Aerial Surveys in the Mattole River Basin
Thermal Infrared and Color Videography

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Report to:

North Coast Regional Water Quality Control Board
5550 Skyline Boulevard, Suite A
Santa Rosa, CA 95403

by:

Watershed Sciences
712 NW 4th Street
Corvallis, OR 97330

Final Report

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Introduction

Thermal infrared remote sensing has been demonstrated as a reliable, cost-effective, and accessible technology for monitoring and evaluating stream temperatures from the scale of watersheds to individual habitats (Karalus et. al., 1996; Torgersen et. al. 1999; Torgersen et. al. 2001). In 2001, the North Coast Regional Water Quality Control Board (NCRWQCB) contracted with Watershed Sciences, LLC (WS, LLC) to map and assess stream temperatures in the Mattole River basin using thermal infrared (TIR) remote sensing.

This report presents longitudinal temperature profiles for each survey stream as well as a discussion of the thermal features observed in the basin. TIR and associated color video images are included in the report in order to illustrate significant thermal features. An associated ArcView GIS[1] database includes all of the images collected during the survey and is structured to allow analysis at finer scales. Appendix A presents a collection of selected TIR and visible band images from the surveys.

Methods

Data Collection

Data were collected using a TIR sensor and a visible band color video camera co-located in a gyro-stabilized mount that attached to the underside of a helicopter. The helicopter was flown longitudinally along the stream channel with the sensors in a vertical (or near vertical) position. Figure 1 illustrates the extent of the TIR surveys and Table 1 summarizes the dates and times of each survey.

TIR images were collected digitally and recorded directly from the sensor to an on-board computer. The TIR sensor detects emitted radiation at wavelengths from 8-12 microns and records the level of emitted radiation in the form of an image. Each image pixel contains a measured value that can be directly converted to a temperature. The raw TIR images represent the full 12 bit dynamic range of the instrument and were tagged with time and position data provided by a Global Positioning System (GPS). Visible band color images were recorded to an on-board digital videocassette recorder at a rate of 30 frames per second. GPS time and position were encoded on the recorded video. The color video camera was aligned to present the same ground area as the TIR sensor.

The survey of the Mattole River was conducted at an altitude of 1800 ft above ground level (AGL). At 1800 ft, the image presents a 192-meter wide footprint with a pixel size of approximately 0.4 meters. Tributaries were surveyed at an average altitude of 1400 ft AGL. At this altitude, the ground footprint width is approximately 150 meters with a

[1] Geographic Information System

0.3-meter pixel size. All surveys were conducted in an upstream direction and the images are generally oriented in the flight direction.

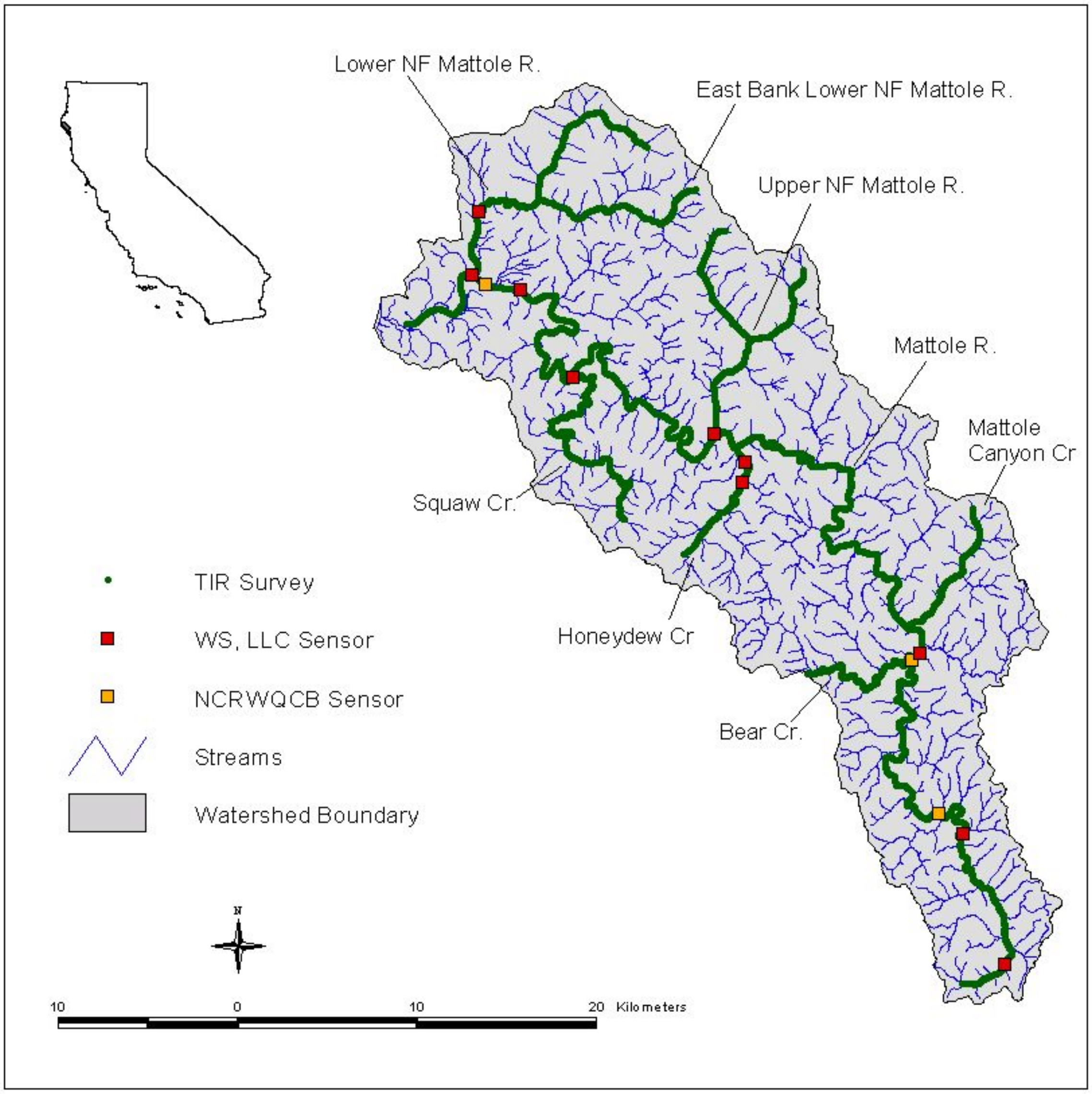


Figure 1 – Map of the Mattole River basin showing streams surveyed using TIR and visible band color video. The map also shows the locations of in-stream sensors used to verify the accuracy of the radiant temperatures.

WS, LLC distributed in-stream temperature data loggers (Onset Stowaways) at 10 locations in the basin prior to the surveys (Figure 1). The in-stream sensors were used to ground truth (i.e. verify the accuracy of) the radiant temperatures measured by the TIR sensor. These locations were supplemented with data provided by the NCRWQCB from 7 additional temperature loggers. The advertised accuracy of the Onset Stowaway sensors used by WS, LLC is ±0.2°C.

Table 1 - Time, date and distance for the Mattole River surveys.

