Airborne Thermal Infrared Remote Sensing
Crooked River, OR

Submitted to:

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Background

In 2005, the Oregon Department of Environmental Quality (ODEQ) contracted with Watershed Sciences, Inc. to provide thermal infrared (TIR) and true color digital imagery of selected streams in the Crooked River basin in Oregon (Figure 1). The data were acquired on August 5-8, 2005, during the mid-afternoon hours (1:00 to 4:00 PM). The flight dates were determined in conjunction with personnel from ODEQ and were designed to capture heat of the day summer thermal conditions in the streams.

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.

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.

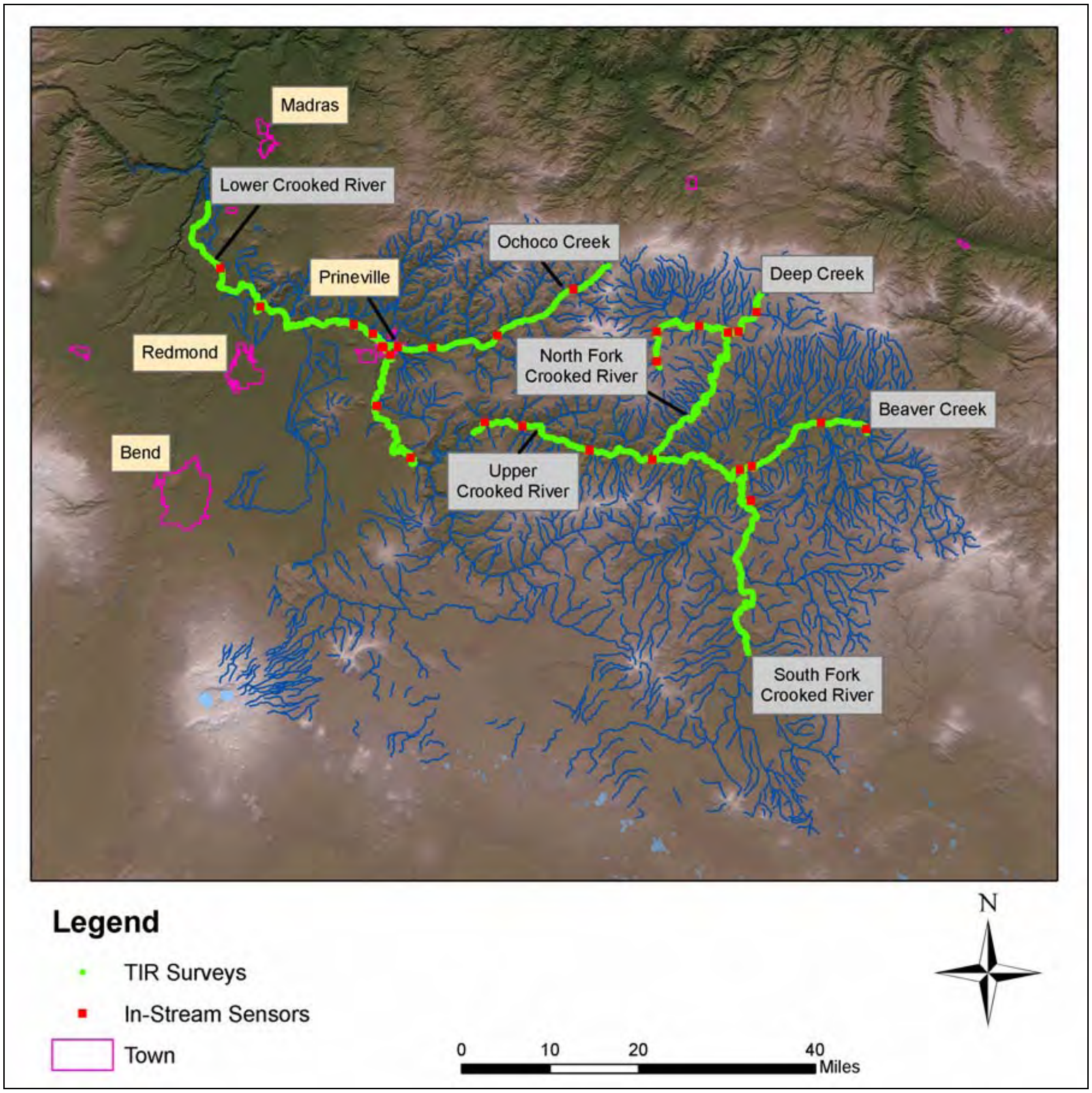

Figure 1 – Map showing the extent of the airborne thermal infrared surveys in the Crooked River Basin on August 5-8, 2005. The map also shows the location of in-stream sensors distributed by Watershed Sciences.

Methods

Data Collection

Instrumentation: 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.

Image Characteristics: The flight plans were designed to capture the width of the active channels at a high spatial resolution. Images were collected sequentially with 40% or greater vertical overlap. The helicopter maintained a flight altitude of 1200 ft above ground level (AGL) for the surveys of the Upper Crooked River, North Fork Crooked River, and Beaver Creek, resulting in an image width of 234 meters (768 ft) and a native pixel resolution of 0.37 meters (2.4 ft). An altitude of 1000 ft AGL was maintained for the remaining surveys, resulting in an image width of 195 meters (640 ft) and a native pixel resolution of 0.31 meters (2.0 ft).

Ground Control: Personnel from Watershed Sciences deployed in-stream data loggers prior to the flights in order to ground truth (i.e. verify the accuracy of) the TIR data. The data loggers were placed at public access points along the survey routes (Figure 1). Additional in-stream data were supplied by different agencies working in the basin including ODEQ, US Forest Service, Oregon Department of Fish and Wildlife (ODFW), and the Crooked River Watershed Council. 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 recorded by a portable weather station placed at the Paulina Guard Station, on the Upper Crooked River.

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 mouths. 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).

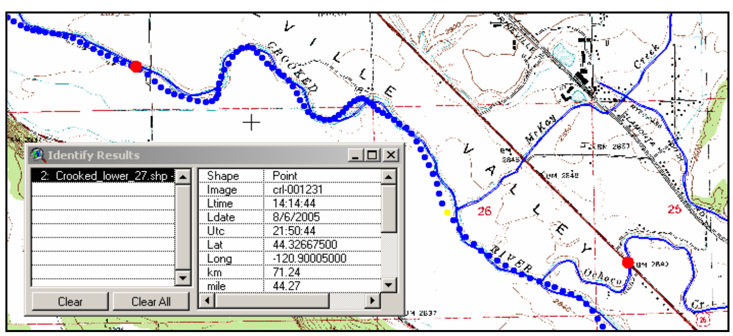

Figure 3 –Each point on the map represents a thermal image location. The inset box shows the information recorded with each image point during acquisition.

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 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). 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. 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.

The purpose of the geo-rectification was to provide more specific orientation and geographic reference for interpreting thermal features observed in the imagery. The quality of the rectification depends on the available control points. Because the image frames cover a small geographic footprint, the number and quality of control points are often limited. This is especially true near the headwaters where the stream is often difficult to see in the imagery and in areas with steep canyon walls with heavy shadowing. Small discrepancies will also exist between the thermal and true color images due to differences in the number and distribution of controls. The images were not ortho-rectified and are not intended to be used as a baseline mapping product.

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).

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. In general, radiant temperatures are not sampled unless the wetted widths are greater than 2-meters.

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.

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. The following image provides an example of three different color maps applied to the same thermal image.

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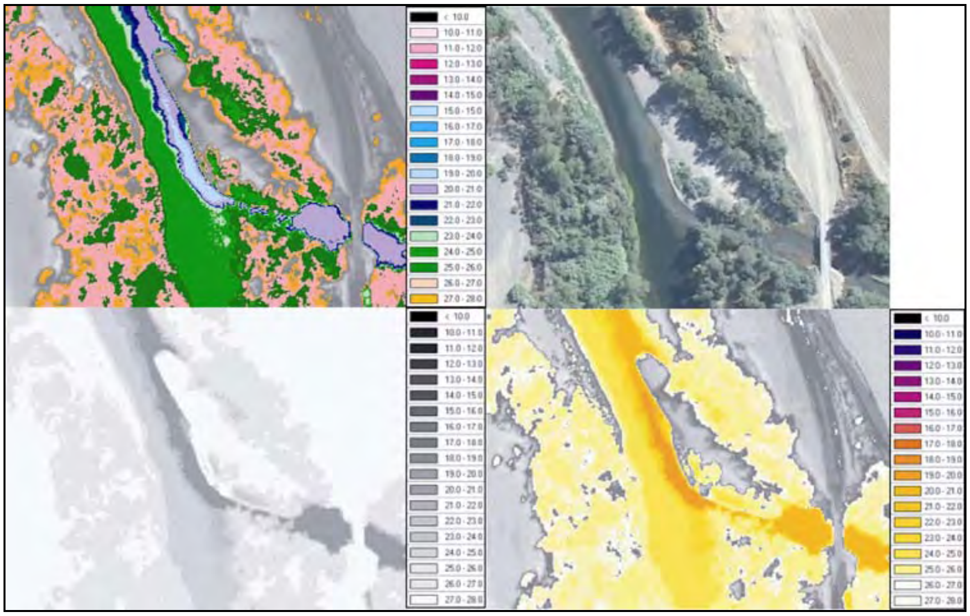
[1] Torgersen, C.E., R. Faux, B.A. McIntosh, N. Poage, and D.J. Norton. 2001. Airborne thermal remote sensing for water temperature assessment in rivers and streams. *Remote Sensing of Environment* 76(3): 386-398.



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.

Weather Conditions

Weather conditions were considered ideal on all four days of the survey with warm air temperatures, low humidity, and clear skies (Figure 4). Table 1 lists the air temperatures and relative humidity recorded during the time frame of the surveys.

Figure 4 - Weather conditions were considered ideal with clear skies, air temperatures in the low 90's (°F), with low humidity during the survey dates. The image on the left was taken on the Lower Crooked River, near Prineville on August 5,, 2005, and the image on the right was taken on the North Fork Crooked River on August 8, 2005.

		Air Temp °F	*Air Temp °C*	*RH %*	*Air Temp °F*	*Air Temp °C*	*RH %*
Date	**Time**	**Helibase**			**Prineville Airport**		
8/6/05	12:00	88.0	31.1	14.2			
	13:00	90.2	32.3	13.1			
	14:00	93.2	34.0	12.3			
	15:00	94.0	34.4	12.0			
	16:00	94.7	34.9	12.0			
	17:00	94.7	34.9	10.9			
8/7/05	12:00	84.4	29.1	11.2	85.1	29.5	15.9
	13:00	88.7	31.5	9.5	88.7	31.5	17.9
	14:00	91.0	32.8	7.8	75.9	24.4	24.9
	15:00	91.7	33.2	9.1	94.0	34.4	12.4
	16:00	91.7	33.2	9.8	96.3	35.7	10.9
	17:00	93.2	34.0	8.8	94.7	34.9	12.0
8/8/05	12:00	85.1	29.5	13.5	88.0	31.1	15.9
	13:00	87.3	30.7	15.4	89.5	31.9	15.1
	14:00	89.5	31.9	13.1	87.3	30.7	17.9
	15:00	91.7	33.2	9.5	86.6	30.3	16.3
	16:00	92.5	33.6	9.1	83.0	28.3	18.3
	17:00	90.2	32.3	12.0	85.1	29.5	12.8

Thermal Accuracy

Table 2 summarizes a comparison between the kinetic temperatures recorded by the in-stream data loggers and the radiant temperatures derived from the TIR images. Data from Watershed Sciences' sensors were supplemented with data from agency sensors. The agency sensors were used primarily to fill in gaps along the stream lengths where access was limited. Ideally, in-stream sensors were located at intervals of 7-10 miles along the survey extent. The combination of Watershed Sciences and Agency sensors resulted in a robust network of points to check radiant temperature accuracy. Ultimately a total of 45 in-stream monitoring sites were used to assess thermal accuracy.

The radiant thermal accuracy was consistent with those observed in past TIR surveys conducted in the region over the past 6 years. The absolute average difference between the kinetic temperatures measured by the in-stream sensors and the radiant temperatures measured by the TIR sensors was consistent with the target accuracy of ±0.5^{o}C. The assessed accuracies were better on the larger streams with obvious vertical mixing such as the Lower Crooked River (i.e. Lake Billy Chinook to Prineville Reservoir), the North Fork Crooked River, and Deep Creek. Conversely, the ranges of differences were greater for streams with low apparent surface flows where differential surface heating and localized subsurface exchanges were an apparent factor.

The analysis of thermal accuracy attempted to use all available in-stream data. However, if there was some uncertainty in the location of the sensor (*as with some of the agency sensors*) or if there was uncertainty about the quality of the in-stream data, the in-stream point was excluded from the analysis. Sensors such as WC-2041 on the Crooked River just upstream of the Ochoco Creek confluence and WC-2040 on the North Fork Crook River recorded kinetic temperatures that were not consistent with the calculated radiant temperatures. Since there was no evidence that the data from these sensors was not of good quality, these data were included in the comparison (Table 2). In some cases, such as the upper North Fork, in-stream sensor data was not used if the stream width was too small (*relative to pixel size*) to obtain an accurate temperature sample.

Table 2 - Comparison of in-stream (kinetic) temperatures and radiant temperatures derived from the TIR imagery for Crooked River Basin surveys.

Sensor ID	Image	Mile	Time	Kinetic *C	Radiant *C	Difference *C
			Ochoco Creek (8/5/06)			
349774	ocho-0051	0.6	13:34	18.1	17.7	0.4
WC-2046	ocho-0051	0.6	13:34	18.5	17.7	0.8
659412	ocho-0167	4.7	13:42	19.2	19.4	-0.2
WC-2052	ocho-0167	4.7	13:42	19.6	19.4	-0.3
ODEQ-32495	ocho-0167	4.7	13:42	16.5	16.8	-0.3
68509	ocho-0287	9.0	13:50	17.5	17.4	0.1
ODEQ-32404	ocho-0316	10.0	13:52	13.7	13.8	-0.2
659413	ocho-0505	18.2	14:14	23.3	22.1	1.2
464407	ocho-0816	29.7	14:25	19.5	19.8	-0.3
USFS-4020	ocho-0826	30.7	14:14	19.4	19.8	-0.4

Sensor ID	Image	Mile	Time	Kinetic *C	Radiant *C	Difference *C
Crooked River (8/6/06) - Lake Billy Chinook to Prineville Reservoir						
USGS	crl00234	12.8	13:43	19.0	19.5	-0.5
540664	crl00549	24.8	14:04	24.0	23.8	0.2
77290	crl01166	42.1	14:46	21.0	21.0	0.0
WC-2033	crl01229	44.0	14:50	22.3	21.9	0.4
WC-2041	crl01250	45.0	14:51	23.6	22.3	1.3
181257	crl01296	47.1	14:55	21.8	21.3	0.4
WC-2034	crl01351	48.7	14:59	19.6	19.1	0.5
345270	crl01353	48.8	14:59	19.0	19.2	-0.2
882337	crl01568	56.8	15:13	14.7	15.5	-0.8
ODEQ-32496	crl01577	57.2	15:14	14.9	15.1	-0.2
ODEQ-32476	crl01687	61.8	15:21	15.7	15.1	0.6
540665	crl01849	68.3	15:32	11.1	11.0	0.1
Crooked River (8/6/06) - Prineville Reservoir to South Fork						
766181	cru-0062	14.2	16:30	30.8	29.9	0.9
WC-2037	cru-0062	14.2	16:30	29.6	29.9	-0.3
464407	cru-0190	19.4	16:38	27.1	27.8	-0.7
WC-2039	cru-0466	30.1	16:57	27.8	26.5	1.3
ODEQ32499	cru0560	34.4	17:03	26.6	27.0	-0.4
WC-2035	cru-0886	49.8	17:25	24.7	25.0	-0.3
South Fork Crooked River (8/7/06)						
345270	sfc0214	7.8	13:23	22.30	22.5	-0.2
ODFW	sfc0439	17.6	13:38	23.05	23.3	-0.3
ODFW	sfc0678	27.4	13:54	23.20	23.4	-0.2
Beaver Creek (8/7/06)						
181257	beav-0056	2.0	14:31	21.6	22.8	-1.2
WC-2049	beav-0153	6.5	14:38	21.7	21.3	0.4
WC-2047	beav-0304	14.1	14:48	21.2	21.8	-0.6
540665	beav-0461	20.0	14:58	22.0	20.6	1.4
North Fork Crooked River (8/8/06)						
540663	nfc-0012	0.0	13:19	24.9	25.4	-0.5
WC-2040	nfc-0014	0.1	13:19	28.2	26.0	2.2
USFS4322	nfc-0635	25.5	14:01	23.3	23.2	0.1
659413	nfc-0646	25.7	14:02	22.2	22.4	-0.2
USFS4465	nfc-0761	30.0	14:10	24.1	23.7	0.4
Deep Creek (8/8/06)						
USFS4322	deep0008	0.0	14:42	24.4	24.4	0.0
659413	deep0023	0.1	14:43	22.8	22.8	0.0
68509	deep0057	1.5	14:46	23.3	23.2	0.1
659412	deep0163	5.4	14:53	21.3	21.8	-0.5
ODEQ-32785	deep0262	8.2	14:59	25.0	24.7	0.3

Results

Lower Crooked River

Longitudinal Temperature Profile

Median sampled temperatures were plotted versus river mile for the Lower Crooked River from its mouth at Lake Billy Chinook to Bowman Dam at the Prineville Reservoir (Figure 5). Tributaries and other sampled surface inflows (i.e. springs/seeps, irrigation returns) are labeled on the profile by river mile and are listed in Table 3. Major features (i.e. highways, diversions, and towns) are also labeled on the profile in order to provide spatial reference when interpreting the spatial temperature patterns.

