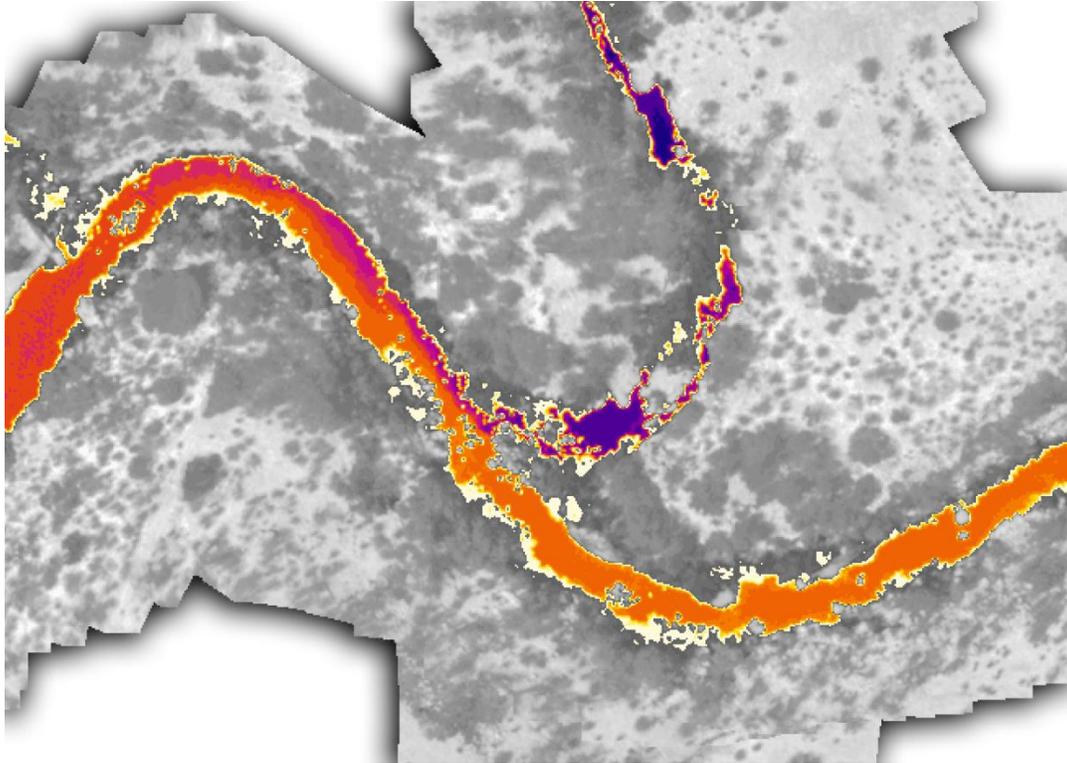
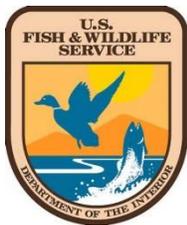


March 7, 2015



Battle Creek Thermal Infrared

Technical Data Report



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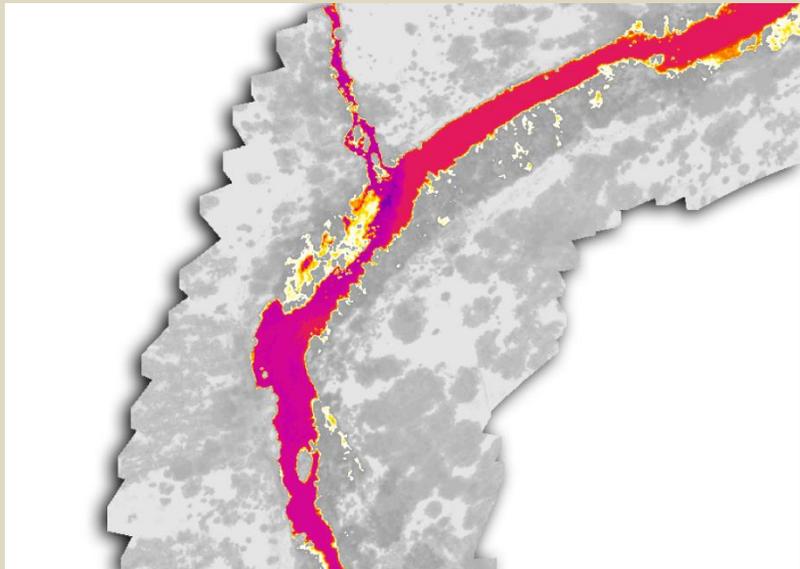
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Cover Photo: Intersection of Battle Creek and Baldwin Creek. The image is composed of thermal infrared imagery using a custom color ramp to highlight stream temperature contrasts.

INTRODUCTION

View of Battle Creek and a tributary. The image is composed of thermal infrared imagery using a custom color ramp to highlight stream temperature contrasts.



In July 2014 Quantum Spatial (QSI) was contracted by the U.S. Fish and Wildlife Service (USFSW) to collect Thermal Infrared (TIR) imagery in the summer of 2014 along the North and South Forks of Battle Creek and four associated tributaries in northern California. The total length of both forks and tributaries was approximately 65 miles. Data were collected to aid USFSW in the development of an Adaptive Management Plan which focuses on identifying cold water refuges for fish in the Battle Creek system.

This report accompanies the delivered TIR data, and documents contract specifications, data acquisition procedures, processing methods, and analysis of the final dataset. Acquisition dates and river miles are shown in Table 1, a complete list of contracted deliverables provided to USFSW is shown in Table 2, and the project extent is shown in Figure 1.

Table 1: Acquisition dates, length, and section collected on the Battle Creek site

Acquisition Dates	River Section	Approximate section Length Flown (mile)
8/23/2014	Battle Creek	13.4
	North Fork	14.7
	Baldwin Creek	2.3
	Juniper Gulch	1.9
8/24/2014	South Fork	27.3
	Soap Creek	1.9
	Ripley Creek	1.6 (no water)

Deliverable Products

Table 2: Products delivered to USFSW for the Battle Creek site

Battle Creek TIR Products Projection: UTM Zone 10 North Horizontal Datum: NAD83 (CORS96) Vertical Datum: NAVD88 (GEOID09) Raster Units: Meters, LTP Units: US mile	
Rasters	0.5 Meter Thermal Infrared Imagine Files GeoTiffs (16-bit): <ul style="list-style-type: none"> • Continuous mosaics of rectified TIR image frames. Layer files included for display by temperature class. Cell Values = Celsius*10
Vectors	Shapefiles (*.shp) <ul style="list-style-type: none"> • Exterior Orientation files (EO) • Sampled TIR Centerline Points • TIR Stream Centerlines • Hand-digitized centerlines of all streams surveyed
Supplemental	Microsoft Excel Files (.xls): <ul style="list-style-type: none"> • Longitudinal temperature profiles (LTP) Maps and figures of the report (*.PNG) Colorramps for all mosaics (*.lyr) in customized for each stream section Un-rectified calibrated frames

Aircraft and sensor used by QSI for TIR imagery acquisition for the Battle Creek.



Planning

The TIR acquisition flight was scheduled for a summer afternoon when temperature contrast between the river's water and the surroundings is maximized, and the river's temperature is most stable. Weather conditions during the survey were considered ideal for thermal imagery acquisition along the Battle Creek with warm temperatures, low humidity and clear skies.

Factors such as satellite constellation availability and weather windows must be considered during the planning stage. Any weather hazards or conditions affecting the flight were continuously monitored due to their potential impact on the daily success of airborne and ground operations. In addition, logistical considerations including private property access and potential air space restrictions were reviewed.

Ground Control

Ground control surveys, including in-stream sensors were conducted to support the airborne TIR acquisition. In-stream sensor data were used to thermally calibrate the captured TIR imagery and temperature values, as well as to perform quality assurance checks on the final thermal imagery products.

