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

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Report to:

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Final Report

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Introduction

In 2002, the Oregon Department of Environmental Quality (ODEQ) contracted with Watershed Sciences, LLC (WS, LLC) to conduct airborne thermal infrared (TIR) remote sensing surveys within the Willamette River basin, OR. The objective of the project was to characterize the thermal regime of selected river segments to support ongoing stream temperature assessments in the basin.

This report is divided into two chapters that address TIR surveys in the Northern and Southern Willamette River Basin separately. It is the aim of this report to 1) document methods used to collect and process the TIR images, 2) present spatial temperature patterns, and 3) highlight interesting features within each basin. Thermal infrared 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.

Methods

Data Collection

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

A consistent altitude above ground level was maintained in order to preserve the scale of the imagery throughout the survey. The ground width and spatial resolution presented by the TIR image vary based on the flight altitudes. The flight altitude is selected prior to the flight based on the channel width and morphology. In flight, images were collected sequentially with approximately 40% vertical overlap. All flights were conducted in the mid-afternoon (13:30-17:00) in order to capture heat of the day conditions.

For each surveyed stream, Watershed Sciences, LLC deployed in-stream data loggers prior to the survey to ground truth (i.e. verify the accuracy) of the TIR data. The WS, LLC data loggers were supplemented with seasonal data loggers deployed by ODEQ and the US Bureau of Land Management (BLM). The in-stream data loggers were ideally located at intervals of 10 river miles or less over the survey route. Meteorological data including air temperature and relative humidity were recorded using portable weather stations (*Onset*).

[1] Geographic Information System

Data Processing

Measured radiance values contained in the raw TIR images were converted to temperatures based on the emissivity of water, atmospheric transmission effects, ambient background reflections, and the calibration characteristics of the sensor. The atmospheric transmission value was modeled based on the air temperatures and relative humidity recorded at the time of the survey. The radiant temperatures were then compared to the kinetic temperatures measured by the in-stream data loggers. The in-stream data were assessed at the time the image was acquired, with radiant values representing the median of ten points sampled from the image at the data logger location. Atmospheric transmission calibrations were fine-tuned to provide the most accurate fit between the radiant and kinetic temperatures.

Once the TIR images were calibrated, they were integrated into a GIS in which an analyst interpreted and sampled stream temperatures. Sampling consisted of querying radiant temperatures (pixel values) from the center of the stream channel and saving the median value of a ten-point sample to a GIS database file (Figure 1). The temperatures of detectable surface inflows (i.e. surface springs, tributaries) were also sampled at their mouth. In addition, data processing focused on interpreting spatial variations in surface temperatures observed in the images. The images were assigned a river mile based on a 1:100k routed GIS stream coverage from the Environmental Protection Agency (*Note: measures assigned from this coverage may not match stream measures derived from other map sources*).

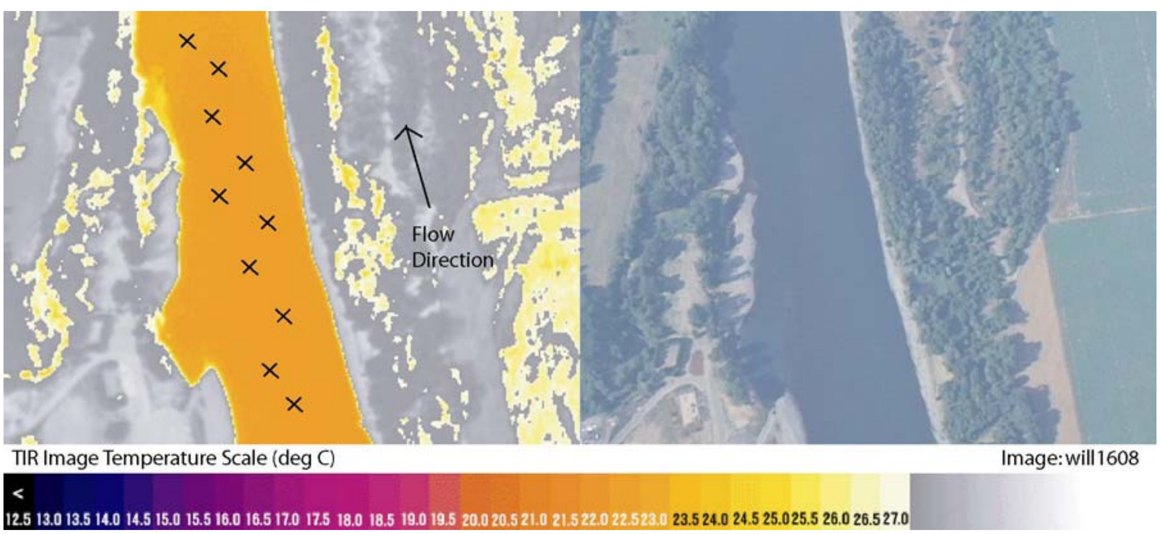

Figure 1 – TIR/color video image pair showing how temperatures are sampled from the TIR images. The black *X's* show typical sampling locations near the center of the stream channel. The recorded temperature for this image is the median of the sample points.

TIR Image Characteristics

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. In the TIR images, indicators of thermal stratification include cool water mixing behind in-stream objects and/or abrupt transitions in stream temperatures. Occurrences of thermal stratification interpreted during analysis are identified in the results section for each surveyed stream.

Thermal infrared radiation received at the sensor is a combination of energy emitted from the water's surface, reflected from the water's surface, and absorbed and re-radiated by the intervening atmosphere. Water is a good emitter of TIR radiation and has relatively low reflectivity (approximately 4 to 6% of the energy received at the sensor is due to ambient reflections). During image calibration, a correction is included to account for average background reflections. However, variable water surface conditions (i.e. riffle versus pool), slight changes in viewing aspect, and variable background temperatures (i.e. sky versus trees) can result in differences in the calculated radiant temperatures within the same image or between consecutive images. The apparent temperature variability is generally less than 0.6^oC (Torgersen et al. 2001). However, the occurrence of reflections as an artifact (or noise) in the TIR images is a consideration during image interpretation and analysis. In general, apparent stream temperature changes of $< 0.6^oC$ are not considered significant unless associated with a point source.

In stream segments with flat surface conditions (i.e. pools) and relatively low mixing rates, observed variations in spatial temperature patterns can be the result of differences in the instantaneous heating rate at the water's surface. In the TIR images, indicators of differential surface heating include seemingly cooler radiant temperatures in shaded areas compared to surfaces exposed to direct sunlight. Shape and magnitude distinguish spatial temperature patterns caused by tributary or spring inflows from those resulting from differential surface heating. Unlike thermal stratification, surface temperatures may still represent bulk water conditions if the stream is mixed. Temperature sampling along the center of the stream channel (Figure 1) minimizes variability due to differences in surface heating rates. None-the-less, differences in surface heating combined with ambient reflection can confound interpretation of thermal features especially near the riverbank.

A small stream width logically translates to fewer pixels "in" the stream and greater integration with non-water features such as rocks and vegetation. Consequently, a narrow channel (relative to the pixel size) can result in higher inaccuracies in the measured radiant temperatures (Torgersen et. al. 2001). In some cases, small tributaries were detected in the images, but not sampled due to the inability to obtain a reliable temperature sample.

Southern Willamette River Valley

Overview

The TIR remote sensing surveys in Southern Willamette Valley include all surveyed streams south of the town of Independence, OR., which were flown on July 21-22, 2002 (Figure 2). The surveyed streams varied considerably in size, channel characteristics, and riparian vegetation and flight parameters were selected to best account for these factors. For example, the Middle Fork (MF) Willamette and Willamette Rivers were surveyed at a flight altitude that provided a wider image footprint (*lower spatial resolution*) to better capture side and off-channel features characteristic to these systems. By contrast, smaller streams in the upper end of the basin including Mosby Creek, Sharps Creek, and Big River were surveyed at lower altitudes (*above ground level*) to provide higher spatial resolution and better visibility through the riparian vegetation. Table 1 summarizes the survey times, extents, and image resolution for each surveyed stream in the Southern Willamette Valley. The weather conditions for the dates and times of the surveys are summarized in Table 2.

Table 1 – Summary of river segments surveyed with TIR and color video in the Southern Willamette River Basin from July 21-22, 2002.

Stream	Survey Date	Survey Time (24 hr)	Survey Extent & Direction	River Miles	Image Width Meter (ft)	TIR Image Pixel Size Meter (ft)
Sharps Creek	21 Jul	13:44-14:15	Mouth to rm 11.0 (u/s)	11.0	107 (353)	0.3 (1.0)
Mosby Creek	21 Jul	15:06-15:52	Mouth to headwaters (u/s)	22.0	107 (353)	0.3 (1.0)
Coast Fork Willamette R	21 Jul	16:04-16:27	Cottage Grove Lake to Big River (u/s)	7.6	107 (353)	0.3 (1.0)
Big River	21 Jul	16:27-16:43	Mouth to rm 7.5 (u/s)	7.5	107 (353)	0.3 (1.0)
Coast Fork Willamette R.	22 Jul	13:51-14:27	Mouth to Cottage Grove Lake (u/s)	28.7	267 (881)	0.8 (2.8)
Middle Fork Willamette R.	22 Jul	15:20-15:34	Dexter Lake to Willamette River (d/s)	15.9	645 (2116)	(2.0) 6.6
Willamette R.	22 Jul	15:34-16:45	Middle Fork Willamette to Independence, OR (d/s)	86.9	645 (2116)	(2.0) 6.6

Flight direction: u/s = upstream, d/s = downstream

Table 2 - Meteorological conditions recorded in the Southern Willamette River Basin, OR on July 21-22, 2002.

	Eugene Airport, OR			Junction City, OR		
	July 21, 2002			July 22, 2002		
Time 24 hr	**Temp °F**	**Temp °C**	**RH (%)**	**Temp °F**	**Temp °C**	**RH (%)**
13:00	81	27.2	34	-	-	-
14:00	83	28.3	32	94	34.4	29
15:00	87	30.6	28	91	32.8	34
16:00	89	31.7	25	91	32.8	33
17:00	89	31.7	25	86	29.9	37

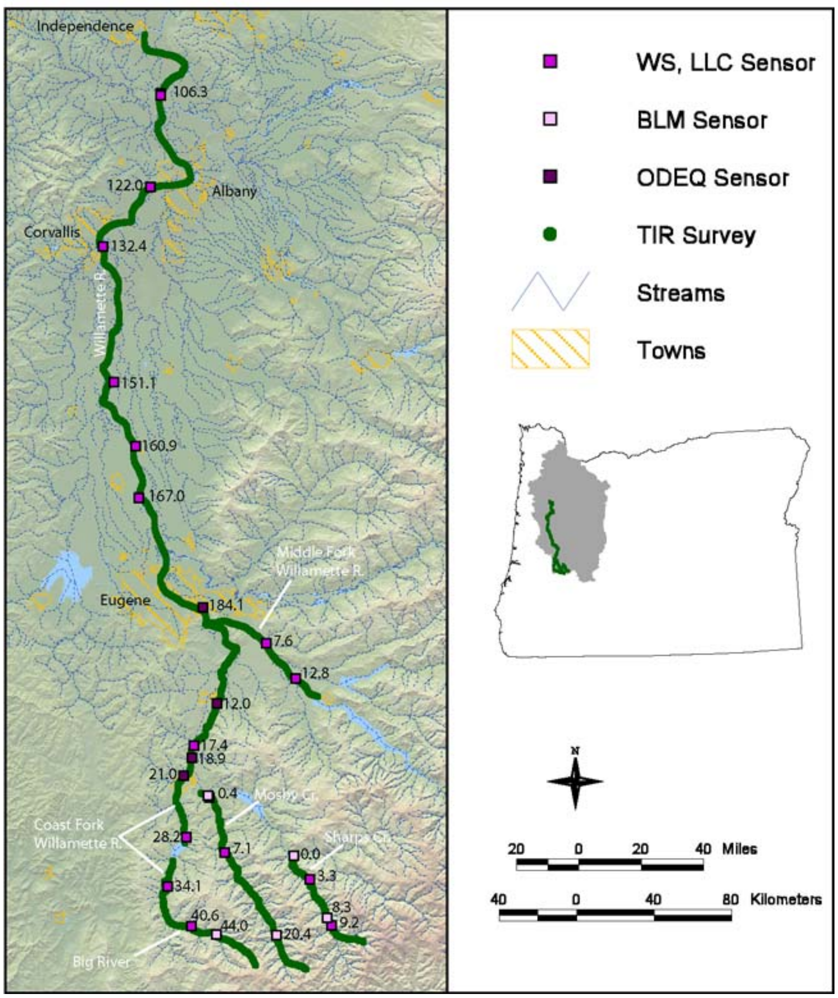

Figure 2 - Map showing streams surveyed using TIR and color video on July 21-22, 2002 in the Southern Willamette River Valley. The map also shows the location (labeled by river mile) of in-stream sensors used to verify the accuracy of the radiant temperatures.

Results

Thermal Accuracy

The average absolute difference between the kinetic temperatures recorded by the in-stream data loggers and the radiant temperatures derived from the TIR images for all in-stream locations was 0.3^{o}C (Table 3; Figure 2). This value was within the desired accuracy (< 0.5^{o}C) for the TIR surveys and was consistent with TIR surveys conducted in the Pacific Northwest over the past five years (Torgersen, 2001). With the exception of the Coast Fork Willamette River, the range of differences between the radiant and kinetic temperatures was ±0.6^{o}C for all in-stream points. Factoring the accuracy of the in-stream data loggers (±0.2^{o}C) and the noise (±0.5^{o}C) characteristic of TIR remote sensing, differences of this magnitude are expected. On the Coast Fork Willamette River, one in-stream point (river mile 12) registered kinetic temperatures that were 2.3^{o}C warmer than the radiant temperatures. The source of the differences at this location was unknown; however, ground truth points both upstream and downstream of this location were consistent with the radiant temperatures. How this result influences the interpretation of the spatial temperature patterns is discussed later in this report.

Temporal Differences

Figure 3 shows in-stream temperature variations for four streams in the Southern Willamette River Basin during the TIR remote sensing surveys. The figure shows the temporal variations in stream temperatures at a single location on each stream and is intended to provide a sense of how stream temperatures changed during the time frame of the flight and the timing of the flight relative to the recorded daily maximum temperatures. On Mosby Creek (river mile 12.4), the TIR survey occurred just prior to the daily maximum stream temperature, which was recorded from 16:20 to 17:00 and the stream temperature rose by 0.5^{o}C during the time span of the survey. On Big River, the maximum stream temperatures were recorded between 15:40 to 16:20 and the TIR was conducted from 16:27 to 16:43, with stream temperatures remaining relatively consistent during that time frame. On the Coast Fork Willamette River (river mile 28.2), the survey was conducted prior to the recorded maximum stream temperature, which occurred at 15:30 on July 22. The TIR survey on the Willamette River (river mile 122.0) was consistent with the maximum stream temperatures, which occurred from 15:34 to 16:45.

Table 3 – Comparison of ground-truth water temperatures (Kinetic) with the radiant temperatures derived from the thermal infrared images for streams surveyed in the Southern Willamette Valley.

Stream	Image	River Mile	Date	Time	Kinetic °C	Radiant °C	Difference °C
				Sharps Creek			
Sharps Cr.	shar0029	0.0	21-Jul	13:46	20.2	19.6	0.6
Sharps Cr.	shar0207	3.3	21-Jul	13:53	21.5	21.2	0.3
Sharps Cr.	shar0546	8.3	21-Jul	14:04	19.8	19.9	-0.1
Sharps Cr.	shar0588	9.2	21-Jul	14:06	19.7	20.0	-0.3
				Mosby Creek			
Mosby Cr.	mosb0037	0.2	21-Jul	15:08	24.6	24.1	0.5
Mosby Cr.	mosb0048	0.4	21-Jul	15:08	22.1	22.3	-0.2
Mosby Cr.	mosb0396	7.1	21-Jul	15:20	23.1	22.9	0.2
Mosby Cr.	mosb0702	12.4	21-Jul	15:30	23.2	23.0	0.2
Mosby Cr.	mosb1196	20.4	21-Jul	15:48	17.7	18.0	-0.3
				Coast Fork Willamette River and Big River			
Coast Fork	cfbr0213	34.1	21-Jul	16:19	21.1	20.6	0.5
Big River	cfbr0529	40.6	21-Jul	16:30	18.2	18.5	-0.3
Big River	cfbr0681	44.0	21-Jul	16:35	16.5	16.7	-0.2
				Coast Fork Willamette River			
Willamette	cfw0001	0.0	22-Jul	13:51	16.7	16.9	-0.2
Coast Fork	cfw0401	12.0	22-Jul	14:05	24.0	21.7	2.3
Coast Fork	cfw0612	17.4	22-Jul	14:12	20.6	20.1	0.5
Coast Fork	cfw0659	18.9	22-Jul	14:13	20.7	20.3	0.4
Coast Fork	cfw0750	21.0	22-Jul	14:16	19.3	19.5	-0.2
Coast Fork	cfw1029	28.2	22-Jul	14:26	15.6	15.5	0.1
				Middle Fork Willamette River and Willamette River			
Middle Fork	mfw0059	12.8	22-Jul	15:23	14.9	15.3	-0.4
Middle Fork	mfw0147	7.6	22-Jul	15:27	16.0	16.5	-0.5
Willamette R.	mfw0304	184.1	22-Jul	15:35	17.5	17.7	-0.2
Willamette R.	will0559	167.0	22-Jul	15:48	18.8	19.1	-0.3
Willamette R.	will0642	160.9	22-Jul	15:52	19.5	19.4	0.1
Willamette R.	will0782	151.1	22-Jul	15:59	20.9	20.5	0.4
Willamette R.	will1046	132.4	22-Jul	16:12	21.1	21.0	0.1
Willamette R.	will1217	122.0	22-Jul	16:23	22.2	21.6	0.6
Willamette R.	will1444	106.3	22-Jul	16:35	22.1	22.0	0.1
Willamette R.	will1447	106.1	22-Jul	16:35	22.3	22.3	0.0

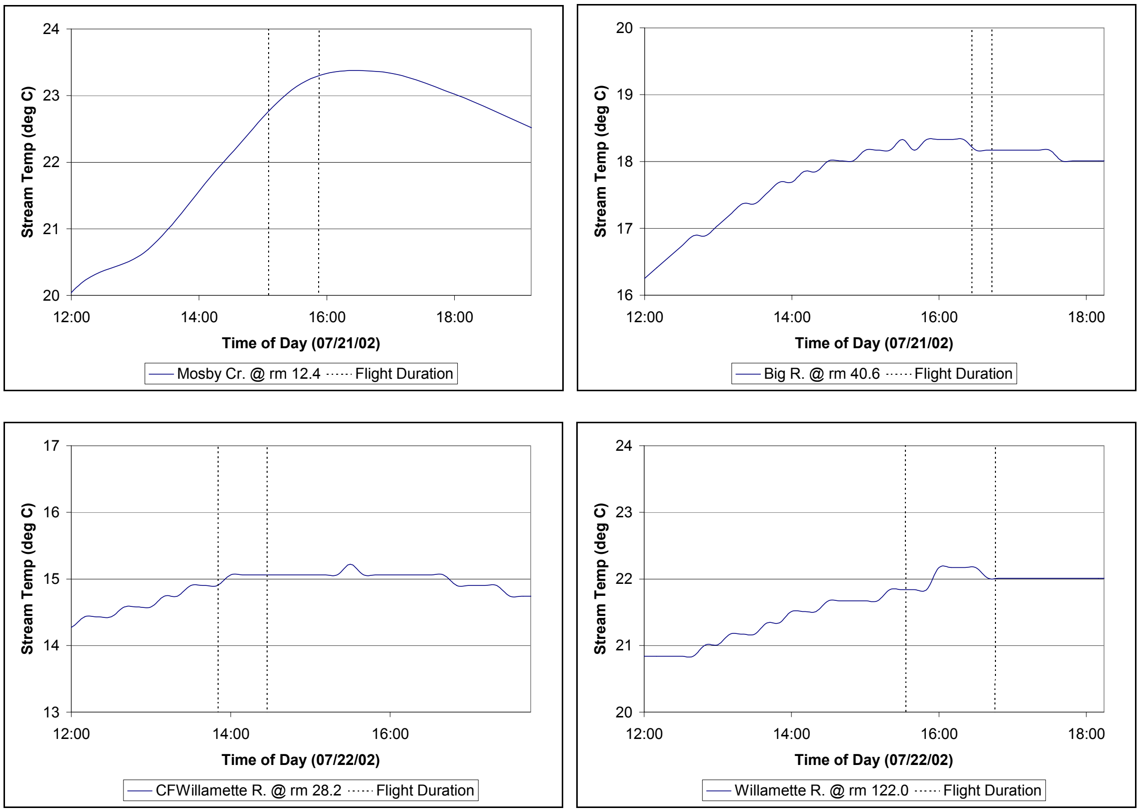

Figure 3 – Stream temperature variation and time of TIR remote sensing over flight at locations on four streams in the Southern Willamette River Basin on July 21-22, 2002.

Longitudinal Temperature Profiles

Willamette River and MF Willamette River

The median temperatures for each sampled image of the Middle Fork (MF) Willamette River and Willamette River were plotted versus the corresponding river mile (Figure 4). The median temperature and name of all surface water inflows (e.g. tributaries, surface springs, etc.) detected and sampled during the analysis are labeled on the plot by river mile with their name and temperatures listed in Table 4. Side channels and sloughs were similarly labeled on the temperature profile. Towns and major tributaries are depicted on the plot to provide additional spatial reference. Figure 5 illustrates the same longitudinal temperature profile with both the kinetic temperatures at the time of the TIR survey and the maximum daily stream temperatures. Since some of the in-stream data loggers were retrieved immediately after the survey, the maximum daily stream temperature was not recorded at all locations.

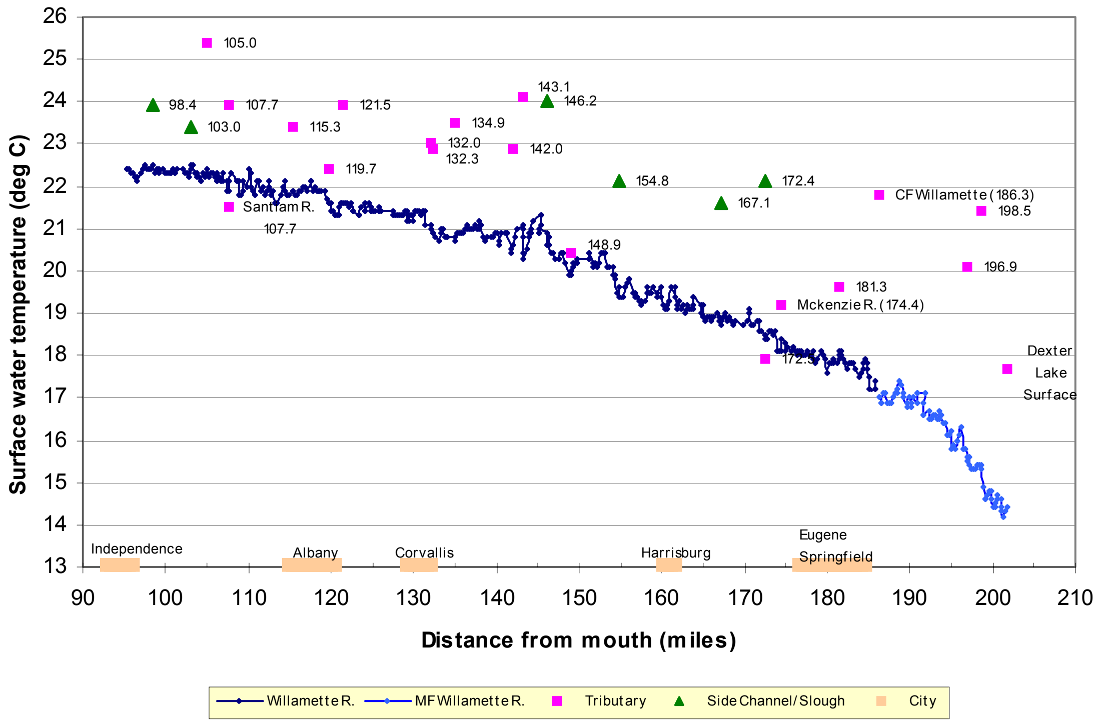

Figure 4 - Median channel temperatures versus river mile for the Middle Fork Willamette River and Willamette River, OR (7/22/02). Tributary and other survey water inflows are labeled on the profile by river mile.

The TIR survey started at Dexter Lake and followed the Middle Fork (MF) Willamette River downstream to the confluence of the Coast Fork (CF) Willamette River. The flight continued on the main stem Willamette River to the town of Independence, OR (*river mile 95.3*). At the outlet of Dexter Lake, stream temperatures in MF Willamette River were ≈14.3°C and warmed steadily downstream reaching ≈17.0°C at the confluence of the CF Willamette River. Radiant temperatures were sampled from surface of Dexter Lake; however, spatial temperature patterns on the lake's surface indicate thermal stratification. Fall Creek (rm 196.9 Willamette R; rm 11.0 MF Willamette R) and Lost Creek (rm 198.5 Willamette R; rm 12.6 MF Willamette R*.)* were the only tributaries sampled on the MF Willamette River and both contributed warmer water to the main stem. The MF Willamette River was characterized through much of the surveyed length by multiple interconnecting channels, which resulted in a large number of backwater and off channel areas (Figure 6).

Table 4 - Tributary temperatures for the Middle Fork Willamette River and the Willamette River, OR. RB = Right Bank, LB = Left Bank looking downstream.

Tributary	Image	River km	River mile	Willamette R. mile	Tributary °C	Mainstem °C	Difference
Middle Fork Willamette River							
Dexter Lake Surface	will0003	25.4	15.8	201.7	17.7	14.4	3.3
Lost Creek (LB)	will0061	20.3	12.6	198.5	21.4	15.4	6.0
Fall Creek (RB)	will0088	17.6	11.0	196.9	20.1	15.6	4.5
CF Willamette R. (LB)	will0274	0.6	0.4	186.3	21.8	17.0	4.8
Willamette River							
Unnamed Canal (RB)	will0356	291.7	181.3	181.3	19.6	17.9	1.7
McKenzie R. (RB)	will0454	280.9	174.4	174.4	19.2	18.1	1.1
Spring (LB)	will0485	277.5	172.5	172.5	17.9	18.4	-0.5
Long Tom R. (LB)	will0809	239.6	148.9	148.9	20.4	19.9	0.5
Lake Creek (RB)	will0898	230.0	143.1	143.1	24.1	21.0	3.1
Albany Channel (LB)	will0907	228.6	142.0	142.0	22.9	20.6	2.3
WF Booneville Channel (LB)	will1019	217.1	134.9	134.9	23.5	20.8	2.7
Muddy Creek (RB)	will1047	213.0	132.3	132.3	22.9	20.9	2.0
Mary's River (LB)	will1053	212.3	132.0	132.0	23.0	21.1	1.9
Little Willamette R. (RB)	will1223	195.6	121.5	121.5	23.9	21.6	2.3
Calapooia River (RB)	will1259	192.6	119.7	119.7	22.4	21.6	0.8
Third Lake (RB)	will1320	185.5	115.3	115.3	23.4	21.9	1.5
Santiam River (RB)	will1422	173.8	107.7	107.7	21.5	22.1	-0.6
Luckiamute R. (LB)	will1423	173.6	107.7	107.7	23.9	22.1	1.8
Unnamed (LB)	will1465	168.9	105.0	105.0	25.4	22.4	3.0
Side Channel/ Slough							
Side Channel (LB)	will0488	277.1	172.4	172.4	22.1	18.5	3.6
Unnamed Slough (LB)	will0556	268.9	167.1	167.1	21.6	18.8	2.8
Side Channel (RB)	will0732	249.5	154.8	154.8	22.1	19.4	2.7
Side Channel (LB)	will0850	235.1	146.2	146.2	24.0	20.6	3.4
Side Channel (LB)	will1500	165.8	103.0	103.0	23.4	22.4	1.0
Side Channel (RB)	will1560	158.5	98.4	98.4	23.9	22.5	1.4

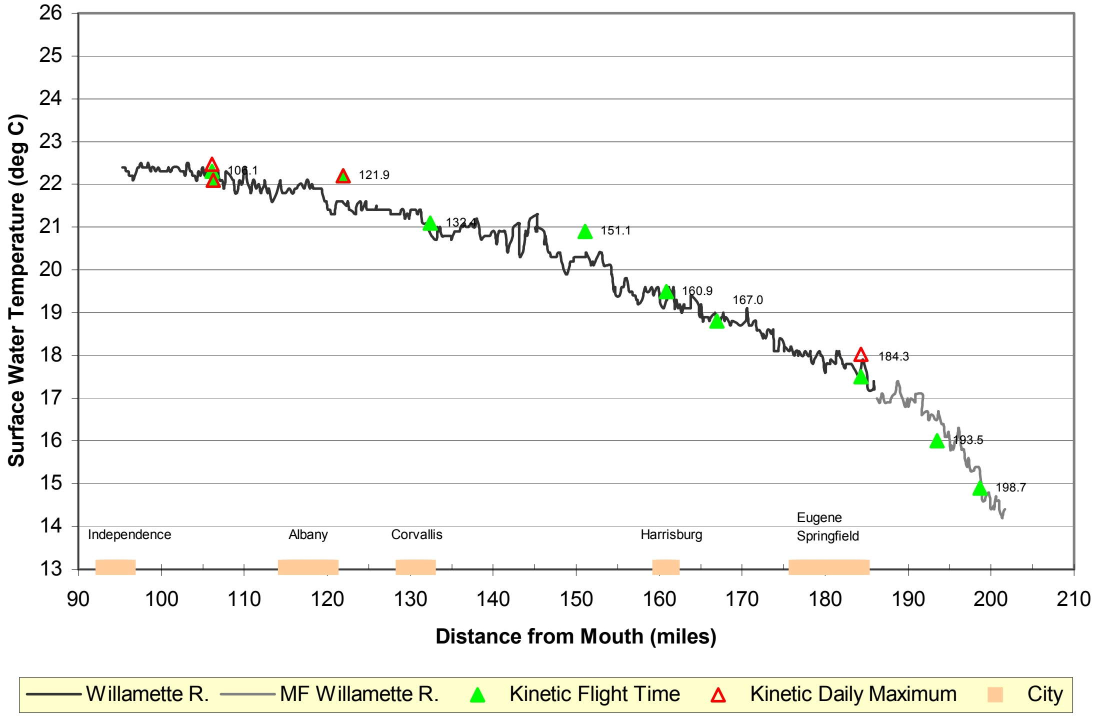

Figure 5 - Median channel temperatures versus river mile for Middle Fork (MF) Willamette River and Willamette River. Kinetic stream temperatures at the time of the survey and maximum daily stream temperatures used to calibrate the TIR images are shown on the profile. (*note: locations with no maximum daily stream temperatures represent stowaways which were retrieved shortly after the survey and did not record a maximum temperature*).

