparian stands, and test how various thinning treatments affect forest health, fire potential, future climate change resilience, wood recruitment potential, etc." The Westside Type F sites would be in addition to the sample units otherwise required for the Extensive Monitoring Project and would not detract from the integrity of that sample scheme.

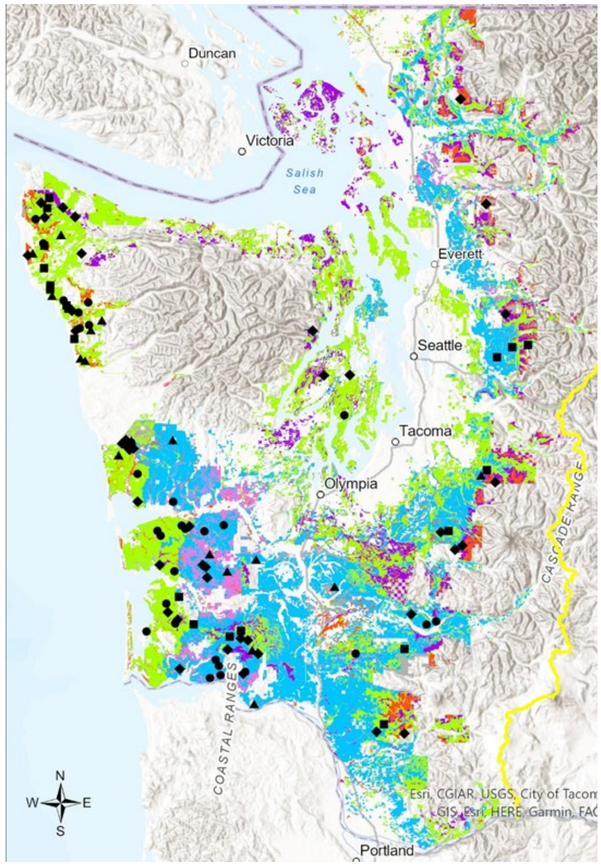

Figure 12. *Location of Westside Type F study sites.*

- **Objectives:** Continued evaluation of riparian functions and comparison with conditions reported in the Exploratory study for each site and summarized for all sites as was done in the exploratory study but limited to metrics that are measured under the extensive monitoring protocols.
- **Implementation:** Any remote sensing assessment would specifically include the riparian buffers and stream reaches from the Westside Type F Riparian exploratory study. Any of those sites that fall within a selected focus watershed (HUC) would be deliberately included in field data collection efforts. The intent would be to limit the data collected and analyzed to remote sensing stand-level data and field sample plot data, not full tree inventories as was done for the Exploratory study.

Recommended Approach

Long-term funding of the Extensive Monitoring Project is essential for understanding the overall impact of the FP Rules. All three potential add-ons complement the core critical questions proposed for this study, and we support incorporating them from a scientific perspective. However, they are not essential to answering the Extensive Riparian Status and Trends Monitoring Project critical questions and the inclusion of the add-ons should not jeopardize the long-term financial sustainability of the Project.

Stream Temperature

Alternative 5, Combine alternatives 3 & 4. Collect data and develop models in focus sub-watersheds as in Alternative 3, although perhaps for a smaller number of subbasins/clusters. Report temperature distributions within those for the focus sub-watersheds. Use the data and model relationships developed in conjunction with other data sources to develop more extensive regional models cooperatively with other entities to predict temperature metrics of interest across the state. As with Alternative 4, clip area of FPHCP lands from the stream temperature prediction maps to summarize data for this study's population of interest from the wider models (Table 5). Results from the higher-accuracy focus watershed models could serve as validation for the broader regional modeling.

Table 5. *Examples of reporting tables for stream or riparian criteria findings on FPHCP lands.*

HUC 12 Intensive	WQ Standards	Schedule L-1 Target	FPHCP Lands Modeled	WQ Standards	Schedule L-1 Target
% Stream length meeting criteria	XX%	XX%	% Stream length meeting criteria	XX%	XX%
% Stream length not meeting criteria	YY%	YY%	% Stream length not meeting criteria	YY%	YY%

Riparian Functions/Conditions

Alternative 5, Integrated Airborne Laser Scanning and Image-based Remote Sensing (FRIS or Sentinel-2) ALS and Image-based remote sensing data provides spatially accurate high-quality information for all desired attributes and on a schedule suitable for both status and trend monitoring. ALS would be used to establish a baseline assessment of riparian forest stand conditions (e.g., cover, height, composition, structure) and function potential (shade, LW supply) in the sample population; stratified by lateral width zones and aggregated at the reach, network, and landscape scales. Image-based forest metrics would be estimated for a representative sample population (common forest type) during same time frame as ALS data and used in comparative analyses to determine relative utility of image-based data for trend monitoring.

The combined remote sensing sources would provide the most cost-effective and dependable approach for repeat surveys as required for trend monitoring.

These recommended approaches readily lend themselves to teaming opportunities with other entities in the state for acquisition and development of statewide data sets and models.

Budget

The estimated costs for both sets of five alternatives (stream temperature and riparian conditions/functions) are presented below in relative terms with “$$$$$” indicating a relatively high cost, “$” indicating a relatively low cost, and a range between. Actual costs will vary depending on a wide-range of factors including data availability/costs, agency coordination/collaboration, personnel costs, etc.

Table 6. *Relative comparison of costs for Stream Temperature Monitoring Alternatives*

Alternative Number	**1**	**2**	**3**	**4**	**5**
Relative Cost	$$$$$	$$$	$$$	$$	$$$$

Table 7. *Relative comparison of costs for Riparian Function/Condition Monitoring Alternatives*

Alternative Number	**1**	**s2**	**3**	**4**	**5**
Relative Cost	$$$$$	$$$	$	$	$$$

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Appendix A - Best Available Science

Washington State

Cooperative Monitoring, Evaluation, and Research Committee (CMER)

Report

Extensive Riparian Status and Trends Monitoring Project, Best Available Science Document

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Contents

Introduction

The Extensive Riparian Status and Trends Monitoring Program – Riparian Vegetation and Stream Temperature Project (Extensive Monitoring Project, ExMo) is intended to evaluate how riparian prescriptions in Forest Practice Rules affect aquatic resources at the landscape-scale. The data generated from the Extensive Monitoring Project will be used to inform State and Federal regulatory agencies to determine if resource objectives and performance targets are being met consistent with the FPHCP and Clean Water Act requirements. This program will also help the Cooperative Monitoring, Evaluation, and Research (CMER) Committee prioritize, plan, conduct, interpret, and assess temporal and spatial scales of inference for other CMER studies and monitoring work.

This document provides information on the Best Available Science (BAS) that can be used to develop the scope of the project and eventually the study design. In this section, we investigate state-of-the-art landscape-scale environmental monitoring strategies and current methods for measuring and reporting riparian characteristics and stream temperature at various temporal and spatial scales. The BAS is organized into three topics: stream temperature, riparian functions/conditions, and amphibian distribution. We address direct sampling as well as stream temperature modeling and measuring riparian stand characteristics via remote sensing. This document serves as a companion to the Extensive Riparian Status and Trends Monitoring scoping document and presents previous work and background information used to develop alternatives.

Other Extensive Stream and Riparian Monitoring Efforts

CMER initiated an extensive riparian status and trends monitoring program for vegetation and temperature in Type F and N ("F" meaning Fish and "N" meaning Non-Fish) streams in 2007 through 2009 on 100m stream reaches identified using a Generalized Random Tessellation Stratified (GRTS) sampling design across FPHCP lands (Ehinger 2013, Washington State Department of Ecology 2019). A GRTS design is a form of spatially balanced probability sampling where surveys are based on a random probability selection process and can incorporate a rotating panel design. The program was suspended after the first round of data collection due to access limitations and budgetary constraints.