In Stream Sensors

QSI team deployed five in-stream water temperature sensors (Onset Hobo Pro) in the Battle Creek and collected the data during the survey period for calibrating and verifying the thermal accuracy of the TIR imagery. In addition, QSI utilized most of the temperature data provided by USFSW for 40 in-stream sensors. QSI's Onset Hobo Pro Loggers were placed in runs or riffles within the river channel to ensure good vertical mixing while minimizing thermal stratification of the water column. QSI sensors were recording data at 1-minute intervals, while USFSW sensors were recording every 30 minutes. Data logger locations are illustrated in Figure 1.

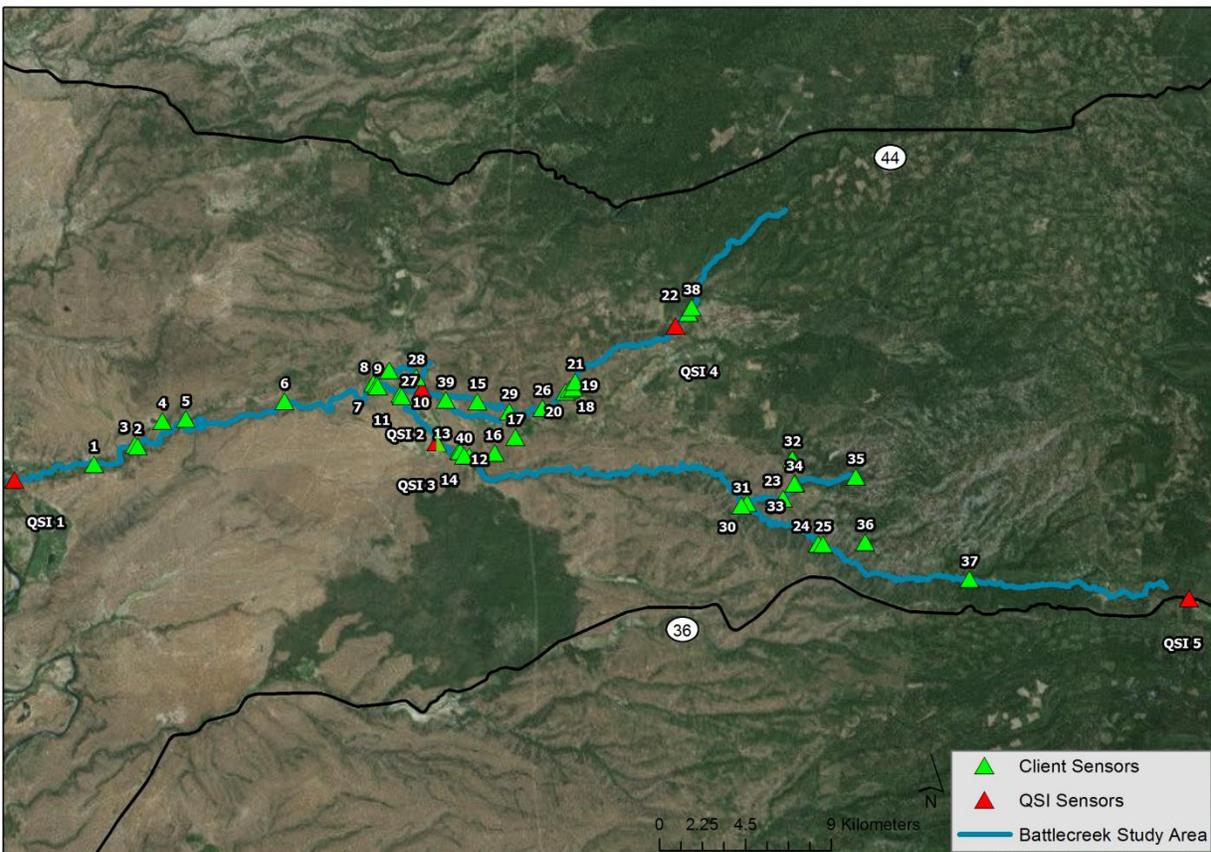


Figure 1: Map of Battle Creek streamlines and sensors locations used for calibration

Airborne Survey

Thermal Infrared

Images were collected with a FLIR system’s SC6000 sensor (8 – 9.2 μm) mounted to a Bell Jet Ranger Helicopter. The SC6000 is a calibrated radiometer with internal non-uniformity correction and drift compensation. The sensor is contained in a composite fiber enclosure attached to the underside of the aircraft which is flown longitudinally along the stream channel. Sensor and acquisition specifications of the TIR method for the Battle Creek study are listed in Table 3.

Table 3: TIR sensor and acquisition settings

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°
Acquisition Dates:	July 23-24, 2014
Flight Above Ground Level (AGL):	400 – 600 meter
Image Footprint Width:	300 meters
Pixel Resolution:	0.5 meter



Photo of a bend along NF Battle Creek taken by QSI acquisition team.

The FLIR SC6000 sensor uses a focal plane array of detectors to sample incoming radiation. A challenge when using this technology is to achieve uniformity across the detector array. The sensor has a correction scheme which reduces non-uniformity across the image frame; however, differences in temperature (typically $<0.5^\circ\text{C}$) can be observed near the edge of the image frame.

To accurately solve for position (geographic coordinates x, y, z), the positional coordinates of the airborne sensor and the attitude of the aircraft were recorded continuously throughout the data collection missions. Position and altitude of the aircraft was measured one time per second (1 Hz) by an onboard differential GPS unit. Also pitch, roll, and yaw (heading) were measured 1 time per second (1 Hz) from an onboard inertial measurement unit (IMU). To allow for post-processing correction and calibration, aircraft/sensor position and attitude data are indexed by accurate GPS time.

The aircraft was flown longitudinally along the stream corridor in order to have the river in the center of the display. The TIR sensor was set to acquire images at a rate of 1 image every second (1 Hz) resulting in at least 60% vertical overlap between images. Flight altitudes were selected to optimize resolution while providing an image ground footprint wide enough to capture the active channel with the stream

occupying 30 – 60% of the image. A target flight altitude of 500 m above ground level was planned for the Battle Creek which results in a native pixel ground sample distance of ≤ 0.5 m.

Due to the width of river and channel sinuosity in few sections, the aircraft was flown in multiple flight lines in order to capture the full floodplain extent of the river. Flight lines were designed for an image side-lap of 80 – 90% and the aircraft was flown at higher altitude for a greater coverage.

Thermal infrared images were recorded directly from the sensor to an on-board computer as raw counts which were then converted to radiant temperatures. The individual images were referenced with time, position, and heading information provided by a global positioning system (GPS) (Figure 2).

