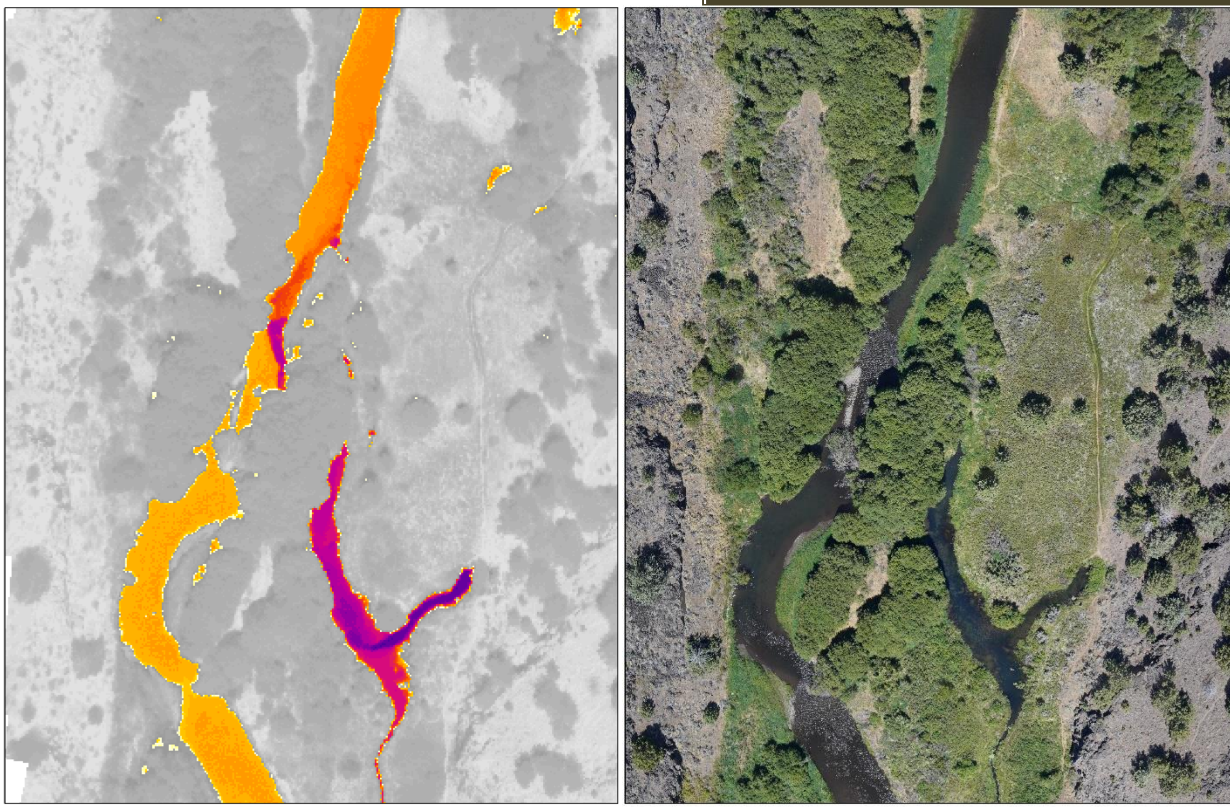
Survey: Aug 13-15, 2020
Report: April 16, 2021



Donner und Blitzen River – Airborne Thermal Infrared and True Color Imagery

Technical Data Report

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Cover Photo: Thermal infrared imagery of cold-water inflow at river km 1.6 of Donner und Blitzen River.

INTRODUCTION

The United States Geological Service (USGS) contracted NV5 Geospatial Solutions (formerly, Quantum Spatial Inc.) to collect thermal infrared (TIR) and true color imagery data during the summer of 2020 for the Donner und Blitzen River and its main tributaries located in southeast Oregon. The airborne data acquisition campaign was completed in three days – August 13th-15th, 2020 – covering a total river length of 159 km. Prior to the TIR data collection, USGS staff deployed data loggers along the survey tributaries to record water temperature throughout the TIR acquisition time frame. The records were shared with NV5's staff and used to calibrate 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 dataset. TIR acquisition dates and times are shown in Table 1, a complete list of contracted deliverables provided to the USGS is shown in Table 2, and the project extent is shown in Figure 2 (River km in this case is based on the centerlines that were manually digitized off the TIR mosaics for this project).

Table 1: TIR acquisition dates and stream reaches collected on the Donner und Blitzen River.

River Survey Description	Survey Date	Time Frame (PDT)	Section River km
Donner und Blitzen River	8/13/2020	13:03 - 13:52	0.0 – 44.7
Deep Creek	8/13/2020	13:52 - 14:00	0.0 – 2.5
Fish Creek	8/13/2020	14:07 - 14:10	0.0 – 14.0
Little Fish Creek	8/13/2020	14:10 - 14:12	0.0 – 6.6
Ankle Creek	8/13/2020	16:21 - 16:26	0.0 – 14.1
East Ankle Creek	8/13/2020	16:15 - 16:20	0.0 – 2.5
Mud Creek	8/13/2020	16:34 - 16:40	0.0 – 9.1
Indian Creek	8/13/2020	16:59 - 17:06	0.0 – 7.8
Big Indian Creek	8/13/2020	16:54 - 16:59	0.0 – 9.0
Little Indian Creek	8/13/2020	16:45 - 16:50	0.0 – 3.2
Little Blitzen River (part 1)	8/14/2020	15:27 - 15:30	0.0 – 17.7
Cold Spring Canyon	8/14/2020	15:44 - 15:55	0.0 -10.8
Dry Creek	8/14/2020	16:00 - 16:05	0.0 – 3.2
Lake Creek	8/14/2020	16:18 - 16: 26	0.0 – 6.7
Ankle Creek Headwaters	8/14/2020	16:47 - 16:52	13.2 – 14.1
Little Blitzen River (part 2)	8/15/2020	15:30 - 15:40	13.1 – 24.5

Deliverable Products

Table 2: Products delivered to the USGS.

<table>
<tr><th colspan="2">Donner und Blitzen River TIR 2020 Products
Projection: UTM Zone 11 North
Horizontal Datum: NAD83 (2011)
Vertical Datum: NAVD88 (GEOID12B)
Units: Meters, Celsius</th></tr>
<tr><td>Rasters</td><td>Thermal Infrared Imagery (0.3 m and 0.5 m resolution):
• Calibrated, rectified images (cell values = Celsius x 10) (*.tif)
• Calibrated imagery mosaics (cell values = Celsius x 10) (*.tif)
• True color 3-band imagery, tiled mosaics(*.tif)
• True color 3-band imagery, AOI mosaics (*.sid)</td></tr>
<tr><td>Vectors</td><td>Analysis Results Shapefiles (*.shp)
• Stream centerlines
• Accuracy assessment
• TIR image center points and sensor exterior orientation (EO)
• Longitudinal temperature profiles (LTP)
• Significant feature sites (SFS)</td></tr>
<tr><td>Supplemental</td><td>• “xlsx” folder contains longitudinal temperature profiles (LTP) and significant feature sites (SFS) 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 or *.tif)</td></tr>
</table>

Thermal Infrared and True-Color Imagery Acquisition Planning

Flight Planning and Timing

In preparation for data collection, NV5's team reviewed the project area and developed a specialized flight plan to ensure complete coverage of the Donner und Blitzen River study area. In agreement with the staff from the USGS, NV5 planned to acquire the data during afternoon hours (13:00 – 17:00 Pacific Daylight Time, GMT-7) to maximize the thermal contrast between the river water and the banks; timing also targeted clear skies and warm air temperatures. The flight plan was designed for a helicopter to follow the river channels at an altitude of 400-500 meters above ground level (AGL) to achieve a ground sampling distance (GSD) of 0.5 meter for the TIR imagery and 0.1 meter for the true-color imagery. The pilot and operator managed to safely fly as low as 150-meter AGL (but mostly within 200 to 300 m) and allowed the generation of TIR imagery at a resolution of 0.3-meter GSD.

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 (tail number N801CL). 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 1). 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 sensor array; however, differences in temperature (typically <0.5° C) might be observed near the edge of the image frame. Flight planning ensured sufficient image overlap so that frame edges could be excluded from the river channel in the TIR image mosaics. The acquired 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 using FLIR software. Sensor and acquisition specifications for the Donner und Blitzen River TIR study are listed in Table 3.

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 missions. The geographical coordinates of the aircraft were measured twice per second (2 Hz) by an onboard differential GNSS unit, while the orientation values were measured 200 times per second (200 Hz) from an onboard inertial measurement unit (IMU). Airborne 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 (1Hz) while maintaining an average flight speed of 50 knots and 200 – 300 meter flying altitude 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 Frame Rate	1 Hz (1 frame per second)
Acquisition Dates:	August 13th - 15th 2020
Flying Height Above Ground Level (AGL):	Planned for 300 meters
Image Ground Footprint Width:	200 – 300 meters
Ground Sampling Distance (GSD)	Planned for 0.5 meter Achieved at 0.3 meter

Figure 1: Sensor installation setup.

True Color Imagery Camera: Sony Alpha ILCE-7RM3

True-color (RGB) imagery was co-acquired during TIR acquisition using a Sony α 7R III, 42-megapixel camera. Image events were set for once every two seconds (0.5 Hz) to achieve forward lap ≥ 60%. At a flying altitude of 300 m AGL the Sony α 7R III achieved a GSD less than 10 cm. Camera specific parameters are detailed in Table 4.

Table 4: Sony Alpha ILCE-7RM3 camera specific parameters.

Sony Alpha ILCE-7RM3	
Focal Length:	40 mm
Spectral Bands:	RGB
Pixel Array:	7952 (H) x 5304 (V)
Pixel Depth	8bit
CCD Pixel Size:	4.6 µm
Field of View (FOV)	49° x 34°
Frame Rate:	1 per 2 seconds (0.5 Hz)
Acquisition Dates:	August 13th - 15th 2020
Flying Height Above Ground Level (AGL):	200 – 300 meters
Image Ground Footprint Width:	Approximately 200 meters
Ground Sampling Distance (GSD)	< 10 cm

Ground Control- Radiometric Calibration

Two sets of ground control data were required for thermal infrared radiometric calibration: in-stream water temperature and atmospheric parameters.

In-Stream Water Temperature Sensors

Water temperatures recorded by in-stream sensors are used to radiometrically calibrate the thermal signature of the imagery. A total of 29 stream temperature data loggers were deployed in the survey area by field crew from the USGS (Figure 2). The data loggers were placed along the mainstem of Donner und Blitzen River and major tributaries where flowing water was present. The data loggers recorded water temperature at intervals of 10 minutes or 1 hour.

Atmospheric Parameters

The atmospheric parameters required for the radiometric calibration are air temperature and relative humidity. Both parameters are commonly recorded by multiple weather stations across the state, three of which were nearby the survey area (listed in Table 5). Data were downloaded from the listed stations to support radiometric calibration.

Table 5: Weather stations nearby the survey area which were used for the TIR calibration process.

Weather Station	Identification Number	Longitude	Latitude	Elevation (m)
Harney County	KORCRANE2	-118.62	43.41	1254
West Burns01	KORBURNS28	-119.07	43.59	1278
Bohnert Paradise	KORBURNS23	-119.01	43.63	1268

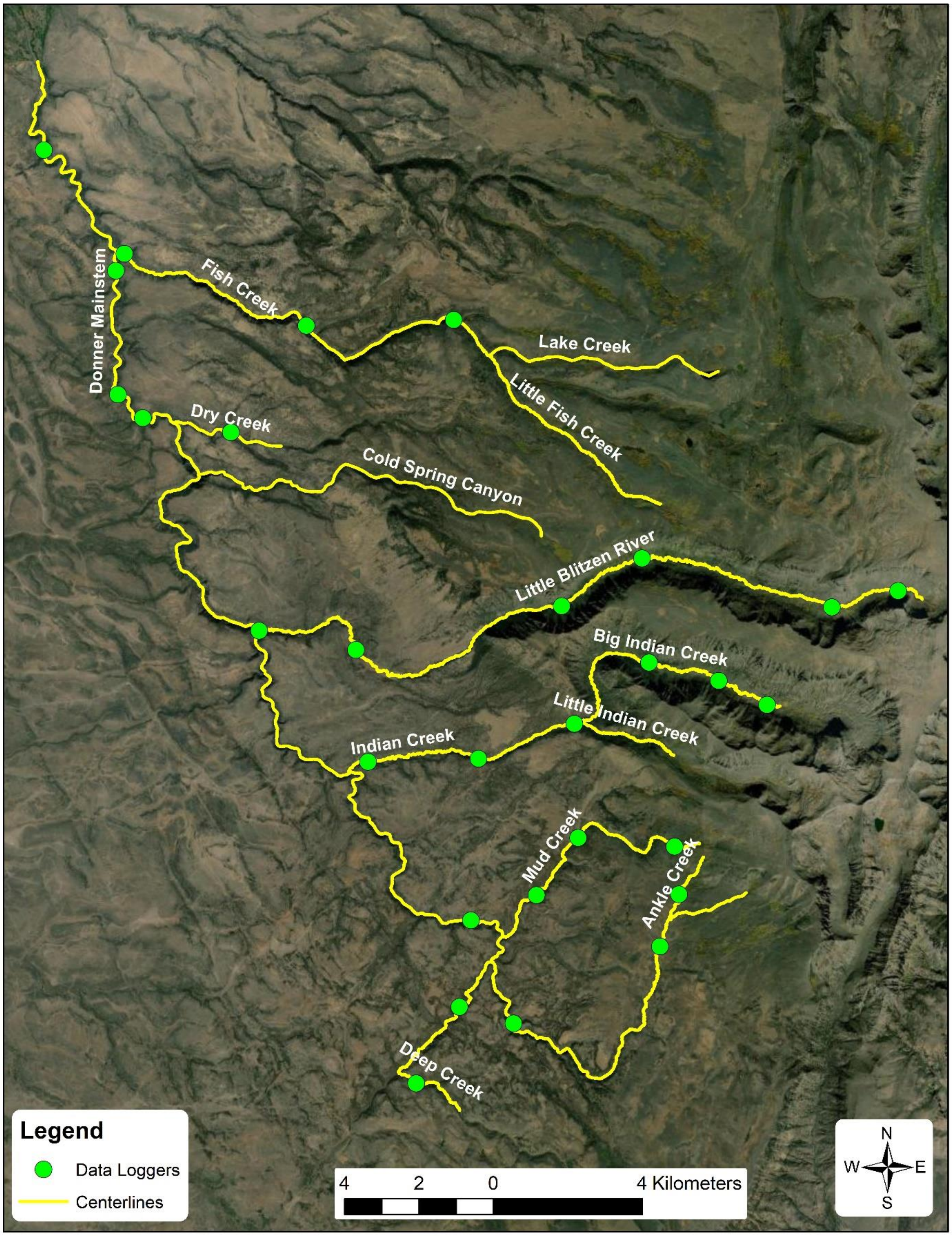

Figure 2: Map of survey area showing the centerlines of the surveyed tributaries and the location of water temperature data loggers. Background aerial imagery is a publicly available true color dataset.

Airborne Survey Execution

All contracted tributaries of the Donner und Blitzen River project were successfully acquired between August 13th – 15th, 2020 and within 13:00 – 15:00 PDT, covering a total river length of 159 km (Table 1). The aircraft was flown over the river where the active channel occupies the center of the frame. Multiple flight lines were flown for a handful sections, where the channel was wider than the image frame or as a precaution due to low flow in the channel. The mainstem of Donner und Blitzen River was flown starting from the downstream end of the river and ending at its headwaters; Deep Creek and all tributaries were flown in the opposite direction, starting at their headwaters (Figure 3). The majority of the tributaries were collected during two flight missions on August 13th, while a single mission was flown on August 14th and another on August 15th to complete the survey. The entire length of most tributaries was fully acquired on the same day with the exception of the headwaters of Ankle Creek and the upper section of Little Blitzen River. Ankle Creek was flown on August 13th and its headwaters area was reflown on August 14th due to a data gap that was identified during the routine post-flight imagery review. This data gap occurred because the water in channel was hardly visible on the operator's onboard monitor of the TIR sensor. The upper section of Little Blitzen (river km 13.1 – 24.5) was flown on August 15th as it was not acquired on the prior day due to data recording error during the flight. Lastly, the entire length of Fish Creek was acquired twice on August 13th, once while acquiring Little Fish Creek and once with Lake Creek. Only the data from the first attempt is used for the analysis; both TIR mosaics are provided.

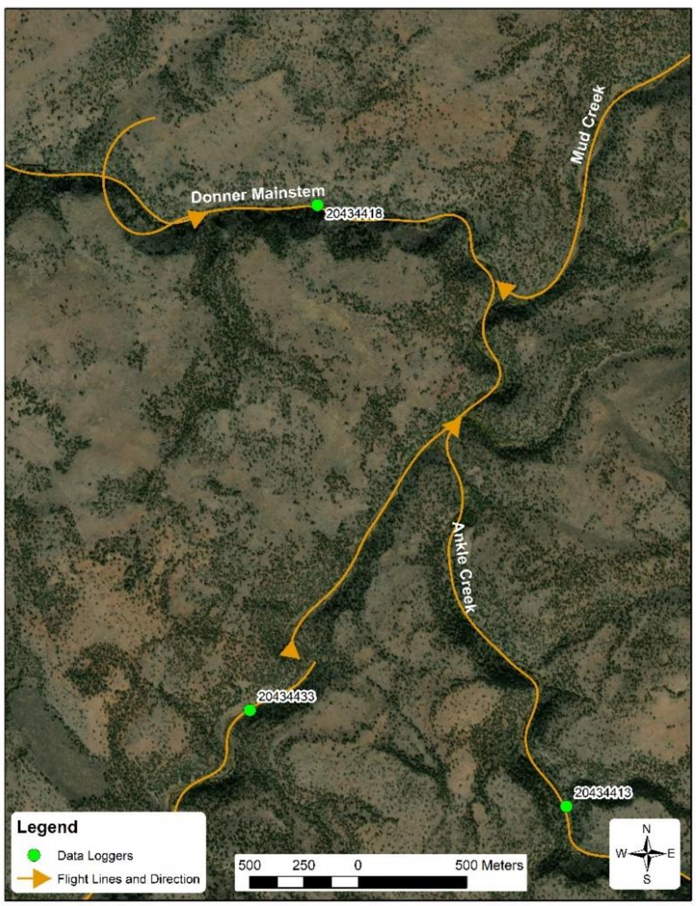

Figure 3: An example of flight lines and direction along the Donner und Blitzen River mainstem, Mud Creek, and Ankle Creek. Background imagery is a publicly available true color data.

Thermal Infrared Data Processing

TIR and RGB Image Mosaicking

Data processing for TIR and RGB images follows a similar workflow. 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 (or RGB images) were input into Inpho's OrthoMaster software to generate orthophotos using an NV5 previously collected LiDAR derived DEM surface at a 2-meter resolution (The LiDAR project was collected in 2020 for Oregon LiDAR Consortium and funded by USGS). 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. The RGB orthos were mosaicked using an automated global color balancing routine to achieve consistent tonality throughout the AOI (Table 6).

Table 6: List of software used in data processing.

Orthophoto Processing Step	Software Used
Calculate camera misalignment angles from a system boresight flight conducted close to the 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. The EO file contains a field of a serial number corresponding to the file name of each RGB with the same serial number.	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

Thermal Infrared Imagery Calibration

Response characteristics of the TIR sensor are measured in a laboratory environment. Response curves relate the raw digital numbers recorded by the sensor to emitted radiance from a black body. The raw TIR images collected during the survey initially contain digital numbers which are then converted to radiance temperatures based on the factory calibration. Thermal infrared radiation received at the sensor is the sum of emitted radiation from the water's surface (e), reflected radiation (r), and transmitted radiation.

$$emissivity + reflectivity + transmisivity = 1$$

This adjustment is performed to correct for attenuation path and the emissivity of natural water which is 0.98[1], reflectivity is 0.02 and transmissivity is 0. The calculated radiant temperatures are adjusted based on the kinetic temperatures recorded at each ground control location (water temperature data logger). The in-stream water temperature data are assessed at the time of image acquisition, with radiant values representing the median of ten points sampled from the image at the data logger location.

