Characterizing stream temperature to support habitat restoration – a review of methods and best practices

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Disclaimer

This document serves as a reference to support habitat restoration work and provides an overview of methods which are up-to-date at the time of writing. However, this is not a prescriptive document and methods and techniques are constantly evolving. The authors encourage readers to use their best judgement and knowledge of individual project sites to make final decisions on how to proceed with temperature measurements.

Abstract

Soto, P.A., and Reid, D.A. 2026. Characterizing stream temperature to support habitat restoration – a review of methods and best practices. Can. Tech. Rep. Fish. Aquat. Sci. 3758: vi + 33 p. https://doi.org/10.60825/dzqf-mt21

Water temperature plays a critical role in aquatic systems, influencing physical factors such as water chemistry, and ecological factors such as species distribution, carrying capacity and metabolic process rates. Cold-water species such as salmonids are particularly sensitive to thermal fluctuations, with prolonged exposure to elevated temperatures often proving detrimental. Extended periods of high-water temperatures are an increasing occurrence in Pacific Region waterways, and as a result, habitat restoration practitioners are increasingly seeking to improve or preserve stream temperature attributes favourable to salmonids and other fish species. To support this work, monitoring of baseline thermal conditions and project effectiveness related to temperature must occur. A broad suite of methods exist to support temperature monitoring; however, it is not always clear which methodology is best suited for a specific site or project objective. Considering the critical need to select a suitable methodology, we provide an overview of temperature monitoring approaches organized into three broad categories - spatial, temporal and hybrid (a combination of both). We also outline information for selecting an optimal temperature characterization and monitoring approach in addition to monitoring methods based on restoration objectives.

Resume

Soto, P.A., and Reid, D.A. 2026. Characterizing stream temperature to support habitat restoration – a review of methods and best practices. Can. Tech. Rep. Fish. Aquat. Sci. 3758: vi + 33 p. https://doi.org/10.60825/dzqf-mt21

La température de l'eau joue un rôle crucial dans les systèmes aquatiques, influençant des facteurs physiques comme la chimie de l'eau, ainsi que des facteurs écologiques comme la répartition des espèces, la capacité de charge et les taux de métabolisme. Les espèces d'eau froide, comme les salmonidés, sont particulièrement sensibles aux fluctuations thermiques, une exposition prolongée à des températures élevées étant souvent préjudiciable. Les périodes prolongées de températures élevées sont de plus en plus fréquentes dans les cours d'eau de la région Pacifique, et par conséquent, les praticiens de la restauration des habitats cherchent de plus en plus à améliorer ou à préserver les caractéristiques de température des cours d'eau favorables aux salmonidés. Pour soutenir ce travail, il est nécessaire de surveiller les conditions de référence et l'efficacité des projets en termes de température. Il existe un large éventail d'approches pour soutenir la surveillance de la température ; cependant, il n'est pas toujours évident de déterminer quelle méthodologie est la mieux adaptée à chaque site ou objectif de projet. Compte tenu de l'importance cruciale du choix d'une méthodologie appropriée, nous présentons un aperçu des approches de surveillance de la température, classées en trois grandes catégories : spatiale, temporelle et hybride (une combinaison des deux). Nous présentons également des informations pour sélectionner des approches optimales de caractérisation et de surveillance de la température, ainsi que des méthodes de surveillance basées sur les objectifs de restauration.

1. Introduction

Water temperature plays a critical role in the aquatic environment, providing a fundamental constraint on many components of aquatic ecosystems. High temperatures in aquatic ecosystems across the Pacific Northwest– including British Columbia, the Yukon, Washington, Oregon and Alaska - are correlated to highly stressful conditions for a broad suite of species, but particularly for salmonids (Jonsson, 2023; Siegel & Crozier, 2020). Increasingly, climate change-induced extreme heat events and severe droughts in the Pacific Region have led to a greater prevalence of stressful conditions for salmonids (Mantua et al., 2010; Siegel & Crozier, 2020; von Biela et al., 2022), in large part due to a strong correlation between low flows and high temperatures in many streams (Arismendi et al., 2013). As a result, an increasing number of management actions, including habitat restoration, are being considered to help mitigate the impacts of elevated stream temperatures. However, to enable successful outcomes of this work, it is essential to have a good understanding of the tools and methods available to best characterize water temperature.

1.1 Relationship Between Temperature and Aquatic Ecology

Water temperature influences physical factors such as surface-groundwater interactions, thermal buffering, dissolved oxygen capacity, nutrient and contaminant transport and water level dynamics (Bonacina et al., 2023; Dugdale et al., 2019; Mohamed et al., 2021a). Temperature also plays an important role in species distribution, metabolism and carrying capacity (Beechie et al., 2023; Buisson et al., 2007; Ouellet et al., 2020).

Salmonids are among many pacific northwest species which have evolved in cooler conditions and as such are significantly impacted by elevated water temperatures through direct and indirect mechanisms. This sensitivity is due in part to their poikilothermic nature, which means their external environment heavily impacts their internal physiology (Wilms, 2024). Salmonids have different thermal tolerances depending on the species and their life stage (Jonsson, 2023; Mayer et al., 2023). However, as Pacific salmon are predominantly a cold-water species, elevated temperatures for extended periods of time are detrimental to most species at most life stages through physiological stress and many other indirect ecological pathways. Physiological stress as a result of significant exposure time to increased temperatures can effect general health, disease resistance, and reproduction through neuroendocrine and cellular stress responses (Nakano et al., 2014). Salmon are also indirectly affected by elevated water temperatures which can lead to an increase in predation vulnerability, decreased growth potential, increased disease, and altered stream productivity and food webs (Lusardi et al., 2020).

Human-induced activities and natural disturbances can significantly alter thermal processes in a river (Chen et al., 2023; Kędra & Wiejaczka, 2018; Raptis et al., 2016; Weber et al., 2017). Activities such as dam construction, loss of riparian vegetation, water withdrawals, urbanization, or changes to physical channel form can lead to elevated stream temperatures

(Cunningham et al., 2023; Grey et al., 2023; Kędra & Wiejaczka, 2018; Liu et al., 2018; Poole & Berman, 2001; Wondzell et al., 2019). Often, these activities may correspond to other reductions in water quality, particularly in the case of urban, agricultural, industrial, or post-wildfire-runoff (Jayasooriya et al., 2020; Moody et al., 2013; Pericherla et al., 2020; Walsh et al., 2005). Climate change impacts tend to exacerbate these issues in the Pacific Northwest with projections of reduced streamflow (and increased thermal sensitivity) and increasing stream temperature during the summer season (Dierauer et al., 2021; Ficklin et al., 2014); as well as growing evidence for temperature derived phenological mismatches in the spring due to milder winter temperatures (Wilson et al., 2023). Collectively, these disturbances can lead to complex interactions in the ecosystem, leading to significant shifts in water temperature mosaics with impacts to the aquatic environment.

1.2 Stream temperature and habitat restoration

An increasing number of habitat restoration projects have either primary or secondary objectives of improving or preserving stream temperature attributes (Beechie et al., 2013). Restoration actions such as off-channel habitat creation (Stoffers et al., 2022), pool deepening (Tranmer et al., 2025), thermal refugia expansion and creation (Moravek et al., 2024) and increasing stream shading through riparian vegetation enhancement (Kalny et al., 2017) have been implemented in recent years (Figure 1). At slightly larger scales, siphoning of cooler water from lakes or reservoirs has been considered in thermally stressed systems (Kurylyk et al., 2015). In nearly all cases, restoration work focusing on temperature management will require a detailed understanding of existing spatial and temporal thermal characteristics, along with specific objectives for different species and life stages (Naman and Reid, 2025). A detailed review of various restoration actions incorporating temperature considerations can be found in Quilbé et al. 2025.