GRTS Sampling was developed by the United States Environmental Protection Agency (EPA) for use by the Environmental Monitoring and Assessment Program (EMAP), which collected field data from 1990 to 2006 (Olsen et al. 1999; Stevens and Olsen 2004; Stoddard et al. 2005). EMAP collected data in 14 western states in EPAs Regions 8, 9, and 10 and was designed to investigate the extent, conditions, and stresses of aquatic resources in western states. Sample locations for EMAP were also selected using a probabilistic sample design strategy aimed to advance the science of ecological monitoring and ecological risk assessment (Blair 2001). After the conclusion of EMAP-West, the National Rivers and Streams Assessment (NRSA) within the National Aquatic Resource Survey (NARS) program continued the monitoring efforts of aquatic resources throughout the country. These programs are housed within the EPA's Office of Water and help demonstrate the applicability of other extensive monitoring programs. The Washington State Department of Ecology initiated the Watershed Health Monitoring Program (WHM) in 2009 to carry on the EMAP-West work in Washington. The WHM uses a GRTS sample to assess stream status and trends across eight regions of Washington (Cusimano et al. 2006).

The United States Department of Agriculture (USDA) and the United States Forest Service (USFS) also have status and trends stream monitoring programs in the Intermountain West and Pacific Northwest.

The USFS runs the Aquatic and Riparian Effectiveness Monitoring Plan (AREMP) that characterizes ecological condition of watersheds and aquatic ecosystems in response to the Northwest Forest Plan (NWFP). The Forest Service has also used the PacFish/InFish Biological Opinion Monitoring Program (PIBO) to monitor stream and riparian habitats throughout the interior Columbia River and Upper Missouri River Basins. These two monitoring programs also use a random sample design when selecting sites for monitoring.

These programs have established positive track records that are important to understand when designing the scoping alternatives for the ExMo Project.

Measuring and modeling stream temperature and riparian stand conditions on a landscape scale

Remote sensing technologies paired with ground-based inventory measurements can produce a validated methodology for assessing forest riparian conditions across a large landscape like Washington state. There have been recent technological advancements in remote sensing technologies and stream temperature modeling techniques. These advancements will help with the development of an extensive riparian status and trends monitoring program. The acquisition and interpretation of remote sensing data related to topography and vegetative characteristics can provide the opportunity to inventory conditions across FPHCP lands. Technologies for riparian characteristics such as Airborne Laser Scanning (ALS), Digital Aerial Photogrammetry (DAP), and Satellite Imagery can be used independently or combined to estimate riparian stand characteristics. These technologies differ in spatial resolution, cost, and temporal scale meaning that certain resources may be more well suited for measuring certain riparian characteristics than others.

Direct stream temperature measurements (empirical data) provide a foundation on which models can be employed to describe stream temperature variation across the landscape. Stream temperature models like Spatial Stream Network (SSN) models and Generalized Additive Models (GAMs) have been validated and are continually being used and updated. SSN models and GAMs can be modified based on user defined parameters and generate an array of stream temperature metrics relevant to biological resources. Direct measurements of stream temperature are an important input necessary for both of these model types, and making use of available data will be necessary to maximize the utility and minimize costs of their use for extensive monitoring.

Stream Temperature

- Water temperature is a key indicator variable for aquatic environments and can significantly influence various aspects of aquatic life. Measured and modeled temperature can be used to develop reporting metrics that can help explain environmental conditions. The processes for sampling and modeling stream temperature have advanced in the last decade and will be a critical component of this project. Technology, data acquisition efforts, modeling, and interpretation methods have now matured to the point where we believe these methods, paired with ground-based measurements, can be used to answer critical questions of the Adaptive Management Program (AMP).

Direct Sampling

Direct measurements of stream temperature, whether temporally discrete or continuous, provide data for assessing stream suitability to support aquatic biota and status relative to water quality standards. Permanent stream monitoring stations and discharge gauging stations (e.g., discharge, gauge height, and temperature) are often managed by local, state, and federal agencies and can provide an abundance of historical and current data. The Washington State Department of Ecology freshwater monitoring unit, for example, manages multiple stream temperature and water quality datasets like the Freshwater Information Network and Freshwater DataStream while the United State Geological Survey (USGS) manages the National Water Information System. These data are publicly available and cover locations throughout the state. Data from these long-term monitoring stations could be used to develop or validate our models or add to our field-based monitoring.

Temperature can be measured directly instream using both permanent and portable temperature loggers. Temperature loggers can be deployed in streams to record continuous data. Due to their compact size and reliability, modern portable temperature loggers have already been applied to monitoring stream temperature in small, forested streams (Ehinger 2013, Ehinger 2019, Reiter et al. 2020, Swartz et al. 2020, McIntyre et al. 2017, Janisch et al. 2012). Continuous data loggers, which provide many instantaneous datapoints throughout a day, require some kind of data aggregation for assessment. Examples of aggregated metrics that can be developed from these data are maximum weekly maximum temperature (MWMT), number of days greater than 18 degrees Celsius, 7-day average of the daily maximum temperatures (7-DADMax), and average daily and monthly temperatures. Maximum seasonal (annual) temperature and the maximum of the seasonal 7-day running average of daily maxima are the most common and are the metrics for which current water quality regulations in Washington are written.

There are different point sampling schemes used for stream monitoring across a landscape. An opportunistic sampling scheme is a research method where the researcher dictates the sampling locations based on opportunistic factors such as presence of road crossings or volunteer landowners and is therefore not randomized. (i.e., easily accessible banks and bridges of streams for potential stream gauges). Randomized sampling selects samples from a population using a random selection process and ensures each potential sample location has an equal opportunity of being selected. These methods can accomplish similar goals depending on research questions and study design. Both the Freshwater Information Network and National Water Information System use opportunistic sampling schemes that represent basins across Washington State and US. These monitoring efforts collect data on water quality, streamflow, and temperature to establish trends in stream health over time. This is in contrast to other monitoring efforts that used a GRTS design, like the previously mentioned WHM and NRSA programs. The GRTS sampling technique developed by Stevens and Olsen (2004) offers a way to monitor and assess natural resources using a spatially balanced approach. This design enables sampling a population at a state or country-wide scale while reducing bias. Additionally, some types of stream temperature models benefit from targeted sampling schemes that maximize the predictive ability of those models (Marsha et al. 2018 and 2021). The appropriate sampling scheme depends on the questions being asked and the method employed to answer them.

Stream Temperature Models

The sampling schemes described above all entail measurements at discrete points or stream reaches that are distributed across a geographic area. Metrics from all those points are summarized to represent conditions and distributions of conditions over the landscape of interest. Recent advances in stream temperature modeling allow the estimation of temperatures at all points along a stream network, including those reaches that are not directly measured. Physical drivers of stream temperatures are well understood from energy balance studies conducted in 1960s and 70s (e.g., Brown 1969; Brown and Krygier 1970). Advances in information on spatial environmental conditions, at high resolution, in addition to new statistical techniques, are now making it feasible to generate accurate stream temperature models for large areas by leveraging limited direct stream temperature measurements with the added knowledge from those additional spatial data.

Multivariate Models

Multivariate stream temperature models are equations and programs that estimate stream temperatures at specific locations based on relationships among multiple input variables, especially shade, elevation, and volume of water. These models range from the very simple elevation/shade/Tmax nomograph used for some cases in Washington state forest practices (Forest Practices Board Manual Section 1 and Glass 2005) to sophisticated Spatial Stream Network (SSN) models that incorporate modern statistical routines and can include many input variables associated with each stream reach (Som et al. 2014).

Spatial Models

Spatial statistical models of all kinds employ multivariate statistics along with spatial and sometimes temporal autocorrelation relationships. Spatial autocorrelation is the tendency for measurements of an attribute to show a pattern of similarity relative to the Euclidean, or straight-line, distance separating them (Isaak et al. 2014). An example of spatial autocorrelation is the pattern of air temperature across a small geographical region where nearby locations tend to have similar temperatures, meaning that if you measure the air temperature or other environmental property at one point, the air temperature (or other property) at a nearby point is likely to be similar. This is an example of a positive spatial autocorrelation. Standard spatial modeling can take advantage of these autocorrelations to generate predictive models for environmental variables.

Spatial Stream Network (SSN) Models

A Spatial Stream Network (SSN) is a framework designed to analyze ecological data collected on stream networks and utilizes autocorrelation among datapoints along the stream network. These differ from standard Euclidean spatial modeling in that they make use of the fact that water and stream temperature flow along streamlines and data at points within watersheds are related along flow lines in addition to the straight-line distances among them. SSN modeling techniques and R language modeling packages developed over the past twenty years by statisticians and biologists with the EPA and US Forest Service Rocky Mountain Research Station (Ver Hoef et al. 2006; Pearse et al. 2020) have facilitated the use of this type of model for many biological factors associated with stream networks, but especially stream temperature, worldwide.

