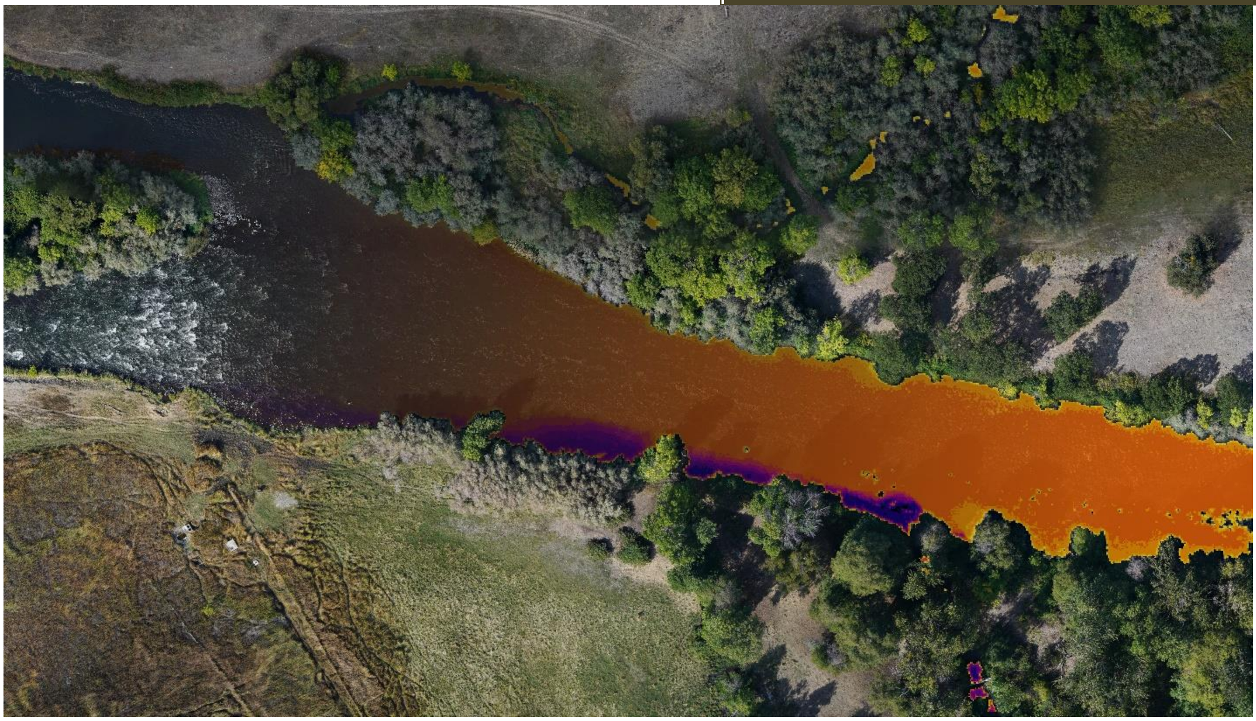
Survey: Sep 22, 2021
Report: July 21, 2022



Upper Klamath River - Thermal Infrared Airborne Imagery - Technical Data Report

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Prepared for

PacifiCorp

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Cover Photo: Shovel Creek's confluence with Klamath River showing the mixing zone along the left bank (River is flowing right to left). Thermal infrared overdyed on top of true color imagery. The true color imagery was co-acquired with the thermal infrared imagery.

This project was funded by PacifiCorp through a contract between E&S Environmental and PacifiCorp.

Thermal infrared imagery was processed, analyzed, and reported by:
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Chris Miwa - Certified Photogrammetrist

INTRODUCTION

E&S Environmental contracted NV5 Geospatial Solutions to collect thermal infrared (TIR) imagery data during the summer of 2021 for the upper section of the Klamath River covering a total river length of 36 km. The survey area covered the river section between John C. Boyle Reservoir (JCB), OR and Copco Reservoir, CA (Figure 1). Smoke conditions persisted throughout the project area during the second half of August preventing NV5's crew from being able to acquire the data. The airborne data acquisition campaign was successful on the second attempt on September 22, 2021. Prior to the TIR data collection, the staff of E&S Environmental deployed four data loggers along the survey area to record water temperature during the TIR acquisition time frame. A complete set of water temperature records were shared with NV5 Geospatial Solutions' staff on September 29, 2021, which was used in calibrating the TIR imagery.

This report accompanies the delivered TIR data and support files, and documents the contract specifications, data acquisition procedures, processing methods, and analysis of the final datasets. TIR acquisition dates and times are shown in Table 1, a complete list of contracted deliverables provided is shown in Table 2, and the project extent is shown in Figure 1.

Table 1: TIR acquisition dates and stream reaches collected on the Upper Klamath River

River Survey Description	Survey Date	Time Frame (PDT)	River Section
Upper Klamath River	September 22, 2021	14:10 – 15:40	JCB Dam to Copco Reservoir (0 – 36 km)

Deliverable Products

Table 2: Delivered products

Upper Klamath River TIR 2021 Products Projection: UTM Zone 10 North Horizontal Datum: NAD83 (2011) Vertical Datum: NAVD88 (GEOID12B) Units: Meters, Celsius	
Rasters	Thermal Infrared Imagery (*.tif): • Calibrated, rectified images (cell values = Celsius x 10) • Calibrated imagery mosaics (cell values = Celsius x 10)
Vectors	Shapefiles (*.shp) • Stream centerlines • Accuracy checks • TIR image center points and sensor exterior orientation (EO) • Longitudinal temperature profile (LTP) • Significant thermal features (STF)
Supplemental	• “xlsx” folder contains longitudinal temperature profiles (LTP) and significant thermal features (STF) in MS Excel format (*.xlsx) • “Color ramps” folder contains customized layer files (*.lyr) for visualization in ArcMap • “Maps and Figures” folder contains maps and figures used for the report (*.png)

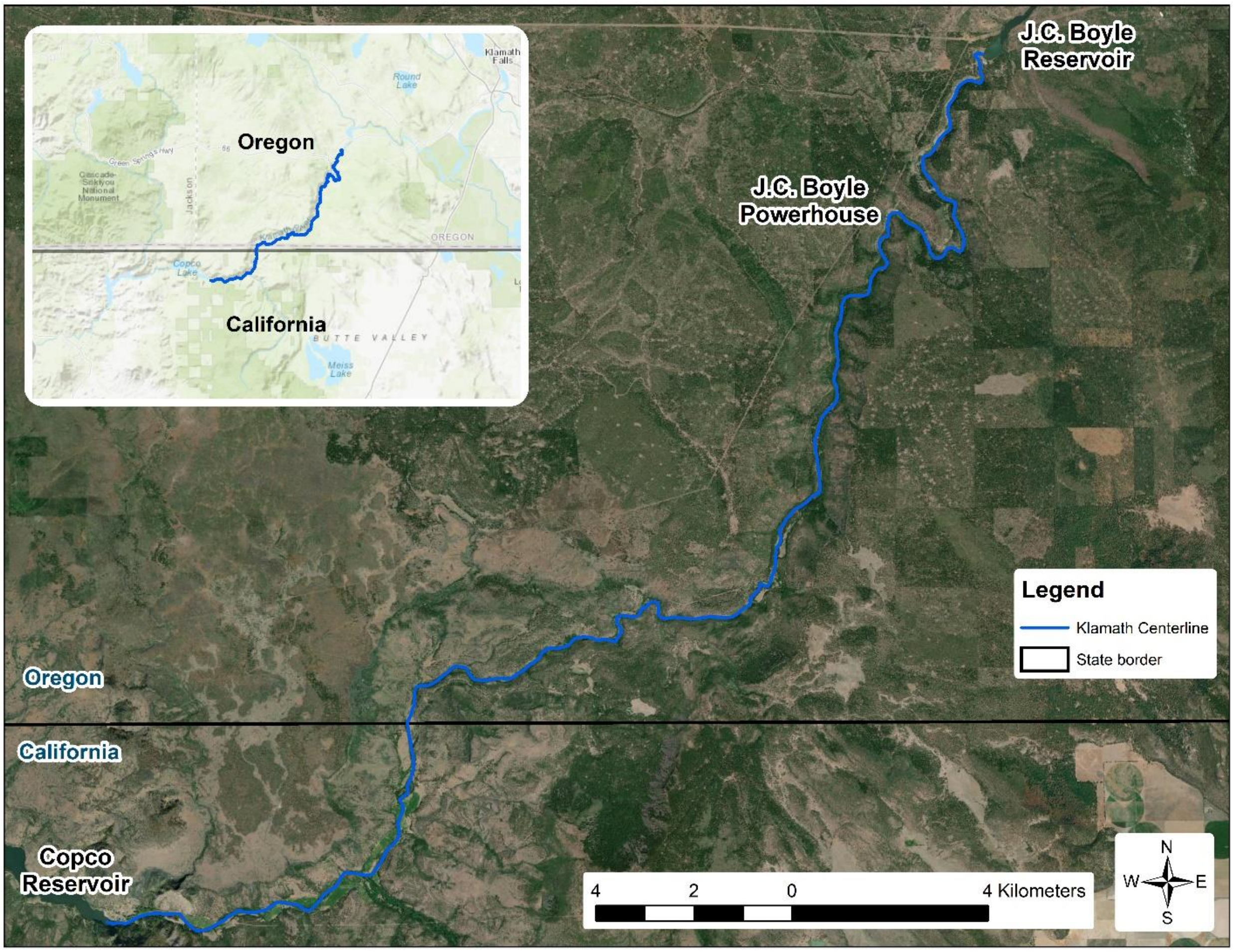

Figure 1: Map of the Upper Klamath River thermal infrared survey area. A total 46 km river section between J.C. Boyle Reservoir, OR and Copco Reservoir, CA.

Thermal Infrared Imagery Acquisition Planning and Execution

Flow Conditions

Halting the operation of the J.C. Boyle Powerhouse was a crucial condition for the success of this project. Therefore, the J.C. Boyle Powerhouse was not operated on the day of the TIR acquisition and the flow downstream of J.C. Boyle Reservoir was mostly provided by the spill from J.C. Boyle Dam. Discharge records at the USGS station (#11510700), which is located downstream of the J.C. Boyle Powerhouse, were approximately 560 cfs (Figure 2).

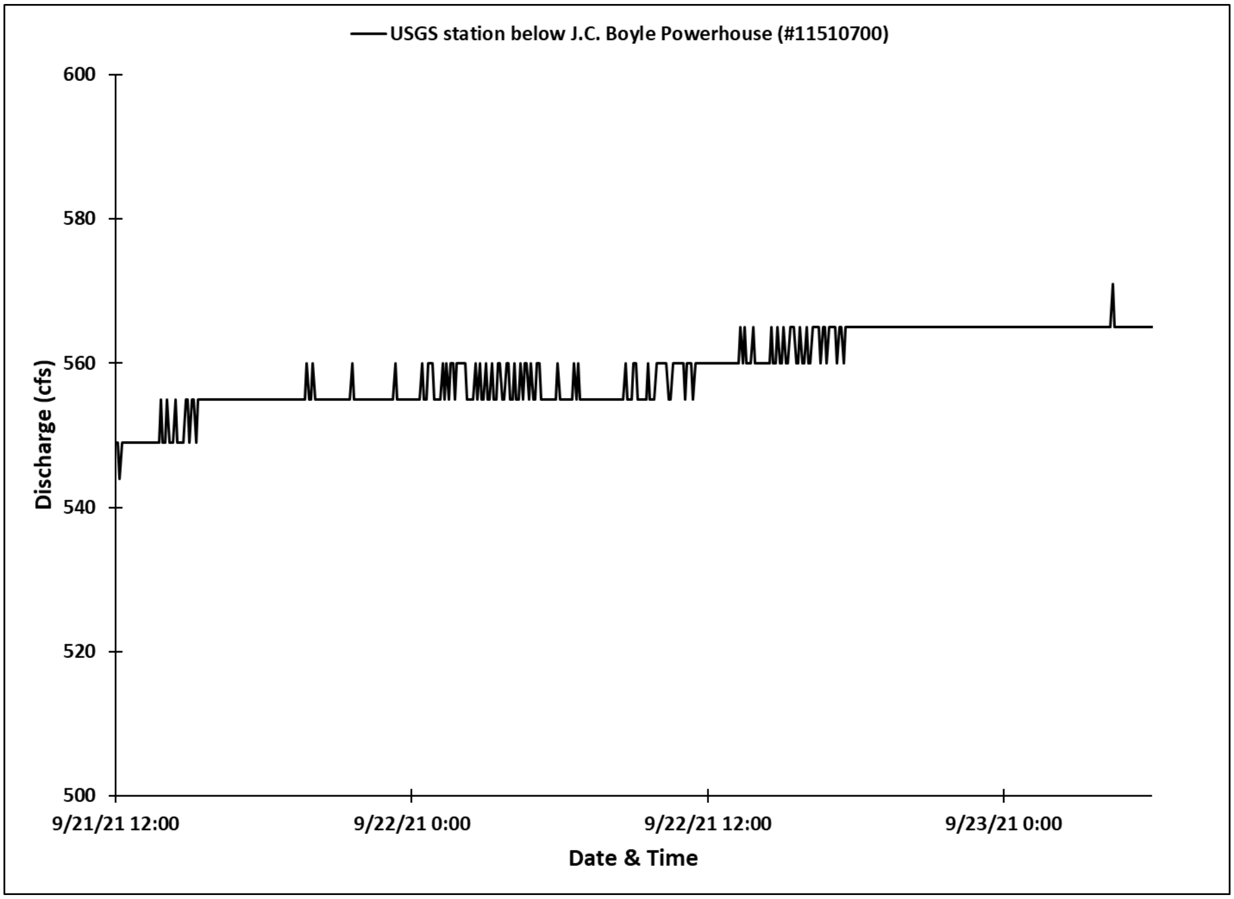

Figure 2: Discharge at USGS station below J.C. Boyle powerhouse (11510700).