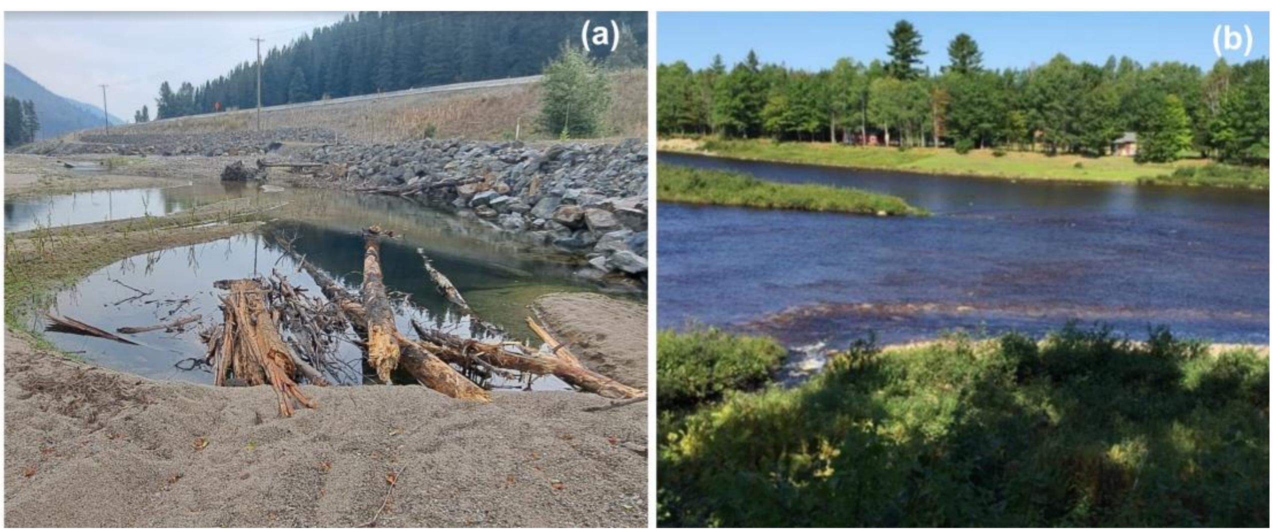

Figure 1: (a) example of pool shading on the Coldwater River near Merritt, BC (image by D. Reid); (b) example anti-mixing baffle to keep cool water from a tributary separated from warmer mainstem water in the Mirimachi River, NB. Image modified from Quilbé et al. 2025.

Understanding and considering the different mechanisms for thermal impacts is also important for considering monitoring and restoration actions. While the overall goal may be to lower or buffer temperatures, other management and restoration actions may work on longer timescales. Therefore, coupling actions that address stream temperature with actions that address other habitat-limiting mechanisms will have more success.

1.3 Characterization of stream temperature

Characterization of water temperature is necessary to identify appropriate restoration objectives, to identify target areas for restoration (e.g. existing or potential thermal refugia), and to monitor both baseline conditions and restoration effectiveness. This characterization may be focused on larger-scale system-wide dynamics (e.g. how widespread logging impacts temperature regimes, see Cunningham et al. 2023) to reach-scale patterns to highly localized features.

Often, a monitoring goal is to identify cold water patches (CWPs). CWPs, usually defined as areas of temperature at least 2 degrees cooler than surrounding water, often serve as vital thermal refugia, allowing salmon and other species to escape increased water temperatures (Sullivan et al., 2021). Quantifying stream temperature at a fine spatial and temporal scale is often necessary to capture thermal refugia and CWPs, and to understand a stream's thermal regime and temperature dynamics. Measuring stream temperature in detail using appropriate methods is a key component of monitoring stream water quality as configuration, size, and temperature of CWPs may vary over time (Sullivan et al., 2021). Temperature regimes can also change at weekly, seasonal or annual scales due to changes in weather, stream morphology, or anthropogenic effects (Sullivan et al., 2021; Leach et al. 2023).

A broad suite of methods are available to support stream temperature characterization, ranging from remote-sensing that characterizes snapshots of fine scale variation across space to continuous localized measurements using data loggers (Mejia et al., 2023). Despite a wide availability of methods, it is not always clear which approach is best suited given project objectives or site characteristics, particularly as the application, benefits, and limitations of newer technologies may not yet be well understood. Given the importance of selecting the appropriate method for temperature characterization, this paper aims to provide an in-depth overview of several temperature collection methods to support stream restoration.

Specifically, in this document we aim to:

1) Review temperature characteristics of interest to restoration practitioners (Section 2)
2) Describe how to access existing sources of temperature data (Section 3)
3) Review spatial, temporal, and hybrid temperature characterization methods (Section 4);
4) Compare temperature monitoring methods (Section 5); and
5) Optimize temperature monitoring methods to meet specific habitat restoration goals (Section 5).

2. Prioritizing temperature monitoring for restoration goals

Both spatial and temporal characterizations of water temperature may be relevant for specific restoration objectives, yet each requires different measurement approaches and methods. Developing clear project objectives and defining site-specific characteristics will help identify the type of thermal information that will be relevant to a project.

A basic starting point for planning temperature-focused restoration in aquatic ecosystems involves reconnaissance work to gain a general understanding of temperature dynamics in the habitat of interest. Prioritizing spatial or temporal temperature characterization will depend on project objectives and existing data (see Table 1). Preliminary spatial exploration could be used at this stage for initial temperature characterization and to determine where more intensive temporal data collection should take place. Conversely, temporal monitoring may be desirable as a first step if spatial homogeneity is expected, problem areas are already known, or if spatial data collection is not feasible. If no information exists for a site, capturing spatial variability in temperature over a larger area may still be the most useful first step during restoration planning, where a focus on differences over large areas is important for initial project prioritization.

Identifying the location, size, and temperature of CWPs within streams is an increasingly common objective of restoration planning (Kurylyk et al., 2015; Mejia et al., 2023), where restoration work may seek to improve or preserve access to cooler areas. Cold water patches may be found at tributary junctions, sites with groundwater upwelling, or in other locations (Figure 2; Isaak & Young, 2023; Kurylyk et al., 2015). Along with CWPs, characterizing the temperature of critical off-channel habitat can also be a key requirement prior to undertaking restoration actions, such as floodplain habitat connectivity projects. Restoration work using this kind of information may include thermal refugia expansion using anti-mixing baffles or excavation, or strategic disconnection or reconnection of off-channel habitat to create or preserve access to high-quality habitat (Naman and Reid, 2025). Each of these approaches will require a distinct monitoring strategy to best locate projects and to determine project effectiveness.

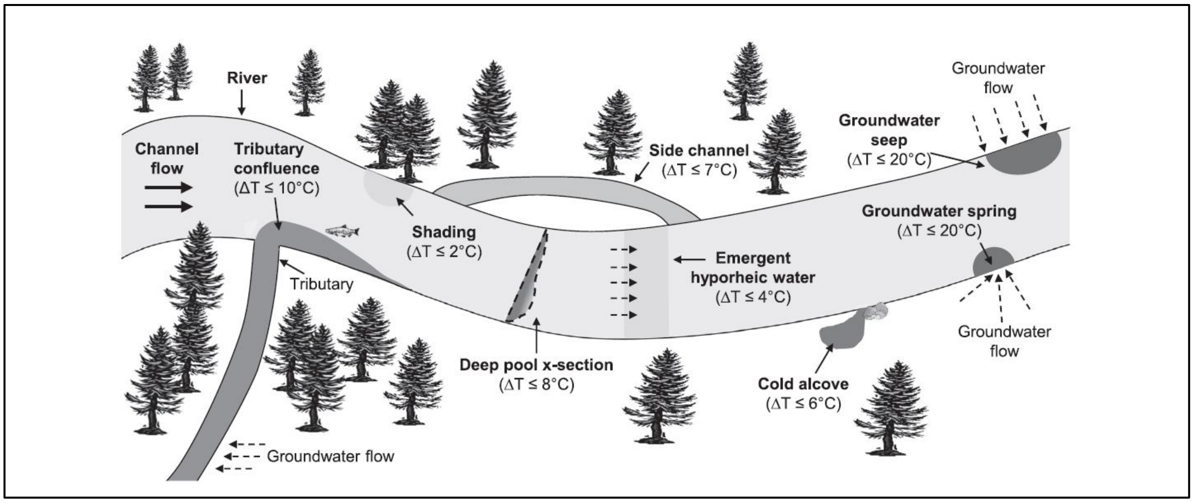

Figure 2. Illustration of different cold water sources and features commonly identified in aquatic systems . Reprinted from Kurylyk et al, 2015. Copyright 2014 by John Wiley & Sons, Ltd.

