Aerial Surveys in the Wenatchee River Basin

Thermal Infrared and Color Videography

December 12, 2002

Report to:

Washington Department of Ecology
P.O. Box 47600,
Olympia, WA 98504-7600

by:

Watershed Sciences, LLC
230 SW Third, Suite 202
Corvallis, OR 97330

Preliminary Report

Table of Contents

Introduction

In 2002, the Washington Department of Ecology (DOE) contracted with Watershed Sciences, LLC (WS, LLC) to conduct airborne thermal infrared (TIR) remote sensing surveys within the Wenatchee River basin, WA. The objective of the project was to characterize the thermal regime of the selected river 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. TIR and associated color video images are included in the report in order to illustrate significant thermal features. An associated ArcView GIS[1] database includes all of the images collected during the survey and is structured to allow analysis at finer scales.

Methods

Data Collection

The TIR survey of the Wenatchee River was originally conducted on August 4, 2002. However, due to deteriorating weather conditions during the flight and due to unseasonably high in-stream flows, the TIR survey was repeated on August 16, 2002 between 14:20 and 16:49. The flight was timed to best capture maximum daily stream temperatures, which typically occur between 14:00 and 17:00. The survey included the Wenatchee River from its mouth upstream to Lake Wenatchee and Icicle Creek from its mouth upstream to Jack Creek, a total of 71.9 river miles (Figure 1).

WA DOE deployed seasonal data loggers at different points in the basin to continuously monitor stream temperatures. Nine of the WA DOE data loggers were used to ground truth (i.e. verify the accuracy) of the TIR data. The data loggers used to ground truth the TIR data were located approximately 10 river miles apart and provided coverage over the full extent of the survey (Figure 1). Meteorological data including air temperature, relative humidity, and wind speed were recorded by two WA Department of Transportation (DOT) weather stations located in the town of Cashmire and on Dryden Road.

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).

[1] Geographic Information System

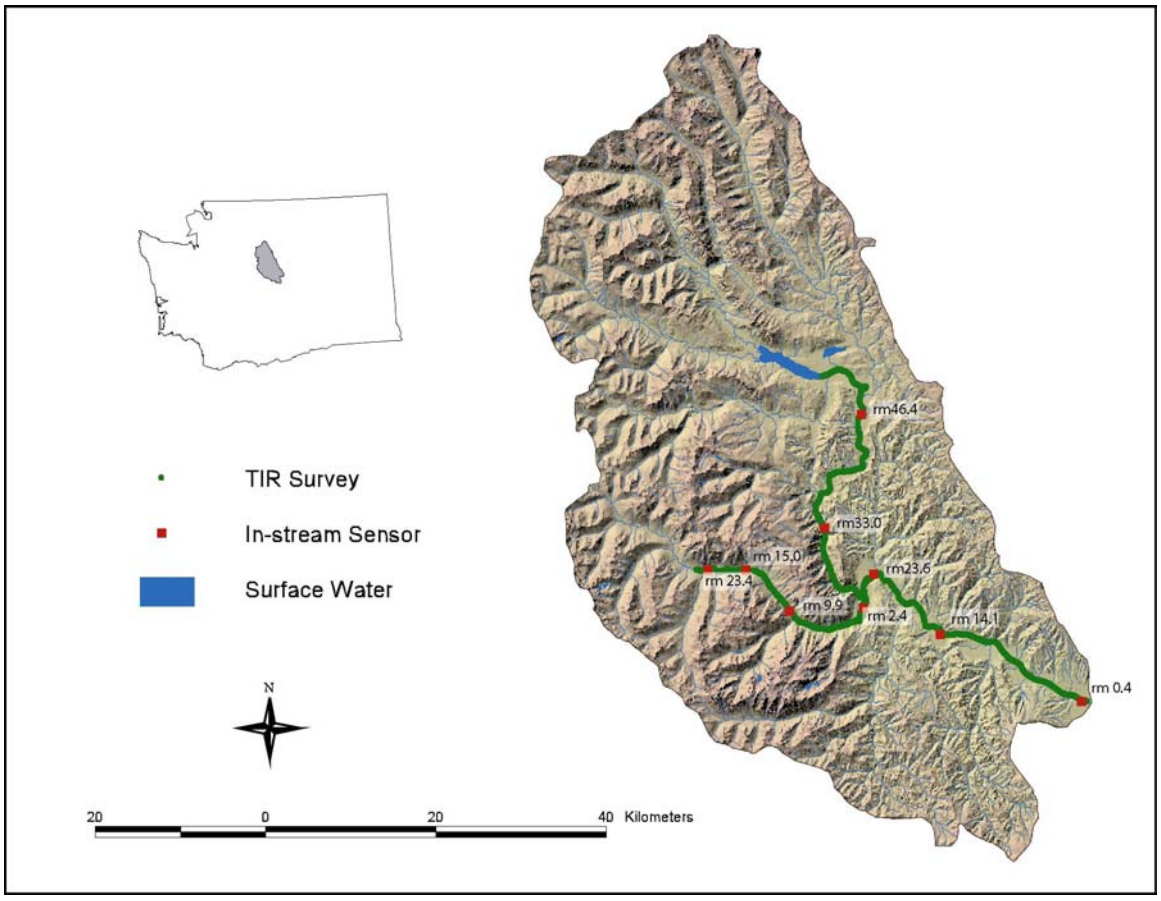


Figure 1 – Map showing the extent of the airborne TIR remote sensing survey conducted in the Wenatchee River basin on August 16, 2002. The map also shows the location of the in-stream sensors labeled by river mile (rm).

Table 1 – Meteorological conditions recorded at WA Department of Transportation weather station located in Cashmire, WA on August 16, 2002.

Time PST*	Temp °C	Temp °F	RH %	Wind Direction	Wind Speed Kts*	Wind Gust Kts*
13:10	29.4	84.9	14.9	172	8	16
14:10	29.4	84.9	9.8	185	13	17
15:10	29.4	84.9	10.2	178	11	16
16:10	30.0	86.0	11.7	166	11	16
17:10	29.4	84.9	13.2	168	9	13
18:10	28.3	82.9	12.4	182	10	13
19:10	24.4	75.9	26.3	0	0	0

*PST - pacific standard time; kts - knots

A consistent altitude above ground level was maintained in order to preserve the scale of the imagery throughout the survey. On the Wenatchee River, the ground footprint presented by a TIR image was approximately 325 m wide with a spatial resolution of 1.0 m. On Icicle Creek, the ground footprint presented by the TIR image was approximately 161 meters wide with a spatial resolution of 0.5 meters. The images were collected sequentially with approximately 40% vertical overlap.

