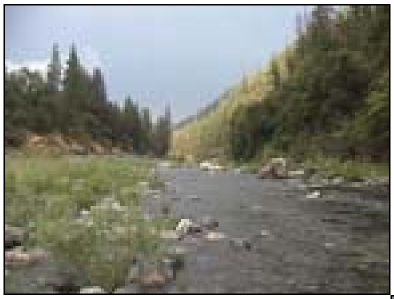
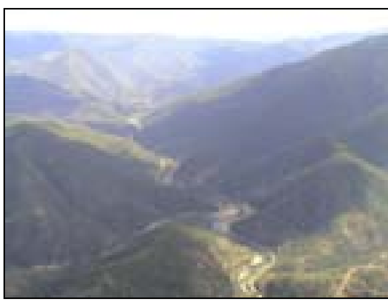
Aerial Surveys using Thermal Infrared and Color Videography

Scott River and Shasta River Sub-Basins

February 26, 2004





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Final Report

Table of Contents

INTRODUCTION **1**

METHODS **1**

Data Collection 1
Data Processing 2

SCOTT RIVER SUB-BASIN **5**

Overview 5
Results 7
Weather Conditions *7*
Flow Levels *8*
Thermal Accuracy *9*
Temporal Differences *11*
Longitudinal Temperature Profiles *12*
Scott River 12
East Fork Scott River 16
South Fork Scott River 18
Shackelford Creek 19
Kidder Creek/Big Slough 22
Discussion 24

SHASTA RIVER SUB-BASIN **25**

Overview 25
Results 26
Weather Conditions *26*
Thermal Accuracy *26*
Temporal Differences *27*
Longitudinal Temperature Profiles *28*
Shasta River 28
Little Shasta River 31
Parks Creek 33
Big Springs Creek 35
Discussion 37

BIBLIOGRAPHY **39**

APPENDIX A - SELECTED IMAGES **A-1**

Introduction

In July 2003, Watershed Sciences, LLC (WS, LLC) conducted airborne thermal infrared remote (TIR) sensing surveys on selected streams in the Scott and Shasta River sub-basins in Northern California. The overriding objective of the survey(s) was to collect TIR and color video imagery in order to characterize spatial temperature patterns in the basin. The imagery and derived data sets are intended to support ongoing total maximum daily load (TMDL) studies and related stream temperature modeling efforts through the California North Coast Regional Water Quality Control Board (NCRWQCB) and the Department of Environmental Science and Policy at the University of California at Davis.

Water temperatures vary naturally along the stream gradient due to topography, channel morphology, substrate composition, riparian vegetation, ground water exchanges, and tributary influences. Stream temperatures are also affected by human activities within the watershed. TIR images provide information about spatial stream temperature variability and can illustrate changes in the interacting processes that determine stream temperature. In most cases, these processes are extremely difficult to detect and quantify using traditional ground based monitoring techniques.

It is the aim of this report to: 1) document methods used to collect and process the TIR images, 2) present spatial temperature patterns and 3) present hypotheses of hydrologic processes influencing spatial temperature patterns based on first-look inspection of the imagery. Thermal infrared and associated true color video images are included in the report in order to illustrate significant thermal features. An associated ArcView 3.2 GIS[1] database includes all of the images collected during the survey and is structured to allow analysis at finer scales.

Methods

Data Collection

Images were collected with TIR (8-12μ) and visible-band cameras attached to a gyro-stabilized mount on the underside of a helicopter. The two sensors were aligned to present the same ground area, and the helicopter was flown longitudinally along the stream channel with the sensors looking straight down. Thermal infrared images were recorded directly from the sensor to an on-board computer in a format in which each pixel contained a measured radiance value. The recorded images maintained the full 12-bit dynamic range of the sensor. The individual images were referenced with time and position data provided by a global positioning system (GPS).

A consistent altitude above ground level was maintained in order to preserve the scale of the imagery throughout the survey. The ground width and spatial resolution

[1] Geographic Information System

presented by the TIR image vary based on the flight altitudes. The flight altitude is selected prior to the flight based on the channel width and morphology. During the flight, images were collected sequentially with 40% or better vertical overlap. The flight was conducted in the mid-afternoon in order to capture heat of the day conditions.

For each survey, WS, LLC deployed in-stream data loggers prior to the survey in order to ground truth (i.e. verify the accuracy of) the TIR data. The in-stream data loggers were ideally located at regular intervals (*10 miles or less*) along the survey route. Due to access limitations in some areas, WS, LLC data were supplemented with additional in-stream monitoring sites provided by the NCRWQCB, the USFS and Fruit Growers Supply, Inc. Meteorological data including air temperature and relative humidity were recorded using a portable weather station (*Onset Computer Corp.*) located in Happy Camp, CA and fixed monitoring stations located in the Scott River Sub-Basin (*operated by: USFS – Callahan and NCRWQCB*) and the Shasta River Sub-Basin (*operated by: CA Dept. of Forestry - Weed*).

Data Processing

Measured radiance values contained in the raw TIR images were converted to temperatures based on the emissivity of water, atmospheric transmission effects, ambient background reflections, and the calibration characteristics of the sensor, including the temperature and transmission of the external optics. The atmospheric transmission value was modeled based on the air temperatures and relative humidity recorded at the time of the survey. The radiant temperatures were then compared to the kinetic temperatures measured by the in-stream data loggers. 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. Calibration parameters were fine-tuned to provide the most accurate fit between the radiant and kinetic temperatures.

Once the TIR images were calibrated, they 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 (Figure 1). The temperatures of detectable surface inflows (i.e. surface springs, tributaries) were also sampled at their mouth. In addition, data processing focused on interpreting spatial variations in surface temperatures observed in the images. The images were assigned river miles based on a 1:24k (*Beta Version*) routed GIS stream coverage provided through Humboldt State University using the dynamic segmentation features of the Arc/Info software. This coverage was the best routed stream layer available for the basin. Never-the-less, it is important to note that measures assigned to the images from this coverage are relative distances along the mapped stream line and may not match distances derived from other sources or ground based surveys. When comparing locations from other sources, it may be necessary to re-assign measures to the data (*images*) based on a common source.

The median temperatures for each sampled image of each surveyed stream 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. Where applicable, tributaries or other features that were detected in the imagery, but were not sampled due to their small size (*relative to pixel size*) or the inability to see the stream through riparian vegetation are included on the profile to facilitate the interpretation of the spatial patterns.

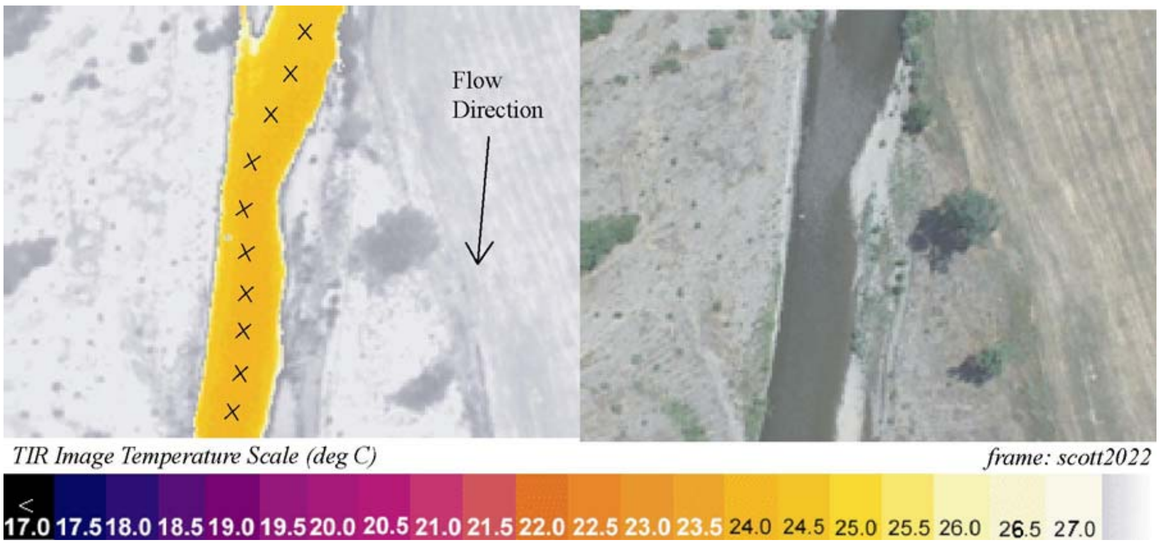


Figure 1 – TIR/color video image pair showing how temperatures are sampled from the TIR images. The black *X's* on the TIR image show typical sampling locations near the center of the stream channel. The recorded temperature for this image is the median of the sample points.

During the analysis, the images were stored in a format (Arc/Info GRID) where each cell (or pixel) contained a calibrated radiant temperature value to 1/10th of degree Celsius. For visual analysis and presenting in reports, the GRID(s) were converted to a pseudo color image in *jpeg* format by applying a specific color to represent a range of temperatures. In this case, the color map was segmented into 0.5^{o}C increments through the full range of water temperatures observed during the analysis. Radiant temperatures in the image that were more than 1.0^{o}C above the warmest water temperature (including tributaries) were assigned shades of gray with white representing the warmest temperatures. Using this color scheme, the converted raster images represent the full range of temperature values in the GRID images, but effectively differentiate the range of water temperatures. Figure 1 provides an example of the converted pseudo-color image. In this example, the water surface temperature is mapped in shades of orange while the terrain and vegetation temperatures are mapped in shades of gray. By applying two different color maps, the scheme provides a better means of visualizing changes in stream temperatures than could be achieved by stretching a single color map over the full image.

TIR Image Characteristics and Limitations

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. In the TIR images, indicators of thermal stratification include cool water mixing behind in-stream objects and/or abrupt transitions in stream temperatures. Occurrences of thermal stratification interpreted during analysis are identified in the results section for each survey. None-the-less, one should recognize the inherent limitations of measuring only surface temperatures. Thermal stratification is not detected in all situations and small, sub-surface seeps may be mixed into the water column without creating a detectable signature at the water surface. Consequently, these fine scale thermal processes may be missed unless these processes directly influence broader scale temperature patterns. In this case, cooling along the stream gradient (*or even lack of heating*) is an indicator of these processes, but should be verified with additional analysis or field surveys.

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 (approximately 4 to 6% of the energy received at the sensor is due to ambient reflections). During image calibration, a correction is included to account for average background reflections. However, variable water surface conditions (i.e. riffle versus pool), slight changes in viewing aspect, and variable background reflection 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 0.6^{o}C (Torgersen et al. 2001). 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 $< 0.6^{o}$C are not considered significant unless associated with a point source.

The accuracy of the radiant temperature values derived from the TIR images are a combination of the radiometric accuracy of the sensor, instrument noise, transmission of energy through the atmosphere, ambient reflections, and slight variations in the way the water surface radiates TIR energy (i.e. emissivity). Past TIR surveys conducted in the Pacific Northwest have shown that an average accuracy of $\pm 0.5^{o}$C is readily achievable by applying the methods used in this study (Torgersen et al. 2001, Faux et al 2001). This methodology uses ground truth sensors located in the stream to adjust the atmospheric transmission model in order to achieve more accurate radiant temperatures. The adjusted calibration is verified against independent sensors to measure overall accuracy and variability. Regardless of methods, a level of variability still exists in the imagery due to instrument noise and variations in conditions at the stream survey (*discussed in the previous paragraph*). The variability of the instrumentation is difficult to separate from other sources. However, the scanned array sensor used on earlier studies exhibited a characteristic noise level of about ±0.4°C that manifested itself as “speckling” in the imagery. The focal plane array sensor used during these studies presents a very clean image without the speckling observed in the older sensors. The new sensor is 10 times more sensitive and reflective differences at the water surface are more apparent in this imagery (*these patterns used to be lost in the noise*). In addition, slight changes in apparent temperature are noted on the edges of the images with the more accurate radiant temperatures in the center. Based on these factors, temperature variations within ±0.5°C should be considered within the noise levels characteristic of TIR remote sensing. The exception to this rule is if the difference has a spatial pattern that is typical of a specific thermal process (i.e. tributary mixing zone, etc.).

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. Shape and magnitude distinguish spatial temperature patterns caused by tributary or spring inflows from those resulting from differential surface heating. Unlike thermal stratification, surface temperatures represent bulk water conditions when the stream is mixed. Temperature sampling along the center of the stream channel (Figure 1) minimizes variability due to differences in surface heating rates. None-the-less, differences in surface heating combined with ambient reflection can confound interpretation of thermal features especially near the riverbank

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 (Torgersen et. al. 2001). In some cases, small tributaries were detected in the images, but not sampled due to the inability to obtain a reliable temperature sample. [2]

Scott River Sub-Basin

Overview

TIR remote sensing surveys in Scott River Sub-Basin were flown on July 25-26, 2003 (Figure 2). Table 1 summarizes the survey times, extents, and image resolution for each surveyed stream. The Scott River was surveyed at a flight altitude that provided a wider image footprint to better capture the wider channel widths and side/off channel features characteristic of the main stem Tributaries were surveyed at lower flight altitudes to provide slightly higher spatial resolution and better visibility through riparian vegetation. Kidder Creek/Big Slough was surveyed at two different altitudes. The lower altitude was used to record radiant temperatures in the stream, but did not provide an

[2] Features that are detected in the imagery, but not sampled for temperature are noted in the comment attribute of the flight point coverage.

image width sufficient enough to capture the multiple channels of the slough. The higher altitude results in a wider image footprint (*lower pixel resolution*) and provides an alternate image set for understanding the surface hydrology within the surveyed segment.

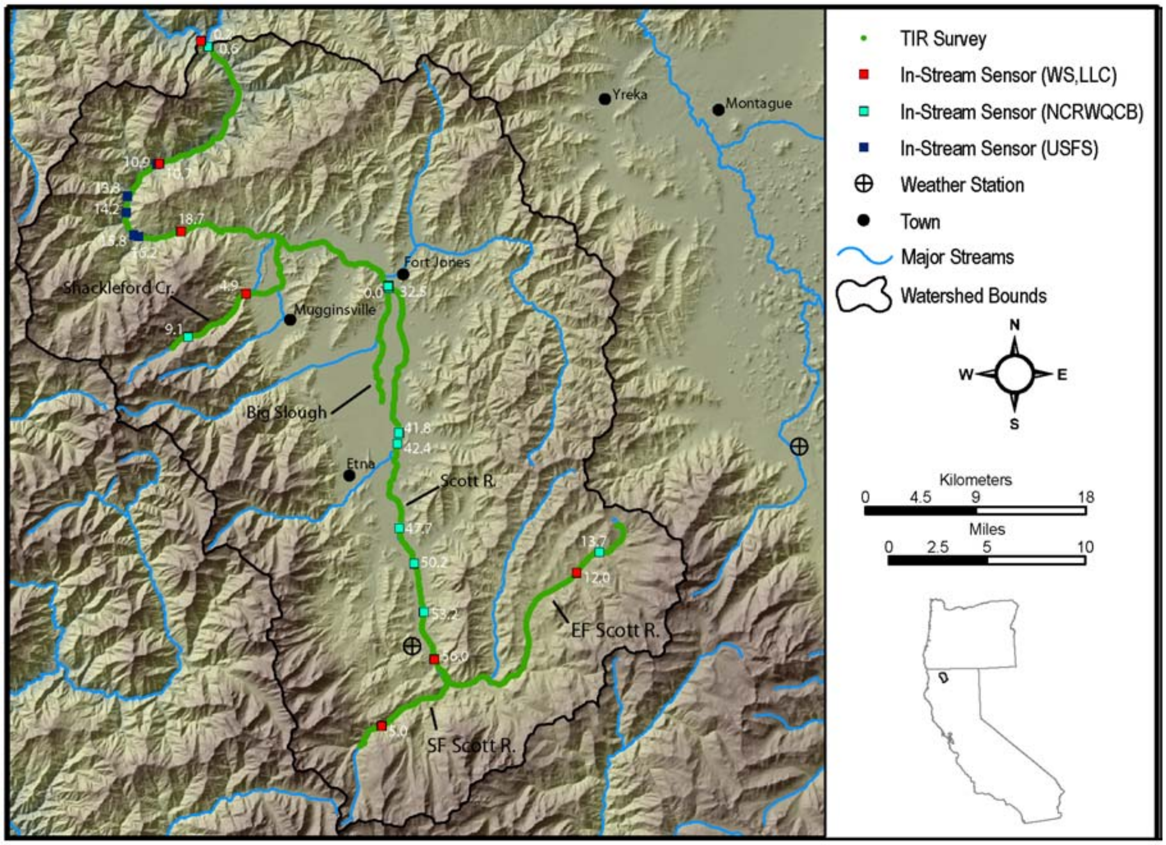


Figure 2 – Map showing the streams surveyed in the Scott River Sub-Basin using TIR and color video on July 25-26, 2003. The map also shows the location of the in-stream sensors used to ground truth the imagery, labeled by river mile.

Table 1 – Summary of river segments surveyed with TIR and color video in the Scott River Sub-Basin on July 25-26, 2003.

Stream	Survey Date	Survey Time (24 hr)	Survey Extent	River Miles	Image Width Meter (ft)	TIR Image Pixel Size Meter (ft)
Scott R.	25-Jul	14:00-15:20	Mouth to East Fork	57.0	193 (635)	0.6 (2.0)
East Fork Scott R.	25-Jul	15:21-15:39	Mouth to Mountain House Cr.	16.1	161 (529)	0.5 (1.7)
Kidder Cr/Big Slough	25-Jul	16:20-16:31	Mouth to rm 10.5	10.5	161 (529)	0.5 (1.7)
Kidder Cr/Big Slough	25-Jul	16:33-16:42	rm 10.5 to mouth	10.5	268 (881)	0.9 (2.8)
Shackelford Cr.	26-Jul	13:49-14:14	Mouth to Back Meadows Cr.	10.1	140 (459)	0.5 (1.4)
South Fork Scott R.	26-Jul	14:31-14:42	Mouth to Jackson Cr.	6.8	161 (529)	0.5 (1.7)

Results

Weather Conditions

Weather conditions for the times of the surveys are summarized in Table 2. Sky conditions were generally clear each survey day and overall conditions were considered good for the TIR surveys. Although air temperatures exceeded 90°F each survey day, air temperatures were generally cooler than those observed the previous week (Figure 3). During the survey dates, scattered thunderstorms formed in the region during the late afternoon and the shift in weather conditions between 16:00 and 17:00 at the Callahan station on the 25th is presumably due to a passing thunderstorm. These thunderstorms were localized and did not impact the TIR surveys.

Table 2 – Meteorological conditions recorded at three different monitoring stations in the survey area for dates and times of the TIR surveys.

	Callahan Station, CA			Scott River (mile 13.1)				Scott River (mile 32.5)			
Time	Air Temp °F	Air Temp °C	RH %	Air Temp °F	Air Temp °C	RH %	Wind Speed (m/s)	Air Temp °F	Air Temp °C	RH %	Wind Speed (m/s)
July 25, 2003											
13:00	87.0	30.6	49	82.9	28.3	49	0.9	79.7	26.5	63	0.9
14:00	88.0	31.1	42	86.2	30.1	39	1.3	82.9	28.3	55	1.3
15:00	94.0	34.4	25	88.5	31.4	36	2.7	86.7	30.4	50	0.4
16:00	95.0	35.0	25	90.3	32.4	31	0.9	87.4	30.8	40	0.9
17:00	66.0	18.9	97	93.0	33.9	20	1.8	89.2	31.8	33	1.8
18:00	65.0	18.3	100	91.0	32.8	24	1.8	88.3	31.3	42	1.8
July 26, 2003											
13:00	92.0	33.3	24	84.2	29.0	38	1.8	85.5	29.7	42	0.4
14:00	93.0	33.9	22	88.0	31.1	30	1.8	88.9	31.6	38	0.9
15:00	95.0	35.0	20	90.1	32.3	26	1.8	90.0	32.2	36	0.9
16:00	95.0	35.0	18	91.2	32.9	27	1.8	91.0	32.8	33	0.4
17:00	93.0	33.9	20	90.9	32.7	29	1.3	89.4	31.9	42	0.9
18:00	87.0	30.6	28	90.7	32.6	29	0.4	86.7	30.4	39	0
July 27, 2003											
13:00	93.0	33.9	22	88.2	31.2	27	0.4	87.4	30.8	37	0.4
14:00	96.0	35.6	19	91.9	33.3	21	0.4	92.5	33.6	28	0
15:00	99.0	37.2	15	94.5	34.7	20	0.9	93.6	34.2	21	0.4
16:00	99.0	37.2	15	94.3	34.6	22	0.9	93.0	33.9	23	0.9
17:00	99.0	37.2	16	95.2	35.1	21	0.9	92.5	33.6	32	0.9
18:00	90.0	32.2	22	95.7	35.4	15	0.9	85.6	29.8	37	0

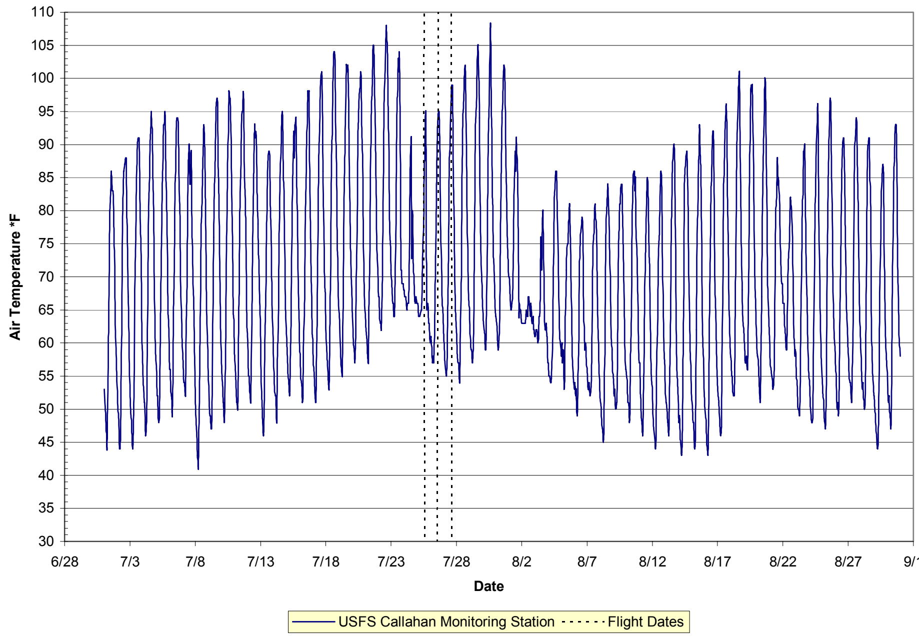


Figure 3 – Continuous air temperatures measured at the USFS Callahan Monitoring Station in the Scott River sub-basin (*source: http://cdec.water.ca.gov/*).

