Aerial Surveys in the Fifteenmile Creek Basin
Thermal Infrared and Color Videography

February 26, 2003

Report to:

Oregon Department of Environmental Quality
811 SW 6th Avenue
Portland, OR 97204

by:

Watershed Sciences, LLC
230 SW 3rd Street, Suite 202
Corvallis, OR 97333

Final Report

Revised: March 31, 2003

Table of Contents

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 in the Fifteenmile Creek Basin, OR. The objective of the project was to characterize the thermal regime of selected stream segments to support ongoing stream temperature assessments in the basin.

This report documents the methods used to collect and process the TIR images. This report also presents spatial temperature patterns derived through analysis of the imagery. 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.

Data Collection

The TIR surveys were conducted on selected streams in the Fifteenmile Creek Watershed and on a segment of the Columbia River near the town of The Dalles, OR on August 1-3, 2002 (Figure 1). The date, time, and extent of each surveyed stream segment are summarized in Table 1. The flights were timed to best capture maximum daily stream temperatures, which typically occur between 14:00 and 17:00.

Table 1 – Summary of river segments surveyed with TIR and color video in the Fifteenmile Creek Basin and along the Columbia River Basin from August 1-3, 2002.

Stream	**Survey Date**	**Survey Time (24 hr)**	**Survey Extent & Direction**	**River Miles**	**Image Width Meter (ft)**	**TIR Image Pixel Size Meter (ft)**
Fifteenmile Cr.	1 Aug	13:54-15:33	Mouth to headwaters	52.2	107 (353)	0.3 (1.0)
Ramsey Cr.	2 Aug	13:19-13:54	Mouth to headwaters	13.1	107 (353)	0.3 (1.0)
Columbia R.	2 Aug	14:57-15:08	Rm 181.4 to Deschutes R.	20.7	1075 (3527)	3.4 (11.0)
Eightmile Cr.	3 Aug	13:28-14:54	Mouth to headwaters	33.5	107 (353)	0.3 (1.0)

[1] Geographic Information System

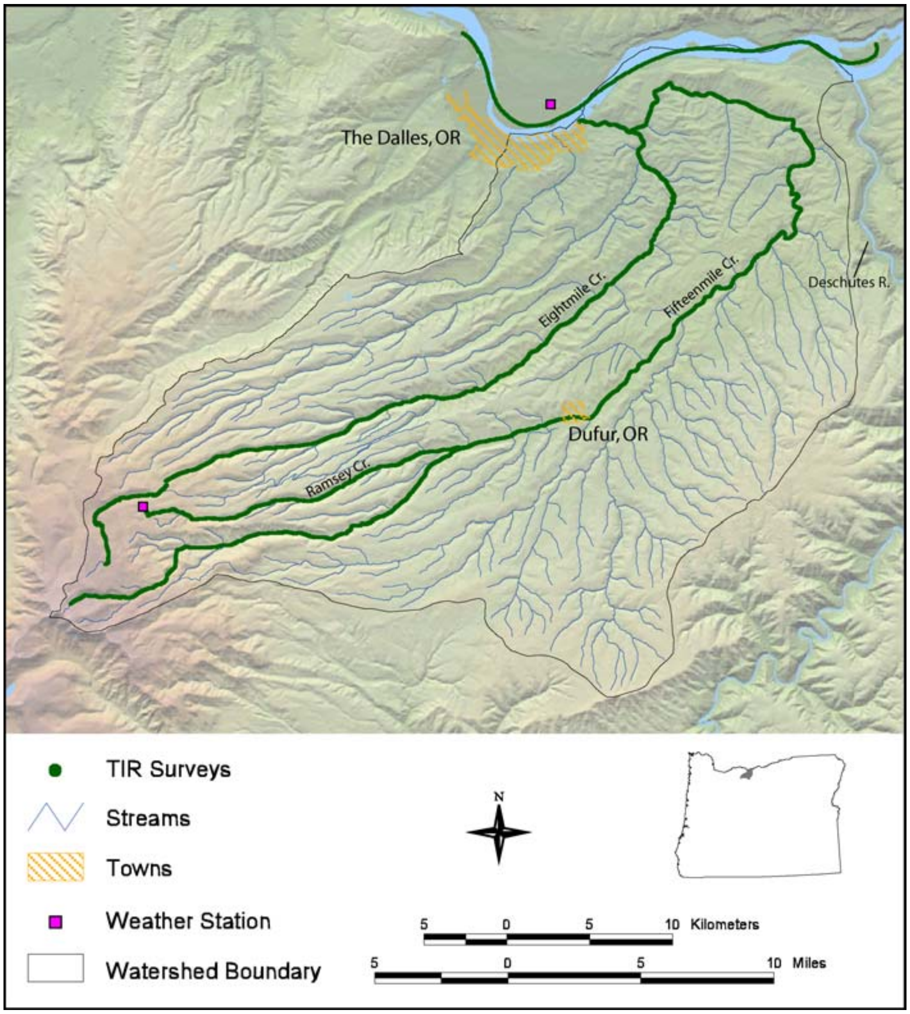


Figure 1 – Map showing the extent of the airborne TIR remote sensing survey conducted in the Fifteenmile Creek Basin and on the Columbia River from August 1-3, 2002.

Watershed Sciences, LLC deployed in-stream data loggers prior to the survey to ground truth (i.e. verify the accuracy) of the TIR data. WS, LLC deployed 10 data loggers in the Fifteenmile Creek watershed. The ODEQ and Oregon Department of Fish and Wildlife (ODF&W) furnished an additional 10 in-stream data points in the Fifteenmile Creek watershed. WS, LLC deployed one in-stream data logger in the Columbia River. Additional in-stream data for the Columbia River were obtained from two continuous monitoring sites maintained by the Army Corp of Engineers[2]. Meteorological data including air temperature and relative humidity were recorded using two portable weather stations (*Onset*). One station was located at the Dalles Airport, WA near the Columbia River. The second station was located in Mt Hood National Forest near Ramsey Creek at river mile 13.1. 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

[2] http://www.nwd-wc.usace.army.mil/TMT/tdg_data/months.html

data logger location. The parameters used to calibrate the TIR images were fined tuned to provide a best fit to the in-stream data.

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 varied based on the flight altitudes. In general, the TIR images presented ground areas between 107 and 150 meters with spatial resolutions between 0.4 and 0.5 meters respectively (Table 1). All surveys were conducted in an upstream direction and the images were collected sequentially with approximately 40% vertical overlap.

Table 2 – Meteorological conditions for the dates and times of the TIR surveys that were recorded using portable weather stations located at The Dalles Airport and along Ramsey Creek, OR at river mile 13.1.

	Ramsey Cr. Weather Station			**The Dalles A/P Weather Station**		
	August 1, 2002					
Time	**Air Temp °F**	**Air Temp °C**	**Relative Humidity %**	**Air Temp °F**	**Air Temp °C**	**Relative Humidity %**
13:30	70.4	21.3	25.2	85	30	15.1
14:00	71.1	21.7	28.0	87	30	14.7
14:30	70.4	21.3	30.8	87	31	12.0
15:00	71.8	22.1	32.8	89	32	13.1
15:30	71.1	21.7	34.7	89	32	18.3
16:00	71.8	22.1	30.8	87	31	22.2
	August 2, 2002					
13:00	58.0	14.5	27.1	74.5	23.6	27.2
13:30	58.7	14.9	26.6	75.9	24.4	24.9
14:00	59.4	15.2	26.1	76.6	24.8	24.9
14:30	60.1	15.6	24.3	77.3	25.2	22.6
15:00	59.4	15.2	24.3	78.7	26.0	22.2
15:30	60.1	15.6	26.1	78.7	26.0	22.2
	August 3, 2002					
13:00	64.9	18.3	32.3	78.7	26.0	23.1
13:30	64.2	17.9	33.3	80.8	27.1	17.1
14:00	65.6	18.7	31.3	81.5	27.5	16.3
14:30	66.3	19.0	31.3	82.2	27.9	13.9
15:00	66.3	19.0	33.7	83.0	28.3	15.9

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. 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 2). 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. The measures assigned from this coverage may not match stream measures derived from other map sources.

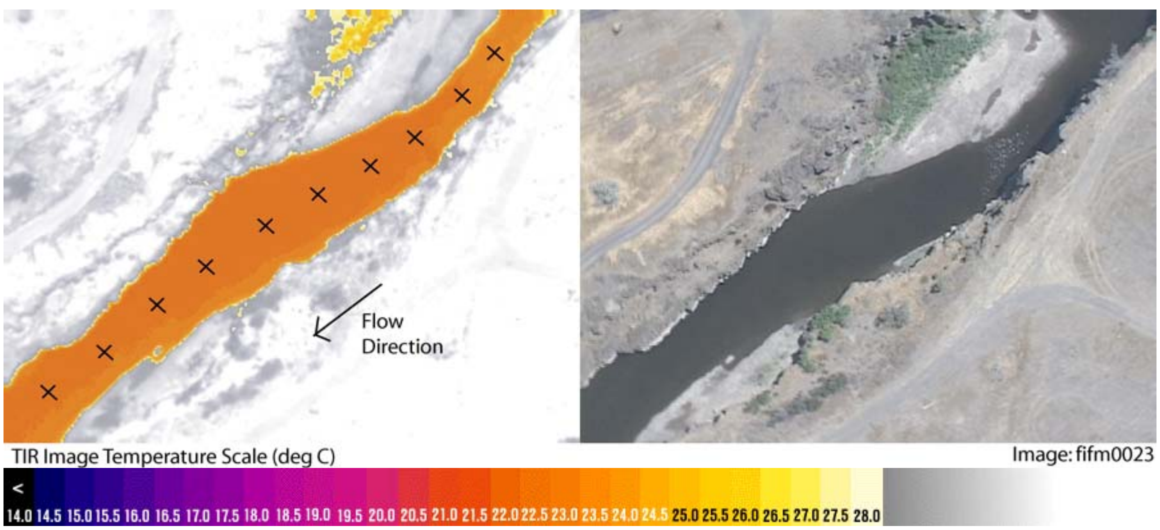


Figure 2 – TIR/color video image pair showing how temperatures are sampled from the TIR images. The black *X's* show typical sampling locations near the center of the stream channel. The recorded temperature for this image is the median of the sample points.

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.

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^{o}C (Torgersen et al. 2001). However, the occurrence of reflections as an artifact (or noise) in the TIR images is a consideration during image interpretation and analysis. In general, apparent stream temperature changes of $< 0.6^{o}$C are not considered significant unless associated with a point source.

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.

Results

Thermal Accuracy

Temperatures from the in-stream data loggers were compared to radiant temperatures derived from the TIR images for each of the surveyed streams (Table 3). For each stream, the average absolute difference (kinetic versus radiant) was within the desired accuracy of $\pm 0.5^{o}$C. Overall, the average difference and the range of differences were also consistent with TIR surveys conducted in the Pacific Northwest over the past 5 years (Torgersen et. al. 2001, Faux et. al. 2001).

The data logger at river mile 3.3 of Fifteenmile Creek recorded a temperature that differed from the measured radiant temperature by more than 1.1°C. An explanation for the difference at this location was not apparent during image calibration. However, spatial temperature patterns derived from the TIR images provide additional context for assessing observed differences and this location is revisited in the discussion of the Fifteenmile Creek longitudinal temperature profile.

On Eightmile Creek, the two most upstream sensors recorded temperatures that were ≈1.0°C cooler than the radiant temperatures derived from the TIR images This difference may indicate a progressive change in the variables (i.e. atmospheric transmission) affecting the calculation of radiant temperatures as the flight progressed upstream to higher elevations. The effect of these differences on the interpretation of the spatial temperatures patterns is discussed further in the results sections of this report.

Table 3 – Comparison of ground-truth water temperatures (kinetic) with the radiant temperatures derived from the TIR images.

Image	River mile	Date	Time 24 hr	Kinetic °C	Radiant °C	Difference °C
Fifteen Mile Cr. (Average Difference : 0.5)						
fifm0027	0.2	1-Aug	13:55	21.5	21	0.5
fifm0157	3.3	1-Aug	13:59	19.2	20.2	-1.1
fifm0946	18.8	1-Aug	14:26	24.2	23.7	0.5
fifm1549	30.0	1-Aug	14:46	21.3	20.8	0.5
fifm1553	30.1	1-Aug	14:46	21.5	21.0	0.5
fifm1566	30.3	1-Aug	14:47	21.1	20.6	0.5
fifm2041	38.8	1-Aug	15:03	15.4	16.0	-0.6
fifm2505	42.5	1-Aug	15:13	13.7	13.5	0.2
fifm3273	50.4	1-Aug	15:27	8.2	7.9	0.3
fifm3276	50.4	1-Aug	15:27	8.2	8.0	0.2
Columbia R. (Average Difference : 0.2)						
col0072	187.8	2-Aug	15:01	21.0	21.1	-0.1
col0076	188.2	2-Aug	15:00	20.8	20.6	0.2
col0066	187.2	2-Aug	15:00	21.0	20.7	0.3
Ramsey Cr. (Average Difference : 0.3)						
ram0006	na	2-Aug	13:19	19.1	18.6	0.5
ram0184	0.0	2-Aug	13:25	15.1	15.5	-0.4
ram1498	10.7	2-Aug	13:47	8.5	8.4	0.1
ram1914	13.1	2-Aug	13:54	5.7	5.9	-0.2
ram1923	13.1	2-Aug	13:54	5.2	5.1	0.1
Eightmile Cr. (Average Difference : 0.4)						
etm0021	n/a	3-Aug	13:28	19.1	18.8	0.3
etm1010	7.5	3-Aug	13:46	20.7	20.1	0.6
etm1553	11.8	3-Aug	13:55	18.3	18.9	-0.6
etm2614	19.0	3-Aug	14:13	14.6	14.7	-0.1
etm3901	28.1	3-Aug	14:36	8.8	7.8	1.0
etm4341	31.4	3-Aug	14:44	6.9	6.0	0.9

Temporal Differences

Figure 3 shows in-stream temperature variations at a single location on three of the surveyed streams. The figure 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 Fifteenmile Creek (river mile 30.0) the TIR survey occurred prior to the daily maximum stream temperature, which was recorded from 16:10 to 17:00 and the stream temperature rose by 1.5^{o}C during the time span of the survey. Similarly, the TIR survey of Eightmile Creek (river mile 19.0) occurred prior to the daily maximum temperatures, which occurred between 17:00 and 18:00. At river mile 19.0, stream temperatures rose by 1.5^{o}C during the time span of the survey. On Ramsey Creek (river mile 13.1), the flight also occurred prior to the daily maximum. However, at this location near the headwaters, stream temperatures changed by < 2.0^{o}C over the course of the entire afternoon.

