Rapid Salmon Habitat Assessment

Guidebook

2024

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Introduction

Salmon are critical to many ecosystems in British Columbia and play a pivotal role in the cultural and food systems of many First Nations communities (Thompson et al., 2019). As anthropogenic and climate impacts continue to change river systems at an unprecedented rate, it has become vital to monitor salmon habitat and document the shifts in habitat dynamics (Hamann et al., 2014). Commonly, habitat monitoring is developed primarily considering only a Western science paradigm, based on a Eurocentric worldview (Wright, 2019). In recent years, attempts have been made to include Indigenous Knowledges (IKs) as data in environmental monitoring. However, without a proper grounding in a research paradigm such as Community Based Participatory Research (CBPR) these efforts often result in an extractive use of IKs (Gearheard et al., 2010). Alternatively, research that features the ethical co-production of knowledge from both Western and Indigenous science perspectives has produced unique insights into landscape dynamics and ecosystem processes (Johnson et al., 2015).

In recent years, modern geospatial technologies, such as commercial unmanned aerial vehicles (UAVs), high-precision global navigation satellite systems (GNSS), and geographic information systems (GIS), have experienced a notable surge in accessibility and user-friendliness. These advancements have opened avenues for developing habitat assessment methodologies that integrate both Western and

Indigenous perspectives. Moreover, these geospatial tools can empower communities to swiftly deploy assessment methods throughout the year and in response to emergent events. The primary aim of this project was to formulate a methodology for conducting an Indigenous community-based Rapid Salmon Habitat Assessment. This innovative approach combines CBPR methods with cutting-edge geospatial technologies and through this methodology, communities can identify and evaluate key salmon habitat metrics tailored to their unique needs. These metrics, identified by communities, can encompass a range of factors, including descriptions of available fish habitat, fish passage, thermal zones, and riparian conditions.

This report provides a comprehensive overview of the project's progression, organized to mirror key stages of the salmon life cycle. Beginning with the "salmon fry stage," the first section delineates the establishment of the project and offers insights into the considerations pivotal to this initial phase. Transitioning to the "salmon smolt stage," the subsequent section highlights the community capacity-building efforts and the training initiatives essential for the implementation of such a project. Moving forward to the "adult salmon stage," the third section outlines the habitat assessment methodology, encompassing the data collection and analysis procedures. The final part of the project, the "returning home" section, highlights the communication of results back to the community and articulates the iterative review cycle for the continuation of monitoring. Concluding the report is a forward-looking section that explores opportunities for future research and development, aiming to refine and expand the efficacy of this methodology for salmon habitat monitoring.

Salmon Fry: Project Establishment

The initial phases of any CBPR project constitute a pivotal and delicate stage. In the context of the salmon life cycle, this phase aligns with the fry stage (Figure 1). Such projects ideally emerge from a community need or aspiration, with the community actively seeking collaborative partnerships (Thompson et al., 2019). Ethical CBPR frameworks underscore the paramount importance of prioritizing community needs and aspirations, thereby identifying project objectives that directly address these concerns (Castleden et al., 2012). In the context of an Indigenous salmon habitat monitoring program, communities would identify a need to create a program or to improve upon an already established program. Once the need is acknowledged, communities would embark on seeking partnerships, either with facilitating organizations or with other communities with successfully established programs. The latter approach can yield particularly significant benefits, as research indicates heightened advantages arising from horizontal knowledge exchanges among communities (Tschirhart et al., 2016).

Executive Summary

This report outlines the full project cycle for the Rapid Salmon Habitat Assessment (RSHA). The progress of the project is tracked through four sections related to the salmon life cycle (fry, smolt, adult, spawner). The RSHA method combines geospatial technologies and community-based participatory methods to enable First Nation communities to plan and conduct salmon habitat monitoring. The RSHA method was developed by three First Nation organizations across different regions of BC (Lower Fraser River, Okanagan Valley, and Skeena Rivers).

Results from the project showed that the inclusion of geospatial technologies in a community-based monitoring program was successful on several levels. Web-based mapping platforms served as a successful engagement tool with communities for identifying sites across a wide region as well as being able to be delivered in an online format. Additionally, the high-resolution imagery was successful in producing time-relevant printed maps for the local scale community engagement sessions. The RSHA method also showed success in detecting key habitat metrics related to usable habitat, fish passage, temperature patches, and riparian conditions.

Future improvements to the RSHA method should focus on three key areas. The first is to investigate the feasibility of machine learning algorithms to improve the efficiency of water detection. The second is to compare and validate the detected metrics to a traditional field-based assessment method. The third area for future improvement to the RSHA method should come from repeated cycles and community reflections on the results, methods, and overall process.

Acronyms

CBPR	Community Based Participatory Research
CHM	Canopy Height Model
DSM	Digital Surface Model
DTM	Digital Terrain Model
GCP	Ground Control Point
GIS	Geographic Information Systems
GNSS	Global Navigation Satellite Systems
GSD	Ground Sample Distance
IK	Indigenous Knowledge
LWD	Large Woody Debris
MOU	Memorandum of Understanding
PPK	Post Processed Kinematic
PPP	Precise Point Positioning
RGB	Red, Green, Blue
RSHA	Rapid Salmon Habitat Assessment
RTK	Real Time Kinematic
UAV	Unmanned Aerial Vehicle

During the early partnership period, it is important that all partners have clear expectations of the project goals. A common tool that is used in these types of partnerships is a memorandum of understanding (MOU), which outlines the details of the project and defines the roles, responsibilities, and expectations of both the community and partners during all phases of the project (Ball & Janyst, 2008). It is also critical during this stage to define the ownership, usage, and sharing of data gathered during monitoring. The co-creation of the MOU document serves to develop trust further and build the relationship between the community and partners by outlining shared goals for the project and ensuring that there are clear ways to enhance two-way learning (Huntington et al., 2011).

The concluding phase of this initial cycle entails evaluating the community's existing capacity to undertake the habitat monitoring program. This evaluation involves conducting a survey aimed at identifying essential equipment, personnel, and training requirements necessary for the community to sustain and perpetuate its program in the long term. Concurrently, while conducting the inventory survey, communities can identify pivotal members suitable for various roles within the monitoring program. Typically, participation levels are structured into three tiers, offering community members opportunities to assume management, technical, observational, or knowledge-keeper roles based on their interests, capabilities, and availability.

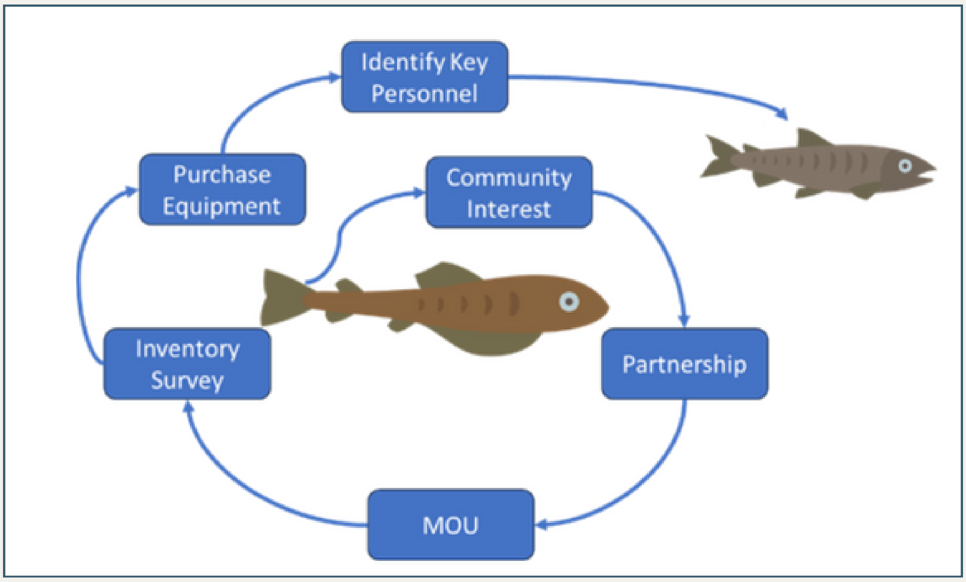

Figure 1: The Salmon Fry stage of the community-based salmon habitat monitoring program.

Salmon Smolt: Capacity Building

The second phase of this program mirrors a transitionary period akin to the salmon smolt life cycle stage. During this phase, the project's emphasis shifts towards community capacity building and training (Figure 2). In this project, community capacity building stands as a fundamental pillar, enabling participating communities to cultivate the necessary skills for the long-term success of the monitoring program. Beyond technical training, it's important to ensure that training opportunities and resources encompass not only technological methodologies but also facilitate engagement with alternative research tools such as community mapping, semi-structured interviews, experiential learning on the land, and storytelling (Huntington et al., 2011). Moreover, given the diverse backgrounds often present in these partnerships, training should incorporate an ethical dimension, particularly for external community partners.

For this project, training was delivered through a variety of mediums. Methods included classroom sessions, workshops, reading materials, instructional videos, and hands-on practice sessions conducted in the field. The technical personnel identified within the communities underwent ground school training essential for obtaining an Advanced Remotely Piloted Aircraft System license. Subsequent to this, practical sessions were conducted using both smaller and larger UAVs to familiarize team members with the requisite skills for executing mapping missions effectively.

Moreover, training encompassing the development of technical competencies pertinent to data collection and analysis was facilitated through a series of workshops, supplemented by manuals, instructional videos, and real-world field exercises. Similarly, instruction in Community-Based methodologies such as community mapping was provided through workshops, a dedicated training manual, and practical exercises conducted during community-hosted events. This multi-faceted approach ensured that participants gained proficiency across various skill domains, empowering them to contribute effectively to the project's objectives.

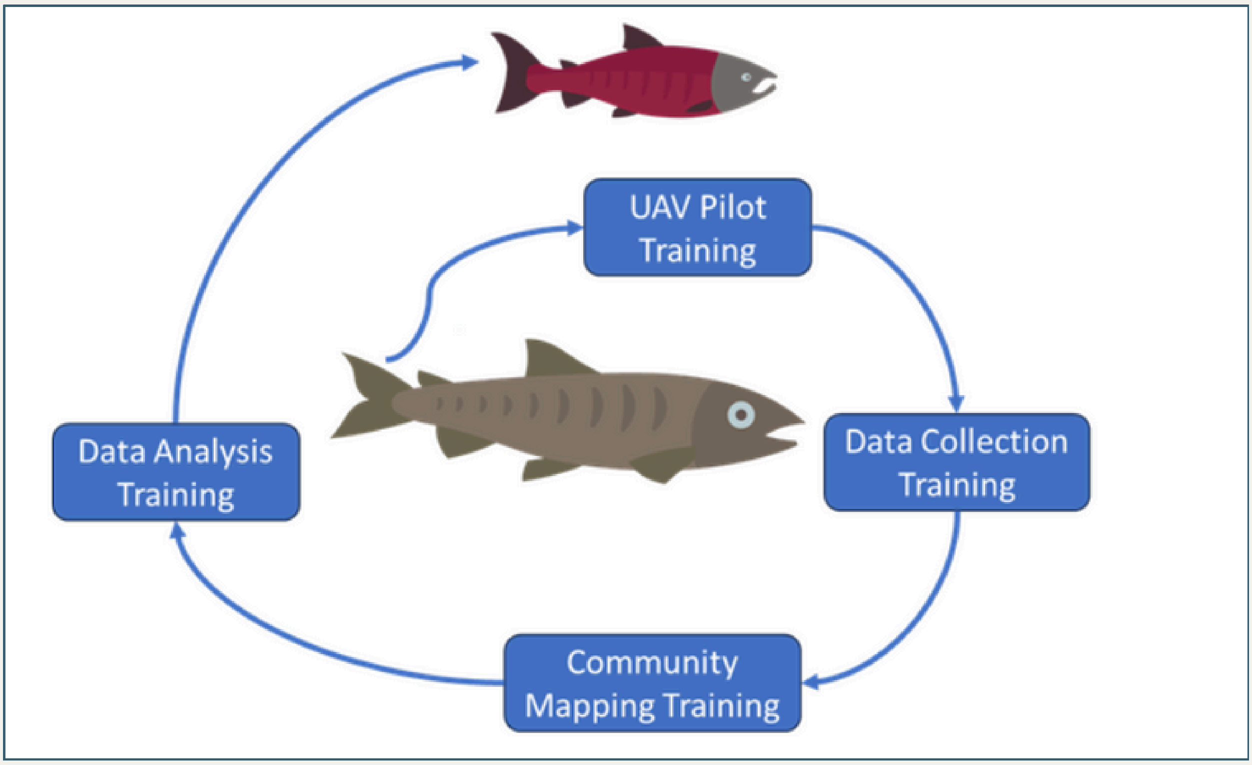

Figure 2: The salmon smolt stage of the community-based salmon habitat monitoring program.

Adult Salmon: Habitat Assessment

As capacity within the community team is strengthened, the project progresses into its third stage, analogous to the adult salmon phase (Figure 3). At the heart of this stage lies the salmon habitat assessment and monitoring, a process comprising several iterative components for the duration of the monitoring program. Initially, potential sites of interest were identified through a community mapping workshop conducted at a regional scale. Subsequently, based on workshop insights, a subset of sites was chosen considering factors like urgency, feasibility of aerial surveying, and the capacity of the monitoring team for the season.

Depending on site characteristics and identified priorities, two distinct types of data collection missions were undertaken: overview data missions and habitat analysis missions. During overview data missions, the imagery alone was captured. This imagery aided in facilitating local-scale community mapping workshops aimed at garnering further insights into each site. Conversely, habitat analysis missions entailed the collection of imagery alongside additional lidar and thermal data. Furthermore, high-precision global navigation satellite systems are utilized to establish ground control and validation points during these missions. After both mission types, the imagery data is integrated into local-scale community mapping workshops. However, while imagery from overview missions primarily supports these workshops, imagery from habitat analysis missions, combined with the supplementary data, is instrumental in the habitat assessments.

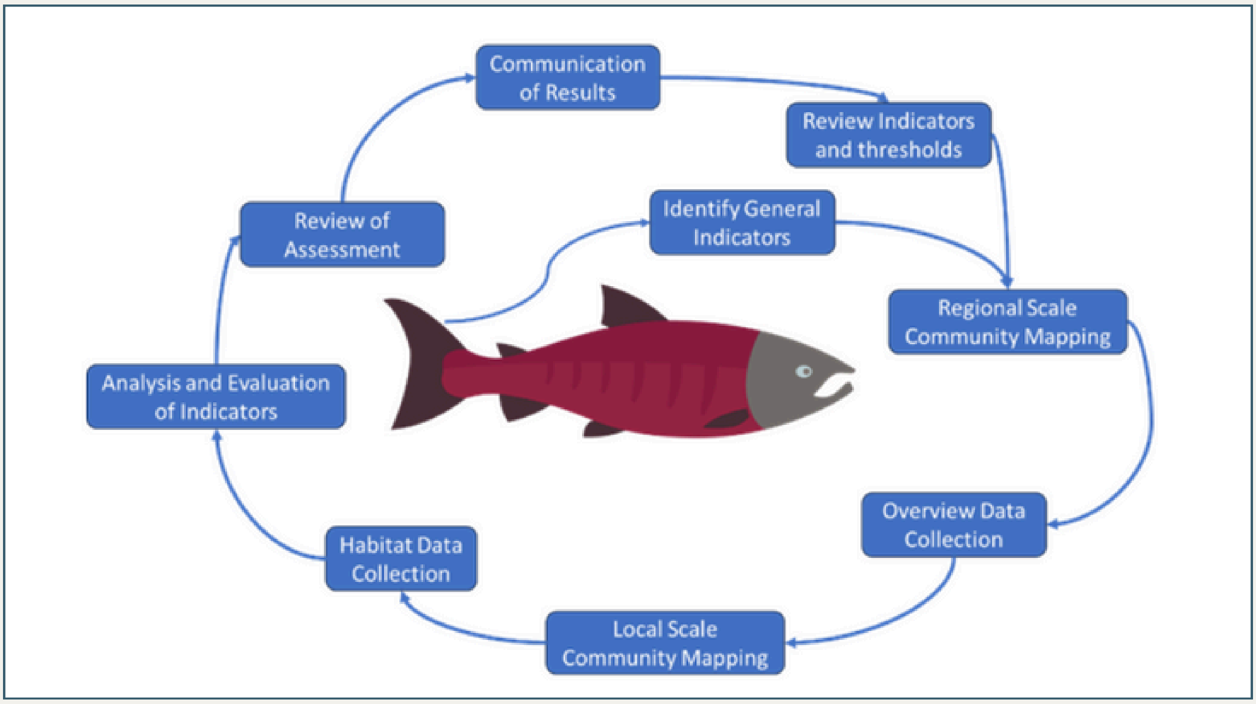

Figure 3: The adult salmon stage of the community-based salmon habitat monitoring program.

Site Selection

Sites utilized to refine the methodology of this project were chosen across four distinct regions: Victoria, Lower Fraser River, Skeena River, and the Okanagan Valley. In the Victoria region, a site on the Leech River near Victoria was selected as a testbed for evaluating UAV data collection techniques. Within the Lower Fraser Region, a web-based community mapping workshop engaged members from Kwantlen, Katzie, Tsawwassen, and Tsleil-Waututh First Nations, resulting in the identification of over 20 sites earmarked for salmon habitat stewardship and monitoring. Among these, Yorkson Creek (Katzie First Nation) and Whonnock Creek (Kwantlen First Nation) were selected for habitat analysis data collection.

In the Skeena Region, another web-based community mapping workshop involved members from Gitksan First Nation and Gitksan Watershed Authorities, leading to the identification of over 24 sites of interest. From this pool, three sites—McCully Creek, Sweetin River, and Nangeese River—were chosen for data collection. Notably, only the McCully Creek site underwent habitat analysis data collection, while the remaining sites had overview data collected.

