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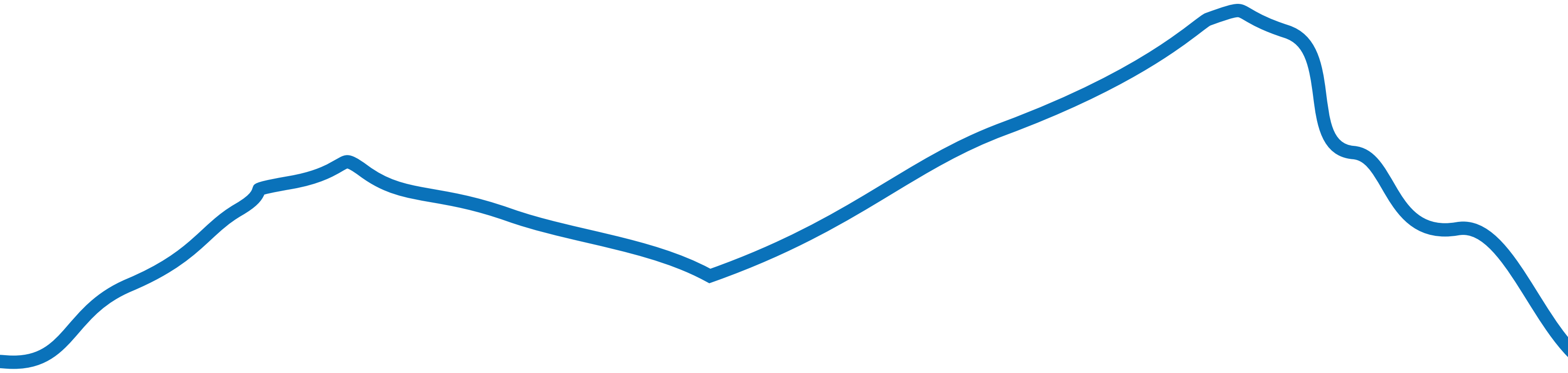

Investigating Thermal Regimes of the Upper Peace River Basin

Summary Report Year 3

Prepared with financial support of the Fish and Wildlife Compensation Program on behalf of its program partners BC Hydro, the Province of BC, Fisheries and Oceans Canada, First Nations and Public Stakeholders

Investigating Thermal Regimes of the Upper Peace River Basin: Summary Report Year Three

FWCP Project No. PEA-F25-F-4053

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Executive Summary

Aquatic ecosystems have been identified as vulnerable to increased air temperatures due to their low thermal inertia and high temperature variability. The spatio-temporal availability of thermal habitats is one of the most important drivers of fish distribution and migrations in freshwater environments. The FWCP and the Environmental Stewardship Initiative between the Tsay Keh Dene Nation and the BC Government have a combined interest in assessing the potential effects of climate change and land cover change on fish populations and habitats and to prioritize conservation of species and habitats most vulnerable to impacts. This project aims to provide a monitoring framework under which the impacts of climate change and land cover on aquatic thermal habitat can be investigated, the extent of cold-water refugia can be identified and insight can be made into thermal habitat availability and its impact on the distribution and abundance of two focal priority species Bull Trout and Arctic Grayling within the Upper Peace River. This project aligns with the Rivers, Lakes and Reservoirs Action and Cross-Ecosystem Action Plan by addressing Priority Actions PEA.RLR.S01.RI.01, PEA.RLRS04.RI.13, PEA.RLR.S03.RI.09, PEA.RLR.S07.RI.22, and PEA.CRE.SO3.ME.02.

In 2024, the focus of equipment deployments was on maintaining the monitoring array within the Parsnip River, Nation River, Omineca River, Osilinka River, Mesilinka River, and Ingenika River. These watersheds were selected because of their importance to First Nations and availability of historical data. In addition, they present a gradient of landscape disturbance which aids in study design and the investigation of impacts on thermal habitat. In total, 89 loggers were deployed and/or active within the instream array. Twenty-one in the Ingenika watershed, 22 in the Mesilinka watershed, 23 in the Parsnip watershed, five in the Nation watershed, eight in the Osilinka watershed, one in the Omineca watershed, two in Pesika River, two in Scott Creek, two in Point Creek, and three in Davis River. Within the Williston Reservoir, the Finlay, Peace and Parsnip reaches were targeted for deployments. Uslika Lake (small lake < 400 ha) and Chuchi Lake (large lake > 400 ha) were also included in the array. All open water deployments recorded hourly water temperature at depths of 30 cm, 1 m, and 5 m.

Sixteen real-time hydrometric stations installed by this project were maintained in 2024. The goal of the 2024 field season was to ensure high quality data is being recorded at the existing stations and to ensure multiple discharge measurements at each station. Both the real-time hydrometric station data and cleaned Tidbit data are currently available from the Northern BC Hydrology Research website (https://bcgov-env.shinyapps.io/nbchydro/). The development of rating curves for real-time hydrometric stations is ongoing, but some stations have accumulated enough data to present reliable discharge data (e.g., Pelly Creek). Initial rating curves were estimated this year at other sites but require further discharge measurements from the 2025 season to confirm accuracy. The development of accurate rating curves for each station is a high priority for the final year of the project.

Water temperature data collected from 2022-2024 was used to fit a linear mixed effects model investigating the impact of air temperature on water temperature (thermal sensitivity) among sites within Bull Trout habitats (i.e., migration corridors and critical spawning habitats). Variation in thermal sensitivity was observed among critical spawning habitats which was a surprising result given the specific habitat requirements of Bull Trout. A next step in the investigation of reach scale patterns in thermal habitat is to investigate what topographical variables influence thermal sensitivity within Bull Trout spawning habitats and explain the unexpected variation in thermal sensitivity.

A preliminary SSNM was built at the watershed scale, predicting temperatures at 5 km intervals along the study streams. this was an important step in developing workflows for the models using newer methods. The preliminary model revealed important insights about the datasets included in the model, and next steps to improve to improve prediction error were identified. These include more observation sites in areas of high leverage, and more fixed effects predictors, than the simple elevation data used in this model. This effort represents a critical step towards meeting the objectives of the project.

Various statistical, machine learning and semi-empirical lumped models were evaluated and compared at basin scale for their performance in simulating freshwater temperatures in river and reservoir. In particular, the semi-empirical Air2Stream model achieved better performance in simulations while requiring less data compared to statistical models, making it a better choice for modeling river systems. In contrast, statistical regression/machine learning models were found to be more effective than Air2Water in capturing the daily variability in reservoir surface water temperature. We recommend using the Air2Stream model for river modeling due to its reliable performance in the river sites. In case of the reservoir modeling, different modeling chains need to be tested to ensure the application of the most suitable modeling framework. In the final year, we will focus on expanding the model as a new prediction tool to additional sites, improving its performance, and applying it to the real-time hydrometric sites deployed by this project. This will provide valuable insights from the modeling framework for priority species as the deployments in this project are coordinated specifically with critical habitats.

For the final year of the project, we have the following list of recommendations, which are specific to the methods of the project. Recommendations for the management of priority species, and FWCP actions will be withheld until final conclusions can be drawn from the data collected and analyzed by this project. The recommendations are as follows:

1. Continued support and advocacy for hydrometric monitoring in remote areas;
2. Prioritize rating curve development to facilitate the application of the WTPS at new real-time hydrometric station sites;
3. Continue data management, and implement data imputation methods where possible to increase the number of available datasets;
4. Maintain live data dashboard and improve project data portal. Increase communication around the availability of the data generated by the project;
5. Coordinate results with concurrently funded FWCP projects (PEA-F25-F-4051, PEA-F25-F-4054) including an assessment of cumulative effects on Bull Trout (see Rossi et al. 2025), and monitoring of Arctic Grayling (Hagen et al. 2025) to provide insights for the objectives of those projects;
6. Continue to improve coordination and dissemination of project data and results with First Nations in the footprint of the Williston Reservoir. Further presentation at community events has been identified as a required step in this process;
7. Host outreach events to communicate the methods and results of the study to regional stakeholders and management agencies. This involves fostering a community of practice which can coordinate on the applications of the methods used in this project in conservation, enhancement and restoration actions;
8. Generate outreach products including a video describing the project and results – fieldwork filming completed.

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This project was made possible with financial support of the Fish and Wildlife Compensation Program on behalf of its program partners BC Hydro, the Province of BC, Fisheries and Oceans Canada, First Nations and Public Stakeholders. Additional funding for the project was provided by the Tsay Keh Dene Nation – BC Environmental Stewardship Initiative, and the British Columbia Ministry of Forests Research Program. We would like to extend our thanks to John Hagen and Eduardo Martins for advice on study design. Fieldwork support was provided by Nathan French, Daniel Krivenko, Ian Clevenger, Daniel Scurfield, Dillon Hamelin, Van Kingsley, Kaylee Barnes, Drew Gilchrist, Shiyuan Jing and Hunter Gleason. An additional thanks to Brett Bastin of Northcoast Helicopters, Ltd. for assistance accessing remote fieldwork sites.

1 Introduction

Climate change is an emerging issue for aquatic ecosystems in British Columbia's (BC) Peace Region (FWCP 2020). Regional climate projections include decreased streamflow, considerably warmer summers, warmer winter temperatures and increased precipitation falling as rain instead of snow (Fraser Basin Council 2019). Aquatic ecosystems have been identified as vulnerable to increased air temperatures due to their low thermal inertia and high temperature variability (IPCC 2014). Despite the general perception that the thermal environment in running freshwater is homogeneous, streams exhibit substantial thermal variability at the reach, watershed and basin scales (Kurylyk et al. 2015). Aquatic ectotherms have adapted to live in these complex thermal regimes where thermal heterogeneity is driven by atmospheric conditions, elevation-temperature gradients, groundwater, topographic complexity, and land cover change (Sagar and Colbourd 2004; Caissie 2006). Indeed, temperature has been described as a master variable for freshwater fishes (Kingsolver 2009). The spatio-temporal availability of thermal habitats is one of the most important drivers of fish distribution and migrations in freshwater environments (Lucas and Baras 2001; Isaak et al. 2010). A contemporary approach to monitoring and modeling freshwater thermal habitat availability is needed to advise modernized land use planning and investigate the causes of observed trends in the abundance and distribution of priority aquatic species Bull Trout (*Salvelinus confluentus*) and Arctic Grayling (*Thymallus arcticus*) as illuminated by other Fish and Wildlife Compensation Program (FWCP) funded projects (O'Connor et al. 2024; Hagen and Stamford 2022).

Due to its influence on the metabolic processes of ectothermic organisms, temperature is a critical abiotic factor to monitor. Ectotherms are animals (e.g., Bull Trout and Arctic Grayling) which have little ability to maintain their body temperature by physiological means. Temperatures beyond optimal conditions instigate a stress response and the ensuing consequences include decreased metabolic scope for activity and growth rate, which impact foraging, predation risk, reproductive capacity and therefore fitness (Barton 2002; Morash et al. 2021). As a result of the strong relationship between ectotherm distribution and environmental temperature, climate change driven range contraction and distribution shifts are forecasted to intensify for aquatic species over the rest of the 21st century (Comte and Grenouillet 2013; IPCC 2014). The contraction of ectotherm distributions under a warming climate is a well-documented phenomenon and only buffered where cold-water refugia is available or where dispersal to more suitable thermal habitats is possible (McCullough et al. 2009; Huey et al. 2012; Ruesch et al. 2012; Al-Chokhachy et al. 2013; Eby et al. 2014). In this context, cold-water (or climate) refugia are defined as habitats where populations or metapopulations retreat to, persist in and colonize from when environmental conditions are unfavourable (Keppel et al. 2012).

The FWCP - Peace Region and other regional stakeholders have a combined interest in assessing the potential effects of climate change and land cover change on fish populations and habitats in order to prioritize conservation of species and habitats most vulnerable to impacts (FWCP 2020a). Additionally, the health and sustainability of aquatic species and the need to monitor change is of high concern for multiple First Nations within the Williston Reservoir footprint (Pearce and Abadzadesahraei 2019). This project seeks to address these concerns by providing a monitoring framework under which the impacts of climate change and land cover on aquatic thermal habitat can be investigated, the extent of cold-water refugia can be identified and insight can be made into thermal habitat availability and its impact on the distribution and abundance of two focal priority species Bull Trout and Arctic Grayling.

Thermal habitat availability has been identified as a limiting factor and data gap for focal priority species Bull Trout, Arctic Grayling and other inventory species in the Upper Peace River basin (UPR) (Stamford et al. 2017; Hagen and Weber 2019). The implications of increased magnitude and variability in water temperatures are of great concern to species fragmented in isolated watersheds as well as migratory species which depend on disparate habitats undergoing seasonal changes in thermal habitat availability (Isaak et al. 2016). The construction of the WAC Bennet Dam and flooding of Williston Reservoir caused a significant loss of riverine habitat and shift to lacustrine habitat eliminating access to large migration corridors for some species (e.g., Arctic Grayling; Stamford et al. 2017), and created new opportunities for other species which could adapt to the new lentic environment (e.g., Bull Trout, Lake Trout; Hagen and Weber 2019; Culling et al. 2020). Furthermore, the development of the UPR has caused the rapid loss of primary forests and ongoing beetle salvage logging and pipeline development have further removed forest cover in tributaries of the UPR. The removal of forest cover has been demonstrated to increase stream temperatures and the subsequent effects on aquatic species have been complex and specific to species and life stage (Moore et al. 2005; Tschaplinski and Pike 2017; Cunningham et al. 2022). Additionally, wildfires have been shown to disproportionately impact stream thermal regimes despite relatively low proportional impact when compared to land use development (Isaak et al. 2010).

We aim to investigate and document patterns in water temperature and their drivers across a range of temporal and spatial scales. Spatial scales of investigation are split between reach (encompassing <10 km of stream length focused on Bull Trout spawning habitats), watershed (encompassing whole tributaries to the Williston Reservoir) and the basin scale (encompassing the entire UPR). Temporal scales of investigation are split between the historical period (1980-2022) and the current study period (2022-2025). By utilizing innovative field techniques, leveraging existing monitoring data and integrating satellite remote sensing archives into a water temperature modeling framework this project will improve the understanding of thermal habitats within the UPR. This initiative will create a reliable water temperature dataset collected at a variety of scales and across elevation and land use gradients which can be applied to concurrently funded monitoring of aquatic fauna across the region. Observed data will be used to develop and integrate models with the objective to describe critical thresholds, extreme events and identify opportunities for conservation of cold-water refugia. The outcomes will be used to address concerns over the impacts of climate and land change on water temperatures and aid in decision-making processes regarding aquatic species conservation status and land-use planning.

1.1 Objectives and Linkage to FWCP Action Plans and Priority Actions

This project focuses on the cumulative effects of climate change, and land cover change on river water temperatures in the UPR. The outcomes of this study will primarily address the priority actions PEA.RLR.S01.RI.01, PEA.RLRS04.RI.13, PEA.RLR.S03.RI.09 and, PEA.RLR.S07.RI.22 of the Rivers, Lakes and Reservoirs Action Plan through the monitoring of thermal habitat and development of thresholds within critical habitats for multiple species listed as focal for FWCP and culturally important for First Nations (FWCP 2020b). The study will also address priority action PEA.CRE.SO3.ME.02 of the Cross-Ecosystem Action Plan by implementing a study aimed at monitoring conservation status and achieving sub-objectives for priority species (FWCP 2020a). By focusing on the critical habitats of priority species the project also addresses a key data gap in the evaluation of limiting factors for Bull Trout and Arctic Grayling (Stamford et al. 2017; Hagen and Weber 2019).

Using a three-scale monitoring and modeling approach, the primary objectives are:

1. Monitor water temperature and flow in priority watersheds of the UPR,
2. Quantify and predict the spatial distribution of thermal habitat suitable for ectothermic animals,
3. Quantify spatio-temporal variability in water temperatures to inform conservation initiatives for priority species,
4. Examine the individual roles of climate change, and land cover change on water temperature over time.

2 Study Area

The project was conducted in selected streams of the UPR or Williston Reservoir watershed (Figure 1). The Peace River is a tributary to the Slave River and subsequently the Mackenzie River which flows into the Arctic Ocean. The UPR was flooded in 1967 by the creation of the W.A.C. Bennet Dam creating the Williston Reservoir. In 2024, the focus was increasing the time series of the expanded monitoring array and to provide an additional year's data into modelling efforts. This built on work from 2023, which prioritized expanding the existing array deployed in 2022 to include more watershed characteristics, particularly in the Nation, Omineca and Osilinka River watersheds. These watersheds were selected because of their importance to First Nations and history of study. In addition, they present a gradient of landscape disturbance which aids in study design and the investigation of impacts on thermal habitat.

Within the target watersheds, six large mainstem rivers, known to contain critical habitat for Bull trout and Arctic grayling, were chosen for study and include the Parsnip River, Nation River, Omineca River, Osilinka River, Mesilinka River and Ingenika River. The Parsnip River and its major tributaries drain a mountainous area in the Hart Ranges of the Rocky Mountains, which lies east of the Rocky Mountain Trench. The Parsnip has turbid water as a result, and high peak flows from late-May to early June. The Nation River drains the Nechacko Plateau, which is characterized by lower elevations and milder conditions compared to neighboring watersheds, which flow through the Omineca and Rocky Mountains. The Mesilinka River originates in the Omineca mountains and has nearly 30 tributaries with lengths greater than 10 km that contribute to the overall discharge of the watershed. Major tributaries of the Mesilinka River include Lay Creek, Kliyul Creek, Tutizika Creek and Tomias Creek. The Osilinka River is the largest tributary of the Omineca River on the western side of the Williston Reservoir and also originates in the Omineca mountains. The Ingenika River begins in the McConnel Range within the Omineca Mountains and flows for approximately 140 km into the Willison Reservoir. Major tributaries of the Ingenika River include Swannell River, Pelly Creek, Wrede Creek and Fredrickson Creek. More detailed descriptions of the above river systems can be found in O'Conner et al. (2024; FWCP Project No. PEA-F24-F-3845).

The Williston Reservoir is located approximately 140 km north of Prince George in northeast BC. At its maximum operating level, the reservoir has a surface area of 1779 km^2 and the total catchment area is 69,930 km^2 (Stockner et al. 2005). The reservoir flooded the low elevation areas (< 700 m ASL) of the Rocky Mountain Trench including the Peace River Canyon, the lower Parsnip and Finlay Rivers as well as the lower sections of many tributaries to what is now the Williston Reservoir.