Flow Levels

River flow levels were not specifically measured as part of the TIR survey. However, since surveys were generally targeted to capture summer low flow conditions, relative flow conditions at the time of the survey can facilitate analysis stream temperatures (Figure 4). As shown, mean daily flow levels in the Scott River (*at Fort Jones, CA*) were on average 90 cfs for the two days of the Scott River surveys. These flows were higher than those measured in the previous week, but considerably lower than those observed in early August. The increased flows near the time of the survey were presumably due to the contribution of thunderstorms.

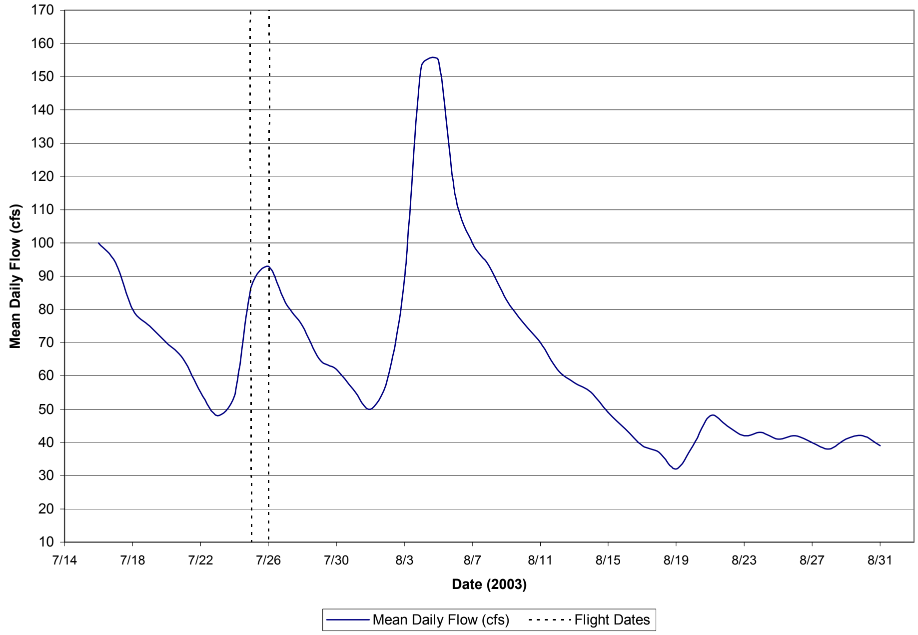


Figure 4 – Mean daily flow levels in the Scott River measured at Ft. Jones, CA (*river mile 34*) and the dates of the of the TIR surveys in the basin.

Thermal Accuracy

Overall, the average absolute differences between the kinetic temperatures recorded by the in-stream data loggers and the radiant temperatures derived from the TIR images were within the desired accuracy (< 0.5°C) on each survey segment (Table 3). With the exception of the upper site on Shackelford Creek, range of differences between radiant and kinetic measurements was ±0.6°C. This range is also consistent with TIR surveys conducted in the Pacific Northwest over the past five years (Torgersen, 2001).

On the Scott River, radiant temperatures were checked against in-stream measurements taken by Watershed Sciences at the time of the survey and further verified with data provided by the NCRWQCB. However, analysis of the longitudinal temperature patterns derived from the TIR imagery illustrated an anomalous[3] jump in radiant temperatures between river miles 12.2 and 17.4. This reach was bracketed by in-stream sensors at river miles 10.7 and 18.7, which verified the consistency and accuracy of radiant temperatures both upstream and downstream of the jump. The US Forest Service provided additional in-stream measurements at 4 sites between river mile 12.2 and 17.4 and these data quantified a consistent bias in radiant temperatures of +2.1°C. Since the bias appeared consistent, the TIR imagery within the anomalous reach was recalibrated to remove the bias. The recalibrated reach is delineated on the spatial temperature profiles presented later in this report.

[3] Review of the raw data and flight notes did not reveal any evidence about the source of the anomaly and it was not observed on any other surveys conducted in the basin or on any other streams surveyed during 2003.

Table 3 – Comparison of ground-truth water temperatures (Kinetic) with the radiant temperatures for streams in the Scott River Sub-Basin.

Image	Source/ Owner	Time 24 hr	River Mile	Kinetic °C	Radiant °C	Difference °C
Scott River (average 0.3°C)						
scott0012	WS, LLC	14:00	0.2	26.6	26.1	0.5
scott0029	NCRWQCB	14:00	0.6	25.6	26.2	0.6
scott0384	WS, LLC	14:12	10.7	23.8	23.9	0.1
scott0389	USFS	14:13	10.9	23.0	24.0	1.0
scott0481	USFS	14:16	13.3	23.4	23.8	-0.4
scott0517	USFS	14:17	14.2	23.1	23.1	0.0
scott0608	USFS	14:21	15.8	22.7	22.6	0.1
scott0621	USFS	14:21	16.2	23.5	23.9	-0.4
scott0715	WS, LLC	14:24	18.7	23.3	23.4	-0.1
scott1281	NCRWQCB	14:44	32.5	26.1	26.2	-0.1
Scott1282	NCRWQCB	14:44	32.5	25.1	25.4	-0.3
Scott1282	NCRWQCB	14:44	32.5	26.1	25.7	0.4
scott1665	NCRWQCB	14:58	41.8	23.8	24.0	-0.2
scott1692	NCRWQCB	14:58	42.4	23.9	24.1	-0.2
scott1692	NCRWQCB	14:58	42.4	23.9	24.1	-0.2
scott1692	NCRWQCB	14:58	42.4	23.6	24.1	-0.5
scott1942	NCRWQCB	15:08	47.7	24.5	24.4	0.1
scott2036	NCRWQCB	15:12	50.3	23.3	23.6	-0.3
scott2036	NCRWQCB	15:12	50.3	23.3	23.6	-0.3
scott2157	NCRWQCB	15:16	53.2	24.7	25.0	-0.3
scott2262	WS, LLC	15:19	56.0	23.3	23.4	-0.1
East Fork Scott River (average 0.5°C)						
scott2712	WS, LLC	15:34	12.0	23.8	24.3	-0.5
scott2763	NCRWQCB	15:36	13.7	20.2	19.8	0.4
Kidder Creek (average 0.2°C)						
kidd0008	NCRWQCB	16:20	0.0	26.8	26.5	0.3
kidd0605	NCRWQCB	16:42	0.0	26.8	26.9	-0.1
Shackelford Creek (average 0.6°C)						
shaq0031	WS, LLC	13:50	n/a	22.8	22.4	0.4
shaq0382	WS, LLC	14:04	4.9	17.7	18.1	-0.4
shaq0382	WS, LLC	14:04	4.9	17.4	17.7	-0.3
shaq0633	NCRWQCB	14:13	9.1	15.7	14.6	1.1
South Fork Scott River (average 0.3°C)						
sfs0063	WS, LLC	14:30	n/a	23.0	22.6	0.4
sfs0336	WS, LLC	14:39	5.0	17.9	18.1	-0.2

Temporal Differences

Figure 5 shows in-stream temperature variations at 2 locations in the Scott River Basin. The figure is intended to provide a sense of how stream temperatures changed during the time frame of the flight. On the Scott River, at river mile 18.7, the survey was conducted prior to the daily maximum stream temperature of 24.7°C at 16:35. At this point, the stream temperature rose 1.2°C (from 23.0°C to 24.2°C) during the time of the survey. On the South Fork Scott River at river mile 5.0, the sensor was retrieved before recording the daily maximum stream temperature. During the survey at that point, the stream temperature rose only 0.15°C.

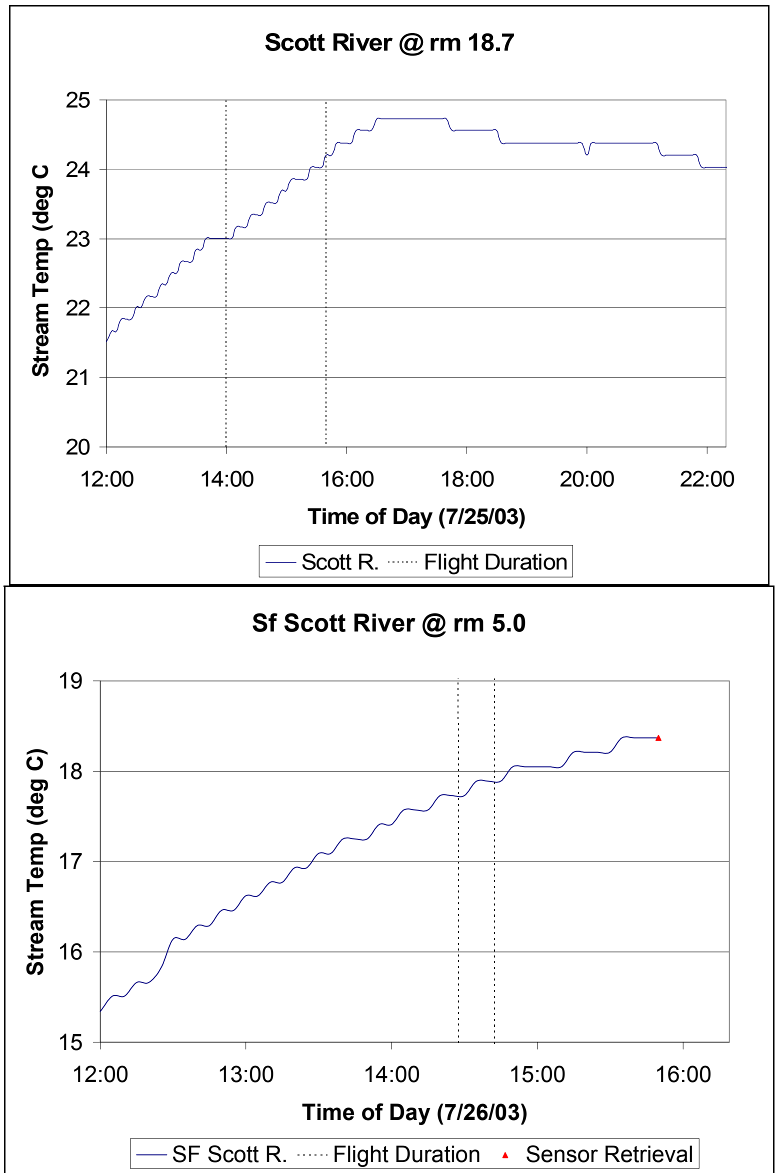


Figure 5 – Stream temperature variation and time of TIR remote sensing flight at a single location on both the Scott and South Fork Scott River surveys.

Scott River

Median radiant temperatures were plotted versus river mile for the Scott River (Figure 6). The plot illustrates the location of surface water inflows (tributaries, springs, seeps), labeled by river mile. The corresponding name and temperature of the surface inflows are summarized in Table 4.

The Scott River is bordered by mine tailings from the confluence of the East and South Forks (rm 57.0) downstream to river mile 51.6. Although radiant water temperatures increased through this reach, numerous (*9 sampled*) cool water springs and seeps were detected that contributed to localized spatial thermal variability. The detection of cool seeps indicates the general occurrence of shallow sub-surface exchanges through this reach that may buffer heating processes. Relatively rapid longitudinal heating ($\approx 3^{o}$C) was observed between river miles 54.3 and 53.5. While the factors driving this increase are not directly apparent, the observed pattern suggests the general absence of sub-surface discharge and a possible losing reach. The increase was followed by one of the larger spring/seep complexes, detected at river mile 52.3 (Figure 7).

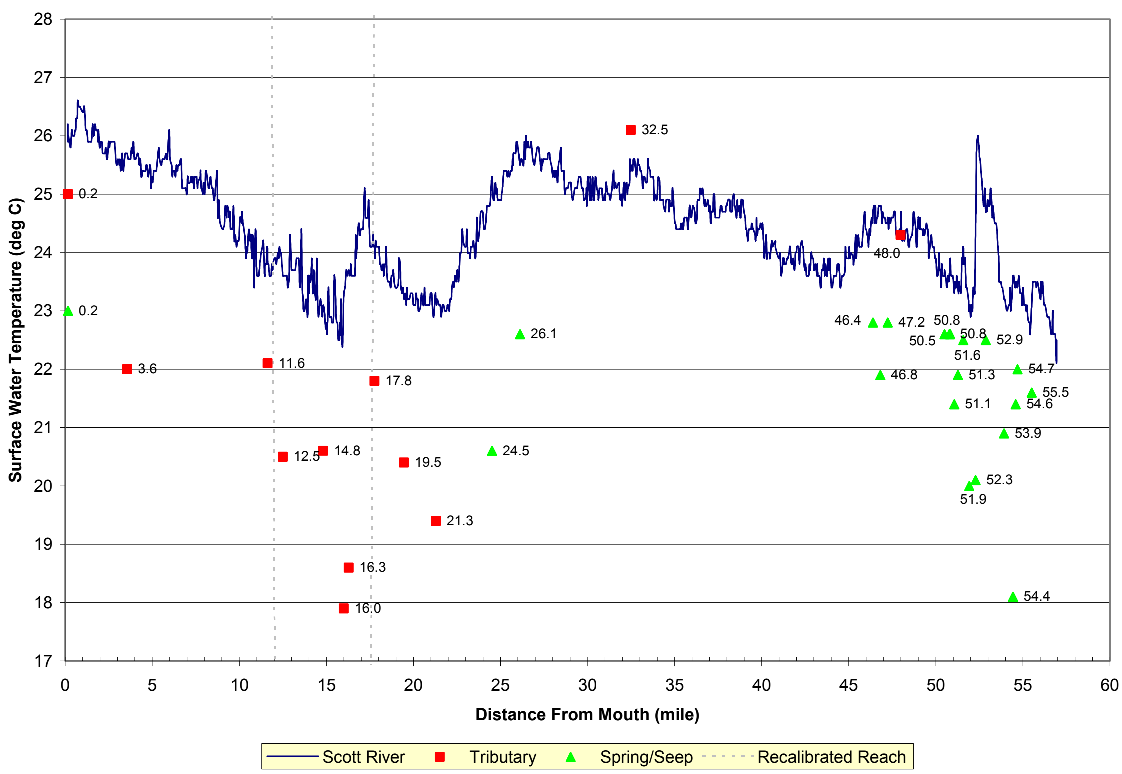


Figure 6 – Median radiant temperature versus river mile for the Scott River measured on July 25, 2003. Surface inflows sampled during the analysis are labeled by river mile.

Table 4 – Tributary temperatures for the Scott River (*LB – left bank, RB – right bank looking downstream*).

Name	Image	km	mile	Tributary °C	Scott River °C	Difference °C
Tributary						
Klamath River (RB)	scott0011	0.2	0.2	25.0	26.2	-1.2
Mill Creek (RB)	scott0127	5.7	3.6	22.0	25.7	-3.7
Tompkins Creek (RB)	scott0419	18.7	11.6	22.1	23.8	-1.7
Unnamed Tributary (RB)	scott0451	20.1	12.5	20.5	23.6	-3.1
Kelsey Creek (LB)	scott0569	23.9	14.8	20.6	23.1	-2.5
Canyon Creek (LB)	scott0615	25.8	16.0	17.9	23.3	-5.4
Boulder Creek (LB)	scott0623	26.2	16.3	18.6	23.7	-5.1
Unnamed Tributary (LB)	scott0676	28.6	17.8	21.8	24.1	-2.3
Isinglass (LB)	scott0739	31.3	19.5	20.4	23.2	-2.8
Unnamed Tributary (LB)	scott0836	34.3	21.3	19.4	23.2	-3.8
Kidder Creek (LB)	scott1282	52.3	32.5	26.1	25.4	0.7
French Creek (LB)	scott1949	77.2	48.0	24.3	24.4	-0.1
Spring/Seep						
Spring (RB)	scott0013	0.3	0.2	23.0	25.9	-2.9
Spring/Seep (LB)	scott0956	39.4	24.5	20.6	25.3	-4.7
Spring/Seep (LB)	scott1018	42.1	26.1	22.6	25.5	-2.9
Spring/Seep (LB)	scott1875	74.7	46.4	22.8	24.7	-1.9
Spring (LB)	scott1897	75.4	46.8	21.9	24.8	-2.9
Spring/Seep (RB)	scott1919	76.0	47.2	22.8	24.6	-1.8
Spring (LB)	scott2047	81.3	50.5	22.6	23.7	-1.1
Spring (RB)	scott2056	81.7	50.8	22.6	23.6	-1.0
Spring/Seep (LB)	scott2058	81.8	50.8	22.6	23.9	-1.3
Spring (RB)	scott2064	82.2	51.1	21.4	23.3	-1.9
Spring (LB)	scott2074	82.5	51.3	21.9	23.4	-1.5
Spring Complex (LB)	scott2088	83.0	51.6	22.5	24.1	-1.6
Spring (LB)	scott2104	83.6	51.9	20.0	23.1	-3.1
Spring (LB)	scott2121	84.2	52.3	20.1	24.4	-4.3
Spring (RB)	scott2145	85.1	52.9	22.5	24.8	-2.3
Spring (RB)	scott2184	86.8	53.9	20.9	23.2	-2.3
Spring (LB)	scott2200	87.6	54.4	18.1	23.6	-5.5
Spring (RB)	scott2206	87.9	54.6	21.4	23.4	-2.0
Spring/Seep (RB)	scott2210	88.0	54.7	22.0	23.4	-1.4
Spring (RB)	scott2246	89.3	55.5	21.6	23.1	-1.5

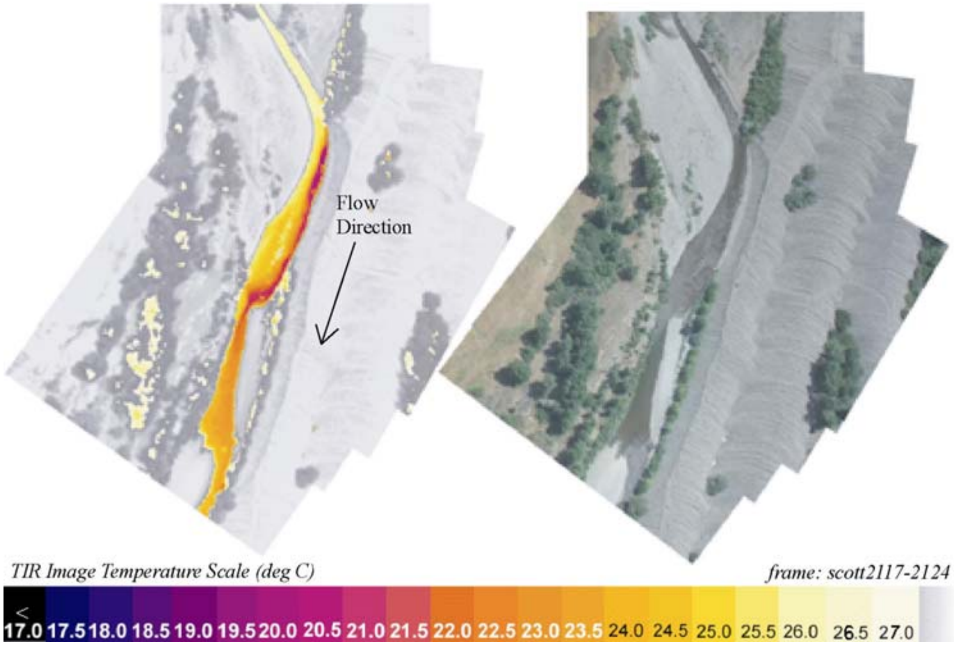


Figure 7 – TIR/color image mosaic showing a sub-surface discharge which appears to emerge from mine tailing along the left bank and decreases water temperatures in the Scott River by ≈3.0°C at river mile 52.3.

Moving downstream of the mine tailings, the longitudinal profile shows a general increase between river miles 52.0 and 46.4 with stream temperatures reaching a local maximum of ≈24.8°C (river mile 46.7). A total of 8 spring/seeps were sampled through this reach. These inflows were observed as seeps emerging from within the channel floodplain and were generally smaller than those observed in the mine tailing reach (Figure 8). Although individually, the seeps appear to have little direct influence on bulk water temperatures, the detection of these areas indicates some level of hyporheic exchange which may collectively buffer stream temperature increases and localized cool water areas at finer scales.

The longitudinal profile shows that stream temperatures decreased by ≈1.5°C between river miles 46.4 and 44.0 before warming steadily downstream to river mile 26.6. This warming trend extends through most of the Scott Valley with a local maximum of ≈25.9°C observed ≈1.2 miles upstream of the mapped Shackelford Creek confluence. Kidder Creek/Big Slough was the only surface inflow detected through this reach and it was slightly warmer than the main stem.

At the time of the flight, stream temperatures decreased by ≈3.0°C between river miles 26.6 and 22.1. This reach generally corresponds to a geomorphic transition from the Scott Valley to a more confined, higher gradient channel that is characteristic of the lower river. Two springs inflows were detected through this reach, which contributed to the cooling trend. Shackelford Creek is a major tributary that joins the Scott River at river mile 24.8. However, Shackelford Creek was not sampled, since no surface water was visible in the creek channel at the confluence of the Scott River.

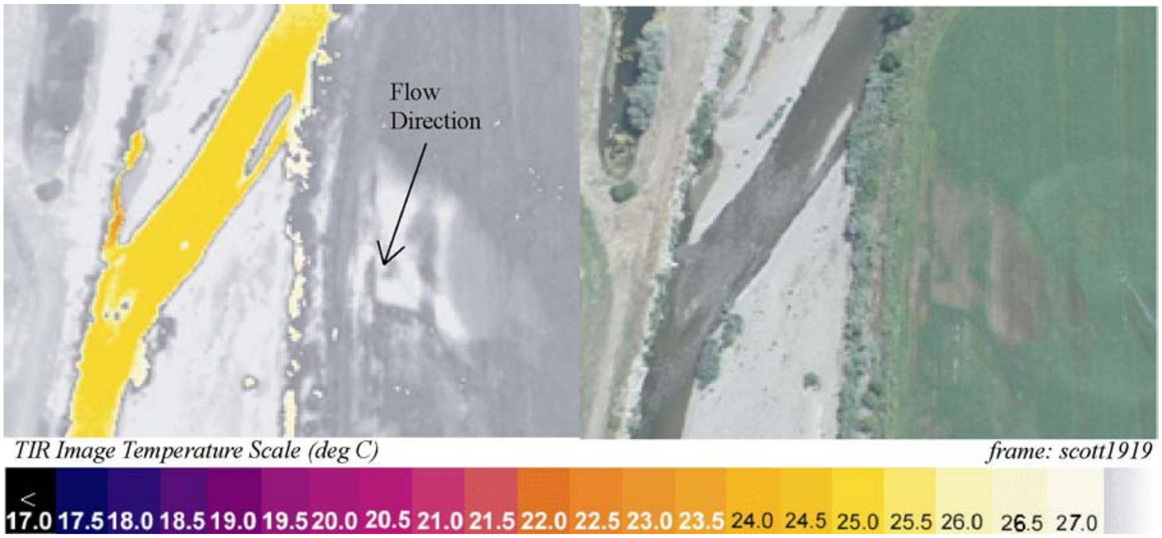


Figure 8 – TIR/color image pair showing an example of a cool water seep detected at river mile 47.2 in the Scott River.

