

# Kenai Mountains to Sea: Using Thermal Infrared Imagery to Implement Long-Term Salmon Conservation

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***Note: This document is best accessed in an interactive web format, and is available at the following URL:***

[https://kenai-watershed-forum.github.io/kenai\\_thermal\\_imagery\\_v2/](https://kenai-watershed-forum.github.io/kenai_thermal_imagery_v2/)

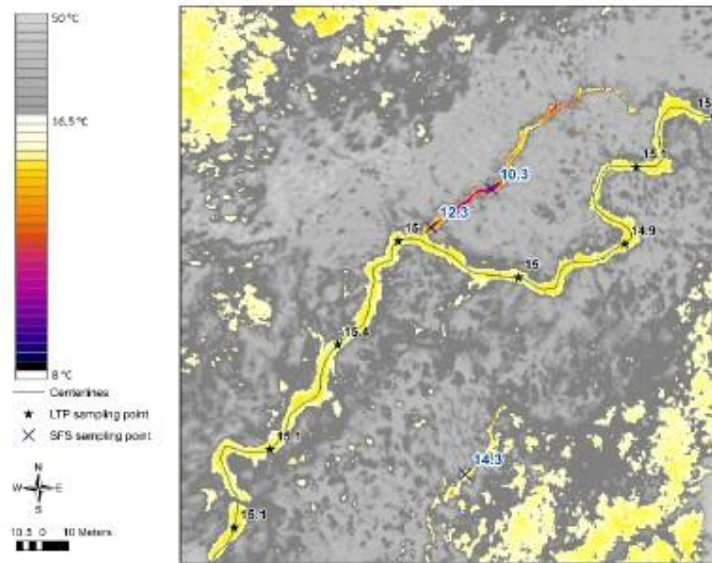
## Acknowledgements

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## Executive Summary



*Example of airborne thermal infrared imagery showing temperature contrast in a stream. A cold water inflow (purple and blue colors) enters the main channel (yellow color). Figure from NV5 Geospatial.*

## From Thermal Infrared Imagery to Conservation Actions

Cold water refugia, or areas within a stream that are persistently colder than surrounding areas, are critical features of wild salmon habitat throughout their range. Stream reaches with cold seeps and springs often result in much cooler water, which are increasingly important for wild salmon to keep cool as water temperatures in many streams have warmed. Some human activities can diminish or extinguish cold water refugia, such as groundwater withdrawal and construction of impervious surfaces. To conserve cold water refugia these sites must first be mapped and identified, and land owners and managers must understand best practices for their conservation.

Since 2020, three community-based organizations - Cook Inletkeeper, Kachemak Heritage Land trust, and Kenai Watershed Forum - have worked together to identify where cold water refugia are found in the Kenai Peninsula lowlands, a region where productive wild salmon habitat intersects with a growing development footprint. We used cutting-edge methods to locate cold water refugia with thermal infrared imagery, a technology similar to night vision goggles that shows heat contrast. Our resulting “treasure map” of cold water refugia locations is a valuable tool for prioritizing conservation and outreach efforts.

In this project we focused our research on tributaries of the Kenai and Kasilof rivers; specifically, in the lower sections of streams outside of the federally-protected Kenai National Wildlife refuge as outlined in the Mountains to Sea planning document (Morton et al. 2015). Our goals for this project were to:

1. Identify land parcels that contain one or more cold water refugia features, and communicate information about these features and possible conservation strategies to land owners; and
2. Use a variety of techniques to communicate our results to over sixty landowners, agencies, and organizations.

Conservation actions that may result from these efforts include parcel acquisition and conservation easements, voluntary compliance, stewardship and restoration projects, and voluntary land agreements or exchanges.

## The Future

Our efforts in applying thermal imagery data for conservation purposes highlights the value of recognizing cold water refugia as an asset for wild salmon habitat (Snyder et al. 2022). The work described here can continue to expand into additional watersheds: there are twenty river corridors of conservation priority described in the Mountains to Sea plan, while we possess aerial thermal infrared imagery on just five (the Anchor river plus the four rivers described in this report) (Mauger, McCarty, et al. 2015).

Beyond gathering additional thermal infrared imagery data , we recommend developing Alaska-specific technical and legal definitions, and applying them towards management needs. Two examples of potential applications follow:

Two examples of potential applications follow:

### *Example: Source Water Protection Areas*

The U.S. Environmental Protection Agency (U.S. EPA) defines “Source Water Protection Areas” for groundwater sources used for drinking water, which delineate geographic areas that contribute to the drinking water supply<sup>1</sup> . Similar logic could apply towards defining the extent of riparian landscape that supplies cold water refugia. Researchers with Kachemak Bay National Estuarine Research Reserve (KBNERR) in Homer, Alaska recently demonstrated that the extent of land that recharges cold water refugia can be delineated by use of a GIS-based model (Gerlach et al. 2021).

As of January 2023 the Kenai Peninsula Borough is in the process of reviewing its permitting process for material extraction sites (i.e. gravel pits). Initial discussions between the Borough and KBNERR have included the possibility of permit reviewers being able to use their maps of subterranean aquifer flow paths to comment on proposed development plans. This cooperation could help ensure that future development minimizes impact on the aquifers that supply cold water refugia, in the same way that defining Source Water Protection Areas help protect drinking water sources.

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<sup>1</sup> <https://www.epa.gov/sourcewaterprotection/delineate-source-water-protection-area>

### *Example: Columbia River Cold Water Refugia*

In an example from the Columbia River in the Pacific Northwest, the U.S. EPA has taken detailed steps to identify, define, and recommend conservation actions for cold water refugia. Here, cold water refugia were defined by quantitative flow volumes and their level of contrast with connected, warmer water bodies<sup>2</sup>. Such efforts could set an example for Alaska to follow in beginning to develop its own technical definitions of cold water refugia.

Existing efforts to technically define cold water refugia have focused on needs of adult upstream migration. However, salmon at all life stages benefit from a mosaic of water temperature environments, such as when juvenile fry migrate between colder and warmer and areas to feed and digest (Armstrong et al. 2013). Thus, it is recommended that future technical definitions also consider the needs of juvenile salmon.

### **Next Steps**

We will continue to use our existing dataset to prioritize land conservation efforts in the Kenai Peninsula lowlands area. Through this project we have surveyed four river corridors of the 20 identified as conservation targets in the Kenai Mountains to Sea Strategic Plan. Specific actions that will support the goals of this project include:

- Identifying where current, future, and retired material extraction sites (i.e. gravel pits) may influence conservation goals in the 20 Mountains to Sea corridors, and supporting efforts to include groundwater considerations in permit reviews.
- Continue to communicate with staff at the Kenai National Wildlife Refuge who initiated an effort in 2022 to gather aerial thermal infrared imagery in local river corridors used by migrating adult Coho salmon<sup>3</sup>. A cost-effective collaboration could result if the Refuge's aerial thermal imagery can be used for the same conservation goals as detailed in this project.
- Continue to communicate with the Alaska Department of Environmental Conservation and other agencies about moving towards formally defined standards for cold water refugia.
- Develop and publish standards for collection and application of thermal imagery in aquatic habitat, similar to published standards for stream temperature monitoring (Mauger, Shaftel, et al. 2015).
- Convert the thermal imagery map files acquired from this project to a format accessible from an online web browser or Google Earth.

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<sup>2</sup> <https://www.epa.gov/columbiariver/columbia-river-cold-water-refuges-plan>

<sup>3</sup> <https://www.peninsulaclarion.com/sports/refuge-notebook-flying-a-remote-sensing-mission-on-the-refuge/>

A two-page project summary titled, “Science Based Land Conservation: Cold Water Stepping Stones” is outlined below in Figure 1. In the online version of this report<sup>4</sup>, download a full size version of the information sheet by clicking on the link below.