Data Acquisition

In preparation for data collection, NV5's team reviewed the project area and developed a specialized flight plan to ensure complete coverage of the Upper Klamath River study area. The Upper Klamath River project data were successfully acquired on September 22, 2021 in one aircraft lift flown between 14:10 – 15:40 PDT, covering a total river length of 36 km (Table 1). This time window ensured optimal conditions to maximize the thermal contrast between the river water and the banks. The timing targeted clear skies, which ensured high solar loading of the riverbanks, and the highest air temperatures possible for the season. The closest weather station was located in Klamath Falls, OR which recorded air temperatures 9.9 – 23.7 °C on September 22. Air temperature during the TIR imagery acquisition was 22.7 – 23.7 °C. Solar radiation loading reached 770 W/m^2 prior to the imagery acquisition and averaged 560 W/m^2 throughout the time window of the imagery acquisition.

The aircraft was flown over the river where the active channel occupies the center of the frame. Multiple flight lines were needed along sections where the channel was wider than the image frame (Figure 3) or significant side channels were identified. The flight plan was designed using a helicopter aircraft to achieve a ground sampling distance of 0.5 meter (m) at an altitude of 400 meters above ground level (AGL). Fortunately, the aircraft crew was able to fly at a lower AGL which supported a final mosaic at 0.3 m resolution and exceeded the planned resolution.

Thermal Infrared Sensor: FLIR SC6000

Thermal infrared images were collected using a FLIR SC6000 LWIR sensor (8 – 9.2 μm) mounted to a Bell 206 Long Ranger helicopter. The sensor was installed in an enclosed fiberglass capsule mounted at the bottom of the helicopter with a designated opening for the down-facing lens (Figure 4). The FLIR SC6000 sensor uses a focal plane array of detectors to sample incoming radiation based on the technology of Quantum Well Infrared Photodetector (QWIP). The sensor's array records the change of state of electrons in a crystal structure reacting to incident photons. This technology is faster and more sensitive than polymer thermal detectors. A cooling mechanism is required for this sensor to stabilize its internal temperature and minimize thermal drift during acquisition. To achieve uniformity across the detector array, a factory scheme is generated to reduce non-uniformity across the image frame. Differences in temperature (typically <0.5 °C) might be observed near the edge of the image frame. Flight planning ensures sufficient image overlap so that frame edges can be excluded from the river channel in the TIR image mosaics. The resulting thermal infrared image frames were recorded directly from the sensor to an on-board computer as raw photon counts which were then converted to radiant temperatures. Sensor and acquisition specifications for the Upper Klamath River TIR study are listed in Table 3.

Figure 3: An example of multiple flight lines (644, 646, and 654) along the Klamath River between river km 7.6 and 8.6.

The positional coordinates of the aircraft (geographic coordinates: latitude, longitude, and altitude) and the orientation (pitch, yaw, roll) were recorded continuously throughout the data collection mission. The geographical coordinates of the aircraft were measured twice per second (2 Hz) by an onboard differential global navigation satellite system (GNSS), while aircraft attitude was measured 200 times per second (200 Hz) by an onboard inertial measurement unit (IMU). Airborne global positioning system (GPS) data were post-processed into a smoothed best estimate of trajectory (SBET) using Applanix PP-RTX data for corrections. To ensure sufficient image overlap and ground sampling distance (GSD), TIR images were acquired at 1 image per second (1 Hz), flight speed was 50 knots on average, and flying altitude targeted 400 meters above ground level (AGL). Images were indexed by GPS time (event time) and paired with the SBET to resolve the exterior orientation of the sensor for each image event.

Table 3: Summary of TIR sensor and acquisition specifications

FLIR System SC6000 (LWIR)	
Wavelength:	8 – 9.2 μm
Noise Equivalent Temperature Differences (NETD):	0.035 °C
Pixel Array:	640 (H) x 512 (V)
Encoding Level:	14 bit
Horizontal Field-of-View:	35.5°
Sensor Focal Length	25 mm
Acquisition Dates:	September 22, 2021
Planned Flying Height Above Ground Level (AGL):	400 meters
Image Ground Footprint Width:	300 – 500 meters
Ground Sampling Distance (GSD)	≤ 0.3 meter

Figure 4: Sensor installation setup.

Ground Control

To calibrate thermal infrared imagery to absolute temperatures, in stream water temperature and atmospheric data are required.

In-Stream Water Temperature Sensors

Water temperature recorded by in-stream temperature sensors are used to radiometrically calibrate the thermal signature of the imagery. A total of four stream temperature data loggers were deployed in the survey area by a field crew from E&S Environmental (Figure 5). The data loggers recorded water temperature at five-minute intervals. The loggers used for this project are HOBO Water Temperature Pro V2 ONSET U22-001[1].

The field crew of E&S Environmental adhered to the following list of guidelines for deploying the data loggers:

1) In well mixed, flowing waters section of the river or stream and not in pools or riffles sections.
2) In a water column deeper than 0.5 meter and shallower than 2 meters to allow for fully submerged data loggers and avoid a stratified water column.
3) Within the channel's thalweg to measure a larger bulk of flowing water in the stream.
4) In a water body with a sufficiently exposed surface to the sky that can be detected by the sensor mounted to the aircraft.
5) Away from the bank where riparian vegetation may block the view from the aircraft.
6) In water stream reaches free from above-water surface features such as boulder and riparian and aquatic vegetation to allow for uniform water temperatures across the stream or the water body.
7) Avoid deploying the sensor in shallow waters where it can be exposed to direct sun light. Sensors under direct sun light heat up and skew the recorded temperature.

Atmospheric Parameters

Radiometric calibration of the TIR imagery requires atmospheric data collected by local weather stations. Records of atmospheric parameters, namely air temperature and relative humidity, were extracted from the closest weather station (Ramon – KORKLAMA97 Klamath Falls, OR) for the time frame of the flight.

[1] https://www.onsetcomp.com/products/data-loggers/u22-001

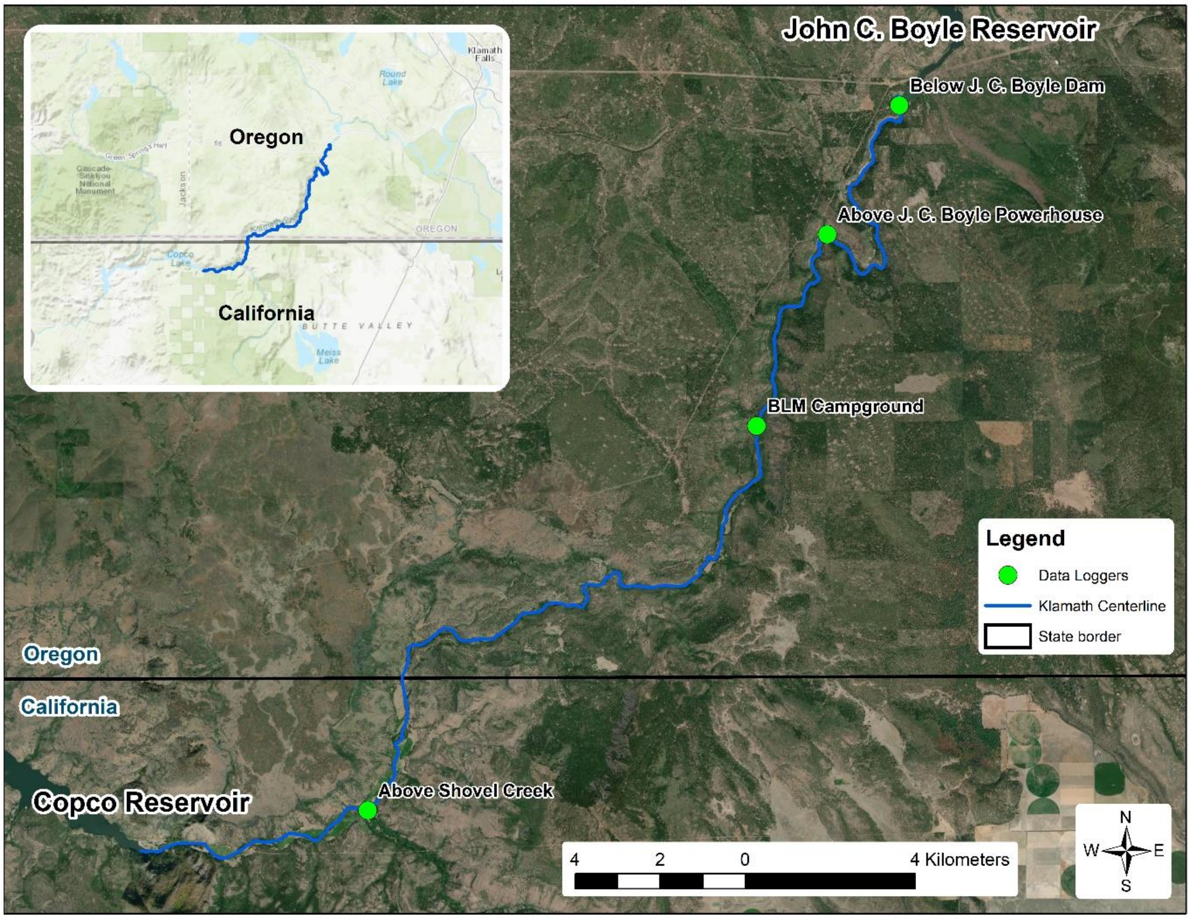

Figure 5: Map of survey area and location of water temperature data loggers that were deployed by the field crew of E&S Environmental.

Thermal Infrared Data Processing

Thermal Infrared Imagery Calibration

The process of TIR calibration connects the thermal radiation recorded by the FLIR sensor and the kinetic temperature of the targeted object. Response curves of the TIR sensor were measured in a laboratory environment as part of the periodic maintenance procedure stated by the sensor's manufacturer. In laboratory environment, the sensor records thermal infrared radiation emitted by a black body as digital numbers which were used to generate the response curves. All objects have physical parameters of emitting, reflecting, and transmitting radiation with varying values as the following equation shows:

$$emissivity + reflectivity + transmisivity = 1$$

In theory, a black body has an emissivity (e) value of 1.0, and reflectivity (r) and transmissivity (t) values of 0.0. However, the TIR calibration is based on the recorded temperature of water which has emissivity value of 0.98[2], reflectivity value of 0.02, and transmissivity value of 0.0. The water surface reflects thermal radiation of the atmosphere, while the water column is opaque and does not transmit radiation in the longwave thermal spectrum.

The process of thermal calibration adjusted for the distance between the water and the sensor and accounted for atmospheric conditions in order to adjust radiance at the sensor based on the kinetic temperatures recorded by water temperature data loggers. Imagery from flight lines that did not cover data loggers, were calibrated based on overlapping imagery from adjacent lines, a technique that is referred to as "line-to-line calibration". Minor deviations from the initial calibration might be needed to achieve the best possible temperature continuity possible throughout the mosaic.

TIR Mosaic Generation

Initially, a boresight calibration flight was processed to calculate the misalignment angles between the sensor and IMU system; this step allows for direct georeferencing of imagery without aerial triangulation. For each production flight, a series of corrections were applied to the aircraft trajectory and orientation using Applanix PP-RTX processing methodologies. Image timestamps were linked to the corrected trajectory to resolve the exterior orientation (EO) of the sensor for each image event. The resulting EO, sensor interior orientation (IO), and calibrated TIR images were input into Inpho's OrthoMaster software to generate orthophotos using a publicly available digital elevation model (DEM). Finally, for the TIR ortho images, a mosaic was generated without applying color balancing and minimal seam line feathering to preserve the original temperature values of the TIR imagery as best possible. Processing steps and software used are detailed in Table 4.

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[2] Baldridge, A. M., S.J. Hook, C.I. Grove and G. Rivera, 2009. The ASTER Spectral Library Version 2.0. Remote Sensing of Environment, vol 113, pp. 711-715.