Temperature and Color Ramps

The final TIR mosaic contains pixel values of degrees Celsius multiplied by 10, values are stored in 16bit unsigned raster format which is much smaller in file size than a 32bit float format raster.

Temperature values of the river occupy a relatively narrow range of the full 16-bit histogram, thus visual representation of the imagery is enhanced by the application of a customized color ramp[2]. Color ramps also highlight different features relevant to the analysis such as spatial variability of stream temperatures and inflows (Figure 4). The color ramps for the TIR mosaics were developed to maximize the contrast for most surface water features and are unique to each tributary or mosaic. A TIR specialist at NV5 customized unique color ramps for each mosaicked reach of the river to improve visual presentation and exported the color ramps as ESRI *lyr files. Color ramps are an important product that is delivered to the end user.

[1] 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.

[2] A quick tutorial on how to use color ramps is included in the deliverables folder.

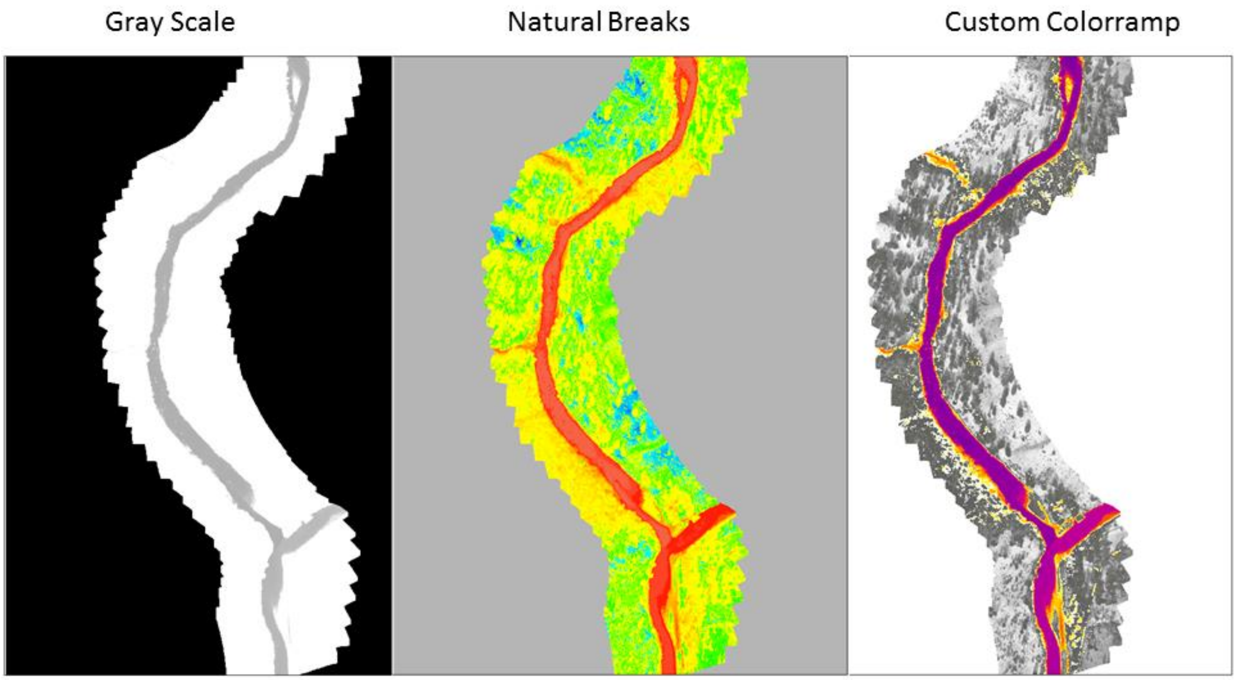

Figure 4: Examples of different color ramps applied to the same TIR image

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's location against the temperature recorded by the respective logger. The goal was to reach a mean absolute error (MAE) of ≤1.0 °C temperature differences between the mosaic and values recorded by the loggers at the time of TIR acquisition. Since it is not feasible to place data loggers for each flight line, in some cases line-to-line calibration was required (between adjacent flight lines) whereby water features in overlapping areas were used as reference, minor deviation from the initial calibration might be needed to achieve the best possible temperature continuity possible throughout the mosaic. Additionally, a single flight line may cover a river section along which multiple loggers were installed. In such scenario, only one logger was used for the calibration and the accuracy of the calibrated imagery was evaluated against the remaining data loggers.

Collecting the TIR imagery in relatively shortest time window possible is an advantage to minimize drift from initial calibration values due to diurnal fluctuation of stream temperatures. This is an important consideration both during the design of the flight plan as well as during the flight. Furthermore, the mosaic's accuracy relies on the recorded temperatures and deployment conditions of the data loggers. Deploying and configuring the data logger following the guidelines listed below is essential to achieving the best mosaic possible:

1) In flowing waters such as rivers or streams and not in pools or riffles sections.
2) In a water column deeper than 0.5 m 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 a 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) Deploying the sensor in shallow water, exposed to direct sun light which has the potential to skew the recorded temperature by representing the temperature of the streambed, or the sensor itself, which has been absorbing heat throughout the day.
8) Synchronize the data loggers using a single machine's timestamp across the survey area.
9) Setup the recording interval to 10 or 15 minutes and as instantaneous water temperature record.

Note: thermal infrared sensors only detect the heat signature at the surface of the object. Water is opaque to longwave radiation, so the only thermal infrared signal emitted from the water body is at its surface. Additionally, it can be assumed that the water column is thoroughly mixed in flowing streams and rivers less than 3 meters in depth.

Assessing the mosaic's accuracy becomes challenging where the logger is positioned in narrow channels, in sections of heavy overhanging canopy, or between boulders. In such sites, 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. An example of this phenomenon is data logger #20131045 deployed in Little Blitzen River, where the channel is narrow (Figure 5 and Figure 6).

The logger's position in most cases is recorded using handheld GPS units with positional uncertainty of a few meters. This error introduces another source of inaccuracy unless the logger's position is corrected based on the TIR imagery which is generated using survey grade positioning system. Adjusting the position relies on information from the field crew, or the client if the latter is providing the data, to accurately position the logger in the stream (Figure 7).

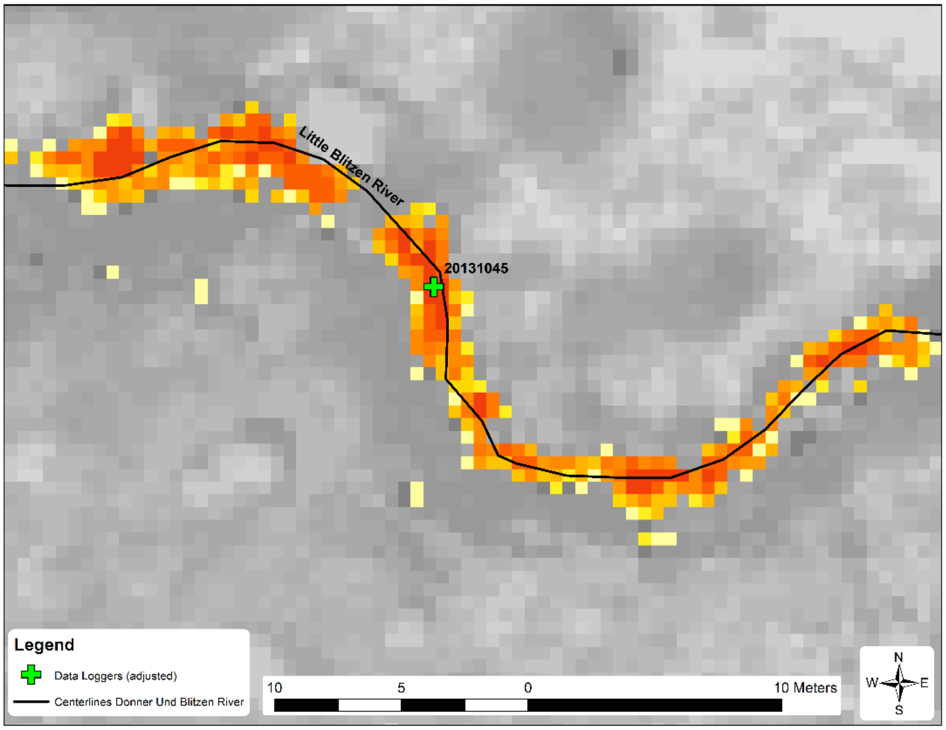

Figure 5: TIR imagery showing data logger #20131045 deployed along the Little Blitzen River's narrow channel.

Figure 6: True color imagery showing data logger #20131045 deployed along the Little Blitzen River's narrow channel.

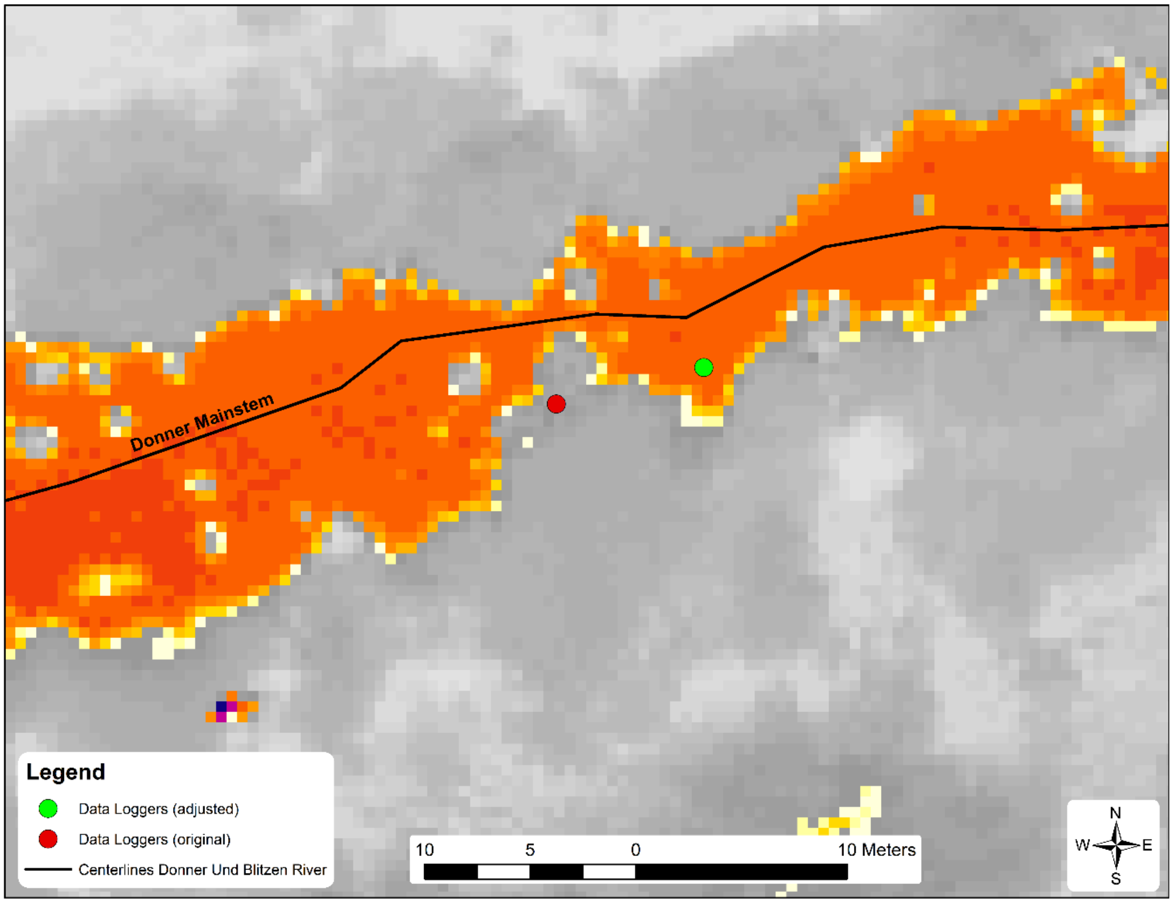

Figure 7: This image shows the original position of the data logger (red) and its adjusted position (green) - logger # 20130933 is near river km 28.8 of the Donner und Blitzen River mainstem.

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 and the locations 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 length of the contracted rivers. As the streams were digitized, care was taken to avoid as many non-water features as possible; however, due to the nature of the streams, aquatic vegetation, boulders, bridges, and other obstructions this could not always be avoided. River lengths were measured cumulatively from the most downstream point in the 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.

Thermal Infrared Mosaic Sampling and Interpretation

Two analysis techniques were used to interpret the TIR data: an interval-based automated sampling of the stream, longitudinal temperature profile (LTP), and a manual point source sampling, significant feature sites (SFS).

Longitudinal Temperature Profile (LTP)

Longitudinal temperature profile (LTP) is a technique in which the water temperature sampled (extracted from the TIR data mosaic) along the digitized centerline of stream. The LTP assists in identifying temperature gradient in the stream and changes due to potential influence of water inflows (tributaries, springs, groundwater upwelling, effluents, etc.). Using a proprietary algorithm, water temperature is sampled at a specified interval along the centerline where statistical data are provided for each temperature sample within a buffered distance (Figure 8). The statistical information includes mean, median, maximum, minimum, and standard deviation of the stream's temperature. Due to the nature of the automated sampling, some sample points inevitably fall on bridges or non-water features skewing the temperatures. These points can be identified as outliers by a high standard deviation and can be excluded from the final LTP. The resulting temperatures are plotted against river kilometers to develop the final LTP.

Significant Feature Sites (SFS)

Significant feature Sites (SFS) is a technique in which features of significant thermal anomalies in the TIR mosaic are identified and sampled to collect their statistical information. Such features may indicate a potential inflow from tributaries, springs, or an expression of subsurface activity or hyporheic inflow. The features are manually identified across the floodplain and the riparian zone where their thermal signature is higher or lower than the river's mainstem (Figure 9). The SFS is provided in two file formats: a shapefile and an *.xlsx table. The point attributes in either format summarizes pixel values within a specified buffer around each location. Due to the nature of the springs and seeps and the scale at which the points were digitized, the statistics for smaller features inevitably include non-water pixels and might impact the statistical summaries. On the contrary, larger features will be under sampled. As such, the entirety of the statistical information should be considered in the analysis. The statistical information includes mean, median, maximum, minimum, and standard deviation of the feature's temperature. The findings were incorporated with the LTP plot to provide spatial context for interpreting temperature patterns.

Calculated Statistic Parameters for LTP and SFS

For the LTP dataset, each sampling point along the centerline holds information summarizing the statistical parameters of the 10 points along the centerline within the defined buffer (Figure 8). The sampling interval is 10 meters and the radius buffer for statistical analysis is 2 meters. The parameters are:

- **Mean and median**: define the mean and median temperature values of all 10 sampled points. The mean temperature is the value used in plots and figures. Median values can be used for further analyses and to identify outlier sampling points.
- **Minimum and maximum**: define the minimum and maximum temperature values among all sampled points.
- **Standard deviation**: defines the standard deviation across all sampled points. This value is important to identify sample points where non-water features fall within the defined buffer. While low standard deviation values represent homogeneous thermal features, high standard deviation indicate that the sample point was too close to a feature at temperature significantly different than the water body. The value of standard deviation is important in selecting invalid sampling points.

For the SFS dataset, each sampling point holds the information summarizing the statistical parameters of all pixels which are contained the 1-meter radius buffer (Figure 9). The list of statistical values is similar to the LTP's list.

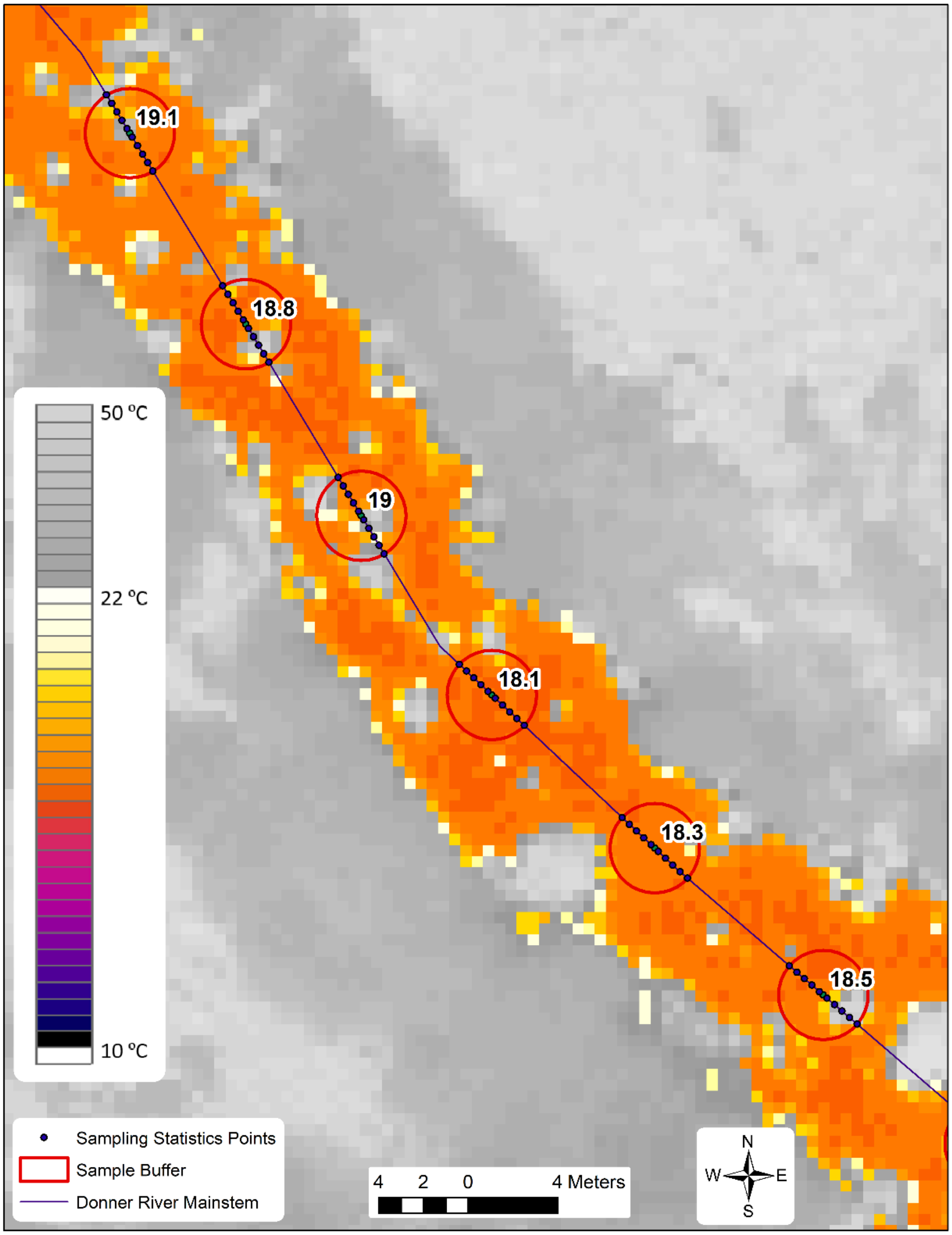

Figure 8: TIR image shows an example of the longitudinal temperatures sampling profile along the stream's centerline. Median water temperature is displayed along the stream's centerline (in °C).