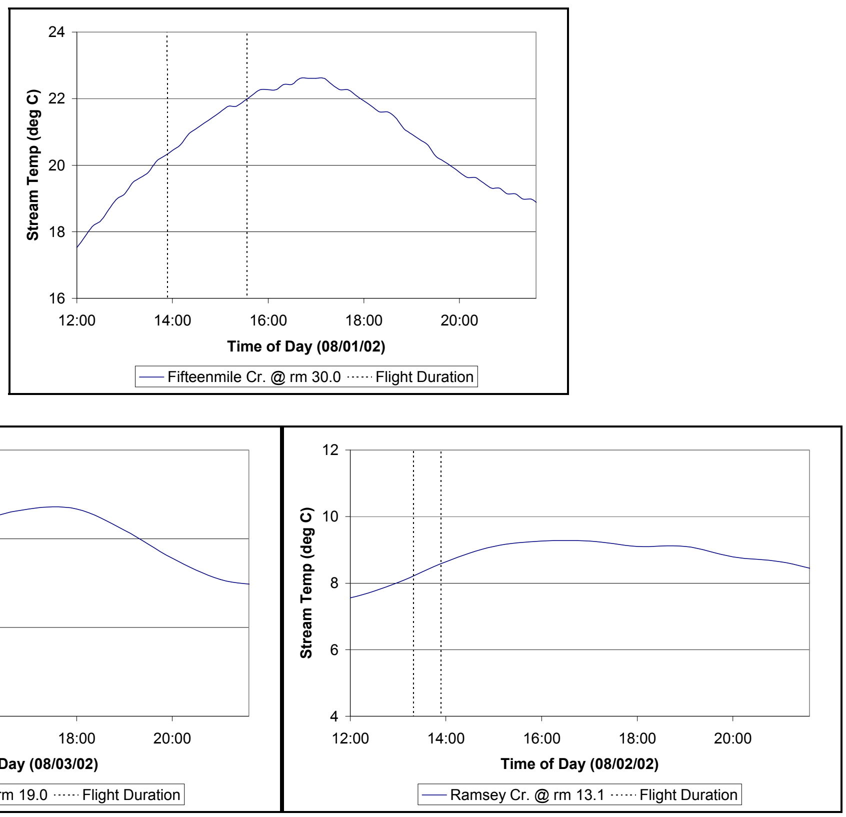


Figure 3 – Stream temperature variation and time of TIR remote sensing over flight for four sensor locations in the Fifteenmile Creek Watershed survey (Aug 1-3, 2002).

Fifteenmile Creek

The median temperatures for each sampled image of Fifteenmile Creek were plotted versus the corresponding river mile (Figure 4). The plot also contains the median temperature of all surface water inflows (e.g. tributaries, surface springs, etc.) that were visible in the imagery. Tributaries that were detected, but not sampled due to size or canopy masking, are also shown on the plot to help facilitate interpretation of the profile. Tributaries that were identified on the 7.5' USGS topographic base maps were labeled by name on the profile.

Overall, stream temperatures in Fifteenmile Creek ranged from ≈5.3^{o}C near the headwaters to a survey maximum of ≈26.4^{o}C at river mile 5.9. The longitudinal temperature profile shows a general pattern of warming from the headwaters downstream to river mile 16.4, a distance of ≈27.0 miles. Although a general warming trend prevails, the profile also shows changes in the longitudinal heating rate along the stream gradient and distinct points with locally cooler water. In the lower 16.4 miles, stream temperatures showed a slight cooling trend with a general increase in local spatial temperature variability (i.e. stream temperatures changes > ±1.0^{o}C over distances of < 0.5 miles).

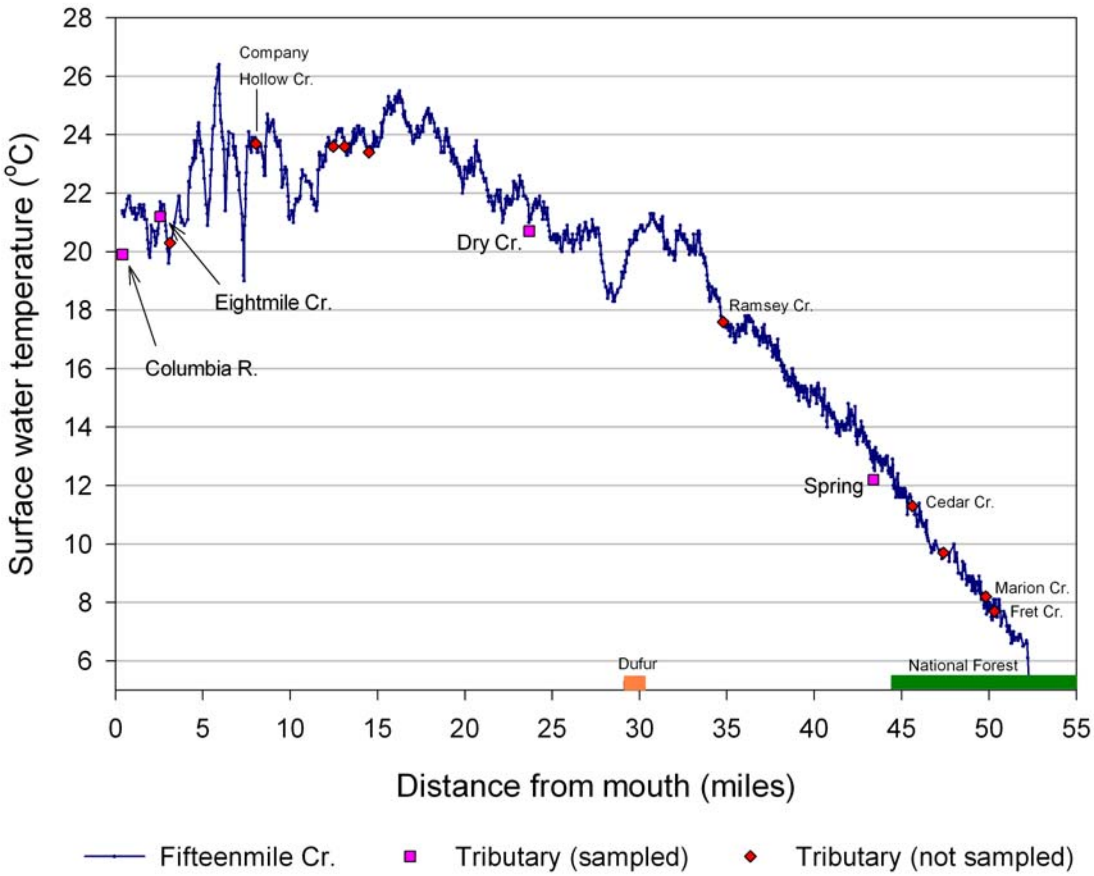


Figure 4 – Median channel temperatures versus river mile for Fifteenmile Creek, OR. Tributary and spring inflows that were sampled during the analysis are labeled on the chart. The profile also shows tributaries that the detected, but not sampled.

Inspection of the TIR images revealed that small impoundments and diversions in stream contributed to the local thermal spatial variability observed in the longitudinal temperature profile. The location of the impoundments and diversions as detected in the TIR images were plotted in relation to the longitudinal temperature profile to help facilitate interpretation of the spatial temperature patterns (Figure 5). Figure 5 also illustrates the in-stream temperatures at the time of the survey and recorded daily maximum stream temperatures (*for 8/1/2002*) at each of the ground truth points. The in-stream measurements show that the time of TIR survey was consistent with the maximum daily temperature for the three points upstream of river mile 38. However, maximum stream temperatures were 1.3 to 2.5^{o}C warmer than those recorded by the TIR survey at the downstream (of river mile 38.0) points.

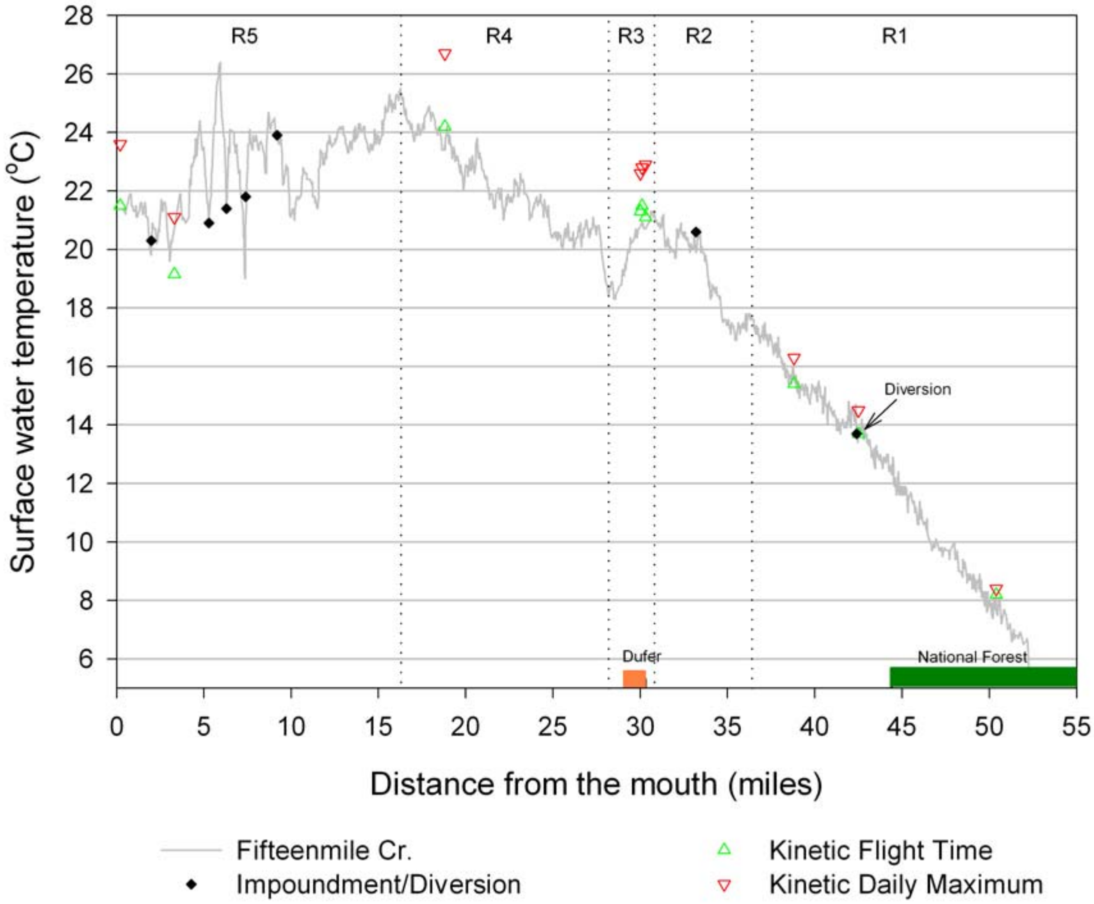


Figure 5 – Median stream temperatures in Fifteenmile Creek versus river miles. The plot also shows the location of in-stream sensors used to calibrate the TIR images with the recorded in-stream (kinetic) temperature at the time of the survey and the recorded maximum temperature on August 1, 2002. Also illustrated are the locations of impoundments and diversions detected in the TIR images. Reaches of consistent thermal response are labeled as R1, R2, etc.

The following paragraphs provide a reach-by-reach discussion of the results of the TIR survey. The reaches were segmented through visual inspection of the longitudinal temperature profile and are intended to delineate the profile based on consistent thermal response. Figure 5 illustrates the extent of each reach (labeled as R1, R2, etc.). Alternate segmentations are possible based on a more rigorous analysis or on a scale of interest.

Reach 1 (river mile 52.3 to 36.4) – Water temperatures in Fifteenmile Creek increased by ≈12.5°C between river mile 52.2 (5.3°C) and river mile 36.4 (17.8°C). Linear regression of surface water temperatures through this reach shows that the increase was almost linear at ≈0.7°C/river mile (R^2 = 0.99). The only apparent discontinuity in the warming temperature trend (*outside of characteristic noise levels*) was observed between river miles 42.3 and 41.5 where stream temperatures dropped by ≈1.0°C (14.7°C to

13.7°C). This localized cooling occurred downstream of a small water diversion observed at river mile 42.4.

An apparent spring at river mile 43.4 was the only surface water inflow sampled through this reach. Although other tributaries were detected, their small size (*relative to pixel size*) and partial masking by the riparian vegetation precluded temperature sampling. Inspection of the profile through this reach does not reveal any points that suggest inflows (surface or sub-surface) with sufficient volume and/or water temperature differences (*from the main stem*) to create discontinuities in the longitudinal profile. Riparian vegetation masked the stream intermittently through this reach, which precluded temperature sampling from some TIR image frames. In the upper reaches of the survey, Fifteenmile Creek was detected and sampled based on high thermal contrast between the stream and terrestrial features (Figure 6).

