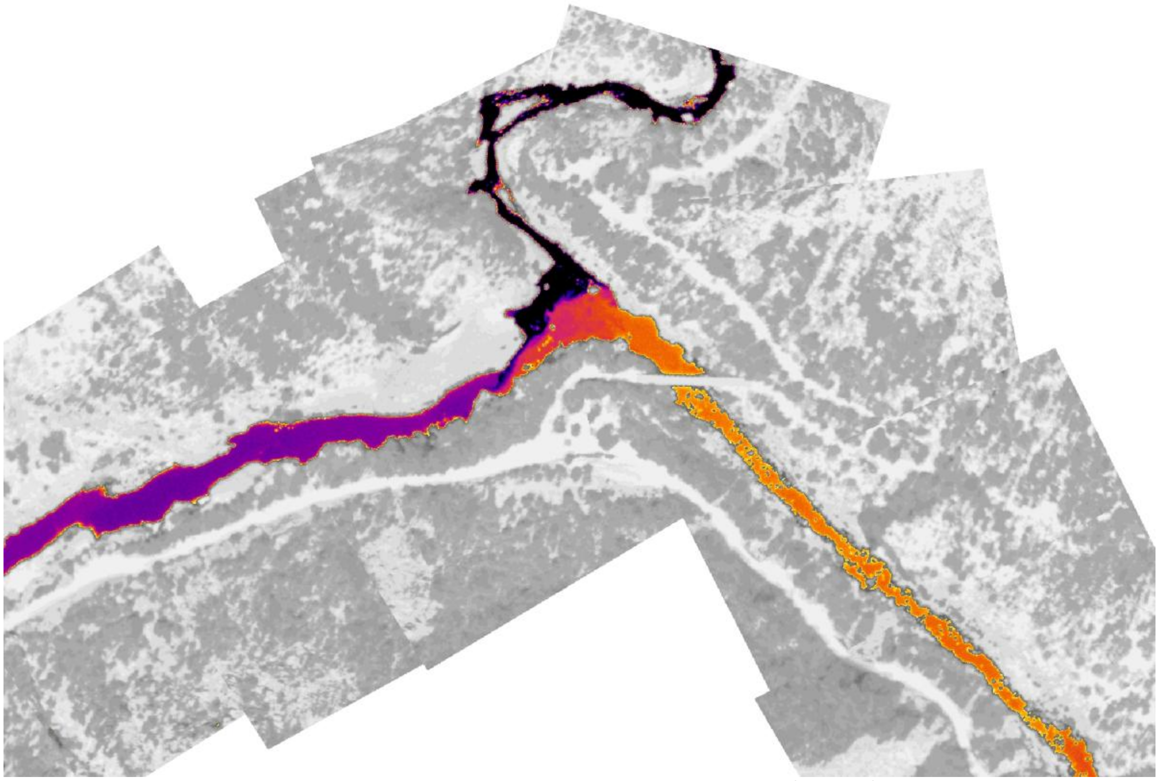
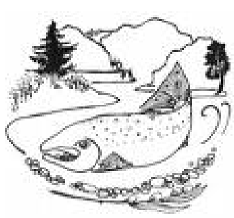
# Airborne Thermal Infrared Remote Sensing
## Salmon River Basin, California



*Confluence of Wooley Creek and Salmon River*

*Submitted to:*



Salmon River Restoration Council
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**Survey Date:** July 22-23, 2009
**Delivery Date:** January 8, 2010

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# Introduction

## *Project Overview*

In 2009, the Salmon River Restoration Council contracted with Watershed Sciences, Inc. to provide thermal infrared (TIR) imagery for approximately 85 river miles in the Salmon River Basin. The TIR acquisition included the mainstem Salmon River, North Fork Salmon River and the South Fork Salmon River (*Figure 1*, *Table 1*). True color image frames were co-acquired along the flight path.

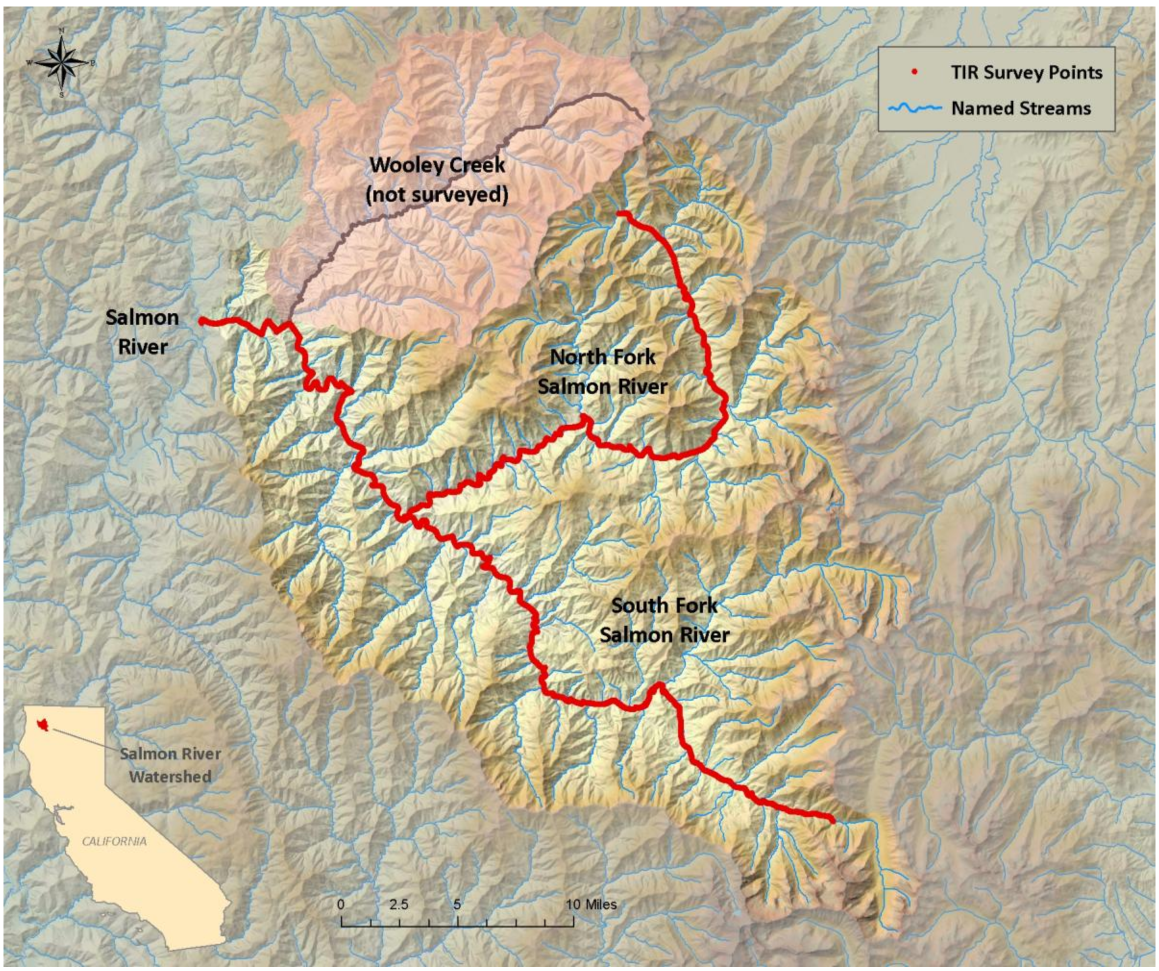



*Figure 1 – Thermal infrared (TIR) survey locations in the Salmon River Basin conducted July 22-23, 2009.*

Airborne TIR remote sensing has proven to be an effective method for mapping spatial temperature patterns in rivers and streams. These data are used to establish baseline conditions and direct future ground level monitoring. The TIR imagery illustrates the location and thermal influence of point sources, tributaries, and surface springs. When combined with other spatial data sets, the TIR data also illustrates reach-scale thermal response to changes in morphology, vegetation, and land-use.

*Table 1 – Stream segments surveyed in the Salmon River basin.*

| River Name | Date Flown | Miles Flown | Location |
|---|---|---|---|
| Salmon | 7/22/2009 | 19.1 | Mouth to NF/SF confluence |
| North Fork Salmon | 7/22/2009 | 32.5 | Mouth to Snowslide Gulch |
| South Fork Salmon | 7/23/2009 | 32.3 | Mouth to Browns Gulch |

## *Project Objectives*

The specific objectives of the TIR image acquisition were:

- Spatially characterize surface temperatures and stream flow conditions in the Salmon River basin.
- Develop longitudinal temperature profiles which illustrate basin-scale stream temperature patterns.
- Identify and map cool water sources and thermal refugia.
- Create GIS compatible data layers (e.g. thermal image mosaics, spring locations, etc.) that can be used to plan future research, direct ground based monitoring and analysis, and protect and restore critical habitat.

## *Data Collection*

Instrumentation: Images were collected with a FLIR system's SC6000 sensor (8-9.2μm) mounted on the underside of a Bell Jet Ranger Helicopter (*Figure 2*). The SC6000 is a calibrated radiometer with internal non-uniformity correction and drift compensation. General specifications of the thermal infrared sensor are listed in Table 2. The natural color images were collected with a Nikon D2X 12.4 Megapixel digital SLR camera with 30mm lens that was co-located with the TIR sensor.


*Figure 2 – Bell Jet Ranger equipped with a thermal infrared radiometer. The sensor is contained in a composite fiber enclosure attached to the underside of the helicopter and flown longitudinally along the stream channel.*

*Table 2 - Summary of TIR sensor specifications*

| | |
|---|---|
| Sensor: | 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: | 18.2° |

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 3*).

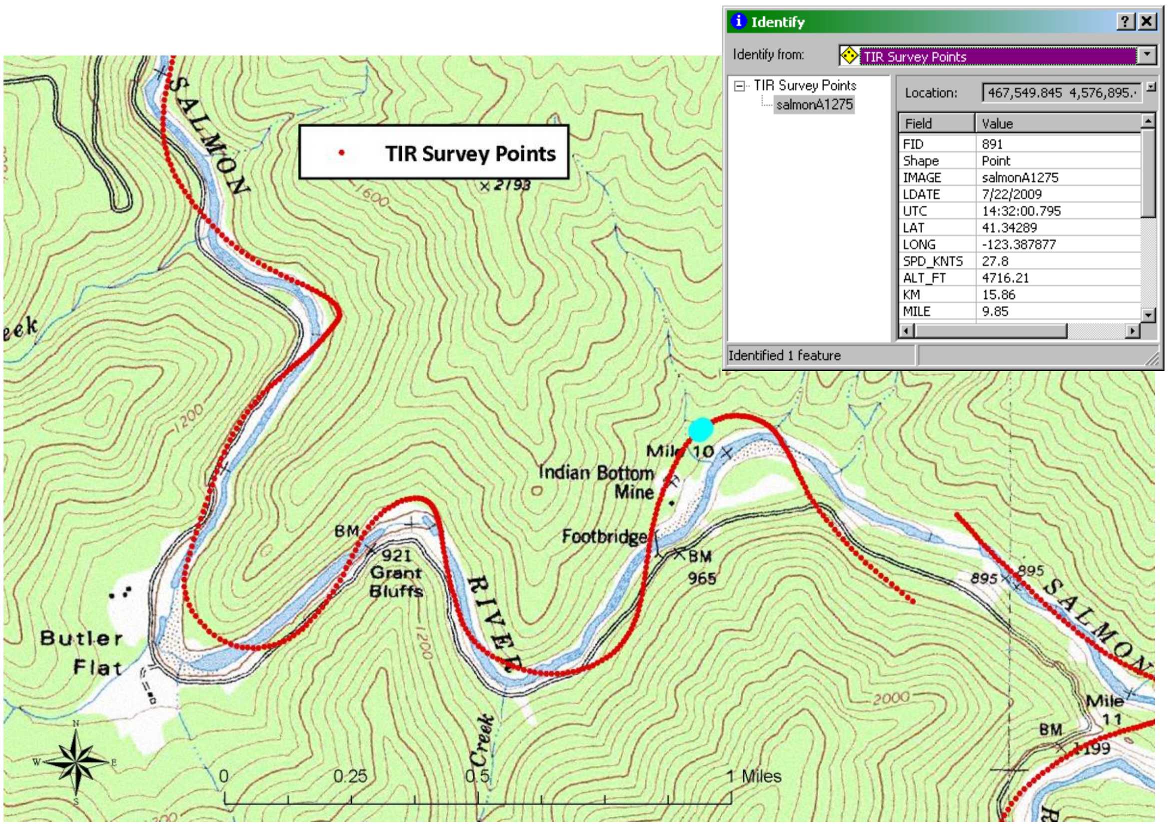


*Figure 3 –Each point on the map represents a thermal image location. The inset box shows the information recorded with each image point during acquisition. River measures were calculated based on the NHD stream layer.*

Image Characteristics: The aircraft was flown longitudinally along the stream corridor in order to capture the river in the center of the display. The objective was for the stream to occupy 30-60% of the image. The TIR sensor is set to acquire images at a rate of 1 image every second resulting in 40-70% vertical overlap between images.

