Airborne Thermal Infrared Remote Sensing
Eel River, CA

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Survey Date: August 11-12 2005
Draft Report Date: October 15, 2005

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Background

The Middle Main and Lower Eel River system in northern California is listed as impaired on California's 2002 303(d) list for sediment and temperature. In response to a consent degree, the US Environmental Protection Agency has initiated a series of studies to develop an understanding of the sources of these impairments and will use the results to calculate TMDLs for each system. The Middle Main Eel River is approximately 75 miles in length and is generally considered to be the area between the town of Dos Rios, CA and the confluence of the South Fork Eel River. The Lower Eel River (above the tidally influenced portion) is approximately 35 miles in length and is between the South Fork confluence and Fernbridge, CA.

Airborne thermal infrared (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. These data have provided the basis for assessing stream temperature dynamics on a number of rivers across the Western United States.

In 2005, Tetra Tech contracted with Watershed Sciences to provide TIR and true color digital imagery of the Lower and Middle Main Eel Rivers in support of the ongoing TMDL effort. The data were acquired on August 11 and 12, 2005 during the mid-afternoon hours (1:50 to 3:40 PM). The flight dates were determined in conjunction with the Tetra Tech project manager and were designed to capture heat of the day, heat of the summer thermal conditions in the river. Prior to the flight, Watershed Sciences' staff distributed in-stream data loggers (*Onset Stowaways and Tidbits*) in the river in order to provide a quantitative assessment of radiant temperature accuracy (Figure 1).

This report details the work performed, including methodology and quantitative assessments of data quality. In addition, the report presents the spatially continuous longitudinal temperature profiles derived from the imagery. These profiles provide a landscape scale perspective of how temperatures vary along the stream gradient and are the basis for follow-on analysis. Sample images are also contained in this document in order to illustrate some of the thermal features, channel characteristics, and hydrologic processes discussed in the report. The images are not meant to be comprehensive, but provide examples of image scenes and interpretations contained in the image database.

Survey Extent

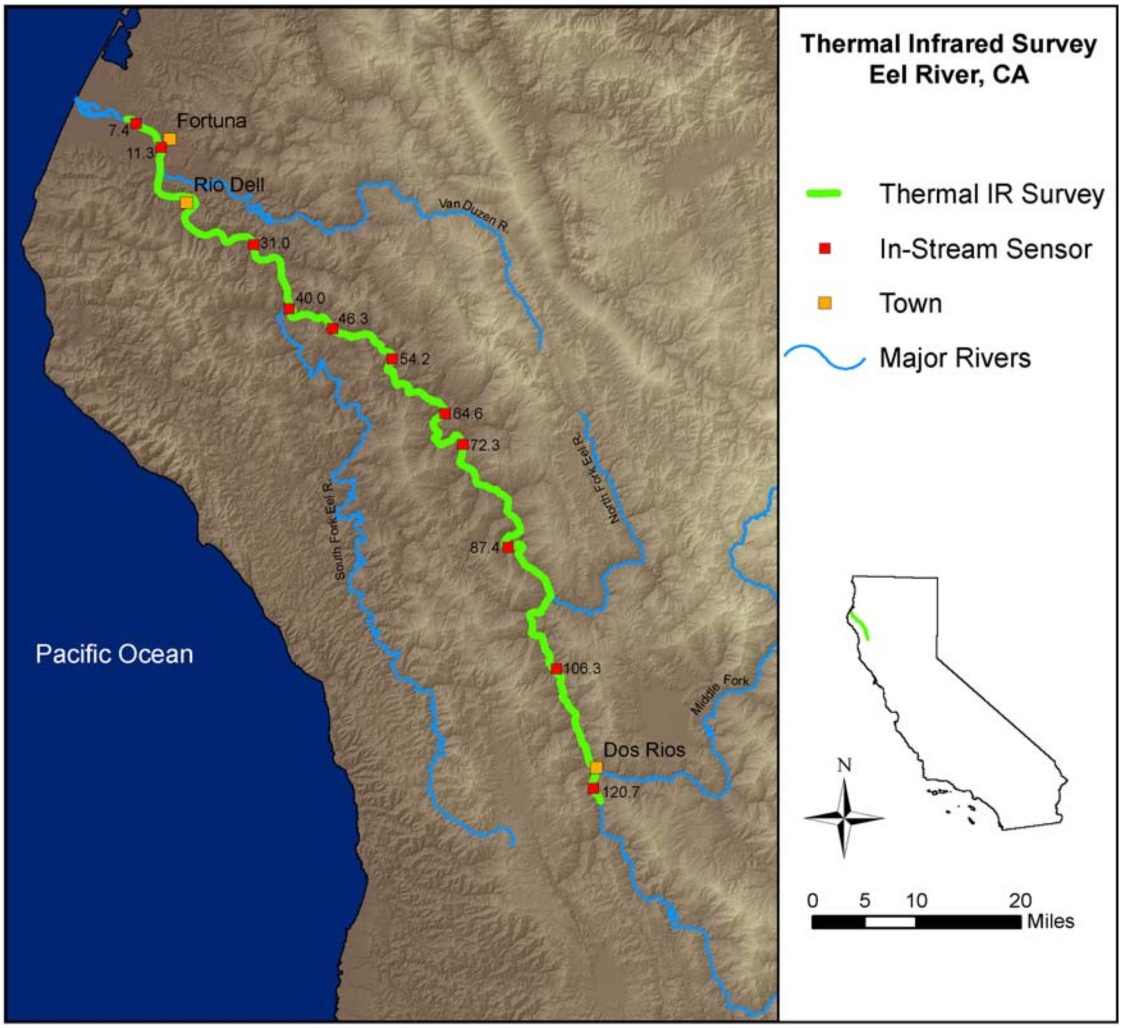


Figure 1 – Map showing the extent of the airborne thermal infrared survey on the Eel River on August 11-12, 2005. The map also shows the location of in-stream temperature monitors labeled by river mile.

Methods

Data Collection

<u>Instrumentation:</u> Images were collected with TIR (8-12μ) and true color digital cameras mounted on the underside of a helicopter (Figure 2). 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 as raw counts, which were than converted to radiance values. The individual images were referenced with time and position data provided by a global positioning system (GPS).

Figure 2 - Bell Jet Ranger equipped with a thermal infrared radiometer and high resolution digital camera. The sensors are contained in a composite fiber enclosure attached to the underside of the helicopter and flown longitudinally along the stream channel.

<u>Image Characteristics:</u> The flight plan was designed to capture the width of the active channel at a high spatial resolution. Images were collected sequentially with 40% or greater vertical overlap. The helicopter maintained a flight altitude of 1800 ft above ground level (AGL) between the town of Dos Rios and the confluence of the South Fork Eel River (mile 40.0), resulting in an image width of 351 meters (1152 ft) and a native pixel resolution of 0.55 meters (3.6 ft). An altitude of 2800 ft AGL was maintained between the South Fork Eel River and the town of Fernbridge (mile 7.3). This altitude resulted in an image width of 546 meters (1793 ft) and a native pixel resolution of 0.85 meters (5.6 ft).