In the Okanagan Valley region, the Okanagan River has been heavily channelized and altered since the 1950's in an effort to manage flood and irrigation control to expand arable land within the valley. Over 80% of the Okanagan River was channelized between Penticton and Osoyoos, with the only natural section of river remaining flowing through the Osoyoos Indian Band. It is within this section that the bulk of the available spawning habitat for Okanagan River Chinook, Sockeye, and Steelhead currently exists. As part of the continued restoration effort for these stocks, this project assisted in the examination of Vaseux Creek, a tributary that flows into the natural section of the river. This creek, like many in the Semi Arid Okanagan Valley, is impacted by water withdrawals for irrigation, and varying groundwater inflows. Vaseux Creek was chosen for this project to assess thermal groundwater inflows, LiDAR for substrate analysis, and orthomosaic imagery to contribute to the understanding of the hydrology of Vaseux, in addition to also having a long standing habitat dataset to develop our RSHA.

Data Collection

Data collection across all sites was collected utilizing the DJI Matrice 300 series UAV platform, complemented by either the P1 sensor for photogrammetry data, the L1 sensor for lidar data, or the H20t sensor for thermal data, in conjunction with the DRTK2 GNSS Base station. Ground control and validation data were gathered employing an SP85 Real Time Kinematic (RTK) GNSS base and rover setup.

In instances where solely overview data were procured, the P1 sensor was deployed to capture imagery, with mission plans optimized for expedited operation or extended battery life, given that printed maps typically do not necessitate imagery resolutions finer than 10 cm. Details of the data collection process for sites identified for habitat analysis are provided in the subsequent sections.

Leech River (Victoria)

Data were collected at Leech River on July 13, 2023. The Leech River flows through the Capitol Regional District Water Supply area and into the Sooke River. GNSS base data were collected for a total of 4.0 hours while the flights for photogrammetry, lidar, and thermography were conducted. The photogrammetry data were collected at the height of 80 m above the ground surface with 80% and 80% forward and side overlap, respectively, at an average speed of 10 m/s. There were a total of 764 Red, Green, Blue (RGB) photos collected. The resulting orthomosaic had a Ground Sample Distance (GSD) of 1.2 cm per pixel. The lidar data were collected at 80 m with 50% side lap at an average speed of 5 m/s.

The cleaned point cloud had an average point density of 398.09 points /m2 with an average point spacing of 0.05 m. Thermal data were collected over a linear corridor focused on the river and 50 m on either side of the centreline. These data were collected at 80 m with 70% and 70% forward and side overlap at an average speed of 2.4 m/s. In total, 413 thermal images were collected. The resulting T orthomosaic produced a GSD of 8.6 cm per pixel. Five ground control targets were deployed for all flights, with centre locations collected with RTK GNSS. When compared to the RTK control points, all datasets showed positional accuracies < 5cm.

Yorkson Creek (Lower Fraser)

Data were collected at Yorkson Creek on March 6, 2022. Yorkson Creek flows through Katzie First Nation and into the Fraser River. GNSS base data were collected for a total of 4.25 hours while the flights for photogrammetry, lidar, and thermography were conducted.

The photogrammetry data were collected at the height of 90 m with 70% and 70% forward and side overlap, respectively, at an average speed of 10 m/s. There were a total of 707 RGB photos collected. The resulting orthomosaic had a GSD of 1.1 cm per pixel. The lidar data were collected at 80 m with 50% side lap at an average speed of 10 m/s. The cleaned point cloud had an average point density of 145.97 points /m2 with an average point spacing of 0.08 m. Thermal data were collected over a linear corridor focused on the river and 10 m on either side of the centreline. These data were collected at a height of 100 m with 80% and 70% forward and side overlap at an average speed of 3 m/s. In total, 356 thermal images were collected. A second corridor flight with similar parameters was conducted perpendicular to the first such that there was thermal imagery over some (2) ground control targets. The second flight resulted in an additional 92 thermal images (448 total). The resulting orthomosaic had a GSD of 1.1 cm per pixel. Three ground control targets were deployed for all flights, with centre locations collected with RTK GNSS. When compared to the RTK control points, all datasets showed positional accuracies <= 6 cm.

Whonnock Creek (Lower Fraser)

Data were collected at Whonnock Creek on March 7, 2022. Whonnock Creek flows through Kwantlen First Nation and into the Fraser River. GNSS base data were collected for a total of 4.25 hours while the flights for photogrammetry, lidar, and thermography were conducted. The photogrammetry data were collected at 80 m with 80% and 80% forward and side overlap at an average speed of 10 m/s. There were a total of 1447 RGB photos collected. The resulting orthomosaic had a GSD of 1.2 cm per pixel. The lidar data were collected at 80 m with 50% side lap at an average speed of 10 m/s. The cleaned point cloud had an average point density of 394.54 points/m2 with an average point spacing of 0.05 m. Thermal data were collected over a linear corridor focused on the river and 50-75 m on either side of the centerline. These data were collected at 80 m with 80% and 70% forward and side overlap at an average speed of 2.4 m/s. In total, 619 thermal images were collected. The resulting orthomosaic had a GSD of 7.7 cm per pixel. Five ground control targets were deployed for all flights, with centre locations collected with RTK GNSS. When compared to the RTK control points, all datasets showed positional accuracies <= 5 cm.

McCully Creek (Skeena)
Data were first collected at McCully Creek between June 17-19, 2022. McCully Creek flows through Gitxsan First Nation, into the Kispiox River, and eventually the Skeena River. GNSS base data were collected for a total of 3.5 hours while the flights for photogrammetry and lidar were conducted. The photogrammetry data were collected at 120 m with 80% and 80% forward and side overlap at an average speed of 15 m/s. There were a total of 4154 RGB photos collected. The resulting orthomosaic had a GSD of 1.48 cm per pixel. The lidar data were collected at 120 m with 30% side lap at an average speed of 8 m/s. The cleaned point cloud had an average point density of 141 points/m2. Four ground control targets were deployed for all flights, with centre locations collected with RTK GNSS. The thermal data were collected over a linear corridor focused on the river and 50 m on either side of the centerline on October 04, 2022. These data were collected at 120 m with 80% and 80% forward and side overlap at an average speed of 2 m/s. A total of 2941 thermal images were collected.

Data Processing

After data collection, each of the main datasets (GNSS, Photogrammetry, Lidar, and Thermal) were then processed from their raw data into derivative data products. Each of these data products was then combined to define the overall wetted area of the stream and remove any instream obstructions such as overstory canopy, gravel bars, cobbles, or large woody debris (LWD). This water area is used to clip all the derivative data products from which habitat metrics are estimated that focus on aspects of available habitat, fish passage, thermal conditions, and riparian cover. Each of these steps is described in more detail in the sections below.

GNSS Processing

Each site's long occupation GNSS base station data were processed into a standard reference frame and epoch to ensure a consistent positioning system for each site over time. Using the NRCAN Precise Point Positioning software, recorded base station observations were converted into UTM positions using the Canadian Spatial Reference System (CSRS) North American Datum 1983 (NAD83) reference frame and the 2002.0 or 1997.0 survey epoch. Observations for each survey are collected in the ITRF 2014 or 2020 reference frame, with the epoch being the survey date (e.g. 2022.3.6 for Yorkson Creek). Using a Precise Point Positioning (PPP) method allows for the correction of timing offsets due to atmospheric and ionospheric effects, as well as correcting for inaccuracies in satellite positioning. Shifting the epoch allows the effects of tectonic movement to be minimized over the long term and data to align with other provincial standard spatial data.

Two different correction shift vectors were calculated from the GNSS data. The first shift vector examined the X, Y, and Z differences between the observed base station position and the PPP-corrected position of the base station. This X, Y, and Z difference (shift-vector) was applied to all RTK rover positions (ground control targets & DRTK base). This shift vector was used by the RTK survey data and during the processing of the lidar data.

A second shift vector was calculated for the photogrammetry and thermal image coordinates. This shift vector was determined by calculating the difference between the observed coordinates from the DRTK base station and the PPP-corrected coordinates of the DRTK base determined from the RTK rover. This shift vector was then applied to the photogrammetry and thermal image coordinates.

Photogrammetry

The observed GNSS coordinate of the image centre at the time of capture is attached to the metadata of each image from the UAV. However, these coordinates are in the ITRF reference frame and have been obtained using real-time information from the uncorrected DRTK position. To shift the image coordinates into the standard reference frame, the second shift vector described above was applied to the UTM coordinates, resulting in a corrected image position dataset.

The imagery was processed using pix4d mapper to create 2D orthomosaic maps as well as 3D point clouds. Images were imported to pix4d, image coordinates were shifted, 2D and 3D reconstruction parameters were set to default, and all outputs used the NAD83 CSRS coordinate system with the appropriate UTM zone and ellipsoidal heights. During processing the coordinates of the Ground Control Point (GCP) targets were imported, and target centres were manually marked in all photos where there was a clear, unobstructed view of the target. All targets were used as GCPs to improve the overall model positional accuracy. The output datasets were evaluated for positional accuracy by recording the easting and northing of each apparent target location in the orthomosaic and comparing them to the positions obtained through the RTK survey. The vertical coordinate for each target was determined by examining the output point cloud and choosing the elevation that best represented the apparent target surface.

LiDAR

The lidar data for each site relies on a direct georeferencing method where the DRTK base station communicates with the UAV platform (rover unit), maintaining very accurate relative positioning between the two. The lidar sensor records the exact orientation of the sensor relative to the aircraft position and the time it takes laser pulses to return after interacting with an object. This combination of the aircraft's position, the orientation of the sensor, and the timing of the laser pulse allow for calculating the position of the target feature. However, that position in absolute space will be relative to and dependent on the accuracy of the coordinate for the DRTK position. As with the photogrammetry data, this position was obtained from the shifted RTK survey data. In some cases (Whonnock Creek), the DRTK position was unavailable and the SP85 base station data was used in a Post Processed Kinematic (PPK) processing method.

Data from each lidar flight was imported into DJI Terra and processed, referencing either the corrected DRTK coordinate (RTK method) or the corrected GNSS base station coordinate (PPK method). Point clouds were produced using the highest quality setting and the NAD83 CSRS coordinate system with the appropriate UTM zone and ellipsoidal heights. The resulting point clouds included all points collected during the mission including those from transits, turns, calibration runs, as well as the main data lines as a single file.

To remove unnecessary data and classify individual flight lines, the lidar trajectories were sorted in QGIS such that the time ranges of data collection were classified into transit points, turn points, calibration points, or line points. Using an R script, these time ranges were used to classify the point clouds, keeping only the points that belonged to the main data collection lines.

After the individual flight lines were classified, the classify overlap tool in ArcGIS Pro was used to identify points from different flight lines that represent the same feature. When this tool identifies two matching points, the point with the lowest scan angle (closer to nadir) is kept. This process greatly reduces the size of the lidar point cloud, making subsequent processing more efficient.
The final step of cleaning the lidar data involves identifying and removing any remaining noise points. This is accomplished using two methods: either visual inspection or an isolated points tool. For the first method, a visual inspection of the point cloud is used to identify any points far above or below the main point cloud. These points can be removed in R or using software like Global Mapper by using commands such as classify above or classify below a certain threshold. The second method is to run an isolated points algorithm either in R or Global Mapper. For this project, a general 5 m3 voxel was used to identify points where less than 5 points fell within the voxel. Points that were selected by either method were classified as noise and removed from the point cloud.

The cleaned lidar point clouds were then used in Global Mapper to classify ground surface points. Parameters for the ground classification varied between sites depending on the conditions and range of topography. However, at each site, a cyclical process was used where a general set of parameters was tested in a few sample areas that highlighted the range of conditions. These parameters were optimized to provide the best general ground classification and then run on the entire point cloud. After the initial ground classification, a digital terrain model (DTM) and hillshade were produced to inspect for areas where the ground classification could be improved. In general, three problem areas were identified: areas with ground gaps, areas with ground peaks, and channel banks or other high-slope areas. Ground gaps were primarily caused by occlusion and points were added or removed from these areas using cross profiles and visual interpretation. Ground peaks, channel banks, and other high slope areas were improved by using polygon zones and re-running the ground classification within the zones with adjusted parameters.

The ground-classified point clouds were used to create normalized (height above ground) point clouds and several raster derivative products. Raster products produced from each of the point clouds included digital terrain models (DTMs), digital surface models (DSMs), slope models, aspect models, and canopy height models (CHMs). The positional accuracy of each lidar dataset was determined using the DTM surface at the surveyed location of each target to assess the vertical component and by examining the point clouds to determine the apparent horizontal position of each target centre.

Thermography

The thermal data at each site is similar to the photogrammetry data in that the observed GNSS coordinates need to be shifted using the calculated shift vector if available. Following the same procedure described above for the photogrammetry data, the thermal image coordinates were shifted into the standard reference frame. Next, to convert digital numbers into apparent temperatures, a radiometric calibration was conducted using the Thermoconverter software. All images were adjusted using local weather conditions obtained from either field observations or the nearest weather station for the day of data collection. As the main feature of interest is water, the emissivity value was set to 0.98, which is a typical emissivity value for water (Dugdale, 2016). The adjusted images were processed into a 2d thermal orthomosaic using the Pix4d software. Ground control points were only used to validate positioning where available and were not used in constructing the orthomosaics. Each output was visually assessed for impacts of thermal drift or other signs of bias.

Habitat Analysis

After all the collected data was processed into data products, each layer was imported into QGIS and reprojected to a common resolution of 10cm using the DTM as a “snap raster” layer. This ensures that the pixels for all the different data layers are the same size and have identical boundaries. The next step of the analysis is to begin dividing the area into three major zones: water, riparian, and outside of scope. Dividing into these zones serves two purposes: first, to focus the area of analysis strictly on the wetted area and second, to reduce the amount of data needed to be used in each step of the analysis.

Generally, the elevation data from the DTM served as a good first-division point. Using the symbology of the DTM layer with a binary classification, a breakpoint elevation was visually determined such that all the channel area was classified as 1 and most of the outside channel area as possible was classified as 0. With the elevation breakpoint determined, the reclassify by table tool was used to create an elevation bitmap mask where channel pixels have a value of 1 and all other pixels have a 'No Data' value. This mask was then used with the Raster Calculator tool to be multiplied with the orthomosaic, thermal mosaic, and CHM to create clipped copies of each. The clipped copies of each of these data were then stacked into a single raster with 5 bands: ortho red channel (B1), ortho green channel (B2), ortho blue channel (B3), thermal (B4), and canopy height (B5).

Each of the different bands in the stacked raster provides information that can be used to help determine if a pixel is water or not. However, tracking this information across many data bands can become challenging, leading to more confusion with automated classification methods. To reduce the complexity in this data a Principal Components Analysis was used to reduce the information contained in the data into a single band. In all cases, over 95% of the variation contained in the stacked dataset was represented by the single band of the first principal component. Using the first component band as an input, an unsupervised classification was performed using the Iso Cluster method in ArcGIS Pro. The Iso Cluster classification was repeated, changing the parameters while attempting to maximize the separation between water and non-water pixels while minimizing the number of overall classes and confusion or mixing between them. Generally, this resulted in 5-10 classes where up to two classes each were definitively water or not water, and the others were mixed (i.e. tree shadow and water shadow).

The classified raster was converted into vector data using the raster pixels to polygons tool, with each pixel being its own polygon. Each class was then visually inspected, and pixels were assigned to either a water class (1) or a non-water class (0). Several additional data layers, including the full-resolution orthomosaic, the slope model, and a relative DEM, were used to aid the interpretation of pixel classes. The resulting layer had all polygons classified as either water or non-water.

In some cases, a tree, branch, or LWD obstructed the view of water, while it was clear that significant water passed below these pixels. In these cases, the pixels were classified as obstructed and were included for estimating habitat metrics such as habitat area but were removed from estimating metrics like temperature or stream shade where the influence of a non-water pixel would impact results. The classified polygons were rasterized back into a mask where all water pixels were set to 1, and all other pixels were set to 'no data.'

A stream centreline was digitized using the full-resolution orthomosaic data, which followed the apparent stream thalweg as best as it could be identified. This centreline was smoothed with a one-pixel (10 cm) tolerance, and sample points were generated at one-meter intervals along the line. Using the data that the water mask had clipped, samples for elevation and temperature were taken at each sample point where there was available data. The elevation data was used to calculate the overall stream gradient (last sample point – first sample point) and an instantaneous stream gradient using a 3 m moving average. The temperature data was used to create a centreline temperature interpolated surface using inverse distance weighting. This surface was subtracted from the temperature mosaic to create a new temperature surface which was relative to the centreline average temperature.

Next, a water edge polygon was created by using the dissolve tool on the water-classified pixel polygons. This water edge polygon was buffered by 50 m, which defined the riparian zone used for analysis. All areas outside of either the water or riparian zones were considered outside the scope of analysis. A treetop detection algorithm was used in R with the height-normalized lidar point cloud to estimate the density and height of large trees in the riparian zone. This algorithm identifies apparent treetops from localized peaks in the data, marks them with a point and records the tree height. The identified tree top points were clipped to only those that fell within the riparian zone for analysis.

The final analysis layer produced was an estimate of potential solar insolation for the wetted area. This layer was produced using the 'r.sun.insoltime' tool in QGIS, which produced the daily sum of solar irradiance. This tool used the DSM, slope, and aspect models as input layers and modelled irradiance (W m-2 day-1) on the Julian day for the summer solstice. The resulting irradiance layer was clipped to the visible water area using the water mask.

The stream centre sample points were split into different reaches based on differences in apparent conditions such as slope, barriers, or geomorphology. Habitat metrics were reported based on the entire sampled area or summarized by reach. Available habitat was estimated as the summed wetted area per reach, and the stream slope was calculated as described above. A threshold of +/- 1° C of the centerline average temperature was used to define cold (< -1° C) and hot (> 1° C) patches, the area of which were summed by the reach and total stream similar to the habitat area. The clipped irradiance layer was converted into pixel polygons similar to the water mask and total irradiance (W m-2 day-1) was summed per reach. Tree top points were also assigned to a reach and tree densities were calculated along with descriptive statistics on tree heights.

Habitat Analysis Results

At each site the sampled area was split into individual reach components to calculate and summaries the habitat metrics. Results from selected sites are presented in the following sections.

Leech River

At the Leech River site, the 234 m of sampled stream length was divided into three main reaches based on breaks in elevation/slope (Figure 4). In total, there was an estimated 980.32 m2 of wetted habitat area (R1: 360.32 m2; R2: 357.95 m2; R3: 262.06 m2). This was further broken into estimated habitat area per sampled stream length to allow for comparisons between stream reaches (Figure 5). In general, the first reach was wider with cobble/gravel bars, the second reach relatively narrow until a series of step pools at the end, and the third reach was relatively wide, consisting mostly of large step pools.