The image shows a project summary sheet with a blue header and a white body. The header contains the title "Science-based Land Conservation" and the subtitle "Cold Water Stepping Stones". The left sidebar features logos for Kenai Watershed Forum and Kachemak Heritage Land Trust, along with text explaining why temperature is important for salmon. The main body contains two paragraphs of text and three photographs: a stream with stepping stones, a fishing boat, and a child holding a fish.

**Science-based Land Conservation**

**Cold Water Stepping Stones**

*Why is temperature important?*

Water temperature affects all phases of the salmon lifecycle, including:

- \* timing of migration
- \* survivorship of eggs
- \* respiration
- \* metabolism
- \* availability of O<sub>2</sub>

Warm water temperature induces stress in salmon and makes them more vulnerable to pollution, predation and disease.

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Anticipating the inevitability of climate-related change to freshwater habitats is essential for the management of Alaska’s salmon populations, which contribute substantially to global wild salmon production and are exceedingly important to Alaska’s ecology, economy, and societal health of Tribal communities.

As water temperatures get warmer in many of Alaska’s streams in the years ahead, cold water refugia – areas within a stream which are persistently colder than adjacent areas – will be critical to the survival and persistence of salmon. Deep pools, overhanging vegetation, and undercut banks can be important cold-water habitats; however, stream reaches with groundwater interactions (i.e. springs and seeps) may result in measurably cooler water. Mapping these cold-water stepping stones that are needed for salmon to make their way up and down otherwise warming streams is the first step towards protecting critical salmon habitat in this time of thermal change.

Figure 1: Project Summary Sheet

<sup>4</sup> [https://kenai-watershed-forum.github.io/kenai\\_thermal\\_imagery\\_v2/](https://kenai-watershed-forum.github.io/kenai_thermal_imagery_v2/)



## 1. Introduction

The following chapters contain data and analysis related to the project conducted 2020 - 2022, “Kenai Mountains to Sea: Using Thermal Infrared Imagery to Implement Long-Term Salmon Conservation.” This work is a collaborative effort between three Kenai Peninsula Nonprofits: Cook Inletkeeper, Kachemak Heritage Land Trust, and Kenai Watershed Forum.

This report is generated in [Posit](#) (formerly known as RStudio) using the R programming language (R Core team, 2021.) and [Quarto](#), an open source technical publishing platform. It is best accessed online at the url [https://kenai-watershed-forum.github.io/kenai\\_thermal\\_imagery\\_v2/](https://kenai-watershed-forum.github.io/kenai_thermal_imagery_v2/).

Source code used to generate this report is available in the project’s GitHub repository at [https://github.com/Kenai-Watershed-Forum/kenai\\_thermal\\_imagery\\_v2](https://github.com/Kenai-Watershed-Forum/kenai_thermal_imagery_v2).

## 2. Project Map

Our research focused on four streams in the Kenai Peninsula lowlands region in southcentral Alaska:

- Three tributaries of the lower Kenai River
  - Moose River
  - Beaver Creek
  - Funny River
- One tributary of the lower Kasilof River
  - Crooked Creek

The ArcGIS Online project map may be accessed below or at ArcGIS Online

(Click Here for Map: <https://arcg.is/0vaueq>).

The online map contains layers with the following data:

- Project Watershed Boundaries
- National Hydrography Database (rivers, lakes, streams, etc)
- Anadromous Waters Catalog
  - Streams
  - Lakes
- Kenai Peninsula Borough Parcel Boundaries
- Thermal Imagery Data from NV5 Geospatial report
  - Significant Thermal Features (identified from thermal imagery)
  - Longitudinal Temperature Profiles (main channel temperatures of study streams)
  - Water Temperature Logger Sites

### 3. Thermal Imagery Data

To acquire and prepare thermal aerial infrared imagery, we worked with [NV5 Geospatial](#)<sup>5</sup> (formerly Watershed Sciences, Inc), a contractor who has led prior efforts in the region to gather thermal aerial infrared data for aquatic habitat research (Watershed Sciences 2010). On July 5, 2020, NV5 collected thermal infrared imagery from a helicopter-mounted camera for the four streams on the Kenai Peninsula lowlands that were the focus of this study (Beaver Creek, Funny River, Moose River, and Crooked Creek). All streams were flown during the afternoon hours in order to maximize the thermal contrast between the river's water and the banks.

The surveys extend for a total length of 59.1 km of the streams. Flight transects proceeded from the mouth of each stream in an upstream direction. The data were collected to aid the team in identifying the spatial variability in surface temperatures as well as thermal influence of point sources, tributaries, and surface springs.

Specific deliverables generated by NV5 Geospatial from the thermal imagery data include:

- Rasters (map image files; .tif and .jpg formats)
- Shapefiles (longitudinal temperature profiles, stream centerlines, others; .shp format)
- Other supplemental items (coordinates of significant thermal features, maps and figures, and others)

The full technical report from NV5 Geospatial describes detailed methods and interpretation of aerial thermal infrared imagery. In the online version of this document<sup>6</sup>, the NV5 report can be downloaded at the below.

The image raster files are of a large size (~3 GB) and may be acquired by contacting staff involved with this project:

- Cook Inletkeeper ([sue@inletkeeper.org](mailto:sue@inletkeeper.org))
- Kenai Watershed Forum ([hydrology@kenaiwatershed.org](mailto:hydrology@kenaiwatershed.org))
- Kachemak Heritage Land Trust ([info@kachemaklandtrust.org](mailto:info@kachemaklandtrust.org)).

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<sup>5</sup> <https://www.nv5.com/geospatial/>

<sup>6</sup> [https://kenai-watershed-forum.github.io/kenai\\_thermal\\_imagery\\_v2/](https://kenai-watershed-forum.github.io/kenai_thermal_imagery_v2/)

### 3.1 Parcel data summary

We generated a table in GIS (ArcMap Pro 10.8.1) of parcels in the Kenai Peninsula Borough that intersect with cold-water inputs (e.g. seeps, springs) within the surveyed areas of Beaver Creek, Crooked Creek, Moose River, and Funny River. We identified a total of  $n = 31$  unique parcels containing a total of  $n = 63$  unique cold water refugia features.

Figure 3.1 below summarizes the ownership type of these parcels by general category of owner type.