In addition to temperature characterization to support restoration planning and prioritization, temperature is also an important metric for evaluating restoration effectiveness. Monitoring temperature before, during, and after work has taken place, along with documenting changes to the spatial characteristics of stream temperature can help provide insight into the effectiveness of different restoration actions (Kurylyk et al., 2015). Similarly, this monitoring can help ensure that there are no negative impacts to the area of interest during the time that work is taking place.

3. Accessing existing temperature data

Existing data sources for an area of interest may be available and can help support data collection planning. For example, many Water Survey of Canada gauge stations collect temperature data concurrently with flow attributes. An additional summary of water temperature data sources can be found in Reid et al. 2024. Other publicly available temperature data sources in western Canada are listed in Table 1.

Table 1 – Sources of publicly available temperature data for western Canada

DATA SOURCE	SUMMARY	LINK/ACCESS
DataStream	Source for hydrometric and water quality data. Data is collected through a variety of local data contributors and put into a standardized format. Temperature data availability is dependent on station.	https://datastream.org/en-ca
Water Survey Of Canada (WSC)	Canadian source for national water resource data. Temperature data is dependent on the station. This data is often not subject to quality control or analysis and should therefore be used with caution.	https://www.canada.ca/en/environment-climate-change/services/water-overview/quantity/monitoring/survey.html

DATA SOURCE	SUMMARY	LINK/ACCESS
Open Government Data Portal	Information and data sets published by Canadian government institutions.	https://open.canada.ca/data/en/organization/dfo-mpo?res_type=dataset
BC Real-Time Water Data Tool	Repository for continuous surface, groundwater and snow data from provincial monitoring stations.	https://bcmoe-prod.aquaticinformatics.net/Data
Columbia Basin Water Hub	Groundwater, climate and hydrometric data collected by Living Lakes Canada and partners through the Columbia Basin Water Monitoring Framework program.	https://data.cbwaterhub.ca/group/
Skeena Salmon Data Centre	Repository for reputable data related to wild pacific salmonids in the Skeena watershed.	https://www.skeenatrust.ca/

4. Methods for characterizing stream temperature

A variety of methods can be used to characterize stream temperature, including *in situ* measurements, remote sensing techniques, and modelling (Figure **3**3). Traditionally, scientists relied on temperature data loggers: small, relatively inexpensive devices that can be placed throughout a stream to record at a high temporal resolution for extended periods of time. Although temperature data loggers remain an essential tool, there are new methods that can be better suited for a variety of needs, particularly those with a spatial component. For example, airborne or drone-mounted Thermal Infrared Remote Sensing (TIR) cameras enable rapid assessment of spatial temperature patterns across broad areas. These methods are described in subsequent sections, organized into approaches which are best suited to capture spatial versus temporal aspects of temperature. While temperature modelling can be an important tool used to better understand temperature dynamics in aquatic ecosystems (Isaak et al., 2014; Piccolroaz et al., 2024; Walsh et al., 2020), the scope of this topic is large and therefore the focus of this paper will be limited to measurement.

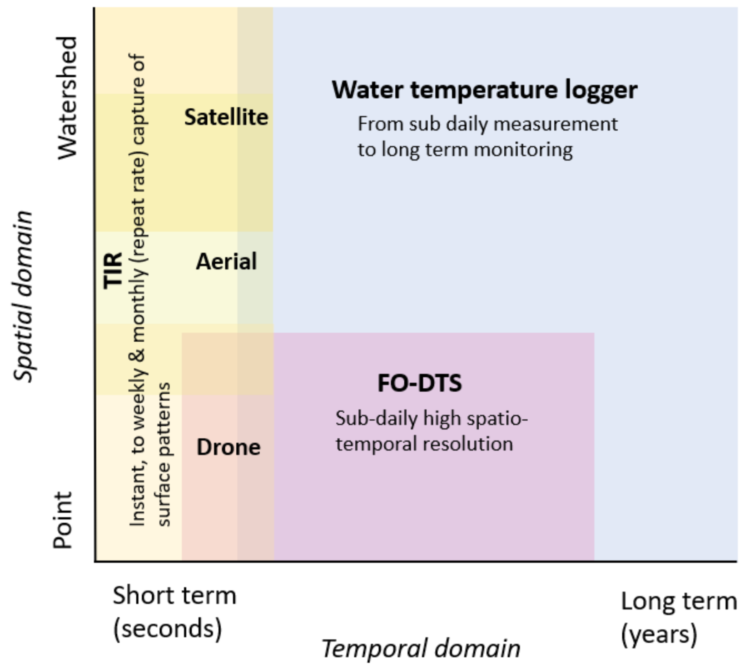

Figure 3. Spatial and temporal domains of different temperature measurement methods. Figure modified from Ouellet et al. 2020. Note that modelling options exist for most spatial and temporal scales shown in this diagram, but are not discussed here. "TIR" refers to Thermal Infrared Imagery. "FO-DTS" refers to Fiber Optic Distributed Temperature Sensing.

4.1 Methods for characterizing spatial thermal information

A variety of methods are available for characterizing spatial composition of stream and river temperature. Different methods may be best suited to different spatial scales, and distinct limitations and trade-offs are present between methods. While repeat instances of spatial data collection can provide limited information on temporal dynamics, the primary application of these methods is geographic coverage. These different methods are discussed in more detail below.

4.1.1 Thermal data from satellite imagery

Several satellites are capable of providing radiance data corresponding to stream temperature (Figure 4; Ouellet et al. 2020). Newer generations of Landsat satellites can provide thermal imagery with resolutions of approximately 100 m (Martí-Cardona et al., 2019). Commercial satellites, such as HotSat-1, offer much finer spatial resolution; however, their imagery can be very expensive to purchase (European Space Agency, n.d.). Given the availability and resolution of the imagery, satellite thermal imagery is often only applicable for use in large river systems or other large bodies of water.

Figure 4. 3.5 m resolution thermal imagery showcasing mangrove environments in Darwin, Australia SatVu, 2023).

4.1.1.1 When to use satellite imagery

Satellite technology can be a valuable tool for getting a snapshot of waterbodies. However, for the snapshot to be effective, the water body needs to be large enough that the imagery resolution (which is typically coarse) is adequate to resolve key features. If this scale is sufficient for the project study area, satellite imagery can be an excellent tool during preliminary investigations to get a good understanding of spatial temperature variability over large areas. Satellite imagery is commonly used to capture dam and reservoir temperature regimes, along with thermal pollution that is occurring at a large scale (e.g. Ling et al., 2017; Naimaee et al., 2024).

4.1.1.2 Advantages of Satellite Imagery

Satellite imagery offers several advantages over other methods. One major benefit is broad spatial coverage, which can provide information for remote or otherwise inaccessible areas. Many satellites also provide regular (though infrequent) observations of a location, enabling long-term monitoring of changes. If there is a historical record of TIR satellite images it may be possible to assess past temperature trends in addition to current ones. Satellites also often capture images across different wavelengths, allowing for the comparison of TIR with other wavelengths (e.g. within the visible spectrum) which may be beneficial depending on project needs (Naimaee et al., 2024). Depending on project area and data resolution requirements, satellite imagery may be acquired at no cost to the user.

4.1.1.3 <u>Limitations of Satellite Imagery</u>

While satellite imagery can be useful for supporting restoration work in a limited set of circumstances, it is unlikely to be the best tool for the job in most instances. The primary limitation is that most low-cost satellite imagery has relatively coarse resolution, rendering it less useful for smaller streams or rivers. While higher resolution imagery (less than 25 m^2) is available, it can be considerably more expensive. As with other thermal cameras, only the surface temperature of water is captured, which may lead to omission of differences in water temperature with depth.