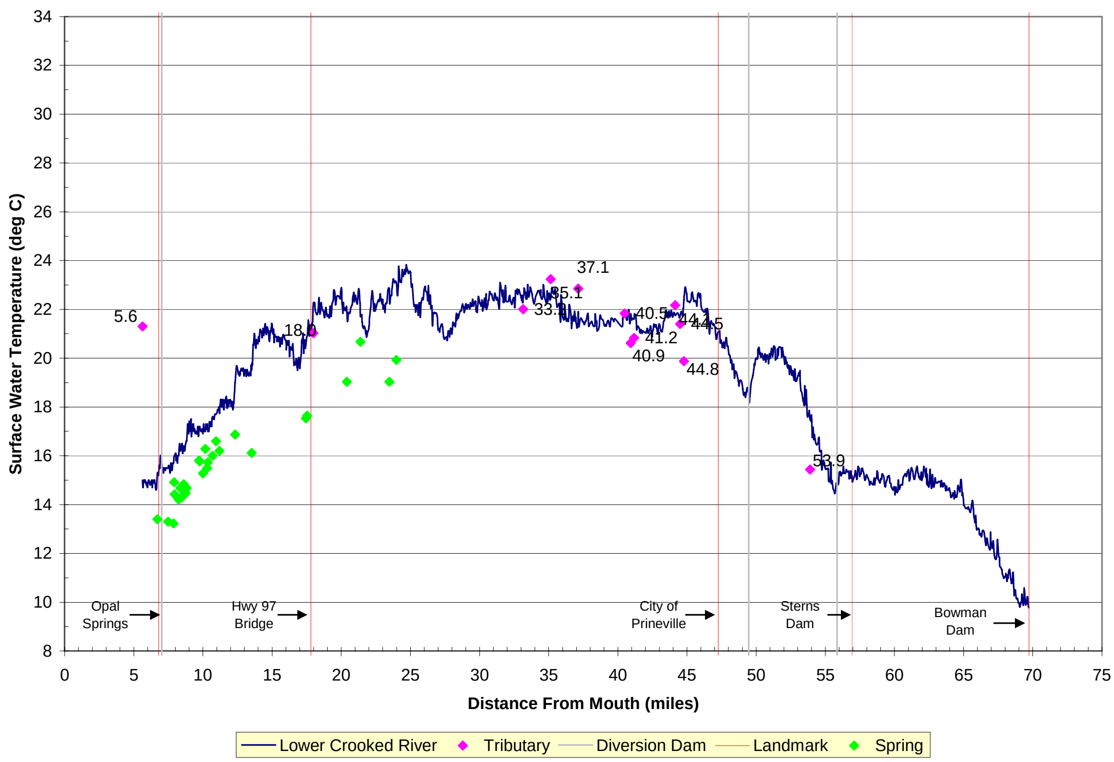


Figure 5 - Median sampled temperatures plotted versus river mile for the Lower Crooked River.

Table 3 - Name, river measure, and radiant temperatures of springs and tributaries sampled on the Lower Crooked River.

Name	Thermal Image #	Kilometer	Mile	Tributary	Crooked River °C	Difference °C
			Springs			
Opal Spring (RB)	crl-000080	10.78	6.7	13.4	15.3	-1.90
Spring (RB)	crl-000097	12.03	7.5	13.3	15.5	-2.20
Spring (LB)	crl-000107	12.66	7.9	13.2	15.7	-2.47
Spring (RB)	crl-000108	12.74	7.9	14.9	16.0	-1.08
Spring (LB)	crl-000109	12.80	8.0	14.4	16.0	-1.58
Spring (LB)	crl-000116	13.26	8.2	14.2	16.0	-1.79
Spring (LB)	crl-000119	13.46	8.4	14.7	16.2	-1.52
Spring (LB)	crl-000121	13.59	8.4	14.3	16.4	-2.12
Spring (LB)	crl-000125	13.85	8.6	14.8	16.4	-1.57
Spring (LB)	crl-000129	14.08	8.8	14.5	16.5	-2.03
Spring (LB)	crl-000131	14.19	8.8	14.7	16.6	-1.92
Spring (LB)	crl-000153	15.64	9.7	15.8	17.1	-1.29
Spring (LB)	crl-000154	15.71	9.8	15.8	17.2	-1.43
Spring (LB)	crl-000159	16.09	10.0	15.3	16.9	-1.62
Spring (LB)	crl-000163	16.38	10.2	16.3	17.0	-0.72
Spring (LB)	crl-000166	16.59	10.3	15.5	17.3	-1.80
Spring (LB)	crl-000167	16.66	10.4	15.7	17.0	-1.27
Seeps (LB)	crl-000176	17.22	10.7	16.0	17.6	-1.60
Seeps (LB)	crl-000182	17.62	11.0	16.6	17.7	-1.10
Spring (LB)	crl-000188	18.02	11.2	16.2	17.7	-1.53
Spring (LB)	crl-000215	19.82	12.3	16.9	19.0	-2.13
Spring (LB)	crl-000250	21.77	13.5	16.1	19.5	-3.39
Spring (LB)	crl-000343	28.06	17.4	17.5	20.6	-3.04
Springs (LB)	crl-000346	28.22	17.5	17.6	20.6	-2.94
Spring (RB)	crl-000422	32.84	20.4	19.0	21.9	-2.88
Spring (LB)	crl-000449	34.42	21.4	20.7	21.7	-1.04
Spring (LB)	crl-000508	37.79	23.5	19.0	22.9	-3.83
Spring (LB)	crl-000525	38.61	24.0	19.9	23.1	-3.15
			Tributary or Surface Flow			
Lake Billy Chinook	crl-000055	9.06	5.6	21.3	15.0	6.30
Unnamed Tributary (LB)	crl-000360	28.95	18.0	21.0	22.3	-1.25
Dry River (LB)	crl-000822	53.36	33.2	22.0	22.5	-0.47
McAllister Slough (LB)	crl-000892	56.56	35.1	23.2	22.5	0.78
Unnamed Tributary (LB)	crl-000983	59.75	37.1	22.9	21.9	0.95
Lytle Creek (RB)	crl-001111	65.14	40.5	21.8	21.7	0.09
Unamed Tributary (RB)	crl-001126	65.87	40.9	20.6	21.8	-1.19
Unnamed Tributary (RB)	crl-001136	66.26	41.2	20.8	21.6	-0.78
McKay Creek (RB)	crl-001229	71.03	44.1	22.2	21.8	0.41
Unnamed Tributary (RB)	crl-001236	71.62	44.5	21.4	21.7	-0.32
Ochoco Creek (RB)	crl-001242	72.05	44.8	19.9	22.4	-2.50
Cool Flume Plume (RB)	crl-001495	86.75	53.9	15.4	17.5	-2.05

Observations and Analysis

The Lower Crooked River exhibited a wide range of in-stream temperatures over the 64.1 mile survey extent between the Prineville Reservoir and Lake Billy Chinook. Radiant water temperatures ranged from a minimum of 9.8°C at the Bowman Dam outlet to a local maximum 23.8°C at mile 24.7. A total of twelve surface inflows were sampled during the analysis. Of these, only five were sources of cooling to the main stem Crooked River. Twenty-eight ground water discharges (i.e. springs and seeps) were detected and sampled during the analysis. All of the springs were detected in the lower 24-miles of the Crooked River.

The Prineville Reservoir has a bottom release at the dam and river temperatures were expectedly cold (9.8°C). Water temperatures warmed rapidly downstream of the dam reaching 15.1°C at river mile 63.0 where they remained relatively consistent (±0.4°C) to the diversion at mile 55.8. Longitudinal heating rates changed significantly downstream of the diversion with surface water temperatures reaching 20.5°C at mile 51.7. Inspection of the topographic base map shows that the diversion is located at the transition from the steep walled Prineville Canyon to a lower gradient reach upstream of the town of Prineville. The rapid increase observed in the longitudinal heating rate is likely due to a change in valley morphology (i.e. lower flow velocity) combined with some loss of in-stream flow.

A decrease of ~2.0°C in surface water temperatures was observed just upstream of a second diversion at river mile 49.5. The source of cooling at this location was not apparent from the imagery. Downstream of the second diversion, water temperatures continued to warm steadily reaching a local maximum of 22.9°C at mile 44.9. Between river mile 44.9 and mile 27.7, surface water temperatures varied between 22.9°C and 20.7°C. Of the 12 tributary inflows sampled during the analysis, nine were observed through this reach. Ochoco Creek (mile 44.8) was 2.5°C cooler than the Crooked River at the confluence and appeared to have a direct cooling influence on the river.

A survey maximum of 23.8°C was observed at river mile 24.7. From this point, the Crooked River exhibited a general cooling trend reaching 14.7°C at Lake Billy Chinook This reach marks a transition from the open valley to the very steep Crooked River gorge downstream of the Hwy 97 crossing. The reach was characterized by a large number of cold springs that were detected in the imagery. These ground water discharges were presumably the main source of cooling in the lower 24.7 miles of the Crooked River.

The Crooked River downstream of Hwy 97 was surveyed with airborne TIR in August 2002. Figure 6 provides a comparison of the 2005 and 2002 surveys of the Crooked River downstream of mile 17.8. The 2002 survey also showed a general cooling trend and a large number of groundwater inflows throughout the survey extent. While cooler overall temperatures were observed in 2002, visual inspection of the profiles shows that spatial temperature patterns were very similar between the two years.

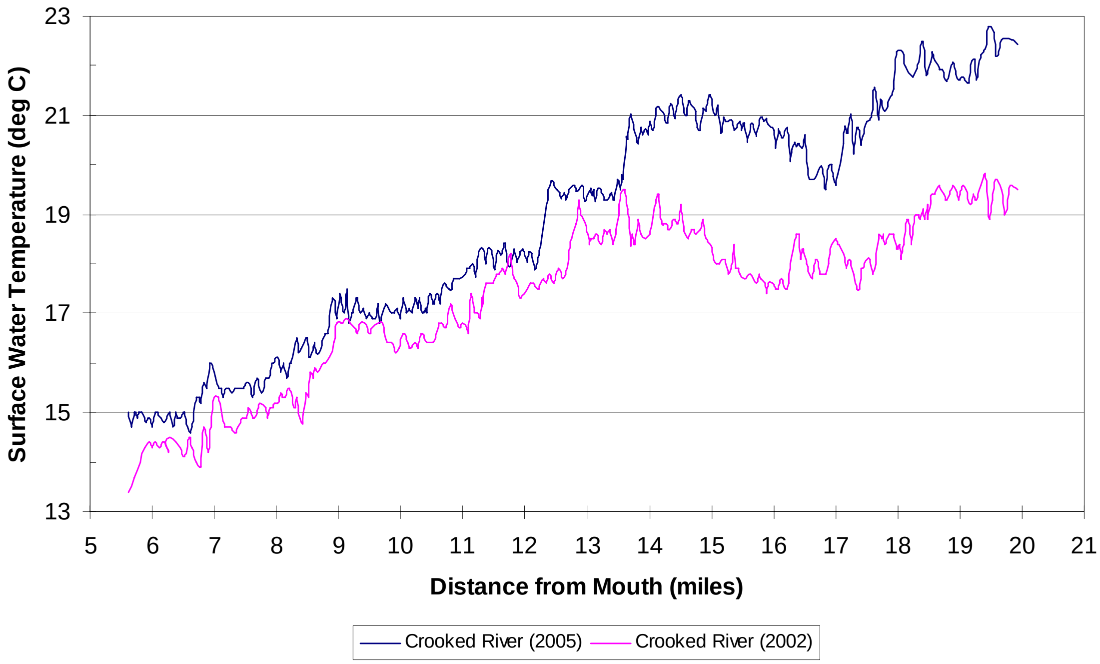
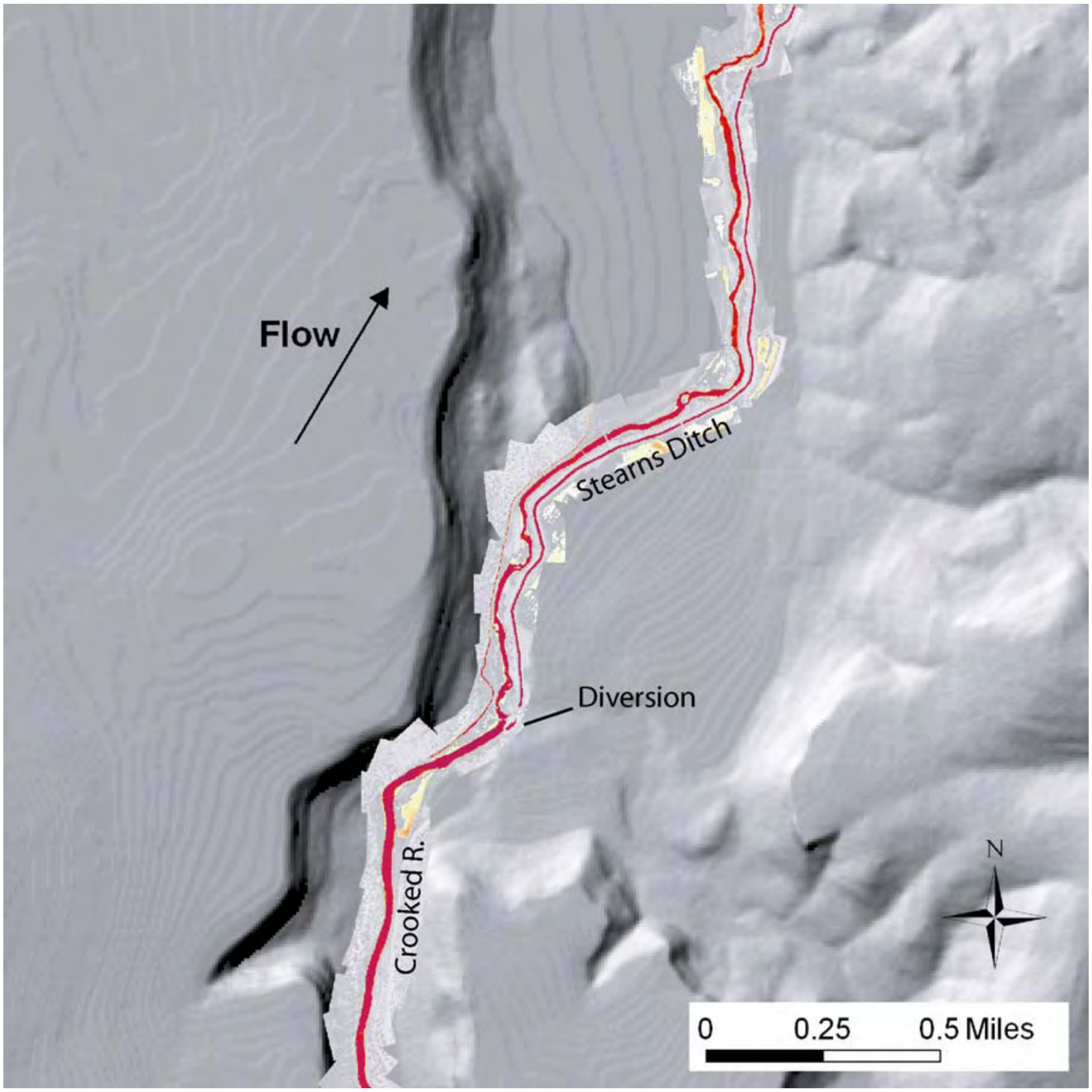
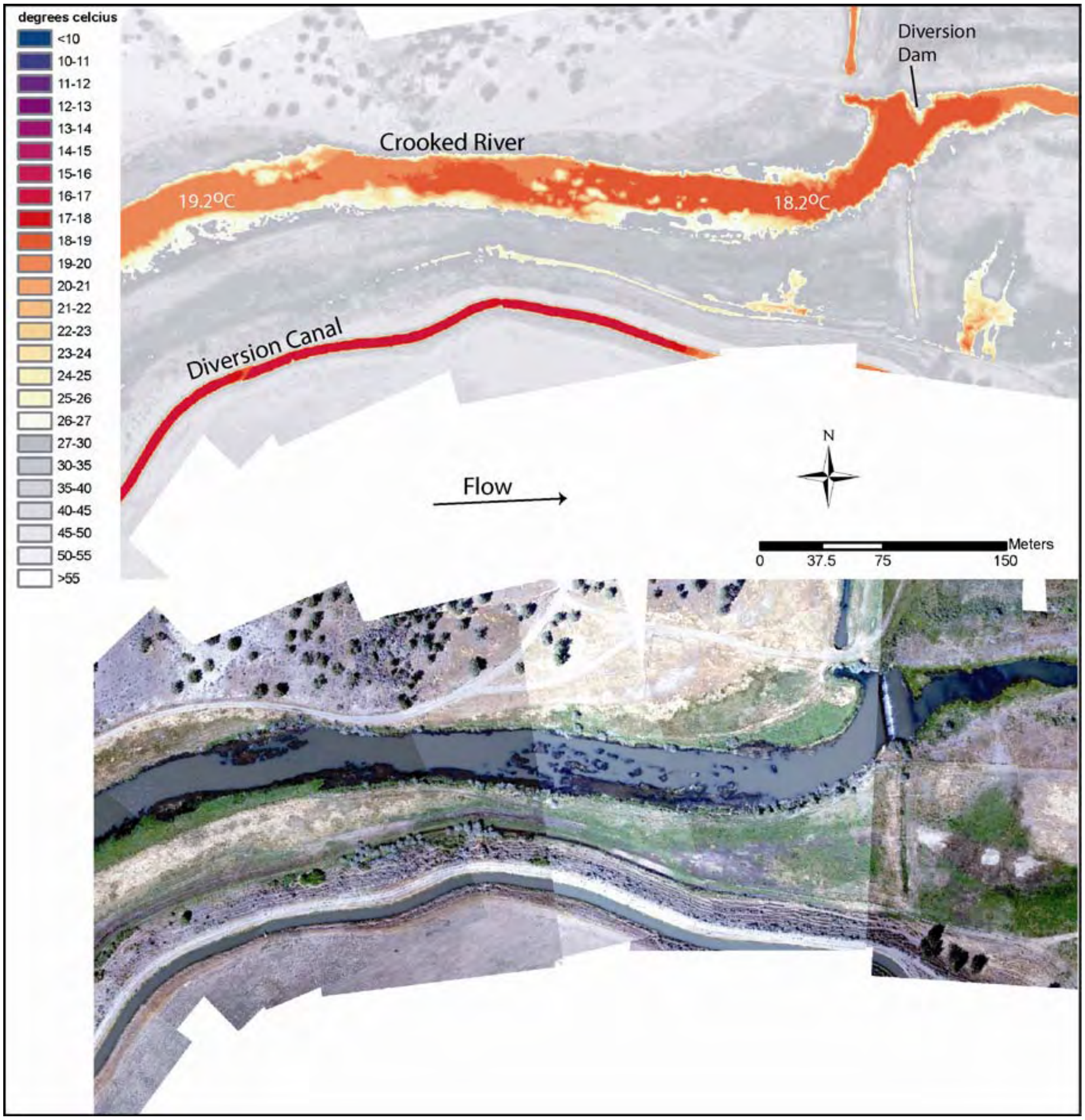


Figure 6 – Comparison of the longitudinal profiles derived from TIR surveys conducted in August 2002 and August 2005.