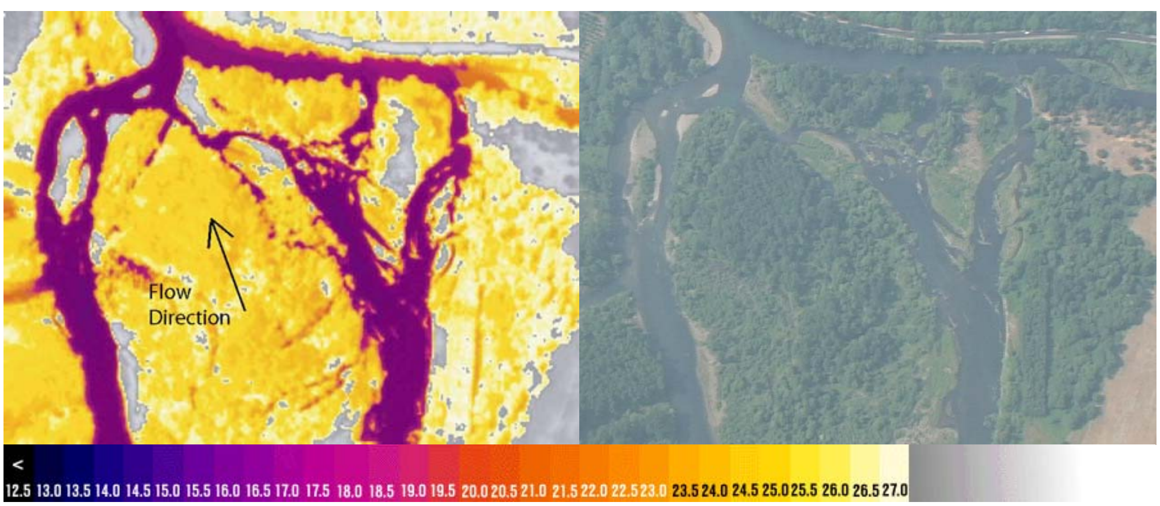

Figure 6 - TIR/color video image pair showing the multiple braided channels characteristic of the MF Willamette River (15.6°C) at river mile 11. The Fall Creek confluence (20.1°C) is visible in the upper right of the image *(frame: will0088). (Note: the haze in the color video image is partially due to smoke from a forest fire).*

From the confluence of the Coast Fork, Willamette River water temperatures continued to increase steadily in the downstream direction reaching ≈20.8°C at river mile 146.1. From this point, bulk water temperatures gained only ≈2.6°C over the next 50.7 miles. Visual inspection of the longitudinal temperature profile shows that stream temperatures remained relatively consistent (20.8°C; ±0.5°C) between river miles 146.1 and 132.1 with an increase in local variability within the first 5 miles (*relative to the rest of the profile*). The lack of detectable temperature increase through this reach suggests a possible change in the physical factors governing downstream heating such as width/depth ratio (e.g. decrease in solar loading) or alternate flow pathways (e.g. buffering through hyporheic flow).

Overall, 18 tributaries and 6 side channels and sloughs were sampled during the analysis of the Willamette River. Of these, only the Santiam River (river mile 107.7) and a small spring (river mile 172.5) contributed cooler water. The basin scale spatial temperature profile (Figure 4; Figure 5) shows little local spatial temperature variability outside the ±0.5°C noise common to radiant temperature sampling. However, the Willamette River has many side channels, sloughs, gravel bars, and islands that often result in lateral temperature variability across the channel (Figure 7). These fine scale thermal features are not reflected in the basin scale pattern, which focused on the center of the channel and prominent surface water inflows. Further analysis is required to identify the hydrologic and biologic significance of these fine scale features within the floodplain.

Coast Fork Willamette River

The median temperatures for each sampled image of the Coast Fork Willamette River from the Middle Fork upstream to Cottage Grove Reservoir were plotted versus the corresponding river mile (Figure 8). The plot also contains the median temperature of all surface water inflows (e.g. tributaries, surface springs, etc.) detected and sampled during the analysis labeled by river mile. Sampled surface water inflows are listed sequentially by river mile in Table 5.

Stream temperatures in the Coast Fork were ≈14.0°C at the outflow of the Cottage Grove Reservoir and generally warmed in the downstream direction reaching ≈22.7°C at its confluence with the Middle Fork. Four tributary inflows were sampled during the analysis of the TIR images and two, a spring at (river mile 9.9) and the Row River (river mile 19.7), contributed cooler water to the Coast Fork. Six features were sampled that were identified as a slough, side-channel, or off-channel areas. The off-channel classification was used as a general term for surface water that directly connected to the main stem, but was not identified as a side channel in the imagery or as a slough on the reference maps.

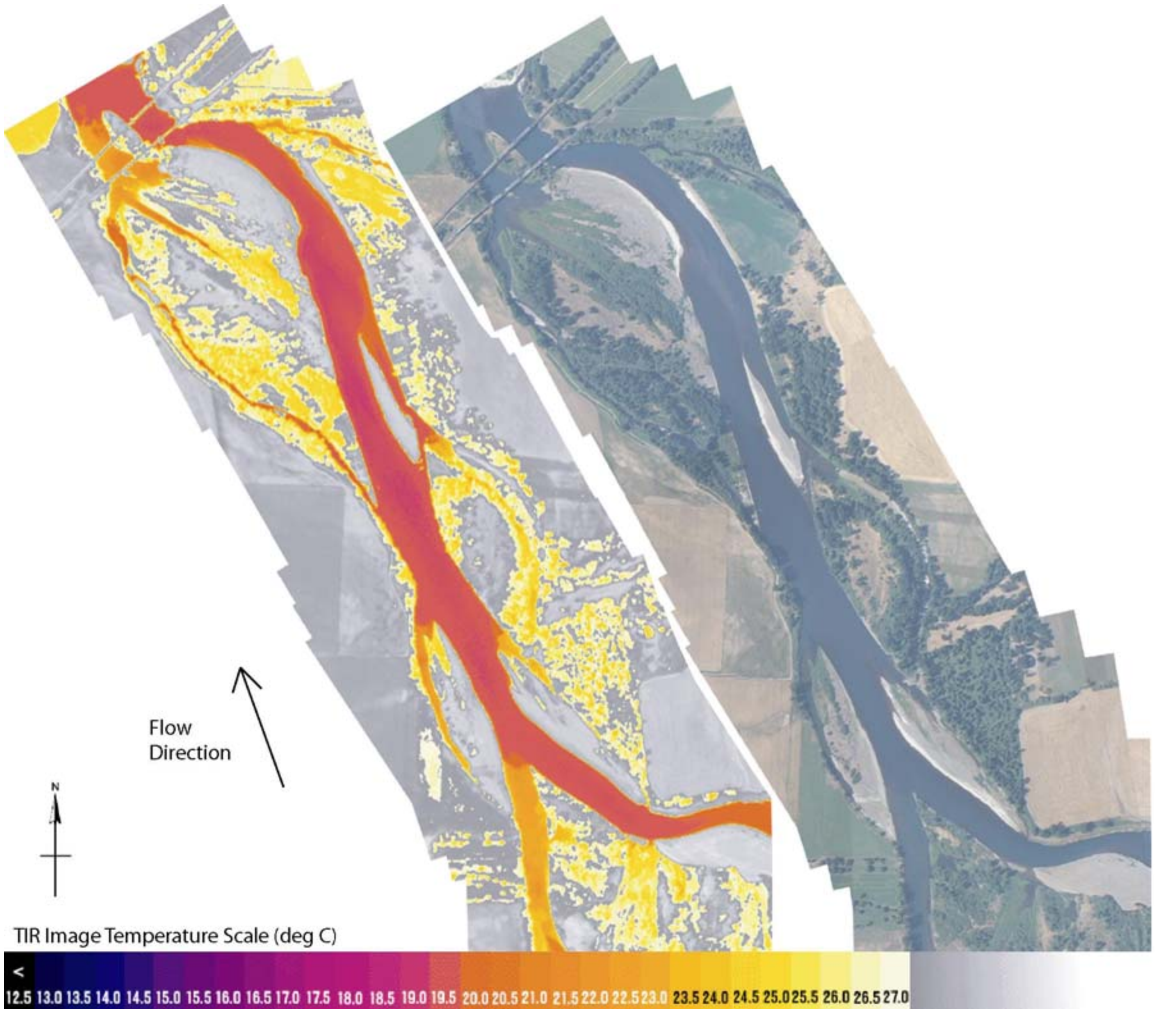

Figure 7 - TIR/color video image pair showing the Willamette River (19.0°C) from river mile 163.8 to 162.3. The image mosaic is one example of how multiple channels, gravel bars, and tributaries create thermal features laterally across the floodplain, while relatively uniform stream temperatures were observed in the main channel. *(frames: will0600-0620).*

Although the Coast Fork generally warmed in the downstream direction, the longitudinal heating rate varied at different points along the stream gradient. Downstream of the Cottage Grove Reservoir (river mile 28.4), water temperatures warmed rapidly reaching 16.4°C at river mile 28.0. Stream temperatures continued to increase (+1.0°C) over the next 4 miles, but at a considerably lower rate. A slight drop (0.7°C) in radiant temperature was observed at river mile 25.3, but the source of this cooling was not apparent from the imagery or reference maps. From river mile 24.0, the Coast Fork flows through the town of Cottage Grove. An increase in the longitudinal heating rate was observed in this reach with stream temperatures reaching 20.1°C at river mile 20.5. Stream temperatures remain relatively consistent (20.1°C) between river mile 20.5 and 16.5. The Row River (19.7°C) enters at river mile 19.7 and was ≈1.0°C cooler than the Coast Fork at the time of the TIR survey. At river mile 16.5, the longitudinal heating rate increased again with stream temperatures reaching 21.8°C at river mile 15.3. Over the lower 15.3 miles, stream temperatures ranged between 21.3 and 23.4°C.

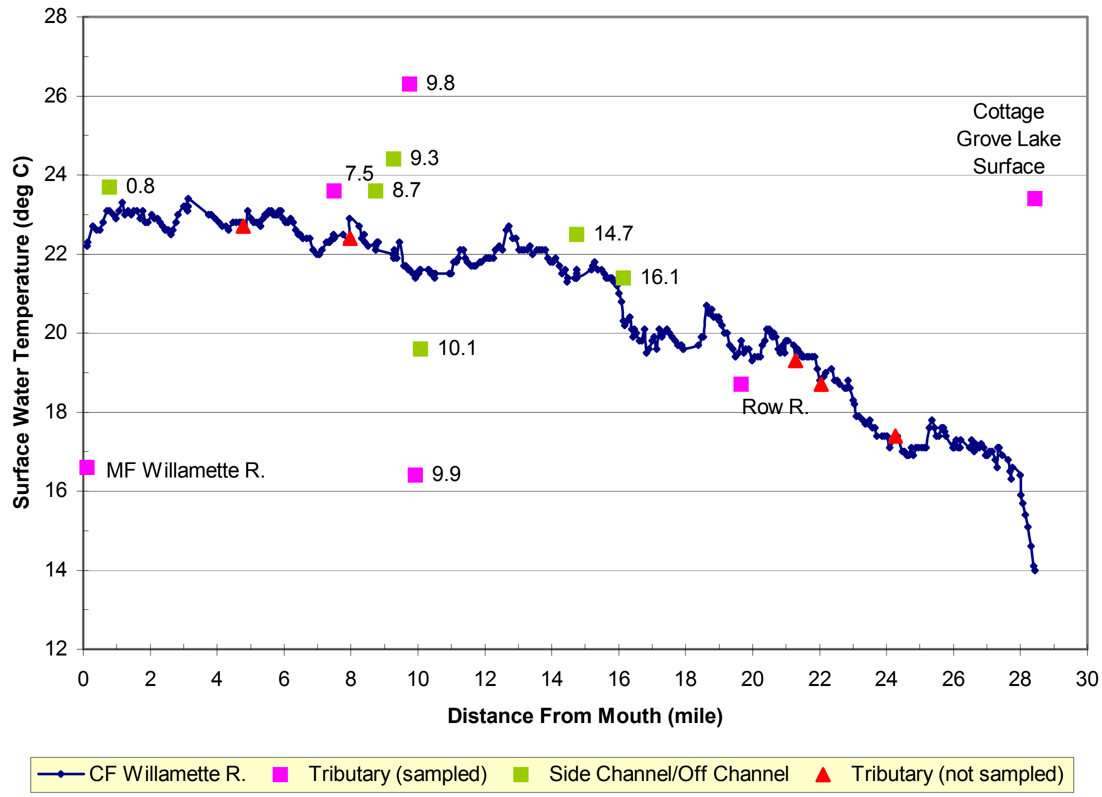

Figure 8 - Median channel temperatures versus river mile for the Coast Fork Willamette River, OR. Tributary and other surface water inflows are labeled on the profile by river mile.

Table 5 - Tributary temperatures for the Coast Fork Willamette River, OR. RB = Right Bank, LB = Left Bank looking downstream.

Tributary Name	Image	Km	Mile	Tributary (sampled) °C	Coast Fork Willamette River °C	Difference
MF Willamette River	cfw0009	0.2	0.1	16.6	22.2	-5.6
Bear Creek (RB)	cfw0263	12.2	7.5	23.6	22.4	1.2
Hill Creek (LB)	cfw0329	15.7	9.8	26.3	21.6	4.7
Spring (RB)	cfw0334	16.0	9.9	16.4	21.4	-5.0
Row River (RB)	cfw0689	31.6	19.7	18.7	19.8	-1.1
Cottage Grove Lake	cfw1039	45.8	28.4	23.4	14.0	9.4
Side Channel/Slough						
Oxley Slough (LB)	cfw0028	1.3	0.8	23.7	23.1	0.6
Off-Channel (LB)	cfw0304	14.4	8.7	23.6	22.1	1.5
Off-Channel (RB)	cfw0309	14.7	9.3	24.4	21.9	2.5
Off-Channel (LB)	cfw0342	16.2	10.1	19.6	21.6	-2.0
Side Channel (RB)	cfw0500	23.6	14.7	22.5	21.4	1.1
Side Channel (LB)	cfw0552	26.0	16.1	21.4	20.3	1.1

Figure 9 illustrates the kinetic temperatures at the time of the TIR survey and the recorded daily maximum stream temperatures plotted in relation to the spatial temperature pattern derived from the TIR images. The figure shows that the radiant temperatures were consistent with kinetic temperatures at four of the five in-stream sites. The radiant temperatures were also consistent with kinetic temperatures measured in the Willamette River just downstream of the Coast Fork confluence (*reference Table 3*). As noted earlier in this report, radiant temperatures were not consistent with kinetic temperatures measured at river mile 12.0. Without knowing the cause of this difference, further interpretation of the longitudinal temperature profile should consider that the radiant temperatures may understate stream temperatures at this location.

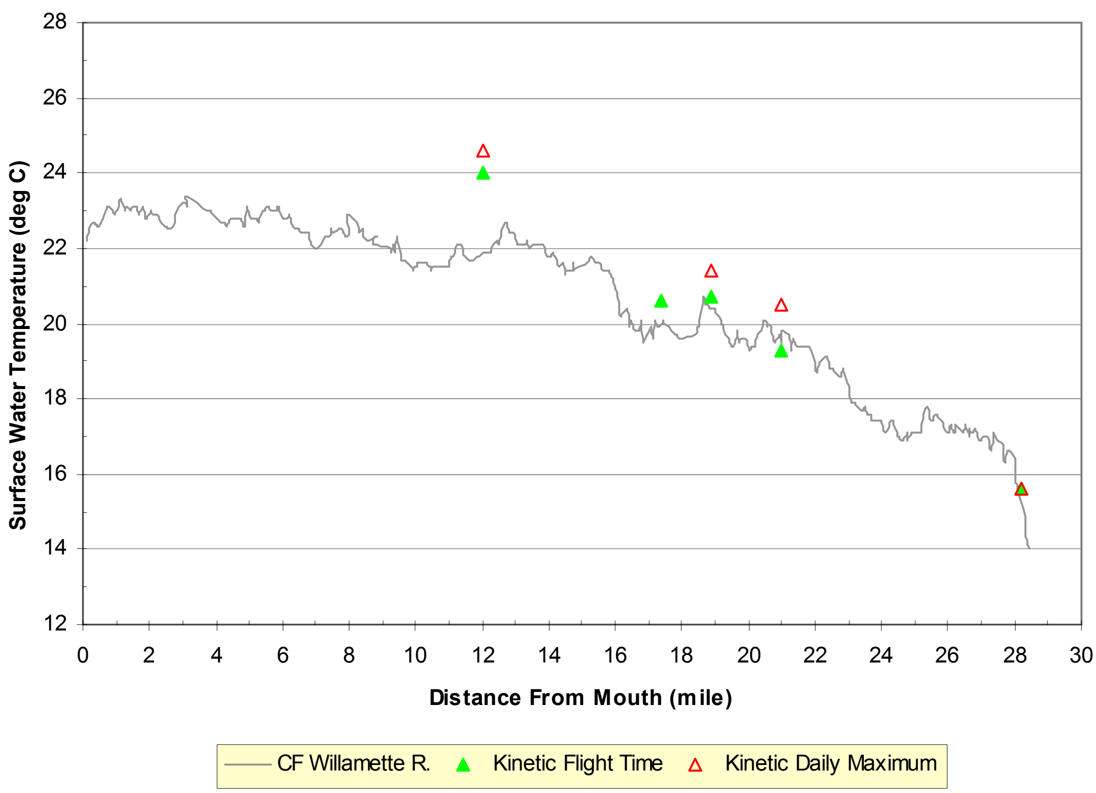

Figure 9 - Median channel temperatures versus river mile for the Coast Fork (CF) Willamette River. Kinetic stream temperatures at the time of the survey and maximum daily stream temperatures used to calibrate the TIR images are shown on the profile. (*Note: locations with no maximum daily stream temperatures were retrieved shortly after the survey and did not record a maximum temperature*).

Upper Coast Fork Willamette River and Big River

The median temperatures for each sampled image of the Coast Fork (CF) Willamette River upstream of Cottage Grove Reservoir and Big River were plotted versus the corresponding river mile (Figure 10). For the purpose of this analysis, the Big River miles are calculated as an extension of the CF Willamette River. The plot also contains the median temperature and name of all surface water inflows (e.g. tributaries, surface springs, etc.) detected and sampled during the analysis. The figure also shows the locations of tributaries that were detected in the imagery, but were too small (*relative to pixel size*) to obtain a radiant temperature. The locations of tributaries that were not sampled were included on the profile facilitate interpretation of local thermal variability observed in the profile.

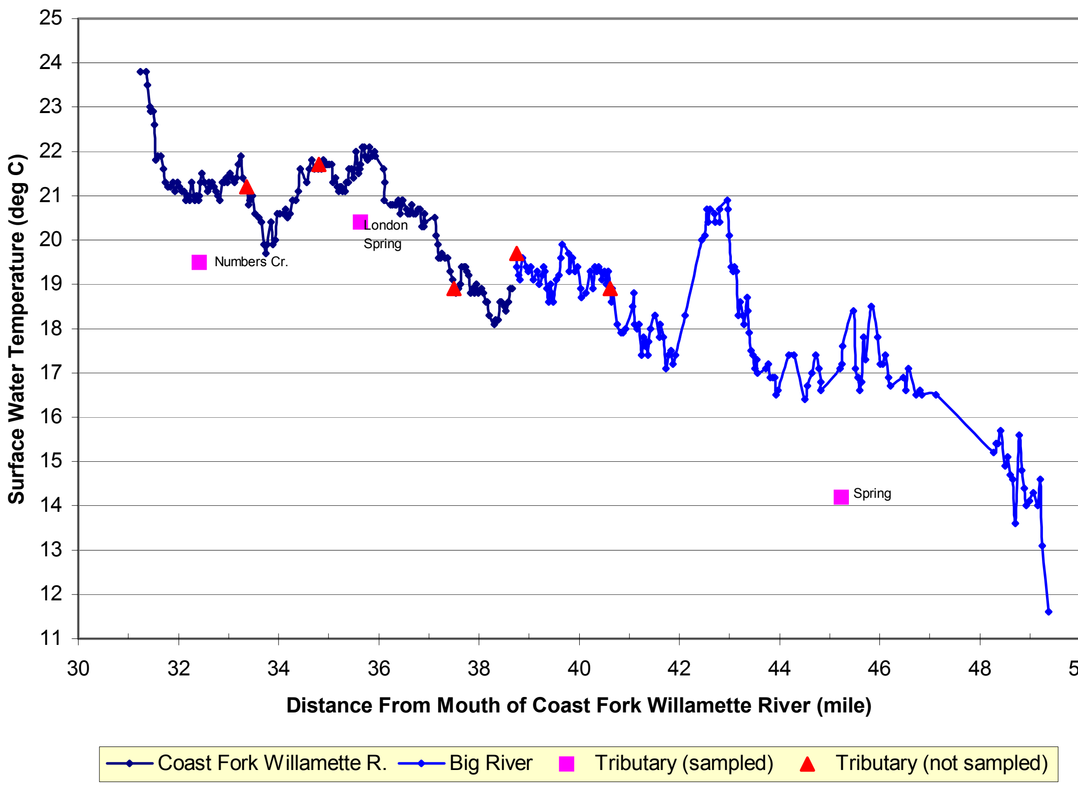

Figure 10 - Median radiant temperatures versus river mile for the Coast Fork Willamette River and Big River. River miles are calculated from the mouth of the Coast Fork Willamette River. The plot also shows the location and names of tributary and other surface water inflows.

Water temperatures in Big River were cool (≈11.6°C) at the upstream end of the survey and generally warmed in the downstream direction. The warming trend continued in the CF Willamette River with stream temperatures reaching ≈21.8°C its outlet to Cottage Grove Lake. While a general pattern of downstream warming prevails, the profile illustrates where changes in longitudinal heating (or cooling) rates occur along the stream gradient. Segments with similar thermal response (warming or cooling) were delineated from the longitudinal profile in order to provide a basis for examining the reach scale characteristics (Figure 11). This segmentation is based on visual inspection of the profile. Alternate segmentations are possible depending on scale of interest or possibly more rigorous mathematical analysis. Figure 11 also shows in-stream temperatures at the time the images were acquired along with the recorded daily maximum temperature. The following paragraphs provide observations from each reach and in some cases present hypotheses on the factors driving the observed spatial temperature patterns.

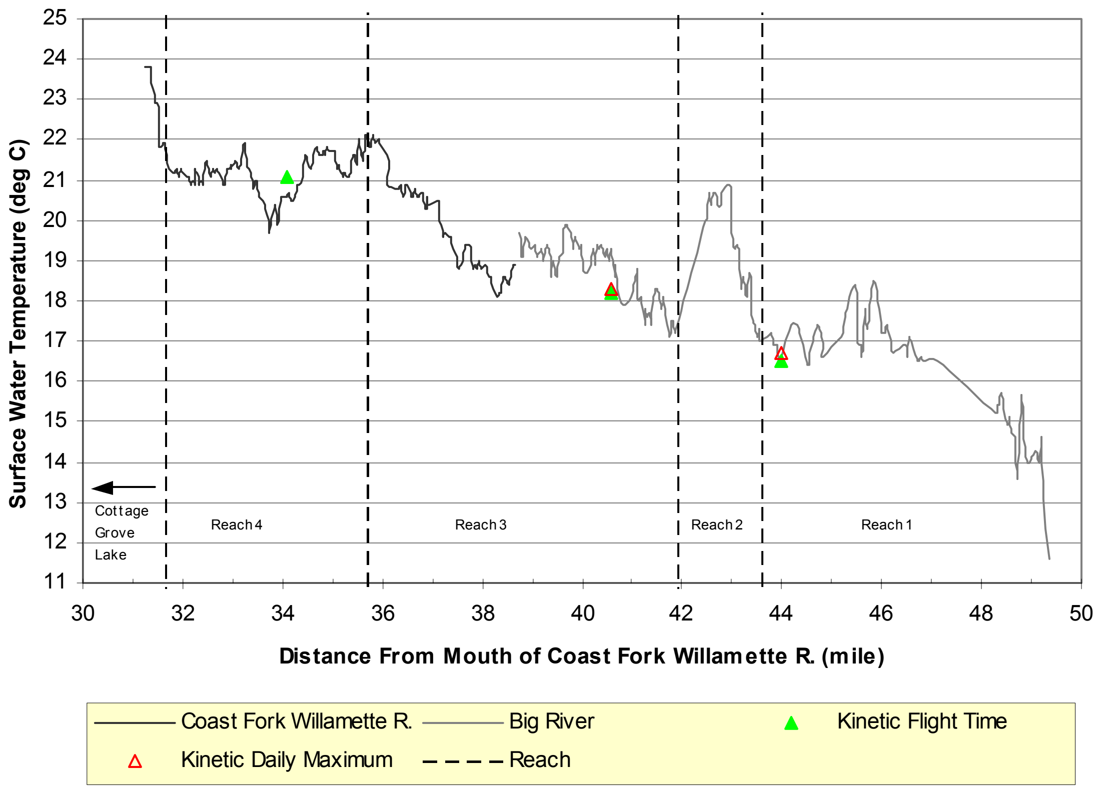

Figure 11 - Median channel temperatures versus river mile for the Coast Fork Willamette River and Big River, OR. Kinetic stream temperatures at the time of the survey and maximum daily stream temperatures used to calibrate the TIR images are shown on the profile.

<u>Reach 1 (river mile 49.4 to river mile 43.7)</u> – Radiant water temperatures in Big River increased from 11.6^{o}C near the headwaters (river mile 49.4) to 17.2^{o}C at river mile 46.6. Between river miles 46.6 and 43.7, stream temperatures exhibited some local spatial variability with apparent temperatures increasing to ≈18.4^{o}C at river miles 45.5 and 45.8 and returning to 17.2^{o}C at river mile 45.2. A spring detected at river mile 45.2 contributes to the observed local variability. Riparian vegetation masked the stream surface intermittently through the entire reach and precluded temperature sampling between river miles 48.3 and 46.8. The riparian masking combined with a small stream size (*relative to pixel size*) prevented identifying any additional sources of thermal

variability or from separating the natural thermal variability from the increased sampling noise inherent to small streams.

Reach 2 (river mile 43.7 to river mile 41.9) – This reach is characterized by an increase in stream temperatures of 3.6°C between river miles 43.7 and 43.0. The rapid stream temperature increase was followed by an equally rapid decrease between river miles 42.6 and 41.9. The result is a distinct local maximum in the overall temperature profile. As with the upstream reach, vegetation masking of the stream surface was a factor in identifying the source of thermal cooling. The stream surface was clearly visible in the TIR imagery where stream temperatures increased (river mile 43.7 and 43.0). However, riparian vegetation masked the stream surface and precluded temperature sampling where the apparent cooling occurred (river mile 42.6 to river mile 41.9). Although not detected in the imagery, Bar Creek enters the Big River at river mile 42.2 and may be a potential source of cooling.

Reach 3 (river mile 41.9 to river mile 35.7) – Stream temperatures generally warmed through this reach increasing from 17.2°C at river mile 41.9 to 22.0°C at river mile 35.7. A decrease (≈1.3°C) in stream temperature was observed at river mile 39.7 that was not associated with a detected (or mapped) point source. Garoutte Creek was detected in the TIR imagery, but was not visible enough to obtain an accurate radiant temperature sample. However, downstream of the Garoutte Creek confluence, the Coast Fork showed a slight cooling trend (≈1.6°C) between river miles 38.8 and 38.3. Stream temperatures increased by ≈3.0°C over the next 2.6 miles. Hambrick Creek was detected (but not sampled) at river mile 37.5 and a slight drop (0.6°C) in main stem temperatures was observed at this location.

Reach 4 (river mile 35.7 to Cottage Grove Lake) – Stream temperatures generally cooled through this reach with a net decrease of ≈0.8°C. A cooling trend (≈0.9°C) was observed between river miles 35.7 and 35.3. London Spring enters the river at mile 35.6 and contributes to this local cooling. After a slight increase, stream temperatures continued to cool downstream of river mile 34.7 reaching a local minimum of 19.7°C at river mile 33.7. No surface water inflows were detected through this reach. Water temperatures in the Coast Fork Willamette River increased downstream of river mile 33.7 and eventually entered Cottage Grove Lake at ≈21.8°C. Interpretation of the TIR images suggests that the lake surface is thermally stratified.

Sharps Creek

The median temperatures for each sampled image of Sharps Creek were plotted versus the corresponding river mile (Figure 12). The plot also contains the median temperature and name of all surface water inflows (e.g. tributaries, surface springs, etc.) detected and sampled during the analysis. The figure also shows the locations of tributaries that were detected in the imagery, but were too small (*relative to pixel size*) to obtain a radiant temperature. The locations of tributaries that were not sampled were included on the profile to help assess the sources of local thermal variability.

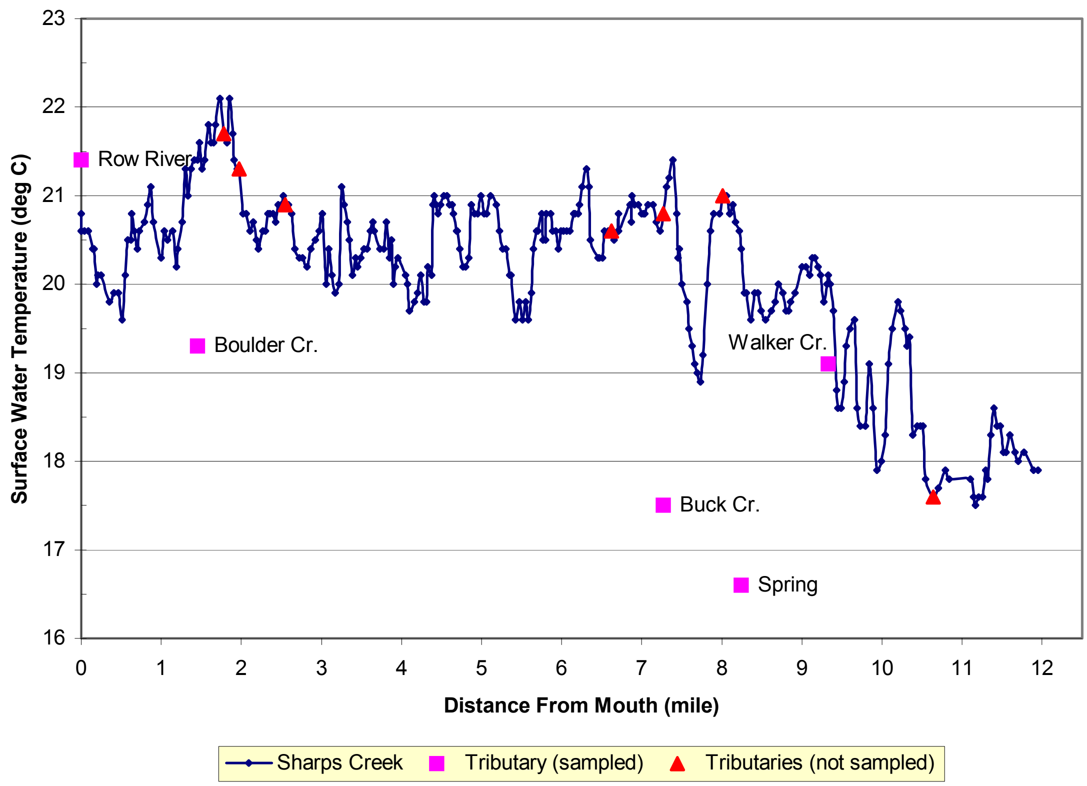

Figure 12 - Median channel temperatures versus river mile for Sharps Creek, OR. Tributary and other surface water inflows are labeled on the profile by name. The plot also shows the location of tributaries that were detected in the imagery but too small to obtain a radiant temperature sample.

Water temperatures in Sharps Creek generally warmed in the downstream direction gaining ≈2.6°C over the length of the 12-mile survey. Radiant temperatures showed a high degree of local spatial variability throughout the profile. In some cases, temperatures shifts corresponded to the location of tributary inflows. However, that was not the case for all points where spatial temperature variations were observed. Notwithstanding local spatial variability, Sharps Creek has reaches with distinct thermal response (warming or cooling), which may be segmented from the overall profile (Figure 13). The segmentation presented here provides a basis for discussing the thermal characteristics of Sharps Creek observed during the survey. Alternate segmentations are possible depending on scale of interest or possibly more rigorous mathematical analysis.