<u>Ground Control</u>: Watershed Sciences deployed in-stream data loggers prior to the flight in order to ground truth (i.e. verify the accuracy of) the TIR data. The data loggers were placed at access points along the survey route (Figure 1). The distribution of the in-stream data loggers allowed for the monitoring of radiant temperatures at regular intervals over the extent of the survey. Meteorological data including air temperature and relative humidity were downloaded from a USFS Remote Automated Weather Station (RAWs) located in the Eel River Watershed (Lat: 40.1383, Long: -123.8236, Alt: 470 ft).

Data Processing

Calibration: The raw TIR images contain digital numbers that were converted to radiance values based on the response characteristics of the sensor. These measured radiance values were then adjusted using a version of the radiation transfer equation (listed below). The path length attenuation was calculated empirically by comparing the measured radiance to the calculated radiance at each ground truth location. Given the high emissivity of water, the reflection term $I(T_{reflect})$ was very low and dropped from the equation. 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.

$$I(T_{measured}) = I(T_{object}) * \varepsilon * \tau + I(T_{reflect}) * (1- \varepsilon) * \tau$$

I(Tmeasured)	=measured radiance
I(Tobject)	= radiance emitted at the water surface at given temperature
I(Tatmosphere)	= radiance emitted by the intervening atmosphere
I(Treflected)	= radiance reflected by surrounding objects
ε	= emissivity of water
τ	= path length attenuation

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 temperatures of detectable surface inflows (i.e. surface springs, tributaries) were also sampled at their mouth. During sampling, the analyst provided interpretations of the spatial variations in surface temperatures observed in the images.

Geo-referencing: The images are tagged with a GPS position at the time they are acquired. Since the TIR camera is maintained at vertical down-look angles, the geographic coordinates provide an accurate index to the location of the image scene. In order to provide further spatial reference, the TIR images were assigned a river mile based on a routed stream layer (Figure 3).

Temperature Profiles: The median temperatures for 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

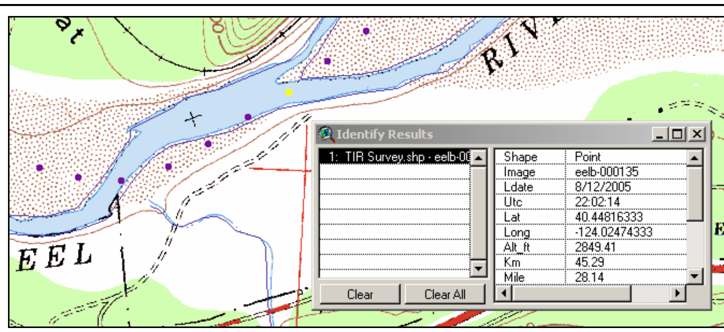


Figure 3 –Each point on the map represents a thermal image location. The inset box shows the information recorded with each image point during acquisition. The point coverage is the basis for follow-on analysis.

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.

Geo-Rectification: The TIR images were geo-rectified to real world coordinates using the most recently available digital orthophoto quads (DOQs). The true color digital images were initially oriented using the position and directional information collected on the aircraft. Individual frames were then geo-rectified manually by finding a minimum of three common ground control points (GCP's) between the true color images and the DOQs. An emphasis was placed on finding control points in or near the river channel, with no points in the upland areas. Control points included fixed features such as large boulders and bed rock outcrops. The images were then warped using a 1st order polynomial transformation. TIR images were geo-rectified using the same general methodology with the true color images used as the control layer.

Wetted-Width Calculations:

Wetted width estimates were made at 500 meter intervals using a semi-automated process based on the geo-rectified TIR images. Once rectified, the TIR images were mosaicked to form a continuous thermal image over the full survey extent. This mosaic was then reclassified into water and not-water pixel values based on the observed range of water temperatures. This image was then converted to a GIS data layer and manually edited so that the layer represented the edge of the water and major islands. A custom GIS extension was then used to calculate the length perpendicular to the aspect of the centerline to each edge (Figure 4).

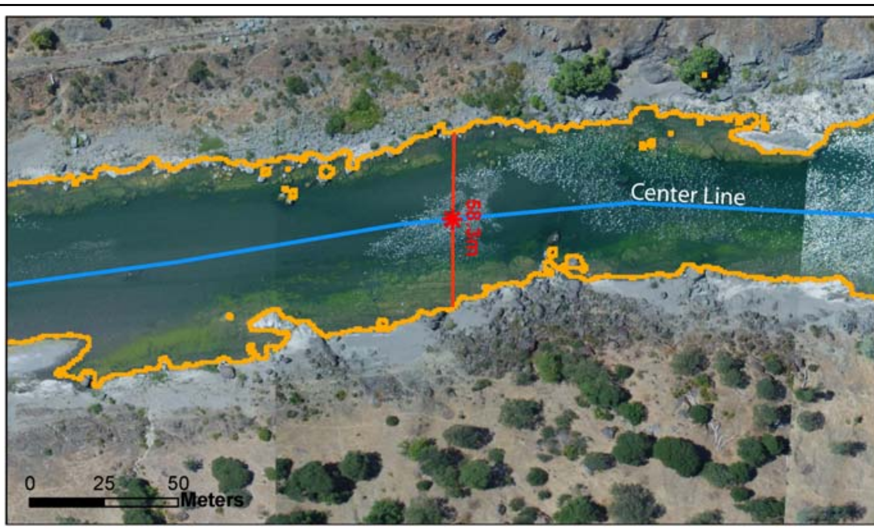


Figure 4 – General method for calculating wetted width by extending a perpendicular line (red) from the node point to the digitize stream edge (orange line).

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. Occurrences of thermal stratification interpreted during analysis are identified in the results section for each survey.

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 (Torgersen et al. 2001[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. Shape and magnitude distinguish spatial temperature patterns caused by tributary or spring inflows from those resulting from differential surface heating. Unlike with thermal stratification, surface temperatures may still represent bulk water conditions if the stream is mixed.

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 was not an issue when sampling radiant temperatures on the main stem Eel River, but is a consideration when sampling the radiant temperatures at tributary mouths. In some cases, small tributaries

[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.

were detected in the images, but not sampled due to the inability to obtain a reliable temperature sample.

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 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. The method used to select a color map for the report images attempts to accomplish both. The map is based on using discrete colors to represent the range of water temperatures observed during the analysis, based on 1^{o}C or 0.5^{o}C increments and a linear gray scale to represent temperatures above the maximum observed water temperature. Figure 5 provides an example of three different color maps applied to the same thermal image.