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.

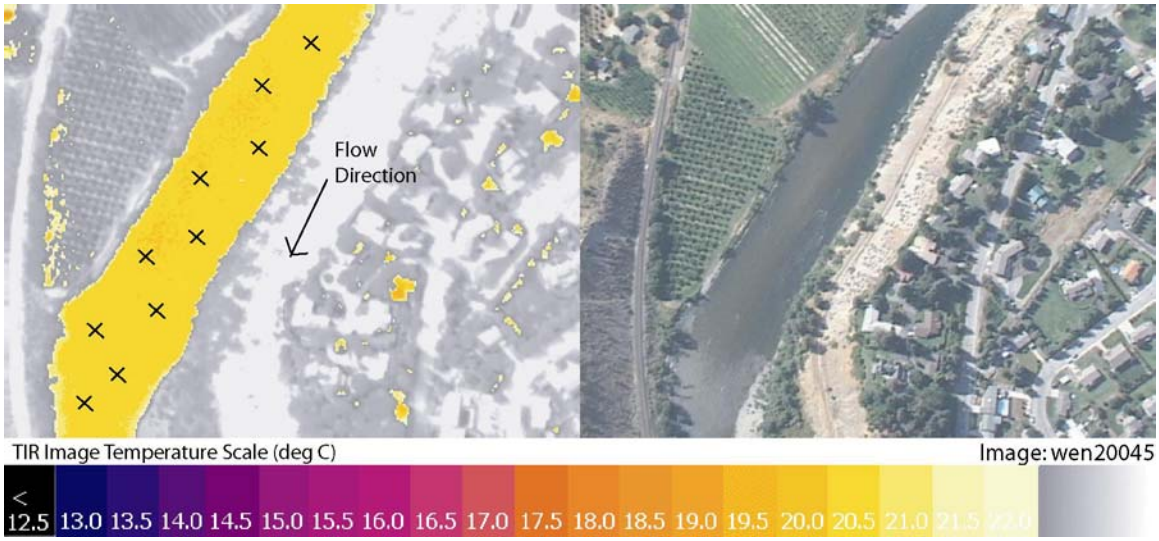


Figure 2 – TIR/color video image pair showing how temperatures are sampled from the TIR images. The black *X's* show typical sampling locations near the center of the stream channel. The recorded temperature for this image is the median of the sample points.

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 stratification was not considered a factor on the free flowing sections of the Wenatchee River and Icicle Creek. However, slight (< 0.7°C) differences in surface water temperatures were observed immediately upstream of impoundments at the Leavenworth Fish Hatchery (Figure 3).

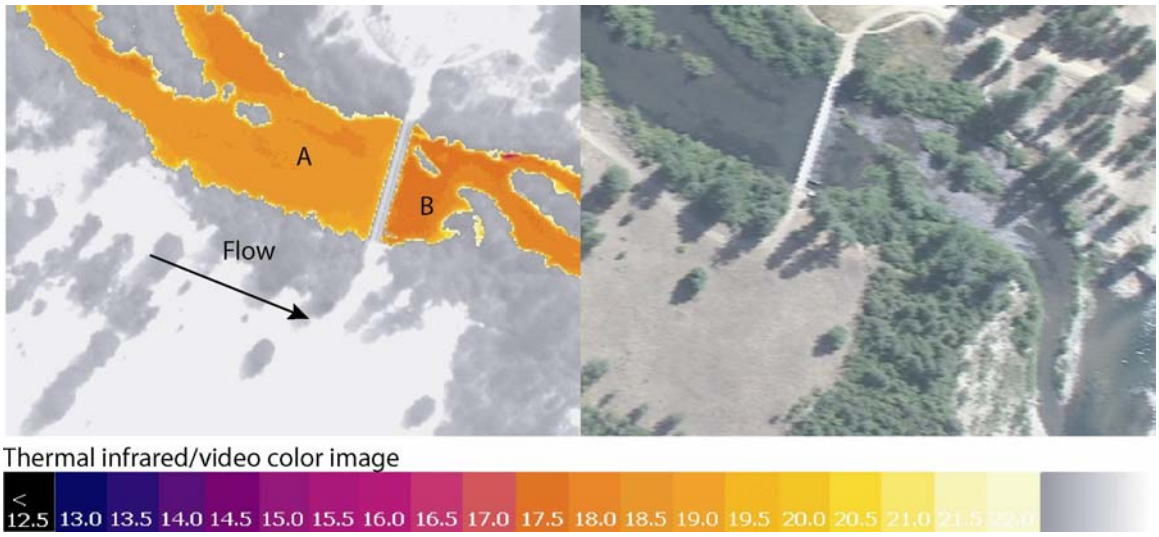


Figure 3 – TIR/color video image pair showing apparent thermal stratification upstream of an impoundment on Icicle Creek at river mile 2.9. Radiant water temperatures were 18.2°C upstream of the dam (*location A*) and 17.4°C downstream (*location B*).

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°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°C are not considered significant unless associated with a point source.

Results

Thermal Accuracy

Nine in-stream data loggers were used to calibrate and assess the accuracy of the TIR data collected on the Wenatchee River and Icicle Creek (Table 2). The 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. The parameters used to calibrate the TIR images were fined tuned to provide a best fit to the in-stream data. The five points on the Wenatchee River showed a range of differences of ±0.4^{o}C between the kinetic (in-stream) and calibrated radiant temperatures. The four points on Icicle Creek showed a range of differences of ±0.5^{o}C between the kinetic (in-stream) and calibrated radiant temperatures. The observed differences were within the desired accuracy for the TIR survey and were consistent with TIR surveys conducted in the Pacific Northwest over the past five years (Torgersen, 2001).

Table 2 – Comparison of ground-truth water temperatures with radiant temperatures derived from the TIR images, August 16, 2002.

Image	*River Mile*	*Time*	*In-Stream Temp ^{o}C*	*Radiant Temp ^{o}C*	*Difference*
Wenatchee River					
Wen21585	46.2	16:41	18.5	18.7	-0.2
Wen21112	33.2	16:25	18.7	18.4	0.3
Wen20736	23.7	16:11	18.4	18.8	-0.4
Wen20440	14.4	16:02	19.8	19.4	0.4
Wen20029	0.8	15:48	20.1	19.9	0.2
Icicle Creek					
Ice20871	17.6	14:50	15.2	14.7	0.5
Ice20708	14.5	14:46	14.8	14.4	0.4
Ice20468	9.5	14:38	16.1	15.8	0.3
Ice20122	2.4	14:25	16.4	16.9	-0.5

Temporal Differences

Figure 4 shows in-stream temperature variations at 2 locations during the TIR remote sensing survey. As illustrated, the Wenatchee River and Icicle Creek flights occurred prior to the recorded daily maximum stream temperature at these locations. In addition, stream temperatures remained relatively consistent at both locations over the time span of the survey.