Figure 13 also shows in-stream temperatures at the time the images were acquired along with the recorded daily maximum temperature. The following paragraphs provide observations from each reach and in some cases present hypotheses on the sources of local temperature variability.

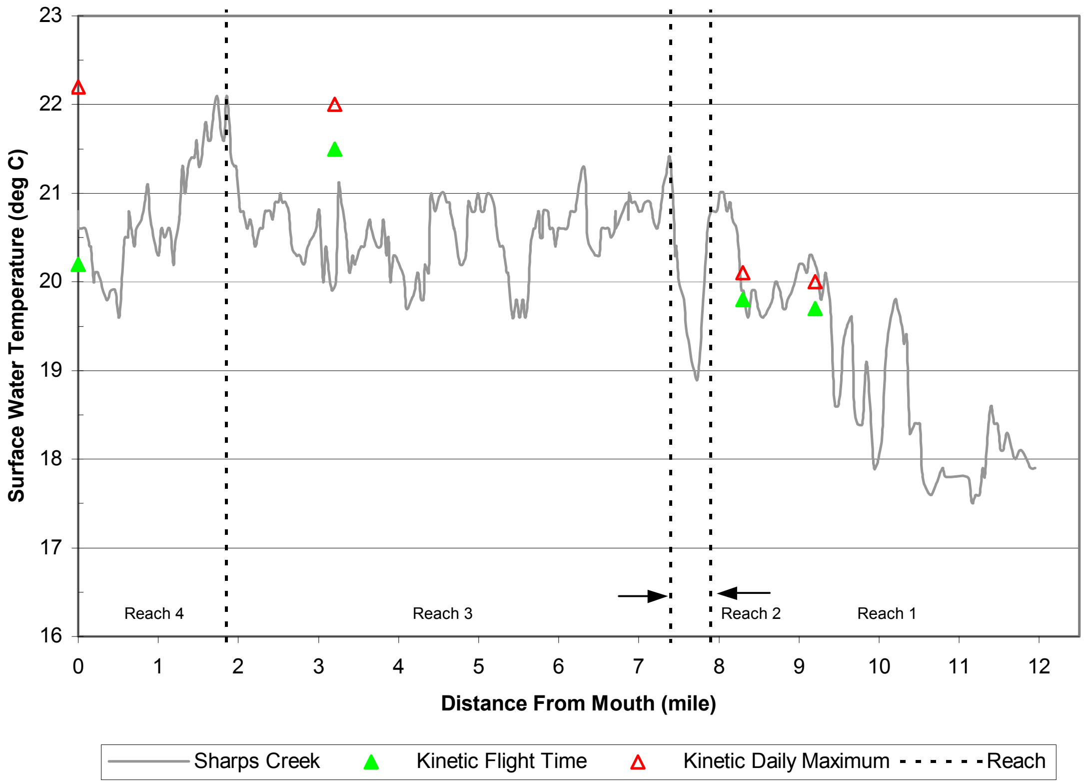

Figure 13 - Median channel temperatures versus river mile for Sharps Creek, OR. Kinetic stream temperatures at the time of the survey and maximum daily stream temperatures used to calibrate the TIR images are shown on the profile.

Reach 1 (river mile 12.0 – 7.9) – Stream temperatures generally increased through this reach rising from 17.9°C at river mile 11.9 to 20.8°C at river mile 8.0. Upstream of river mile 10.5 (confluence of Martin Creek), Sharps Creek became progressively more difficult to detect through the forest canopy. Small stream widths and near canopy both increase the inaccuracies of the radiant temperature samples and make it more difficult to assess the sources of variability. Between river mile 10.5 and 9.3, stream temperatures showed a cyclical pattern of longitudinal heating and cooling. The largest temperature change occurred between river miles 10.5 and 10.0 where stream temperatures warmed and then cooled by ≈2.0°C. Downstream of river mile 10.5, the stream was progressively more visible through the forest canopy. The observed increase in longitudinal heating may be attributed to greater exposure of the stream surface to direct solar radiation. Sources of cooling in this reach were not evident from the thermal imagery. Past TIR surveys have shown that stream temperatures often respond dramatically and locally to relatively small subsurface discharges. In-stream sensors at river miles 8.3 and 9.2

recorded kinetic temperatures consistent (i.e. within 0.5°C) with the radiant temperatures and the stream temperatures at the time of the survey were slightly (0.5°C) less than the recorded daily maximum temperatures.

<u>Reach 2 (river mile 7.9 – 7.4)</u> – Stream temperatures showed decrease of 2.1°C between river mile 7.9 and 7.4. An apparent surface spring (16.6°C) was detected at river mile 8.2 which contributed cooler water than Sharps Creek. However, the spring was detected upstream of the measured temperature decrease and did not appear to be responsible for the observed decrease in main stem temperatures (Figure 14). No other point sources were detected within this reach. The stream temperature decrease suggests sub-surface influences near river mile 7.8.

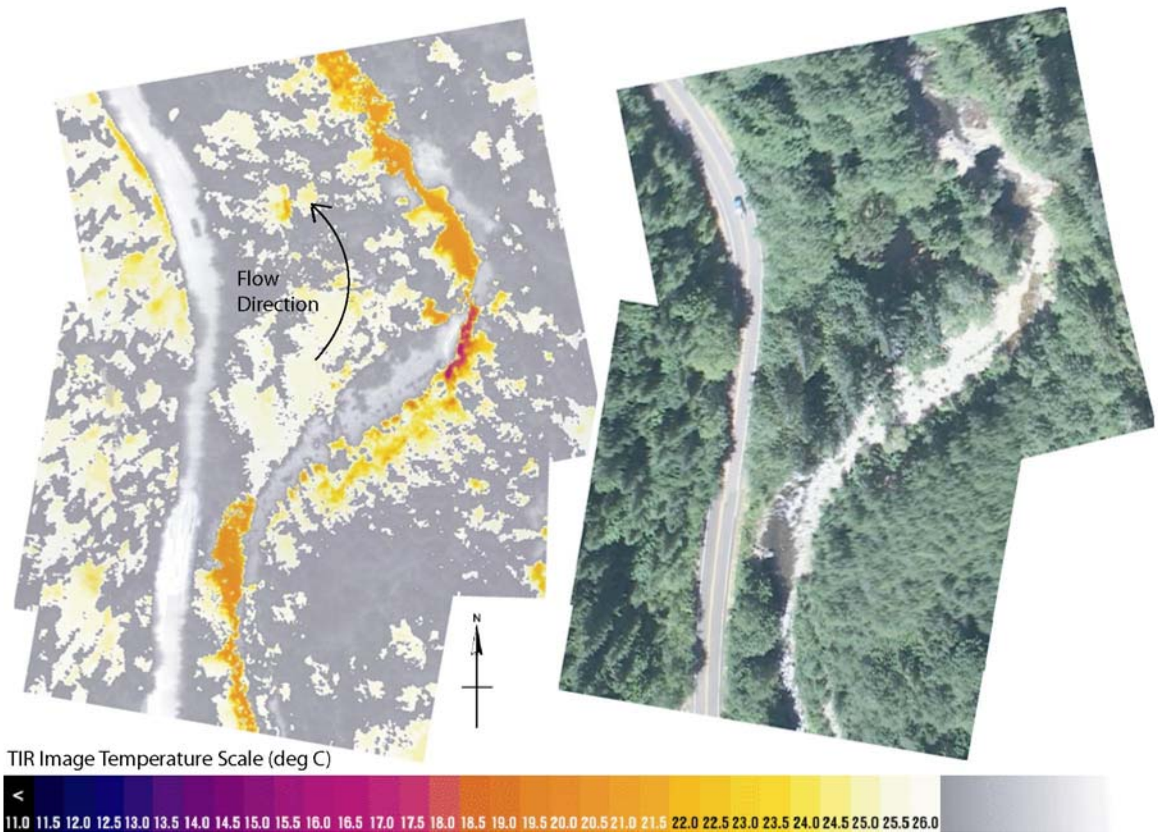

Figure 14 - TIR/color video image pair showing the location of a spring (16.6°C) on the right bank of Sharps Creek (20.4°C) at river mile 8.2 *(frames: shar0540-0544).*

<u>Reach 3 (river mile 7.4 – 1.9)</u> – Radiant temperatures through this reach were on average 20.6°C and ranged from 22.0°C at river mile 1.9 to a local minimum of 19.6°C at river mile 5.5. Buck Creek (17.5°C) contributed cooler water to the main stem and was the only tributary sampled through this reach. The TIR images of this reach showed that factors such as differences in surface characteristics (*riffles versus pools*) and in ambient reflections (*trees versus sky*) contributed to the observed variability in this reach. However, these factors typically result in spatial thermal variations of < ±0.5°C while stream temperatures within this reach varied by ±1.2°C. Stream temperatures decrease of > 1.0°C were observed at river miles 5.8, 4.4, and 3.3. The in-stream sensor at river mile

3.2 recorded a kinetic temperature that was ≈0.5°C warmer than the radiant temperature at the same location.

Reach 4 (river mile 1.9 – mouth) – Water temperatures in the lower 1.9 miles of Sharps Creek decreased from ≈22.1°C to ≈20.5°C with a local minimum of 19.6°C. Boulder Creek (19.3°C) enters the main stem at river mile 1.5 and contributes to the observed cooling trend. As with the upstream reaches, the sources of cooling could not be positively identified from the stand-alone images. However, the spatial temperature patterns observed in the images suggest that inter gravel flow may result in local cooling with subsequent heating occurring in the shallow pools and bedrock areas (Figure 15).

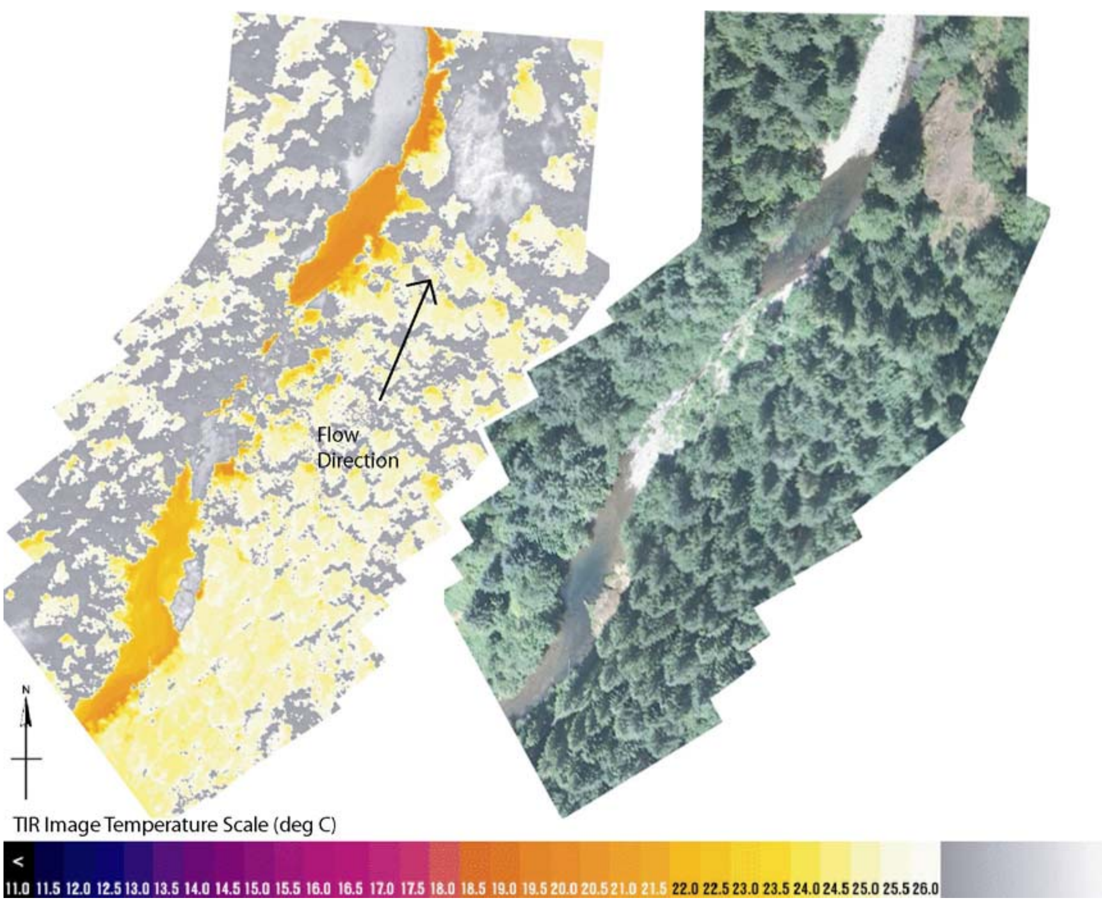

Figure 15 - TIR/color video mosaic pair illustrating Sharps Creek at river mile 0.6. Radiant stream temperatures show an apparent decrease from 20.5°C in the upstream stream pool to19.6°C below the gravel bar. The temperature decrease over this spatial scale (≈0.1 miles) suggests sub-surface flow through the gravel bar as a possible source of cooling at this location (*frame: shar0070*).

Mosby Creek

The median temperatures for each sampled image of Mosby Creek were plotted versus the corresponding river mile (Figure 16). The plot also contains the median temperature and name of all surface water inflows (e.g. tributaries, surface springs, etc.) detected and sampled during the analysis.

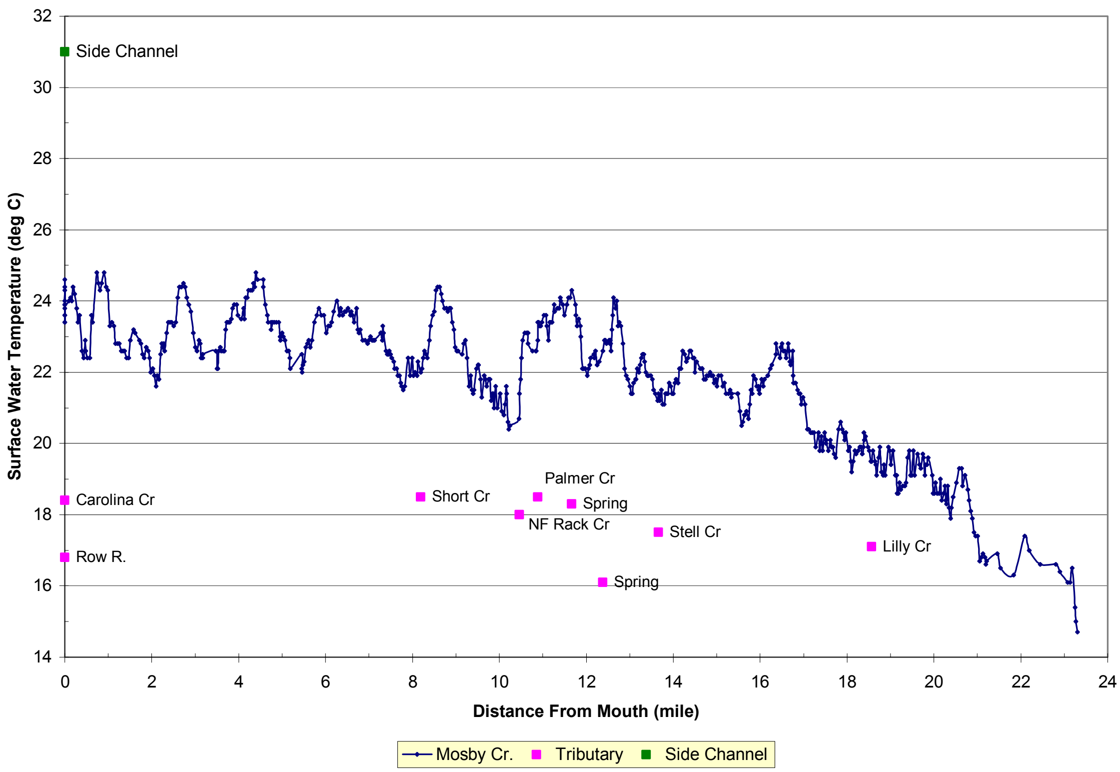

Figure 16 - Median channel temperatures versus river mile for Mosby Creek, OR. Tributary springs, and side channel inflows are labeled on the profile by name.

As with Sharps Creek, the longitudinal temperature profile may be segmented into reaches with distinct thermal response (warming or cooling) (Figure 17). The segmentation presented here provides a basis for discussing the thermal characteristics of Mosby Creek observed during the survey. Alternate segmentations are possible depending on scale of interest or possibly more rigorous mathematical analysis. Figure 17 also shows in-stream temperatures at the time the images were acquired along with the recorded daily maximum temperature. The following paragraphs provide observations from each reach and in some cases present hypotheses on the sources of local temperature variability.

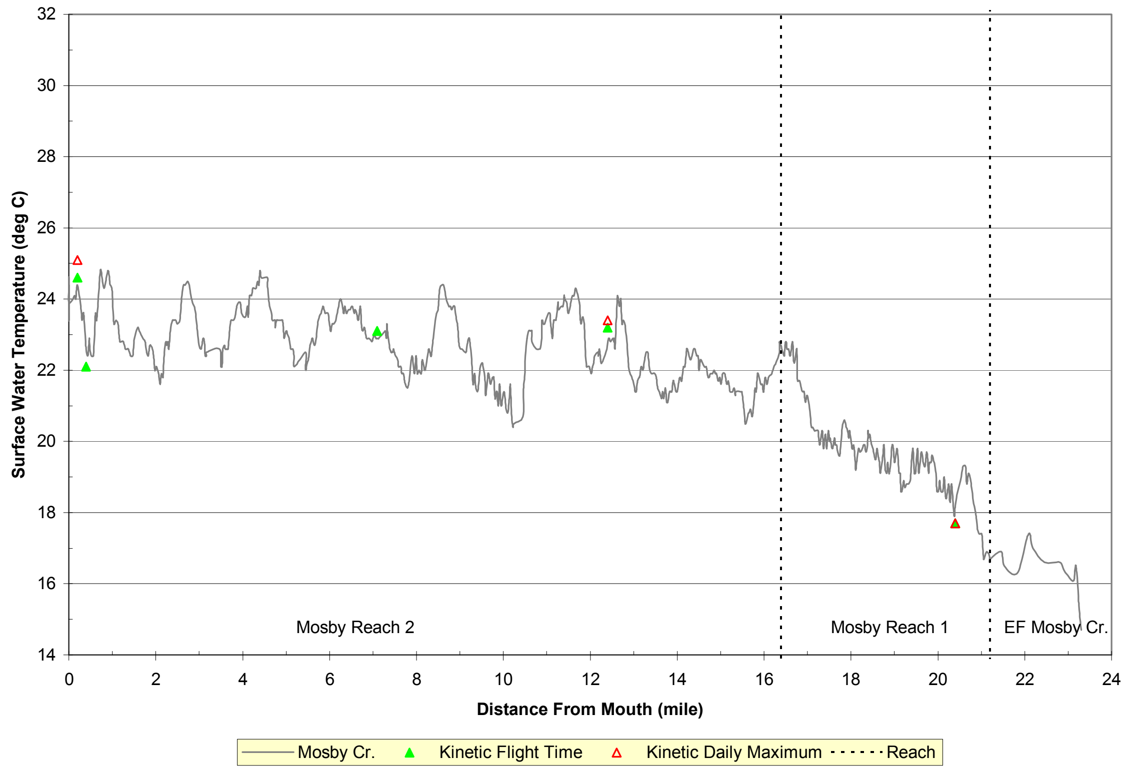

Figure 17 - Median channel temperatures versus river mile for Mosby Creek, OR. Kinetic stream temperatures at the time of the survey and maximum daily stream temperatures used to calibrate the TIR images are shown on the profile.

East Fork (EF) Mosby Cr. (river mile 23.2 to 21.2) – The airborne TIR survey continued up the EF Mosby Cr. for approximately 2.1 miles. EF Mosby Creek was small (*relative to pixel size*) and masked by riparian vegetation for much of its length. Radiant temperatures samples were taken intermittently when the stream surface was visible. Sampled stream temperatures in the EF ranged from 14.7°C at the upstream end of the EF to 16.7°C at the confluence with the Middle Fork and the start of the main stem of Mosby Creek.

Mosby Reach 1 (river mile 21.2 to 16.5) – Overall, water temperatures increased in the downstream direction by 6.0°C through this reach. The in-stream data logger at river mile 20.4 indicated that the radiant temperatures were consistent with kinetic temperatures at the time of the survey and with daily maximum temperatures at this point. From the EF confluence, stream temperatures increased rapidly (2.2°C) over the first 0.7 miles of Mosby Creek. This increase was followed by an apparent decrease of ≈1.3°C between river mile 20.6 and 20.4. The source of cooling could not be positively determined from the imagery. However, the cooling occurs between the confluences of Cove Creek and the West Fork Mosby Creek. Although, neither of these tributaries was detected in the TIR imagery, their influence (surface or sub-surface) is a possible factor in the observed cooling in main stem temperatures. Stream temperature continued to increase steadily between river mile 20.4 and 17.3 with observed local variations characteristics of the noise levels (±0.5°C) observed in TIR sampling. Lilly Creek enters Mosby Creek through this reach and was observed as a source of cooling at river mile 18.6.

The longitudinal heating rate increased between river miles 17.3 and 16.1 gaining ≈2.5°C over this 0.9 mile segment (Figure 18). The TIR/color video imagery or base maps did not reveal any alterations in riparian vegetation, channel aspect, or other factors that would suggest possible reasons for the change in the downstream heating rate.

Mosby Reach 2 (river mile 16.4 to confluence with the Row River) – Radiant water temperatures remained above 20.4°C over the lower 16.4 miles of Mosby Creek with a high degree of local spatial variability (*ranging between 20.4°C to 24.8°C*). The local spatial variations made it difficult (and probably irrelevant) to quantify an overall net change in stream temperatures. For example, stream temperatures were 22.4°C both at river mile 16.4 and at river mile 0.6, but were 24.0°C at the mouth. Consequently, the location and possible sources of local temperature variations define the thermal regime of the lower 16.5 miles of Mosby Creek.

Stream temperatures showed a ≈2.0°C decrease between river miles 16.4 and 15.8. This decrease was not associated with any detected point source inflows. However, a 1°C drop in stream temperature was observed at river mile 15.9, which corresponds to the mapped location of Dry Creek (Figure 19). Although Dry Creek was not detected in the imagery, the decrease in stream temperatures suggests possible sub-surface discharge from the Dry Creek channel. Four tributaries and two springs were detected between river miles 13.7 and 8.2 and were all sources of cooling to the main stem. The two springs (river miles 11.7 and 12.4) detected during the analysis were not identified on the USGS 7.5' topographic maps. The springs were relatively small and were classified as springs based on their temperature (*when compared to prevailing terrestrial and water temperatures*) and their location relative to the stream's edge (Figure 20).

Downstream of Short Creek (river mile 8.2), stream temperatures continued a pattern of local cooling of ≈1.5 to 2.0°C followed by a rapid increase. No additional point source inflows were detected until the confluence of Caroline Creek, which entered just upstream of the Mosby Creek mouth. The sources of cooling in this stream segment were not apparent from the stand-alone imagery. At its mouth, Mosby Creek was ≈5.0°C warmer than the Row River.

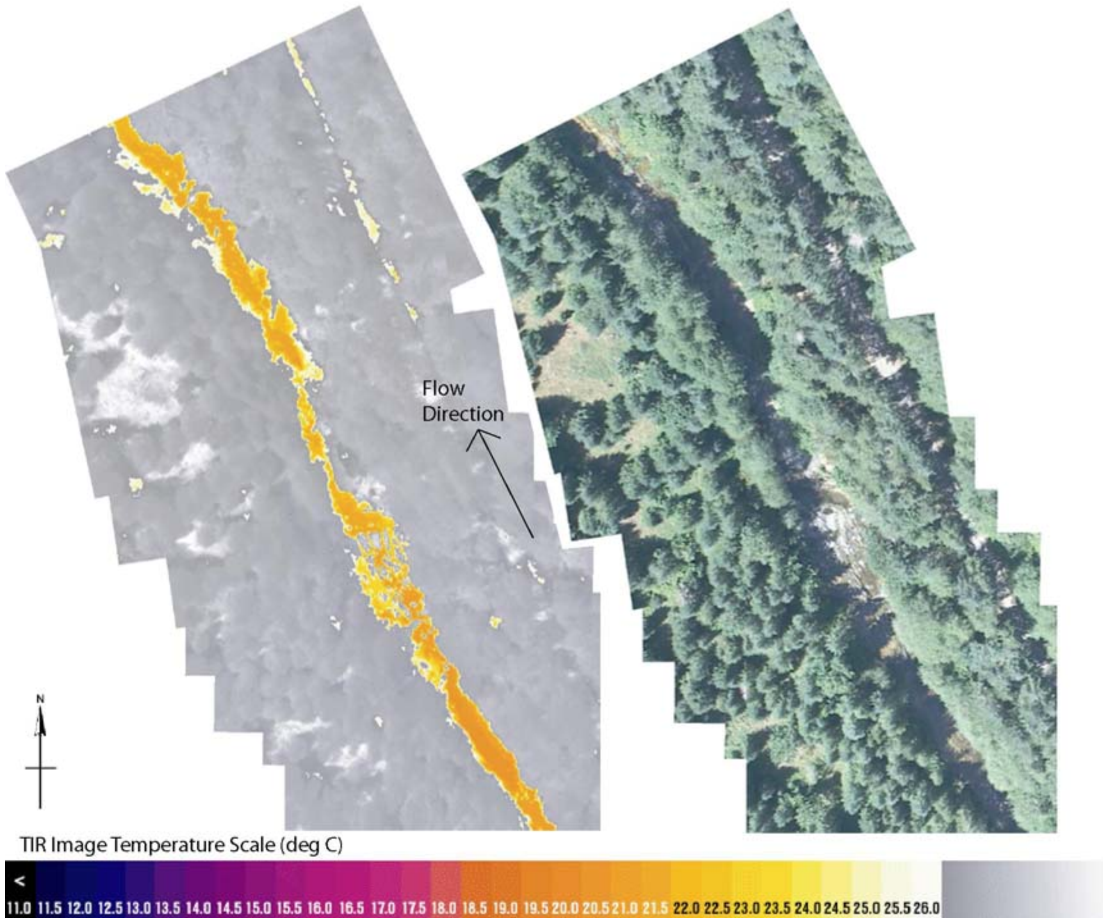

Figure 18 - TIR/color video image showing Mosby Creek at river mile 17.2. A longitudinal increase in apparent stream temperatures of 0.7°C was observed at this location. The reason for the rapid increase was not directly apparent from the imagery (*frames: mosb0981-0988*).

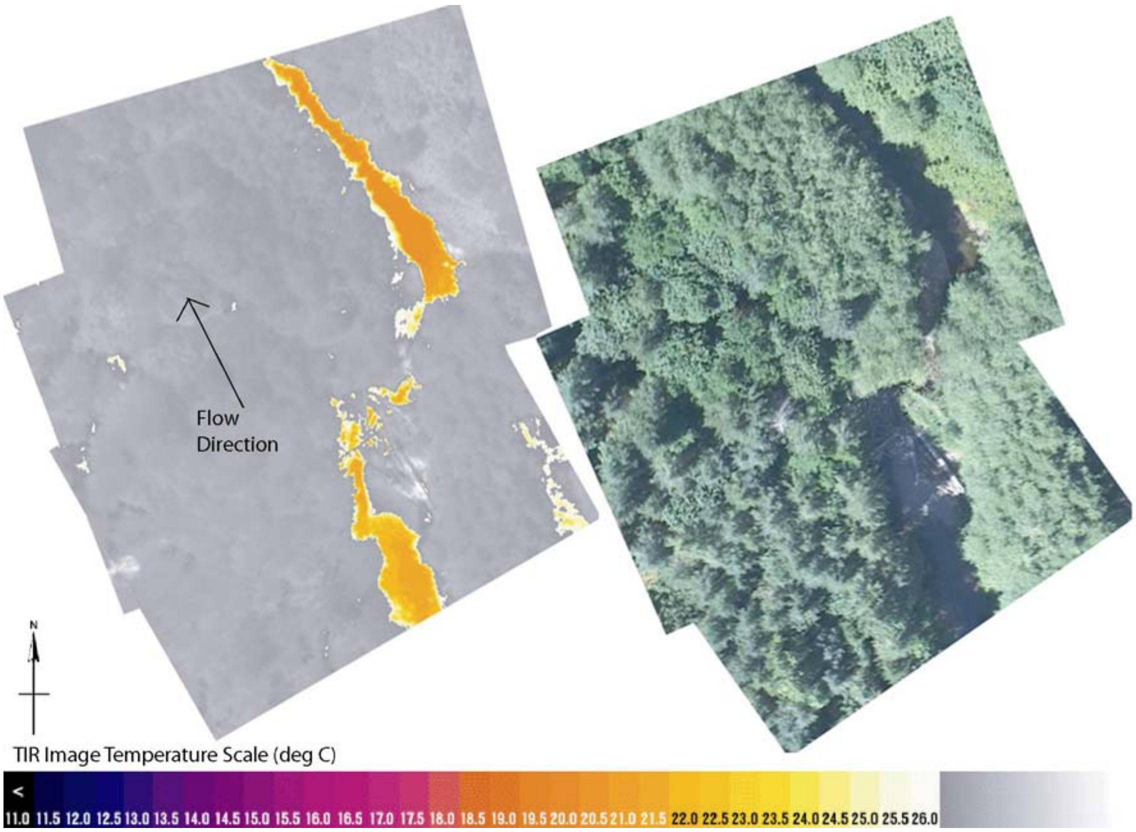

Figure 19 – TIR/color video image showing Mosby Creek at river mile 15.9. A 1.0^{o}C drop in radiant temperatures was recorded at this location, which corresponds to the mapped location of Dry Creek (*frames: mos0920-0922*).

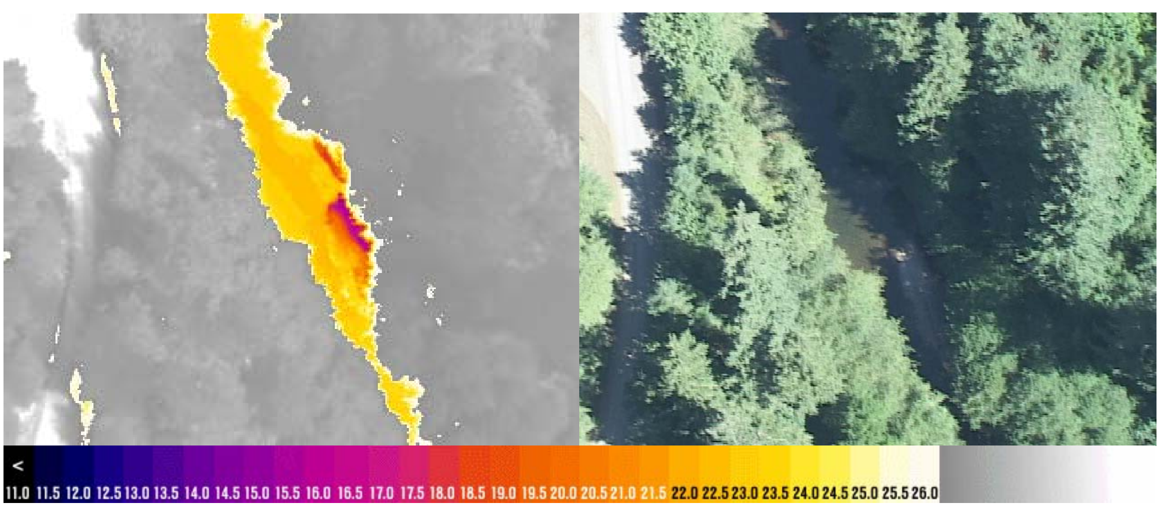

Figure 20 - TIR/color video image showing Mosby Creek (22.4^{o}C) at river mile 12.4. The flow direction is from the top to bottom of the image. A possible spring (16.1^{o}C) is visible along the LB (*looking downstream*). Although visible shadows make classification difficult, the location has visible surface water and is considerably cooler than other shadowed areas (*frame: mos0699*).