The combination of spatial data and assessment of autocorrelations among those data within an SSN is what makes SSN modeling a useful tool. Spatial data can be characterized in different ways. A 2-D coordinate system displays accurate locations of data points on a map while a network coordinate system displays the location of data points relative to each other. A dendritic ecological network (DEN) and SSN combine the 2-D coordinate system and network coordinate system to represent 2-D geographical data in a connected network (Peterson et al. 2013). The SSN model can leverage data from clustered measurement location that show the relationships among the branches of streams at their junctions. The characteristics of streams (e.g., longitudinal connectivity, flow direction, branched layout) makes them prime candidates for SSN application. The structure and water-driven continuity of streams influence the spatial relationships within a stream network. There are software packages like SSN for R that facilitate using SSNs for stream data analysis. These tools use network relationships, such as stream flow, upstream shade, upstream water temperatures, combined with euclidean spatial relationships for those variables (such as rainfall or geology) that do not follow streamlines to calculate the necessary spatial information and fit the models to specific data sets (Ver Hoef et al. 2014). Overall, SSNs are a powerful approach for ecologists studying streams. By accounting for the unique spatial structure of stream networks, SSNs provide more accurate and insightful analyses of ecological patterns and processes in these vital ecosystems. Fuller et al. (2021) expanded on SSN model predictions by comparing thermal infrared imagery (TIR) data with SSN model predictions. The study also explored how landscape features, like tributary junctions, influence temperature variations. TIR provides highly detailed data on specific stream reaches, while SSN models offer broader predictions for entire networks. Temperature trends agreed for TIR and SSN predictions throughout 81.7% of the mainstem river kilometer reaches. SSN models provide a spatially extensive prediction for thermal diversity across entire networks including heavily shaded headwater streams.

Current SSN stream temperature modeling approaches conceptually refine the weighting that is applied to instream temperature measurements beyond the simple weighting scheme used in randomly distributed stream sampling approaches, such as that used by the previous extensive stream temperature monitoring effort conducted by CMER in 2008-2009 (Ehinger 2013, Washington State Department of Ecology 2019). That effort applied equal weight to all temperatures measured within each of the three project strata: Eastern Washington Type F streams; Western Washington Type F streams; and Western Washington Type N streams. Effectively, the data from 150 temperature measurement locations were weighted only by the stream type and the side of the Cascade Crest – a very coarse weighting strategy. Developing regional models within Washington that incorporate physical factors demonstrated to affect stream temperature allows the development of far more appropriate weights to assign to measured temperatures and to apply them to stream lengths with conditions similar to those at the measurement locations. By comparing modelled stream temperatures to those of direct measurements one can test the accuracy of a model and therefore determine appropriate weighting. Moreover, the relationships discovered between driving physical factors (geology, climate, slope, elevation, etc.) and stream temperature through the model mean better temperature predictions can be made for locations with conditions that do not exactly match those at measured locations, based on sound, proven physical relationships.

The first large-scale application of SSN modeling was the NorWeST program. The USFS Rocky Mountain Research Station compiled the NorWeST database from which they developed the NorWeST model and SSN modeling tools with the EPA and other researchers. The NorWeST database compiled all publicly-available stream temperature data from the northwestern United States as of 2014. This database is available for use but is not updated.

The stream temperature data in the NorWeST database were used to develop a series of spatial stream network models to generate historical and future models of August mean temperatures in 1-kilometer stream reaches for the western US. From the solicited data, August temperatures were queried to create an average August temperature metric (AugTw). The AugTw metric incorporates a number of spatial and temporal covariates (elevation, slope, lake %, glacier proportion, annual precipitation, northing coordinate, base-flow index, drainage area, riparian canopy, air temperature, discharge, and tailwater occurrence) (Isaak et al. 2017a). The three subregions for Washington had validation accuracies (R^2) of 0.90 and Root Mean Square Prediction Error (RMSPE) of 1.0^oC (Isaak et al. 2017a). Application of the NorWeST modeled temperature data has been diverse. The number of data gaps filled in by modeled temperatures enabled the classification of stream regimes based on thermal metrics in the Western United States. The thermal regime classes developed show how different metrics interrelate and contribute to overall regime variation (Isaak et al. 2020).

The NorWeST model also includes 36 climate scenarios which allows researchers to assess the potential impact of future climate change on stream temperatures (Isaak et al. 2017a). Aquatic species exhibit distinct thermal boundaries. Modeled temperatures have been used to estimate climate vulnerability of aquatic species (Al-Chokhachy et al. 2016, Anderson et al. 2019, Rubenson and Olden 2020). Conservation planning can also be assessed with the projected stream temperatures. By combining temperature data with habitat occupancy models, stream segments can be identified where conservation initiatives are predicted to be most valuable (Isaak et al. 2017b).

The NorWeST stream temperature model data, while a valuable resource in itself for large-scale regional questions, does have some limitations to consider. The NorWeST model was an initial, coarse effort to develop such models across the Pacific Northwest (Isaak et al. 2014; Isaak et al. 2017a). The data provide temperature predictions at 1-kilometer intervals. This means it does not capture smaller scale variations in stream temperature that can be caused by local factors. The resulting temperature data are based on a statistical model. While that model was built from a large amount of real-world data, there is still inherent uncertainty in any model's prediction.

Although the NorWeST model was demonstrated to have high accuracy on a broad scale for the one temperature metric modeled, a Chehalis Basin/Washington Coast study effort showed that the NorWeST wide-scale model did not accurately predict temperatures at the smaller, watershed-scale (Winkowski 2023). The NorWeST model had 2.7^oC cooler stream temperature predictions in the Chehalis Basin than temperatures that were observed. Modeled temperatures in the Coastal Salmon Recovery Region followed a similar trend where over 80% of NorWeST predictions were cooler than observations in the region (Winkowski 2023). The Washington Coast study team subsequently worked with the NorWeST SSN team to develop a series of regional models for the Chehalis River basin, north coastal watershed areas, and Willapa Bay based on an enhanced set of input temperature monitoring and physical data, which they then validated (Winkowski 2023). They also compared the sub-regional models with one using all the data for the Washington coastal area and used that to make predictions of future stream temperature responses to hypothetical climatic variations. Winkowski (2023) found that the overall coastal Washington regional model predicted temperatures as well as the two best subregional watershed models and much better than the Willapa Bay model and so used the one regional model for all further analyses. They did not test the performance of sub-regional watershed models on neighboring watersheds to assess how extensible they were.

Generalized Additive Models (GAM)

A generalized additive model (GAM) is a statistical technique used for modeling relationships in data. A GAM is an extension of regular linear regressions that can capture more complex patterns, especially when those patterns are not straight lines (Wood 2017). The GAM can capture non-linear relationships and model relationships between variables that curve in different directions making them useful for real-world data where things are rarely perfectly linear. GAMs can help explain complex interactions and analyze how the effect of one variable on the outcome depends on another variable. GAM models lack the inherent spatial component that SSNs like the NorWeST model contain. Stream temperature predictions can be made at discrete locations, but further spatial modelling will be required to estimate continuous stream temperature data.

Additional stream temperature models have been made since the inception of the NorWeST model. Siegel and Volk (2019) developed daily mean temperature models (average error less than 1.54^oC) for four different Columbia River tributaries in the Pacific Northwest. They compared simple linear models and general additive models (GAM). GAM models performed better overall, especially in larger watersheds. Accuracy of temperature predictions increased when using aggregated monthly means rather than daily means. Smaller, simpler watersheds (drainage 474-1300 km^2) produced more accurate predictions and may require fewer sensor sites. Siegel et al. (2022) continued to develop stream temperature GAM models for daily means. This model included a flexible lagged air temperature variable. The models demonstrated that stream temperatures in snow-dominated sites had longer air temperature lag periods and stronger warm season buffering compared to rain-dominated sites. Watersheds with greater snowpack are likely to see better climate variability buffers than those that lose or have reduced snowpack. Daily Pacific Northwest stream temperature models were expanded to include different covariates. Antecedent air temperature and mean area-standardized flow covariates were added to another novel model to capture the complex spatiotemporal patterns of stream temperatures (Siegel et al. 2023). This model divided reaches into rain, snow, and transitional reaches based on average snow accumulated in drainage area (rain <20mm, transitional 20-100mm, and snow >100m). The daily model performed well with a Root Mean Square Error (RMSE) of 1.76 and MAE of 1.32^oC. This model, similar to Siegel et al. (2022), showed streams with greater snowpack influence had slower responses to change in air temperature compared to rain-dominated reaches, even after snow had melted.