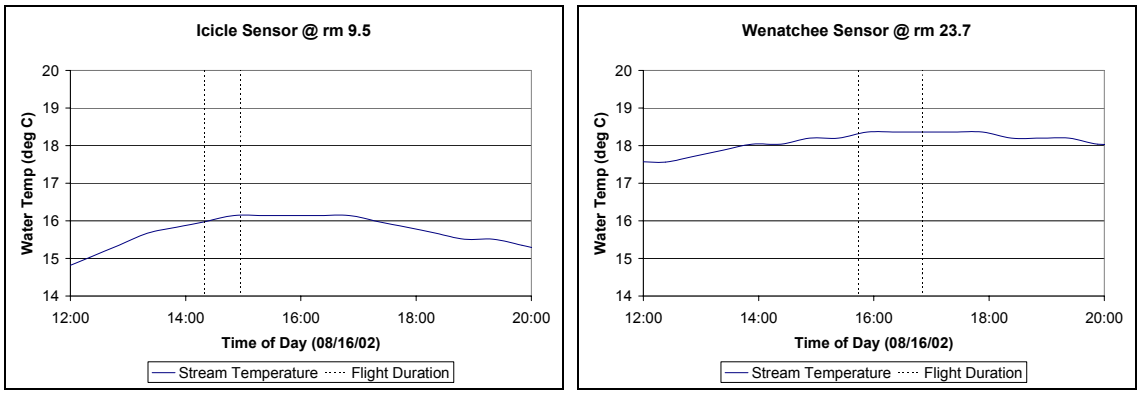


Figure 4 – Stream temperature variation and time of TIR remote sensing over flight for one location in each the Wenatchee River and Icicle Creek, WA (8/16/02).

Longitudinal Temperature Profiles

Wenatchee River

The median temperatures for each sampled image of the Wenatchee River were plotted versus the corresponding river mile (Figure 5). The plot also contains the median temperature of all surface water inflows (e.g. tributaries, surface springs, etc.) that were visible in the imagery. Tributaries are listed sequentially by river mile in Table 3.

At the outlet of Lake Wenatchee (river mile 53.5), stream temperatures were ≈17.6°C and increased steadily downstream reaching ≈19.0°C at river mile 48.9. Nason Creek was observed as a source of thermal loading within this segment. At river mile 48.1, the Chiwawa River contributed cooler water and lowered main stem temperatures by ≈0.6°C. From the Chiwawa River confluence downstream to river mile 24.4 (at the town of Leavenworth), radiant surface temperatures remained consistently between 18.1°C and 18.9°C. A total of 6 tributary and 4 spring inflows were sampled through this 23.7-mile reach and all were observed as cooling sources to the Wenatchee River. The detected spring inflows appeared to originate within the channel as flood plain spring brooks (Figure 6). The consistent temperatures and the detection of flood plain spring brooks suggest that sub-surface recharge within the channel flood plain may play a role in buffering stream heating processes between river miles 48.1 and 24.4. Stream temperatures begin to increase downstream of the town of Leavenworth reaching 20.3°C at river mile 9.8. The start of this warming reach roughly corresponds to the downstream end of the Tumwater Canyon. In the lower 9.8 miles, stream temperatures varied between 20.3°C and 19.7°C with a slight apparent decrease ≈0.7°C near the confluence with the Columbia River.

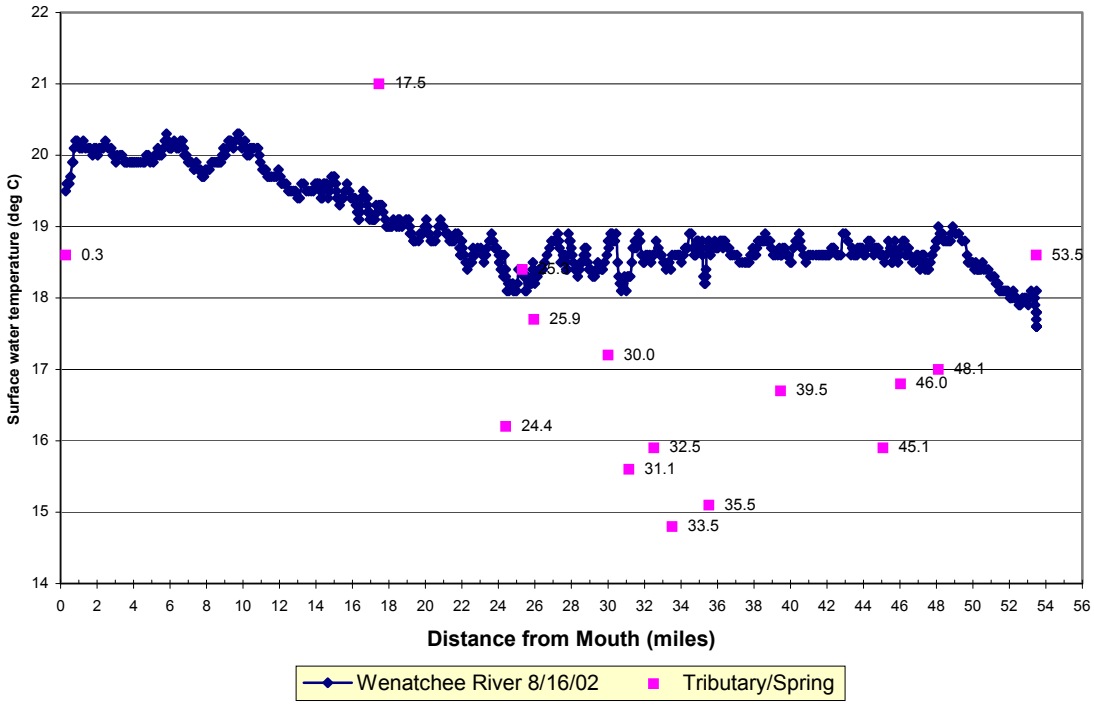


Figure 5 - Median channel temperatures versus river mile for the Wenatchee River, OR along with the location of detected inflows including tributaries.

Table 3 – Tributary temperatures for the Wenatchee River, WA. RB = Right Bank, LB = Left Bank looking downstream.