Stream	Date	Time (PM)	Survey Extent
Mattole R.	19-July	2:23 – 4:03	Mouth to Headwaters
Bear Cr.	20-July	1:55 – 2:11	Mouth to Forks
Mattole Canyon Cr.	20-July	2:14 – 2:32	Mouth to Headwaters
Honeydew Cr.	20-July	2:38 – 2:49	Mouth to 1.5 mi. us UEF Honeydew Cr.
Upper NF Mattole R.	20-July	2:51 – 3:23	Mouth to Rattlesnake Cr.
Oil Cr.	20-July	2:51 – 3:23	Mouth to Devil's Cr.
Rattlesnake Cr.	20-July	2:51 – 3:23	Mouth to Fox Camp Cr.
Squaw Cr.	20-July	3:30 – 4:34	Mouth to Headwaters
Lower NF Mattole R.	20-July	4:42 – 5:10	Mouth to Headwaters
EB NF Mattole R.	20-July	5:13 – 5:29	Mouth to Headwaters

Meteorological conditions for July 19 were acquired from remote automated weather stations (RAWs) located at Cooskie Mountain within the Mattole Basin, Arcata, CA near the Mad River, and Alder Point, CA near the Eel River. The weather stations were operated by the USFS, USGS, and CA Department of Forestry respectively. On July 20th, weather data was collected at Cooskie Mountain, Arcata, CA, and from a portable weather station located within the basin. Weather data from the two days of the survey are summarized in Table 2.

Table 2 – Meteorological conditions recorded in and around the Mattole River basin for the dates and times of the TIR surveys.

Date 7/19/01	*Cooskie Mtn Elev. (2950')*		*Arcata* Elev. (33')*	*Alder Point Elev. (923')*	
Time (PM)	*Temp °C (°F)*	*RH (%)*	*Temp °C (°F)*	*Temp °C (°F)*	*RH (%)*
14:00	15.0 (59)	76	15.5 (60)	25.0 (77)	51
15:00	15.0 (59)	76	15.5 (60)	26.7 (80)	50
16:00	15.0(59)	77	14.9 (58)	25.0 (78)	51
17:00	14.4 (58)	75	13.9 (57)	22.2 (72)	59
Date 7/20/01	*Cooskie Mountain Elevation (2950')*		*Arcata Elev. (33')*	*Portable Station (Elevation ≈800')*	
13:00	12.2 (54)	78	16.1 (61)	21.0 (70)	50
14:00	13.3 (56)	77	16.7 (62)	21.7 (71)	51
15:00	15.0 (59)	72	16.1 (61)	24.4 (76)	41
16:00	13.3 (56)	74	15.6 (60)	23.6 (75)	43
17:00	13.3 (56)	71	17.2 (63)	19.8 (68)	53
18:00	12.8 (55)	76	16.7 (62)	19.0 (66)	53

**only air temperatures were available at this site.*

Data Processing

A computer program was used to create an ArcView GIS point coverage containing the image name, time, and location it was acquired. The coverage provided the basis for assessing the extent of the survey and for integrating with other spatially explicit data layers in the GIS. This allowed WS, LLC to identify the images associated with the ground truth locations. The data collection software was used to extract temperature values from these images at the location of the in-stream recorder. The radiant temperatures were then compared to the kinetic temperatures from the in-stream data loggers. The image points were associated with a river kilometer within the GIS environment. The river kilometers were derived from 1:100K "routed" stream covers from the Environmental Protection Agency (EPA). The route measures provide a spatial context for developing longitudinal temperature profiles of stream temperature.

In the laboratory, a computer algorithm was used to convert the raw thermal images (radiance values) to ARC/INFO GRIDS where each GRID cell contained a temperature value. A GIS program was used to display the GRID associated with an image location selected in the point coverage. The GRID was color-coded to visually enhance temperature differences, enabling the user to extract temperature data.

Figure 2 illustrates a color coded GRID displayed in the ArcView environment. This GRID illustrates the confluence of the Mattole River and Bear Creek. The legend on the left of "Grid View" specifies the temperature range associated with each color. The other view window shows the point coverage with the displayed GRID location highlighted in yellow. Each green point in the "Mattole Albers" view represents another image location. Once in the GRID format, the images were analyzed to derive the minimum, maximum, and median stream temperatures. To derive these measures, a computer program was used to sample the GRID cell (temperature) values in the stream channel. Ten sample points were taken longitudinally in the center of the stream channel. Figure 3 provides an example of how temperatures are sampled. The red "x"s on the psuedo-color TIR image shows typical sample locations. Samples were taken to provide complete coverage without sampling the same water twice. Where there were multiple channels, only the main channel (as determined by width and continuity) was sampled. Side channels that had water temperatures different than the main channel were sampled as tributaries. For each sampled image, the sample minimum, maximum, median, and standard deviation was recorded directly to the point coverage attribute file. The median value is the most useful measure of stream temperatures because it minimizes the effect of extreme values.

The temperature of tributaries and other detectable surface inflows were also sampled from images. These inflows were sampled at their mouth using the same techniques described for sampling the main channel. If possible, the surface inflows were identified on the USGS 24K base maps. The inflow name and median temperature were then entered into the point coverage attribute file.

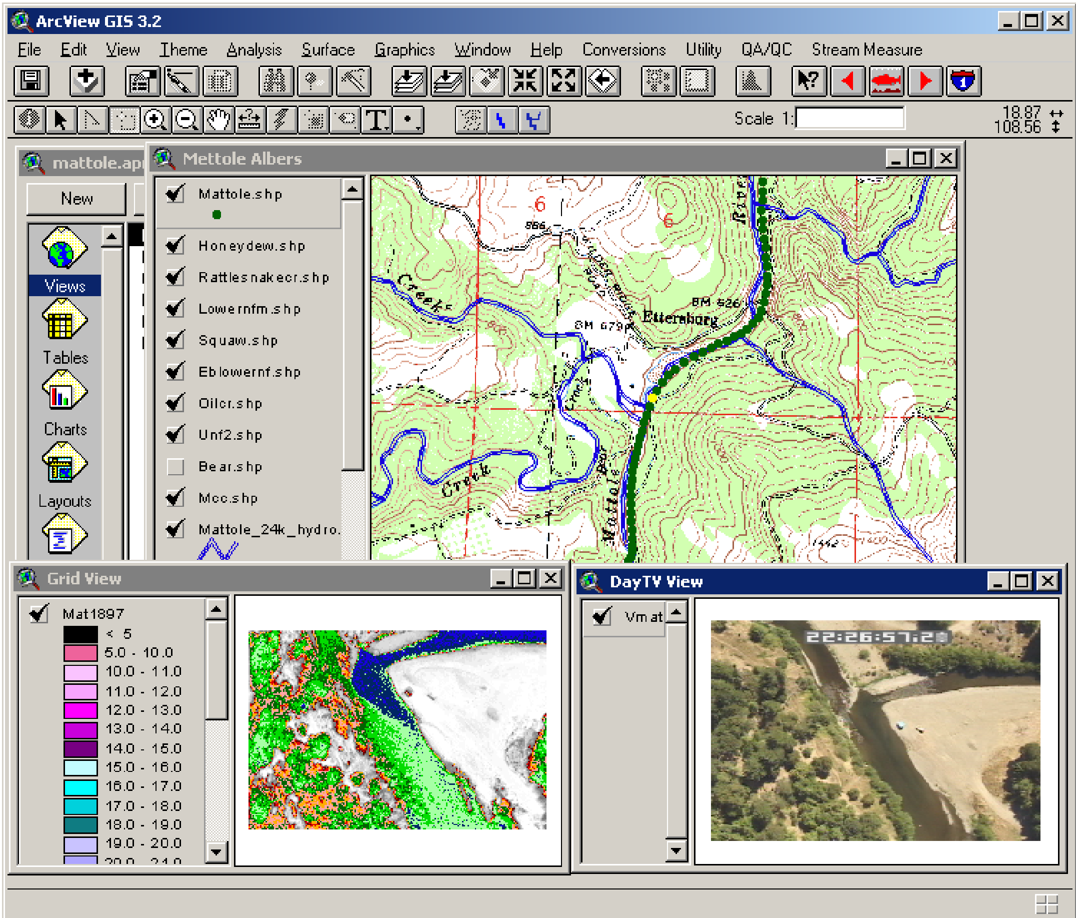
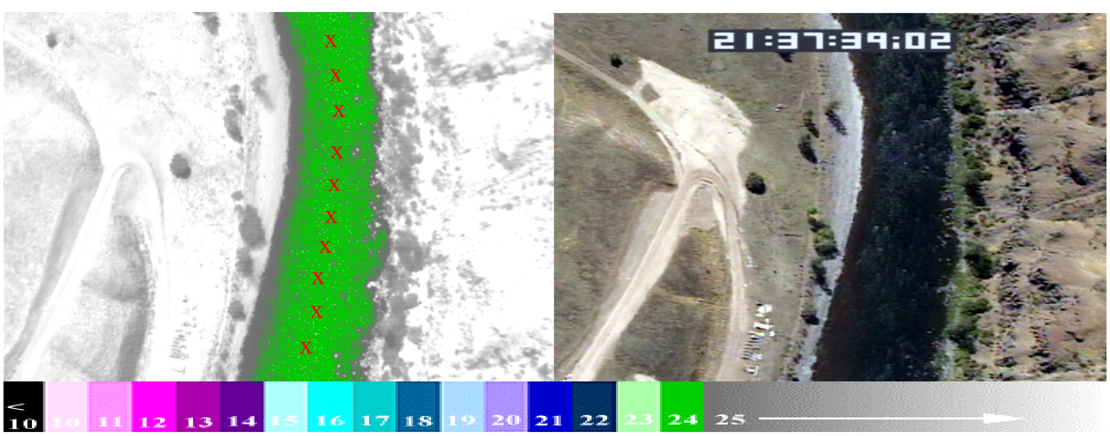