Restoration practitioners may also become frustrated by the lack of control over when the imagery is captured. Timing can be critical for capturing key temperature data, and delays could result in missing specific events that could have otherwise been captured with more precise methods. Moreover, if there is cloud cover in a study area during the time the satellite passes through, the satellite cannot accurately capture TIR data. Lastly, TIR satellite imagery may require significant post processing to provide a useable output. Typically, the more processed a product is, the more expensive it will be.

4.1.2 Thermal data from aircraft-mounted Forward-Looking Infrared (FLIR) imagery

Airborne thermal mapping from helicopters or planes (Figure 5) predates many other methods, with the application used to support stream temperature characterization for at least the last 25 years (Faux et al., 2001). This approach provides a middle ground between satellite and Unoccupied Aerial Vehicle (UAV)-derived thermal imagery, though the specific imagery characteristics will be a function of the camera used and flight conditions, such as height above ground.

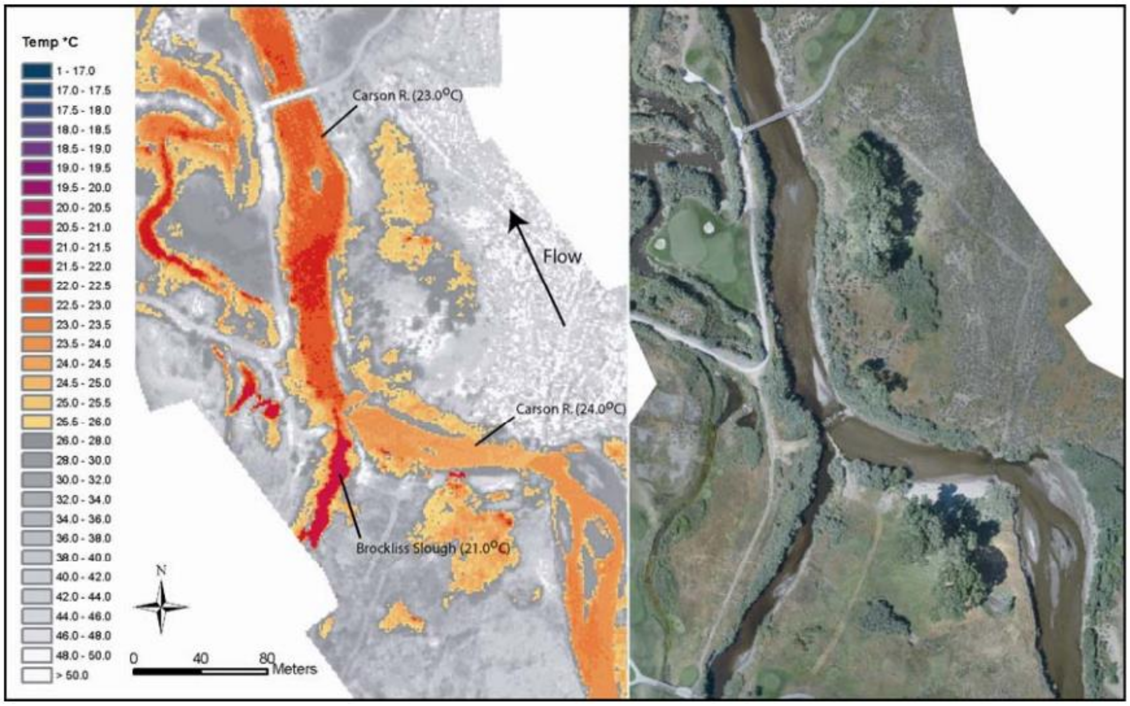

Figure 5. Example of thermal imagery generated from helicopter-mounted FLIR camera flown over the Carson River, NV. Image from Brock, 2006 (Watershed Sciences, 2006).(Watershed Sciences, 2006).

4.1.2.1 When to use aircraft-mounted FLIR imagery

Depending on the scale of the system, airborne (plane or helicopter) thermal imagery could be used to support both reconnaissance efforts or detailed mapping work related to restoration projects, such as identification of thermal refugia (Dugdale et al. 2015). The scale of coverage is somewhat flexible with this method, ranging from moderately large areas, such as small-medium watersheds (e.g. Dugdale et al., 2015; Faux et al., 2001), to smaller areas, such as individual or collections of channel reaches (Faux et al. 2001). Smaller areas flown at lower heights are likely best captured using helicopters, as opposed to fixed-wing mounted sensors.

4.1.2.2 Advantages of aircraft-mounted FLIR imagery

Thermal infrared (TIR) airborne data acquisition has good imagery resolution with relatively high temperature precision (e.g. ± 1.0 °C from − 5 °C to 35 °C; Wawrzyniak et al., 2016). Areal coverage can be moderate to large, and there is flexibility and rapid deployment compared to satellite. Moderately large areas can be flown in a quick time frame, and overhead cloud cover is not typically an obstacle to collecting good data provided that the aircraft can operate beneath the cloud.

4.1.2.3 Limitations of aircraft-mounted FLIR imagery

While airborne mapping can be an excellent source of high-quality thermal images, it can be expensive. The largest limitation is the cost associated with contracting aircraft and processing services. In addition, aircraft flying speed needs to be considered when choosing the aircraft. In most cases a helicopter, as opposed to fixed-wing plane is required for habitat restoration applications. Costs can increase substantially if repeat flights are required, and as with all spatially-focused methods described here, individual flights will capture only a snapshot of conditions.

Aerial imagery from planes or helicopters is more versatile than from satellites, but small streams or areas beneath forest canopies can be challenging to capture resulting in inaccessibility to certain types of habitat. Use of ground control points or other fixpoints may be required to ensure high positional accuracy.

A limitation across all thermal imagery (airborne or drones) is that only the water surface temperature is captured. The degree of vertical mixing and resulting changes in temperature with depth are highly variable and depend on local site characteristics, with some studies showing no significant differences in the water column (Casas-Mulet, 2020), but others documenting variability (Tranmer, 2025; Dugdale et al., 2019). As a result, caution is warranted when interpreting findings if minimal vertical mixing is suspected.

4.1.3 Thermal data from UAV/drone mapping

Unoccupied aerial vehicles (UAVs), otherwise known as drones, have become a valuable instrument for remote sensing as they are able to rapidly collect data in a wide range of environments. They have become a go-to resource for qualitative site overviews, and more recently, with the advancement of TIR (thermal infrared) cameras, an increasingly valuable tool for measuring stream temperatures (see Figure 6).

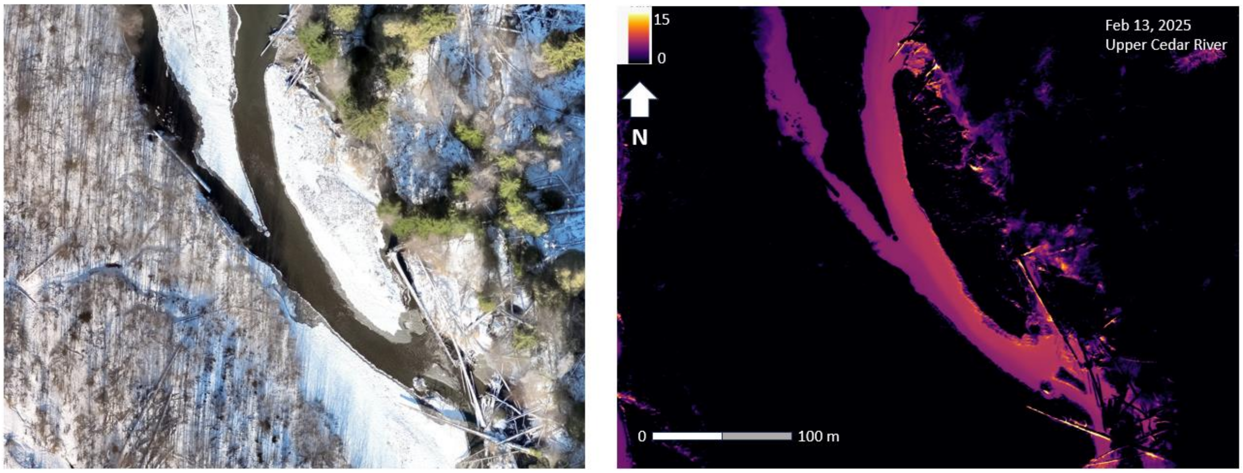

Figure 6. Data collected using a quadcopter-style drone can yield good thermal mapping results when paired with a suitable thermal camera. Relative to ground-based or aircraft-mounted methods, drone-based data collection is rapidly becoming a preferred method to obtain stream temperature data, though several limitations remain and processing time is significant. On the left is an orthomosaic of optical imagery, while the right shows the corresponding thermal orthomosaic.