A flight altitude of 4000 ft (1219 m) was selected for the project which resulted in a native pixel ground sample distance of 0.6 m (2.0 ft). The flight altitude was selected in order to optimize resolution while providing an image ground footprint wide enough to capture the active channel (*Table 3*).

*Table 3 - Summary of Thermal Image Acquisition Parameters*

| | |
|---|---|
| Flight Above Ground Level (AGL): | 4000 ft (1219 m) |
| Image Footprint Width: | 1280 ft (390 m) |
| Pixel Resolution: | 0.6 m (2.0 ft) |

The airborne survey attempted to cover all surface water within the floodplain including side channels and tributary junctions. Surface water not captured in the image field of view was flown separately to ensure complete coverage.

Ground Control: The Salmon River Restoration Council provided Watershed Sciences, Inc. with data from 13 in-stream sensors deployed throughout the summer months by various organizations working in the basin. In-stream temperatures were assessed at the time frame of the flight for calibrating and verifying the thermal accuracy of the TIR imagery. The sensor data were generally recorded at 1-hour intervals and values were interpolated between readings to determine stream temperatures at the time of image acquisition. The data logger locations are illustrated in Figure 4.

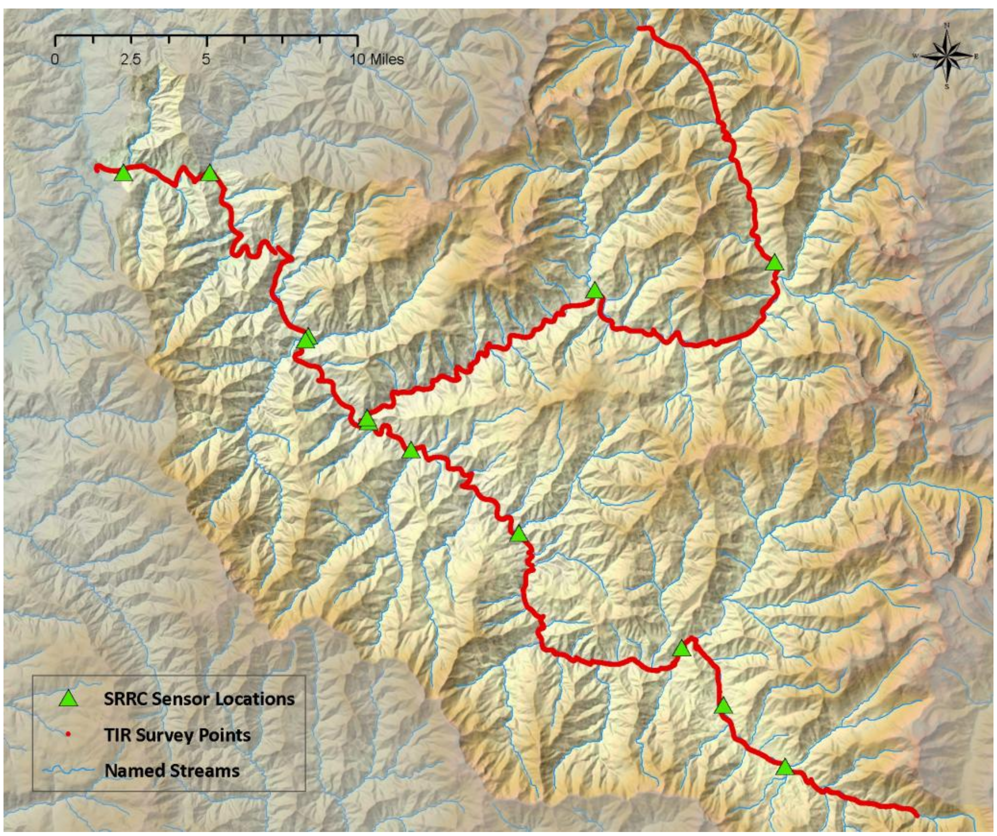



*Figure 4 – Location of sensors deployed by the Salmon River Restoration Council.*

## *Data Processing*

Calibration: Prior to the season, the response characteristics of the TIR sensor are measured in a laboratory environment. The response curves relate the raw digital numbers recorded by the sensor to emitted radiance from the black body. The raw TIR images collected during the survey initially contain digital numbers which are then converted to radiance temperatures based on the pre-season calibration.

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

Interpretation and Sampling: Once calibrated, the images were integrated into a GIS in which an analyst interpreted and sampled stream temperatures. Sampling consisted of querying radiant temperatures (pixel values) from the center of the stream channel and saving the median value of a ten-point sample to a GIS database file. The temperature of detectable surface inflows (i.e. surface springs, tributaries) was also sampled at their mouths. During sampling, the analyst provided interpretations of the spatial variations in surface temperatures observed in the images.

Temperature Profiles: The median temperatures for the stream in each sampled image were plotted versus the corresponding river mile to develop a longitudinal temperature profile. The profile illustrates how stream temperatures vary spatially along the stream gradient. The location and median temperature of all sampled surface water inflows (e.g. tributaries, surface springs, etc.) are included on the plot to illustrate how these inflows influence the main stem temperature patterns. Radiant temperatures were only sampled along what appeared to be the main flow channel in the river.

Geo-referencing: The images are tagged with a GPS position and heading at the time they are acquired (*Figure 3*). Since the TIR camera is maintained at vertical down-look angles, the geographic coordinates provide a reasonably accurate index to the location of the image scene. Due to the relatively small footprint of the imagery and independently stabilized mount, image pixels are not individually registered to real world coordinates. The image index is saved as an ESRI point shapefile containing the image name registered to an X and Y position of sensor location at time of capture. In order to provide further spatial reference, the TIR images were assigned a river mile based on a routed stream layer.

Geo-Rectification: The individual TIR frames were manually geo-rectified by finding a minimum of six common ground control points (GCPs) between the image frames and the NAIP imagery. Both 2005 and 2009 NAIP imagery were used. The images were then warped using a 1$^{st}$ order polynomial transformation. Images were not corrected for terrain displacement. The true color images were not rectified.

## *Thermal Image Characteristics*

Surface Temperatures: 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 temperature. Thermal infrared data accurately represents bulk water temperatures where the water column is thoroughly mixed; however, thermal stratification can form in reaches that have little or no mixing. Thermal stratification in a free flowing river is inherently unstable due to variations in channel shape, bed composition, and in-stream objects (i.e. rocks, trees, debris, etc.) that cause turbulent flow and can usually be detected in the imagery.

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%). However, variable water surface conditions (i.e. riffle versus pool), slight changes in viewing aspect, and variable background temperatures (i.e. sky versus trees) 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 $0.5^{o}C$.[1] However, the occurrence of reflections as an artifact (or noise) in the TIR images is a consideration during image interpretation and analysis. In general, apparent stream temperature changes of $< 0.5^{o}C$ are not considered significant unless associated with a surface inflow (e.g. tributary).

Differential Heating: In stream segments with flat surface conditions (i.e. pools) and relatively low mixing rates, observed variations in spatial temperature patterns can be the result of differences in the instantaneous heating rate at the water's surface. In the TIR images, indicators of differential surface heating include seemingly cooler radiant temperatures in shaded areas compared to surfaces exposed to direct sunlight.

Feature Size and Resolution: A small stream width logically translates to fewer pixels "in" the stream 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 inaccuracies in the measured radiant temperatures. This is a consideration when sampling the radiant temperatures at tributary mouths and surface springs.

Temperatures and Color Maps: The TIR images collected during this survey consist of a single band. As a result, visual representation of the imagery *(in a report or GIS environment*) requires the application of a color map or legend to the pixel values. The selection of a color map should highlight features most relevant to the analysis (i.e. *spatial variability of stream temperatures*). For example, a continuous, gradient style color map that incorporates all temperatures in the image frame will provide a smoother transition in colors throughout the entire image, but will not highlight temperature

[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.

differences in the stream.  Conversely, a color map that focuses too narrowly cannot be applied to the entire river and will washout terrestrial and vegetation features (*Figure 5*).

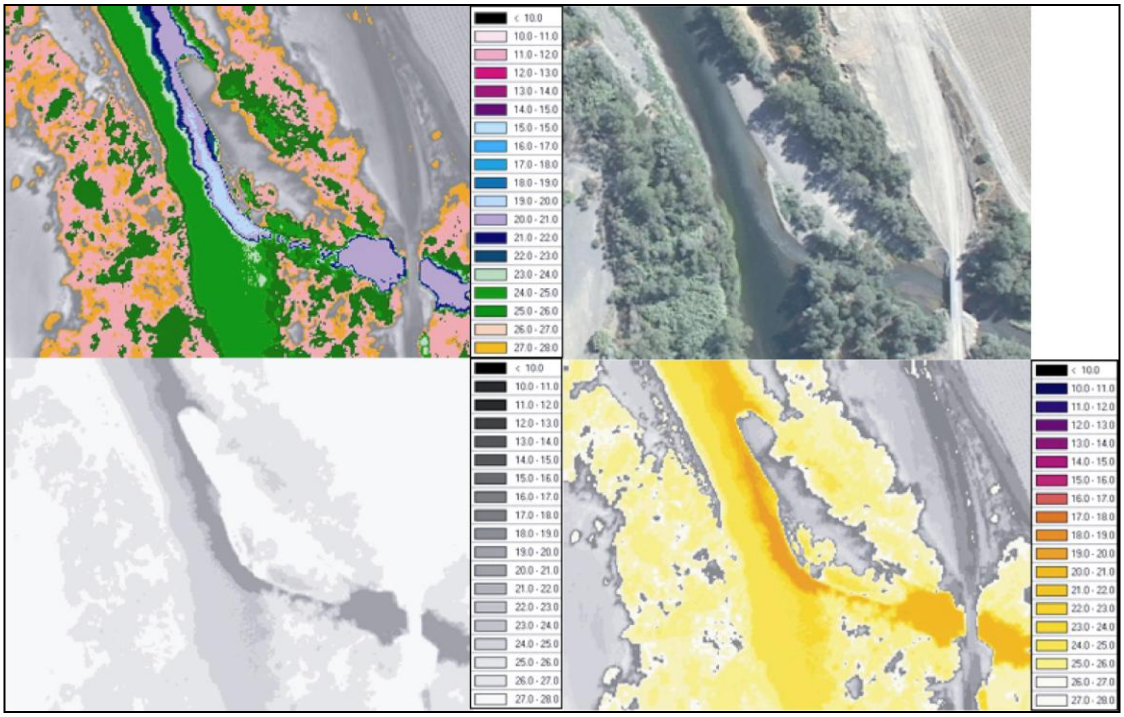


*Figure 5 - Example of different color maps applied to the same TIR image.*

Image Uniformity:  The TIR sensor used for this study 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 $<0.5^{o}$C) can be observed near the edge of the image frame.  The uniformity differences within frames and slight differences from frame-to-frame are often most apparent in the continuous mosaics.