Figure 2 – ArcView display showing a color-coded temperature GRID in one window and the geographic location of the GRID in the other. The orientation of the image is always in the flight direction, which in this case is upstream and opposite the map.



TIR/visible band color image

Figure 3 – Image pair showing typical temperature sampling locations. Temperatures are presented in ^{o}C.

Visible band images corresponding to the TIR images were extracted from the database using a computer-based frame grabber. The images were captured to correspond to the TIR images and provide a complete coverage of the stream. The video images were "linked" to the corresponding thermal image frame in the ArcView GIS environment.

Data Limitations

TIR sensors measure thermal infrared energy emitted at the water's surface. Since water is essentially opaque to thermal infrared wavelengths, the sensor is only measuring water surface temperature. TIR data accurately represents bulk water temperatures in reaches where the water column is thoroughly mixed. However, the imagery may not represent bulk temperatures in reaches where a thermally stratified surface layer has formed. Although thermal stratification was detected at isolated areas (river miles 41.3 and 52.1), the Mattole River was generally mixed and thermal stratification was not considered a factor in the overall temperature analysis. There were no detectable signs of thermal stratification in the tributaries of the Mattole River.

In addition to vertical mixing, TIR reflections and spatial resolution may also influence the accuracy of the radiant temperatures. The TIR reflections result from changes in background parameters and water surface conditions. Torgersen (2001) documented a difference in the apparent temperatures between pools and riffles, which were related to differences in reflective characteristics at the waters surface. The differences in apparent temperatures between pools and riffles are typically on the magnitude of 0.5^{o}C. When the stream channel is narrow relative to the pixel size, there are a greater number of hybrid pixels that integrate non-water features such as rocks and vegetation. Consequently, small channel widths can result in higher inaccuracies and more "noise" in the temperature samples.

The ability to detect the stream in the TIR image depends on thermal contrast between the water and surrounding terrain. During the surveys in the Mattole River basin, the apparent temperature of vegetation and other terrestrial features were often similar (i.e. within $\pm 2.0^{o}$C) to measured water temperatures. While this does not impact the accuracy of the TIR derived temperatures, the reduced contrast made detection of the stream channel difficult and limited the interpretation of off-channel features. The visible band imagery was used extensively for interpretation of the TIR images. The reduced contrast was observed on all streams, but was notably worse in the middle reaches of tributaries with small channel widths and immediate riparian vegetation.

Results

Thermal Accuracy

Temperatures from the in-stream data loggers were compared to radiant temperatures derived from the imagery for each survey stream (Table 3). The data were assessed at the time the image was acquired, with the radiant values representing the median of ten points sampled from the image at the data logger location. Each surveyed stream was calibrated separately based on the meteorological conditions recorded at the time of the survey. If a consistent difference was observed for all the in-stream sensors, the parameters used to convert radiant values to temperatures were adjusted to provide a better fit to the in-stream sensors. Since a large air temperature gradient was noted between the coast and inland sites (Table 2), imagery from the Mattole River survey was calibrated using a linear increase in air temperatures moving inland. The results showed that radiant temperatures were within 1.0^{o}C of in-stream temperatures recorded by data loggers for all streams surveyed. The average difference of ±0.4^{o}C observed on the Mattole River was consistent with TIR surveys conducted in the PNW since 1994 (Torgersen et. al. 2001).

Table 3 – Comparison of ground-truth water temperatures with radiant temperatures derived from the TIR images, July 19 - 20, 2001.

Stream	Image	River Mile	Time PM	In-stream Temp ^{o}C	Radiant Temp ^{o}C	Difference
July 19						
Mattole R.	mat0144	6.0	2:27	23.9	22.9	1.0
Mattole R.	mat0165	6.7	2:28	22.9	23.1	-0.2
Mattole R.	mat0211	7.8	2:29	24.3	23.8	0.5
Upper NF Mouth	mat1050	29.3	2:58	26.2	26.3	-0.1
Mattole R.	mat1879	48.7	3:26	23.4	23.2	0.2
Bear Cr. mouth	mat1898	49.2	3:26	22.0	22.4	-0.4
Mattole R.	mat2438	59.6	3:48	17.9	18.5	-0.6
Mattole R.	mat2566	62.0	3:49	20.1	20.3	-0.2
July 20						
Mattole R.	ber0017	0.0	1:55	21.4	21.1	0.3
Bear Cr.	ber0049	0.0	1:56	20.5	20.9	-0.4
SF Bear Cr.	ber0470	6.8	2:10	15.7	16.3	-0.6
NF Bear Cr.	ber0470	6.9	2:10	16.1	16.1	0.0
Mattole Canyon Cr.	mcc0021	0.0	2:14	21.9	21.5	0.4
Mattole Canyon Cr.	mcc0063	0.3	2:17	23.0	23.6	-0.6
Honeydew Cr.	hon0052	0.7	2:40	21.3	20.9	0.4
Honeydew Cr.	hon0109	1.7	2:41	21.3	20.9	0.4
Upper NF Mattole R.	unf0035	0.0	2:52	25.5	25.7	-0.2
Upper NF Mattole R.	mat1050	29.3	2:57	26.2	26.3	-0.1
Squaw Cr.	squ0028	0.0	3:31	20.9	20.6	0.3
Lower NF Mattole R.	lnf0212	0.0	4:48	23.9	24.1	-0.2
Lower NF Mattole R.	lnf0333	2.4	4:52	22.5	22.3	0.2

Temporal Differences

Figure 4 shows in-stream temperature variation at two ground truth locations for the Mattole River, at river miles 6.0 and 62, as well as the time frame of the TIR remote sensing flights. At river mile 6.0, stream temperatures changed by 1.1°C over the course of the survey. The daily stream temperature maximum at this location occurred between 4:20 pm and 5:50 pm. At river mile 62.0, stream temperatures increased by 0.9°C over the course of the survey. The daily stream temperature maximum (20.7°C) at this location occurred at 5:10 pm.