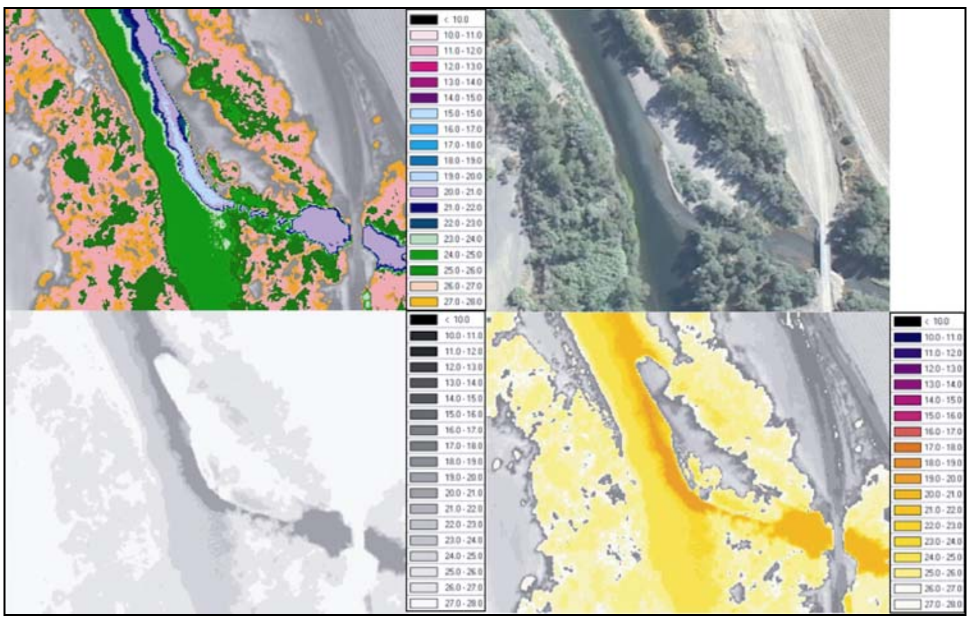


Figure 5 - Example of different color maps applied to the same TIR image.

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. A calibration is performed on the ground, which provides a uniformity correction. However, due to lens distortion and variable transmission effects, slight radiometric differences can exist between the center and edge of the images. These differences are typically small, with resulting temperature variations ranging from 0.2 to 0.4^{o}C. These differences are not normally an issue, but are noticeable when multiple frames are mosaicked.

Results

Weather Conditions

Weather conditions recorded at the Eel Camp RAWs stations during the dates of the survey.

Time	Air Temp °F	Air Temp °C	Dew Point °F	RH %
August 11, 2005				
12:45	91	32.8	52.6	29
13:45	95	35.0	44.8	18
14:45	96	35.6	35.2	12
15:45	95	35.0	32.2	11
16:45	96	35.6	33.0	11
August 12, 2005				
12:45	92	33.3	51.1	25
13:45	95	35.0	32.2	11
14:45	94	34.4	31.5	11
15:45	93	33.9	32.9	12
16:45	95	35.0	29.9	10

Weather conditions were considered ideal with clear skies, air temperatures in the mid 90's (°F), low humidity, and calm winds.

Thermal Accuracy

Table 1 summarizes a comparison between the kinetic temperatures recorded by the in-stream data loggers and the radiant temperatures derived from the TIR images. The average absolute temperature accuracies were within the desired accuracy of ±0.5°C. The range of temperature differences was generally consistent with those observed during other surveys conducted over the past six years. At two sites, mile 87.5 and 46.3, radiant temperatures were 0.8°C and 0.9°C cooler than the measured in-stream temperatures. The factors contributing to the larger differences were not apparent from the imagery.

Table 1 - Comparison of in-stream (kinetic) temperatures and radiant temperatures derived from the TIR imagery.

Image Frame	**Mile**	**Time 24 hr**	**Kinetic °C**	**Radiant °C**	**Difference °C**
11-Aug-05 (avg. abs. difference = 0.4°C)					
eela-000028	120.7	13:50	25.6	25.5	0.1
eela-000290	106.3	14:08	26.4	26.6	-0.1
eela-000633	87.5	14:31	27.7	26.9	0.8
eela-000922	72.3	14:50	27.4	27.3	0.1
eela-001069	64.6	15:00	27.3	27.4	-0.1
eela-001305	54.2	15:16	26.8	26.2	0.6
eela-001487	46.3	15:28	26.1	25.2	0.9
eela-001623	40.0	15:37	24.1	24.5	-0.3
12-Aug-05 (avg. abs. difference = 0.2°C)					
eelb-000011	40.0	14:51	23.6	23.9	-0.3
eelb-000105	31.0	14:59	24.0	23.7	0.3
eelb-000314	11.3	15:18	23.0	22.8	0.2
eelb-000361	7.4	15:22	23.1	23.3	-0.1

Longitudinal Temperature Profile

Median sampled temperatures were plotted versus river mile for the Eel River from mile 122.5 (upstream of the town of Dos Rios) to the town of Fernbridge (mile 7.3) (Figure 6). Tributaries and other sampled inflows (i.e. springs/seeps, irrigation returns) are labeled on the profile by river mile and summarized in the associated table (Tables 2 and 3).

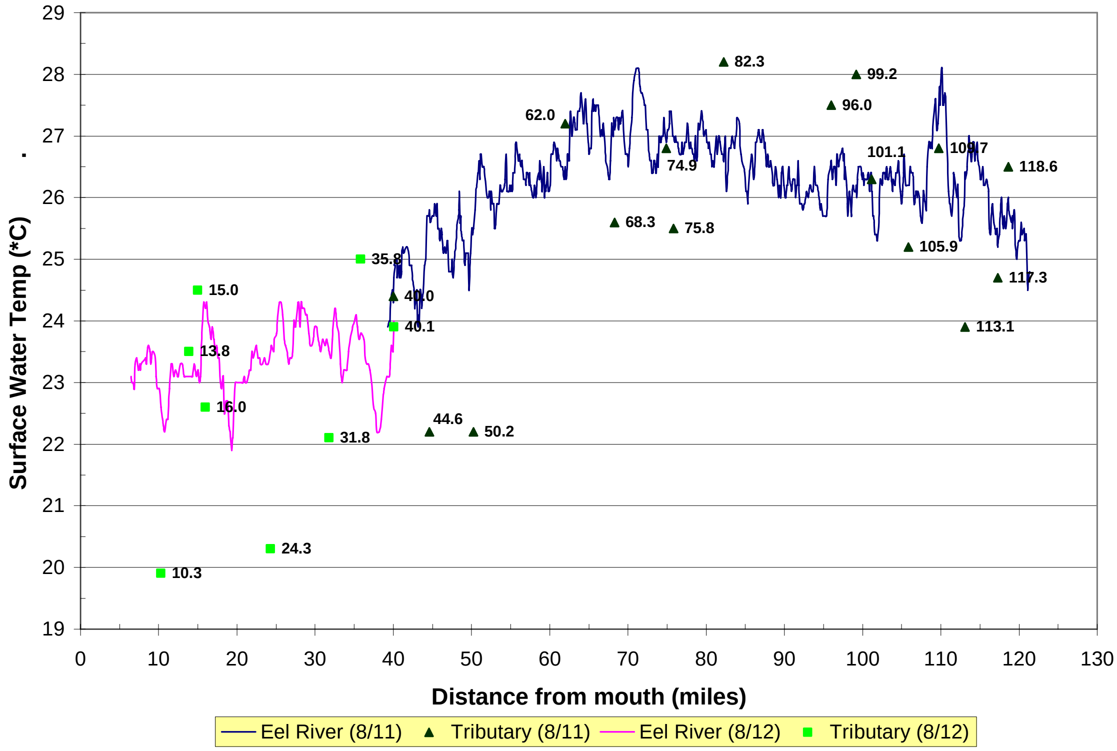


Figure 6 - Median sampled temperatures plotted versus river mile for the Eel River. Tributaries and other sampled inflows (i.e. springs/seeps, irrigation returns) are labeled on the profile by river mile

Table 2 – Location and radiant temperature of tributaries sampled between Dos Rios and the South Fork Eel River from the August 11 survey.