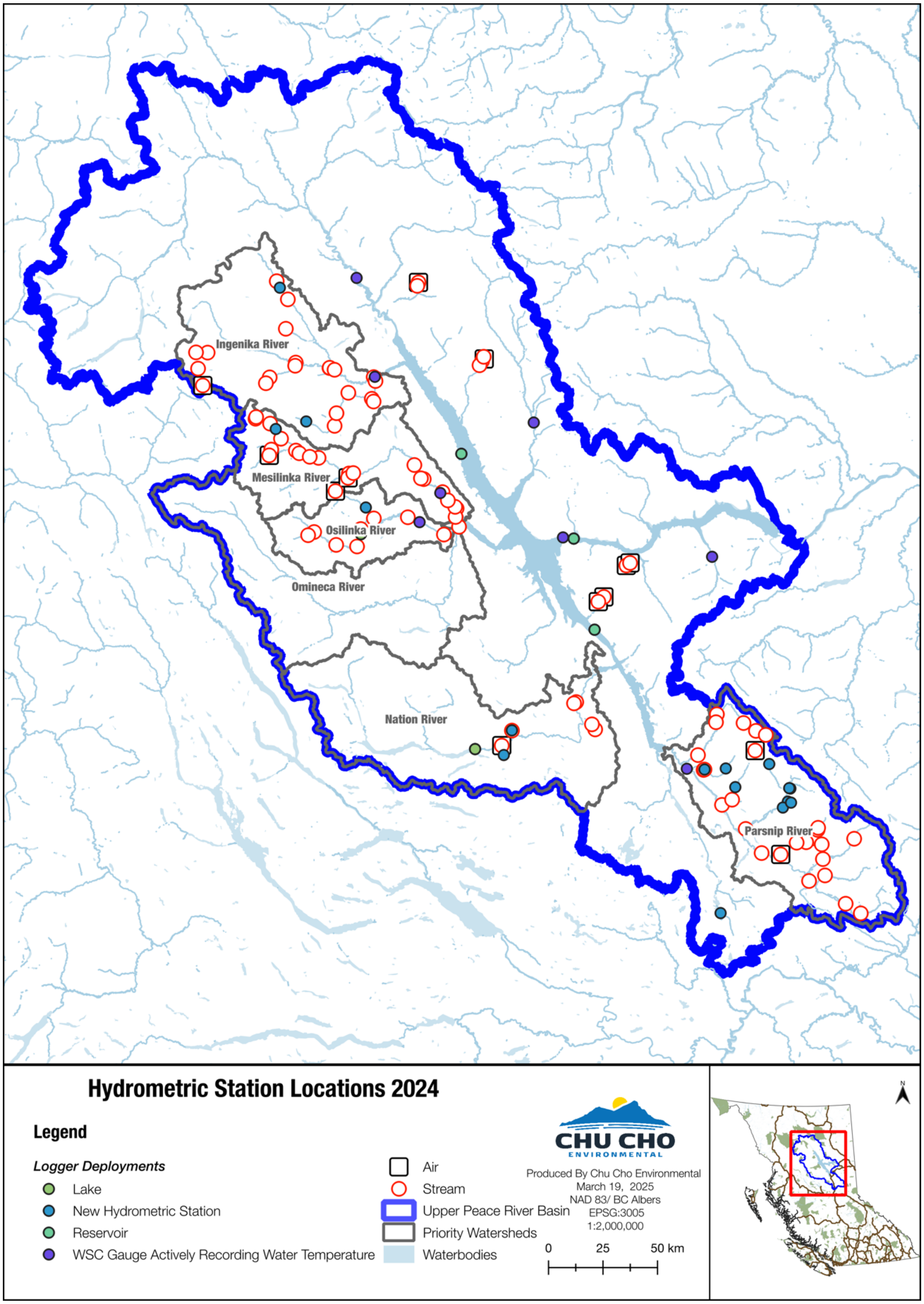

Figure 1. Temperature and hydrology monitoring locations in the Upper Peace River Basin, 2024. The map displays rapid deployment sites, existing water survey of Canada (WSC) stations, and new real-time hydrometric stations. The Upper Peace River Basin is highlighted in blue, and the priority watersheds are bordered in grey.

3 Methods

3.1 Modelling Framework

The project builds off previous temperature monitoring efforts within the UPR (Zemlak and Langston 1997; Williamson 2006; Martins et al. 2022) and past regional applications of the proposed modeling tools (Islam et al. 2019; O'Connor 2023; Bevington et al. In review). This project makes use of modeling tools to simulate reservoir, lake and river water temperatures in a three-scale monitoring and modeling approach which can address objectives at the reach, watershed, and basin scales. Exploratory data analysis and empirical presentation of water temperature patterns at the reach-scale in Bull Trout critical habitats will assess immediate conditions for priority species Bull Trout. Critical habitats are those habitats that are required for a species to complete its life history strategy (Hagen et al. 2015). Spatial Stream Network (SSN) modeling is in use to address watershed scale patterns in thermal habitat availability. The SSN outputs will assist in development of additional modeling tools which support the estimation of species distribution and abundance (Isaak et al. 2017). Two semi-empirical lumped water temperature models, Air2Water and Air2Stream and several statistical and machine-learning models: Multiple Linear Regression (MLR), Generalized Additive Models (GAM), Random Forest (RF), and Feedforward Artificial Neural Networks (ANN) are in use to simulate basin scale thermal regimes of several rivers and lakes, including the Williston Reservoir. Each modeling tool complements the other scales of inference to create a robust research framework (Figure 2). A background of the SSN, Air2Water, and Air2Stream models, and their past applications has been described in detail in previous summary reports for this project (O'Connor et al. 2024; FWCP Project No PEA-F24-F-3845), and the MLR and ANN models are discussed in the year 2 summary report (O'Conn0r et al., 2024).

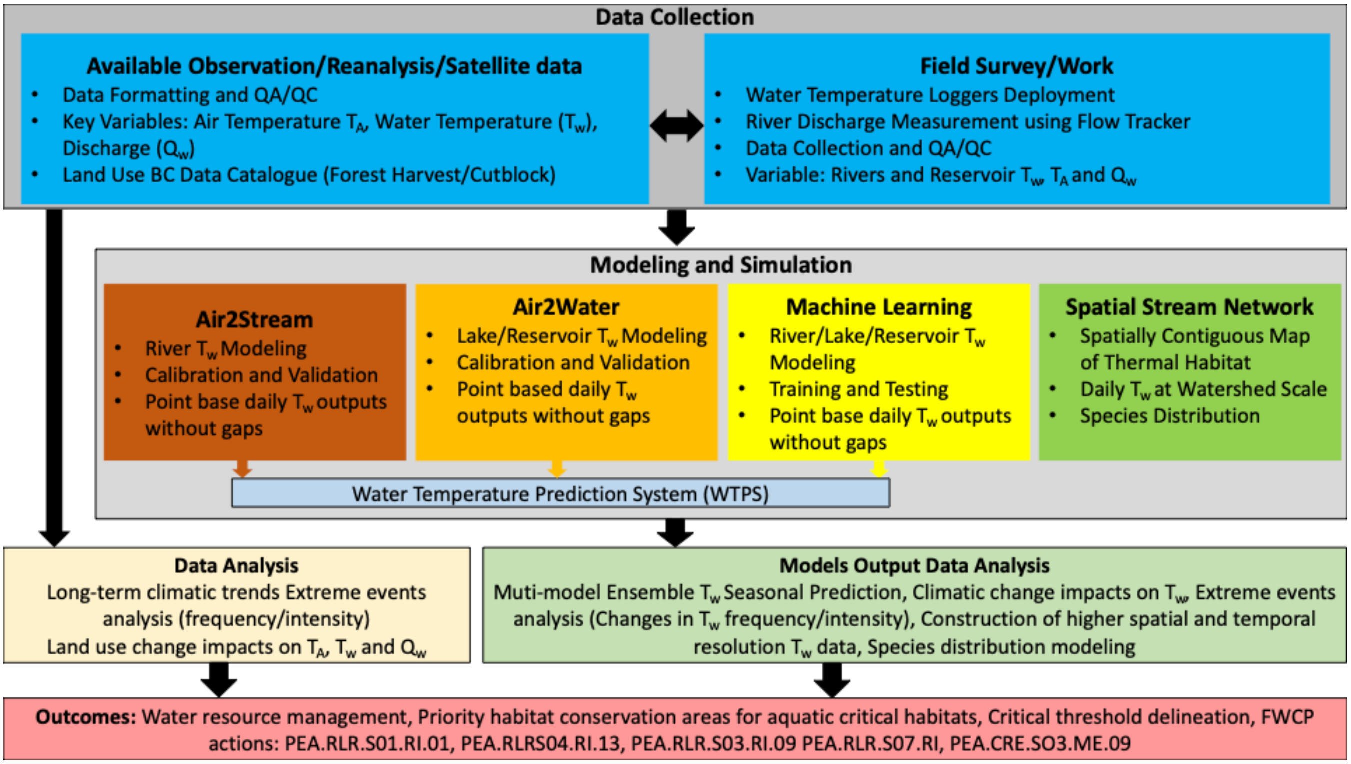

Figure 2. Research framework outlining data collection, modeling tools and overall outcomes of the project.

3.2 Integration of New Statistical and Machine-Learning Models

In year 3, water temperature modeling is enhanced by integrating two new predictive models: Generalized Additive Model (GAM) (Dominici et al., 2002) and Random Forest (RF) model (Breiman, 2001) alongside existing Air2Water, Air2Stream, MLR and ANN modeling approaches. With addition of new modeling techniques, this project underscores the importance of employing diverse modeling chains to improve predictive accuracy despite data limitation.

3.2.1 Generalized Additive Model (GAM)

The GAM model (Hastie & Tibshirani, 1986) is a statistical model that extends MLR by incorporating nonlinear smoothing functions such as splines, polynomials, kernel functions, and local regression (Dominici et al., 2002). This flexibility enables the GAM to capture complex relationships between predictor variables and the response variable to model nonlinear effects such as seasonality (Laanaya et al., 2017; Dominici et al., 2002). We developed the GAM models using the following general equation:

$$\mathrm{y} = \beta 0 + f1(\mathrm{X1}) + f2(\mathrm{X2}) + \cdots + f\mathrm{n}(\mathrm{Xn}) + \epsilon$$

where the y is a water temperature, β0 is the y-intercept, $f_1, f_2, \ldots, f_n$ denotes the spline smoothing functions for each variable, and **ϵ** represents independent and normally distributed residual errors

3.2.2 Random Forest (RF)

The RF model is an ensemble machine-learning method that combines multiple decision trees to improve predictive accuracy (Breiman, 2001). It works by aggregating predictions from individual trees, using voting for classification or averaging for regression (McClarren, 2021). This uses random subsets of data and variables to build decision trees which helps to reduce overfitting and balances the bias-variance trade-off, improving overall model performance (Almeida & Coelho, 2023; Hani et al., 2023; Schonlau & Zou, 2020).The RFs model can handle both linear and non-linear relationships between predictors and water temperature (Feigl et al., 2021) and is based on the following equation:

$$y = \frac{1}{N} \sum_{i=1}^{N} \mathrm{Ti}\ (X)$$

Where y is predicted output (e.g., water temperature), N is total number of decision trees in the forest, and Ti(X) represents the i^{th} tree for the input feature vector (X).

3.3 Monitoring Equipment Deployments

Deployment of monitoring equipment was focused on the previously defined critical habitats for focal aquatic species (Stamford et al. 2017; Hagen et al. 2020; Hagen and Stamford 2021). The deployment strategy was also optimized for modeling inference. The new monitoring equipment bolsters available data from the WSC hydrometric stations and increase the project's ability to make inferences relevant to aquatic ectotherms. Of the fifteen WSC stations in the study area, seven are currently recording stream temperature (Table 1). Equipment deployments in 2022 were focused on the Parsnip, Mesilinka and Ingenika River systems. In 2023, the deployments focused on the proposed expansion of the monitoring array into the Nation, Omineca, Osilinka Rivers. The 2024 field season was focused on maintaining and improving the monitoring array. Stream and river temperatures were monitored using three types of instruments: Existing WSC hydrometric stations, rapid deployments of HOBO Tidbit temperature loggers, and new real-time hydrometric data stations. Lake and reservoir temperatures were monitored using rapid deployment HOBO Tidbit loggers.

3.3.1 Water Survey of Canada Hydrometric Stations

There are 15 active WSC stations within the study area, six of which are actively recording real-time water temperature data (Table 1; Figure 1). Two of the WSC stations are situated in the Williston Reservoir, and the remainder are found in tributary streams. One of two reservoir stations are recording water temperature data (Table 1), and five of 13 stream-based stations are recording water temperature data. All stream-based stations are found in high-order, low elevation, large mainstem rivers that are direct tributaries to Williston Reservoir.

Table 1. Active Water Survey of Canada stations within the Upper Peace River basin.

Station Name	Station ID	Latitude	Longitude	Status	Water Temperature Data Availability
Ingenika River above Swannell River*	07EA004	56.72605	-125.118386	Active	2002-2010; 2022 to 2025
Finlay River above Akie River*	07EA005	57.13271	-125.247204	Active	2002-2010; 2022 - 2025
Akie River near the 760 M Contour	07EA007	57.19254	-124.90845	Active	2002 - 2010
Ospika River above Aley Creek	07EB002	56.524738	-123.938808	Active	2002 - 2025
Omineca River above Osilinka River	07EC002	55.911637	-124.568078	Active	2002 - 2021
Nation River near the Mouth	07ED003	55.427625	-123.633471	Active	2002 - 2010
Nation River near FSJ	07ED001	55.2000008	-124.2333298	Active	NA
Parsnip River above Misinchinka River	07EE007	55.082403	-122.912034	Active	2002 to 2025
Chuchinka Creek near the Mouth	07EE009	54.530208	-122.611008	Active	NA
Pack River at Outlet of McLeod Lake	07EE010	54.987001	-123.039235	Active	2002 - 2021
Carbon Creek near the Mouth	07EF004	55.946402	-122.658709	Active	2007 - 2025
Williston Lake Near Schooler Creek	07EF003	56.1063919	-122.7161102	Active	NA
Williston Lake at Lost Cabin Creek	07EF002	56.049968	-123.7481918	Active	2023 to 2025
Mesilinka above Gopherhole Creek	07EC003	56.2449989	-124.6446686	Active	2002 – 2010; 2022 to 2025
Osilinka near End Lake*	07EC004	56.1269417	-124.801918	Active	2002 to 2025

*Time series contains missing data

3.3.2 Rapid HOBO Tidbit Temperature Loggers

3.3.2.1 Stream Deployments

The deployment design follows elevation gradients, and encompasses areas of high leverage, and critical habitats for Arctic Grayling and Bull Trout (Zimmerman 2006; Stamford et al. 2017; Hagen and Weber 2019). Rapid temperature logger deployment locations were selected during an initial desktop review; however, relocation and the addition of several loggers was necessary due to practical site access considerations (Figure 1). Deployment location coordinates were recorded with a handheld GPS. Discrete temperature readings were taken with handheld thermometers at the time of temperature logger installs and during site visits to validate observed temperature data.

The method used to deploy most temperature loggers utilizes an underwater two-part epoxy to solidify a perforated PVC housing to an available rockface or manmade structure (Isaak et al. 2013). A HOBO Tidbit MX2203 temperature logger is housed within the PVC housing and deployed at a minimum of 30 cm below the water surface. Alternatively, temperature logger housings were installed on a cinderblock and fastened to the shore using a cable in locations where large cobbles or boulders were not available.

Air temperature was recorded at selected sites throughout the study area (Figure 1) using the same Hobo Tidbit loggers, or the Hobo Pendent data logger. Loggers were attached to tree's trunks near breast height several meters back from the top of bank with enough shading from overhead branches to prevent sun exposure.

3.3.2.2 Reservoir Deployments

Within the Williston Reservoir, the Finlay, Peace and Parsnip reaches were targeted for deployments. During installations, logger deployment locations were adjusted based on an evaluation of woody debris at site locations to ensure logger strings would not snag upon retrieval. Reservoir temperatures were monitored using HOBO Tidbit temperature loggers attached to rope and buoys. The highly reflective buoys were anchored to the reservoir bottom with a cinderblock and temperature sensors recorded hourly water temperature at depths of 30 cm, 1 m, and 5 m.

3.3.2.3 Lake Deployments

In 2023 the project team identified that the modeling framework was also easily applied to smaller lakes in the region. Applying the Air2water models to nearby lakes could give insight into how a shifting climate could differentially impact regulated and non-regulated lakes in the Williston Reservoir watershed. Using the same deployment methodology as Williston reservoir, Uslika Lake (small lake < 400 ha) and Chuchi Lake (large lake > 400 ha) were selected in 2023 for temperature string deployments given their ease of access, surface area, and location within the priority watersheds for the project. Both lakes were monitored again in 2024.

3.3.3 New Real-time Hydrometric Stations

The new hydrometric stations measure, in real-time, the timing and quantity of water in the rivers of interest and the water temperature. This is completed by recording the water level every 10 minutes and having a precise network of surveyed benchmarks to reliably ensure that the water level sensor does not move or shift over time. Water level measurements are then converted to a volume of water over time (discharge), typically reported as m^3/s. This is done by building a rating curve of water level (corrected to stage) with multiple instantaneous river discharge measurements. Instantaneous measurements can be done using a variety of instruments, for example a FlowTracker2 (https://www.ysi.com/flowtracker2), and typically involved wading across the stream. When wading is not possible, discharge can be measured with an Acoustic Doppler Current Profiler, Salt Dilution, or more recently from Image Velocimetry techniques. This project, focused on summer conditions and all these systems were wadable during the summer field work.

Hydrometric data collection in BC follows the 2009 Resources Information Standards Committee (RISC) "Manual of British Columbia Hydrometric Standards". The RISC standards are used in this project to ensure the data is of high quality and suitable for broad use. The RISC standards include a rigorous process of grading hydrometric datasets to communicate the quality and the processing decisions of the datasets to future users.

Our real-time data is currently available from the Northern BC Hydrology Research website (https://bcgov-env.shinyapps.io/nbchydro/) and will also be uploaded to the BC Government Aquarius hydrometric data portal following completion of quality assurance and quality checks (https://aqrt.nrs.gov.bc.ca/). Rating curves are currently in draft form and require further discharge measurements from the 2025 season to confirm accuracy. The preliminary rating curves and discharge data are not yet available to the public. This follows a common review period of 1 to 2 years between data acquisition and publication, similar to the Water Survey of Canada.

Considering that station sites are very difficult and costly to access, detailed cross-sectional profiles and stream gradient measurements are collected at each stations site. These can be used to estimate discharge using only river stage from our sensors, the cross-sectional geometry, and the friction coefficients of the streambed. Manning's equation is a widely used formula in hydraulic engineering for calculating the velocity of flow in open channels based on channel shape, roughness, slope, and area of flow. Once the flow velocity is calculated, streamflow can be estimated using Manning’s equation:

$$v = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}}$$

Where v is the cross-sectional average velocity (m/s), n is Manning's roughness coefficient, R is the hydraulic radius (m), which is the cross-sectional area of flow divided by the wetted perimeter, S is the slope of the energy grade line, which is approximately equal to the slope of the channel bed for uniform flow.

With velocity, streamflow (Q) can be calculated by multiplying the cross-sectional area and the velocity calculated above. An understanding of the channel's roughness is required to select an appropriate coefficient. Manning's equation is particularly useful for estimating flow in natural streams where the flow is uniform and steady. However, it's essential to understand that the accuracy of the flow estimates using Manning's equation will depend on the precision of the inputs (cross-sectional measurements, Manning's n, and slope) and the assumption that the flow conditions meet the criteria for which Manning's equation applies (mainly uniform flow). For non-uniform flow conditions, adjustments or different methods may need to be considered.

The field installation for these stations includes a stilling well made of perforated PVC pipe that allows for the water level sensor to have a calm and stable signal, unaffected by waves and ripples (Figure 3). The stilling well is anchored to a large boulder using very robust rock-climbing hardware. Alternatively, if no boulders are available, large trees or rebar were used to stabilize the stilling well (Figure 3). The data loggers used for the new hydrometric stations provide data directly to a database in real-time over the Iridium satellite network.

Crooked River at 200 Rd (Pack Watershed)

Upper Swannell River DS of Orion Creek (Ingenika Watershed)

Tenakihi Creek at Thutade FSR (Osilinka Watershed)

Upper North Anzac River (Parsnip Watershed)

Sylvester Creek at FSR (Nation Watershed)

Suschona Creek at FSR (Nation Watershed)

Figure 3. Field photos of the new hydrometric station installations in the Nation, Ingenika, Osilinka, Parsnip and Pack River watersheds.

Custom-made “do-it-yourself" prototype data loggers from the Ministry of Forest Omineca Research Team, called “RemoteLogger” were used. The loggers use the open-source Arduino coding language with a small microcontroller unit that has an SD card, lithium battery, solar panel, and Iridium modem. The real-time data is sent to a PostgreSQL database and can be visualized in real-time from the web app. This is very useful for decision making, data backups, and fieldwork prioritization. The RemoteLogger costs about $900 in equipment, compared to the $10-20k per station from commercial providers. The Arduino code, parts lists, and wiring diagrams schematics of the RemoteLogger are public and open source (Bevington 2024a) and the project is seeing increased interest for expanded documentation and functionality. A research paper is being written about the data loggers and is currently in draft form (Bevington et al., *in prep.*).