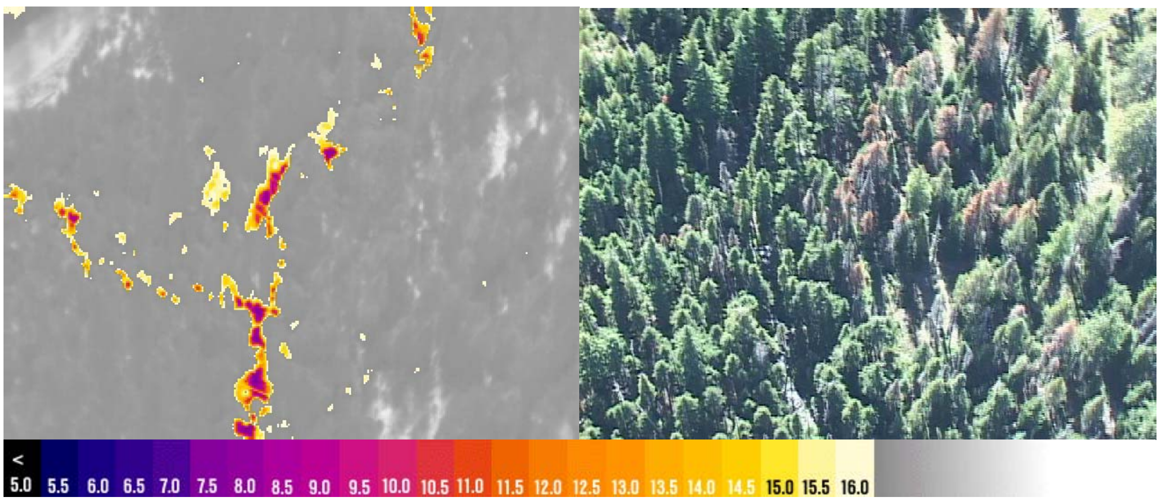


Figure 6 – TIR/video image pair showing the confluence of Fifteenmile Creek (7.7°C) and Fret Creek (not sampled) at river mile 50.3 just downstream of the Fifteenmile Creek Campground. The image illustrates the detection of Fifteenmile Creek through the riparian canopy based on high thermal contrast between the stream and surround features. Fret Creek was too small (relative to pixel size) to permit temperature sampling. (*Frame: fifm3261*)

Reach 2 (river mile 36.4 – river mile 30.8) – Stream temperatures remained consistent (±0.5°C) between river miles 36.0 and 35.0 before the heating rate increased again (≈2.0°C/river mile) with stream temperatures reaching ≈20.6°C at river mile 33.5. Ramsey Creek enters Fifteenmile Creek through this reach (river mile 34.8), but was masked by riparian vegetation at the mouth and could not be sampled. Between river miles 33.5 and 36.4, stream temperatures continued to increase, but at a lower longitudinal rate. An apparent decrease in stream temperature ≈0.9°C was observed between river miles 32.3 and 32.1. No surface inflows were sampled or detected at this location and the source of cooling was not apparent from the imagery.

Reach 3 (river mile 30.8 - river mile 28.2) – This reach, which includes the town of Dufer, is characterized by an apparent stream temperature decrease of ≈2.8°C. The physical factors contributing to this apparent cooling were not evident in the TIR imagery or through inspection of the USGS 7.5' topographic reference maps. The confluence of Pine Creek was detected at river mile 29.9; however, there was not sufficient surface water visible in the TIR images to obtain an accurate temperature sample. Surface inflow from Pine Creek was not considered a source of cooling observed through this reach.

Reach 4 (river mile 28.2 – river mile 16.3) – This reach is characterized by a general increase in stream temperatures with areas of local spatial thermal variability. Overall, stream temperatures increased from ≈18.4°C at river mile 28.2 to ≈25.5°C at river mile 16.3. Stream temperatures increased by 2.5°C between river miles 28.2 and river mile 27.7. The increased longitudinal heating at this location suggests a change in the physical factors that contributed to the apparent cooling in the upstream reach (reach 3). Stream temperature remained consistent (±0.6°C) over the next 2.5 miles with no net change in stream temperature. Although stream temperatures generally warmed between river mile 25.5 and 16.3, the longitudinal temperature profile shows some localized cooling through this section with minimums observed at river miles 23.7, 22.3, 19.9, and 17.1. At river mile 23.7, a slight decrease in main stem temperatures was observed near the confluence of Dry Creek (20.7°C). Dry Creek was the only surface water inflow detected through this reach and it contributed water that was slightly cooler (-0.5°C) than the main stem. The surface of Fifteenmile Creek is exposed to direct solar loading through much of this reach (Figure 7) and the occurrences of localized cooling (-1.0°C to -1.8°C) over relatively short distances (i.e. < 1.0 mile) suggests diffuse sub-surface discharge through this reach.

Reach 5 (river mile 16.3 – mouth) – Surface water temperatures were generally warm through this reach with measured temperatures ranging between 26.4°C and 19.0°C. The reach was further characterized by an overall net decrease in stream temperature with a high degree of local thermal variability. Eightmile Creek (river mile 2.6) was the only surface water inflow detected through this reach and it contributed water that was only slightly less (0.5°C) than the main stem at the time of the survey.

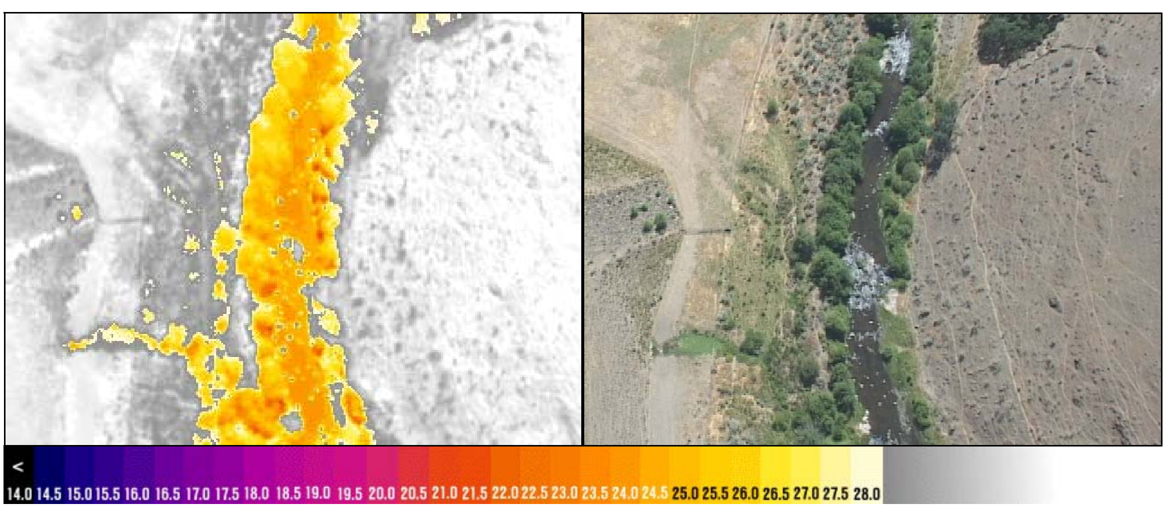


Figure 7 – TIR/color video image showing Fifteenmile Creek (23.9°C) at river mile 17.2. Spatial temperature patterns show localized cooling between river miles 17.9 and 17.1.

Although no surface inflows were detected at this location, the USGS 7.5' topographic maps show the confluence of Douglas Hollow and Fifteenmile Creek. Flow direction is from the top to bottom of the image. (*Frame: fifm0867*).

Between river miles 16.3 and 14.6, stream temperatures decreased from 25.3 to 23.5. Although no inflows were detected through this reach, the USGS 7.5' topographic reference maps show Kelly Spring at river mile 15.5. Stream temperatures remained consistent (±0.5°C) over the next 2.2 miles before showing a decrease to 21.4°C at river mile 11.5. The sharp drop in stream temperatures at river mile 11.5 suggests sub-surface discharge. A similar decrease (1.5°C) in stream temperature was also observed between river miles 10.8 and 10.2.

The high degree of local thermal variability observed at river miles 7.4, 6.3, and 5.3 were associated with small impoundments in the stream (Figure 5). Stream temperatures were generally warmer and more spatially variable upstream of the impoundment and cooler downstream (Figure 8). The cooler water downstream may suggest thermal stratification immediately behind the impoundments. However, it may also suggest infiltration through and around the impoundment.

The stream temperature decreases at river mile 4.4 and subsequent decreases at river mile 3.0 were not associated with an impoundment. The sharp temperature drops at these locations suggest some subsurface discharge through this reach. In addition, the in-stream sensor located at river mile 3.3-recorded kinetic temperatures that were cooler (≈1.1°C) than the radiant temperatures. The differences (kinetic versus radiant) at this location may also suggest diffuse sub-surface discharge where the in-stream data logger near the bottom of the stream reads a cooler temperature than the mixed condition measured at the stream surface.

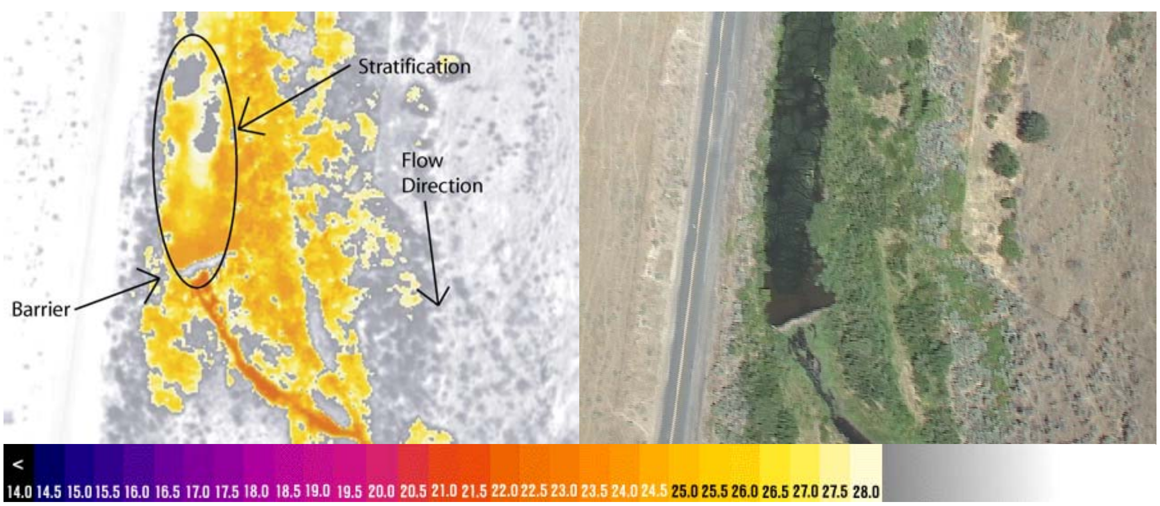


Figure 8 - TIR/color video image pair showing dam/impoundment in Fifteenmile Creek at river mile 5.3. The water upstream the obstruction ranges from 22-24°C while the water downstream is a constant 20.9 degrees (*frame: fifm0274*).

Ramsey Creek

The median temperatures for each sampled image of Ramsey Creek were plotted versus the corresponding river mile (Figure 9). The plot also shows the in-stream temperatures at the ground truth locations at the time of the TIR survey and the recorded daily maximum stream temperatures on August 2, 2002. The TIR survey was consistent with maximum daily temperatures at the monitoring sites at river mile 10.7 and 13.1, but was 1.8^{o}C cooler than the maximum daily stream temperatures recorded at the mouth of Ramsey Creek.

Stream temperatures at the upstream end of the survey were cold (≈4.8^{o}C) and warmed progressively in the downstream direction. A pond at river mile 11.3 resulted in some local thermal variability with an apparent 1.5^{o}C temperature increase immediately downstream of the pond. Stream temperatures reached ≈15.2^{o}C at river mile 3.6 with local variability generally within the ±0.5^{o}C variation characteristic of TIR remote sensing surveys. Riparian vegetation intermittently masked the surface of Ramsey Creek throughout the 14-mile survey. Consequently, samples were taken when surface water was visible in the images and could not be acquired from every image frame (Figure 10). No tributaries or other surface water inflows were detected during the analysis of the Ramsey Creek imagery.

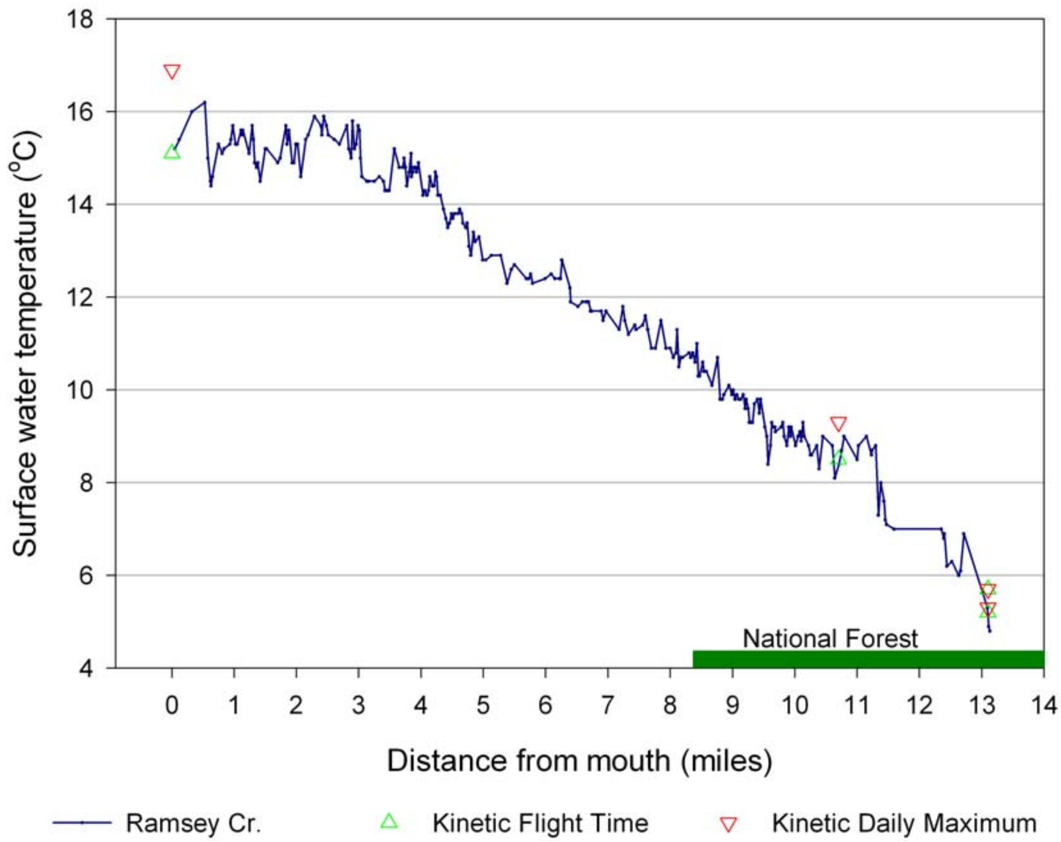


Figure 9 – Median channel temperatures versus river mile for Ramsey Creek, OR. The plot also shows in-stream (kinetic) temperatures at the time of the TIR survey and the daily maximum stream temperatures.