Tributary Name	Image	km	mile	Tributary	Eel River	Difference
Middle Fork Eel R. (RB)	eela-000067	190.9	118.6	26.5	26.0	0.5
Burger Cr. (LB)	eela-000089	188.8	117.3	24.7	25.2	-0.5
Woodman Cr. (LB)	eela-000166	182.0	113.1	23.9	26.4	-2.5
Shell Rock Cr. (LB)	eela-000298	170.4	105.9	25.2	26.2	-1.0
Blue Rock Cr. (LB)	eela-000387	162.8	101.1	26.3	26.1	0.2
Bell Springs Cr. (LB)	eela-000427	159.6	99.2	28.0	26.2	1.8
North Fork Eel Cr. (RB)	eela-000483	154.5	96.0	27.5	26.6	0.9
Chamise Creek (LB)	eela-000730	132.4	82.3	28.2	26.6	1.6
Ticknor Cr (RB)	eela-000855	122.0	75.8	25.5	27.0	-1.5
Jewett Cr. (LB)	eela-000874	120.6	74.9	26.8	26.9	-0.1
Steelhead Creek (LB)	eela-000991	109.9	68.3	25.6	27.1	-1.5
Dobbyn Creek (RB)	eela-001145	99.8	62.0	27.2	26.5	0.7
Cameron Creek (RB)	eela-001384	80.9	50.2	22.2	25.5	-3.3
Kapple Creek (RB)	eela-001519	71.8	44.6	22.2	25.8	-3.6
South Fork Eel R. (LB)	eela-001623	64.4	40.0	24.4	24.3	0.1

Table 3 - Location and radiant temperature of tributaries sampled between the South Fork Eel River and the town of Fernbridge.

Tributary Name	Image	km	mile	Tributary °C	Eel River °C	Difference °C
South Fork Eel River (LB)	eelb-000010	64.5	40.1	23.9	24.0	-0.1
Larabee Cr. (RB)	eelb-000057	57.6	35.8	25.0	23.8	1.2
Bear Creek (LB)	eelb-000097	51.1	31.8	22.1	23.5	-1.4
Dinner Creek (LB)	eelb-000174	39.1	24.3	20.3	23.5	-3.2
Howe Creek (LB)	eelb-000263	25.7	16.0	22.6	24.2	-1.6
Price Creek (LB)	eelb-000276	24.1	15.0	24.5	23.2	1.3
Van Duzen River (RB)	eelb-000290	22.3	13.8	23.5	23.1	0.4
Rohner Creek (RB)	eelb-000325	16.6	10.3	19.9	22.6	-2.7

Observations and Analysis

Middle Main Eel River (Dos Rios to South Fork)

Radiant water temperatures in the Middle Main Eel River ranged from 23.9°C to 28.2°C over the 82-mile survey extent (Figure 7). A total of 15 tributaries were sampled during the analysis, of which 7 contributed cooler water to the main stem. A number of other tributaries were detected, but were too small (*relative to pixel size*) to obtain an accurate temperature sample. In some cases, surface flow was detected within the tributary channel, but disappeared in the alluvial floodplain prior to reaching the active channel.

Over the extent of the survey, stream temperatures exhibited a relatively high degree of local variability, with temperatures shifts of 0.7-2.0°C often observed within distances of less than one mile. Sampled tributary locations correlated with decreases in water temperatures. This was particularly apparent with some of the cooler tributaries such as Woodsman Creek (mile 113.1), Steelhead Creek (mile 68.3), Cameron Creek (mile 50.2), and Kapple Creek (mile 44.6). However, these tributary inflows did not result in strong or extended mixing plumes, which might suggest an immediate thermal response from the surface flow. Conversely, water temperature decreases were also observed downstream of tributaries that had radiant temperatures which were warmer than, or consistent with (*i.e. within 0.5°C*), the main stem. For example, the North Fork (mile 96.0) contributed water that was 0.9°C warmer than the main stem at the time of the survey, but a 0.8°C decrease was observed immediately downstream of the confluence.

Localized cooling is typically the result of mass transfer either through sub-surface discharge or through surface inflows. The thermal response downstream of tributary junctions (both warmer and cooler) suggests that tributary channels are conduits for sub-surface flow which are cooling sources to the Eel River. The detection of tributaries that disappeared as they entered the alluvial floodplain support the idea that the shallow, subsurface flow through the large alluvial deposits that are common in the river contributed to the local thermal variability observed throughout the river. The detection of small seeps at the downstream end of some gravel bars further supports this assertion.

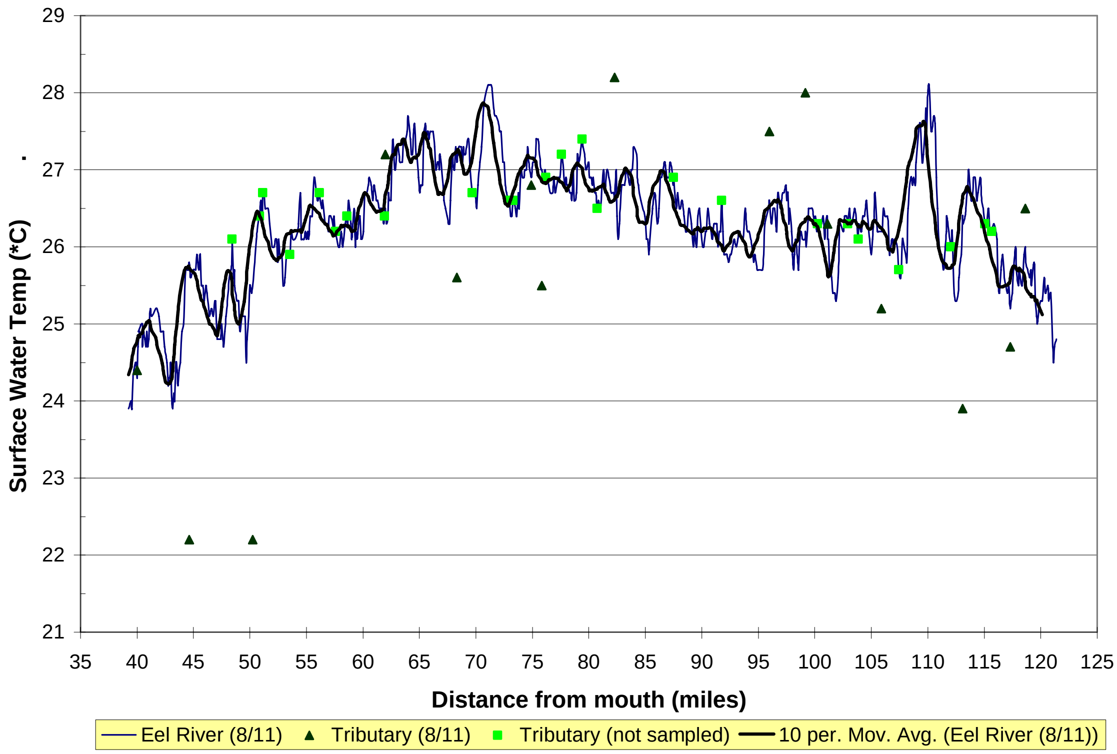


Figure 7 - Longitudinal profile with both sampled and detected (not sampled) tributaries along Middle Main Eel River. The plot also shows a moving average trend line derived from the sampled data.