4.1.3.1 When to Use UAVs

TIR drone technology is suitable for conducting site reconnaissance at the reach to catchment scale, collecting temperature data in inaccessible areas, for collecting multiple imagery types concurrently, and for combining with ground-based georeferenced data to obtain precise spatial positioning. The high resolution and precision of drone-mounted thermal cameras are also helpful for resolving small habitat features.

4.1.3.2 Advantages of UAVs

A primary advantage of using UAVs for temperature monitoring is that imagery can be captured over small waterways which are difficult to access using satellite or aircraft-mounted TIR cameras. Additionally, RGB imagery can be collected concurrently with TIR imagery, providing valuable contextual information. Many consumer drones can link with ground-based georeferenced benchmarks through RTK (real-time kinematic) positioning systems, allowing for a high degree of spatial accuracy (within 10 cm) and easy comparison with other data sources.

UAVs are relatively simple and rapid to deploy, allowing for repeat visits or short-notice deployments. Modern TIR sensors offer high resolution imaging (e.g. Mavic 3T: 640 × 512, Zenmuse H30T: 1280×1024), which help reveal small yet important habitat features, such as cold water patches. Most processing can be done in-house using a variety of commonly available software packages. Data collection cost can be lower than for other methods (i.e. airborne FLIR).

4.1.3.3 Limitations of UAVs

While drones can be an excellent tool for rapid acquisition of high-resolution stream temperature data, several limitations must be considered. First, the effort and time required to process imagery is significant. Proprietary image formats often require conversion to use in photogrammetry software. Additionally, image calibration against field measurements is often required to correct for sensor drift due to camera heating during flights. Solar radiation and long flight times have the most significant effects on drone TIR image temperature drift (Dugdale et al., 2019). While various methods for correcting sensor drift have been published (Aragon et al., 2020; Kelly et al., 2019; Ribeiro-Gomes et al., 2017; Yuan & Hua, 2022, Szostak et al., 2023), most require several additional processing steps.

Field conditions can also pose a challenge for collecting good quality thermal data from drone-mounted cameras. For example, thick vegetation can obscure channel areas and create hazards for drone operation. Without distinct features to use as control points during image alignment, photogrammetry software may produce incomplete or distorted thermal orthomosaics. If a drone relies on a vision positioning system, the drone may struggle to stabilize and maintain its position over uniform reflective surfaces such as water (Román et al., 2024). As discussed with other methods, drone cameras will only capture temperature conditions in the surface layer of water.

Although drone costs have decreased in recent years, certain factors can still make TIR drone data acquisition expensive. High-resolution cameras and drone hardware remain expensive relative to simple temperature loggers, and post-processing software can be very costly. Proprietary image output formats from common drone manufacturers may not include temperature metadata directly accessible by most consumer photogrammetry packages, requiring an extra conversion step (Jiang et al., 2024).

Finally, training, licensing and approvals are often required to collect thermal data using drones. While the degree of licensing and approvals will depend on the drone used and locations flown, becoming certified to operate drones across all areas can be a time-consuming process.

4.1.4 Manual field measurements

4.1.4.1 Overview

Perhaps the simplest and most widely-applied method for collecting spatial thermal data is using manual field measurements with handheld temperature probes at known or marked locations (Figure 7). A wide range of probe types are available, ranging from simple thermometers to more complex multi-sensor sondes. In all cases, the spatial resolution will be a function of data requirements and project resources as opposed to limitations from the equipment. However, this method is most often applied to collect relatively sparse (i.e. low spatial density) measurements.

Figure 7. Collection of manual temperature measurement using a hand held water quality meter. Handheld cameras, such as the FLIR E5 Pro shown on the right, can be useful for locating sites for more detailed measurements (Image from ITM Instruments).

To guide probe measurements, handheld thermal cameras can also serve as useful tools. These cameras are compact and versatile, allowing for easy use in field settings and allow for rapid visualization over relatively large areas while travelling along waterways. While high-resolution handheld thermal imagers are costly, lower-resolution versions can provide good functionality at a more reasonable price.

4.1.4.2 <u>When to use Manual Measurement</u>

Manual temperature measurements with handheld probes are often required to calibrate results from other methods (e.g. thermal drone mapping) but may also be of value on their own. The ease of deployment and rapid and direct data collection method makes this a sensible approach for reconnaissance, particularly over small areas. Handheld thermometers are also well suited to collection of measurements in very small streams or in areas obscured by vegetation where overhead methods aren't suitable. Longitudinal or cross-sectional transects with probe measurements at fixed intervals can help provide systematic spatial temperature data.

4.1.4.3 <u>Advantages of Manual Measurement</u>

High-quality hand-held temperature probes can provide very accurate data relative to some of the other methods listed here. Manual measurements are also capable of capturing data locations obscured by overhead vegetation or other obstacles. Measurements can be taken with spatial precision (assuming access is possible), such as a key habitat feature type. The degree of temperature stratification in deeper areas can be easily determined by placing the probe at different depths, which can help validate other types of data collection and is also in itself useful information. This method is very simple to deploy and has the lowest cost and training requirements of any approach.

4.1.4.4 Limitations of Manual Measurement

Limited spatial coverage and temporal resolution are the primary drawbacks of temperature characterization using handheld probes. In practice, only small areas can effectively be covered in reasonable detail, and hard-to-access locations will be omitted or under-sampled. Repeat sampling is possible (and is often done) but temporal resolution will depend on site visit frequency and time availability.

4.2 Methods for characterizing temporal thermal data

While many restoration projects will require at least some degree of spatial thermal data to help with site selection and prioritization, temporal thermal information is also often required, especially when considering baseline and effectiveness monitoring. Approaches focusing on temporal data collection are listed below.

4.2.1 Temperature Data Loggers

4.2.1.1 Overview of Temperature Loggers

Temperature data loggers are small, relatively inexpensive devices that measure temperature at defined intervals over a set period of time. They are typically capable of measuring up to ± 0.2-0.5°C accuracy, though this may vary with temperature (measurements < 0°C tend to be less accurate) and logger type (Jones & Allin, 2010; United States Environmental Protection Agency (EPA), 2014). Loggers come in a variety of price ranges and accuracies. Selecting a logger with the appropriate, accuracy, precision, battery life, and data accessibility should be selected to meet data requirements (Figure 8). Information on each logger type can be found on manufacturers websites or product documentation. Many other types of sensors, such as water level or dissolved oxygen sensors can also monitor temperature concurrently. An example time series of temperature data collected to support a restoration project is shown in Figure 9.

Figure 8. A variety of commercially available temperature loggers commonly used in environmental monitoring. Devices shown include: (A) Onset HOBO® Water Temp Pro v2; (B) Onset TidbiT® v2; (C) Gemini Tinytag Aquatic 2; (D) Thermochron LogTag®; (E) MadgeTech Temp101A; and (F) Maxim Integrated Thermochron iButton®. Figure from U.S. Environmental Protection Agency (EPA), 2014.