Tributary	Image	km	mile	Tributary °C	Wenatchee R. °C	Difference °C
Columbia River (LB)	Wen20017	0.5	0.3	18.6	19.5	-0.9
Peshastin Creek (RB)	Wen20542	28.1	17.5	21.0	19.3	1.7
Spring (LB)	Wen20805	39.3	24.4	16.2	18.4	-2.2
Icicle Creek (RB)	Wen20836	40.7	25.3	18.4	18.4	0.0
Icicle Canal (RB)	Wen20862	41.7	25.9	17.7	18.4	-0.7
Spring (RB)	Wen21000	48.3	30.0	17.2	18.8	-1.6
Cabin Creek (RB)	Wen21041	50.1	31.1	15.6	18.3	-2.7
Spring (RB)	Wen21095	52.3	32.5	15.9	18.6	-2.7
Unnamed (RB)	Wen21131	53.9	33.5	14.8	18.6	-3.8
Chiwaukum Cr. (RB)	Wen21213	57.2	35.5	15.1	18.8	-3.7
Spring (LB)	Wen21381	63.5	39.5	16.7	18.6	-1.9
Unnamed (RB)	Wen21553	72.5	45.1	15.9	18.6	-2.7
Beaver Creek (LB)	Wen21585	74.1	46.0	16.8	18.7	-1.9
Chiwawa River (LB)	Wen21646	77.4	48.1	17.0	19.0	-2.0
Nason Creek (RB)	Wen21801	86.1	53.5	18.6	17.7	0.9

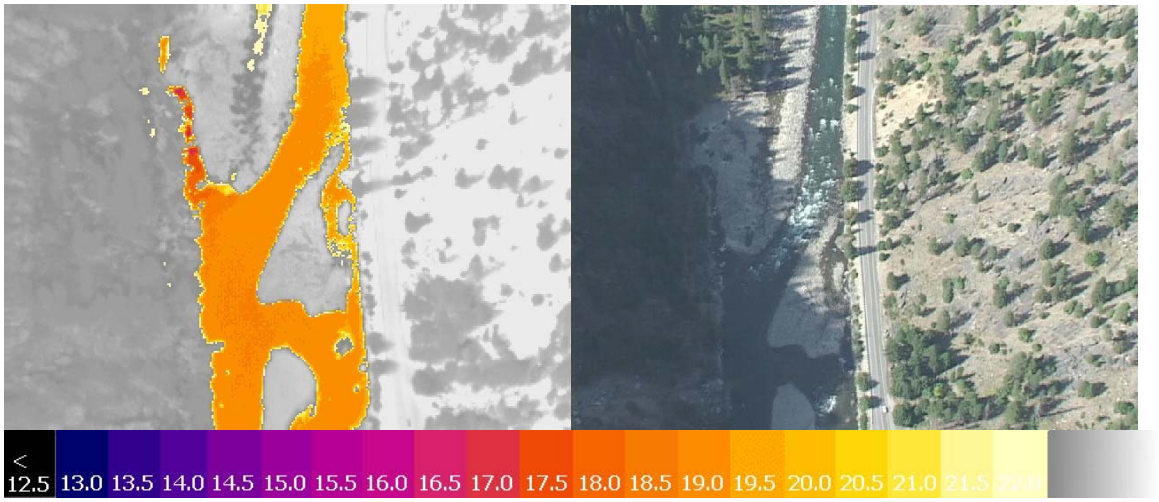


Figure 6 - TIR/color video image pair showing an apparent spring brook (17.2°C) along the right bank of Wenatchee River (18.8°C) at river mile 30.0. Flow direction is from the top to bottom of the image. *(frame: Wen21000).*

Icicle Creek

The median temperatures for each sampled image of the Icicle Creek were plotted versus the corresponding river mile (Figure 7). 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 are listed sequentially by river mile in Table 4.

At the upstream end of the survey near Jack Creek (river mile 17.6), stream temperatures in Icicle Creek were approximately 14.8°C at the time of the survey. Seven cool water inflows, including Jack Creek (Figure 8), were sampled within 1.5 miles downstream of the Jack Creek confluence. These sources contributed to an apparent decrease (-0.6°C) in main stem temperatures between river mile 17.6 and 16.1. Stream temperatures remained at ≈14.4°C over the next 1.7 miles before showing a consistent downstream increase between river miles 14.3 and 3.6. A total of 13 surface water inflows were detected through this 10.7-mile reach and 10 contributed cooler water to Icicle Creek. Five of the 13 inflows detected through this reach were identified as surface springs with four detected between river mile 11.9 and 12.5. Surface water temperatures increased rapidly on both branches of the diversion for the Leavenworth Fish Hatchery (river mile 3.6 to 2.8). The TIR imagery showed indicators of mild thermal stratification upstream of the impoundments on both channels around the hatchery (Figure 3). Stream temperatures dropped to ≈17.0°C downstream of the hatchery and then increased to ≈17.4°C at the mouth. Overall, stream temperatures in Icicle Creek increased by ≈3.0°C over the 18.5-mile survey with heating occurring primarily in the lower 14.4 stream miles.