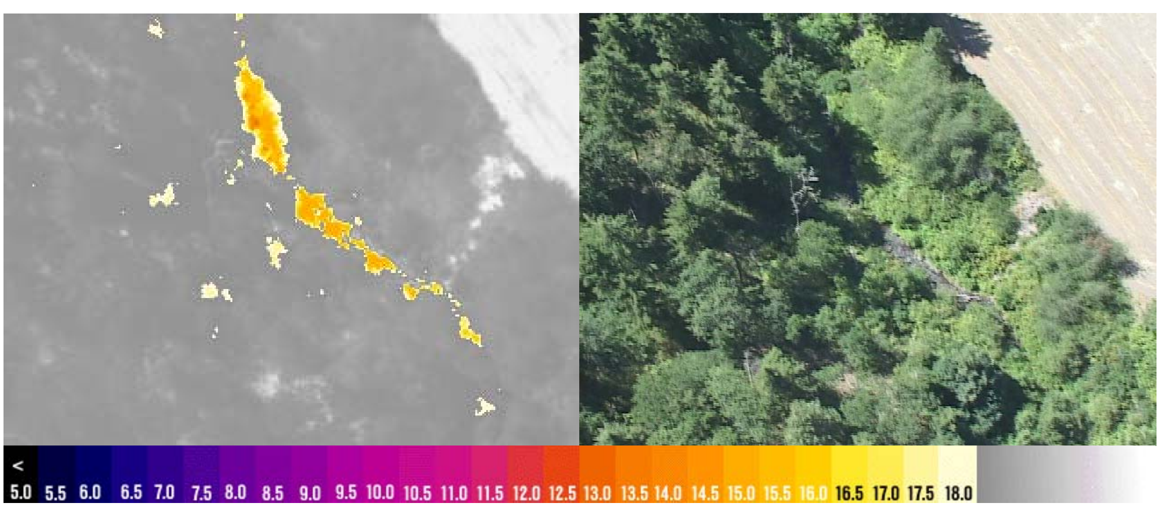


Figure 10 – TIR/color video image showing Ramsey Creek at river mile 3.7. The image shows an example of how riparian vegetation masked the stream surface intermittently throughout the survey route (*frame: ram0619*).

Eightmile Creek

The median temperatures for each sampled image of the Eightmile Creek were plotted versus the corresponding river mile (Figure 11). Tributaries inflows were detected during the processing of the TIR imagery over the extent of the survey. However, with the exception of Fifteenmile Creek, the surface inflows were too small (*relative to pixel size*) to obtain an accurate temperature sample. To facilitate interpretation of the spatial temperature patterns, the location of the detected tributaries were also plotted on Figure 11. The tributaries were assigned the temperature of the main stem in order to illustrate their location on the longitudinal temperature profile.

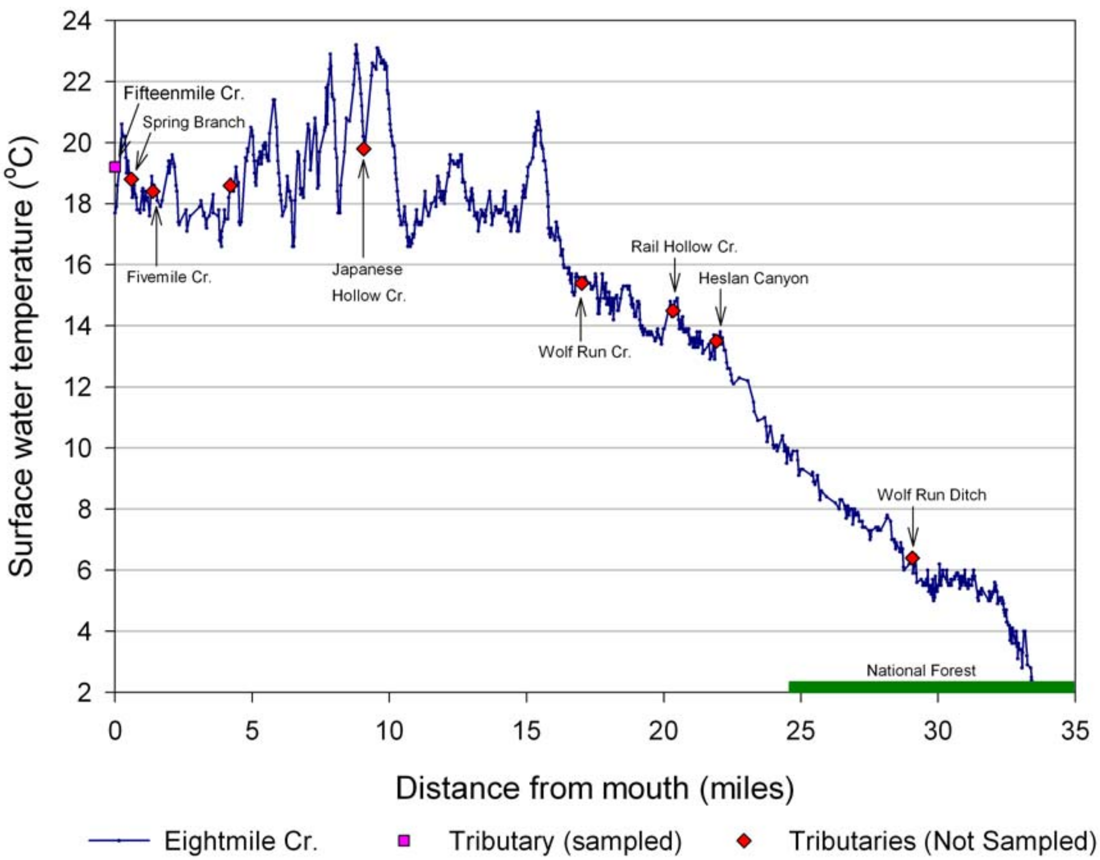


Figure 11 - Median channel temperatures versus river mile for Eightmile Creek along with the location of surface water inflows. The plot also shows the location of detected tributaries that were not sampled due to their size.

Spatial temperature patterns in Eightmile Creek were similar to those observed in Fifteenmile Creek. Stream temperatures were cool near the headwaters at river mile 33.4 and showed a general pattern of downstream warming to river mile 15.4. Thermal variability increased between river mile 15.4 and the mouth with areas of abrupt shifts in the longitudinal heating rate (warming and cooling). For discussion purposes, the longitudinal temperature profile can be segmented in to three reaches that display consistent thermal response (Figure 12). The reaches were segmented through visual inspection of the profile and alternate segmentations are possible based on a more rigorous analysis. Figure 12 also illustrates the in-stream temperatures at the time of the survey and recorded daily maximum stream temperatures (*for 8/3/2002*) at each of the ground truth points.

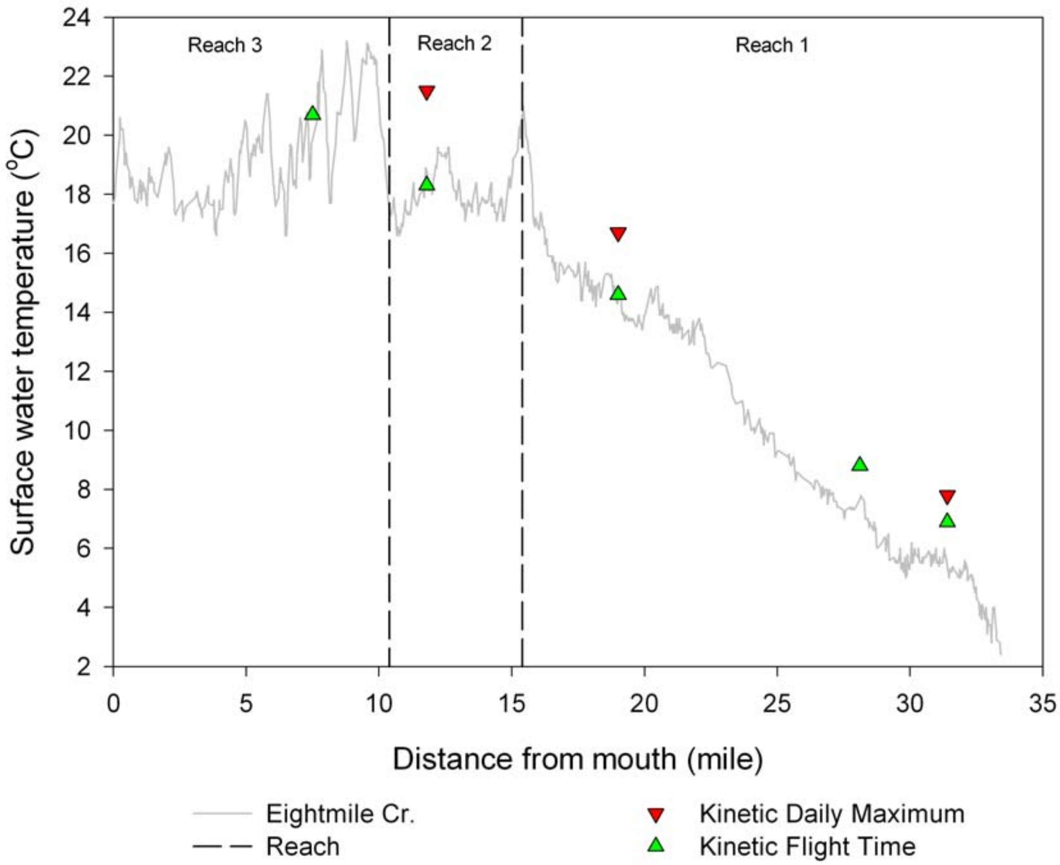


Figure 12 – Median channel temperatures versus river mile for Eightmile Creek The profile shows the location of in-stream sensors used to ground truth the thermal infrared images with the recorded in-stream (kinetic) temperature at the time of the survey and the recorded maximum temperatures. In-stream locations that do not have a point for daily maximum temperature were retrieved immediately after the flight and did not record the daily maximum.

<u>Reach 1 (headwaters to river mile 15.4)</u> - Stream temperatures generally warmed downstream the headwaters (river mile 33.4) reaching 17.2°C at river mile 15.9. The in-stream data loggers at river miles 28.1 and 31.4 indicate that kinetic temperatures were warmer ≈1.0°C than the sampled radiant temperatures at the upstream end of the survey (i.e. above river mile 28.0). While one might expect that actual temperatures near the headwaters are warmer (*by at least 1.0°C*) than the 2.4°C measured in the TIR images, the differences do not change the overall shape or interpretation of the temperature patterns.

Stream temperatures remained relatively consistent (≈5.8°C) between river miles 31.3 and 29.2 before increasing steadily to river mile 15.9 with little local variations. One notable location was an apparent 1.4°C temperature decrease at river mile 20.2, which coincided with the confluence of Eightmile Creek and Rail Hollow. The decrease in stream temperatures at this location suggests possible cool water influences through the tributary channel. The longitudinal heating rate increased abruptly at river mile 15.9 with stream temperatures showing an apparent 3.8°C increase over the next 0.5 miles. The factors contributing to the abrupt increase in radiant temperatures were not apparent from the TIR images or from the USGS 7.5' base maps.

<u>Reach 2 (river mile 15.4 – river mile 10.4)</u> – Radiant temperatures showed an abrupt decrease (3.8°C) between river mile 15.4 and 14.7. No tributary or spring inflows were detected at this location that would explain this response. The remainder of the reach was characterized by relatively consistent temperature (≈17.8°C) with some localized warming observed between river miles 13.2 and 12.6 and localized cooling observed between river mile 12.4 and 10.9. The lack of significant longitudinal heating and some cooling through this reach suggests possible buffering from sub-surface sources. The in-stream data logger at river mile 11.8 shows a maximum daily temperature of 21.5°C, an increase of 3.2°C from the time of the TIR survey.

<u>Reach 3 (river mile 10.4 – mouth)</u> - Stream temperatures increased abruptly at river mile 10.5 reaching ≈22.5°C by river mile 9.9. From this point, water temperatures showed a high degree of local thermal variability with an overall net decrease in stream temperature. At river mile 9.1, the sharp decrease (3.2°C) in temperatures coincided with the location of Japanese Hollow Creek. Although Japanese Hollow Creek was not sampled, the decrease in main stem temperatures at this location suggests a possible cold-water influence through the channel. Further inspection of the TIR images and reference maps did not reveal any obvious associations between the observed spatial temperature patterns and surface water or in-channel features. Local temperature changes occurred over short spatial distances without direct detection of any surface or sub-surface inflows (Figure 13). The observed thermal variability in this reach may reflect a series of surface/sub-surface exchanges, which occur within the stream channel over relatively short spatial distances (i.e. <0.5 miles). In summer low flow conditions, the stream responds rapidly to relatively small sub-surface inflows and subsequently heats rapidly in the absence of these inflows.