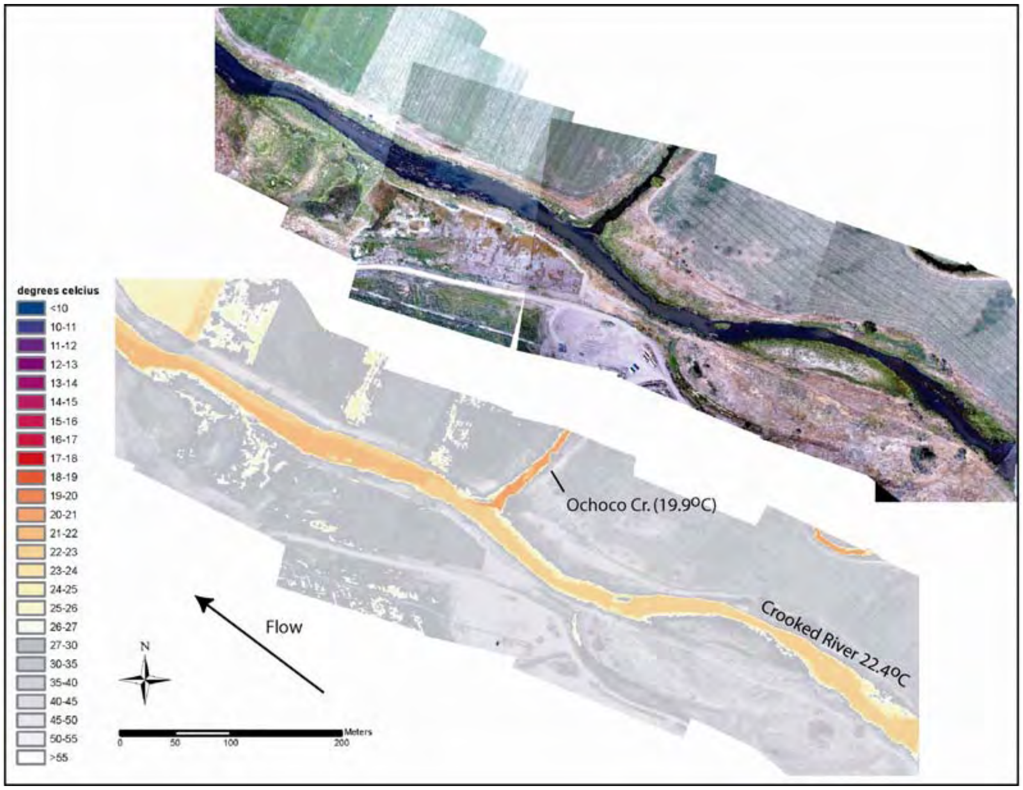
Selected Imagery



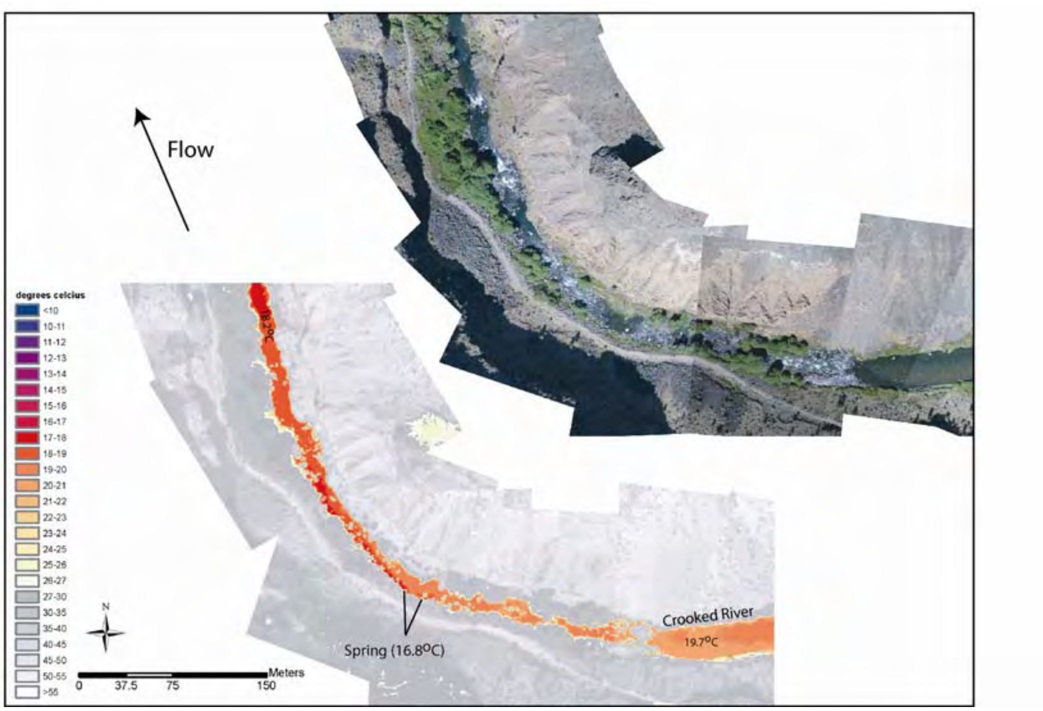
The image above shows the TIR mosaic draped over a hillshade of the 10-meter digital elevation model. Longitudinal heating rates increased downstream of the diversion dam at river mile 55.9. Valley morphology also changes at this location as the Crooked River emerges from the canyon into the less confined valley. The increase in longitudinal heating rate at this location was probably due to a combination of factors.



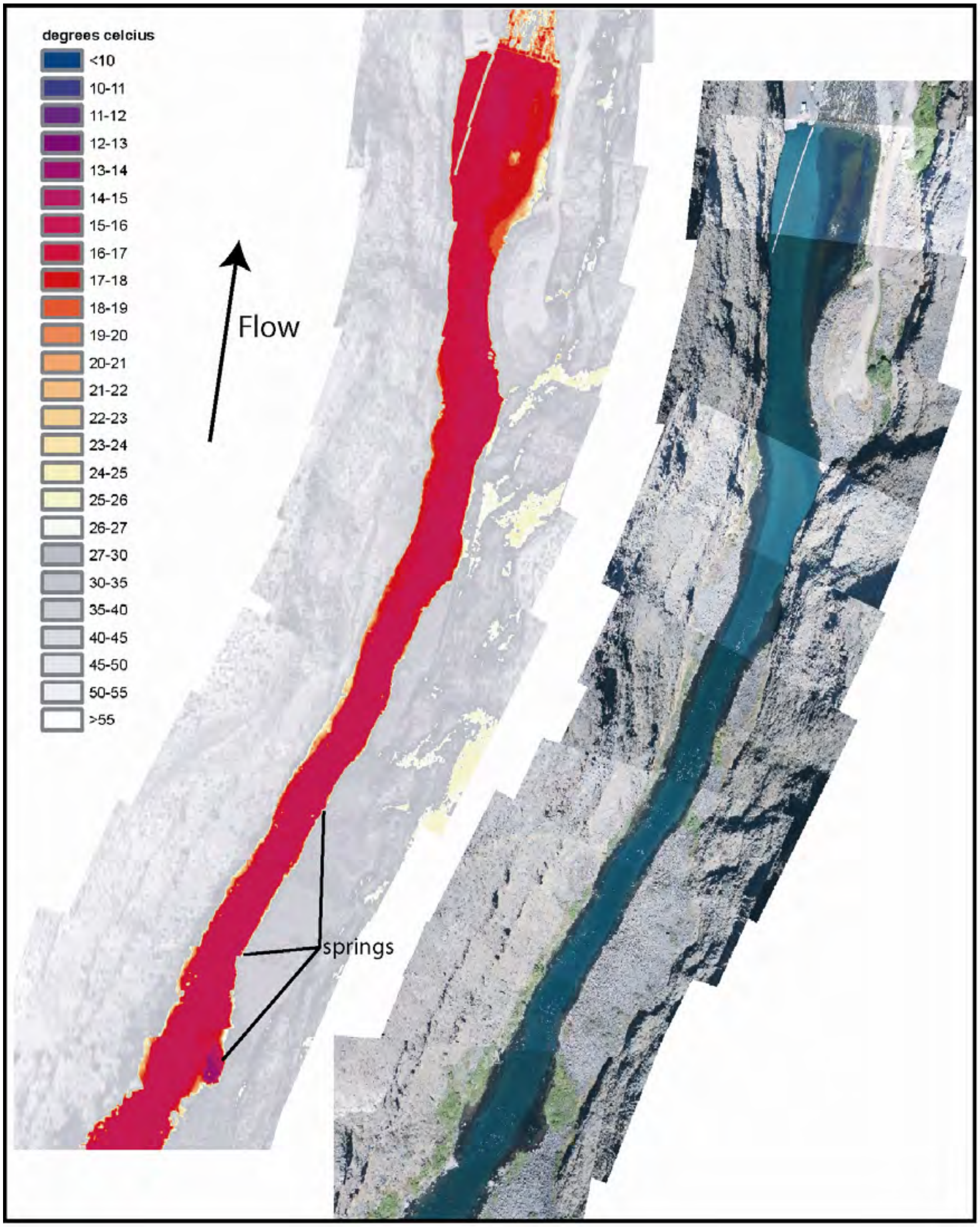
The TIR (top) and true color (bottom) images show the Crooked River at mile 49.5. A sharp decrease in radiant stream temperatures were observed just upstream of the diversion. The source of cooling was not apparent from the imagery. It is also important to note that the surface temperatures in the diversion canal are cooler than the bulk temperatures in the Crooked River. The canal is diverted ~6 miles upstream at the Stearns Dam. While no definitive conclusions can be made from the imagery alone, the canal may have a smaller width to depth ratio than the Crooked River resulting in a decreased longitudinal heating rate.



The TIR image (bottom) and true color image (top) shows the confluence of Ochoco Creek and the Crooked River. Ochoco Creek (19.9^{o}C) was observed as source of cooling to the Crooked River.



The TIR image (bottom) and true color image (top) shows a spring discharge along the left bank. A network of springs were detected in the lower 17.5 river miles.



The TIR image (left) and true color image (right) show the Crooked River at mile 7.5. The image shows some of the springs visible along the right bank. The diversion dam at Opal Springs is visible at the top of the image.

Upper Crooked River

Longitudinal Temperature Profile

Median sampled temperatures were plotted versus river mile for the Upper Crooked River from the Prineville Reservoir upstream to the confluence with the South Fork Crooked River and Beaver Creek (Figure 7). Tributaries and other sampled inflows (i.e. springs/seeps, irrigation returns) are labeled on the profile by river mile. The location and temperatures of tributaries and other sampled inflows are listed in Table 4.

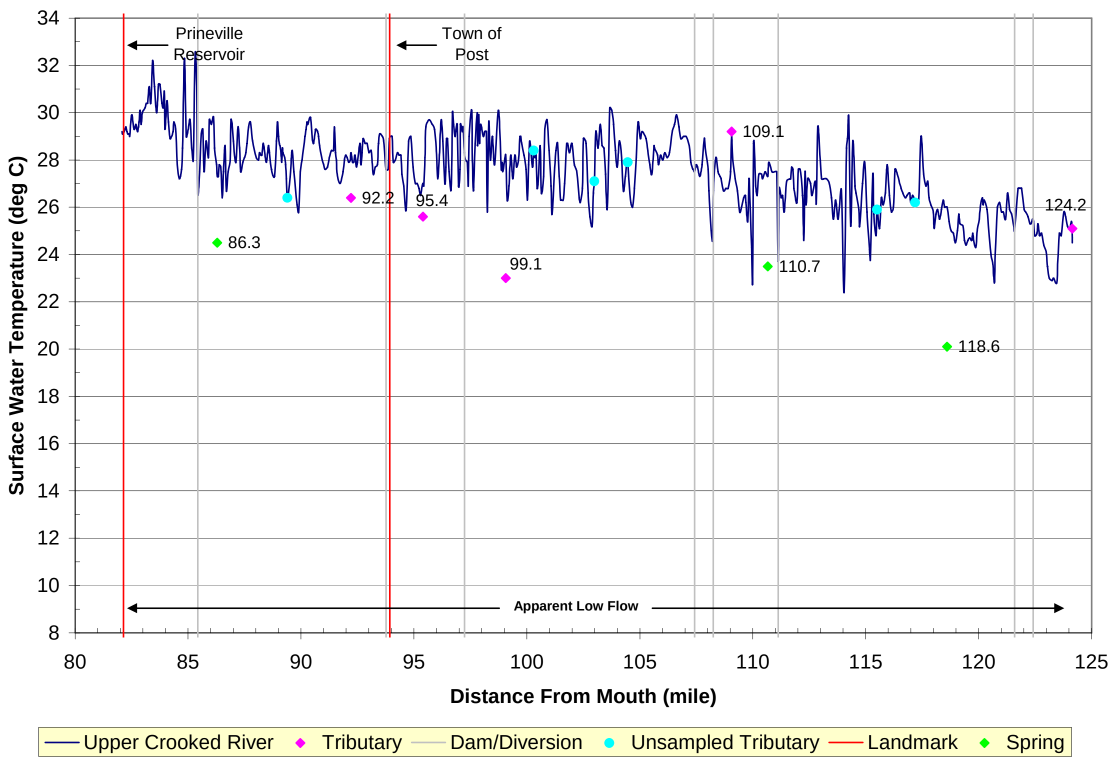


Figure 7 - Median sampled temperatures plotted versus river mile for the Upper Crooked River. River miles are calculated from the mouth of the Crooked River at Lake Billy Chinook.

Table 4 - Name, river measure, and radiant temperatures of inflows sampled on the Upper Crooked River.

	IMAGE	KM	MILE	Tributary °C	Crooked R. °C	Difference °C
Spring (LB)	cru-000118	138.87	86.3	24.5	27.3	-2.8
Spring (LB)	cru-000697	178.10	110.7	23.5	27.3	-3.8
Spring (LB)	cru-000858	190.87	118.6	20.1	26.0	-5.9
Horse Heaven Creek (RB)	cru-000255	148.39	92.2	26.4	28.3	-1.9
Newsome Creek (LB)	cru-000326	153.53	95.4	25.6	27.0	-1.4
Cool Water Midstream ( )	cru-000443	159.42	99.1	23.0	28.2	-5.2
North Fork Crooked River (RB)	cru-000663	175.52	109.1	29.2	29.0	0.2
South Fork Crooked River (LB)	cru-000990	199.80	124.2	25.1	24.5	0.6

Observations and Analysis

Radiant water temperatures in the Upper Crooked River (*i.e. Prineville Reservoir to Beaver Creek*) exhibited a high degree of local thermal variability with measured surface temperatures ranging from 22.4°C to 32.5°C. Of the six surface inflows sampled during the analysis, four contributed cooler water the main stem river.

Although flows were not measured as part of the airborne survey, the high degree of the spatial thermal variability observed in the profile is characteristic of streams under very low flow conditions. Inspection of the true color imagery and field observations showed river segments with no obvious mixing and low apparent velocities (*based on wetted channel widths, flow measurements, and flow conditions*). Similar spatial temperature patterns associated with extreme temperatures and low flow conditions have been observed on other TIR studies in the Pacific Northwest.[2, 3]

The ground level picture above shows flow conditions in the Crooked River upstream of Prineville Reservoir on 8/6/06.

The variability observed in the profile is due to the interaction of a number of factors. Differential heating at the stream surface and possible thermal stratification in the deeper pools are probable contributors to the observed spatial temperature variations. The transition from a thermally stratified condition to a well mixed condition can result in apparent temperature decreases in the temperature profile. Similarly, a transition from a partially mixed to a stratified condition can suggest a rapid apparent increase in stream temperatures.

A high degree of spatial thermal variability in small streams is also indicative of the influence of shallow sub-surface discharge on relatively warm streams. This pattern has been observed during other TIR surveys throughout the region. In these cases, sub-surface upwelling creates a dramatic, but localized decrease in stream temperatures. Stream temperatures then warm up rapidly when exposed to heating processes and mix with the warmer surface water.

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[2] *Aerial Survey in the John Day River Basin, OR, Thermal Infrared and Color Videography. Watershed Sciences, Inc. Report to Oregon State University and Bureau of Reclamation, Feb. 2004.*

[3] *Aerial Thermal Infrared Remote Sensing, Palouse River Basin, OR/ID. Watershed Sciences, Inc. Report to WA Department of Ecology, May 13, 2006.*

The interaction of multiple processes such as sub-surface discharges and differential surface heating confounds direct interpretation of the TIR imagery. However, the contribution of sub-surface discharge should not be discounted as a source of thermal variability. Follow-on analysis may examine channel morphology (i.e. gradient, channel width, and complexity) in areas where relatively large decreases in stream temperature were observed in the TIR data. These parameters can be used as indicators of the potential for sub-surface exchange in any given reach segment.

Merged Longitudinal Temperature Profile

Figure 8 illustrates the combine longitudinal temperature profile for the full surveyed length of the Crooked River. The profile provides a stark contrast of thermal conditions in above and below the Prineville Reservoir.