Stream temperatures showed an overall warming trend in the lower 26 river miles. At river miles 16.3 and 16.0 respectively, Boulder Creek and Canyon Creek contributed cooler water to the Scott River and disrupted the general warming trend by lowering main stem temperatures by about 2.0°C to ≈22.6°C. Downstream of Canyon Creek, stream temperatures resumed an overall warming trend reaching ≈26.5°C at its confluence with the Klamath River. Of the 11 tributary inflows that were sampled during the analysis, nine entered the river in the lower 26 miles and all contributed water that was cooler than the main stem.

In order to provide additional context for interpreting spatial temperature patterns, median radiant temperatures were plotted in relation to the in-stream temperatures at the time of the survey and to the recorded daily maximum temperatures (Figure 9). Maximum values were only available for the WS, LLC sensors. As shown, radiant temperatures were consistent (±0.6°C) at the time of the survey. At the uppermost ground truth site, the stream temperature at flight time matched the daily maximum temperature. At the lower three sites (i.e. downstream of river mile 19), the daily maximum temperatures were 1.1-1.4°C warmer than at flight time, but the general shape of the profile remained consistent.

Figure 6 and Figure 9 both delineate the survey segment that was recalibrated to remove an anomalous temperature bias from the TIR images. Both figures illustrate that with the bias removed the spatial temperature patterns were consistent with prevailing trends upstream and downstream of the recalibrated area. Figure 9 additionally shows the location and temperature of in-stream sensors used to assess the radiant temperatures in this reach. Although the upstream end of this bias was well defined, the downstream end was less obvious and caution should be taken when interpreting temperature patterns at the downstream transition (e.g. river miles 12.0 to 12.5).

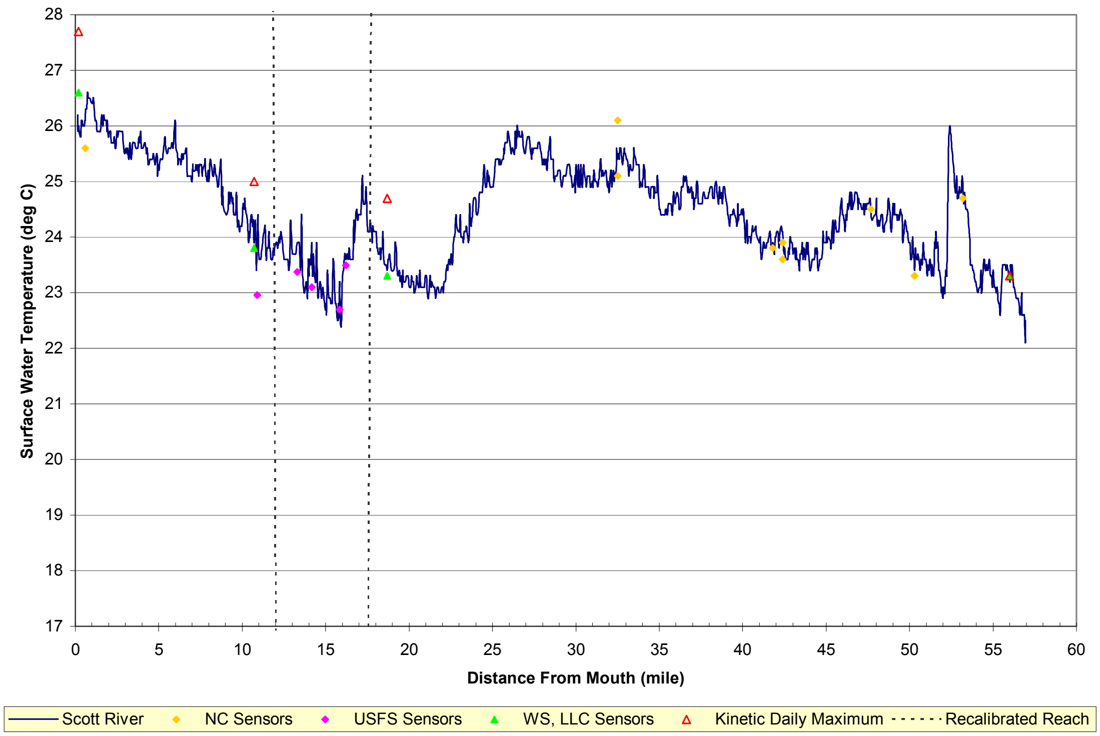


Figure 9 – Median stream temperatures versus river mile for the Scott River. The plot also shows the recorded kinetic temperatures at the time of the survey and the maximum daily stream temperatures at the ground truth locations.

East Fork Scott River

Median channel temperatures derived from the TIR images were plotted versus river mile for the East Fork Scott River (Figure 10). The location and name of sampled tributaries are illustrated on the plot by river mile and are listed in Table 5.

The East Fork Scott River was small (*channel width relative to pixel size*) upstream of the Crater Creek confluence at river mile 14.4 and, in some locations, difficult to detect through the riparian vegetation. The inflow of Crater Creek lowers water temperatures in the East Fork to ≈18.1°C, however stream temperatures warmed rapidly downstream of the confluence reaching ≈23.6°C by river mile 12.6. Over the next 1.6 miles, stream temperatures varied between 23.0°C and 24.4°C. Three springs sampled within this reach contributed to the observed spatial thermal variability, but did not contribute sufficient flow to reduce bulk temperatures in the East Fork below 23.0°C. Downstream of the spring at river mile 10.9, stream temperatures warmed again reaching ≈25.1°C by river mile 10.3. From river mile 10.3 to the South Fork confluence, stream temperatures remained above 24.0°C with only local spatial variability observed along the thermal profile. Four spring/seep discharges and five tributaries were sampled in the lower 10 stream miles which contributed (at least in part) to the observed variability. Big Mill Creek at river mile 2.8 contributed flow that was ≈2.9°C cooler and its contribution lowered East Fork water temperatures by ≈1.5°C.

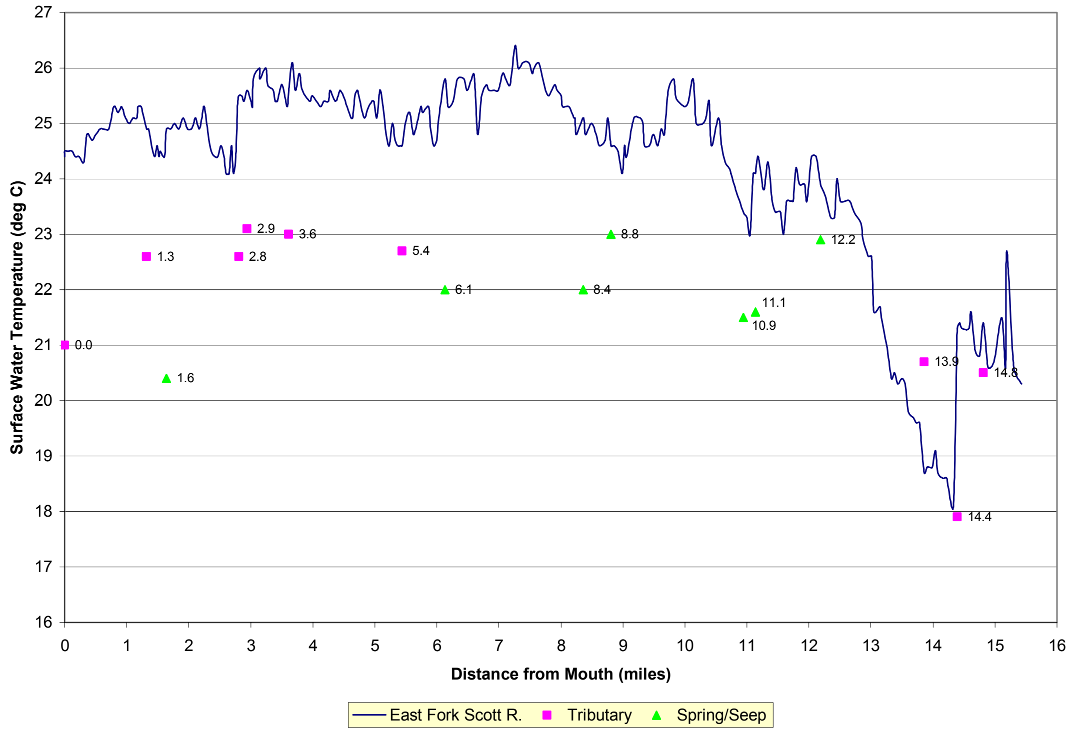


Figure 10 – Median channel temperatures versus river mile for the East Fork Scott River.

Table 5 - Tributary temperatures for the East Fork Scott River.

Name	Image	km	mile	Tributary °C	EF Scott R. °C	Difference °C
Tributary						
South Fork Scott River (LB)	scott2298	0.0	0.0	21.0	24.4	-3.4
Unnamed Tributary (LB)	scott2343	2.1	1.3	22.6	24.9	-2.3
Big Mill Creek (LB)	scott2401	4.5	2.8	22.6	25.5	-2.9
Spring/Seep (LB)	scott2408	4.7	2.9	23.1	25.6	-2.5
Mule Creek (LB)	scott2437	5.8	3.6	23.0	25.6	-2.6
Grouse Creek (LB)	scott2501	8.8	5.4	22.7	24.6	-1.9
Houston Creek (LB)	scott2769	22.3	13.9	20.7	18.7	2.0
Crater Creek (LB)	scott2784	23.2	14.4	17.9	21.3	-3.4
Unnamed Tributary (LB)	scott2799	23.8	14.8	20.5	21.4	-0.9
Spring/Seep						
Spring (LB)	scott2357	2.6	1.6	20.4	24.9	-4.5
Spring (RB)	scott2524	9.9	6.1	22.0	25.8	-3.8
Spring (RB)	scott2594	13.5	8.4	22.0	25.1	-3.1
Spring (LB)	scott2610	14.2	8.8	23.0	24.6	-1.6
Spring (RB)	scott2676	17.6	10.9	21.5	23.4	-1.9
Spring (RB)	scott2683	17.9	11.1	21.6	24.1	-2.5
Spring (LB)	scott2717	19.6	12.2	22.9	23.9	-1.0

(LB – left bank, RB – right bank looking downstream)

South Fork Scott River

Median channel temperatures derived from the TIR images were plotted versus river mile for the East Fork Scott River (Figure 11). The location and name of sampled tributaries are illustrated on the plot by river mile and are listed in Table 6. As shown in the profile, stream temperatures increased steadily gaining 3.8°C over the length of the survey. Five inflows were sampled during the analysis including three springs. At its mouth, the South Fork was observed as a cooling source to the Scott River.

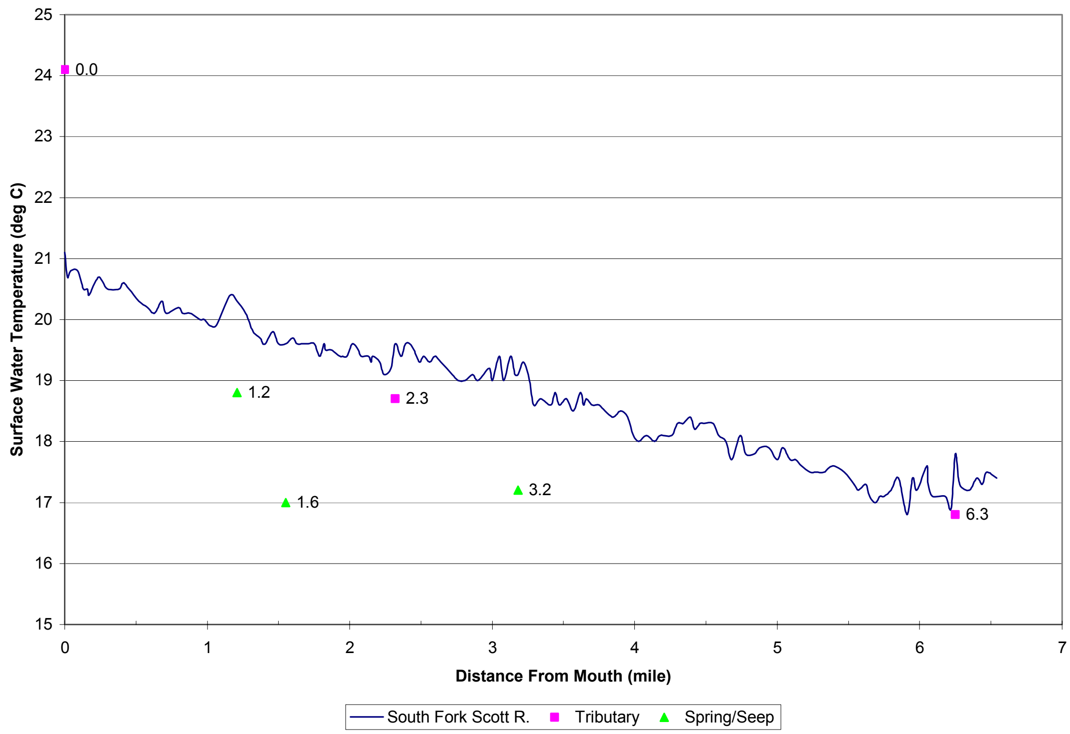


Figure 11 – Median channel temperatures versus river mile for the South Fork Scott River.

Table 6 - Tributary temperatures for the South Fork Scott River

Name	Image	km	mile	Tributary °C	SF Scott R. °C	Difference °C
Tributary						
East Fork Scott R. (RB)	sfs0108	0.0	0.0	24.1	21.1	3.0
Boulder Creek (RB)	sfs0217	3.7	2.3	18.7	19.6	-0.9
Jackson Creek (LB)	sfs0395	10.1	6.3	16.8	17.8	-1.0
Spring						
Spring (LB)	sfs0160	1.9	1.2	18.8	20.3	-1.5
Spring (RB)	sfs0174	2.5	1.6	17.0	19.6	-2.6
Spring (RB)	sfs0258	5.1	3.2	17.2	19.1	-1.9

(*LB – left bank, RB – right bank looking downstream*)

Shackelford Creek

Median channel temperatures were plotted versus river mile for Shackelford Creek (Figure 12). The location and name of sampled tributaries, springs, and other surface inflow are illustrated on the plot by river mile and are listed in Table 7. The Shackelford Creek channel contained no detectable surface water through two segments, which are delineated on the profile. The profile also identifies the locations of flow diversions detected in the imagery.

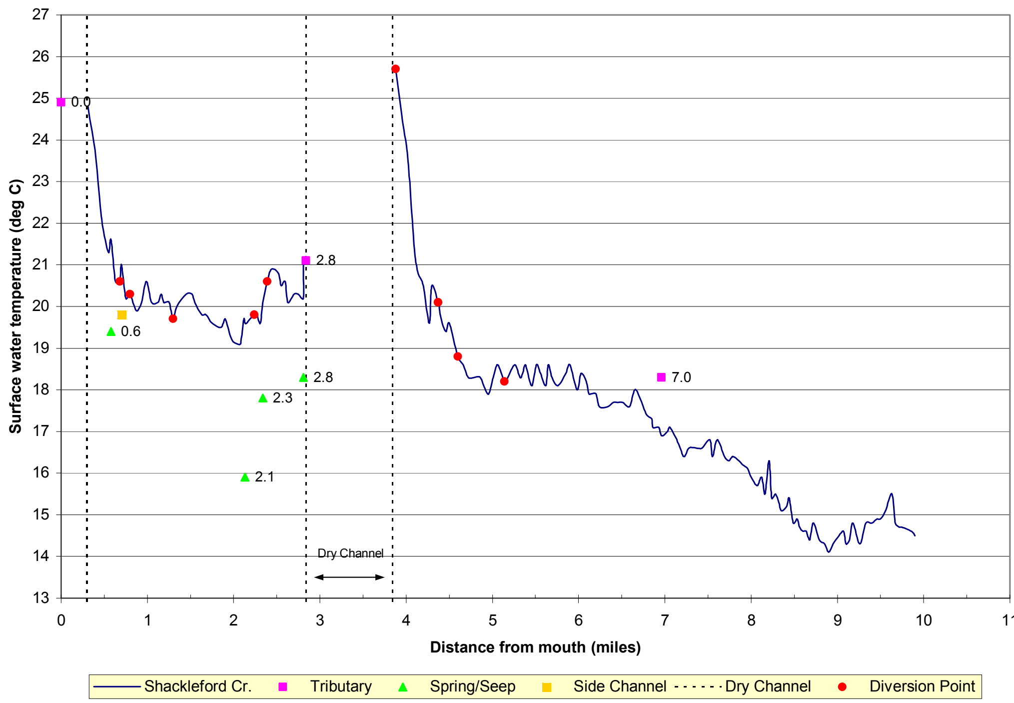


Figure 12 – Median channel temperatures versus river mile for Shackelford Creek. The plot shows the location of surface water inflows labeled by river mile.

Table 7 - Tributary temperatures for Shackelford Creek.

Name	Image	km	mile	Tributary °C	Shackelford Cr. °C	Difference °C
Tributary						
Scott River	shaq0076	0.0	0.0	24.9	n/a	n/a
Mill Cr. (RB)	shaq0285	4.6	2.8	21.1	21.2	-0.1
Big Meadows Cr. (LB)	shaq0537	11.2	7.0	18.3	16.9	1.4
Spring/Seep						
Spring/Seep (RB)	shaq0103	0.9	0.6	19.4	21.6	-2.2
Spring (LB)	shaq0183	3.4	2.1	15.9	19.6	-3.7
Spring (RB)	shaq0196	3.8	2.3	17.8	20.1	-2.3
Seep (LB)	shaq0284	4.5	2.8	18.3	21.1	-2.8
Side Channel						
Side Channel (LB)	shaq0111	1.1	0.7	19.8	21.0	-1.2

(*LB – left bank, RB – right bank looking downstream*)

At the upstream end of the survey (river mile 9.9), water temperatures in Shackelford Creek were cool with measured radiant temperatures ≈14.5^{o}C and remained relatively cool to river mile 9.0 before warming steadily to 18.2^{o}C at river mile 6.0. While the confluences of several small tributaries were detected through this reach, only Big Meadows Creek at river mile 7.0 was visible enough to obtain a radiant temperature sample. Water temperatures remained ≈18.2^{o}C over the next mile before exhibiting rapid longitudinal heating from river mile 5.0 to river mile 3.9. This segment of rapid longitudinal heating corresponds spatially to the point where Shackelford Creek transitions from its canyon to the Quartz Valley. In addition, four diversion dams were identified between river miles 5.1 and 3.9. Reduced flow volumes (from the diversions) combined with decreased stream gradient (*and hence velocity*) were seemingly the overriding factors driving the rapid longitudinal heating. The diversion at river mile 3.9 removes most of the remaining surface flow and the channel goes dry just downstream.

Downstream of river mile 3.9, the Shackelford Creek channel remains dry to river mile 2.8 where the inflow from Mill Creek reintroduces surface flow. At the confluence, radiant water temperatures in Mill Creek were approximately ≈21.1^{o}C. Several small cool water seeps were detected near the confluence suggesting a level of shallow, sub-surface exchange (Figure 13). The in-channel seeps combined with a larger spring inflow at river mile 2.1 (Figure 14) contributing to the slight cooling trend observed between river miles 2.8 and 2.1. Rapid longitudinal heating was observed from river mile 0.9 to where the channel was dry at river mile 0.3. A series of five flow diversions were detected between river miles 2.5 and 0.7. As with the reach upstream of Mill Creek, the rapid longitudinal heating in the lower stream mile was presumably due to the reduced flow volumes.

Recall that the ground truth process revealed that radiant temperatures were approximately 1.1^{o}C cooler than kinetic temperatures measured at river mile 9.1 (Table 3). In order to assess how this difference may impact interpretation of the spatial temperature patterns, the kinetic temperatures at flight time were plotted in relation to the longitudinal temperature profile (Figure 15). The plot shows that, while the radiant temperature profile may show a slightly higher magnitude, both the radiant and kinetic temperatures show warming between the two ground truth points. Available information was not sufficient to determine if the in-stream sensor or the radiant temperatures provide a truer representation of bulk temperatures at this location.

Figure 13 – TIR/color video image showing the confluence of Mill Creek (21.1°C) and the dry channel of Shackelford Creek at river mile 2.8. Small cool water seeps are visible in the TIR images suggesting at least some level of sub-surface exchange in the channel.

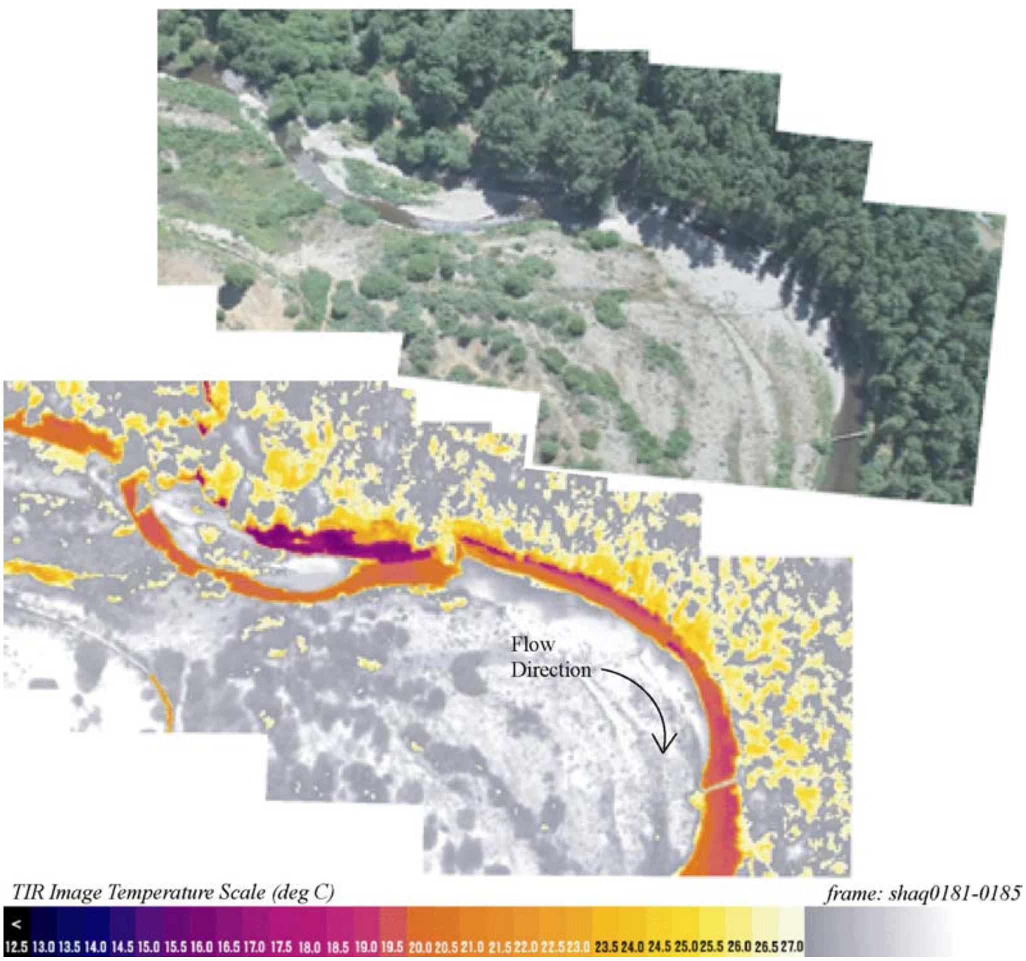


Figure 14 – TIR/color video image showing a spring inflow along the left bank of Shackelford Creek at river mile 2.1.