# Weather Conditions

Weather conditions on the dates of the survey were considered ideal with warm temperatures, low humidity and clear skies. Data from seasonal in-stream thermographs will be needed to assess how water temperatures on the day of the flight compare to average and maximum summer temperatures. Table 4 summarizes the weather conditions observed at Sawyers Bar, California on July 22-23, 2009.

*Table 4 – Weather conditions on July 22-23, 2009 measured at Sawyers Bar/Forks of Salmon (RAWS Station: MSWBC1) (http://www.wunderground.com)*

| PDT | Air Temp (°F) | Air Temp (°C) | Relative Humidity | Wind Speed (mph) | Wind Direction |
|---|---|---|---|---|---|
| **Salmon/North Fork Salmon: 7/22/2009** | | | | | |
| 14:13 | 94.0 | 34.4 | 13% | 7.0 | WSW |
| 14:33 | 94.0 | 34.4 | 13% | 7.0 | WSW |
| 14:43 | 94.0 | 34.4 | 13% | 7.0 | WSW |
| 15:13 | 98.0 | 36.7 | 12% | 8.0 | WSW |
| 15:23 | 98.0 | 36.7 | 12% | 8.0 | WSW |
| 15:33 | 98.0 | 36.7 | 12% | 8.0 | WSW |
| 15:43 | 98.0 | 36.7 | 12% | 8.0 | WSW |
| 16:13 | 98.0 | 36.7 | 12% | 8.0 | WSW |
| 16:23 | 98.0 | 36.7 | 12% | 8.0 | WSW |
| 16:33 | 98.0 | 36.7 | 12% | 8.0 | WSW |
| 16:43 | 98.0 | 36.7 | 12% | 8.0 | WSW |
| **South Fork Salmon: 7/23/2009** | | | | | |
| 14:13 | 95.0 | 35.0 | 19% | 6.0 | WSW |
| 14:23 | 95.0 | 35.0 | 19% | 6.0 | WSW |
| 14:33 | 95.0 | 35.0 | 19% | 6.0 | WSW |
| 15:12 | 97.0 | 36.1 | 13% | 8.0 | WSW |
| 15:33 | 97.0 | 36.1 | 13% | 8.0 | WSW |
| 15:43 | 97.0 | 36.1 | 13% | 8.0 | WSW |
| 16:12 | 101.0 | 38.3 | 13% | 7.0 | WSW |
| 16:22 | 101.0 | 38.3 | 13% | 7.0 | WSW |
| 16:33 | 101.0 | 38.3 | 13% | 7.0 | WSW |
| 16:42 | 101.0 | 38.3 | 13% | 7.0 | WSW |

## Thermal Accuracy

The Salmon River Restoration Council provided temperature data from 13 in-stream data loggers that were active during the time frame of the flight (*Figure 4*). Table 5 summarizes a comparison between the kinetic temperatures recorded by the in-stream data loggers and radiant temperatures derived from the TIR images.

*Table 5 – Comparison of radiant temperatures derived from the TIR images and kinetic temperatures from the in-stream sensors*

| Stream | Serial | Image | Mile | Km | Time | In-Stream | Radiant | Difference |
|---|---|---|---|---|---|---|---|---|
| **Mainstem Salmon River (7/22)** | | | | | | | | |
| Salmon | SMS01_0 | salmonA0192 | 0.91 | 1.46 | 14:12 | 22.4 | 22.3 | 0.1 |
| Salmon | SMS05_0 | salmonA0710 | 4.85 | 7.81 | 14:22 | 19.2 | 22.0 | -2.8 |
| Salmon | SMS13_0 | salmonA1821 | 14.38 | 23.15 | 14:41 | 22.1 | 22.4 | -0.3 |
| Salmon | SMS13_5 | salmonA1841 | 14.57 | 23.44 | 14:41 | 22.9 | 22.5 | 0.4 |
| SF Salmon | SSF00_2 | salmonA2351 | 19.17 | 30.86 | 14:51 | 22.5 | 22.6 | -0.1 |
| NF Salmon | SNF00_1 | salmonA2357 | 19.27 | 31.03 | 14:51 | 23.6 | 23.3 | 0.3 |
| **North Fork Salmon River (7/22)** | | | | | | | | |
| SF Salmon | SSF00_2 | salmonA2351 | 0.00 | 0.00 | 14:51 | 22.5 | 22.5 | 0.0 |
| NF Salmon | SNF00_1 | salmonA2357 | 0.10 | 0.17 | 14:51 | 23.6 | 23.5 | 0.1 |
| NF Salmon | SNF11_4 | salmonA4305 | 11.53 | 18.56 | 15:29 | 23.8 | 23.8 | 0.0 |
| NF Salmon | SNF20_5 | salmonA5413 | 21.84 | 35.15 | 15:49 | 20.6 | 20.6 | 0.0 |
| **South Fork Salmon River (7/23)** | | | | | | | | |
| SF Salmon | SSF02_5 | salmonb0550 | 2.36 | 3.79 | 14:07 | 23.3 | 23.5 | -0.2 |
| SF Salmon | SSF08_5 | salmonb1617 | 8.44 | 13.58 | 14:26 | 21.7 | 21.9 | -0.2 |
| SF Salmon | SSF19_1 | salmonb3692 | 19.65 | 31.63 | 22:05 | 22.3 | 22.6 | -0.3 |
| SF Salmon | SSF22_5 | salmonb4547 | 23.20 | 37.34 | 15:19 | 22.2 | 21.5 | 0.7 |
| SF Salmon | SSF26_0 | salmonb4855 | 26.55 | 42.73 | 15:25 | 19.9 | 19.5 | 0.4 |

In general, the differences between radiant and kinetic temperatures were consistent with other airborne TIR surveys conducted by Watershed Sciences in the Pacific Northwest and within the target accuracy of ±0.5$^{o}$C. However, two sensors were outside the target range of measured radiant temperatures.

The radiant temperatures in the Salmon River at mile 4.85 (SMS05_0) exhibited a large difference (2.8$^{o}$C) compared to the in-stream measurements. However, the radiant temperatures were within tolerance for both the immediate lower (SMS01_0) and upper (SMS13_0) sensors using the same image calibration parameters. Inspection of the imagery shows the large cooling influence of Wooley Creek immediately downstream of the sensor location. We suspect that the sensor readings are being influenced by the mixing of Wooley Creek with the mainstem and sub-surface temperatures measured by the in-stream sensor were not indicative of surface temperatures measured by the thermal camera.

## Results

Median channel temperatures were plotted versus river mile for the streams in the survey area. Tributaries, seeps and springs sampled during the analysis are included on the longitudinal profiles to provide additional context for interpreting spatial temperature patterns. River miles were based on a routed version of the NHD stream layer[2]. The routes of Salmon and the South Fork Salmon were slightly modified to give more accurate river mile measures, particularly in areas of tight bends. The adjusted routes are included in the data.

While the natural morphology of rivers exists on a continuum, for the purposes of this analysis, features were grouped into defined categories. Seeps and springs were differentiated mainly by size. Larger cold water sources with a defined source were considered springs, while smaller more diffuse features were designated as seeps. Hyporheic flow is a particular type of seep typically seen originating from the downstream end of sandbars as surface flows mingle with shallow groundwater resulting in cooler temperatures. On occasion, it is not possible to determine the source of a feature based on the available imagery, particularly in areas of deep shadow high in the watershed. Care should be taken to verify features of interest in the field.

Due to the nature of the project, the focus of the survey was to depict thermal conditions during peak summer temperatures. Given the warm temperatures on the days of the survey, features such as hot springs or warm sloughs and ponds may have been 'washed out' in comparison to the surrounding terrestrial landscape. Figures 6, 7, and 8 contain the longitudinal temperature profiles for the Salmon, North Fork Salmon, and South Fork Salmon Rivers respectively. Tables 6, 7, and 8 show the thermal features for each river. Each longitudinal profile and table is followed by a discussion of the thermal trends of the stream and sample images for each. The discussion and images contained in this report are not meant to be comprehensive, but provide a description of the major thermal trends and examples of river features and interpretations.

[2] U.S. Department of the Interior, U.S. Geological Survey. URL: http://nhd.usgs.gov/index.html

## *Salmon River*

## Longitudinal Temperature Profile

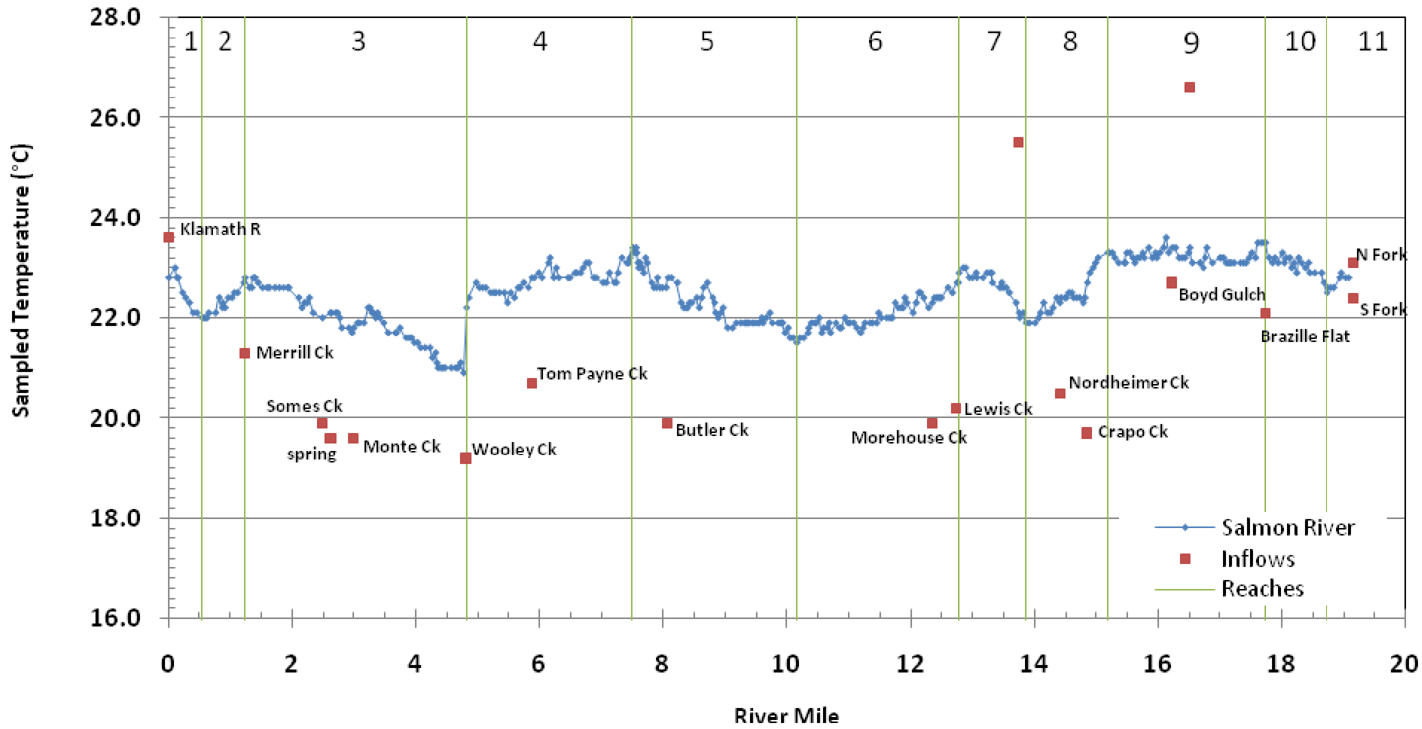



*Figure 6 - Median channel temperatures plotted versus river mile for the Salmon River. The locations of detected surface inflows are illustrated on the profile and listed in Table 6.*