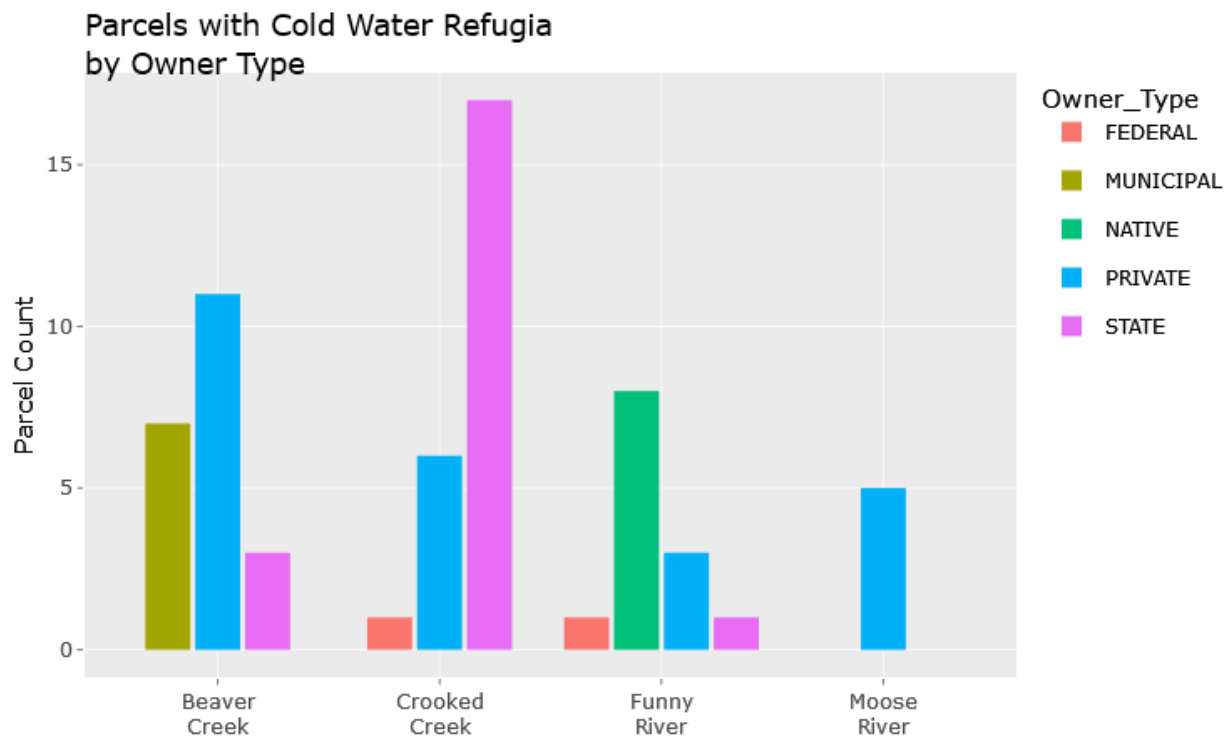


Figure 3.1: Parcel ownership by land owner type for lands containing cold water refugia in our study streams

### 3.2 Ground truth data

On July 7-8, 2021, we visited a subset of sites identified by the NV5 Geospatial report as cold-water features. We visited 12 of 63 total sites. We recorded surface water temperatures of the identified features as well as the adjacent main stem using a Hach Sension 5 portable meter. The average time difference between main stem temperature observation and off-channel observation was 13.9 minutes. We created a graphic sketch of the layout of each feature, and recorded site photos.

In the online version of this document<sup>7</sup>, field forms, including site sketches, can be accessed at the download link below.

In general, we observed symmetry in the pattern of temperature contrast for both our ground-truthed data as well as temperatures observed from the thermal aerial infrared dataset. This indicates that the temperature contrasts identified from the aerial imagery are persistent and not ephemeral.

Figure 3.2 through Figure 3.4 visualize water temperature data sourced from the significant features in aerial imagery on July 20, 2020 along with ground-truthed measurements from July 7-8, 2021.

Note that the temperature data reported from thermal infrared imagery observations consists of multiple statistics, whereas the ground-truth values consist of a single observation. Multiple statistics are reported for the aerial thermal infrared temperature values as a result of the sampling method used, wherein ten surface temperatures within a two-meter radius are evaluated. See the, “Interpretation and Sampling” section in the technical report from NV5 Geospatial, available for download above (NV5 Geospatial 2021).

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<sup>7</sup> [https://kenai-watershed-forum.github.io/kenai\\_thermal\\_imagery\\_v2/](https://kenai-watershed-forum.github.io/kenai_thermal_imagery_v2/)

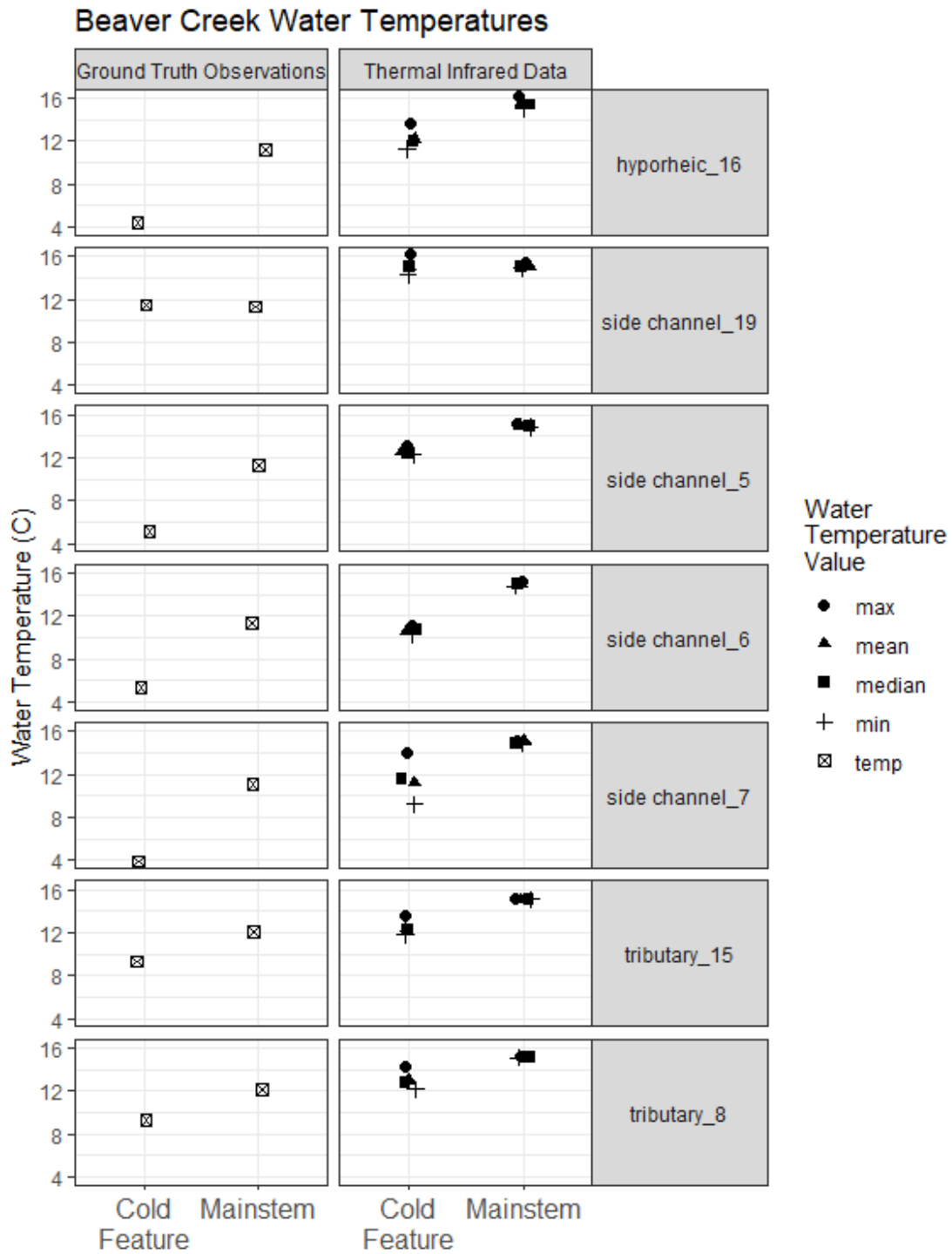


Figure 3.2: Beaver Creek water temperatures, ground truth and thermal infrared imagery observations.