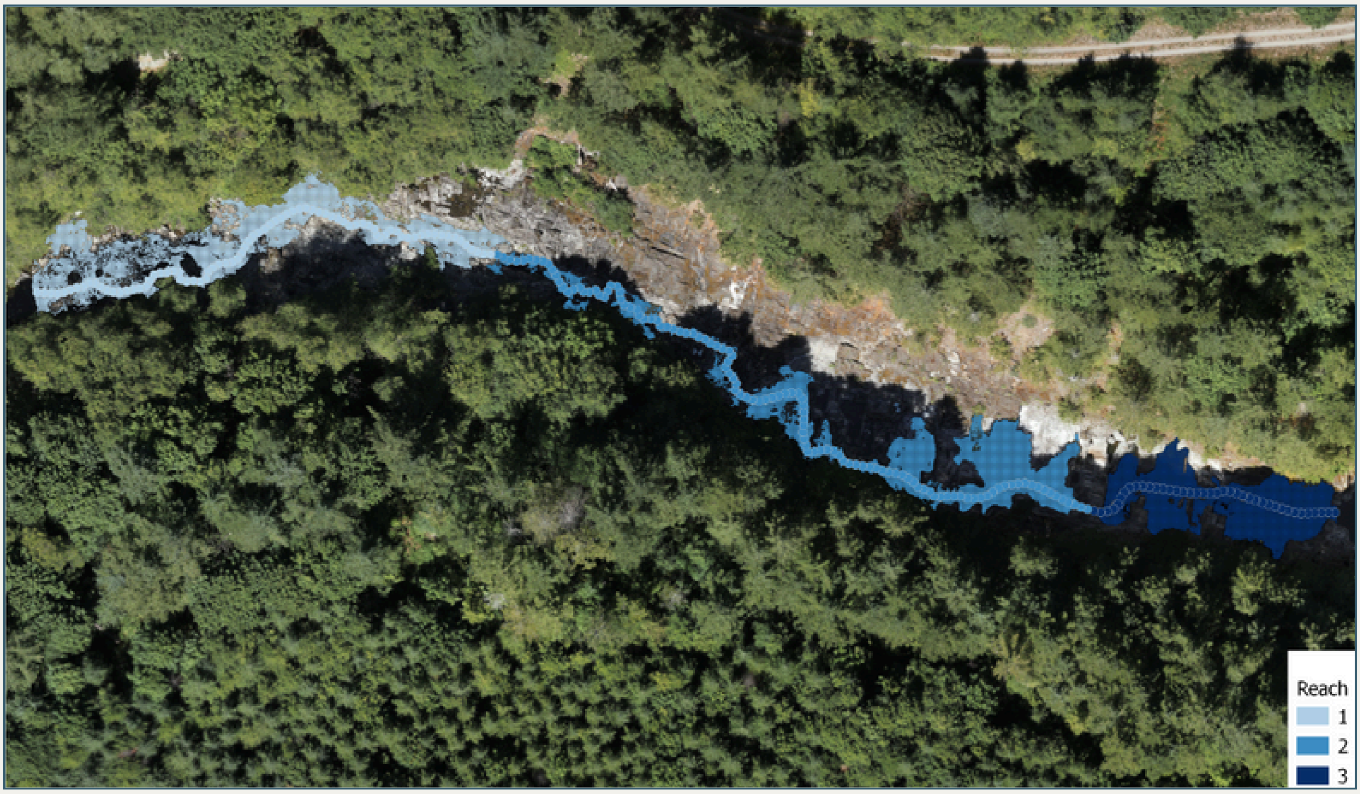

Figure 4: Leech river orthomosaic showing the centreline sample points (circles) and detected wetted area (shaded) for Reach 1 (light blue), Reach 2 (medium blue), Reach 3 (dark blue).

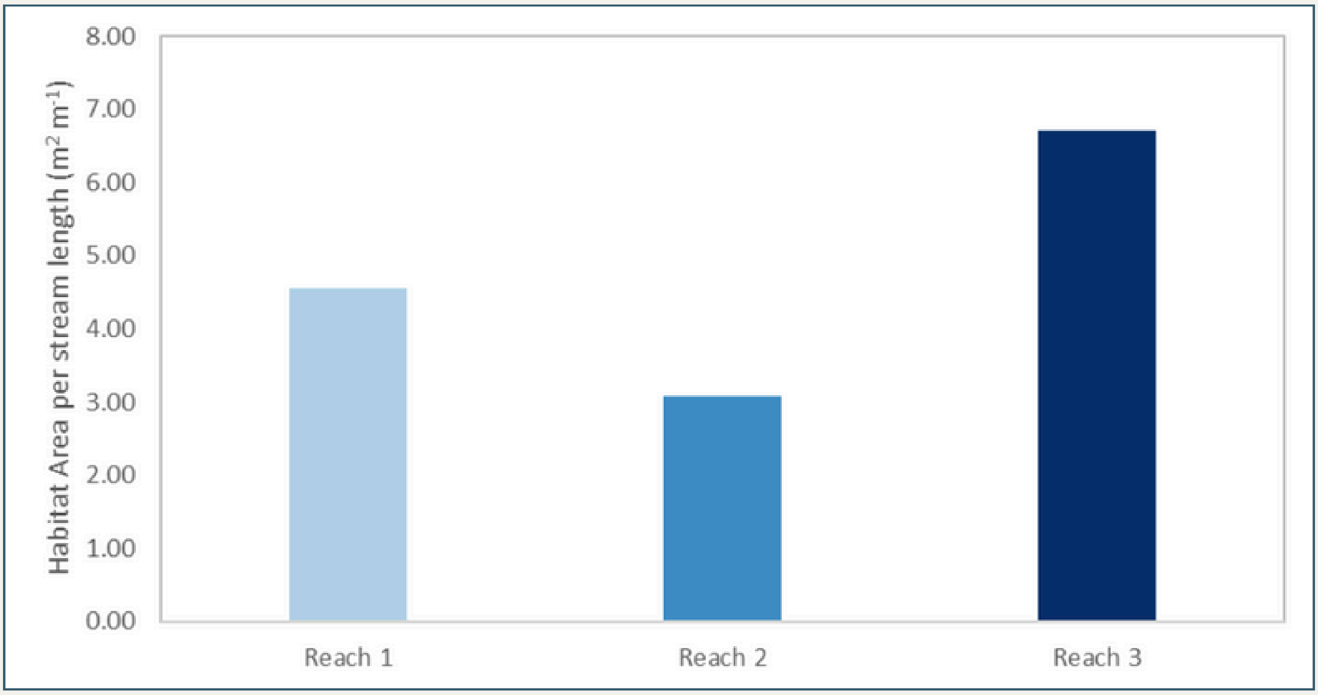

Figure 5: Total wetted habitat area per sampled stream length by reach.

The elevation data shows similar characteristics for the different stream reaches (Figure 6a). Overall, the sampled area had an average stream gradient of 4.74% with average gradients of 1.46%, 2.48%, and 11.72% in reaches 1, 2, and 3, respectively. While the average stream gradient may indicate that there are only passage issues in reach 3, the moving average slope plot indicates that there may be some issues in reach 2 as well. In the transition between reach 1 and 2 as well as near the step pools at the end of reach 2 the average slope plot highlights some transitions that approach or exceed a 20% gradient (Figure 6 b).

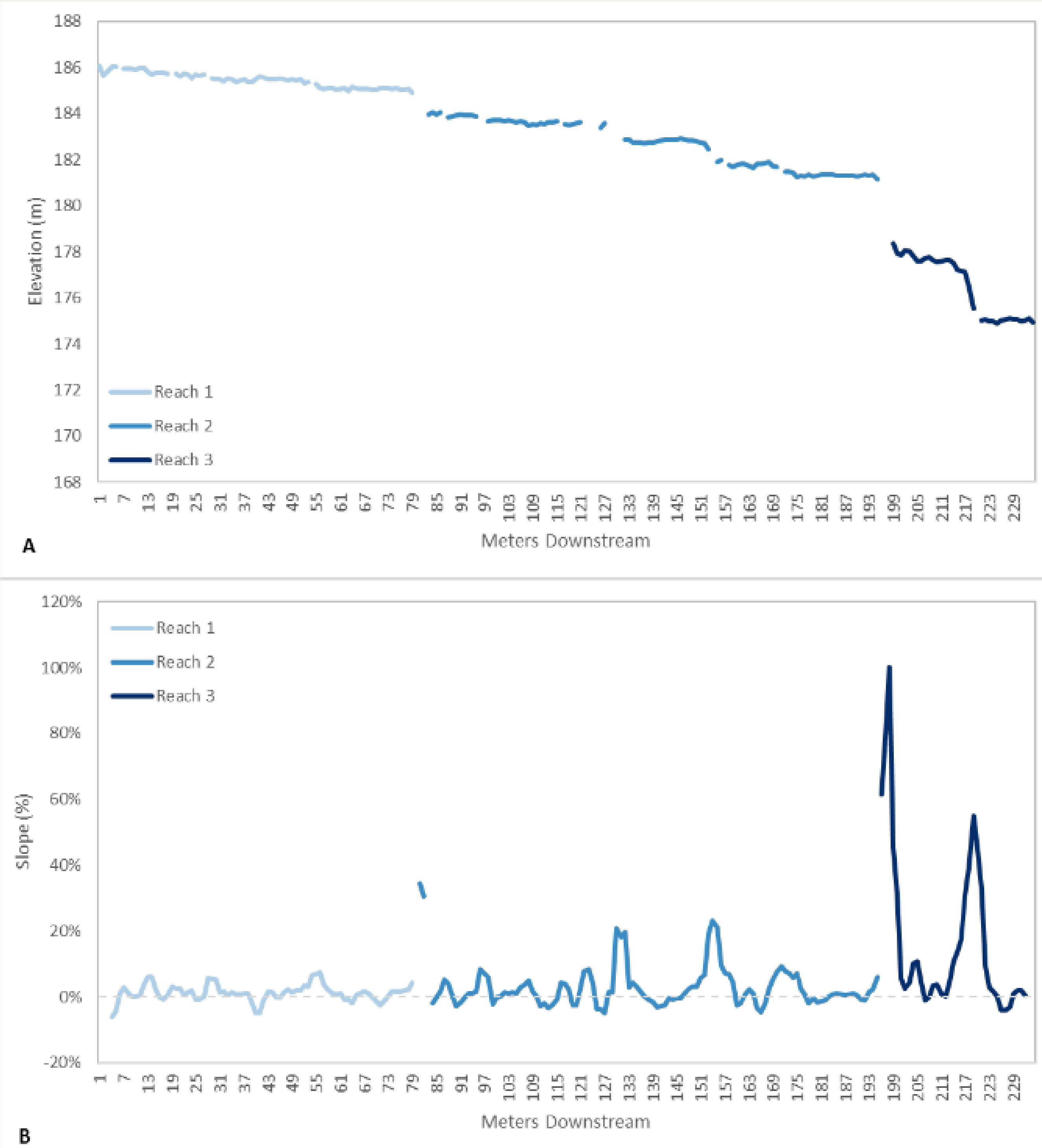

Figure 6: Instantaneous stream elevation (A) and 3 m moving average percent slope (B) for Reach 1 (light blue), Reach 2 (medium blue), Reach 3 (dark blue).

The thermal data for Leech River showed that generally, reach 1 and reach 3 have similar temperatures, whereas reach 2 had slightly higher temperatures, particularly in the narrow section near 120 m downstream (Figure 7). When looking at the relative temperature patches the majority of all reaches were dominated by hot water patches (Figure 8). In terms of the wetted area in each reach, cold patches comprised 8.96%, 6.48%, and 0% for reaches 1, 2, and 3, respectively. This is compared to the proportion of wetted area for hot patches being 34.2%, 39.2%, and 23.3% respectively, for reaches 1, 2, and 3. In total, 1.6% and 33.1% of the detected wetted area for Leech River were comprised of cold and hot patches, respectively.

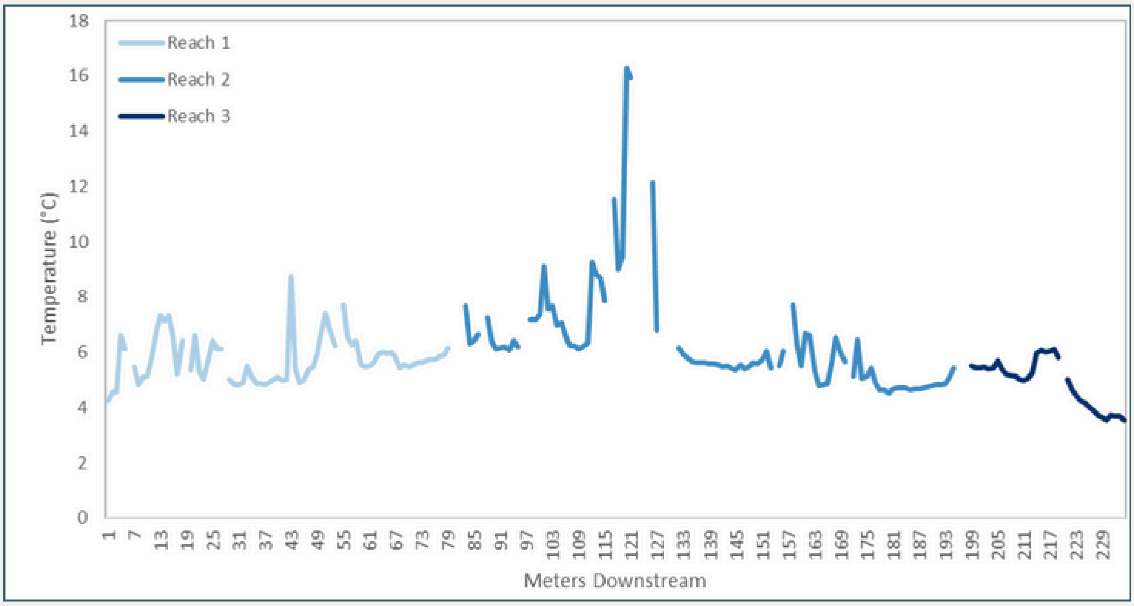

Figure 7: Instantaneous stream temperature for Reach 1 (light blue), Reach 2 (medium blue), Reach 3 (dark blue).

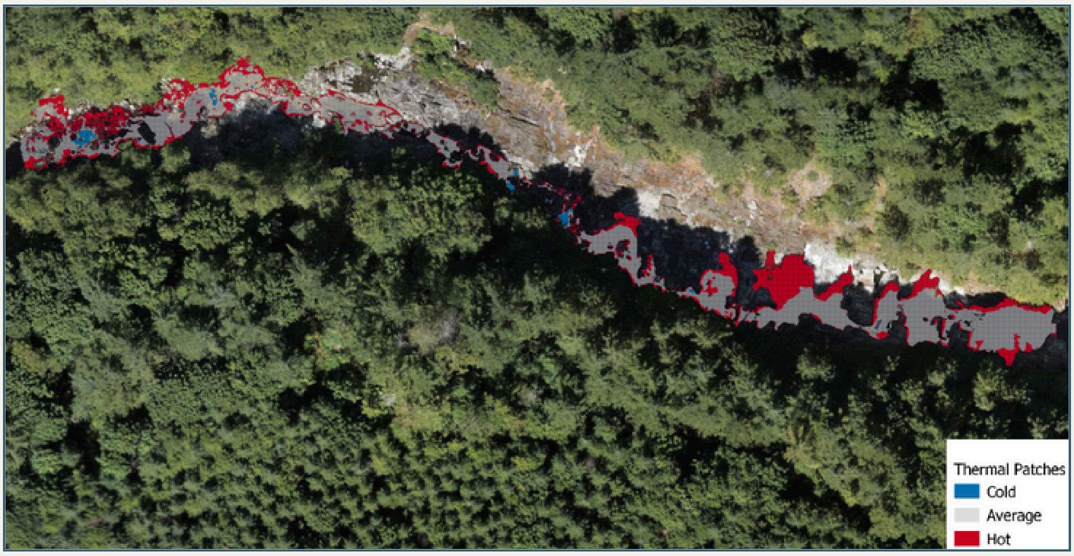

Figure 8: Relative stream temperatures for cold (blue < -1 °C), average (+/- 1 °C), and hot (red > +1 °C) patches.

The riparian tree density was very similar among all reaches where, on average, the total stems per hectare was 147, which ranged from 145 to 149 within the individual reaches. This was similar for tree heights, where reach 1 had slightly larger trees on average compared to the other two reaches (Figure 9). However, despite the slightly taller trees, the first reach showed higher average solar irradiation compared to the other two reaches (Figure 10). This was primarily due to the large rocky outcrop area towards the end of reach 1 (Figure 11). Additionally, there were very few pieces of large woody debris found at the Leech River site, with a total of 0.03 pieces per meter of sampled stream.

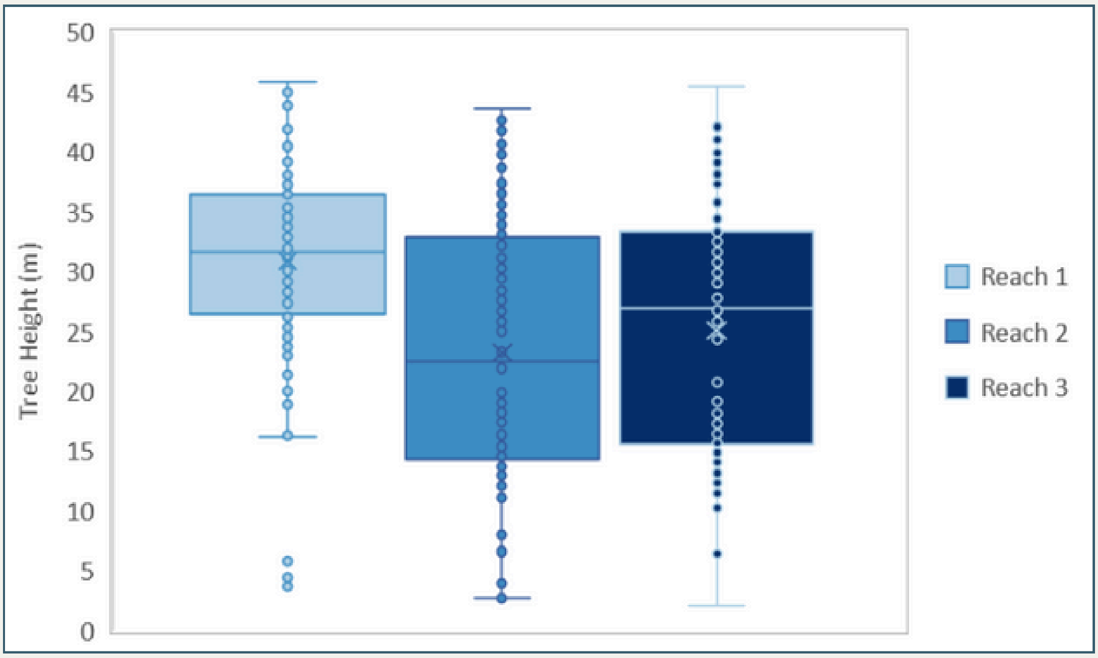

Figure 9: Dominate tree heights for Reach 1 (light blue), Reach 2 (medium blue), and Reach 3 (dark blue).