Two different vented pressure transducers were used for this project. The Hydros-21 3-in-1 which measures water level, temperature, and electrical conductivity (~$900 each), and the OTT-PLS 500 that has water level and temperature (~$2,900 each). The two major advantages of the OTT-PLS 500 over the Hydros-21 are that it is much more accurate (<3mm accuracy) and it can freeze solid without breaking. For those locations with turbidity measurements, GeoScientific Analite 195 sensors were used. Sites were selected because they are upstream of WSC stations, are at high elevations, are relevant to Bull Trout spawning habitats, and fill a spatial monitoring gap. Once on site, the selection of the actual monitoring location considers site access, reach stability, stability of stream bank, and availability of a downstream control.

In addition to real-time data loggers and vented transducers, we added stand-alone “throw-in” level loggers and barometric pressure sensors as backups to our RemoteLoggers. This increases the redundancy of our stations and adds independent validation of our measurements.

3.3.4 Hydrometric Station Watershed Characteristics

The new hydrometric monitoring stations attempt to fill gaps in the UPR. These gaps can be thought of both spatially, and in terms of watershed characteristics. Spatial gaps can be assessed by finding areas with no, or very little monitoring, whereas gaps in watershed characteristics are more difficult to characterize.

A new research tool called WatershedBC was developed by the Ministry of Forests, to characterize watershed attributes for both the WSC stations and the new RemoteLogger stations (Bevington 2024b). WatershedBC summarizes physiographic characteristics (e.g. watershed area, hypsometry, stream profile, Melton Ratio, etc.), land cover characteristics (e.g. glacier, wetland, and lake area), forest disturbance characteristics (e.g. roads, harvest and fire history), water allocations (e.g. water licenses, reservoirs, etc.), and climate change (e.g. climateBC normal and future projections).

3.4 Summary of Reach Scale Thermal Habitat Patterns in Bull Trout Spawning Habitats

Water temperature data collected during the 2023 field season and from previously funded FWCP projects (PEA-F22-F-3424) were selected and analyzed to investigate and compare reach-scale thermal habitat patterns. Data collection sites were categorized into deployments within previously delineated Bull Trout spawning habitats or migration corridors, which are utilized by adults during their upstream migrations in the early summer months (Hagen et al. 2023). The sites were selected due to data availability, location within priority watersheds, and focus as an index stream for Bull Trout population monitoring (O’Connor et al. 2024). The spread of sites across the basin provides insight into thermal habitat patterns at the reach scale, across a north-south gradient of nearly the entire basin (Table 2).

Water temperature data was aggregated from three sources including HOBO Tidbit deployments (n = 7), new hydrometric stations (n = 2), and WSC Gauges (n = 2). HOBO Tidbit deployments were completed in five Bull Trout spawning habitat reaches during annual redd surveys (O’Connor et al. 2024; Misinchinka Creek, Scott Creek, Davis River, Pesika Creek, Silver Creek and Mesilinka River). New hydrometrics stations are deployed seasonally and were installed in two Bull Trout spawning habitat reaches in May 2023 (section 4.1.3; Lay Creek and Pelly Creek). Temperature data was gathered from two WSC gauges (Parsnip River and Ingenika River; Table 2). These sites were selected due to data availability and location within priority watersheds, Bull Trout spawning habitats or metapopulation core areas. The spread of sites across the basin provides insight into thermal habitat patterns within reaches and across a north-south gradient of nearly the entire basin.

Table 2. Water temperature monitoring sites used in the analysis of reach-scale thermal habitat patterns.

Site	Bull Trout Metapopulation Core Area*	Data Source	Habitat Type	Elevation (m)	Latitude (°N)	Time Series
Pelly Creek	Finlay Reach	New Hydrometric	Spawning Habitat	989	57.09	2022-07-18 to 2025-01-01
Ingenika River	Finlay Reach	WSC 07EA004	Migration Corridor	686	56.73	2021-09-01 to 2024-10-31
Lay Creek	Omineca	New Hydrometric	Spawning Habitat	1195	56.51	2022-07-16 to 2025-01-01
Mesilinka River	Omineca	WSC 07EC003	Migration Corridor	729	56.33	2022-10-31 to 2024-10-31
Misinchinka River	Parsnip	New Rapid	Spawning Habitat	1021	55.22	2021-09-18 to 2023-09-18
Parsnip River	Parsnip	WSC 07EE007	Migration Corridor	693	55.08	2021-09-01 to 2024-10-31
Davis River	Finlay Reach	New Rapid	Spawning Habitat	962	56.79	2021-09-24 to 2023-09-19
Pesika Creek	Lower Finlay	New Rapid	Spawning Habitat	1287	57.11	2021-09-23 to 2023-09-20
Scott Creek	Parsnip Reach	New Rapid	Spawning Habitat	858	55.80	2021-09-19 to 2023-09-22
Point Creek	Peace Reach	New Rapid	Spawning Habitat	798	55.93	2022-09-18 to 2024-09-21

*'Core areas' are putative metapopulations comprised of fish that are genetically similar and demographically linked (Hagen et al. 2019).

Water temperature data was aggregated and cleaned following methods outlined in Sowder and Steel (2012). Individual data files were summarized, and the daily minimum, maximum and variance were inspected for anomalous conditions such as air exposure. Water temperature has a much lower magnitude, and variance than air temperature making air exposure easily identifiable (Sowder and Steel 2012). Subsequently, time series were plotted and individually inspected further for anomalous conditions which might indicate air exposure. None of the time series used in the analysis of reach scale thermal habitat patterns were found to be compromised by a dewatering event.

Empirical data summaries were calculated for water temperature time series across three ecologically relevant time periods to identify thermal patterns across sites or critical threshold exceedances. Data summaries describing magnitude included the minimum weekly average temperature (mWAT), average weekly average temperature (AWAT), maximum weekly average temperature (MWAT), and variability was described by average weekly coefficient of variation (AWCV).

The time periods over which these metrics were summarized were chosen based on adfluvial Bull Trout life history stages (Hagen and Weber 2019). The adult migration period July 1 to August 24, 2024, encompasses adfluvial Bull Trout migrations from the Williston Reservoir to their spawning habitats. This period also corresponds to "summer thermal conditions". The second period of interest was the adult spawning window from August 25 to September 14, 2024. The juvenile incubation period September 15, 2023, to June 14, 2024, was selected to summarize thermal conditions during egg incubation up to emergence based on the Davis River average emergence date of June 14 estimated by Williamson (2006). Lastly, the rearing period June 15 to October 15, 2024, was selected to represent thermal conditions for rearing juveniles and parr. Accumulated thermal units (ATU) were calculated for the incubation period and the entire year (beginning September 15) for those sites with complete time series in Bull Trout spawning habitats. ATU is often used to investigate how temperature impacts juvenile development and was calculated by taking the daily mean temperature and accumulating those daily means across the period of interest (incubation or annual; Neuheimer and Taggart 2007). Data summaries for 2024 are presented here, but data for project years 2022-2023 are available in O'Connor et al. (2024).

Air temperature time series were extracted for each site from the ERA5-land reanalysis product available through Google Earth Engine (Gorelick et al. 2017). ERA5-Land has a spatial resolution of 9 km^2 and air temperature data is available from 1981 to present at hourly intervals 2 m above earth surface level (Muñoz-Sabater et al. 2021). To rationalize its use in a linear regression O'Connor et al. (2023) compared data at two sites (Misinchinka River and Pesika Creek) where air temperature observation data was available. Their findings were that air temperature data extracted from the ERA5-Land reanalysis product was suitable for use in the thermal sensitivity analysis when compared to observed data (Pearson correlation coefficients: 0.89 for the Misinchinka River and 0.91 for Pesika Creek). Given this, the ERA5-Land time series pulled for this analysis were simply visually inspected to identify any deviations from seasonal norms.

Thermal sensitivity was estimated to investigate the influence of air temperature on water temperature variation at ten sites (Table 2; Snyder et al. 2015; Mochnacz et al. 2022). Groundwater upwelling has been shown to be a key characteristic of Bull Trout spawning habitats and to increase overwintering survival of rearing fry (Baxter and McPhail 1999; Williamson 2006). A low thermal sensitivity is expected within Bull Trout spawning habitats due to the habitat requirements within spawning reaches (i.e., critical habitats) and their typical role as climate refugia in large mountainous watersheds experiencing rapid warming (Isaak et al. 2015).

The thermal sensitivity index was estimated by the coefficient of a linear mixed model in which weekly mean air temperature (prediction) was regressed on weekly mean water temperature (response) at each site, including year as a random effect. These metrics were calculated over the time series lengths presented in Table 2. Weekly time steps were used because they typically provide more precise description of thermal sensitivity. Negative air temperatures were removed from the dataset prior to analysis due to their deviation from the linear approximation and recognition that this is the limit at which further cooling forms ice (Kelleher et al. 2012). Thermal sensitivity was categorized into low (0-0.44) moderate (0.45-0.55) and high sensitivity (>0.56) which provides a first order estimate of how a stream will respond to climate change (Kelleher et al. 2012; Mochnacz et al. 2022).

3.5 Spatial Stream Network Model

A preliminary spatial stream network model (SSNM) was developed for the priority watersheds of this project. SSN models accommodate covariance structures based on flow directionality, branching structures and weighting of tributaries by size to account for spatial autocorrelation in stream temperature datasets, which improves predictive accuracy compared to non-spatial traditional linear models (Ver Hoef and Peterson 2010; Peterson and Ver Hoef 2010). The model was created using the SSNbler and SSN2 packages in R Statistical Software (Peterson et al. 2024; Dumelle et al. 2024; R Core Team 2025). A more detailed description of SSN model formulation is presented by Isaak et al. (2014), and a description of their past applications in the Omineca and Peace regions was reviewed in O'Connor et al. (2024).

The primary objectives of the development of this preliminary model in 2024 were to:

1) Clean and prepare available water temperature data necessary for fitting the SSNM to observed data;
2) Establish a workflow for development of a stream network model utilizing newly developed SSNbler and SSN2 packages;
3) Investigate observed patterns in semivariance and establish that the data attained by this project is adequate for development of accurate model predictions.

Temperature data from HOBO Tidbit loggers, WSC stations and real-time hydrometric stations was cleaned as described in Section 3.4, and MWAT was summarized over the summer feeding period for Arctic grayling (July 1 to September 15th). This time period was selected because it's critical for somatic growth, and the period over which Arctic grayling are exposed to the upper limits of their thermal niche (O'Connor 2023). This time period was selected for a preliminary model run, but it's important to consider SSN models are flexible and can accommodate multiple data summaries necessary to make inferences into the impacts of thermal regimes on species ecology (e.g., spawning periods etc.)

Fifty-four water temperature data time series for the 2024 summer feeding period with at least 60% record completion were utilized as observation data to fit the model. A stream network shapefile was pulled from the British Columbia Freshwater Atlas using the fwapgr package in R (Caslys Consulting 2010; Dalgnaro and Thorley 2025), and prediction points at 5 km intervals were created from the streams layer. Elevation (m) was collected for each observation and prediction point from the Digital Elevation Model for British Columbia available on the BC Data Catalogue. The use of a single fixed effect covariate simplified the model selection process for an initial model build. Elevation has been widely used in SSNM applications as a fixed effect given its direct relationship air temperature and stream size in mountainous watersheds (Steel et al. 2016; Marsha et al. 2021; O'Connor 2023). The observation points, prediction points and streams layer were used to create a spatial stream network object, which holds descriptions of the topological relationships between points on the network and is necessary to estimate spatial parameters and fit the SSNM (Figure 4; Peterson et al. 2024).

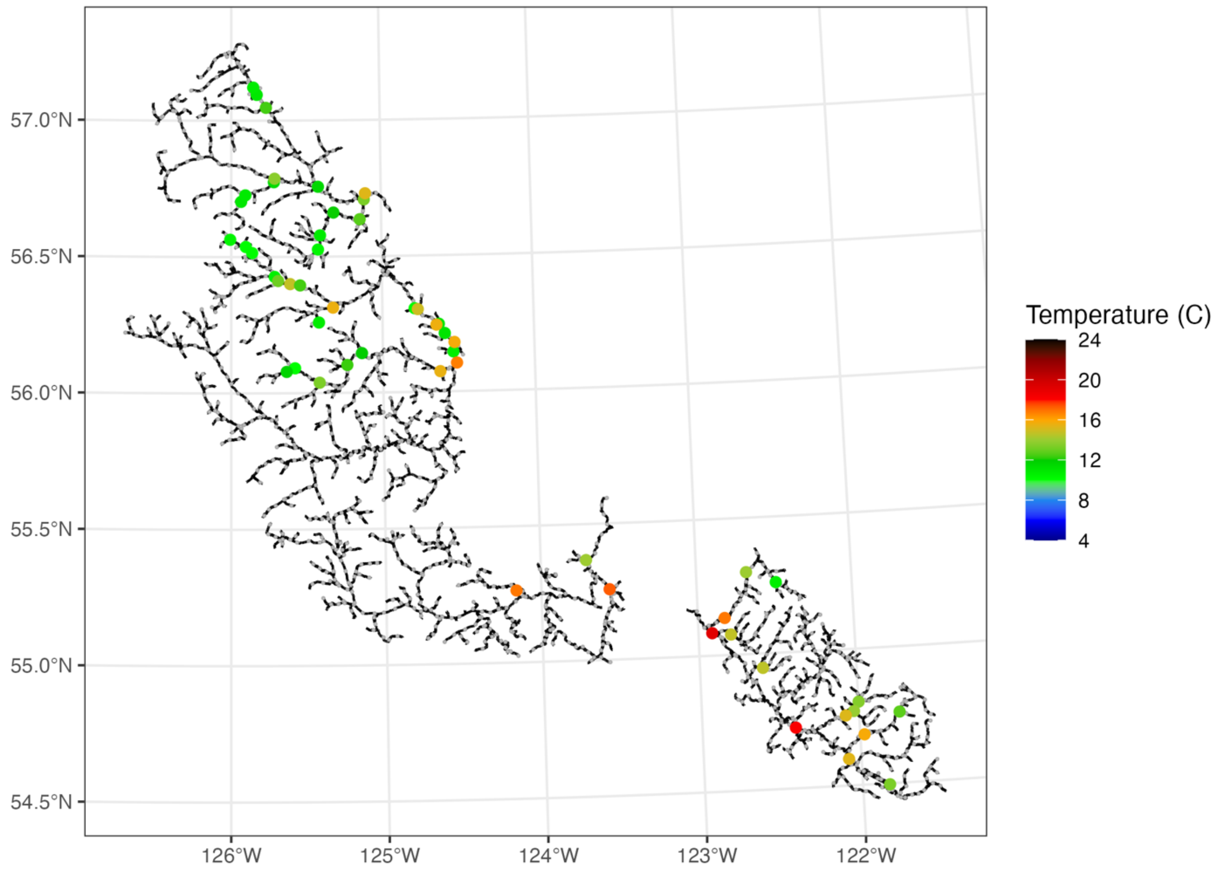

Figure 4. Observation points, prediction points (grey) and the streams used in the stream network model. Observation points display observed maximum weekly average temperature (°C) summarized over July 1 to September 15 2024.

Model selection was completed following the methods outlined in detail in O'Connor (2023). The various covariance function types included in the SSN2 package were assembled into a matrix, and the SSN model was iteratively run on every combination of covariance functions to determine which combination rendered the lowest mean square prediction error (MSPE).

3.6 Basin Scale Model Comparison and Evaluation

In 2024, Roknaldini et al. (in preparation) expanded their modeling evaluation study by incorporating additional statistical and machine learning models, including Generalized Additive Models (GAM) and Random Forest (RF) models, to assess various approaches for simulating freshwater temperatures in northern BC. These new models were implemented at four benchmark sites across the region including the Parsnip River above Misinchinka River (WSC 07EE7), the Upper Fraser River at Shelley (WSC 08KB001), Lost Cabin Creek at the Williston Reservoir (WSC 07EF002), and Atlin Lake (WSC 09AA001). This expansion aimed to provide a more thorough evaluation of predictive models' performance across different types of water bodies.

Roknaldini et al. (in preparation) used a comprehensive set of independent variables to develop statistical and machine-learning models for the rivers, including air temperature, relative humidity, wind speed, precipitation, solar radiation, day of the year (representing seasonal variations), and streamflow. For the reservoir and lake sites, the same set of variables were used, except streamflow was replaced with water level. The study used different time periods for rivers, reservoir and lake simulations based on data availability. The datasets were divided into a training set (70% of the data) and a validation set (30%) to assess model performance on unobserved data. For Parsnip River (2000–2015 for training; 2016–2022 for validation), Upper Fraser River (2006–2017 for training; 2018–2022 for validation), Williston Reservoir (2011–2015 for training; 2016–2017 for validation), and Atlin Lake (2001–2016 for training; 2017–2022 for validation). The analyses focused on the warmer months, (May 1 to September 30). Data including water temperature, water level, and streamflow used in the analysis, were sourced from two WSC hydrometric stations. Additional meteorological data were sourced from the NASA POWER database (Prediction of Worldwide Energy Resources).

To evaluate model accuracy, an inter-model performance comparison was conducted for all predictive models at each site. Subsequently, a multi-model Water Temperature Prediction System (WTPS) was developed by ensembling different models to forecast seasonal water temperature on a daily scale. This system, which integrates an ensemble of models, was evaluated by applying it to real-world forecasts at three different sites, including daily water temperatures at the Parsnip River, Upper Fraser River and Atlin Lake during the warm months (May 1–September 30) of 2023 and 2024, without relying on observed water temperature data for the target years. Available historical data were used to train WTPS across each site: Parsnip River (2000–2022), Upper Fraser River (2006–2022), and Atlin Lake (2001–2022) and predicted water temperature for the warm months of 2023 and 2024 at all sites.

The performance of the Air2Water model was also evaluated across three lentic waterbodies: Williston Reservoir, Atlin Lake, and Fraser Lake to assess its efficiency in capturing daily water temperature variations and to investigate the model's limitations previously observed at Williston Reservoir. Water temperature data were obtained from WSC hydrometric stations for Williston Reservoir and Atlin Lake, while Fraser Lake's data was sourced from the Freshwater Fish Ecology Laboratory (FFEL) at UNBC. WSC hydrometric stations record water temperature using submersible water level sensors primarily designed for monitoring water levels, with temperature data recorded to identify probable sensor-related issues. At Williston Reservoir, water level fluctuations result in temperature readings at depths ranging from 2 to 18 meters. A similar situation exists at Atlin Lake, but at shallower depths. In contrast, Fraser Lake employs surface buoys with loggers, ensuring more consistent and accurate surface temperature monitoring.

4 Results

4.1 Monitoring Equipment Deployments

4.1.1 Rapid HOBO Tidbit Temperature Loggers

Rapid HOBO Tidbit temperature logger data discussed below has been cleaned and inspected and is now hosted and available on the Northern BC Hydrology Research Shiny App (https://bcgov-env.shinyapps.io/nbchydro/).

4.1.1.1 Stream Deployments

HOBO Tidbit MX2203 (Maxim Integrated, USA) water temperature instruments were installed or maintained from July 3 to 13, 2024. Downloads, maintenance and removal, if necessary, occurred in September, October, and November 2024. In total, 89 loggers were deployed and/or active within the 2024 stream array. Twenty-one in the Ingenika watershed, 22 in the Mesilinka watershed, 23 in the Parsnip watershed, five in the Nation watershed, eight in the Osilinka watershed, one in the Omineca watershed, two in Pesika River, two in Scott Creek, two in Point Creek, and there in Davis River (Figure 1). Due to the risk of losing loggers during the ice-covered months of winter, most loggers are removed during the fall download fieldwork. Exceptions are data loggers that are deployed within index sections of a concurrently funded FWCP project (Rossi et al. 2025; FWCP project No. PEA-F25-F-4054) and only downloaded once annually during Bull Trout redd counts. These streams include Davis River (three loggers), Pesika Creek (two loggers), upper Pelly Creek (two loggers), upper Misinchinka River (three loggers), Scott Creek (two loggers) and Point Creek (two loggers). A weather event September 21, 2024, prevented the crew from downloading data loggers in headwater tributaries in the Parsnip River. Two loggers were lost from streams during summer 2024 (one from Scott Creek and one from the Table River).