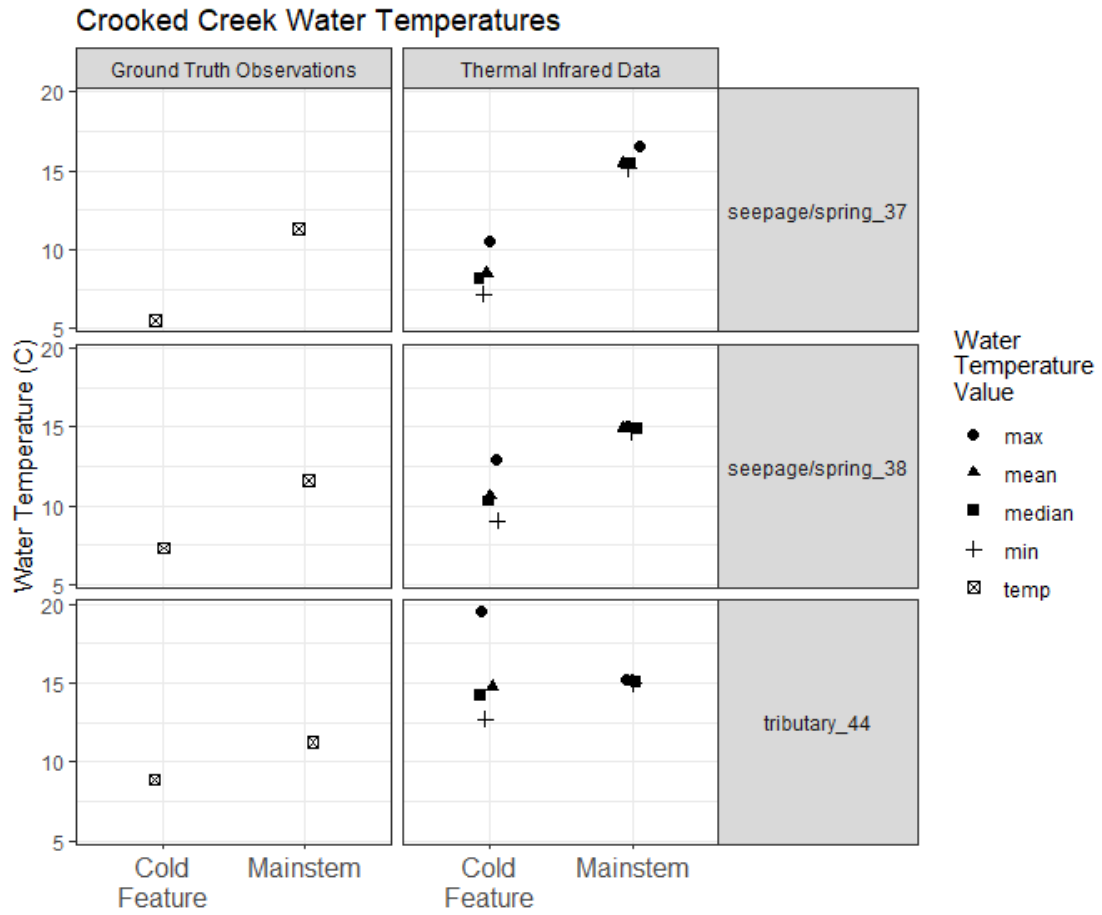


Figure 3.3: Crooked Creek water temperatures, ground truth and thermal infrared imagery observations.

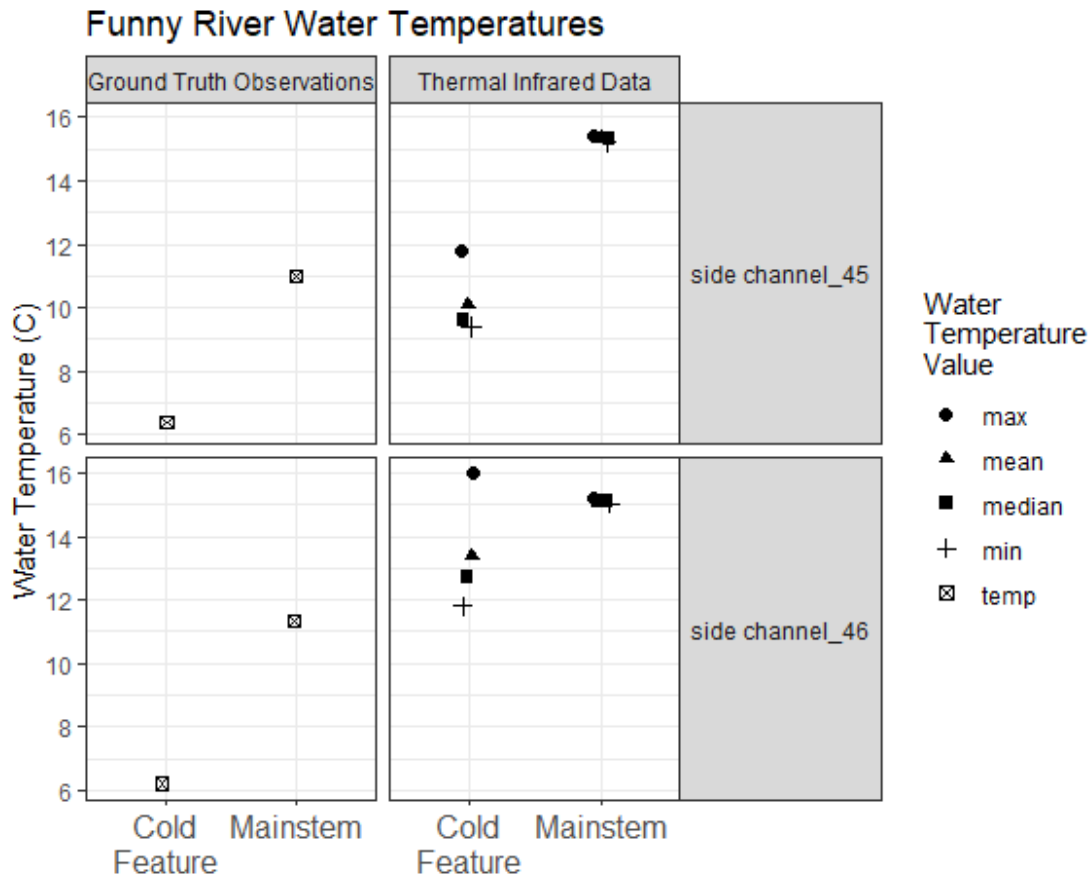


Figure 3.4: Funny River water temperatures, ground truth and thermal infrared imagery observations.

### 3.3 Collaborative Assessment

Researchers with participating organizations assessed conservation strategies within each study watershed and recorded their notes on a shared platform. These collective notes are being used internally to inform strategy for outreach approaches with local property owners.

Data sources used to assess parcel-specific conservation strategies include:

- Custom maps for each significant thermal feature, including information about the parcel or parcels that it occupies
- Information about individual thermal features from the NV5 Geospatial Report, including mean value and contrast with the main stem
- The [ArcGIS Online project map](#)



In the online version of this document, project collaborators may access the Thermal Imagery Database Google Sheet using the link below:

Link: [Thermal Imagery Collaborative Assessment](#)

An example map is shown in Figure 3.5.

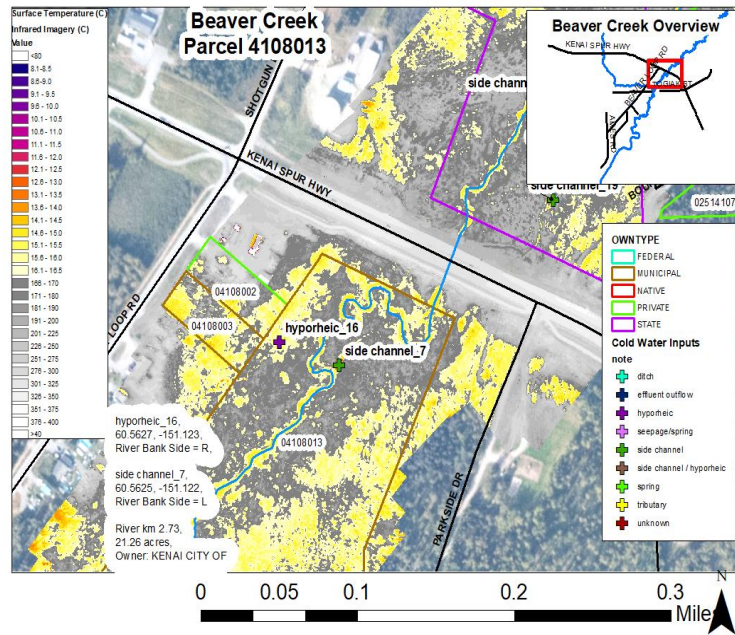


Figure 3.5: Example of airborne thermal infrared imagery map with parcel overlay.