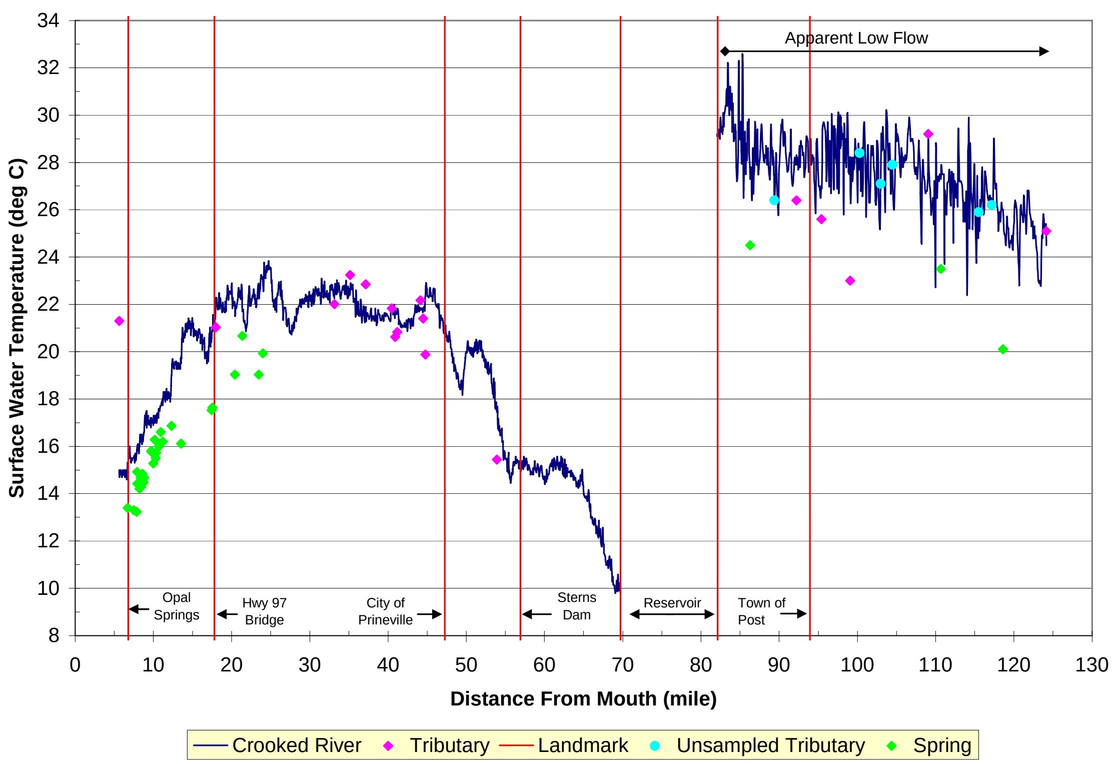
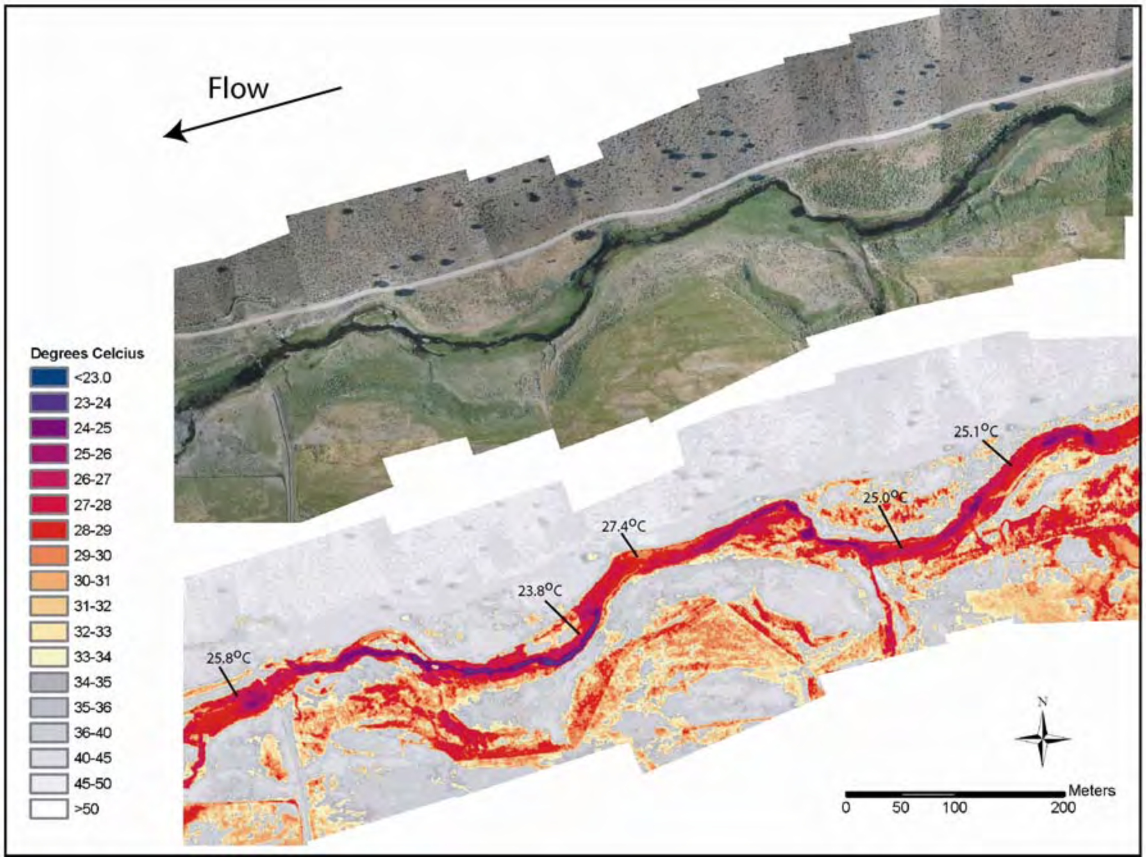
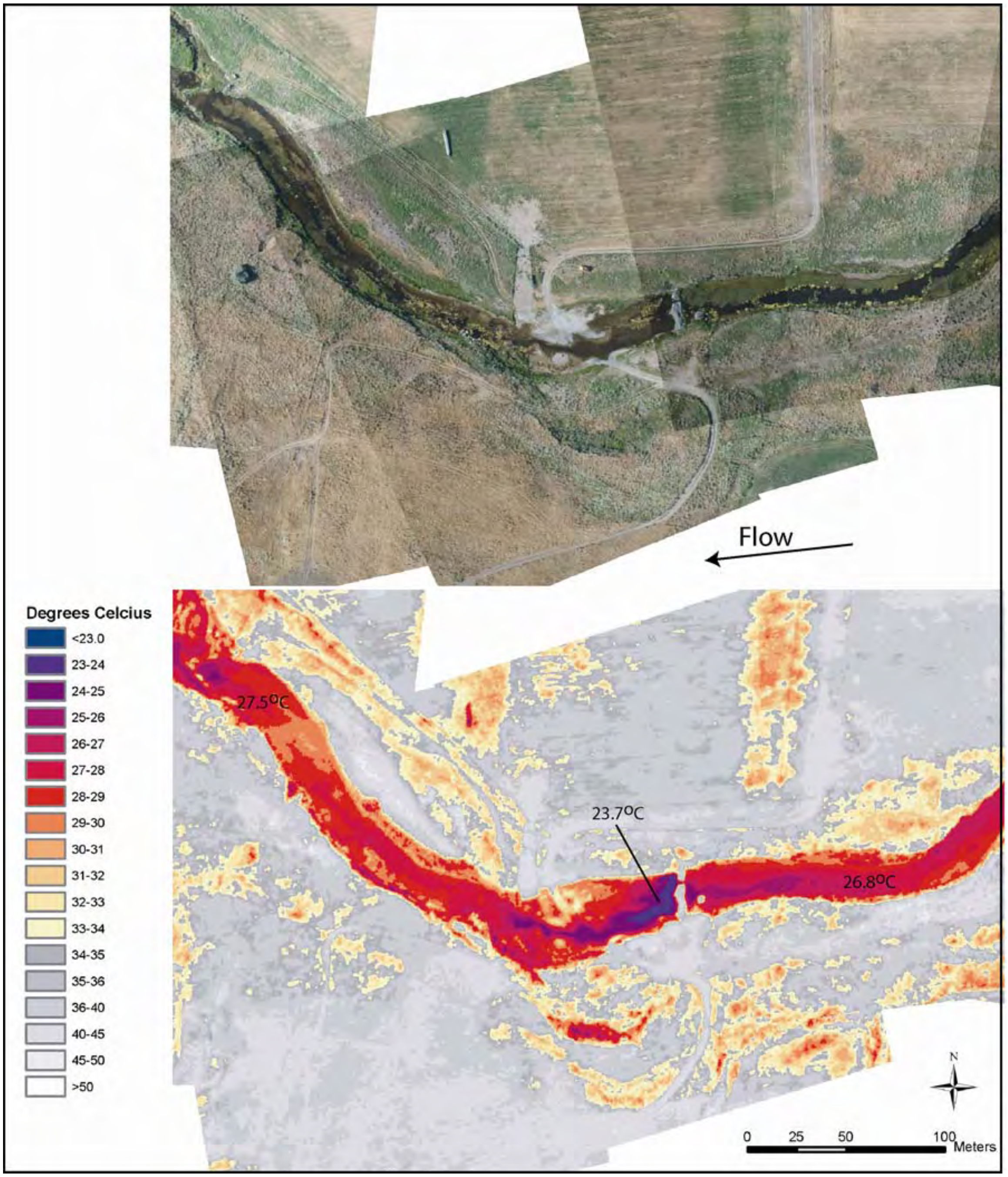


Figure 8 - Median sampled temperatures plotted versus river mile for the Crooked River.

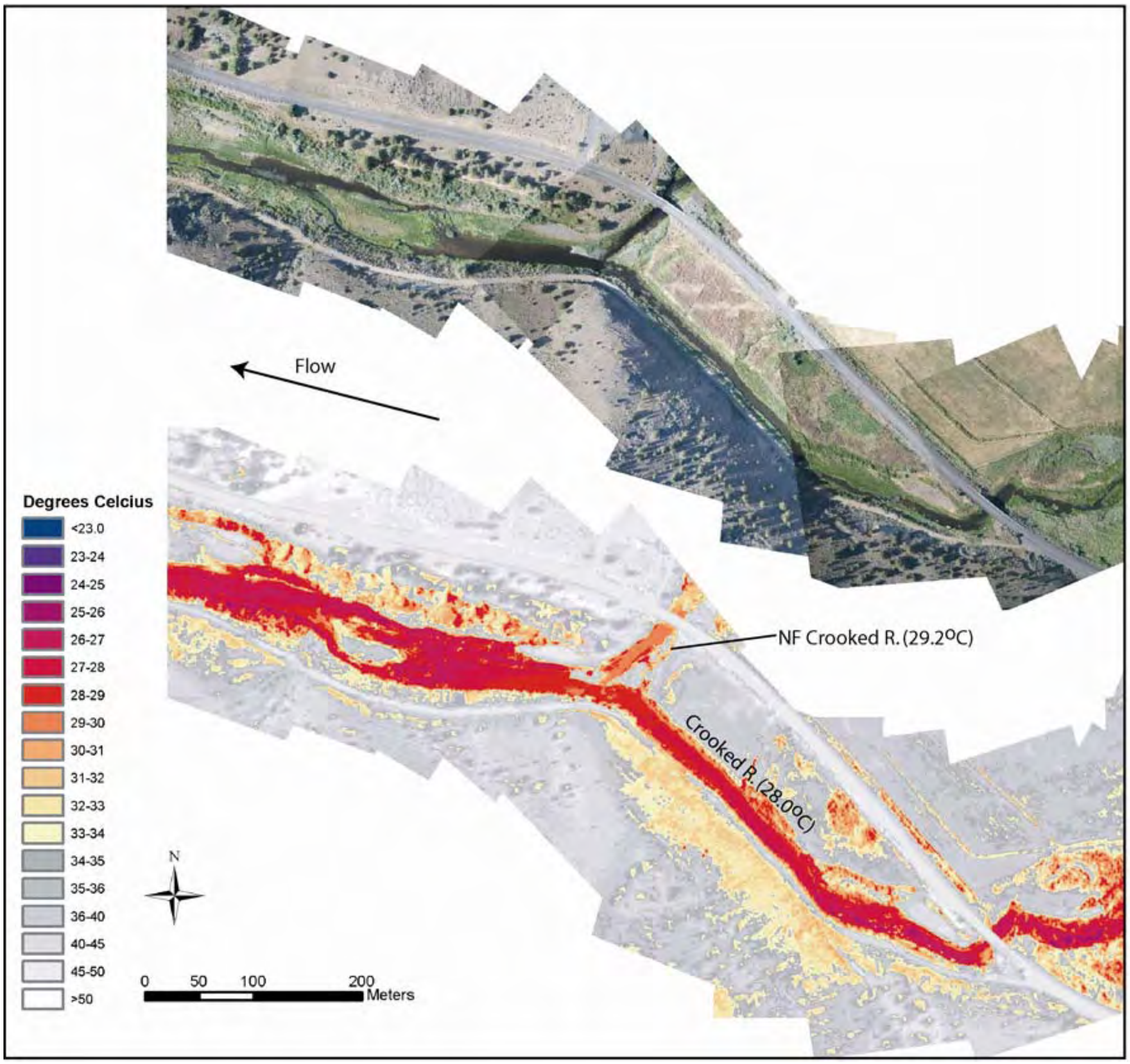
Selected Imagery



The TIR image (bottom) and true color image (top) illustrate conditions in the Crooked River at mile 115.5. The TIR image illustrates the high degree of local spatial temperature variability observed in the Crooked River above Prineville Reservoir. The temperatures shown on the thermal image represent median values of samples taken from the center of the channel from individual frames. The observed thermal variability is due cooler water mixing to the surface at riffles and river bends, however, it is difficult to determine through inspection of the imagery if the cooler water originates from sub-surface up-welling or if there is differential heating (or stratification on the pools).



The TIR image (bottom) and true color image (top) shows the Crooked River at river mile 111.2. The thermal image shows cooler water emerging from beneath an apparent impoundment. Within 50 meters of the impoundment, the cooler water is no longer detectable at the surface. These locally cool areas contributed to the local spatial variability observed in the longitudinal temperature profile. In the true color image, algae and other aquatic vegetation is apparent in the channel providing some indication of flow conditions. The images illustrate channel and flow conditions characteristic of the river above Prineville Reservoir.



The TIR image (bottom) and true color image (top) illustrate the confluence of the North Fork Crooked River and the Crooked River at mile 109.1. Surface water temperatures on both streams exceeded 28.0°C at the time of the flight.

Ochoco Creek

Longitudinal Temperature Profile

Median sampled temperatures were plotted versus river mile for Ochoco Creek from its mouth at the Crooked River to Ahalt Creek near the headwaters (Figure 9). Tributaries and other sampled inflows (i.e. springs/seeps, irrigation returns) are labeled on the profile by river mile. Table 5 lists the name and location of each sampled inflow.

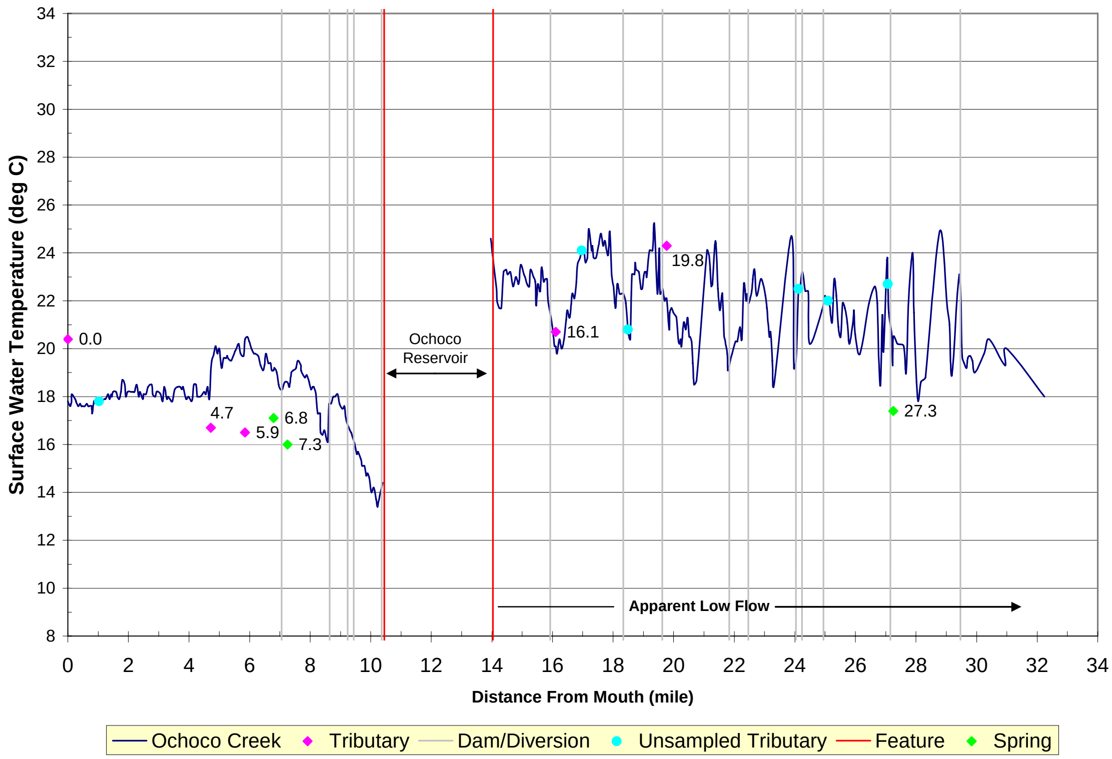


Figure 9 - Median sampled temperatures plotted versus river mile for Ochoco Creek.

Table 5 - Name, river measure, and radiant temperatures of inflows sampled on the Ochoco Creek.

	Image	km	Mile	Tributary °C	Ochoco Cr. °C	Difference °C
Spring						
Spring (RB)	ocho-000222	10.93	6.8	17.1	19.1	-2.0
Spring (RB)	ocho-000235	11.67	7.3	16.0	18.6	-2.6
Spring (LB)	ocho-000753	43.86	27.3	17.4	20.5	-3.1
Tributary						
Crooked River (LB)	ocho-000029	0.00	0.0	20.4	17.8	2.6
OID Canal Overflow (RB)	ocho-000167	7.60	4.7	16.7	19.1	-2.4
Unnamed Tributary (RB)	ocho-000198	9.41	5.9	16.5	20.4	-3.9
Lawson Creek (LB)	ocho-000445	25.93	16.1	20.7	20.1	0.6
Marks Creek (RB)	ocho-000548	31.81	19.8	24.3	22.1	2.2

Observations and Analysis

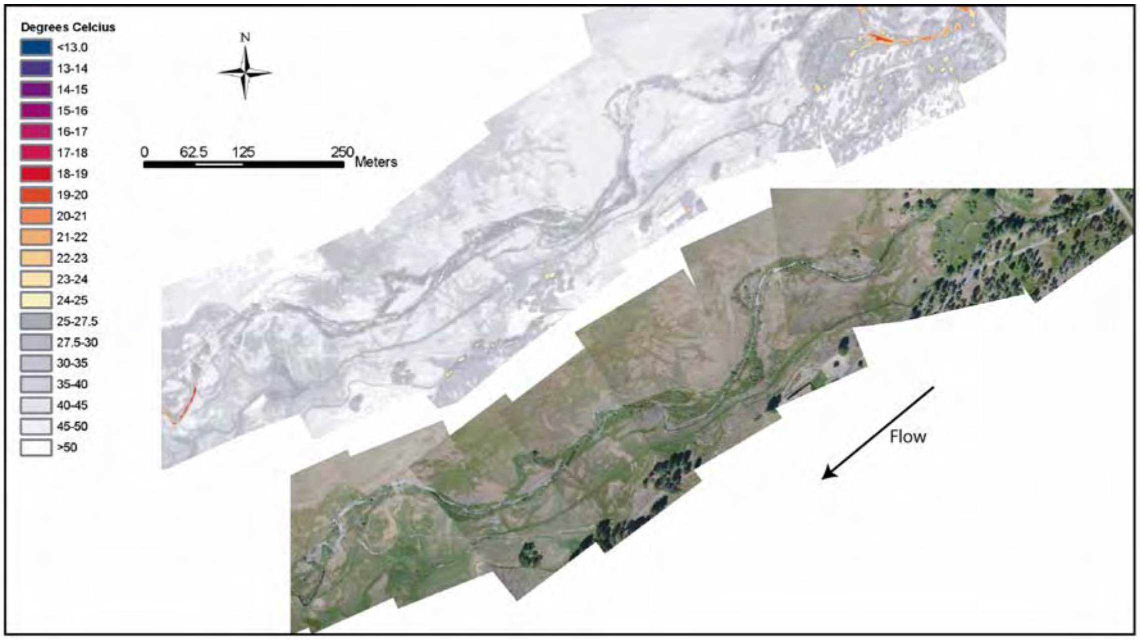
Radiant temperatures in Ochoco Creek exhibited a similar temperature pattern to those observed in the main stem Crooked River.

Above the reservoir, surface temperatures exhibited a high degree of spatial variability with temperatures ranging between 17.8°C and 24.9°C. As with the Upper Crooked River, these rapid changes in temperature over short distances suggests a combination interacting factors. Under very low flow conditions, stream temperatures often respond dramatically to relatively small inflows such as shallow sub-surface upwelling. The cooler inflows often decrease water temperatures locally, but then warm up quickly when exposed to heating processes. The artifacts associated with TIR remote sensing are also more pronounced under low flow conditions. Differential heating at the water surface can result in apparent temperature changes as the stream transitions from mixed to stratified conditions. Small stream widths also increase the probability of hybrid pixels in the temperature sample and consequently more "noise" in the resulting profile. The combination of interacting factors makes it difficult to draw conclusions about the processes driving temperatures based on interpretation of the TIR images alone.