In 2024, air temperature data was downloaded from Davis River, Matetlo Creek, Mesilinka River, Nation River, Point Creek, Scott Creek (two sites), and Tutizika River for a total of eight sites (Figure 1). Three active air loggers were not retrieved due to weather prohibiting site access including Ingenika River, Pesika Creek and an Unnamed tributary to Reynolds Creek.

4.1.1.2 Reservoir Deployments

From June 18 to 20, 2024, nine HOBO Tidbit temperature loggers were deployed in the Williston Reservoir (Figure 1) in the Peace (three loggers), Parsnip (three loggers) and Finlay Reaches (three Loggers). The Peace Reach Loggers were downloaded on September 28, 2024; however, the Parsnip and Finlay reach loggers were lost due to unknown reasons.

4.1.1.3 Lake Deployments

On July 12, and 13, three HOBO Tidbit temperature loggers were deployed in Chuchi Lake Uslika Lake, respectively (Figure 1). The Chuchi Lake loggers were downloaded and removed September 23, and the Uslika Lake Loggers were downloaded and removed October 5, 2024.

4.1.2 New Real-time Hydrometric Stations

Hydrometric monitoring for this project did not expand in 2024 (Table 3). The goal of the 2024 field season was to ensure high quality data is being recorded at the existing stations and to ensure multiple discharge measurements at each station. The stations proved to be very reliable in 2024. The stations were also left in place for the 2024-2025 winter season, which will facilitate access and installation during the 2025 season, compared to years past where stations were removed in the fall and re-installed in the spring. In 2024, the FlowTracker 2 died in the field during the early summer deployments. This reduced the number of successful discharge measurements attained. This failure occurred at the Pelly Creek West of Mt Russel station (07EA0001), which is helicopter access. Nevertheless, 34 discharge measurements were completed in 2024, compared to 20 in 2022 and 43 in 2023, for a total of 97 discharge measurements to date for this project (Table 3).

Table 3. Metadata for the sixteen real-time hydrometric stations installed by this project.

#	Station Name (Access)	ID	Lat, Lon (WGS84)	RT	Elev. (m)	Active Years (Status)	Q Count '22/'23/'24
INGENIKA WATERSHED							
1	Pelly Cr West of Mt Russel (H)	07EA0001	57.0946, -125.8280	Yes	989	2022 – 2025 (A)	1 / 2 / 2
2	Up. Swannell Riv DS of Orion Cr (H)	07EA0002	56.5451, -125.6340	Yes	1281	2022 – 2025 (A)	1 / 3 / 2
MESILINKA WATERSHED							
3	Lay Cr at Thutade FSR (T)	07EC0001	56.5146, -125.8610	Yes	1195	2022 – 2025 (A)	2 / 3 / 2
OMINECA WATERSHED							
4	Tenakihi Cr at Thutade FSR (T)	07EC0002	56.1902, -125.1970	Yes	914	2022 – 2025 (A)	1 / 2 / 2
NATION WATERSHED							
5	Sylvester Cr at FSR (T)	07ED0001	55.2648, -124.1612	Yes	908	2023 – 2025 (A)	0 / 3 / 2
6	Suschona Cr at FSR (T)	07ED0002	55.1645, -124.2242	Yes	907	2023 – 2025 (A)	0 / 3 / 1
PACK RIVER WATERSHED							
7	Crooked Riv at 200 Rd (T)	07EE0010	54.4848, -122.7178	Yes	903	2023 – 2025 (A)	0 / 1 / 4
PARSNIP WATERSHED							
8	Anzac Riv at East Anzac FSR (T)	07EE0001	54.9808, -122.1770	Yes	871	2022 – 2025 (A)	2 / 4 / 3
9	Little Anzac (T)	07EE0002	54.9826, -122.1850	Yes	865	2021 – 2025 (A)	2 / 0 / 3
10	Fast Crat BC Rail (T)	07EE0003	55.0762, -122.7850	Yes	735	2022 – 2025 (A)	6 / 6 / 5
11	Reynolds Cr at Reynolds FSR (T)	07EE0004	54.9980, -122.5705	Yes	793	2022 – 2025 (A)	3 / 3 / 3
12	Upper North Anzac Riv (H)	07EE0005	55.085, -122.3190	Yes	1030	2022 – 2025 (A)	2 / 2 / 0
13	Bracey Cr at Crocker FSR (T)	07EE0007	54.9278, -122.1998	Yes	877	2022 – 2025 (A)	0 / 4 / 3
14	Crocker Cr at Crocker FSR (T)	07EE0009	54.9045, -122.2378	Yes	804	2023 – 2025 (A)	0 / 6 / 2
15	Coulbourne Cr at FSR (T)	*NA*	55.0763, -122.6323	No	808	2023 – 2025 (AN)	0 / 1 / 0
16	Bracey Cr abv Unnamed Trib. (T)	*NA*	54.9228, -122.1776	No	930	2021 – 2022 (D)	0 / 0 / 0

Note: Q = Discharge measurement; A = Active real-time; AN = Active not real-time, D = Decommissioned; H = Helicopter access; T = Truck access; RT = Realtime telemetry; Cr = Creek; Riv = River; Mt = Mountain; DS = Downstream; FSR = Forest Service Road

Preliminary rating curves exist where possible, however each station has different quality in terms of its life history. The following paragraphs summarize the main status of each station, following the station order in Table 3.

Pelly Creek West of Mt Russel (07EA0001) has a good preliminary rating curve. The station and benchmarks have been stable over the entire timeseries (Figure 5). The river right location of the Upper Swannell River DS of Orion Creek station was inaccessible due to helicopter safety concerns and high water. Consequently, the station was installed on river left, about 20 m upstream from the typical monitoring location. As such, the rating curve needed to be restarted. The Lay Creek at Thutade FSR station was moved three times in three years and, consequently, has three separate partial rating curves for the three separate gauging locations. Tenakihi Creek at Thutade FSR (07EC0002) has been in the same location since the beginning but has experienced a significant wildfire and there are hundreds of large trees that have fallen into the creek, which impacts the stage-discharge relationship.

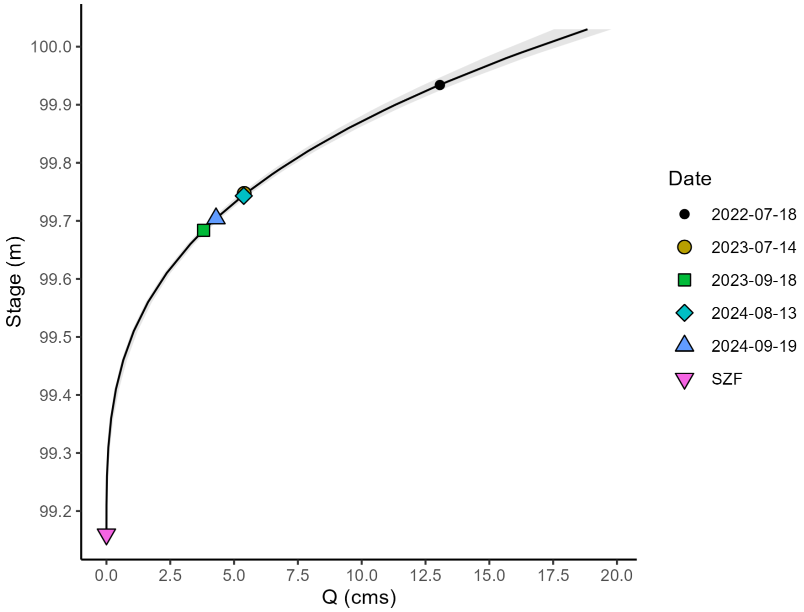

Figure 5. Preliminary rating curve for Pelly Creek West of Mt Russel. Discharge (Q) in cubic metres per second (cms) is on the x-axis and stage is on the y-axis. Points are manual measurements of stage and discharge. The curve is extended 20% beyond the range of observations.

Reliable rating curves for both Sylvester Creek at FSR (07ED0001) and Suschona Creek at FSR (07ED0002) are near completion. Crooked River at 200 Rd (07EE0010) is also progressing well towards a rating curve. These three stations are in much lower elevation and warmer systems and provide insight into contrasting watersheds compared to the rest of the higher elevation stations.

The Anzac River at East Anzac FSR (07EE0001) and Little Anzac (07EE0002) stations have been moved multiple times over the years due to vandalism, and unstable gauging locations. The sites are now located in excellent long term monitoring locations and are progressing towards a rating curve. The Fast Creek at BC Rail (07EE0003) station was installed prior to the beginning of this project and has a reliable rating curve. Reynolds Creek at Reynolds FSR (07EE0004) was moved in 2023, and again in 2024. It was originally located in a riffle downstream of the bridge on river right, then moved closed to the bridge in 2023 dues to very low water levels, and then in 2024 was moved to a very nice gauging pool in 2024.

Upper North Anzac River (07EE0005) has been a very challenging location fraught with sensor failures and animal damage. For this reason, the preliminary rating curve will benefit from one more season. Bracey Creek at Crocker FSR is located in an excellent location and had a stable rating curve until a large tree fell down and caused a large amount of sedimentation that has changed the channel cross section. Crocker Creek at Crocker FSR (07EE0009) is a challenging location with steep bedrock access. It moved three times over it's life history. Coulbourne Creek at FSR only has one discharge measurement so far, and Bracey Creek above Unnamed Tributary was decommissioned in 2022.

The preliminary rating curve for Pelly Creek was applied to the corrected time series stage data from the hydrometric station to produce a timeseries of discharge that can be compared to the WSC station downstream (Figure 6).

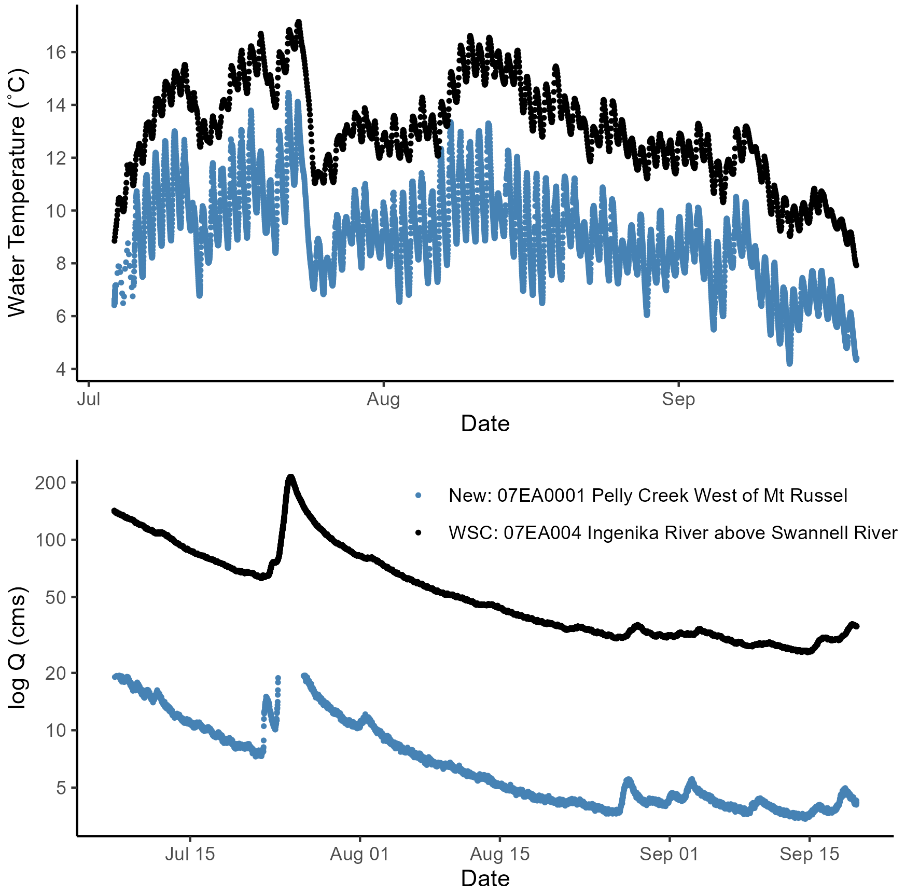

Figure 6. Preliminary discharge timeseries from 07EA0001 Pelly Creek West of Mt Russel and comparison to the WSC station 07EA004 Ingenika River above Swannell River.

4.1.3 Water Survey of Canada Temperature Data

Water temperatures from the WSC stations in the study area were operational for much of 2024 (Figure 7). The Finlay River, Omineca River, and Nation River stations only had partial coverage and the Pack River data appears questionable (much colder than all other stations, very widespread between years, and approaches 5°C in July). These sites are presented in Figure 7 to demonstrate that there are limitations with WSC stream temperature data. Water Survey of Canada (WSC) stream temperature data is often reported from the water level sensor, which can be in an external well drilled next the stream. For this reason, some of the WSC station data should be validated with sensors in the main stem. Daily average water temperatures were generally above average in 2024 with the warmest temperatures in late July 2024.

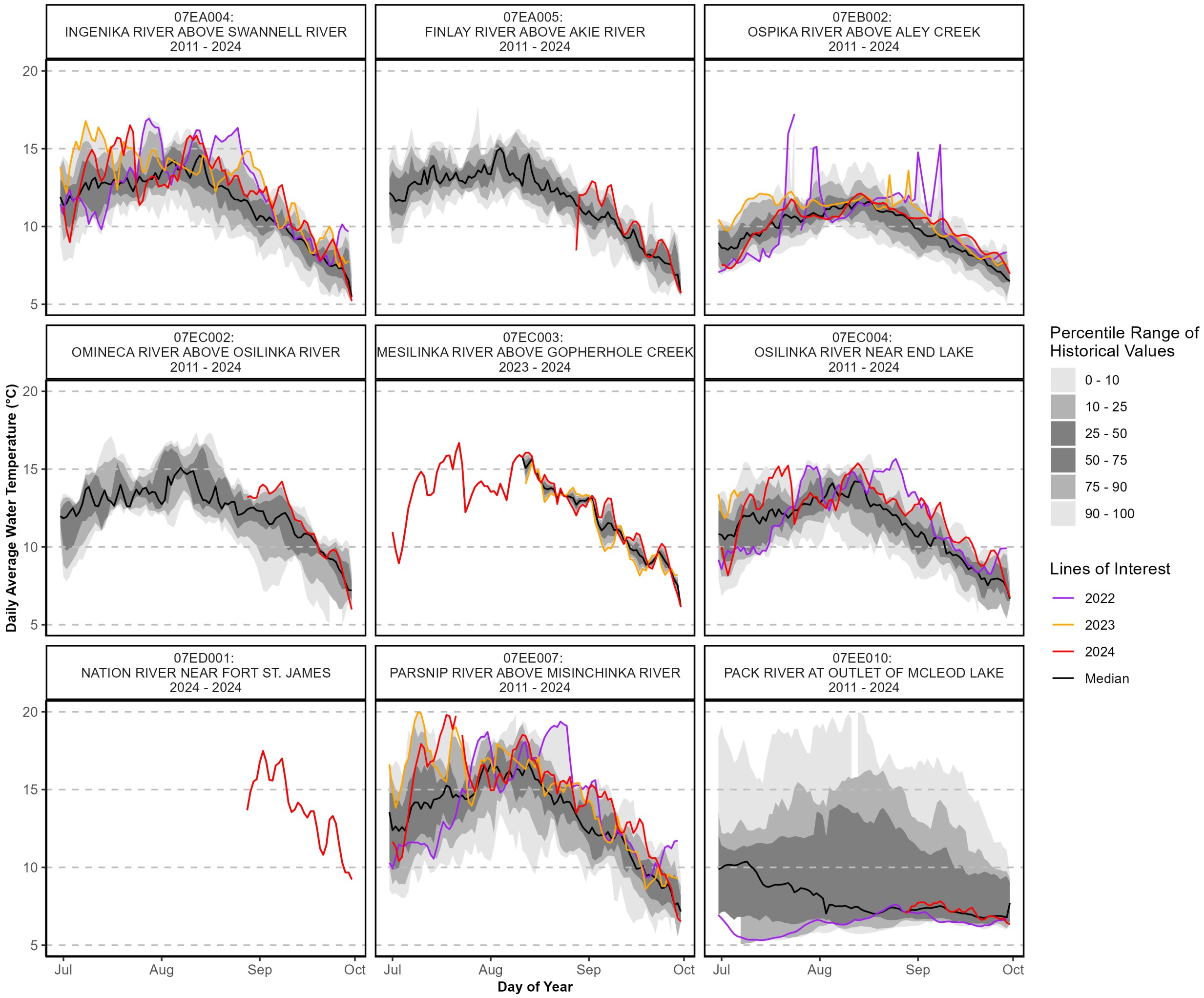

Figure 7. Daily water temperature percentiles from active WSC gauges for rivers of interest within the study area from 2011 to 2024. Each panel represents a different monitoring site, displaying the percentile range of historical temperature values (shaded gray areas) alongside temperature trends for selected years (2022 in purple, 2023 in orange, and 2024 in red). The black line represents the median historical temperature.

4.2 Summary of Reach Scale Thermal Habitat Patterns in Bull Trout Spawning Habitats

Similar to observations made in 2022 and 2023, exceedances of ecologically relevant thermal limits for Bull Trout (11ºC and 13ºC) in 2024, were limited to the migration corridor sites (WSC stations) in lower elevation mainstem rivers (Figure 8). Additionally, very few exceedances occurred in spawning habitats, suggesting all monitored spawning habitats are continuing to meet the thermal habitat requirements of Bull Trout (Table 4). The lower Parsnip River continues to stand out as one of the warmer stream reaches of the upper Peace River (Bull Trout rearing period MWAT 19.17ºC), potentially excluding Bull Trout during the summer months. Point Creek stands out in 2024 as an exceptionally cold stream, showing the lowest MWAT (7.22ºC) during the migration period, which contains the warmest months of the year.

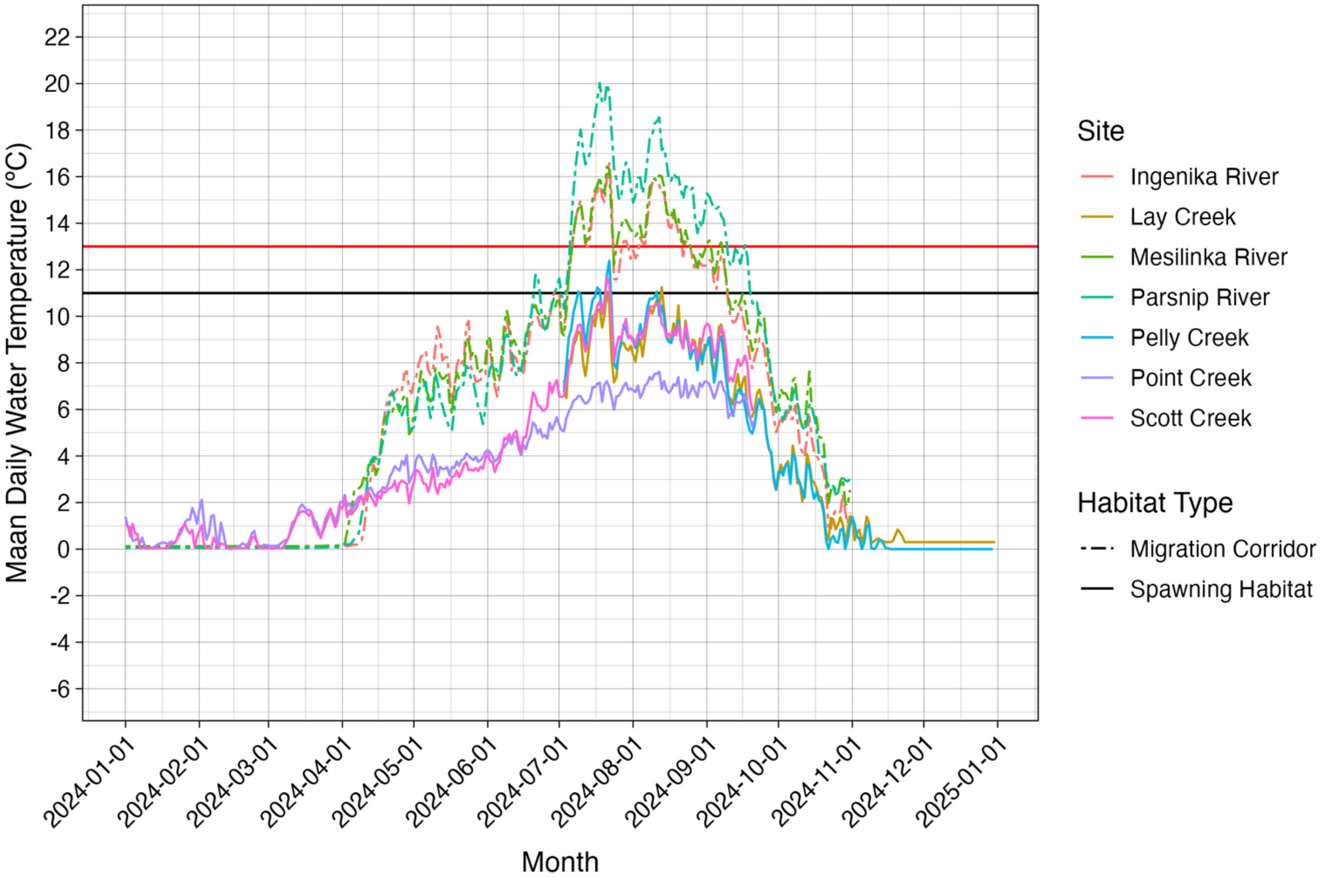

Figure 8. Average Daily Water Temperature in 2024 from sites selected for analysis of reach-scale thermal habitat patterns. The black horizontal line indicates 11ºC, a provincially designated thermal threshold for Bull Trout (Parkinson et al. 2016) and the red horizontal line highlight exceedances of 13ºC above which feeding, and occurrence are known to decrease (Selong et al. 2001; Mochnacz et al. 2022).