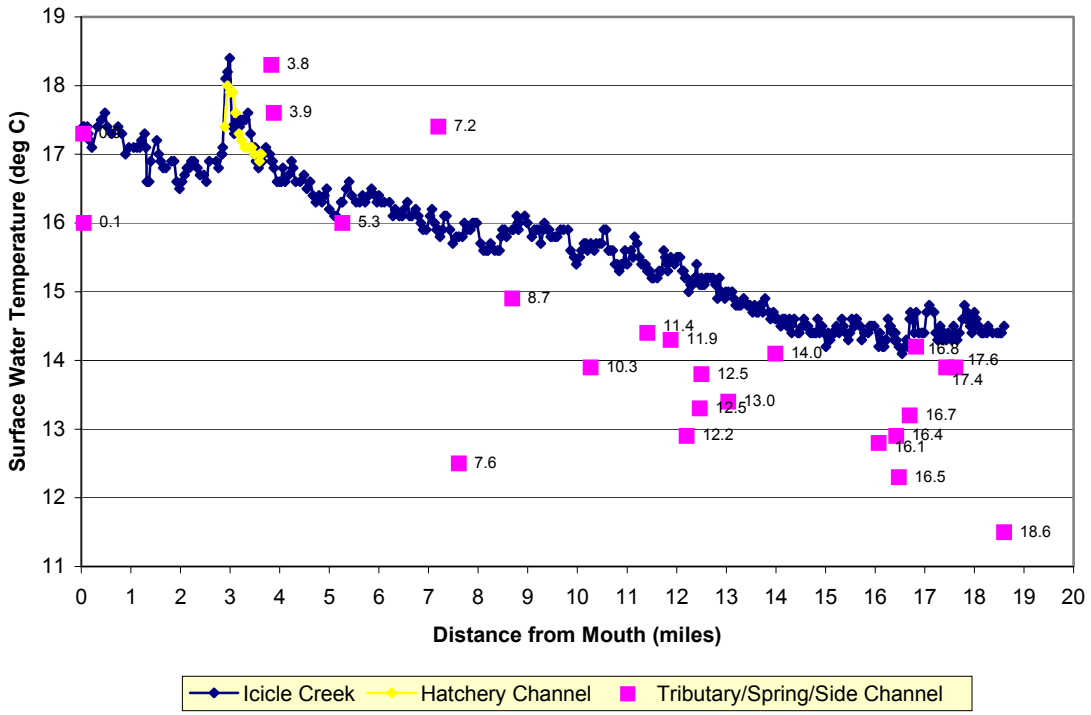


Figure 7 - Median channel temperatures versus river mile for Icicle Creek, WA along with the location of sampled inflows including tributaries, springs, and side channels.

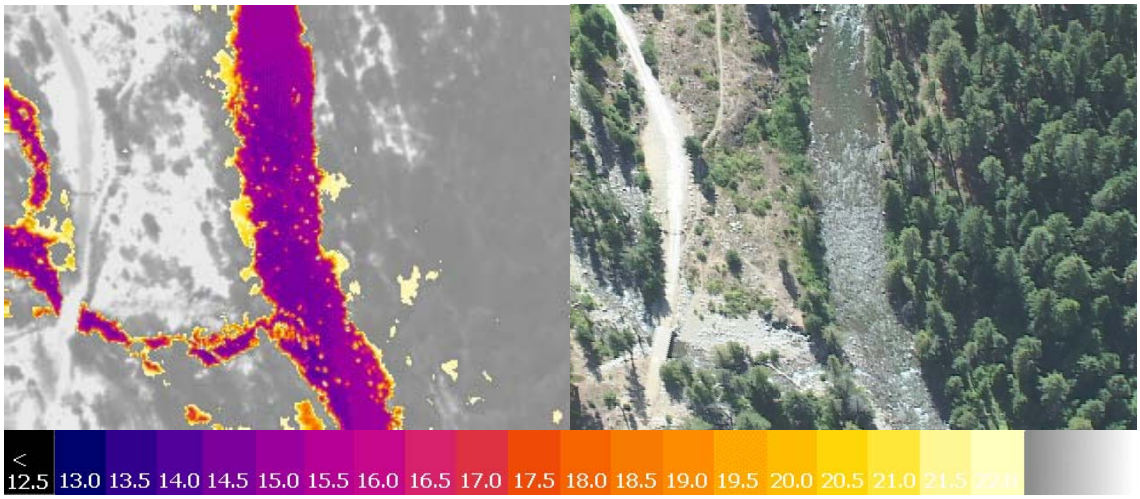


Figure 8 – TIR color video image showing the confluence of Icicle Creek (14.4°C) and Jack Creek (13.9°C) at river mile 17.6. Icicle Creek flows from the top to bottom of the image and Jack Creek flows in from the left side of the image.

Table 4 - Tributary temperatures for Icicle Creek, WA. RB = Right Bank, LB = Left Bank looking downstream.

Tributary	image	km	mile	Tributary °C	Icicle Cr °C.	Difference °C
Wenatchee River (LB)	ice20017	0.1	0.0	17.3	17.4	-0.1
Spring Brook (LB)	ice20018	0.1	0.1	16.0	17.4	-1.4
Side Channel (RB)	ice20233	6.2	3.8	18.3	16.9	1.4
Side Channel (LB)	ice20235	6.3	3.9	17.6	16.8	0.8
Snow Creek (RB)	ice20281	8.5	5.3	16.0	16.3	-0.3
Side Channel (RB)	ice20361	11.6	7.2	17.4	15.9	1.5
Rat Creek (RB)	ice20379	12.3	7.6	12.5	15.8	-3.3
Mountaineer/Eightmile Creek (RB)	ice20428	14.0	8.7	14.9	15.9	-1.0
Unnamed (RB)	ice20501	16.5	10.3	13.9	15.7	-1.8
Unnamed (RB)	ice20554	18.4	11.4	14.4	15.3	-0.9
Spring (LB)	ice20577	19.1	11.9	14.3	15.5	-1.2
Spring (RB)	ice20595	19.6	12.2	12.9	15.2	-2.3
Spring (LB)	ice20609	20.1	12.5	13.3	15.1	-1.8
Spring (RB)	ice20611	20.1	12.5	13.8	15.2	-1.4
Jay Creek (LB)	ice20638	21.0	13.0	13.4	15.0	-1.6
Spring (RB)	ice20684	22.5	14.0	14.1	14.6	-0.5
Chatter Creek 2 (LB)	ice20789	25.9	16.1	12.8	14.2	-1.4
Chatter Creek 1 (LB)	ice20814	26.4	16.4	12.9	14.3	-1.4
Spring (RB)	ice20816	26.5	16.5	12.3	14.2	-1.9
Trout Creek (RB)	ice20827	26.9	16.7	13.2	14.6	-1.4
Side Channel/Jack Creek (RB)	ice20834	27.1	16.8	14.2	14.7	-0.5
Spring (RB)	ice20861	28.1	17.4	13.9	14.3	-0.4
Jack Creek (RB)	ice20975	28.4	17.6	13.9	14.4	-0.5
Spring (RB)	ice21035	29.9	18.6	11.5	14.5	-3.0

Discussion

A TIR remote sensing survey was successfully conducted on the Wenatchee River and Icicle Creek in the Wenatchee River basin, WA. 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. Point pattern maps are another method of visualizing spatial temperature patterns along the stream gradient (Figure 9). Individual TIR and color video image frames organized in an ArcView allow viewing temperature patterns and channel characteristics at finer spatial scales.