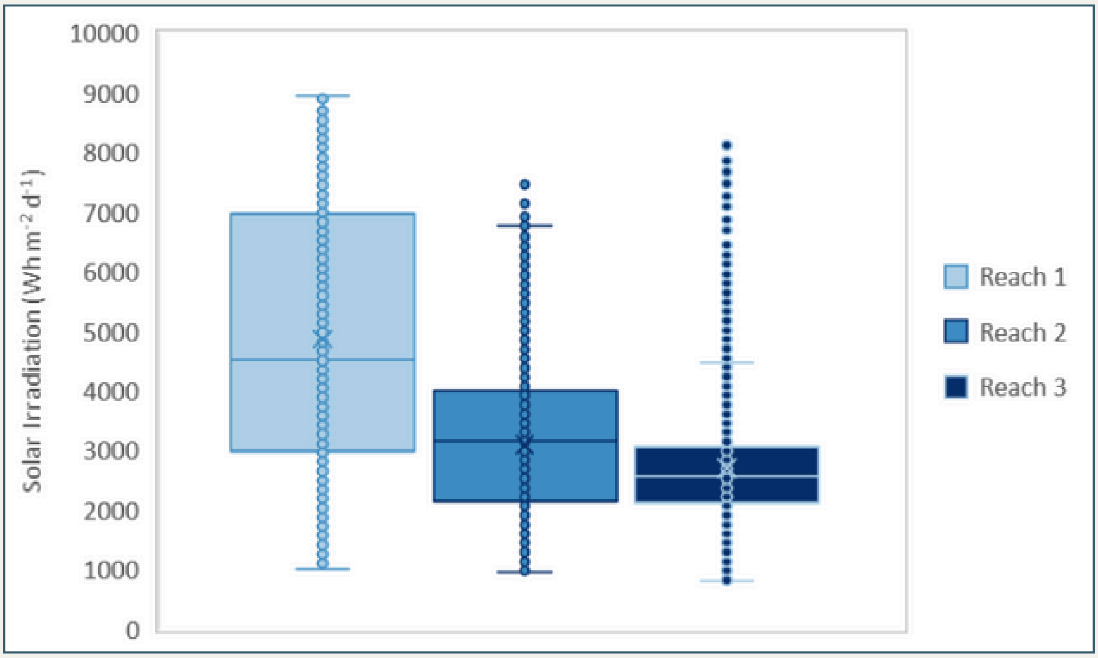

Figure 10: Total solar irradiation (Wh m-2 d-1) for Reach 1 (light blue), Reach 2 (medium blue), and Reach 3 (dark blue).

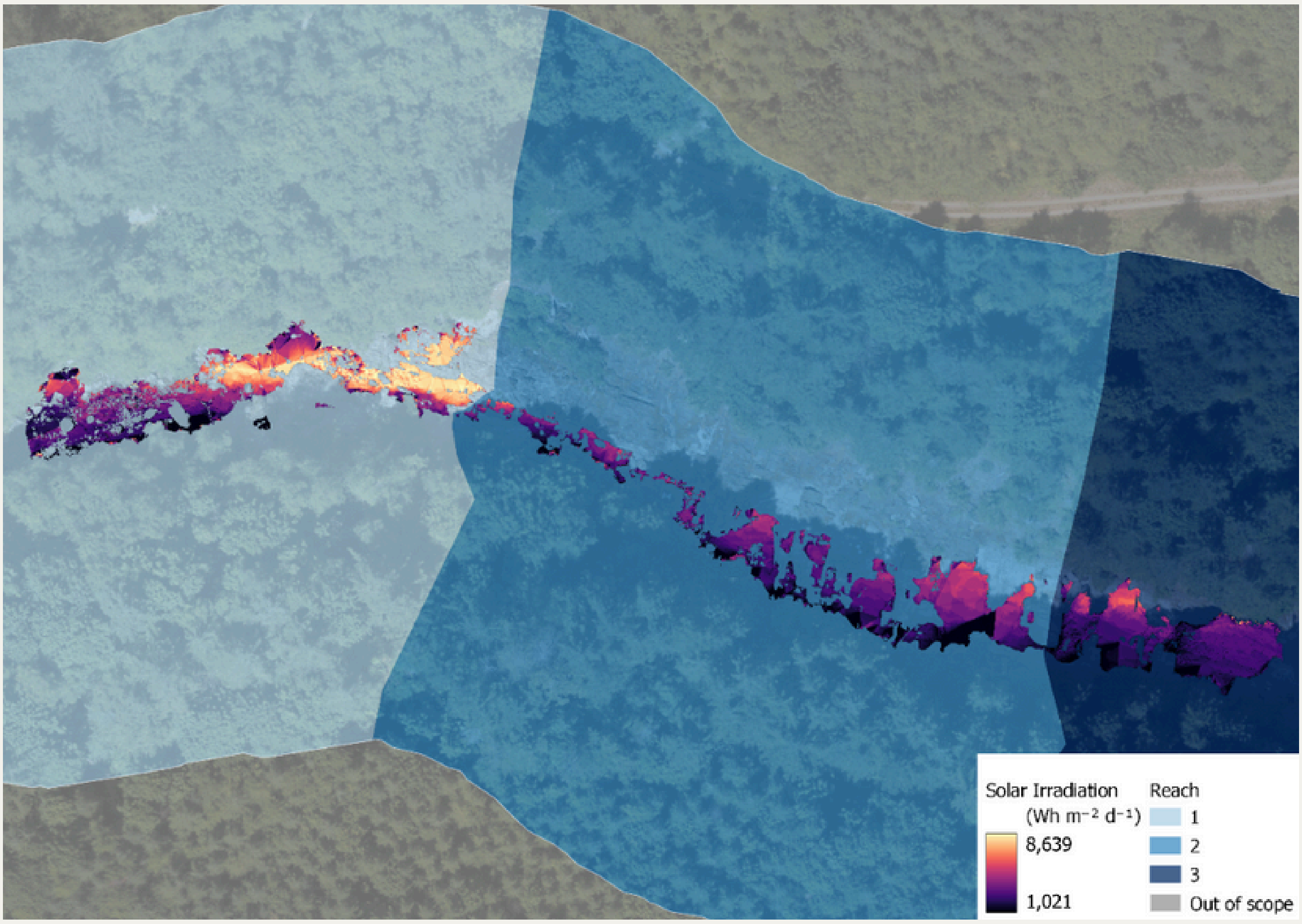

Figure 11: Total solar irradiation (Wh m-2 d-1) for Reach 1 (light blue), Reach 2 (medium blue), and Reach 3 (dark blue).

Yorkson Creek

At the Yorkson Creek site, the 1,028 m of sampled stream length was divided into 3 main reaches based on physical breaks such as the pumping station and bridge (Figure 12). In total, there was an estimated 10,127.46 m2 of wetted habitat area (R1: 706.10 m2; R2: 7,547.52 m2; R3: 1,873.84 m2). This was further broken into estimated habitat area per sampled stream length to allow for comparisons between stream reaches (Figure 13). In general, the first reach was less wide, with a larger pool near the pump station, whereas the second and third reaches were very similar.

Figure 12: Yorkson Creek orthomosaic showing the detected wetted area (shaded) for Reach 1 (light blue), Reach 2 (medium blue), and Reach 3 (dark blue).

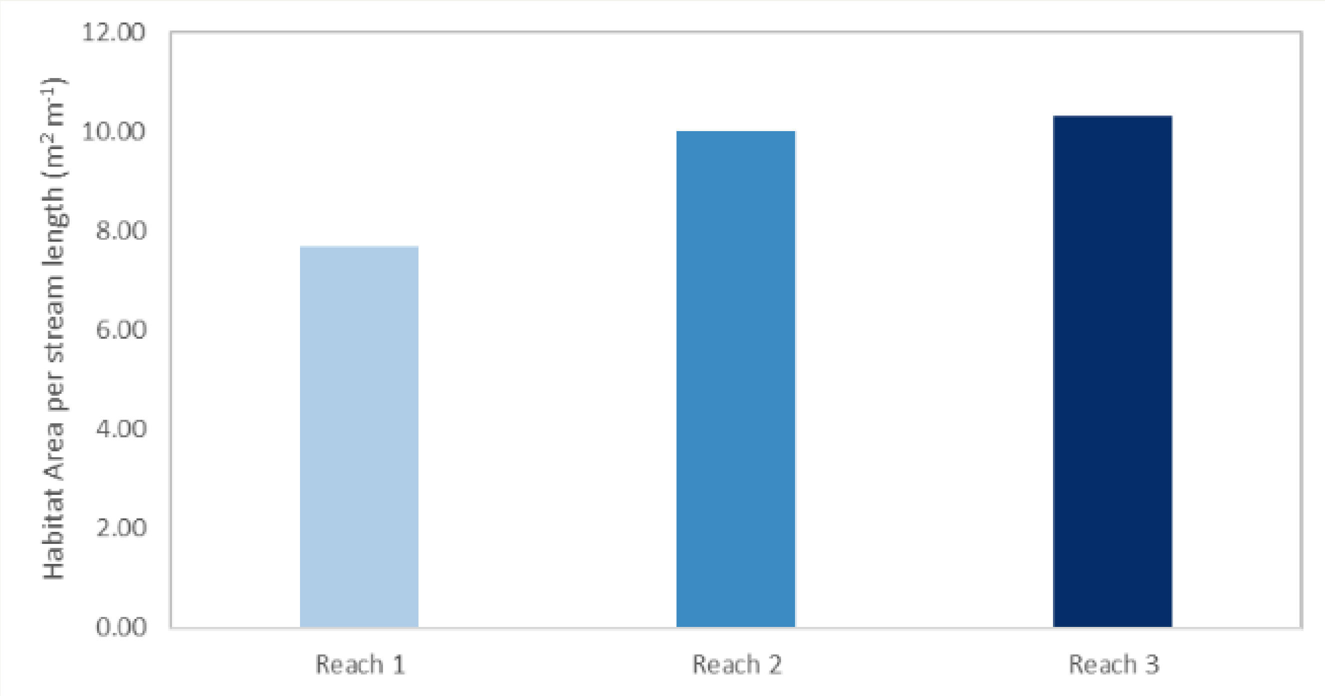

Figure 13: Total wetted habitat area per sampled stream length by reach.

The elevation data shows that each reach has similar gradient characteristics (Figure 14a). Overall, the sampled area had an average stream gradient of 0.38% with average gradients of -0.07%, 0.35%, and 0.11% in reaches 1, 2, and 3, respectively. There are minor fluctuations in elevation and slope, with one large peak around the 90 m mark, which is an artifact introduced from the pumping station (Figure 14).

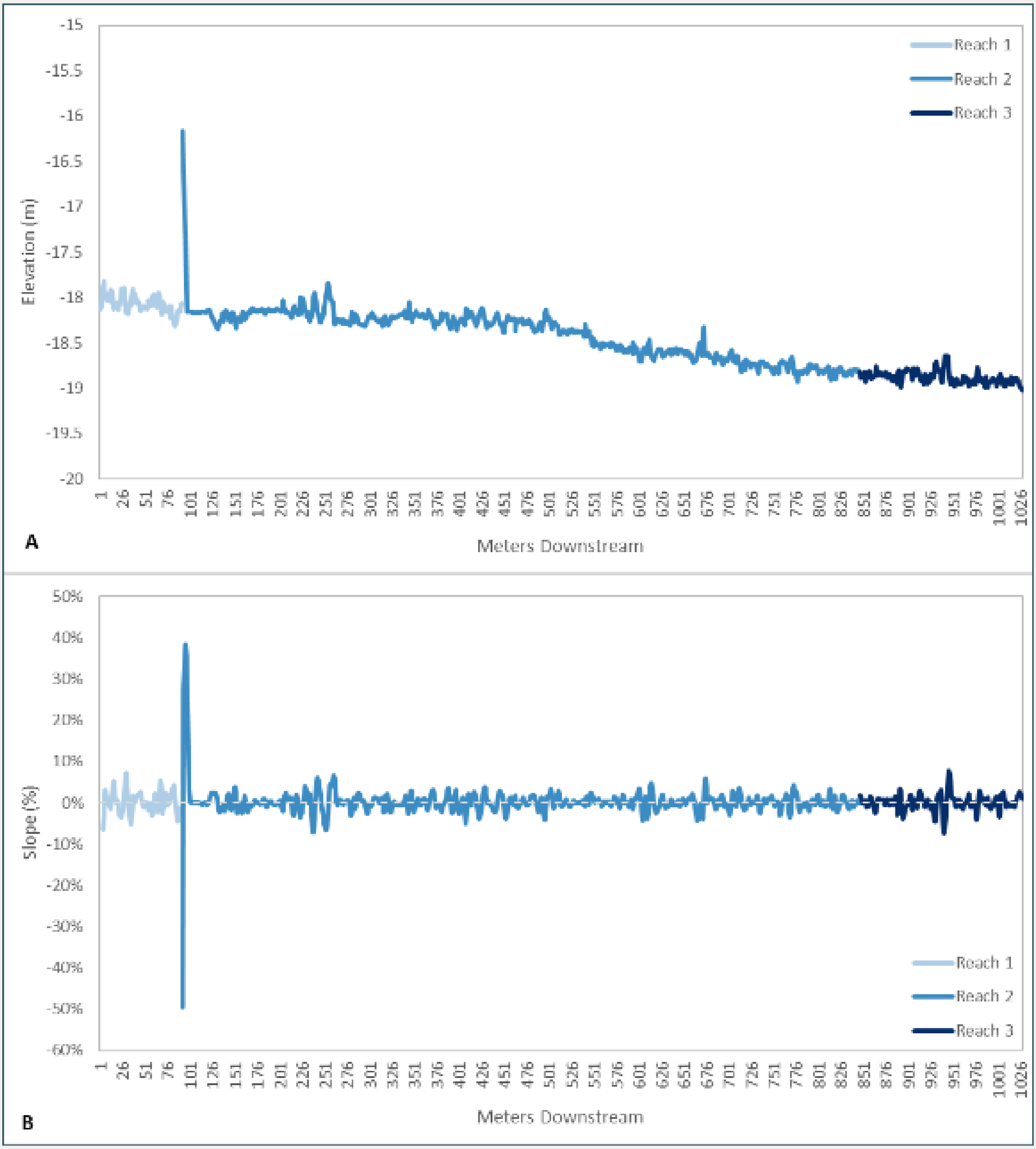

Figure 14: Instantaneous stream elevation (A) and 3 m moving average percent slope (B) for Reach 1 (light blue), Reach 2 (medium blue), and Reach 3 (dark blue).

The thermal data for Yorkson Creek showed a general downstream warming trend (Figure 15). When looking at the relative temperature patches, most reaches had a small amount of cold and hot water patches (Figure 8). In terms of the unobstructed wetted area in each reach, cold patches comprised 0.5%, 0.2%, and 11.7% for reaches 1, 2, and 3, respectively. This is compared to the proportion of unobstructed wetted areas for hot patches being 5.5%, 3.0%, and 7.1%, respectively, for reaches 1, 2, and 3. In total, 2.5% and 4% of the unobstructed wetted area for Yorkson Creek were comprised of cold and hot patches, respectively.

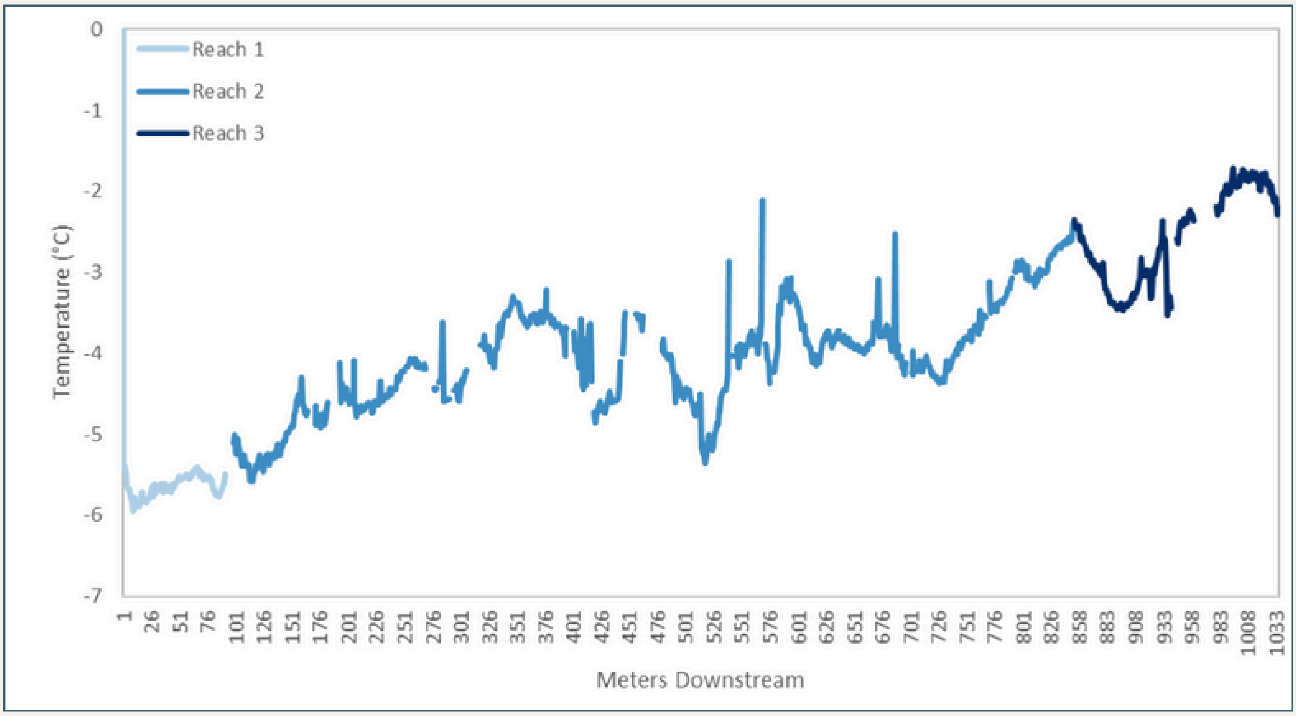

Figure 15: Instantaneous stream temperature for Reach 1 (light blue), Reach 2 (medium blue), Reach 3 (dark blue).