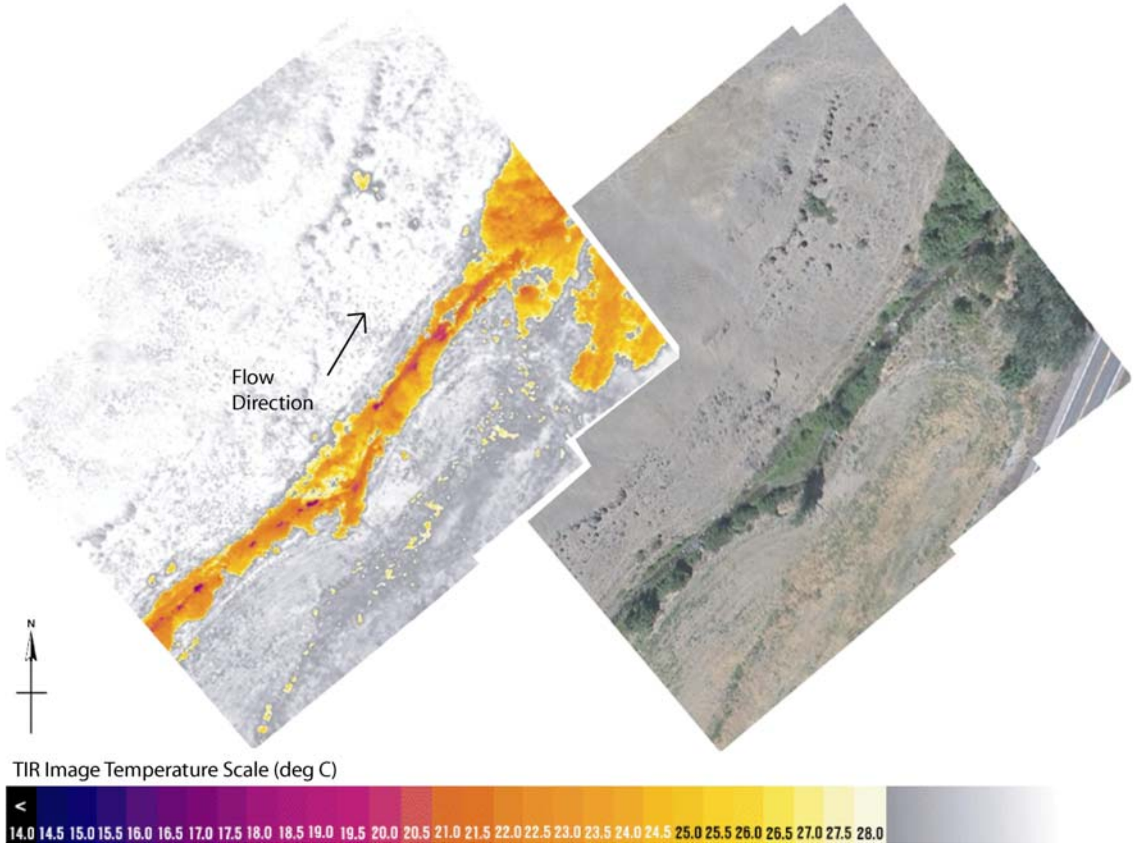


Figure 13 – TIR/color video images showing Eightmile Creek at river mile 7.7. Radiant stream temperatures at the upstream end of the image were 21.8°C and 20.4°C at the downstream end. The source of cooling was not obvious from the imagery.

Columbia River

The median surface temperatures from the Columbia River were plotted versus river mile (Figure 14). Although the survey was flown at an altitude of 10,000 ft above ground level, the river looks wider than the image width at some points upstream of the Dalles Dam. In these cases, the survey followed the left bank of the river.

The Deschutes River at river mile 200 was the only tributary sampled during the analysis. The Deschutes River contributed cooler water (18.6°C) to the Columbia and the thermal plume of the Deschutes inflow was visible along the left bank of the Columbia (Figure 15). Fifteenmile Creek and Chenoweth Creek were detected during the survey, but were to small (*relative to pixel size*) to obtain a temperature sample.

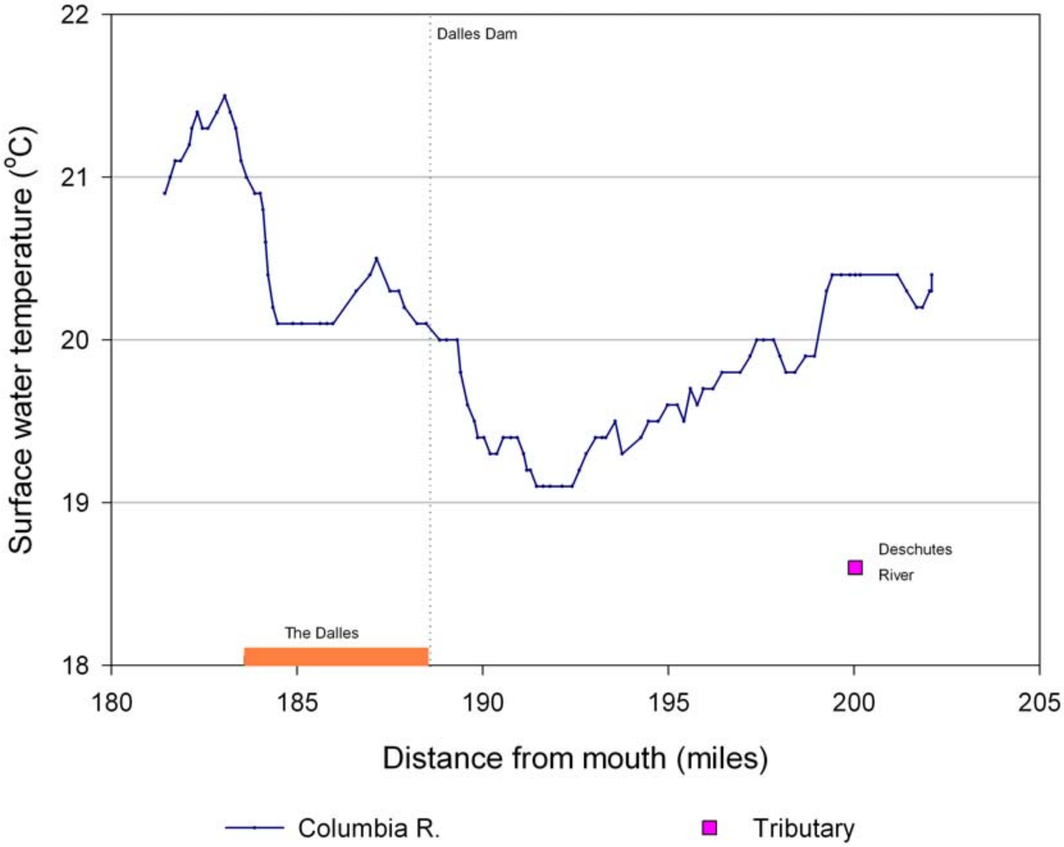


Figure 14 - Median surface water temperatures versus river mile for the Columbia River.

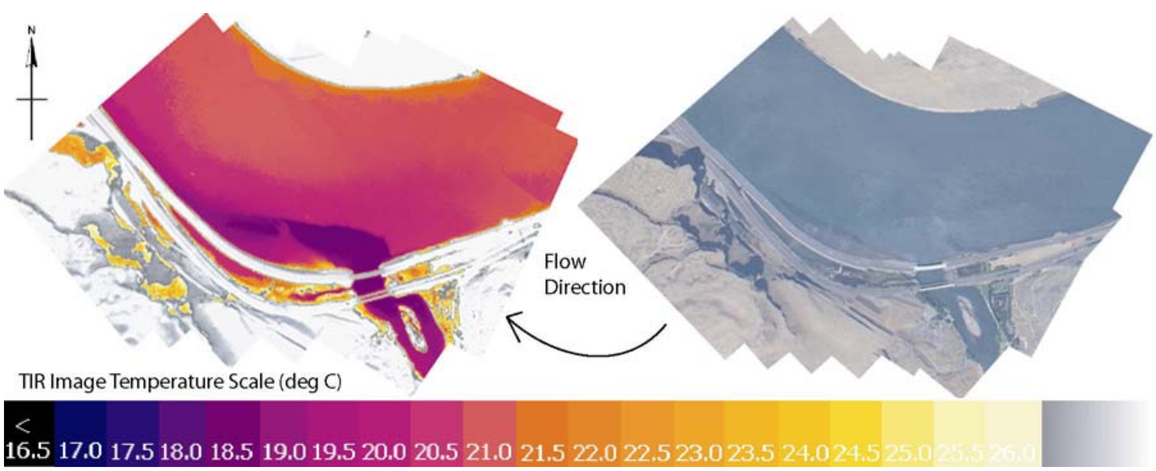


Figure 15 - TIR/color video image mosaic showing the confluence of the Columbia River (20.4°C) and Deschutes River (18.6°C) at river mile 200. The width of the Columbia River channel at the mouth of the Deschutes River is approximately 2,600 ft.

No significant water temperature differences were detected above or below the Dalles Dam (Figure 16). This suggests that the Columbia River was not thermally stratified in the pool upstream of the dam. Overall, sampled radiant temperatures showed an apparent cooling trend (≈1.3^{o}C) between the Deschutes River confluence and the Dalles Dam. Downstream of the dam, stream temperatures increased by 1.1^{o}C between the dam and the confluence of Chenoweth Creek (river mile 183.2). However, the length of the survey (20.7 miles) and the spatial distribution of in-stream sensors did not allow an assessment of possible noise due to the increased path length (sensor to river) used for the Columbia River.

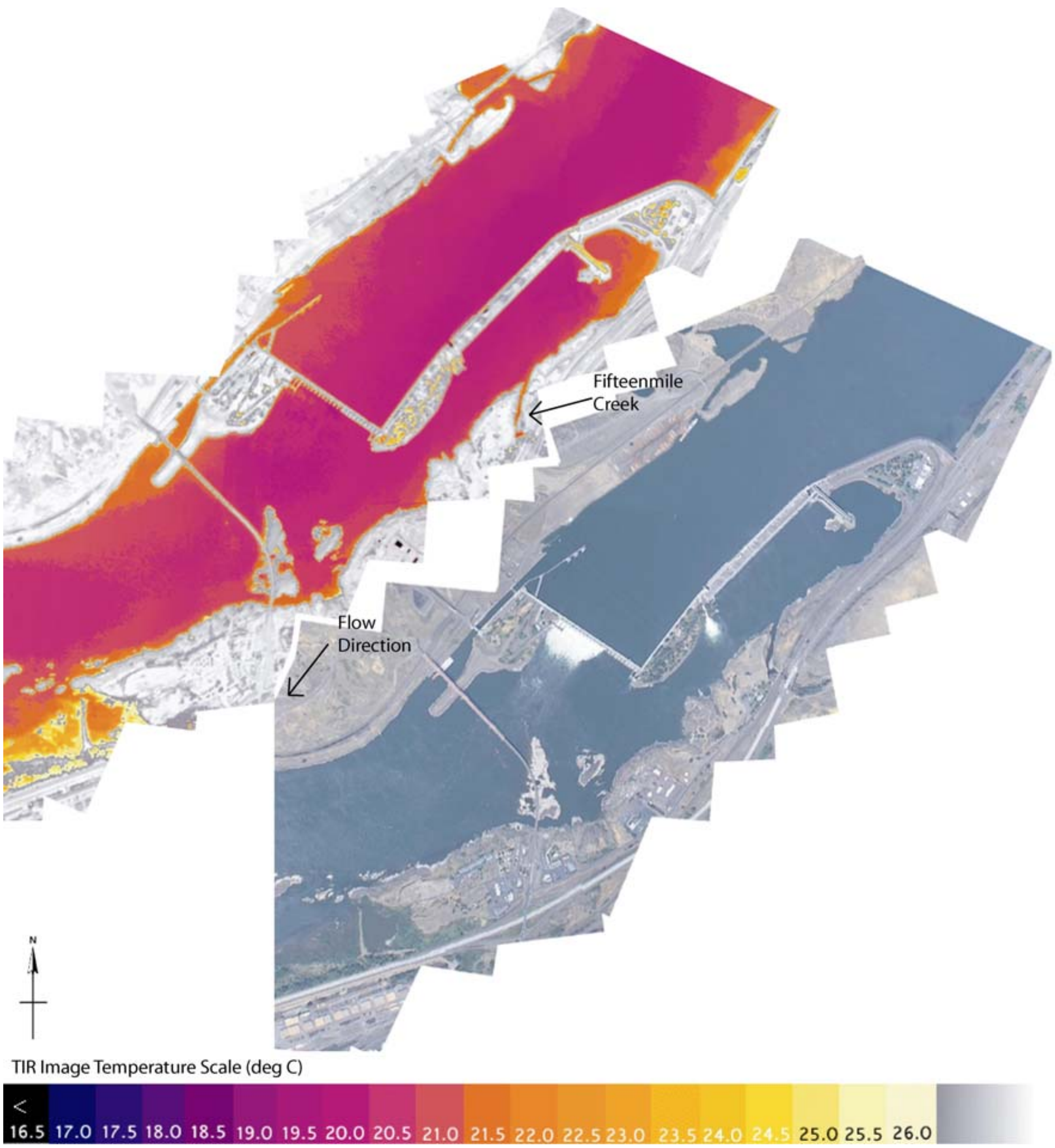


Figure 16 - TIR/color video image mosaic showing the Dalles Dam on the Columbia River at river mile 188. The image shows no significant temperature difference in surface temperatures in the pool upstream of the dam and the mixing area below the dam.

Discussion

TIR remote sensing surveys were successfully conducted on selected streams and rivers in the Fifteenmile Creek Watershed. 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. For example, when not detected directly as a surface spring, ground water influence is often inferred based on observed temperature patterns and general spatial associations to features presented on the 7.5' USGS topographic based maps (i.e. dry tributaries, springs, geomorphology, etc.). These hypotheses are considered a starting point for more rigorous spatial analysis and fieldwork. Individual TIR and color video image frames are organized in an ArcView database to allow viewing temperature patterns and channel characteristics at finer spatial scales.