Laanaya et al. (2017) assessed several modelling techniques for predicting water temperature. The study compared four models: generalized additive model (GAM), logistic regression, residuals regression, and linear regression. They evaluated these models using data on water temperature, air temperature, and river discharge. The GAM model outperformed the others in terms of accuracy (RMSE) and capturing non-linear relationships between water temperature and the other factors. Linear regression was the second-best model, followed by residuals regression and lastly logistic regression. Overall, the study suggests GAM is a better choice for modelling water temperature due to its flexibility in handling complex relationships. Generalized Additive Models were used to predict thermal regime changes in dammed rivers fed by snowmelt in Australia (Coleman et al. 2021). The model considered factors influencing stream temperature such as air temperature, flow rates, and characteristics of rivers unregulated by dams. The GAM predicted temperatures were compared to collected temperatures to assess model effectiveness. Mean daily GAM temperatures were modelled with a RMSE of 1.30^oC showing the models comparability and reliability. Georges et al. (2021) implemented GAM models to understand how water temperatures fluctuate around extreme temperature events in streams. They used temperature sensor data collected every 10 minutes over 7 years at 94 locations across a specific hydrologic network. The GAM model successfully captured temperature changes around extreme events. Their combination of GAMs and differential equations provided a new way to analyze stream heating dynamics around extreme temperature events.

Mechanistic Models

Mechanistic models predict stream temperatures based on understandings of the physical processes that result in water heating. These models calculate energy flows using stream flow mechanics and thermodynamic balance equations for given locales. Like the network models above, mechanistic models also rely on the input of multiple geomorphic, hydrologic, vegetative, and other spatial parameters to condition the energy balance and other mechanistic processes they model. However, rather than relying simply on correlations among those parameters, mechanistic models use mathematical equations to simulate known physical processes. Use of mechanistic models requires an understanding of the underlying processes being modeled to select the appropriate input and assess reasonableness of model results.

Mechanistic models that predict maximum stream temperatures have been around since the 1970s. These models are based on early thermodynamic energy balance studies on forest streams conducted by George Brown and his colleagues (Brown 1969; 1970; 1972). These models have been elaborated on over the years and are still in general use. TFWTEMP (Doughty et al. 1993) is cited in the Washington Forest Practices Board Manual Section 1. QUAL2 is a series of models currently used by the Department of Ecology. Originally developed in the 1980s for the US EPA by Brown and Barnwell (1987), it has evolved in sophistication over the years since (Chapra et al. 2008). QUAL2Kw models many water quality parameters in addition to water temperature and requires selection of appropriate process parameters and input data. The model's current iteration is QUAL2KW, v. 6 (https://ecology.wa.gov/Research-Data/Data-resources/Models-spreadsheets/Modeling-the-environment/Models-tools-for-TMDLs). Version 6 can predict water temperature and other water quality constituents in non-steady, non-uniform stream flows and for the input of up to a year of time-varying input data. PtWQ is a simplified version of QUAL2Kw that can predict water quality at a single reach using energy balance equations based on reduced parameter inputs (available at the same web site as above).).

Visualizing Ecosystem Land Management Assessments Model (VELMA)

The US EPA's Visualizing Ecosystem Land Management Assessments (VELMA) Model assesses the effectiveness of different environmental scenarios to heuristically evaluate water quality, water quantity, and erosion responses in receiving water bodies. VELMA considers factors like rain, runoff, impervious surface, and soil properties to track water flow and contaminant movement. One application is to evaluate how green infrastructure improvements can reduce toxic loading, movement of nutrients such as nitrogen, and inputs of other point and non-point pollution. The model relies upon assumptions of vegetation, soil, and water response to various management practices across different spatial and temporal scales. VELMA can be used to consider the impact of climate change on the effectiveness of these green infrastructure solutions.

The VELMA model has been applied to forested landscapes to estimate effects of harvest on stream hydrology and nutrient cycling. Abdelnour et al. (2011) investigated how the amount of forest harvest and its distribution across a catchment affects streamflow. They used the VELMA model to simulate different harvest scenarios in the Pacific Northwest. The results through different harvest scenarios, ranging from a 2% to 100% harvest, showed that the amount of streamflow increased proportionally to the amount of forest harvested. In the 100% harvest scenario stream discharge initially increased by about 29% and returned to pre-clearcut levels within 50 years. Another modeling effort, with a standardized 20% harvest, resulted in greater increases in streamflow when harvest was closer to the stream channel compared to harvests further away. Abdelnour et al. (2013) also studied how harvesting trees in a Pacific Northwest forest catchment changes the cycling of carbon and nitrogen. VELMA was used to simulate forest conditions before and after a clear-cut harvest compared to a natural disturbance. The model's results showed that before harvest losses of carbon and nitrogen from the forest were minimal. After harvest losses increased to approximately 20% higher than the control values for five years post-harvest. The increase is attributed to reduced uptake of nitrogen by plants, faster decomposition of organic matter in the soil, and wetter soil conditions. For our purposes, the VELMA model could be used to fill in data gaps such as streamflow for SSN model. VELMA outputs influence stream temperature, so the combination of VELMA and other models may be an effective way of modeling stream temperature.

Model Discussion

Comparative research between stream temperature models helps highlights the characteristics of the models previously discussed. An array of commonly used models, including spatial stream networks and generalized additive models, were compared to assess their ability to predict stream temperature in different watersheds in Idaho (Holthujzen 2017). The accuracy, drawbacks, and computing time was compared among these different modelling techniques. General additive models processed 50,000 stream predictions the fastest at 14 seconds, while the SSN took the longest at 10 days. The pre-processing of spatial data necessary for the SSN adds to its complexity and processing time. The study showed the highest overall accuracy of stream temperature predictions was the SSN model based on root mean square error (RMSE) values (Holthuijzen 2017).

Turschwell et al. (2016) ran a similar model comparison between SSN and other models to predict stream temperatures in a watershed in Australia. The objective was to determine when to aggregate and when to not aggregate data based on daily temperature loggers to show temporal variability in addition to spatial. Data loggers were deployed in 60 sites capturing 80 days’ worth of data in the summer. Prediction sites were generated in 50m intervals along the stream. While some aspects of temperature, like overall warmth and duration of warm periods, can be accurately predicted using aggregated data, other aspects, like the frequency of temperature fluctuations, require daily temperature data. Processing time for aggregated data was much shorter than it was for daily models. SSN models provided more accurate predictions compared to the other models tested. Although the findings of Turschwell et al. were specific to SSN models, the results are relevant to any type of sampling or modeling effort.

The stream temperature models listed above each have their own unique advantages but also have limitations. SSN models require an abundance of high-quality data, intensive data preparation from both GIS and other statistical software, expertise in statistical understanding of the models, and also a high computational demand. GAM models tend to assume that the effects of different predictor variables on the response variable are additive, meaning, the model cannot directly capture complex interactions among variables. GAM model flexibility can lead to overfitting when provided with limited data. The VELMA model also requires an abundance of fine-scale high quality data to generate accurate results. Like all models, VELMA has inherent uncertainties which arise from simplifications, data limitations, and inherent variability of natural systems. All of these models are limited to some degree by data gaps, quality of data, computational demands, and resolution of data. Quality and resolution of input data, including hydrography, are of crucial importance but have seen tremendous improvements in recent months with the availability of high-resolution lidar and aerial imagery statewide.

Riparian Stand Conditions

Riparian forest stands are structurally diverse environments (e.g., height, density, species composition) with spatially large vertical and horizontal variability (Villarin et al. 2009; Richardson and Danehy 2007). Therefore, quantifying stand attributes can be challenging given the spatial and temporal scale necessary for inference. Below we review both ground-based and remote sensing methodologies that have been commonly used to inventory riparian stands along Type F and N streams.