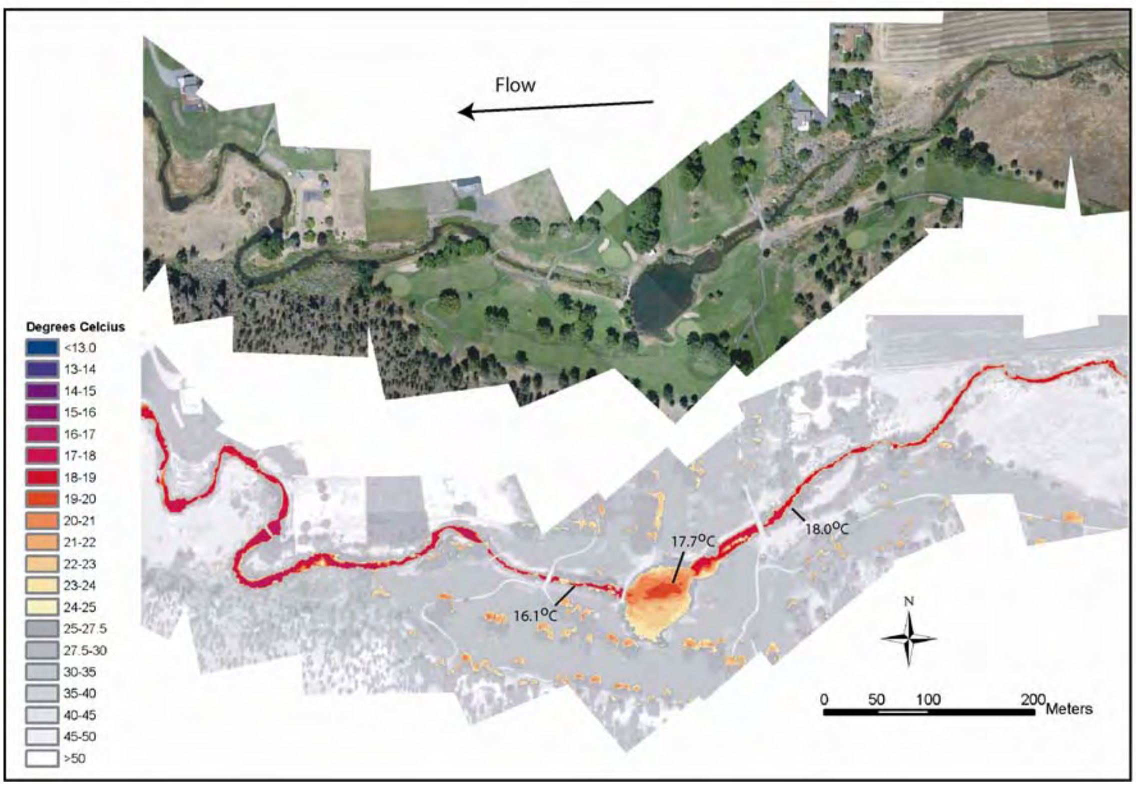
Below the reservoir, stream temperatures were relatively cool (13.4°C), but warmed steadily downstream reaching 17.7°C at mile 8.7. Stream temperatures exhibited an ~2.0°C decrease immediately downstream of a diversion dam at mile 8.6 before increasing again to 19.5°C at mile 7.6. Two tributaries were sampled between Ochoco Reservoir and the Crooked River. A cool inflow (*identified as the overflow from OID's Crooked River Canal by the Watershed Council*) was observed at river mile 4.7 and appeared to have a direct cooling influence on Ochoco Creek.

The ground level image above shows Ochoco Creek at mile 4.6. The image illustrates flow and mixing conditions in the creek at this location.

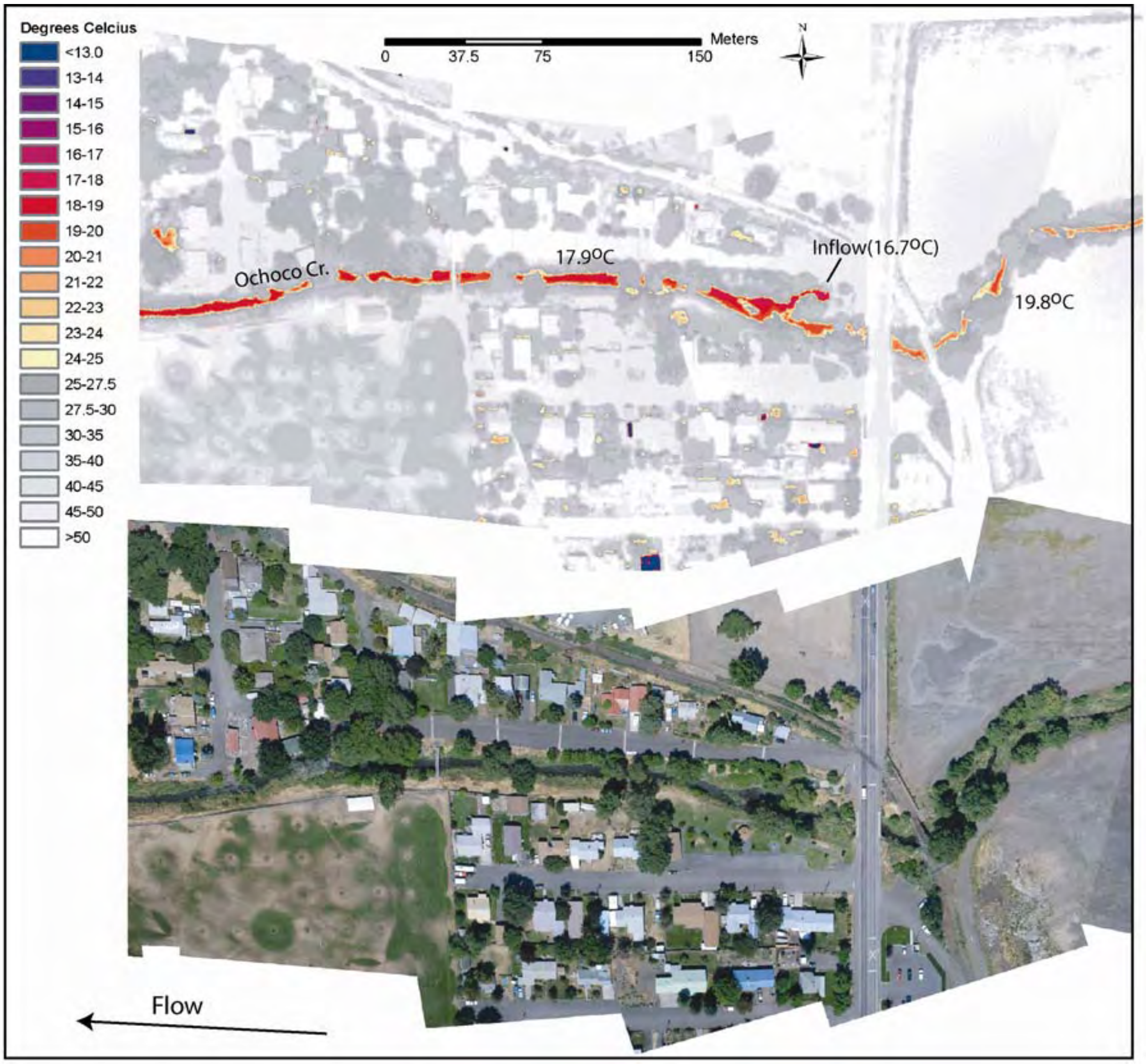
Selected Imagery



The TIR image (top) and the true color image (bottom) show Ochoco Creek at river mile 23.5. Surface water was intermittent in the upper reaches of Ochoco Creek.



The TIR image (bottom) and true color image (top) show Ochoco Creek at mile 8.6. A temperature decrease of 1.6°C was observed just downstream of the impoundment.



The TIR image (top) and true color image (bottom) show Ochoco Creek at river mile 4.7. A cool water discharge enters the creek just below the road crossing and lowers bulk main stream temperatures. The discharge was identified as the overflow from Ochoco Irrigation District's Crooked River canal.

South Fork Crooked River

Longitudinal Temperature Profile

Median sampled temperatures were plotted versus river mile for the South Fork Crooked River from its mouth at the Crooked River to the marshes at the headwaters (Figure 10). Tributaries and other sampled inflows (i.e. springs/seeps, irrigation returns) are labeled on the profile by river mile. Table 6 lists the name and location of each sampled inflow.

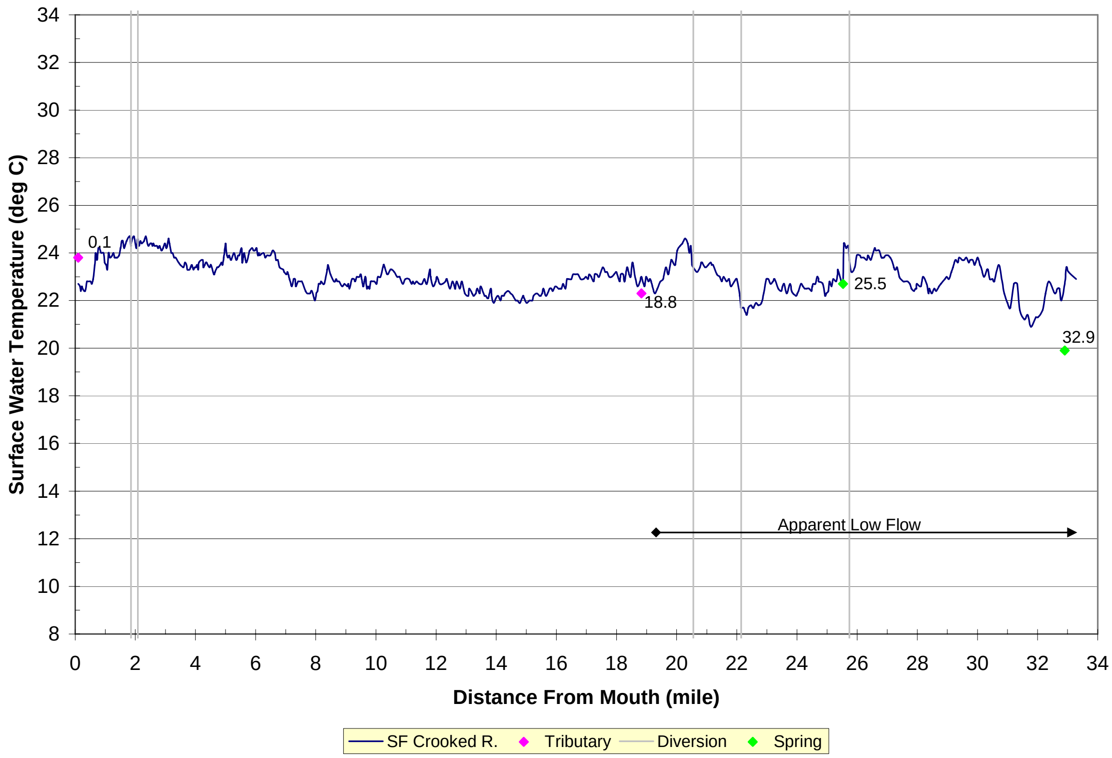


Figure 10 - Median sampled temperatures plotted versus river mile for the South Fork Crooked River.

Table 6 - Name, river measure, and radiant temperatures of inflows sampled on the South Fork Crooked River.

Tributary Name	Image	km	mile	Tributary °C	SF Crooked R. °C	Difference °C
Beaver Creek (RB)	sfc-000026	0.2	0.1	23.8	22.7	1.1
Twelvemile Creek (RB)	sfc-000473	30.3	18.8	22.3	23.0	-0.7
Spring (RB)	sfc-000635	41.1	25.5	22.7	22.8	-0.1
Spring (RB)	sfc-000877	52.9	32.9	19.9	22.7	-2.8

Observations and Analysis

Spatial temperature patterns in the South Fork Crooked River were similar to those observed in the upper main stem. Like the upper main stem, radiant temperatures were generally warm over the 33-mile survey length ranging between 20.9°C and 24.7°C. The longitudinal profile highlighted a considerable amount of local spatial variability with radiant temperatures often varying by 2-3°C over distances of less than 0.2 miles. In some cases the relatively large temperatures changes were correlated to surface water inflows (mile 25.5) and to the influence of an impoundment on flow conditions (miles 20.6, 22.1, and 25.7).

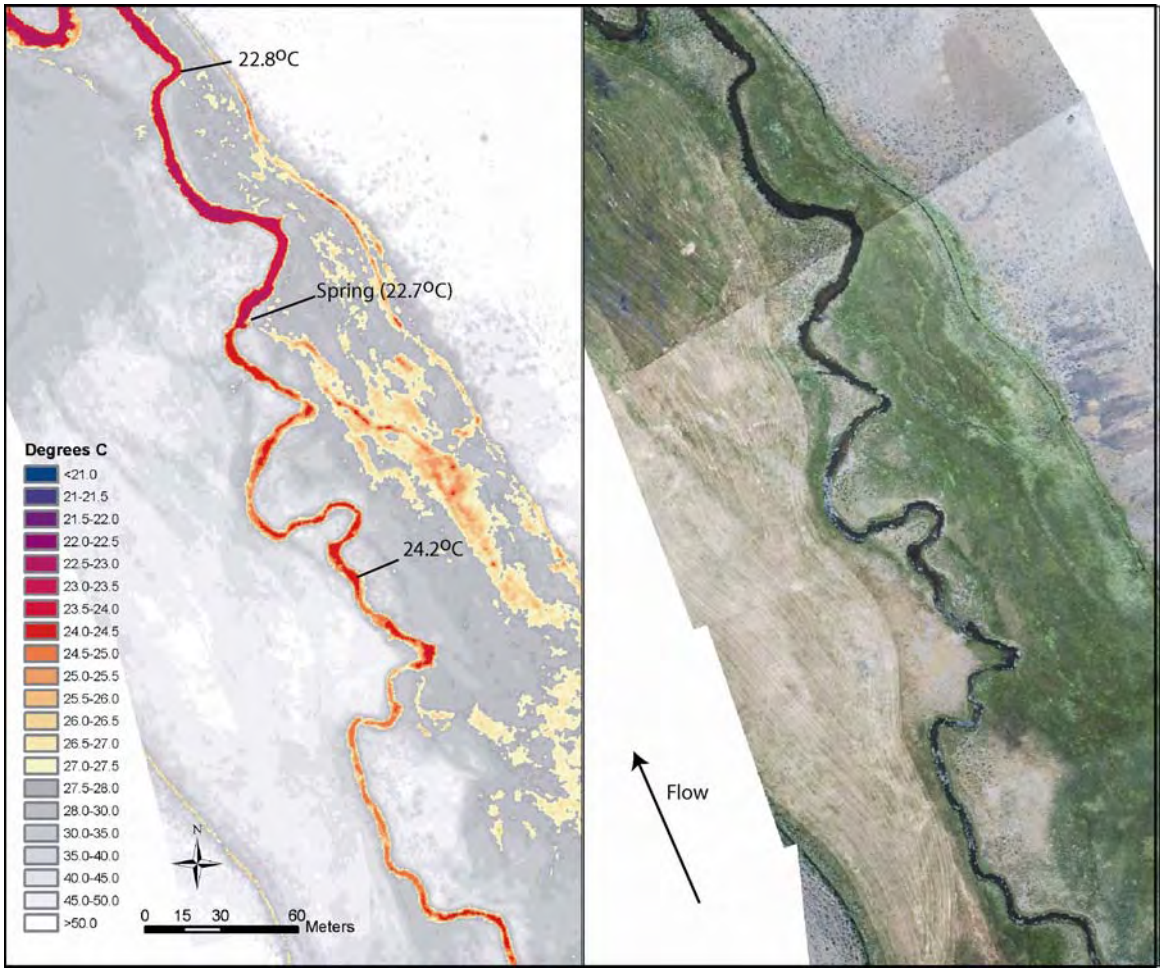
In general, the spatial temperature patterns observed in the South Fork were characteristic of a river with relatively low in-stream flows. A higher degree of local variability was observed in the lower gradient meadows near the headwaters (i.e. upstream of mile 27.0). In this area, the presumably lower in-stream flows and velocities resulted in a dramatic response to any sub-surface influence followed by rapid heating when exposed to heating processes. The lower gradient also may result in a higher probability of thermal stratification especially upstream of diversions and other impoundments.

Between mile 27.0 and 18.6, the South Fork flows through a series of marsh areas (*as indicated on the 1:24K USGS topographic maps*) with the valley intermittently constricted by topography. Radiant temperatures continued to exhibit local spatial variability, but to a lesser degree than observed in the upper meadow. Rapid local temperatures changes at miles 20.6, 22.1, and 25.7 appeared directly related to impoundments in the stream. The source of cooling at river mile 22.8 was not apparent through inspection of the imagery.

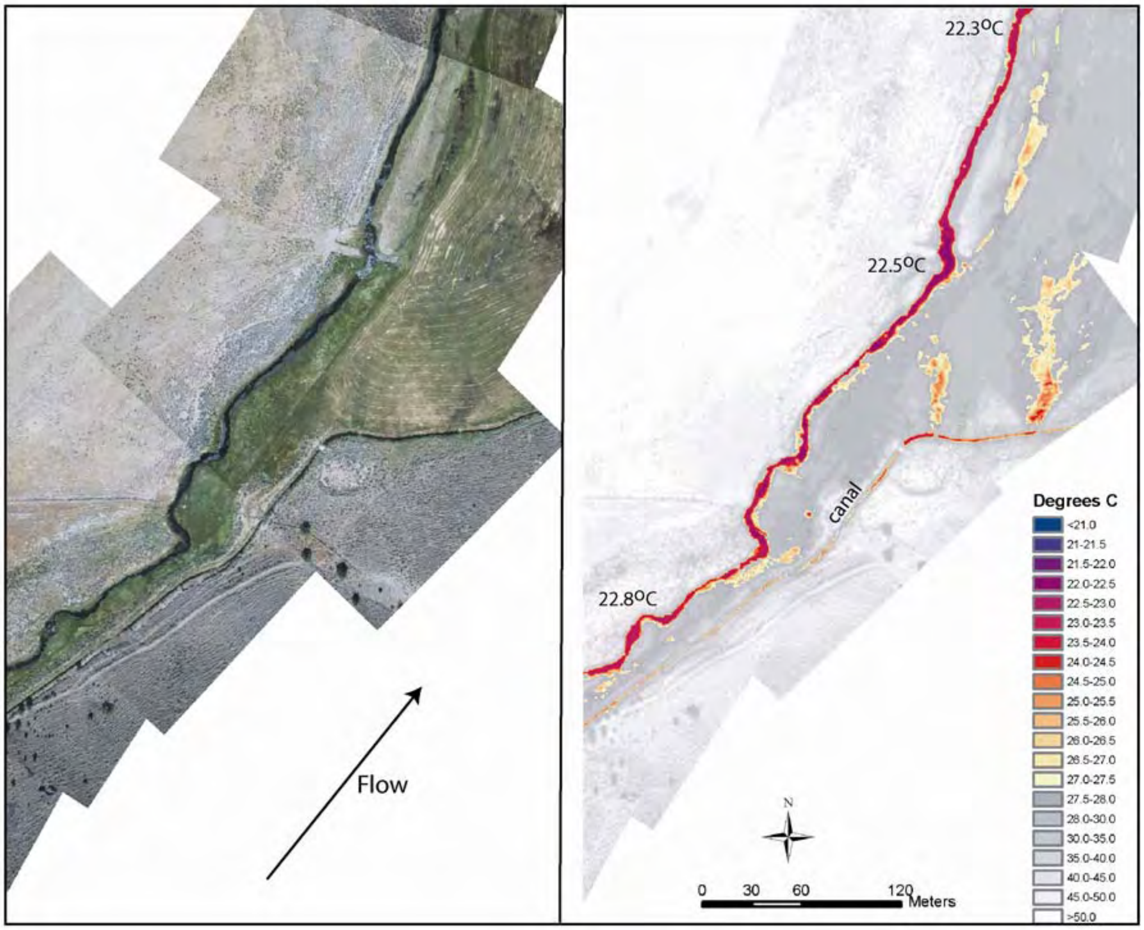
At river mile18.6 the South Fork enters a canyon reach below Twelve Mile Creek. Radiant temperatures decreased from 24.6°C to 19.3°C at the downstream end of the marsh near the Twelve Mile Creek confluence. The temperature decrease in relation to the change in valley morphology suggests that sub-surface flow in the marsh is being forced back into the active channel and having a cooling influence on bulk water temperatures. Within the canyon reach (~mile 18.6 to 11.0) radiant temperatures exhibited reach scale warming/cooling patterns, but considerably less local spatial variability.