Follow-on

The following is a list of potential uses for these data in follow-on analysis (based on Faux et. al. 2001 and Torgersen et. al. 1999):

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

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

Bibliography

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

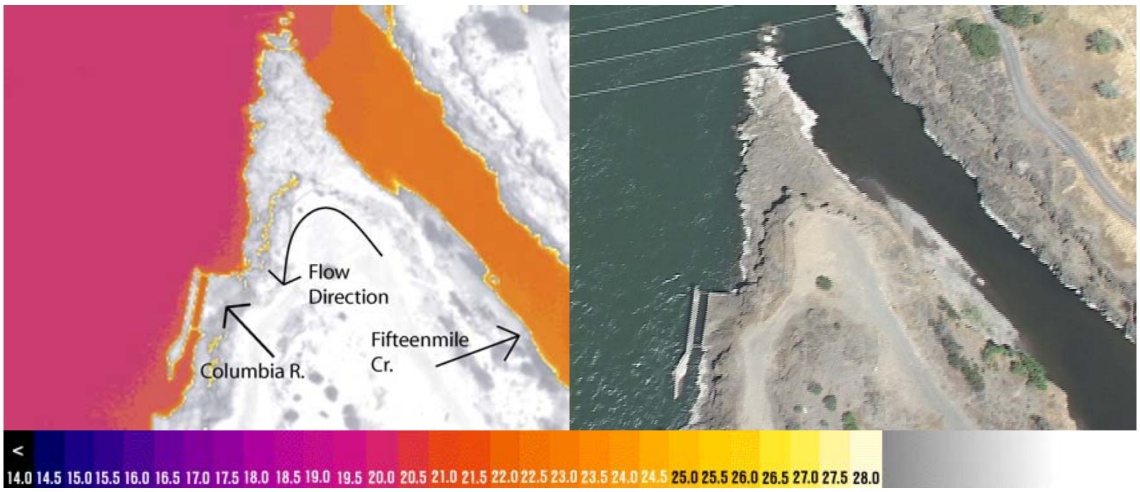
Torgersen, C., R. Faux, and B. McIntosh. 1999. **Aerial survey of the Upper McKenzie River: Thermal infrared and color videography**. Report to the USDA, Forest Service, McKenzie River Ranger District.

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

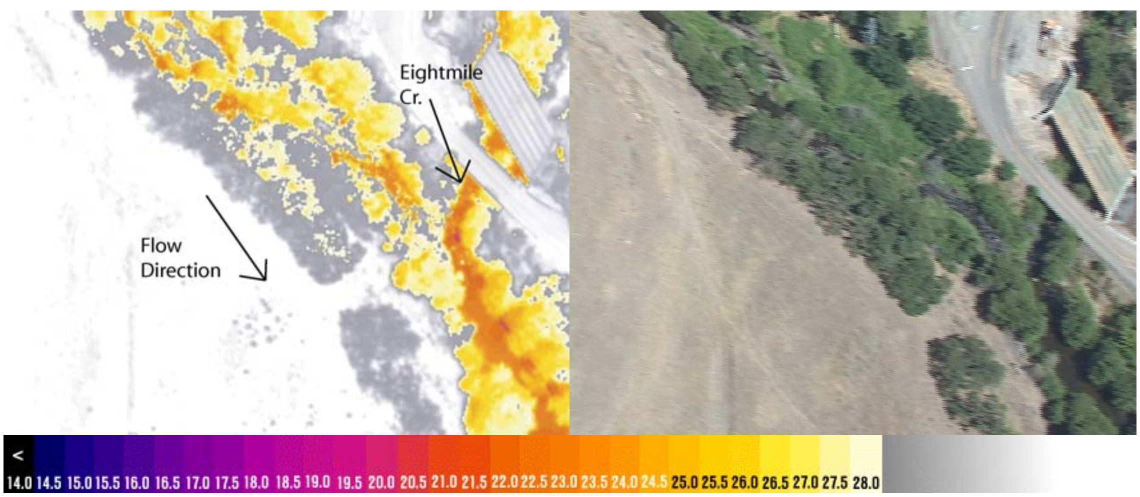
Appendix A – Selected Images

Selected Images from Fifteenmile Creek

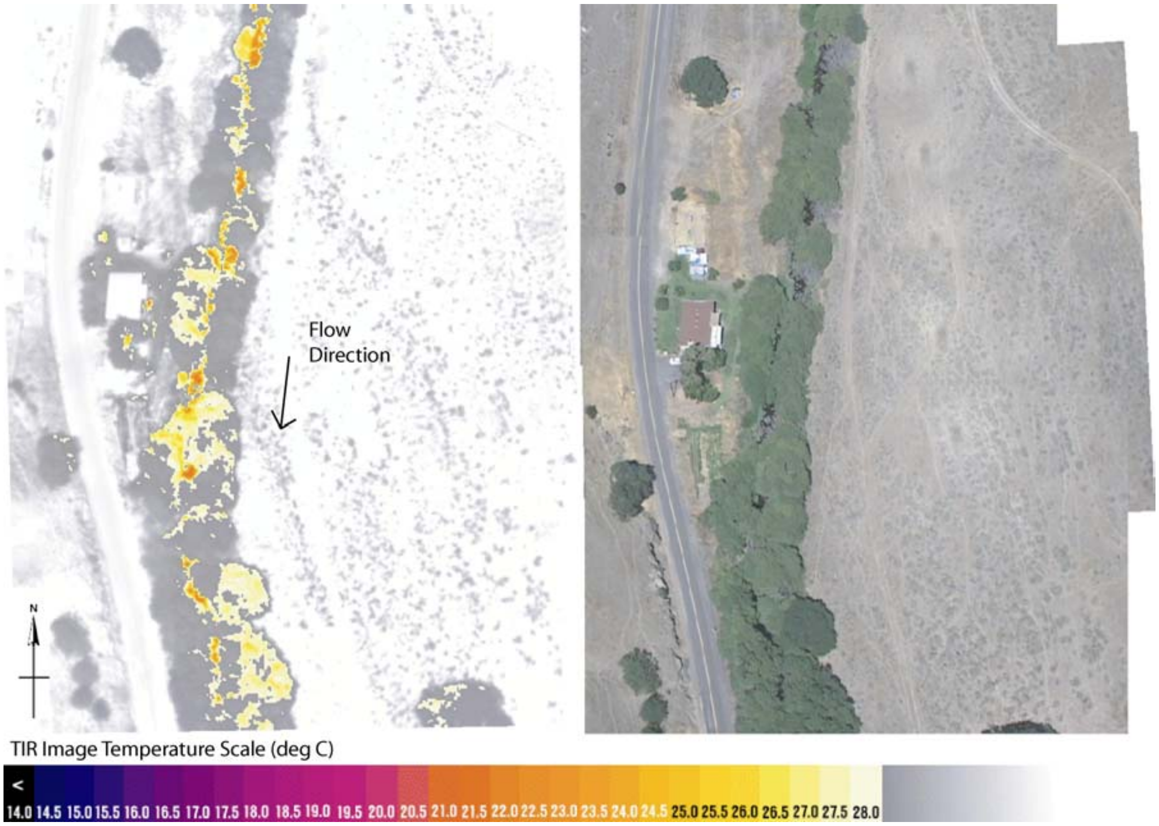
Note: Due to the wide range of temperatures observed on Fifteenmile Creek, two different color maps were applied to the thermal infrared (TIR) images. A 14-28^{o}C color map was applied to image frames fifm0008 to fifm2544. A 5-16^{o}C color maps was applied to images fifm2020 to fifm3688.



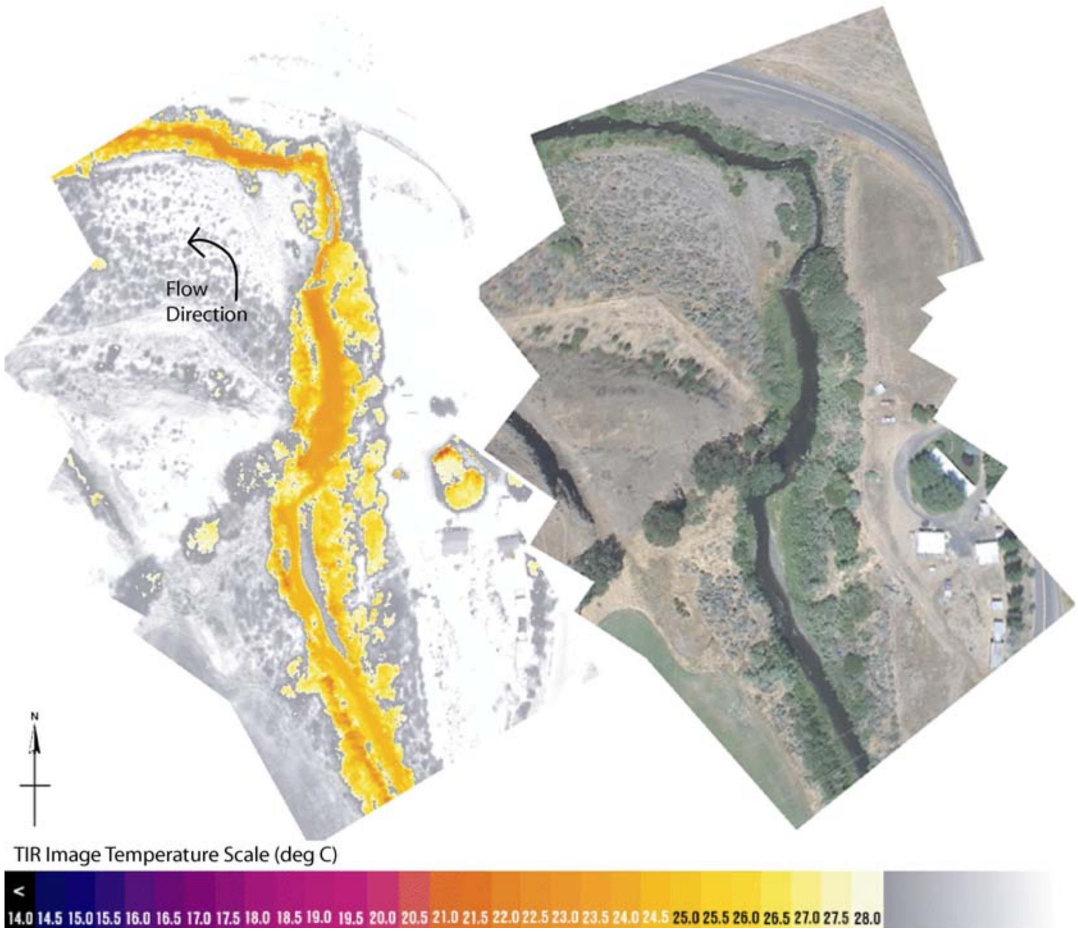
TIR/color video image pair showing the confluence of Fifteenmile Creek (21.4^{o}C) to the left bank of the Columbia River (19.9^{o}C) (*frame: fifm0019*).



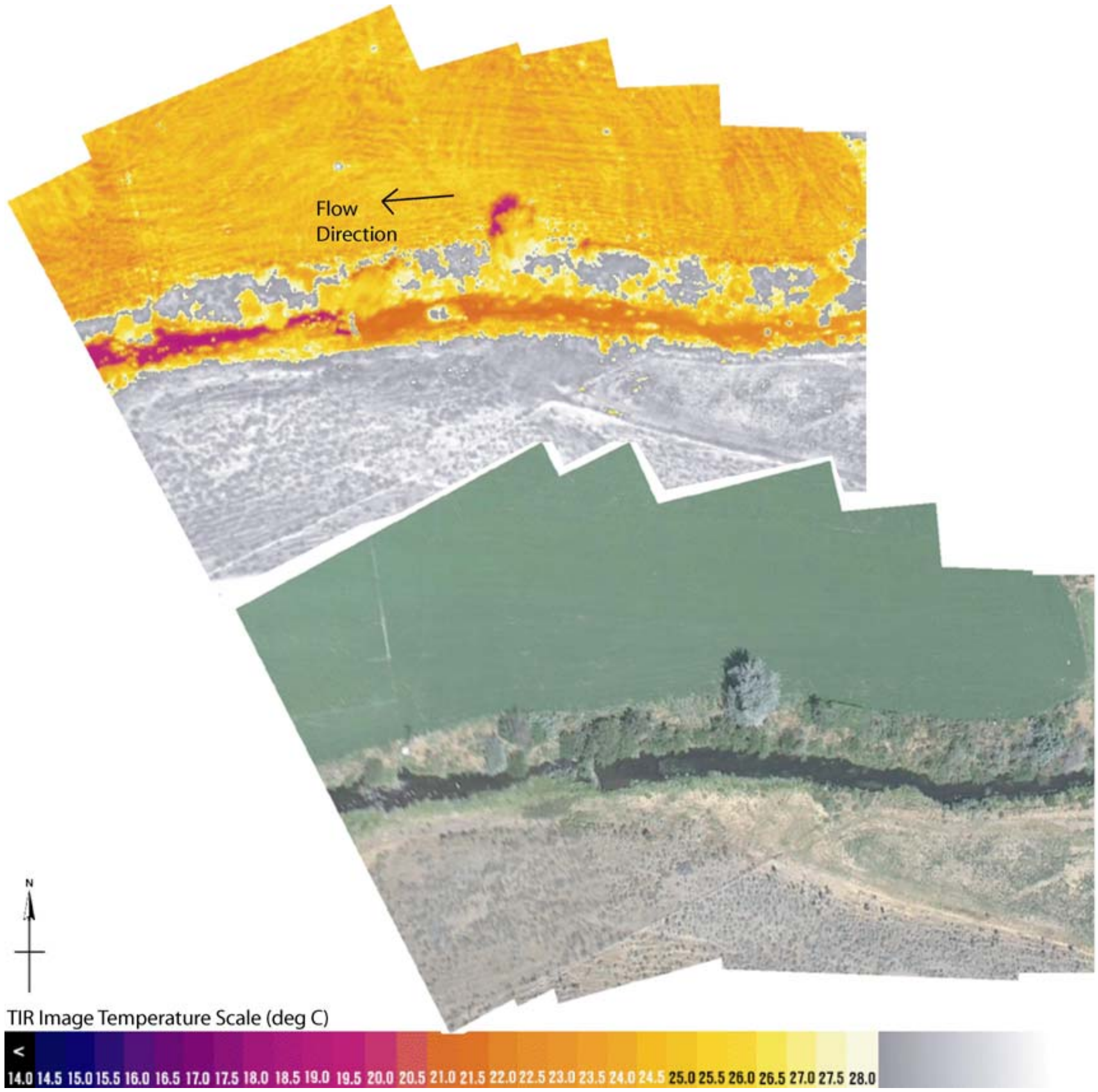
TIR/color video image pair showing the confluence of Eightmile Creek (21.2^{o}C) to the left bank of Fifteenmile Creek (21.7^{o}C) at river mile 2.6 (*frame: fifm0130*).