Table 4: Processing step for TIR mosaic generation

Orthophoto Processing Step	Software Used
Calculate camera misalignment angles from a system boresight flight conducted close to survey area.	Applanix CalQC v8.4
Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data. Develop a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with sensor head position and attitude recorded throughout the survey.	Applanix POSPac MMS v8.4
Calculate exterior orientation (EO) for each image event by linking the event time stamps with the SBET and boresight misalignment angles.	Applanix POSPac MMS v8.4
Convert raw (*.seq) TIR data into thermally calibrated TIFF images.	Examine IR v1.5
Import DEM and generate individual ortho images.	Inpho OrthoMaster v10.1
Mosaic orthorectified imagery, generating seams between individual photos.	OrthoVista v10.1

Temperature and Color Ramps

The final TIR mosaic contains pixel values of degrees Celsius multiplied by 10, stored in a 16bit unsigned integer raster format. Temperature values occupy a relatively narrow range of the full 16bit histogram; thus, visual representation of the imagery is enhanced by the application of a customized color ramp. Color ramps also highlight different features relevant to the analysis, such as spatial variability of stream temperatures and inflows (Figure 6). The color ramps for the TIR mosaics were developed to maximize contrast for most surface water features and are unique to each tributary or mosaic. A TIR specialist at NV5 customized unique color ramps to improve visual presentation of the TIR mosaic and exported the color ramps as ESRI layer files (*.lyr). Color ramps are an important product that is delivered to the end user.

Accuracy Assessment Methodology

The radiometric accuracy of the final TIR mosaic was assessed by comparing sampled pixels of the mosaic (where water features were present) at the data logger locations against the temperature recorded by the respective logger.

The goal was to reach a mean absolute error (MAE) of ≤1.0 °C temperature difference between the mosaic and logger-recorded values at the time of acquiring the TIR imagery. The threshold of MAE ≤1.0 °C accounts for impeded errors of the data logger (≤0.2 °C) and the FLIR sensor (≤0.035 °C). Collecting the data in the shortest time window possible is advantageous to avoid deviation from calibrated values due to the natural diurnal fluctuation of rivers. Furthermore, the mosaic's accuracy relies on the recorded temperatures and deployment conditions of the data loggers.

Assessing the mosaic's accuracy becomes challenging where the logger is positioned where there is no cluster of pixels with uniform temperatures in the mosaic. Such sites lead to "blended pixels" in the TIR mosaic. A blended pixel is one that represents two or more objects with varying temperatures, i.e. water and non-water features. Examples of such sites are narrow channels, water surfaces obscured by above-surface boulders and vegetation (riparian or aquatic), and the mixing zone of tributaries or point-source inflow.

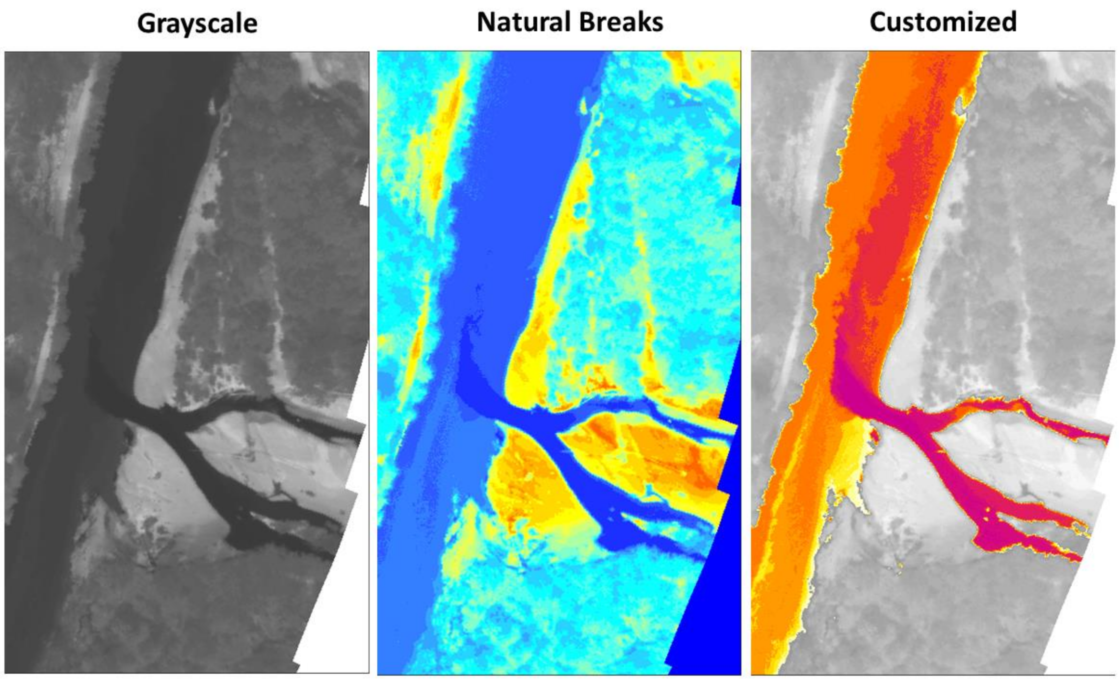

Figure 6: Examples of different color ramps applied to the same TIR image.

Interpretation and Feature Extraction

To begin interpretation of thermal infrared data, a trained analyst reviewed the final mosaics to obtain a detailed understanding of the temperature distribution across the survey area. An emphasis was put on identifying the thermal signature of water bodies and streams. This was also the first step in identifying the thermal signature and location of potential inflow sources of cold/hot water.

A stream centerline was digitized using the TIR mosaics including stream names (*at a scale of 1:5,000*). This step was performed for the entire contracted river length. As the centerline was digitized, care was taken to avoid non-water features where possible, such as aquatic vegetation, boulders, and overhanging canopy. However, a few non-water features cannot always be avoided, such as bridges. River length was measured cumulatively from the most downstream point in the area of interest (AOI) towards the most upstream point. Therefore, the calculated length represents only the streams within the surveyed AOI and is not relative to the overall river network outside the AOI. The standard set of Klamath River miles that have been established from the confluence with the Pacific Ocean were included by referencing the nearest standard river mile in the results tables associated with the longitudinal temperature profile and the significant thermal features that were extracted from the TIR mosaic.

Thermal Infrared Mosaic Sampling and Interpretation

Two analysis techniques were used to interpret the TIR data: 1) an interval-based automated sampling of the stream to generate a longitudinal temperature profile (LTP) and 2) a manual point source sampling to identify significant thermal features (STF).

Longitudinal Temperature Profile

The LTP is the result of sampling the TIR mosaic at fixed intervals along the previously digitized centerline of the study area. The LTP contributes to interpretation of the temperature gradient along the stream due to potential influence from water inflows (e.g., tributaries, springs, groundwater upwelling, effluents, etc.). Using a proprietary algorithm, the sampling results were stored in a geospatial data file format (ESRI shapefile) and were plotted against river distance. For each interval, the algorithm extracted the pixel values from the TIR mosaic at 10 points along the centerline within a 2-meter distance from the interval point (Figure 7). The results were summarized in terms of statistical parameters of mean, median, maximum, minimum, and standard deviation. Sampling points with high standard deviation were marked as outliers because they could have fallen on non-water features.

Significant Thermal Features

STFs are thermal anomalies in the TIR mosaic that represent potential inflows from springs, hyporheic inflow, or tributaries. The anomalies were manually identified before running an algorithm to extract values of all pixels inside a 1-meter buffer area (Figure 8). The algorithm also measured their distance from the centerline and attributes to them a river km along the centerline of the study area (closest point on the centerline). For each STF, temperature results were summarized in statistical parameters of mean, median, maximum, minimum, and standard deviation of the pixels inside the 1-m buffer. All values above were summarized in a geospatial data file format (ESRI shapefile) and plotted against river distance with the LTP results. The defined buffer area for the STF could be larger than the identified feature (e.g. a small spring or hyporheic zone) or smaller (e.g. inflow from tributary). Therefore, the minimum extracted value could better represent the STF in some cases, whereas the median could better represent others.

Calculated Statistic Parameters

The statistical parameters summarize the temperature values of all 10 sample points for the LTP and all pixels inside the buffered area for the STF.

- Mean and median: define the mean and median temperature values of all 10 sampled points/pixels.
- Minimum and maximum: define the minimum and maximum temperature values among all points/pixels. The minimum is used to plot STF results where the interest is to identify cold inflow and the maximum is used to identify hot inflow.
- Standard deviation: defines the standard deviation across all sampled points/pixels. This value is important to identify sample points that represent non-water features. A low standard deviation indicates homogeneous thermal features among the sample points and a high standard deviation indicates that the set of sample points includes features (e.g., exposed rocks/boulders) with temperature significantly different than the water body. The value of standard deviation is important for identifying and removing invalid sample points.

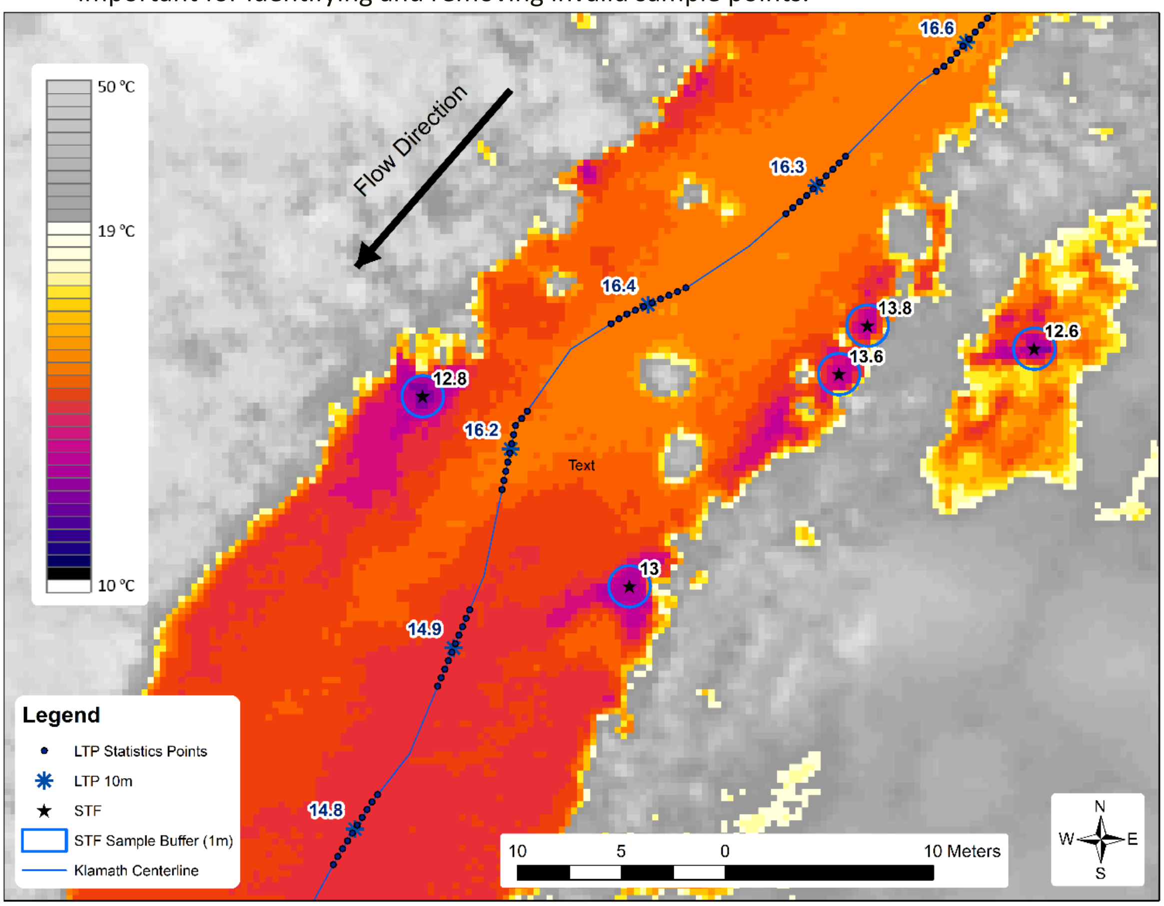

Figure 7: Example sets of sample points (n = 10 per set) used to generate the longitudinal temperatures profile (LTP) with 10 meter spacing along the river centerline. Sample point and buffer of the significant thermal features (STF) are also shown. Water temperature is displayed in units of °C.