*Table 6 - Tributaries, inflows and selected side channels sampled along the Salmon River (with left or right bank designation looking downstream) are listed.*

| Tributaries | Kilometer | River Mile | Tributary Temp (°C) | Mainstem Temp (°C) | Difference |
|---|---|---|---|---|---|
| Klamath River | 0.00 | 0.00 | 23.6 | 22.8 | 0.8 |
| Merrill Creek (R) | 1.98 | 1.23 | 21.3 | 22.8 | -1.5 |
| Somes Creek (L) | 3.99 | 2.48 | 19.9 | 22.0 | -2.1 |
| spring (R) | 4.22 | 2.62 | 19.6 | 22.1 | -2.5 |
| Monte Creek (L) | 4.81 | 2.99 | 19.6 | 21.8 | -2.2 |
| Wooley Creek (R) | 7.75 | 4.81 | 19.2 | 22.2 | -3.0 |
| Tom Payne Creek (R) | 9.45 | 5.87 | 20.7 | 22.8 | -2.1 |
| Butler Creek (L) | 12.99 | 8.07 | 19.9 | 22.8 | -2.9 |
| Morehouse Creek (R) | 19.85 | 12.34 | 19.9 | 22.3 | -2.4 |
| Lewis Creek (L) | 20.50 | 12.74 | 20.2 | 22.7 | -2.5 |
| Nordheimer Flat ( L) | 22.13 | 13.75 | 25.5 | 22.0 | 3.5 |
| Nordheimer Creek (L) | 23.20 | 14.42 | 20.5 | 22.4 | -1.9 |
| Crapo Creek (R) | 23.90 | 14.85 | 19.7 | 22.7 | -3.0 |
| Boyd Gulch (R) | 26.10 | 16.22 | 22.7 | 23.4 | -0.7 |
| Otter Bar pond (R) | 26.56 | 16.50 | 26.6 | 23.4 | 3.2 |
| Brazille Flat (L) | 28.54 | 17.73 | 22.1 | 23.5 | -1.4 |
| South Fork Salmon R (L) | 30.82 | 19.15 | 22.4 | 22.9 | -0.5 |
| North Fork Salmon R (R) | 30.83 | 19.16 | 23.1 | 22.9 | 0.2 |

## Observations

The entire 19 miles of the Salmon River were surveyed for thermal features on July 22, 2009 from the mouth at the Klamath River to the confluence of the North Fork and South Fork Salmon Rivers. Stream temperatures were quite stable ranging from 20.9°C at the confluence with Wooley Creek (RM 4.81) to 23.7°C at Fong Wah Bar. Fifteen tributaries, 1 pond, and 1 spring were sampled in the imagery. Flow rates on the day of the survey were well below the historic average at the only active USGS monitoring gage in the watershed (*Appendix A*). The daily discharge at Somes Bar was 278 cubic feet per second.

In general, the Salmon River flows through a narrow forested canyon with steep chutes, pool/riffle reaches, and sandbars. Only Wooley Creek (RM 4.81) and Nordheimer Creek (RM 14.42) contribute significant surface flow to the mainstem. Wooley Creek is the only point source to have a significant impact on the thermal profile, dropping bulk water temperatures by 1.7°C (22.7→21.0°C) (*Salmon Image 1*).

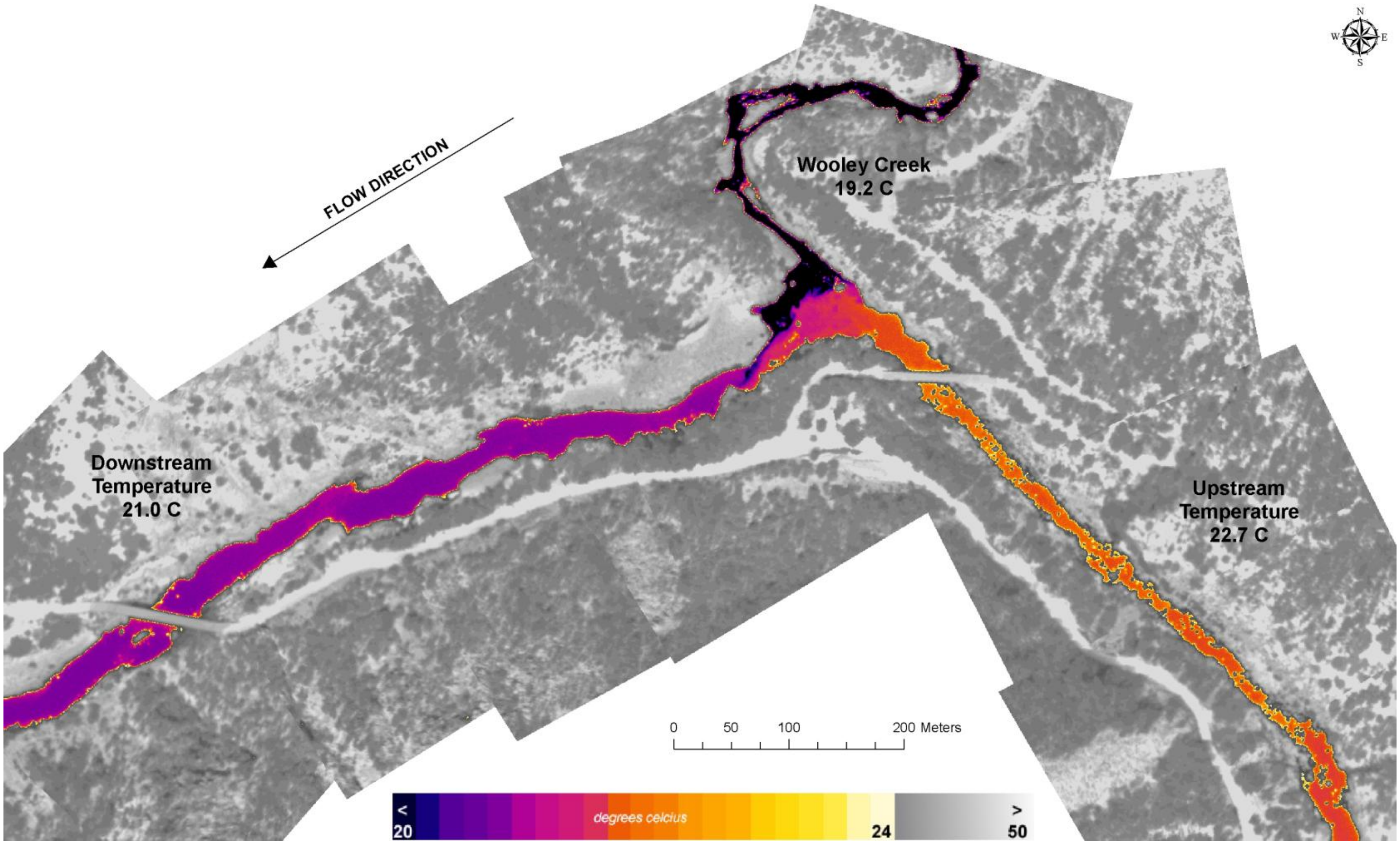
At the watershed scale, in the absence of point sources, three types of thermal trends can be seen in the longitudinal profile: increasing temperatures, stable temperature plateaus, and decreasing temperatures. On a warm summer day with temperatures in the mid-nineties, radiant water temperatures would be expected to increase as the river flows downstream. Reaches with stable temperatures or decreasing temperatures indicate zones of groundwater influence in the absence of cool surface inflows such as Wooley Creek. Subsurface contributions commonly appear in areas where there are changes in river morphology, geology or valley type. These groundwater interactions may result in detectable point sources (i.e. seeps and springs) or they may be more diffuse.

On the Salmon, reaches 1, 3, 5, 7, and 10 (as noted on the longitudinal profile) had temperature increases of one degree or more over varying distances. This type of warming indicates that diurnal heating is controlling the thermal profile in these reaches. Reach 3 warms rapidly after the confluence with Wooley Creek. The valley is wider and more exposed along this reach allowing for more direct radiant heating. Reach 10 is also more open than other sections of the river which may explain the increased temperatures. Reach 7 appears to flow through a bedrock area denuded of vegetation which may be preventing groundwater interactions (*Salmon Image 2*). It is not immediately apparent from the available imagery why there is warming in reaches 1 and 5.