Table 4. Summarized 2024 thermal metrics from sites selected for analysis of reach-scale thermal habitat patterns. Thermal metric summaries where text is underlined highlight exceedances of 11°C a provincially designated thermal threshold for Bull Trout (Parkinson et al. 2016) and those with red text highlight exceedances of 13°C above which feeding, and occurrence are known to decrease (Selong et al. 2001; Mochnacz et al. 2022).

Thermal Metric	Pelly Creek*	Ingenika River	Lay Creek*	Mesilinka River	Parsnip River	Point Creek*	Scott Creek*
Migration Period 2024-07-01 to 2024-08-24							
mWAT (ºC)	8.10	11.16	7.73	11.07	12.25	5.64	7.40
AWAT (ºC)	9.58	13.64	9.07	14.00	16.29	6.71	9.29
MWAT (ºC)	10.92	15.28	10.11	13.49	19.17	7.22	10.49
AWCV (%)	0.15	0.07	0.18	0.08	0.08	0.15	0.14
Spawning Period 2024-08-25 to 2024-09-14							
mWAT (ºC)	6.49	10.27	6.89	10.69	12.67	6.09	7.69
AWAT (ºC)	7.85	11.88	8.16	12.23	14.28	6.67	8.54
MWAT (ºC)	8.37	13.01	8.69	12.97	15.39	6.97	9.05
AWCV (%)	0.11	0.04	0.14	0.06	0.07	0.12	0.12
Incubation Period 2023-09-15 to 2024-06-14							
mWAT (ºC)	NA	0.03	NA	0.12	0.05	0.07	0.02
AWAT (ºC)	NA	2.90	NA	3.17	2.99	2.38	2.08
MWAT (ºC)	NA	9.30	NA	11.06	11.06	6.13	6.81
AWCV (%)	NA	0.31	NA	0.21	0.24	0.35	0.54
Rearing Period 2024-06-15 to 2024-10-15							
mWAT (ºC)	3.19	4.94	3.26	6.20	5.91	4.25	4.50
AWAT (ºC)	7.52	10.71	7.38	11.29	12.57	6.26	8.28
MWAT (ºC)	10.92	15.28	10.11	15.60	19.17	7.22	10.49
AWCV (%)	0.15	0.07	0.18	0.08	0.08	0.13	0.14
ATU - Incubation	NA	769.80	NA	835.31	787.21	633.93	527.15
ATU - Annual	NA	1917.25	NA	2016.68	2139.96	1222.52	1315.76

* Site is within a previously delineated Bull Trout critical spawning habitat.

Similar to the results for summarized thermal metrics, the migration corridor sites showed a high thermal sensitivity to air temperature and were all categorized in the high thermal sensitivity category (Table 5). Interestingly Davis River and Scott Creek were also categorized as highly thermal sensitive. Davis River has amongst the highest estimated spawner production in Williston Reservoir tributaries and is prioritized as a top candidate for conservation actions (Hagen et al. 2023). Scott Creek has shown a negative population growth rate for spawner abundance and has a barrier restricting spawner access to upper portions of the watershed (Rossi et al. 2025). Pelly Creek, Pesika Creek and Lay Creek were all categorized as intermediate. Point Creek and Misinchinka River were both categorized as low sensitivity, and present as exceptionally cold streams, highlighting their importance as potentially outstanding thermal refugia (Figure 9).

Table 5. Results from the thermal sensitivity analysis for each site in 2023. The thermal sensitivity index was expressed as the slope of the linear regression relationship between weekly mean water temperature and air temperature.

Site	Thermal Sensitivity Index	Standard Error	Thermal Sensitivity Category
Pelly Creek	0.53	0.04	Moderate
Ingenika River	0.63	0.03	High
Lay Creek	0.47	0.05	Moderate
Mesilinka River	0.75	0.05	High
Misinchinka River	0.37	0.04	Low
Parsnip River	0.84	0.04	High
Davis River	0.61	0.06	High
Pesika Creek	0.53	0.04	Moderate
Point Creek	0.31	0.03	Low
Scott Creek	0.56	0.04	High

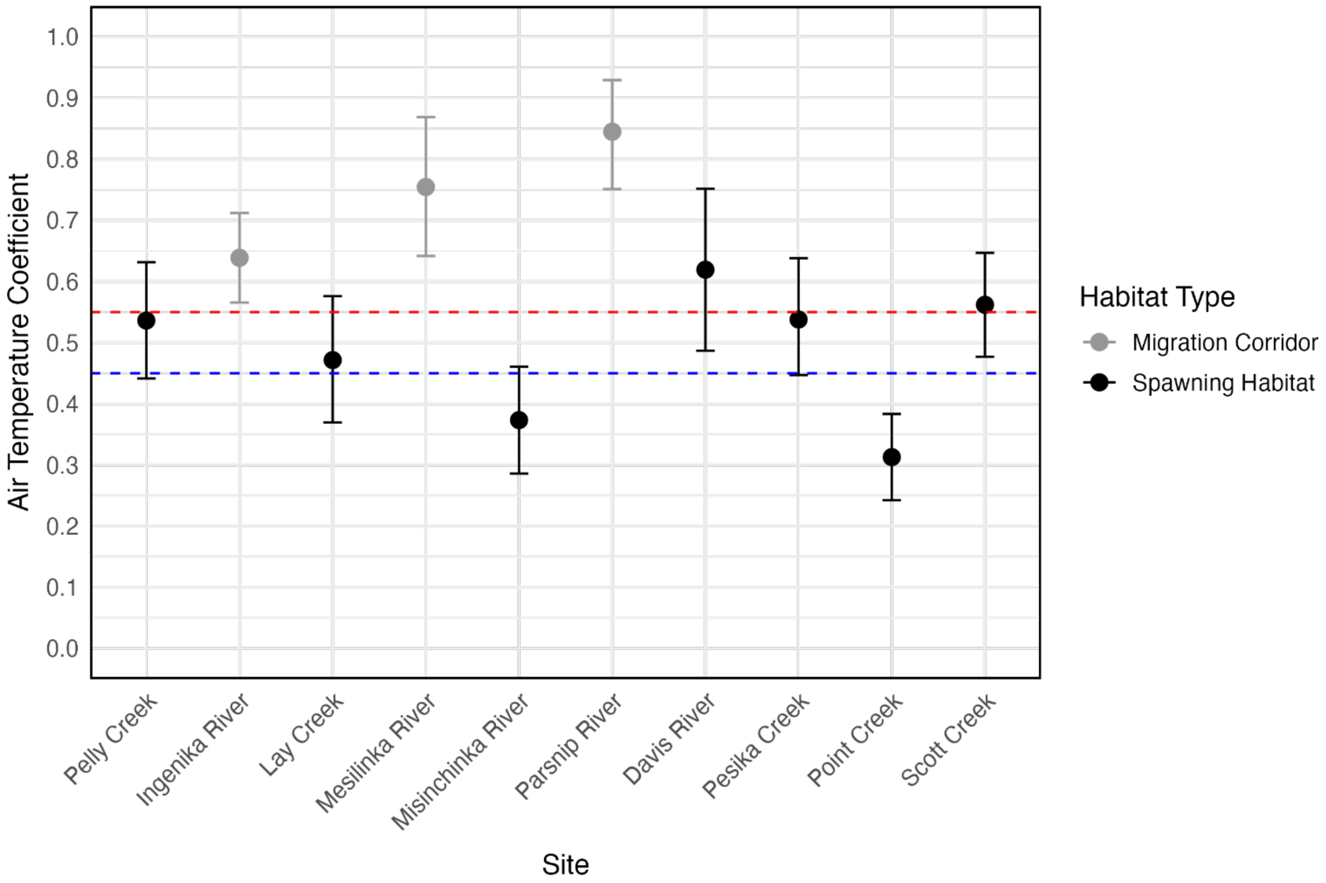

Figure 9. Air temperature coefficients (points) and 95% confidence intervals (error bars) from generalized linear models of weekly average air temperature (predictor) regressed on weekly average water temperature data from 2022-2024. Thermal sensitivity expressed as the air temperature coefficient provides an estimate of the influence of air temperature on water temperature and is categorized into low (0-0.44), moderate (0.45-0.55) and high sensitivity (>0.56). The blue and red horizontal dashed lines delineate the transitions between categories. The color shade of points and error bars corresponds to the habitat type a site is within.

4.3 Spatial Stream Network Model

The model which provided the lowest MSPE (1.81ºC) included a Mariah tail-up, linear tail-down and magnetic Euclidean covariance functions. The Euclidean covariance function and elevation covariate explained most of the variation in MWAT (0.975) over the summer feeding period (Table 6).

Table 6. Variability in maximum weekly average temperature explained by fixed effects in the spatial stream network model.

Fixed Effect	Proportion of Variability
Elevation	0.241
Mariah Tail-up	0.018
linear Tail-down	0.006
Magnetic Euclidean	0.734
Nugget (error)	0.0003

The model residuals suggest the SSNM is underpredicting warmer sites, with one instance of prediction error greater than 6ºC (Figure 10). This prediction error should be corrected by including more sites in areas of high leverage, improving inference into spatial patterns in semivariance and increasing the number of explanatory fixed effects known to influence water temperature (e.g., air temperature or other climate and landscape variables).

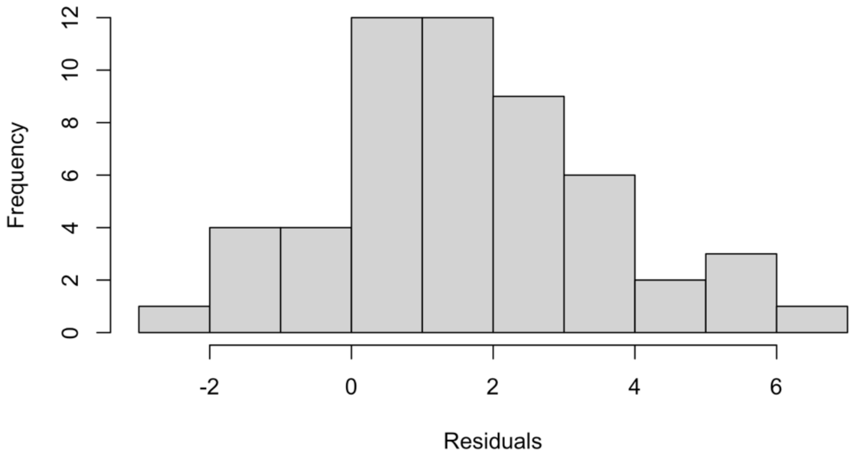

Figure 10. Histogram of residuals from the spatial stream network model. Residuals are calculated as the response (maximum weekly average temperature) minus the fitted values for the response.

Stream network model predictions reveal warmer conditions predominantly present in the lower elevation streams in the southwest portion of the UPR basin (Nation River and lower Parsnip River; Figure 11). The Ingenika River and high elevation portions of the Parsnip River stand out as cold stream reaches. Given the model diagnostics presented above, it's reasonable to assume that MWAT predictions in unmonitored stream reaches (e.g., upper Omineca River) have some prediction error, and should be interpreted with caution until the SSNM can be refined.

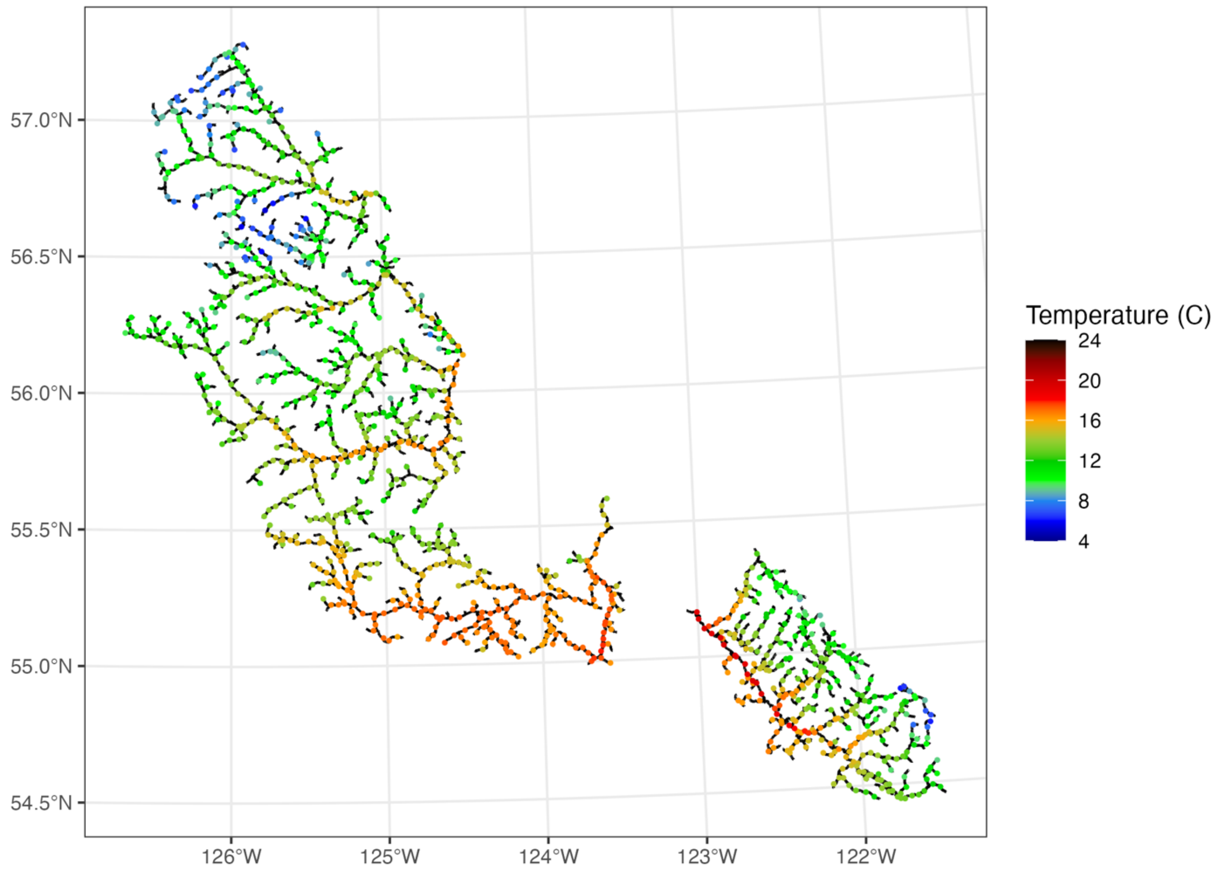

Figure 11. Predictions of maximum weekly average temperature during July 1 to September 15, 2024 generated by the spatial stream network model for study streams in the upper Peace River basin.

4.4 Basin Scale Model Comparison and Evaluation

The predictive performance of RF and GAM models for the Parsnip River (2016–2022) and Upper Fraser River (2018–2022) during their validation periods is presented in (Figure 12). The MAE ranged from 0.7°C to 0.9°C and RMSE from 0.8°C to 1.2°C across both sites, with GAM generally showing slightly lower errors. Both models effectively captured seasonal and daily water temperature variations; however, RF exhibited a colder bias during peak temperatures at Parsnip River and a warmer bias from May to August at Upper Fraser River.

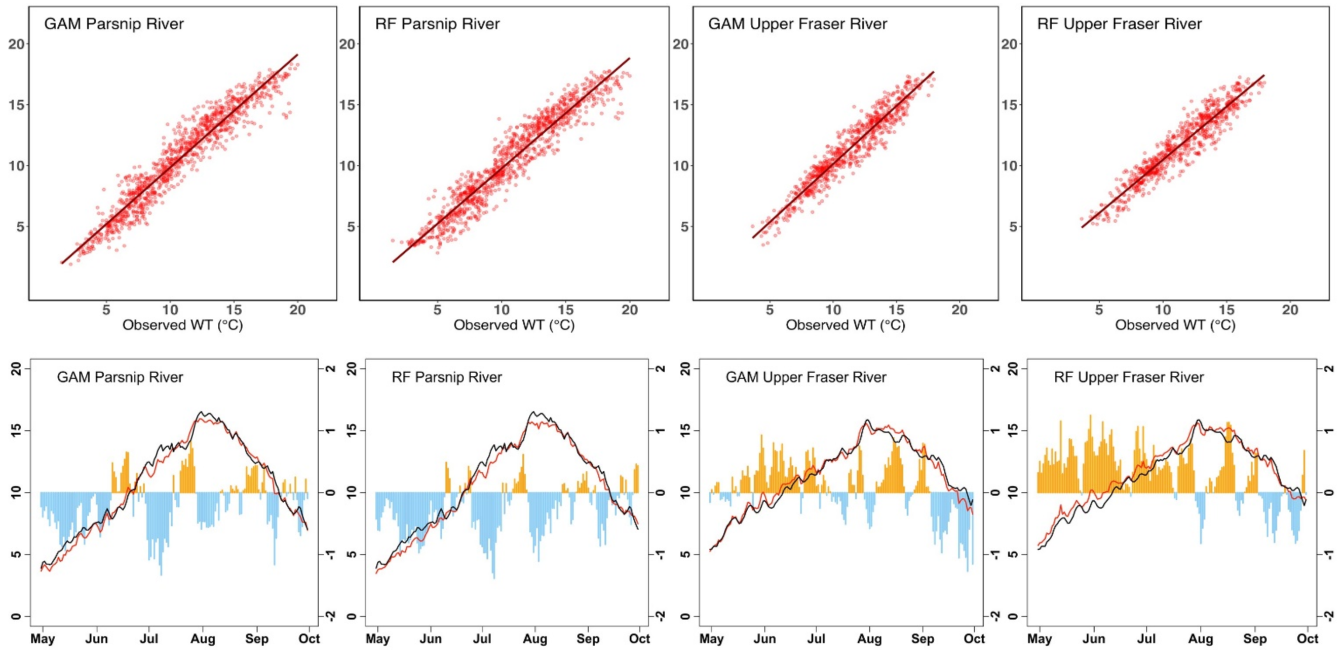

Figure 12. Comparison of predictive performance and seasonal biases of GAM and RF models for water temperature (WT) in the Parsnip River and Upper Fraser River from May to September. Scatter plots show observed vs. simulated WT and time series plots represent observed (black) and simulated WT (red) with bias (orange = warm, blue = cold).