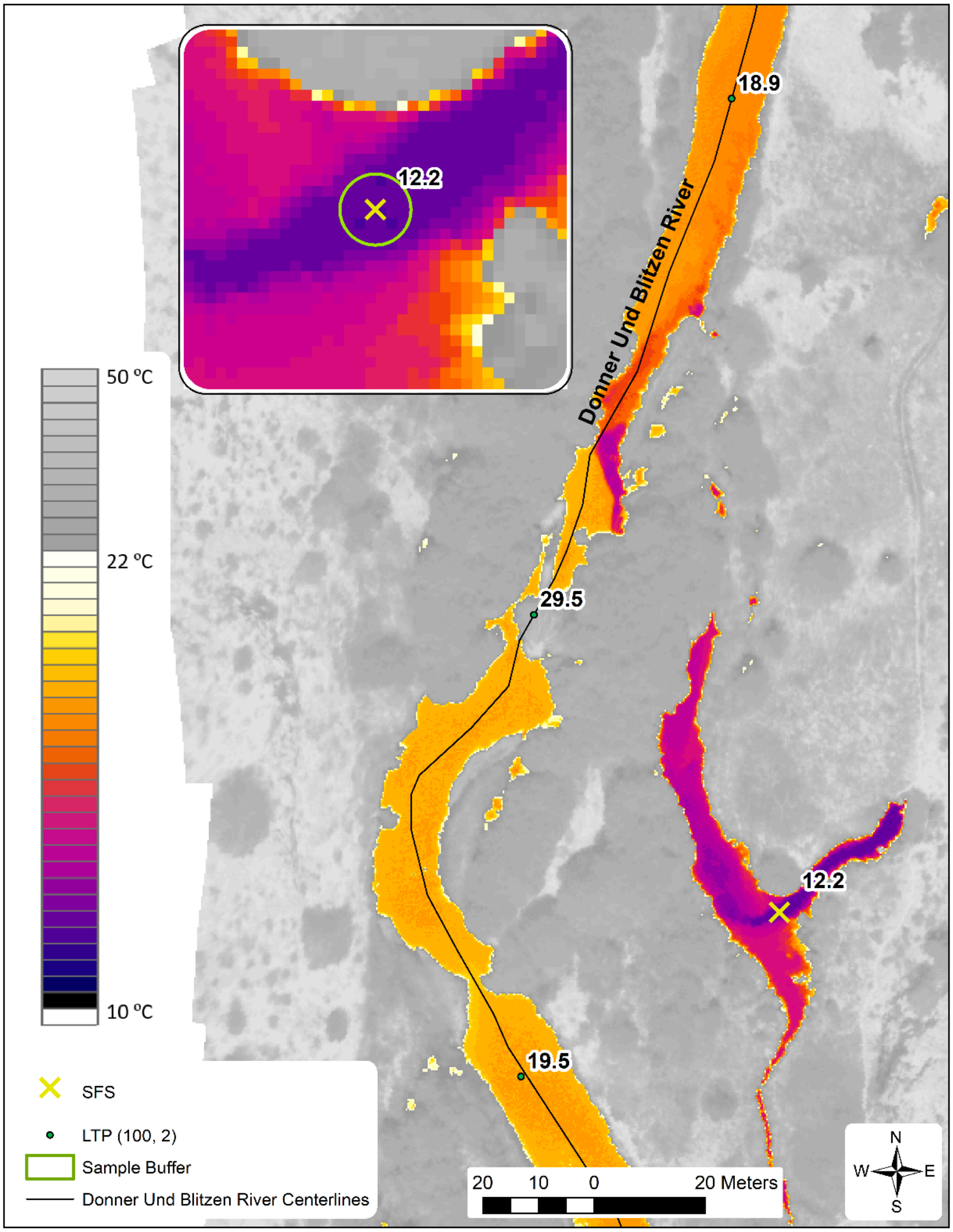

Figure 9: TIR image showing an example of the location and temperature of significant feature sites (SFS) along the Donner und Blitzen River mainstem at river km 1.6. Water from a spring appears to flow into the main channel at temperature of 12.2 °C. The median water temperature in Donner und Blitzen River decreased from 19.5 to 18.9 °C as a result (River flows from south to north).

Table 7: Summary of the processing and analyses steps used in the thermal infrared 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 imagery	*<TIMESTAMP >.tif*	Incorporate the spatial location and sensor's orientation into creating orthorectified imagery. The file name of each TIR image corresponds to the time it was taken (UTC time format).	OrthhoVista -or- AgiSoft
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 intervals. Each point was assigned a river kilometer measurement and the TIR radiant temperature was sampled based on an average of 2-meter sample radius buffer out from the center point along the centerline.	ArcMap v. 10.5 NV5 script
Identify and sample significant features sites	*SFS_<STREAM>.shp*	Manually digitize and sample significant features. The sampling utilizes NV5's customized tools for 1-meter radius buffer.	ArcMap v. 10.5 NV5 script
Plot longitudinal profiles	*LTP_SFS_<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-of-relevance to the project's objectives. The analysis reviews the stream's longitudinal temperature profile, features at the edge of the water, as well as point source and non-point source inflows (tributaries, side channels, groundwater upwelling, seepage, effluents, springs, hyporheic) in the floodplain. Identifying such features relies on visual inspection by a trained analyst and automated sampling algorithms. While the visual inspection is qualitative, it requires professional judgement to identify the span of river water temperature and isolate 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 longitudinal temperature profile (LTP) and the significant feature sites (SFS). Both datasets are provided in spatial (shapefile) and tabular formats. The LTP's statistical results are then used to generate graph and plots of stream temperatures against river distance. The SFS's results are also incorporated with the LTP plot to provide spatial context for interpreting temperature gradients and patterns.

Accuracy Assessment Results

TIR imagery was calibrated based on in-stream water temperature data from the loggers that were deployed in the streams. The final mosaic is considered within the specified accuracy requirements when the mean absolute error (MAE) is ≤1.0 °C. The accuracy assessment is based on the data recorded by all data loggers covered by each stream section or mosaic.

Worth noting for the calibration and accuracy assessment for the Donner und Blitzen project:

1- Water temperature recording intervals: the provided data loggers recorded water temperature at one of two intervals: every 10 minutes for some and every 1 hour for others. While TIR imagery was acquired at 1Hz (1 frame per second) and flight lines lasted anywhere between 1 minute to several minutes, the 10-minute interval is most suitable to calibrate TIR imagery and to generate mosaics at higher accuracy. For TIR imagery calibration based on 1-hour interval, calibrated flight lines could have occurred between recorded water temperature, timewise. Therefore, there is a potential of generating a less accurate final mosaic when compared to the recorded water temperature.

2- Narrow channels: deploying the water temperature loggers in narrow channels can lead to inaccurate temperatures in the final mosaics due to temperature sampling uncertainty. Since the accuracy assessment relies on extracting the values of pixel contained within 1-meter radius buffer – similar to the method of significant features sites, there is a higher chance of sampling TIR pixels of non-water features such as the stream banks, boulders, or overhanging canopy. As a result, inaccurate statistical values might be derived. An example is Ankle Creek which mostly flows in a narrow channel that does not exceed 2 meters (Figure 10 and Table 8). In this case the mean sampled pixels within the 1-meter buffer are 3.6 ^{o}C warmer than the water temperature recorded by the data logger.

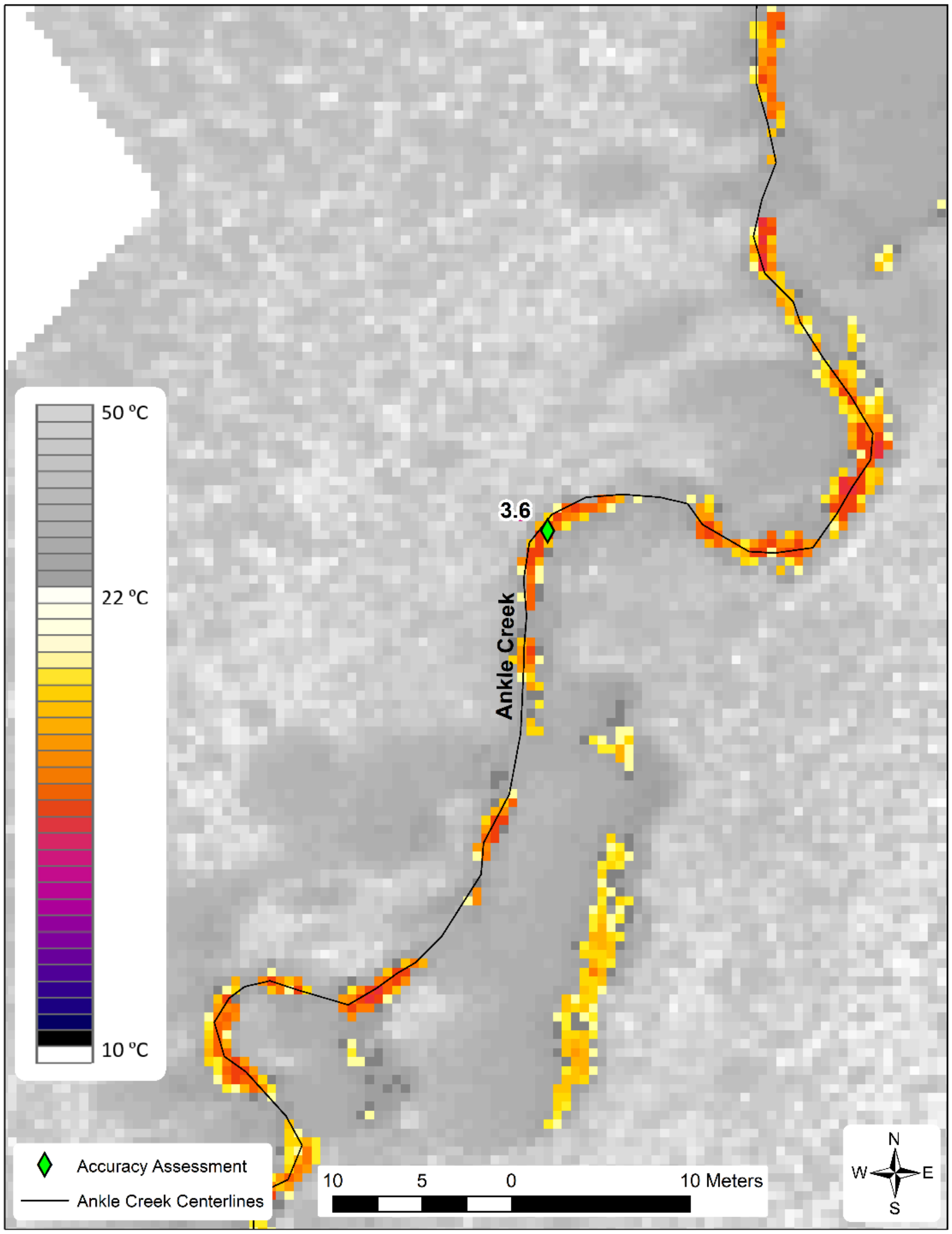

Figure 10: TIR map showing the location of data logger #20130917 at river km 10.77 of Ankle Creek as well as error value of +3.6 °C between the final mosaic and the logger's recorded water temperature.

Table 8: accuracy assessment for Ankle Creek showing high error value due to deploying the logger in a narrow channel.

Date / Time	Water Temperature (°C)	Logger #	Flight Line #	Mean Mosaic Temperature (°C)	Error (°C)
20200813 16:00	11.2	20434429	281	18.4	7.2
20200813 17:00	19.9	20434413	281	21.3	1.4
20200813 16:20	15.9	20130917	281	19.5	3.6

3- Selected data logger for calibration: While a flightline may cover multiple data loggers, only one is required to calibrate the entire flightline; the final mosaic is checked against all relevant data loggers for accuracy assessment. All water temperature data loggers are assumed to have been uniformly calibrated and minor accuracy variability is excepted. There are, however, situations where the accuracy varies significantly which can be attributed to a number of factors:
    a. The logger(s) were deployed in a narrow river channel site leading to incoherent mosaic sampling (Figure 10).
    b. Data loggers are recording at different time intervals leading to misalignment in water temperature. This is the result of the diurnal fluctuation of water temperature in streams.
    c. The distance between data loggers and the travel time for the aircraft between loggers' sites within the same flightline. This is the result of the diurnal fluctuation of water temperature in streams.

4- Splitting flightlines: A single flightline can be split into different sections if it covers two or more tributaries containing their own data loggers. This is the case for Big Indian Creek and Indian Creek where both were covered by flightline #285 from the headwaters to the confluence with Donner und Blitzen River. The flightline was split into two sets of images, each of which was calibrated separately using the relevant data loggers (3 data loggers for each tributary). The final mosaic for Big Indian Creek covered 3 data loggers that were deployed in Big Indian Creek and a fourth that was deployed in Indian Creek. The accuracy assessment showed that Big Indian Creek's mosaic met the accuracy threshold for the 3 data loggers deployed within the tributary's extent, while it had high error when compared to the one deployed in Indian Creek (Table 9). These results suggest excluding data logger # 20434416 from the accuracy assessment of Big Indian Creek.

Table 9: accuracy assessment for Big Indian Creek showing high error value due to deploying the logger in a narrow channel. The final accuracy assessment for Big Indian Creek should exclude logger #20434416.

Date / Time	Water Temperature (°C)	Logger #	Flight Line #	Mean Mosaic Temperature (°C)	Error (°C)
20200813 17:00	13.4	20130993	285	13.7	0.3
20200813 17:00	13.3	20434425	285	13.2	-0.1
20200813 17:00	14.0	20434416	285	16.9	2.9
20200813 17:00	17.1	20130970	285	17.6	0.5

Given the abovementioned stipulations, the methodology for accuracy assessment was revised and has been expanded beyond the standard approach. While the standard approach used the mean temperature value of the mosaic's sampled pixels within the 1-meter buffer to calculate the mean absolute error (MAE) and the root mean square error (RMSE), the revised accuracy assessment also includes the calculated values of MAE and RMSE from the median pixel values and the minimum pixel values within the 1-meter buffer (Table 10).

Table 10: Error values between radiant temperatures derived from the TIR mosaic and kinetic water temperature recorded by in-stream data loggers.

Mosaic / Tributary	Error Assessment	Error Value Mean (°C)	Error Value Median (°C)	Error Value Minimum (°C)
01 Donner Blitzen mainstem	Mean	-0.1	-0.1	-0.2
	MAE	0.2	0.2	0.2
	RMSE	0.2	0.3	0.3
02 Deep Cr.	Mean	0.1	0.0	-0.2
	MAE	0.1	0.0	0.2
	RMSE	0.0	0.0	0.0
03 Ankle Cr.	Mean	4.1	3.8	2.4
	MAE	4.1	3.8	2.4
	RMSE	4.7	4.6	3.7
05 Mud Cr.	Mean	2.7	2.2	0.3
	MAE	2.7	2.2	0.3
	RMSE	2.9	2.4	0.4
06 Indian Cr.	Mean	0.5	0.2	-0.1
	MAE	0.5	0.2	0.1
	RMSE	0.6	0.2	0.1
07 Big Indian Cr.	Mean	0.9	0.5	0.1
	MAE	1.0	0.6	0.5
	RMSE	1.5	0.9	0.6
09a Little Blitzen River (Aug 14)	Mean	0.6	0.5	0.4
	MAE	0.6	0.5	0.4
	RMSE	0.7	0.7	0.6
09b Little Blitzen River (Aug 15)	Mean	1.1	0.0	-0.8
	MAE	1.1	0.6	1.0
	RMSE	1.1	0.6	1.4
12a Fish Cr.	Mean	1.3	1.1	0.8
	MAE	1.3	1.1	1.1
	RMSE	1.6	1.4	1.2

Longitudinal Temperature Profiles and Significant Features Sites

The longitudinal temperature profile (LTP) is an informative tool to detect stream temperature gradients and the response to water inflow sources, geomorphological drivers, physical and biological (effective shade by topography and riparian vegetation), and atmospheric conditions. It is common to plot the sampled mean or the median stream temperature against river length, though the other calculated statistical information (especially the median) can be more suitable for narrow and channels intermittent flow in order to exclude non-water features. Additional approach to exclude non-water features is by excluding results of high standard deviation and high minimum/maximum temperatures. The final LTP data excludes most of the non-water features that were accidentally sampled by the automated algorithm. However, further refinement might be required by the end user based on local information and familiarity with the survey area. The LTPs that are presented in this analysis were generated from a 10-meter interval and a 2-meter buffer along the digitized centerlines of each tributary and non-water features were excluded as possible.

Significant feature sites (SFS) were identified based on their unique thermal signature and proximity to the active channel. The SFS dataset assists in explaining changes to the longitudinal temperature profile in response to water inflow sources such as tributaries, springs, hyporheic zones, or side channels. The majority of identified SFS were at temperatures colder than the mainstem mostly leading to a cooling gradient or a thermal stability. Nevertheless, warmer tributaries or side channels were also identified. A comprehensive version of the data was also plotted to include both the LTP and the SFS along the tributary's channel. The sampling method of SFS summarizes the statistical values of all mosaic's pixels within 1-meter buffer around the point of the identified feature.

The analysis was successful for the mainstem and the major tributaries where the active channel was sufficiently wide to sample the mosaic. LTP sampling was configured to sample the mosaic along the centerline at a 10-meter interval and a 2-meter radius buffer. SFS sampling was configured to sample the mosaic within 1-meter radius buffer from the manually identifies feature point. The LTP sampling results were filtered to exclude sampling points that could have fallen on non-water features such as overhanging vegetation, boulders, logs in the channel, and similar objects. Points with a standard deviation higher than 0.5 °C and a minimum of 21 °C.

Donner und Blitzen River Mainstem

A total of 44.7 km section of Donner und Blitzen River mainstem was flown on Aug 13, 2020. Its centerline was digitized and the longitudinal temperature profile (LTP) was sampled at a 10-meter interval. A total of six (6) tributaries flow into the mainstem were sampled in addition to 13 significant feature sites (SFS) which were identified along the river's banks (Figure 11). The LTP for the Donner und Blitzen River shows alternating downstream warming and cooling gradients. The downstream warming gradients are common and can be attributed to the solar loading and heat exchange between the water in the channel and the air along the course of the river. However, the cooling gradients were the result of cold-water inflows from tributaries (such as Ankle Creek and Mud Creek) and mostly coincided with the identified cold springs and seepages along the river (such as the inflow at river km 14.6, just downstream of Dry Creek, shown in Figure 12). The median temperature of the identified inflow was 12.1 °C, while the mainstem's temperature was 17.4 °C and resulted in reducing the river temperature to 16.9 °C. LTP results and thermal infrared mosaics showed a number of tributaries contributed warmer water to Donner und Blitzen River (Indian Creek and Little Blitzen River).