Discussion

Thermal infrared remote sensing surveys were successfully conducted on selected streams in the Southern Willamette River valley. Spatial temperature patterns were developed by sampling radiant temperatures from the TIR images and plotting them versus river mile. The spatial temperature patterns were unique for each surveyed stream and provide a basis for better understanding thermal spatial variability along the stream gradient. Tributaries in the upper basin showed a high degree of local spatial variability in stream temperature. In some cases the source of cooling were attributed to point source influence. However, the factors contributing to the observed spatial temperature response was not always obvious from the imagery and will require further analysis. The larger rivers showed patterns of downstream warming with less local spatial variability in bulk water temperatures. However, TIR images of the larger systems showed that temperatures often varied laterally within the floodplain, but these fine scale variations were not reflected in the basin scale spatial temperature patterns.

Northern Willamette Valley

Overview

TIR remote sensing surveys in Northern Willamette Valley were conducted on July 31, 2002. The surveys included Johnson Creek and segments of Eagle Creek, North Fork Eagle Creek, and Bear Creek (Figure 21). Table 6 summarizes the survey times, extents, and image resolution for each surveyed stream in the Northern Willamette Valley. The weather conditions for the dates and times of the surveys are summarized in Table 7.

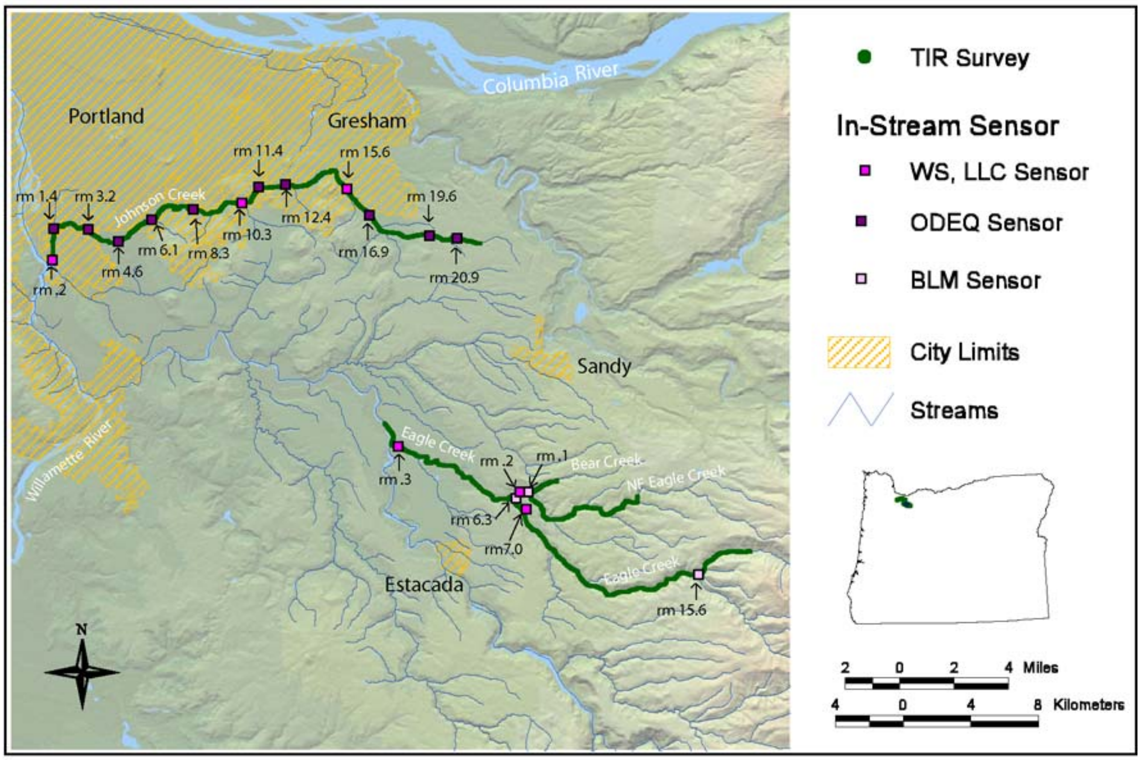

Figure 21 - Map showing streams surveyed using TIR and color video on July 31, 2002 in the Northern Willamette River Valley. The map also shows the location of in-stream sensors (identified by river mile) used to verify the accuracy of the radiant temperatures.

Table 6 – Summary of river segments surveyed with TIR and color video in the Northern Willamette River Basin on July 31, 2002.

Stream	Survey Date	Survey Time (24 hr)	Survey Extent & Direction	River Miles	Image Width Meter (ft)	TIR Image Pixel Size Meter (ft)
Johnson Creek	31 Jul	13:32-14:35	Mouth to headwaters	21.5	97 (318)	0.3 (1.0)
Eagle Creek	31 Jul	15:14-15:54	Mouth to Wilderness Bnd.	16.5	129 (423)	0.4 (1.3)
NF Eagle Creek	31 Jul	16:01-16:20	Mouth to rm 5.0	5.0	97 (318)	0.3 (1.0)
Bear Creek	31 Jul	16:25-16:34	Mouth to rm 1.0	1.0	97 (318)	0.3 (1.0)

Table 7 - Meteorological conditions recorded at two locations in the Northern Willamette River Basin on July 31, 2002 during the time frame of the TIR surveys.

Troutdale Airport, OR			
Time	°F	°C	RH%
13:30	69.0	20.6	47.4
14:00	71.1	21.7	41.2
14:30	72.5	22.5	40.2
15:00	73.2	22.9	39.7
15:30	74.5	23.6	35.7
16:00	75.2	24.0	34.7
16:30	76.6	24.8	33.7
17:00	78.0	25.6	29.9
Eagle Fern Park, OR			
Time	°F	°C	RH%
13:30	71.8	22.1	44.0
14:00	71.8	22.1	43.0
14:30	74.5	23.6	38.9
15:00	75.2	24.0	35.9
15:30	75.2	24.0	33.4
16:00	73.2	22.9	32.5
16:30	74.5	23.6	40.9
17:00	73.8	23.2	34.4

Results

Thermal Accuracy

On Johnson Creek, fourteen in-stream sensors were used to verify the accuracy of the radiant temperatures derived from the TIR images. The average absolute difference between the kinetic temperatures recorded by the in-stream data loggers and the radiant temperatures derived from the TIR images for all in-stream locations was 0.2°C (Table 8, Figure 21). Differences ranged from -0.4°C to 0.5°C. These values were within the desired accuracy (< 0.5°C) for the TIR surveys and were consistent with TIR surveys conducted in the Pacific Northwest over the past five years (Torgersen, 2001).

Five in-stream sensors were used to verify the accuracy of the radiant temperatures on Eagle Creek and three were used on the NF Eagle Creek. Differences between the kinetic temperatures and radiant temperatures for these two survey segments ranged from -0.4 to 0.5. Factoring in the accuracy of the in-stream data loggers (±0.2°C) and the thermal noise level (±0.5°C) characteristic of TIR remote sensing, differences of this magnitude were expected.

Table 8 – Comparison of ground-truth water temperatures (Kinetic) with the radiant temperatures derived from the TIR images.

Stream	Image	River mile	Date	Time	Kinetic °C	Radiant °C	Difference
Johnson Creek							
Johnson Cr	john0018	0.2	31-Jul	1:32 PM	19.3	19.4	0.1
Johnson Cr	john0029	0.3	31-Jul	1:32 PM	19.2	19.5	0.3
Johnson Cr	john0085	1.4	31-Jul	1:34 PM	19.9	19.8	-0.1
Johnson Cr	john0186	3.2	31-Jul	1:38 PM	17.5	18.0	0.5
Johnson Cr	john0265	4.6	31-Jul	1:40 PM	20.2	20.1	-0.1
Johnson Cr	john0365	6.1	31-Jul	1:44 PM	19.6	19.8	0.2
Johnson Cr	john0560	8.2	31-Jul	1:52 PM	17.5	17.7	0.2
Johnson Cr	john0566	8.3	31-Jul	1:52 PM	17.6	17.5	-0.1
Johnson Cr	john0722	10.3	31-Jul	1:58 PM	17.7	17.6	-0.1
Johnson Cr	john0803	11.3	31-Jul	2:00 PM	19.9	19.8	-0.1
Johnson Cr	john0881	12.4	31-Jul	2:03 PM	19.1	18.8	-0.3
Johnson Cr	john1185	15.6	31-Jul	2:15 PM	17.2	16.8	-0.4
Johnson Cr	john1294	16.9	31-Jul	2:18 PM	17.1	17.5	0.4
Johnson Cr	john1693	20.9	31-Jul	2:33 PM	15.3	15.4	0.1
Eagle Creek							
Eagle Cr	eag0068	0.3	31-Jul	3:16 PM	19.7	19.4	0.3
Eagle Cr	eag0410	6.4	31-Jul	3:30 PM	17.8	17.3	0.5
Eagle Cr	eag0465	7.2	31-Jul	3:30 PM	16.6	17.0	-0.4
Eagle Cr	eag1046	15.6	31-Jul	3:50 PM	14.7	14.7	0.0
SF Eagle Cr	eag1042	15.6	31-Jul	3:50 PM	14.3	13.9	0.4
NF Eagle Creek							
Eagle Cr.	nfe0041	0	31-Jul	4:00 PM	17.7	17.6	0.1
NF Eagle Cr	nfe0078	0.2	31-Jul	4:03 PM	15.4	15.6	-0.2
NF Eagle Cr	nfe0125	0.5	31-Jul	4:04 PM	15.6	15.5	0.1
Bear Creek							
NF Eagle Cr	bear0133	0	31-Jul	4:30 AM	15.6	15.9	-0.3

Temporal Differences

Figure 22 shows in-stream temperature variations at single locations in Johnson Creek, Eagle Creek, and NF Eagle Creek. The plots are intended to provide a sense of the temperature changes during the course of the TIR survey and also an indication of the timing of the TIR survey in relation to the daily maximum temperature. At river mile 8.2, stream temperatures increase by ≈0.5°C during the time span of the survey. As illustrated, the TIR survey of Johnson Creek occurred prior to the recorded daily temperature maximum, which was recorded at approximately 16:10. The timing of TIR survey on Eagle Creek and the NF Eagle Creek was consistent with the recorded daily maximum temperature.

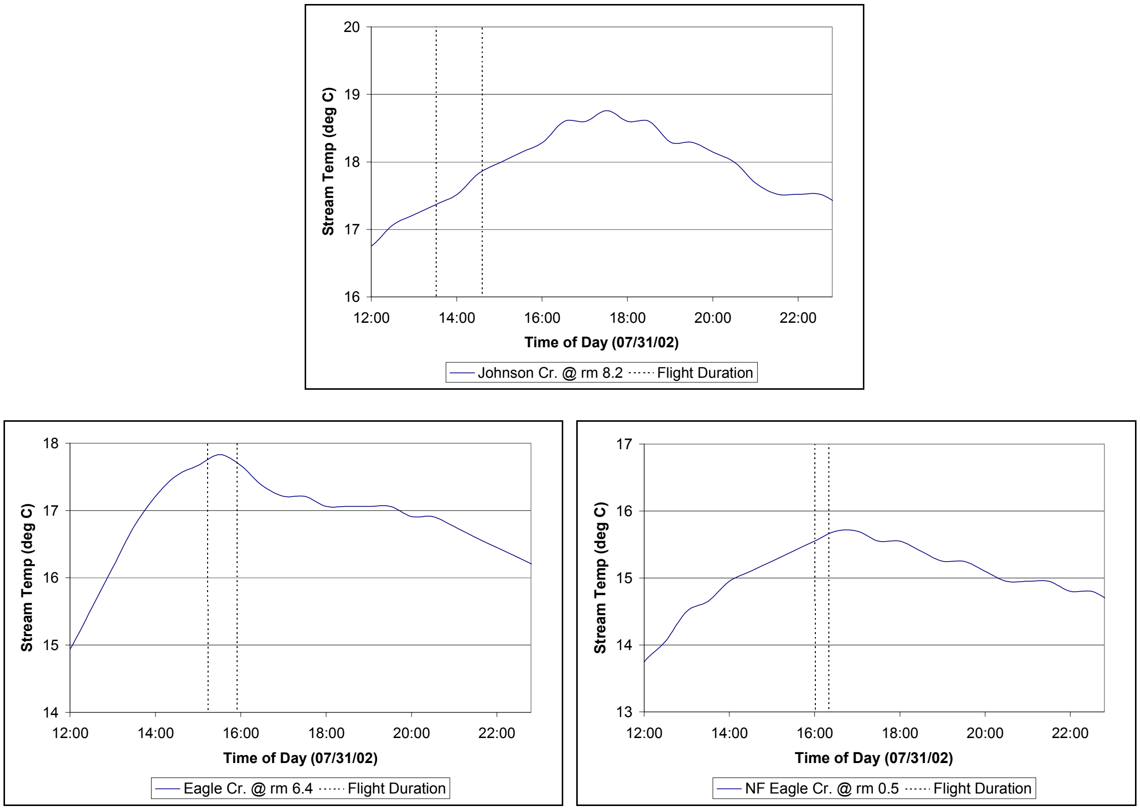

Figure 22 – Stream temperature variation and time of TIR remote sensing over flight for a sensor location on Johnson, Eagle and North Fork Eagle Creeks on July 31, 2002.

Longitudinal Temperature Profiles

Johnson Creek

The median temperatures for each sampled image of Johnson Creek were plotted versus the corresponding river mile (Figure 23). The plot also contains the median temperature and name of all surface water inflows (e.g. tributaries, surface springs, etc.) detected and sampled during the analysis. Johnson Creek flows primarily through urban and residential areas with 78% of the TIR survey occurring within the Portland and Gresham urban growth boundaries. At different points along the survey, the stream width was relatively small (*relative to pixel size*) and occasionally masked by riparian vegetation (Figure 24). Radiant stream temperatures were sampled in areas where the water's surface was clearly visible in the imagery. Consequently, temperature samples were intermittent in some stream segments, especially upstream of river mile 15.0.

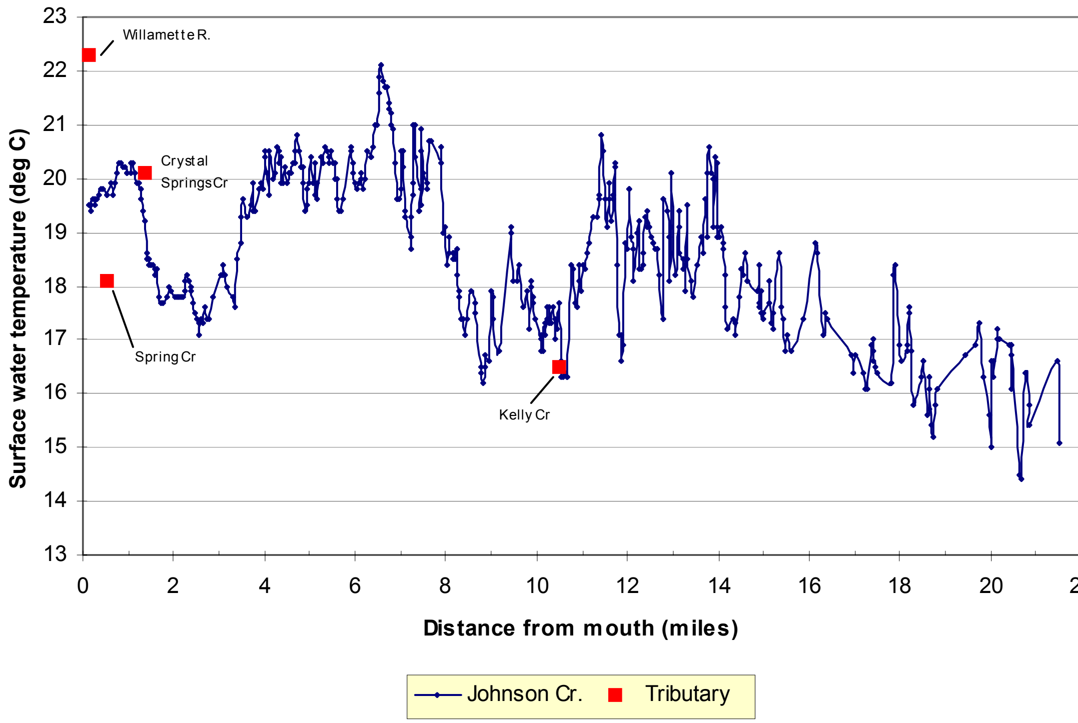

Figure 23 - Median channel temperatures versus river mile for Johnson Creek, OR. Tributary and other surface inflows are labeled on the figure.

Figure 24 – Ground level photograph (*left*) and airborne color video image (*right; frame: john 1037*) pair showing Johnson Creek at river mile 15.6. The ground level photo was taken looking downstream from the bridge. The images illustrate the stream width and riparian vegetation conditions characteristic of some of Johnson Creek in the upper reaches.

Radiant temperatures in Johnson Creek showed distinct patterns of warming and cooling along the stream gradient (basin scale). Superimposed on the basin scale temperature profile are patterns of apparent thermal variability at the local scale (*i.e.*

distances of < 200 meters). The combination of flow and riparian conditions on Johnson Creek made it generally difficult to identify the sources of local spatial thermal variability. As mentioned earlier (*see: TIR image characteristics*), smaller streams characteristically show increased spatial temperature variability due to both an increase in the number of hybrid pixels (*i.e. noise*) and increased response to relatively small energy transfers (*i.e. actual temperature change*). A challenge in TIR image interpretation of small streams is to separate the noise from true thermal response.

The basin scale profile can be delineated into reaches that exhibit consistent longitudinal heating (*and/or cooling*). Figure 25 provides an example of how the reaches may be segmented from the overall profile. The segmentation presented in this report is based on visual inspection of the longitudinal temperature profile. Alternate segmentations are possible depending on scale of interest or possibly more rigorous mathematical analysis. The plot also shows the in-stream temperatures at the time the images were acquired along with the recorded daily maximum temperature. The kinetic temperatures show that the radiant temperatures were less than the maximum daily stream temperatures at the time of the survey, but that the overall spatial temperature patterns were consistent. The following paragraphs describe each reach (Figure 25) and provide some hypotheses on the sources of local temperature variability.

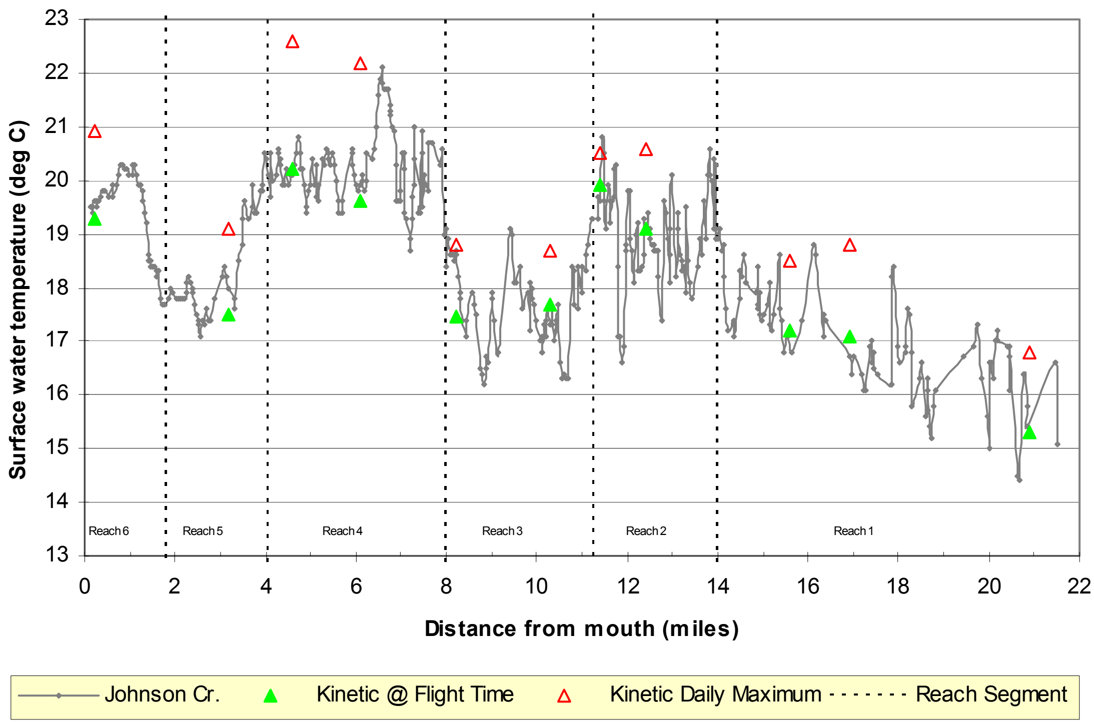

Figure 25 - Median radiant channel temperatures versus river mile for Johnson Creek, OR. The figure also shows the kinetic water temperatures at the time of the thermal infrared survey and maximum daily stream temperatures. Reaches with consistent thermal response are delineated on the plot.

<u>Reach 1 (River mile 21.5 to river mile 14.0)</u>: Stream temperatures in Johnson Creek showed a general warming trend with stream temperatures increasing from ≈15.1°C (rm 21.5) to ≈17.3°C at (rm 14.4). The reach was characterized by small stream widths (Figure 26) and zones where the stream surface was masked by riparian vegetation. The combination resulted in intermittent temperature samples in some locations. The inability to see the stream continuously from the air made it difficult to positively identify the sources of local variability. While a component of the temperature variability in the profile should be attributed to sampling noise, changes in the visible surface water suggest that the stream is losing water to and gaining water from sub-surface pathways through this reach. These exchanges combined with rapid thermal loading of relatively small pockets of surface water characteristically result in a high degree of local spatial thermal variability. Although no surface water inflows were sampled through this reach, the USGS 7.5' topographic map and GIS stream coverage show three intermittent streams entering Johnson Creek between river miles 17.6 and 17.9. The mapped tributaries and a corresponding decrease in an apparent stream temperature at river mile 17.5 suggest sub-surface flow through these channels. Another decrease in stream temperature was observed at river mile 15.9. In-stream data loggers (kinetic temperatures) confirm a slight (*-0.3°C in the daily maximum*) decrease in stream temperatures between river mile 16.9 and 15.6. The stream surface was masked by riparian vegetation (Figure 24) and only 6% of the 110 images collected between river miles 16.9 and 15.6 had enough visible surface water to obtain radiant temperature samples. The riparian masking of the stream surface suggests an overall decrease in solar loading and subsequent decrease in longitudinal heating rates. The USGS 7.5' topographic map also shows three perennial surface streams entering Johnson Creek within this reach, which may contribute to cooling by providing conduits for shallow sub-surface flow to the stream. Finally, the longitudinal temperature profile shows an apparent increase in temperatures between river mile 15.6 (17.1°C) and river mile 14.6 (18.6°C) followed by a subsequent decrease at river mile 14.3 (17.4°C). Surface water was more visible throughout this reach than further upstream, which allowed for more continuous temperature sampling. The TIR images show evidence of differential surface heating (*i.e. surface temperature differences in direct sunlight versus shaded areas*) and no obvious mixing (Figure 27). Consequently, the local temperature variability between river miles 15.6 and 14.3 might be due to surface heating with bulk water temperatures closer to those at river mile 14.4 (i.e. 17.3°C)

<u>Reach 2 (river mile 14.0 to river mile 11.3):</u> Overall, apparent stream temperatures in Johnson Creek showed no net change through this reach with average water temperatures ≈19.0°C. However, a high degree of apparent thermal variability at the local scale was observed with surface temperatures ranging 4.2°C (*16.6°C at river mile 11.9 to 20.8°C at river mile 11.4*). At the upstream end of the reach (river mile 14.0), stream temperatures increased rapidly reaching 20.6°C at river mile 13.8. Review of the TIR and color video images show less riparian masking of the stream surface and greater exposure to direct solar radiation, which may account for the rapid increases in stream temperatures. The TIR images also show spatial temperature variations indicative of differential surface heating combined with relatively slow vertical mixing (Figure 28). The spatial temperature patterns indicate longitudinal warming in bulk water temperature between river miles 14.0 and 13.0, but that radiant temperatures may exaggerate the level of local

spatial variability due to differential heating at the stream surface (Figure 28). The longitudinal profile shows an apparent drop in stream temperatures at river mile 11.9 (16.6°C). Review of the TIR imagery and topographic reference maps did not provide an indication to the possible source of cooling at this location. Further analysis and field verification are required to determine possible sources and potential biological significance of this location.

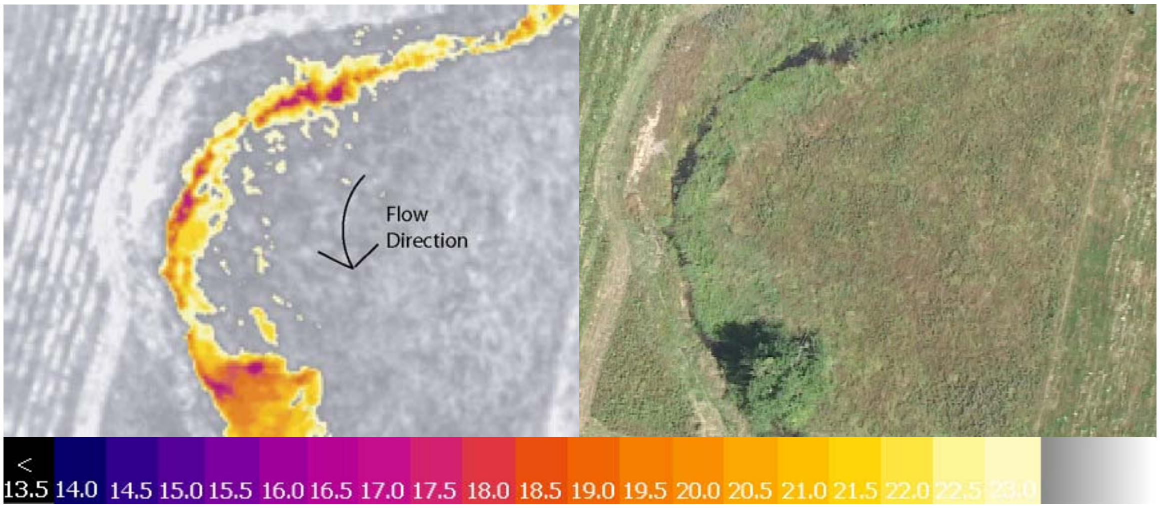

Figure 26 - TIR/color video image showing Johnson Creek (16.9°C) at river mile 18.0. The image pair shows the narrow channel width and little visible surface water. (*frame: john1397*)

Figure 27 - TIR/color video image showing Johnson Creek (18.2°C) at river mile 14.5. The image pair illustrates flow and riparian conditions characteristic of this reach and some evidence of differential heating at the stream surface (*frame: john1053*).

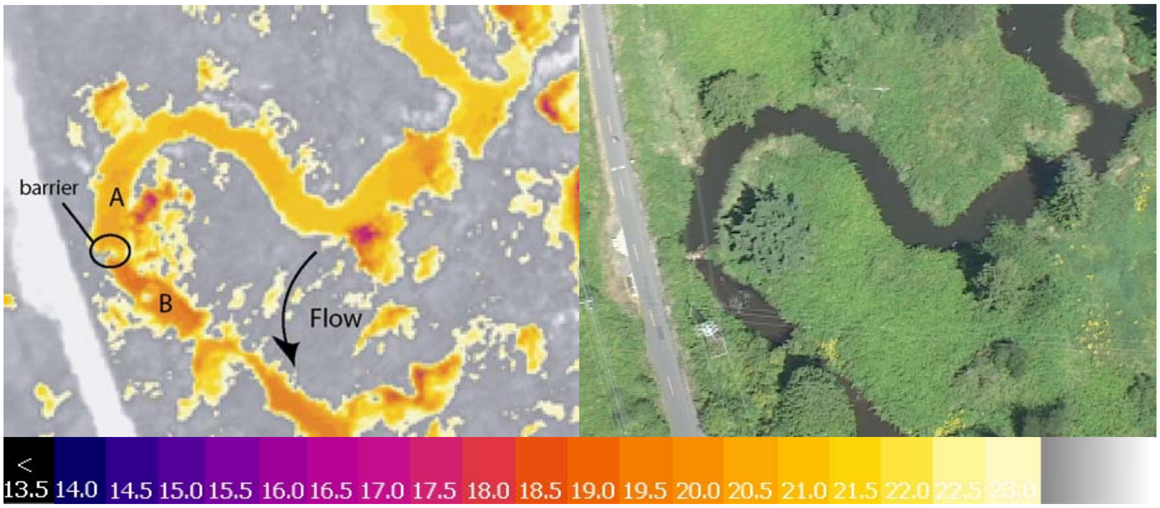

Figure 28 - TIR/color video image showing Johnson Creek at river mile 13.9. Flow direction is from the top to bottom of the image. Surface water temperatures are 20.4^{o}C upstream of the small impoundment (A) and 18.5^{o}C downstream (B). (*frame: john0999*)

<u>Reach 3 – (river mile 11.3 – river mile 8.0)</u>: Stream temperatures decreased between river mile 11.4 (≈19.3^{o}C) and 10.9 (≈17.6^{o}C) and then remained near 17.6^{o}C until river mile 8.0. The decrease in temperatures was consistent with the kinetic temperatures recorded at river mile 11.4 and 10.3. Kelly Creek (16.5^{o}C) enters Johnson Creek at river mile 10.5 and was a source of cooling. The decrease in main stem temperatures occurs upstream of the confluence of Kelly Creek and the source of the cooling is not apparent from the imagery. However, in general, a decrease in longitudinal temperatures over relatively short distances (<0.4 miles) suggests subsurface influences. The sources of local spatial variability within this reach are difficult to positively identify due to intermittent masking by riparian vegetation. However, as with the upper reaches, differential heating combined with reflective differences at the water's surface likely contribute to apparent stream temperature differences.

<u>Reach 4 (river mile 8.0 to river mile 4.0)</u> – Stream temperatures showed an apparent increase of ≈3.4^{o}C between river mile 8.4 (≈17.1^{o}C) and 7.9 (≈20.5^{o}C). Stream temperatures remained consistent (average 19.8^{o}C) through the reach. A rapid increase in apparent temperatures was observed between river mile 7.0 and 6.4 with stream temperatures reaching a local maximum of 22.1^{o}C at river mile 6.6. The TIR and color video images show that the stream surface is exposed to direct solar radiation through much of this reach which characteristically results in increased longitudinal heating (Figure 29). However, the subsequent decrease in stream temperatures at mile 6.4 (to 20.4^{o}C) suggests that surface temperatures may not represent bulk stream temperatures through this reach.