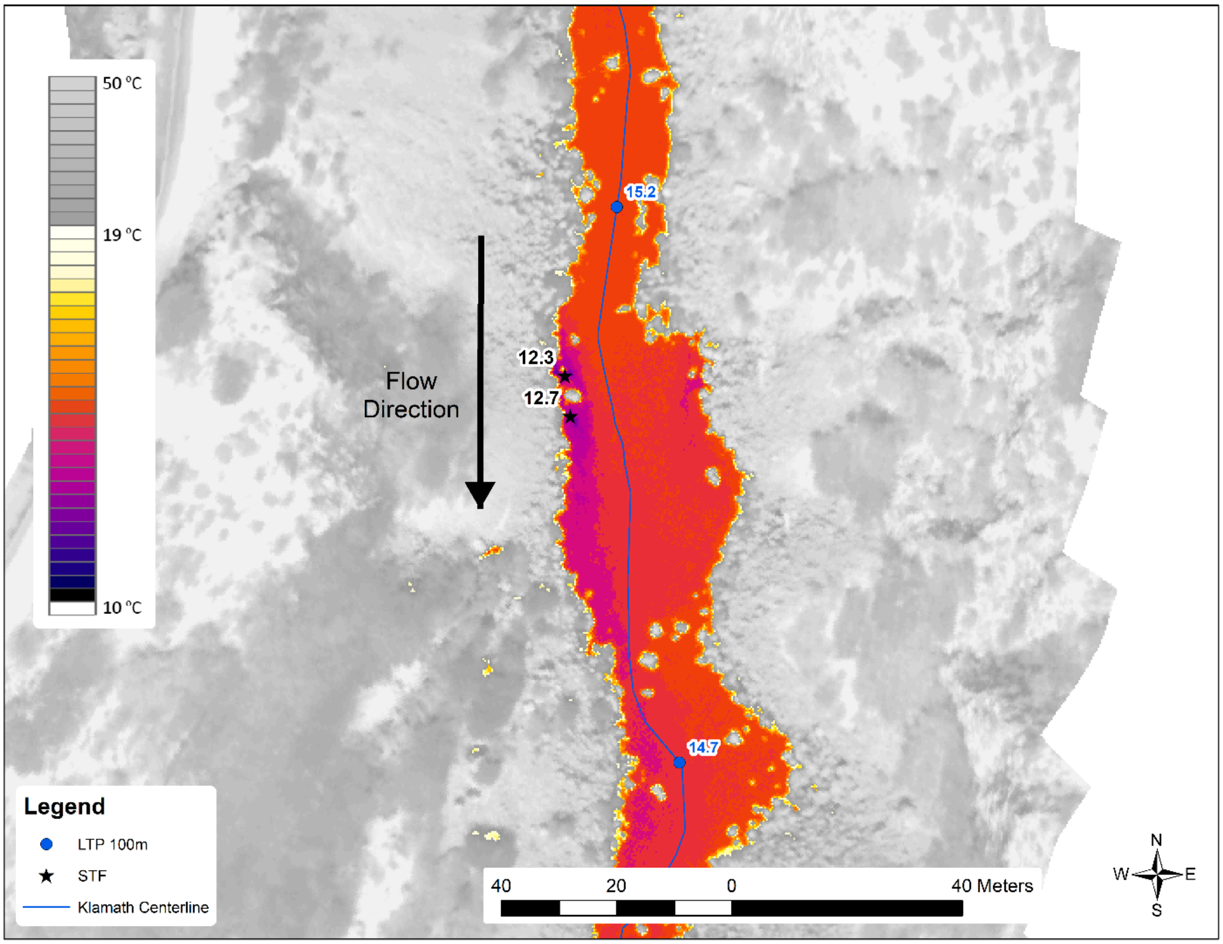

Figure 8: An example longitudinal temperature profile (LTP) at 100 m intervals along the river centerline and significant thermal features (STF). Water temperature is displayed in units of °C.

Table 5: Summary of the processing and analyses steps used in the thermal analysis

Processing and Analyses Steps	Data File	Description	Software used
Calibrate thermal imagery	*<TIMESTAMP >.tif*	Convert raw TIR image digital number to radiance temperatures based on the sensor's factory calibration. Adjust radiant temperatures based on the ground control kinetic temperatures.	FLIR ResearchIR v. 1.50.3
Generate orthorectified thermal imagery	*<TIMESTAMP >.tif*	Incorporate the spatial location and sensor's orientation into creating orthorectified thermal imagery.	Inpho v10.1
Develop color ramp	*<STREAM>_<SECTION>.lyr*	Develop a color ramp that highlights spatial variability of stream temperatures.	ArcMap v. 10.5
Digitize stream centerline along main flow path seen in TIR imagery	*Centerline_ <STREAM>.shp*	Streamlines were digitized and routed based on the final thermal mosaics in order to best represent the centerline/main flow path.	ArcMap v. 10.5
Create longitudinal temperature profile	*LTP_<STREAM>.shp*	Using automated NV5 tools, a GIS point layer was generated from the stream center line layer at 10-meter and 100-meter intervals. Each point was assigned a river kilometer measurement and the TIR radiant temperature was sampled based on an average of 10 sample points located within a 2-meter distance along the centerline.	ArcMap v. 10.5 NV5 script
Identify and sample significant features sites	*STF_<STREAM>.shp*	Manually digitize and sample significant features sites. Sampling all pixels inside a 1-meter buffer area radiating from the digitized point.	ArcMap v. 10.5 NV5 script
Plot longitudinal profiles	*LTP_STF_<STREAM>.xlsx*	Plot temperature against river km for the longitudinal profile and the manually identified features.	Excel

Thermal Infrared Analysis

The TIR analysis focused on utilizing the thermal signatures to identify features that were relevant to the project objectives. The analysis provides a review of the longitudinal thermal gradient of the stream, significant features at the edge of the stream channel, and point source and non-point source inflows (e.g., tributaries, side channels, groundwater upwelling, seepage, effluents, springs, and hyporheic flow) in the floodplain. Identification of such features relies on visual inspection by a trained analyst and automated sampling algorithms. While the visual inspection is qualitative, it assists in identifying the span of river water temperature and isolating it from the temperature of the banks. The results of running the automated sampling algorithms are quantitative and are provided in two statistical datasets: the LTP and STF. Both datasets are provided in shapefile and tabular formats. The LTP was generated by plotting the mean stream temperature at a specified interval against the stream's length. Significant features along the river and in the survey area were incorporated with the LTP plot to provide spatial context for interpreting temperature patterns.

Accuracy Assessment Results

TIR imagery was calibrated using in-stream temperature data from the loggers that were distributed along the river channel. The accuracy assessment, a comparison between the water temperatures recorded by the in-stream data loggers and the radiant temperatures derived from the TIR mosaic, is summarized in Table 6. The final mosaic is considered within the specified accuracy requirements when the mean differences between TIR radiant and in-stream kinetic temperatures, also known as the mean absolute error (MAE), is ≤1.0 °C. The accuracy assessment is based on the data recorded by all data loggers within a single river section or mosaic. The thermal infrared mosaic was within this accuracy threshold (Table 6 and Table 7).

Table 6: Summary of accuracy assessment values.

Mosaic	Mean Absolute Error (°C)	Minimum Error (°C)	Maximum Error (°C)
Klamath River	0.1	0	0.3

Table 7: Error values between radiant temperatures derived from the TIR mosaic and kinetic water temperature recorded by in-stream data loggers.

Serial Number	Location	Calibration Temperature (°C)	Date/Time	Mean (°C)	Error (°C)
21101788	Below J.C. Boyle Dam	16.4	20210922 14:10	16.4	0.0
21130737	Above J.C. Boyle Powerhouse	15.0	20210922 14:15	15.0	0.0
21101783	BLM Campground	16.1	20210922 14:25	16.3	0.2
21101789	Above Shovel Creek	15.6	20210922 15:20	15.9	0.3

Longitudinal Temperature Profiles and Significant Thermal Features

The LTP of a stream is an informative tool to detect stream temperature gradients and the response to water inflow sources. It is common to plot the mean water temperature against river length, though the other calculated statistical information (especially the median) can be used as well. The final LTP data excludes most of the non-water features that were accidentally sampled by the automated algorithm. An easy approach to exclude non-water features is by excluding results of high standard deviation and high minimum/maximum temperatures. However, further refinement might be required by the end user based on local information and familiarity with the survey area.

Significant thermal features were identified based on their unique thermal signature and proximity to the active channel. The STF information assists in explaining the changes to LTP or localized water temperature differences. The STF identification focuses on locating tributaries entering the mainstem, hyporheic flow at the river edge, side channels, and agricultural backflow. The majority of identified STF were at temperatures colder than the mainstem, mostly leading to a cooling gradient. Warm inflow can also be identified along the water's edge. Significant thermal features such as tributaries, side channels, or point sources/sinks were identified and plotted along with the LTP. Groundwater upwelling appears colder than the mainstem in the summer, providing a strong indicator of the interaction between the stream and its floodplain. The method for sampling STF was to summarize statistics for all mosaic pixels within 1-meter radius of the STF center point. Tributaries and side channels are usually larger than the designated 1-meter buffer, while the hyporheic, spring, and groundwater inflows vary in size.

Klamath River

A total of 36 km of centerline for the Klamath River were digitized and sampled at 10-meter and 100-meter intervals to generate the LTP. Additionally, a total of 119 STF and 3 tributaries were identified and plotted in Figure 9 and displayed in spatial form in Figure 11. The overall thermal gradient for the river shows:

1) A sharp drop in temperature due to a cold spring entering the river near river km 35.5 (Figure 12). This feature was located just downstream of J.C. Boyle Dam.
2) The river exhibited a downstream cooling gradient with additional cold springs entering the channel especially at river km 34.7 (Figure 13).
3) A downstream warming gradient initiated near the J.C. Boyle Powerhouse tailrace at river km 28.8 and continued until river km 25 (Figure 14).

4) Rock Creek (river km 18) was warmer than the mainstem (Figure 15).
5) Generally steady temperatures with moderate downstream cooling occurred until river km 5.
6) The river warmed up and cooled again while entering Copco Reservoir (river km 5 to 0) reflecting the mixing zone's temperature at the water surface.

It is important to note that a downstream warming gradient is a common feature resulting from solar loading and warmer air temperature. Tributaries warmer than the mainstem (e.g., Rock Creek) also were apparent in the TIR data but their contribution to the warming gradient is negligible given relative low flow compared to the mainstem. However, the large number of cold springs entering the Klamath River caused the river to cool along the section between J.C. Boyle Reservoir and the powerhouse tailrace. Cold springs entering the river throughout the course of the survey area contributed to maintaining a steady temperature for the majority of river length. See examples for cold inflow from a spring (Figure 10), Shovel Creek (Figure 16), and Long Creek (Figure 17). Also see the thermal signature of the Klamath River across the surveyed section of the confluence with Copco Reservoir in Figure 18.

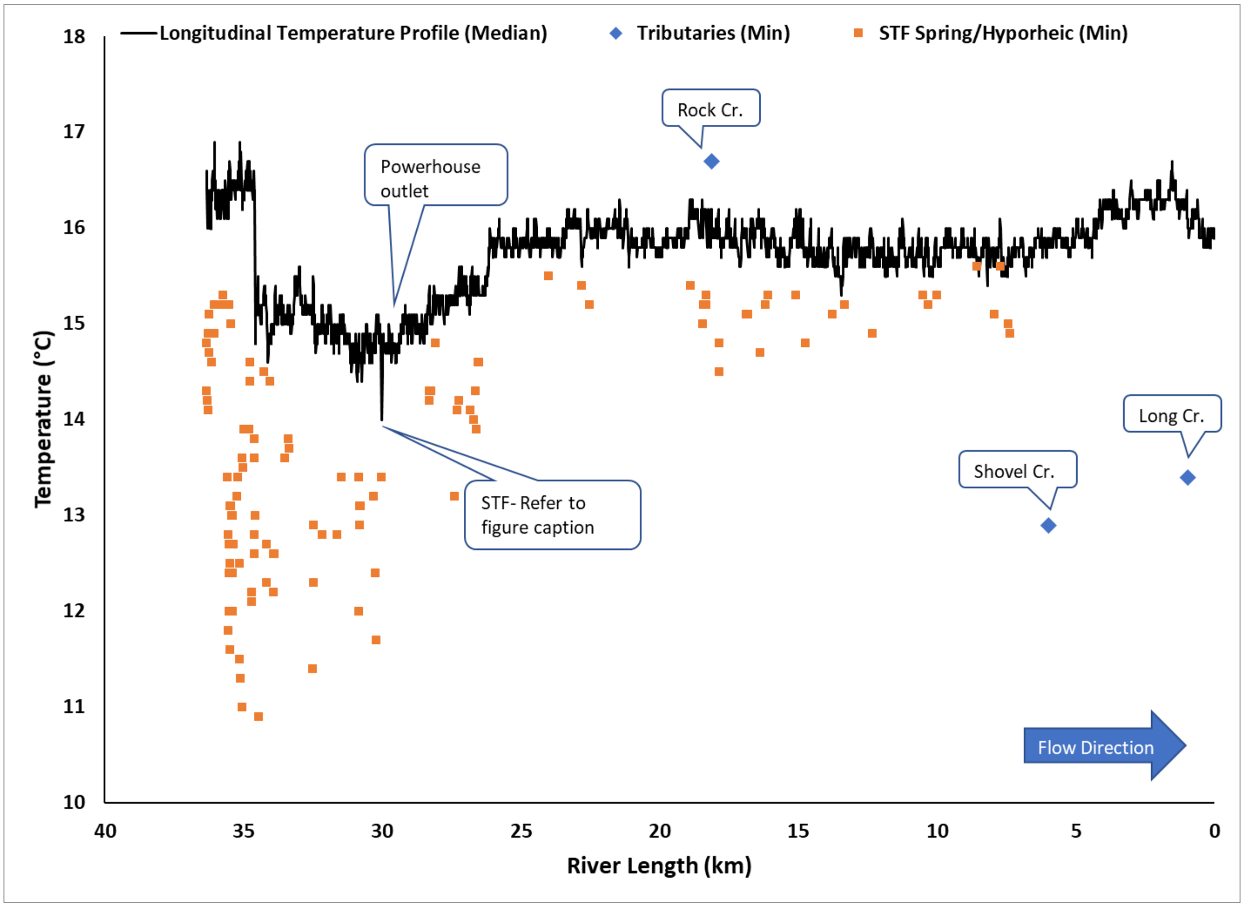

Figure 9: Longitudinal temperature profile (LTP) and identified significant thermal features (STF) plotted against river length for the Klamath River. Tributary temperatures just prior to the confluence with the Klamath River are also shown. Plotting the median temperature (°C) of the LTP and minimum temperature (°C) of tributaries and STF. A special STF at river km 30 is a spring in the middle of the channel where the flow was low and water was shallow allowing for the mixing zone to explicitly appear in the data (also refer to Figure 10).