Figure 16: Relative stream temperatures for cold (blue < -1 °C), average (+/- 1 °C), and hot (red > +1 °C) patches.

The riparian tree density varied among the groups, with reach 2 having the highest (126 stems per hectare), followed by reach 3 (70 stems per hectare) and reach 1 (33 stems per hectare). However, the tree heights showed that, on average, tree height increased with distance downstream, and the majority of trees in reach 1 were below 5 m (Figure 17). The impact of smaller trees can somewhat be identified in the potential solar irradiation data where, on average, reach 1 had high amounts of irradiation despite all reaches having a large range of irradiation values (Figures 18 & 19). Additionally, there were very few pieces of LWD found at the Yorkson Creek site, with a total of 0.21 pieces per meter of sampled stream.

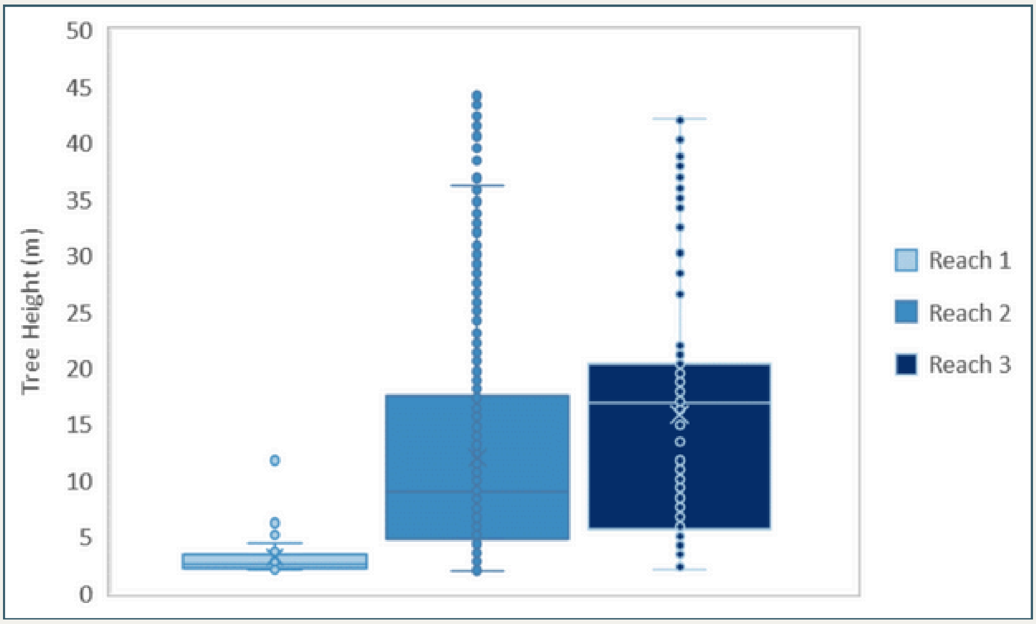

Figure 17: Dominate tree heights for Reach 1 (light blue), Reach 2 (medium blue), and Reach 3 (dark blue).

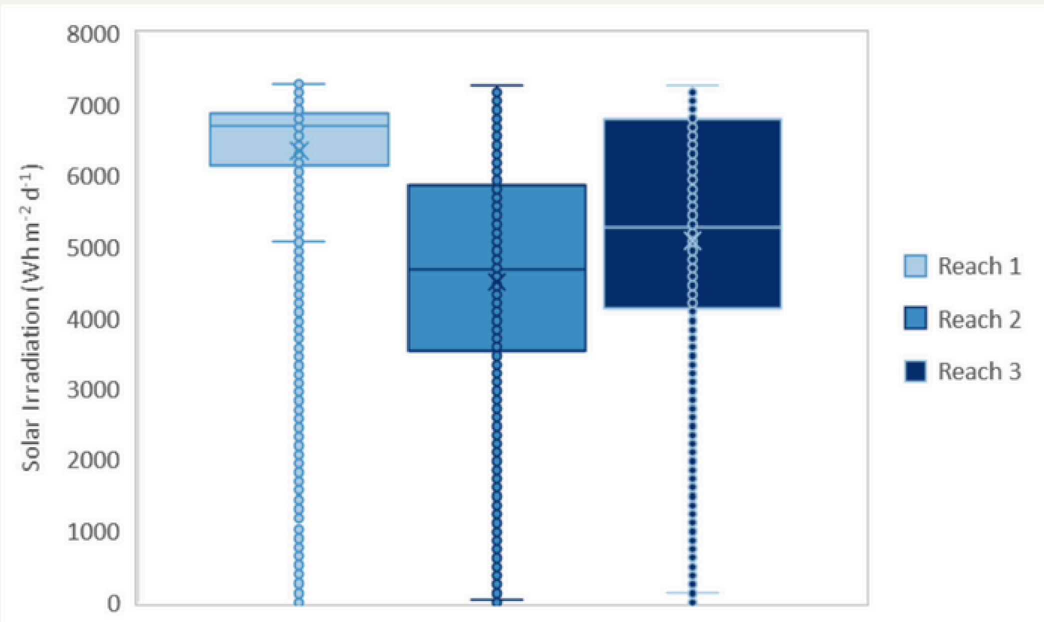

Figure 18: Total solar irradiation (Wh m-2 d-1) for Reach 1 (light blue), Reach 2 (medium blue), and Reach 3 (dark blue).

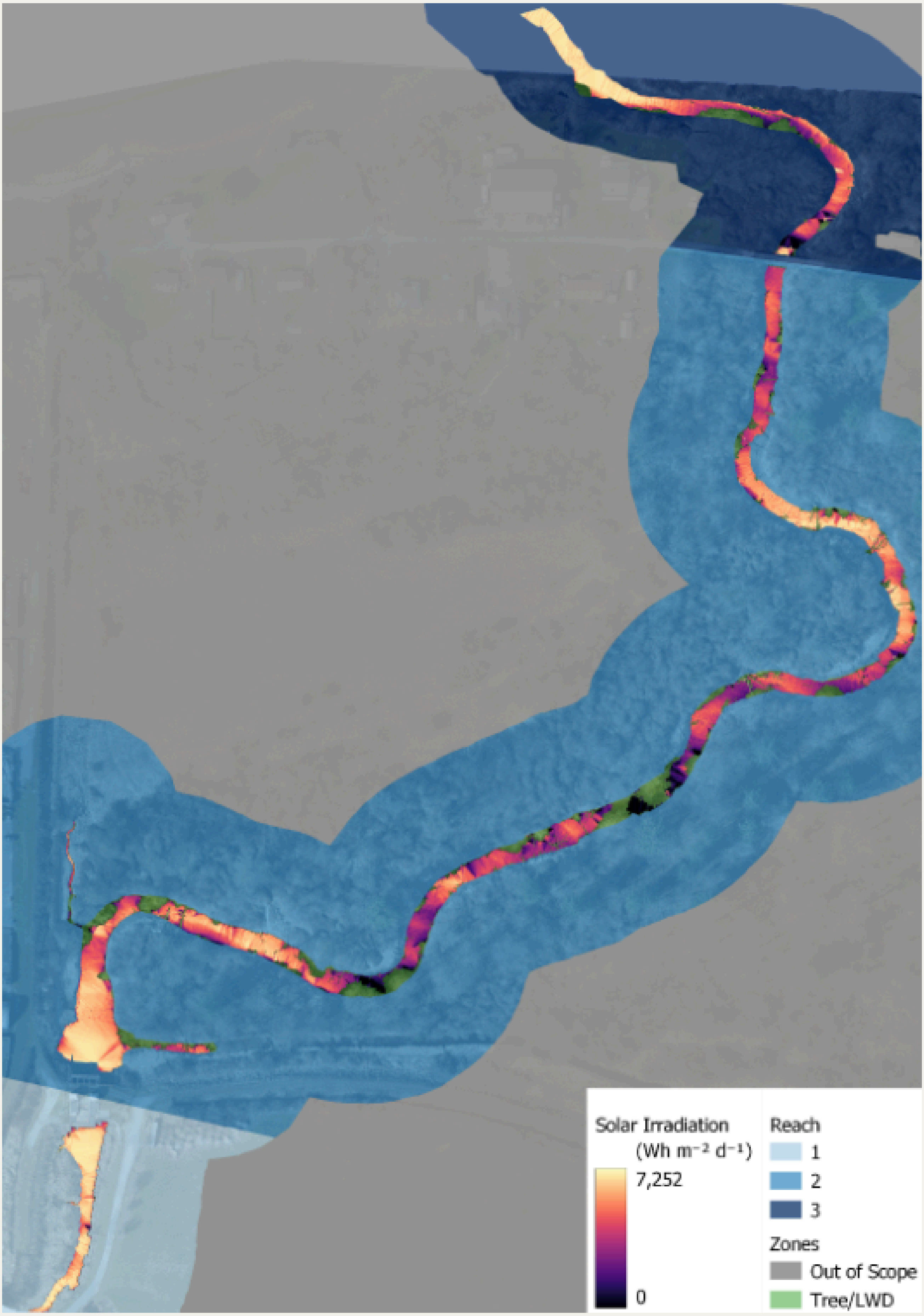

Figure 19: Total solar irradiation (Wh m-2 d-1) for Reach 1 (light blue), Reach 2 (medium blue), and Reach 3 (dark blue).

Whonnock Creek

At the Whonnock Creek site, the 461 m of sampled stream length was divided into 2 main stream reaches, York Creek and Whonnock Creek (Figure 20). In total, there was an estimated 3415.73 m2 of wetted habitat area (Yrk: 1262.12 m2; Wnk: 2153.61 m2). This was further broken into estimated habitat area per sampled stream length to allow for comparisons between stream reaches (Figure 21). In general, the Whonnock Creek had a larger habitat area per stream length largely due to a large pool by the railway culvert.

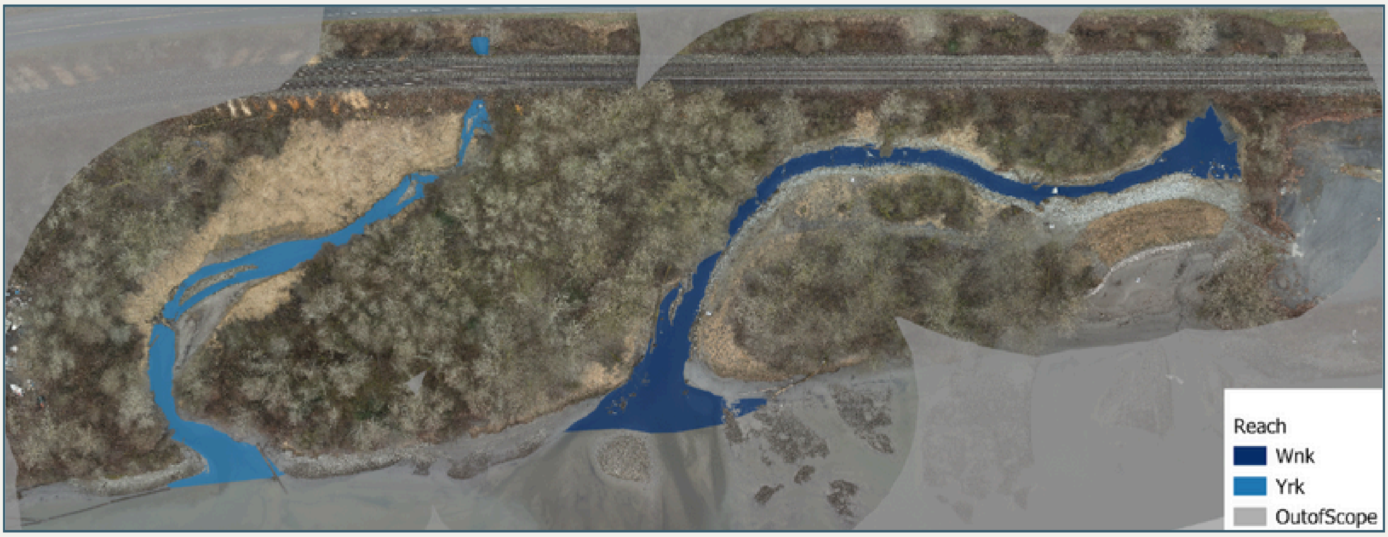

Figure 20: Whonnock Creek orthomosaic showing the detected wetted area (shaded) for York Creek (Yrk - medium blue), and Whonnock Creek (Wnk - dark blue).

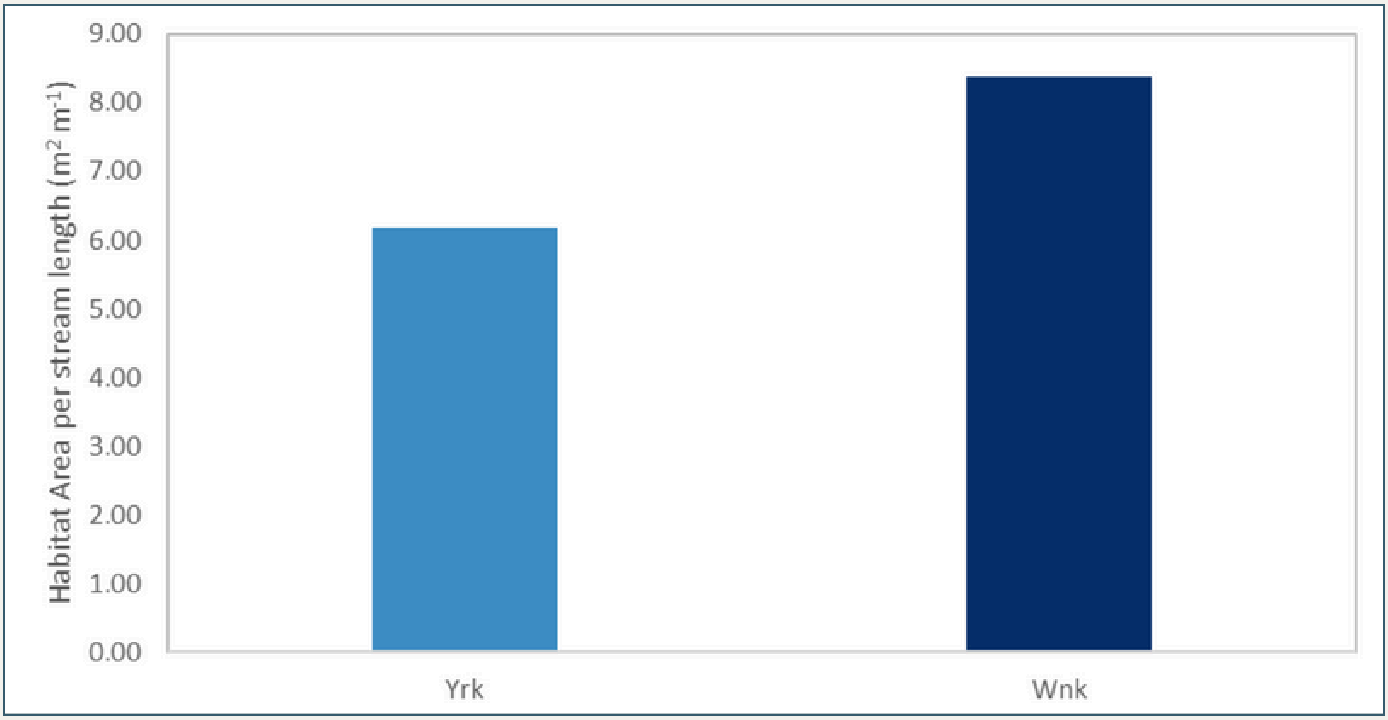

Figure 21: Total wetted habitat area per sampled stream length by reach.

The elevation data shows that each reach has similar gradient characteristics (Figure 22a). Whonnock Creek showed a more consistent slope towards the Fraser River level, where York Creek was more variable. Overall, the sampled reaches had average gradients of 0.47%, and 0.77% in York and Whonnock Creeks respectively. There are minor fluctuations in elevation and slope, with larger peaks associated with woody debris (Figure 22).