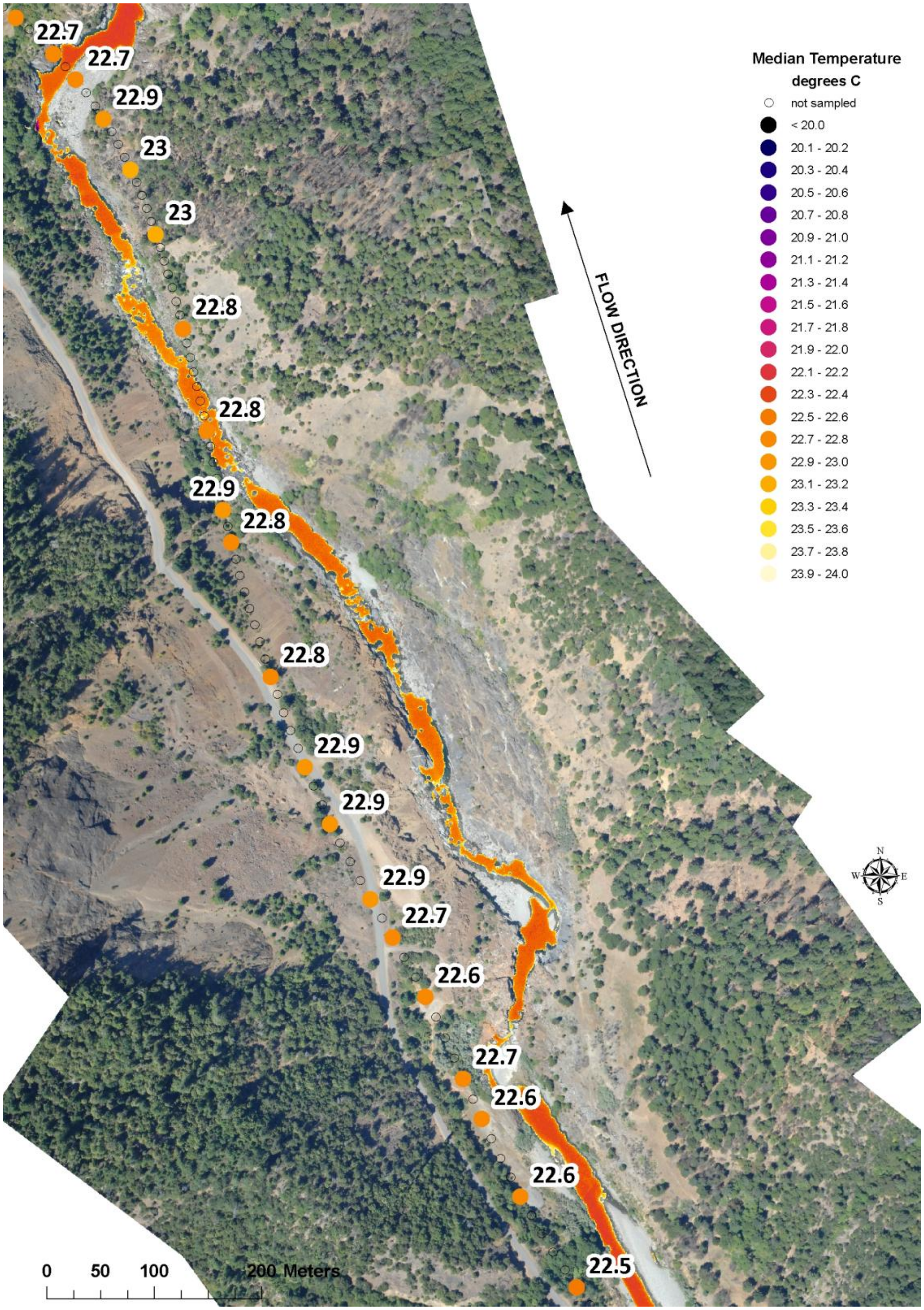
Reach 9 (RM 15.18-17.73) has relatively stable temperatures over a 2.5 mile distance (23.1→23.7°C). This type of thermal plateau indicates that daytime heating is being tempered by cooling influences. No large surface inflows were seen in this reach; however, several major gulches intersect the river in this location: Fong Wah Gulch, Logan Gulch, and Boyd Gulch. Boyd Gulch, though small, sampled cooler than the mainstem at 22.7°C, as did a small pool seen on Brazille Flat (22.1°C). Logan Gulch and Fong Wah Gulch were too small to be sampled. In areas where drainages intersect, it is common to see subsurface interactions resulting in cooler temperatures. Though they were too small to be sampled, the seep at river mile 16.12 and the hyporheic flow (RM 16.66) are indicators of groundwater interactions.

In reaches where the subsurface interactions outpace diurnal heating, cooling trends can be seen. Reaches 2, 4, 6, 8, and 11 are all examples of this type of cooling. The cooling in reach 11 is likely due to subsurface interactions caused by the confluence of the North Fork and South Fork drainages. Merrill Creek impacts Reach 2 by contributing a point source seep (21.3°C) and likely more diffuse groundwater not visible in the imagery. Reaches 4 and 6 both flow through very narrow sections of the canyon and likely have a great deal of subsurface interaction. Reach 8 is being heavily influenced by Crapo Creek and Nordheimer Creek (*Salmon Image 3*). The continued cooling trend downstream of Nordheimer Creek suggests some continued subsurface influence that could not be directly detected in the imagery.

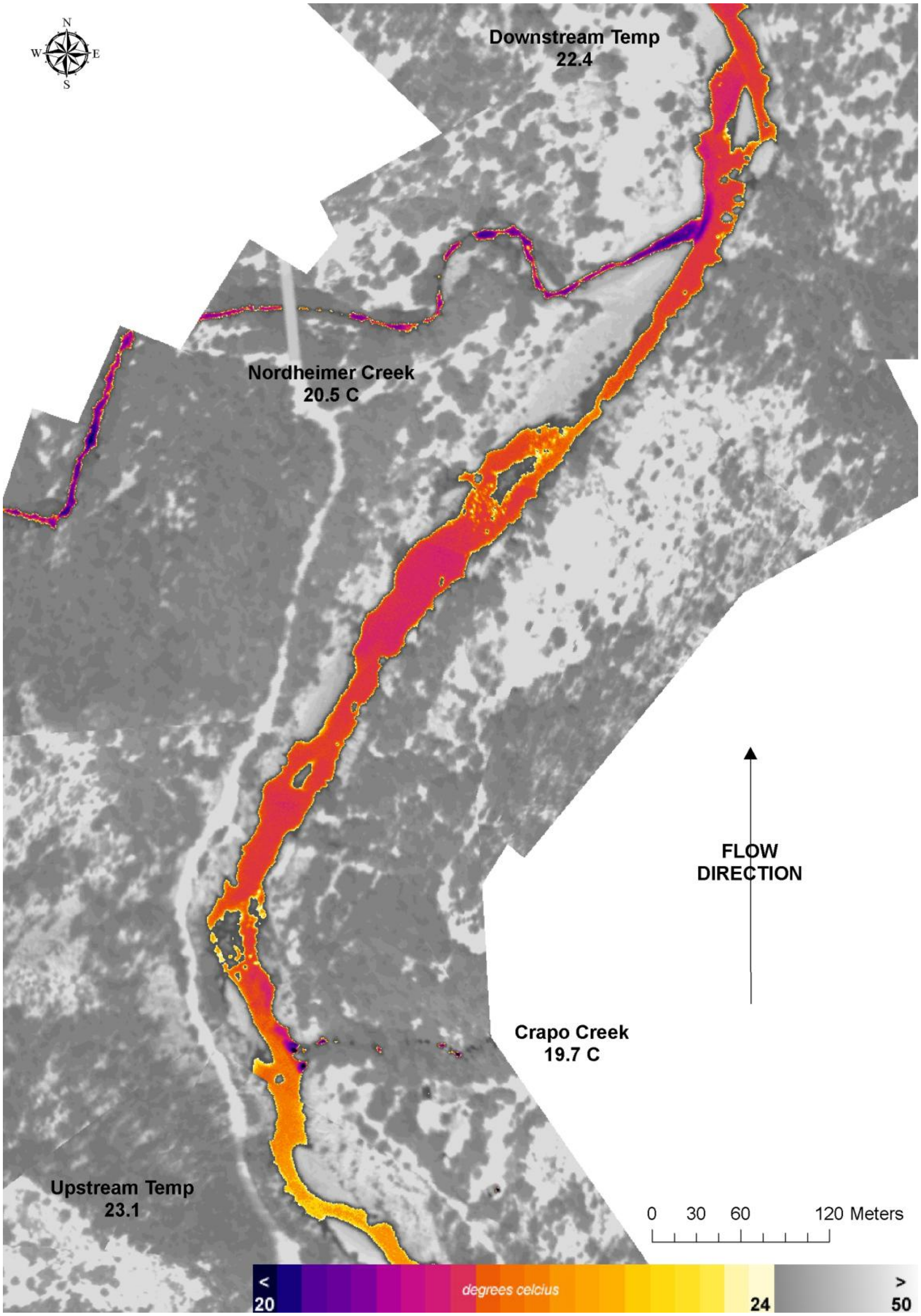
## Sample Images




*Salmon Image 1 – The TIR mosaic below shows the confluence of the Salmon River and Wooley Creek. Wooley Creek acts as a cooling source to the Salmon dropping bulk temperatures by 1.7°C.*




*Salmon Image 2 – The TIR/true color image above shows the bedrock chute at river mile 13 in Reach 7 of the longitudinal profile. Temperatures rise along this reach indicating that diurnal heating is controlling the thermal signature. Because the riverbed is bedrock at this point, it is unlikely that there is any hyporheic interaction in this location.*




*Salmon Image 3 – The TIR image above shows the confluence of Crapo Creek (RM 14.85) and Nordheimer Creek (RM 14.42) with the Salmon River. Both tributaries act as cooling influences to the mainstem dropping the bulk water temperatures along Reach 8.*

## *North Fork Salmon River*

### Longitudinal Temperature Profile

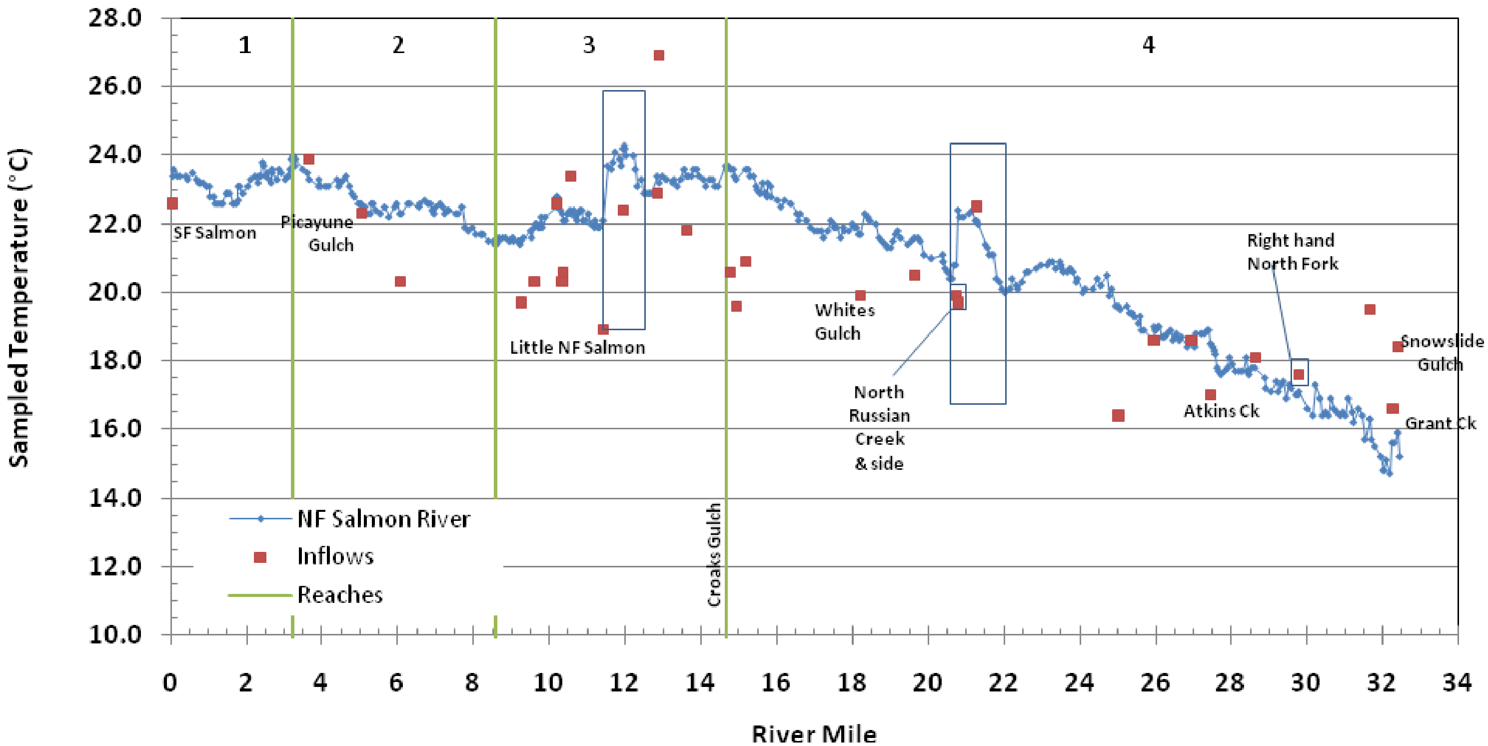



*Figure 7- Median channel temperatures plotted versus river mile for the North Fork Salmon River. The locations of detected surface inflows are illustrated on the profile and listed in Table 7.*