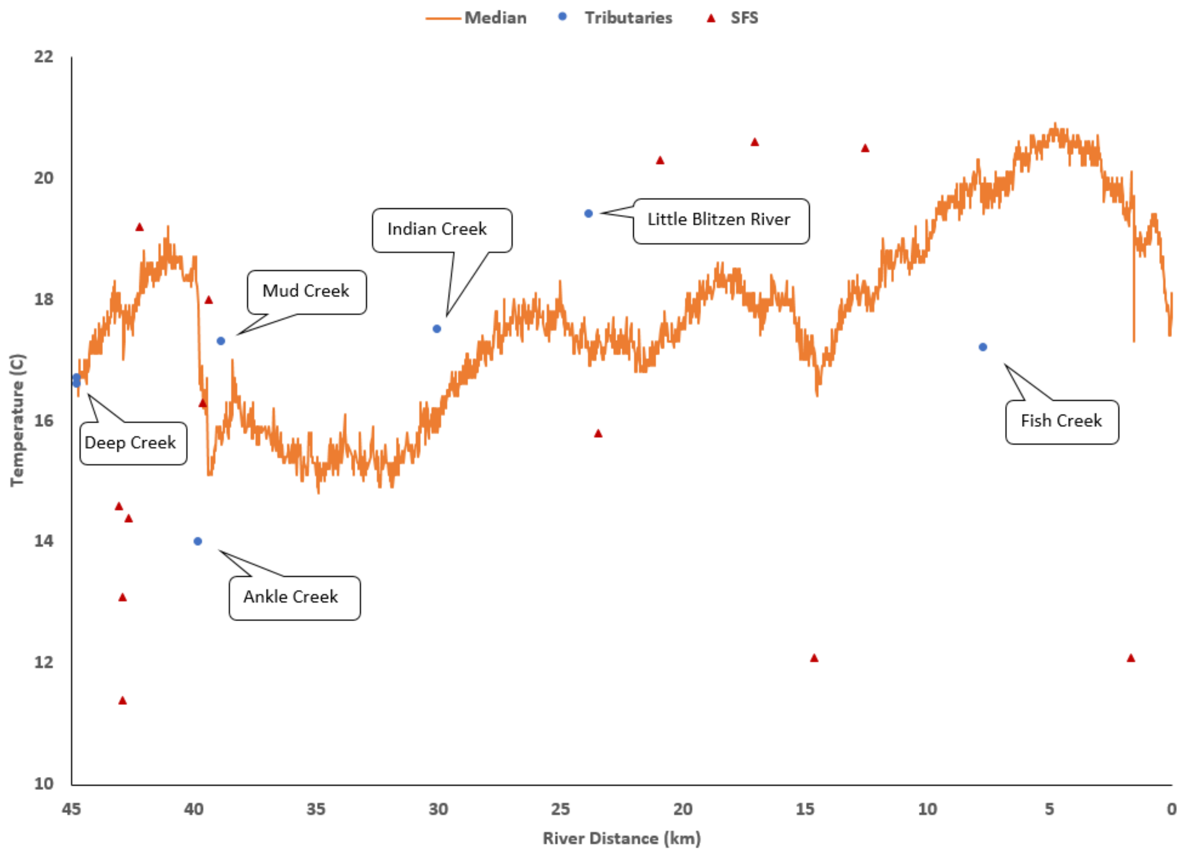

Figure 11: Longitudinal temperature profile (LTP), tributaries, and identified significant feature sites (SFS) plotted against river length for the Donner und Blitzen River mainstem. Data points in the plot are those of the median sampled water temperatures of the sampled pixels of the mosaic.

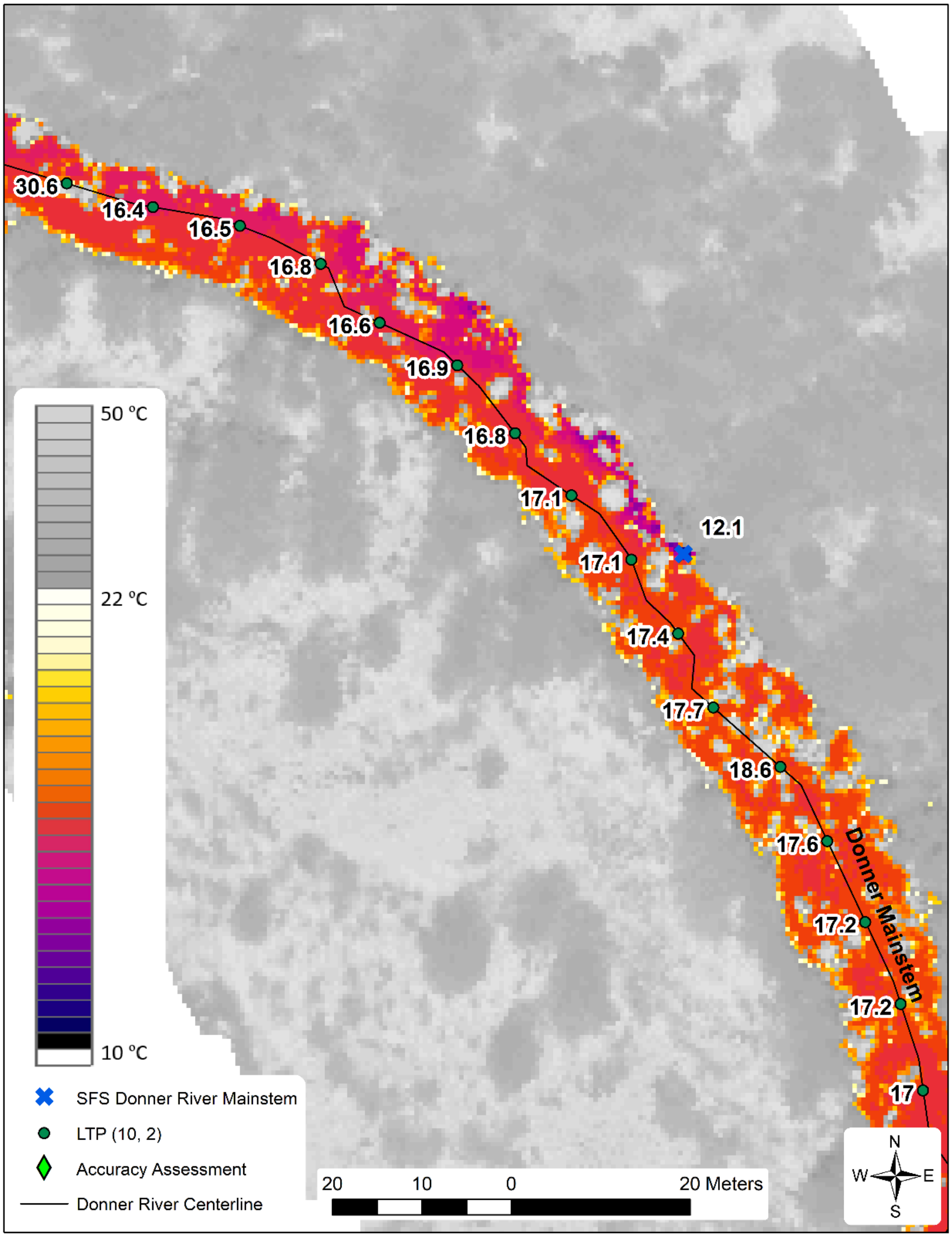

Figure 12: Thermal infrared map for a cold-water inflow (at 12.1 °C) entering the mainstem Donner und Blitzen River which was flowing at ~17.2 °C. The identified inflow was at river km 16.4.

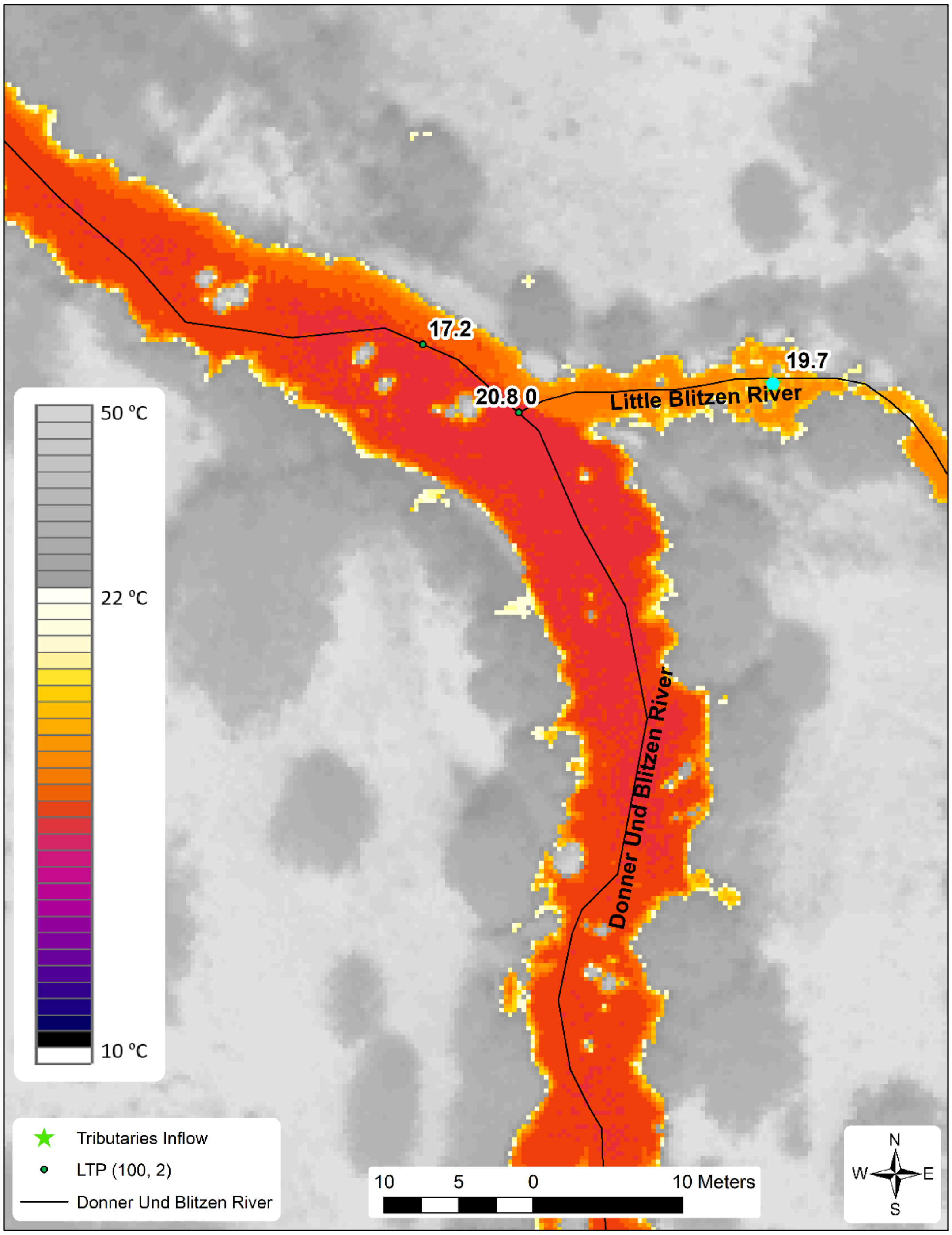

Figure 13: Thermal infrared map showing the warm water of Little Blitzen River flowing into Donner und Blitzen River. Little Blitzen flowed at temperature of 19.7 °C, while Donner und Blitzen River was ~17.2 °C.

Deep Creek

A total of 2.5 km section of Deep Creek was flown on Aug 13, 2020. Its centerline was digitized and sampled for LTP at a 10-meter interval before filtering out sampling points that fell on non-water features. There were no identifiable SFS across the surveyed section of Deep Creek. The refined LTP plot (Figure 14) shows a relatively subtle warming gradient along Deep Creek where the water temperature started at 16 °C upstream and reached 17 °C at the confluence with Donner und Blitzen River (Figure 15).

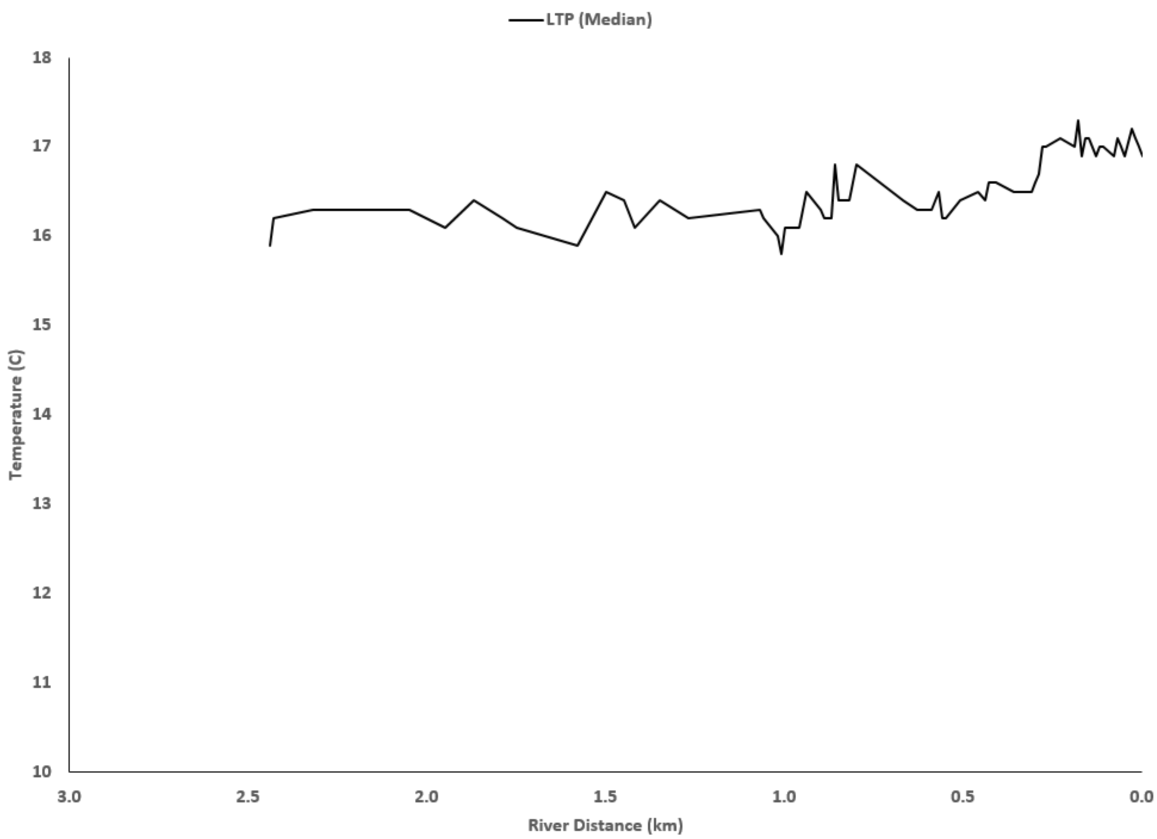

Figure 14: Longitudinal temperature profile (LTP) for Deep Creek.

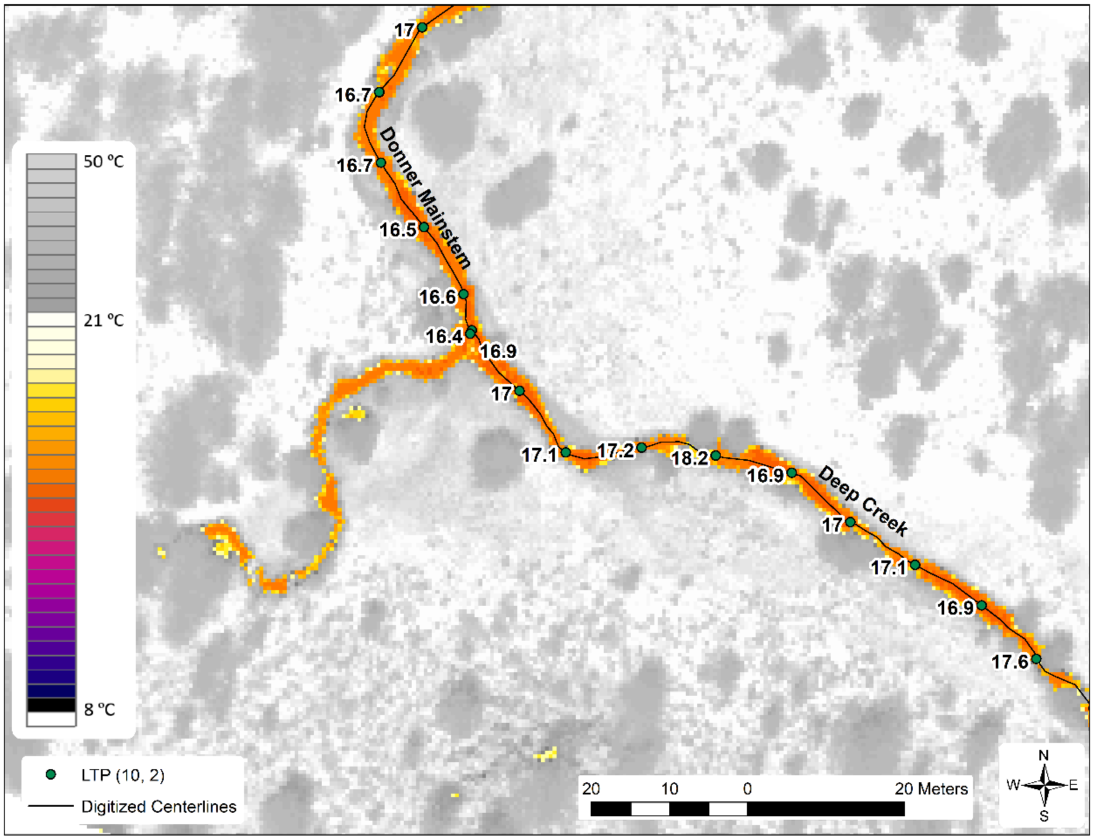

Figure 15: Thermal infrared map showing Deep Creek flowing into Donner und Blitzen River as the main source of flow.

Ankle Creek and East Ankle Creek

A total of 14.1 km section of Ankle Creek and 2.5 km section of East Ankle Creek were flown on Aug 13, 2020. Its centerline was digitized and sampled for LTP at a 10-meter interval before filtering out sampling points that fell on non-water features. Water was not easily detectable along the section upstream of river km 10.5 due to low flow, narrow channel, and overhanging vegetation (Figure 16). Therefore, most of the LTP's sampling points were removed. Ankle Creek appears to have a rapid warming gradient especially after the cold inflow from East Ankle Creek at river km 11.9 and the meandering channel section between river km 10.5 and 9.8. Potential cold inflow seepage and springs were identified along the course of the surveyed section. An example is at river km 4.0 were the inflow was at temperature 16 – 18 °C while water in the creek was 20 – 21 °C (Figure 18). The response was localized and noticeable as water temperature dropped but increased again along the downstream section.

There was not enough noticeable flow along the surveyed section of East Ankle Creek to generate an informative plot. A handful number of SFS were identified and were colder than the water found in the channel (Figure 17).

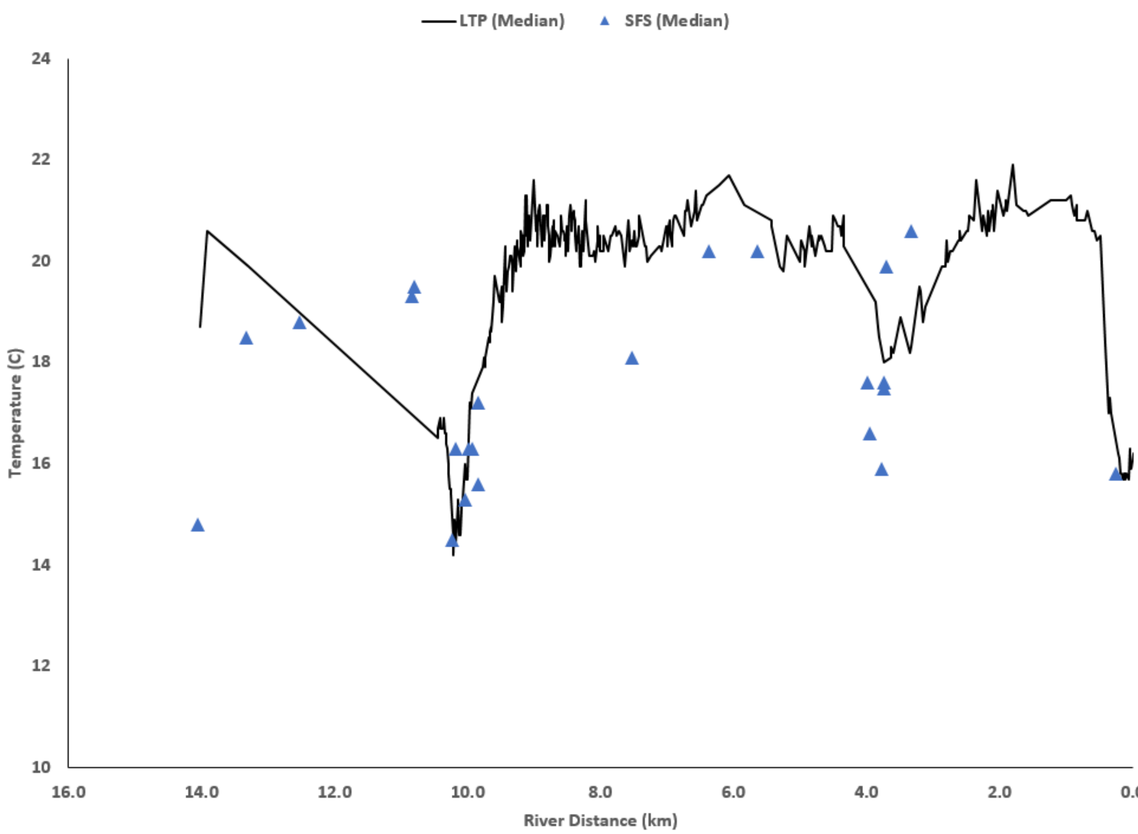

Figure 16: Longitudinal temperature profile (LTP) and identified significant feature sites (SFS) plotted against river length for the Ankle Creek.