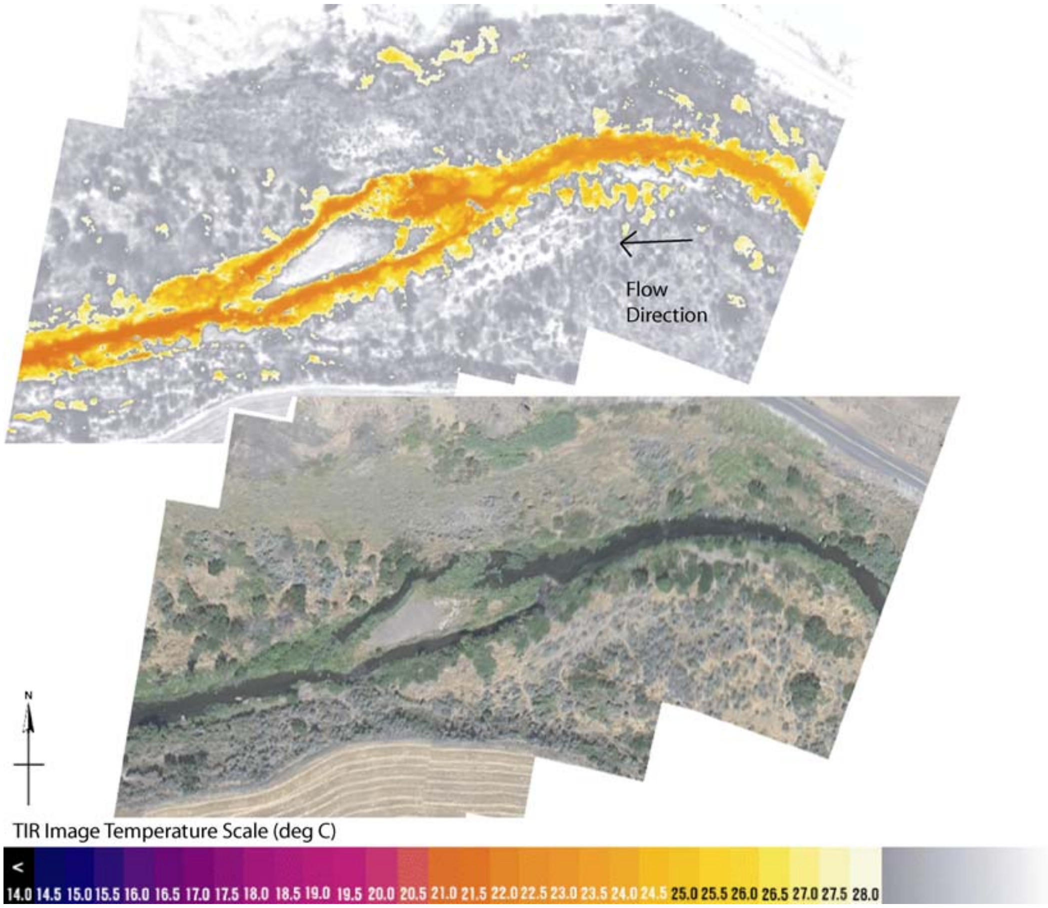
TIR/color video image pair showing a small reach of Fifteenmile Creek at river mile 3.5 which was too canopied to obtain a reliable temperature sample (*frames: fifm0178-0182*).



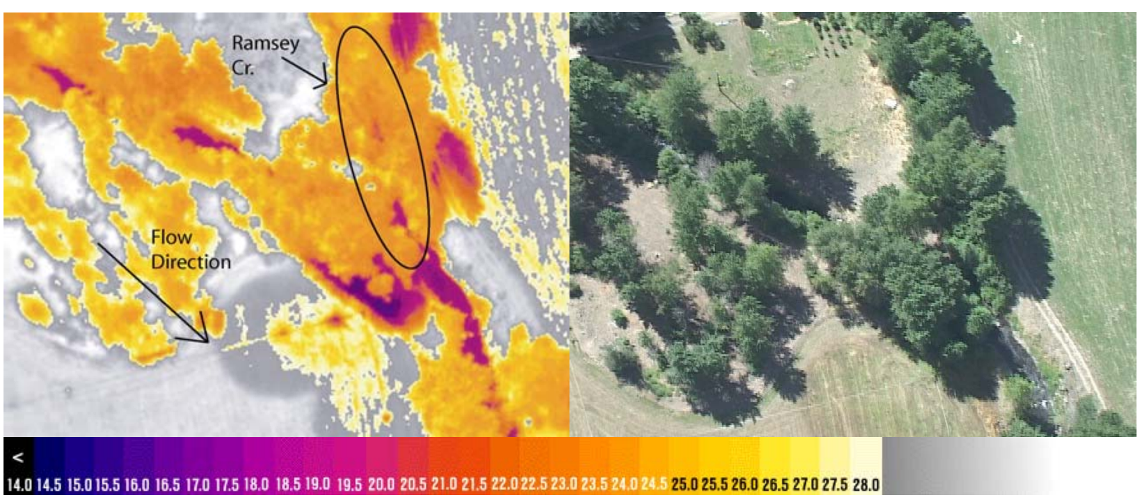
TIR/color video image pair showing a rapid change in temperature (24.2-22.6^{o}C) in Fifteenmile Creek moving in the downstream direction at river mile 5.6 (*frames: fifm0284-0289*).



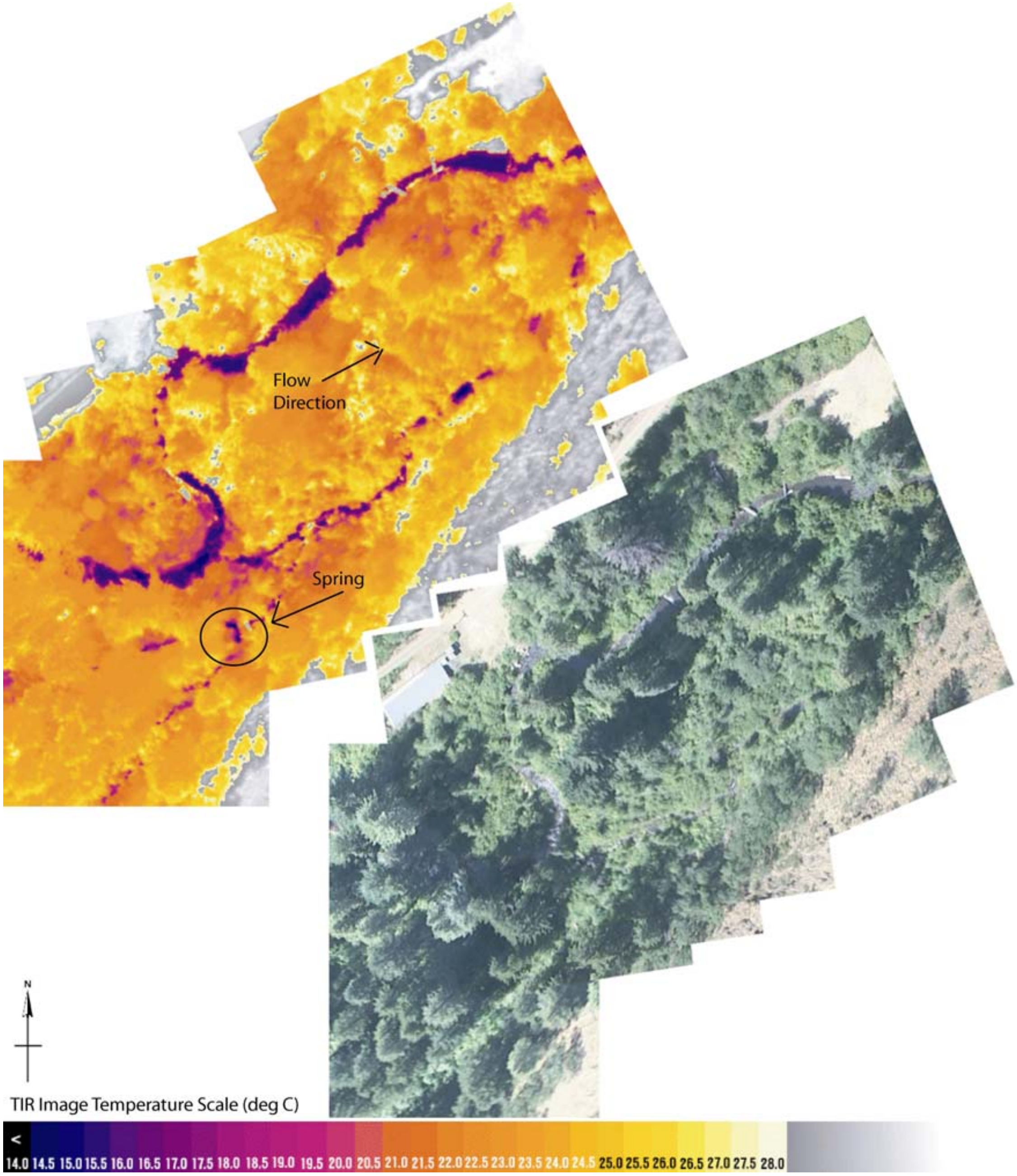
TIR/color video image pair showing a small dam in Fifteenmile Creek at river mile 7.4 Stream temperatures are 19.0°C downstream of the impoundment and 21.8°C upstream. Small barriers such as this account for much of the local thermal variability observed in Fifteenmile Creek. (*frame: fifm0378-fifm0384*)



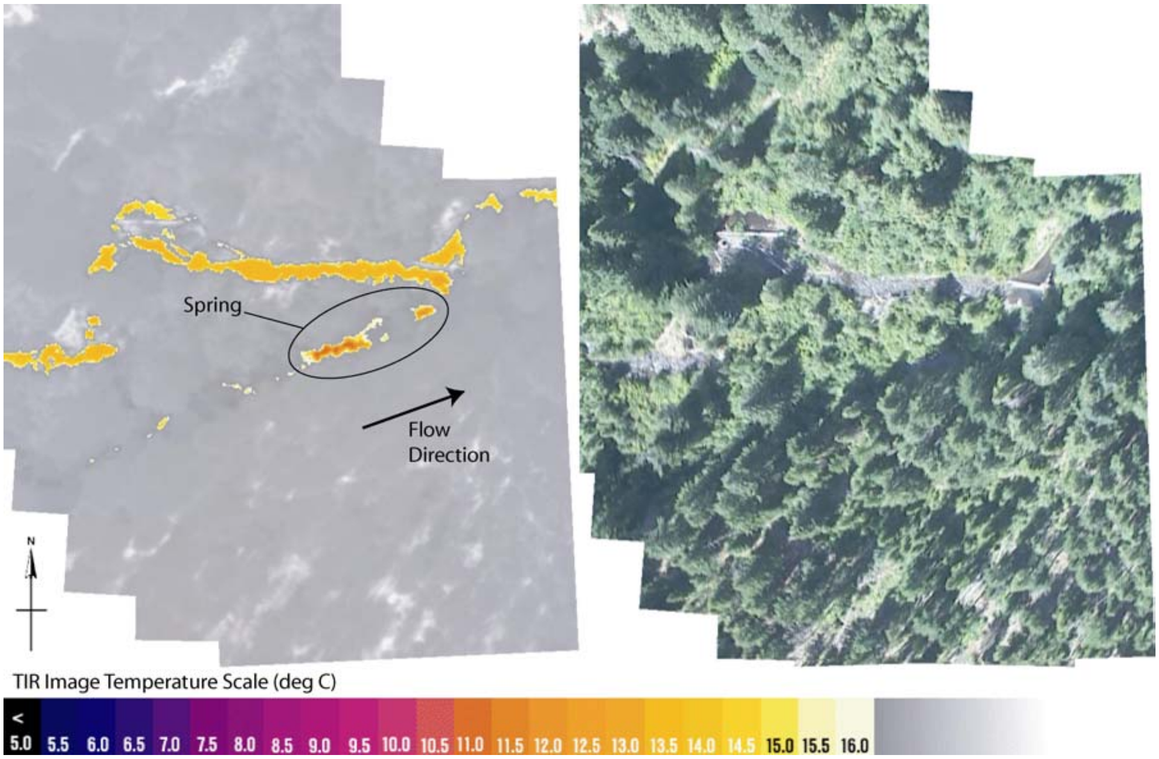
TIR/color video image pair showing Fifteenmile Creek at river mile 11.5. Stream temperatures show an apparent decrease of 1.9°C at this location. The source of cooling was not apparent from the imagery. (*Frame: fifm0593-600*)



TIR/color video image pair showing the confluence of Fifteenmile Creek (17.6°C) and Ramsey Creek at river mile 34.8. Riparian vegetation masked Ramsey Creek and precluded sampling temperatures at this location. (*Frame: fifm1818*)