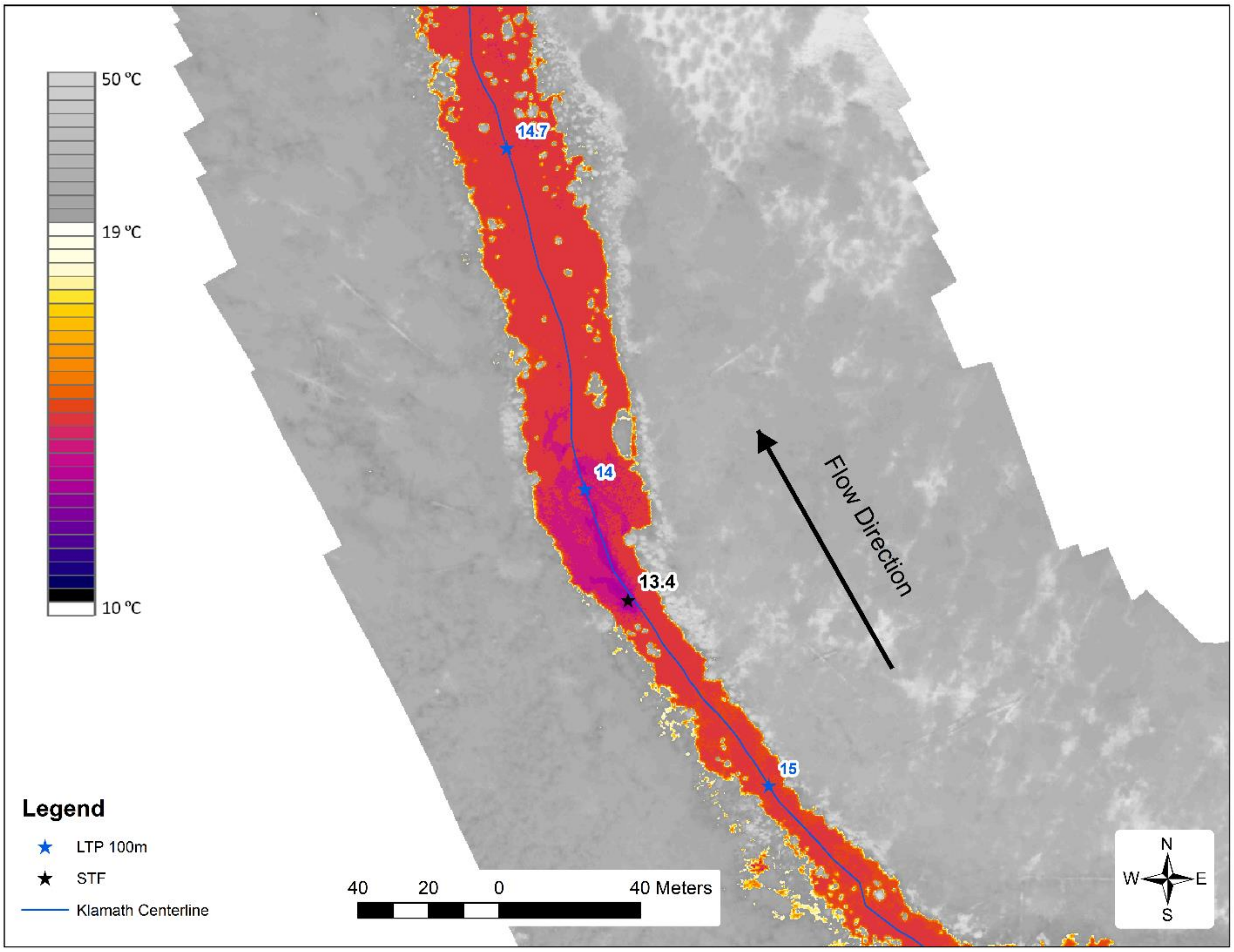

Figure 10: Thermal infrared map showing cold springs at the center of the channel at river km 30.0.

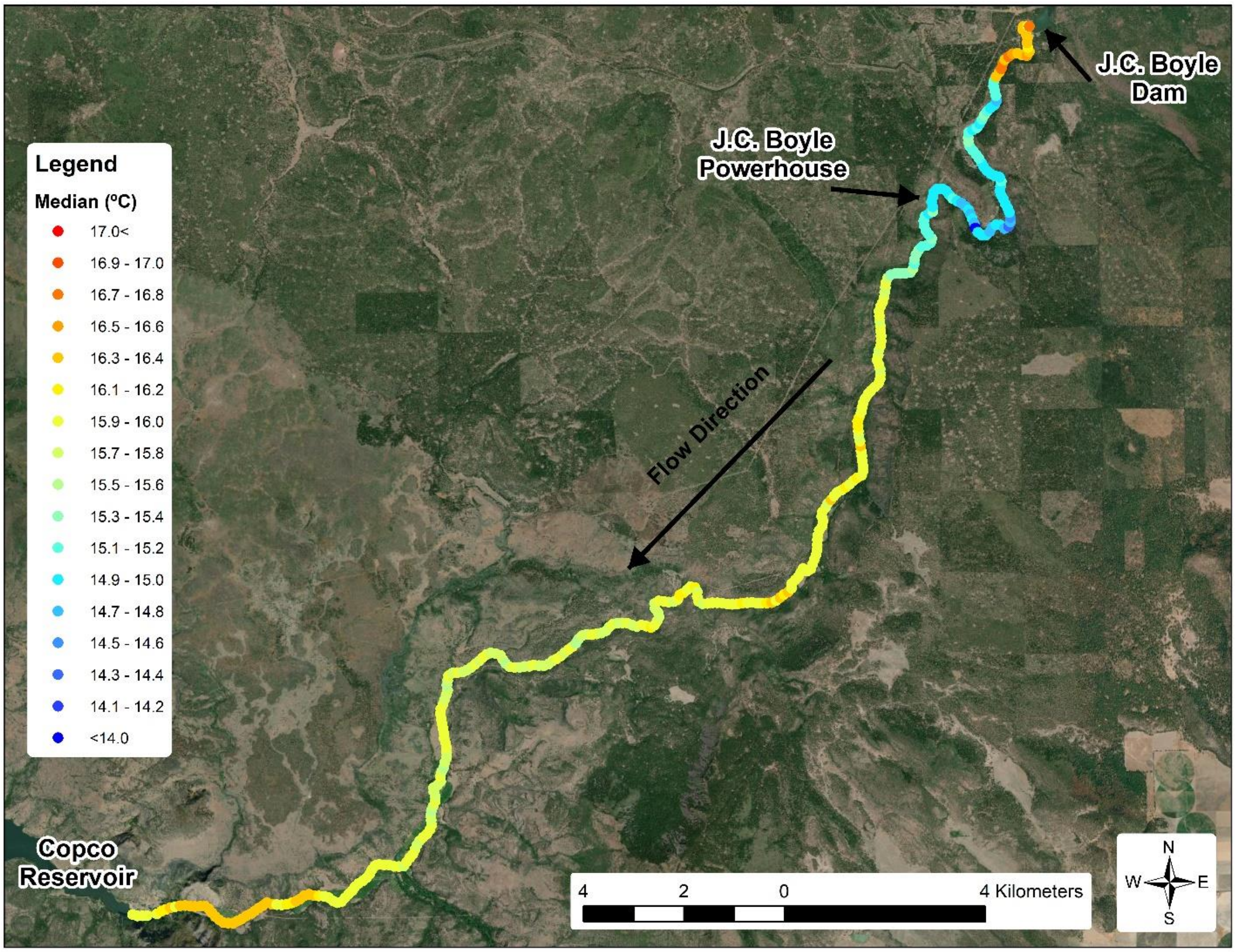

Figure 11: Longitudinal temperature profile (LTP) overlaid on publicly available true color imagery showing the spatial gradient along the Klamath River. Points are colored by the median temperature (ºC).

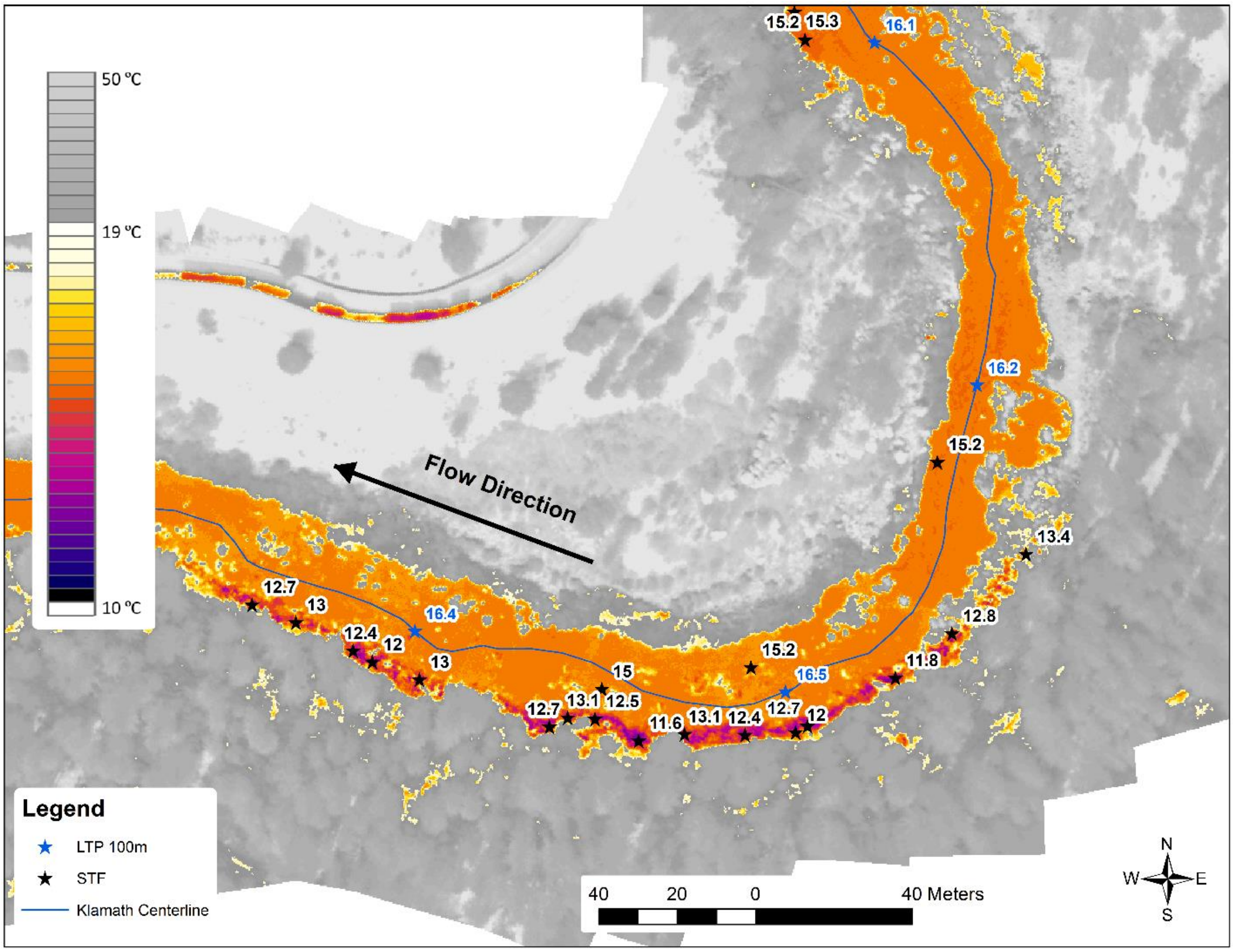

Figure 12: Thermal infrared map showing cold springs entering the channel at river km 35.5.