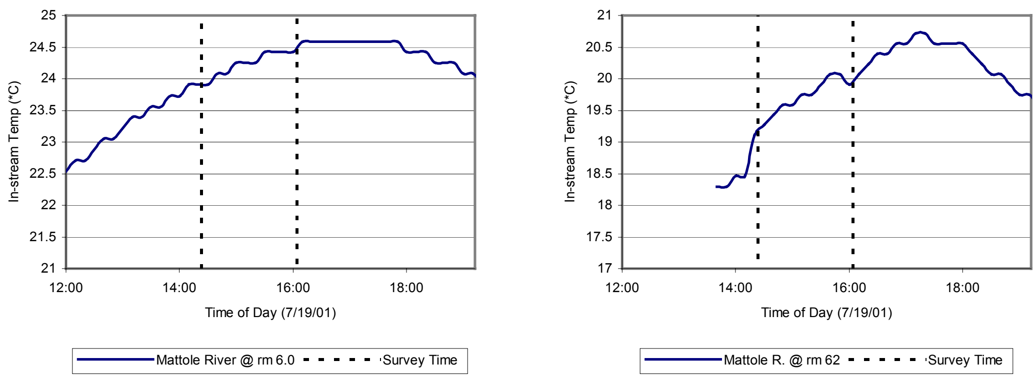


Figure 4 – Stream temperature variation and time of TIR remote sensing over flight for two locations in the Mattole River.

Longitudinal Temperature Profiles

Mattole River

The median temperatures for each sampled image of Mattole River were plotted versus the corresponding river mile (Figure 5). The plot also contains the median temperature of all surface water inflows (e.g. tributaries, canals) and off-channel features (side-channels, backwaters). Tributaries are labeled in Figure 5 by river mile with their name and temperature listed in Table 4. The Mattole River was surveyed upstream from approximately 1.5 miles inland until the river was no longer visible in the imagery. The survey was started inland from the coast because of a marine cloud layer that persisted into the mid-afternoon. The remnants of the low clouds are visible on some the first images of the survey. Near the headwaters, the Mattole River was intermittently visible through the riparian canopy. Stream temperature samples were taken when the stream was visible and, as a result, the sampling frequency was lower in the upper basin.

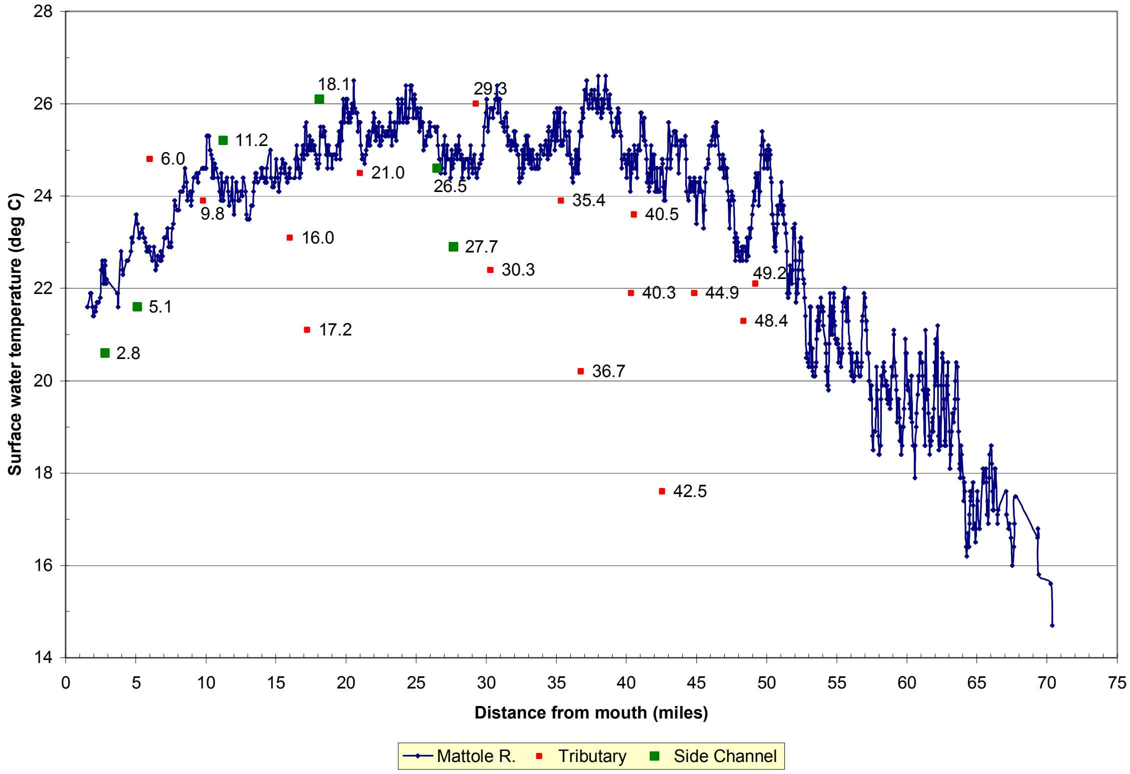


Figure 5 - Median channel temperatures versus river mile for Mattole River, CA, along with the location of surface water inflows (7/19/01).

At the most upstream sample at river mile 71.4, the Mattole River was ≈14.7°C. From river mile 71.4, stream temperatures warmed in the downstream direction and reached

a local maximum of 25.4°C at river mile 49.7. No tributaries or other surface water inflows were detected through this reach. As the survey progressed up the river, the flood plain became more confined and the immediate riparian vegetation masked incoming surface water. The Mattole River also showed a higher level of spatial variability between river mile 49.7 and the end of the survey than in downstream reaches. The apparent variability is due in part to the increased noise from hybrid pixels and TIR reflections (*see data limitations*). However, smaller streams often exhibit higher spatial variability due to the more pronounced effect of energy inputs on smaller flow volumes.

Stream temperatures dropped by ≈3.7°C between river mile 49.7 and 48.7. Bear Creek and Blue Slide Creek entered the Mattole River through this reach and both contributed water that was cooler than the mainstream. From river mile 48.8 to 46.2, stream temperature increased rapidly and reached a local maximum of 25.4°C. Over the next 36.2 miles (river mile 46.2 and 10.0), stream temperatures varied between 23.3°C and 26.5°C. The longitudinal profile (Figure 5) shows that temperature response in this reach correlated to cooler tributary inputs. Of eleven tributaries sampled through this reach, ten contributed water that was cooler than the mainstream. Westlund Creek empties into

Mattole River at river mile 36.7 and lowers mainstream temperatures to from 26.5°C to 24.5oC. Another prominent influence was Honeydew Creek at river mile 30.3, which lowered mainstream temperatures from approximately 26.0°C to 24.4°C. The imagery also showed a number of cool water seeps within the channel floodplain (Appendix A – Frames 1638 and 1426) within this reach.

The Mattole River showed overall cooler temperatures between river mile 10 and the mouth. The Lower North Fork Mattole River and McGinnis Creek both enter the mainstream in the lower 10 miles. The possible forces driving the generally cooler stream temperatures through this reach were not apparent from the imagery. However, the cloud layer that persisted near the coast until early afternoon may be a factor. Tidal influence is another possible contributing factor. However, these potential factors were not quantified as part of the airborne survey.

Table 4 - Tributary and side channel temperatures for Mattole River, CA. River miles correspond to data labels shown in Figure 5.