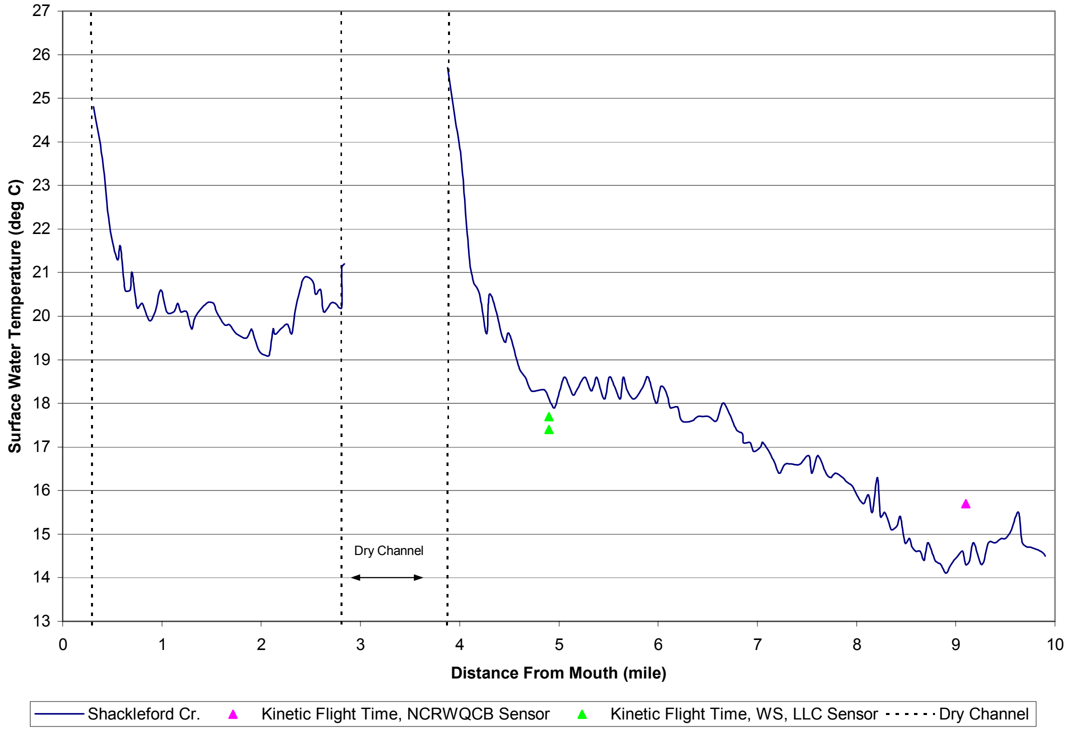


Figure 15 – Median channel temperatures versus river mile for Shackelford Creek. The plot also shows measured in-stream temperatures at the time of the flight.

Kidder Creek/Big Slough

Kidder Creek was surveyed from its mouth to the confluence with Big Slough and then continued on Big Slough to its confluence with Patterson Creek. Median channel temperatures were plotted versus river mile for both survey segments (Figure 16). The location and name of sampled tributaries are illustrated on the plot by river mile and are listed in Table 8.

Surface temperatures were above 25.4^{o}C over the full 3.6 miles of Kidder Creek and exhibited a slight warming trend (+1.2^{o}C) in the downstream direction. Spatial temperature patterns showed relatively little local thermal variability (*outside of characteristic noise levels*) and no distinct surface inflows were sampled during the analysis.

Big Slough similarly exhibited warm radiant temperatures, but showed considerably more spatial thermal variability upstream of river mile 6.0. Upstream of river mile 6.0, radiant water temperatures in Big Slough showed more dramatic swings with a maximum surface temperature of 33.0^{o}C recorded at river mile 6.9. Interpretation of the imagery indicated that areas of Big Slough were thermally stratified. The stratified areas typically occurred behind impoundments and on wide stream bends and can be identified by warmer, but localized (often unstable), surface temperatures. Images with thermally stratified reaches are identified in the associated database. Stability in surface temperatures downstream of river mile 6.0 suggests a possible change in the conditions (i.e. mixing rates, flow levels) that allowed the formation of stratified areas.

Kidder Creek and Big Slough meandered through the relatively low gradient valley and had multiple channels (both active and inactive) over much of the surveyed length. Consequently, side channels and off channel features were often outside the image footprint. In order to capture these features, the Kidder Creek and Big Slough survey was repeated at a higher altitude (i.e. wider image footprint). The higher altitude flight was not sampled for temperature, but the images are included in the database and provide an addition spatial reference for assessing spatial temperature patterns in Kidder Creek and Big Slough.

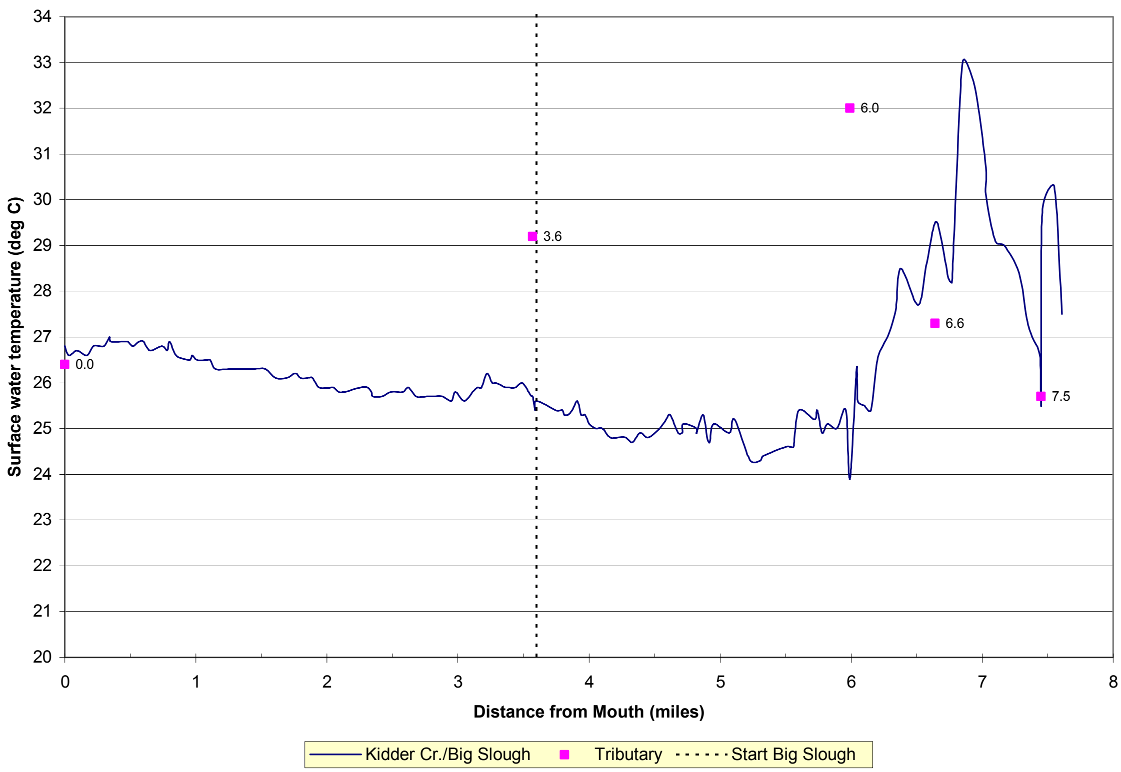


Figure 16 – Median channel temperatures versus river mile for Kidder Creek and Big Slough. The plot shows the location of surface water inflows labeled by river mile.

Table 8 - Tributary temperatures for Kidder Creek and Big Slough.

Tributary Name	Image	km	mile	Tributary °C	Kidder Cr. Big Slough °C	Difference °C
Scott River (RB)	kidd0007	0.0	0.0	26.4	26.8	-0.4
Kidder Creek (LB)	kidd0151	5.8	3.6	29.2	25.7	3.5
Unnamed Tributary (LB)	kidd0244	9.6	6.0	32.0	23.9	8.1
Unnamed Tributary (LB)	kidd0266	10.7	6.6	27.3	29.5	-2.2
Unnamed Tributary (LB)	kidd0297	12.0	7.5	25.7	25.6	0.1

LB = left bank; RB = right bank.

Discussion

Airborne thermal infrared remote sensing has provided a measure of spatial temperature patterns for selected streams in the Scott River Basin. The results showed temperatures in the Scott River varied at different spatial scales along the stream gradient. At the upstream end of the survey, spatial temperature patterns were characterized by springs and seeps, which were detected at numerous locations within the mine tailings. Temperatures downstream exhibited reach scale patterns of both warming and cooling. This report provides some hypotheses and observations on the observed reach scale patterns, but more in-depth analysis is needed to develop a complete picture of thermal processes in the basin.

Shackelford Creek and the South and East Fork Scott Rivers each showed unique spatial temperature patterns. The TIR and associated true color images provide a basis for further analysis of channel conditions and temperature dynamics in these streams. Shackelford Creek in particular showed a wide range of temperatures over the 10-mile survey extent.

Shasta River Sub-Basin

Overview

TIR remote sensing surveys in the Shasta River Sub-Basin were flown on July 26-27, 2003 (Figure 17). Table 9 summarizes the survey times, extents, and image resolutions for each surveyed stream. The Shasta River was surveyed at a flight altitude that provided a wider image footprint to better capture the wider channel widths and side/off channel features characteristic of the main stem Tributaries were surveyed at lower flight altitudes to provide slightly higher spatial resolution and better visibility through riparian vegetation.

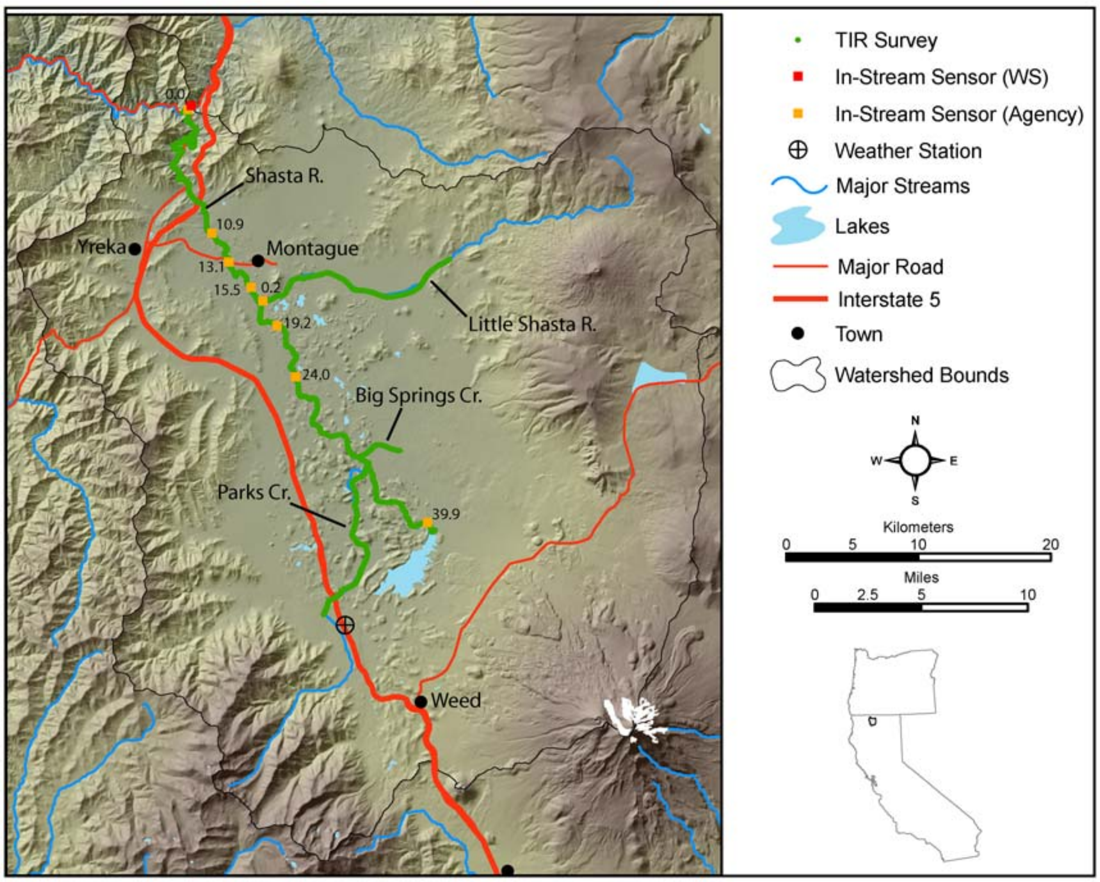


Figure 17 – Map showing the streams surveyed in the Shasta River Sub-Basin using TIR and color video on July 26-27, 2003. The map also shows the location of the in-stream sensors used to ground truth the imagery, labeled by river mile.

Table 9 – Summary of river segments surveyed with TIR and color video in the Shasta River Sub-Basin on July 26-27, 2003.

Stream	Survey Date	Survey Time (24 hr)	Survey Extent	River Miles	Image Width Meter (ft)	TIR Image Pixel Size Meter (ft)
Shasta R.	26-Jul	15:40-16:52	Mouth to Dwinnel Dam	40.5	150 (494)	0.48 (1.54)
Little Shasta R.	27-Jul	13:39-13:59	Mouth to Main Canal	12.6	150 (494)	0.48 (1.54)
Parks Cr.	27-Jul	14:06-14:27	Mouth to I-5 Bridge	10.0	128 (423)	0.41 (1.32)
Big Spring Cr.	27-Jul	14:33-14:36	Mouth to Big Springs Lake	2.6	171 (564)	0.54 (1.76)

Results

Weather Conditions

Weather conditions for the times of the surveys are summarized in Table 2.

Thermal Accuracy

Table 10 summarizes the differences between the kinetic temperatures recorded by the in-stream data loggers and the radiant temperatures derived from the TIR images. On average, radiant temperatures were within the desired accuracy (< 0.5°C) for streams with in-stream monitoring sites. Due to access limitations, no in-stream sensors were deployed in Big Springs Creek or Parks Creek. As a result, no data are available to assess the radiant temperature accuracy on these streams. However, flights on these streams occurred within ½ hour of the Little Shasta survey. Due to the proximity of time and distance, the calibration parameters used to correct the TIR images on the Little Shasta River were considered applicable to Big Springs and Parks Creek.

On the Shasta River, radiant temperatures were ≈0.9°C warmer than measured in-stream temperatures at the upper-most monitoring site (river mile 39.9). The factors contributing to this difference were not apparent from the imagery. At the three closest downstream monitoring sites (i.e. river miles 15.5, 19.2, and 24.0), radiant temperatures were slightly cooler than kinetic. The impacts, if any, which these differences have on observed spatial temperature patterns, are addressed during the discussion of the longitudinal profiles.

Table 10 – Comparison of ground-truth water temperatures (Kinetic) with the radiant temperatures for streams in the Shasta River Sub-Basin.

Image	Time 24 hr.	River Mile	Kinetic °C	Radiant °C	Difference °C
Shasta River (average 0.4)					
shas0041	15:41	0.0	26.1	26.6	-0.5
shas0622	16:01	10.9	24.2	24.2	0
shas0795	16:07	13.1	23.7	23.7	0
shas0925	16:11	15.5	23.6	23.2	0.4
shas1105	16:17	19.2	23.2	22.8	0.4
shas1315	16:24	24.0	23.3	22.7	0.6
shas2052	16:51	39.9	20.9	21.8	-0.9
Little Shasta River (average 0.4)					
lshasta0045	13:33	n/a	25.4	25.9	0.5
lshasta0052	13:39	n/a	23.0	22.6	-0.4
lshasta0071	13:40	0.24	27.4	27.6	0.2

Temporal Differences

Figure 18 shows an in-stream temperature variation at the mouth of the Shasta River for the date of the Shasta River survey. The figure is intended to provide a sense of how stream temperatures changed during the time frame of the flight. The survey began prior to, but continued into, the time of the daily maximum stream temperature of 26.4°C, which occurred from 16:00 to 18:10. Temporal data for other monitoring sites and streams were only available for the time of the survey.

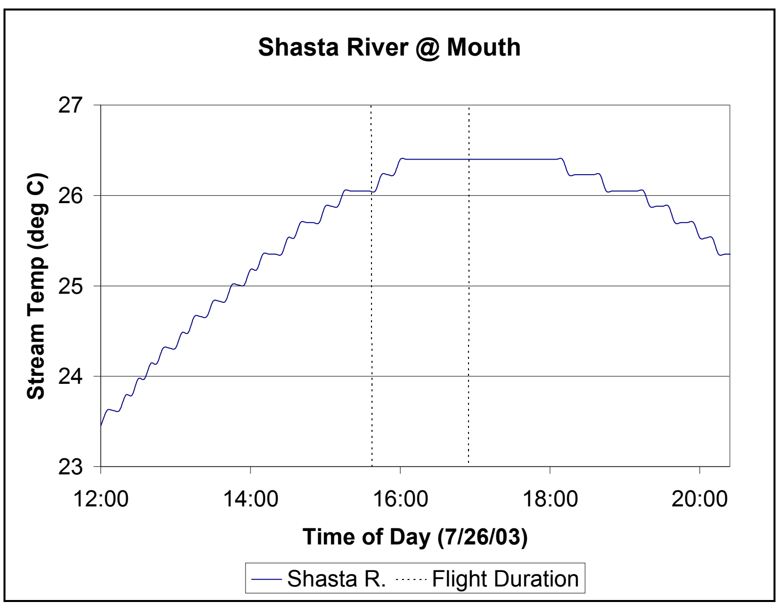


Figure 18 – Stream temperature variation and time of TIR remote sensing flight at a single location on the Shasta River Survey on 7/26, 2003.

Longitudinal Temperature Profiles

Shasta River

Median radiant temperatures were plotted versus river mile for the Shasta River (Figure 19). The plot illustrates the location of surface water inflows (tributaries, springs, seeps) labeled by river mile. The corresponding name and temperature of the surface inflows are summarized in Table 11. Due to the length of the survey, the median radiant temperatures were also plotted in relation to the kinetic temperatures at the time of the survey (Figure 20). This plot provides additional context for examining the differences between kinetic and radiant temperatures and for understanding how these differences may alter the interpretation of the observed spatial temperature patterns.

Figure 19 – Median radiant temperature versus river mile for the Shasta River measured on July 26, 2003. Surface inflows sampled during the analysis are labeled by river mile and listed in Table 11.

Table 11 – Tributary temperatures for the Shasta River.

Name	Image	km	mile	Tributary °C	Shasta R. °C	Difference °C
Tributary						
Klamath R (RB)	shas0036	0.0	0.0	25.8	26.5	-0.7
Yreka Cr (LB)	shas0477	12.5	7.8	23.4	24.2	-0.8
Oregon Slough (RB)	shas0688	18.9	11.7	26.6	24.2	2.4
Little Shasta R (RB)	shas0968	26.2	16.3	25.9	23.1	2.8
Unnamed Tributary (LB)	shas1182	34.0	21.1	21.8	23.4	-1.6
Willow Cr (LB)	shas1354	40.6	25.2	26.1	22.3	3.8
Big Springs Cr (RB)	shas1759	54.3	33.7	21.7	21.9	-0.2
Hole in The Ground Cr (RB)	shas1804	55.9	34.7	17.3	21.6	-4.3
Parks Cr (LB)	shas1807	56.0	34.8	23.5	21.6	1.9
Unnamed (RB)	shas2079	65.1	40.5	22.4	21.7	0.7
Spring						
Spring (LB)	shas2029	63.3	39.4	14.8	22.5	-7.7

(*LB – left bank, RB – right bank looking downstream*).

Figure 20 – Median stream temperatures versus river mile for the Shasta River. The plot also shows the kinetic temperatures at the time of the survey and the maximum daily stream temperature at the ground truth locations.

At the upstream end of the survey, water temperatures in the Shasta River were shaped in part by surface inflows. At river mile 39.4, a spring lowered stream temperatures in the Shasta River from 22.5°C to 19.3°C. Stream temperatures warmed rapidly downstream of the spring before exhibiting an overall cooling trend of 4.0°C between river miles 37.2 and 35.8. The source of the apparent cooling was not directly apparent from the imagery. However, the sharp decrease in water temperatures over a relatively short distance suggests a cooling influence. Moving downstream, Parks Creek was a source of warm water at river mile 34.8 and increased main stem temperatures by 1.7°C. The warm inflow came from the southern channel of Parks Creek while the northern channel did not contain enough flow to obtain a radiant temperature sample.

Downstream of Parks Creek, water temperatures in the Shasta River showed definitive reach scale thermal patterns, but no longer exhibited dramatic response to detected inflows (i.e. tributaries, springs, etc). Local variability along the longitudinal profile was generally characteristic of the ±0.5°C noise common to TIR remote sensing. A slight cooling trend was observed between river mile 33.7 and 30.3. The general cooling trend was observed downstream of the confluence with Big Spring Creek - although radiant temperatures at the mouth of Big Spring Creek did not vary significantly from those in the Shasta River. Longitudinal heating was observed between river miles 30.3 and 23.5 and again between river mile 16.4 and the Klamath River confluence. A consistent water temperature of 23.0oC was observed between river miles 23.5 and 16.4 Given the warm air temperatures (≈36oC) and general exposure of the stream surface to direct solar loading, a constant water temperatures or cooling through a given stream segment suggests a buffering or cooling source within that reach.

Little Shasta River

Median channel temperatures derived from the TIR images were plotted versus river mile for the Little Shasta River (Figure 21). Visual inspection of the topographic base maps (DRGs) showed numerous mapped surface inflows throughout the surveyed segment. However, analysis of the imagery showed these inflows contained little or no surface water at the time of the survey. Consequently, no surface inflows (tributaries, springs, seeps, irrigation returns, etc.) were sampled. Similarly there was very little visible surface flow in the Little Shasta River throughout much of the survey extent. Discontinuities in the amount of visible surface water naturally resulted in irregular sampling intervals. This was especially true upstream of river mile 6.0.