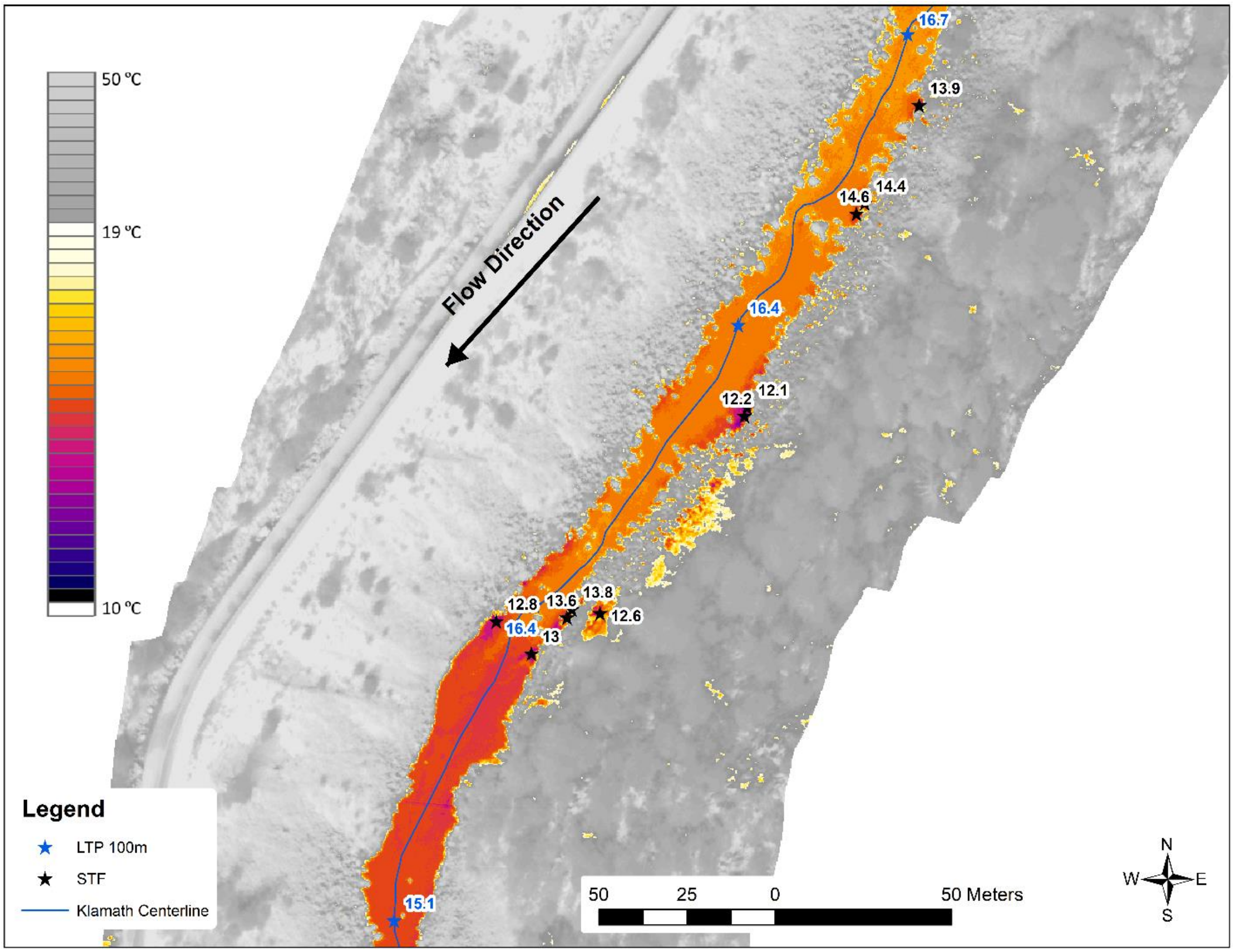

Figure 13: Thermal infrared map showing cold springs entering the channel at river km 34.7.

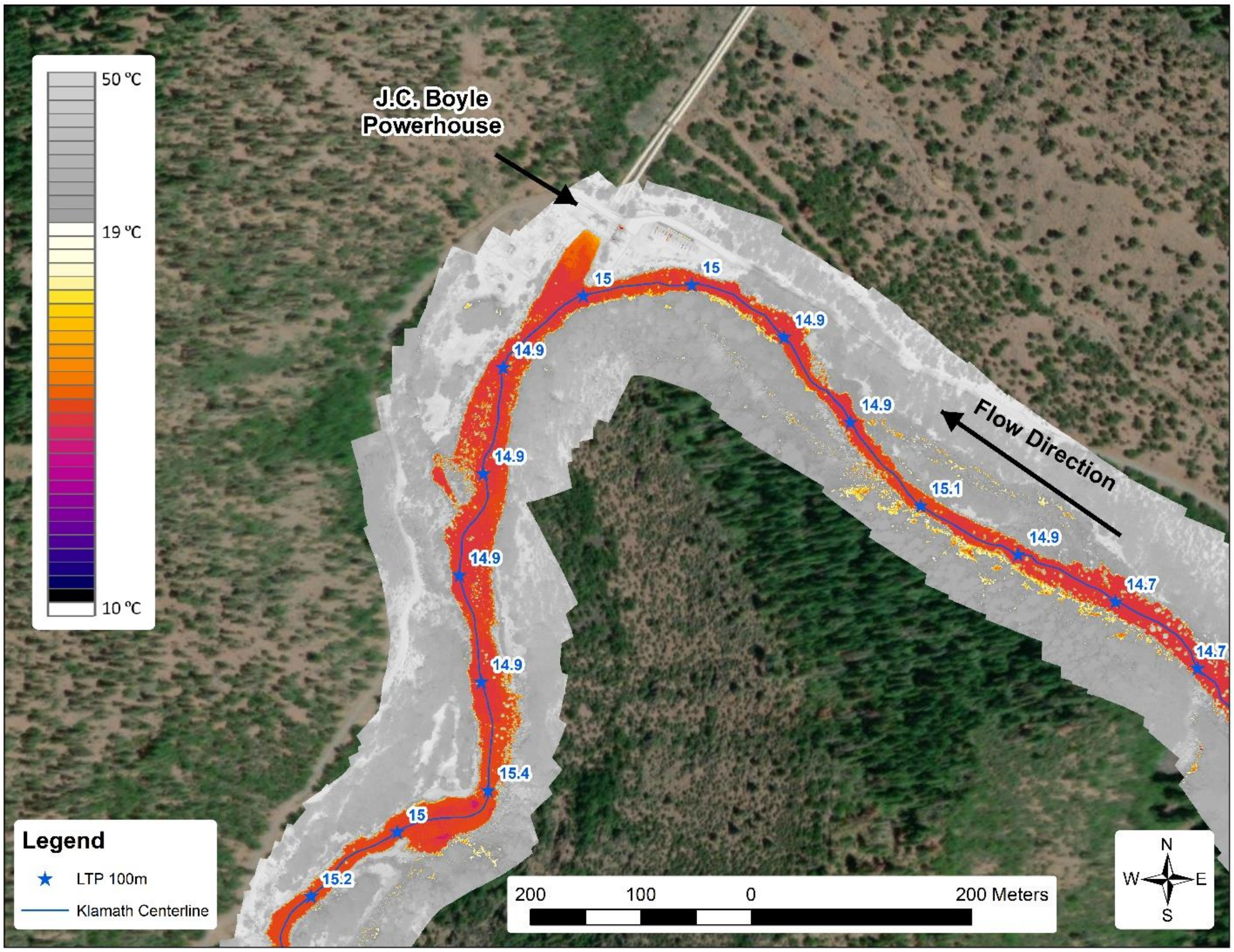

Figure 14: Thermal infrared map the area of river near the J.C. Boyle Powerhouse tailrace at river km 25.0.

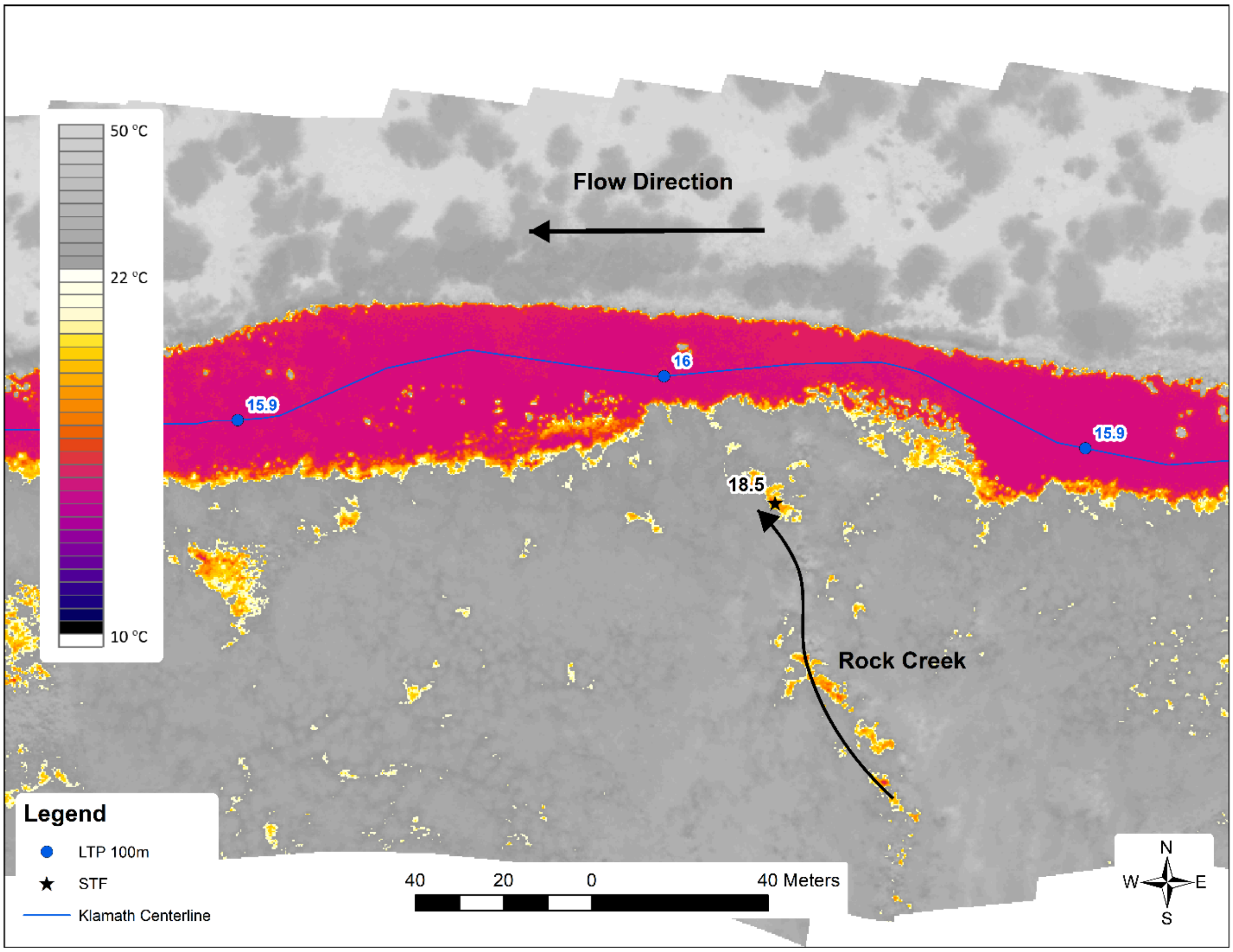

Figure 15 Thermal infrared map for the confluence of Rock Creek (18.5 °C) with the Klamath River (15.9 °C) at river km 18.1.

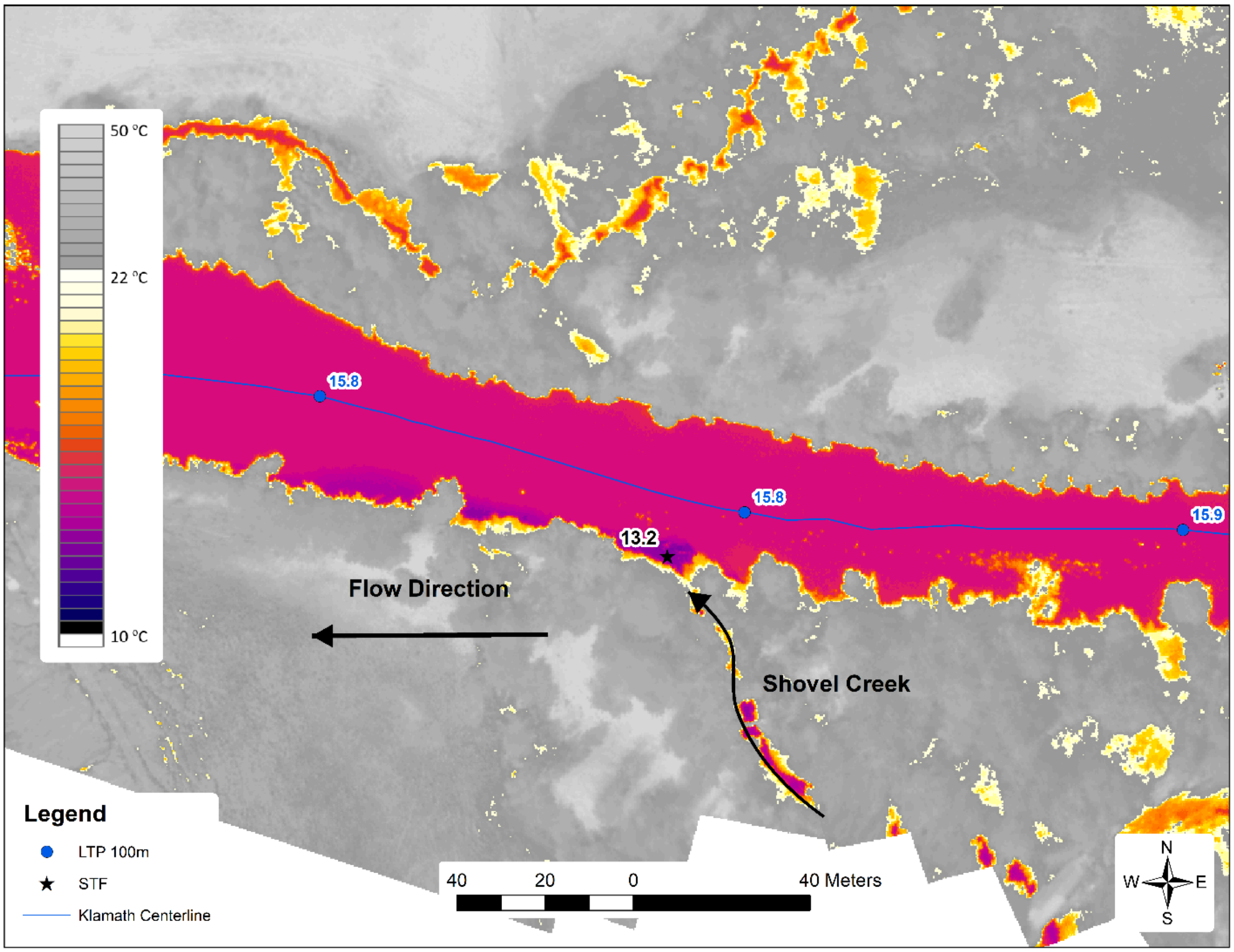

Figure 16: Thermal infrared map for the confluence of Shovel Creek (13.2 °C) with the Klamath River (15.8 °C) at river km 6.0.