## 4. Water Temperature Loggers

In order to supplement aerial thermal infrared imagery and cold-feature ground truthing data, we deployed water temperature loggers in the lower reach of each study stream to collect continuous time series of water temperature. We used Onset HOBO Temp Pro V2 loggers, deployed and maintained according to published regional standards (Mauger, Shaftel, et al. 2015).

This section describes methods to visualize and perform basic quality checks on continuous temperature loggers deployed in the study streams. All data files (.csv) used in these analyses can be downloaded from this project's [GitHub repository](#).

### 4.1 Locations

See the Project Map (Section 2) section of this report for locations of water temperature logger sites. The ArcGIS Online layer titled, "Water Temperature Logger Sites" displays these locations.

Locations will also be reflected in the Alaska Center for Conservation Science's AKOATS map ([Alaska Online Aquatic Temperature Site](#))<sup>8</sup> in Spring 2023.

### 4.2 Additional Data Preparation

Some water temperature time series downloaded from loggers required additional examination in order to prepare them for submission to AKOATS. See Appendix A, Temperature Logger Data Preparation for additional details.

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<sup>8</sup> <https://accs.uaa.alaska.edu/aquatic-ecology/akoats/>

## 5. Applications

We applied our findings of where cold-water inputs were located towards education and outreach opportunities in the Central Kenai Peninsula region. We used a variety of methods including comments on public land management plans, direct mailers, cooperative planning with peer researchers, and communication with state and federal agency staff.

We applied our findings of where cold-water inputs were located towards education and outreach opportunities in the Central Kenai Peninsula region. We used a variety of methods including comments on public land management plans, direct mailers, cooperative planning with peer researchers, and communication with state and federal agency staff.

We used the thermal features map layer generated from this project as a tool to help generate comments on a the [City of Kenai 2021 Land Management Plan](#), which highlighted a number of parcels in the Beaver Creek corridor, and recommended parcel-specific actions (e.g. retain, sell, re-zone).

We created a separate map showing parcels highlighted in the plan, with management status available in a point and click format. The parcels were superimposed on a several layers highlighting ecological values such as wetlands and anadromous streams, as well as the thermal features identified in this project. Methods are described in a separate stand-alone document at <https://rpubs.com/kwf/867931>.

Access the City of Kenai Land Management Plan Comments Map here:  
<https://arcg.is/10q9Kq>.

In the online version of this document, access PDFs of submitted Public Comments at the download link below.

### 5.1 Landowner Outreach

#### 5.1.1 Letters

We composed a letter addressed to private landowners whose property contains cold-water features that flow into one of our study streams. This letter describes the nature of the project and the value of cold-water features to salmon habitat. Landowners are invited to contact the researchers if they would like more information about their specific property.

In the online version of this document<sup>9</sup>, access the letter to landowners with the download link below.

#### 5.1.2 Postcard

We designed and mailed a postcard to landowners whose property contains cold-water features that flow into one of our study streams. The postcard notifies landowners that

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<sup>9</sup> [https://kenai-watershed-forum.github.io/kenai\\_thermal\\_imagery\\_v2/](https://kenai-watershed-forum.github.io/kenai_thermal_imagery_v2/)

their specific parcels are of high conservation value, and encourages them contact project scientists to learn more about best practices.

In the online version of this document<sup>10</sup>, access the postcard to landowners with the download link below.

### 5.1.3 Communication with local State and Federal Agency Staff

We met with state and federal agency staff to discuss the nature of our research and its applications to discuss use of this data.

- In conversations with staff from the Alaska Department of Environmental Conservation (ADEC), we learned more about the process by which new research such as ours may be applied in the future. Emerging research on how water quality issues may affect freshwater fish habitat is typically first evaluated by the Alaska Department of Fish and Game (ADF&G) before being evaluated in a regulatory context such as ADEC. With that in mind, our final reports will be made available to ADF&G staff..
- On June 1, 2022 we met with staff of the Kenai National Wildlife Refuge to discuss the nature of thermal infrared imagery gathered in summer 2022 for a separate U.S. FWS project related to adult Coho salmon movement. These data are currently being evaluated, and it is our hope that they may later also be applicable for the purposes of identify cold water refugia in the conservation priority corridors identified in the Mountains to Sea report (Morton et al. 2015)

### 5.1.4 Local interest in Conservation Easement

We also communicated with the Snowshoe Gun Club, one of the larger private landowners in the lower Beaver Creek corridor. The Club's ground footprint currently is set back several hundred yards from adjacent riparian zones and can be considered compatible with fish habitat management.

The Club has expressed interest in placing a conservation easement on part of their current land holdings, and an adjacent parcel also set on Beaver Creek they hope to acquire that is currently in private ownership. We provided a custom map to highlight cold water refugia features on these parcels, available for download below [Figure 5.1](#). Discussions will continue with the Club to determine interest in moving forward with a potential conservation easement.

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<sup>10</sup> [https://kenai-watershed-forum.github.io/kenai\\_thermal\\_imagery\\_v2/](https://kenai-watershed-forum.github.io/kenai_thermal_imagery_v2/)

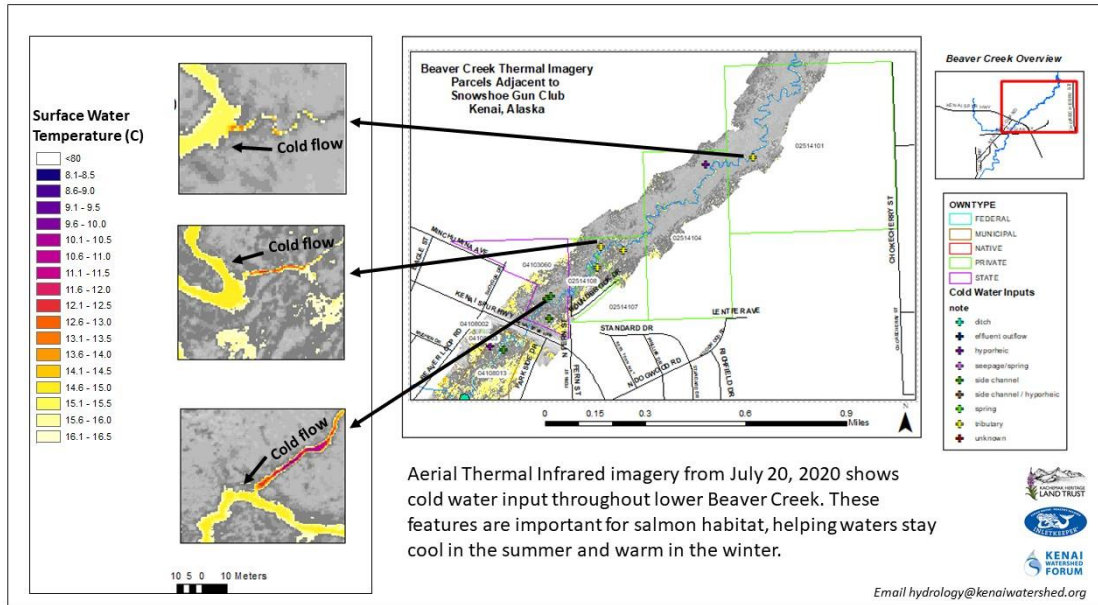


Figure 5.1: Cold water refugia site highlights near Snowshoe Gun Club

## 6. Summary

The following are general observations regarding conservation potential for each of the stream corridors in this study. The stream distance and property ownership information cited is from (Morton et al. 2015). For more details on land ownership and watershed-specific conservation opportunities, see the Mountains to Sea report.