Tributary Name	Image	Km	Mile	Tributary Temp °C	Mattole R. Temp °C	Difference
Lower North Fork (RB)	mat0145	9.7	6.0	24.8	22.8	2.0
McGinnis Cr (RB)	mat0269	15.8	9.8	23.9	24.6	-0.7
No Name (RB)	mat0491	25.7	16.0	23.1	24.4	-1.3
Squaw Creek (LB)	mat0535	27.7	17.2	21.1	24.9	-3.8
Unnamed Inlet (LB)	mat0704	33.8	21.0	24.5	25.6	-1.1
Upper North Fork (RB)	mat1051	47.1	29.3	26.0	24.5	1.5
Honeydew Creek (LB)	mat1087	48.8	30.3	22.4	25.9	-3.5
Dry Creek (RB)	mat1317	56.9	35.4	23.9	25.2	-1.3
Westlund Creek (RB)	mat1370	59.1	36.7	20.2	25.6	-5.4
Fourmile Creek (LB)	mat1519	64.9	40.3	21.9	24.5	-2.6
No Name (LB)	mat1528	65.3	40.5	23.6	25.1	-1.5
Sholes Cr. (LB)	mat1617	68.5	42.5	17.6	24.8	-7.2
Grindstone Cr (RB)	mat1714	72.2	44.9	21.9	24.4	-2.5
Blue Slide Cr (RB)	mat1866	77.8	48.4	21.3	22.9	-1.6
Bear Cr (LB)	mat1898	79.2	49.2	22.1	24.4	-2.3
Side Channel						
Side Channel (LB)	mat0051	4.6	2.8	20.6	22.5	-1.9
Side Channel (RB)	mat0109	8.3	5.1	21.6	23.4	-1.8
Side Channel (LB)	mat0320	18.1	11.2	25.2	23.9	1.3
Side Channel (RB)	mat0574	29.2	18.1	26.1	24.9	1.2
Side Channel (RB)	mat0938	42.7	26.5	24.6	25.5	-0.9
Side Channel (RB)	mat0987	44.6	27.7	22.9	24.8	-1.9

Bear Creek

Bear Creek was flown from the mouth upstream to the forks, approximately 6.9 river miles (Figure 6). Tributaries are labeled in Figure 6 by river mile with their name and temperature listed in Table 5. The mouths of the North and South Forks had approximately the same temperature (≈16.4°C) at the time of the over flight. Stream temperatures generally increased in the downstream direction reaching ≈21.0°C at the confluence with the Mattole River. Three surface inflows were detected between the forks and the mouth and each contributed water that was cooler than the mainstream. However, these tributary inputs also appeared to have small flow relative to Bear Creek and did not have detectable influence on the general temperature pattern. Between river mile 1.4 and 0.9, stream temperatures increased from 18.4°C to 21.1°C. This is the most rapid longitudinal heating observed in the profile and corresponded to the transition from the Bear Creek canyon to the more open floodplain near the confluence with the Mattole River.

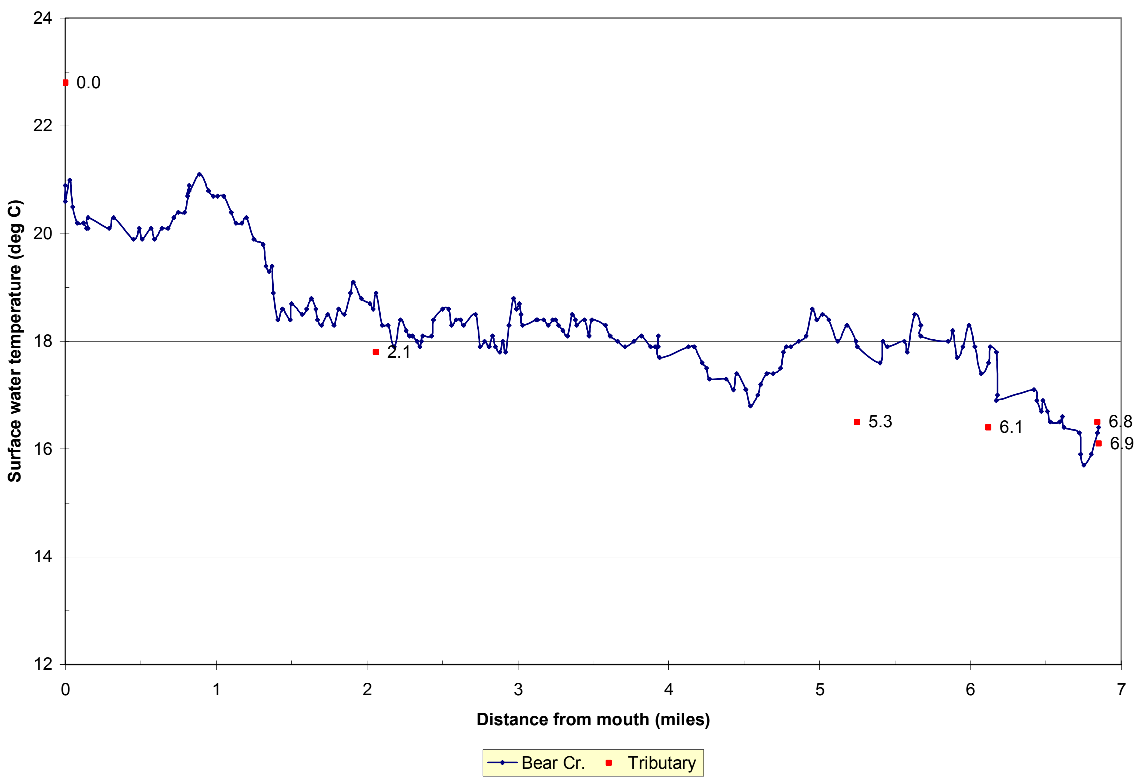


Figure 6 - Median channel temperatures versus river mile for Bear Creek, CA, along with the location of surface water inflows (7/20/01).

Table 5 - Tributary and side channel temperatures for Bear Creek, CA. River miles correspond to data labels shown in Figure 6.

Tributary Name	Image	km	mile	Tributary Temp ^{o}C	Bear Cr. Temp ^{o}C	Difference
Mattole River (RB)	ber0043	0.0	0.0	22.8	20.9	1.9
Jewett Creek (LB)	ber0169	3.3	2.1	17.8	18.9	-1.1
No Name (LB)	ber0382	8.5	5.3	16.5	17.9	-1.4
Side Channel (RB)	ber0423	9.9	6.1	16.4	17.6	-1.2
South Fork (RB)	ber0469	11.0	6.8	16.5	16.3	0.2
North Fork (LB)	ber0470	11.0	6.9	16.1	16.4	-0.3

Mattole Canyon Creek

Mattole Canyon Creek was surveyed from its mouth at Mattole River upstream to the point where no surface water was detected in the imagery (Figure 7). The stream was dry at its mouth and had small width throughout the extent of the survey. The small width combined with some riparian canopy prevented temperature sampling through some reaches. Although the stream was surveyed to river mile 6.4, the upstream most temperature sample was at river mile 5.4. At river mile 5.4, sampled temperatures were relatively warm (≈22.0^{o}C) and stream flows were very low. Stream temperatures generally increased in the downstream direction and reached a maximum temperature of 27.3^{o}C at river mile 0.5. Over the survey reach stream temperatures varied considerably over short longitudinal distances, ranging between 20.4^{o}C and 27.3^{o}C. The high degree of temperature variation from image to image appears to be due to extremely low flow conditions. One unnamed tributary was detected during the survey and its location is shown on the profile (Figure 7).