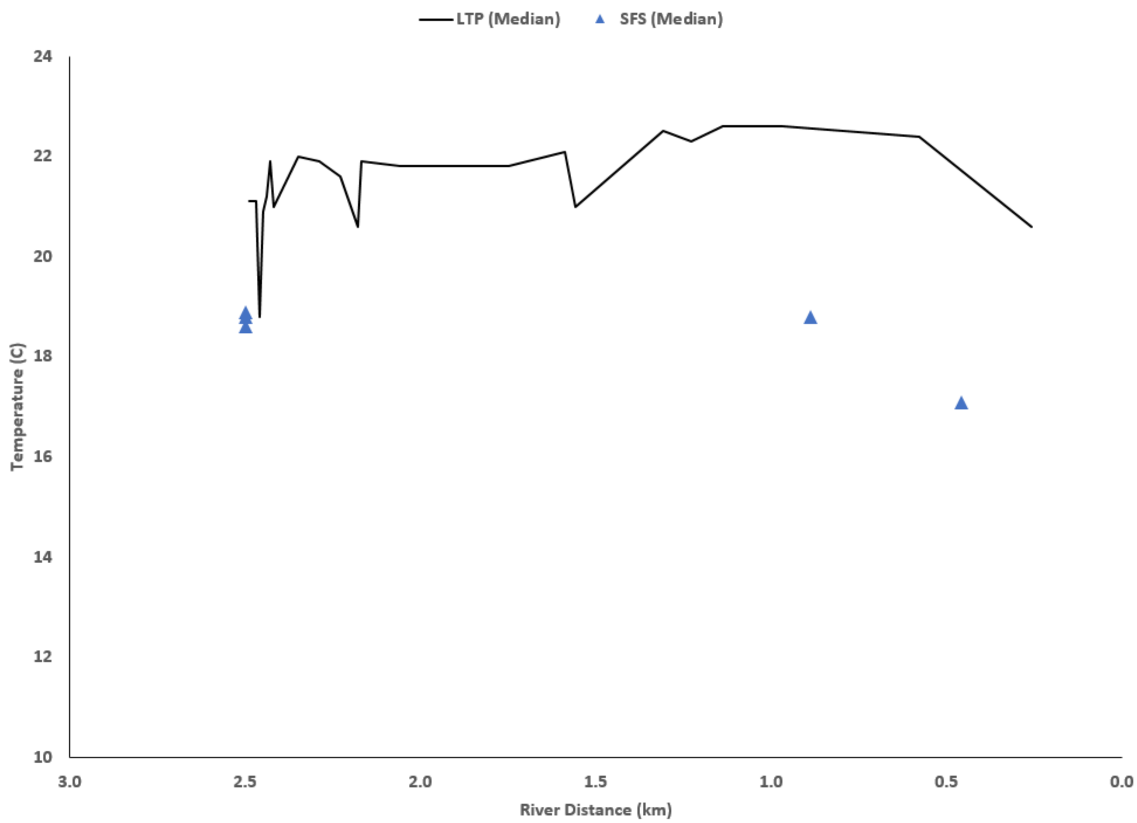

Figure 17: Longitudinal temperature profile (LTP) and identified significant feature sites (SFS) plotted against river length for East Ankle Creek.

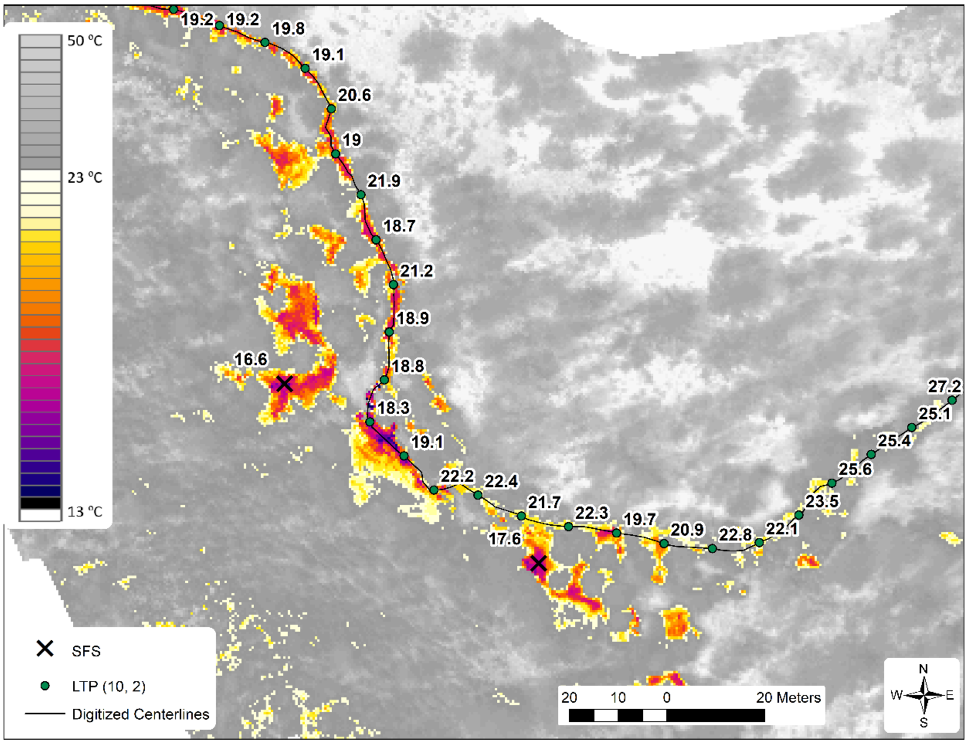

Figure 18: Thermal infrared map showing cold inflow points from potential seepage along river km 4.0.

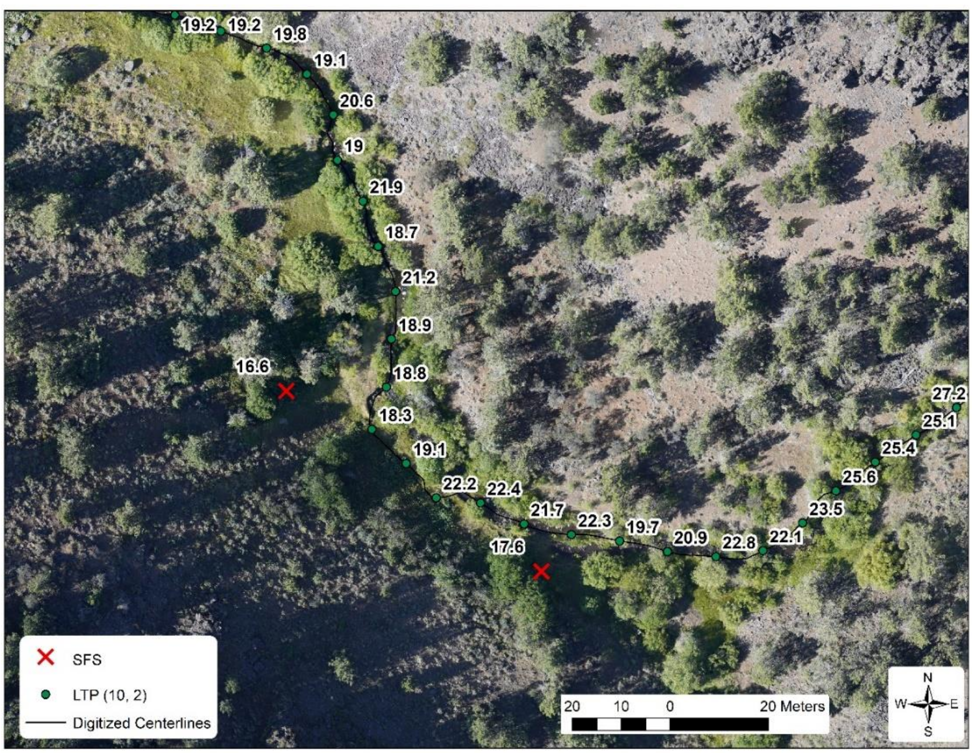

Figure 19: visible color imagery showing the sites of potential cold inflow points to Ankle Creek at river km 4.0. Although the identified points coincide with tree-shaded areas, the creek's response of cooling water in the channel confirms cold seepage inflows.

Mud Creek

A total of 9.1 km section of Mud Creek was flown on Aug 13, 2020. Its centerline was digitized and sampled for LTP at a 10-meter interval before filtering out sampling points that fell on non-water features. Water was not easily detectable along the section making it impossible to identify any thermal gradient along the section (Figure 20). The manually identified and sampled SFS points (Figure 21) provide a general understanding of the water temperature range flowing in the channel during the summer survey which ranges between 14 and 20 °C (example is shown in Figure 22).

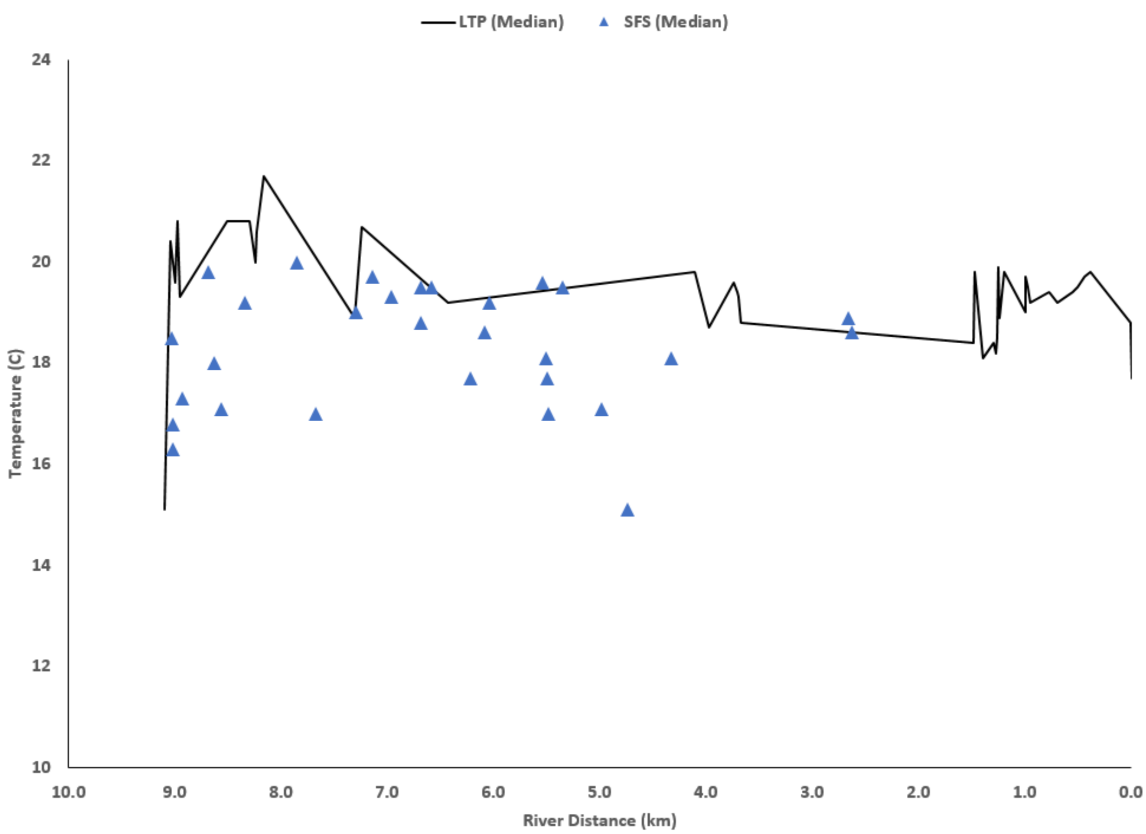

Figure 20: Longitudinal temperature profile (LTP) and identified significant feature sites (SFS) plotted against river length for Mud Creek. Data points in the plot are those of the median sampled water temperatures of the sampled pixels of the mosaic.

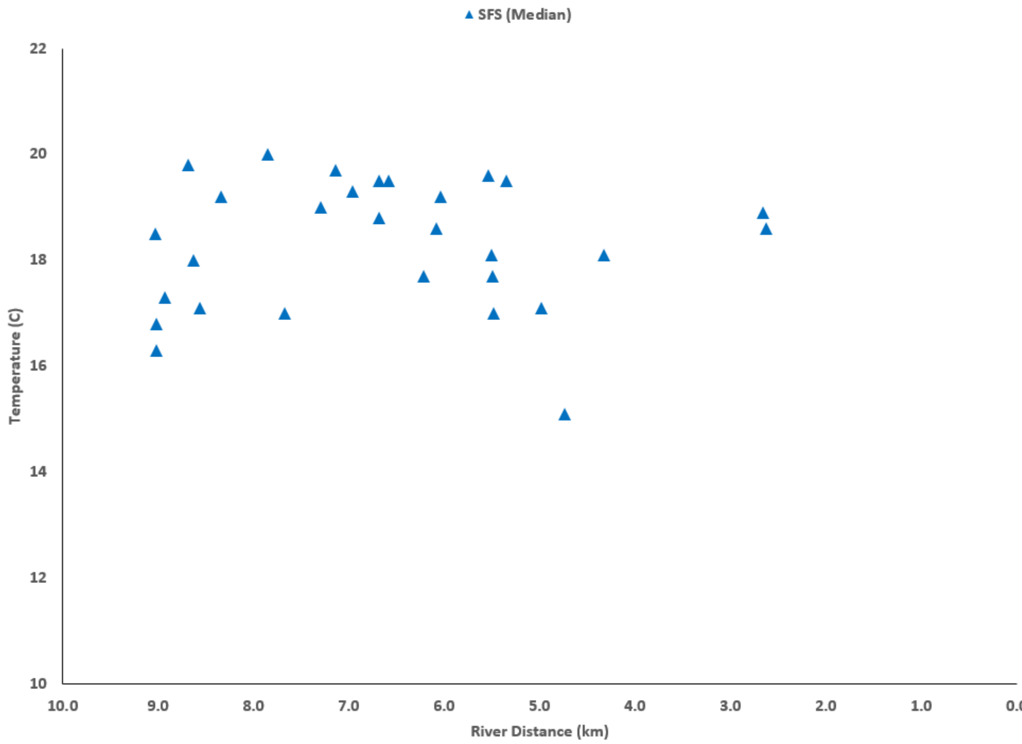

Figure 21: Identified significant feature sites (SFS) plotted against river length for Mud Creek. Data points in the plot are those of the median sampled water temperatures of the sampled pixels of the mosaic.

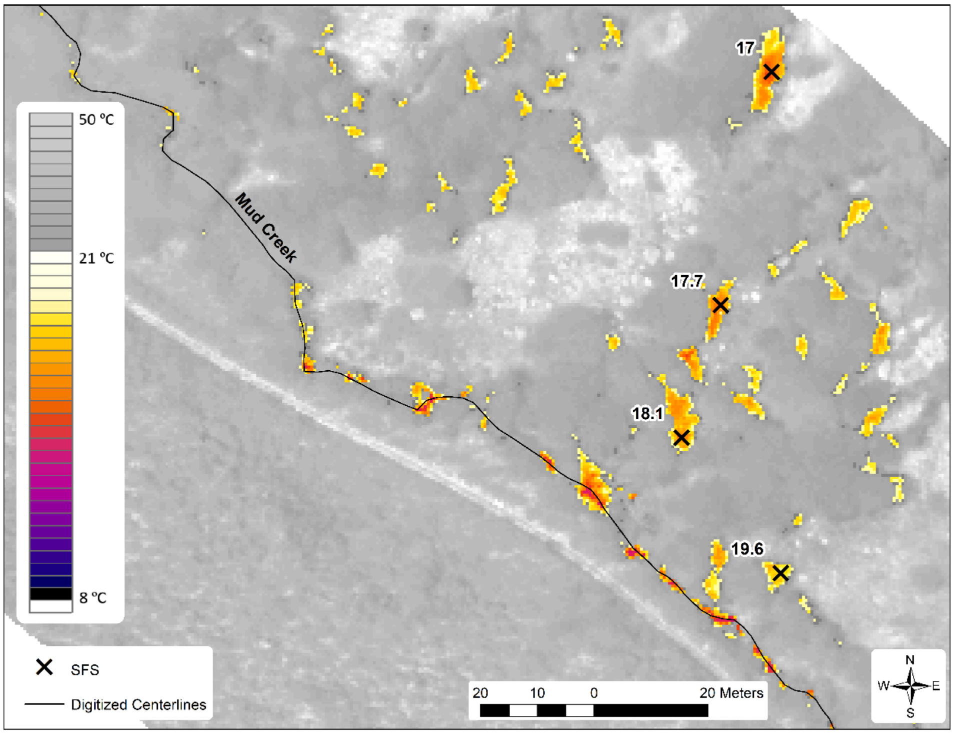

Figure 22: Thermal infrared map showing a sample of the identified SFS points and their temperatures near the active channel of Mud Creek at river km 5.5.

Indian Creek

A total of 7.8 km section of Indian Creek was flown on Aug 13, 2020. Its centerline was digitized and sampled for LTP at a 10-meter interval before filtering out sampling points that fell on non-water features. There was sufficient flow along this section of the stream to sample the TIR mosaic and generate the LTP and SFS plot (Figure 23). A steady and gradual downstream warming was noticeable as water temperature increased from 14.4 to 19.4 °C. All identified SFS features were warmer than the water in the channel suggesting that the creek's warming gradient is partially a result of this warm inflow in addition to the solar loading and the heat exchange with the atmosphere. Furthermore, Indian Creek was a source of warm water to Donner und Blitzen River (Figure 24 and Figure 25).