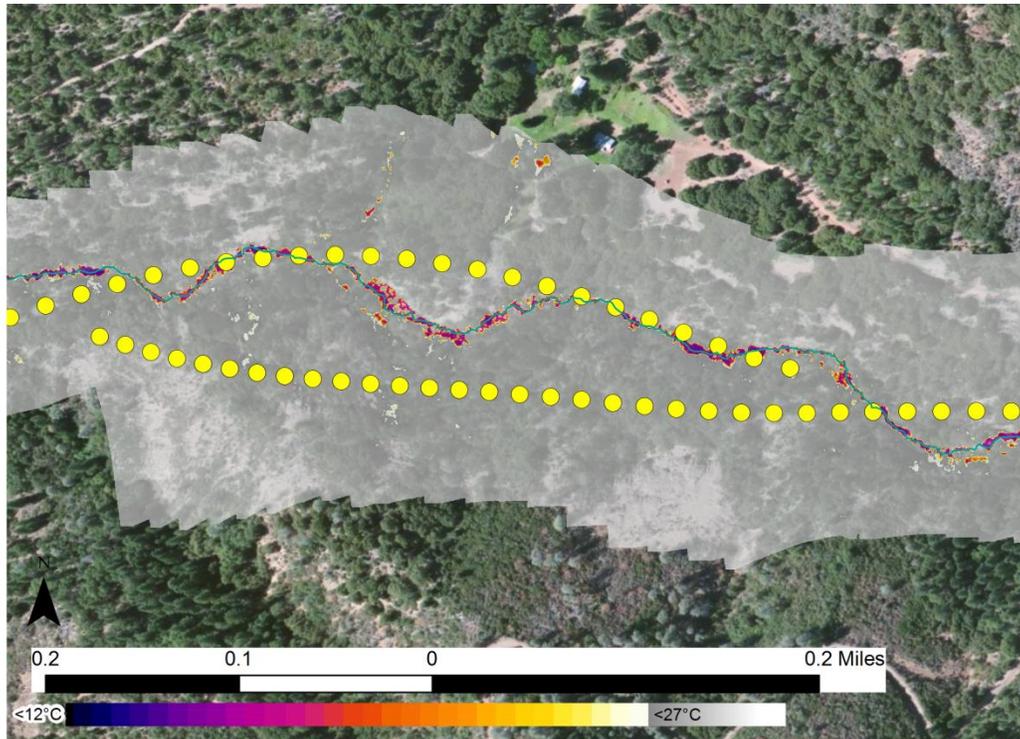
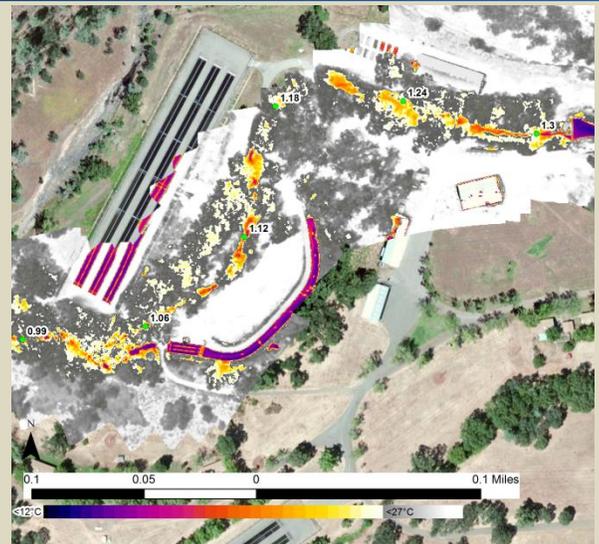


Figure 2. The figure above shows two flight lines (yellow marks) on top of thermal infrared images and true color orthophoto.

Baldwin Creek between river mile 1 and 1.3 showing the diversion channel and ponds (Thermal IR mosaic on top of true color images).



Thermal Infrared

Geo-Rectification

A boresight flight was conducted on July 27th, 2014 over the Corvallis, OR airport designed to include opposing flight lines as well as different flying heights. Images from the boresight flight were then aerially triangulated using LPS 2013, and the results were processed in IPAS CO v1.3 to compute camera misalignment angles (ω , ϕ , κ). These angles were then used in subsequent exterior orientation (EO) transformations.

Trajectory, aircraft position and attitude for the survey date were incorporated into an EO file using IPAS CO v1.3. Each flight date EO file contains the following information for per image event: easting, northing, height, ω , ϕ , κ . Within LPS 2013, the EO file and USDA publicly available DEM were used to remove geometric distortion in the thermal imagery. After orthorectification, a subset of imagery was chosen that provided ample coverage of the study area but reduced overlap in the final mosaic, which minimized resampling of temperature values. The image mosaics were created within OrthoVista v5.5 with mosaic settings adjusted to use the most nadir part of each image with minimal blending along image seams.

Temperature and Color Ramps

The TIR images collected during this survey consist of a single band. As a result, visual representation of the imagery requires the application of a color ramp to the pixel values. The selection of a color ramp should highlight features most relevant to the analysis (i.e., spatial variability of stream temperatures) (

Figure 3). The color ramps for the TIR mosaics were developed to maximize the contrast of the majority of the surface water features and are unique by date. The color ramp can be modified by the end user to highlight features or temperature ranges of interest.

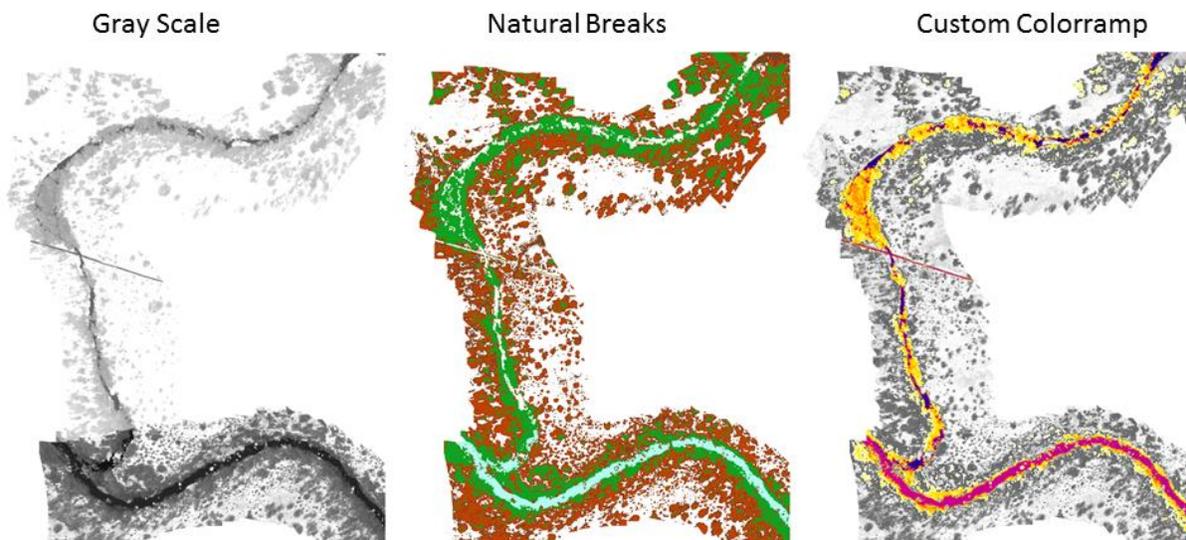


Figure 3. Examples of different color ramps applied to the same Battle Creek TIR image at the confluence between Baldwin Cr. (entering from north) to the North Fork Battle Creek.

Sensor 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.

The calculated radiant temperatures are adjusted based on the kinetic temperatures recorded at each ground control location. This adjustment is performed to correct for path length attenuation and the emissivity of natural water (0.96). The in-stream water temperature data are assessed at the time the image is acquired, with radiant values representing the median of ten points sampled from the image at the data logger location.

Interpretation and Sampling

Once calibrated and rectified, TIR images were integrated into a GIS format in which an analyst interpreted and sampled TIR stream temperatures. To begin the thermal analysis, a stream centerline shapefile was digitized (*at a scale of 1:5,000*) from the thermal mosaics for all named streams found in the National Hydrography (NHD) layer. As the streams were digitized off the thermal imagery, care was taken to avoid as many non-water features as possible; however, due to the nature of the streams, aquatic vegetation and obstructions could not always be avoided. Local knowledge of named features may differ from the information available to QSI. River kilometers are cumulative from the mouth of the stream or the edge of the project AOI and may need adjustment based on local knowledge of the downstream channel network outside the AOI.

Longitudinal Temperature Profile

In order to provide further thermal interpretation, the median bulk water temperature for the river was sampled at 100 meter (~330 feet) intervals using an automated tool created by QSI. The sample consists of a 10 point average of temperatures taken longitudinally along the stream channel within 1 meter (~3.3 feet) buffer distance. Due to the nature of the automated sampling, some sample points inevitably fall on bridges or obvious non-water features skewing the temperatures. These points could be ignored from the final shapefile. Points which had calculated standard deviations in temperature greater than 2.0° C were considered 'mixed' and automatically deleted. The resulting temperatures were plotted versus river kilometer to develop a longitudinal temperature profile (LTP). The profile illustrates how stream temperatures vary spatially along the stream gradient and highlights any landscape scale trends. The location of named surface water inflows (e.g., tributaries, surface springs, etc.) are included on the plot to illustrate how these inflows influence the mainstem temperature patterns.

Significant Features

As a further qualitative analysis, a point shapefile was also digitized (*at a scale of 1:1,500*) from the thermal imagery to highlight areas of water temperature anomalies. Most commonly, these points are located at the edge of the channel with temperature significantly different than the main channel.