Ground-Based Inventory

A ground-based inventory of riparian timber stand structure and composition is a reliable and repeatable methodology for estimating area-based metrics (e.g., density, age, basal area, mortality), tree-based metrics (e.g, species, DBH, total height, live crown height) and RMZ lateral distribution relative to the stream channel. Typically, sampling of riparian stands is implemented with either circular plots or rectangular strips of various sizes and spacing (e.g., fixed, random distances between plots). Randomly located strip plots (73 m long) perpendicular to the stream were used by CMER to assess the range and distribution of riparian stand conditions for the Eastside Type F Riparian Assessment Project (Bonoff et al. 2008). The plot data facilitated estimates of stand characteristics (species, DBH, density) by regulatory zones widths and spatial inference to forest stand types. In another CMER study, large rectangular plots (92 m long by 18 to 46 m wide), randomly selected, were used to assess post-harvest riparian stand conditions, riparian ecological functions and desired future condition (DFC) potential for the Westside Type F Riparian Management Zone Exploratory Study (Black et al. 2024). This plot design enabled summaries of riparian attributes for the core, inner, and outer zones of RMZ's as well as landscape-scale inference. The USDA Forest Service implemented a status and trends monitoring program that includes strip plot sampling to assess riparian stand characteristics (Archer et al. 2008). The sample plots are located along streams in randomly selected study watersheds and are sampled every five years in a large rotating panel sample design. Each of these monitoring studies implemented different methodologies and utilized plots of different size and configuration. Therefore, it is difficult to directly compare the accuracy of each method to quantify riparian stands attributes (e.g., density, DBH, basal area) . Consequently, Marquardt et al. (2010) examined a range of circular and rectangular plot configurations and compared the data for each method to study areas that had a compete stand inventory including tree mapping. They found that narrow (3.6 m wide) rectangular strip plots (perpendicular to stream) out-performed several other field inventory methods for estimating tree height, basal area (BA) and stand density in second-growth riparian stands of western Oregon.

With all ground-based assessments the variability of attribute estimates is dependent on sample size. For example, the findings from the Eastside Type F Riparian Assessment Project were used to estimate variability of the sample population (Bonoff et al. 2008). The analysis found that estimates of average numbers of trees and basal area within the regulatory zone were within +/- 14% and 13% of the mean, respectively. Given these data, they estimated the sample size would have to be increased from 103 to 174 sites to achieve a sampling error of +/- 10% for basal area and 220 sites for stand density (SAGE

2008). They did not evaluate how estimates may vary for other attributes (e.g., tree height, species), for smaller areas (e.g., core, inner, outer) within the RMZ, or for specific stand types. Bonoff et al. (2008) noted that other attributes and categories (ecoregion, land owner) could be assessed using traditional sampling techniques, but inference would be limited due to reduced sample size for finer levels of detail.

Remote Sensing

Remote sensing data with field validation is an approach for assessing riparian forest conditions at the spatial scales (local reach, basin, landscape) utilized in extensive monitoring. Moskal and Cooke (2015) compared aerial imagery, Airborne Laser Scanning (ALS, also referred to as airborne LiDAR data), and satellite sensor data products based on published studies and concluded that data from ALS and the National Agriculture Imagery Program (NAIP) were good candidate data sources-- ALS because of accuracy and reliability to quantify stand attributes, and NAIP because of the spatial/spectral capabilities that are similar to high resolution satellite data, but available at lower cost. Moskal and Cooke (2017) concluded that ALS technology is the most efficient tool for hydrological mapping and most suitable for mapping height and modeling basal area and DBH of timber in riparian forests. Similarly, Tompalski et al. (2017) demonstrated that ALS data provided detailed and accurate digital terrain models (DTMs) under forest canopy, which in turn enabled the characterization of detailed stream networks, stream properties (width, gradient, shade), and associated vegetation characteristics (height, cover) in adjacent riparian ecotones of coastal forests in BC, Canada. Moskal and Cooke (2017) concluded that ALS data was not suitable for evaluating conifer-deciduous classification and recommended further research into fusion of ALS with NAIP imagery to improve the classification of stand type. Some researchers have reported that ALS is not suitable for species identification (Stoddart et al. 2023) but others have demonstrated high classification accuracy (88%) of conifer-deciduous stands using intensity metrics (i.e., laser beam return strength varies by reflectivity of vegetation) and structural features (Orka et al. 2009, Li et al. 2013).

The WDFW is using 4-band NAIP imagery (1-m resolution) to map land cover (e.g., trees, shrubs, bare ground, buildings, roads and visible surface water) and land cover changes over time (Pierce 2015; n). The mapping is facilitated by object-based image analysis (e.g., eCognition software) which uses homogenous groupings of pixels to define landscape features and cover classes. Random Forest classification and accuracy optimization techniques were used in repeat surveys to detect changes such as tree canopy loss and impervious surface increase due to land development (builds and roads).The recent availability of digital aerial photogrammetry (DAP) and the creation of image-based point clouds from NAIP stereo imagery (4 band RGB-NIR, collected at 0.6 m spatial resolution) have emerged as an alternative data source to ALS for three-dimensional characterization of forests. Studies in coastal coniferous forests of WA and BC compared ALS to DAP and found good similarity between area-based metrics (e.g., height, BA, volume) from the two data sources and that accuracy of modeled metrics generally improved with increasing canopy cover (White et al. 2015, Strunk et al. 2020). Another DAP study to assess forest structure change in the Colville area found that canopy cover, dominant height, and a canopy clumping index were reliable DAP metrics, in comparison to ALS, for describing forest structure (Saberi et al. 2022). Creasy et al. (2021) demonstrated the use of DAP to characterize forest structure through the detection of trees and tree groups in open-canopy ponderosa pine forests. The WDNR is now using DAP from 2019 NAIP to model area-based (20 m resolution) forest metrics statewide for the Remote-Sensing Forest Resource Inventory System (RS-FRIS; Gould and Ricklefs 2021). Higher resolution mapping is feasible with NAIP imagery but requires new modeling for estimating forest metrics (e.g., Khatri-Chhetri et al. 2024).

Satellite remote sensing technology (e.g., Landsat) has proven useful for many applications including land cover classification change detection, and resource monitoring (Banskota et al. 2014, Hansen et al. 2013). Since the launch of Landsat in 1972, new satellites (commercial and non-commercial) offering higher spatial and temporal resolutions have been launched . The Sentinel-2 launch in 2015 by the Copernicus Program of the European Space Agency has proven favorable due to the higher spatial (10 m) and temporal (5 days) resolution, greater multispectral capabilities, and low cost (Phiri et al. 2020). For example, Fang et al. (2023) examined the accuracy of Sentinel-2 derived forest metrics and reported the relative root mean square errors of 17.9%, 21.0%, and 23.0% for estimates of canopy cover, DBH, and tree heights compared to field plots. Similarly, Tamiminia et al. (2024) integrated Sentinel multispectral imagery with a space-based LiDAR system, Global Ecosystem Dynamics Investigation (GEDI), to generate a 10-m wall-to-wall canopy height map for coniferous forests in New York with a mean absolute error of 2.02 m. These and other studies show that the use of Sentinel-2 data with machine-learning classifiers can produce relatively high accuracies for canopy height, forest inventory, forest health indicators, species identification and subcanopy light regime (Schwartz et al. 2024, Tamiminia et al. 2024, Fang et al. 2023, Bhattarai et al. 2021, Blickensdorfer et al. 2024, Stoddart et al. 2023).

Remote Sensing Comparisons

A summary of the remote sensing data resolutions and assessment capabilities by type is shown in Table 1. This comparison shows that ALS provides the most accurate measures of forest structure (i.e., cover, height, crown width) and produces the most accurate estimates of forest inventory metrics. Both DAP and satellite data can provide effective measures and estimates of forest metrics pending the availability of an accurate Digital Elevation Model (DEM) for developing digital surface models (DSM). Also, the spectral capabilities of DAP and satellites facilitate accurate conifer/deciduous classification, and the additional multispectral/temporal capabilities of satellites facilitate species identification and some aspects of forest health assessment.