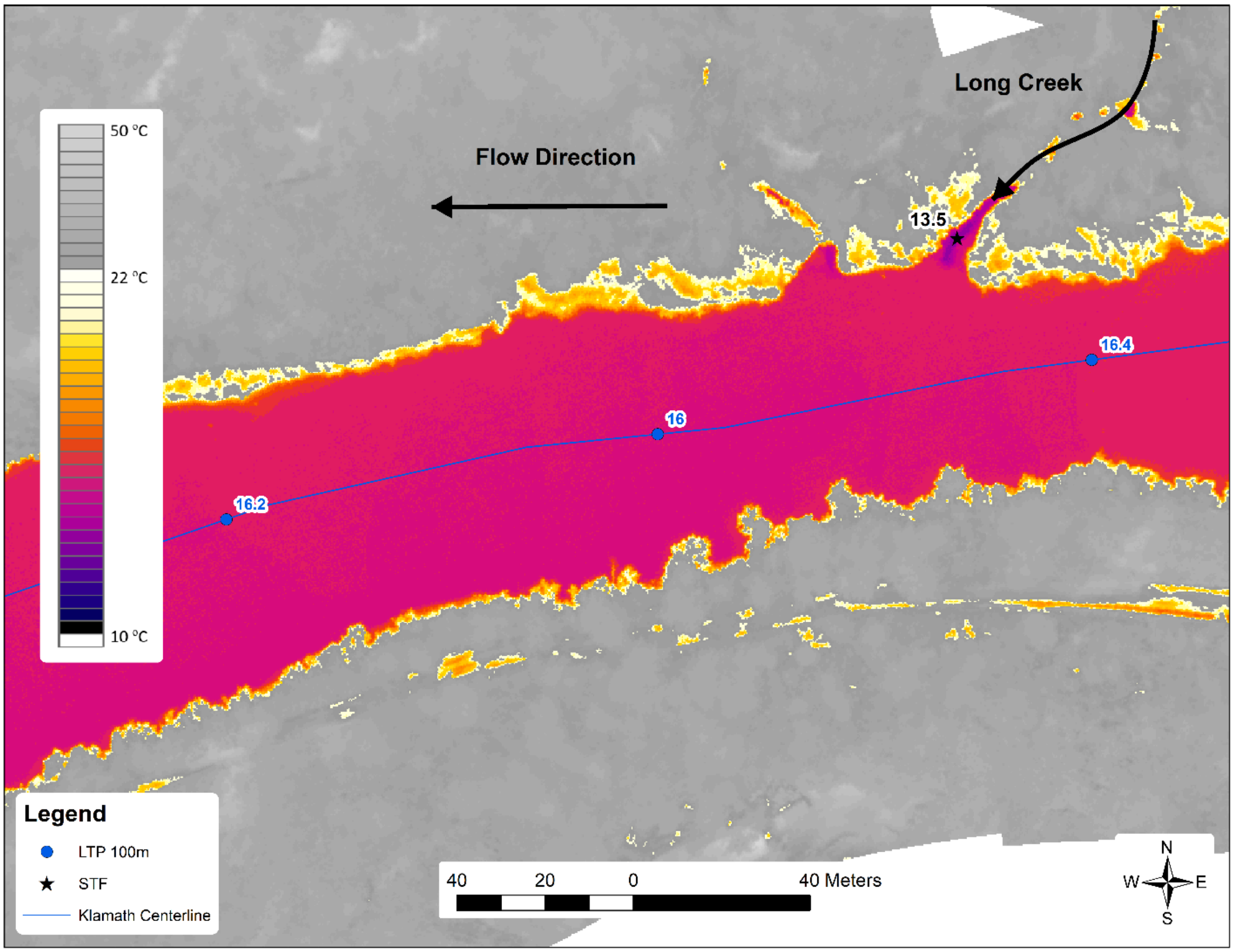

Figure 17: Thermal infrared map for the confluence of Long Creek (13.5 °C) with the Klamath River (16 °C) at river km 1.0.

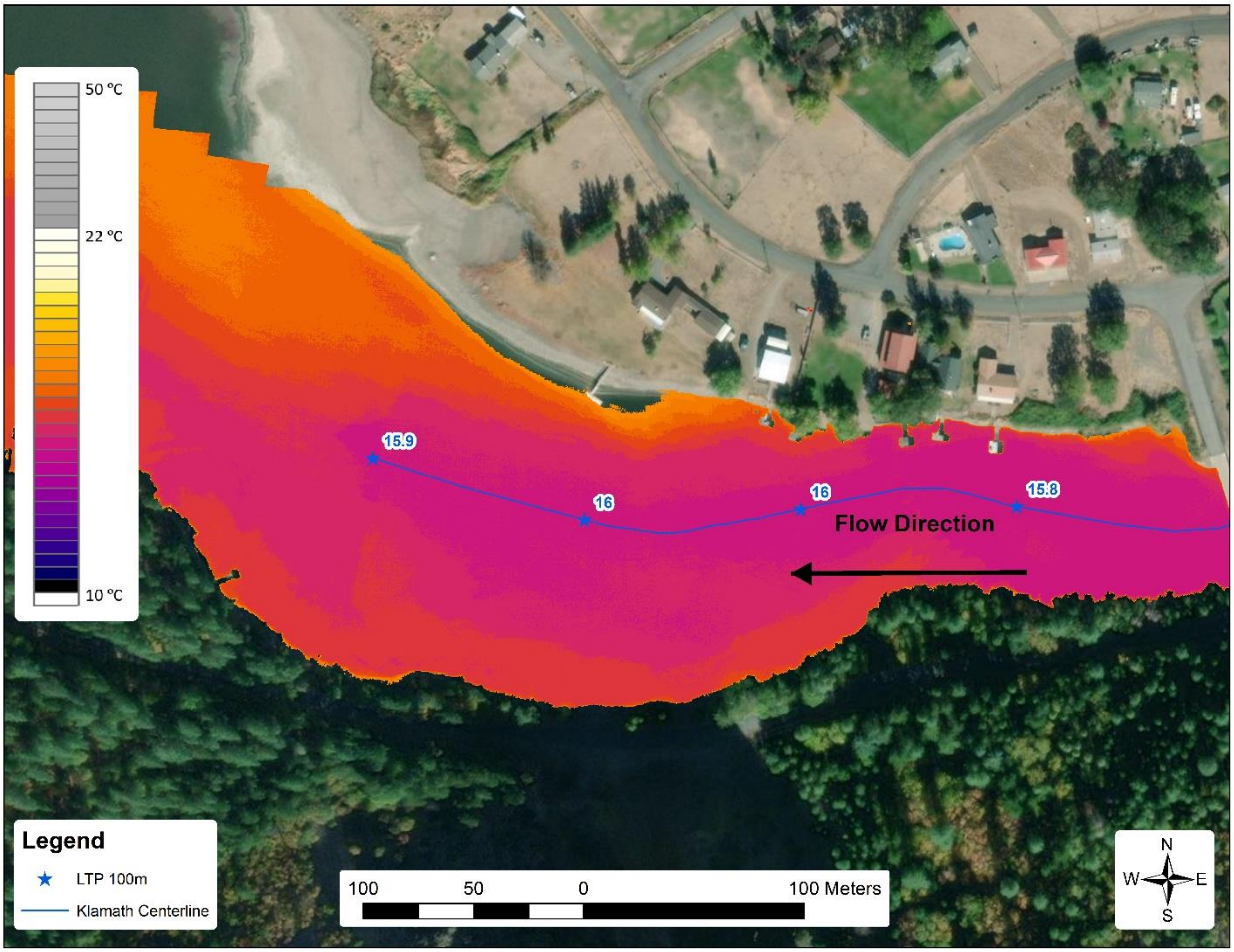

Figure 18: Thermal infrared map showing the mixing zone of the Klamath River flowing into Copco Lake.

Significant Thermal Features

The following table details temperature statistics for significant thermal features along the Upper Klamath River.

notes	Bank[3]	River (km)[4]	River (mile)[5]	Mean (ºC)[6]	Median (ºC)[7]	Min (ºC)[8]	Max (ºC)[9]	Standard Deviation (ºC)[10]	MILE[11]
Spring/Hyporheic	L	36.32	22.57	14.8	14.7	14.3	16.0	0.406	225
Spring/Hyporheic	L	36.31	22.56	15.0	14.9	14.8	15.3	0.126	225
Spring/Hyporheic	L	36.28	22.54	14.4	14.4	14.2	15.1	0.236	225
Spring/Hyporheic	L	36.27	22.53	14.5	14.4	14.1	15.5	0.322	225
Spring/Hyporheic	R	36.25	22.52	15.5	15.2	14.9	17.1	0.579	225
Spring/Hyporheic	R	36.24	22.52	15.0	14.9	14.7	15.6	0.232	225
Spring/Hyporheic	R	36.23	22.51	15.5	15.4	15.1	16.0	0.233	225
Spring/Hyporheic	L	36.23	22.51	15.4	15.4	15.1	16.0	0.215	225
Spring/Hyporheic	R	36.12	22.44	15.2	15.0	14.6	17.2	0.596	224
Spring/Hyporheic	R	36.05	22.40	15.8	15.7	14.9	16.5	0.437	225
Spring/Hyporheic	R	36.05	22.40	15.8	15.5	15.2	18.2	0.836	224
Spring/Hyporheic	R	35.72	22.19	15.6	15.5	15.3	16.7	0.266	224
Spring/Hyporheic	R	35.71	22.19	15.4	15.4	15.2	15.8	0.124	224
Spring/Hyporheic	R	35.58	22.11	15.7	15.6	15.2	16.3	0.294	224
Spring/Hyporheic	L	35.56	22.10	16.5	16.5	13.4	19.4	1.635	224
Spring/Hyporheic	L	35.54	22.08	15.4	15.3	12.8	19.3	1.500	224
Spring/Hyporheic	L	35.53	22.07	13.1	12.9	11.8	15.1	0.763	224
Spring/Hyporheic	L	35.50	22.06	13.5	13.4	12.0	15.3	0.887	224
Spring/Hyporheic	L	35.50	22.06	13.4	13.2	12.7	14.9	0.629	224
Spring/Hyporheic	L	35.49	22.05	13.4	13.4	12.4	14.7	0.594	224
Spring/Hyporheic	R	35.49	22.05	16.0	16.1	15.2	16.7	0.496	224
Spring/Hyporheic	L	35.47	22.04	14.3	14.1	13.1	17.3	0.843	224
Spring/Hyporheic	L	35.46	22.03	13.6	13.6	12.5	15.3	0.741	224
Spring/Hyporheic	L	35.46	22.04	12.8	12.8	11.6	13.6	0.477	224

[3] Left (L) of right (R) bank where the STF is located, bank association is relative to flow direction or when facing downstream
[4] River distance (km) along the digitized centerline that is closest to the STF location
[5] River distance (mile) along the digitized centerline that is closest to the STF location
[6] Mean temperature (ºC) of sampled pixels of the TIR mosaic inside the buffered area of STF sampling point
[7] Median temperature (ºC) of sampled pixels of the TIR mosaic inside the buffered area of STF sampling point
[8] Minimum temperature (ºC) of sampled pixels of the TIR mosaic inside the buffered area of STF sampling point
[9] Maximum temperature (ºC) of sampled pixels of the TIR mosaic inside the buffered area of STF sampling point
[10] Standard deviation temperature (ºC) of sampled pixels of the TIR mosaic inside the buffered area of STF sampling point
[11] Refers to nearest standard river mile mark provided by PacifiCorp