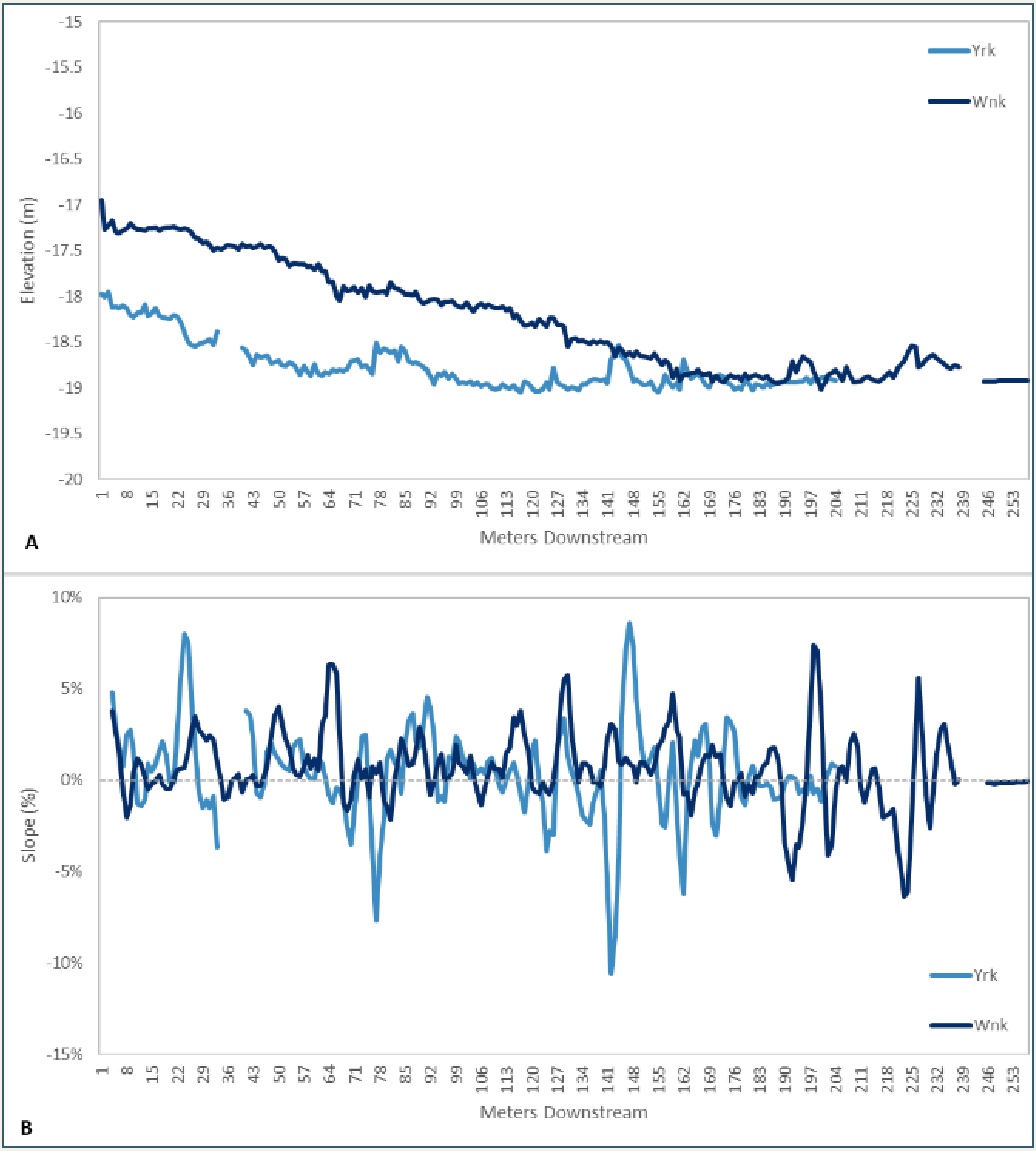

Figure 22: Instantaneous stream elevation (A) and 3 m moving average percent slope (B) for York Creek (Yrk - medium blue), and Whonnock Creek (Wrk - dark blue).

The thermal data at the Whonnock Creek site showed cooling trends in the initial sections as pools transitions into faster moving water, and then warming trends as the streams approached the Fraser River water (Figure 23). When looking at the relative temperature patches, most reaches had mostly hot water patches along the water edges (Figure 24). In terms of the unobstructed wetted area in each reach, cold patches comprised 0.2%, and 0.0%, for York Creek and Whonnock Creek respectively. This is compared to the proportion of unobstructed wetted areas for hot patches being 11.5%, and 8.7%, respectively, for Yorkson and Whonnock Creeks. In total, 0.1% and 9.8% of the unobstructed wetted area for Yorkson Creek were comprised of cold and hot patches, respectively.

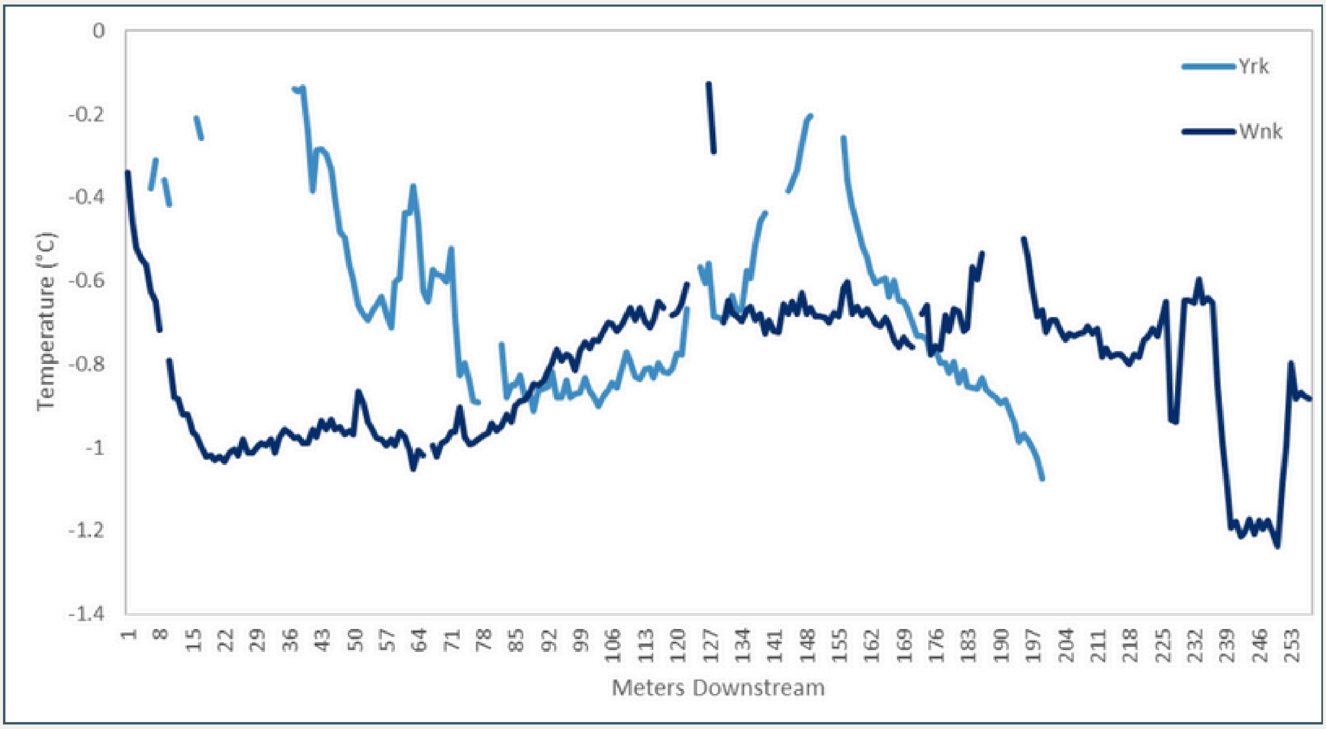

Figure 23: Instantaneous stream temperature for York Creek (Yrk - medium blue), Whonnock Creek (Wnk - dark blue).

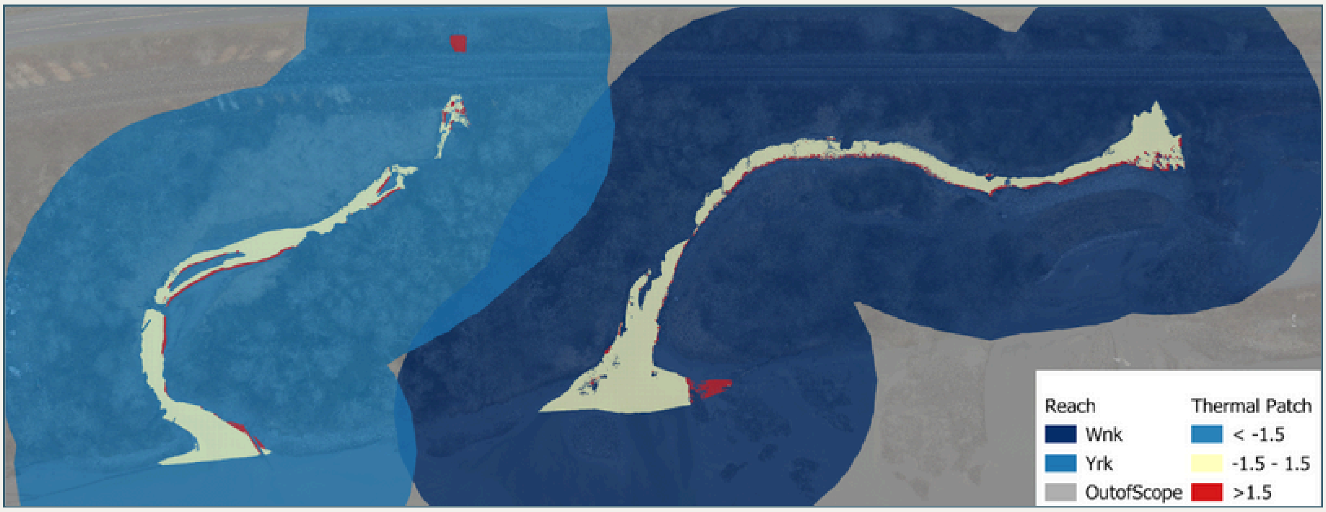

Figure 24: Relative stream temperatures for cold (blue < -1 °C), average (+/- 1 °C), and hot (red > +1 °C) patches.

The riparian tree density was similar between creeks, with York Creek having slightly higher (93 stems per hectare) density than Whonnock Creek (88 TPH). However, the tree heights showed that, on average, tree height was higher in Whonnock Creek compared to York Creek (Figure 25). Interestingly, despite having larger trees the Whonnock Creek reach showed higher average amounts of solar irradiation compared to the York Creek reach, possibly linked to the difference in tree density (Figures 26 & 27). Similar to the Yorkson and Leech sites, there were very few pieces of LWDs found at the Whonnock Creek site, with a total of 0.12 pieces per meter of sampled stream.

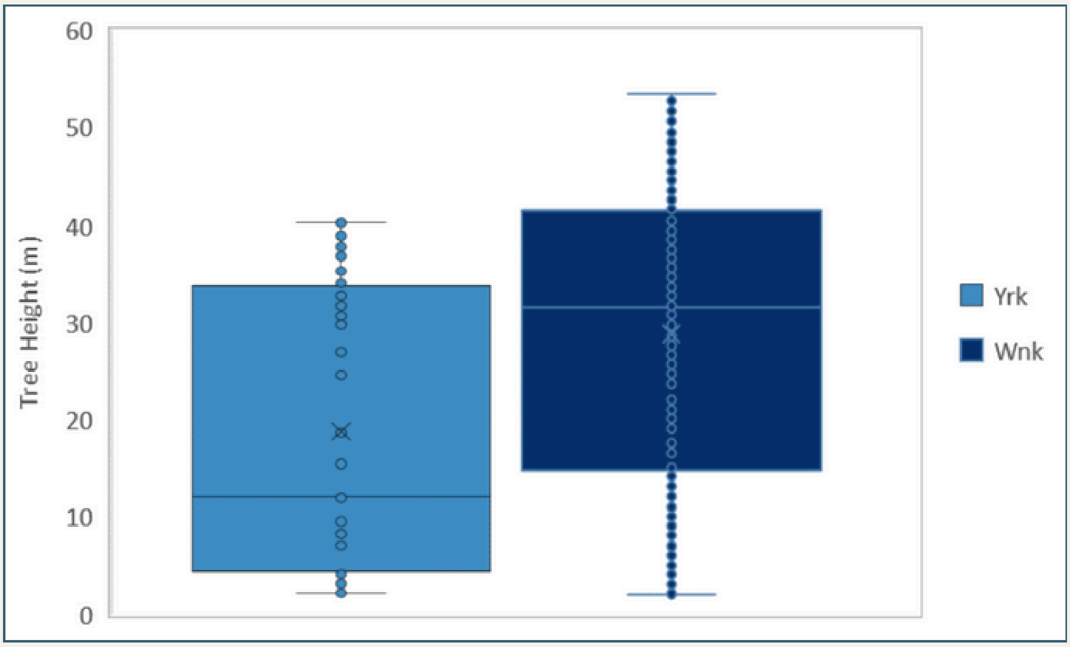

Figure 25: Dominate tree heights for Reach 1 (light blue), Reach 2 (medium blue), and Reach 3 (dark blue).

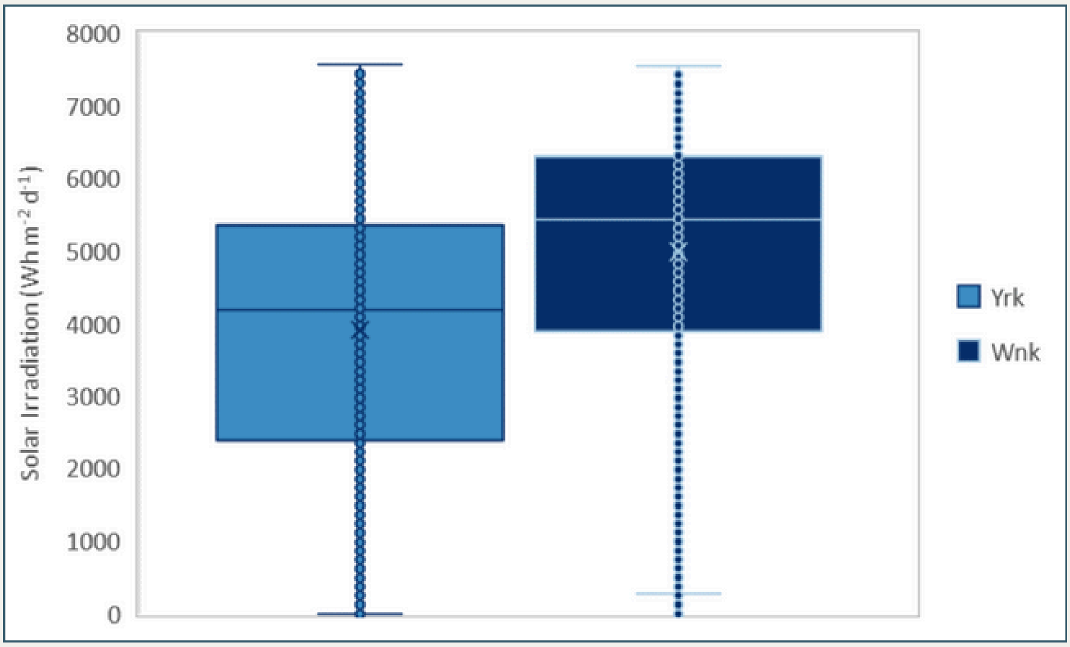

Figure 26: Total solar irradiation (Wh m-2 d-1) for Reach 1 (light blue), Reach 2 (medium blue), and Reach 3 (dark blue).

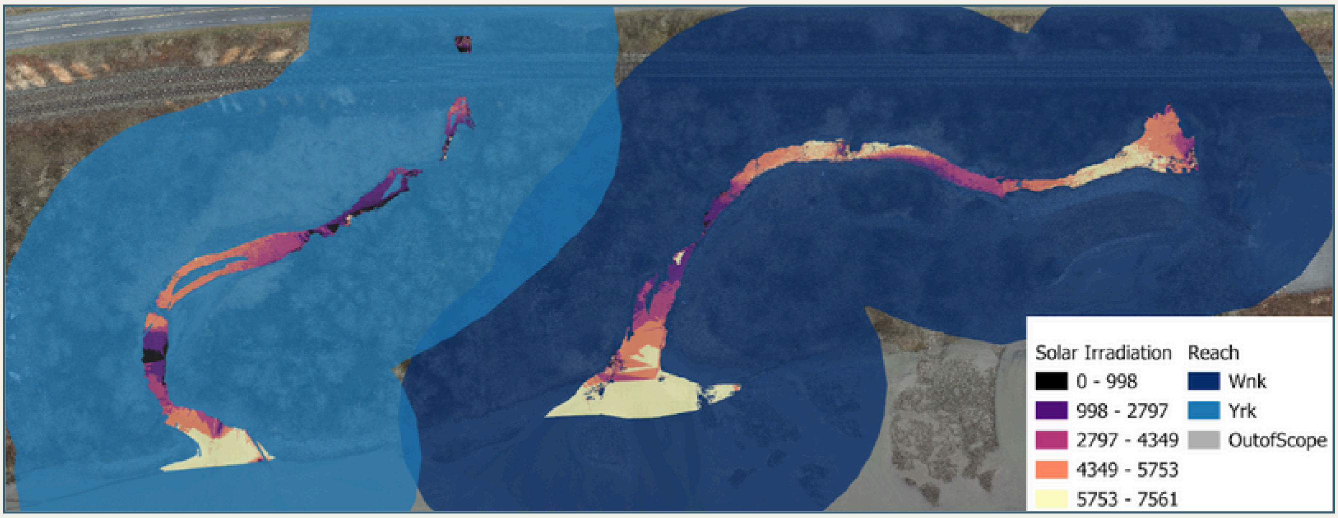

Figure 27: Total solar irradiation (Wh m-2 d-1) for Reach 1 (light blue), Reach 2 (medium blue), and Reach 3 (dark blue).

McCully Creek

At the McCully Creek site in 2022, the 4385 m of sampled stream length was divided into 3 main reaches, the upper and lower McCully creek branches (MC1, MC2) as well as part of the Kispiox River (KSX) (Figure 28). In total, there was an estimated 234,068.8 m2 of wetted habitat area (MC1: 28,318.27 m2; MC2: 12,128.96 m2; KSX: 193,621.5 m2). This was further broken into estimated habitat area per sampled stream length to allow for comparisons between stream reaches (Figure 29). In general, MC1 was longer and less wide than MC2 which was considerably shorter but had one main flooded channel near its entrance into the Kispiox River.