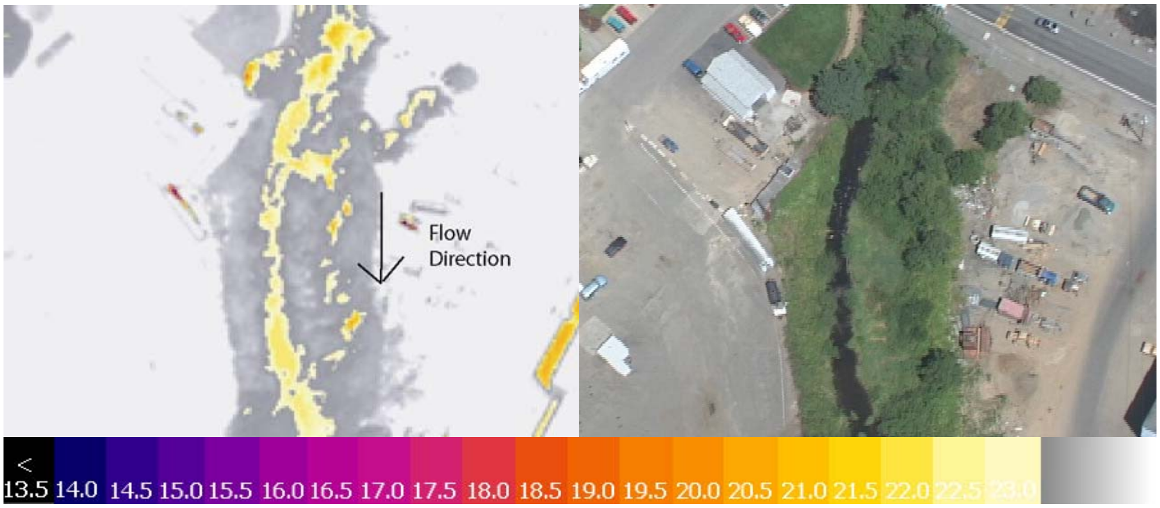

Figure 29 - TIR/color video image pair showing the channel characteristics of Johnson Creek (21.8°C) at river mile 6.6 (*frame: john0406*).

<u>Reach 5 (river mile 4.0 to river mile 1.8</u>*)*<u>:</u> Stream temperatures decreased by ≈2.5°C between river mile 4.0 and 3.3. The stream surface was masked by riparian vegetation throughout much of this reach and the source of cooling was not apparent from the imagery. Stream temperatures were consistently about 17.8°C (±0.6°C) between river mile 3.5 and 1.8.

<u>Reach 6 (river mile 1.8 to mouth):</u> Stream temperatures increased by ≈2.4°C between river mile 1.8 and 1.1. This increase in longitudinal heating rate suggests a change in the energy balance that maintained relatively consistent stream temperatures in Reach 5. Spring Creek (18.1°C) contributed cooler water to Johnson Creek at river mile 0.5. At the time of the survey, Johnson Creek (19.5°C) contributed cooler water to the Willamette River (22.3°C).

Eagle Creek

The median temperatures for each sampled image of the Eagle Creek were plotted versus the corresponding river mile (Figure 30). The plot also contains the median temperature and name of all surface water inflows (e.g. tributaries, surface springs, etc.) that were visible in the imagery. The wetted channel was bordered closely by riparian vegetation including mature conifers over most of the survey length (Figure 31). The riparian vegetation did not negatively affect the TIR images or the development of the longitudinal temperature profile, but did result in visible shadows across the stream on most of the color video images.

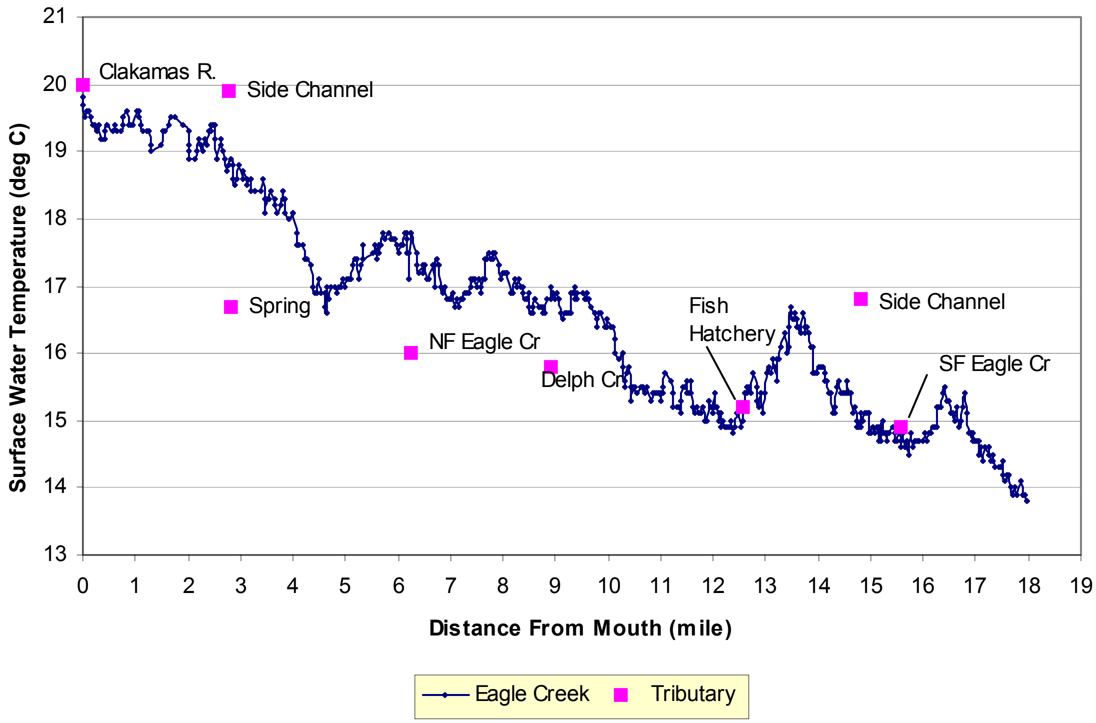

Figure 30 - Median channel temperatures versus river mile for Eagle Creek, OR. Tributary and other surface inflows are labeled by name on the plot.

Figure 31 - Ground level photograph (*left*) and a TIR/color video image (*right*) of the same section of Eagle Creek at river mile 6.9. The images show stream and riparian conditions characteristic of the Eagle Creek TIR survey. (*frame: eag0465*)

Overall, stream temperatures in Eagle Creek warmed in the downstream direction increasing from 13.8°C at the upstream end of the survey (river mile 18.0) to 19.5°C at its confluence with the Clackamas River. The longitudinal temperature profile also shows where the rates of longitudinal heating change along the stream gradient and locations where the stream cools. The overall temperature profile can be segmented to highlight reaches of consistent thermal response (Figure 32). The segmentation is based on visual inspection of the longitudinal temperature profile and other segmentations are possible based on scale of interest or more rigorous analysis of the spatial temperature patterns. Figure 32 also shows the kinetic temperature at the time of the TIR and the recorded daily maximum temperatures at each location. The following paragraphs discuss the characteristics of each reach and in some cases offer hypotheses on the potential factors driving the observed thermal response.

Reach 1 (river mile 18.0 to 13.5) - Water temperatures in Eagle Creek show an overall downstream warming trend through this reach with some local variability. From river mile 18.0, stream temperatures increase at a consistent rate reaching a local maximum of 15.5°C at river mile16.4. Between river mile 16.4 and 15.6 stream temperatures decrease to ≈14.6°C and remain below 15.0°C to river mile 14.8. The South Fork Eagle Creek (14.9°C) enters Eagle Creek at river mile 15.6. The 7.5' topographic map shows two unnamed tributaries entering Eagle Creek at river miles 15.7 and 15.9, which may contribute to the observed cooling through this reach. The tributary at river mile 15.7 was detected in the TIR images, but could not be sampled because it was only partially visible through the forest canopy. Stream temperatures increased again downstream of river mile 14.8 reaching 16.7°C at river mile 13.5.

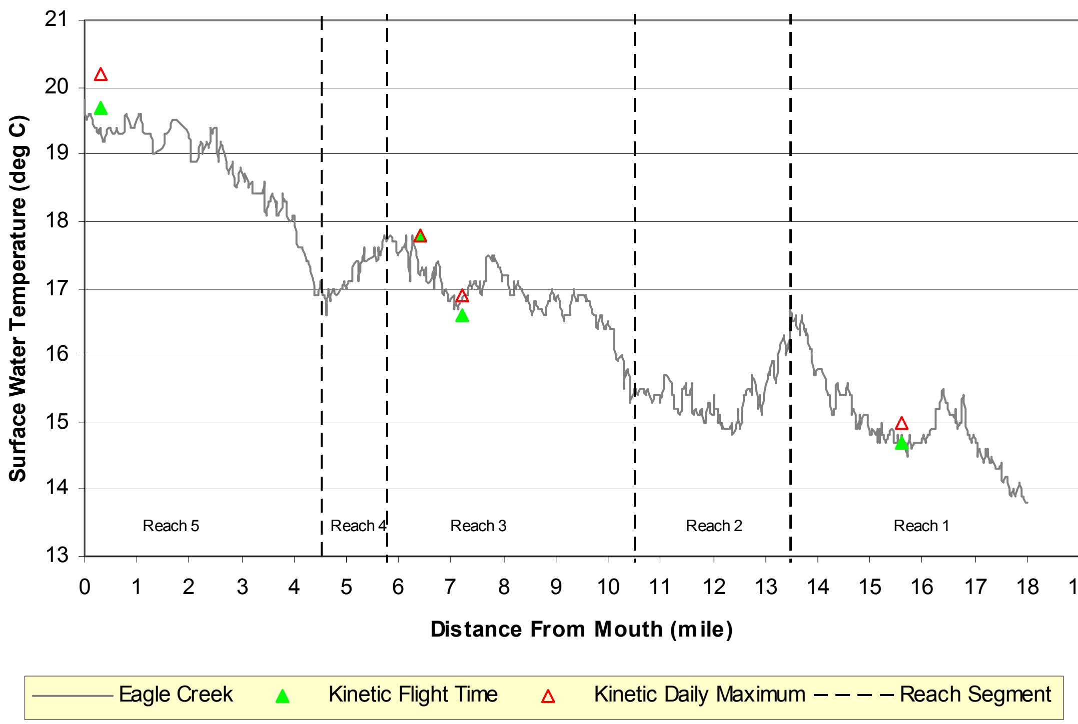

Figure 32 - Median radiant channel temperatures versus river mile for Eagle Creek, OR. The figure also shows the kinetic water temperatures at the time of the thermal infrared survey and maximum daily stream temperatures. Reaches with consistent thermal response are delineated on the plot.

Reach 2 (river mile 13.5 to river mile 10.5) – Stream temperatures showed a consistent decrease from 16.7°C to 15.0°C between river mile 13.5 and 12.4. River mile 12.4 is approximately 0.3 miles downstream of the Eagle Creek fish hatchery and the fish hatchery return was the only surface water inflow sampled (*or mapped)* through this reach. The factors contributing to the observed cooling through this reach were not apparent from the imagery or through examination of the USGS 7.5' topographic map.

Reach 3 (river mile 10.5 to river mile 5.8) – Stream temperatures again showed downstream warming increasing from 15.4°C at river mile 10.5 to 17.7°C at river mile 5.8. The highest rate of heating occurred over the first 0.6 miles of this reach with stream temperatures reaching 17.0°C at river mile 9.4. Stream temperatures increase at a slower longitudinal rate from river mile 9.4 to 7.8 and show an apparent 0.7°C decrease from river mile 7.8 to 7.2. Review of the 7.5' USGS topographic map shows that this temperature decrease occurs downstream of the Eagle Fern Youth Camp and that terrain gradients increase through this area. Shifts in channel morphology are often observed as areas of sub-surface discharge into the stream, which causes a subsequent local decrease in stream temperature. Stream temperatures increase again between river miles 7.2 and 5.8. Delph Creek (river mile 8.9) and the North Fork Eagle Creek (river mile 6.2) (Figure 33) both contribute cooler water to Eagle Creek in this reach.

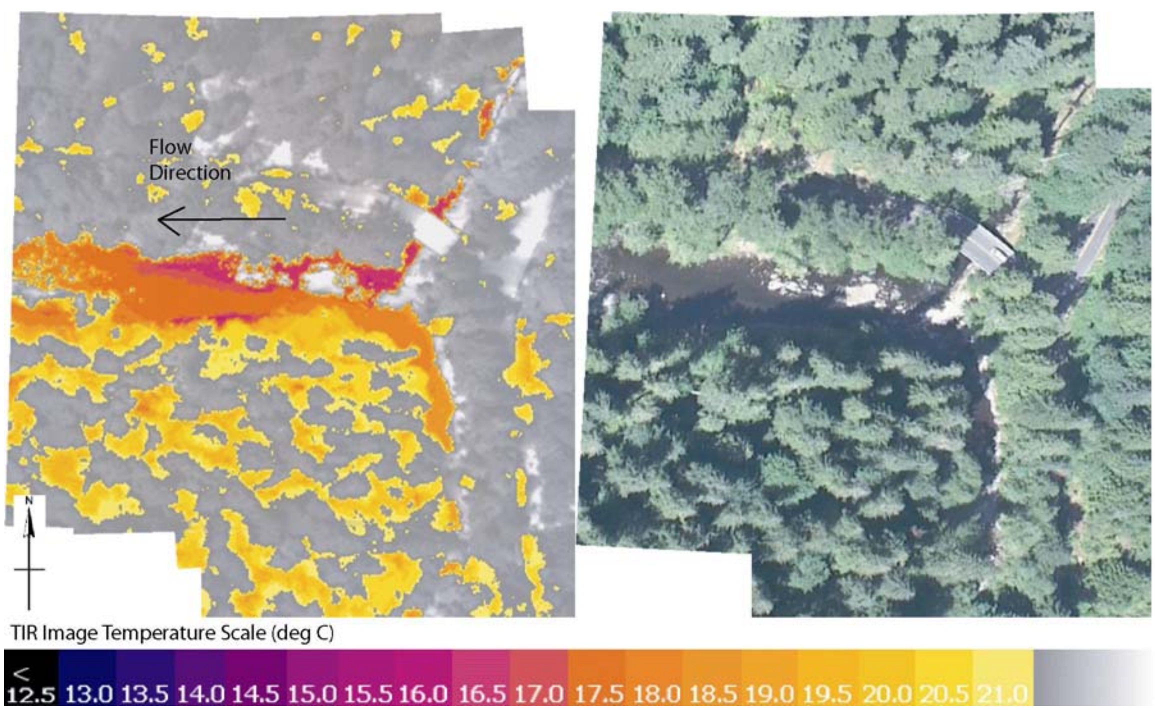

Figure 33 - TIR/color video image pair showing the confluence of North Fork (NF) Eagle Creek (16.0°C) to the right bank of Eagle Creek (17.8°C) at river mile 6.2 (*frames: eag0407-0410*).

Reach 4 (river mile 5.8 to river mile 4.5) – Stream temperatures show a consistent decrease from 17.8°C at river mile 5.8 to 16.6°C at river mile 4.6. No surface water inflows were detected through this reach, which occurs about 0.4 miles downstream of the North Fork Eagle Creek confluence. There were no indicators of direct cooling sources through this reach. However, the USGS 7.5' topographic base map shows a confined canyon with falls occurring in the stream at river mile 5.6 suggesting that geomorphic factors may influence the energy balance controlling stream temperatures through this reach.

Reach 5 (river mile 4.5 to Clackamas River) – Stream temperatures increased from 16.9°C at river mile 4.6 to 19.6°C at its confluence with the Clackamas River. A bulk of longitudinal heating was observed between river miles 4.5 and 2.5 with an ≈0.5°C increase occurring over the lower 2.5 river miles. The in-stream sensor at the mouth of Eagle Creek indicated that the radiant temperatures at the time of the flight were lower than the recorded daily maximum of 20.2°C.

North Fork Eagle Creek

The median temperatures for each sampled image of the North Fork Eagle Creek were plotted versus the corresponding river mile (Figure 34). The plot also contains the median temperature and name of all surface water inflows (e.g. tributaries, surface springs, etc.) that were visible in the imagery.

At the upstream end of the survey near Gabenheim Creek (river mile 6.0), stream temperatures in the North Fork Eagle Creek were ≈15.2°C. The average radiant temperature for the survey was 15.5°C with local variations of ±0.7°C. A local maximum of ≈16.2°C was observed at river mile 4.7 and a survey minimum of ≈14.9°C was observed at river miles 1.9 and 5.7. Although the local variation in stream temperatures is close to what is typically considered noise in the TIR images (*reference the discussion of TIR image characteristics*), two locations stand out in the longitudinal temperature profile. A 1.0°C decrease was observed at river mile 4.6 near the confluence of Little Eagle Creek (15.7°C). Little Eagle Creek was small (*relative to pixel size*) and partially masked by vegetation at the confluence and, consequently, may have cooler temperatures than indicated by the sample due to the greater occurrence of hybrid pixels. Stream temperatures in the North Fork Eagle Creek appear to continue to cool downstream of Little Eagle Creek and remained near 15.1°C to river mile 3.8. An apparent decrease in temperatures was also observed from river mile 2.3 to river mile 1.9. No surface water inflows were detected through this reach.

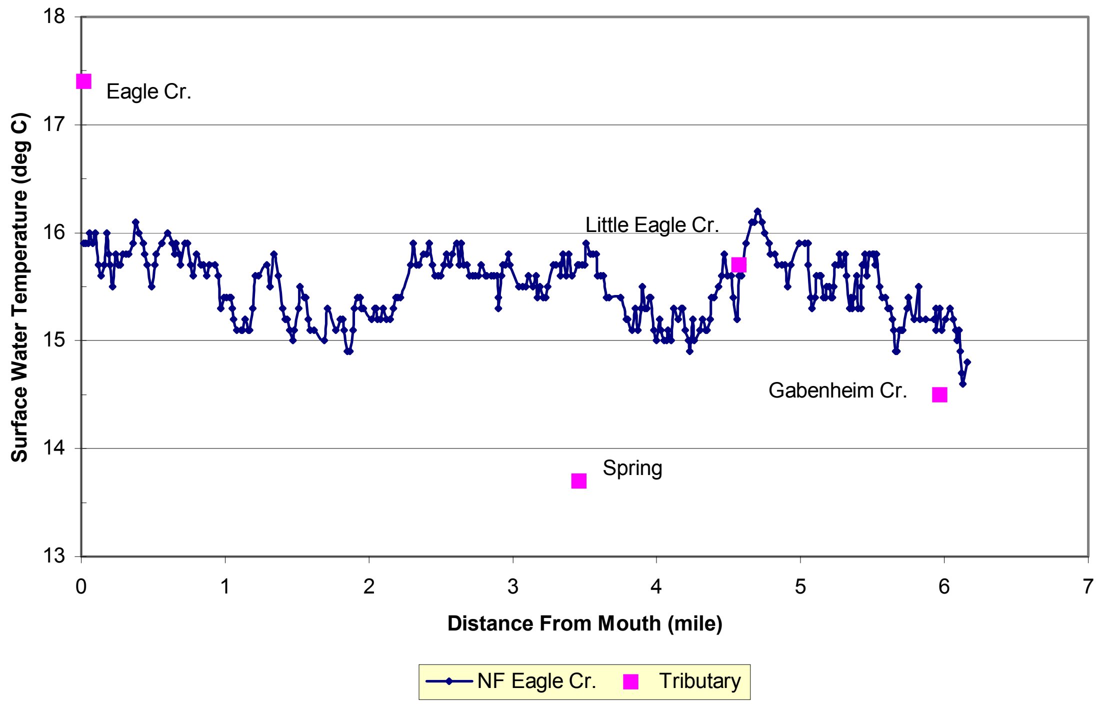

Figure 34 - Median channel temperatures versus river mile for North Fork Eagle Creek, OR. Tributary and other surface inflows are labeled on the plot.

Bear Creek

Bear Creek was surveyed from the North Fork Eagle Creek confluence upstream for approximately 1.3 miles. Bear Creek was masked almost entirely by riparian vegetation for the entire length preventing accurate temperature sampling (Figure 35).

Discussion

Thermal infrared remote sensing surveys were successfully conducted on streams in the Northern Willamette River Basin. Longitudinal temperature profiles were produced for each surveyed stream, which illustrate broad scale spatial temperature patterns and the location and influence of tributary and surface water inflows. This report presents the longitudinal temperature profiles and provides some hypotheses on the processes influencing spatial temperature patterns at this scale based on analysis of the TIR imagery and topographic base maps.

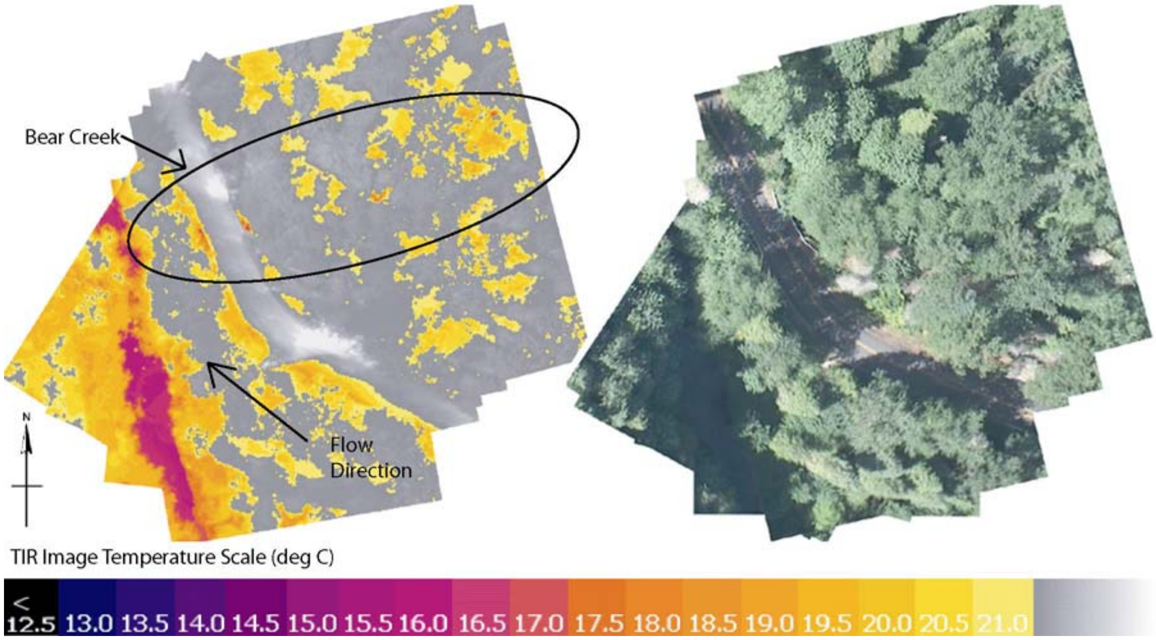

Figure 35 - TIR/color video image showing the confluence of the NF Eagle Creek (15.9°C) and Bear Creek. Bear Creek is almost entirely masked by riparian vegetation, which prevented temperature sampling over the 1.3 mile survey.

Follow-on

The data and results produced by the TIR surveys should be considered a starting point for more rigorous analysis and field work. Individual TIR and color video image frames are organized in an ArcView database to allow viewing temperature patterns and channel characteristics at finer spatial scales. The following is a list of potential uses for these data in follow-on analysis (based on Faux et. al. 2001 and Torgersen et. al. 1999):

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

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

3. What is the temperature pattern within critical reach and sub-reach areas? Are there thermal refugia within these reaches that are used by coldwater fish species during the summer months?

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

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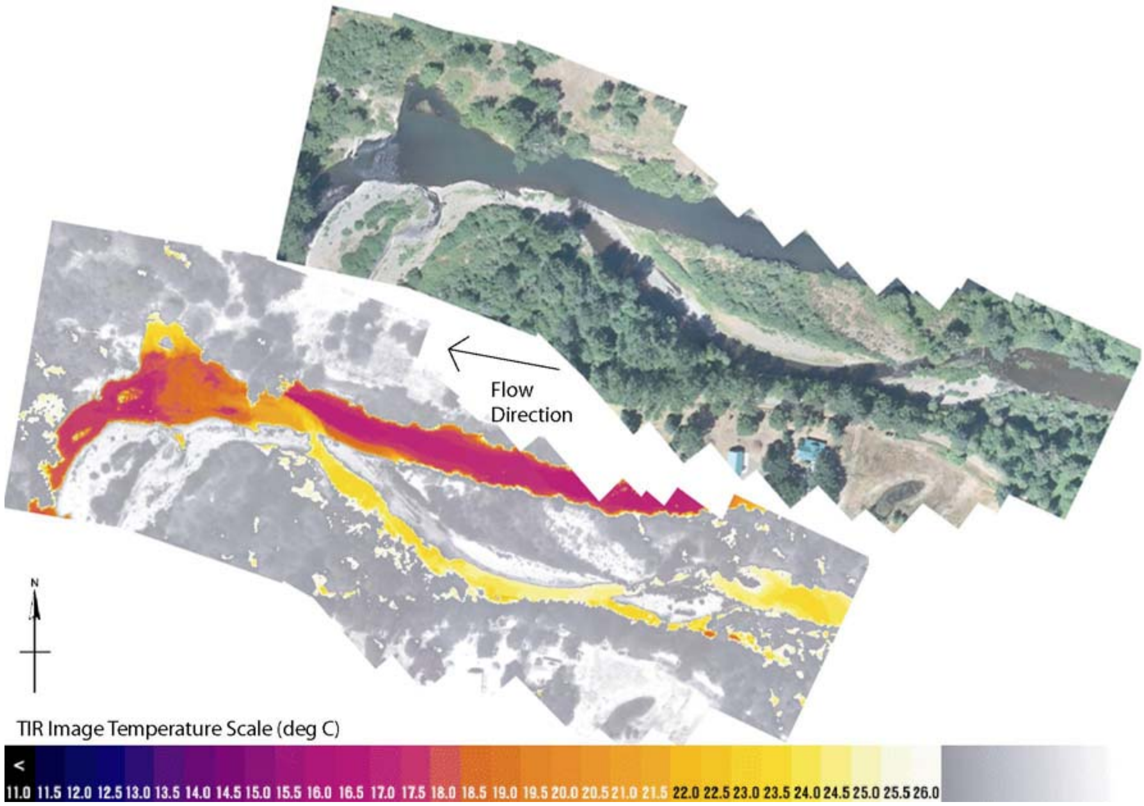
Torgersen, C., R. Faux, and B. McIntosh. 1999. **Aerial survey of the Upper McKenzie River: Thermal infrared and color videography**. Report to the USDA, Forest Service, McKenzie River Ranger District.

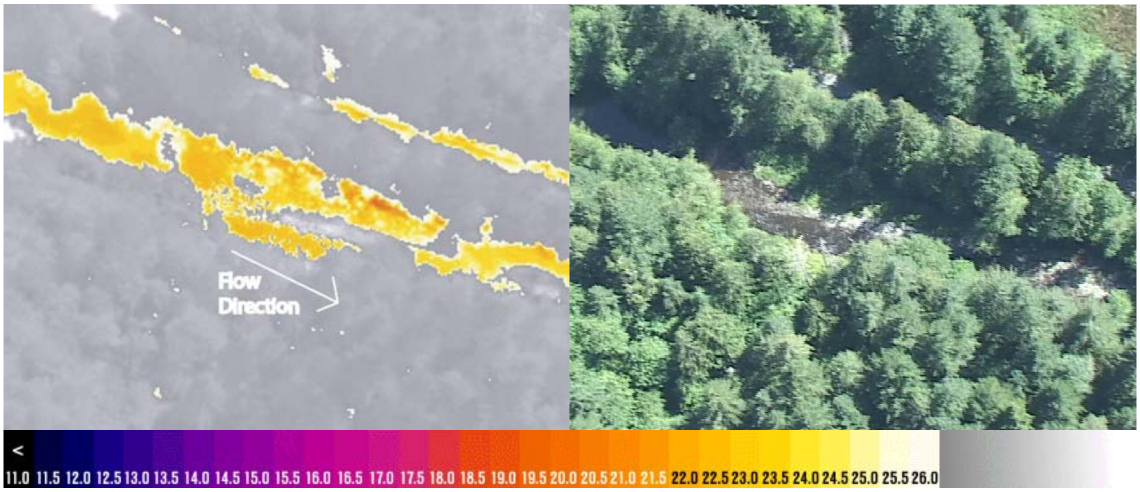
Torgersen, C.E., R. Faux, B.A. McIntosh, N. Poage, and D.J. Norton. 2001. Airborne thermal remote sensing for water temperature assessment in rivers and streams. *Remote Sensing of Environment* 76(3): 386-398.

Appendix A: Southern Willamette River Basin
Selected Images

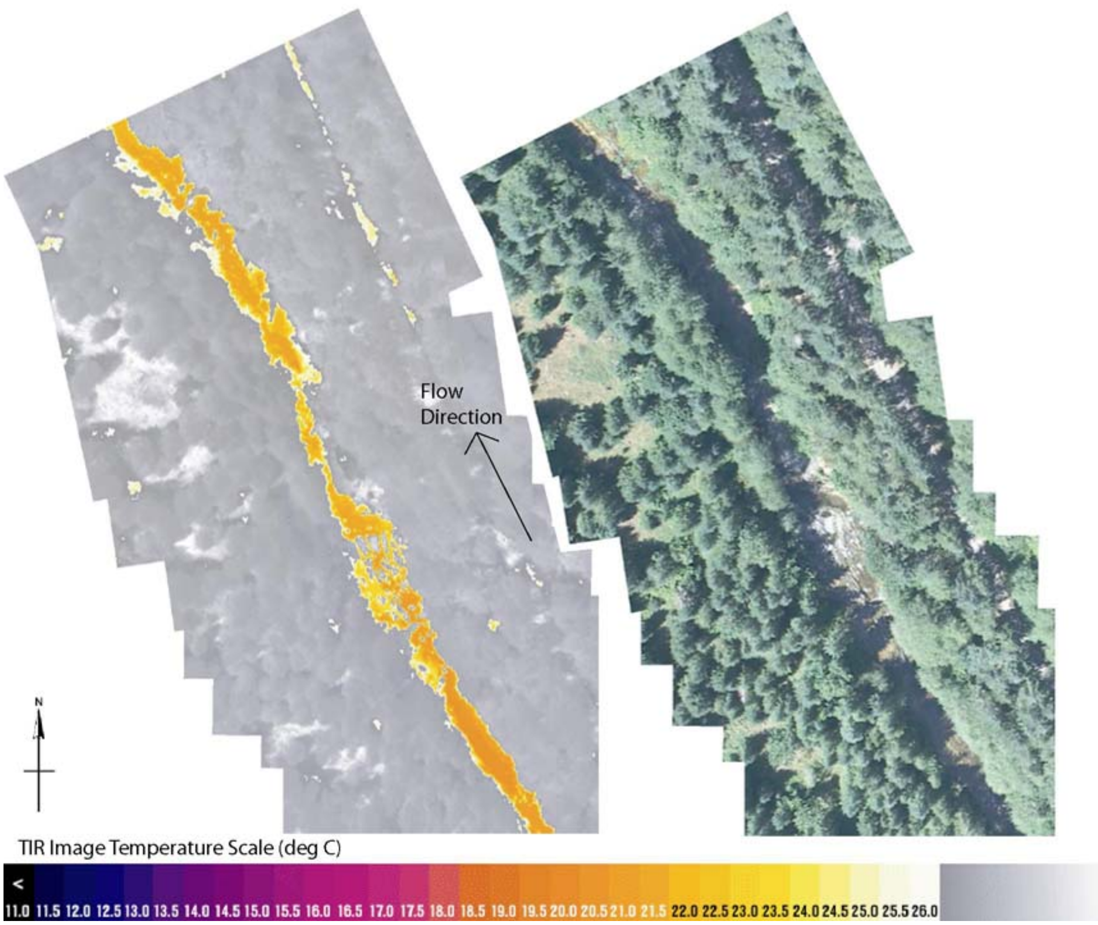
Mosby Creek



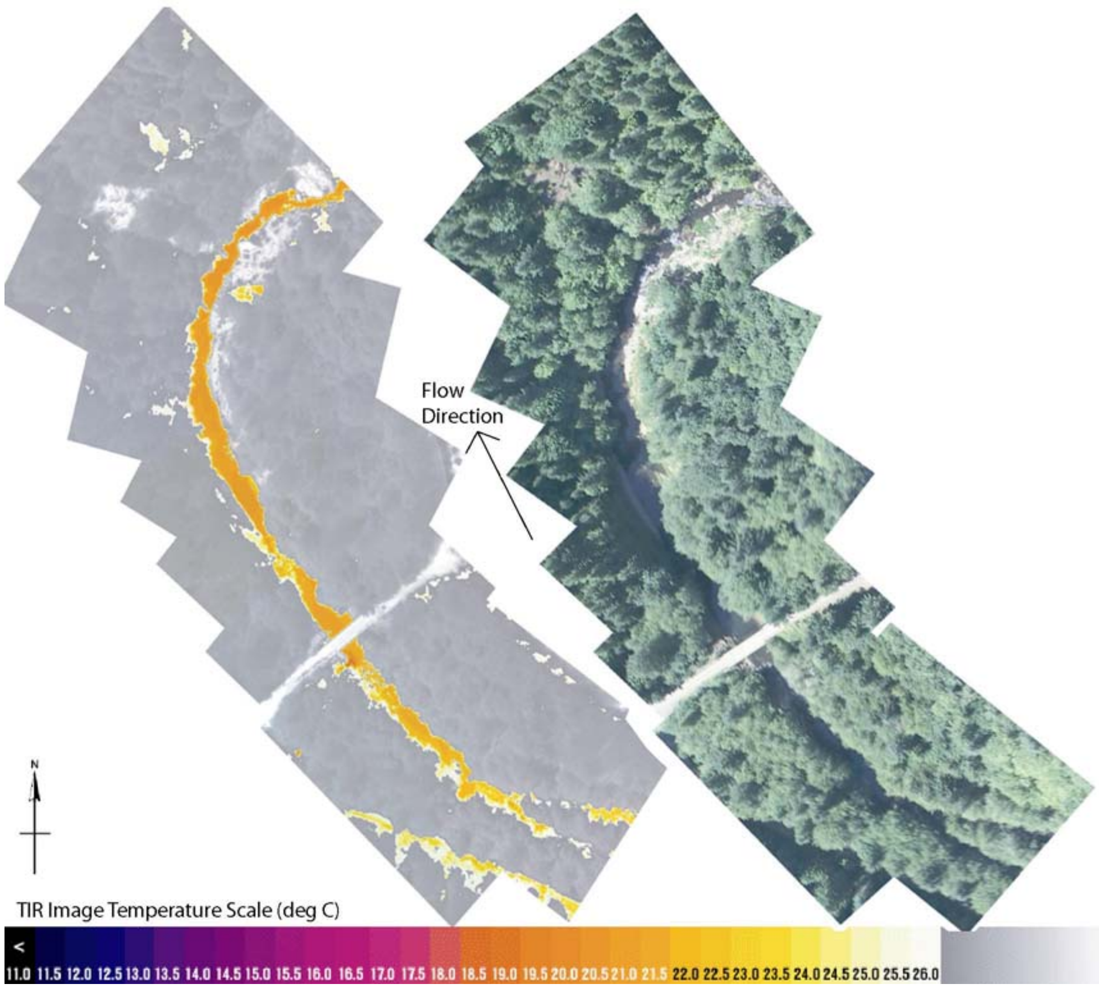
TIR/color video image pair showing the confluence of Mosby Creek (23.6°C) and the Row River (16.8°C). Carolina Creek (18.4°C) enters on the left bank of Mosby Creek just upstream of its confluence with the Row River *(frames: mosb0007-0022)*.