The utility of ALS for assessing forest metrics depends on the availability of reliable inventory models for different forest types. Currently, reliable models that are applicable across a range of forest types are limited and more research is needed to develop standardized toolkits capable of generating consistent and accurate data products at local and regional scales (Goodbody et al. 2024). Further, the development of new models is problematic because the modeling must be based on the availability of representative field data that are collected within the timing of ALS acquisition (Cooke and Devine 2020). Because the existing high-quality ALS was derived over several years (i.e., 2017 – 2023) and the acquisition timing differs by location, the availability and potential development of reliable inventory metrics may be limited for certain regions. Further, the high acquisition cost of ALS creates uncertainty about the timing of future surveys; a key concern that will need to be addressed for planning trend monitoring. In contrast, statewide l DAP (potentially biannual) and high-frequency Sentinel-2 surveys facilitate inventory modeling with temporally suitable forest plot data (past and future).

The spatial resolution of remote sensing data is important for accurately delineating location-based features (e.g., channel network, RMZ boundary, location of harvest units and roads). Additionally, the location and lateral (i.e., distance from stream edge) and longitudinal distributions of riparian forest characteristics (e.g., height, cover) are very important for assessing ecological function potential (i.e., large wood input, shade, litter fall) which is inversely related to distance from the channel edge. The high resolution of ALS (1-2 m pixel) is best suited for spatial delineation and facilitates assessing function potential by RMZ zone category (e.g., core, inner, outer) or for any lateral-width-band (e.g., 10 m, 20 m, 30 m from stream edge). The vertical resolution of ALS is very important for producing accurate DEMs and for deriving height-based metrics from ALS or from image-based point clouds that rely on ALS-derived DEMs. A concern for trend monitoring is the vertical accuracy of DEMs used to make comparisons among vegetation metrics that are derived from multitemporal surveys and from different sensors. For example, Viedma (2022) compared low-pulse density ALS to that from high-pulse density ALS and found the vertical error of DEMs ranged from 0.02 to −2.09 m with RMSE ranging from 0.54 to 2.5 m. After correction of the DEM data, Viedma (2022) found the vertical error of DEMs dropped significantly and changes in vegetation height were decoupled from vertical errors of DEMs.

The 10-m and 20-m pixel scales for satellite and DAP, respectively, can only approximate spatial delineation of stand characteristics because the metric estimates are derived from point data summarized at the pixel scale. Consequently, the stand composition within a 30-m wide buffer monitoring area may be characterized by a subsample of pixels that can occur partially over the stream, within the buffer, and partially outside the zone of interest. The latter may be suitable for characterizing riparian composition over an entire basin but less suitable for assessing the lateral distribution of riparian conditions and functions. For example, Saberi et al. (2022) found that the current DAP products were less reliable for detecting small changes across small areas but reliably identified large changes across the landscape. Comparison of vegetation height metrics among multitemporal DAP or satellite surveys would need to consider the accuracy of DEM height data, as noted for ALS.

Making a decision about an appropriate data type for trend monitoring requires identification of appropriate time intervals for repeat surveys. The time interval between surveys must be long enough for changes in riparian stands to be detectable by remote sensing and long enough for changes (e.g., cover, height, density, composition) to occur. Consequently, detecting change requires that the magnitude of change is greater than the horizontal and vertical accuracy of the remote sensing data type (Hopkinson et al. 2008). As shown in Table 1, ALS clearly has the highest spatial resolution and is the default DEM source for developing image-based point clouds. Therefore, ALS data are increasingly being used to provide accurate and up-to-date information to quantify stand growth, changes in biomass, stand structure, and effects of fire over large area. For example, Hudak et al. (2014) demonstrated that repeat ALS surveys (six-year interval) accurately quantify spatially explicit biomass and carbon dynamics in managed mixed conifer forests of northern Idaho. McCarley et al. (2017) used multi-temporal (three-year interval) ALS along with Landsat Thematic Mapper to quantify the effects of wildfire on canopy cover and forest structure for the 2012 Pole Creek Fire in central Oregon. Similarly, Chamberlain et al. (2021) used two ALS datasets((separated by ten-year interval) to show how different forest restoration prescriptions led to changes in the horizontal and vertical structural complexity (i.e., increased canopy height, increased regeneration density, reduced canopy cover, and decreased complexity of canopy patch edges [fractal dimension index]) of conifer stands in the Ellsworth Creek Preserve of southwestern Washington.

DAP and satellite imagery are being used for change detection. For example, Goodbody et al. (2018) demonstrated the utility of DAP to accurately and reliably provide highly detailed spatial, spectral, and structural information on forest regeneration in western BC, Canada. Saberi et al. (2022) used DAP to measure changes in the proportions of forest structure classes in the Colville National Forest over four years. Xu et al. (2023) used Sentinel satellite data for monitoring seasonal changes in the area of riparian zones surrounding the Three Gorges Reservoir, China.

***Table 8**. Description of remote sensing types and associated capabilities for assessing riparian forest stand characteristics.*

	Remote Sensing Type		
Attribute	**Airborne Laser Scanning (ALS)**	**Digital Aerial Photogrammetry (DAP)**	**Sentinel-2 satellites**
Description of Data			
Source	•WDNR ALS Portal •https://www.dnr.wa.gov/ALS	•WDNR GIS Open Data (FS-FRIS) •https://data-wadnr.opendata.arcgis.com	•Copernicus Prog, European Space Agency •https://sentinel.esa.int/web/sentinel
Cost	•2023 flights by NV5 $370/ac	•Available to State agencies at no-cost, subject to change	•Publicly available no/low-cost
Data type	laser scanning	red-green-blue (RGB), near-infrared (NIR)	•RGB and NIR, 10m •other multispectral products, 20m to 60m
Temporal resolution	•Existing data 2017 - 2023 •Repeat surveys not scheduled	•Existing data 2021 •Repeat survey to-be-determined; potentially every two years(?)	•Existing 2015 to present •Repeat every 5 days
Spatial resolution	1m x 1m	20m x 20m	10m x 10m
Forest Stand Assessment Capability			
Stand location	Direct measurement	Direct measurement	Direct measurement
Cover	Direct measurement	Direct measurement	Direct measurement
Canopy height	Direct measurement	Effective estimate	Effective estimate
Inventory metrics	Accurate* estimates of: height, BA, DBH, density, and volume	Effective* estimates of: height, BA, DBH, density, and volume	Effective estimates of height, DBH

Metric modeling	User develops	Source agency supported	User develops
Structural complexity	Direct measurement	Effective estimate	Effective estimate
Conifer/deciduous	Effective estimate	Accurate estimate	Accurate estimate

**Accurate indicates measurement/estimates are comparable to field plot data. Effective indicates measurement/estimates are suitable for area-based metric estimates (e.g., BA/ac)*

Modeling Future Conditions

- Models can be used to assess sensitivities to various factors and can be used to project conditions in the future under hypothetical future conditions. For example, various stand growth models (DFC [organon], FVS, CRYPTOS, FPS etc.) could be used to predict future changes in canopy height, density and basal area of riparian stands. Such data could inform questions relating to riparian ecological functions (shade, large wood recruitment). For example:
- How long before stands may improve shade or large wood potential to achieve a desired target?
- What stands are likely or unlikely to achieve desired targets and where?
- What stands may benefit from active management schemes (thinning, gaps) and how long will it take for improvements to occur?
- How does climate change influence growth and associate functions, and where?

Stream-Associated Amphibian Distribution

The FPHCP is written to protect salmonids, 48 other fishes and seven species of stream-associated amphibians : Coastal and Rocky Mountain Tailed Frogs (*Ascaphus truei* and *A. montanus*), Cascade, Columbia, and Olympic Torrent Salamanders (*Rhyacrotriton cascadae*, *R. kezeri*, and *R. olympicus*), Dunn's Salamander (*Plethodon dunni*), and Van Dyke's Salamander (*P. vandykei*). An Overall Performance Goal under Schedule L1 of the Forests and Fish Report (Appendix N of the FPHCP) is to "*Support the long-term viability of other covered species.*" In this context, "*other covered species*" refers to those listed stream-associated amphibians. TFW Policy expressed interest in including monitoring for stream-associated amphibians, specifically as a cost-efficient add-on to the broader project goals, as a key resource as a part of the Extensive Monitoring Project effort under the FP AMP via the AMPA's April 2022 memo to CMER.