### 6.1 General Recommendations by Stream Corridor

#### 6.1.1 Beaver Creek

Beaver Creek runs a total of 21.8 river miles before meeting the Kenai River, with 4.0 of those miles in the lower section outside the Kenai National Wildlife Refuge. Land ownership in the lower Beaver Creek corridor can be described as very parcelized, with the majority of parcels directly adjacent to the creek in private ownership (20 of 28), most of them accessible via Beaver Loop Road. We found 21 of these parcels contained cold water refugia features (Figure 3.1).

In the context of near-term potential conservation opportunities, several categories are highlighted. Several parcels belonging to the City of Kenai are recommended in the 2021 Land Management Plan for rezoning to recognize their conservation value. Our submitted comments support this goal. Additionally, the 160-acre parcel that Snowshoe Gun Club is considering for conservation easement status also stands out. We intend to continue the dialogue with the Club to ensure that the opportunity for potential easement status can be easily accessed when they choose to proceed.

### 6.1.2 Funny River

Funny River runs a total of 67 river miles before meeting the Kenai River, with 4.5 of those miles in the lower section outside the Kenai National Wildlife Refuge. The lower Funny River riparian corridor can be described as primarily under ownership of private individuals, the Alaska Department of Natural Resources (ADNR), and the regional native corporation Cook Inlet Regional Incorporated (CIRI).

In the context of near-term potential for conservation opportunities, several categories are highlighted. An ADNR parcel that parallels Funny River Road contains a significant cold-water feature that we visited on foot to ground truth. Future road improvement projects would ideally be cognizant of such features and take efforts to minimize impact from impervious surfaces.

An additional parcel owned by CIRI approximately 4 miles upstream contains a cluster of six cold-water features. This parcel also contains tributaries not currently documented as anadromous but very likely are. We intend to communicate the conservation values of this parcel to CIRI so that they may be best informed for future land management decisions.

### 6.1.3 Moose River

Moose River runs a total of 137 river miles before meeting the Kenai River, with 2.2 of those miles in the lower section outside the Kenai National Wildlife Refuge.

We identified a minimal number of cool-water refugia features in the lower Moose River. All of these features lie on privately owned parcels. In our efforts to contact Moose River landowners to share educational materials we failed to receive responses.

We intend to continue seeking opportunities to communicate with Moose River landowners. Future community opportunities and events will likely present new opportunities to share our findings with specific landowners.

### 6.1.4 Crooked Creek

Crooked Creek runs a total of 45.9 river miles before meeting the Kasilof River, with 16.8 of those miles in the lower section outside the Kenai National Wildlife Refuge. In the context of near-term potential for conservation opportunities, several categories are highlighted. The majority of cold-water features (17/25) lie on state-owned land, and are generally clustered together in close groups.

An ADNR parcel that parallels the Sterling Highway and adjacent subdivisions contains several significant cold water features that we visited on foot to ground truth. Future road and home improvement projects would ideally be cognizant of such features and take efforts to minimize impact from impervious surfaces. We recommend a follow-up meeting with ADNR officials to highlight these results.

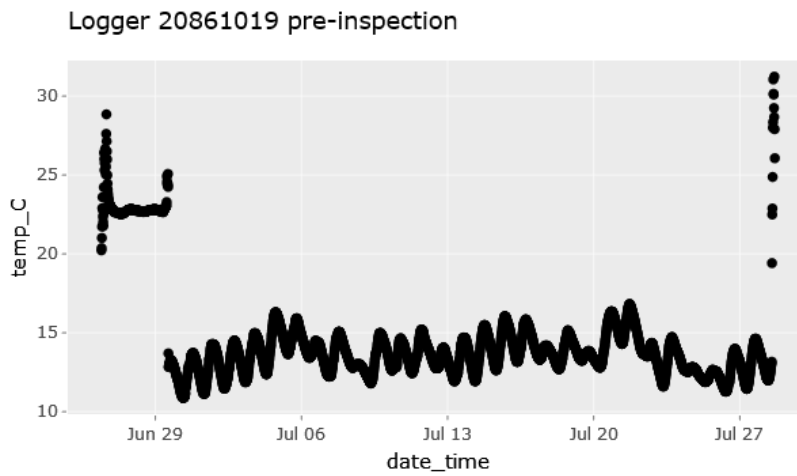
## References

- Armstrong, Jonathan B., Daniel E. Schindler, Casey P. Ruff, Gabriel T. Brooks, Kale E. Bentley, and Christian E. Torgersen. 2013. "Diel Horizontal Migration in Streams: Juvenile Fish Exploit Spatial Heterogeneity in Thermal and Trophic Resources." *Ecology* 94 (9): 2066–75. <https://doi.org/10.1890/12-1200.1>.
- Gerlach, Mary E., Kai C. Rains, Edgar J. Guerrón-Orejuela, William J. Kleindl, Joni Downs, Shawn M. Landry, and Mark C. Rains. 2021. "Using Remote Sensing and Machine Learning to Locate Groundwater Discharge to Salmon-Bearing Streams." *Remote Sensing* 14 (1): 63. <https://doi.org/10.3390/rs14010063>.
- Mauger, Sue, Marie McCarty, Mandy Bernard, and Branden Bornemann. 2015. "Science-Based Land Conservation: Conservation Strategies to Protect Key Salmon Habitat in Lower Kenai Peninsula Watersheds." <https://inletkeeper.org/wp-content/uploads/2017/10/Science-based-Land-Conservation-report.pdf>.
- Mauger, Sue, Rebecca Shaftel, E. Jamie Trammell, Marcus Geist, and Dan Bogan. 2015. "Stream Temperature Data Collection Standards for Alaska: Minimum Standards to Generate Data Useful for Regional-Scale Analyses." *Journal of Hydrology: Regional Studies* 4 (September): 431–38. <https://doi.org/10.1016/j.ejrh.2015.07.008>.
- Morton, J M, D R Magness, M McCarty, D Wigglesworth, R Ruffner, M Bernard, N Walker, et al. 2015. "Kenai Mountains to Sea: A Land Conservation Strategy to Sustain Our Way of Life on the Kenai Peninsula." [https://kenaiwatershed.org/wp-content/uploads/2019/03/Kenai-Mountains-to-Sea-Strategic-Plan\\_5nov2016\\_compressed.pdf](https://kenaiwatershed.org/wp-content/uploads/2019/03/Kenai-Mountains-to-Sea-Strategic-Plan_5nov2016_compressed.pdf).
- NV5 Geospatial. 2021. "Kenai Rivers - Thermal Infrared Airborne Imagery Technical Data Report." Homer, Alaska.
- R Core team. 2021. *A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>.
- Snyder, Marcía N., Nathan H. Schumaker, Jason B. Dunham, Joseph L. Ebersole, Matthew L. Keefer, Jonathan Halama, Randy L. Comeleo, et al. 2022. "Tough Places and Safe Spaces: Can Refuges Save Salmon from a Warming Climate?" *Ecosphere* 13 (11). <https://doi.org/10.1002/ecs2.4265>.
- Watershed Sciences. 2010. "Airborne Thermal Infrared Remote Sensing: Anchor River Basin, Alaska." Homer, Alaska. <https://inletkeeper.org/wp-content/uploads/2017/10/Airborne-Thermal-Infrared-Remote-Sensing-Anchor-River-Basin-Alaska.pdf>.