*Table 7 – Tributaries, inflows and selected side channels sampled along the North Fork Salmon River (with left or right bank designation looking downstream) are listed.*

| Inflows | Kilometer | River Mile | Inflow Temp (°C) | Mainstem Temp (°C) | Difference |
|---|---|---|---|---|---|
| SF Salmon River (L) | 0.10 | 0.06 | 22.6 | 23.4 | -0.8 |
| side channel (R) | 5.89 | 3.66 | 23.9 | 23.3 | 0.6 |
| Picayune Gulch ( L) | 8.09 | 5.03 | 22.3 | 22.6 | -0.3 |
| Unnamed Gulch (L) | 9.75 | 6.06 | 20.3 | 22.3 | -2.0 |
| spring (L) | 14.88 | 9.25 | 19.7 | 21.5 | -1.8 |
| Peck Gulch (R) | 15.45 | 9.60 | 20.3 | 21.9 | -1.6 |
| side channel (R) | 16.41 | 10.20 | 22.6 | 22.8 | -0.2 |
| Cronan Gulch (R) | 16.64 | 10.34 | 20.3 | 22.3 | -2.0 |
| seep/side channel (L) | 16.69 | 10.37 | 20.6 | 22.1 | -1.5 |
| wetland (R) | 16.98 | 10.55 | 23.4 | 22.4 | 1.0 |
| Little NF Salmon R (R) | 18.38 | 11.42 | 18.9 | 22.1 | -3.2 |
| seeps (L) | 19.21 | 11.94 | 22.4 | 24.2 | -1.8 |
| Glasgow Gulch (L) | 20.67 | 12.84 | 22.9 | 23.4 | -0.5 |
| wetland (L) | 20.76 | 12.90 | 26.9 | 23.2 | 3.7 |
| side channel (L) | 21.92 | 13.62 | 21.8 | 23.4 | -1.6 |
| hyporheic flow/side chan (L) | 23.80 | 14.79 | 20.6 | 23.6 | -3.0 |
| spring on side channel (R) | 24.03 | 14.93 | 19.6 | 23.3 | -3.7 |
| Jessups Gulch (L) | 24.45 | 15.19 | 20.9 | 23.6 | -2.7 |
| Whites Gulch (L) | 29.33 | 18.22 | 19.9 | 21.7 | -1.8 |
| side channel (L) | 31.61 | 19.64 | 20.5 | 21.6 | -1.1 |
| N Russian Creek (L) | 33.37 | 20.73 | 19.9 | 20.8 | -0.9 |
| side channel (L) | 33.46 | 20.79 | 19.7 | 22.4 | -2.7 |
| Unnamed (L) | 34.24 | 21.28 | 22.5 | 22.1 | 0.4 |
| Unnamed (R) | 40.27 | 25.02 | 16.4 | 19.6 | -3.2 |
| Big Twin Creek (R) | 41.77 | 25.96 | 18.6 | 19.0 | -0.4 |
| Big Creek (L) | 43.35 | 26.94 | 18.6 | 18.6 | 0.0 |
| Atkins Creek (R) | 44.20 | 27.46 | 17.0 | 18.5 | -1.5 |
| Deer Pen Creek (R) | 46.07 | 28.63 | 18.1 | 17.8 | 0.3 |
| Right Hand NF Salmon (L) | 47.94 | 29.79 | 17.6 | 17.1 | 0.5 |
| Deer Lick Creek (R) | 50.95 | 31.66 | 19.5 | 16.3 | 3.2 |
| Grant Creek (L) | 51.90 | 32.25 | 16.6 | 15.6 | 1.0 |
| Snowslide Gulch (L) | 52.14 | 32.40 | 18.4 | 15.9 | 2.5 |

## Observations

The North Fork Salmon River was flown on July 22, 2009 from the mouth to Snowslide Gulch for a total of 32.5 river miles. Nineteen tributaries, 5 seeps and springs, 2 wetlands, and 5 side channels were sampled as inflows. Several dozen drainages were seen in the imagery but were not sampled due to lack of water or small size. No active USGS flow gages were found for the river.

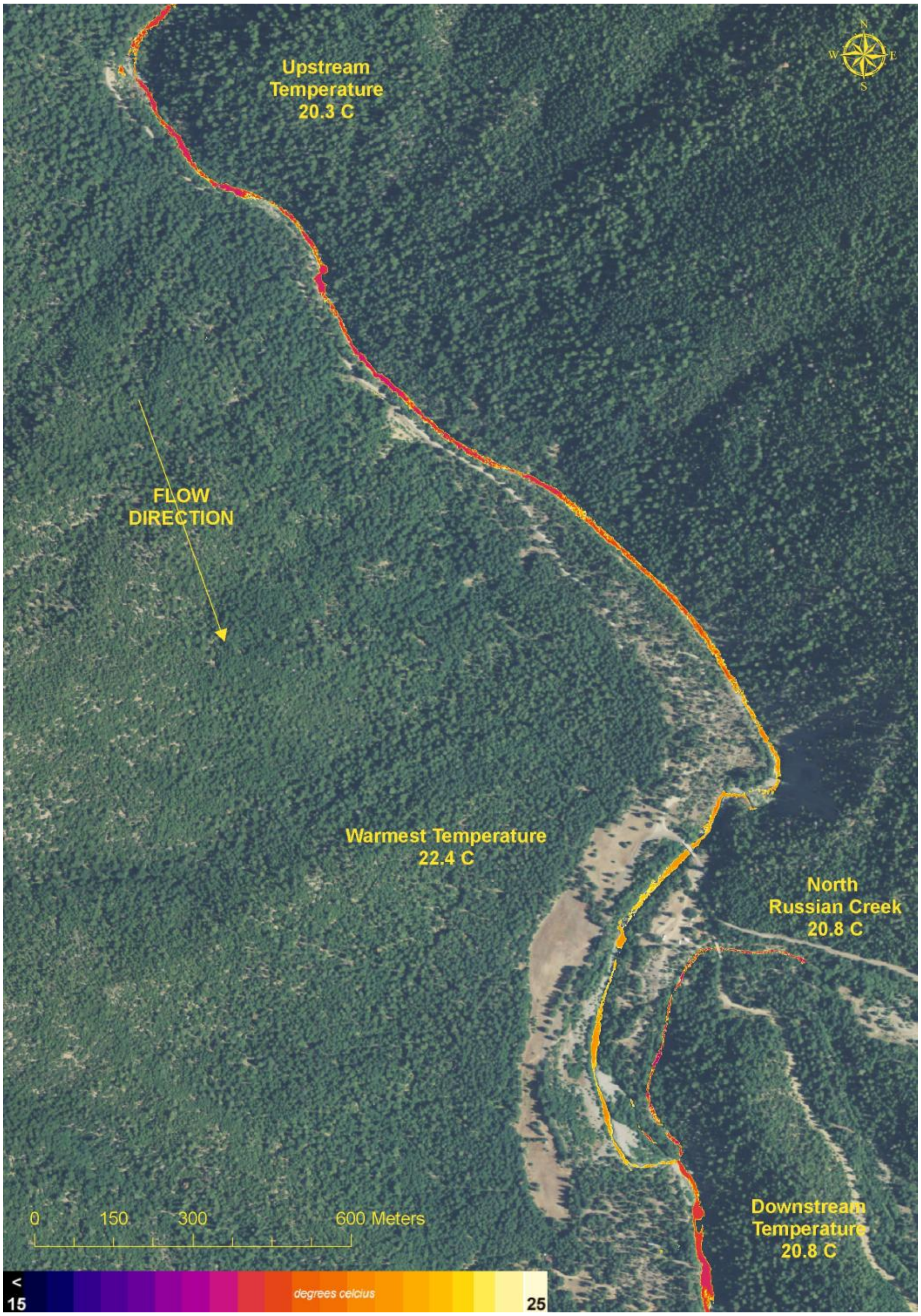
A steady warming trend is seen along Reach 4 in the upper watershed from Snowslide Gulch (RM 32.40) downstream to Croaks Gulch (RM 14.66) (14.8→23.7℃). The major deviation along this reach occurs from river mile 20.57-22.03. In this short reach, temperatures jump from 20.0°C to 22.4°C, and then drop back to 20.4°C in short succession. In the NAIP imagery, it appears that the river flows from a narrow confined canyon into a wider open valley at Idlewild Campground likely allowing for more direct radiant heating (*North Fork Image 1*). The river returns to a more stable temperature pattern below the confluence of North Russian Creek (RM 20.73).

Downstream of Croaks Gulch (Reach 3), temperatures decrease two degrees over 6 miles (23.7→21.4°C). A similar thermal trend as the one seen near Idlewild Campground can be seen from river mile 11.42 to 12.50, with a widening of the valley resulting in rapid warming. Temperatures then cool 1.6°C at the confluence with the Little North Fork Salmon River (23.7→22.1°C). The overall decreasing temperatures are caused both by the point source influence of the Little South Fork and assumed subsurface interactions from the numerous drainages along this reach of stream. Several small seeps were also seen along this reach.

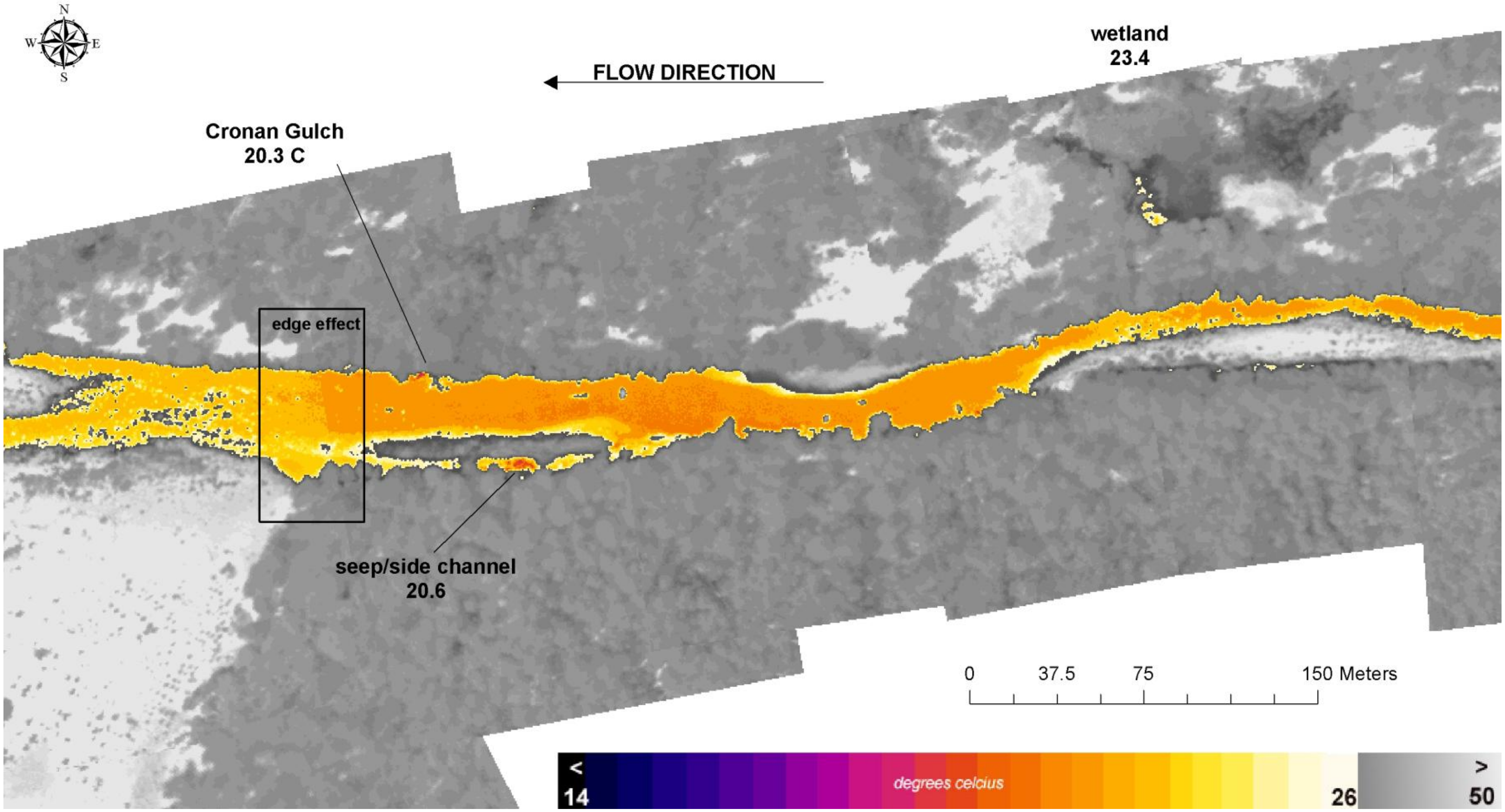
From river mile 8.57 downstream to river mile 3.24, a 2.5°C warming is seen indicating a lack of subsurface influence throughout this reach. There is no visible evidence in the imagery to explain this shift in the thermal profile. Further morphological studies would be needed to assess what causes the inflection in temperatures seen at river mile 8.57 (Reach 2).