Among vertebrates, herpetofauna (e.g., amphibians and reptiles) have the highest proportion of declining species worldwide (Alroy 2015, IUCN 2016, Stuart et al. 2004). More locally, amphibian populations have experienced declines and range contractions as a result of disease, competition with introduced species, and habitat degradation and conversion (Sparling et al. 2001, Stuart et al. 2004). Stream-associated amphibians are uniquely adapted to the physical conditions of headwater streams, including substrate composition (Dupuis and Steventon 1999, Grialou et al. 2000, Stoddard and Hayes 2005) and water temperature (Bury 2008, Pollett et al. 2010), both of which may be influenced by forest practices (McIntyre et al., 2021).

An effort that would allow the AMP to evaluate the current status and future trends for stream-associated amphibians occupancy and/or abundance could be added to the proposed Extensive Riparian

Status and Trends Monitoring Project. While advances are being made in techniques for assessing species abundance through eDNA sampling, at this time, eDNA results are most reliably indicative of presence or occupancy for stream-associated amphibians (Breton et al., 2022). Environmental (e)DNA sampling for stream-associated amphibians is one approach for easily evaluating species occupancy across the landscape of interest and is reasonable to consider in tandem with the broader Extensive Monitoring Project effort, specifically when crews will already be visiting stream sites throughout the state conducting surveys as a part of this extensive monitoring effort. The inclusion of amphibian sampling would provide an improvement over historical efforts that have been inconsistent and limited in geographic and temporal scope. This add-on is one cost-effective alternative that provides a broad benefit with minimal additional cost or effort as related to alternative approaches (e.g., a separate effort to sample stream-associated amphibian occupancy or abundance (Halstead et al. 2020, Lacoursiere-Roussel et al. 2016). The approach is relatively inexpensive, requires relatively little effort in terms of time, is minimally invasive to habitat and species, and does not require expert knowledge about species or habitats (Svenningsen et al. 2022). Other species beyond the amphibians of interest could also be added to this effort, if desired.

The distributions or range (i.e., geographic extent or spatial pattern of species occupancy) of the stream-associated amphibian species listed for consideration under the FPHCP vary considerably throughout the state (Jones et al., 2005). Coastal Tailed Frog generally occurs in Washington throughout the Cascade Mountains, Olympic Peninsula, and Coast Ranges, whereas Rocky Mountain Tailed Frog is restricted to a small portion of Washington in the extreme southeastern corner of the state. The three torrent salamander species are geographically separated within the State, with the Olympic Torrent Salamander restricted in distribution to the Olympic Peninsula, the Columbia Torrent Salamander to the Willapa Hills in the southwestern portion of the State, and the Cascades Torrent Salamander located in the southern Cascades of Washington State. The two terrestrial salamanders (Dunn's and Van Dyke's) are also restricted in Washington to the west of the Cascades, with Dunn's Salamander occurring only in the southwestern portion of the state and the Van Dyke's Salamander occurring in three disjunct locations (similar to the three torrent species) in the Olympic Peninsula, southwestern Willapa Hills, and south Cascades. Though there is reasonably good documentation of species distributions, range-wide as well as within Washington State specifically, relatively little is known about the current status and trends of occupancy or population abundances within those ranges for these species. Much research has been restricted in geographic range (e.g., Olympics, Cascades) or limited in scope to specific landowners (e.g., State, Federal, private timber companies). As such, up-to-date information on the status of species either in terms of continued occupancy at historically occupied sites, or trends in abundance (i.e., numbers of individuals from a given species within a given area) at known sites, is very limited.

Some research has concluded that stream-associated amphibian populations are sensitive to forestry practices (Araujo et al. 2013, Moore 2005, Grizzel and Wolff 1998, Jackson et al. 2007, Janisch et al. 2012, Johnson and Jones 2000) though some reviews have discussed the inferential strength of these and other relevant publications (Kroll 2008, Martin et al. 2021), including our own research at CMER which demonstrated a negative response to timber harvest in non-fish-bearing basins with clearcut harvest through 15 years post-harvest (McIntyre *in prep*). However, few efforts have documented the status of stream-associated amphibians across the landscape through time, especially as it relates to whether trends at a basin scale translate to changes that can be generalized across the range of the species, or in this case, within lands subject to the FPHCP in Washington State. Exceptions do exist, however, for example Kroll et al. (2010) evaluated spatial and temporal variation in stream-associated amphibian occupancy in western Oregon and Washington as a function of landscape-level covariates. Though efforts to understand stream-associated amphibians, including their population status, behaviors, limitations, and considerations for conservation, have grown substantially over recent years, much remains unknown about these species. For example, torrent salamanders have been characterized as extremely sedentary, with home ranges of about 2 m or less for a majority of recaptured individuals (Nijhuis & Kaplan, 1998; Nussbaum & Tait, 1977; Welsh & Lind, 1992). However, more recent observations have confirmed individuals moving in-stream for much greater distances, e.g., 122 m for a single individual over 6 days (Tyson and Hayes 2010). These apparently different results likely reflect the limited spatial scopes of the earlier efforts. Nonetheless, individual movement under various management options and in the face of climate change is an important consideration for species such as these, that are largely restricted to streams, riparian areas, or periods of high rainfall to facilitate overland movement. Opportunities for movement and recolonization from adjacent headwater watersheds may be restricted in the downstream direction via fish-bearing reaches (Lowe and Bolger 2002, Richardson and Danehy 2007) and over-ridgeline movement may become more restricted under changing climate scenarios in the face of headwater streams drying in a downstream direction (Olson & Burton, 2019). Both of these potential scenarios may be exacerbated on the timber-managed landscape through decreased movement through areas that have gaps in overhead canopy (Cecala et al. 2014) that form barriers to dispersal. It is also important to note that study designs upon which conclusions are based are variable, and conclusions drawn from retrospective efforts or those lacking consideration of the implications of potentially variable detection probabilities may be less reliable (Kroll et al., 2009b).

Amphibians are often considered among the vertebrate groups most susceptible to environmental modification. Due to amphibians' limited dispersal abilities, dual life histories, and explicit microhabitat and physiological requirements (Lawler et al. 2010, Welsh and Ollivier 1998), they are frequently preferred as indicator species for monitoring environmental conditions (Wake 1991). However, some have contended that the use of amphibians as ecological indicators may be problematic because taxa may respond differentially to environmental conditions throughout their geographic distribution or range, with differences in occupancy or abundance reflecting factors other than habitat quality, e.g., predation and disease (Kroll et al. 2009a). Furthermore, the same characteristics that make amphibians good indicators for environmental change may have implications for accurately estimating occupancy and abundance using conventional amphibian survey methods (e.g., visual encounter surveys, seining, dip-netting; (Bailey et al. 2004, Price et al. 2012). Effective monitoring to assess species status, including evaluating trends and identifying potential threats, is complicated by imperfect rates of detection (MacKenzie et al. 2002 and 2003, Schmidt 2003). Detectability has been shown to vary among species, sampling methods, observers, time periods, habitat types, and weather (Bailey et al. 2004, de Solla et al. 2005, Pellet and Schmidt 2005, McIntyre et al. 2012). Ignoring variation in detectability when estimating population parameters such as occupancy and abundance leads to unreliable data, regardless of the sampling method used. This is particularly true with the incidence of false negatives (MacKenzie et al. 2002, Schmidt 2003), frequently resulting in underestimation of species occupancy and distribution (Mazerolle et al. 2007, Pellet and Schmidt 2005). Methods that account for detection in estimates are available, such as capture–mark–recapture, distance sampling, and repeat surveys with the use of binomial mixture models (Mazerolle et al. 2007, Royle 2004). However, these methods can be time-consuming and expensive to implement relative to some other commonly used visual encounter surveys (MacKenzie et al. 2002).

Relatively recent advances in the use of eDNA as a monitoring tool show promise in providing a less invasive tool with accurate detection probabilities and estimates of occupancy(Halstead et al. 2020, Lacoursiere-Roussel et al. 2016). The eDNA method relies on the detection of species via traces of DNA shed from sources that may include feces, secreted mucous membranes, gametes, and skin cells (Haile et al. 2009, Taberlet et al. 2012). The use of eDNA in sampling and monitoring programs has been shown to increase detection rates for some species (Pilliod et al. 2013, Smart et al. 2015). It may also increase the observation time windows of surveys, at least for some species, especially those for which surface activity may be limited to particular seasons or environmental conditions, e.g., amphibians, reducing the need for extensive taxonomic expertise and financial resources (Lacoursiere-Roussel et al., 2016). Furthermore, eDNA is considered less invasive and disruptive as it does not require marking individuals or repeat surveys (Moss et al. 2022; Valentini et al. 2016). However, as with any sampling approach, eDNA has limitations and researchers must carefully evaluate research goals, objectives, and sampling considerations when designing a sampling protocol for any research effort (Beng and Corlett 2020). Potential considerations in the use of eDNA in a sampling protocol include imperfect detection, inability to assign life stage, inability to assess abundance, and eDNA spatial and temporal dynamics (Beng and Corlett 2020).