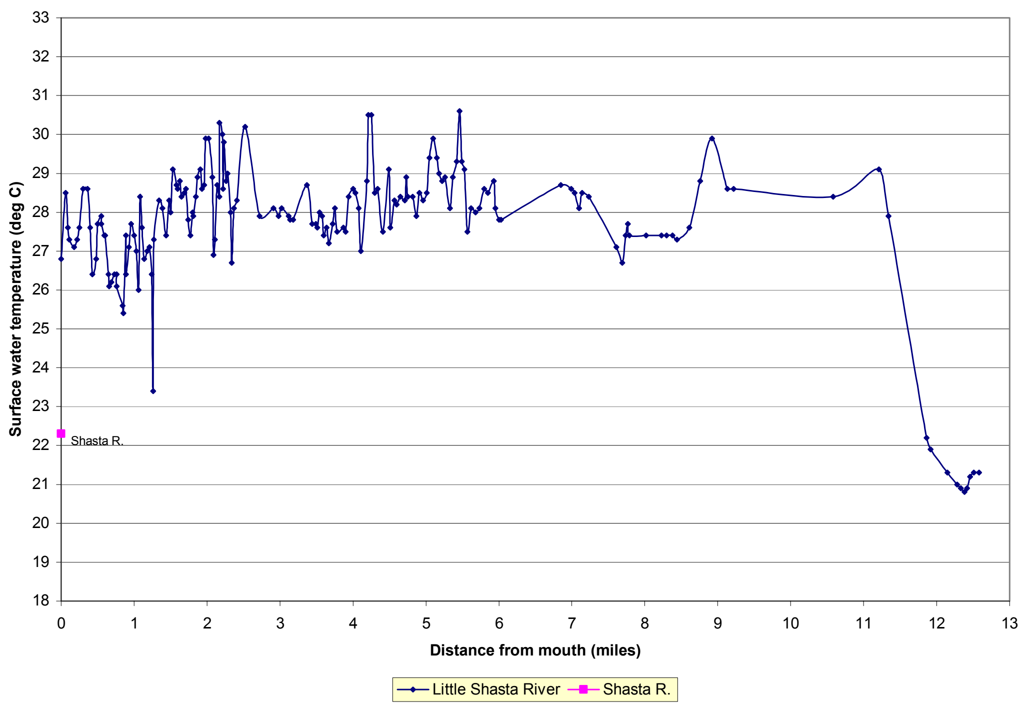


Figure 21 – Median channel temperatures versus river mile for the Little Shasta River (7/27/03)

The average median water temperature in the Little Shasta River was 28.0°C between river mile 11.3 and the mouth. Radiant temperatures varied considerably between sample points with apparent changes of up to 3.0°C observed within 0.2 river miles. This level of variability is not unusual for streams with very low surface flows because temperatures generally respond dramatically to relatively small inputs. However, on the Little Shasta River, the TIR images revealed very few indicators of sub-surface exchanges (seeps or springs) or obvious surface inputs that may result in a high degree of local thermal variability. Under very low flow or poorly mixed conditions, variability in surface temperature may also be the result of differential surface heating and/or locally stratified segments. These factors probably contributed significantly to the observed spatial temperature patterns observed on the Little Shasta River (Figure 22).

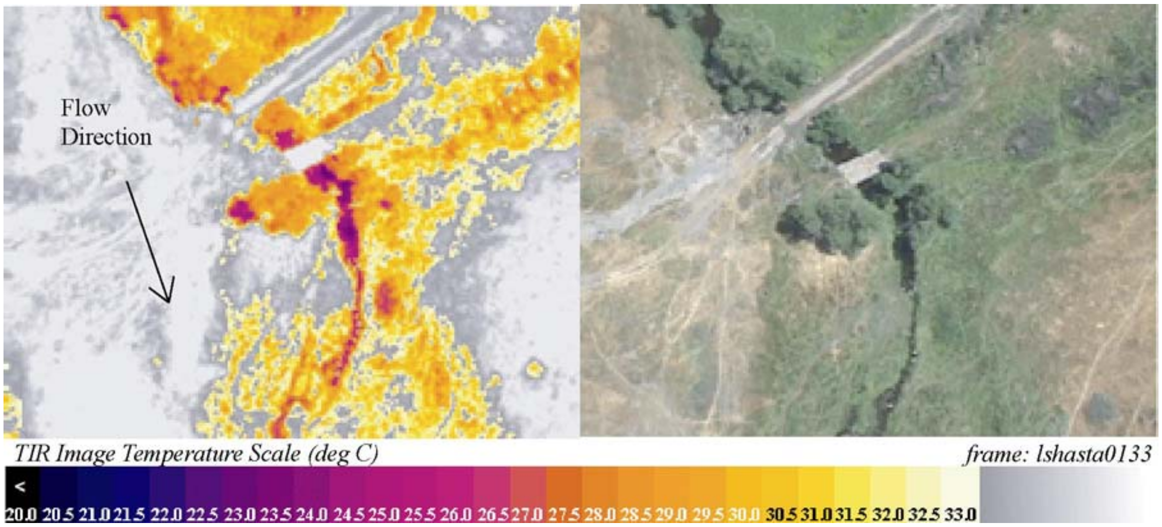


Figure 22 – TIR/color video image showing an example of the localized surface temperature variability on Little Shasta River at river mile 1.3. Median surface temperature upstream of the bridge were 25.7°C while surface temperatures of 23.3°C were recorded in the shaded area downstream of the bridge. The difference suggest differential surface heating in the shaded areas or thermal stratification upstream of the bridge.

Parks Creek

Visual inspection of the topographic base map shows that Parks Creek is characterized by multiple water withdraws, surface returns, and tributary inflows as it progresses through the Shasta Valley East of Interstate 5. At the confluence of the Shasta River, the survey started along the Northern channel of Parks Creek and continued along the mapped line for approximately 10 stream miles past the Interstate 5 crossing. Along this route, the airborne imagery also showed the interconnectedness and variability of the surface hydrology associated with Parks Creek (Figure 23). As with the other surveys, median channel temperatures derived from the TIR images were plotted versus river mile for Parks Creek (Figure 24). The location of sampled tributaries and other surface inflows are illustrated on the plot by river mile and are listed in Table 12.

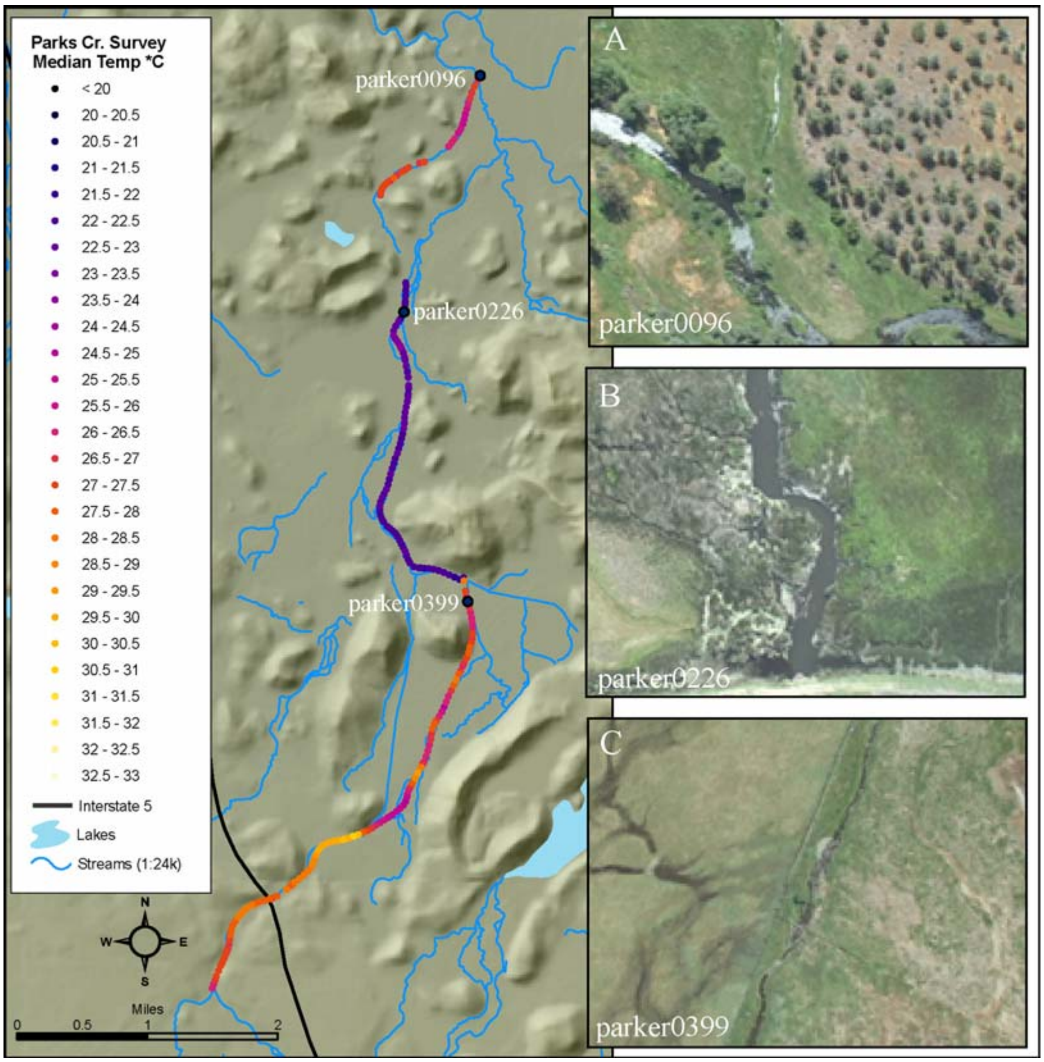


Figure 23 – A series of three true color video images illustrating changes in channel characteristics over the 10-mile survey length of Parks Creek. Image A shows the mouth of Parks Creek, illustrating the narrow channel width compared with the Shasta River. Image B shows Parks Creek at river mile 2.6, with a wider channel than is seen upstream at river mile 5.7 (Image C).

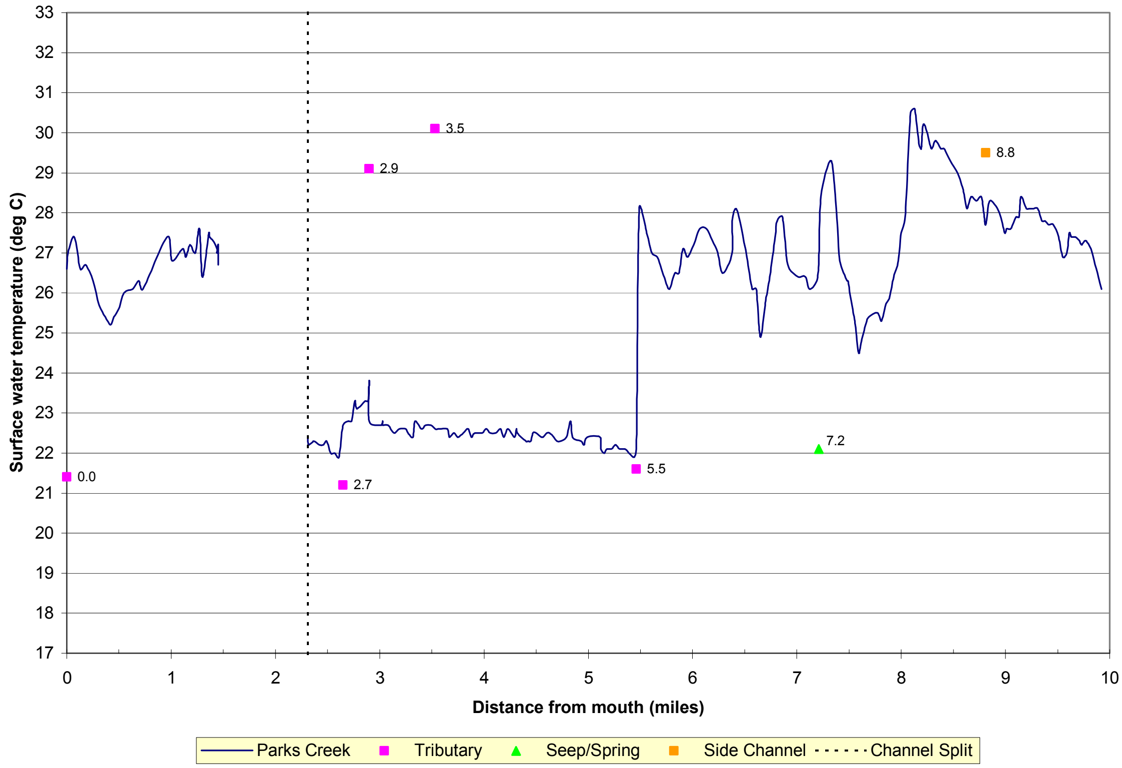


Figure 24 – Median channel temperatures versus river mile for Parks Creek.

Table 12 - Tributary temperatures for Parks Creek.

Name	Image	km	mile	Tributary °C	Parks Cr. °C	Difference °C
Tributary						
Shasta River (RB)	parker0096	0.0	0.0	21.4	26.6	-5.2
Unnamed (RB)	parker0230	4.3	2.7	21.2	22.7	-1.5
Unnamed (LB)	parker0243	4.7	2.9	29.1	23.8	5.3
Unnamed (LB)	parker0270	5.7	3.5	30.1	22.6	7.5
Unnamed (RB)	parker0390	8.8	5.5	21.6	22.1	-0.5
Seep/Spring						
Seep (LB)	parker0461	11.6	7.2	22.1	26.8	-4.7
Side Channel						
Side Channel (RB)	parker0533	14.2	8.8	29.5	27.7	1.8

(*LB – left bank, RB – right bank looking downstream*)

Between river miles 9.9 and 5.5, water temperatures were generally warm, ranging from 24.6°C to 30.6°C. Parks Creek appeared to have very little surface flow through this reach and water temperatures appeared to respond dramatically to any mass transfers (inputs or losses). For example, a decrease in surface temperatures of ≈3.2°C was observed immediately downstream of an apparent cool water seep at river mile 7.2. The seep contributed cooler water locally to the stream, but water temperatures heated rapidly again in the absence of the cooling process. At river mile 5.5, Parks Creek is joined by a canal carrying cooler water (≈21.6°C). The inflow of the canal dictated the temperature of Parks Creek. In contrast to the upper reach, stream temperatures showed little local variability from river mile 5.5 to river mile 2.9, with an overall increase of only 0.9°C. The stream channel had almost no riparian vegetation through this reach and the overall lack of heating through this reach suggests other possible buffering sources. Downstream of rive mile 2.4, Parks Creek splits into two channels. In the Northern channel (*the one followed by the survey*) the stream disperses into several channels for the first 0.9 miles with no clearly discernable main channel. While the channels were visible in the TIR imagery, the thermal signature appeared due to saturated vegetation with no detectable surface water. Consequently, no radiant temperature samples could be acquired in this reach.

Big Springs Creek

Median channel temperatures were plotted versus river mile for Big Springs Creek (Figure 25). The location of sampled tributaries, springs, and other surface inflow are illustrated on the plot by river mile and are listed in Table 13.

The imagery showed considerable vegetation in the stream channel over the full extent, but surface water was clearly visible. Although the in-channel vegetation created interesting thermal patterns in the TIR images, radiant temperatures were only sampled from the surface water. True to its name, Big Springs Creek contained four springs detected within 0.4 miles downstream of the outlet of Big Springs Lake. The spring influences reduced water temperatures in Big Springs Creek to ≈15.6°C at river mile 1.9. Downstream of the springs, temperatures increased rapidly reaching 21.0°C at river mile 0.7 before remaining consistent (21.0°C; ±0.5°C) to the confluence of the Shasta River.

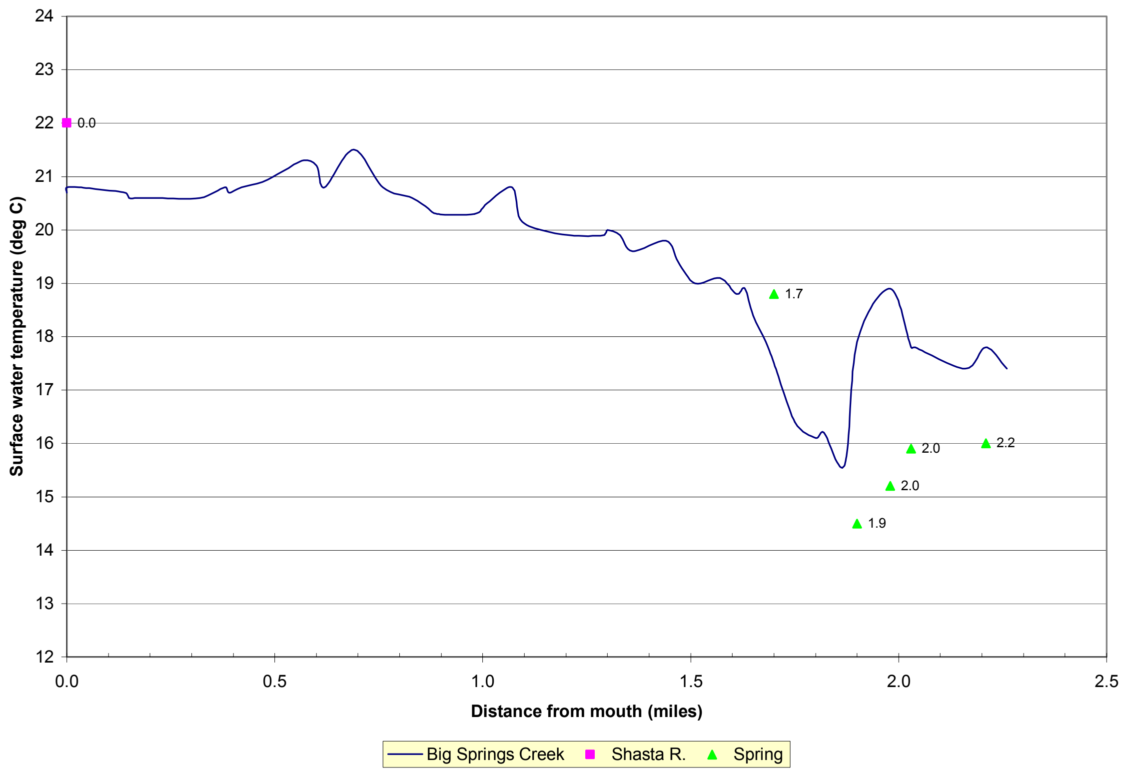


Figure 25 – Median channel temperatures versus river mile for Big Springs Creek. The plot shows the location of surface water inflows labeled by river mile.

Table 13 - Tributary temperatures for Big Springs Creek (7/27/03).

Name	Image	km	mile	Shasta R. °C	Tributary °C	Difference °C
Shasta River (LB)	big0007	0.0	0.0	22.0	20.7	1.3
Spring						
Spring (LB)	big0075	2.7	1.7	18.8	17.5	1.3
Spring (RB)	big0084	3.1	1.9	14.5	17.9	-3.4
Spring (RB)	big0086	3.2	2.0	15.2	18.9	-3.7
Spring (LB)	big0088	3.3	2.0	15.9	17.8	-1.9
Spring (RB)	big0093	3.6	2.2	16.0	17.8	-1.8

(*LB – left bank, RB – right bank looking downstream*)

Discussion

Thermal infrared remote sensing surveys were successfully conducted on selected streams in the Shasta River Basin. Longitudinal temperature profiles were developed for each surveyed stream that illustrates broad scale spatial temperature patterns. Downstream of the Parks Creek confluence, the shape of the Shasta River profile is defined by variations in longitudinal heating rates with one reach showing little or no heating and another showing a general cooling trend. More comprehensive analysis is required to determine the combination of factors contributing to the variations in heating (or cooling) rates along the stream gradient.

Analysis of the imagery showed that Parks Creek and the Little Shasta River had relatively little surface water. The spatial temperature patterns of both streams were generally characteristic of low volume streams with a high degree of local spatial variability in reaches with little apparent surface water. In Parks Creek, the amount of visible surface water varied longitudinally based primarily on mass transfers in the channel, while the Little Shasta River had very little visible surface water throughout the full survey extent. On these streams, further analysis may put a greater emphasis on the true color images for assessing channel and surface water characteristics.

Follow-on

This report presents the longitudinal temperature profiles and provides some hypotheses on the processes influencing spatial temperature patterns. Theses hypotheses are considered a starting point for more rigorous spatial analysis and fieldwork. Individual TIR and color video image frames are organized in an ArcView database to allow viewing of the temperature patterns and channel characteristics at finer spatial scales. The following is a list of potential uses for these data in follow-on analysis (based on Faux et. al. 2001 and Torgersen et. al. 1999):

1. The patterns provide a spatial context for analysis of seasonal temperature data from in-stream data loggers and for future deployment and distribution of in-stream monitoring stations. How does the temperature profile relate to seasonal temperature extremes? Are local temperature minimums consistent throughout the summer and among years?

2. The database provides a method to develop detailed maps and to combine the information with other spatial data sets. Additional data sets may include factors that influence heating rates such as stream gradient, elevation and aspect, vegetation, and land-use. In viewing the temperature patterns in relation to other spatial factors, correlations are often apparent that provide a more comprehensive understanding of the factors driving temperature patterns at different spatial scales.

3. What is the temperature pattern within critical reach and sub-reach areas? Are there thermal refugia within these reaches that are used by coldwater fish species during the summer months? Do cool water tributaries represent potential thermal refugia? What is the availability/extent of the cool water habitat represented by these sources?

4. The TIR and visible band images provided with the database can be aggregated to form image mosaics. These mosaics are powerful tools for planning fieldwork and for presentations.

5. Stream temperature profiles provide a spatially continuous data set for the calibration of reach and basin scale stream temperature models.

6. Digitized color video images provide a means to evaluate in-stream habitat and riparian/floodplain conditions at the time of the survey.

Bibliography

Faux, R.N., H. Lachowsky, P. Maus, C.E. Torgersen, and M.S. Boyd. 2001. **New approaches for monitoring stream temperature: Airborne thermal infrared remote sensing**. Inventory and Monitoring Project Report -- Integration of Remote Sensing. Remote Sensing Applications Laboratory, USDA Forest Service, Salt Lake City, Utah.