Inspection of the longitudinal profile shows two prominent spikes between miles 110.8-108.3 and miles 72.2-70.5 where radiant temperatures reached maximums of greater than 28^{o}C. Inspection of the TIR imagery did not show any evidence of thermal stratification or other artifacts of remote sensing that would account for these gains. Such rapid longitudinal heating is often observed in smaller streams where surface flow is lost (*e.g. withdrawal or to the sub-surface*) or in the absence of a buffering source (*e.g. hyporheic discharge*). Review of the imagery between river mile 110.8 and 108.3 shows small seeps along a gravel bar (mile 110.3) and cooler water from a side channel at mile 109.7. The spatial temperature pattern at these locations suggest that surface flow is lost, resulting in a lower surface flow volume and increased downstream heating followed by discharge back into the channel and subsequent cooling.

In order to highlight reach scale patterns, a trend line (10-sample moving average) was generated from the sample points (Figure 7). The trend line shows that in addition to the local variability, general temperature patterns were also observed in the Middle Main Eel River. At the upstream end of the survey near Dos Rios, water temperatures were ~25.0^{o}C and showed a general warming trend, reaching ~27.4^{o}C at mile 62.7. Moving downstream, water temperatures exhibited a general cooling trend reaching ~24.3^{o}C at the South Fork confluence. The reason for this cooling trend was not directly apparent from the imagery. However, this trend has been observed on other coastal streams in Northern California (*Redwood Creek, Mattole River*). The trend is presumably due to morning fog and generally cooler air temperatures as the river moves closer to the coast.

Lower Main Eel River (South Fork to Fernbridge)

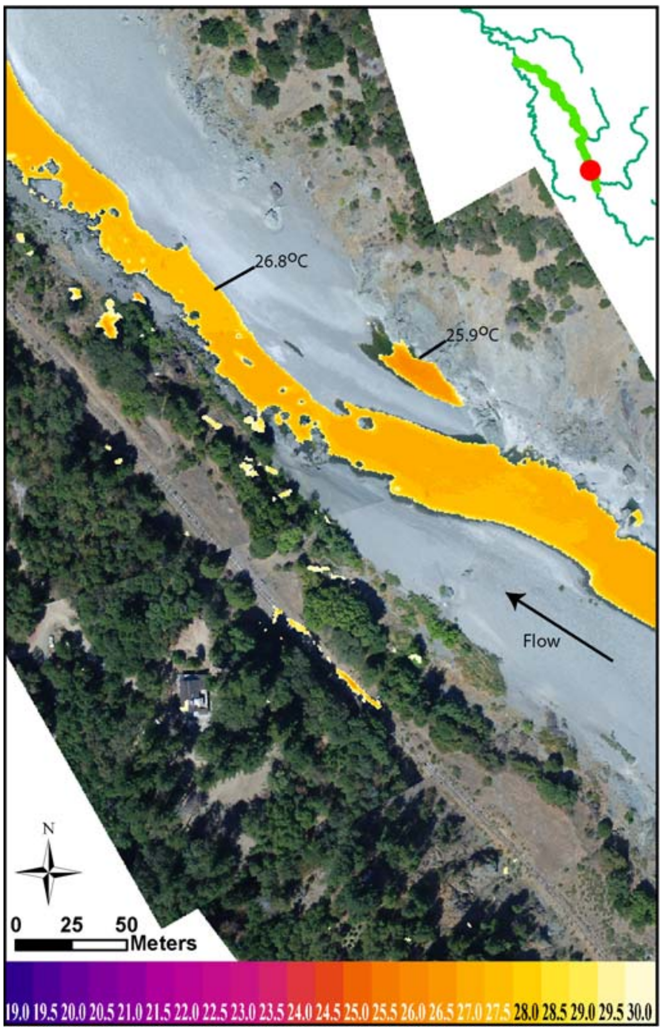
The Lower Main Eel River was flown earlier in the day than the Middle Main Eel River, resulting in slightly cooler temperatures at the South Fork confluence. Radiant water temperatures in the South Fork were similar to those observed in the main stem with a decrease in water temperatures of ~1.7^{o}C occurring between the South Fork confluence and mile 37.9. Inspection of the TIR imagery shows cooler surface water parallel to the large gravel bar downstream of the South Fork confluence. Seven other tributaries were sampled in the lower river. Of these, four contributed water that was cooler than the main stem.

Radiant water temperatures in the lower river were generally cooler than the middle main, with water temperatures ranging from 21.9^{o}C to 24.3^{o}C. However, like the middle main, the lower river continued to exhibit a relatively high degree of local variability. The overall cooler water temperatures were presumably due to the proximity to the coast where cooler air temperatures and morning fog buffered heating processes. The cooler overall thermal conditions were exemplified in the imagery where terrestrial vegetation was often cooler than the in-stream water temperatures.

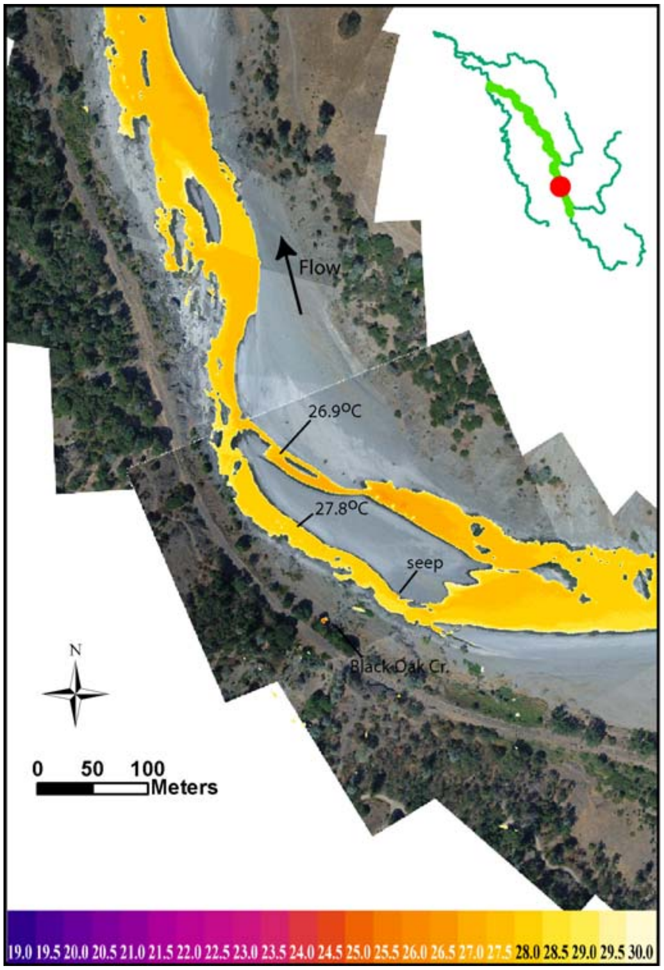
Water temperatures exhibited some local variability between mile 37.9 and mile 25.4, before decreasing to 21.9^{o}C at mile 19.4. Water temperatures increased steadily again between mile 19.4 and 15.7, reaching a local maximum of 24.3^{o}C. A sharp decrease in main stem temperatures was observed downstream of the confluence of Howe Creek at mile 16.0. A subsequent decrease in main stem temperatures was observed between miles 11.6 and 10.5. The potential sources of cooling at these locations were not directly apparent from the imagery.