Conventional methods (e.g., light-touch, rubble-rouse) of detecting the presence of stream-associated amphibians present disadvantages including limited survey windows (Petitot et al. 2014) and consideration of environmental conditions necessary to increase and standardize rates of detection. The use of eDNA techniques has been shown to provide high detection probabilities in many cases, often requiring only a single site visit with replicate water samples per visit to quantify detection probabilities and obtain unbiased estimates of species occurrence (Halstead et al. 2020). The use of eDNA for evaluating stream-associated amphibian populations has increased recently with the development of species-specific markers and advances in the understanding of life history and dispersal (Goldberg et al. 2016). Recent research suggests that that eDNA can be a more effective and efficient in detecting stream-obligate species (Halstead et al. 2020, Kamoroff et al. 2023). However, the utility and accuracy of eDNA for detecting terrestrial salamanders (i.e., Dunn's and Van Dyke's Salamanders) has not been established and as such the Project Team recommends focusing on in-stream breeding amphibians (e.g., tailed frogs and torrent salamanders) in this proposed effort. More specifically, eDNA results can greatly improve herpetological surveys, offering superior sensitivity, coverage and efficiency, and increasing the detection probability for rare and elusive species, especially for the detection of terrestrial life stages (e.g., adults (Lacoursiere-Roussel et al. 2016). Environmental (e)DNA detectability and concentration depend on production rates of individuals, environmental conditions, density of animals, and their residence time (Pilliod et al., 2013). Since this monitoring approach relies on detection of species-specific eDNA, false negatives and false positives are both possible (Cristescu & Hebert, 2018). For example, predators may transfer eDNA for a species into an unoccupied area via amphibian remains or predator excrement. Though this phenomenon has not been documented for stream-associated amphibians, it has been documented for fish in aquatic systems (Guilfoyle et al., 2017; Merkes et al., 2014). However, note that recent efforts have developed both methodological techniques and statistical modelling tools that help researchers account for uncertainties when both false negatives and false positives are possible (Guillera-Arroita, 2017; Miyata et al., 2021; Tingley et al., 2020).

Startup costs for the use of eDNA can be high when one considers total costs, including for example primer development for individual species (Smart et al. 2016). However, primers have been developed for all focal FP-designated amphibians of interest (Coastal Tailed frog, and three torrent salamander species). Therefore, the cost associated with eDNA monitoring in the proposed context would include the additional time needed to navigate to eDNA sample collection points and collect samples, equipment costs (e.g., pump sampler and filters), and the cost of laboratory analysis. The time spent to navigate to and collect samples depends on the site and study design considerations, including the number and distribution of samples to be collected. The goal would be to borrow the pump samplers required for this effort, thus eliminating this cost. The current cost of self-contained eDNA filter packs (recommended) is approximately $18. Finally, one current estimate for the cost of sample analysis is $85 per sample. However, multiple species can be evaluated for each sample and since the three torrent salamander species are distributed geographically, each eDNA sample can be used to evaluate Coastal Tailed Frog, the species of torrent salamander relevant to the location of the specific study site, and other species of interest, if desired. Though some field ecologists may conclude that the cost of molecular analyses would offset any advantage of such an approach, studies comparing the costs and benefits of different approaches have revealed that eDNA is often generally cost-effective when compared to traditional field surveys (Ficetola et al. 2019). The use of eDNA as a sampling tool would provide the opportunity for a consistent and relatively efficient approach to evaluating amphibian occupancy and trends in conjunction with the general Extensive Monitoring effort.

Scientists with the Washington Department of Fish and Wildlife (WDFW) are currently developing and implementing an Aquatic Biodiversity Program (ABP) that does this, funded in the 2023-2024 biennial budget under Biodiversity and Climate Change Resilience. As a part of this effort, staff from WDFW Fish Program are collecting eDNA samples throughout Washington watersheds. Specific watersheds will be sampled on an annual basis, and these watersheds will be rotated over time. Within watersheds, samplers will filter water samples and use a metabarcoding approach to detect a suite of aquatic species including fish, mussels, and amphibians. This approach will allow for occupancy modeling of species across space and time, along with the inclusion of field-collected and GIS-based habitat and environmental covariates that inform the probability of occupancy for individual species.

Summary and Conclusions

The Best Available Science review focuses on the state of the science of different methodologies and tools for collecting and estimating riparian stand conditions and stream temperatures across a large landscape like Washington state. There have been recent technological advancements in remote sensing and stream temperature modeling techniques. The review examines the reliability and utility of Airborne Laser Scanning (ALS), Digital Aerial Photogrammetry (DAP), and Satellite Imagery. These technologies differ in spatial resolution, cost, and temporal scale. Certain technologies may be more well suited for measuring certain riparian characteristics than others.

Stream temperature models like Qual2KW, Spatial Stream Network (SSN) models and Generalized Additive Models (GAMs) are currently being used and refined in the PNW and can generate an array of stream temperature metrics relevant to biological resources. Direct measurements of stream temperature as well as stream cover and other physical stream conditions contemporaneous with those temperatures are important inputs necessary for all of these models.

Remote sensing technologies and stream temperature models continue to advance, evolve, and change. What works, and is available, today may be outdated or unavailable for future sampling events. So continual evaluation of remote sensing technologies and stream temperature monitoring and modeling should remain a part of the extensive monitoring program moving forward.

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Appendix B – History of Washington Hydrography

Forest practices rules are based around the DNR Forest Practices hydrography layers for water courses (wchydro) and water bodies (bhydro). These GIS layers were the first statewide hydrography developed for the state and were initially extracted from USGS 1:24,000 quad maps. The layers are known to be highly imprecise and incomplete. In the early 2000s, the Federal government decided to create a nationwide dataset with a consistent set of attributes that all agencies could use. That National Hydrographic Dataset (NHD) used the DNR wc- and wbhydro layers as a basis and allowed entities to specify modifications and corrections. From then on, the DNR Forest Practices hydrography and the NHD have diverged, with both datasets receiving different edits over the past 20 years. The NHD was made static in 2023, and USGS is making no further updates. All current and future efforts in the Federal program are dedicated to development of the nationwide 3DHP hydrographic dataset.

With the advent of widespread high-accuracy lidar-derived topographic mapping, the USGS began development of a new nationwide hydrography based on that, a program they call 3DHP (hydrography from 3-dimensional data). The Department of Ecology is the Washington lead entity working with the USGS on nationwide hydrography development (https://ecology.wa.gov/research-data/data-resources/geographic-information-systems-gis/hydrography-program-washd). As of 2024, Washington has nearly complete, statewide coverage of high-accuracy lidar-based topography. Hydrography development from that topography has been completed or is in progress for a few watersheds (WRIAs) and counties, but the overall effort is not scheduled for completion until 2029. In the meantime, other entities are proceeding with generation of lidar-derived hydrography themselves for their limited ranges of interest, and these could potentially be compiled to create a working hydrographic network that meets the needs of the Forest Practices Extensive Monitoring Program.

In particular, the DNR State Lands Division has high-resolution hydrographic layers developed to allow management of State lands but that also includes adjacent forestlands. That hydrography is available for internal DNR projects, such as this one for the FP Adaptive Management Program. The most recent version is complete for eastern Washington and is based on lidar data available as of early 2024. Some small holes remain due to lack of high-quality lidar data in spots; those lidar gaps have since been filled and the gaps in hydrography will also be filled in the near future. The west side of the state should be available in 2025, which means it will be useable for this extensive monitoring effort. The DNR hydrographic data include "depth-to-water" index and watershed areas for streamline segments. Those data can be combined with the Department of Ecology channel migration zone polygon GIS layer to estimate channel edges, and riparian buffer polygons from those, that should be accurate enough for this extensive monitoring effort. Further assessment of the accuracy of such polygon location relative to the needs of the Extensive Monitoring Project will be part of the study design phase of this program.