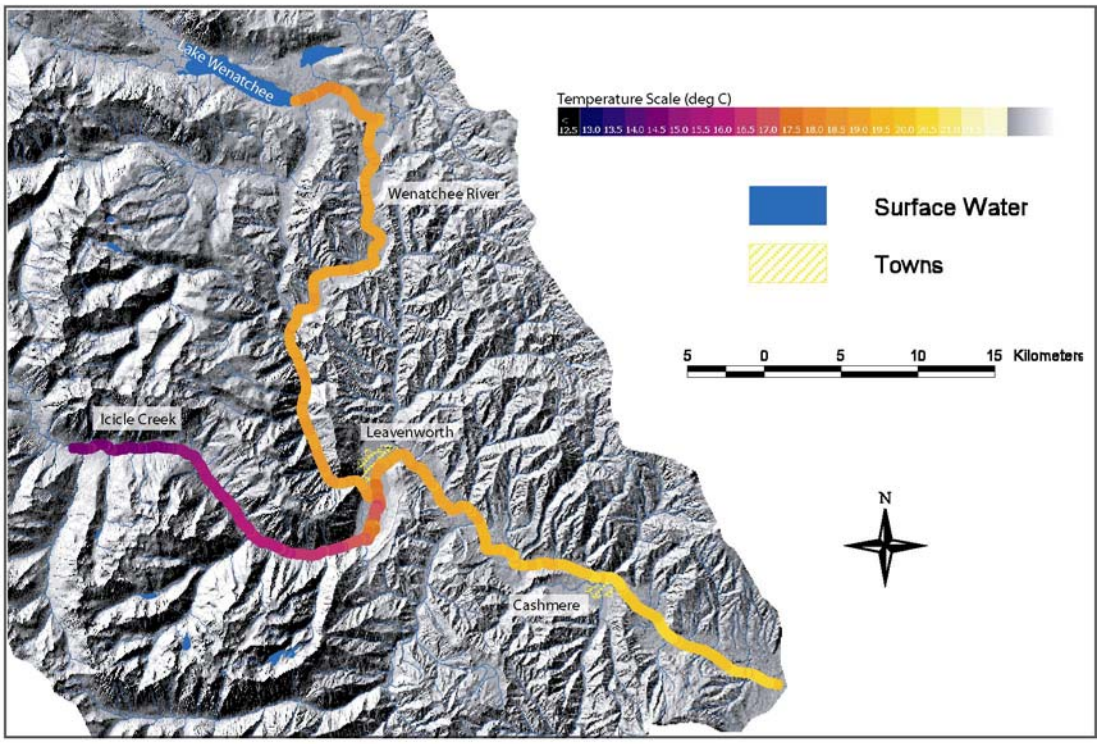


Figure 9 - Point pattern map showing median stream temperatures at the time of the TIR survey layered over a shaded relief map (based on 10 meter digital elevation model (DEM)) of the basin. The map also shows the location of tributary and spring inflows sampled during the analysis.

On August 13, 2001, a TIR remote sensing survey was conducted on the Wenatchee River from river mile 23.2 upstream to Lake Wenatchee (WS, LLC, 2001). A comparison of the longitudinal temperature profiles between the two years provides additional insights into the river's thermal regime (Figure 10). From the Chiwawa River confluence downstream to Jolanda dam, absolute stream temperatures were on average 2.2^{o}C warmer on the day of the 2001 survey. However, the spatial temperatures were consistent between years with no (*detectable*) net temperature increases occurring either

year. The 2001 TIR data showed a higher degree of local variability (±0.7°C) through this reach than did the data from the 2002 survey (±0.5°C). The most obvious difference is downstream of Jolanda Dam. The 2001 TIR survey showed an increase in stream temperature between river mile 29.2 and 23.2 that was not recorded in the 2002 survey.

TIR surveys conducted in consecutive years in other basins have shown that, while absolute temperatures changed, spatial patterns of warming and cooling remain consistent between years. The increased longitudinal heating downstream of the dam suggests a difference in the relative flow (above and below the dam) between years. Follow-on analysis should confirm the increase in stream temperature in 2001 using in-stream data. In addition, the follow-on analysis should examine the in-stream flow levels through this reach between years to determine the influence (if any) that Jolanda Dam has on downstream flow levels in the Wenatchee River. The increased local spatial variability in 2001 is also consistent with lower in-stream flow rates.

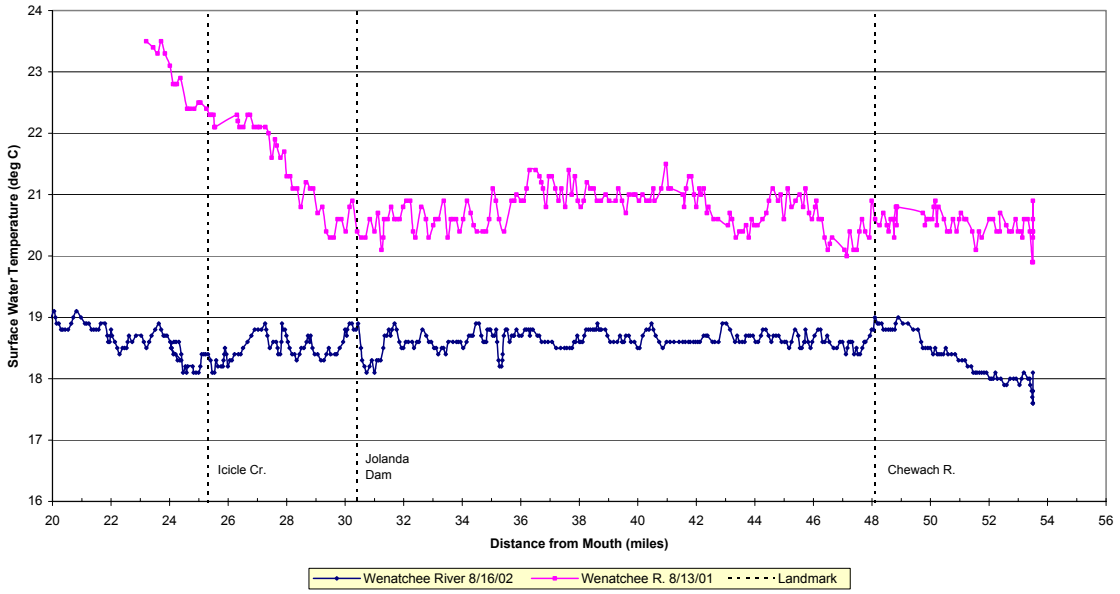


Figure 10 – Comparison of stream temperature patterns measured during TIR remote sensing surveys conducted on August 13, 2001 and August 16, 2002. The plot also shows the location of landmark features in the basin.

Comparison surface temperatures from the TIR images and kinetic temperatures recorded by in-stream data loggers showed that the radiant temperatures were within ±0.5°C, which was the specified tolerance for the survey. The in-stream data provide also provides a temporal context for assessing the spatial temperature patterns (Figures 11 and 12). On the Wenatchee River, the TIR flight was consistent with the recorded daily maximum temperatures. On Icicle Creek, the TIR flight was conducted prior to the daily maximum temperatures recorded at three of the four in-stream locations.