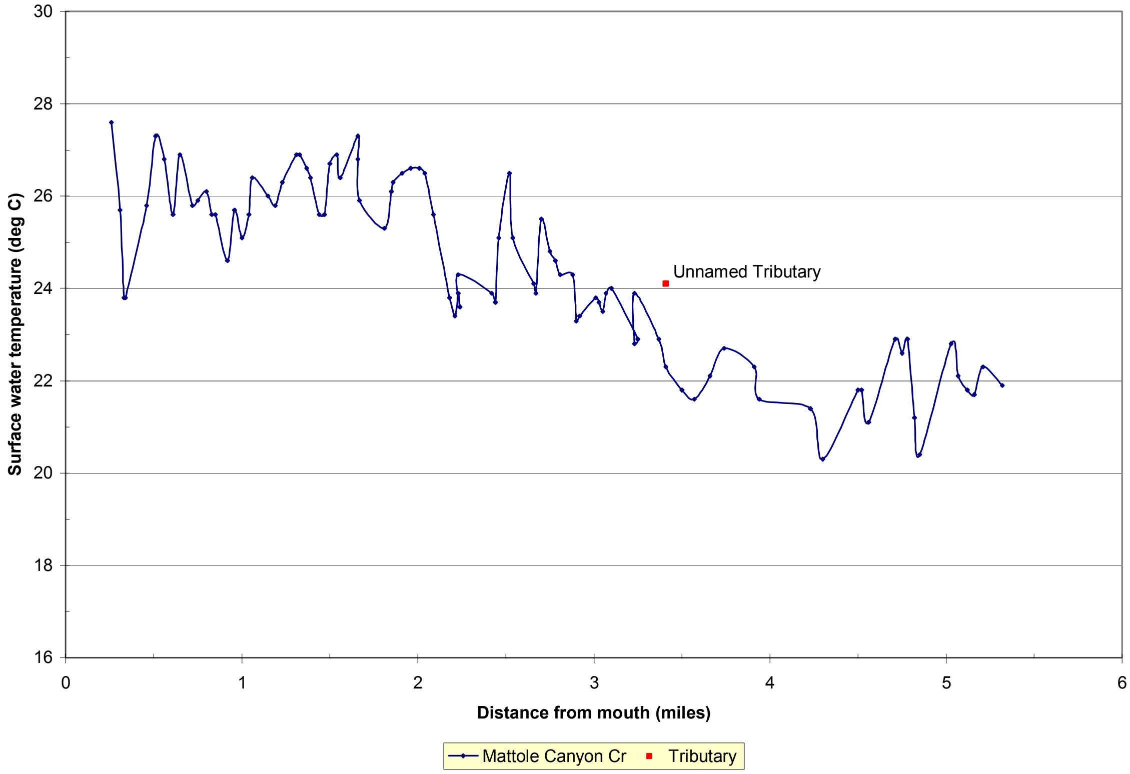


Figure 7 - Median channel temperatures versus river mile for Mattole Canyon Creek, CA, along with the location of surface water inflows (7/20/01).

Honeydew Creek

Honeydew Creek was surveyed for approximately 5.7 miles and the median temperature from each sampled image was plotted versus river mile (Figure 8). At the upstream end of the survey, Honeydew Creek was relatively cold at 14.2°C. Stream temperatures increased from 14.2°C to 17.3°C between river mile 5.6 and 3.2, an average longitudinal heating rate of 1.3°C per mile. Between river miles 3.2 and 1.8, the average longitudinal heating rate increased 2.6°C per mile. From mile 1.8 to the mouth, Honeydew Creek remained consistently near 21.1°C (±0.6°C) and, at the time of the over flight, was essentially the same temperature as the Mattole River. No tributaries were detected during the survey.

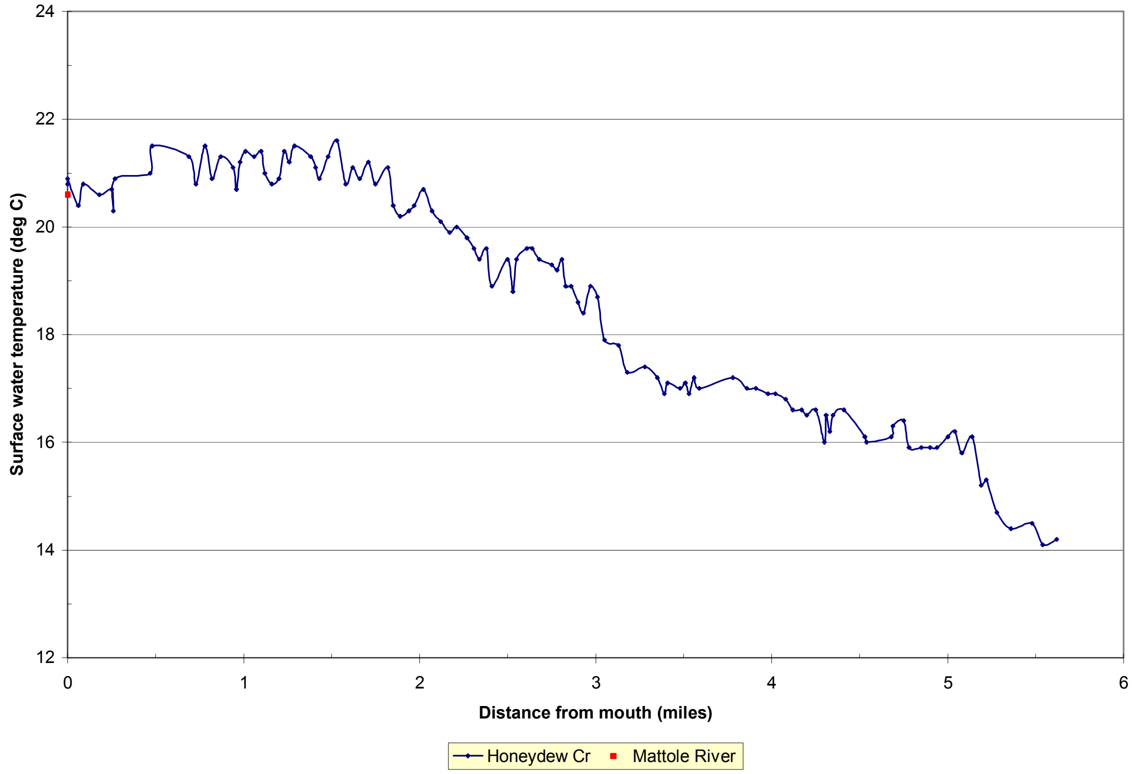


Figure 8 - Median channel temperatures versus river mile for Honeydew Creek, CA, along with the location of surface water inflows (7/20/01).

Upper North Fork Mattole River

Upper North Fork Mattole River was surveyed from the mouth upstream to the confluence of Rattlesnake Creek and Oil Creek. The survey continued up Rattlesnake Creek to the confluence of Fox Camp Creek. At Fox Camp Creek, no surface water was visible from Rattlesnake Creek so the survey followed the water up Fox Camp Creek until it was not longer visible (≈0.8 miles). Oil Creek was similarly surveyed upstream until surface water was no longer visible in the presented image. As with Rattlesnake Creek, the survey followed the surface water, which included ≈1.8 miles of Devils Creek. The median channel temperatures for each sampled image of the Upper North Fork Mattole River and tributaries were plotted versus river mile (Figure 9).

Rattlesnake Creek provided most of the flow to the Upper North Fork Mattole River. At the upstream end of the Rattlesnake Creek survey, stream temperatures were relatively cold at 12.3^{o}C. Moving downstream, temperatures increased rapidly reaching ≈ 20.3^{o}C at river mile 6.7. Stream temperatures remained consistently between 20.0^{o}C and 21.5^{o}C over the next mile before dropping slightly at the confluence with the Upper North Fork Mattole River. No tributaries were sampled on Rattlesnake Creek.

At the upstream end of the Oil Creek survey, stream temperatures were relatively warm at 16.5°C and stream flows were very low. Stream temperatures warmed rapidly in the downstream direction and reached a local maximum near the mapped confluence with Oil Creek at river mile 8.0. Moving downstream, temperatures decreased at river mile 7.0 and again at river mile 5.7. However, the source of the cooling at these locations was not apparent from the imagery. Stream temperatures increased prior to the confluence with the Upper North Fork Mattole River. Over the survey reach, stream temperatures varied considerably from image to image, ranging between 24.8°C and 19.1°C from the mouth to the start of Devil's Creek. The high degree of temperature variation from image to image appears to be due to extremely low flow conditions. In addition, small channel widths result in a higher numbers of hybrid pixels, which contribute to noise in the profile.