The performance of GAM and RF models for the Williston Reservoir (2016–2017) and Atlin Lake (2017–2022) sites during their respective validation periods is illustrated in Figure 13. At the Reservoir, both models showed good agreement with observed water temperatures, where RF captured more variability and better reflected daily fluctuations, while GAM exhibited a smoother response, slightly underestimating extreme variations. Bias plots reveal that RF had larger deviations during peak temperature periods, whereas GAM maintained greater stability. For both models RMSE and MAE values ranged from 0.8°C to 1.0°C. At Atlin Lake, both models effectively tracked temperature patterns while consistently reproducing colder temperatures throughout the season. However, the GAM model maintained a slightly closer simulation to observation, allowing it to better capture peak temperatures. The RMSE and MAE values in Atlin Lake fell within the range of 1.3°C to 1.4°C, indicating comparable predictive accuracy for both models.

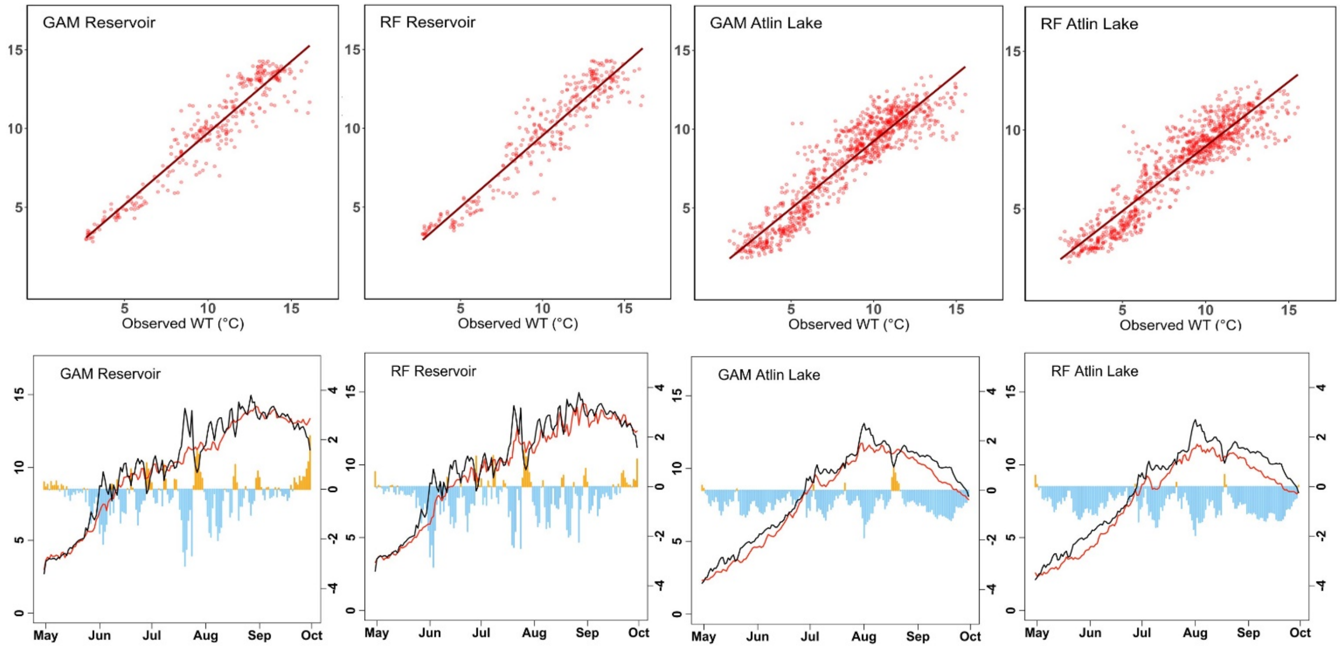

Figure 13. Comparison of predictive performance and seasonal biases of GAM and RF models for water temperature (WT) in the Williston Reservoir and Atlin Lake during warm months (May–September). Scatter plots show observed vs. simulated WT and time series plots represent observed (black) and simulated WT (red) with bias (orange = warm, blue = cold).

In addition to GAM and RF models, several statistical, machine learning and hybrid models (MLR, ANN, Air2Stream and Air2Water) were also applied across basins to develop a comprehensive multi-model WTPS. The WTPS was tested at the Parsnip River, Upper Fraser River, and Atlin Lake sites to predict water temperatures during the warm months of 2023 and 2024, yielding promising results (Figure 14). In the Parsnip River, the model effectively captured seasonal variability with high consistency, resulting in an RMSE of 1.5°C and MAE of 1.4°C. In the Upper Fraser River, the model successfully tracked seasonal and daily variations while exhibiting a cold bias during peak summer months, with an MAE of 1.2°C and RMSE of 1.4°C. In Atlin Lake, the model effectively captured both short-term fluctuations and long-term patterns, despite slightly cold bias during peak temperatures, yielding an RMSE of 1.5°C and MAE of 1.3°C. Considering minor biases, the ensemble predictions consistently reflected observed temperature patterns across all sites.

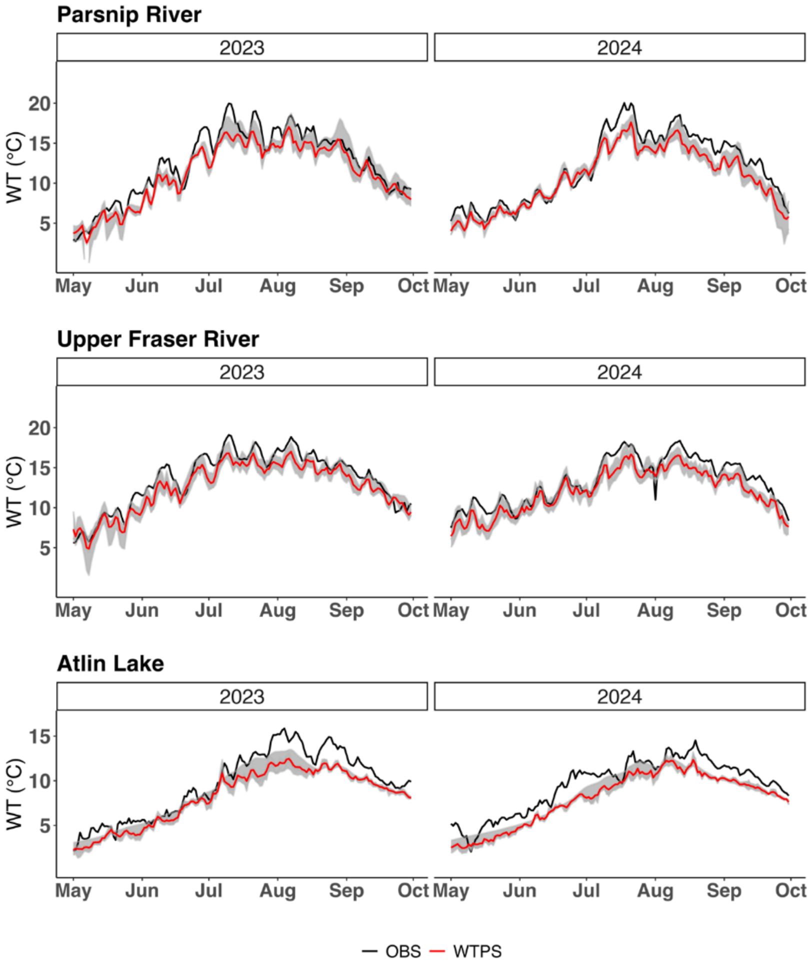

Figure 14. Performance of WTPS in predicting water temperature for the Parsnip River, Fraser River, and Atlin Lake during warm months (May–September) of 2023-2024. The red line shows the WTPS ensemble prediction, the black line represents observed temperatures, and the gray shading indicates the prediction range from all models included in the WTPS.

Further analysis of the Air2Water model's performance across Williston Reservoir, Atlin Lake, and Fraser Lake (Figure 15) revealed significant variability, likely influenced by differences in water temperature monitoring methods and their impact on air-water temperature correlations. At Williston Reservoir, where water temperature was recorded at greater depths, the model had difficulty capturing daily variations, resulting in an excessively smoothed response. While it reasonably tracked seasonal patterns, it failed to represent short-term variations accurately. This limitation was reflected in the weak correlation between air and water temperatures of 0.17 in this site. At Atlin Lake, which employed the same monitoring method, but within a shallower depth range, the model showed improved performance but still exhibited some smoothing of daily temperature variations. The air-water temperature correlation of 0.56 indicates the model was less restrictive compared to Williston Reservoir. In contrast, at Fraser Lake, where water temperature was monitored using surface buoys, the model achieved the highest accuracy. Air2Water effectively captured both seasonal trends and daily fluctuations, demonstrating reduced bias and stronger alignment with observed data. The strong correlation of 0.79 between air and water temperatures further supports the model's effectiveness in this site.

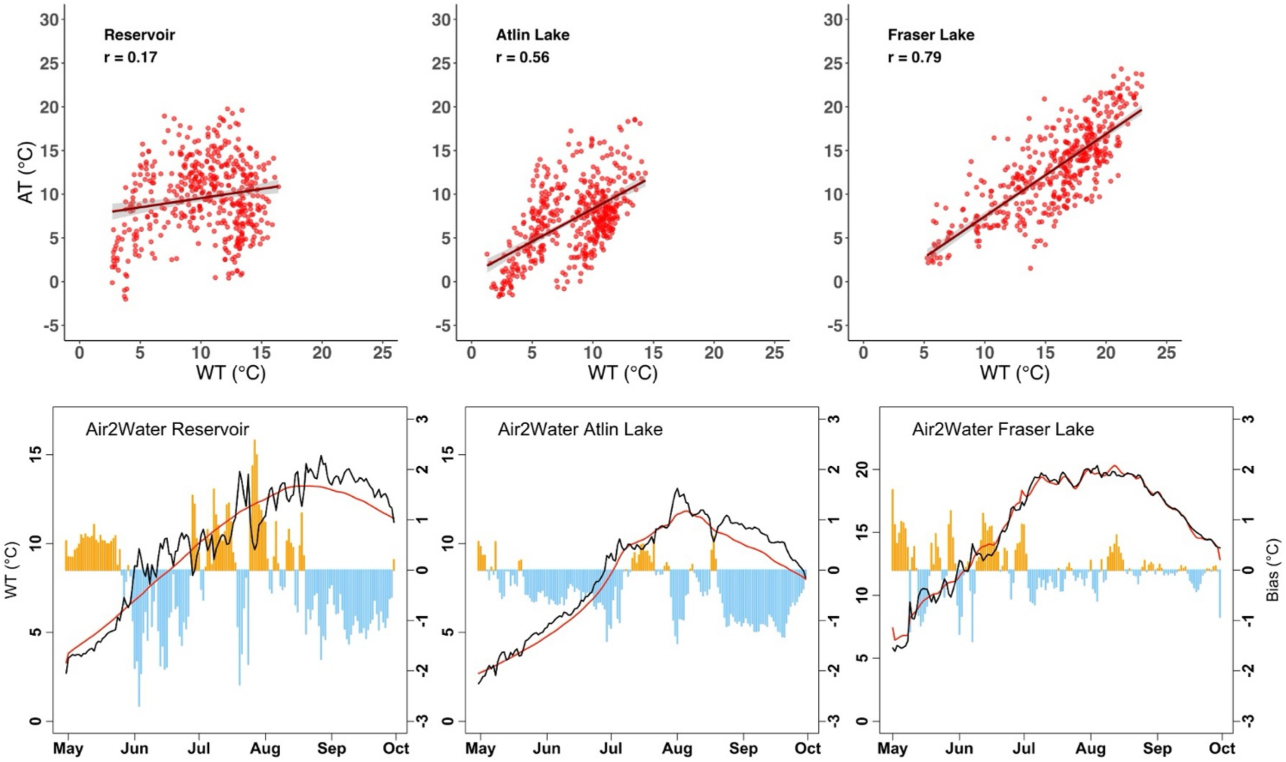

Figure 15. Air2Water model performance in relation to air-water temperature correlation across three locations. The top row illustrates the correlation between observed air temperature (AT) and water temperature (WT) at Williston Reservoir (2018-2020), Atlin Lake (2020–2022), and Fraser Lake (2020-2022) during warm months (May–September). The bottom row presents Air2Water model performance at these sites, highlighting how AT-WT correlation influences model accuracy, with stronger correlations (Fraser Lake) leading to better predictions and weaker correlations (Williston Reservoir) resulting in greater bias and smoothed responses.

5 Discussion

5.1 New Real-time Hydrometric Stations

The new hydrometric stations from this project are capturing critical data in a period of widespread and continued drought in the Omineca Region. Moreover, the areas covered by the new stations are underrepresented in existing Water Survey of Canada datasets, which emphasizes their importance for not only monitoring but also for modelling (Figure 1). These stations play a critical role in this study to calibrate and validate models. The data, however, continues to be tentative until more discharge measurements are completed. Typically, hydrometric stations receive a minimum of 6 site visits per year where discharge and stage are both surveyed across the entire range of annual flows, however due to the remote locations involved in this project, we visit the stations between 2 and 3 times per year. As a result, we have focussed our efforts on developing low-flow rating curves that estimate discharge within 10 percent of the stage values where we have reliable discharge measurements (e.g., Figure 5, Figure 6). This means that our data will not be suitable for calculations such as mean annual discharge but will be useful for discharge during low-flow periods, which is the period of interest in this study.

5.2 Summary of Reach Scale Thermal Habitat Patterns in Bull Trout Spawning Habitats

Investigations into reach scale thermal habitat patterns have revealed patterns identified in the published literature on thermal suitability and refugia in headwater basins (e.g., Isaak et al. 2016), but also revealed surprising variation. Low thermal sensitivity and cold temperatures, in addition to groundwater influence and low disturbance, exemplify the spawning habitat requirements of Bull Trout (Baxter and McPhail 1996; Rieman and McIntyre 1993). Similar to past observations (O'Connor et al. 2023, 2024) very few exceedances of thermal thresholds have been observed at sites within critical spawning habitats in the UPR. Some interannual variation has been identified, but overall, monitored spawning habitats are meeting thermal habitat requirements of Bull Trout (i.e., <11ºC; Parkinson et al. 2016). Among the summarized thermal metrics from Bull Trout spawning habitats, exceedances of 11ºC have only been observed in Lay Creek, Pelly Creek, and Scott Creek, with the highest recorded exceedance reaching 11.7ºC.

Thermal exceedances in migration corridor sites, however, were again pervasive in 2024, which is not a surprising result given their low elevation. In three years of observed data, the highest exceedances, and starkest contrast in thermal sensitivity between the migration corridor and spawning habitats has been in the Parsnip River (and Misinchinka River spawning habitat). Following the Parsnip is Mesilinka River migration corridor sites, and the coldest conditions were observed in the Ingenika River. Indeed, the disparity in thermal sensitivity seems to increase the farther south the sites are (Figure 9).

The variation among sites raises concerns for the sensitivity of some critical spawning habitats. Davis River and Scott Creek were both categorized as high thermal sensitivity, and their 95% CI overlapped the high and moderate categories. This is concerning as Davis River and Scott Creek have both been ranked priority #1a for conservation and enhancement actions, given their high population size, contribution to the total abundance in Williston tributaries, and pristine habitat condition (Hagen et al. 2023). Pesika Creek (priority #1), Lay Creek (priority #1) and Pelly Creek (priority #2) were categorized as moderate sensitivity, but their 95% CI overlapped both the high and low categories. Point Creek (priority #1a) and Misinchinka River (priority #1a) were categorized as low, but only the 95% CI for Misinchinka

River overlapped the moderate category. An initial observation is that aspect, and high valley confinement are common characteristics of Point Creek and Misinchinka River, however it is interesting these are not the highest elevation, or most northern tributaries in the watershed, stressing the importance of reach specific attributes in driving thermal sensitivity (Caissie 2006).

A next step in the investigation of reach scale patterns in thermal habitat is to continue to improve the modeled inferences. The extension of the thermal sensitivity analysis to a linear mixed effects model incorporating multiple years of data provided interesting results, similar to the yearly models, but improved the interpretability of results and estimation of variation at individual sites. The model passed basic assumption tests (e.g., data normality and residual homoscedasticity), but similar to yearly linear models presented in past reports, slight skewing in the observed data could be corrected using logarithmic transformations (O’Connor et al. 2024). The use of the ERA5-Land reanalysis product and its validity for the analysis could be re-evaluated using multiple years of data before final conclusions are presented.

With multiple years of observation data, the project is nearing a point where geomorphic and climatic variables can be investigated as covariates in an analysis of thermal sensitivity. Other available predictor variables which could influence thermal sensitivity include elevation, aspect, valley confinement, latitude, stream size, annual precipitation and other watershed physical characteristics (for a more detailed review of potential predictors, see Caissie 2006). A linear mixed model approach has been applied in the published literature to assess drivers of multiple thermal metrics (Mochnacz et al. 2022) and presents an interesting avenue for FWCP to identify stream reaches with characteristics that reduce thermal sensitivity where conservation and enhancement investments can be focused.

5.3 Spatial Stream Network Model

The preliminary spatial stream network model presented here performed well, despite the relatively small sample size (n = 54 sites) and use of a single fixed effect (elevation). The model’s predictive accuracy needs to be improved to justify its use in species distribution and abundance modeling coordinated with other FWCP projects (PEA-F25-F-4051, PEA-F25-F-4054). To facilitate this, more fixed effects and observation sites across multiple years of data need to be included.

Additional climate and landscape variable datasets are available and have been utilized by other components of this project. Now that a modeling workflow has been established, additional fixed effects predictors can be included and model selection processes can be developed, which can prioritize amongst influential predictors.

Multiple sites from the 2024 temperature dataset did not meet the time series completion threshold used in the data preparation steps for this preliminary model (> 60%). Moving forward, we recommend an imputation process be applied to sites without complete time series following methods applied in O’Connor (2023). Data time series can be incomplete for several reasons including battery failure, vandalism of sites or inability to access sites for annual downloads. Temperature data imputation has been shown to be an effective way to increase the number of available observation datasets and improve predictive accuracy of SSNMs (Isaak et al. 2018; O’Connor 2023). Additionally, the inclusion of additional sites in areas of high leverage is an important next step in improving the SSNM predictive accuracy.

There is little guidance available on suitable sample sizes for SSNM predictions (e.g., 50-100 sites for large watersheds; Isaak et al. 2014). Insights from previously funded FWCP projects, and published research suggest the number of sites is, at times, less important than the spatial distribution of sites (Martins et al. 2022; Marsha et al. 2018). The most likely source of prediction error in this model is considerable differences in the thermal regimes of study streams (e.g., Nation

River – warm lake headed watershed vs. Ingenika River – cold, high elevation watershed). Hydrological complexity between watersheds, and the resulting prediction error has been highlighted by other studies using SSN models (O'Sullivan et al. 2021). For this project, the identification of prediction error at low elevation, warmer sites present a drawback of the SSN model, but also an opportunity to identify areas of high leverage and include additional observation datasets in those watersheds. The inclusion of more sites in areas of high leverage will improve the model's predictive ability. Additional data is available but was not included in this preliminary model due to limited time and budget to clean and prepare data.

The data preparation and cleaning process associated with the methods in this project is highly labour intensive and given there is a limit to available time (i.e., budget), it is important to incrementally improve modeling workflows year over year to meet the objectives of the project. The initial SSNM presented here is the result of an important step in the establishment of a functional workflow. Next steps outlined above will improve the predictive accuracy of the model in anticipation of its application to research questions about the distribution and abundance of cold-water adapted ectotherms, and the influence of climatic and landscape variables on thermal regimes.