Point attributes include the stream name associated with the point sampled, river km and river mile, statistical data (mean, minimum, maximum, and standard deviation) for both the point itself and the closest sampled point of the long profile, the XY-UTM coordinate (NAD_1983_UTM_Zone_10N), and the distance from the digitized centerline. The temperature at the point was also calculated (*by bilinear interpolation for all pixels in a radius of 1 meter*). However, due to the nature of the location of these digitized points, smaller features likely include mixed pixels (which will artificially raise the sampled temperature), while larger features could be ignored (see Figure 4).

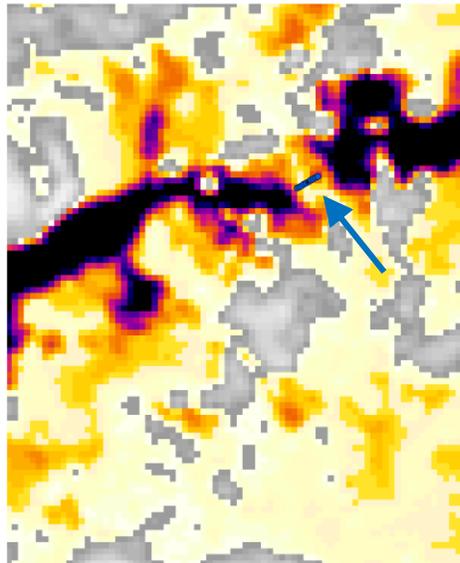


Figure 4. Shows a sample of 10 points along the digitized centerline (buffer of 1 meter) which can be ignored from calculating the LTP for the South Forth of Battle Creek.

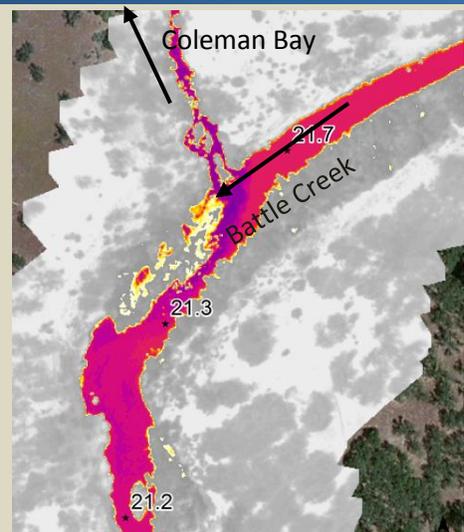
All analysis steps with their accompanying data file names are summarized in Table 4.

Table 4: Summary of the analysis steps used in the thermal analysis

Analysis Step	Data File	Description	Software used
Colorramp	<i><STREAM_SECTION>.lyr</i>	Develop a colorramp that highlights spatial variability of stream temperatures.	ArcMap v. 10.1
Calibrated thermal imagery	<i><STREAM_SECTION>.tif</i>	Convert raw TIR image digital number to radiance temperatures based on the sensor's factory calibration. Adjust radiant temperatures based on the recorded ground control kinetic temperatures.	ExamInIR v. 1.50.3
Digitize stream centerline along main flow path seen in TIR imagery	<i><STREAM_SECTION>_Centerline.shp</i>	Stream lines were digitized and routed based on the final thermal mosaics in order to best represent the centerline/main flow path.	ArcMap v. 10.1
Longitudinal temperature profile sampling	<i><STREAM_SECTION>_LTP.shp</i>	Using automated WSI tools, a GIS point layer was automatically generated from the routed stream layer at 100-meter intervals. Each point was assigned a river mile measure and the TIR radiant temperature was sampled based on an average of 10-meter sample length radiating out from the center point along the centerline (Figure 4).	ArcMap v. 10.1 QSI script

Manual sampling	<STREAM_SECTION>_point_sampling.shp	Identifying features with significant temperatures anomalies from the thermal mosaics at a 1:1,500 scale (e.g., at tributary confluences, at the edge of the channel). Calculate the temperature of the point using bilinear interpolation for all pixels in a radius of 1 meter.	ArcMap v. 10.1 QSI script
Longitudinal profiles plots	<STREAM_SECTION>_long_temp_profile.xls	Plot temperature against river km for the longitudinal profile and the manually identified features.	Excel

Figure shows the temperature change in Battle Creek due to the inflow from Coleman Canal at Coleman Bay. Temperature drop of approximately 0.4 °C.



Thermal Infrared Accuracy Assessments

Expected Accuracy

Thermal infrared radiation received at the sensor is a combination of energy emitted from the water's surface, reflected from the water's surface, and absorbed and re-radiated by the intervening atmosphere. Water is a good emitter of TIR radiation and has relatively low reflectivity (~ 4 to 6%). In general, apparent stream temperature changes of < 0.5° C are not considered significant unless associated with a surface inflow (e.g., tributary). However, certain conditions may cause variations in the accuracy of the imagery.

Thermal infrared sensors measure TIR energy emitted at the water's surface. Since water is essentially opaque to TIR wavelengths, the sensor is only measuring water surface temperatures. Thermal infrared data accurately represents bulk water temperatures where the water column is thoroughly mixed; however, temperature differences (thermal stratification) can form in the vertical water column in reaches that have little or no mixing.

Variable water surface conditions (i.e., riffle versus pool), slight changes in viewing aspect, and variable background terrestrial temperatures (i.e. shaded vs. not) can result in differences in the calculated radiant temperatures within the same image or between consecutive images. The apparent temperature variability is generally less than 0.5° C (Torgersen et al. 2001¹). The occurrence of

¹ Torgersen, C.E., R. Faux, B.A. McIntosh, N. Poage, and D.J. Norton. 2001. Airborne thermal remote sensing for water temperature assessment in rivers and streams. *Remote Sensing of Environment* 76(3): 386-398.

reflections as an artifact (or noise) in the TIR images is a consideration during image interpretation and analysis.

A small stream width translates to fewer pure stream pixels and greater integration with non-water features such as rocks and vegetation. Consequently, a narrow channel (relative to the pixel size) can result in higher variability and inaccuracies in the measured radiant temperatures as more 'mixed pixels' are sampled. This is a consideration especially when sampling the radiant temperatures at tributary mouths and surface springs.

TIR imagery was calibrated using in-stream temperature sensors that both QSI team deployed and USFWS provided along the Battle Creek. The full list of sensors and calibration can be found in the calibration Excel file accompanied to the data.

TIR Analysis

Due to the nature of the project, the focus of the survey was to investigate thermal conditions during peak summer temperature and to generate a longitudinal thermal profile of the Battle Creek. This analysis refers to both the North and South forks of Battle Creek. The color ramp for TIR mosaics was developed to maximize the contrast of the majority of the surface water features. Given the warm temperatures on the days of the survey, sloughs and tributaries warmer than the majority of the bulk water temperatures may appear in the grayscale portions of the color ramp. The color ramps can be modified by the end user to highlight features or temperature ranges of interest.

In the most basic terms, the LTP emphasizes three thermal gradient spatially related sections: downstream warming, downstream cooling and thermally neutral river sections. Downstream warming is the result of positive net heat change along the river section that is mainly due to heat gain from atmospheric forces (e.g., shortwave radiation) and warm inflow of tributaries and groundwater. Downstream cooling is the result of negative net heat change along the river section that is mainly due to heat loss by atmospheric forces (e.g., longwave radiation and evaporation) and cold inflow of tributaries and groundwater. Thermally neutral sections are sections where all forces offset each other and little to no change in temperature occurs over a spatial scale.

The longitudinal profile was generated by plotting median stream temperature versus river distance for the Battle Creek. Significant features along the river are included on the longitudinal profile plot to provide additional context for interpreting spatial temperature patterns. Apparent stream temperature changes of $< 0.5^{\circ}\text{C}$ are not considered significant unless associated with a surface inflow (e.g. tributary). While the groundwater could not easily be discerned in the imagery, the LTP of the river is was more informative in this type of summer survey showing the downstream heating in bulk water temperatures.

Longitudinal Temperature Profiles

Mean channel temperatures were plotted versus river distance for the Battle Creek based on the longitudinal sampling profile for each of the forks and tributaries. Significant tributaries and sloughs sampled during the analysis were included on the longitudinal profiles to provide additional context for interpreting spatial temperature patterns.