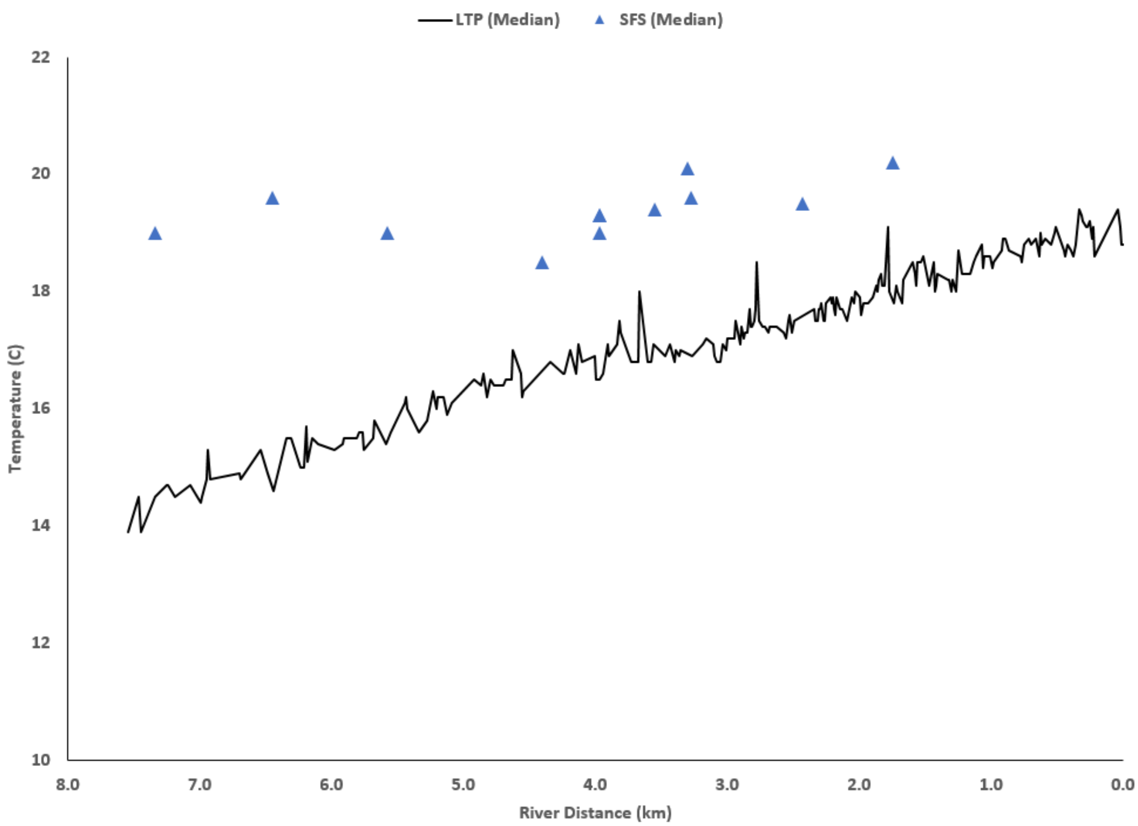

Figure 23: Longitudinal temperature profile (LTP) and identified significant feature sites (SFS) plotted against river length for the Indian Creek. Data points in the plot are those of the median sampled water temperatures of the sampled pixels of the mosaic.

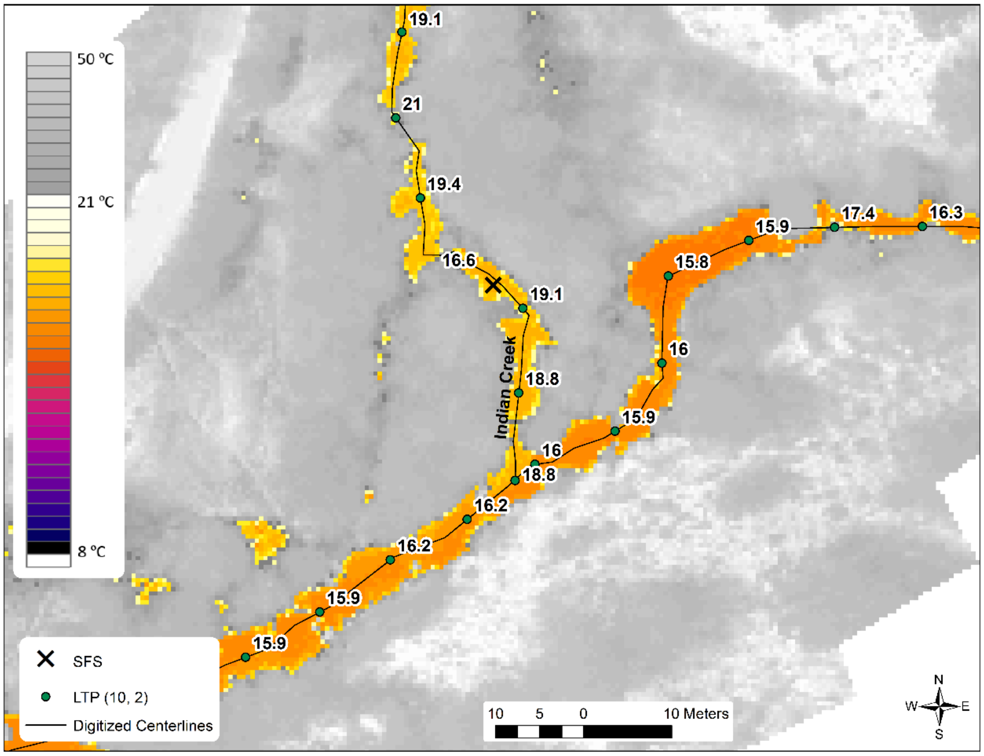

Figure 24: Thermal infrared imagery showing the warm flow of Indian Creek into Donner und Blitzen River and the increase of temperature profile along the downstream section.

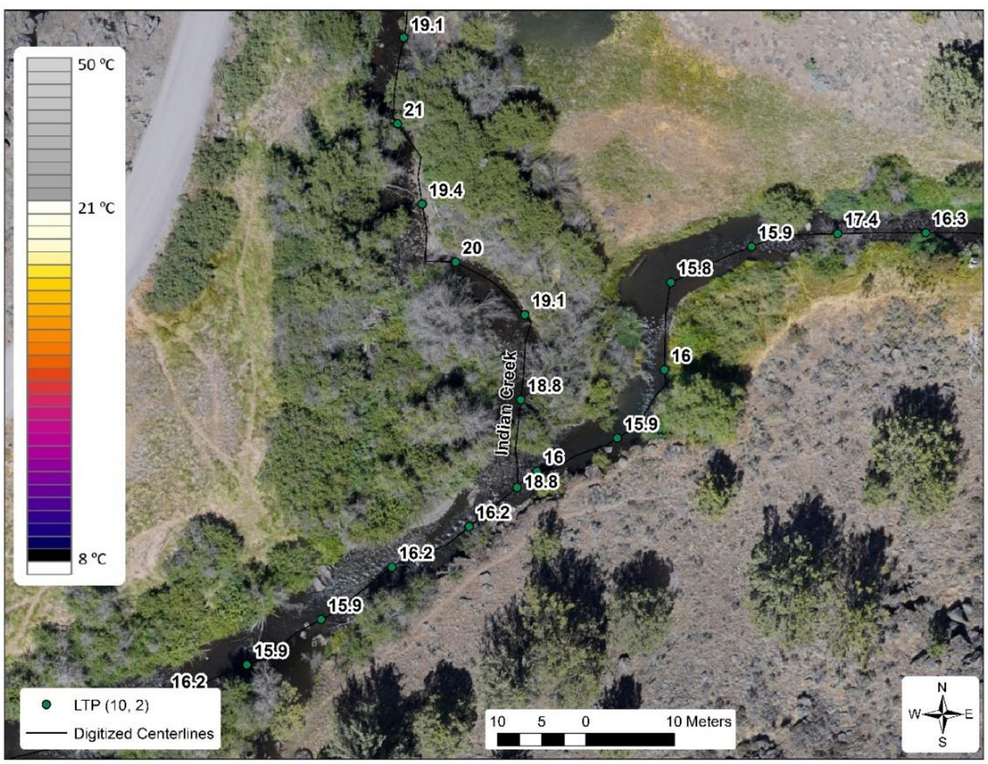

Figure 25: Visible color imagery showing the confluence of Indian Creek with Donner und Blitzen River.

Big Indian Creek

A total of 9.0 km section of Big Indian Creek was flown on Aug 13, 2020. Its centerline was digitized and sampled at 10-meter interval for the LTP analysis. However, the lack of water in the channel prevented the generation of an informative LTP data. Instead, significant features along the channel and the banks were identified and sampled (Figure 26). The overall temperature ranges if the SFS showed lower temperatures along the upstream section than the downstream section. Several SFS points were warmer than the water in the channel (Figure 27). A deeper investigation of the identified points through comparing the TIR mosaic and the visible color imagery suggest possible false identification for some of the SFS points. Some of the identified point coincided with tree-shaded spots (Figure 28). Nevertheless, all identified were kept in the delivered shapefiles and plots to allow for an independent review by the data users down the road.

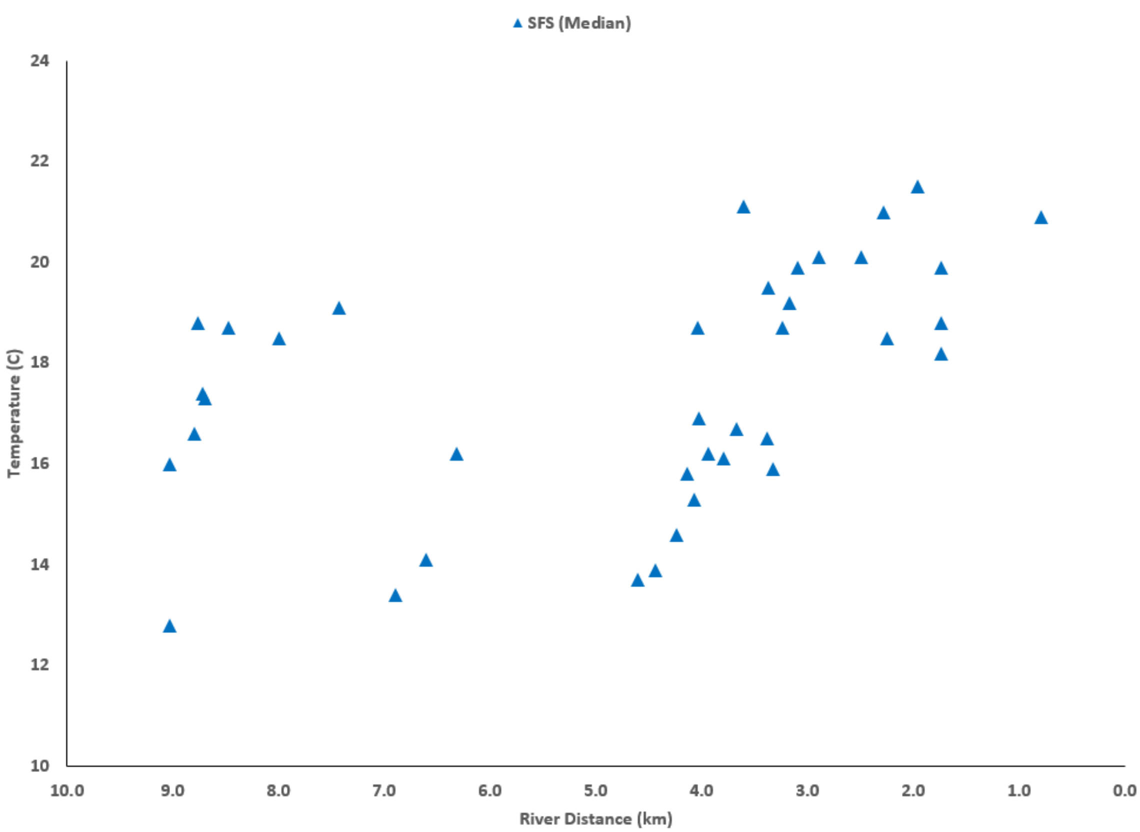

Figure 26: Identified significant feature sites (SFS) plotted against river length for Big Indian Creek.

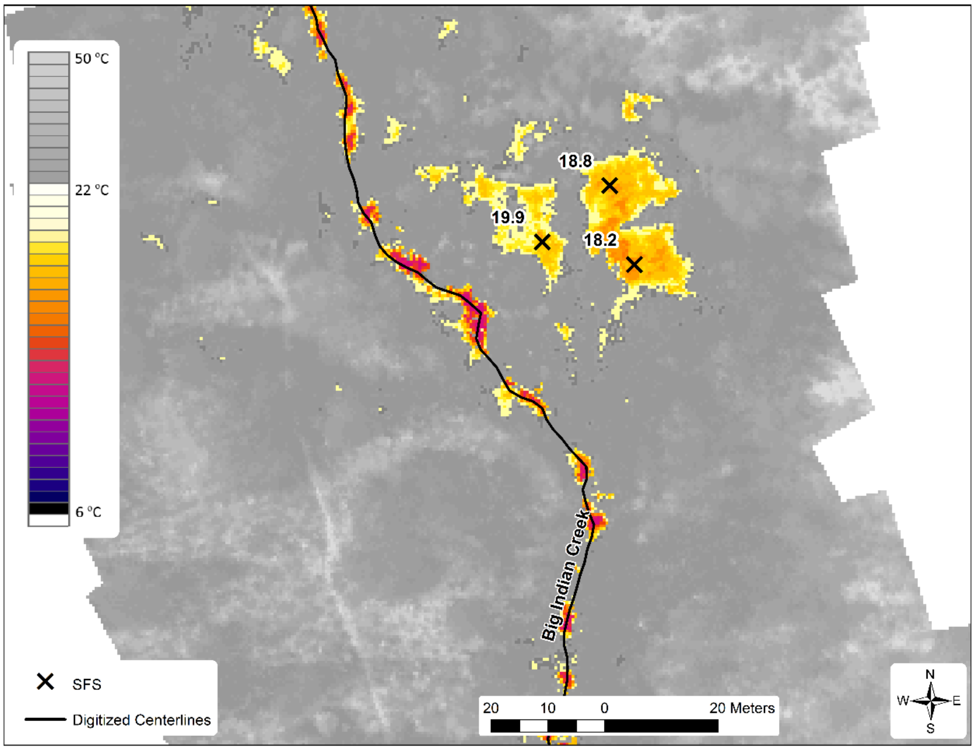

Figure 27: Thermal infrared imagery showing the location and temperature of example SFS points that were warmer than the water in the channel.

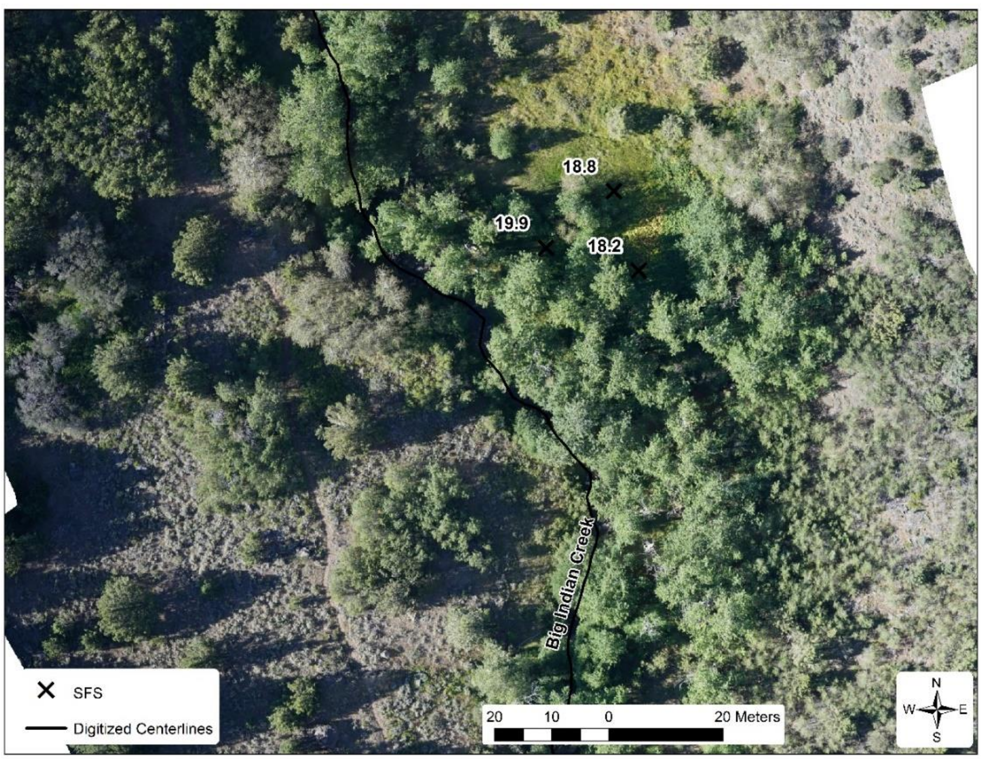

Figure 28: Visible color imagery showing the location and temperature of example SFS points.

Little Indian Creek

A total of 3.2 km section of Big Indian Creek was flown on Aug 13, 2020. Its centerline was digitized and sampled at 10-meter interval for the LTP analysis. Similar to Big Indian Creek, the lack of water in the channel prevented the generation of an informative LTP data and the SFS plot was generated instead (Figure 29). The SFS plot shows a semi-downstream warming gradient as the temperature of the identified SFSs increased the more downstream they were. Figure 30 and Figure 31 show examples of the identified SFS locations and temperatures overlaying a TIR mosaic and visible color imagery.

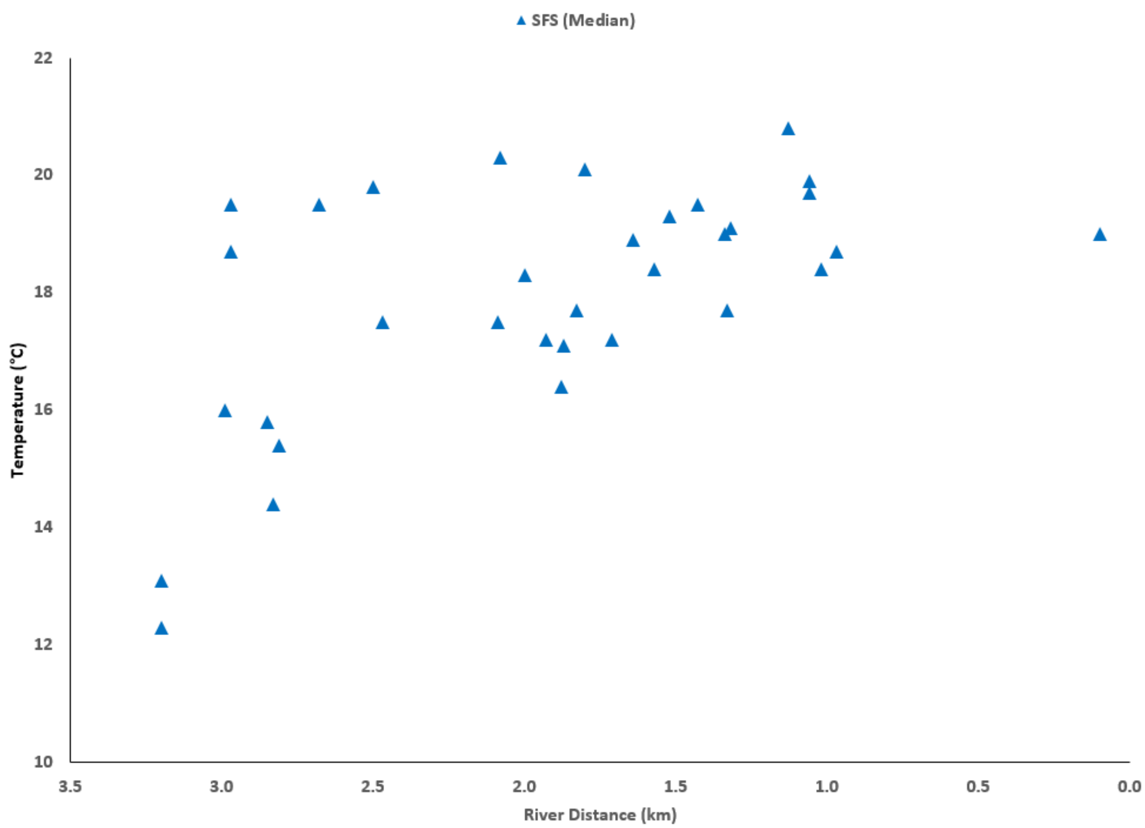

Figure 29: Identified significant feature sites (SFS) plotted against river length for Little Indian Creek

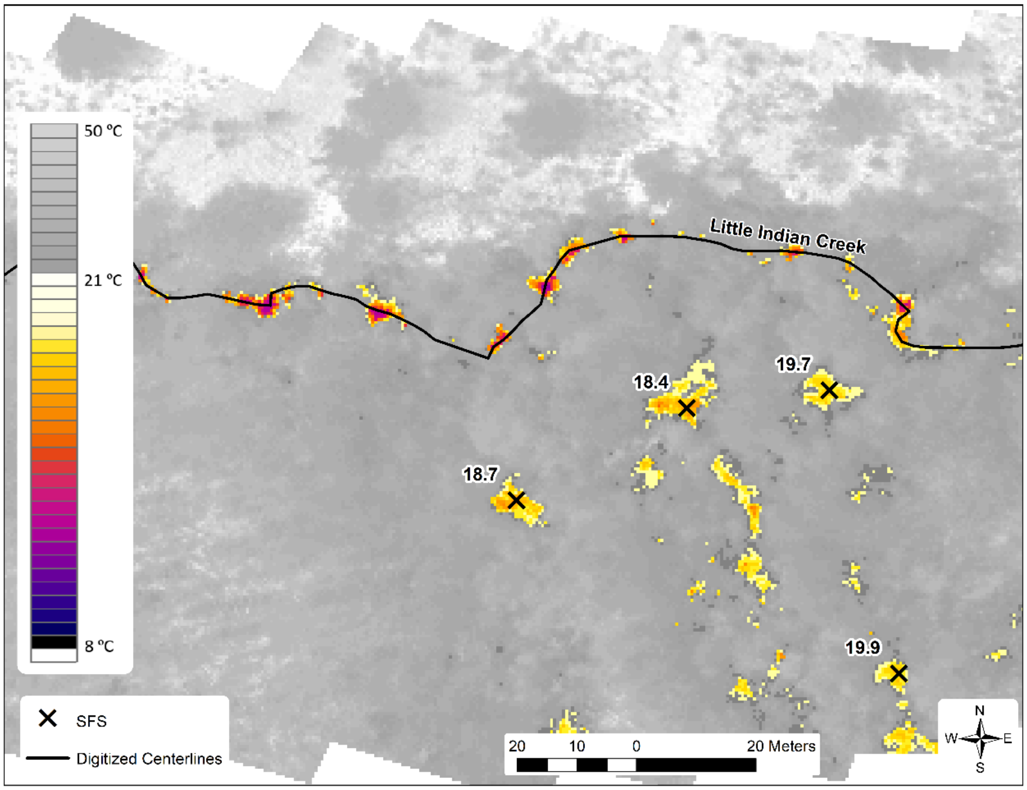

Figure 30: Thermal infrared imagery showing the location and temperature of example SFS points.