5.4 Basin Scale Model Comparison and Evaluation

The findings of Roknaldini et al. (in preparation) demonstrated that GAM and RF models exhibited comparable predictive performance across multiple study sites, effectively capturing seasonal and daily water temperature variations. At the Parsnip River and Upper Fraser River, GAM outperformed RF slightly, with RF showing a cold bias at Parsnip River and a warm bias at Upper Fraser River. In the Williston Reservoir and Atlin Lake, both models performed similarly, within Williston Reservoir, RF capturing slightly more daily fluctuations. At Atlin Lake, both models consistently reproduced colder seasonal trends with minimal accuracy differences. Additionally, the WTPS produced reliable daily and seasonal temperature predictions across all tested sites, with small cold biases. Additionally, the WTPS provided reliable daily and seasonal temperature predictions at all tested sites, with small cold biases. By combining multiple models, WTPS helps reduce uncertainty and makes up for the weaknesses of individual models, leading to more consistent water temperature predictions across different study sites.

The assessment of Air2Water across multiple sites highlighted its strong dependence on water temperature monitoring methods. At Williston Reservoir, where temperature data were recorded at varying depths, the model struggled to capture daily fluctuations. In contrast, its performance improved at Atlin Lake, where measurements were taken closer to the surface, and it was most effective at Fraser Lake, where buoy-based monitoring ensured consistent surface temperature data. This suggests that the challenges encountered at Williston Reservoir and Atlin Lake, given the reliance of the Air2Water model on only air temperature and surface water temperature, are attributed to data adequacy rather than inherent model limitations. However, it is important to acknowledge that the Air2Water model has demonstrated strong performance in Fraser Lake, as well as other lakes in previous studies (Heddam et al., 2020; Jia & Luo, 2022; Ptak et al., 2024; Zhu et al., 2020). This suggests that for accurate predictions in the reservoir and lakes using the Air2Water model, data should be collected from surface water using appropriate methods, such as buoy systems; otherwise, the model fails to capture daily variations effectively, reducing its accuracy. When surface water data is unavailable, statistical and machine learning models are recommended as alternative approaches to improve prediction accuracy.

This study highlighted that the northern BC lacks reliable water temperature prediction systems. The newly developed WTPS fills that gap and offers a promising tool to reduce uncertainty in water temperature forecasts. The WTPS combines the strengths of statistical, machine learning, and semi-empirical lumped models to forecast water temperatures while addressing their individual limitations. Additionally, there is potential to investigate the application of

WTPS trained on long-term data from a well-monitored site to predict water temperatures at untrained stations, such as nearby new real-time hydrometric stations, providing valuable predictions despite small biases.

Another key future application of the WTPS is its ability to predict water temperatures under future climate scenarios. While the models can effectively predict water temperatures for lakes and reservoirs by assuming consistent responses to meteorological drivers, river modeling will require the inclusion of streamflow projections. This enhancement will provide more accurate projections for river systems, offering critical insights to inform future decision-making and adaptive strategies in response to climate change.

This study also showed that the current monitoring of water temperature in the Williston Reservoir by WSC is not reliable for successful reservoir modeling using the Air2Water model. However, the new monitoring sites established through this project, with 3-4 years of data collected so far, provide a more reliable source for reservoir modeling using the Air2Water model. This capability, which was previously limited due to data quality, is now feasible. While, this short-term (3-4 years) data is adequate for Air2Water, longer-term monitoring is needed for machine learning and WTPS applications. Therefore, continued operation of the monitoring network would be a highly valuable resource for future water temperature modeling in the Williston Reservoir.

6 Conclusion and Recommendations

Objective 1 of this project *Monitor water temperature and flow in priority watersheds of the UPR* has been met and is providing critical data to support the prioritization of conservation and enhancement actions based on thermal habitat availability. Multiple monitoring and modeling approaches across temporal and spatial scales are required to achieve the remaining objectives of this project. Objectives 2-4 require extensive effort to clean collected data, then develop models which can provide insights into thermal habitat patterns over time and space. This report presents preliminary results that support the effectiveness of our modeling framework. The creation and routine maintenance of a monitoring array (Objective 1) has allowed the project team to focus on the developing analyses of collected data, and begin to address Objectives 2-4 at the reach, watershed, and basin scales.

The investigation of reach scale thermal habitat patterns has revealed predictable patterns in headwater and mainstem river sites but has also provided initial insight into variation in thermal sensitivity across different sites in each habitat type (migration corridors and spawning habitats). Variation among critical spawning habitats is an important conclusion given the specific habitat requirements of Bull Trout. A next step at this scale of inquiry is to identify the watershed characteristics which produce low thermal sensitivity. This effort will require another year of data collection, additional sites included in the analysis, and collection of variables which are known to influence thermal sensitivity that are available across all spawning habitats.

In 2024, the project team had three goals in developing a preliminary SSNM. First was the effort to clean and prepare data from rapid deployment HOBO Tidbit loggers for use in model development, which is an annual undertaking. This was completed, and all data which has been cleaned and inspected to date is available on the Northern BC Hydrology Research Shiny App (https://bcgov-env.shinyapps.io/nbchydro/). This effort revealed some sites are being removed from the observation dataset based on completion thresholds, and a data imputation process should be pursued to increase the number of complete time series that can be used in a SSNM. Second, was the creation of a workflow in R Statistical Software to create a SSNM under new methods than past applications, which has been completed. Key next steps are the improvement of model selection and inclusion of more fixed effects (e.g., air temperature, precipitation etc.). The third objective was to assess the model's ability to predict temperatures and be used in the assessment of priority species abundance and distribution. The results presented here show a clear need to include more observation datasets, but specifically more datasets from warmer stream reaches. These data are available, but additional data cleaning and preparation time is required. The results of the SSNM presented here are preliminary and intended as a progress update but shows promise for its use to meet project objectives given further refinement.

Multiple modeling approaches are essential for achieving Objective 3 of this project *Quantify spatio-temporal variability in water temperatures to inform conservation initiatives for priority species*. The study by Roknaldini et al. (in preparation) identified the limitations of the current water temperature monitoring by WSC in the Williston Reservoir for reliable Air2Water model applications. However, using statistical and machine learning approaches offers a more effective way to improve water temperature predictions by utilizing a wider range of input data, instead of solely depending on observed air and water temperature data. The new monitoring sites established through Objective 1 of this project now provide sufficient data for the successful application of the Air2Water model in the reservoir during the final year of project. In year 2025 we will apply this model using 3-4 years of data, the improved data quality enables the model to capture daily variations, a capability that was previously limited due to inadequate data.

The WTPS developed in this study also demonstrates potential in reducing uncertainty and addressing the limitations of individual models. In the final year, we will focus on expanding the WTPS application as a new prediction tool to additional sites across northern BC, improving its performance, and applying it to the real-time hydrometric site deployed in UPR basin during this project. This will provide valuable insights from the modeling framework for priority species as the deployments in this project are coordinated specifically with critical habitats.

For the final year of the project, we have the following recommendations, which are specific to the methods of the project. Recommendations for the management of priority species, and FWCP actions will be withheld until final conclusions can be drawn from the data collected and analyzed by this project. The recommendations are as follows:

1. Continued support and advocacy for hydrometric monitoring in remote areas;
2. Prioritize rating curve development to facilitate the application of the WTPS at new real-time hydrometric station sites;
3. Continue data management, and implement data imputation methods where possible to increase the number of available datasets;
4. Maintain live data dashboard and improve project data portal. Increase communication around the availability of the data generated by the project;
5. Coordinate results with concurrently funded FWCP projects (PEA-F25-F-4051, PEA-F25-F-4054) including an assessment of cumulative effects on Bull Trout (see Rossi et al. 2025), and monitoring of Arctic Grayling (Hagen et al. 2025) to provide insights for the objectives of those projects;
6. Continue to improve coordination and dissemination of project data and results with First Nations in the footprint of the Williston Reservoir. Further presentation at community events has been identified as a required step in this process;
7. Host outreach events to communicate the methods and results of the study to regional stakeholders and management agencies. This involves fostering a community of practice which can coordinate on the applications of the methods used in this project in conservation, enhancement and restoration actions;
8. Generate outreach products including a video describing the project and results – fieldwork filming completed.

7 Outreach Activities

1. Presentation by Bryce O'Connor titled "Thermal Habitat Across Multiple Scales: Investigating Thermal Regimes of the Upper Peace River Basin" at the FWCP-sponsored Natural Resource and Environmental Studies Institute Colloquium March 1, 2023.

2. Project was presented and feedback was sought during a meeting with the Tsay Keh Dene Language and Culture Committee Meeting March 30, 2023.

3. Poster presentation by Kaylee Barnes titled "Assessing Thermal Habitat Conditions in the Parsnip River Basin, British Columbia" at the UNBC Research Week Monday, Prince George, February 27, 2023. See Figure 15.

4. Poster presentation by Kaylee Barnes titled "Assessing Thermal Habitat Conditions in the Parsnip River Basin, British Columbia" at the Western Division of the Canadian Association of Geographers (WDCAG), University of the Fraser Valley, Abbotsford, March 10-11, 2023.

5. Presentation by Siraj ul Islam titled "Monitoring and modeling of riverine thermal regimes in northern British Columbia" at the Canadian Geophysical Union (CGU) annual meeting. Banff, Alberta from May 7 to May 10, 2023.

6. Poster presentation by Behnoosh Roknaldini titled "Investigating Water Temperature Changes in the Upper Peace River Basin" at the UNBC, Prince George, November 3, 2023.

7. Presentation by Behnoosh Roknaldini titled "Investigating the use of statistical and hybrid models to simulate freshwater temperature in northern British Columbia, Canada" at the Western Division of the Canadian Association of Geographers (WDCAG) Conference, Okanagan College, Kelowna, British Columbia, March 15-16, 2024.

8. Project was presented and feedback was sought during traditional ecological knowledge interviews conducted in Tsay Keh Dene from February 28th to March 1st, 2024.

9. Project was presented and feedback was sought during Science Week in March 2024 and May 2025. Science Week is an annual event in Tsay Keh Dene hosted by TKD Lands, Resources and Treaty Operations and Chu Cho Environmental.

10. Presentation by Bryce O'Connor titled "Thermal Habitat Across Multiple Scales: Investigating Thermal Regimes of the Upper Peace River Basin" at the Yukon Fish Community of Practice Speaker Series May 15, 2024.

11. Presentation by Bryce O'Connor titled "Thermal Habitat Across Multiple Scales: Investigating Thermal Regimes of the Upper Peace River Basin" at the American Fisheries Society Washington-BC Chapter Annual Meeting in Vancouver BC. Bryce O'Connor presented in the Thermal Refugia symposium March 11, 2025.

12. A project overview was featured in the January/February 2025 edition of The Tracker: Tsay Keh Dene News, a quarterly community newsletter distributed by Tsay Keh Dene Nation.

13. An update poster was presented to Tsay Keh Dene community members during an engagement session in Tsay Keh Dene January 30th and 31st, 2025 among other FWCP funded projects.

14. Presentation by Bryce O'Connor at Nak'azdli Whut'en Wildlife Week May 5th, 2025. This project was highlighted in relation to other FWCP funded CCE projects.

15. Ongoing support and maintenance of public dashboard of project datasets.

8 References

Al-Chokhachy, R., Alder, J., Hostetler, S., Gresswell, R., and Shepard, B. 2013. Thermal controls of Yellowstone cutthroat trout and invasive fishes under climate change. Global Change Biology 19(10): 3069–3081. doi:10.1111/gcb.12262.

Almeida, M. C. and Coelho, P. S. 2023. Modeling river water temperature with limiting forcing data: Air2stream v1.0.0, machine learning and multiple regression. Geoscientific Model Development, 16(14), 4083–4112. https://doi.org/10.5194/gmd-16-4083-2023.

Armstrong, J.B., Fullerton, A.H., Jordan, C.E., Ebersole, J.L., Bellmore, J.R., Arismendi, I., Penaluna, B.E., and Reeves, G.H. 2021. The importance of warm habitat to the growth regime of cold-water fishes. Nature Climate Change 11(4): 354–361. doi:10.1038/s41558-021-00994-y.

Barnes, K., Islam, S., O'Connor, B., Bevington, A., and Caryk, J. *In preparation.* Assessing thermal habitat conditions in the Parsnip River Basin, British Columbia.

Barton, B.A. 2002. Stress in Fishes: A Diversity of Responses with Particular Reference to Changes in Circulating Corticosteroids. Integrative and Comparative Biology 42(3): 517–525. doi:10.1093/icb/42.3.517.

Baxter, J.S., and McPhail, J.D. 1999. The influence of redd site selection, groundwater upwelling, and over-winter incubation temperature on survival of Bull Trout (Salvelinus confluentus) from egg to alevin. Canadian Journal of Zoology 77(8): 1233–1239. doi:10.1139/z99-090.

Benjamin, J.R., Heltzel, J.M., Dunham, J.B., Heck, M., and Banish, N. 2016. Thermal Regimes, Nonnative Trout, and Their Influences on Native Bull Trout in the Upper Klamath River Basin, Oregon. T Am Fish Soc 145(6): 1318–1330. doi:10.1080/00028487.2016.1219677.

Bevington, A. R. (2024a). RemoteLogger. Github. https://github.com/bevingtona/RemoteLogger.

Bevington, A. R. (2024b). watershedBC (v0.1) Prototype: R Shiny app to summarize watershed attributes on demand in British Columbia. Github. https://github.com/bcgov/watershedBC.

Bevington, A.R., Gleason, H., Kingsley, V., Rex, J., Foord, F., Gantner, N. and Pillipow, R. *In review.* Spatial distribution of projected stream temperature warming, Bowron River Watershed, British Columbia. Confluence: Journal of Watershed Science and Management.

Breiman, L. 2001. Random forests. Machine Learning, *45*(1), 5–32. https://doi.org/10.1023/A:1010933404324.

Bruce, P.G. and P.J. Starr. 1985. Fisheries resources and fisheries potential of Williston Reservoir and its tributary streams. Volume II Fisheries resources potential of Williston Lake Tributaries – A preliminary overview. Fisheries Technica Circular No 69: 100pp.

Caissie, D. 2006. The thermal regime of rivers: a review. Freshwater Biology 51(8): 1389–1406. doi:10.1111/j.1365-2427.2006.01597.x.

Casas-Mulet, R., Saltveit, S. J. and Alfredsen, K. T., 2016. Hydrological and thermal effects of hydropeaking on early life stages of salmonids: A modelling approach for implementing mitigation strategies. Science of the Total Environment 573, 1660–1672.

Caslys Consulting Ltd. 2010. GeoBC Freshwater Atlas User Guide. Victoria, B.C.

Comte, L., and Grenouillet, G. 2013. Do stream fish track climate change? Assessing distribution shifts in recent decades. Ecography 36(11): 1236–1246. doi:10.1111/j.1600-0587.2013.00282.x.

Cowie, D.M. and B.G. Blackman. 2012. An Investigation of the Distribution and Relative Abundance of Arctic Grayling (Thymallus arcticus) in the Ingenika River 2004. Fish and Wildlife Compensation Program – Peace Region Report No. 352.

Cowie, D.M., and Blackman, B.G. 2003. 2001-2002 Arctic Grayling (Thymallus arcticus) fry surveys in the Omineca and Osilinka rivers. Peace/Williston Fish and Wildlife Compensation Program, B.C. PWFWCP Report No. 276.

Cowie, D.M., and Blackman, B.G. 2004. Arctic Grayling (Thymallus arcticus) fry surveys in the Nation River, 2004. Peace/Williston Fish and Wildlife Compensation Program, B.C. PWFWCP Report No. 314.

Culling, B., Euchner, T., Ward, T., Cooke, S. 2020. Peace Reach Lake Trout Movements Final Report – Year 4 (Fish and Wildlife Compensation Program Peace Project No. PEA-F20-F-2948). Report prepared by Diversified Environmental Services for Fish and Wildlife Compensation Program – Peace Region, Prince George, BC.

Cunningham, D.S., Braun, D.C., Moore, J.W., and Martens, A.M. 2022. Forestry influences on salmonid habitat in the North Thompson River Watershed, British Columbia. Canadian Journal of Fisheries and Aquatic Sciences. doi:10.1139/cjfas-2022-0255.

Dalgarno, S., Thorley, J. (2025). fwapgr: Client for BC Freshwater Atlas fwapg API. R package version 0.1.0.9015, commit 781a4d0c1765e411a6b6e617719a5d15d7936dd9, <https://github.com/poissonconsulting/fwapgr>

Dominici, F., Daniels, M., Zeger, S. L., & Samet, J. M. 2002. Air Pollution and Mortality: Estimating Regional and National Dose-Response Relationships. *Journal of the American Statistical Association*, *97*(457), 100–111. https://doi.org/10.1198/016214502753479266.

Dumelle M, Peterson EE, Ver Hoef JM, Pearse A, Isaak DJ (2024). SSN2: The next generation of spatial stream network modeling in R. Journal of Open Source Software, 9(99), 6389, https://doi.org/10.21105/joss.06389.

Eby, L.A., Helmy, O., Holsinger, L.M., and Young, M.K. 2014. Evidence of Climate-Induced Range Contractions in Bull Trout Salvelinus confluentus in a Rocky Mountain Watershed, U.S.A. Plos One 9(6): e98812. doi:10.1371/journal.pone.0098812.

ECL. 1997. Fish Habitat Inventory of the Mesilinka River and Tributaries. Forest Renewal BC - Peace/Williston Fish & Wildlife Compensation Program. Report ID: 10572.

EDI. 2001. Mesilinka River Watershed Restoration Plan (2000-2004). EDI Project No. 519-04.

Essig, D.A., C.A. Mebane, and T.W. Hillman. 2003. Update of Bull Trout Temperature Requirements. Idaho Department of Environmental Quality, Boise, ID.

Farley, A. L. 1979. Atlas of British Columbia. University of British Columbia Press, Vancouver, B.C.

Feigl, M., Lebiedzinski, K., Herrnegger, M., & Schulz, K. (2021). Machine-learning methods for stream water temperature prediction. Hydrology and Earth System Sciences, 25(5), 2951–2977. https://doi.org/10.5194/hess-25-2951-2021.

Fraser Basin Council, 2019. Climate Projections for the BC Northeast Region. Reported prepared by the Northeast Climate Risk Network, June 2019. Available online at: https://www.fraserbasin.bc.ca/_Library/CCAQ/fbc_ne_climatereport_web.pdf.

Fish and Wildlife Compensation Program (FWCP), 2020a. Peace Region Cross-Ecosystem Action Plan. Report prepared for the Fish and Wildlife Compensation Program – Peace Region, Prince George, BC. Available online at: https://fwcp.ca/app/uploads/2020/08/Action-Plan-Peace-Region-Cross-Ecosystem-Aug-11-2020.pdf.

Fish and Wildlife Compensation Program (FWCP), 2020b. Peace Region Rivers, Lakes and Reservoirs Action Plan. Report prepared for the Fish and Wildlife Compensation Program – Peace Region, Prince George, BC. Available online at: https://fwcp.ca/app/uploads/2020/08/Action-Plan-Peace-Region-Rivers-Lakes-Reservoirs-Aug-11-2020.pdf.

Fullerton, A.H., Torgersen, C.E., Lawler, J.J., Faux, R.N., Steel, E.A., Beechie, T.J., Ebersole, J.L., and Leibowitz, S.G. 2015. Rethinking the longitudinal stream temperature paradigm: region-wide comparison of thermal infrared imagery reveals unexpected complexity of river temperatures. Hydrological Processes 29(22): 4719–4737. doi:10.1002/hyp.10506.

Gorelick, Noel, Matt Hancher, Mike Dixon, Simon Ilyushchenko, David Thau, and Rebecca Moore. "Google Earth Engine: Planetary-scale geospatial analysis for everyone." Remote Sensing of Environment 202 (2017): 18-27.

Hani, I., St-Hilaire, A., & Ouarda, T. B. M. J. 2023. Machine-learning modeling of hourly potential thermal refuge area: A case study from the Sainte-Marguerite River (Quebec, Canada). River Research and Applications, 39(9), 1763–1782. https://doi.org/10.1002/rra.4191

Hagen, J., Williamson, S., Stamford, M., and Pillipow, R. 2015. Critical Habitats for Bull Trout and Arctic Grayling within the Parsnip River and Pack River watersheds. Prepared for: McLeod Lake Indian Band.