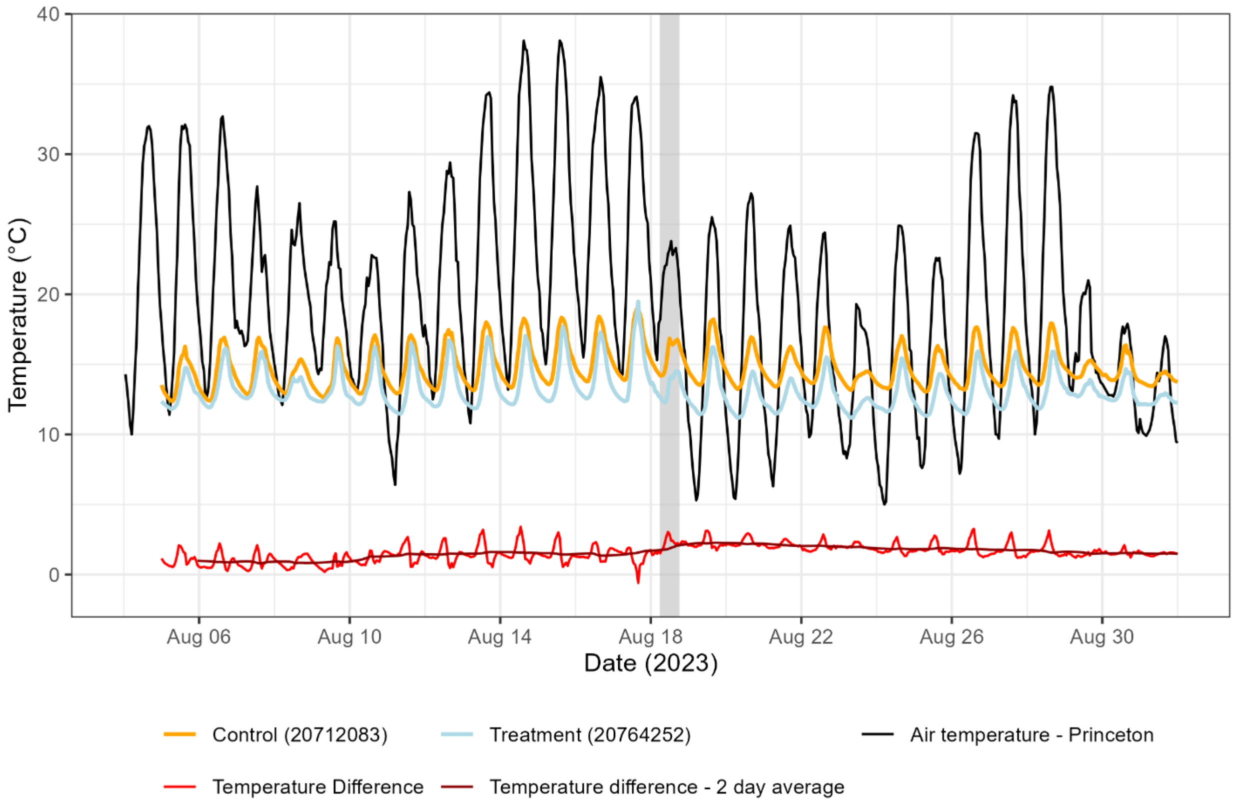

Figure 9. Example time series from two temperature loggers located in off-channel habitat adjacent to the Coldwater River, BC. The grey vertical bar indicates the date of pool deepening and shading which sought to improve temperature conditions.

4.2.1.2 When to Use Loggers

Data loggers are well suited for understanding stream temperature dynamics over time. Most loggers can be deployed in the water for long periods of time and data does not need to be downloaded frequently. Temperature loggers are also a good choice for collecting data at specific locations, such as at certain depths in the water column, or in locations which are difficult to sample using other methods, such as below forest canopies. Finally, capturing short-term temperature variability is possible with temperature loggers given their high temporal resolution.

4.2.1.3 Advantages of Loggers

Temperature data loggers are a relatively inexpensive technology that offers good temporal resolution without the need for substantial maintenance or frequent site visits. They can be rapidly deployed with minimal equipment, and post processing is straightforward and inexpensive. Depending on the logger, data download frequency can be less than once per year.

Data loggers can be placed at precise locations and depths which can help clarify complex spatiotemporal interactions within systems. Comparison between sites is straightforward, and rapid fluctuations in water temperature can easily be captured and compared.

4.2.1.4 <u>Limitations of Loggers</u>

Temperature data loggers are well suited for many study designs; however, caution is required when collecting data in areas with high flows, high traffic or expansive boundaries. Loggers placed in high flow or high traffic systems may be at risk of getting swept away or tampered with. Additionally, if terrain is difficult, or stream discharges are high, it may be dangerous to install or retrieve loggers. Extensive ground truthing may be required prior to logger installation to ensure data loggers are in representative locations.

If direct sunlight hits data loggers, temperature readings can be affected. As a result, they are best deployed inside a protective shield, such as a piece of white plastic piping.

While data processing is straightforward, some quality control/assurance is required, and this can be time consuming if data is noisy or the data record is long.

4.3 Hybrid methods

Hybrid methods correspond to those approaches which can capture both temporal and spatial information concurrently. While any method can be applied to this effect with sufficient spatial coverage or frequency of measurement, those listed below provide relatively efficient (in the case of logger networks) and cutting edge (in the case of Fiber-Optic Distributed Temperature Sensing) options for obtaining detailed spatial and temporal data concurrently.

4.3.1 FO-DTS (Fiber Optic Distributed Temperature Sensing)

4.3.1.1 <u>Overview of FO-DTS</u>

Fiber-optic distributed temperature sensing (FO-DTS) uses a long fiber-optic cable to capture data along a length of stream. The system is composed of cables which measure light scattered by an emitted laser at fixed distances. Water temperature influences the scattering characteristics of the light within the fiber, enabling temperature measurements to be obtained continuously along the cable length (Figure 10). It is commonly used for pipeline monitoring, quantifying contaminant and nutrient exchange, locating groundwater inflows, and measuring hyporheic exchange (Selker et al. 2006; Le Lay et al., 2019; Mohamed et al., 2021a; Ouellet et al., 2020).

Temperature measurements can be accurate to 0.01° C but this largely depends on the specific instrument, cable, deployment design and calibration procedures employed (Hausner et al., 2011; Tyler et al., 2009). Larger spatial sampling intervals (such as at 2 m distances) will be more precise than a 0.25 m segment if collected for the same length of time, and as a result users can tailor their spatial and temporal measurement resolution to best fit sites and objectives (United States Environmental Protection Agency (EPA), 2024).