Selected Images

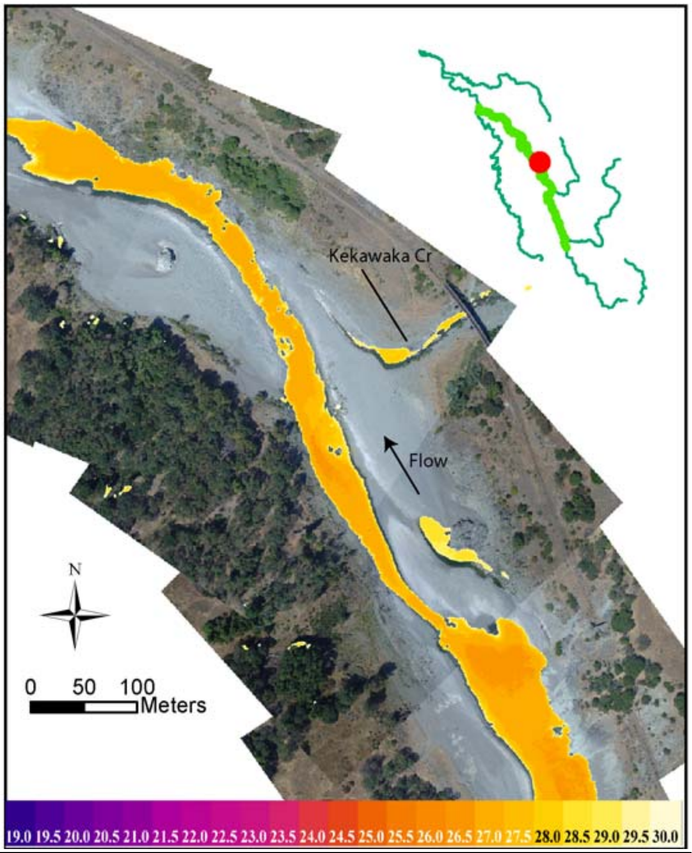
The following pages contain examples of imagery that show features and processes discussed in the previous section. Radiant water temperatures in the TIR images are color coded with the scale displayed on the bottom. The TIR images are displayed over the true color digital images. Values above the maximum observed water temperatures are transparent.



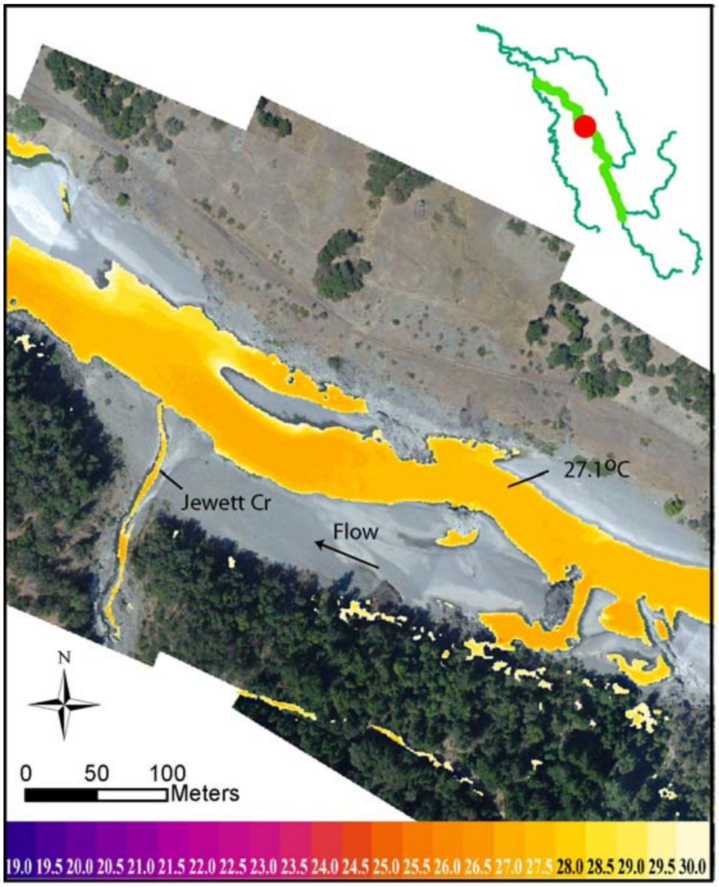
<u>Eeala-000156; mile 113.6</u>: Isolated pools off the main channel were common in the Eel River. This pool off the right bank has a surface temperature that is cooler (25.9°C) than those in the main channel (26.8°C). The cooler water within the floodplain suggests flow within the hyporheic zone and a potential local cooling source for the river.