TIR/color video image pair showing the confluence of Short Creek (18.5°C) to the left bank of Mosby Creek (22.0°C) at river mile 8.2 *(frame: mosb0462)*.

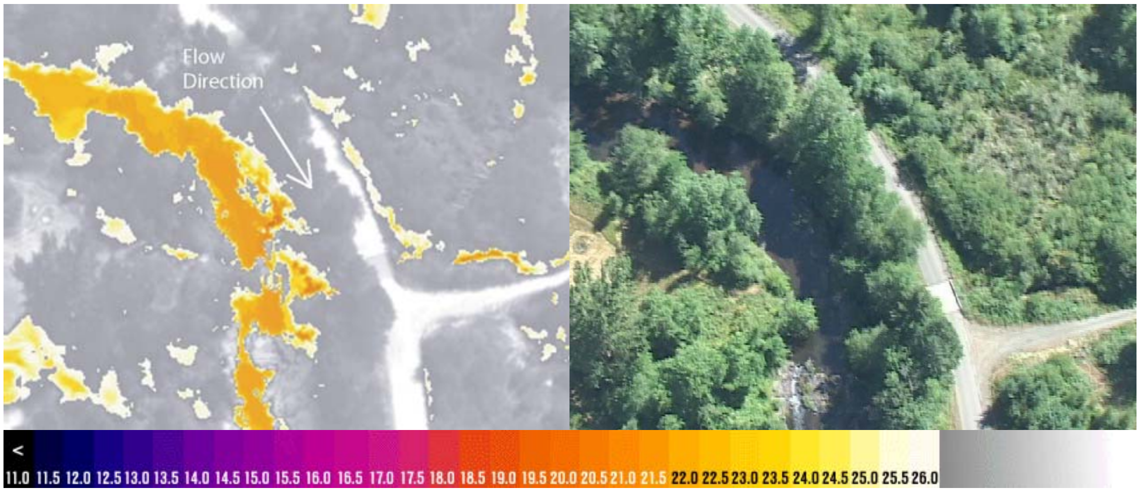


TIR/color video image pair showing warm areas (~22.7°C) along both banks of Mosby Creek (21.1°C) at river mile 17.0 *(frames: mosb0984-0987)*.

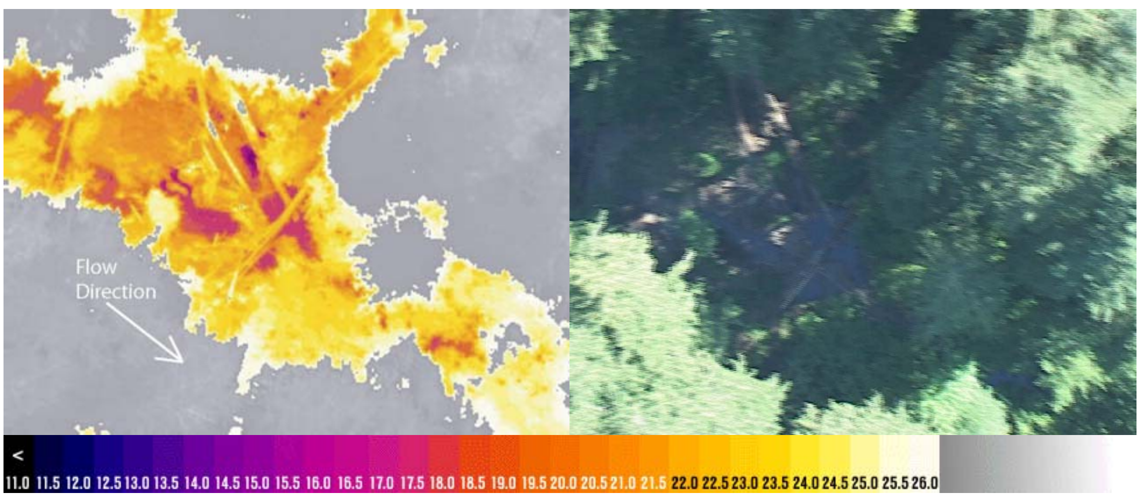


TIR/color video image pair showing the confluence of the North Fork Rack Creek (18.0°C) to the left bank of Mosby Creek. The North Fork Rack Creek lowers mainstream temperatures from 21.8 to 20.4 degrees C at river mile 10.4. While the NF Rack Creek is itself canopied, its influence can be seen just upstream the bridge along the left bank *(frames: mosb0581-0588).*

Coast Fork Willamette River** (upstream Cottage Grove Lake)* ***and Big River

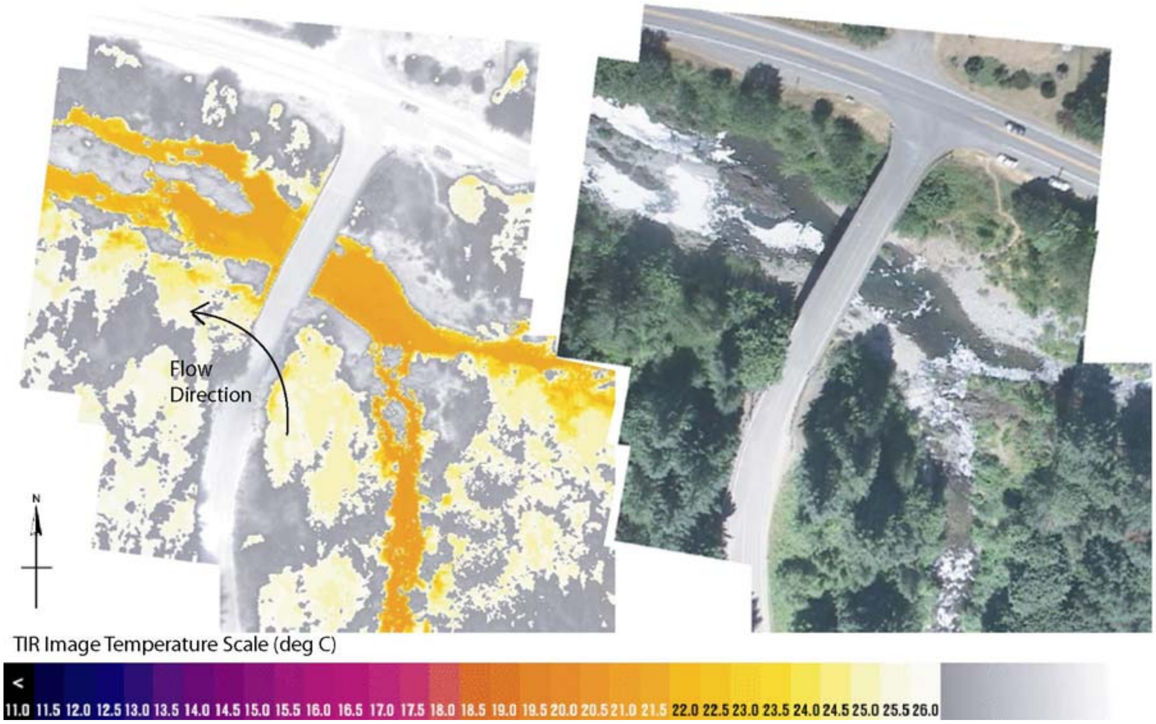


TIR/color video image pair showing the confluence of Numbers Creek (19.5^{o}C) to the left bank of the Coast Fork Willamette River (21.0^{o}C) at river mile 32.4 *(frame: cfbr0139).*

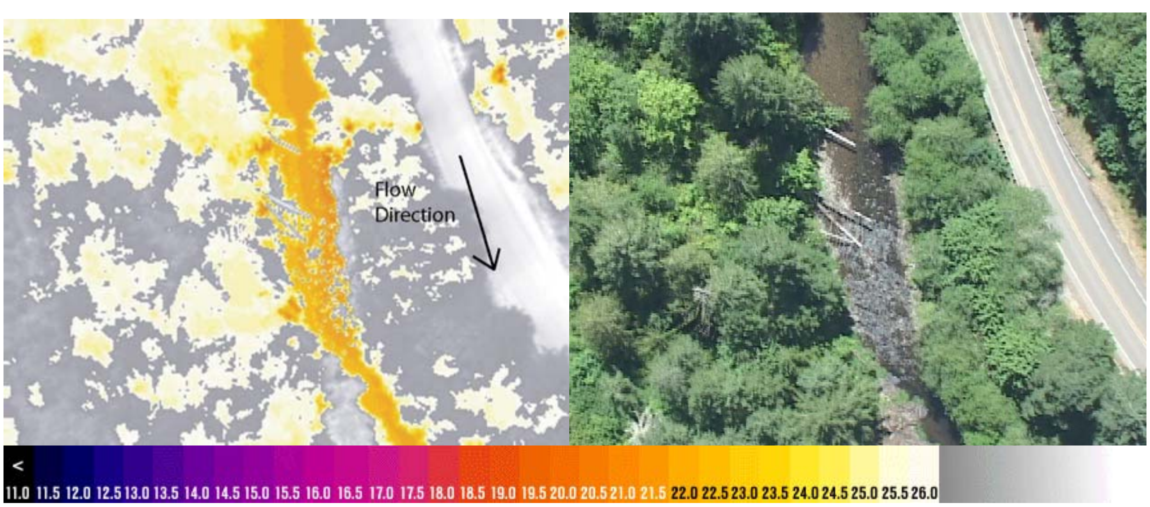


TIR/color video image pair showing a spring (14.2^{o}C) along the left bank of Big River (17.2^{o}C) at river mile 6.6 *(frame: cfbr0730).*

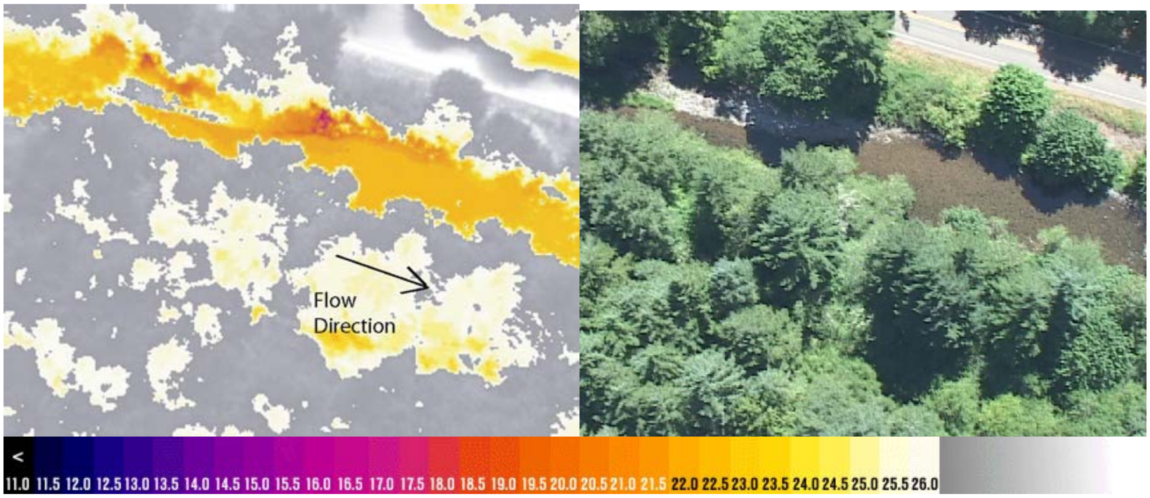
Sharps Creek



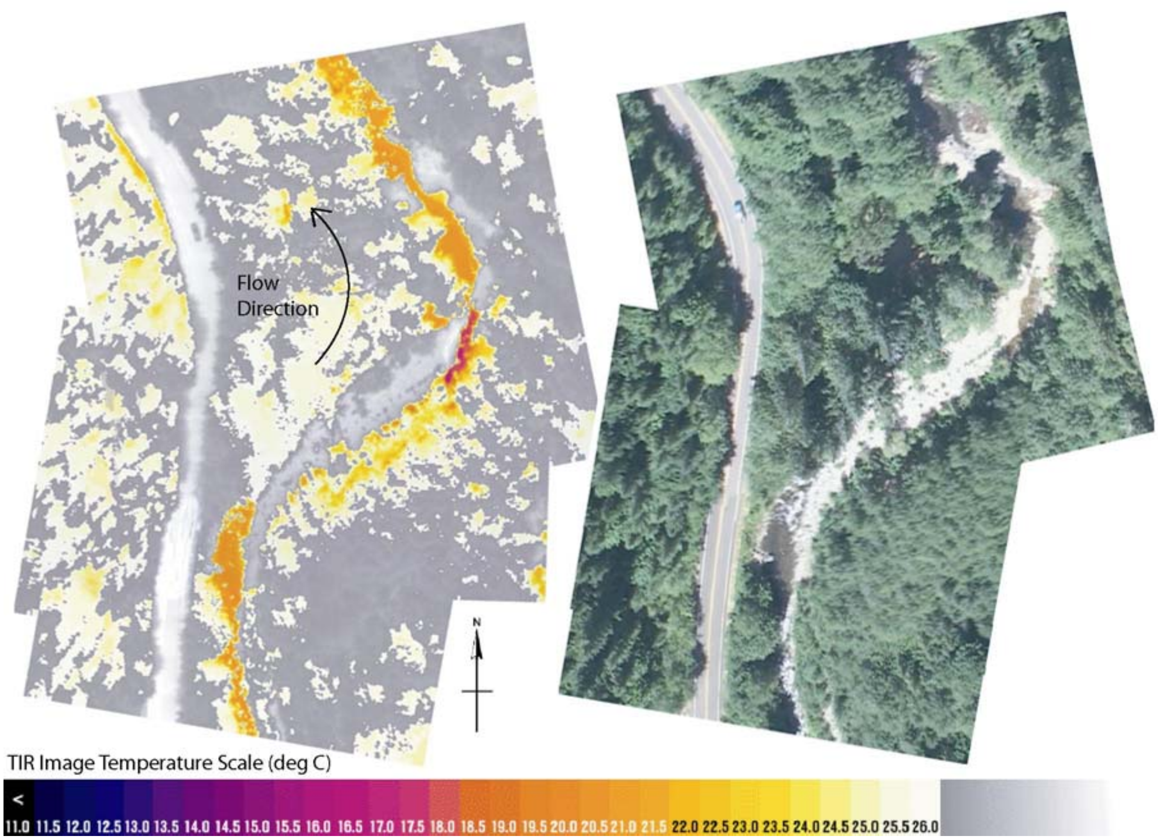
TIR/color video image pair showing the confluence of Sharps Creek (20.6°C) to the left bank of Row River (21.5°C) *(frames: shar0038-0042)*.



TIR/color video image pair showing Boulder Creek (19.3°C) empties into the left bank of Sharps Creek (21.4°C) at river mile 21.4 *(frame: shar0114)*.

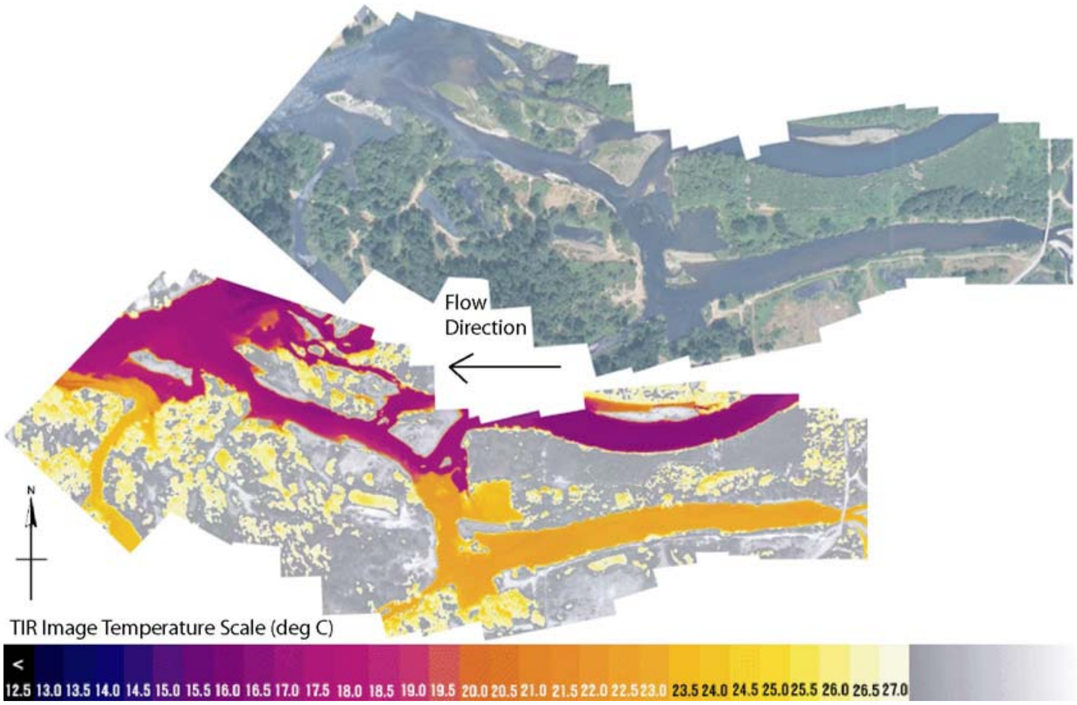


TIR/color video image pair showing the location of an apparent spring on the left bank of Sharps Creek at river mile 1.8. The spring measures approximately 16.0°C while the main stem of Sharps Creek is 21.7°C *(frame: shar0133).*

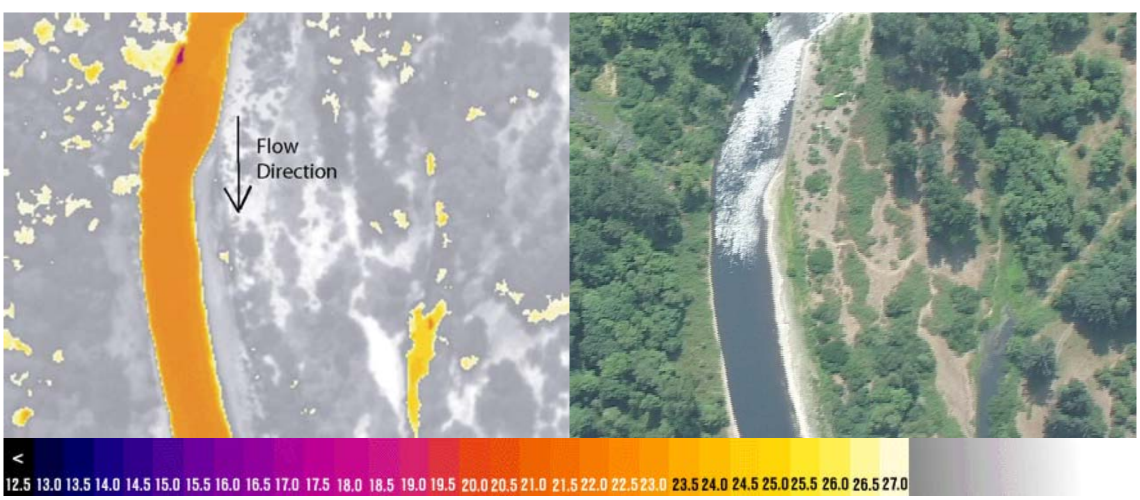


TIR/color video image pair showing the location of an apparent spring (16.6°C) on the right bank of Sharps Creek (20.4°C) at river mile 8.2 *(frames: shar0540-0544).*

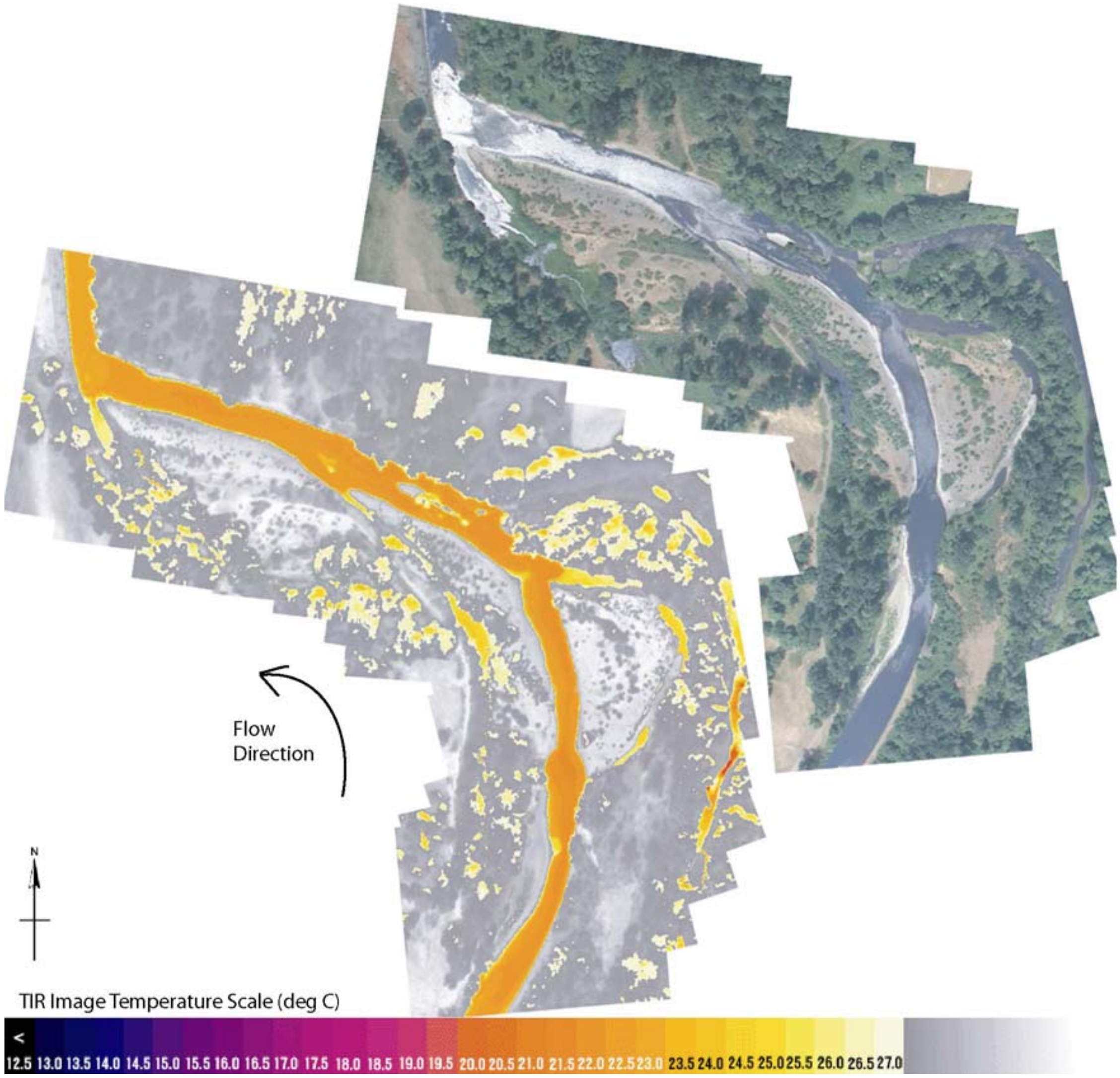
Coast Fork Willamette River *(downstream Cottage Grove Lake)*



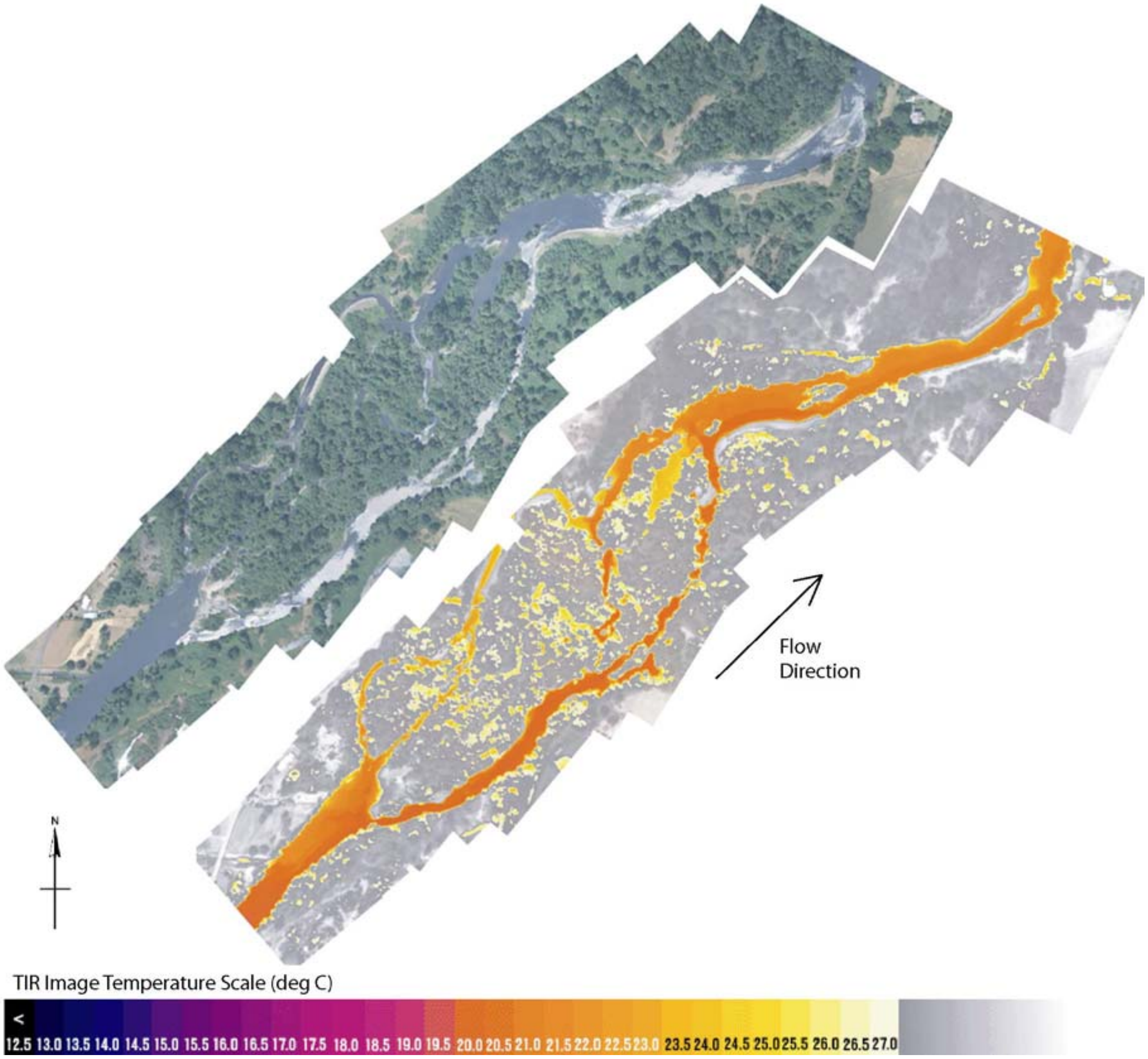
TIR/color video image pair showing the confluence of Coast Fork (CF) Willamette River (21.4°C) to the left bank of MF Willamette River (15.2°C) at two different points *(frames: cfw0001-0020)*.