Hagen, J., and Weber, S., 2019. Limiting Factors, Enhancement Potential, Critical Habitats, and Conservation Status for Bull Trout of the Williston Reservoir Watershed: Information Synthesis and Recommended Monitoring Framework. Report prepared for the Fish and Wildlife Compensation Program – Peace Region, Prince George, BC. Available online at: http://a100.gov.bc.ca/pub/acat/public/viewReport.do?reportId=57250.

Hagen, J., Spendlow, I., Pillipow, R. 2020. Critical Spawning Habitats and Abundance of Bull Trout in the Williston Reservoir Watershed, 2019. Report prepared for the Fish and Wildlife Compensation Program – Peace Region, Prince George, BC. Available online at: https://a100.gov.bc.ca/pub/acat/documents/r58663/2019WillistonReddsRedacted_1591830304445_1829686125.pdf.

Hagen, J., and Stamford, M. 2021. Ingenika River Arctic Grayling 2004-2020. Report prepared by Chu Cho Environmental LLP for the Fish and Wildlife Compensation Program – Peace Region, Prince George, BC. FWCP Project No. PEA-F21-F-3209. Available online at: https://a100.gov.bc.ca/pub/acat/documents/r59158/PEA_F21_F_3209_1622501304141_967641590A.pdf.

Hagen, J., and M. Stamford. 2022. 2021 Parsnip Arctic Grayling critical habitats and abundance: towards an effective habitat stewardship framework. Report prepared for the Fish and Wildlife Compensation Program – Peace Region, Prince George, BC. FWCP Project No. PEA-F22-F-3407.

Hagen, J., Sary, Z., O'Connor, B. 2022. Williston Bull Trout Spawner Abundance and Critical Habitats: How Effective Stewardship Can Be Achieved in the Basin: 2021. Chu Cho Environmental LLP, Prince George, BC. xii + 62 pp.

Hagen, J., Pearce, S., O'Connor, B. 2023. Williston Bull Trout Spawner Abundance and Critical Habitats: Delineation of Critical Habitats within the Upper Peace Ecological Drainage Unit 2014 – 2022. Chu Cho Environmental LLP, Prince George, BC. 85 pp.

Hagen, J., Stamford, M., Ferraro, M., O'Connor, B. 2025. West Shore Arctic Grayling Abundance and Critical Habitats: Mesilinka Snorkel Surveys 2024. Chu Cho Environmental LLP, Prince George, BC.

Heddam, S., Ptak, M., & Zhu, S. 2020. Modelling of daily lake surface water temperature from air temperature: Extremely randomized trees (ERT) versus Air2Water, MARS, M5Tree, RF and MLPNN. Journal of Hydrology, 588, 125130.

Huey, R.B., Kearney, M.R., Krockenberger, A., Holtum, J.A.M., Jess, M., and Williams, S.E. 2012. Predicting organismal vulnerability to climate warming: roles of behaviour, physiology and adaptation. Philosophical Transactions of the Royal Society B: Biological Sciences 367(1596): 1665 1679. doi:10.1098/rstb.2012.0005.

Intergovernmental Panel on Climate Change (IPCC), 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland.

Isaak, D. J., Luce, C. H., Rieman, B. E., Nagel, D. E., Peterson, E. E., Horan, D. L., Parkes, S. and Chandler, G. L, 2010. Effects of climate change and wildfire on stream temperatures and salmonid thermal habitat in a mountain river network. Ecological Applications 20:1350–1371.

Isaak, Daniel J.; Horan, Dona L.; and Wollrab, Sherry P. 2013. A simple protocol using underwater epoxy to install annual temperature monitoring sites in rivers and streams. General Technical Report RMRS-GTR-314. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 21 p.

Isaak, D.J., and Rieman, B.E. 2013. Stream isotherm shifts from climate change and implications for distributions of ectothermic organisms. Global Change Biology 19(3): 742–751. doi:10.1111/gcb.12073.

Isaak, D.J., Young, M.K., Nagel, D.E., Horan, D.L., and Groce, M.C. 2015. The cold-water climate shield: delineating refugia for preserving salmonid fishes through the 21st century. Global Change Biology 21(7): 2540–2553. doi:10.1111/gcb.12879.

Isaak, D. J., Young, M. K., Luce, C. H., Hostetler, S. W., Wenger, S. J., Peterson, E. E., Hoef, J. M. V., Groce, M. C., Horan, D. L., and Nagel, D. E., 2016. Slow climate velocities of mountain streams portend their role as refugia for cold-water biodiversity. Proceedings of the National Academy of Sciences 113(16): 4374–4379. doi:10.1073/pnas.1522429113.

Isaak, D.J., Hoef, J.M.V., Peterson, E.E., Horan, D.L., and Nagel, D.E. 2017. Scalable population estimates using spatial-stream-network (SSN) models, fish density surveys, and national geospatial database frameworks for streams. Canadian Journal of Fisheries and Aquatic Sciences 74(2): 147–156. doi:10.1139/cjfas-2016-0247.

Isaak, D.J., Luce, C.H., Chandler, G.L., Horan, D.L., and Wollrab, S.P. 2018. Principal components of thermal regimes in mountain river networks. Hydrology and Earth System Sciences 22(12): 6225–6240. doi:10.5194/hess-22-6225-2018.

Islam, S., Hay, R. W., Déry, S. J., & Booth, B. P., 2019. Modelling the impacts of climate change on riverine thermal regimes in western Canada's largest Pacific watershed. Scientific reports, 9(1), 1-14.

Jia, T., & Luo, Y. 2022. Using Air2water Model to Predict the Water Temperature of Fuxian Lake. In B.-J. He, D. Prasad, G. Pignatta, & J. Jupesta (Eds.), Climate Change and Environmental Sustainability (pp. 29–35). Springer International Publishing.

Keppel, G., Niel, K.P.V., Wardell-Johnson, G.W., Yates, C.J., Byrne, M., Mucina, L., Schut, A.G.T., Hopper, S.D., and Franklin, S.E. 2012. Refugia: identifying and understanding safe havens for biodiversity under climate change. Global Ecology Biogeography 21(4): 393–404. doi:10.1111/j.1466-8238.2011.00686.x.

Kelleher, C., Wagener, T., Gooseff, M., McGlynn, B., McGuire, K., and Marshall, L. 2012. Investigating controls on the thermal sensitivity of Pennsylvania streams. Hydrological Processes. 26(5): 771–785. doi:10.1002/hyp.8186.

Kingsolver, J.G. 2009. The Well-Temperatured Biologist. American Naturalist 174(6): 755–768. doi:10.1086/648310.

Kurylyk, B. L., MacQuarrie, K. T. B., Linnansaari, T., Cunjak, R. A., and Curry, R. A., 2015. Preserving, augmenting, and creating cold-water thermal refugia in rivers: concepts derived from research on the Miramichi River, New Brunswick (Canada). Ecohydrology 8(6): 1095–1108. doi:10.1002/eco.1566.

Laanaya, F., St-Hilaire, A., & Gloaguen, E. 2017. Water temperature modelling: Comparison between the generalized additive model, logistic, residuals regression and linear regression models. Hydrological Sciences Journal, 62(7), 1078–1093. https://doi.org/10.1080/02626667.2016.1246799

Lucas, M. C. and Baras, E., 2001. Migration of Freshwater Fishes. Blackwell Science Ltd, Oxford.

Marsha, A., Steel, E.A., Fullerton, A.H., and Sowder, C. 2018. Monitoring riverine thermal regimes on stream networks: Insights into spatial sampling designs from the Snoqualmie River, WA. Ecological Indicators 84: 11–26. doi:10.1016/j.ecolind.2017.08.028.

Marsha, A. L., Steel, E. A., and Fullerton, A. H., 2021. Modeling thermal metrics of importance for native vs non-native fish across stream networks to provide insight for watershed-scale fisheries management. Freshwater Science: 000–000. doi:10.1086/713038.

Martins, E., O’Connor, B., Bottoms, J., Clevenger, I., Auger-Methe, M., Power, M., Patterson, D., Shrimpton, M., Cooke, S., 2022. Spatial Ecology of Arctic Grayling in the Parsnip Core Area. Report prepared for the Fish and Wildlife Compensation Program – Peace Region, Prince George, BC. Project Number: PEA-F22-F-3388.

McClarren, R. G. 2021. Decision Trees and Random Forests for Regression and Classification. In R. G. McClarren, Machine Learning for Engineers (pp. 55–82). Springer International Publishing. https://doi.org/10.1007/978-3-030-70388-2_3.

McCullough, D.A., Bartholow, J.M., Jager, H.I., Beschta, R.L., Cheslak, E.F., Deas, M.L., Ebersole, J.L., Foott, J.S., Johnson, S.L., Marine, K.R., Mesa, M.G., Petersen, J.H., Souchon, Y., Tiffan, K.F., and Wurtsbaugh, W.A. 2009. Research in Thermal Biology: Burning Questions for Coldwater Stream Fishes. Reviews in Fisheries Science 17(1): 90 115. doi:10.1080/10641260802590152.

Mochnacz, N.J., Taylor, M.K., Docker, M.F., and Isaak, D.J. 2022. An ectothermal paradox: bull trout populations diverge in response to thermal landscapes across a broad latitudinal gradient. Environmental Biology of Fishes: 1–21. doi:10.1007/s10641-022-01339-0.

Moore, R.D., Sutherland, P., Gomi, T., and Dhakal, A. 2005. Thermal regime of a headwater stream within a clear-cut, coastal British Columbia, Canada. Hydrological Processes 19(13): 2591–2608. doi:10.1002/hyp.5733.

Morash, A.J., Speers-Roesch, B., Andrew, S., and Currie, S. 2021. The physiological ups and downs of thermal variability in temperate freshwater ecosystems. Journal of Fish Biology. doi:10.1111/jfb.14655.

Morgan, A.M., and O'Sullivan, A.M. 2023. Cooler, bigger; warmer, smaller: Fine-scale thermal heterogeneity maps age class and species distribution in behaviourally thermoregulating salmonids. River Research and Applications 39(2): 163–176. doi:10.1002/rra.4073.

Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D. G., Piles, M., Rodríguez-Fernández, N. J., Zsoter, E., Buontempo, C., and Thépaut, J.-N.: ERA5-Land: a state-of-the-art global reanalysis dataset for land applications, Earth System Science Data, 13, 4349–4383, https://doi.org/10.5194/essd-13-4349-2021, 2021.

Neuheimer, A.B., and Taggart, C.T. 2007. The growing degree-day and fish size-at-age: the overlooked metric. Canadian Journal of Fisheries and Aquatic Sciences 64(2): 375–385. doi:10.1139/f07-003.

O'Connor, B. 2023. Linking Spatial Stream Network Modeling and Telemetry Data to Investigate the Thermal Habitat Use by Adult Arctic Grayling. Master of Science Thesis, University of Northern British Columbia, Prince George, BC.

O'Connor, B., Roknaldini, B., Islam, S., Bevington, A., Ferraro, M. 2024. Investigating Thermal Regimes of the Upper Peace River Basin: Summary Report Year Two. Report prepared for the Fish & Wildlife Compensation Program – Peace Region. FWCP Project No. PEA-F24-F-3845. xxiv + 49 pp.

O'Connor, B., Ferraro, M., Hagen, J. 2024. Williston Bull Trout Spawner Abundance and Critical Habitats: Evaluation of Monitoring Requirements and Limiting Factors Analysis. Chu Cho Environmental LLP, Prince George, BC. xi + 58 pp.

Parkinson, E.A., Lea, E.V., Nelitz, M.A., Knudson, J.M., and Moore, R.D. 2016. Identifying Temperature Thresholds Associated with Fish Community Changes in British Columbia, Canada, to Support Identification of Temperature Sensitive Streams. River Research and Applications 32(3): 330–347. doi:10.1002/rra.2867.

Pearce, T., and S. Abadzadesahraei, 2019. First Nations Information Gathering on Kokanee, Bull Trout and Arctic Grayling: Tsay Keh Dene Nation. Report prepared for the Fish and Wildlife Compensation Program – Peace Region, Prince George, BC. Project Number: PEA-F19-F-2866. Available online at: https://a100.gov.bc.ca/pub/acat/public/viewReport.do?reportId=57247.

Peterson, E.E., and Hoef, J.M.V. 2010. A mixed-model moving-average approach to geostatistical modeling in stream networks. Ecology 91(3): 644–651. doi:10.1890/08-1668.1.

Peterson E. E., Dumelle, M., Pearse A., Teleki D., and Ver Hoef, J. M. (2024). SSNbler: Assemble SSN objects in R. R package version 0.1.0.

Piccolroaz, S., Toffolon, M. and Majone, B. A., 2013. A simple lumped model to convert air temperature into surface water temperature in lakes. Hydrological and Earth System Sciences. 17: 3323–3338.

Picolroaz, S., Calamita, E., Majone, B., Gallice, A., Siviglia, A., and Toffolon, M. 2016. Prediction of river water temperature: a comparison between a new family of hybrid models and statistical approaches. Hydrological Processes, 30(21), 3901–3917. https://doi.org/10.1002/hyp.10913

Piccolroaz, S., Toffolon, M., Robinson, C., and Siviglia, A. 2018. Exploring and Quantifying River Thermal Response to Heatwaves. Water 10(8): 1098. doi:10.3390/w10081098.

Ptak, M., Zhu, S., Amnuaylojaroen, T., Li, H., Szyga-Pluta, K., Jiang, S., Wang, L., & Sojka, M. 2024. Utilizing Multi-Source Datasets for the Reconstruction and Prediction of Water Temperature in Lake Miedwie (Poland). Remote Sensing, *16*(15), 2753. https://doi.org/10.3390/rs16152753

R Core Team (2025). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>.

Rieman, B.E., and J.D. McIntyre. 1993. Demographic and habitat requirements for the conservation of bull trout Salvelinus confluentus. USDA, Forest Service, Intermountain Research Station, General Technical Report INT-302, Ogden, UT.

Roknaldini, B., Islam, S., O'Connor, B., and Bevington, A. in preparation. Investigating the use of statistical and hybrid models to simulate freshwater temperatures in northern British Columbia, Canada.

Rossi, K., O'Connor, B., and Hagen, J. 2025. Williston Bull Trout Spawner Abundance and Critical Habitats: Summary Report Year 3. Chu Cho Environmental LLP, Prince George, BC. xi + 60 pp

Rubenson, E.S., and Olden, J.D. 2020. An invader in salmonid rearing habitat: current and future distributions of smallmouth bass (Micropterus dolomieu) in the Columbia River Basin. Canadian Journal of Fisheries and Aquatic Sciences 77(2): 314–325. doi:10.1139/cjfas-2018-0357.

Ruesch, A.S., Torgersen, C.E., Lawler, J.J., Olden, J.D., Peterson, E.E., Volk, C.J., and Lawrence, D.J. 2012. Projected Climate-Induced Habitat Loss for Salmonids in the John Day River Network, Oregon, U.S.A. Conservation Biology 26(5): 873–882. doi:10.1111/j.1523-1739.2012.01897.x.

Sagar, R. M., and Corbould, F. B., 2004. Summary of microclimate data for the Williston Reservoir watershed, 1998 to 2004. Peace/Williston Fish and Wildlife Compensation Program Report No. 295. 20pp plus appendices.

Schonlau, M., & Zou, R. Y. 2020. The random forest algorithm for statistical learning. The Stata Journal: Promoting Communications on Statistics and Stata, *20*(1), 3–29. https://doi.org/10.1177/1536867X20909688

Selong, J.H., McMahon, T.E., Zale, A.V., and Barrows, F.T. 2001. Effect of Temperature on Growth and Survival of Bull Trout, with Application of an Improved Method for Determining Thermal Tolerance in Fishes. Transactions of the American Fisheries Society 130(6): 1026–1037. doi:10.1577/1548-8659(2001)130<1026:eotoga>2.0.co;2.

Shrestha, R. R., Pesklevits, J. C., Bonsal, B. R., Brannen, R., Guo, T., & Hoffman, S. 2024. Rising summer river water temperature across Canada: Spatial patterns and hydroclimatic controls. Environmental Research Letters, 19(4), 044058. https://doi.org/10.1088/1748-9326/ad365f

Sowder, C., and Steel, E.A. 2012. A Note on the Collection and Cleaning of Water Temperature Data. Water 4(3): 597–606. doi:10.3390/w4030597.

Snyder, C.D., Hitt, N.P., and Young, J.A. 2015. Accounting for groundwater in stream fish thermal habitat responses to climate change. Ecological Applications 25(5): 1397–1419. doi:10.1890/14-1354.1.

Stamford, M., Hagen, J., and Williamson, S., 2017. Limiting Factors, Enhancement Potential, Conservation Status, and Critical Habitats for Arctic Grayling in the Williston Reservoir Watershed, and Information Gaps Limiting Potential Conservation and Enhancement Actions. Report prepared for the Fish and Wildlife Compensation Program – Peace Region, Prince George, BC. Available online at: http://a100.gov.bc.ca/pub/acat/public/viewReport.do?reportId=52757.

Steel, E.A., Sowder, C., and Peterson, E.E. 2016. Spatial and Temporal Variation of Water Temperature Regimes on the Snoqualmie River Network. JWARA Journal of America Water Resoures Association 52(3): 769–787. doi:10.1111/1752-1688.12423.

Stockner, J., Langston, A., Sebastian, D., and Wilson, G. 2005. The Limnology of Williston Reservoir: British Columbia's Largest Lacustrine Ecosystem. Water Quality Research Journal 40(1): 28–50. doi:10.2166/wqrj.2005.003.

Strohm, J., Hagen, J. and Stamford, M. 2020. Ingenika River Arctic Grayling 46 Years Post-Flooding: 2019 Snorkeling Counts in Index sites. Report prepared by Chu Cho Environmental LLP for the Fish and Wildlife Compensation Program – Peace Region. FWCP Project No. PEA-F20-F-2963.

Toffolon, M. and Piccolroaz, S., 2015. A hybrid model for river water temperature as a function of air temperature and discharge. Environmental Research Letters. 10, 114011.

Tschaplinski, P.J., and Pike, R.G. 2017. Carnation Creek watershed experiment—long-term responses of coho salmon populations to historic forest practices. Ecohydrology 10(2): e1812. doi:10.1002/eco.1812.

Ver Hoef, J. M., and Peterson, E. E., 2010. A moving average approach for spatial statistical models of stream networks. Journal of the American Statistical Association 105:6–18.

Webb, B.W., Hannah, D.M., Moore, R.D., Brown, L.E., and Nobilis, F. 2008. Recent advances in stream and river temperature research. Hydrological Processes 22(7): 902–918. doi:10.1002/hyp.6994.

Williamson, C. J., 2006. Characterization of Spawning Habitat, Incubation Environment and Early Growth and Development in Bull Trout (Salvelinus Confluentus) from Pristine Streams of Northern British Columbia. Master of Science Thesis, University of Northern British Columbia, Prince George, BC. ISBN: 978-0-494-28425-4.

Yang, D., & Peterson, A. 2017. River Water Temperature in Relation to Local Air Temperature in the Mackenzie and Yukon Basins. ARCTIC, 70(1). https://doi.org/10.14430/arctic4627

Zemlak, R., and Langston, A.R. 1997. Water Temperatures of the Nation and Mesilinka River Systems, 1997. Peace/Williston Fish and Wildlife Compensation Program, Report No. 127.

Zhu, S., Nyarko, E. K., Hadzima-Nyarko, M., Heddam, S., & Wu, S. 2019. Assessing the performance of a suite of machine learning models for daily river water temperature prediction. PeerJ, 7, e7065. https://doi.org/10.7717/peerj.7065

Zhu, S., Ptak, M., Yaseen, Z. M., Dai, J., & Sivakumar, B. 2020. Forecasting surface water temperature in lakes: A comparison of approaches. Journal of Hydrology, *585*, 124809. https://doi.org/10.1016/j.jhydrol.2020.124809

Zimmerman, D.L. 2006. Optimal network design for spatial prediction, covariance parameter estimation, and empirical prediction. Environmetrics 17(6): 635–652. doi:10.1002/env.769.