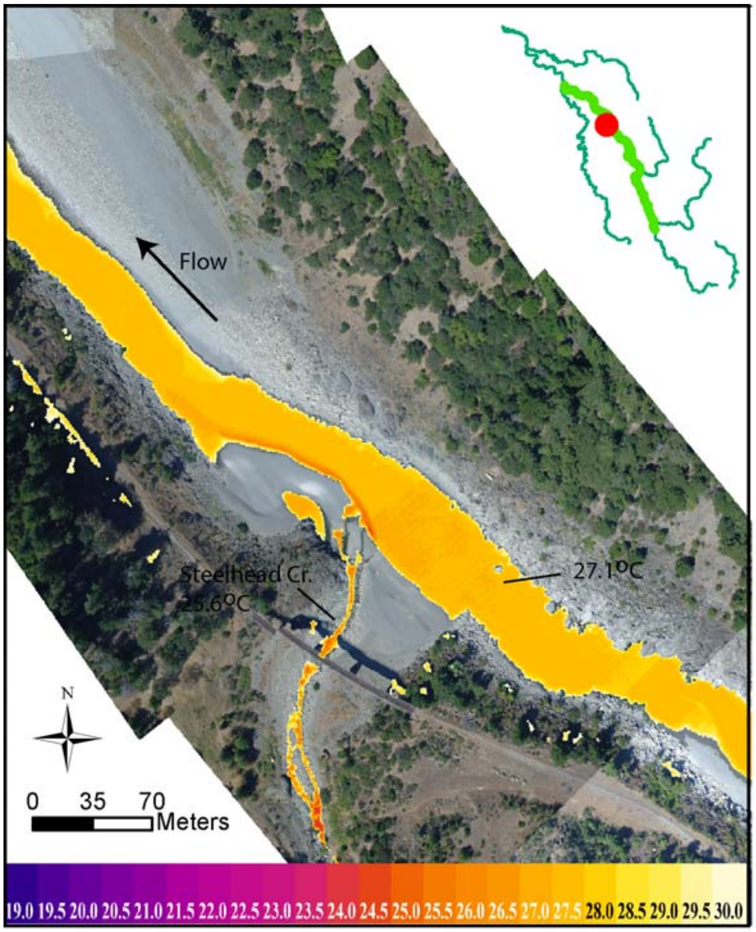
<u>Eela-000224-226; mile 109.8</u>: The image above shows a split channel in the Eel River. The radiant temperature of the left channel is 27.8°C while the right channel is 26.9°C. A thermal mixing plume is evident at the downstream end of the split. An apparent seep is also visible on the inside of the left channel. Black Oak Creek enters the left channel near the top of the gravel bar; however, the stream surface was not sufficiently visible to obtain a temperature sample.



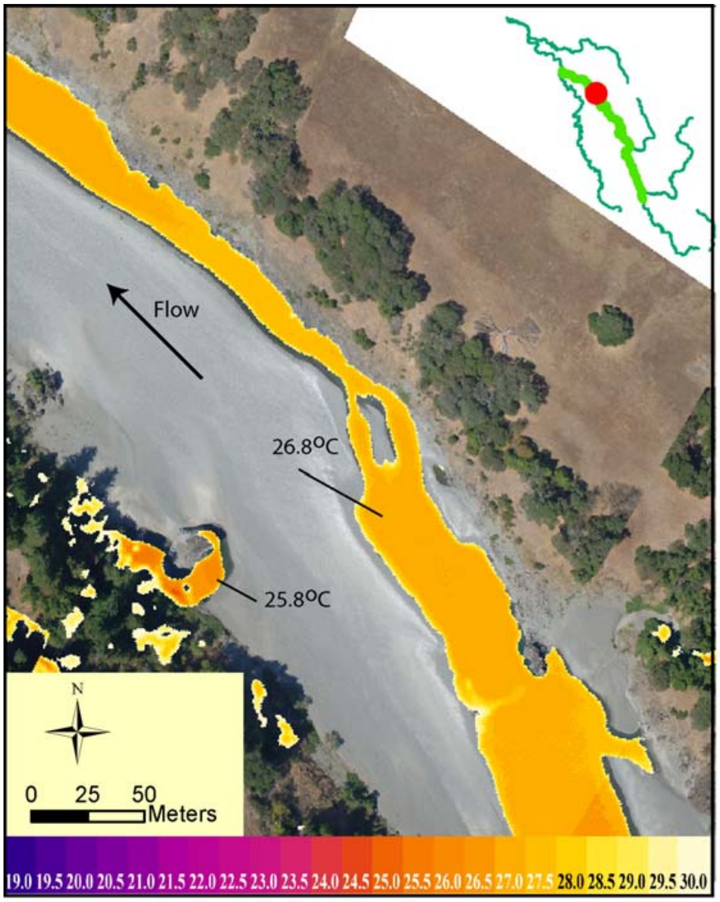
Eela-000756-757; mile 80.7: The image above shows the confluence of the Eel River (26.5°C) and Kekawaka Creek. Surface flow is visible in Kekawaka Creek near the bridge and on the right side of the floodplain but disappears prior to entering the main channel. This was common on many of the tributaries to the Middle Main Eel River. Local cooling near the mouths of several tributaries suggests that flows from these creeks are reaching the main channel through sub-surface pathways.



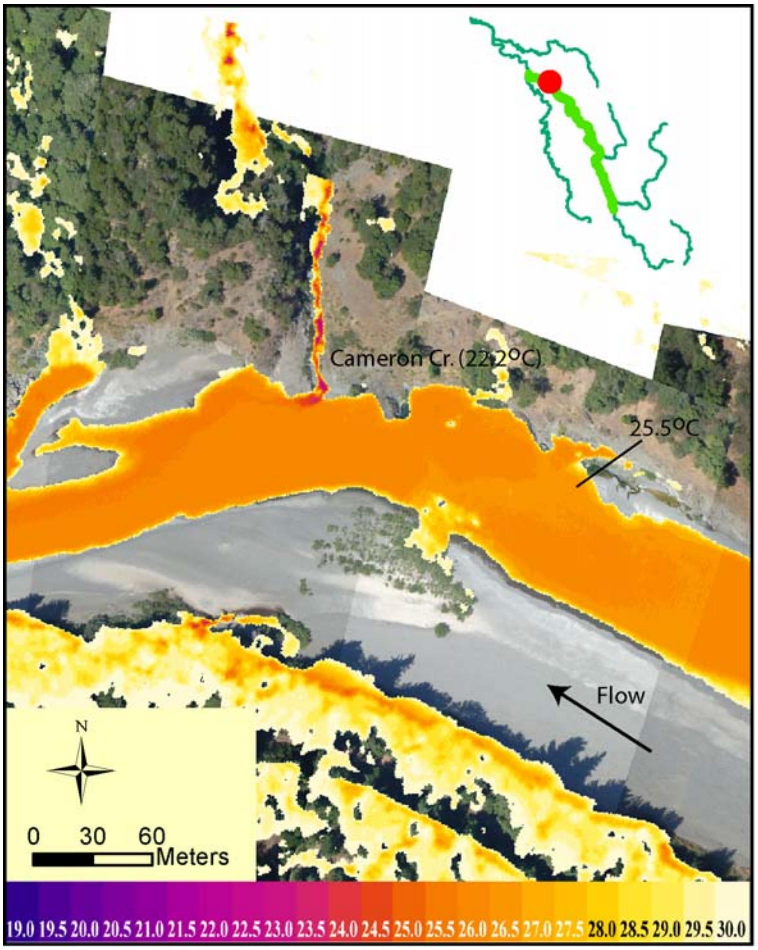
Eela-000875; mile 74.9: The image above shows the confluence of the Eel River (27.1°C) and Jewett Creek. The image also shows spatial variability in surface temperatures with warmer water along the right bank. This image sequence is a good example of thermal conditions, gravel bars, and off-channel features in the Middle Main Eel River.