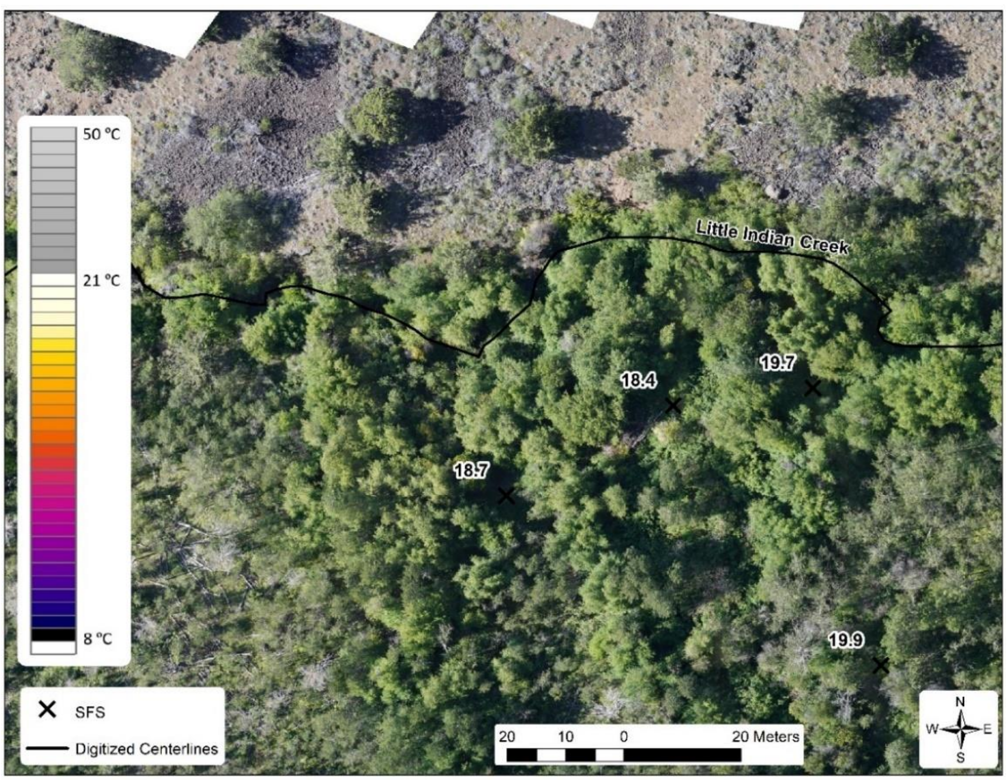

Figure 31 Visible color imagery showing the location and temperature of example SFS points.

Little Blitzen River

Little Blitzen River was acquired on two days: The downstream section from the confluence with Donner und Blitzen River to river km 17.7 and the upstream section from river km 13.1 to 24.5 was acquired on Aug 15. Therefore, each TIR mosaic was sampled separately and the results are shown in separate and combined plots.

The downstream section showed a steady and gradual cooling between river km 17 to 10 followed by a warming gradient until the confluence with Donner und Blitzen River. The presence of seepage and potential hyporheic inflow of cold temperatures along the cooling section suggests a significant hydrologic connectivity across this section's floodplain (Figure 32). The coldest median temperature that was sampled was 13.8 around river km 10. The identified SFS points were warmer than the channel after that which may have a role in the warming gradient. Stream flow between river km 12 and 8 was not as visible to the TIR sensor which ended up excluding a significant portion of the LTP's points.

Water along the most upstream section (river km 24.5 to 20) was discontinuous and the LTP was not properly generated (Figure 33). In order to better represent water temperature along this section, more SFS points were manually placed and sampled. The SFS points were shown to be colder than the water in the channel suggesting that this section is significantly influenced by the identified seepage inflows. Along sections where there were legitimate results, the thermal gradient appeared to be switching from warming to cooling around river km 16-17. This was a repeated gradient and similar to the results shown in the prior day's data (Figure 32). The sampling results (LTP and SFS) from both days were also combined into one figure to emphasize the repeated thermal gradient in both days (Figure 34).

When comparing the TIR and the visible color imagery, some of the identified points appeared to be falsely identified as they represented tree-shaded areas (Figure 35 and Figure 36). However, further investigation is required to determine the validity of these points.

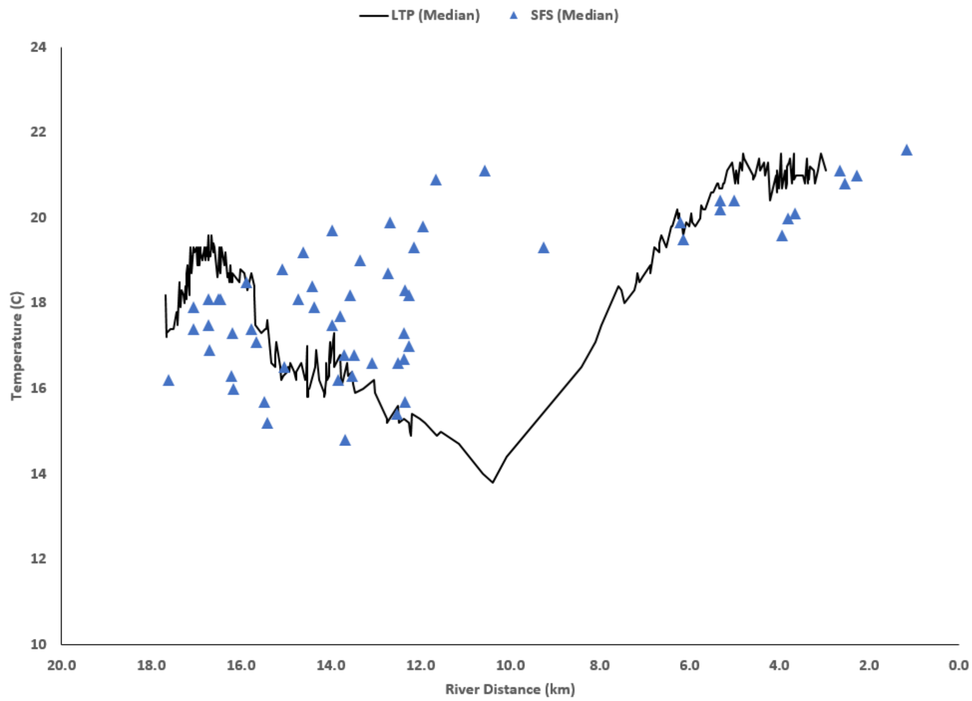

Figure 32: Longitudinal temperature profile (LTP) and identified significant feature sites (SFS) plotted against river length for the downstream section of Little Blitzen River. Data points in the plot are those of the median sampled water temperatures of the sampled pixels of the mosaic.

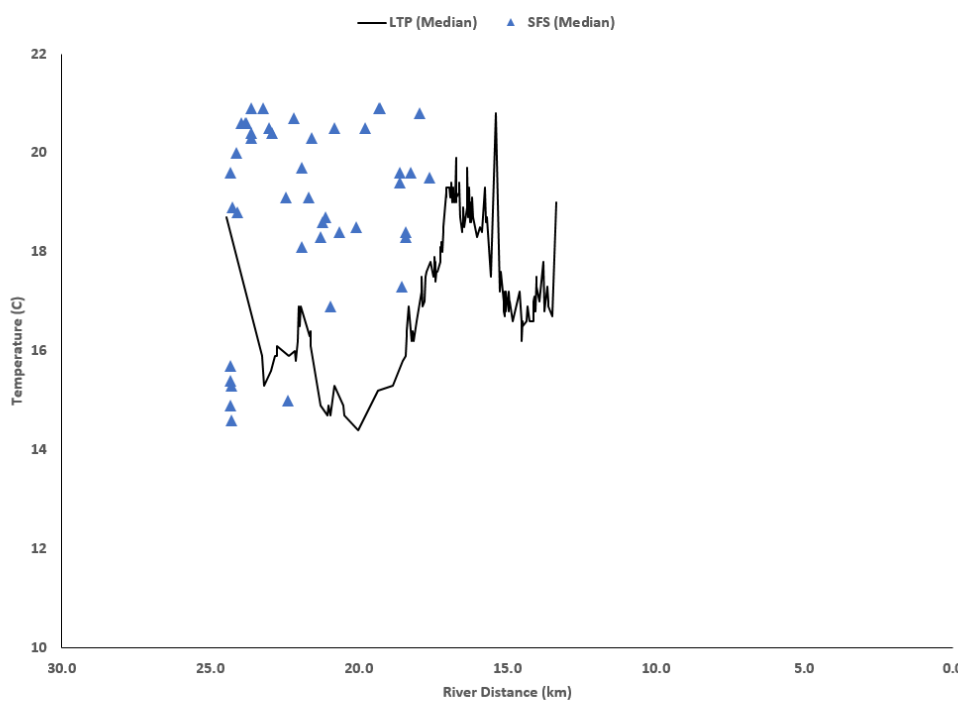

Figure 33: Longitudinal temperature profile (LTP) and identified significant feature sites (SFS) plotted against river length for the upstream section of Little Blitzen River. Data points in the plot are those of the median sampled water temperatures of the sampled pixels of the mosaic.

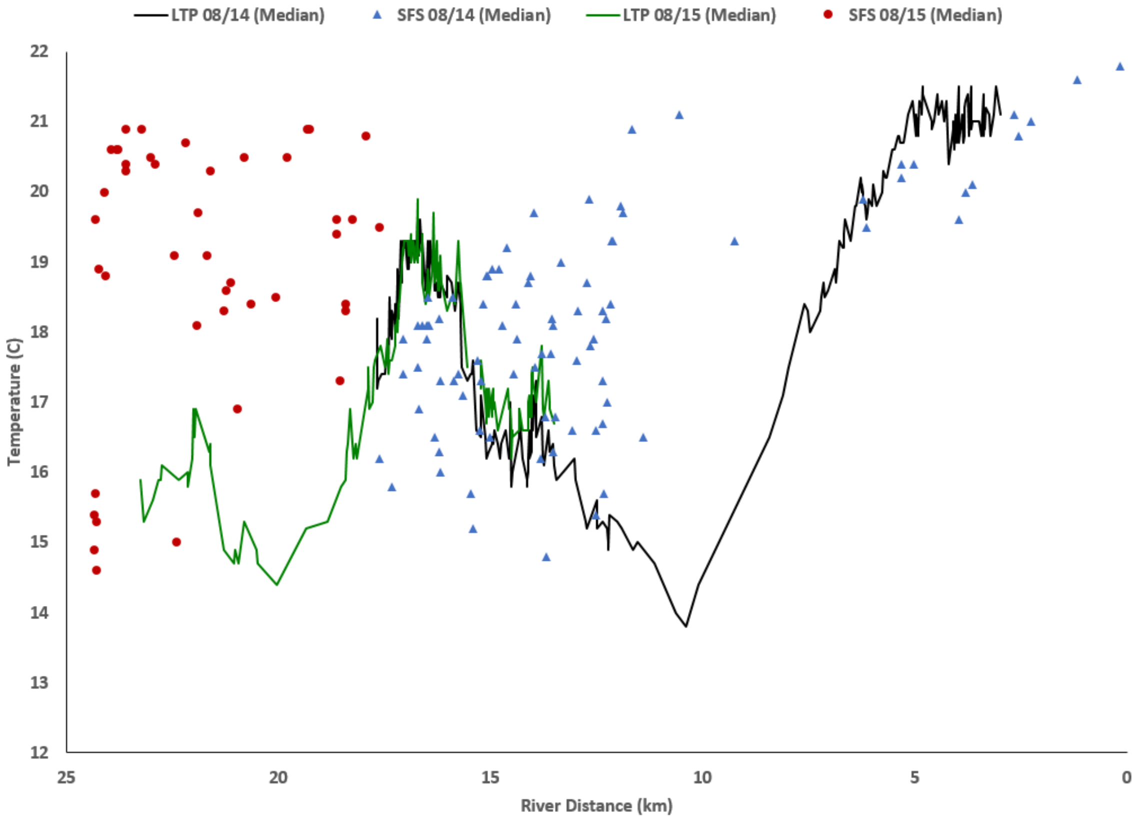

Figure 34: Longitudinal temperature profile (LTP) and identified significant feature sites (SFS) plotted against river length for both the downstream and the upstream sections of Little Blitzen River. The downstream part of the river was collected between 15:27 – 15:30 on 8/14 and the upstream part was collected between 15:30 and 15:40 on 8/15. Despite collecting each part of the river on a different, but consecutive, day, their temperatures aligned so perfectly and showed a repeated gradient of warming then a cooling gradient along the overlapping section of the river. Data points in the plot are those of the median sampled water temperatures of the sampled pixels of the mosaic.

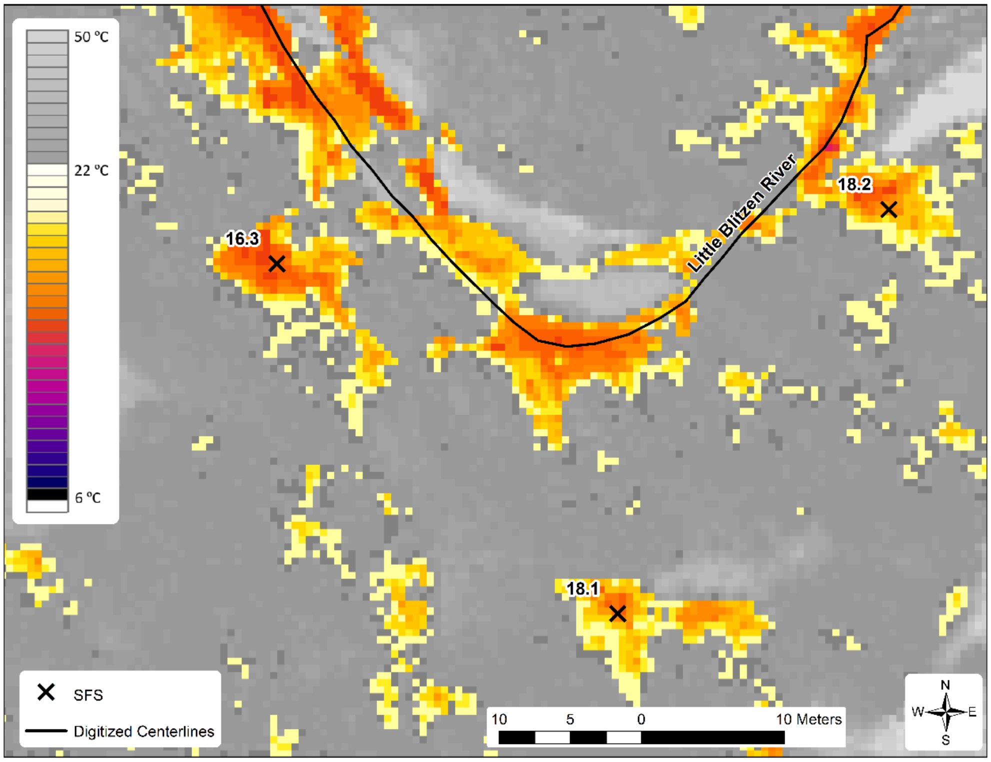

Figure 35: Thermal infrared imagery showing SFS points that could have been falsely categorized near river km 13.5.

Figure 36: visible color imagery showing SFS points that could have been falsely categorized at river km 13.5.

Fish Creek and Little Fish Creek

The entire length of fish Creek (14 km) was acquired twice: the first collection was with Little Fish Creek (6.6 km) on Aug 13 and the second collection was with Lake Creek (6.7 km) on Aug 14. The centerlines were digitized and sampled at 10-meter interval for the LTP analysis. However, low flow and discontinuous pattern of narrow channel prevents the results from being as informative as shown in Figure 37 and Figure 38. Presenting the manually identified SFS points separately (Figure 39) shows a downstream warming gradient for Little Fish Creek. It worth noting that Fish Creek provides cold water to Donner und Blitzen River (Figure 40 and Figure 41). Please note that the values of the statistical analysis were extracted from the tributary's TIR mosaic and not from the mainstem's mosaic.

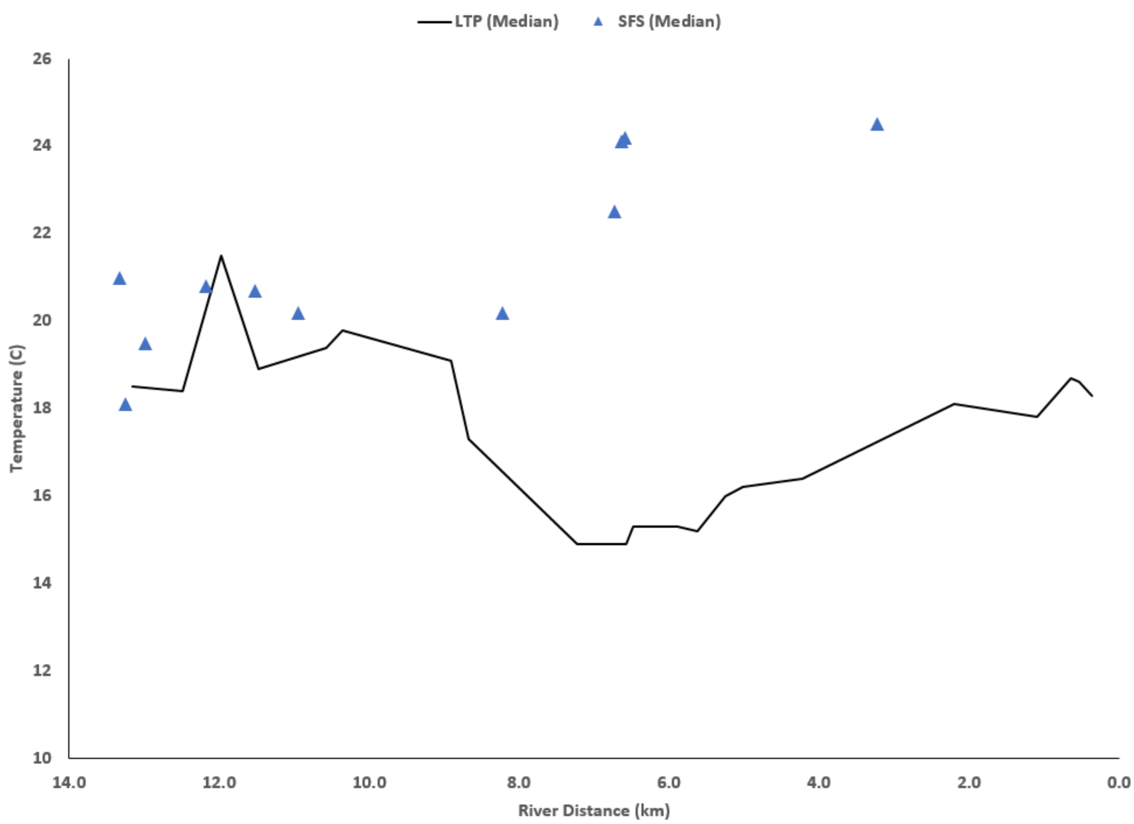

Figure 37: Longitudinal temperature profile (LTP) and identified significant feature sites (SFS) plotted against river length for Fish Creek. Data points in the plot are those of the median sampled water temperatures of the sampled pixels of the mosaic.