Battle Creek and Baldwin Creek

Battle Creek

Approximately 13.4 miles of stream length were surveyed on July 23, 2014 covering the section of Battle Creek starting from Gover Road to the confluence between the North Fork and the South Fork of Battle Creek (Figure 5). Despite a narrow channel and overhanging riparian vegetation, the LTP for Battle Creek clearly showed downstream warming trend. In addition, the influence of cold water inflow and tributaries was noticeable (Coleman Fish Hatchery, the overflow from Coleman Forebay, and Baldwin Creek).

Baldwin Creek

Nearly 2.3 miles of Baldwin Creek were also surveyed on July 23, 2014 starting from the confluence with Battle Creek. The LTP for Baldwin Creek fluctuated significantly because of the dense vegetation and narrow stream (Figure 6). Diversion ponds and dams were noticeable through the thermal infrared imagery, but also through the LTP between river miles 1.4 and 0.8. The temperature profile also showed that water temperature dropped downstream of the diversion dam at river mile 0.8.

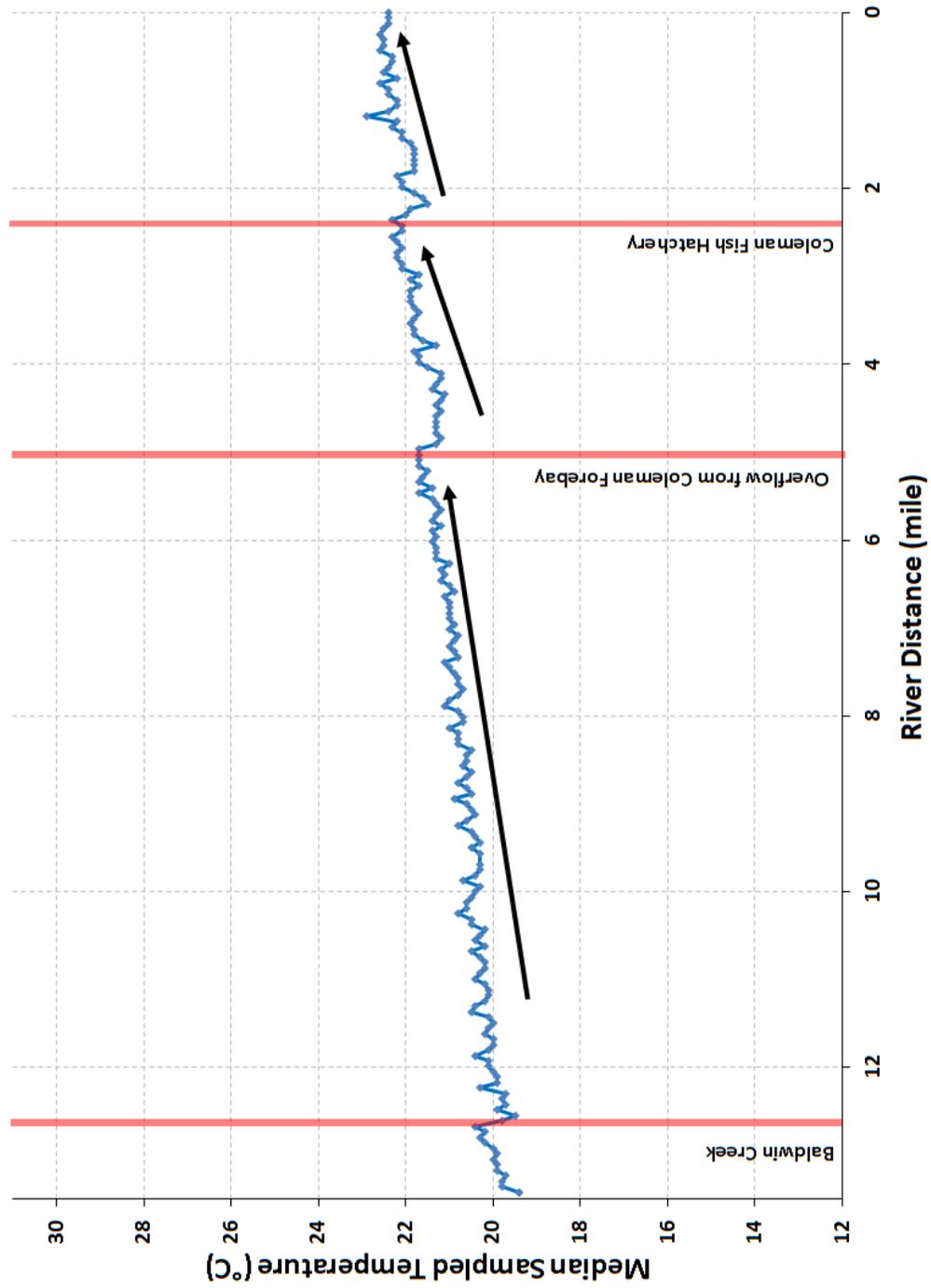


Figure 5. The figure above shows the longitudinal temperature profile for Battle Creek below the confluence of the North and South Forks of Battle Creek.

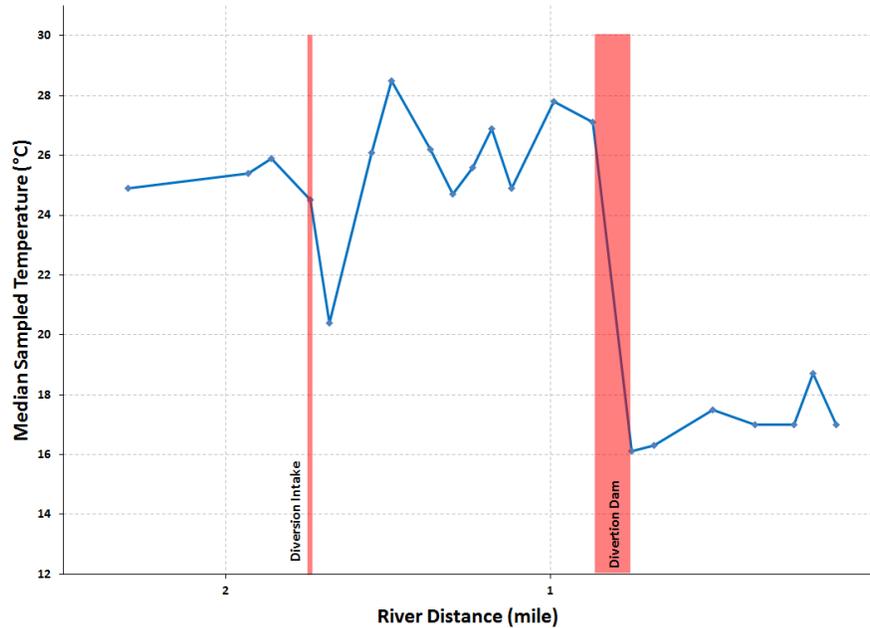


Figure 6. The figure above shows the LTP for Baldwin Creek.

North Fork Battle Creek and Juniper Gulch

North Fork Battle Creek

Approximately 14.7 km of stream length were surveyed on July 23, 2014 covering the section between the confluence with the South Fork and the headwaters (Figure 5). Large variance was noticed in the LTP due to both small stream size and dense, overhanging riparian vegetation, the automated longitudinal sampling tool was not as successful as expected and sampled temperatures of banks, rocks, or vegetation. Despite this temperature variance, the LTP showed a general trend of downstream warming between river mile 14.7 until river mile 10, close to the confluence with Baily Creek and a diversion is located {there was no information available about this specific diversion}. Along this section, the mean water temperature increased from 17 °C to 24 °C. Water temperature dropped between river mile 8.5 at the confluence of Millseat Creek and river mile 5.6 at the confluence of Digger Creek. Then, the downstream warming resumes until the confluence between the North Fork and the South Fork of Battle Creek. Lastly, warm water inflow from Juniper Gulch at river mile 1.6 caused approximately 1.0 °C increase in stream temperature.