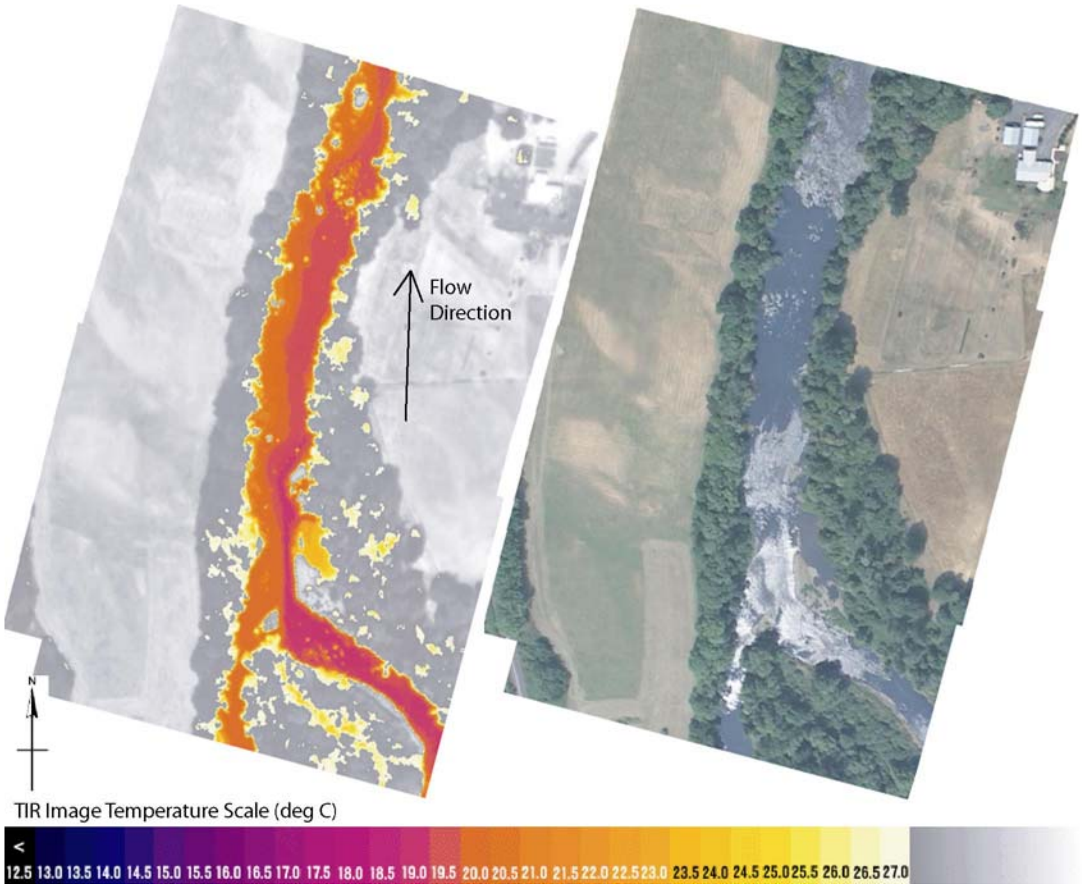
TIR/color video image pair showing an apparent spring (15.8°C) on the right bank of the CF Willamette River (21.8°C) at river mile 12.1 *(frame: cfw0334)*.



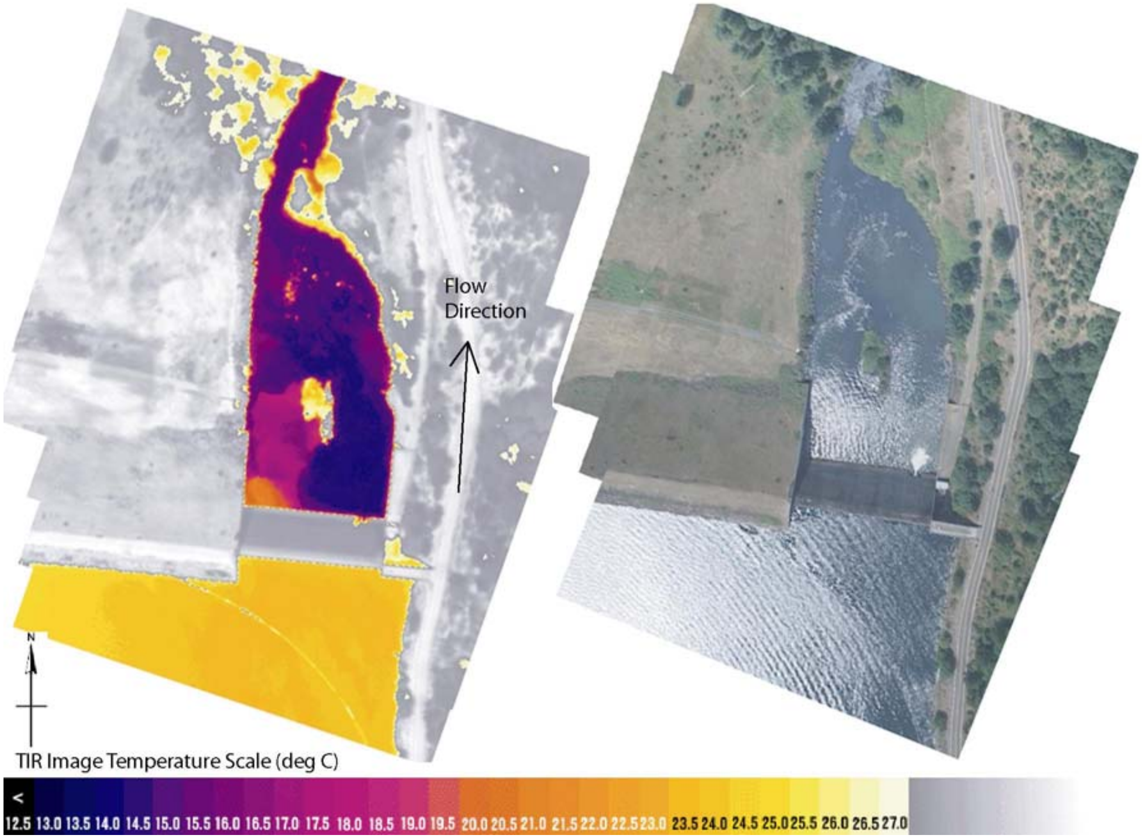
TIR/color video image pair showing multiple channels of the CF Willamette River (21.6^{o}C) at river mile 9.3. The channel farthest downstream on the left bank measures 25.4^{o}C while the channel on the right bank measures 31.4^{o}C with an small seep located farther upstream *(frames: cfw0304-0320)*.



TIR/color video image pair showing a warmer side channel (21-23^{o}C) on the left bank of the CF Willamette River (21.0^{o}C) between river miles 15.8 and 16.8 *(frames: cfw0541-0586).*

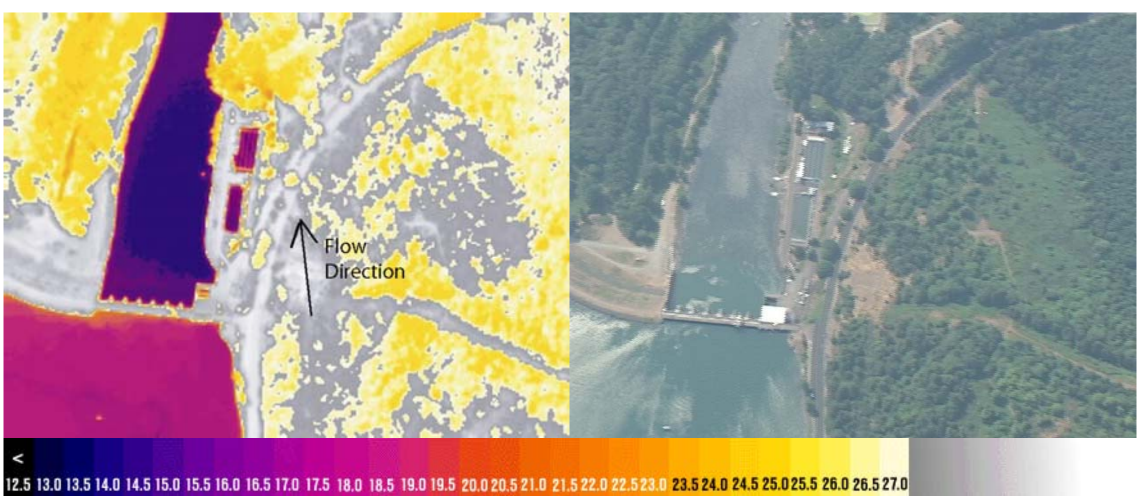


TIR/color video image pair showing the confluence of Row River (19.2^{o}C) to the right bank of the CF Willamette River (20.3^{o}C) at river mile 19.6 *(frames: cfw0683-0689)*.

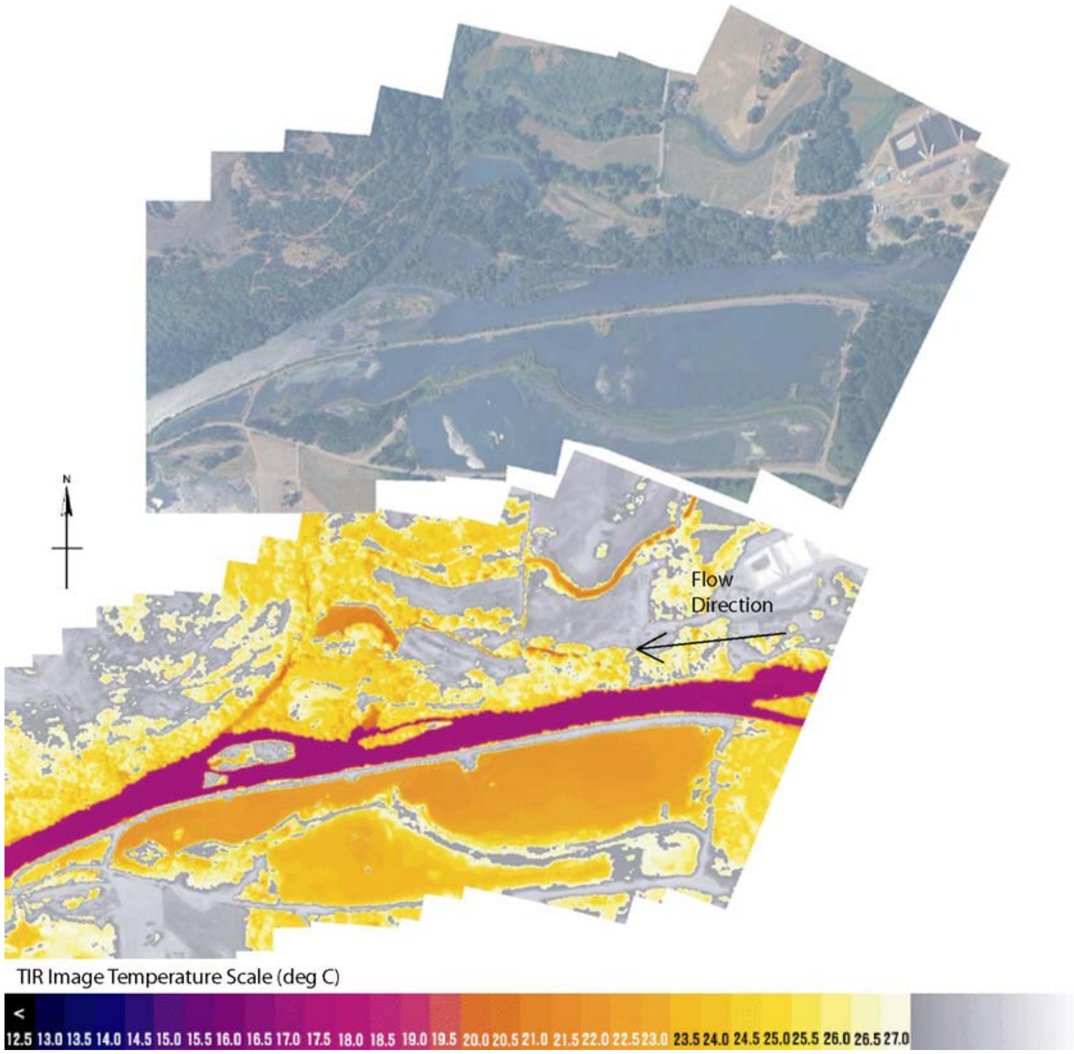


TIR/color video image pair showing the outflow of Cottage Grove Lake (lake surface = 24.6°C) to continue the lower CF Willamette River (14.8°C) at river mile 28.4 *(frames: cfw1035-1039).*

Middle Fork Willamette River

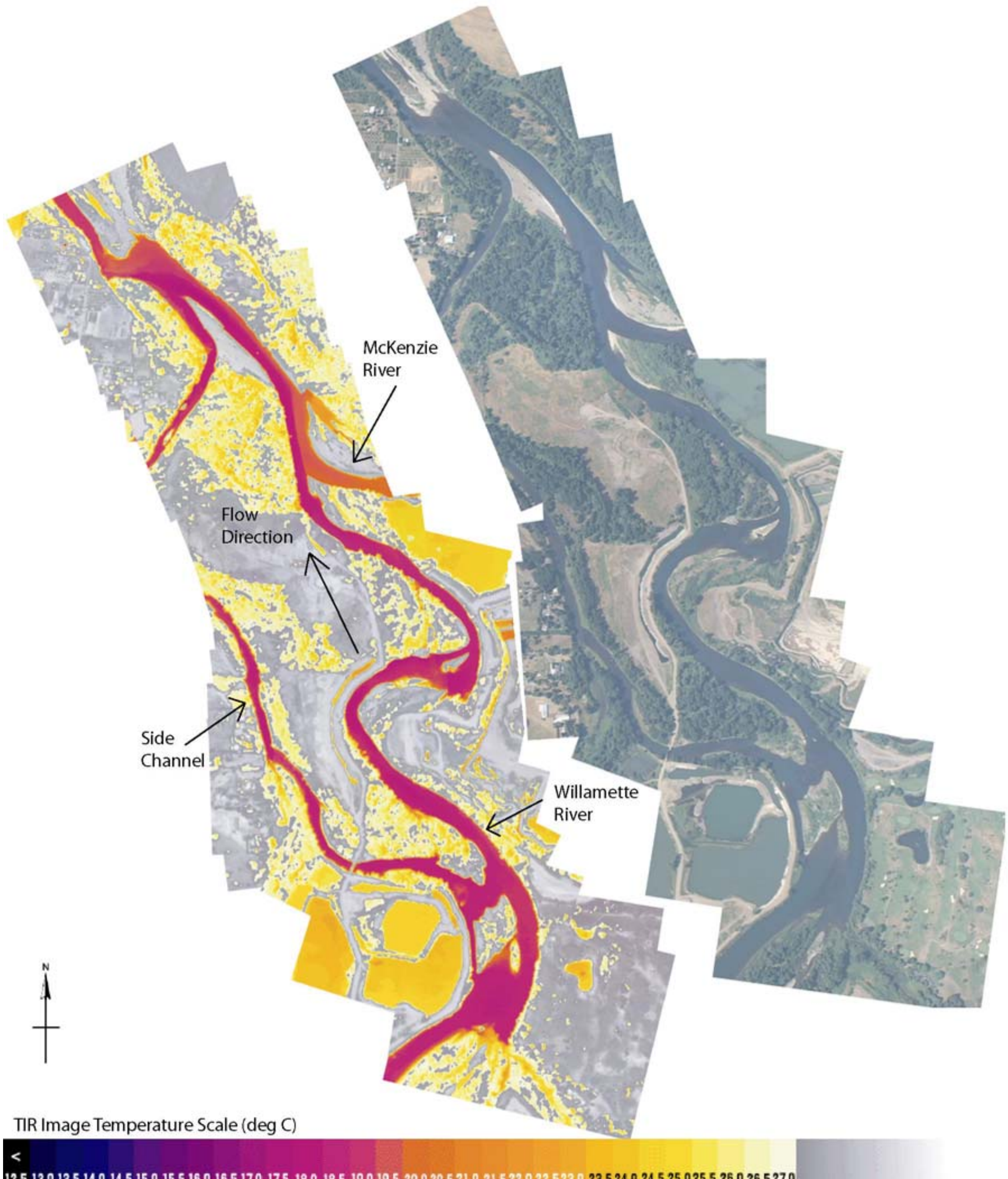


TIR/color video image pair showing the Middle Fork (MF) Willamette River (14.4) flowing out of Dexter Lake *(frame: will0003).* The surface of Dexter Lake (17.7°C) showed signs of thermal stratification.

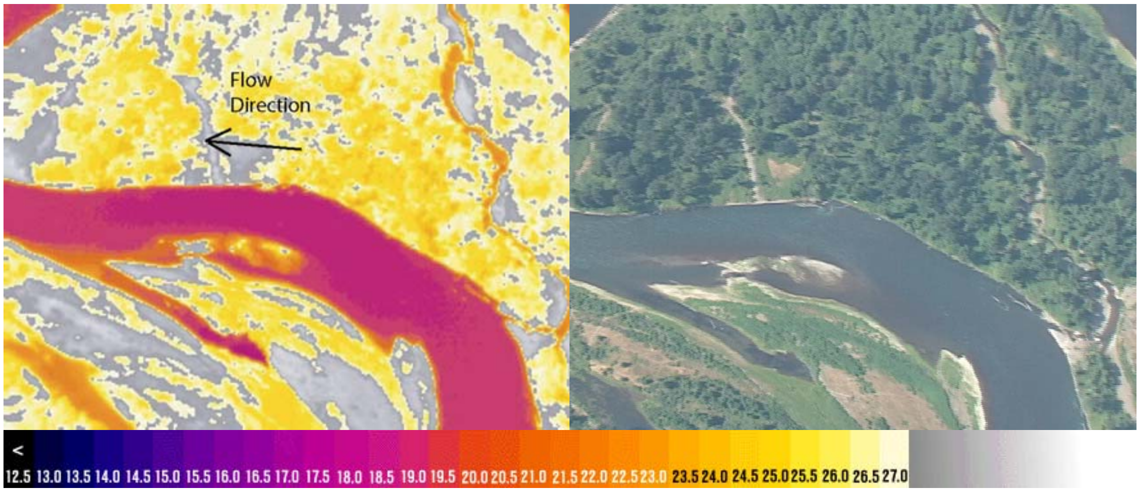


TIR/color video image pair showing the location of a pond on the left bank which is 4 to 5 degrees warmer than the main stem MF Willamette River (17°C) at river mile 2.1 *(frames: will0240-0255)*.

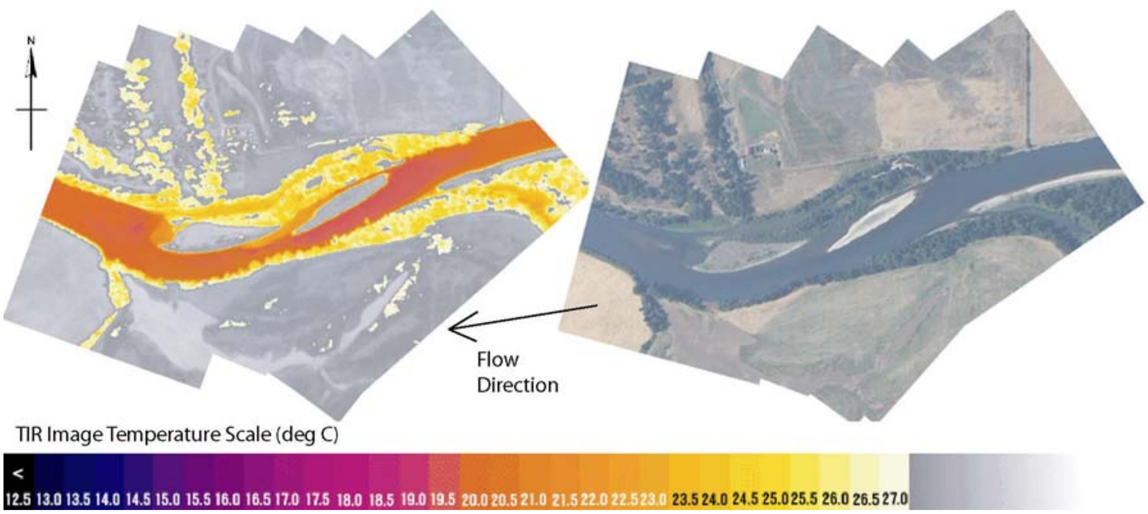
Willamette River



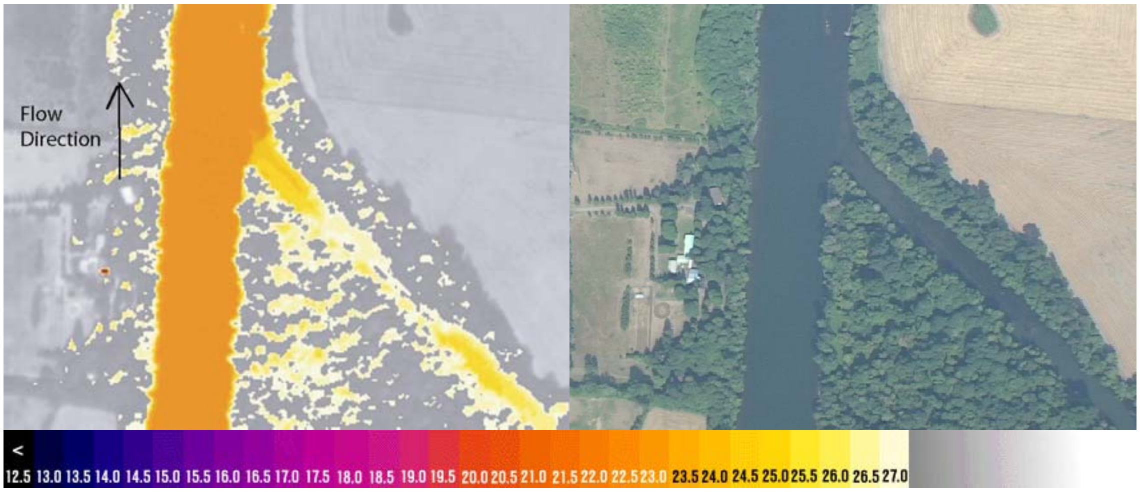
TIR/color video image pair showing the confluence of McKenzie River (19.2^{0}C) to the right bank of Willamette River (18.1^{0}C) at river mile 173.7 *(frames: will0434-0467).* The large side channel along the left bank of the Willamette River meandered just outside the sensor field of view.



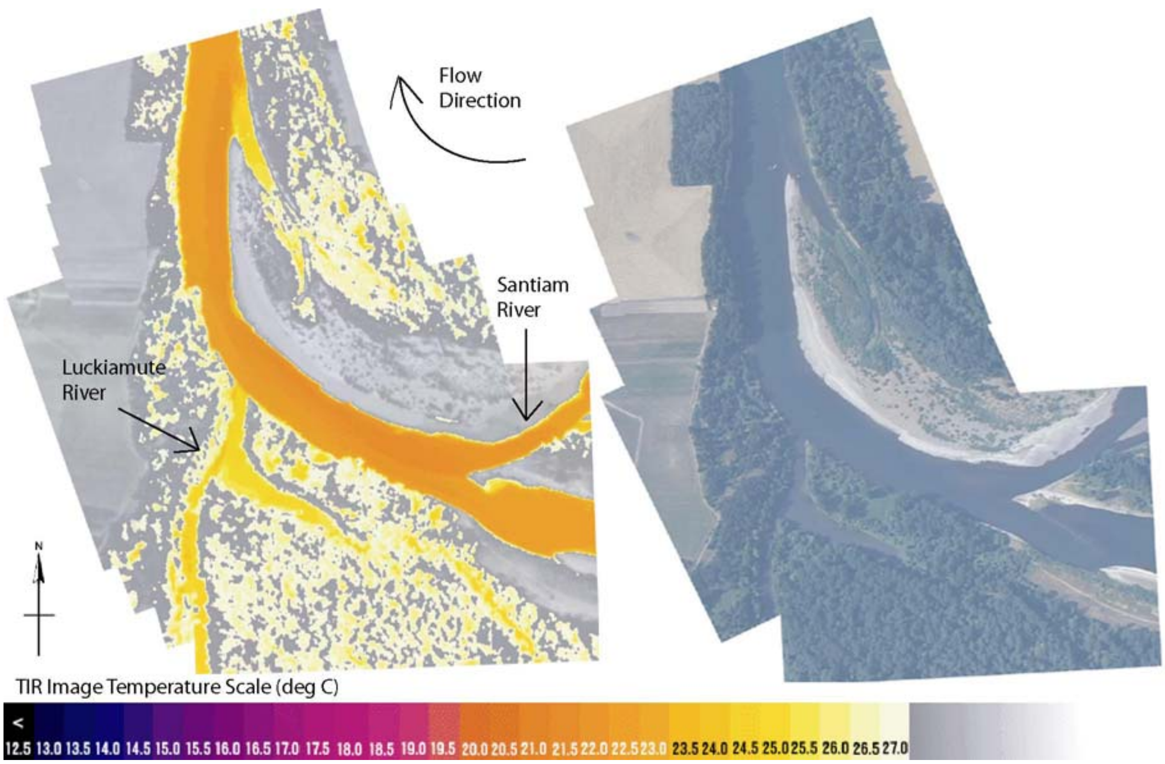
TIR/color video image pair showing a cool seep (17.8^{o}C) on the left bank of Willamette River (18.5^{0}C) at river mile 172.5 *(frame: will0485)*.



TIR/color video image pair showing the location of a warm side channel along the right bank at river mile 155.2. The side channel on the right bank is approximately 23^{o}C while the mainstream of Willamette River is 19.4^{o}C *(frames: will0731-0738)*.



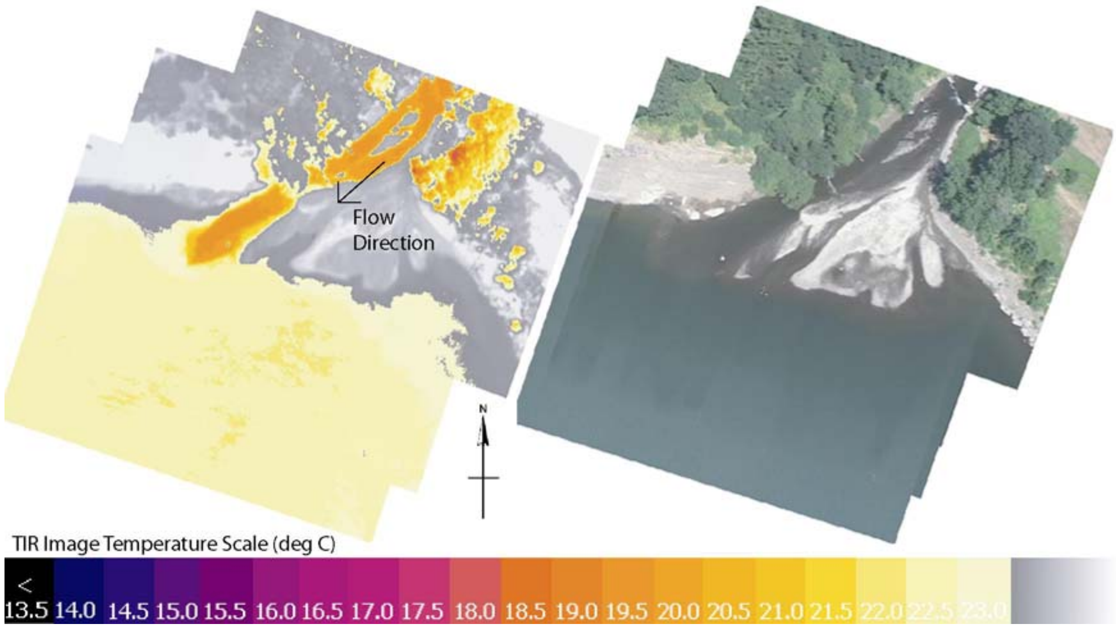
TIR/color video image pair showing the confluence of Little Willamette River (23.9^{o}C) to the right bank of Willamette River, which is 21.6^{o}C at river mile 121.5 *(frame: will1223)*.



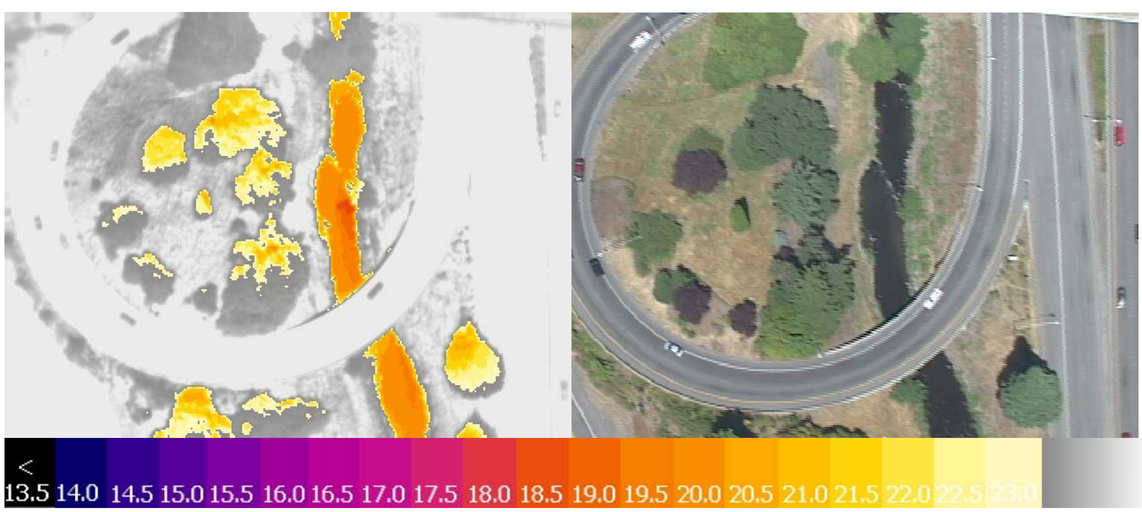
TIR/color video image pair showing the location of confluence of Santiam River (21.5^{o}C) to the right bank of Willamette River (22.1^{o}C) at river mile 107.7. Just downstream of this confluence, the Luckiamute River (23.9^{o}C) empties into the left bank of Willamette River *(frames: will1422-1430)*.