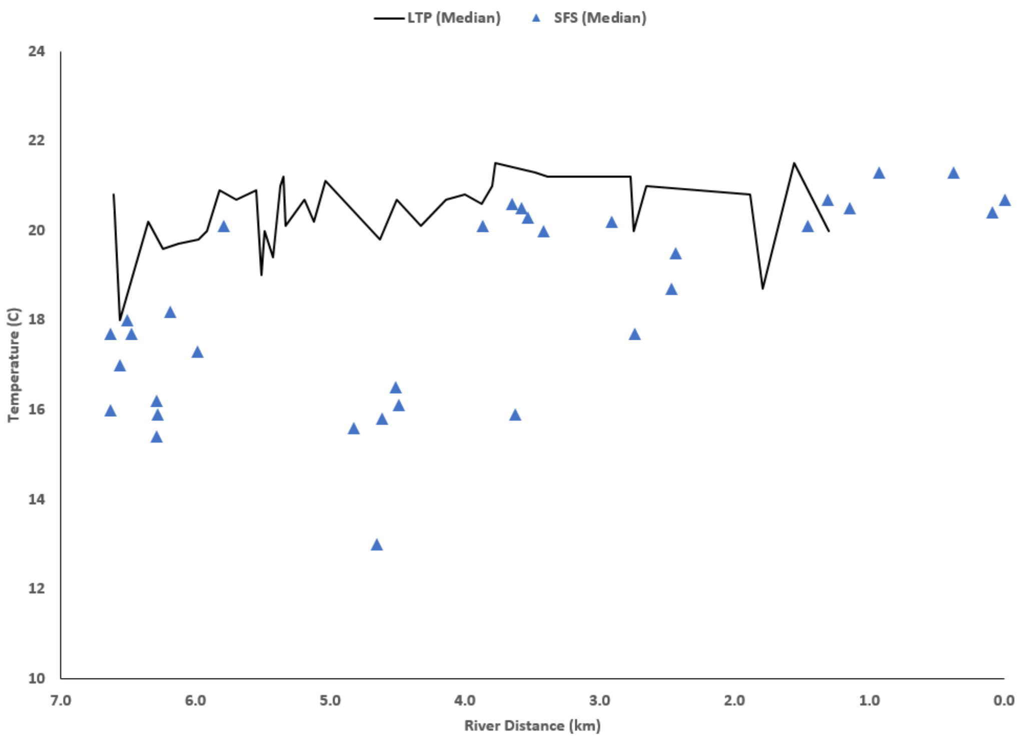

Figure 38: Longitudinal temperature profile (LTP) and identified significant feature sites (SFS) plotted against river length for Little Fish Creek. Data points in the plot are those of the median sampled water temperatures of the sampled pixels of the mosaic.

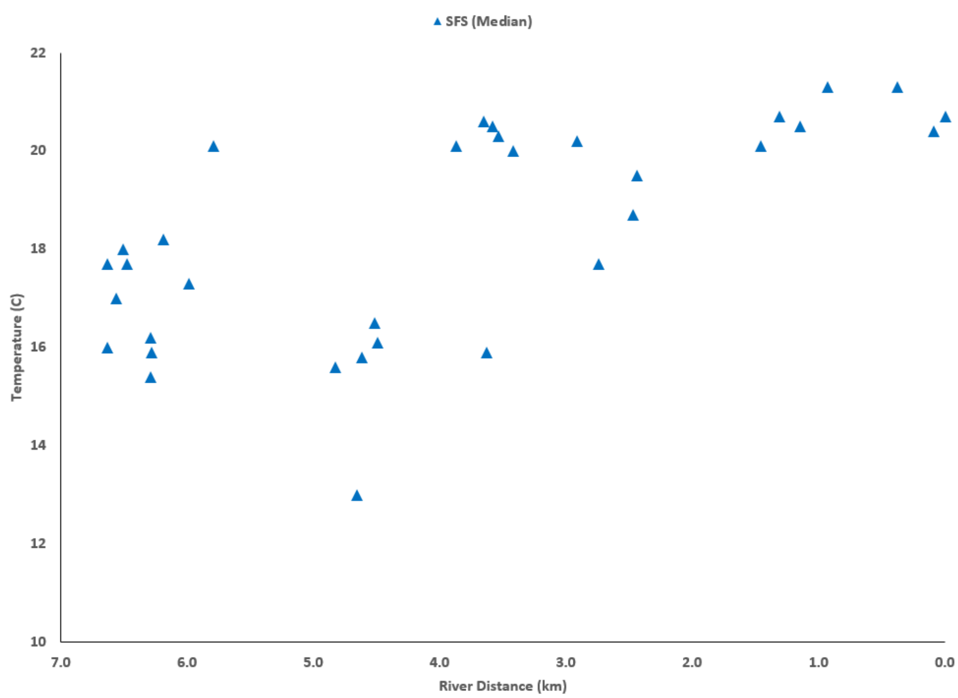

Figure 39: Identified significant feature sites (SFS) plotted against river length for Fish Creek. Data points in the plot are those of the median sampled water temperatures of the sampled pixels of the mosaic.

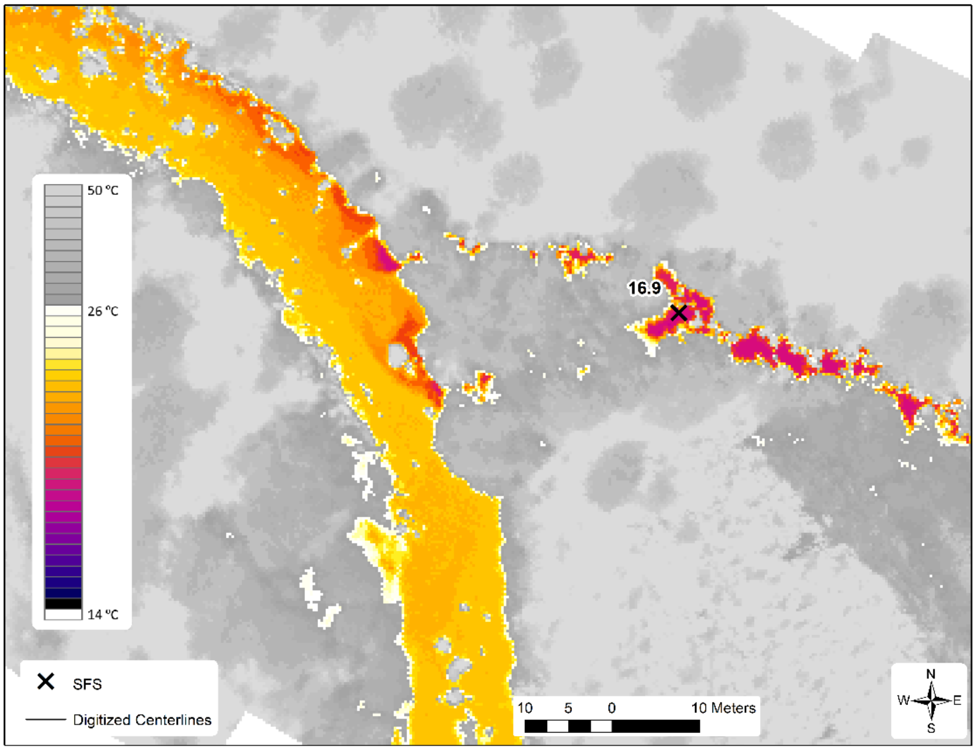

Figure 40: Thermal infrared Imagery showing cold water from Fish Creek (16.9 °C) flowing into Donner und Blitzen River which was warmer.

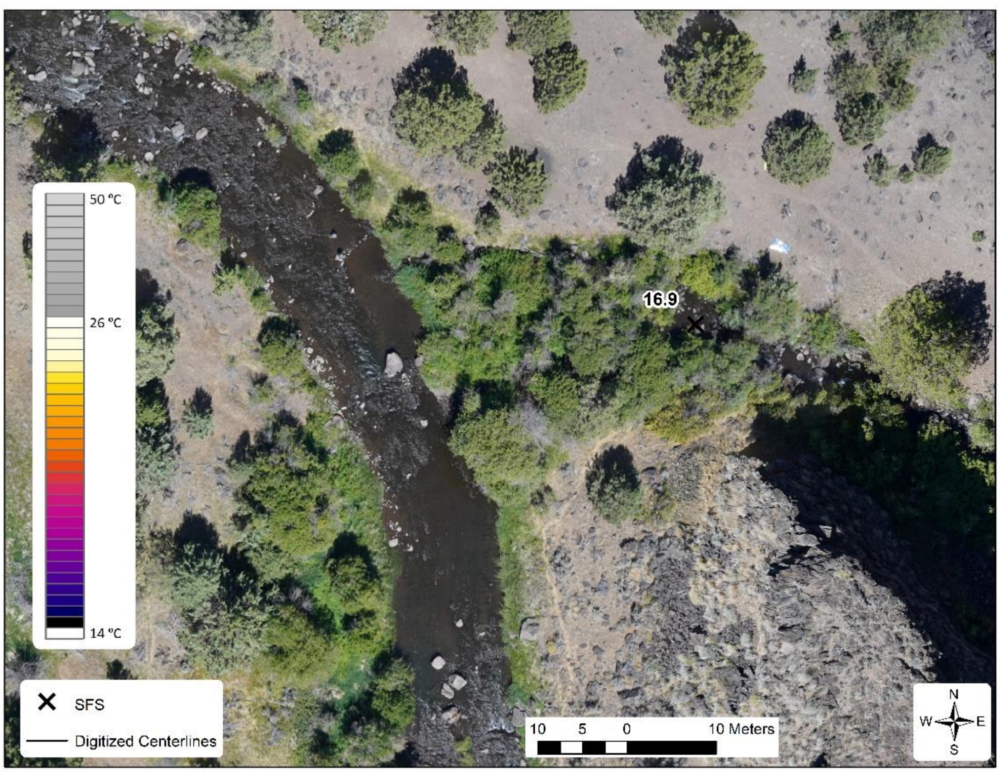

Figure 41: Visible color imagery showing the confluence of Fish Creek with Donner und Blitzen River.

Lake Creek

A total length of 6.7 km of Lake Creek was acquired along with a portion of Fish Lake on Aug 14, 2020. Its centerline was digitized and sampled at 10-meter interval for the LTP analysis. However, there was not enough water in the channel to generate an informative LTP results. Alternatively, a large number of SFS points were identified and sampled to show a robust cooling gradient followed by a warming gradient (Figure 42). The lowest median temperature that was sampled reached ~12.0 °C between river km 3 and 4. The TIR data and SFS sampling results showing the downstream cooling gradient indicate that although Lake Creek originates off of Fish Lake, there might additional sources of colder seepage and subsurface flow to cause the cooling effect (Figure 43 and Figure 44).

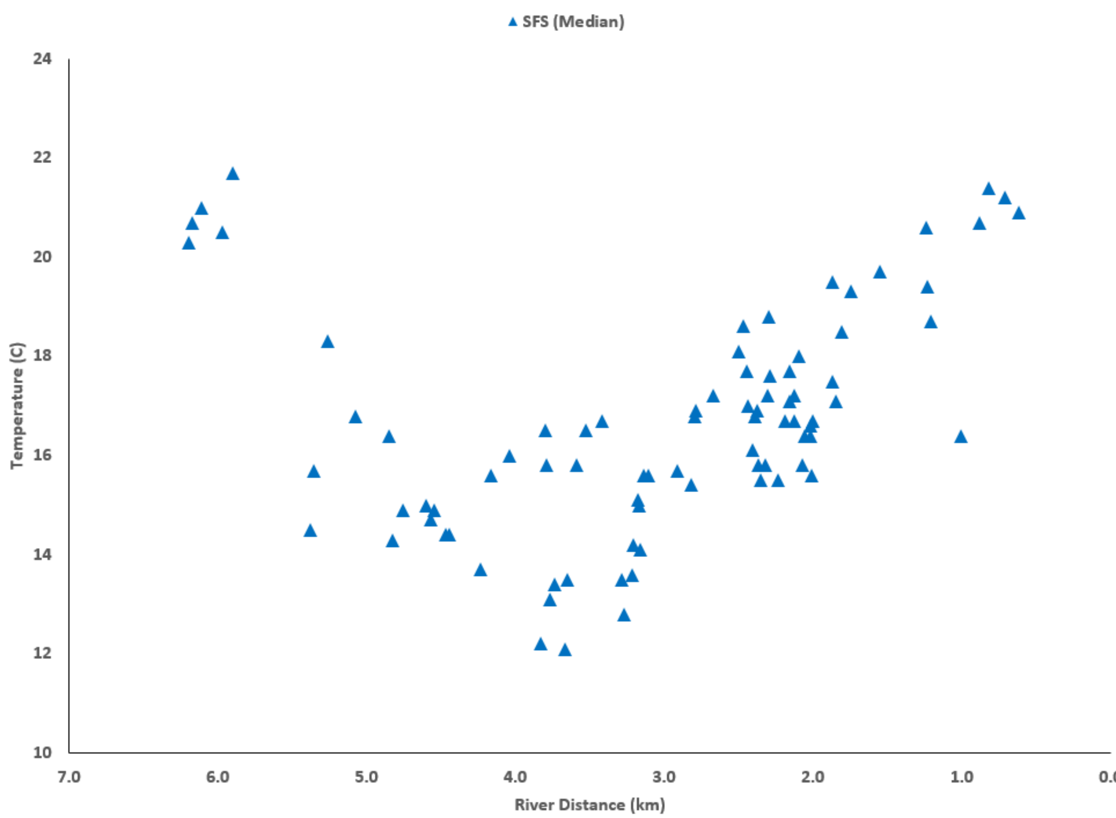

Figure 42: Identified significant feature sites (SFS) plotted against river length for Lake Creek. Data points in the plot are those of the median sampled water temperatures of the sampled pixels of the mosaic.

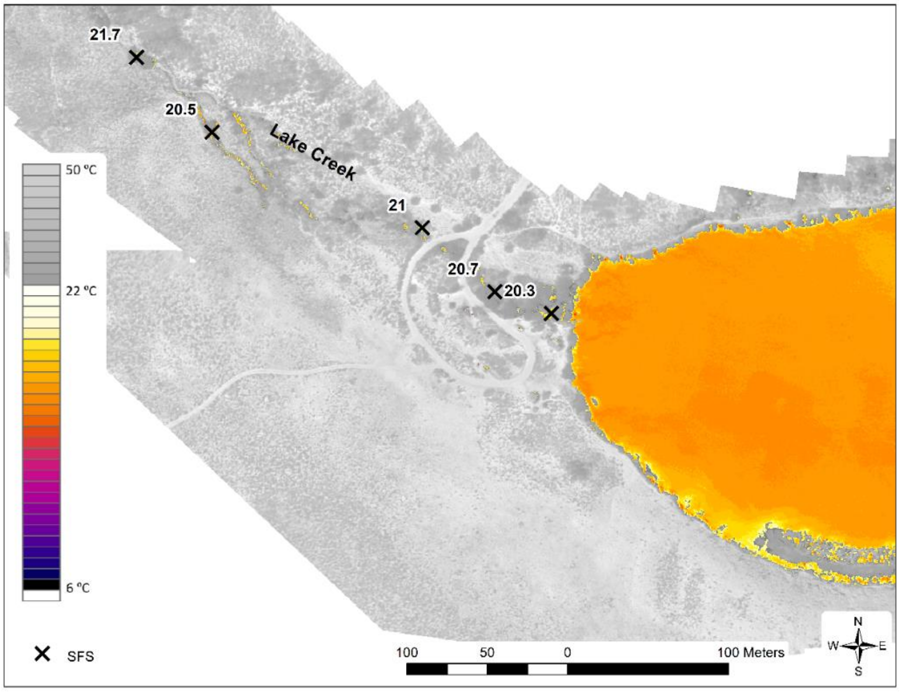

Figure 43: Thermal infrared imagery showing the manually identified SFS points downstream of Fish Lake and marking the start of Lake Creek.

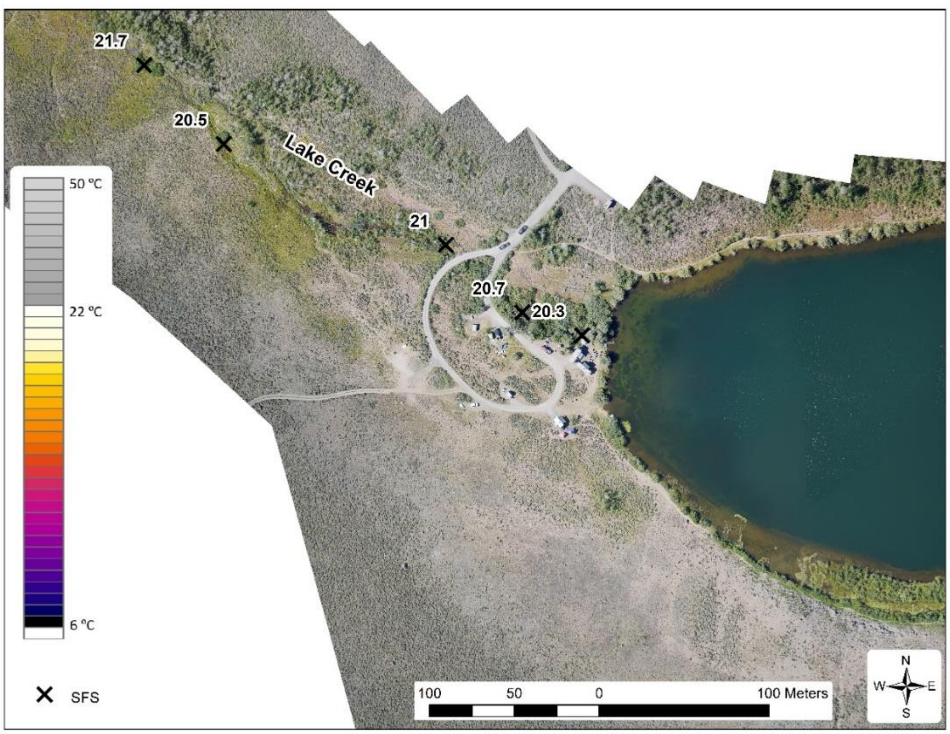

Figure 44: Visible color imagery showing the manually identified SFS points downstream of Fish Lake and marking the start of Lake Creek.