Juniper Gulch

Approximately 1.9 km of Juniper Gulch were surveyed on July 23, 2014. TIR imagery indicated that the flow of Juniper Gulch was spread across the floodplain. The LTP for Juniper Gulch showed that water temperature was relatively high ranging between 25 °C and 31 °C (Figure 8). High water temperature in this case can be attributed to long exposure to solar radiation and warm air.

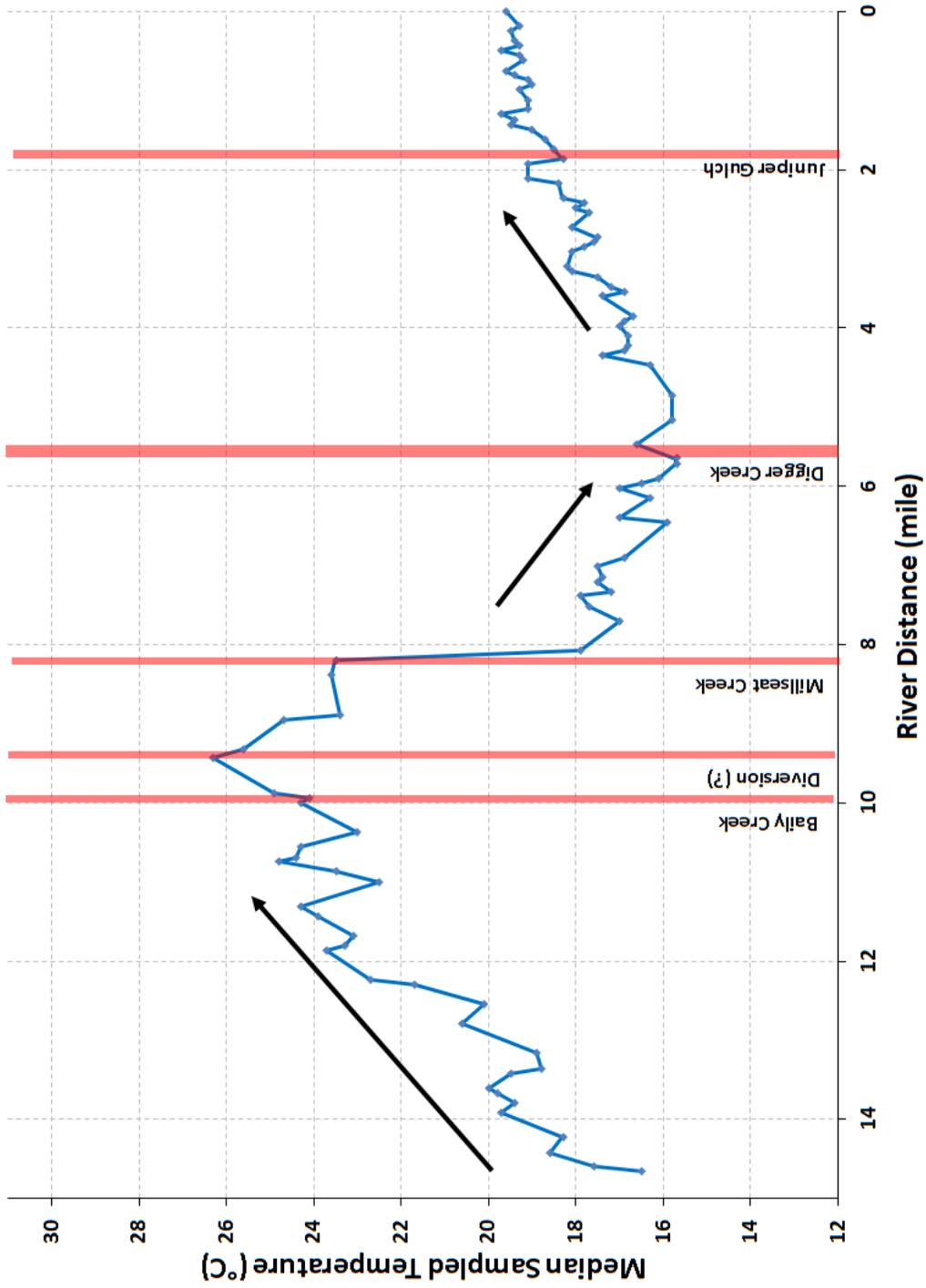


Figure 7. The figure above shows the LTP for North Fork Battle Creek between the headwaters and the confluence with South Fork Battle Creek.

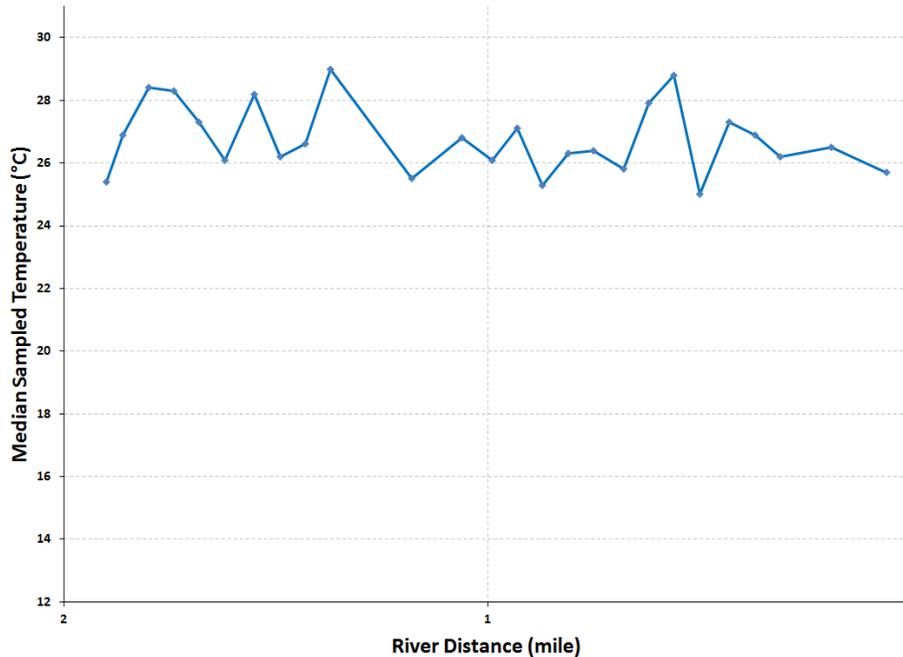


Figure 8. The figure above shows the LTP for Juniper Gulch.

South Fork Battle Creek and Soap Creek

South Fork Battle Creek

Approximately 27.3 miles of the South Fork Battle Creek were surveyed on July 24, 2014 beginning at the confluence with the North Fork Battle Creek to the headwaters. The LTP (Figure 9) showed high occurrence of noise along the upper most 7 miles of the South Fork Battle Creek (the section upstream of the confluence with Panther Creek) and were not clearly sampled. Although the thalweg of stream was colder than its surroundings, the noise captured by the LTP indicates that there was low to no water discharge in the stream. Additionally, cold features (water or streambed) may reflect a shaded, dry streambed, or - if there were water flowing in the stream- the narrow stream channel masked by overhanging riparian vegetation.

A series of downstream warming trends followed by quick drops in water temperature were present in the LTP. The first downstream warming trend began at the confluence with Panther Creek at river mile 20.6. Both the thermal imagery and the LTP clearly showed cold water (13.0 °C) present in the South Fork Battle Creek in the vicinity of the confluence of Panther Creek at river mile 20.6. A downstream warming trend began at river mile 20.6 increasing stream temperatures to 21 °C before it dropped to 18.6 °C at river mile 15.6 coinciding with a diversion in place. The warming-cooling pattern in stream temperature was repeated along three additional sections due to unnamed spring at river mile 11.5 (also shown in Figure 11), South Fork Powerhouse at river mile 8.8 (also shown in Figure 12), and Inskip Powerhouse Effluent at river mile 2.9 (also shown in Figure 13).