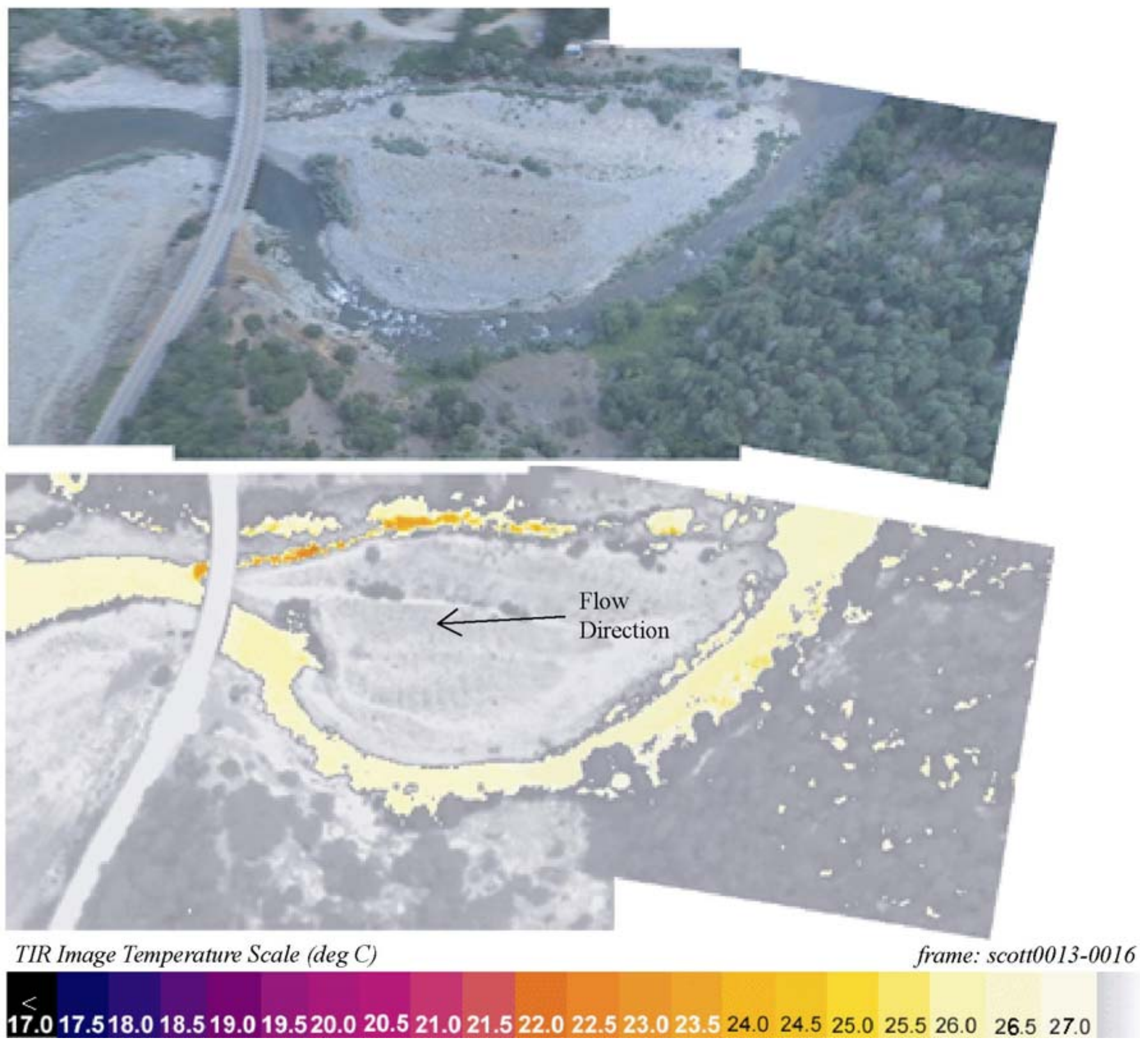
Torgersen, C., R. Faux, and B. McIntosh. 1999. **Aerial survey of the Upper McKenzie River: Thermal infrared and color videography**. Report to the USDA, Forest Service, McKenzie River Ranger District.

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.

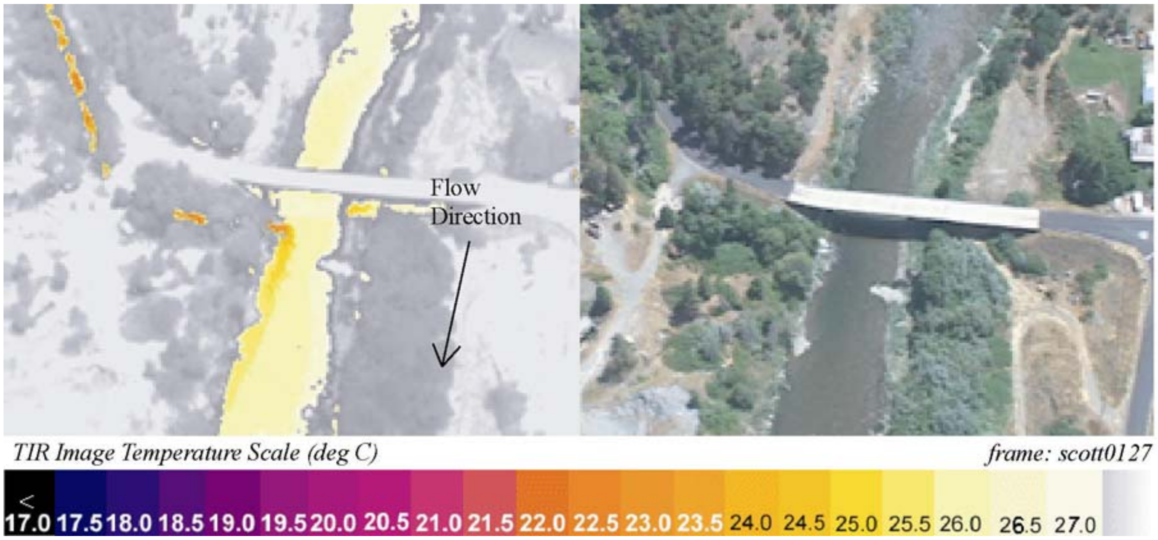
Appendix A - Selected Images

The following images were selected to show interesting features along each of the surveyed streams. References to right or left bank are considered looking downstream.

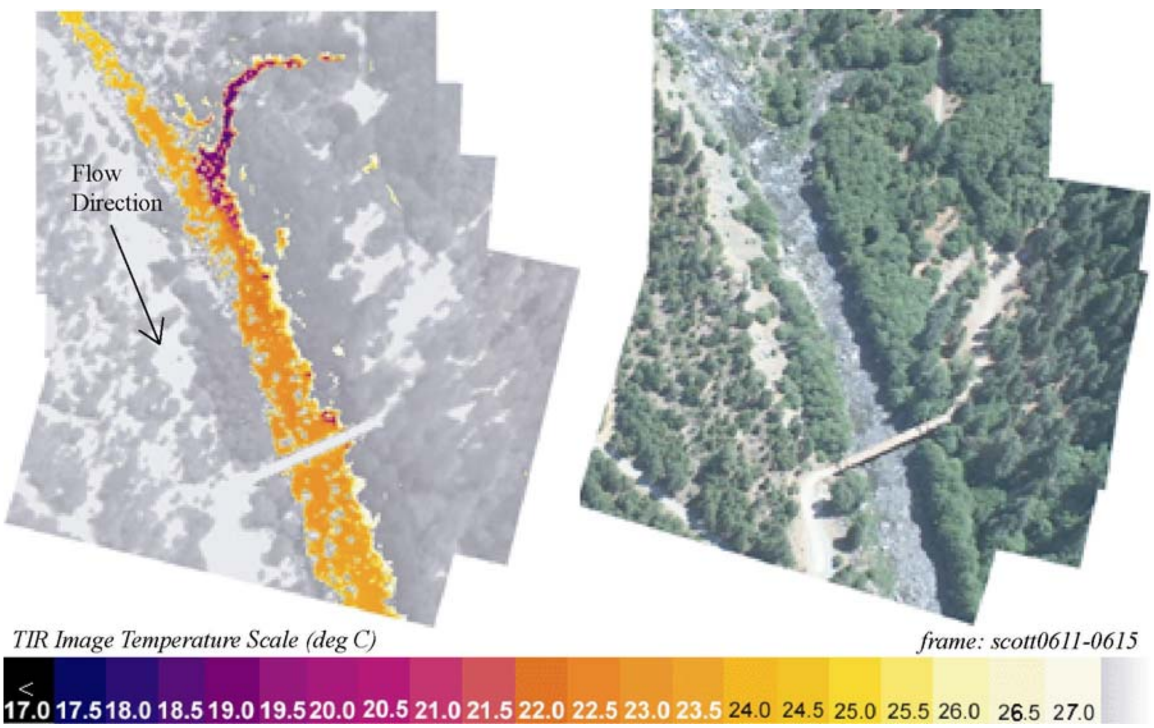
Scott River



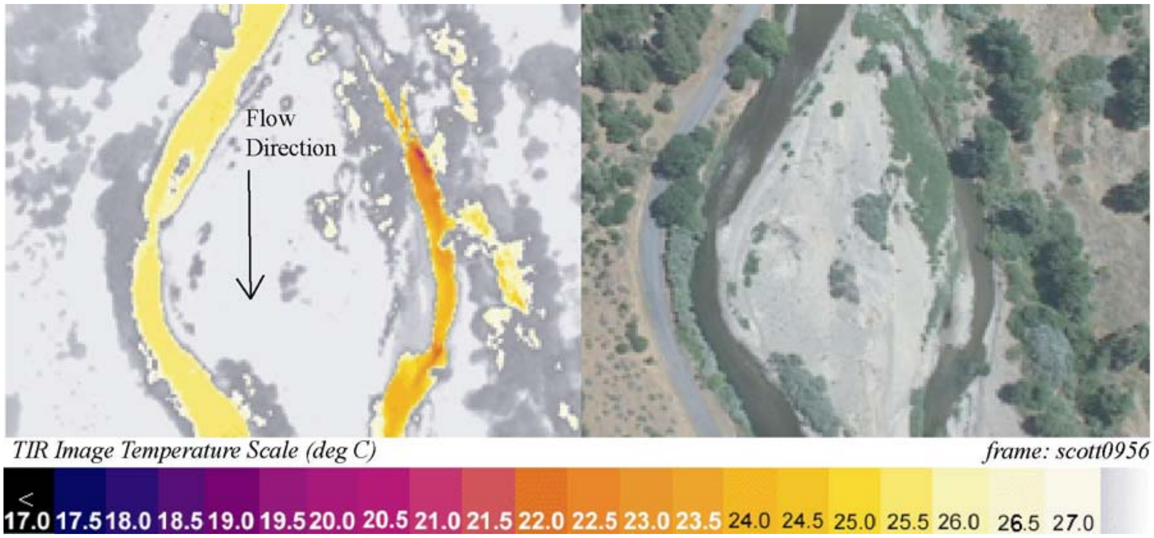
TIR/color video image pair showing a spring (22.1°C) in the side channel on the right bank of the Scott River (25.9°C) at river mile 0.2.



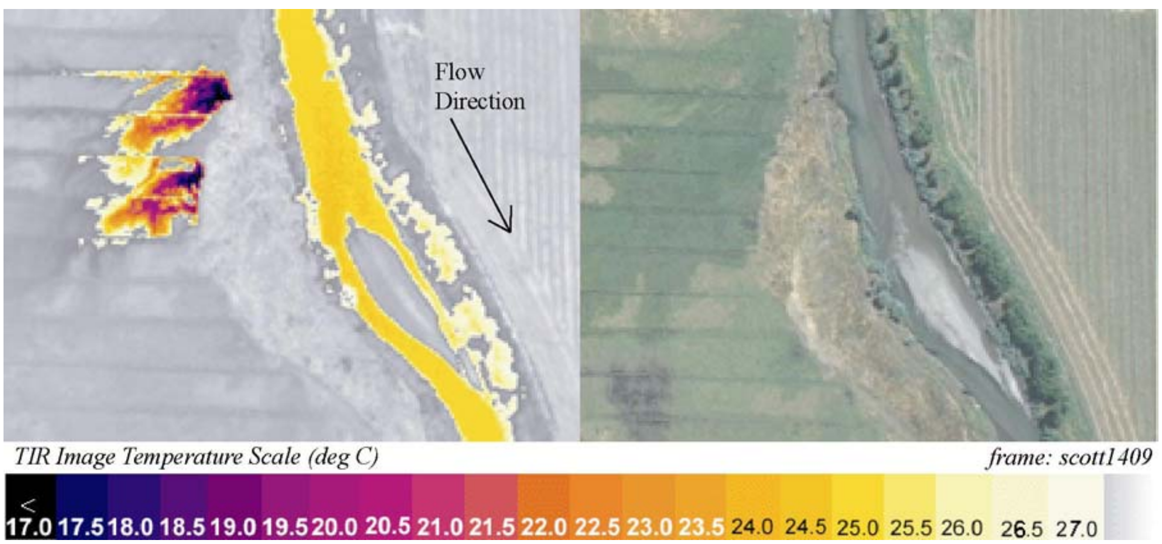
TIR/color video image pair showing Mill Creek (20.9 °C) on the right bank of the Scott River (25.6 °C) at river mile 3.6.



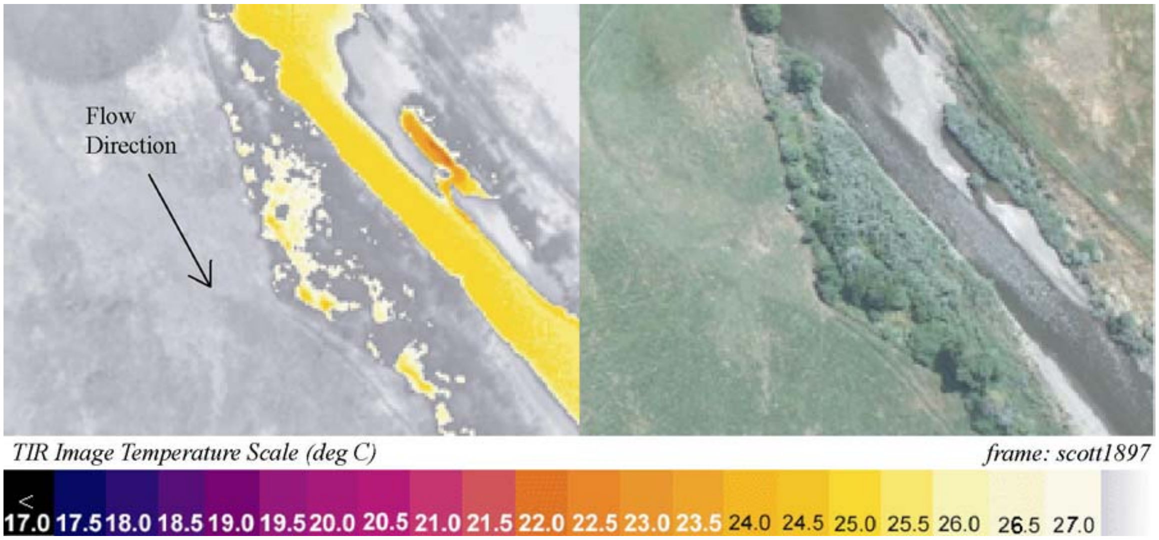
TIR/color video image pair showing Canyon Creek (17.9 °C) on the left bank of the Scott River (22.6 °C) at river mile 15.9.



TIR/color video image pair showing a spring/seep emerging from within the left bank channel of the Scott River (25.3 ^{o}C) at river mile 24.5.

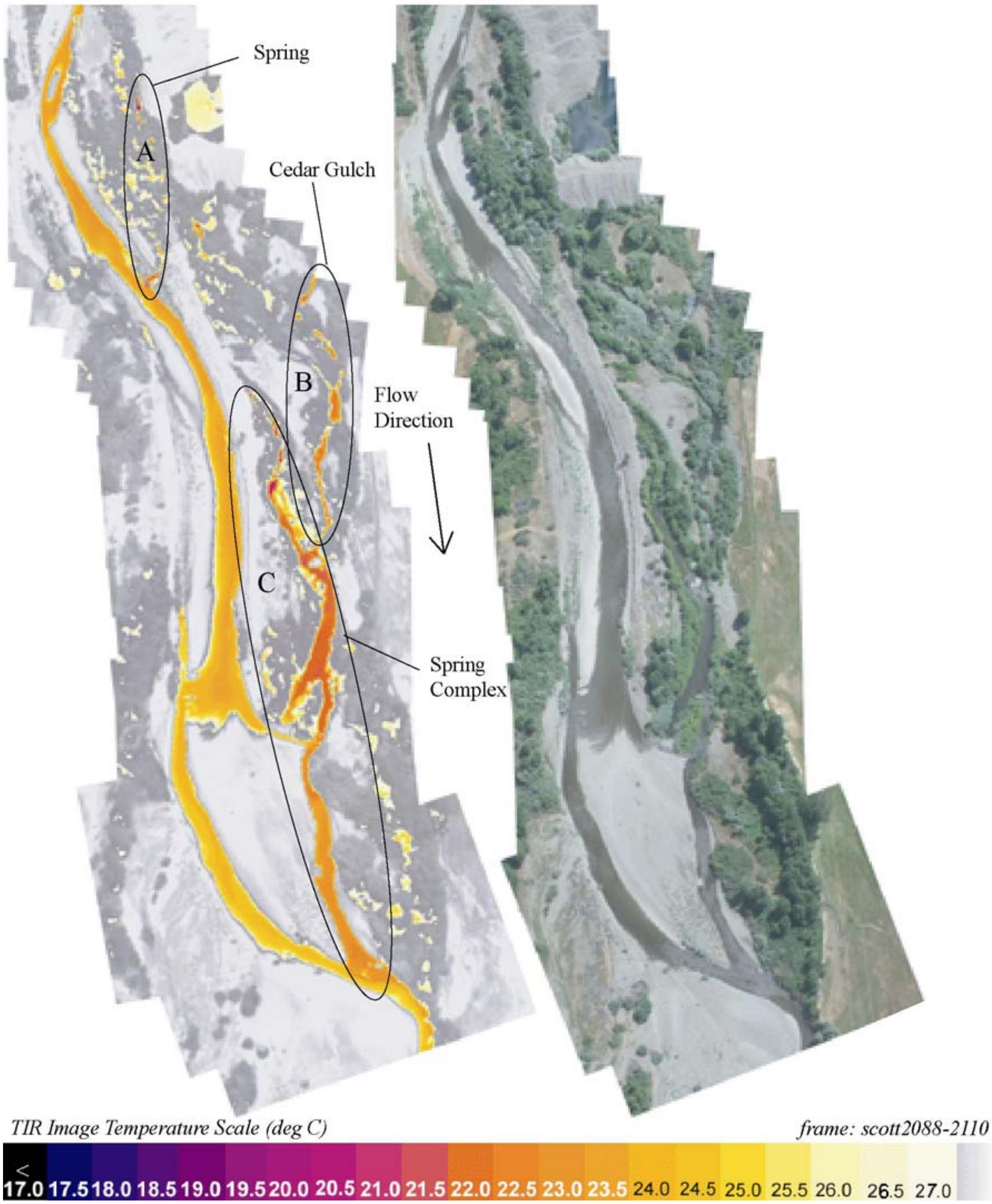


TIR/color video image pair showing a thermal signature in a field near right bank of the Scott River (24.5 ^{o}C) at river mile 36.5. This thermal signature is presumed due to transpiring vegetation from irrigation or recent rain.

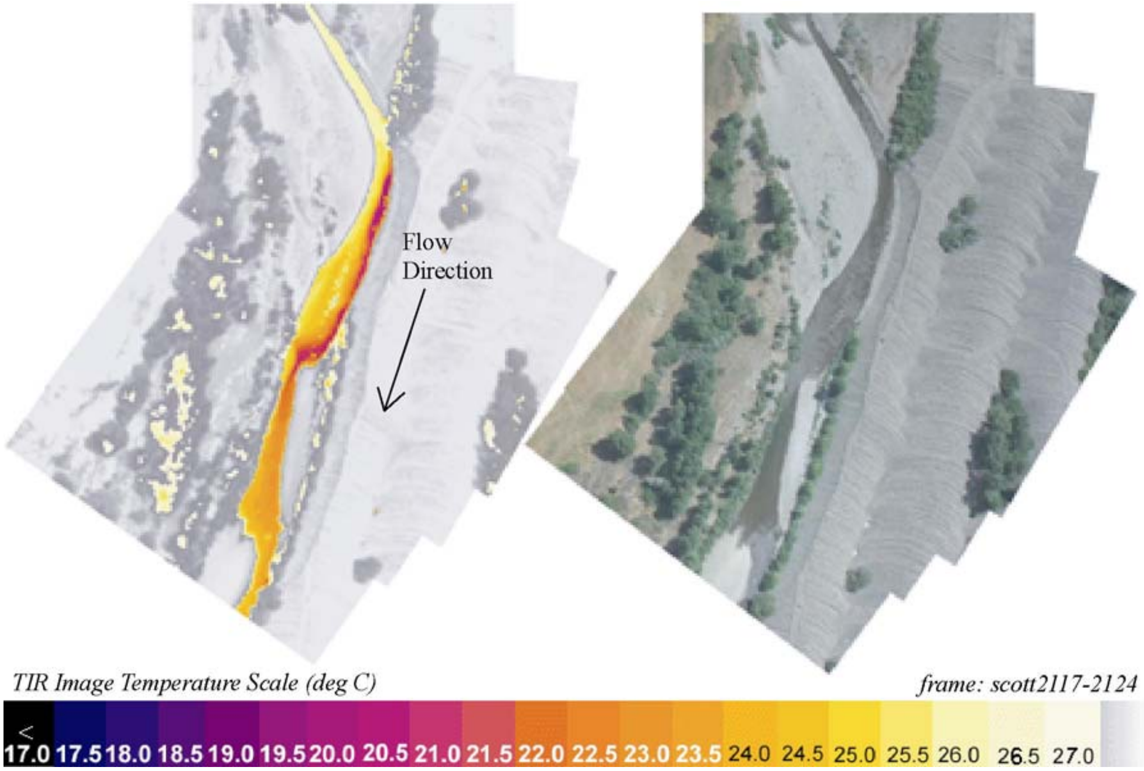


TIR/color video image pair showing a spring/seep (21.9 ^{o}C) on the left bank of the Scott River (24.8^{o}C) at river mile 46.8.

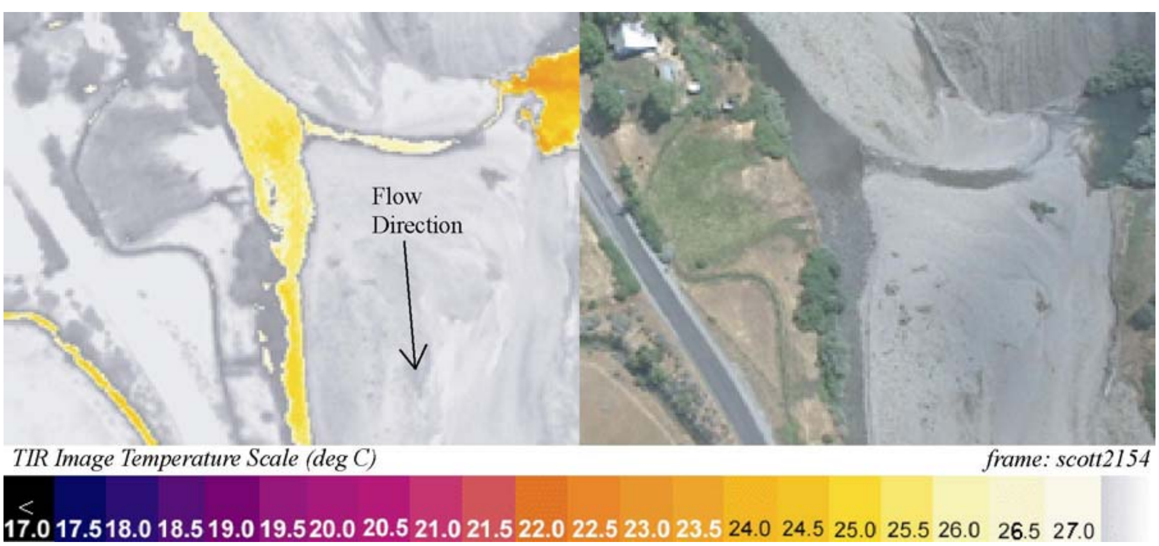
TIR/color video image pair showing a warm side channel on the left bank (bottom portion) and a spring/seep (21.4 ^{o}C) on the right bank (top portion) of the Scott River (23.4 ^{o}C) at river mile 51.0.