At river mile 8.0, radiant temperatures in the South Fork warmed rapidly reaching 24.1°C by mile 6.6. Between mile 6.6 and mile 0.7, water temperatures were warm varying between 23.1°C and 24.7°C. A sharp decrease in temperatures was observed between river mile 0.7 and the river's mouth. The source of cooling near the mouth was not directly apparent from the imagery.

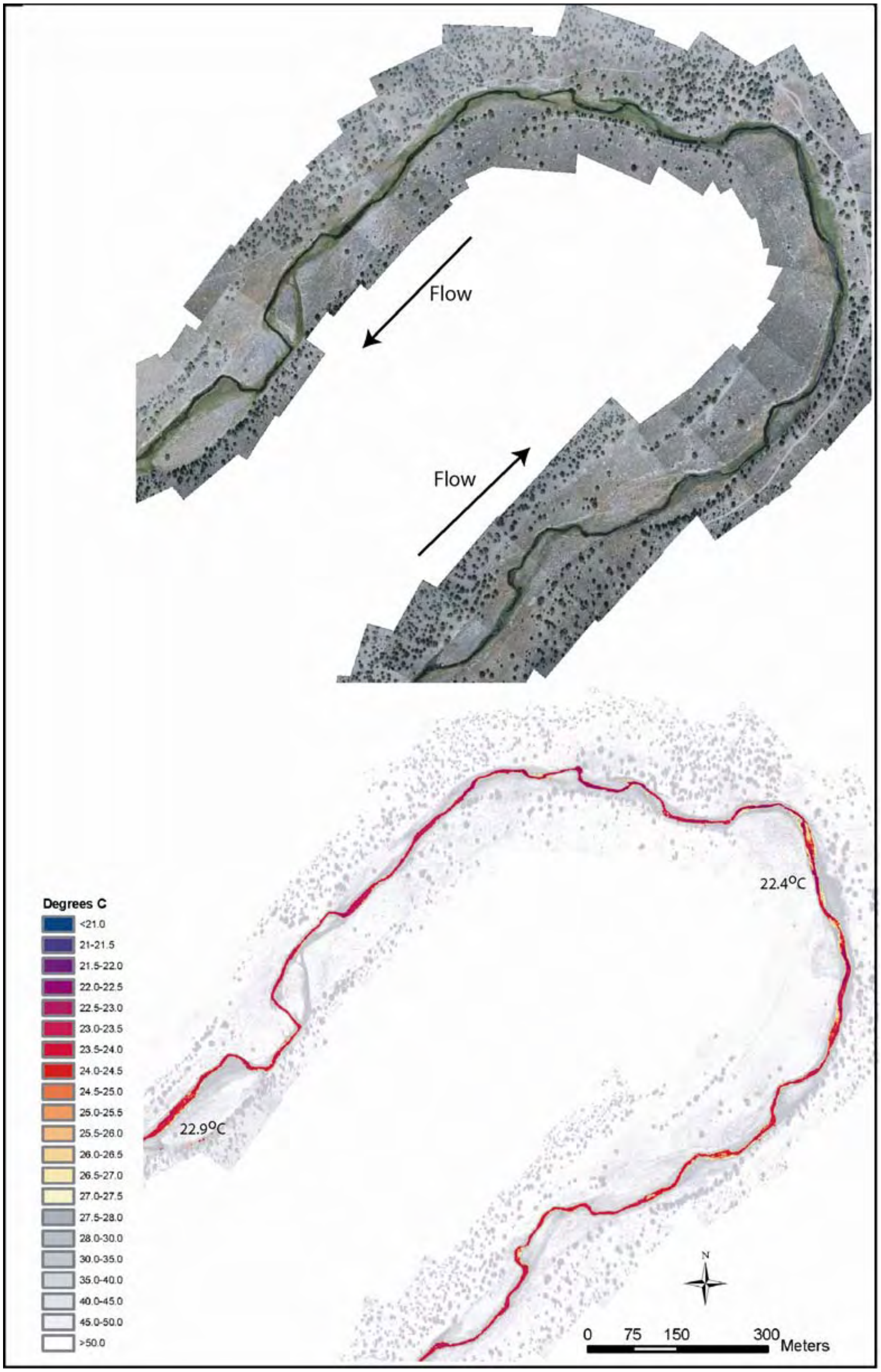
Selected Imagery



The TIR (left) and true color image (right) shows the South Fork Crooked River at mile 25.5. The image pair provides an example of the local spatial temperature variability that was characteristic of the upper river. The images above illustrate an apparent sub-surface discharge along the right bank which lowers main stream temperatures by 1.4°C.



The TIR image (right) and the true color image (left) shows the South Fork Crooked River at mile 19.4. Surface water temperatures in the South Fork Crooked River exhibited a rapid downstream cooling trend between river miles 20.3 and 19.4 with temperatures decreasing from 24.6°C to 22.3°C. The source of cooling was not apparent from the imagery, but the decrease in bulk water temperatures suggests groundwater influence. The river shows less local spatial thermal variability downstream of this location.



The TIR (bottom) and true color (top) images show the South Fork Crooked River at mile 8.0. Radiant water temperatures begin to increase rapidly at this location reaching 24.1°C by river mile 6.6. Follow on analysis should examine the morphology associated with this reach.

Beaver Creek

Longitudinal Temperature Profile

Median sampled temperatures were plotted versus river mile for Beaver Creek from its mouth at the Crooked River to the confluence of the North and South Forks of Beaver Creeks (Figure 11). Tributaries and other sampled inflows (i.e. springs/seeps, irrigation returns) are labeled on the profile by river mile.

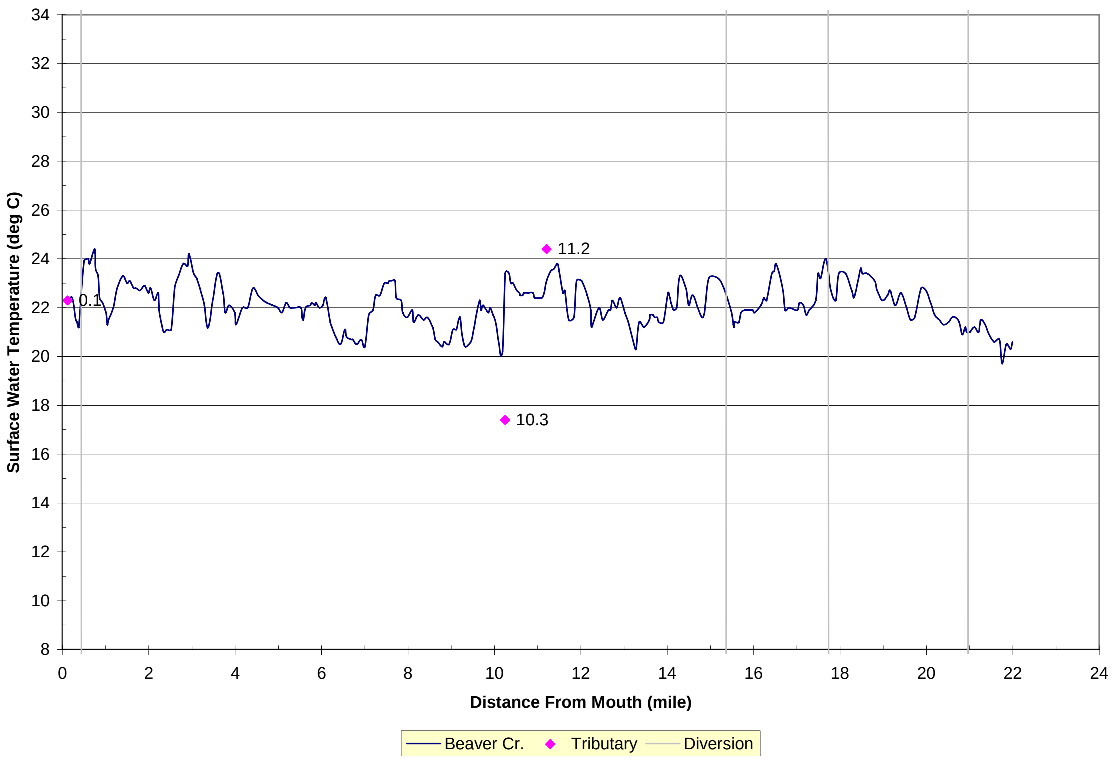


Figure 11 - Median sampled temperatures plotted versus river mile for Beaver Creek.

Table 6 - *Name, river measure, and radiant temperatures of inflows sampled on Beaver Creek.*

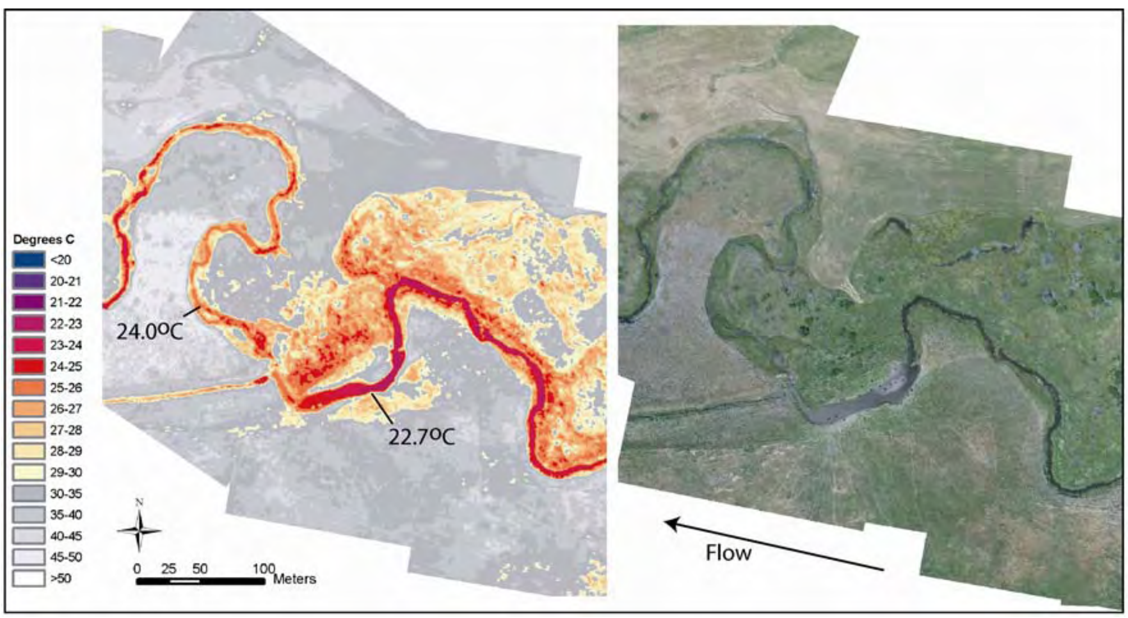
Tributary Name	Image	km	mile	Tributary °C	Beaver Cr. °C	Difference °C
SF Crooked River (LB)	beav-000011	0.2	0.1	22.3	22.3	0.0
Paulina Creek (RB)	beav-000229	16.5	10.3	17.4	23.4	-6.0
Wolf Creek (RB)	beav-000248	18.0	11.2	24.4	23.1	1.3

Observations and Analysis

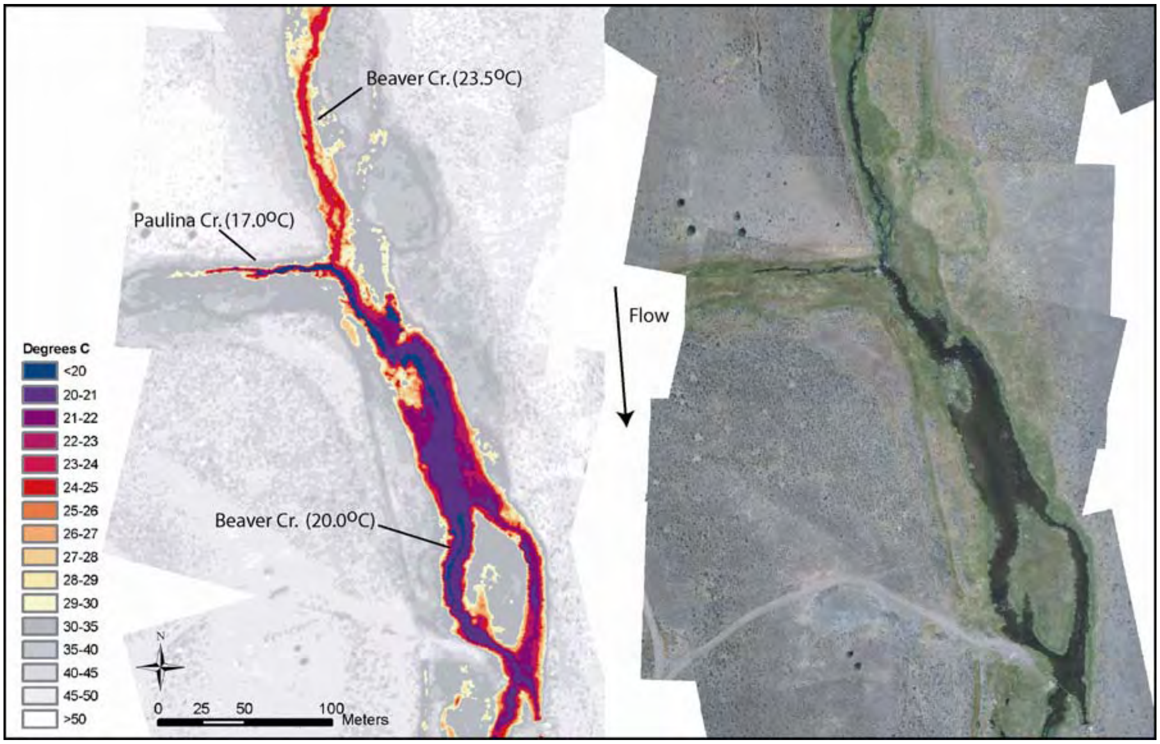
Radiant water in Beaver Creek generally warmed in the downstream direction, but also showed a considerable degree of local thermal variability. As with the South Fork Crooked River, the observed spatial temperature pattern was characteristic of a stream with relatively low flows. Over the 22-mile survey extent, measured radiant temperatures ranged between 20.0°C and 24.4°C. In some cases, the in-stream temperatures changed by more than 2.0°C over distances of less than ½ mile. Although it was not always possible to identify the sources of variability through inspection of the TIR imagery, the temperature pattern suggests intermittent exchange between surface and shallow sub-surface flows. As sub-surface flow discharges into the channel it has a dramatic influence on bulk temperatures. However, this inflow warms quickly as it mixed with the warmer surface water and is exposed to heating processes. Conversely, flow lost from the stream results in lower volumes in the channel and potentially higher longitudinal heating rates.

Only two tributaries were sampled during the analysis of the imagery, Paulina Creek (mile 10.3) and Wolf Creek (mile 11.2). Paulina Creek (*see the selected imagery*) had a cooling influence on bulk water temperatures in the main stem.

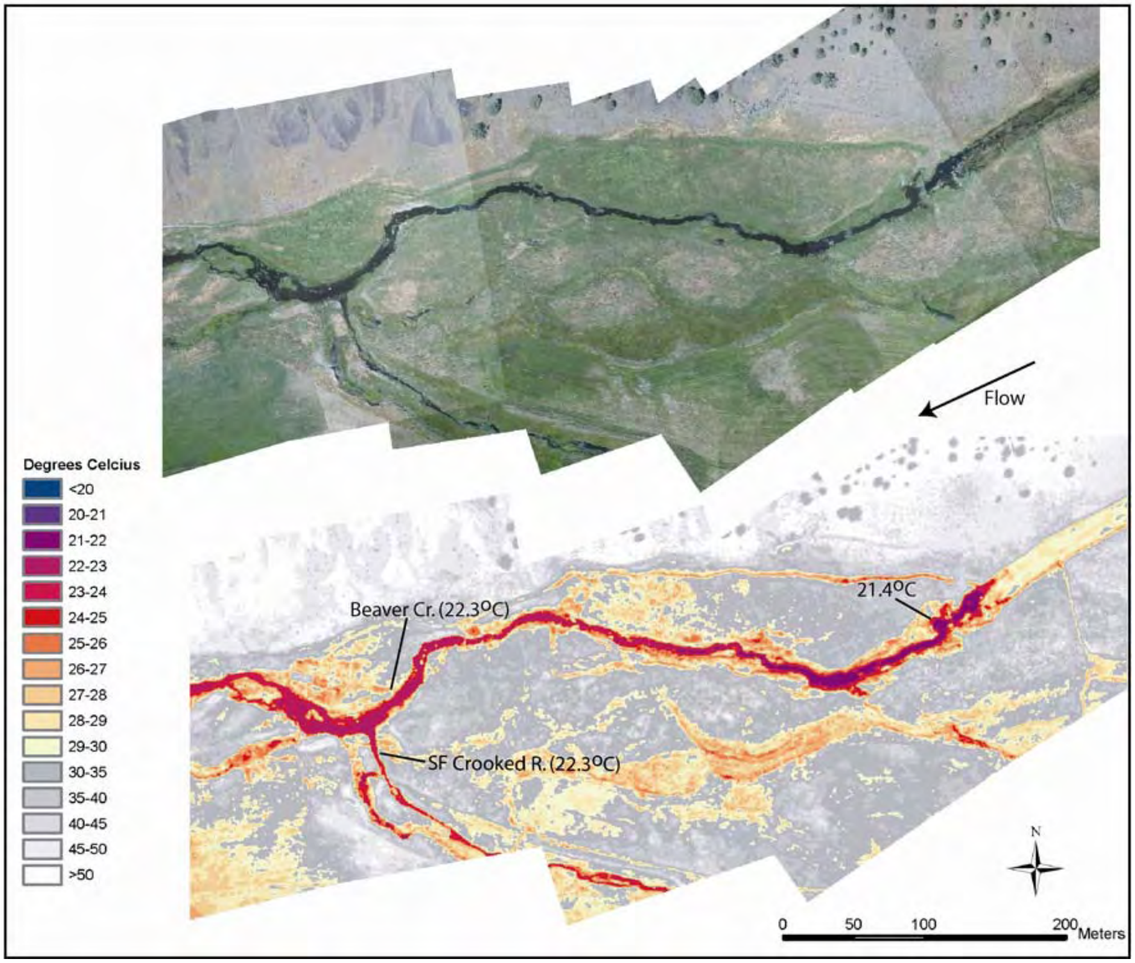
Selected Imagery



The TIR (left) and true color (right) image shows Beaver Creek at river mile 17.7. The images illustrate channel conditions characteristic of Beaver Creek and differences in surface temperatures above and below the diversion.