A short cooling followed by warming is seen in the lower 3 miles of river (Reach 1) resulting in an overall temperature swing of 1.4°C (24.0→22.6→23.4°C).

## Sample Images




*North Fork Image 1 – The TIR/NAIP image above shows the local spatial thermal variability at Idlewild Campground. At this location, the river emerges from a narrow forested canyon into a more open meadow area for a short distance. Temperatures warm significantly through this reach perhaps due to the increased solar exposure. Temperatures return to a more stable thermal profile below the confluence with North Russian Creek.*




*North Fork Image 2 - .The TIR image above shows a short section of Reach 3 at Cronan Gulch (RM 10.64). The decreasing temperatures in Reach 3 indicate subsurface interactions like what is seen at the intersection of the North Fork and Cronan Gulch, and the small seep on the side channel on river left. The wetland seen along this reach indicates a shallow water table which allows for more hyporheic exchange and ultimately cooler temperatures. This image also shows an example of the edge effect seen when mosaicing the individual thermal frames. It is no unusual to see ±0.2°C variability between frames which can be visible in the mosaic. We choose not to blend or feather the imagery in order to maintain the native temperature values.*

## *South Fork Salmon River*

### Longitudinal Temperature Profile

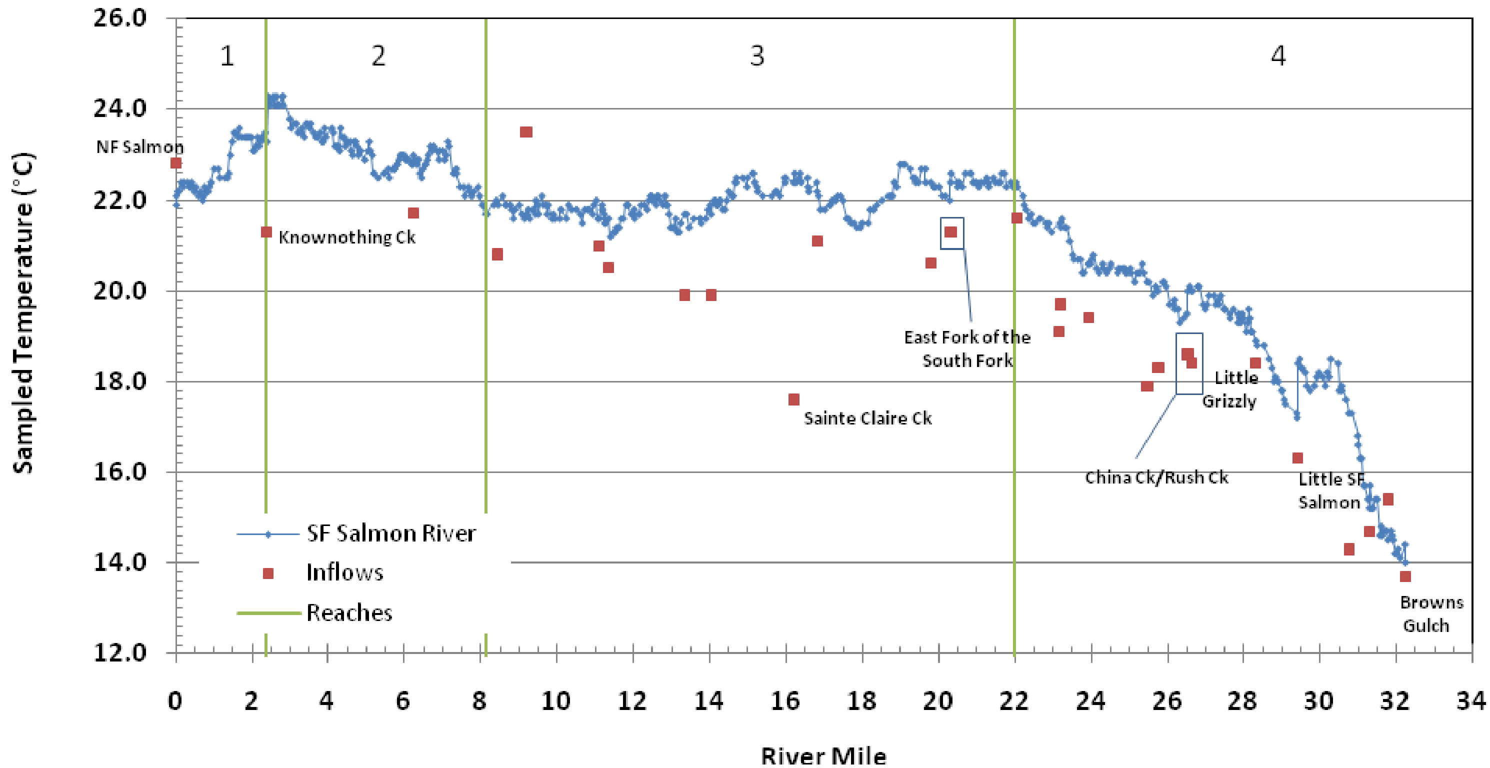



*Figure 8 - Median channel temperatures plotted versus river mile for the South Fork Salmon River. The locations of detected surface inflows are illustrated on the profile and listed in Table 8.*

*Table 8 – Tributaries, inflows and selected side channels sampled along the South Fork Salmon River (with left or right bank designation looking downstream) are listed.*

| Tributary | Kilometer | River Mile | Trib Temp (°C) | Mainstem Temp (°C) | Difference |
|---|---|---|---|---|---|
| Salmon River ( ) | 0.00 | 0.00 | 22.3 | 21.9 | 0.4 |
| North Fork Salmon R (R) | 0.00 | 0.00 | 22.8 | 22.1 | 0.7 |
| Knownothing Creek ( L) | 3.83 | 2.38 | 21.3 | 23.3 | -2.0 |
| Methodist Creek (L) | 10.01 | 6.22 | 21.7 | 23.0 | -1.3 |
| Black Bear Creek (R) | 13.58 | 8.44 | 20.8 | 21.9 | -1.1 |
| side channel (R) | 14.79 | 9.19 | 23.5 | 21.7 | 1.8 |
| seep (L) | 17.85 | 11.09 | 21.0 | 21.6 | -0.6 |
| Smith Creek (L) | 18.27 | 11.35 | 20.5 | 21.6 | -1.1 |
| Plummer Creek (L) | 21.45 | 13.33 | 19.9 | 21.7 | -1.8 |
| seep (L) | 22.58 | 14.03 | 19.9 | 21.7 | -1.8 |
| Sainte Claire Creek (L) | 26.11 | 16.22 | 17.6 | 22.6 | -5.0 |
| side channel/Unnamed (L) | 27.05 | 16.81 | 21.1 | 22.2 | -1.1 |
| side channel (L) | 31.85 | 19.79 | 20.6 | 22.4 | -1.8 |
| EF SF Salmon River (R) | 32.71 | 20.32 | 21.3 | 22.6 | -1.3 |
| side channel/Unnamed (L) | 35.50 | 22.06 | 21.6 | 22.3 | -0.7 |
| seep (L) | 37.29 | 23.17 | 19.1 | 21.5 | -2.4 |
| seep (R) | 37.34 | 23.20 | 19.7 | 21.4 | -1.7 |
| Black Gulch (L) | 38.53 | 23.94 | 19.4 | 20.6 | -1.2 |
| side channel (L) | 40.99 | 25.47 | 17.9 | 20.2 | -2.3 |
| seep (L) | 41.44 | 25.75 | 18.3 | 20.0 | -1.7 |
| China Creek (L) | 42.69 | 26.53 | 18.6 | 20.0 | -1.4 |
| Rush Creek (R) | 42.84 | 26.62 | 18.4 | 20.0 | -1.6 |
| Little Grizzly Creek (L) | 45.58 | 28.32 | 18.4 | 18.9 | -0.5 |
| Little SF Salmon (L) | 47.34 | 29.42 | 16.3 | 18.4 | -2.1 |
| Unnamed (L) | 49.49 | 30.75 | 14.3 | 17.3 | -3.0 |
| seep (R) | 50.37 | 31.30 | 14.7 | 15.2 | -0.5 |
| Unnamed (L) | 51.15 | 31.78 | 15.4 | 14.5 | 0.9 |
| Browns Gulch (L) | 51.88 | 32.24 | 13.7 | 14.0 | -0.3 |

## Observations

Thirty-two miles of the South Fork Salmon River were surveyed on July 23, 2009 from the mouth upstream to Browns Gulch. Stream temperatures ranged from 14.0°C at Browns Gulch to 24.3°C above Knownothing Creek. Fifteen tributaries, 6 seeps, and 5 side channels were detected in the imagery. The majority of the sampled inflows had very low flows, and dozens of side drainages were seen in the imagery that did not have sufficient flows for accurate sampling. No active USGS flow gages were found on the South Fork Salmon River.

For the entire length of the survey, the South Fork Salmon River flows through a narrow steep forested canyon with numerous intersecting drainages. Four watershed scale reaches can be seen in the longitudinal temperature profile. The upper 10 miles of river (Reach 4: RM 22.00-32.24) showed a rapid warming trend as expected on a hot summer day (14.0→22.4°C). Reach 3, from river mile 22.00 downstream to river mile 8.12, shows a fairly stable thermal profile with temperatures fluctuating only 1.6°C (21.2→22.8°C) over

14 miles. Further warming is seen in Reach 2 from river mile 8.12 downstream to Knownothing Creek (RM 2.38), and then a final cooling is seen to the confluence with the North Fork Salmon River (Reach1).