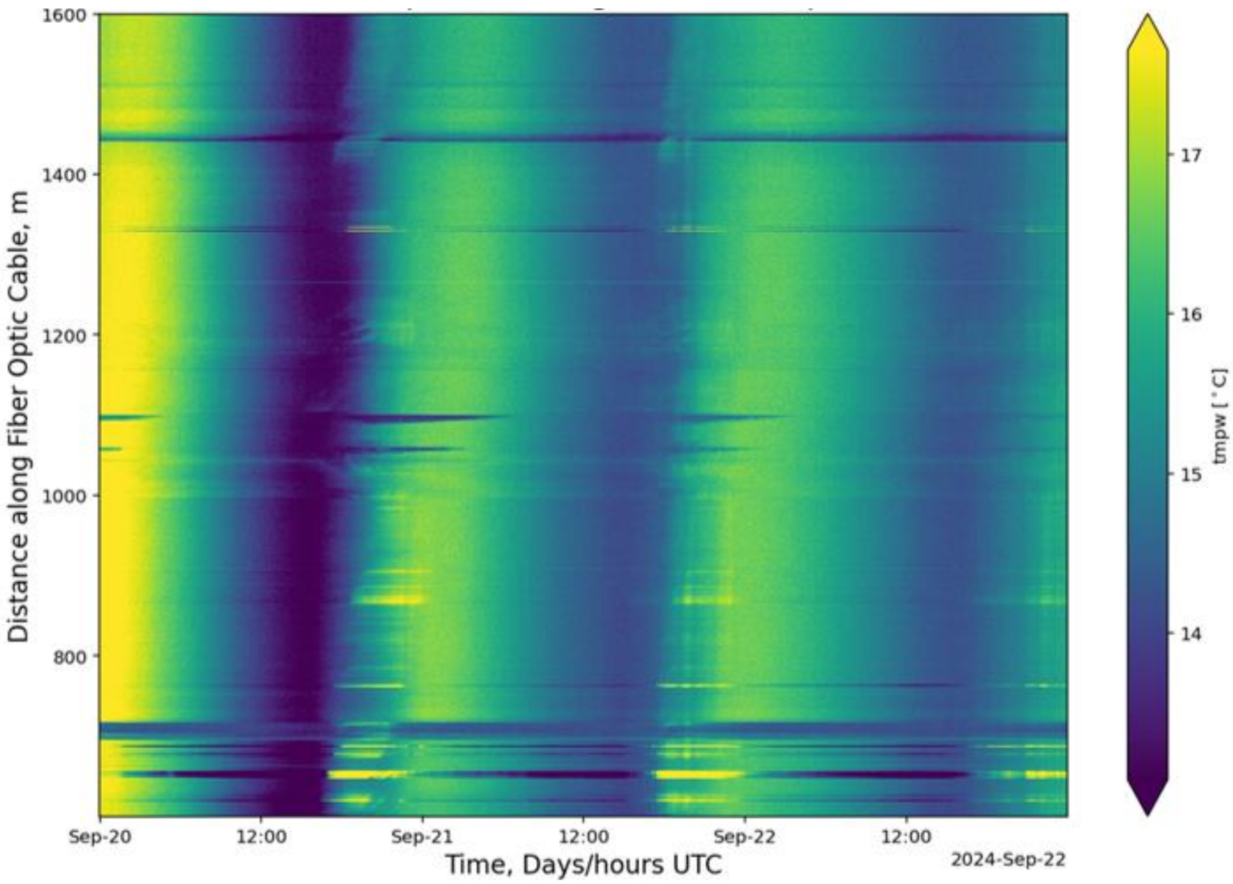

Figure 10. Plot showing a time series of Time vs Distance along Fiber Optic cable at a project on Vancouver Island, BC. Streaks of darker blue are locations of cold water patches. Data provided by the Province of British Columbia (Water, Land and Resource Stewardship) with permission.

4.3.1.2 __When to use FO-DTS__

When FO-DTS systems are set up correctly, they can provide high spatial and temporal resolution of temperature. The system is best utilized when very high-resolution temperature profiles are required along extended reaches of stream. FO-DTS can provide continuous, consistent and accurate measurements along the deployed cables. It is very well suited for the measurement of hyporheic water exchange.

4.3.1.3 __Advantages of FO-DTS__

FO-DTS is relatively flexible regarding configuration and installation of the cable networks. Cable set up, spatial resolution, and temporal resolution can all be tailored to the specific study site and objective. Due to this flexibility, FO-DTS can be well equipped for acquisition of temperature data across cross sections or along profiles of water bodies.

FO-DTS also produces very fine resolution data. This can be advantageous when seeking to characterize small-scale features in rivers such as individual pool temperature dynamics or groundwater-surface water exchanges that are challenging to measure with other methods.

4.3.1.4 Limitations of FO-DTS

Deploying and operating FO-DTS systems can be a major ordeal and careful consideration is required prior to deciding on its use. FO-DTS may be difficult and time consuming to set up (Ouellet et al., 2020; Smith et al., 2024), and an external power source is required. Power sources may be challenging to install and maintain in remote areas. A significant amount of labor is also needed during the initial stage of FO-DTS deployment as the cable must be installed with great care due to its relatively fragile nature.

Sediment and debris moving through waterways can pose difficulties for FO-DTS systems. Cables can get buried in sediment, scoured out, and damaged from moving wood and bedload which can compromise data (Mohamed et al., 2021). Solar radiation penetrating through the water column can also affect temperature readings (Mohamed et al., 2021b; Neilson et al., 2010).

FO-DTS can be an expensive method for stream temperature characterization, though the specific cost will depend on the size of the area to be measured. The system involves specialized equipment and reliable power supply, and the fiber optic cables may only withstand a limited number of deployments before they become damaged and unusable.

Lastly, data-processing can be expensive and time consuming (Mohamed et al., 2021a) particularly if extensive data corrections are required. QA/QC may be required as a result of temperature drift, cable breaks, or if the cable dries out due to water level changes. FO-DTS is typically suited for collection of linear (one-dimensional) temperature data as it may be even more difficult and labour intensive to structure cable into 2D or 3D patterns (Smith et al., 2024).

4.3.2 Logger networks

4.3.2.1 Overview

Logger networks are a collection of temperature loggers deployed at multiple, strategically selected locations within a stream or watershed (Figure 11). These networks may be designed to capture both longitudinal, lateral and vertical stream temperatures. Loggers with the appropriate accuracy, precision, battery life, and data accessibility should be selected.

4.3.2.2 When to use Logger Networks

Logger networks are appropriate for use when detailed, long-term temperature data are required across river channels or watersheds. They are well-suited to capture temperature in different depths and across a series of locations. The main strength of loggers remains their temporal accuracy and resolution and the spatial resolution is entirely a function of deployment density.

4.3.2.3 Advantages of Logger Networks

As described above, temperature data loggers are simple and reliable systems which are much easier to deploy than, for instance, FO-DTS cables. In many applications, a network of temperature loggers can capture essential elements of spatial and temporal variability in water temperature. They are inexpensive, simple to deploy, and do not require significant maintenance or frequent site visits.

4.3.2.4 Limitations of Logger Networks

Data logger networks can be somewhat time consuming to deploy, maintain and recover, depending on the number of loggers required and site characteristics. As with any field equipment left in place, loggers are at risk of theft, vandalism, or damage from the public. While data processing is straightforward for individual loggers, the processing effort will scale in proportion to the number of loggers deployed. It is critical that the timestamp and logging interval are consistent between loggers, otherwise data processing effort increases significantly. In addition, deploying a pressure transducer or temperature sensor out of the water may be required to determine if/when submerged temperature loggers have gone dry.

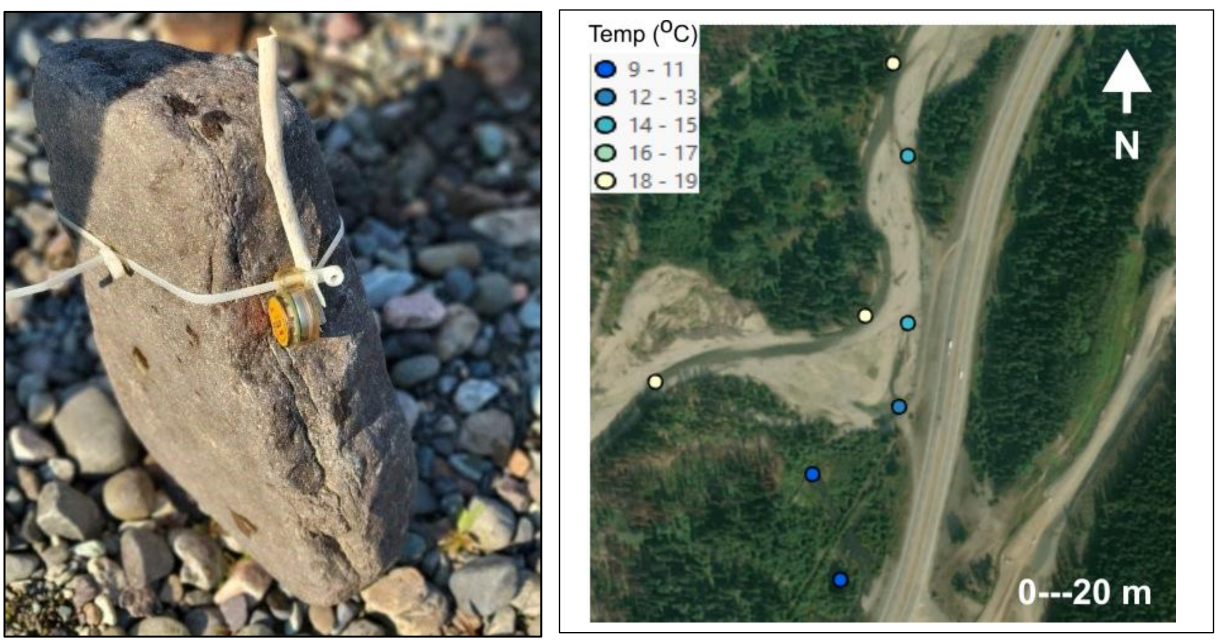

Figure 11. (left) Image of HOBO TidbiT data logger deployed in field. (right) Map depicting temperature logger locations and values.