The TIR (left) and true color image (right) shows the confluence of Paulina Creek and Beaver Creek. Paulina Creek had a dramatic influence on water temperatures in Beaver Creek lowering main stream temperatures by ~3.5°C. The cooler temperatures and the lack of visible surface water in Paulina Creek suggest that the discharge from Paulina Creek is comprised of sub-surface flow following the tributary channel.



The TIR (bottom) and true color (top) images show the confluence of Beaver Creek and the South Fork Crooked River. There was no significant different in surface water temperatures between the streams at the time of the over-flight. Algea was often visible on the surface of Beaver Creek and masks radiant water temperatures. In this image, the surface water visible downstream of the algae is 21.4°C, but warms up quickly gaining 0.9°C within a ~200 meters.

North Fork Crooked River

Longitudinal Temperature Profile

Median sampled temperatures were plotted versus river mile for the North Fork Crooked River from its mouth at the Crooked River upstream past the confluence of Gray Creek (Figure 12). Tributaries and other sampled inflows (i.e. springs/seeps, irrigation returns) are labeled on the profile by river mile.

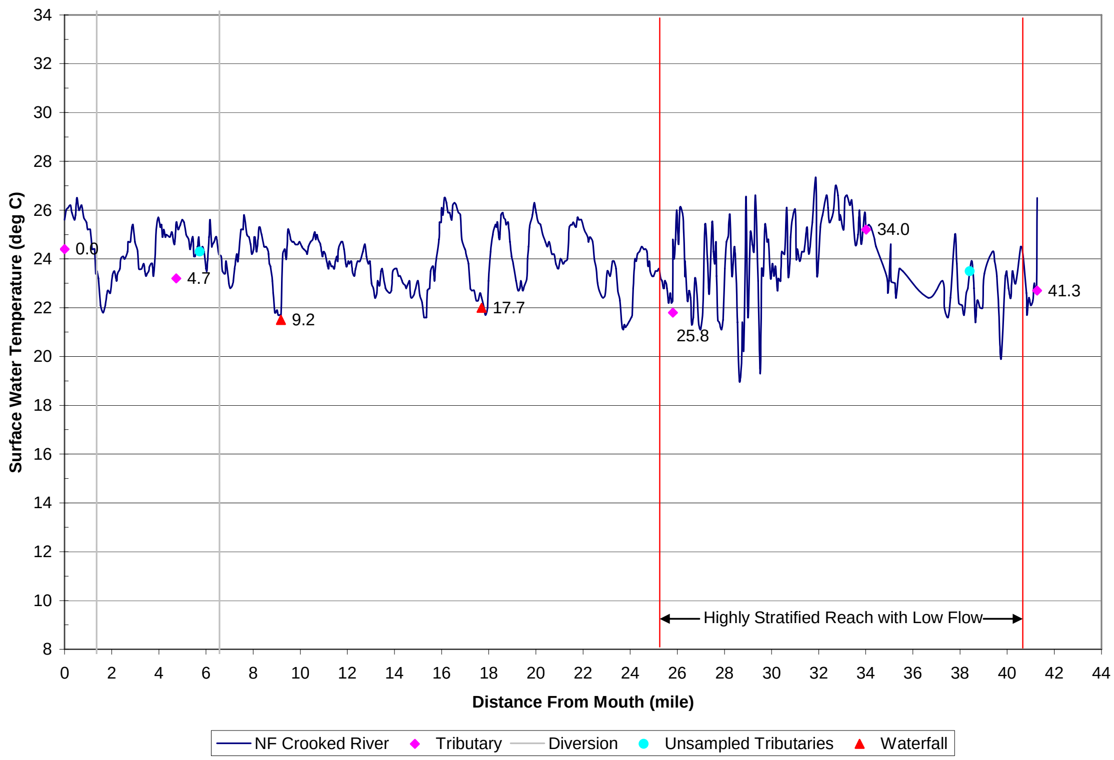


Figure 12 - Median sampled temperatures plotted versus river mile for the North Fork Crooked River.

Table 7 - *Name, river measure, and radiant temperatures of inflows sampled on the North Fork Crooked River.*

Tributary Name	Image	km	mile	Tributary °C	NF Crooked R. °C	Difference °C
Crooked River (LB)	nfc-000011	0.0	0.0	24.4	24.4	0.0
Unnamed Trib. (RB)	nfc-000111	7.6	4.7	23.2	25.5	-2.3
Deep Creek (LB)	nfc-000647	41.5	25.8	21.8	24.7	-2.9
Ross Creek (LB)	nfc-000852	54.7	34.0	25.2	25.3	-0.1
Gray Creek (LB)	nfc-001147	66.4	41.3	22.7	26.5	-3.8

Observations and Analysis

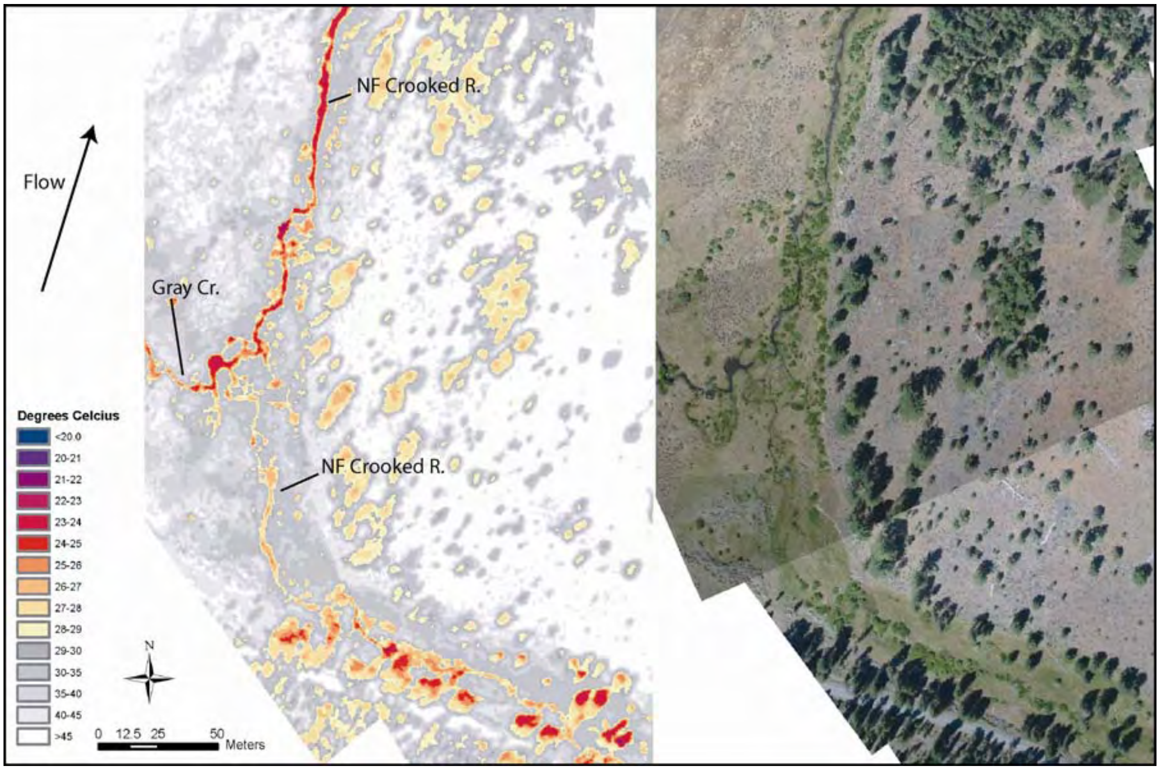
The aerial survey of the North Fork Crooked River concluded at the confluence of Gray Creek (22.6^{o}C) at mile 41.3. Gray Creek appears to contribute most of the flow to the North Fork as very little surface flow is visible upstream of the confluence.

Moving downstream, the North Fork travels through the Big Summit Prairie (river miles 37.6 and 29.8) where radiant water temperatures exhibited a relatively high degree of local spatial variability. In general, surface temperatures increased to a local maximum of 27.3^{o}C at river 31.9 before showing an overall cooling trend to ~22.0^{o}C at mile 26.6. Within this general pattern, sampled temperatures varied by up to 5.8^{o}C. This local spatial temperature variability observed is probably due to a number of factors. The low gradients combined with lower overall flows near the headwaters results in conditions conducive to rapid surface heating over relatively short longitudinal distances. Although no tributary inflows were sampled through the prairie, inspection of the topographic base layers shows a number of mapped tributaries (Dudley, Elliot, Johnson, Allen, and Rose Creeks) entering the North Fork within the Big Summit Prairie. These tributary channels combined with the stream's sinuosity increases the probability of sub-surface exchange within the stream channel. The sub-surface exchange (both loss and gain) combined with high longitudinal heating rates can result in the high spatial temperature variability.

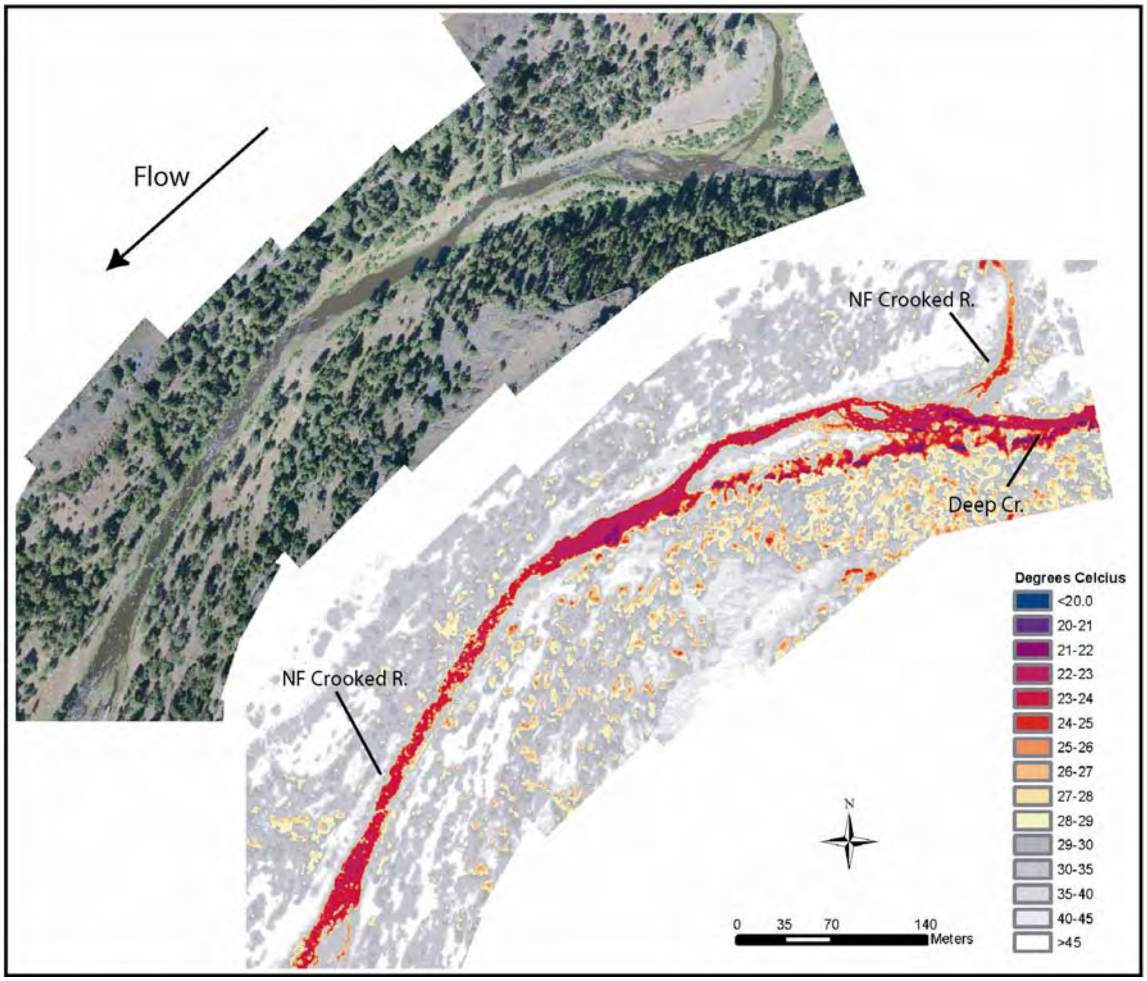
At river mile 25.8, Deep Creek (21.8^{o}C) contributed cooler water to the North Fork Crooked River (24.7^{o}C). Longitudinal temperature patterns were distinctly different downstream of the Deep Creek confluence. The flow contribution of Deep Creek appeared to eliminate the extreme local variability observed in the upstream reaches. Between the Deep Creek confluence and river mile 15.4, radiant water temperatures ranged from 21.1^{o}C to 26.5^{o}C with alternating patterns of warming and rapid cooling. No surface water inflows were sampled through this reach and inspection of the topographic base maps show the river traveling through confined canyon. A sharp decrease in radiant water temperatures was observed downstream of a waterfall at river mile 17.7. Follow-on analysis should examine spatial temperature in the North Fork in relation to morphology changes along the river gradient (i.e. valley form, stream gradient, etc.).

From a local minimum of 21.6^{o}C at river mile 15.4, radiant water temperatures increased steadily to 25.2^{o}C at river mile 9.5 before showing a sharp decrease downstream of a waterfall (reference sample images). Water temperatures increased rapidly again reaching 25.3^{o}C at mile 8.3. As illustrated in the longitudinal temperature profile, water temperatures exhibited considerable local variability in the lower 8.3 river miles. Two diversions and one sampled tributary (*unnamed*) appeared to contribute to the observed variability. At its mouth, water temperatures in the North Fork Crooked River (25.6^{o}C) were warmer than those observed in the mainstem (24.4^{o}C).