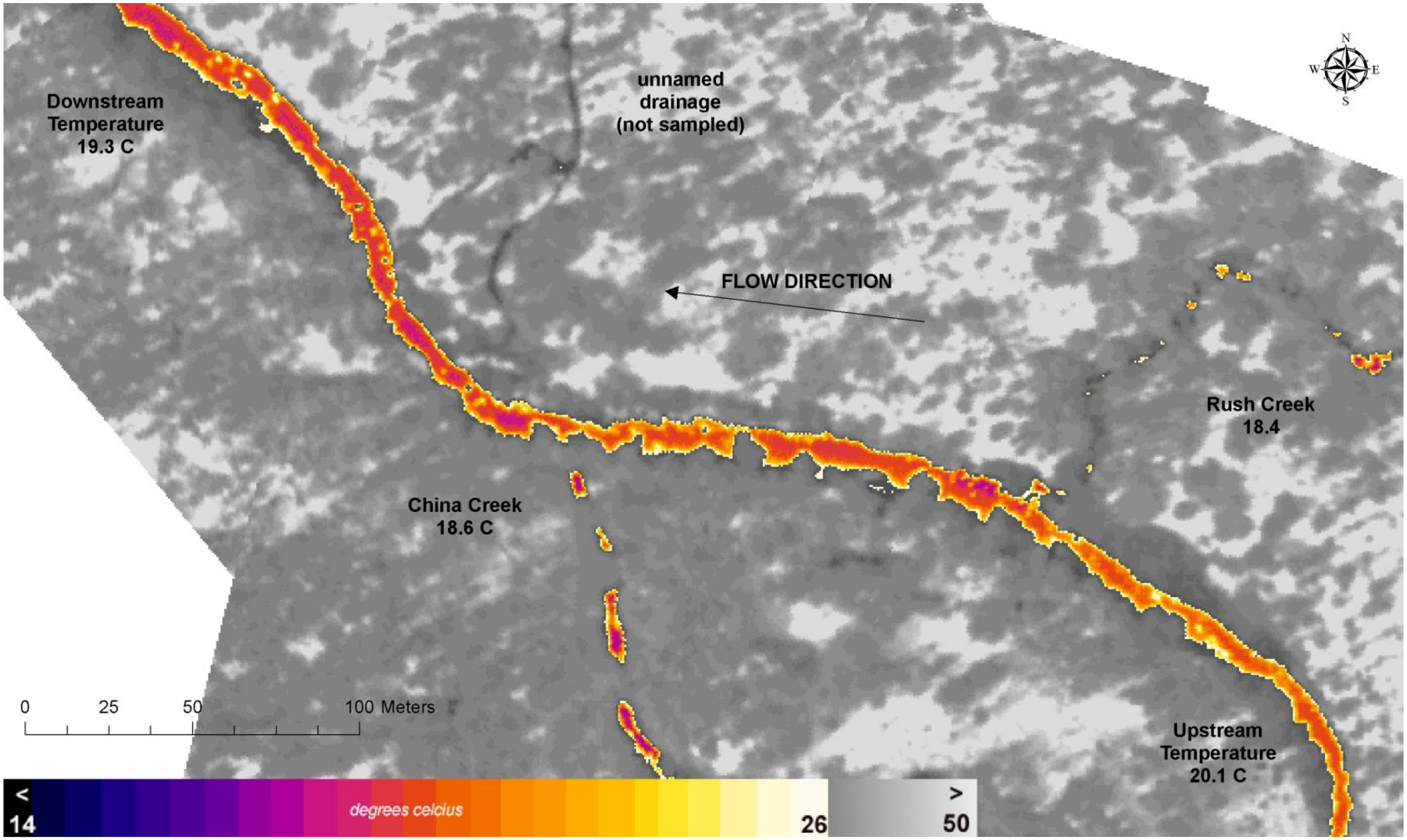
Localized fluctuations can be seen within each reach. At river mile 28.32 at the confluence of Little Grizzly Creek, a decrease in the rate of warming occurs causing an inflection point in the longitudinal profile. This inflection point indicates a shift in the thermal equilibrium, likely as a result of increased subsurface interaction.

Temperature changes of less than ± 0.5°C should be interpreted with caution due to the accuracy limitations of the thermal imagery. However, four point source impacts of 0.5°C or more can be seen in the profile at the confluences with the Little SF Salmon (RM 29.42), China and Rush Creeks (RM 26.53; *South Fork Image 1*), East Fork of the South Fork Salmon River (RM 20.32) and Knownothing Creek (RM 2.38).

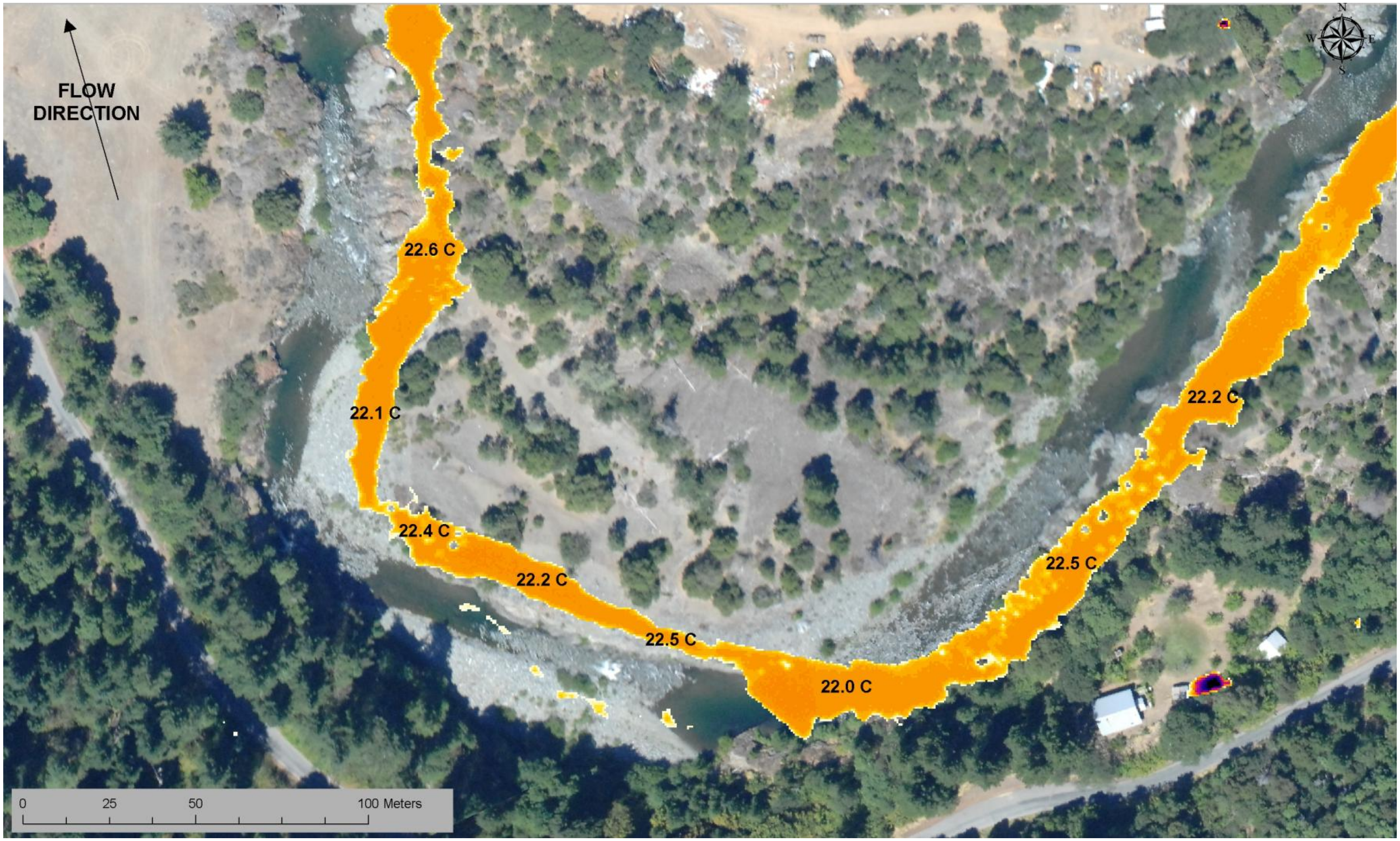
Some of the local spatial variability observed in this profile appears to be due to differences in pool/riffle sequences along the South Fork. Torgersen et al.[3] documented a potential 0.5°C radiant temperature variability between pools and riffles due to differences in spectral versus diffuse reflectance at the water surface (pool versus riffle). The experience of Watershed Sciences, Inc. over the past ten years confirms this observation, but the level of variability depends on the sensor wavelength and observation angle (*South Fork Image 2*).

[3] 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.

## Sample Images




*South Fork Image 1- The TIR image above shows the confluence of China Creek, Rush Creek, and an unnamed drainage with the South Fork Salmon River at river mile 26.53. The cumulative effect of these three drainages drops the bulk water temperature of the South Fork from 20.1°C to 19.3°C in 0.5 miles. Rush Creek is a good example of a stream that appears to have little to no surface water flow, but is providing cold water to the main channel.*




*South Fork Image 2 – The TIR/true color image pair at river mile 0.58 shows the type of variability seen in pool/riffle sequences.. The images are offset in order to show the location of the pools and riffles in the true color imagery.*

# Deliverables

The TIR imagery is provided in two forms: 1) individual un-rectified frames and 2) a continuous geo-rectified mosaics at 0.6-m. The mosaic allows for easy viewing of the continuum of temperatures along the stream gradient, but also shows edge match differences and geometric transformation effects. The un-rectified frames are useful for viewing images at their native resolutions and are often better for detecting smaller thermal features. A GIS point layer is included which provides an index of image locations, the results of temperature sampling, and interpretations made during the analysis.

Deliverables are provided on a Passport storage drive:

| |
|---|
| Geo-Corrected Mosaics, surveys, and shapefiles are projected in:<br>**Universal Transverse Mercator, Zone 10, NAD 1983, Meters** |

1. Hydrography – Relevant hydrography shapefiles

2. Longprofiles - Excel spreadsheet containing the longitudinal temperature profiles

3. Thermal_Mosaics - Continuous image mosaic of the geo-rectified TIR image frames at 0.6-m resolution in ERDAS Imagine (*img) format). Cell value = radiant temperature * 10

4. Thermal_Surveys - Point layers showing image locations, sampled temperatures, and image interpretations

5. Thermal_Unrectified - Calibrated TIR images in ERDAS Imagine (*img) format. Cell value = radiant temperature * 10. Radiant temperatures are calibrated for the emissive characteristics of water and may not be accurate for terrestrial features. These images retain the native resolution of the sensor

6. True_Color_Images – Unrectified true color Nikon frames

7. True_Color_Surveys – Point shapefiles showing the approximate image location of the uncertified true color frames

8. Salmon_River_TIR_July_2009.mxd – An AcrMap project containing all the thermal mosaics and survey shapefiles displayed with pre-defined color ramps

9. Salmon_River_TIR_Report.pdf - A PDF copy of this report

# Appendix A –Daily Discharge Rates

**Source:** USGS Surface-Water Daily Data for the Nation
**URL:** http://waterdata.usgs.gov/nwis/dv

## *Salmon River at Somes Bar (USGS 11522500)*

| DATE | Daily Mean Discharge (cubic feet per second) |
|---|---|
| **July-20** | 298 [A] |
| **July-21** | 286 [A] |
| **July-22** | 278 [A] |
| **July-23** | 271 [A] |
| **July-24** | 263 [A] |
| **July25** | 255 [A] |
| [A] - Approved for publication -- Processing and review completed. | |