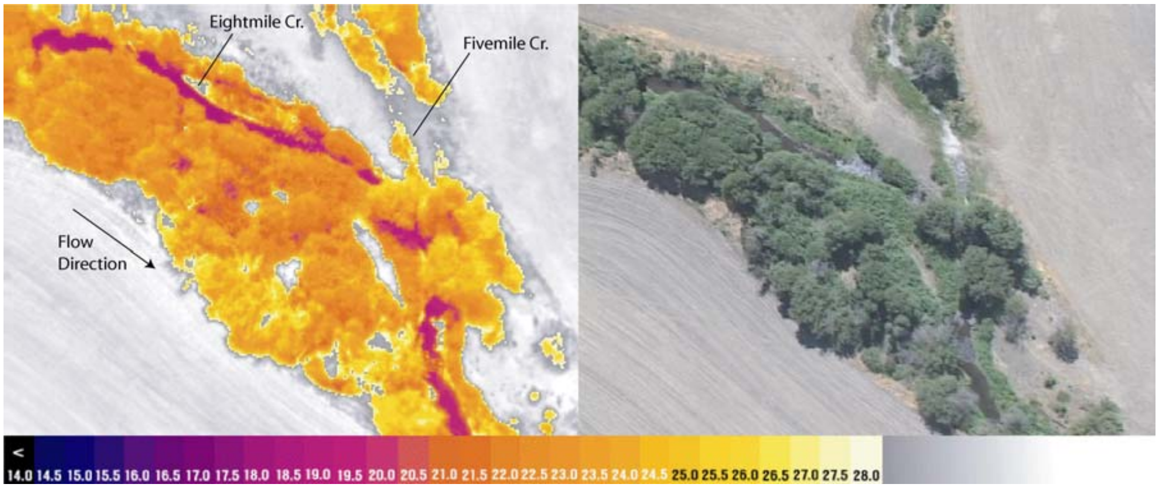
TIR/color video image pair showing the location of a possible spring or side channel (13.2^{o}C) on the right bank of Fifteenmile Creek (15.3^{o}C) at river mile 38.9 (*frames: fifm2050-2055*).



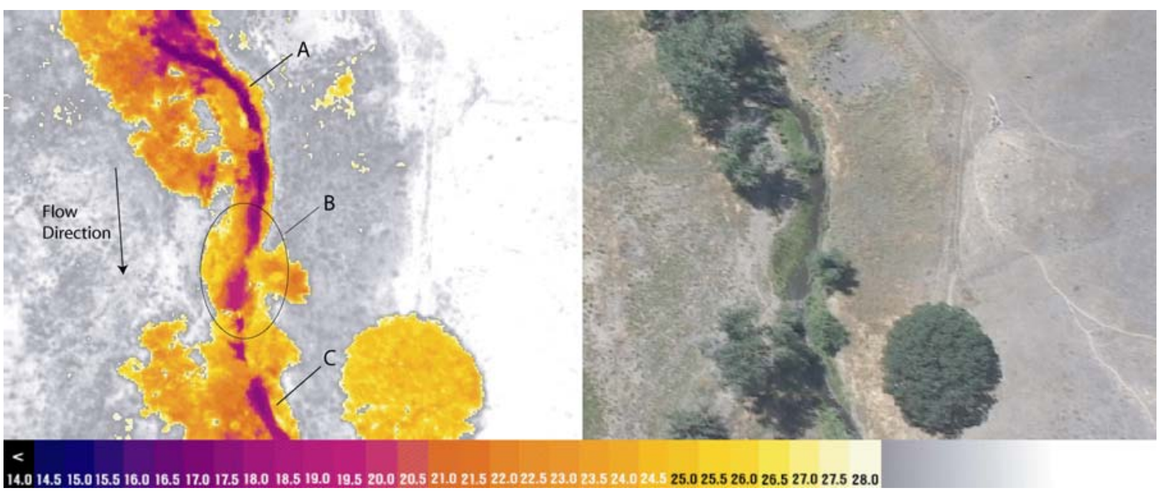
TIR/color video image pair showing a spring (12.2^{o}C) on the right bank of Fifteenmile Creek (13.2^{o}C) at river mile 43.4 (*frame: fifm2612-2616*).

Selected Images from Eightmile Creek

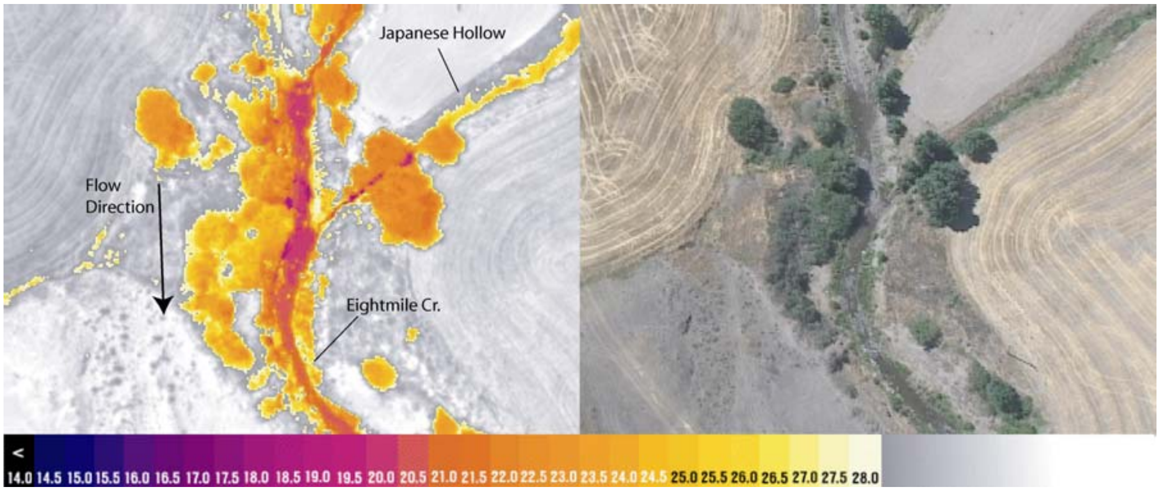
<u>Note:</u> As with Fifteenmile Creek, a wide range of water temperatures were observed on Eightmile Creek. Consequently two different color maps were applied to the thermal infrared (TIR) images. A 14-28°C color map was applied to image frames etm0077 to etm2893. A 5-16°C color maps was applied to images etm2240 to etm4725.



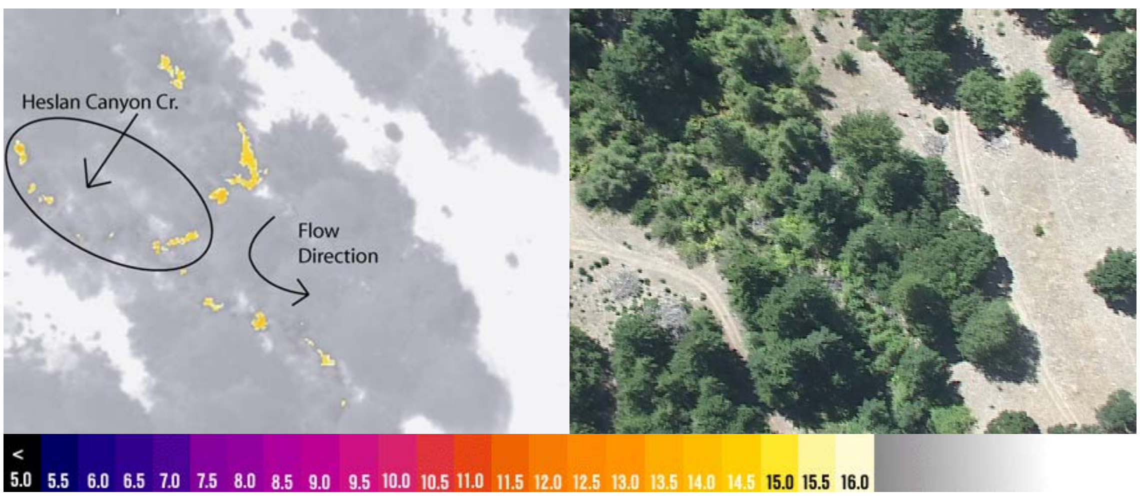
TIR/color video image pair showing the confluence of Eightmile Creek (18.4°C) and Fivemile Creek at river mile 1.4. Although surface water is visible in the Fivemile Creek channel, radiant temperatures were not sampled since there was very little thermal contrast between surface water and the surrounding vegetation. The median radiant temperature of the visible surface water is ≈24.0°C. (*frame: etm0239*)



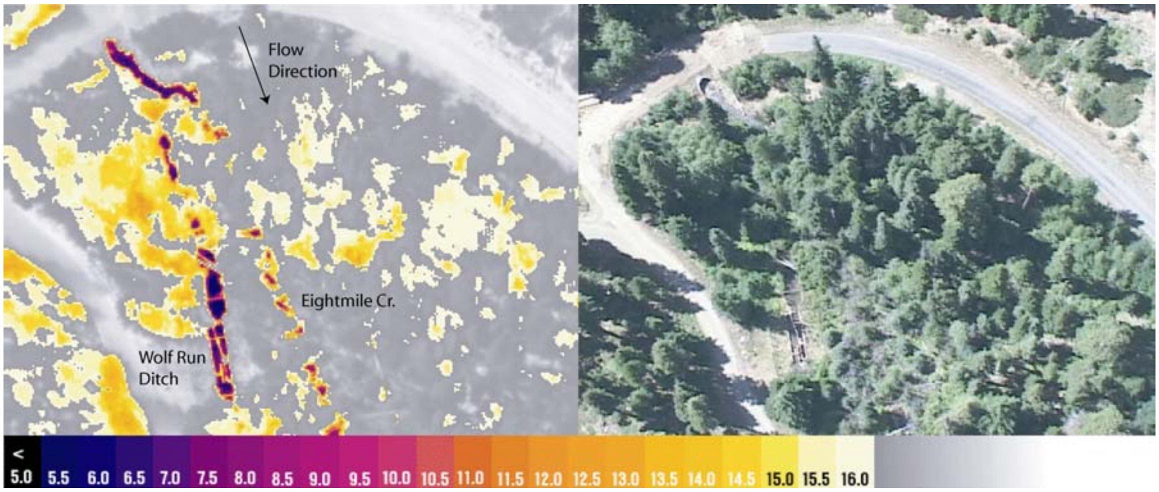
TIR/color video image showing Eightmile Creek (16.6°C) at river mile 6.5. The image pair is an example of the local spatial thermal variability observed at different points along Eightmile Creek. Radiant temperatures are ≈16.6°C at location “A”. A small impoundment is visible at the downstream end of Location “B” and the impoundment appears to cause some level of thermal stratification. Surface temperatures at Location “B” were ≈19.3°C. Downstream of the impoundment at Location “C” stream temperatures were ≈17.4°C. (*frame: etm0874*)



TIR/color video image pair showing the confluence of Eightmile Creek (19.8°C) and Japanese Hollow at river mile 9.1. The images some surface water is visible at the mouth of Japanese Hollow, but no surface water immediately upstream. The images also show channel conditions at this location.



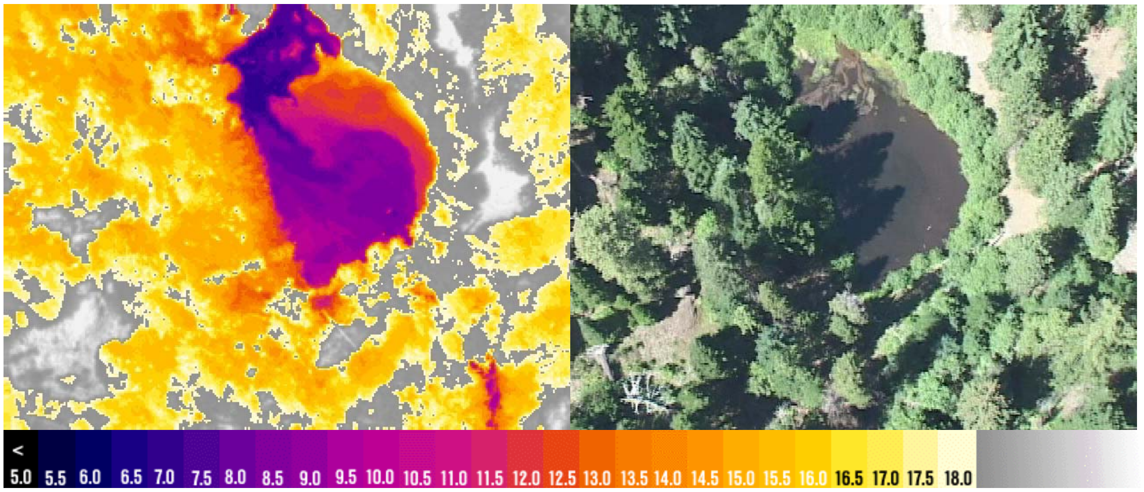
TIR/color video image pair showing the confluence of Heslan Canyon Creek to the right bank of Eightmile Creek (13.5°C) at river mile 21.9. This tributary was not sampled due to masking by the riparian canopy (*frame: etm3068*).



TIR/color video image showing the split of Eightmile Creek (6.4°C) and Wolf Run Ditch at river mile 29.1. (*frame: etm4053*)

Selected Images from Ramsey Creek

TIR/color video image showing Ramsey Creek (15.4°C) at river mile 0.1. The image pair is an example of how riparian vegetation masked the stream even in the lower reaches and surface water was visible only intermittently (*frame: ram0197*).



TIR/color video image showing a reservoir in Ramsey Creek at river mile 11.3. The outflow of the reservoir is mostly masked by riparian vegetation, but is visible near the bottom of the image. The TIR image shows the inflow to the lake ($\approx 7.0^{o}$C) and surface water temperatures on the lake surface. (*frame: ram1577*)