5. A comparative evaluation of temperature measurement methods

A summary of methods outlined above is presented in Table 2. Table 3 contains a comparative overview of methods organized by restoration objective.

Table 2: A comparison of temperature data collection options

Method	Cost	Field effort	Processing effort	Repeatability[a]	Other considerations	Key references
Spatial						
Satellite	Low - High[b]	Low	Moderate	Moderate	New sensors are being brought online and resolution is increasing.	European Space Agency, n.d.; Ling et al., 2017; Martí-Cardona et al., 2019; Naimaee et al., 2024; Ouellet et al., 2020.
Aerial FLIR	High	Low	Moderate	Moderate	Flying speed of aircraft needs to be considered. Often a plane will not be able to fly slow enough and a helicopter will need to be used.	Dugdale et al., 2015; Faux et al., 2001; Watershed Sciences, 2006; Wawrzyniak et al., 2016
Drone	Moderate	High	High	High	Significant variability in image quality depending on sensor. Repeatability and accuracy dependent on georeferencing.	Aragon et al., 2020; Dugdale et al., 2019; Jiang et al., 2024; Kuhn et al., 2021; Ribeiro-Gomes et al., 2017; Román et al., 2024; Szostak et al., 2023; Tranmer et al., 2025; Vélez-Nicolás et al., 2021; Yuan & Hua, 2022
Manual measurements	Low	Moderate	Low	High	Level of effort will depend on spatial extent of coverage.	Ouellet et al., 2020
Temporal						
loggers	Low	Moderate	Moderate	High	Can provide high temporal resolution data.	Jones & Allin, 2010; U.S. Environmental Protection Agency (EPA), 2014

Method	Cost	Field effort	Processing effort	Repeatability[a]	Other considerations	Key references
Manual measurements	Low	Moderate	Low	High	Lower temporal resolution.	-
Hybrid						
DTS	High	High	High	Moderate	Typically only used in a research setting.	Hausner et al., 2011; Le Lay et al., 2019; Mohamed et al., 2021; Ouellet et al., 2020; Smith et al., 2024; Tyler et al., 2009; United States Environmental Protection Agency (EPA), 2024
Logger networks	Moderate	High	Moderate	High	Spatial resolution a function of placement, but can be high over small areas.	Ulaski et al., 2023; Roon et al., 2021

[a] Corresponds to the ease of undertaking comparable, repeat measurements under similar conditions

[b] Cost varies based on satellite, with some open source (i.e. no cost) options available.

Table 3 – A comparative overview of methods aligned by monitoring objective.

Monitoring Goal	Spatial resolution	Temporal resolution	Recommended method(s)	Considerations
Locate thermal refugia (or cold water patches)	Small - medium scales (0-10 km of river)	Low frequency (single instance)	Drone-based TIR remote sensing; Manual temperature measurements	Thermal drone is effective but only in larger systems under certain conditions. Processing can be time consuming. Desktop analysis ahead of fieldwork can help reduce field time.
Locate groundwater inputs	Small - medium scales (0-10 km of river)	Low frequency (single instance)	Manual temperature measurements; Drone-based TIR remote sensing	Temperature anomalies can indicate GW inputs. Best used during low-flow periods for contrast, or during winter where warmer flows tend to rise to surface. Ground validation improves confidence.
Monitor persistence of known refugia/GW inputs	Small - medium scales (0-10 km of river)	High frequency	Water temperature loggers	Locations must be known in advance and be accessible to deploy loggers.
Track changes in temperature during periods of drought	Small - large scales (0->100 km of river)	Moderate frequency (daily to weekly)	Aerial FLIR Imagery; Drone-based TIR remote sensing; Water temperature loggers	For aerial and drone remote sensing, the pilots must be available during the period of drought and potentially after to assess changes. Vertical temperature stratification must me minimal for imagery methods to succeed. For temperature loggers, they must be put in in advance of drought to capture changes.
Track changes to temperature following flow release	Small - medium scales (0-10 km of river)	Low frequency	Water temperature loggers	Flow release timing must be known in advance to be able to put loggers in preemptively.
Increasing Hyporheic exchange	Small scales (1-100 m)	High frequency	FO-DTS; water temperature loggers	FO-DTS detects fine-scale temperature variability. Requires access to both ends of the fiber and specific deployment expertise. For water temperature loggers, analysis ahead of time may be required for optimal logger placement.

Monitoring Goal	Spatial resolution	Temporal resolution	Recommended method(s)	Considerations
Assess point-in-time stream connectivity and temperature	Small - medium scales (0-10 km of river)	Low frequency	Drone based TIR remote sensing	Drone flights must be timed correctly to be able to assess connectivity or specific temperature patterns.
Evaluate riparian restoration outcomes	Small - medium scales (0-10 km of river)	High frequency	Water temperature loggers	Knowing how and where riparian plants will grow is required in advance of effective logger placement. Shade and vegetation recovery can take several years to influence temperature.
Assess habitat suitability	Small-large scales (0->100 km of river)	Low to moderate frequency	Water temperature loggers; Manual surveys; TIR remote sensing	Depending on the scale required, different methods may be used. Scale should be a primary factor when choosing methodology.
Monitor long term trends of reaches (that had channel modifications, restoration etc.)	Small - medium scales (0-10 km of river)	High frequency	Water temperature loggers	Requires pre- and post-restoration monitoring. Shade and vegetation recovery can take several years to influence temperature.
Detailed research on groundwater/surface water dynamics	Small-medium scales (0-10 km of river)	High frequency	FO-DTS	Requires access to both ends of the fiber and specific deployment expertise. More than one cable may be required depending on study area.
Monitor changes in spatial streamflow temperature patterns	Small - medium scales (0-10 km of river)	Low frequency	Drone-based TIR remote sensing combined with temperature loggers	Flight timing needs to be intentionally chosen to capture any changes in temperature patterns resulting from seasonal or climactic changes. Temperature loggers can be helpful for ensuring suitable mixing and for tying spatial and temporal data together.

6. Summary and conclusions

In an era of a rapidly warming climate, habitat restoration in aquatic systems requires an increased focus on maintaining suitable temperature regimes for a range of aquatic organisms. Habitat restoration actions which target water temperature require a good understanding of temperature patterns and dynamics both pre- and post-project implementation. Multiple methods are available to collect temperature data to meet a variety of objectives. This document has provided an overview of existing sources of water temperature data, and a range of methods capable of characterising water temperature across different spatial and temporal scales. We have also organized the methods to help habitat restoration practitioners select data collection methods based on specific restoration objectives.

For most applications in small to medium size streams, temperature data loggers will continue to prove invaluable given their low cost, ease of deployment, and reliability. However, drones mounted with thermal cameras are rapidly becoming a viable option for high-quality data collection . As imagery processing becomes more streamlined, this method holds promise as a go-to approach into the future. A combination of methods is most likely to help restoration practitioners achieve specific objectives.

While we have provided a comparison of methods based on best available information, monitoring choices will be highly dependent on site details and conditions. Methods continue to evolve rapidly: the costs and operational feasibility of certain methods listed here may change, and some approaches, previously impractical to implement at scale, may become viable options in the near future.

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