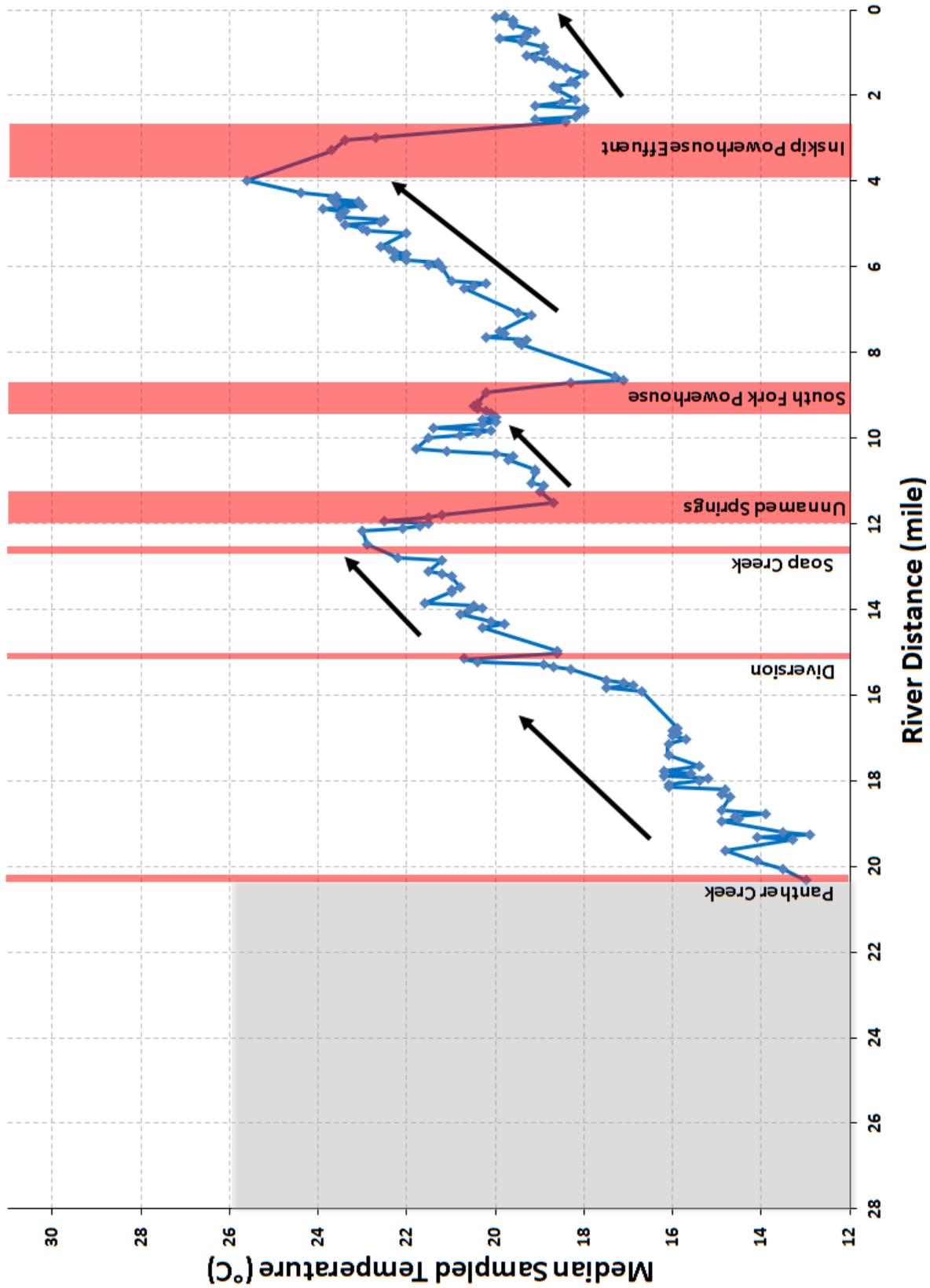


Figure 9. The figure above shows the LTP for the South Fork Battle Creek.

Soap Creek

Approximately 2 miles of Soap Creek were surveyed beginning at the confluence with South Fork Battle Creek. Despite narrow stream channel and dense riparian vegetation, water in the channel was isolated based on temperature captured in the thermal images (Figure 14). However, the automated longitudinal sampling tool was not successful and sampled features that were identified as banks, rocks, or vegetation (Figure 10). NOTE: The lower most point on the plot falls in the main stem of the South Fork Battle Creek.

Ripley Creek

Thermal IR imagery indicated the there was no water flowing in Ripley Creek. Therefore, there was no option to generate the LTP.

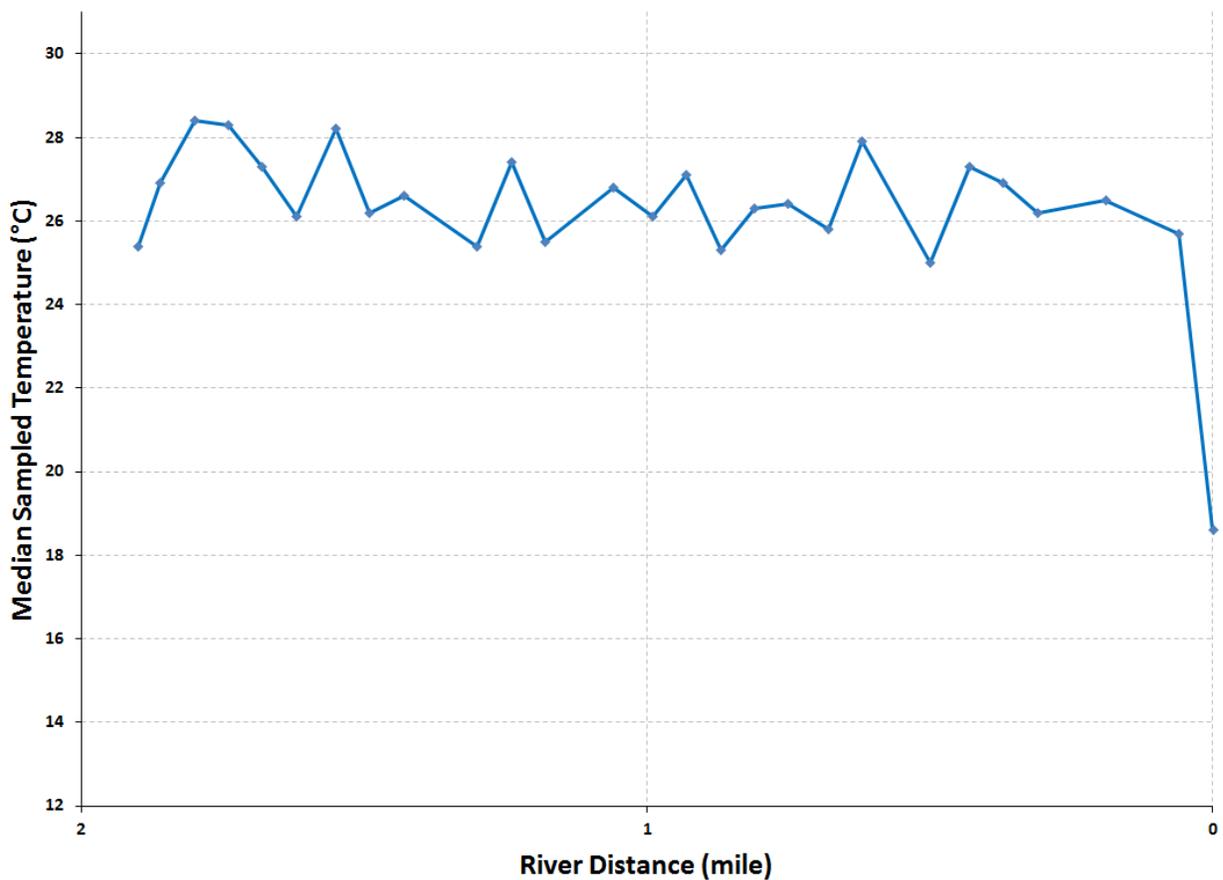


Figure 10. The figure above shows the LTP for Soap Creek.