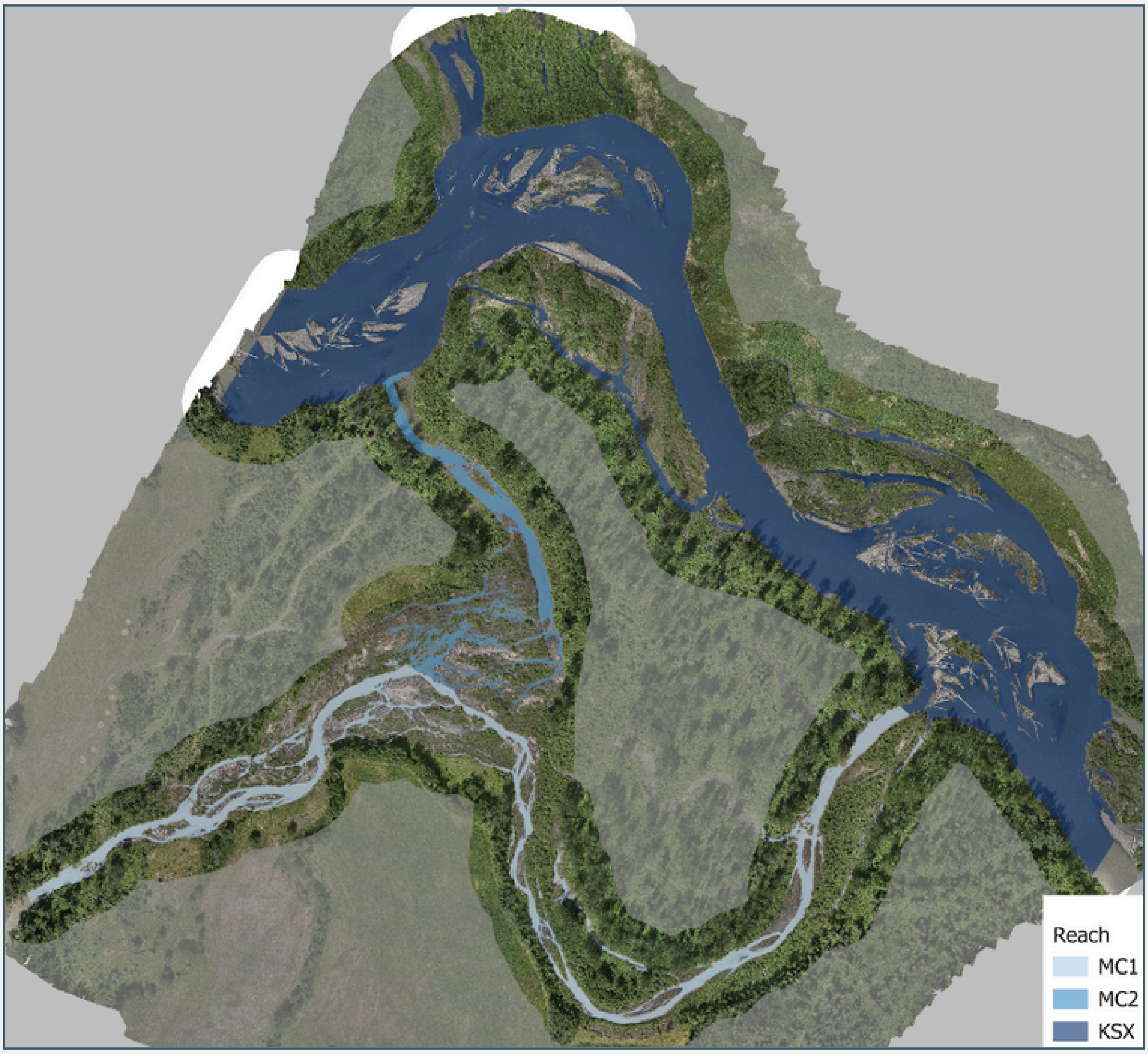

Figure 28: McCully Creek orthomosaic showing the detected wetted area (shaded) for MC1 (light blue), MC2 (medium blue), and KSX (dark blue).

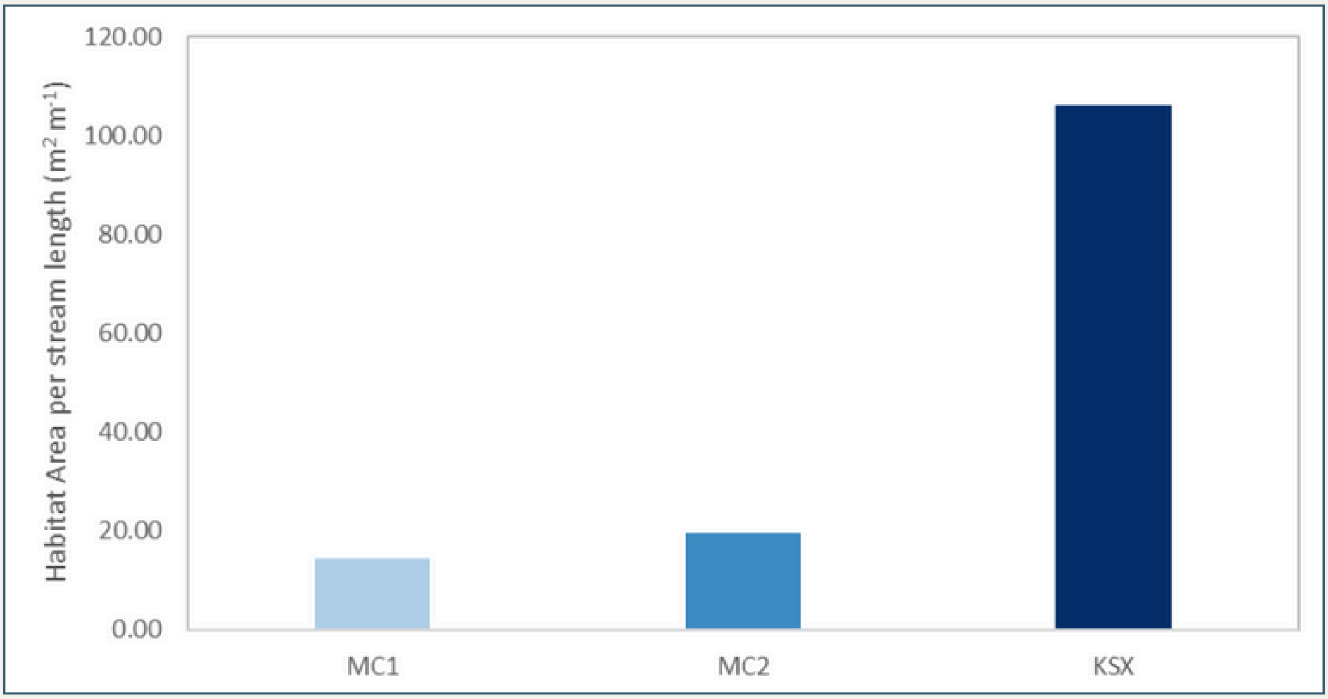

Figure 29: Total wetted habitat area per sampled stream length by reach.

The elevation data shows that the first several hundred meters of the MC1 and MC2 reaches are at a higher relative gradient than the main channel of the Kispiox River. Interestingly, the gradient of MC2 as it departs from MC1 is considerably less than the continuation of MC1 (Figure 30a). Overall, the sampled area had average gradients of 0.64%, 0.31%, and 2.93% in MC1, MC2, and KSX, respectively. There are similar fluctuations in instantaneous slope with larger peaks largely attributed to artifacts remaining from log jams, gravel bars, or other in-channel obstructions (Figure 30b).

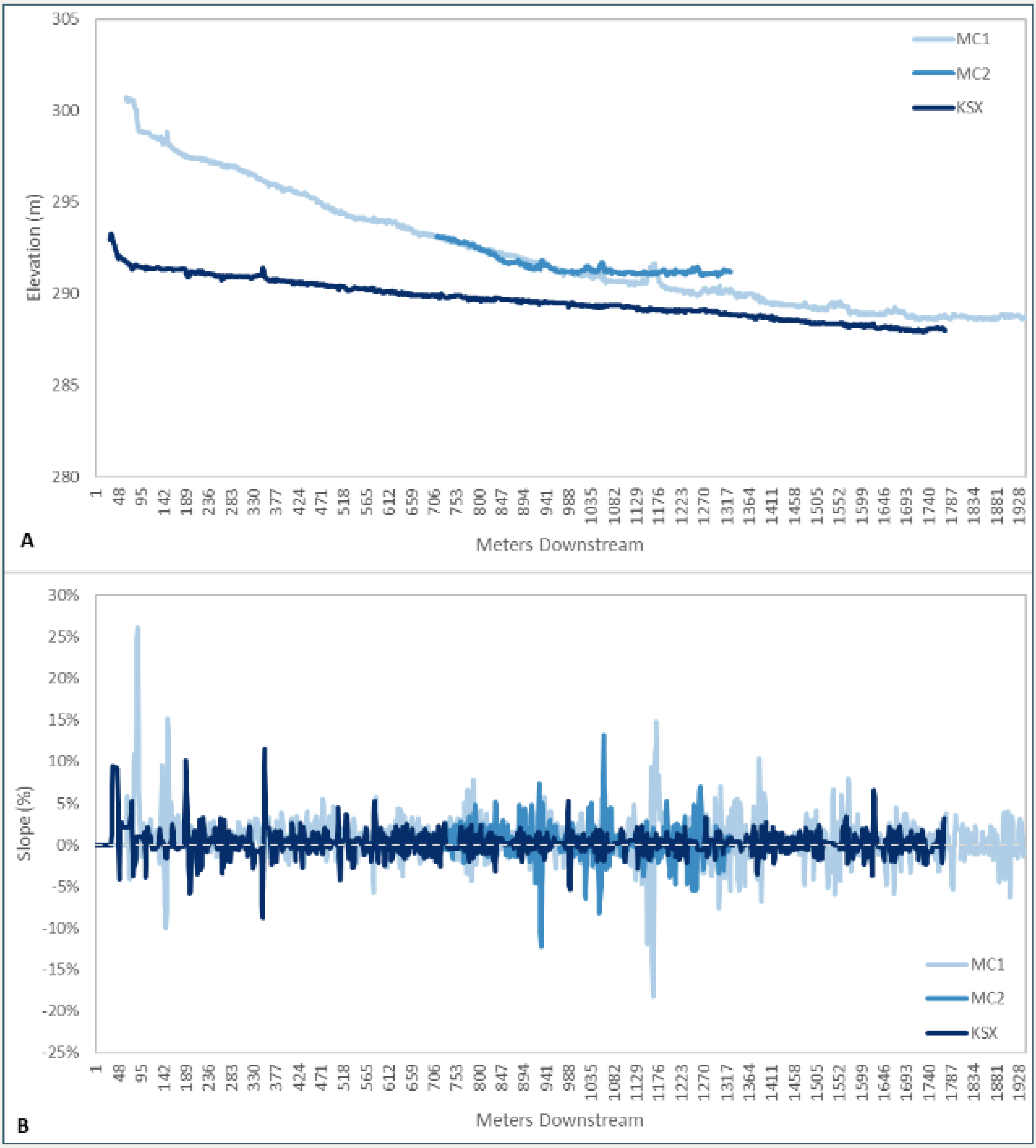

Figure 30: Instantaneous stream elevation (A) and 3 m moving average percent slope (B) for McCully Creek 1 (light blue), McCully Creek 2 (medium blue), and Kispiox River (dark blue).

The initial thermal data for McCully Creek was collected in a separate collection in October 2022 and with changes in time, and positioning, the imagery did not align with the water mask created with the other datasets. This prevented the thermal patch analysis, but a profile was collected along MC1 which showed a slight downstream warming trend (Figure 31). Large spikes in temperature were largely associated with sample pixels that were close to exposed gravel bars with the changes in water level (Figure 31).

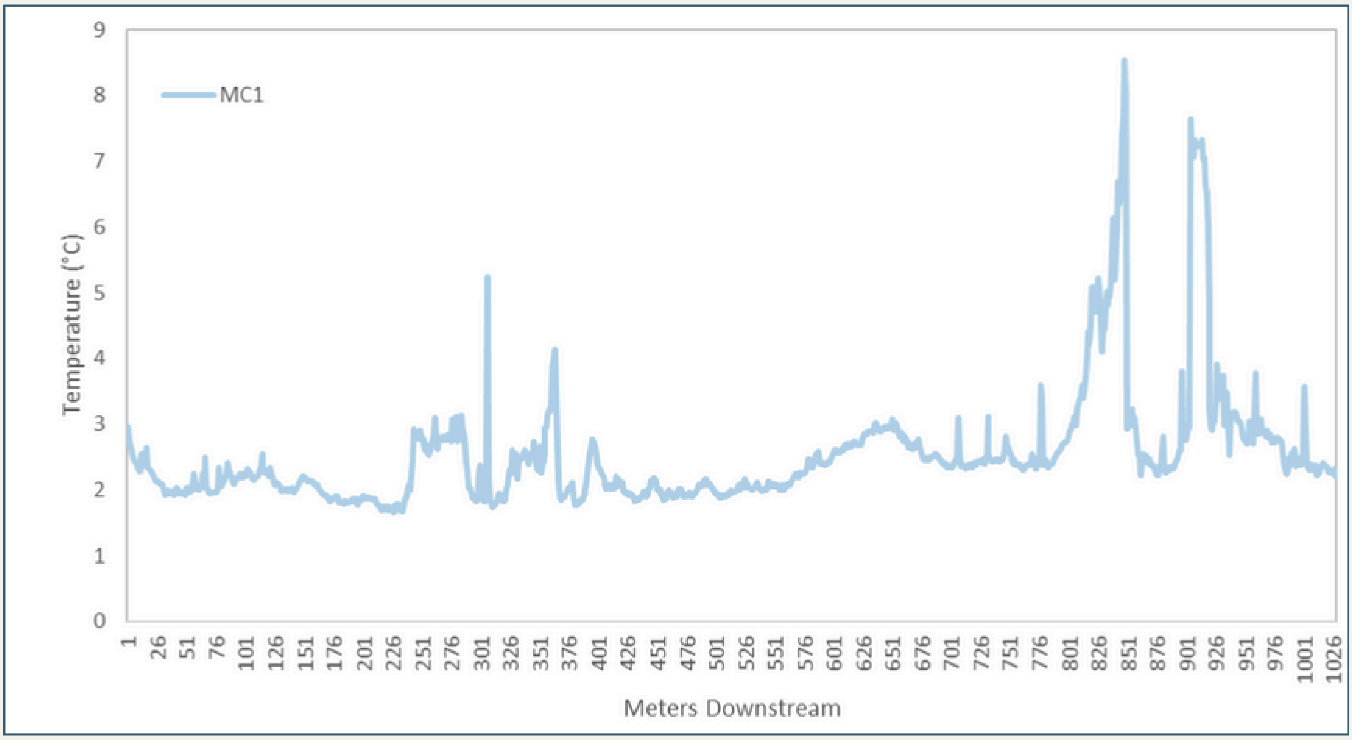

Figure 31: October instantaneous stream temperature for MC 1 (light blue).

The riparian tree density varied among the reaches, with the MC2 having marginally higher (154 stems per hectare (STH)), density than the MC1 (152 STH) and KSX (146 STH) reaches. However, the tree heights showed that, on average, tree height was highest in the MC1 reach, and the majority of trees in all reaches were below 5 m (Figure 32). The impact of smaller trees can somewhat be identified in the potential solar irradiation data where, on average, the KSX reach had the lowest range of riparian tree heights and higher amounts of irradiation (Figures 33 & 34). The KSX reach also had the largest amount of detected large woody debris with 4.05 pieces per meter of sampled stream length compared to 0.89 and 0.99 in the MC1 and MC2 reaches respectively.

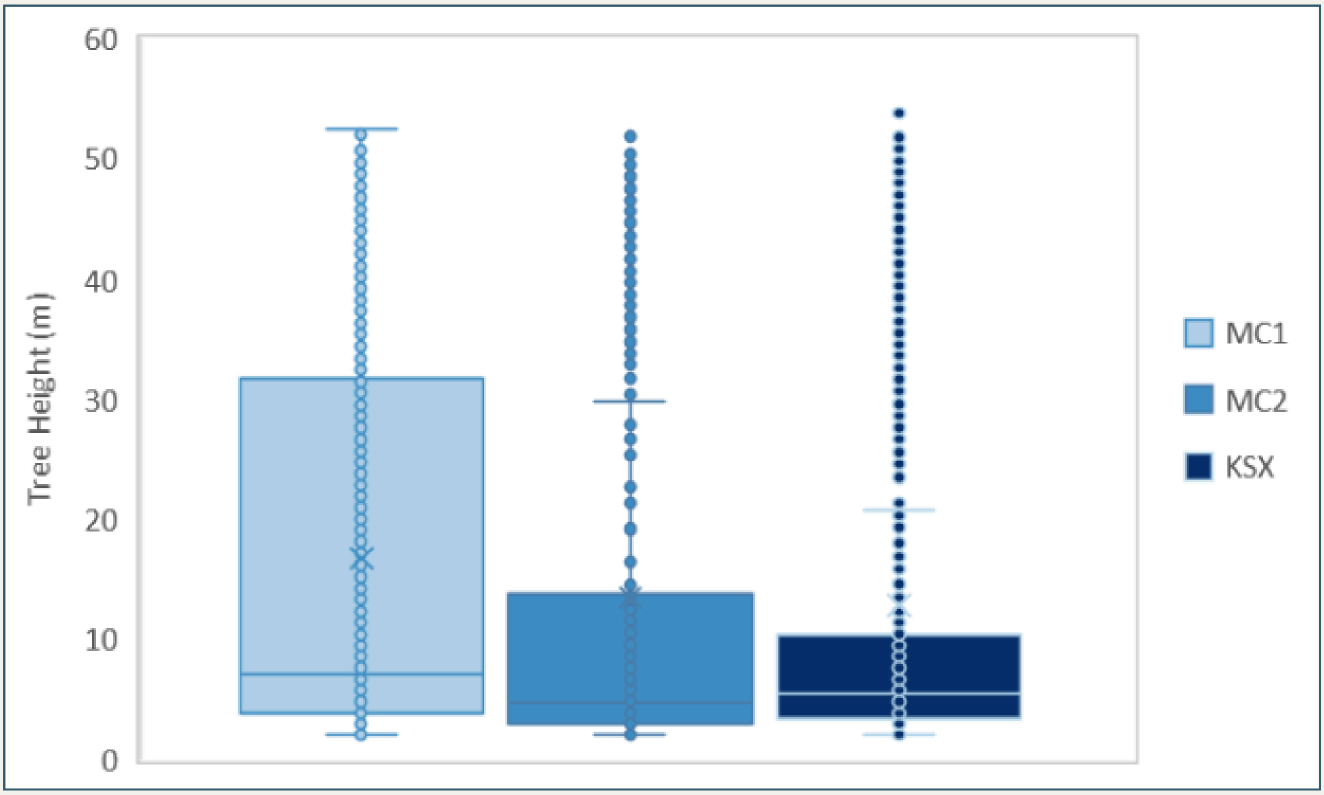

Figure 32: Dominate tree heights for MC1 (light blue), MC2 (medium blue), and KSX (dark blue).