TIR/color video image pair showing a spring complex (C) (22.5 °C) on the left bank of the Scott River (24.1 °C). Cedar Gulch (B) can be seen on the left bank of the Scott River; however, because it's confluence with the Scott cannot be determined, it was not sampled. There is also a spring (A) (20.0 °C) on the left bank of the Scott upstream of Cedar Gulch, at river mile 52.0.

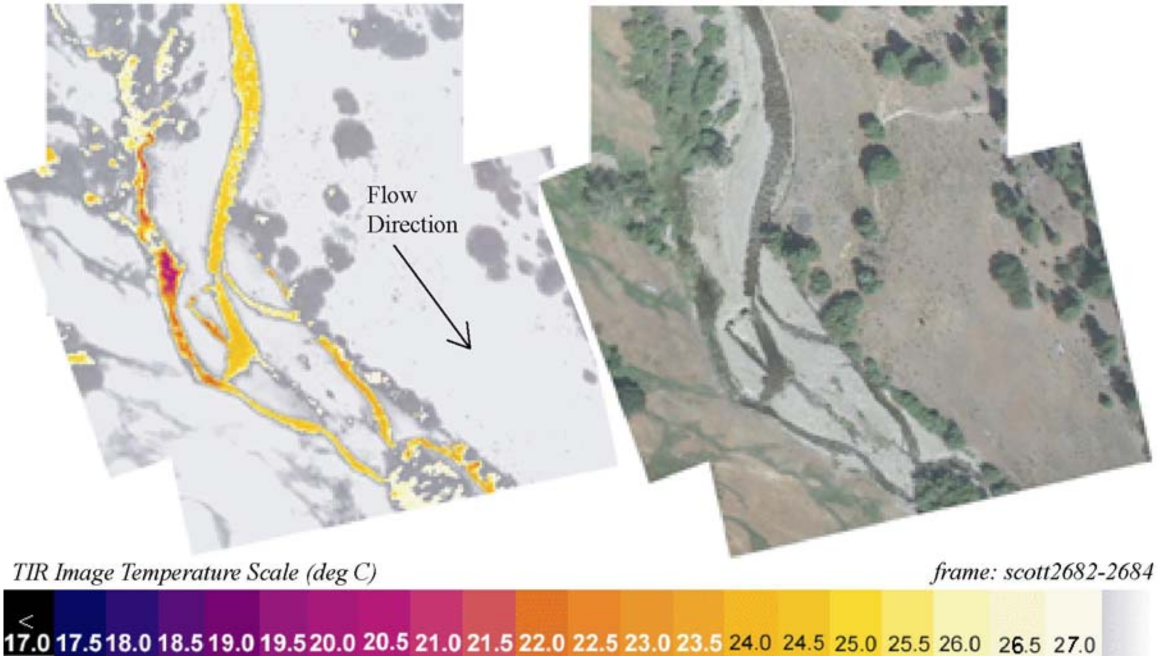


TIR/color video image pair showing a spring (20.1 ^{o}C) emerging from mine tailings along the left bank of the Scott River at river mile 52.3. As a result of this spring, the main stem temperature drops from 25.8 ^{o}C to 23.4 ^{o}C.

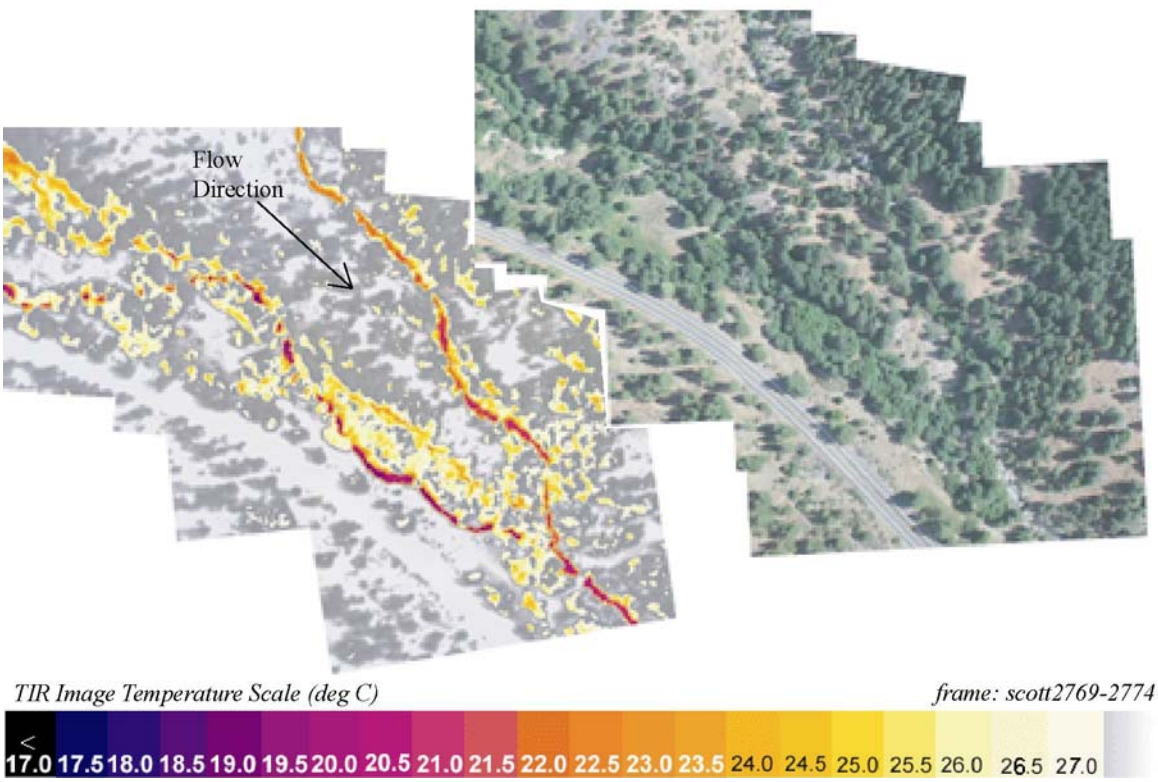


TIR/color video image pair showing cool surface water in the mine tailings near the Scott River (25.3 ^{o}C) at river mile 53.1.

East Fork Scott River

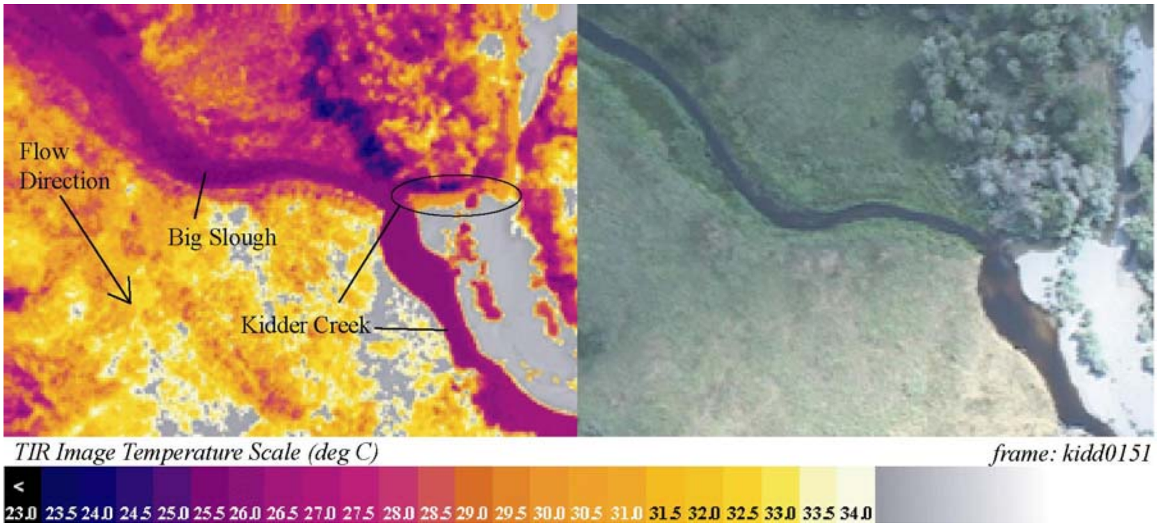


TIR/color video image pair showing a spring (21.6 °C) along the right bank of the EF Scott River (24.1 °C) at river mile 11.1.

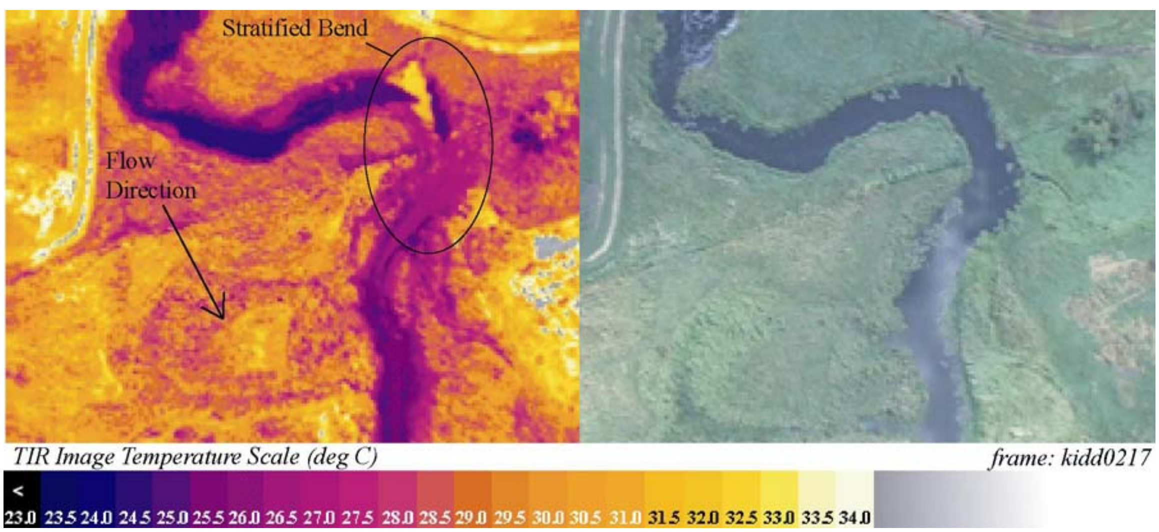


TIR/color video image pair showing Houston Creek (20.7 °C) on the left bank of the EF Scott River (18.7 °C) at river mile 13.9.

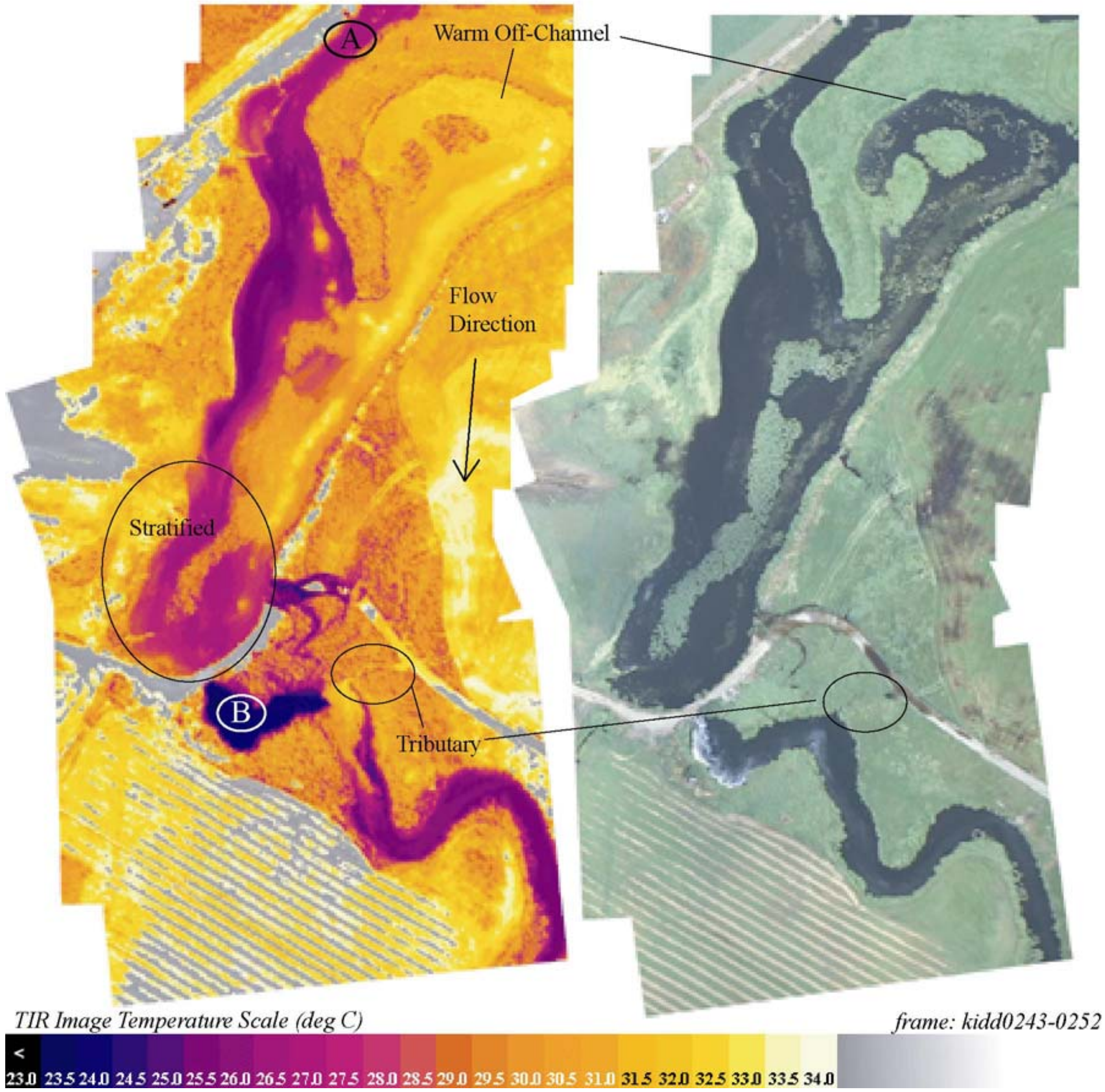
Kidder Creek/Big Slough



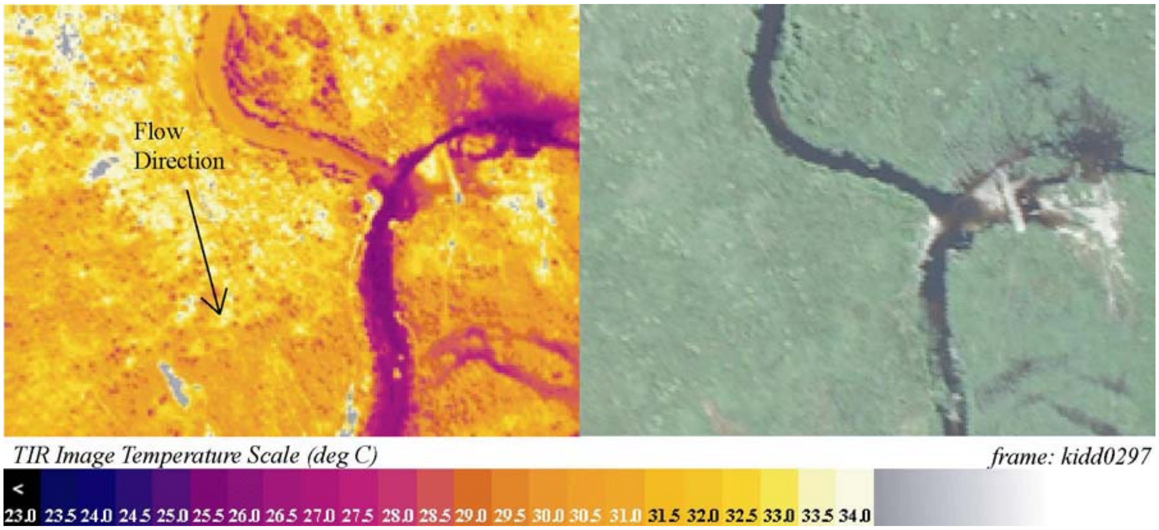
TIR/color video image pair showing the confluence of Big Slough (25.7^{o}C) and Kidder Creek (29.2^{o}C) at river mile 3.6 of Kidder Creek.



TIR/color video image pair showing a region of Big Slough (25.2^{o}C) at river mile 5.1. The surface temperature pattern around the bend indicates a thermally stratified condition.

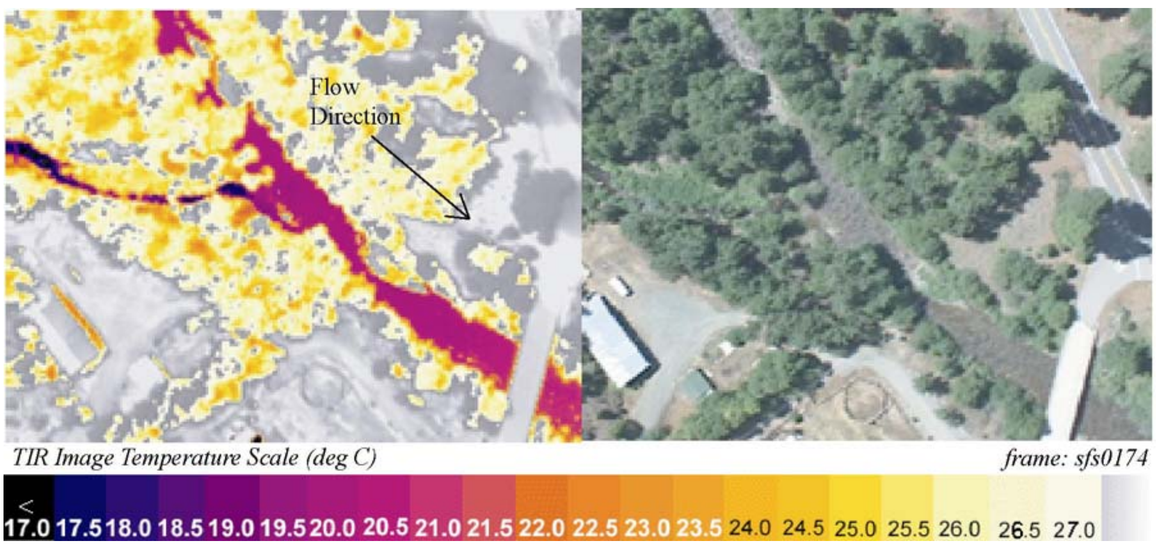


TIR/color video image pair showing a stratified stretch of Big Slough with an unnamed warm tributary (32.0°C) on the left bank, in the bottom half of the image. The temperature at point A is 25.4°C while the temperature directly downstream of the bridge (B) is 23.9°C (river mile 6.0).

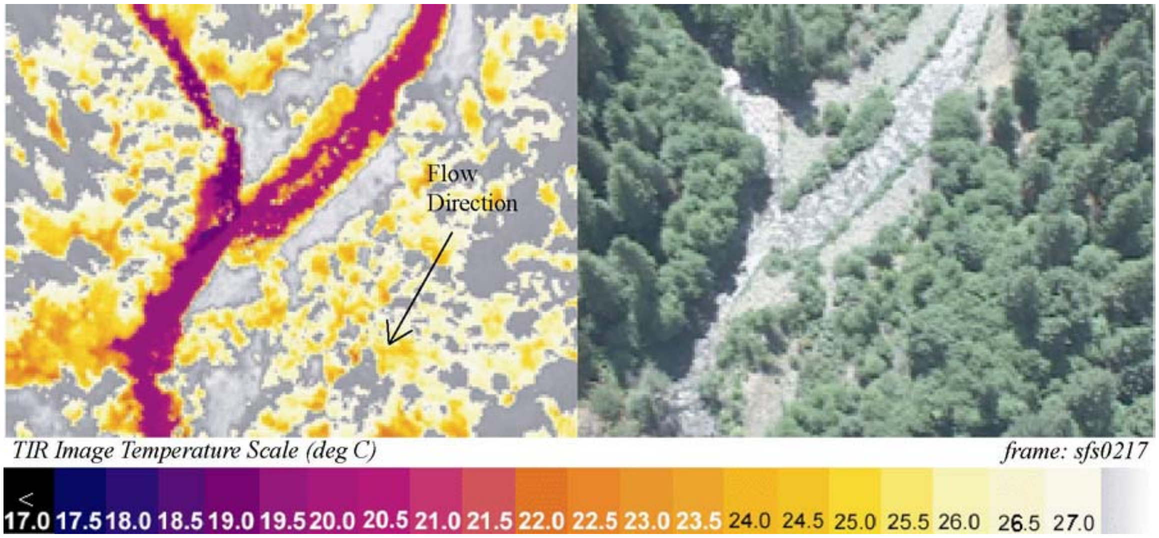


TIR/color video image pair showing a transition in Big Slough from a stratified state to a mixed condition moving downstream at river mile 7.5.

South Fork Scott River

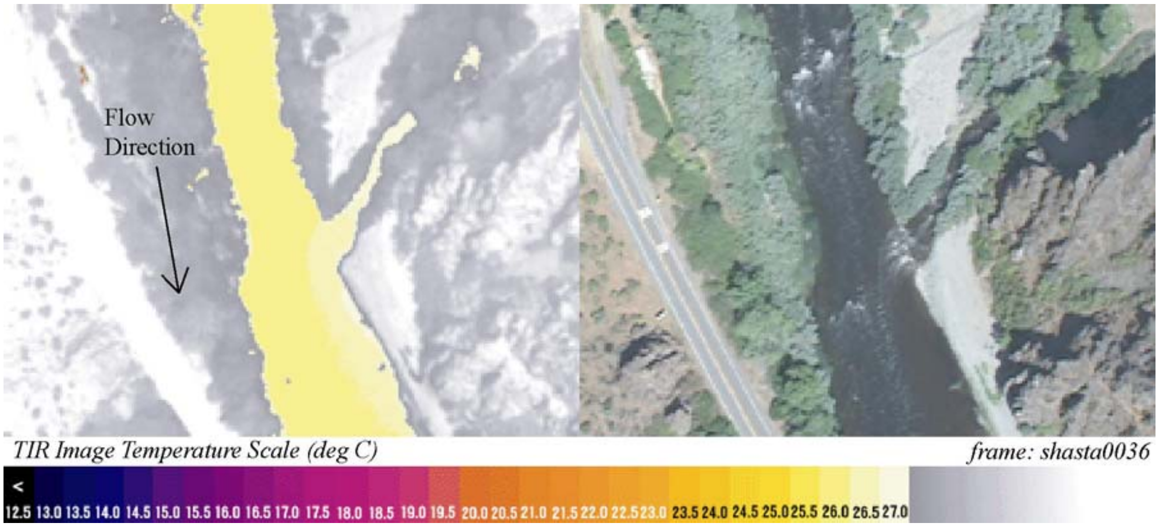


TIR/color video image pair showing a spring (17.0 ^{o}C) on the right bank of the SF Scott River (19.6 ^{o}C) at river mile 1.6.