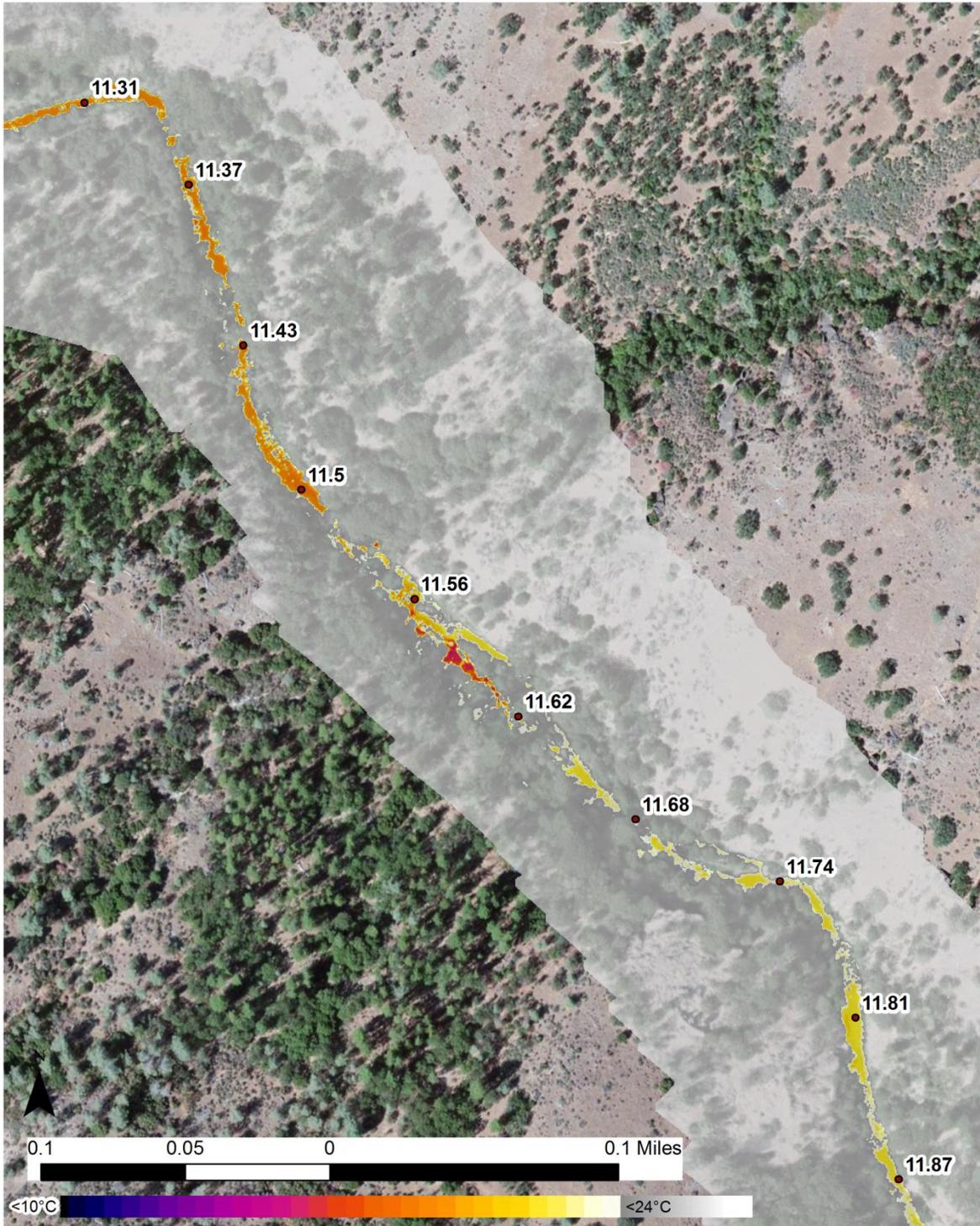


Figure 11. The figure above is of the South Fork Battle Creek between river mile 11.3 and 11.9 showing an unnamed springs location as a cold area in the stream's thalweg. Highlighted is the river mile.



Figure 12. The figure above is of the South Fork Battle Creek between river mile 8.4 and 9.2 showing the SF Powerhouse effluents. Highlighted is the river mile.



Figure 13. The figure above is of the South Fork Battle Creek between river mile 2.5 and 3.3 showing the Inskip Powerhouse effluents. Highlighted is the river mile.

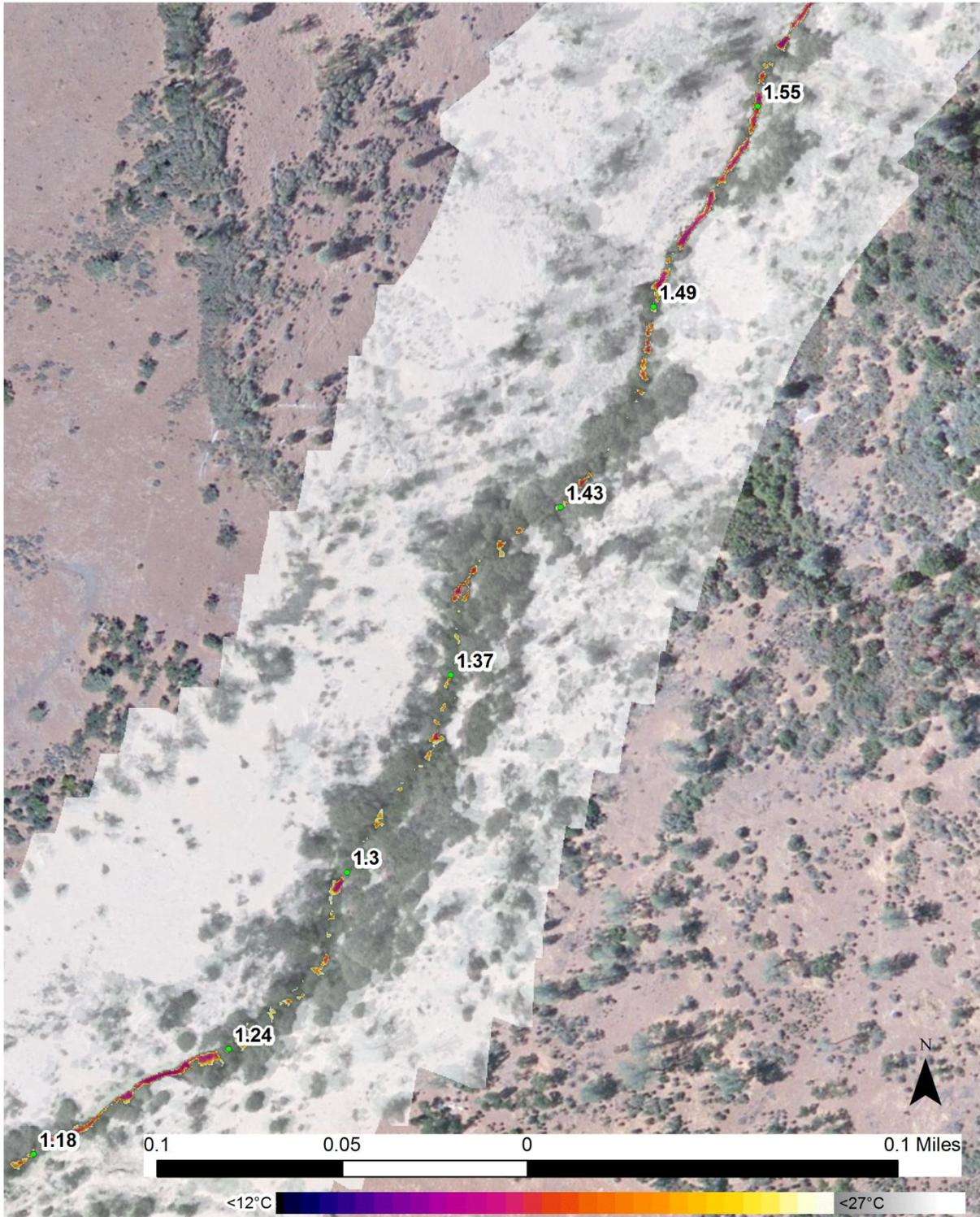


Figure 14. The figure above shows the thermal imagery of Soap Creek overlaying natural color aerial photo between river mile 1.1 and 1.6.