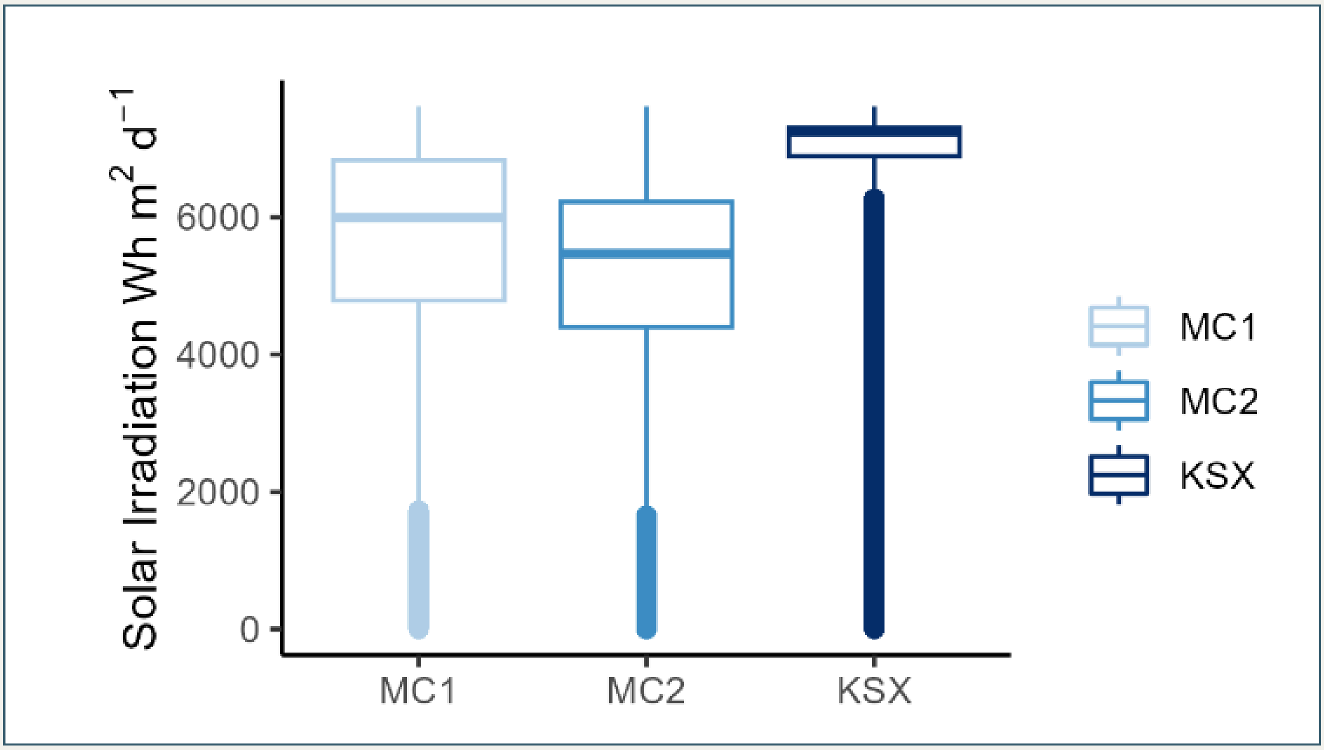

Figure 33: Total solar irradiation (Wh m-2 d-1) for MC1 (light blue), MC2 (medium blue), and KSX (dark blue).

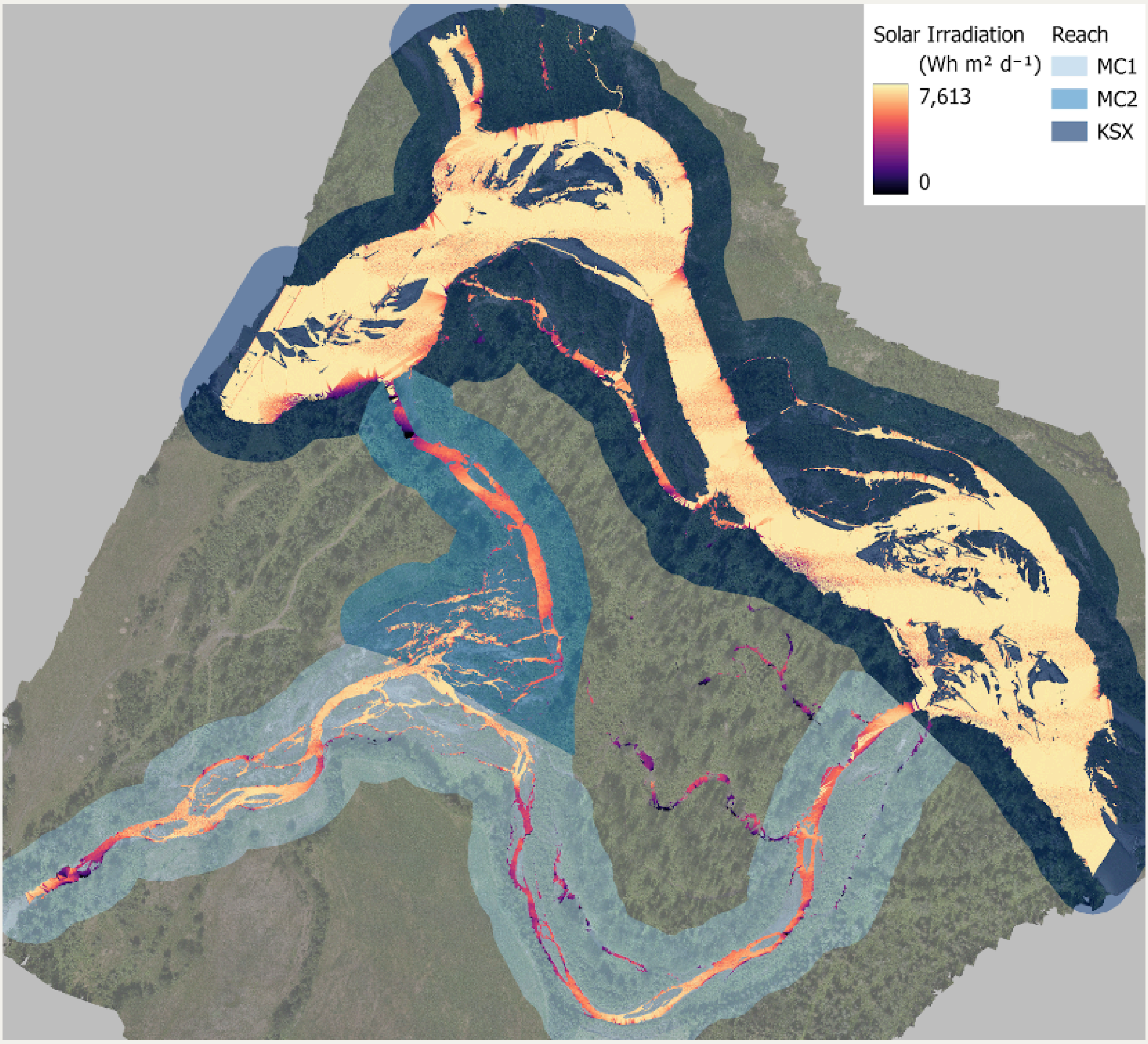

Figure 34: Total solar irradiation (Wh m-2 d-1) for MC1 (light blue), MC2 (medium blue), and KSX (dark blue).

Local Scale Community Mapping

Local-scale community mapping sessions were conducted for five sites with three partner communities. During these sessions, community members were asked to respond to five questions using large-format printed maps created from the high-resolution orthomosaics of each site. The five questions or prompts provided to community members were:

1. Identify and describe barriers or challenges to salmon habitat restoration
2. Identify and describe current initiatives to enhance salmon habitat
3. Identify and prioritise areas of interest for salmon stewardship monitoring
4. What information is needed to enhance salmon habitat?
5. Is there anything else important to include?

Responses to these prompts were recorded on a response sheet and, when appropriate, associated with a corresponding marker on the printed map. Responses, identified markers, and maps were returned to each of the partner organizations. In order to protect sensitive or confidential information provided by communities, a high-level summary of themes that emerged from these sessions is provided below.

Community Mapping Themes

Themes from the community mapping sessions varied depending on the geographic context of the different sites. For example, issues identified in highly urbanized areas differed from those in more rural communities. Common themes are summarised in Table 1. Barriers to restoration identified by attendees included ongoing development in the watersheds, historical and ongoing impacts from industrial agriculture, logging, and fish passage barriers. Community members identified a range of initiatives to enhance salmon habitat, including restoration and monitoring work done by communities and other organizations working within the same watersheds. Community members contributed rich and detailed information about salmon presence and use of different sites, including areas important for spawning, holding and rearing. Members also shared detailed information about physical habitat characteristics and changes over time, including areas of groundwater upwelling, areas of erosion and deposition, and changes to channel morphology. Other information shared by communities included changes to local wildlife populations and impacts to salmon unrelated to habitat (e.g., fishing, hatcheries, fish farms). Important areas for fishing and hunting need community oversight and involvement with any monitoring and restoration activities undertaken within these areas.

Table 1. Themes identified during community mapping sessions.

Guiding Question	Key Themes
Identify and describe barriers or challenges to salmon habitat restoration	Historical and ongoing impacts from development, forestry, and agricultureCumulative effects from multiple concurrent sourcesBarriers impeding fish passage
Identify and describe current initiatives to enhance salmon habitat	Identification of both community-led initiatives and those being led by external organisationsInitiatives included:Past and future restoration projectsWater quality monitoringInvasive species monitoringHydrometric monitoring
Identify and prioritise areas of interest for salmon stewardship monitoring	Identification of specific geographic areas for monitoring. Sites typically had one or more of the following features:Particularly important for salmon life history (e.g., known spawning area)Culturally important areas (e.g., current and historical fishing sites)Sites impacted by development, pollution, etc.Restoration areas
What information is needed to enhance salmon habitat?	Access to historical information (e.g., historical maps and air photos)Temperature, flow, and water quality monitoringNeed for monitoring of activities (e.g., agriculture, construction projects) that may be impacting fish habitat
Is there anything else important to include?	Salmon presence and use of different sitesPhysical habitat characteristics and change over timeChanges to local wildlife populationsImpacts to salmon unrelated to freshwater habitat (e.g., fishing, hatcheries, fish farms)Culturally important areasNeed for community oversight and involvement of monitoring and restoration initiatives

Spawning Salmon: Returning Home

After one or multiple cycles of the Adult Salmon phase comes the final phase of the project analogous to the spawning salmon. At the heart of this stage lies the review of results and methods, and communication of results back to community. This stage can be conducted on an annual basis or as needed, and can also be incorporated into the selection of new target sites for another cycle of the Adult Salmon monitoring phase. Critical to this is that communities retain the ownership and control of all raw, intermediate, and analysis data. Additionally, results should be communicated back to community members using accessible media in addition to any technical reports. For this project a series of community specific infographics were created for distribution back to community members. Finally, the review and reflection portion of this stage allows for the individual habitat metric results to be compared to other knowledge sources or previous monitoring results to enhance decision making processes surrounding salmon habitat health related to each site. As capacity within communities grows the monitoring cycle can be repeated adding additional sites or new metrics determined to be important to salmon habitat health.

Future Work

Future work for improving the Rapid Salmon Habitat Assessment (RSHA) method can be divided into three main areas. The first area of improvement focuses on enhancing the efficiency of water detection in UAV imagery. While geospatial methods can quickly acquire data over large areas, the current method for detecting water is significantly impacted by marginal in situ conditions (such as weather and shadows) or missing data, which increases the need for manual intervention. Enhancing water detection and classification using machine learning algorithms should be evaluated for ease of use, accuracy, and implementation time to improve this aspect of the RSHA.

The second main area of improvement involves validating the selected habitat metrics. After addressing the first area of improvement, a comparison of the geospatial RSHA method should be conducted against a commonly practiced field-based assessment method, such as the Fish Habitat Assessment Procedures (FHAP) (Johnston & Slaney, 1996). Conducting this comparison at the same site or sites would allow for direct validation of the geospatial habitat metrics and an effort-per-area comparison between the two methods.

The third main area of improvement is through the reflection of a repeated monitoring cycle. A key component of community-based projects is the learning that comes from reflecting on a process or project and implementing changes or improvements based on those learnings. Therefore, the RSHA methodology is designed to evolve and improve through the insights gained and the increased capacity of communities conducting monitoring cycles, as well as through future adoption by other communities.

Acknowledgements

This RSHA protocol emerged from the Knowledge and perspectives of First Nation community members from across BC. The project team would like to thank all those involved in this project, including the people, lands, waters, and non-human relations for their collaboration and trust in this process.

Thank you to our project partners and the community members at q̓ic̓əy̓ (Katzie), q̓ʷa:n̓ƛ̓ən̓ (Kwantlen), and sc̓əwaθən məsteyəx (Tsawwassen) First Nations who welcomed us into their communities and supported the development of our procedures. Thank you, as well, to participants from the remaining three FNFLF member First Nations, kʷikʷəƛ̓əm (Kwikwetlem), xʷməθkʷəy̓əm (Musqueam), and səlilwətaɬ (Tsleil-Waututh) who supported this work by providing input and guidance along the way.

Thank you to the Gitksan Watershed Authority for their partnership on this project. We would especially like to thank Alicia Fernando, Tim Wilson, Rob Matthews, and Taylor Wale for their assistance in collecting the data for this project. We are grateful to the community members who shared their knowledge and expertise with us. Our deepest thanks go to Huwilp Xhliiyemlaxha and Wii Muugilsxw for allowing us to conduct this work on their territories.

Thank you to all of our partners across Syilx Okanagan Nation, particularly SnPink'tn (Penticton Indian Band) , Osoyoos Indian Band, and Westbank First Nation who collaborated on community mapping and drone survey work throughout the project. We would also like to thank our partners from the Columbia River Salmon Reintroduction Initiative (Secwépemc (Shuswap), Ktnuaxa Nations, ONA Syilx, DFO, and the Province of BC) for allowing us to pilot our methods while supporting salmon reintroduction works.

All the project partners would like to express our gratitude to our colleagues at the University of Victoria Map Shop/ Big Little Maps. Thank you specifically to Jason Kelley, Carly Palmer, Crystal Tremblay, Christopher Bone, and Roger Stephen for sharing your expertise with us and for ensuring that all work was carried out in a respectful and productive way. Your commitment to changing the narrative of salmon habitat assessment in BC and ensuring First Nations leadership in these processes is deeply appreciated.

References

Ball, J., & Janyst, P. (2008). Enacting research ethics in partnerships with indigenous communities in Canada: "Do it in a good way". Journal of Empirical Research on Human Research Ethics, 3(2), 33–51. https://doi.org/10.1525/jer.2008.3.2.33

Castleden, H., Morgan, V. S., & Lamb, C. (2012). "I spent the first year drinking tea": Exploring Canadian university researchers' perspectives on community-based participatory research involving Indigenous peoples. Canadian Geographer, 56(2), 160–179. https://doi.org/10.1111/j.1541-0064.2012.00432.x

Dugdale, S. J. (2016). A practitioner's guide to thermal infrared remote sensing of rivers and streams: Recent advances, precautions and considerations. Wiley Interdisciplinary Reviews: Water, 3(2), 251–268. https://doi.org/10.1002/wat2.1135

Gearheard, S., Pocernich, M., Stewart, R. E., Sanguya, J., & Huntington, H. P. (2010). Linking Inuit knowledge and meteorological station observations to understand changing wind patterns at Clyde River, Nunavut. Climatic Change, 100(2), 267–294. https://doi.org/10.1007/s10584-009-9587-1

Hamann, E. J., Kennedy, B. P., Whited, D. C., & Stanford, J. A. (2014). SPATIAL VARIABILITY IN SPAWNING HABITAT SELECTION BY CHINOOK SALMON (ONCORHYNCHUS TSHAWYTSCHA) IN A WILDERNESS RIVER. River Research and Applications, 30(9), 1099–1109. https://doi.org/10.1002/rra.2704

Huntington, H. P., Gearheard, S., Mahoney, A. R., & Salomon, A. K. (2011). Integrating Traditional and Scientific Knowledge through Collaborative Natural Science Field Research: Identifying Elements for Success. Arctic, 64(4), 437–445. https://doi.org/10.14430/arctic4143

Johnson, N., Alessa, L., Behe, C., Danielsen, F., Gearheard, S., Gofman-Wallingford, V., Kliskey, A., Krümmel, E.-M., Lynch, A. H., Mustonen, T., Pulsifer, P. L., & Svoboda, M. (2015). The Contributions of Community-Based Monitoring and Traditional Knowledge to Arctic Observing Networks: Reflections on the State of the Field. Arctic, 68(5), 28–40. https://doi.org/10.14430/arctic4447

Johnston, N. T., & Slaney, P. A. (1996). Fish habitat assessment procedures. Watershed Restoration Project, Ministry of Environment, Lands and Parks and Ministry of Forests.

Thompson, K.-L., Reece, N., Robinson, N., Fisher, H.-J., Ban, N. C., & Picard, C. R. (2019). "We monitor by living here": Community-driven actualization of a social-ecological monitoring program based in the knowledge of Indigenous harvesters. Facets, 4(1), 293–314. https://doi.org/10.1139/facets-2019-0006

Tschirhart, C., Mistry, J., Berardi, A., Bignante, E., Simpson, M., Haynes, L., Benjamin, R., Albert, G., Xavier, R., Robertson, B., Davis, O., Verwer, C., de Ville, G., & Jafferally, D. (2016). Learning from one another: Evaluating the impact of horizontal knowledge exchange for environmental management and governance. Ecology and Society, 21(2), 41. https://doi.org/10.5751/es-08495-210241

Wright, A. L., Gabel, C., Ballantyne, M., Jack, S. M., & Wahoush, O. (2019). Using Two-Eyed Seeing in Research With Indigenous People: An Integrative Review: The International Journal of Qualitative Methods, 18, 160940691986969. https://doi.org/10.1177/1609406919869695