In the Upper North Fork Mattole River, stream temperatures decreased by ≈2.0°C between the Oil Creek confluence at river mile 4.2 and river mile 2.9. Temperatures increased again over the lower 2.9 miles and the Upper NF Mattole entered the Mattole River at 25.1°C. In addition to Oil Creek, two tributaries were sampled during the analysis.
An unnamed tributary was detected at river mile 3.5, which was a cooling source to the mainstream. Prior to entering the Mattole River, the stream splits into two channels and a cool water seep was detected at the head of the left side channel (*looking downstream*).

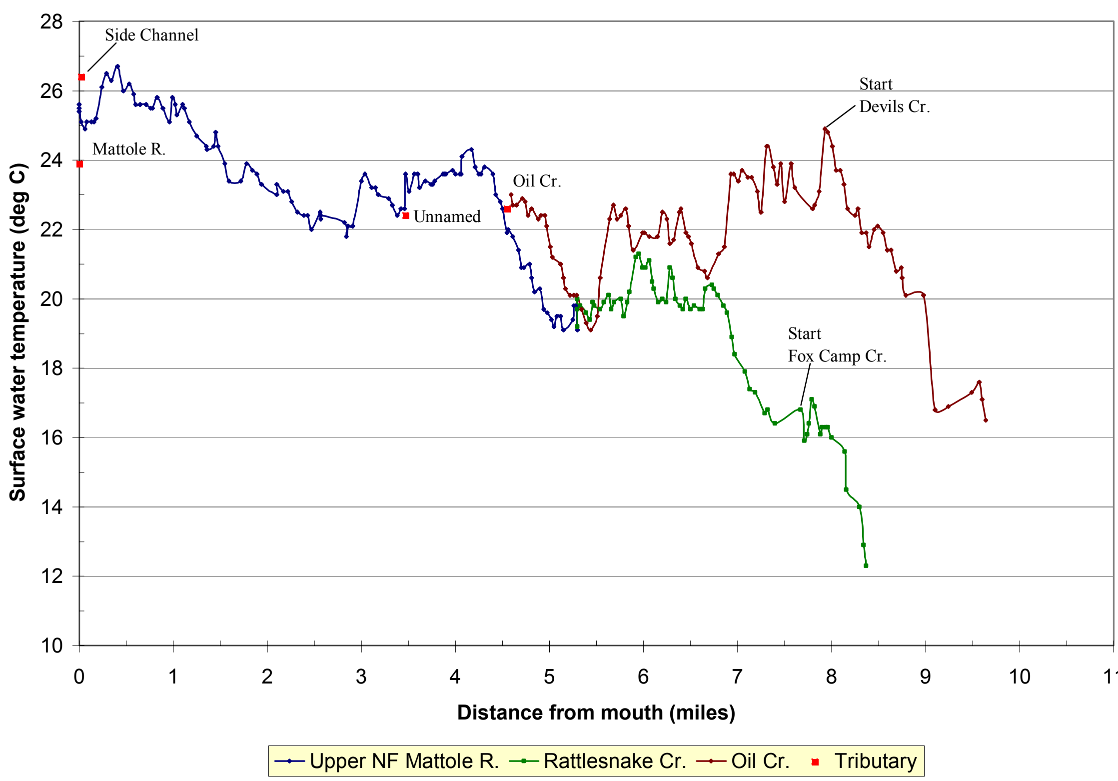


Figure 9 - Median channel temperatures versus river mile for Upper NF Mattole River, CA, along with the location of surface water inflows (7/20/01).

Squaw Creek

Squaw Creek was surveyed upstream from the mouth to the headwaters, a distance of 11.7 miles. As with the other tributaries, the median temperatures for each sampled image of Squaw Creek was plotted versus the corresponding river mile (Figure 10). The upper reaches of Squaw Creek were partially masked with riparian vegetation and detection of the stream was further hindered by low contrast between stream and vegetation temperatures.

At the upstream end of the survey, Squaw Creek was relatively cold at 13.1°C. Stream temperatures increased steadily in the downstream direction reaching 19.3°C at river mile 7.8. For the next mile, temperatures remained consistently near 18.9°C (±0.5°C). From river mile 6.8, stream temperatures continued to increase in the downstream direction reaching a maximum of 22.9°C at river mile 0.6. A drop in temperature of almost 2°C was observed near river mile 4.2, but the source of cooling was not apparent from the imagery. A slight cooling trend was observed near the mouth and Squaw Creek was a cooling source to the Mattole River. No tributaries were detected over the course of the survey.

Figure 10 - Median channel temperatures versus river mile for Squaw Creek, CA, along with the location of surface water inflows (7/20/01).

Lower North Fork Mattole River

The Lower North Fork (NF) Mattole River was surveyed from the mouth upstream 12.3 miles; approximately 1.3 miles from the watershed divide (Figure 11). Between river miles 12.3 and 9.6, the Lower NF showed a high degree of temperature variation with apparent stream temperatures ranging between 13.0^{o}C and 16.6^{o}C. In general, the stream was hard to see through this reach due to its small size and riparian canopy. Detection of the stream was further hindered by low thermal contrast between the water surface and surrounding vegetation. As a consequence, the analysis could not distinguish the sources of thermal variability in this reach including the relative contribution of hybrid pixels and other artifacts of the processing to the observed variability.

From river mile 9.6 to 7.3, sampled temperatures varied by ≈1.5^{o}C with a minimum temperature of 15.7^{o}C observed at river mile 7.3. Moving downstream, temperatures increased rapidly reaching 22.6^{o}C at the confluence of the East Bank Lower NF Mattole River, which contributed water that was warmer than the mainstream. At river mile 4.8, stream temperatures decreased by ≈2.2^{o}C reaching a local minimum of 20.6^{o}C at river mile 4.1. No tributary inflows were detected through this reach and the source of cooling was not directly apparent from the imagery. However, the imagery begins to show a more open floodplain with gravel bars that is characteristic of the lower reaches. The observed drop in temperature along with a general transition in floodplain characteristics suggests sub-surface exchange through this reach. Stream temperatures increased steadily between river mile 4.1 and the confluence with the Mattole River.

The East Bank Lower NF Mattole River was surveyed from the mouth upstream 6.4 miles (Figure 12). As with other small tributaries in the basin, the survey followed the water, which ultimately led up Sulphur Creek. Stream flows were low and showed a high degree of temperature variation near the headwaters. Like the Lower NF, detection of the stream was difficult due to the small channel size and low thermal contrast between the water surface and the surrounding vegetation.

Overall, the East Bank Lower NF showed a general downstream warming trend throughout the survey extent. At the upstream end, stream temperatures increased from about 15.5^{o}C at river mile 6.1 to ≈18.0^{o}C at river mile 2.7. Stream temperatures showed an increase in the longitudinal heating rate between river mile 2.7 and the confluence with the Lower NF. This inflection in the longitudinal temperature profile occurs at a terrain elevation of about 600 ft mean sea level (MSL), which is approximately the same elevation at which increased stream heating occurred on the Lower NF (Figure 11). One tributary was detected on the East Bank Lower NF and it was slightly cooler than the mainstream.