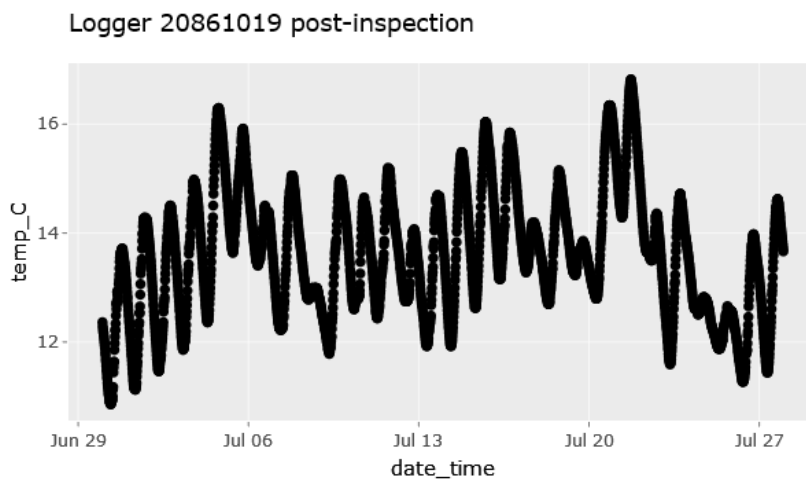
## Appendix A — Temperature Logger Data Preparation

### A.1 Water Temperature Logger Data QA/QC

Water temperature data retrieved from the field was subjected to a basic quality assurance process before being incorporated into the analysis dataset. We visually inspected each water temperature time series and excluded data indicative of pre/post deployment or exposure. [Figure A.1](#) and [Figure A.2](#) provide a visual example of water temperature time series prior to and post quality assurance processes.



*Figure A.1: Example of water temperature time series prior to quality assurance process*



*Figure A.2: Example of water temperature time series after quality assurance inspection*



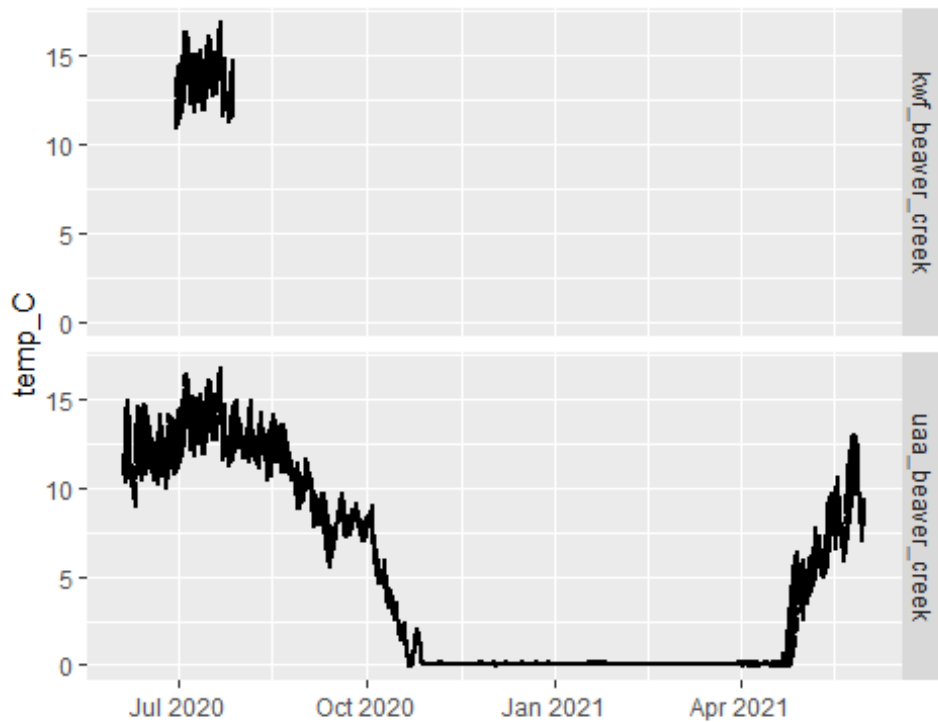
### A.1.1 Additional data preparation

The following sections describe additional details on data preparation specific to each water temperature logger site.

#### A.1.1.1 Beaver Creek

Loggers at the Beaver Creek logger site were deployed in early summer 2020. As part of a separate research project, Alaska Center for Conservation Science (University of Alaska Anchorage) established a logger site several hundred meters upstream also in Summer 2020.

We examined if data from the two sites are similar enough to use as a proxy for each other when data observations are missing. Time series from both sites are shown in figure [Figure A.3](#), and simultaneous values from both sites are presented in figure [Figure A.4](#).



*Figure A.3: Water temperature time series from Lower Beaver Creek at two nearby sites.*

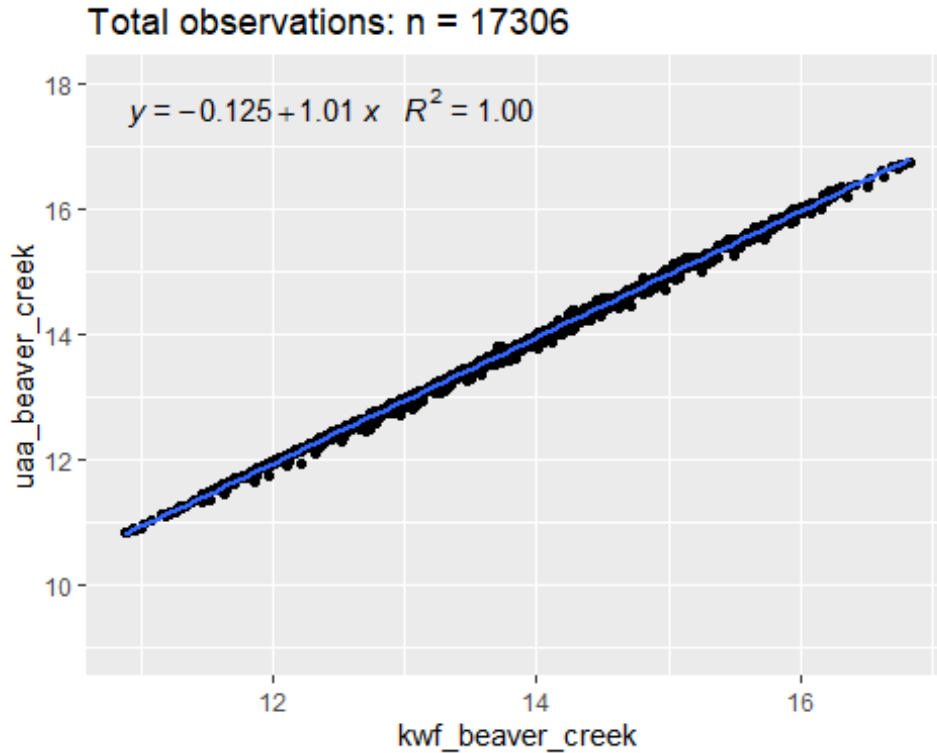


Figure A.4: Regression of simultaneous water temperature observations from two nearby sites in Beaver Creek.

The average absolute difference in temperature between the two logger sites in Beaver Creek is  $0.06 \pm 0.05$  C (mean  $\pm$  sd). For most applications, a substitution of data from either of these sites in Lower Beaver Creek will still accurately represent water temperature.

#### A.1.1.2 Lower Crooked Creek

Lower Crooked Creek has two adjacent water temperature monitoring locations within 20 m of each other. Further details on these two sites are described below, and figure @fig-cc-map shows locations of the two sites.



Figure A.5: Lower Crooked Creek temperature monitoring sites

#### A.1.1.2.1 Lower Crooked Creek Real-time temperature monitoring site

Cook Inletkeeper maintains a site installed by Beaded Stream (Anchorage, AK) that records air and water temperature data in real-time and streams these data live at <https://inletkeeper.org/our-work/healthy-habitat/real-time-temperature-sites/crooked-creek/>. Water and air temperature data has been recorded and streamed from this site at hourly intervals since summer 2017.

Temperature data from this location can be downloaded as a csv file directly from the above Inletkeeper web link. However, **as of 2023-01-23 there is an error with the publicly available csv file**. The publicly available csv file has incorrect time stamps after 12/31/2019. Beaded Stream staff is aware of the error, and says the remedy will require an in-person visit to the field. In the meantime, [contact Beaded Stream staff](#) to request access to most current data.