Appendix B: Northern Willamette River Basin
Selected Images

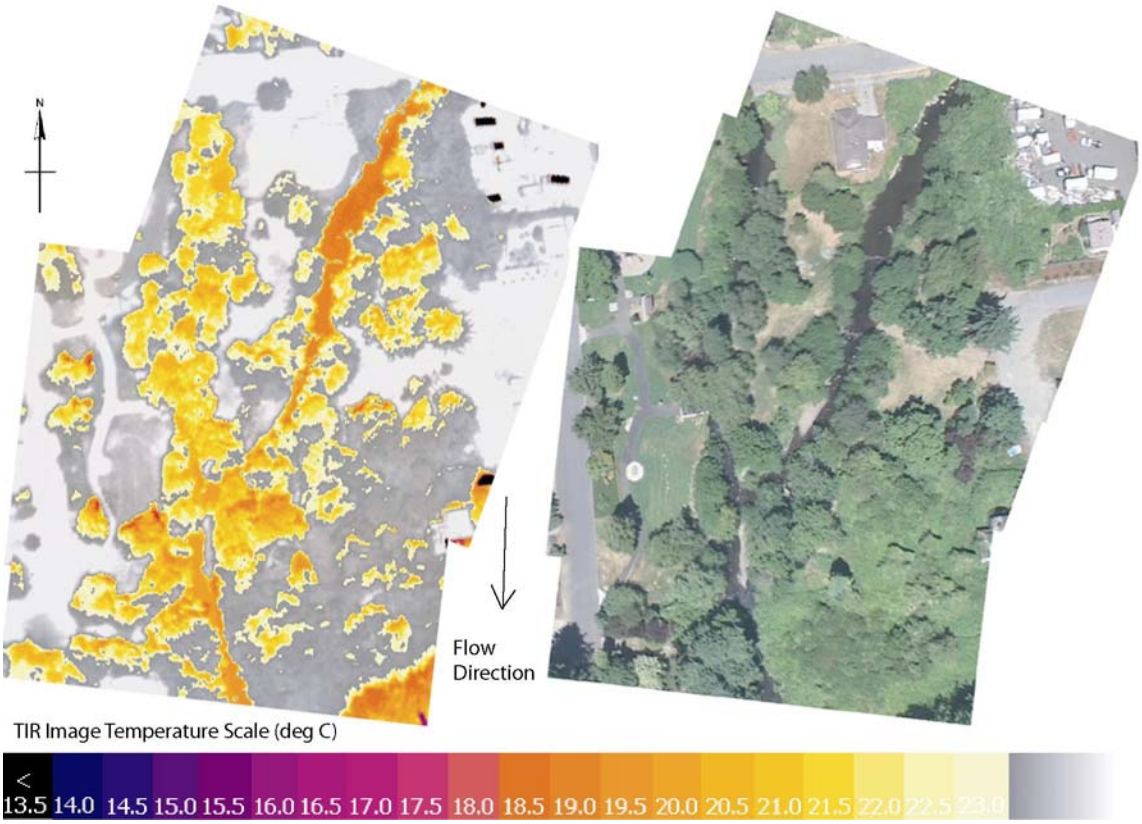
Johnson Creek



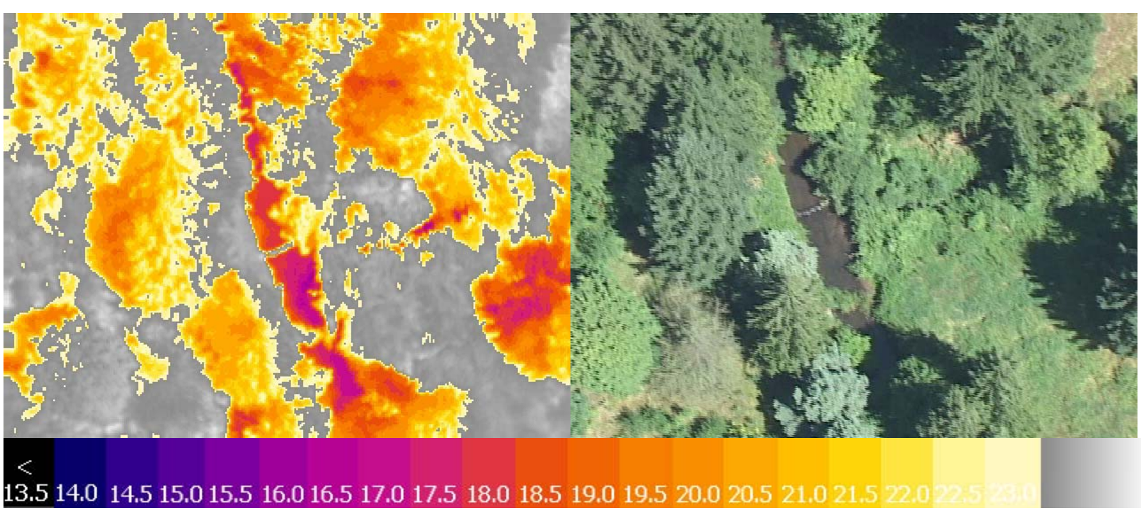
TIR/color video image pair showing the confluence of Johnson Creek (19.1°C) to the left bank of Willamette River (22.3°C) (*frames: john0012-0015*).



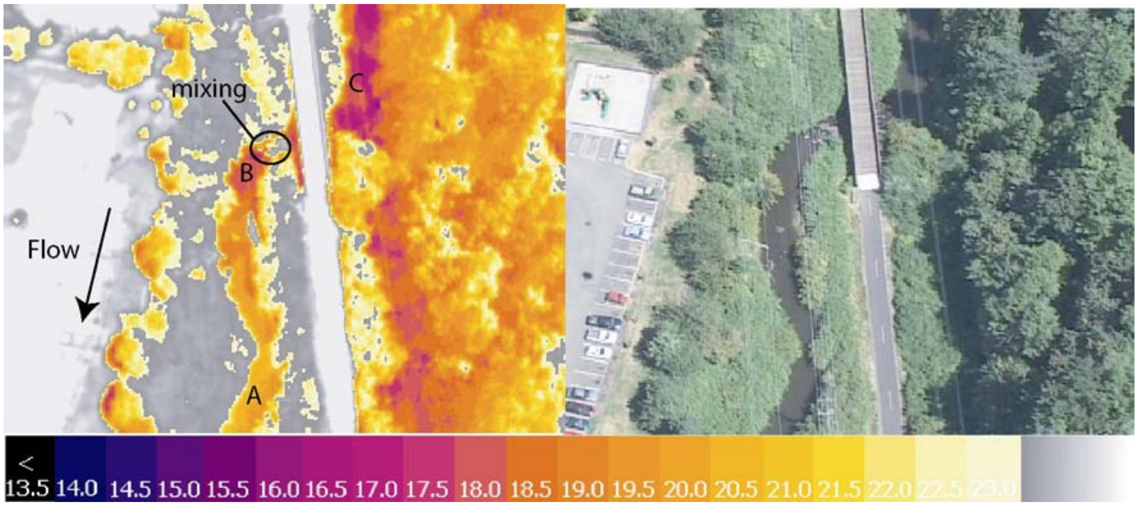
TIR/color video image pair showing the addition of Spring Creek (18.1°C) to the left bank of Johnson Creek (19.7°C) at river mile 0.5 (*frame: john0040*). Flow direction is from the top to bottom of the image.



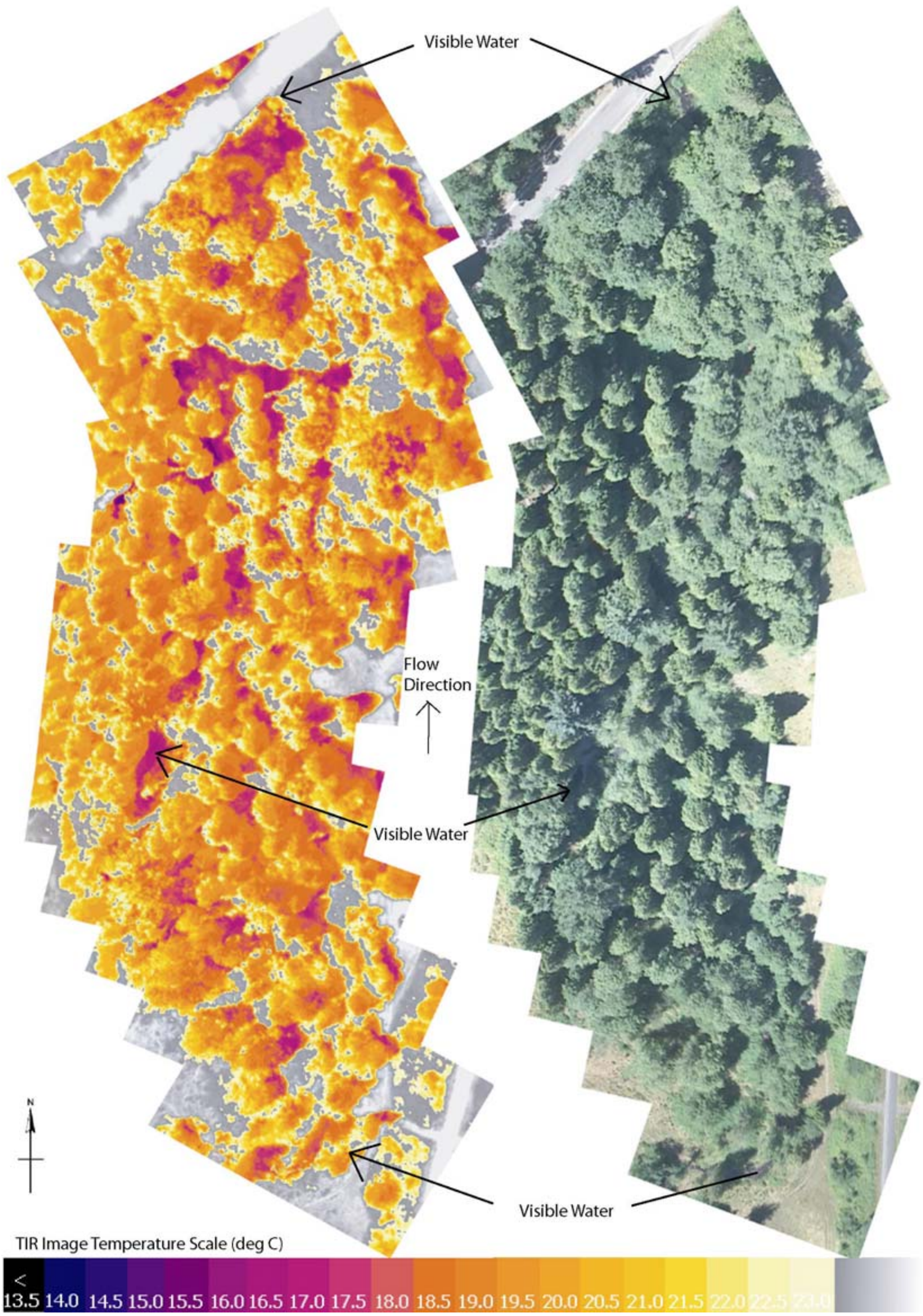
TIR/color video image pair of the confluence of Crystal Springs Creek (20.1°C) to the right bank of Johnson Creek (19.2°C) at river mile 1.4 (*frames: john0084-0087*).



TIR/color video image pair showing Kelly Creek (16.5°C) entering into the left bank of Johnson Creek (17.7°C) at river mile 10.5 (*frame: john0733*).

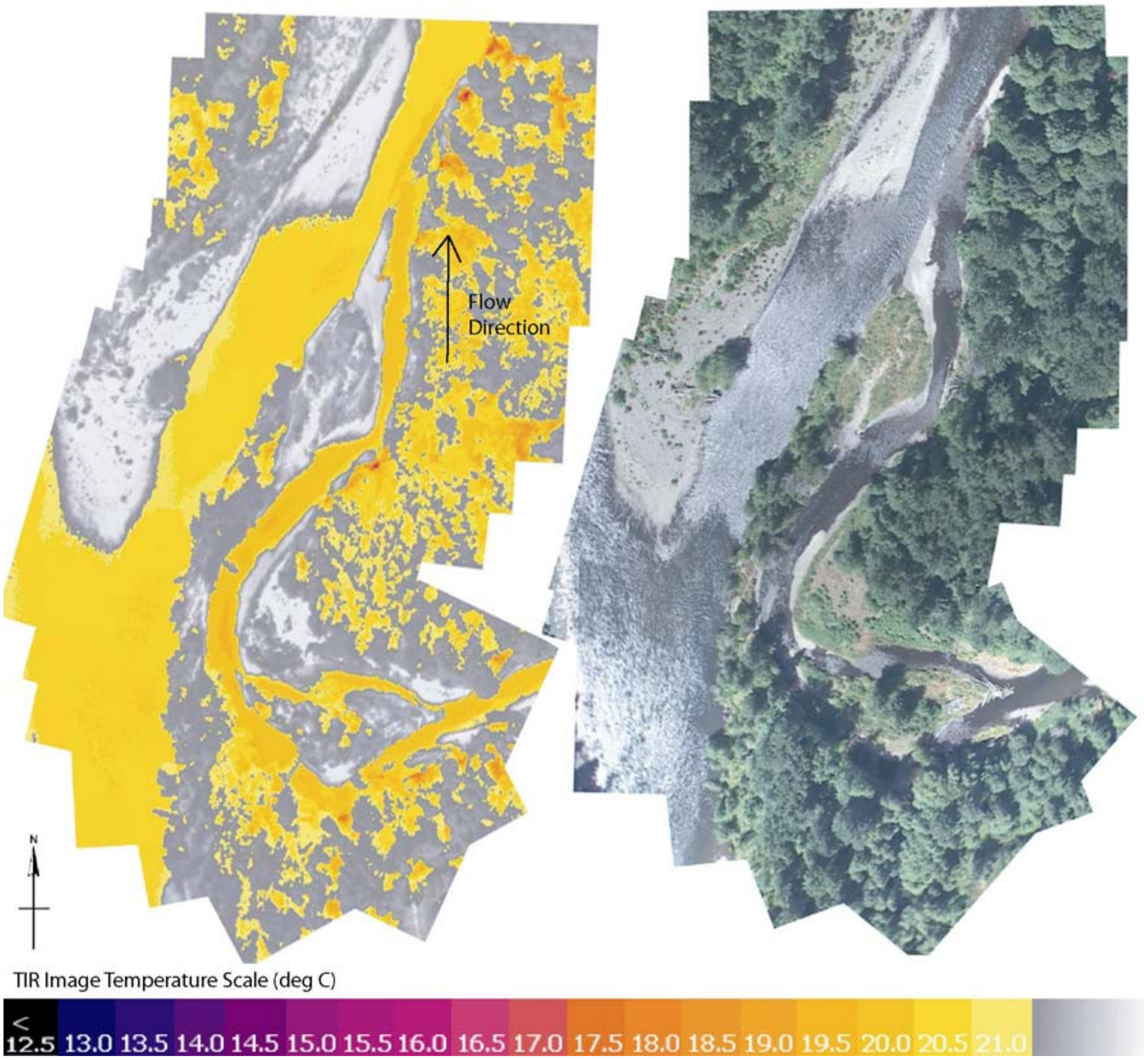


TIR image/color video pair showing partial thermal stratification in Johnson Creek at river mile 11.8. Apparent stream temperatures are 17.4°C upstream of the bridge (location C) and 17.7°C in the mixing area downstream of the bridge (Location B). Surface temperatures increase abruptly downstream of mixed area to 19.9°C (location B).

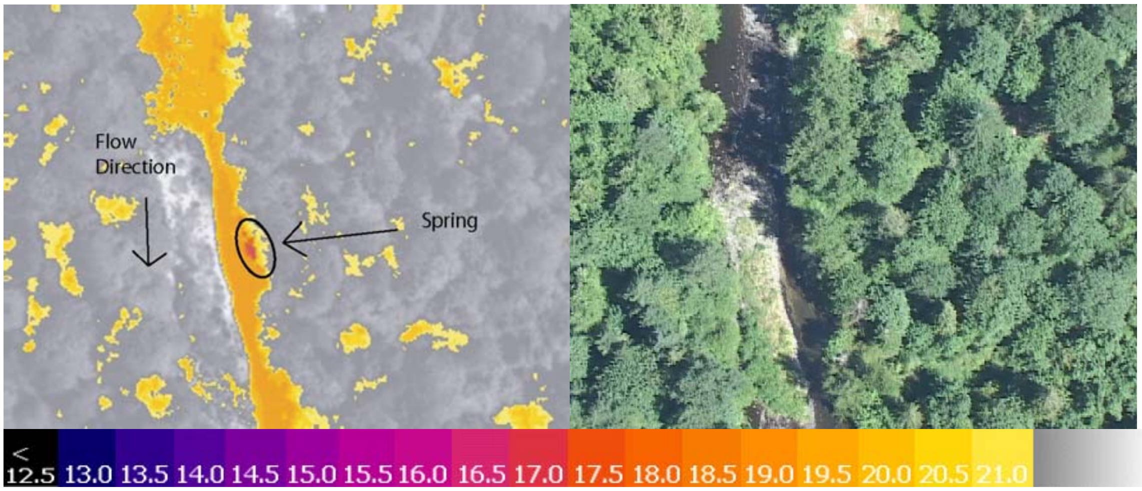


TIR/color video image pair showing one of many sections of Johnson Creek which were too canopied to obtain a continuous sample of the mainstream temperature. The visible water portions which were sampled, but resulted in discontinuities in the longitudinal temperature profile (*frames: john1304-1315*).

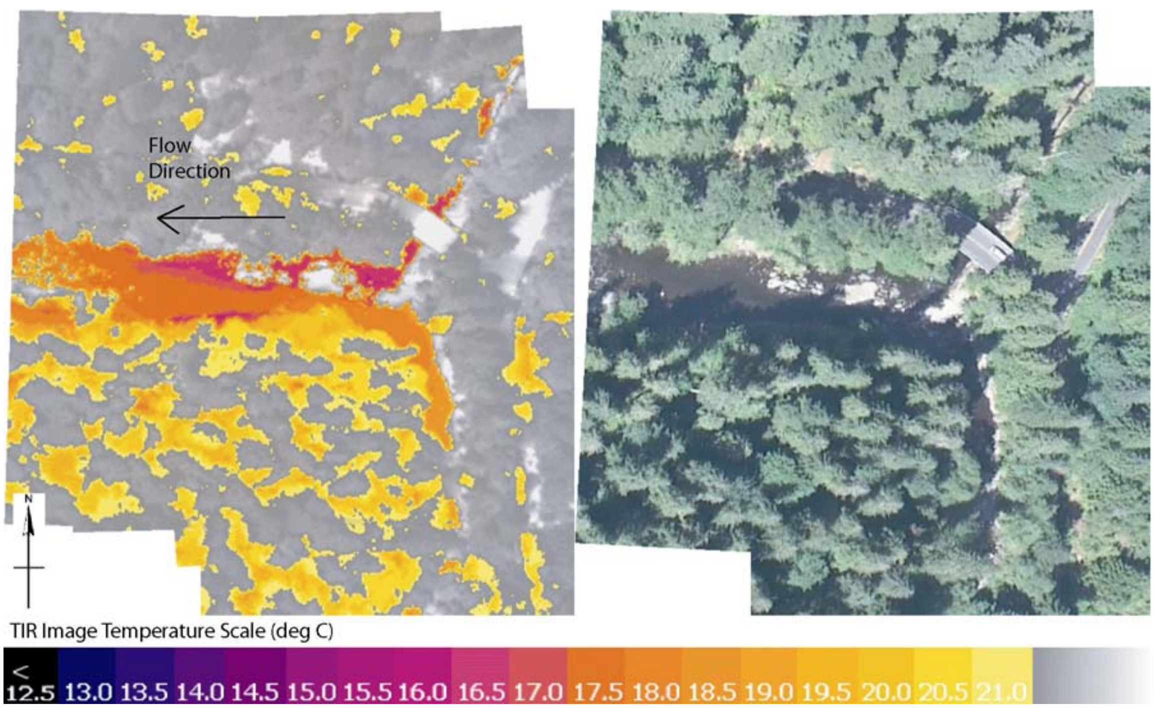
Eagle Creek



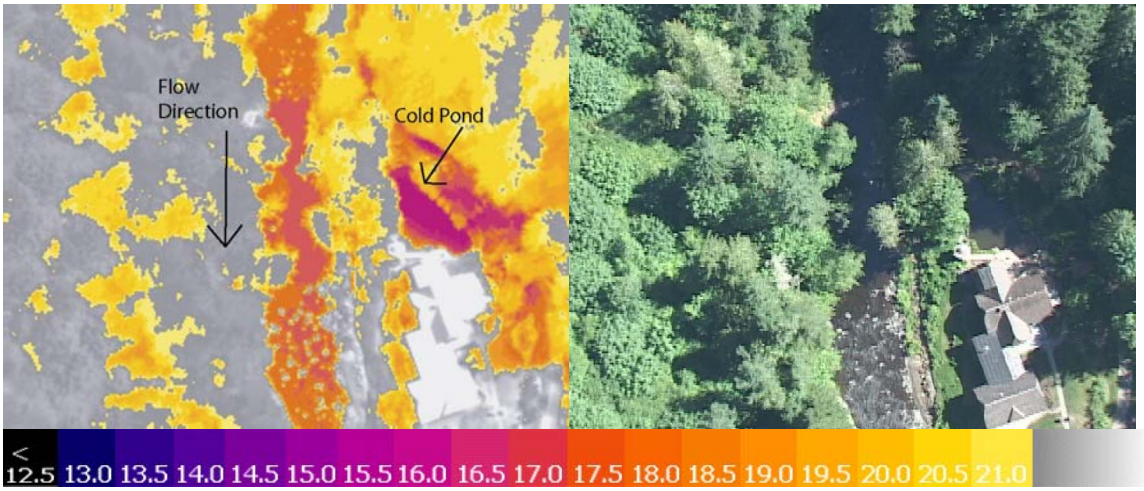
TIR/color video image pair showing the confluence of Eagle Creek (19.8°C) to the left bank of the Clackamas River (20.0°C) (*frames: eag0043-0057*).



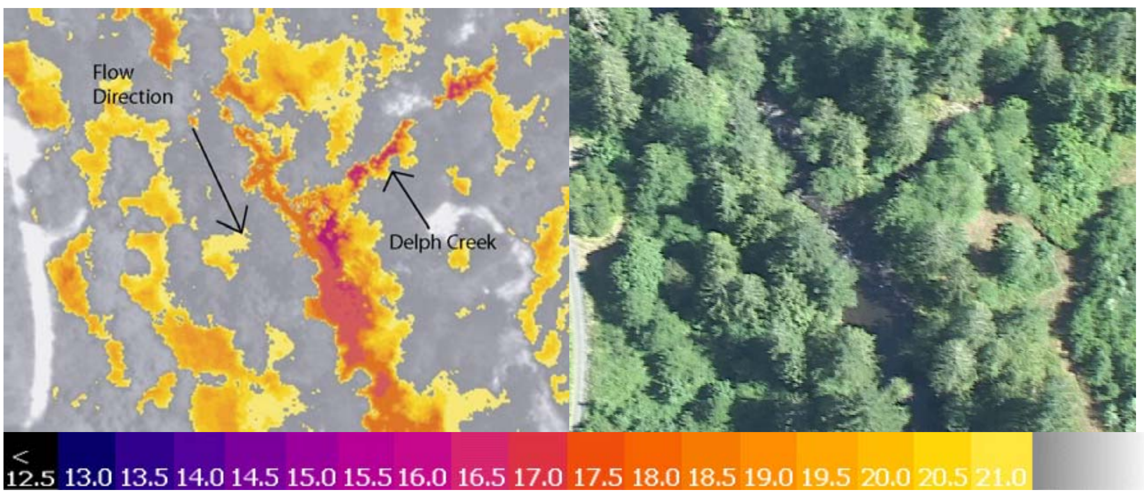
TIR/color video image pair showing a spring (16.7^{o}C) on the left bank of Eagle Creek (18.9^{o}C) at river mile 2.8 (*frame: eag0226*).



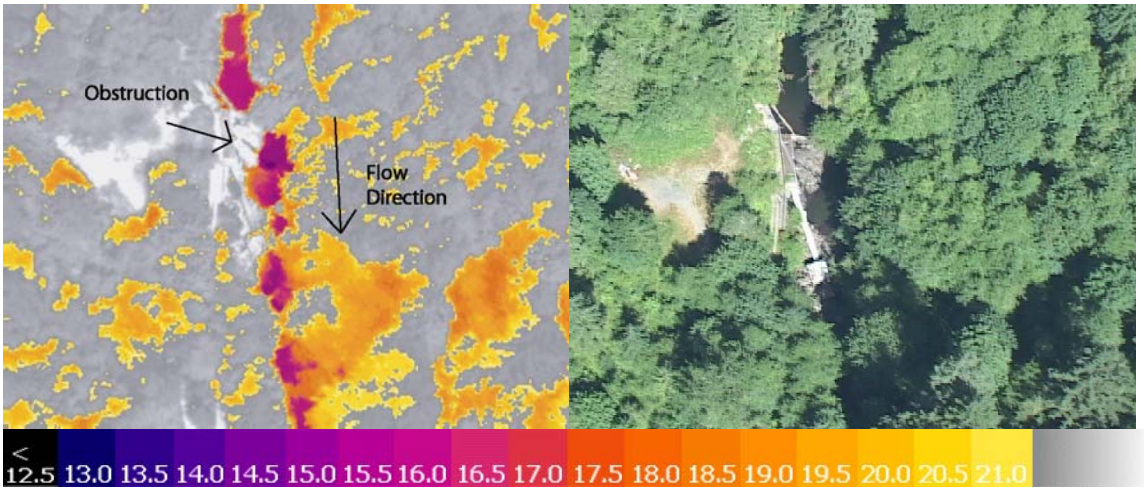
TIR/color video image pair showing the confluence of North Fork (NF) Eagle Creek (16.0^{o}C) to the right bank of Eagle Creek (17.8^{o}C) at river mile 6.2 (*frames: eag0407-0410*).



TIR/color video image pair showing a pond (15.6°C) on the left bank of Eagle Creek at river mile 8.6 (*frame: eag0550*).

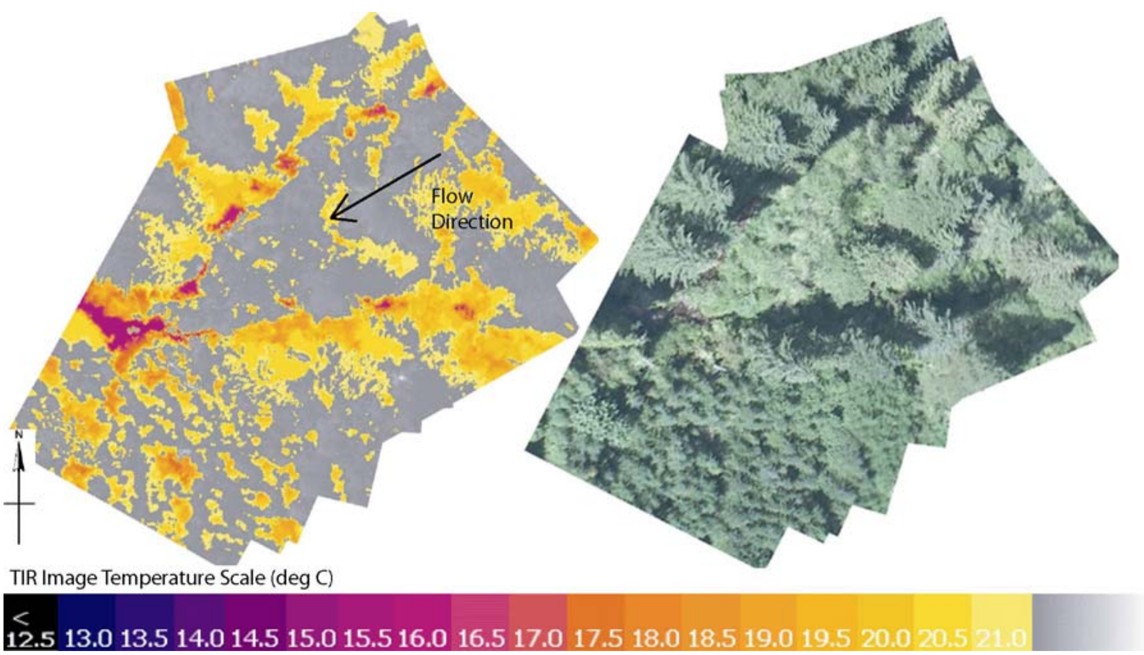


TIR/color video image pair showing the confluence of Delph Creek (15.8°C) to the left bank of Eagle Creek (17.4°C) at river mile 8.9 (*frame: eag0573*).

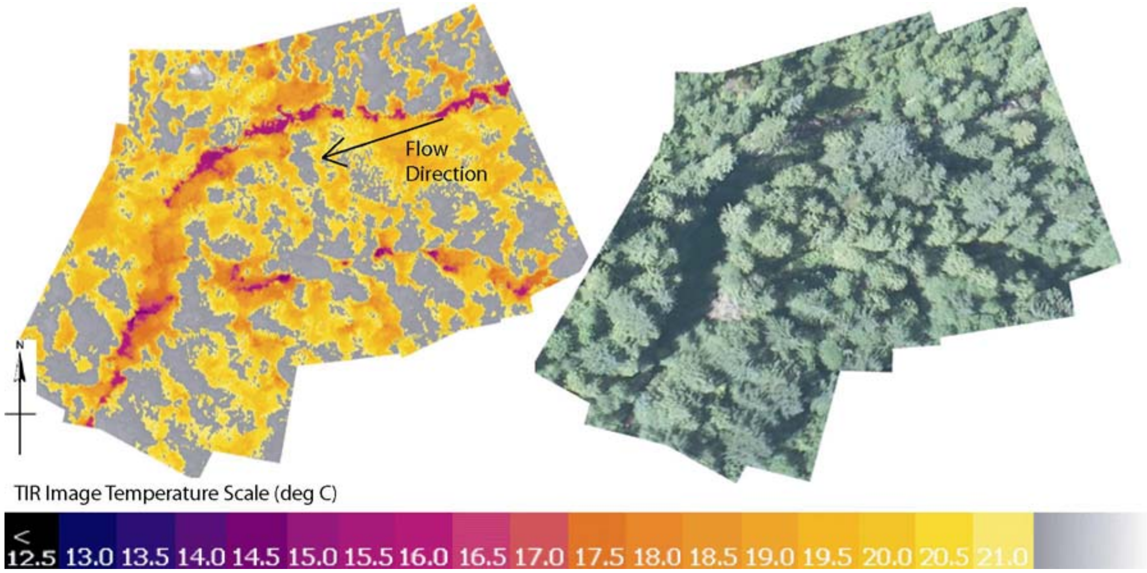


TIR/color video image pair showing an obstruction in Eagle Creek at river mile 13.0. Stream temperatures upstream of the obstruction was 15.5°C while the downstream temperature is 14.6°C (*frame: eag0840*).

North Fork Eagle Creek

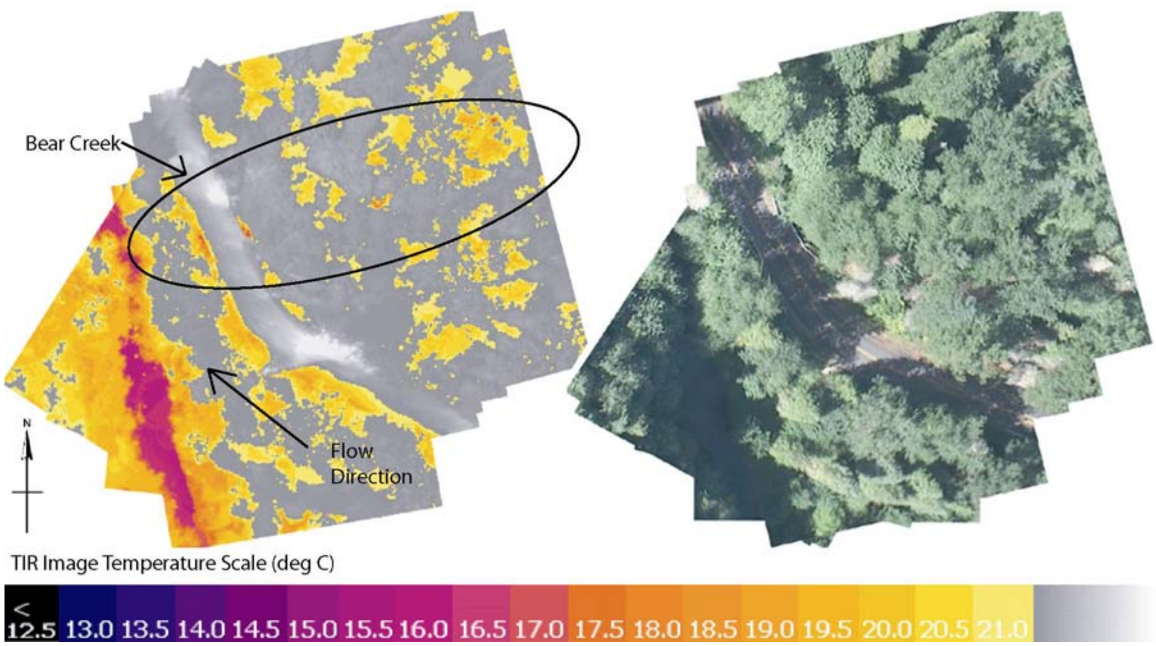


TIR/color video image pair showing the confluence of Little Eagle Creek (15.7°C) to the left bank of NF Eagle Creek (15.3°C) at river mile 4.6 (*frames: nfe0808-0817*).



TIR/color video image pair showing the confluence of Gabenheim Creek (14.5°C) to the left bank of NF Eagle Creek (15.3°C) at river mile 6.0 (*frames: nfe1064-1072*).

Bear Creek



TIR/color video image pair showing the mouth of Bear Creek at the confluence of NF Eagle Creek. The image illustrates how the riparian vegetation masked the stream surface and prevented sampling of radiant temperatures (*frames: bear0136-0146*).