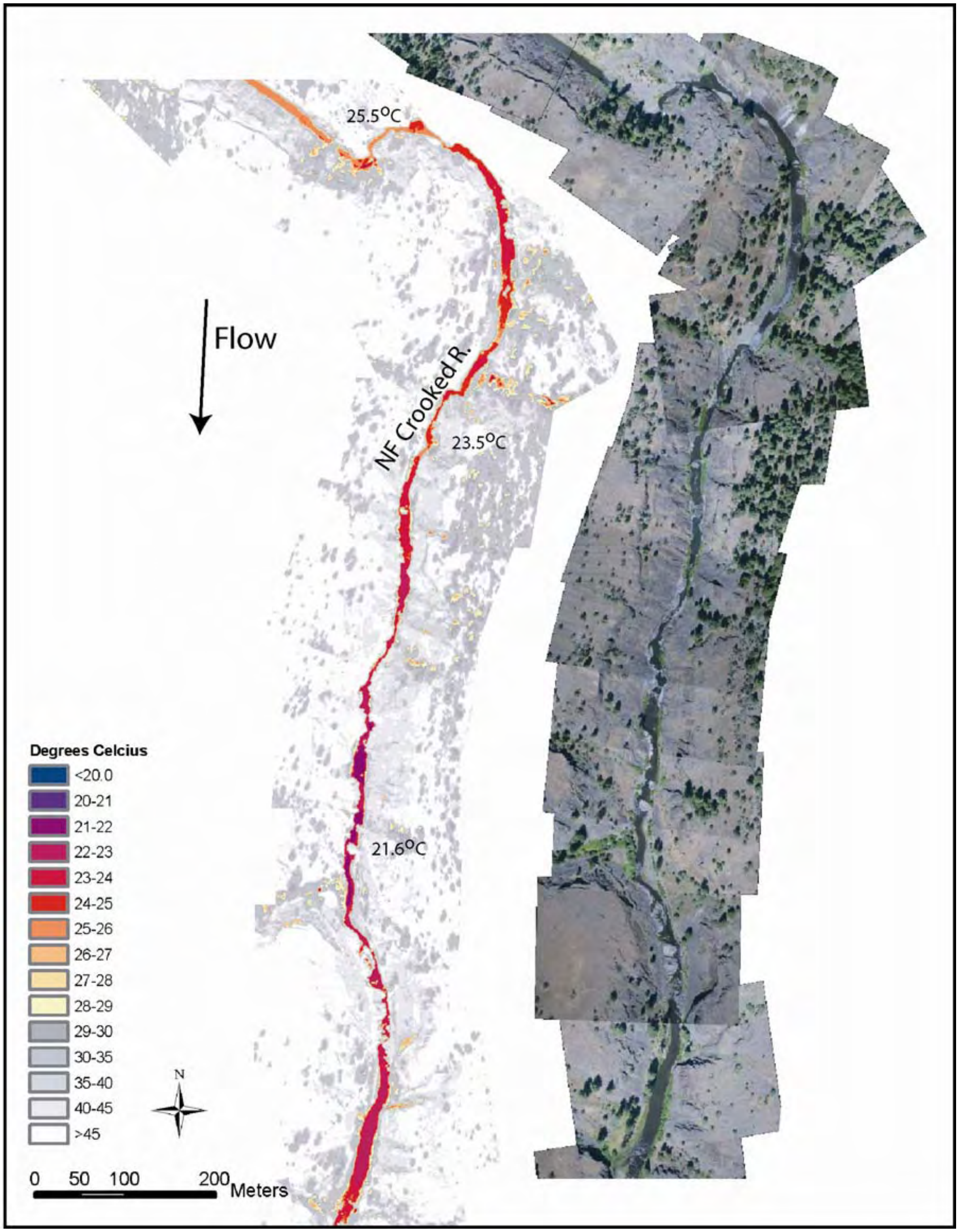
Selected Imagery



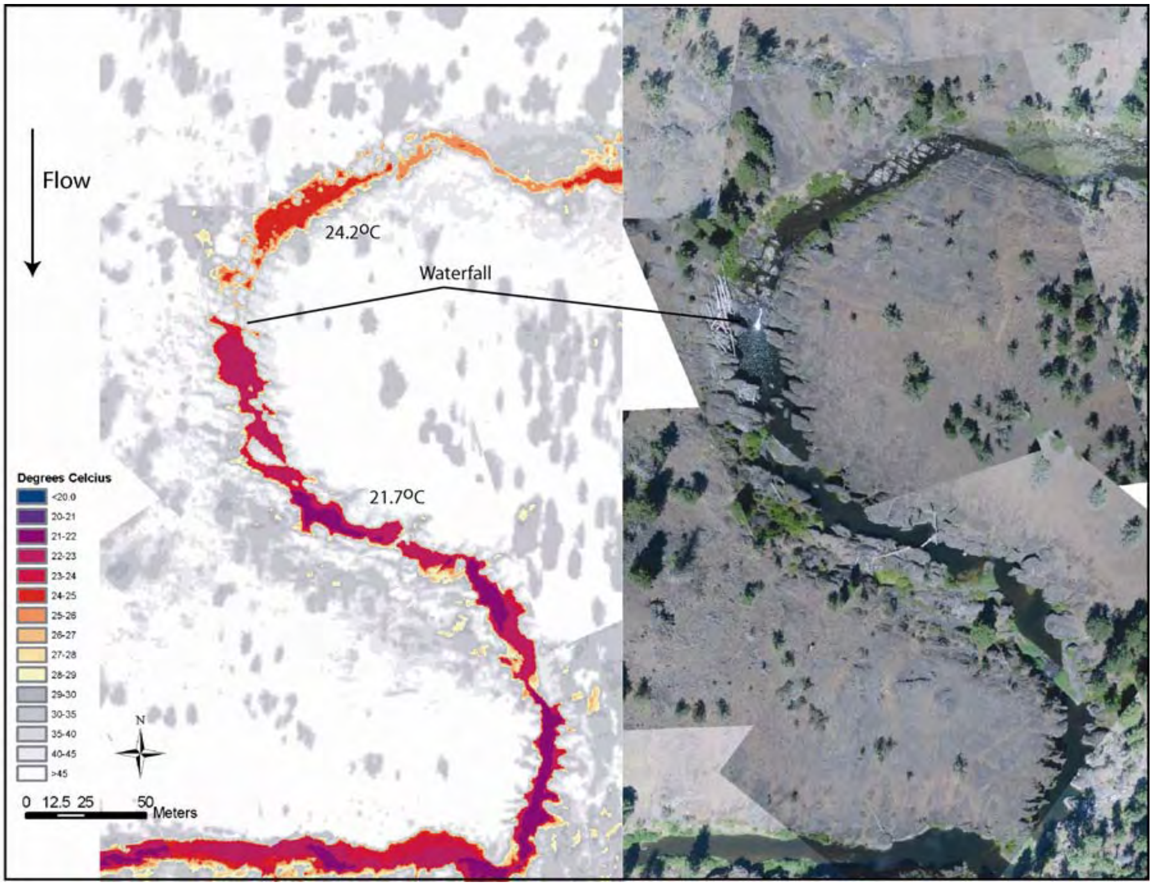
The TIR (left) and true color (right) images show the confluence of Gray Creek (22.6^{o}C) and the North Fork Crooked River (22.7^{o}C) at mile 41.3. Radiant temperatures were not sampled upstream of Gray Creek due to the size of the stream and an inability to detect visible surface water.



The TIR (bottom) and true color image (top) show the confluence of the NF Crooked River (24.7°C) and Deep Creek (21.8°C) at mile 25.8. Deep Creek was a cooling source to the NF Crooked River. Upstream of Deep Creek, the longitudinal temperature patterns were characteristic of low flow streams with thermal stratified segments.



The TIR (left) and true color (right) images show the North Fork Crooked River at mile 15.4. A significant decrease in radiant water temperatures (-3.9°C) was observed through this reach segment. The source of cooling was not obvious from just inspection of the imagery. The longitudinal temperature pattern changed downstream of this reach exhibiting a more consistent pattern of down stream heating.



The TIR (left) and true color (right) images show the NF Crooked River at mile 9.2. Radiant water temperatures decreased dramatically from upstream to downstream of the waterfall suggesting possible ground water upwelling due to the sharp change in gradient.

Deep Creek

Longitudinal Temperature Profile

Median sampled temperatures were plotted versus river mile for Deep Creek from its mouth at the North Fork Crooked River upstream past the confluence of Happy Camp Creek (Figure 13). Tributaries and other sampled inflows (i.e. springs/seeps, irrigation returns) are labeled on the profile by river mile.

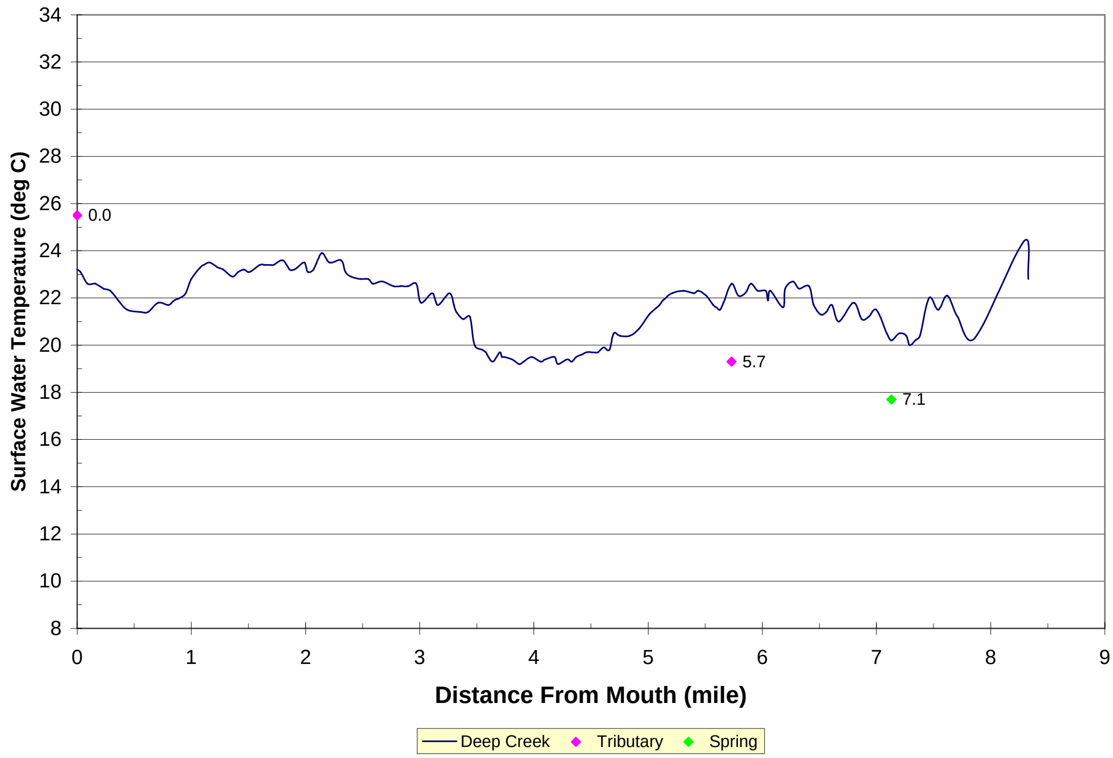


Figure 13 - Median sampled temperatures plotted versus river mile for Deep Creek.

Table 8 - *Name, river measure, and radiant temperatures of inflows sampled on Deep Creek.*

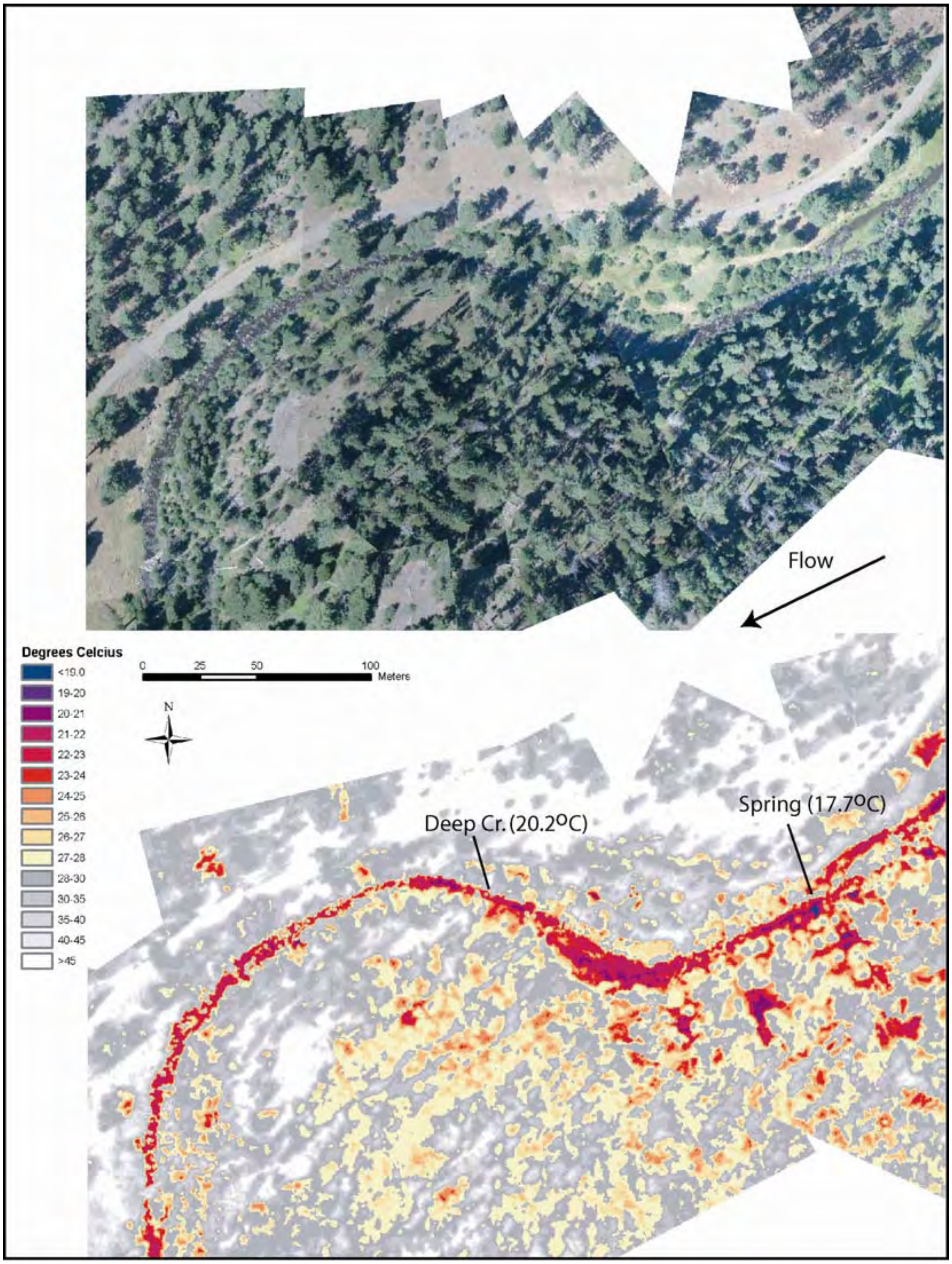
Tributary Name	Image	km	mile	Tributary °C	Deep Cr. °C	Difference °C
NF Crooked River (RB)	deep-000017	0.0	0.0	25.5	23.2	2.3
Unnamed Tributary (LB)	deep-000173	9.2	5.7	19.3	22.6	-3.3
Spring (RB)	deep-000234	11.5	7.1	17.7	20.2	-2.5

Observations and Analysis

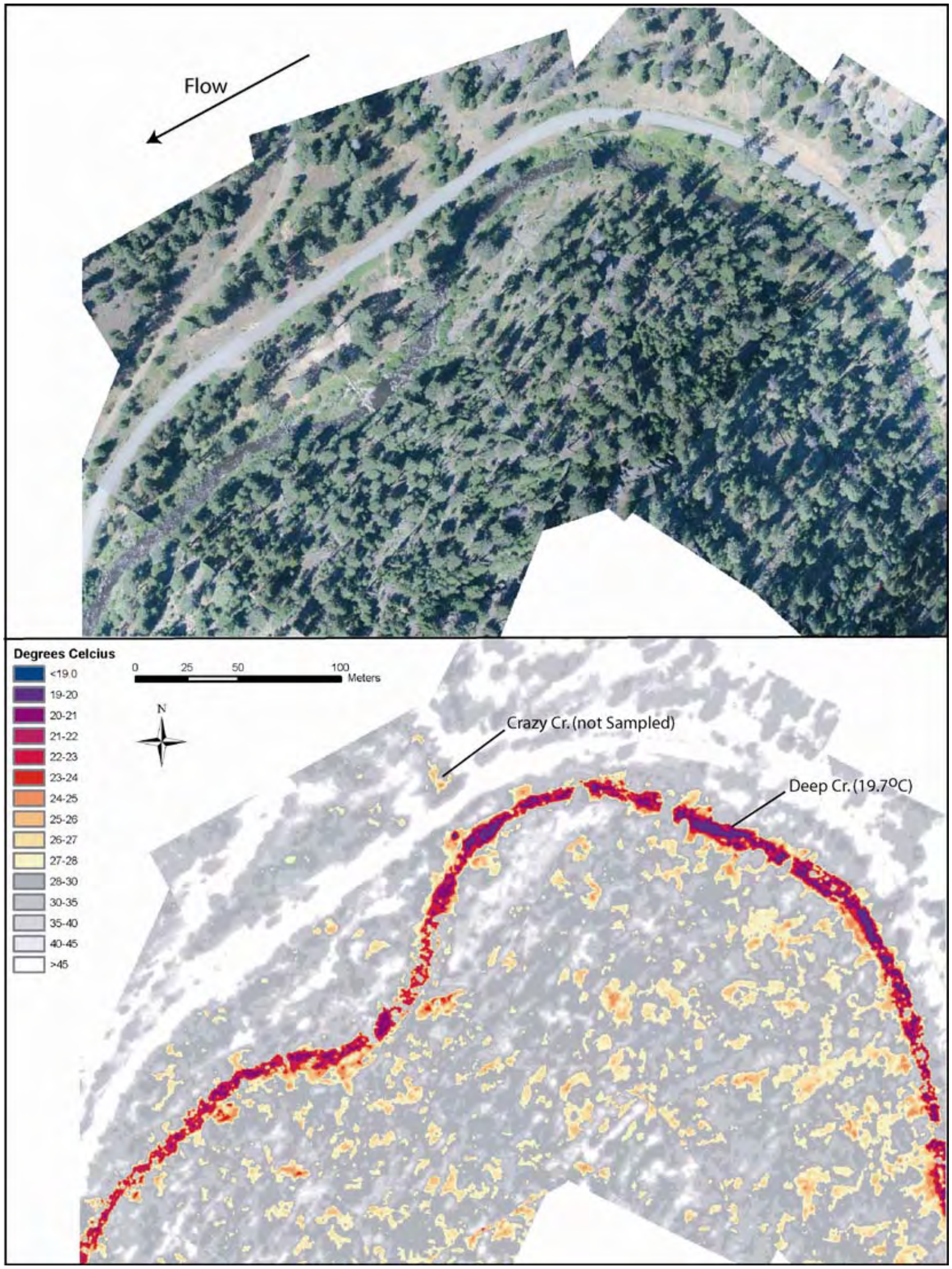
Radiant water temperatures in Deep Creek did not exhibit the high degree of local variability observed on many of the streams surveyed in the Upper Crooked River Basin. Distinct cooling trends were observed between miles 5.3 and 4.2 and between miles 1.1 and 0.6. The cooling trend observed between miles 5.3 and 4.2 occurs in a confined, high gradient section of the stream between the confluences of Little Summit Creek (mile 5.4) and Big Spring Creek (mile 4.4). The source of cooling through this reach was not apparent from the imagery. Further analysis is needed to determine the relatively influence of the topography (i.e. possible terrain shading during the early afternoon) and/or tributaries. The cooling reach between miles 1.1 and 0.6 seems to occur as the stream transitioned from a relatively confined stream segment to a more open, lower gradient segment suggesting a possible area of upwelling.

One tributary and one apparent spring were sampled during the analysis. Four additional tributaries and one spring were detected during the analysis, but were too small to obtain and accurate radiant temperature sample.

Selected Imagery



The TIR (bottom) and true color (top) images show Deep Creek at mile 7.1. An apparent spring (17.7°C) is visible along the right bank. Cooler terrain temperatures created by the shadows of the vegetation makes positive identification difficult.



The TIR (bottom) and true color (top) images illustrate Deep Creek at the confluence of Crazy Creek at river mile 3.6. Crazy Creek is detected in the thermal image, but there was not sufficient visible surface water to obtain an accurate temperature sample.

Summary

Airborne thermal infrared surveys were successfully conducted on selected streams in the Crooked River basin for the ODEQ. A total of 45 in-stream data loggers were used to calibrate and verify the accuracy of the radiant temperatures. The results showed that the radiant temperatures were generally within the expected accuracy (i.e. an average absolute accuracy of $\pm 0.4^{o}C$ was desired). However, a wider range of differences were observed on Beaver Creek and the Upper Crooked River (i.e. above Prineville Reservoir). The differences may have been due (at least in part) to the high degree of local temperature variability observed in these streams and some uncertainty as to the precise location of the in-stream sensor.

Overall, the TIR data showed how temperatures varied spatially over the survey extents, and identified several areas of locally cooler water. In addition, the imagery shows the characteristics of the channel, including reaches with no surface flow. The locations of sub-surface discharge back into the channel often had cooler radiant temperatures and may represent areas of thermal refugia for cool-water fish species during the summer months. Tributaries and other surface inflows (i.e. springs) were detected during the analysis, but the sources of cooling were not always directly apparent from the imagery.

In general, the spatial temperature patterns observed in the basin appeared to be strongly influenced by flow and velocity conditions. A relatively high degree of local spatial variability was observed in Upper Crooked River, Upper Ochoco Creek (i.e. above the reservoir), the South Fork Crooked River, Upper North Fork Crooked River, and Beaver Creek. The local variability appeared directly related to flow and velocity conditions in the river. Morphology also appeared to have a large influence on spatial temperatures patterns with dramatic decreases in bulk water temperatures observed at transitions in valley and/or channel morphology.

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 to be a starting point for more rigorous spatial analysis and fieldwork.

Deliverables

The TIR imagery is provided in two forms: 1) individual un-rectified frames and 2) 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 ~1-mile geo-rectified mosaics at 8 inch resolution.

Deliverables are provided on a set of DVD's:

Geo-Corrected Imagery are stored as: **Oregon Lambert, NAD83, Units = Int. Feet.**

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.

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

Nikon_Mosaics – Geo-Rectified true color imagery mosaics in ~1-mile segments at 8-inch resolution.

Longprofile - Excel spreadsheet containing the longitudinal temperature profiles.

Surveys – Point layers showing image locations, sampled temperatures, and image interpretations.