The data with correct time stamps from 2017-08-15 though 2021-10-26, obtained directly from the internal Beaded Stream dashboard, is also available for download at this link from GitHub: [Download Lower Crooked Creek Realtime Temperature Data](#).

#### A.1.1.2.2 Lower Crooked Creek HOBO TempPro V2 logger site

A pair of HOBO Temp Pro V2 loggers are installed at a location 20 m upstream from the real-time temperature logger site. Water temperature is recorded at 15-minute intervals.

During a site visit on 7/28/2021, we discovered that this pair of loggers potentially resided within a small, previously unidentified cold water plume incoming from the river-left bank. (On the ArcGIS Online project map, this feature is identified as “tributary\_44.” It was unclear if the local cold water seep was influencing the loggers in way such that they would not represent main channel temperature.

In order to determine if HOBO logger data prior to 7/28/2021 is influenced by the cold seep, we performed the following steps:

1. *Relocated loggers.* On 7/28/2021, we modified logger deployment such that one logger was directly upstream of the cold water seep, and one remained in its original location within the seep.
2. *Compared temperature data upstream vs. downstream of the seep.* We observed consistently cooler temperatures in the downstream logger, with an average absolute difference of  $1.47 \pm 0.30$  °C (mean  $\pm$  sd). Figure @fig-cc-plots displays time series from both loggers as well as the difference values where simultaneous data from both locations exists.

From these data we observe that the small cold water tributary consistently affected main stem temperature where the loggers recorded temperature. Temperature contrast was much less apparent in cooler months, after approximately September 1st, 2021. Thus, the data from these HOBO loggers prior to 7/28/2021 in the location downstream of the small cold water tributary should not be considered representative of main channel Crook Creek temperatures.

We reviewed all paper field forms from the lower Crooked Creek site from 2015 - present ([link here](#)) to determine the time extent that HOBO loggers may have been influenced by the cold water tributary. These notes suggest that the period extended from from 5/31/2019 - 7/28/2021. Prior to 5/31/2019 there is not evidence on file that can confirm whether or not the loggers were deployed within the cold water plume.

One possible explanation for why technicians failed to observe the cold water seep when they installed the HOBO loggers in Summer 2019 is that high discharge level in the Crooked Creek main channel temporarily masked the localized effect of cold water input. These results highlight the value of regular site visits to re-verify that the site is well-mixed, or checking temperatures beyond the minimum of five observations across a transect.

Additionally, these results exemplify the role of cold water inputs in maintaining thermal refugia for salmonids in watersheds such as Crooked Creek. Note in figure [Figure A.6](#) that water temperature within the cold water plume in the main channel was often 1.5 °C cooler than the non-influenced location. Temperature differentials of this nature help allow salmonids to access a diverse portfolio of thermal environments important to functions throughout their life cycle such as migration, metabolism, and foraging.

### Lower Crooked Creek Hobo Loggers and Difference Values Fall 2021

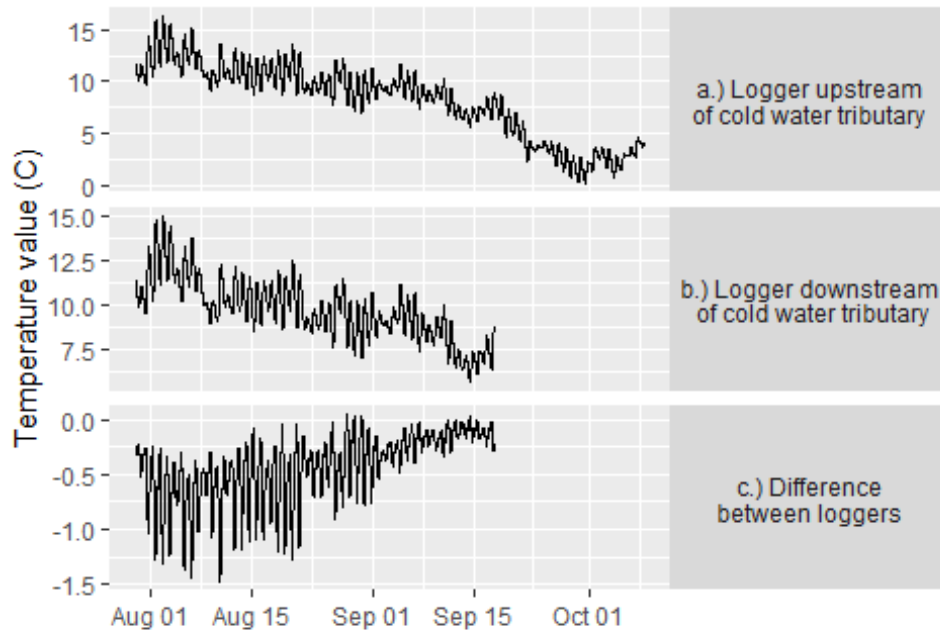


Figure A.6: Water temperature time series from Lower Crooked Creek at two nearby loggers (~3 m apart). a.) Upstream of a small coldwater tributary, b.) downstream of small coldwater tributary, c.) difference values between the loggers. Note different y-axis ranges.

### A.1.2 Extent of water temperature time series

Figure A.7 displays temporal extent of currently available water temperature at each site.

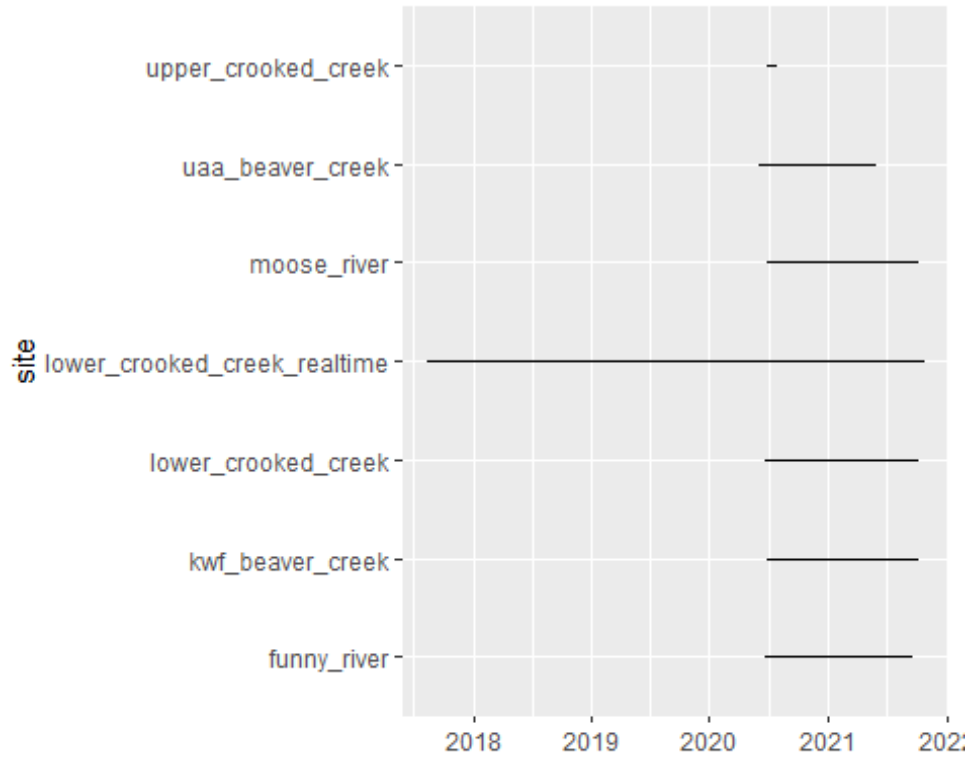


Figure A.7: Temporal extent of water temperature logger data