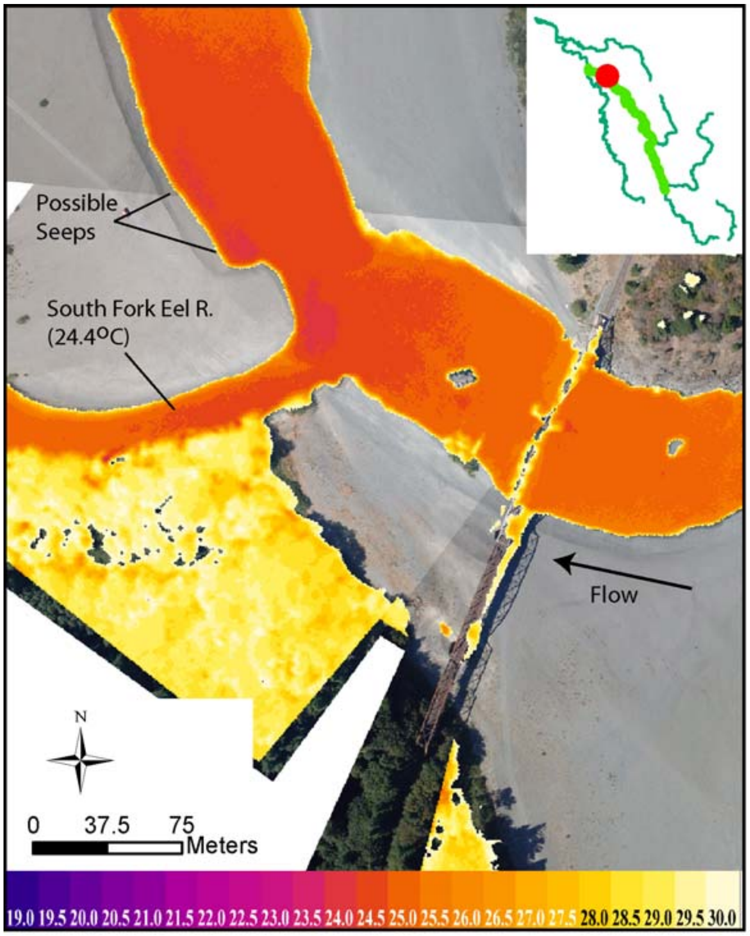
Eela-000990-992; mile 68.3: The image above shows the confluence of Steelhead Creek (25.6ºC) and the Eel River (27.1ºC). Although temperatures in Steelhead Creek were considered warm, it was a cooling source to the Eel River, with a decrease in main stem temperatures observed downstream of the confluence.



Eela-001165; mile 61.1: The image above shows a small, cooler pool (25.8^{o}C) off the left bank of the Eel River (26.8^{o}C). The source of the cool water was not apparent from the imagery, but as in other examples, the presence of cooler water in the floodplain suggests some level of sub-surface flow through the alluvium.



Eela-001384; mile 50.2: The image above shows the confluence of Cameron Creek (22.2°C) and the Eel River (25.5°C). Cameron Creek was one of the cooler tributaries sampled during the analysis.



Eela-001623; mile 40.1: The image above shows the confluence of the South Fork Eel River (24.4^{o}C) and the Middle Main Eel River (24.3^{o}C). While the temperatures of the South Fork and the Middle Main were essentially equal, a temperature decrease was observed during both the August 11th and August 12th surveys. Slightly cooler surface temperatures were observed along the gravel bar downstream of the confluence.

Summary

A TIR survey was successfully conducted on the Middle Main and Lower Eel River. A total of 11 in-stream data loggers were used to calibrate and verify the accuracy of the radiant temperatures. The results showed the average absolute difference between kinetic and radiant temperatures were within the desired accuracy of ±0.4^{o}C, with the differences ranging between -0.3^{o}C and 0.9^{o}C. A longitudinal temperature profile was developed by sampling radiant temperatures along the stream gradient. Interpretation of the TIR imagery in relation to the longitudinal profile can provide insight into the physical processes driving the observed temperature patterns.

The TIR imagery is provided in three forms: 1) individual un-rectified frames, 2) individual geo-rectified frames, and 3) a continuous geo-rectified mosaic. 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. The native resolution is 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. The true color digital images are provided as ~2.5-mile geo-rectified mosaics.

Radiant temperatures in the Eel River were warm with measurements ranging between 23.9 and 28.1^{o}C. In lab and field studies, Welch et al. (2001)[2] observed that juvenile Coho preferentially distributed to temperatures <18.0^{o}C in the Mattole River in Northern California. Surface temperatures recorded in the Middle Main Eel River generally approached sub-lethal and incipient lethal temperatures for salmonids. Consequently, juvenile health in the Middle Main Eel River under current conditions will depend on finding areas of thermal refuge.

While the TIR imagery did not show dramatic temperatures differences in the channel, interpretation revealed evidence of cool water seeps throughout the system. These areas were often subtle with temperature differences of 0.5-2.0^{o}C and were typically detected at the downstream end of gravel bars and cooler off-channel areas. The longitudinal temperature profile further illustrated localized spatial thermal variability with cooling common downstream of tributary junctions. These results suggest that shallow sub-surface flow is an important physical process in creating and maintaining locally cool areas in the Eel River.

The high resolution digital images illustrated a large number of pools in the Eel River. While depth measurements were not part of the airborne survey, the deep pools, combined with the evidences of sub-surface flow, suggest the possibility of vertical

[2] Welsh, H. Hartwell et al. 2001. Distribution of Juvenile Coho Salmon in Relation to Water Temperatures in Tributaries of the Mattole River, California. North American Journal of Fisheries Management 21:464-470, 2001.

temperature gradients. Several studies of Northwest California streams including the Middle Fork Eel River have documented the presence of thermally stratified pools and their use by cold-water fish species (Nielsen and Lisle, 1994[3]; Nakamoto 1994[4]). Further analysis may utilize the true color digital images to identify deep pools.

The TIR imagery and derived data sets 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. This report provides some hypotheses on the processes influencing spatial temperature patterns at this scale based on analysis of the TIR imagery. These hypotheses and observations are considered a starting point for more rigorous spatial analysis and fieldwork.

Deliverables

Deliverables are provided on a set of DVD's:

All Geo-Corrected Imagery are stored as: UTM Zone 10; NAD83

DVD-1

TIR Images (Un-rectified) - Calibrated TIR images in ESRI GRID Format. GRID cell value = radiant temperature * 100. 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.

TIR Images (Geo-rectified) – Calibrated TIR images in ESRI GRID Format. These image were rectified to real world coordinates

TIR Image Mosaic – Continuous image mosaic of the geo-rectified TIR image frames.

Colormap – A color map for displaying water temperatures in the TIR imagery.

Longprofile - Excel spreadsheet containing the longitudinal temperature profile.

Coverages – Point layer showing image locations, sampled temperatures, and image interpretations.

Report - This report.

[3] Nielson, J.L. and T.E. Lisle. 1994. Thermally stratified pools and their use by steelhead in Northern California streams. Transactions of the American Fisheries Society. 123:613-626.

[4] Nakamoto, R.J. 1994. Charateristics of pools used by adult summer steelhead oversummering in the New River, California. Transactions of the American Fisheries Society. 123:757-765.

DVD-2

TrueColor – Geo-Rectified true color imagery from river mile 7.5 to 40.

DVD-3

TrueColor – Geo-Rectified true color imagery from river mile 40 to 80.

DVD-4

TrueColor – Geo-Rectified true color imagery from river mile 80 to 122.