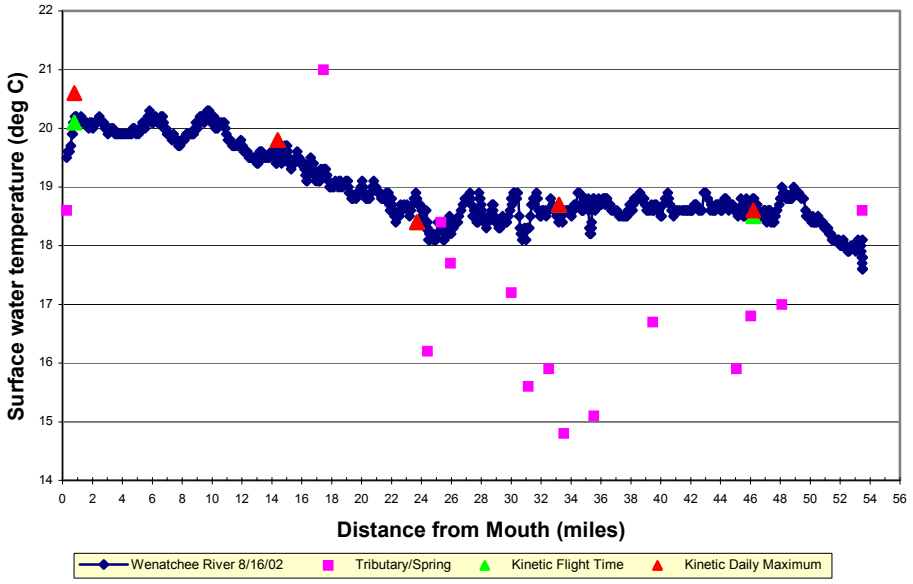


Figure 11 – Median temperatures of the Wenatchee River versus river miles. The plot shows location of in-stream sensors used to calibrate the TIR images with the recorded in-stream (kinetic) temperature at the time of the survey and recorded maximum temperature.

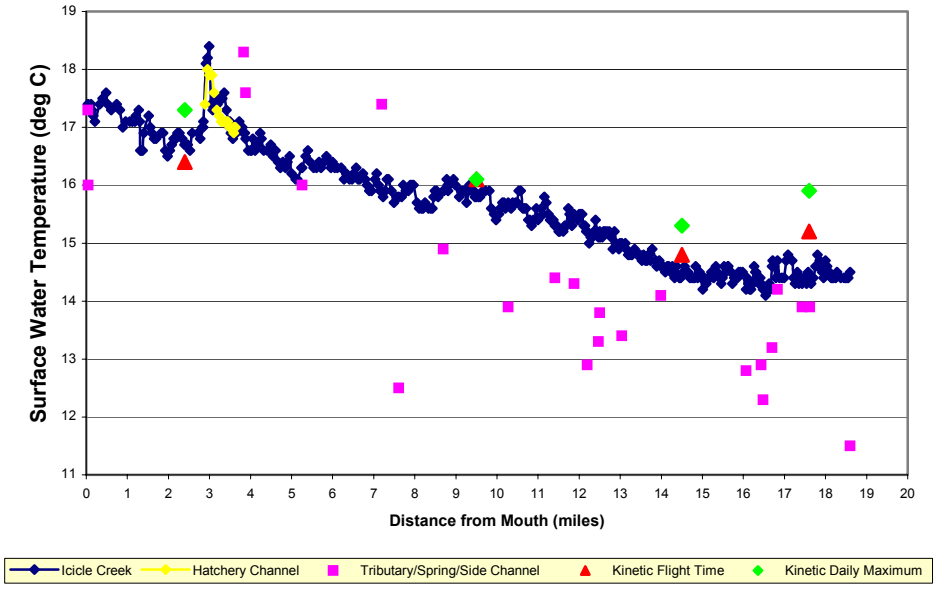


Figure 12 – Median temperatures of the Icicle Creek versus river miles. The plot shows location of in-stream sensors used to calibrate the TIR images with the recorded in-stream (kinetic) temperature at the time of the survey and recorded maximum temperature.

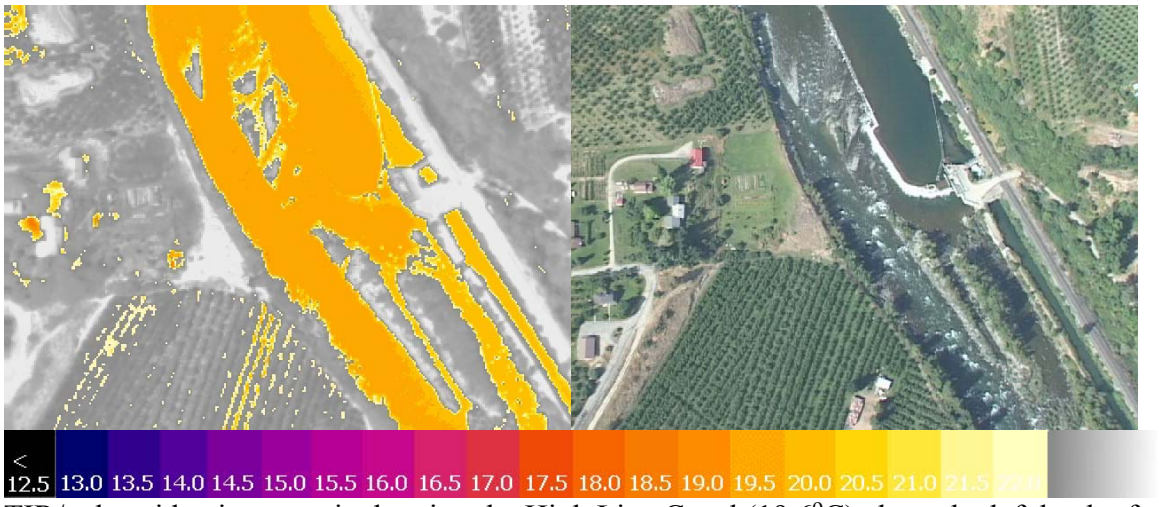
Bibliography

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.