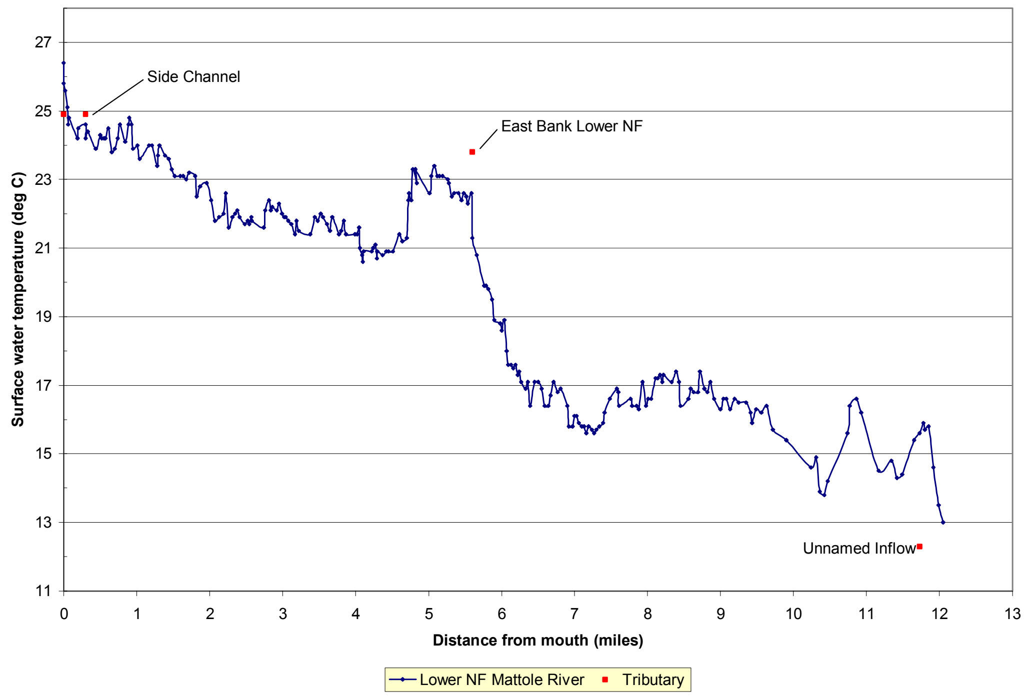


Figure 11 - Median channel temperatures versus river mile for Lower North Fork Mattole River, CA, along with the location of surface water inflows (7/20/01).

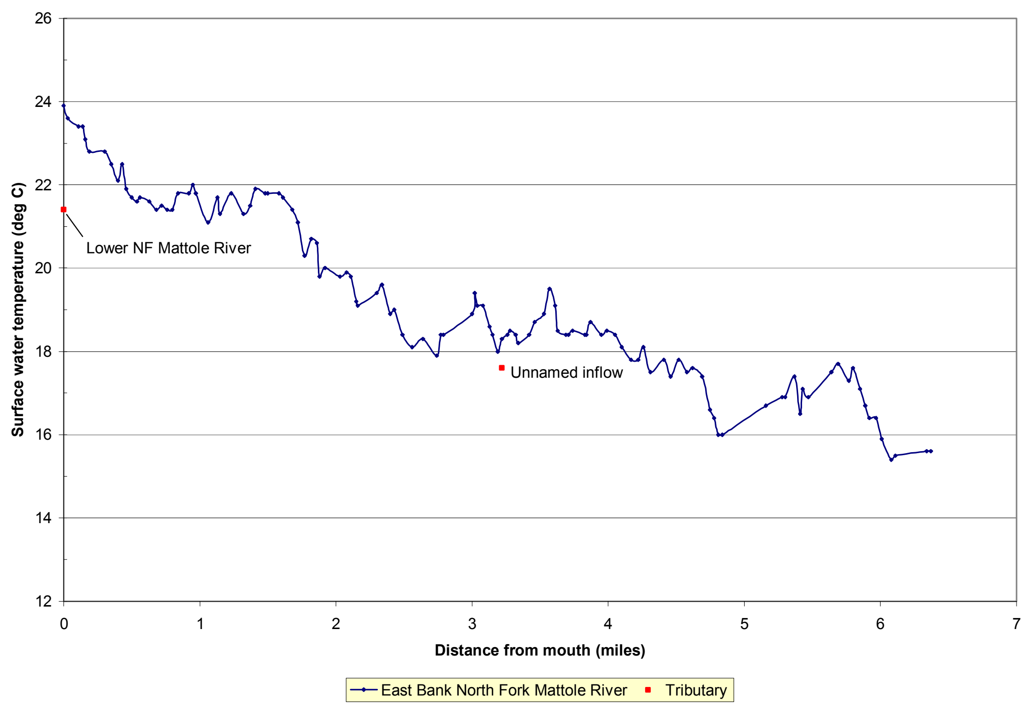


Figure 12 – Median channel temperatures versus river mile for the East Bank Lower North Fork Mattole River, CA along with the location of surface water inflows (7/20/01).

Summary

TIR remote sensing was used to map stream temperatures for the Mattole River, CA and major tributaries in the basin. The data were collected during the mid-afternoon on July 19th and 20th in order to capture low flow, high summer temperatures in support of total maximum daily load (TMDL) development. Air temperature and relative humidity gradients were measured between coastal and inland recording sites, which influenced the methods used to calibrate TIR imagery of the Mattole River. Overall, the thermal accuracy of the TIR images was within the specified tolerance of ±0.5°C and was consistent with other airborne surveys conducted in the Pacific Northwest over the past four years.

At the time of the flight, bulk stream temperatures in the Mattole River exceeded 22.0°C for over 70% of the surveyed length. Reach-scale thermal variability between the coast and river mile 50 was attributed to tributary inflows and cool water seeps. The cool water seeps were primarily detected at the downstream end of gravel bars and appeared to originate from intergravel flow within the floodplain. Spatial variability in the temperature profile was also observed between the headwaters and river mile 50, but the sources of this variability were not apparent from the imagery. On the day of the flight, a marine cloud layer persisted near the coast until the early afternoon and resulted in generally cooler air temperatures than observed inland. The marine layer likely influences the rate of stream temperature warming in the lower river and may have contributed to the generally cooler temperatures noted in the lower 10-miles of the Mattole River. Tidal influences on stream temperatures in the lower river were not evaluated as part of the airborne survey.

Longitudinal temperature profiles were derived for each of the tributaries surveyed in the basin. The tributaries generally showed downstream warming. However, the shape of the pattern, the absolute temperature increase, and the amount of spatial variability differed between streams. Although flow levels were not measured as part of the airborne surveys, the imagery suggests low flow levels on several of the surveyed streams. For instance, no surface water was detected in Mattole Canyon Creek at its confluence with the Mattole River. Higher spatial thermal variability is often observed under low flow conditions due to the relative influence of small energy inputs. As with the mainstream, small cool water seeps were observed on several tributaries.

Appendix A contains example visible band and thermal infrared images for surveys conducted in the Mattole River basin. The TIR images were color mapped to highlight the range of water temperatures found in the stream. As mentioned previously (*see data limitations*), low thermal contrast existed between the stream and bank-side vegetation at several locations. The low contrast made it more difficult to see the stream and distinguish off channel features, but did not generally impact the ability to obtain accurate temperature samples. Color mapping of the images often exaggerates the impact of low thermal contrast within the image scene. The raw TIR images provided with the database allow remapping the TIR images to highlight specific features in reaches where thermal contrast is low.

The TIR surveys lay a basic groundwork to integrate the CA TMDL process into watershed planning and restoration. In particular, water temperature modeling can provide a powerful tool to address the biophysical parameters that are driving stream temperature patterns and suggest multiple pathways for remediation. In addition, the longitudinal temperature patterns provide a robust template to construct a monitoring program, in particular the deployment of in-stream temperature sensors.

Follow-on

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 how the stream is thermally structured.

3. What is the temperature pattern within critical reach and sub-reach areas? The TIR surveys in the Mattole River basin showed a number of cool water seeps that originated with the channel floodplain. Do these seeps represent thermal refugia that are used by coldwater fish species during the summer months?

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. The longitudinal temperature profiles provided in this report provide a spatially extensive, high resolution reference for water temperature status in the basin. Because stream temperature patterns can change as a result of landscape alteration or disturbance, the data provided in this report can be used to assess the impacts of land-use practices and the effects of restoration efforts in the basin.

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

7. Color videos as well as digitized visible band images provide a means to evaluate in-stream habitat and riparian/floodplain conditions at the time of the survey.

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