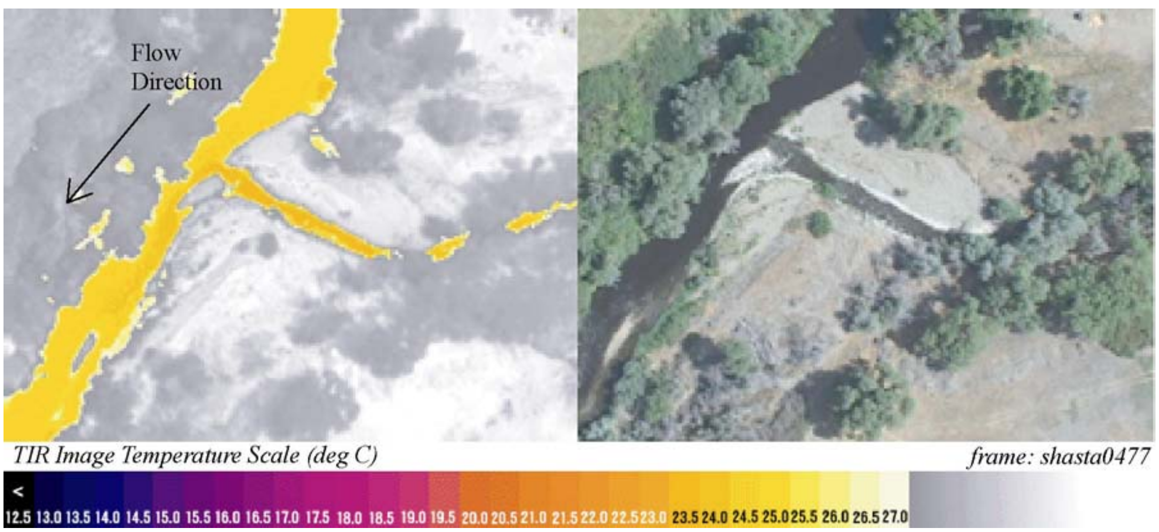


TIR/color video image pair showing the confluence of Boulder Creek (18.7 °C) on the right bank of the SF Scott River (19.6 °C) at river mile 2.3.

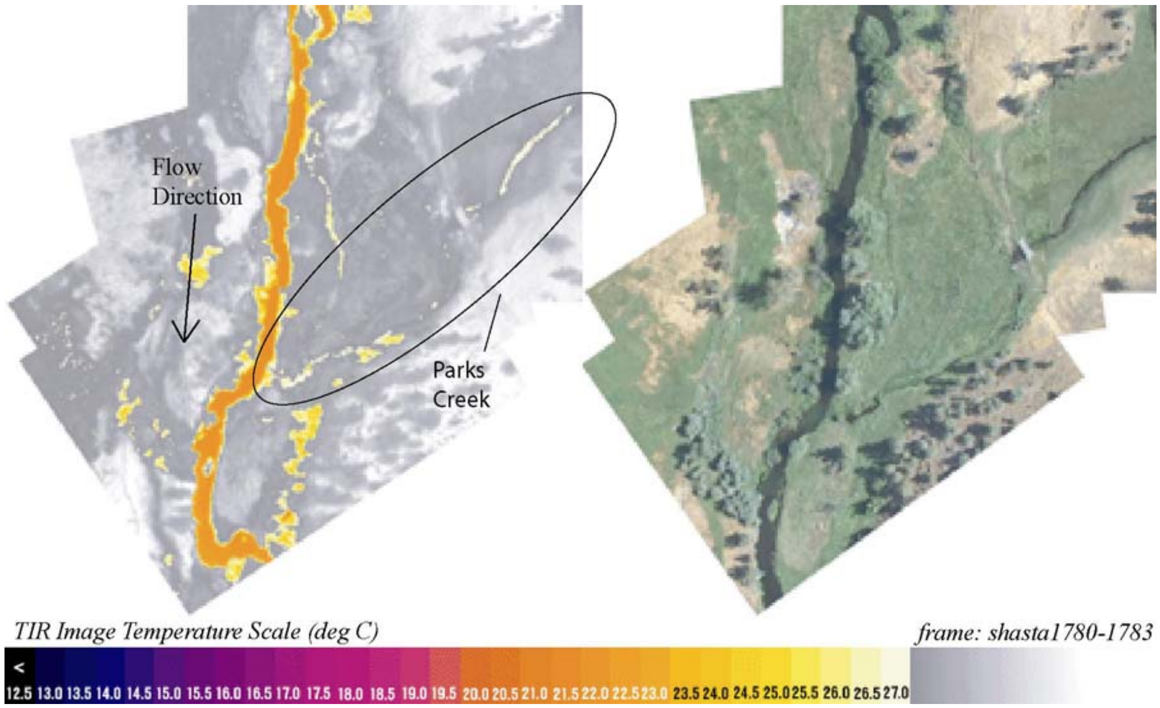
Shasta River



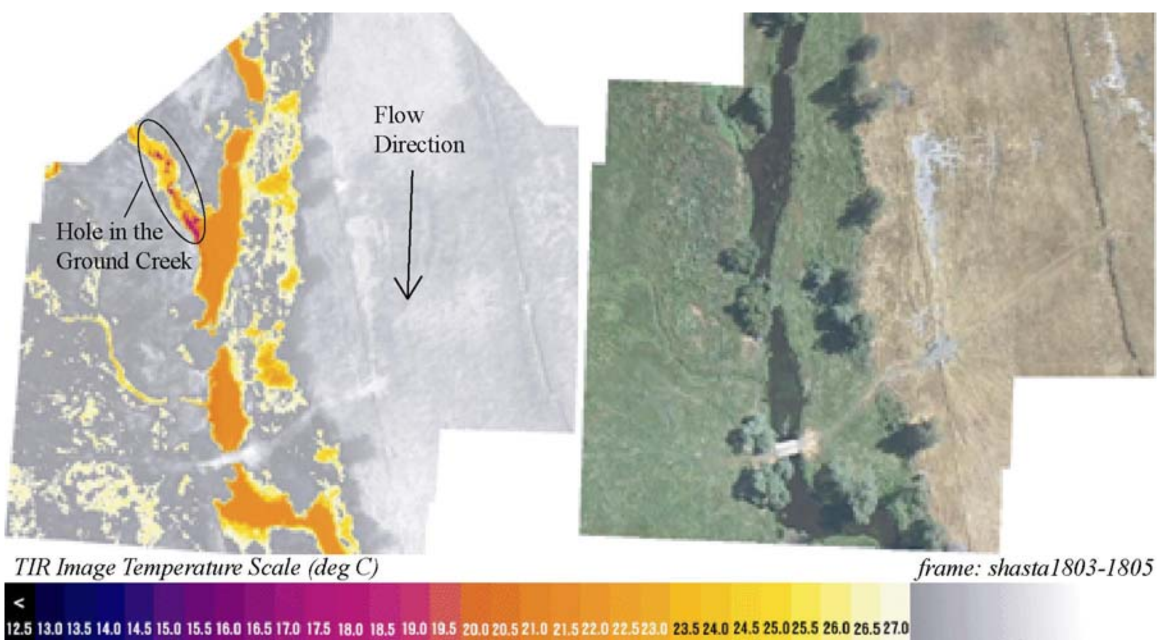
TIR/color video image pair showing the confluence of the Klamath River (25.8^{o}C) and the Shasta River (26.5^{o}C).



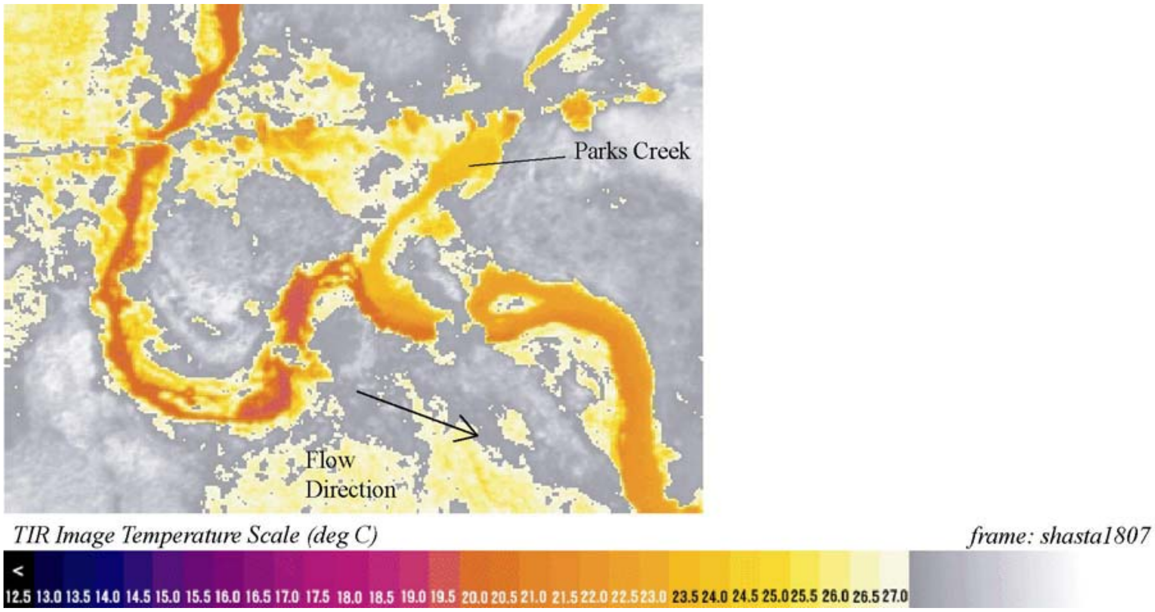
TIR/color video image pair showing Yreka Creek (23.4^{o}C) on the left bank of the Shasta River (24.2^{o}C) at river mile 7.8.



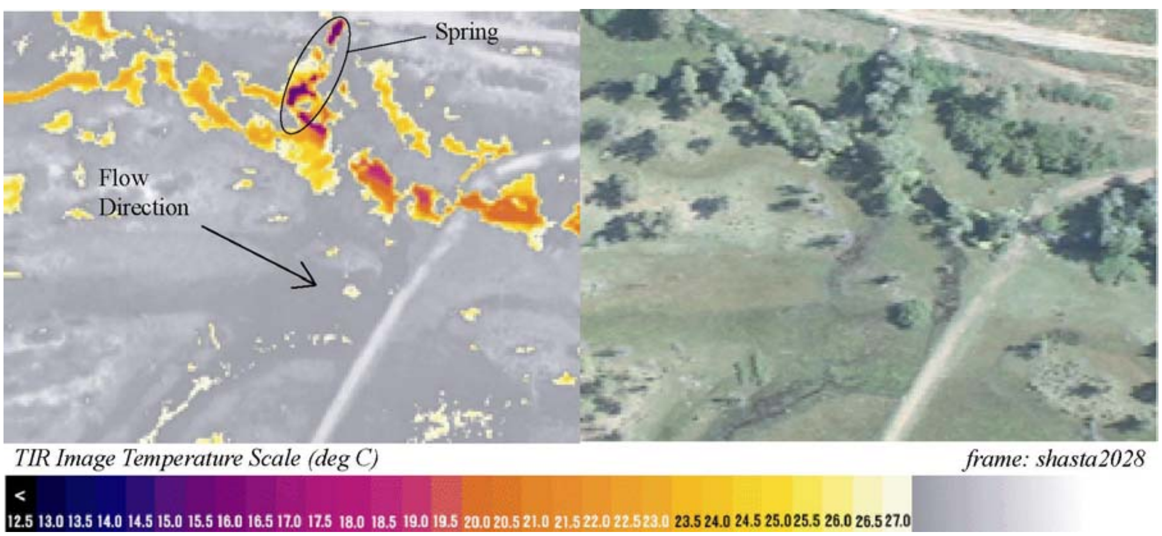
TIR/color video image pair showing the downstream confluence of Parks Creek (north channel) to the left bank of the Shasta River (21.7°C) at river mile 34.2. However, due to the lack of visibility at the mouth of Parks Creek, it was not sampled in this image.



TIR/color video image pair showing the confluence of Hole in the Ground Creek (17.3°C) to the right bank of the Shasta River (21.6°C) at river mile 34.7.

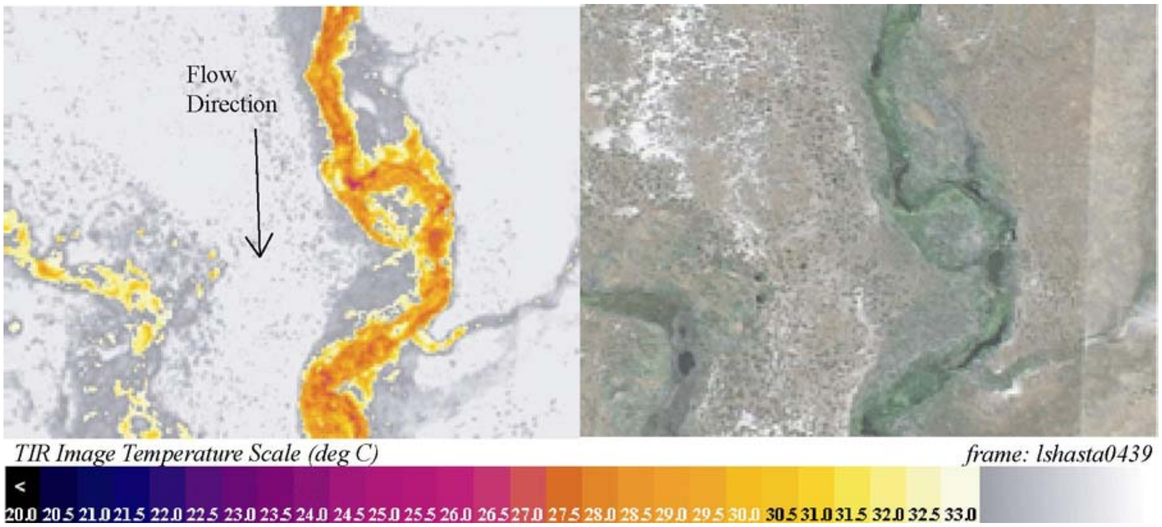


TIR/color video image pair showing the upstream confluence of Parks Creek (23.5°C) to the left bank of the Shasta River (21.6°C) at river mile 34.8.



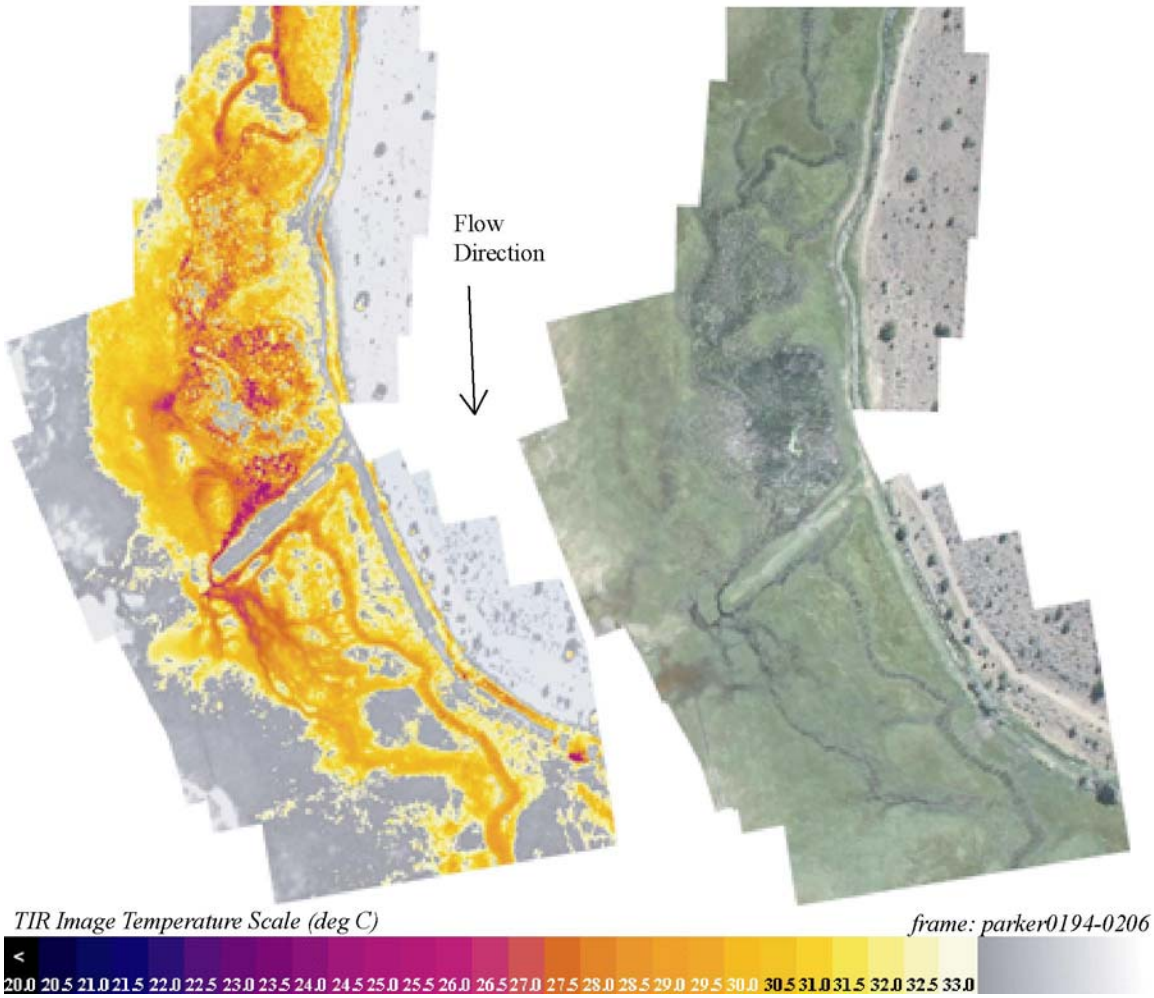
TIR/color video image pair showing a spring (14.8°C) on the left bank of the Shasta River (22.3°C) at river mile 39.3.

Little Shasta River

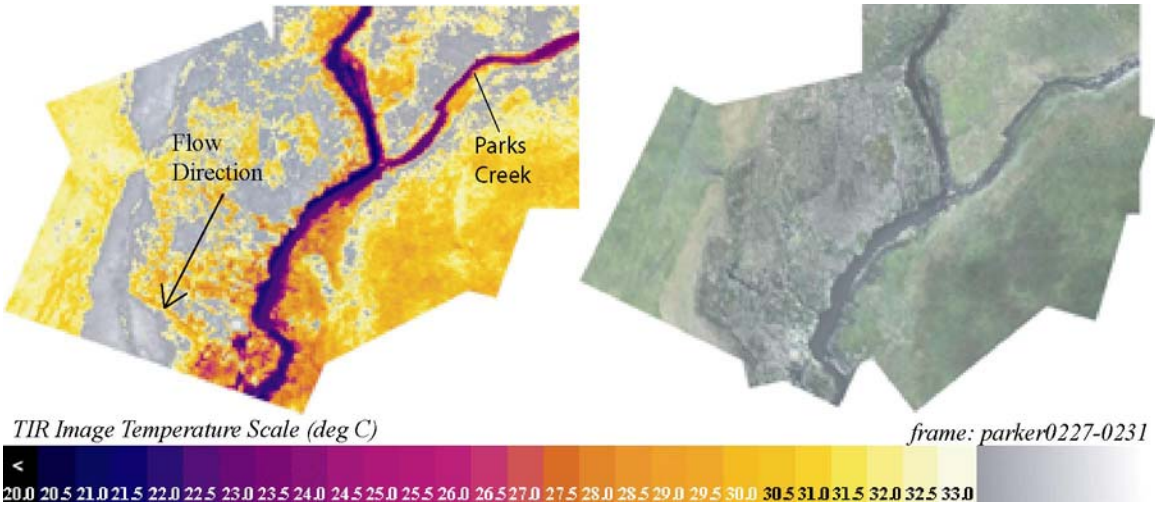


TIR/color video image pair showing a region of Little Shasta River at river mile 8.0 which is typical of the conditions of Little Shasta River through much of its length.

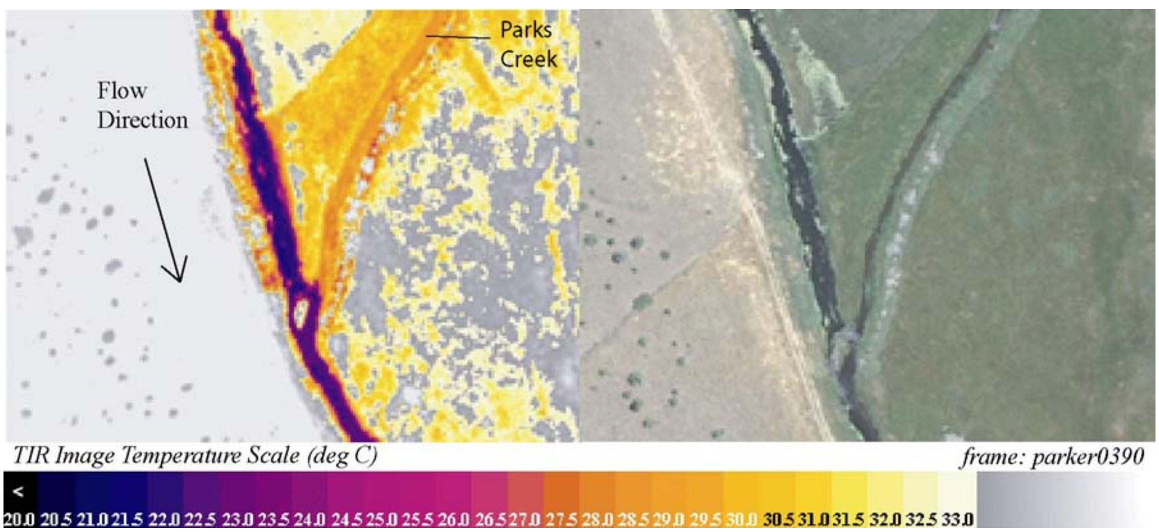
Parks Creek



TIR/color video image pair showing a largely undefined channel at river mile 2.2 of Parks Creek (26.7°C).



TIR/color video image pair showing an unnamed tributary (21.2°C) on the right bank of Parks Creek (22.7°C) at river mile 2.6.



TIR/color video image pair showing an unnamed tributary (21.6°C) on the right bank of Parks Creek (28.1°C) at river mile 5.5.