Spring/Hyporheic	L	35.45	22.03	14.1	14.0	13.1	15.9	0.700	224
Spring/Hyporheic	L	35.45	22.03	15.8	15.9	15.0	16.7	0.430	224
Spring/Hyporheic	L	35.44	22.02	13.6	13.5	12.7	15.5	0.754	224
Spring/Hyporheic	L	35.41	22.00	14.0	13.9	13.0	15.6	0.705	224
Spring/Hyporheic	L	35.39	21.99	13.7	13.7	12.4	15.7	0.947	224
Spring/Hyporheic	L	35.39	21.99	13.4	13.3	12.0	16.0	1.100	224
Spring/Hyporheic	L	35.37	21.98	14.7	14.7	13.0	17.3	1.026	224
Spring/Hyporheic	L	35.36	21.97	14.4	14.4	12.7	16.6	1.010	224
Spring/Hyporheic	L	35.23	21.89	15.2	14.9	13.2	18.0	1.220	224
Spring/Hyporheic	L	35.20	21.87	15.0	14.5	13.4	20.1	1.501	224
Spring/Hyporheic	L	35.14	21.84	13.4	13.3	11.5	15.6	1.099	224
Spring/Hyporheic	L	35.13	21.83	13.6	13.4	12.5	15.6	0.900	224
Spring/Hyporheic	L	35.10	21.81	13.1	12.8	11.3	17.4	1.397	224
Spring/Hyporheic	L	35.09	21.80	12.7	12.8	11.3	14.9	0.956	224
Spring/Hyporheic	L	35.05	21.78	15.2	15.2	11.0	22.7	2.793	224
Spring/Hyporheic	L	35.02	21.76	15.9	15.3	13.6	19.2	1.646	224
Spring/Hyporheic	L	35.01	21.76	15.9	15.4	13.5	21.5	1.896	224
Spring/Hyporheic	R	34.96	21.72	18.2	17.7	13.9	24.1	3.117	224
Spring/Hyporheic	L	34.78	21.61	14.6	14.4	13.9	16.8	0.647	224
Spring/Hyporheic	L	34.75	21.59	15.0	15.0	14.6	16.3	0.317	224
Spring/Hyporheic	L	34.75	21.59	14.9	14.7	14.4	17.0	0.557	224
Spring/Hyporheic	L	34.68	21.55	12.9	12.7	12.2	15.5	0.718	224
Spring/Hyporheic	L	34.68	21.55	12.9	12.6	12.1	16.4	0.924	224
Spring/Hyporheic	L	34.61	21.50	14.2	14.1	13.6	14.8	0.346	224
Spring/Hyporheic	L	34.61	21.51	14.2	14.2	12.6	16.5	0.903	224
Spring/Hyporheic	L	34.61	21.50	14.8	14.7	13.8	18.4	1.015	224
Spring/Hyporheic	R	34.59	21.49	13.4	13.3	12.8	16.2	0.746	224
Spring/Hyporheic	L	34.58	21.49	13.7	13.5	13.0	16.4	0.642	224
Spring/Hyporheic	R	34.45	21.41	11.5	11.4	10.9	13.2	0.572	224
Spring/Hyporheic	L	34.25	21.28	14.9	14.7	14.5	16.3	0.453	223
Spring/Hyporheic	R	34.17	21.23	13.5	13.1	12.3	17.5	1.168	223
Spring/Hyporheic	R	34.16	21.23	13.2	13.1	12.7	16.7	0.670	223
Spring/Hyporheic	L	34.03	21.14	14.5	14.5	14.4	14.7	0.076	223
Spring/Hyporheic	L	33.92	21.08	13.7	13.5	12.6	15.6	0.662	223
Spring/Hyporheic	L	33.90	21.07	13.3	13.2	12.2	15.2	0.718	223
Spring/Hyporheic	R	33.88	21.05	16.7	15.4	12.6	27.2	4.062	223
Spring/Hyporheic	L	33.49	20.81	15.5	15.4	13.6	18.2	1.205	223
Spring/Hyporheic	L	33.38	20.74	14.6	14.6	13.8	16.5	0.501	223
Spring/Hyporheic	L	33.34	20.72	14.5	14.2	13.7	16.4	0.730	223
Spring/Hyporheic	R	32.49	20.19	12.5	12.3	11.4	14.8	1.079	223
Spring/Hyporheic	R	32.47	20.18	13.6	13.3	12.9	15.5	0.726	222
Spring/Hyporheic	R	32.46	20.17	13.1	13.1	12.3	14.4	0.485	222
Spring/Hyporheic	R	32.15	19.98	13.5	13.3	12.8	16.5	0.771	222

Spring/Hyporheic	L	31.63	19.66	14.2	13.6	12.8	19.0	1.615	222
Spring/Hyporheic	L	31.45	19.54	16.1	14.4	13.4	28.4	4.290	222
Spring/Hyporheic	L	30.83	19.16	13.2	13.0	12.0	15.5	0.872	222
Spring/Hyporheic	L	30.82	19.15	13.6	13.6	13.4	14.2	0.158	222
Spring/Hyporheic	L	30.79	19.13	13.9	13.9	13.1	15.4	0.598	222
Spring/Hyporheic	L	30.79	19.13	14.1	13.6	12.9	17.0	1.011	222
Spring/Hyporheic	L	30.77	19.12	14.1	13.9	13.1	16.2	0.689	222
Spring/Hyporheic	L	30.29	18.82	15.5	15.2	13.2	18.7	1.515	221
Spring/Hyporheic	L	30.23	18.78	14.1	13.8	12.4	18.1	1.388	221
Spring/Hyporheic	L	30.19	18.76	13.0	13.1	11.7	14.4	0.741	221
Spring/Hyporheic	L	30.03	18.66	13.5	13.4	13.4	13.6	0.065	221
Spring/Hyporheic	L	28.29	17.58	14.6	14.5	14.3	14.9	0.173	220
Spring/Hyporheic	R	28.28	17.57	14.2	14.2	14.2	14.3	0.047	220
Spring/Hyporheic	L	28.24	17.55	14.4	14.4	14.3	14.6	0.069	220
Spring/Hyporheic	R	28.07	17.44	15.0	15.0	14.8	15.2	0.106	220
Spring/Hyporheic	L	27.39	17.02	14.4	14.4	13.2	15.6	0.622	220
Spring/Hyporheic	L	27.29	16.96	14.2	14.2	14.1	14.2	0.039	219
Spring/Hyporheic	L	27.21	16.91	14.6	14.5	14.2	15.7	0.314	219
Spring/Hyporheic	L	26.82	16.66	14.5	14.4	14.1	15.2	0.269	219
Spring/Hyporheic	L	26.68	16.58	14.6	14.4	14.0	15.6	0.343	219
Spring/Hyporheic	L	26.63	16.55	15.2	15.1	14.3	18.0	0.703	219
Spring/Hyporheic	L	26.61	16.54	14.7	14.6	13.9	16.8	0.621	219
Spring/Hyporheic	L	26.52	16.48	14.9	14.8	14.6	15.6	0.229	219
Spring/Hyporheic	L	26.49	16.46	14.8	14.8	14.6	15.2	0.131	219
Spring/Hyporheic	L	23.98	14.90	15.6	15.6	15.5	15.8	0.083	217
Spring/Hyporheic	R	22.80	14.17	15.5	15.5	15.4	15.6	0.063	217
Spring/Hyporheic	R	22.53	14.00	15.7	15.7	15.2	18.3	0.555	217
Spring/Hyporheic	L	18.87	11.73	15.7	15.5	15.4	16.2	0.246	214
Spring/Hyporheic	L	18.45	11.46	15.9	15.5	15.0	19.1	1.000	214
Spring/Hyporheic	L	18.41	11.44	15.4	15.3	15.2	16.0	0.157	214
Spring/Hyporheic	L	18.31	11.38	15.4	15.4	15.2	16.3	0.194	214
Spring/Hyporheic	R	18.31	11.38	15.5	15.5	15.3	15.8	0.149	214
Rock cr.	L	18.12	11.26	18.5	18.5	16.7	20.2	0.912	214
Spring/Hyporheic	L	17.83	11.08	14.7	14.7	14.5	14.9	0.104	214
Spring/Hyporheic	R	17.83	11.08	15.2	15.1	14.8	16.4	0.424	214
Spring/Hyporheic	L	16.86	10.48	15.4	15.4	15.1	15.8	0.163	213
Spring/Hyporheic	L	16.82	10.45	15.4	15.4	15.1	15.7	0.122	213
Spring/Hyporheic	R	16.37	10.17	14.8	14.8	14.7	15.0	0.062	213
Spring/Hyporheic	R	16.19	10.06	15.3	15.3	15.2	15.5	0.080	213
Spring/Hyporheic	L	16.10	10.00	15.5	15.5	15.3	15.6	0.078	212
Spring/Hyporheic	L	15.09	9.38	15.5	15.5	15.3	15.9	0.133	212
Spring/Hyporheic	L	14.73	9.15	14.9	14.9	14.8	15.0	0.063	212
Spring/Hyporheic	L	13.77	8.56	15.3	15.3	15.1	15.4	0.093	211

Spring/Hyporheic	L	13.34	8.29	15.4	15.4	15.2	15.6	0.108	211
Spring/Hyporheic	L	12.31	7.65	15.1	15.1	14.9	15.3	0.081	210
Spring/Hyporheic	L	10.50	6.52	15.5	15.5	15.3	15.6	0.053	209
Spring/Hyporheic	R	10.32	6.42	15.4	15.4	15.2	15.5	0.075	209
Spring/Hyporheic	R	10.00	6.22	15.4	15.4	15.3	15.5	0.064	209
Spring/Hyporheic	R	8.57	5.33	15.7	15.7	15.6	15.8	0.051	208
Spring/Hyporheic	R	7.94	4.93	15.7	15.8	15.1	16.6	0.403	208
Spring/Hyporheic	L	7.71	4.79	15.8	15.7	15.6	16.1	0.128	207
Spring/Hyporheic	R	7.43	4.62	15.2	15.1	15.0	15.4	0.112	207
Spring/Hyporheic	R	7.37	4.58	15.0	15.0	14.9	15.1	0.051	207
Shovel Cr.	L	5.99	3.72	13.2	13.1	12.9	13.4	0.117	206
Long Cr.	R	0.98	0.61	13.5	13.5	13.4	13.9	0.112	203

Shapefiles Headers

The following are the headers details of the LTP, STF, and Accuracy shapefiles:

LTP:

Header	Explanation
GNIS_NAME	the river name
Rvr_meas_m	river length (meter) at which temperature was sample, starting from the downstream end
Rvr_km	river length (km) at which temperature was sample, starting from the downstream end
Rvr_mile	river length (miles) at which temperature was sample, starting from the downstream end
Mean	mean water temperature, a result of 10 sampled points along the centerline within the specified buffer
Median	median water temperature, a result of 10 sampled points along the centerline within the specified buffer
Min	minimum water temperature, a result of 10 sampled points along the centerline within the specified buffer
Max	maximum water temperature, a result of 10 sampled points along the centerline within the specified buffer
Std_Dev	standard deviation water temperature, a result of 10 sampled points along the centerline within the specified buffer
MILE	River mile post according to standardized data which was provided by PacifiCorp

STF:

Header	Explanation
Id	unused filed- can be used by end user to recategorize points
notes	note about the significant feature
Strm_Name	stream name closest to the location of the significant feature
L_R_Bank	the location of the significant feature, left or right bank, relative to the centerline
M_Off_str	distance of the significant feature from the closest stream (meter
Rvr_meas_m	river length (meter) where the significant feature was found, starting from the downstream end
Rvr_km	river length (km) at which temperature was sample, starting from the downstream end
Rvr_mile	river length (mile) where the significant feature was found, starting from the downstream end
Mean	mean water temperature at the significant feature, a result all pixels within the specified buffer
Median	median water temperature at the significant feature, a result all pixels within the specified buffer
Min	minimum water temperature at the significant feature, a result all pixels within the specified buffer
Max	maximum water temperature at the significant feature, a result all pixels within the specified buffer
Std_Dev	standard deviation water temperature at the significant feature, a result all pixels within the specified buffer
MILE	River mile post according to standardized data which was provided by PacifiCorp

Accuracy:

Header	Explanation
Name	logger's name provided by client
Tw_C	water temperature by the logger at the time of acquiring the specific flight line (see below)
Date_Time	date and time at which the water temperature was recorded and coinciding with the time window of acquiring TIR flightline that covers the logger's site
Flight_lin	flightline's serial number covering the logger's site
Strm_Name	stream name closest to the location of the significant feature
L_R_Bank	the location of the significant feature, left or right bank, relative to the centerline
M_Off_str	distance of the significant feature from the closest stream (meter
Rvr_meas_m	river length (meter) where the significant feature was found, starting from the downstream end
Rvr_km	river length (km) at which temperature was sample, starting from the downstream end
Rvr_mile	river length (mile) where the significant feature was found, starting from the downstream end
Mean	mean water temperature at the significant feature, a result all pixels within the specified buffer
Median	median water temperature at the significant feature, a result all pixels within the specified buffer
Min	minimum water temperature at the significant feature, a result all pixels within the specified buffer
Max	maximum water temperature at the significant feature, a result all pixels within the specified buffer
Std_Dev	standard deviation water temperature at the significant feature, a result all pixels within the specified buffer