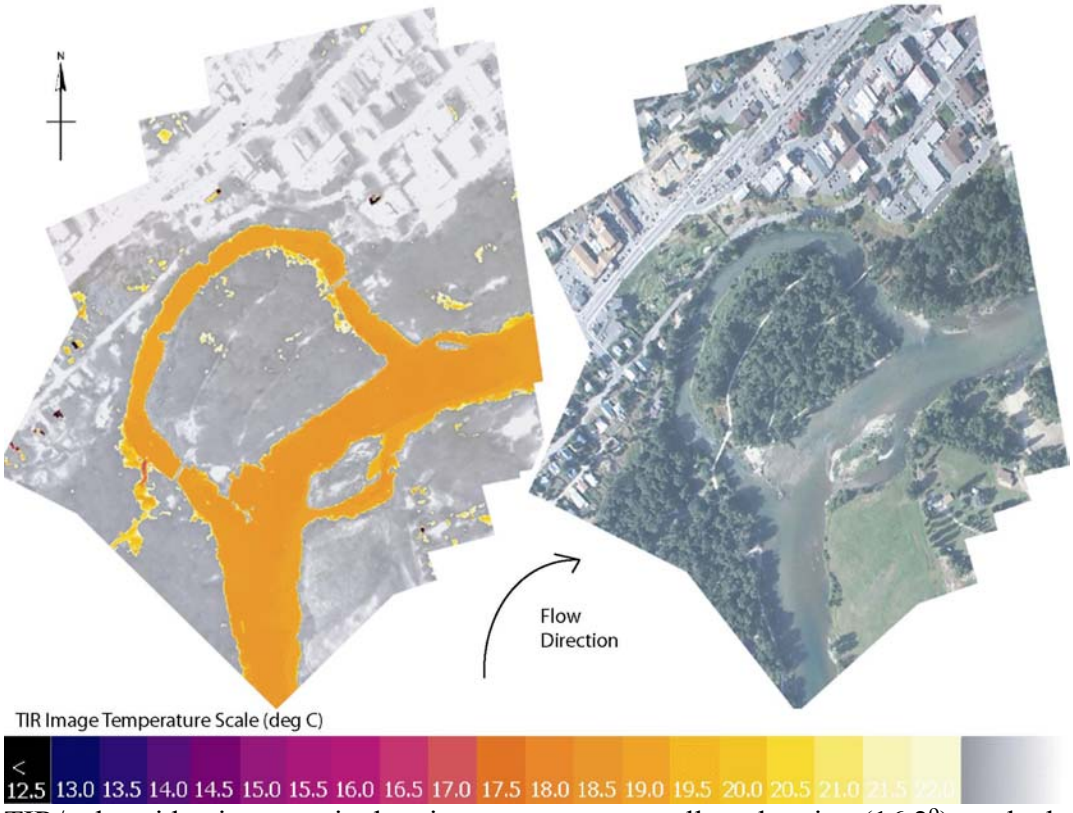
WS, LLC. 2001. *Aerial Remote Sensing Surveys in the Methow, Entiat, and Wenatchee River Sub-Basins Thermal Infrared and Color Videography*. Report to Pacific Watershed Institute, Olympia, WA

Appendix A – Selected Images

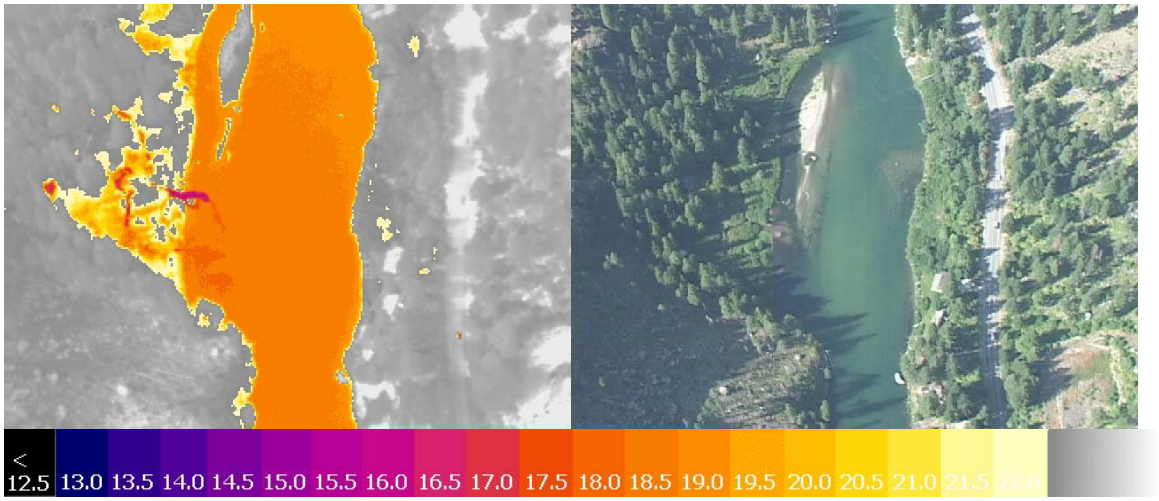
Wenatchee River



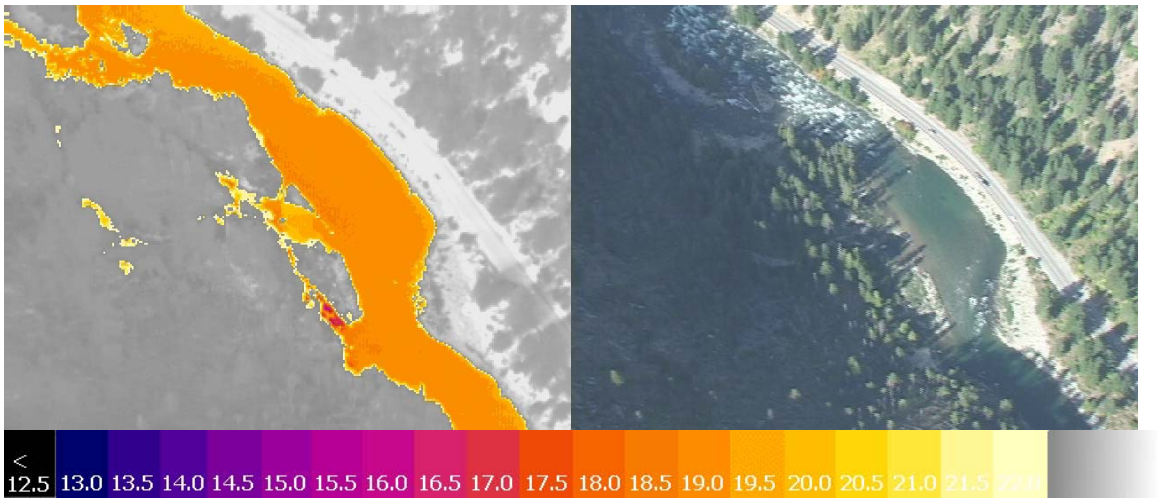
TIR/color video image pair showing the High Line Canal (19.6°C) along the left bank of Wenatchee River (19.1°C) at river mile 17.2 *(frame: Wen20533).*



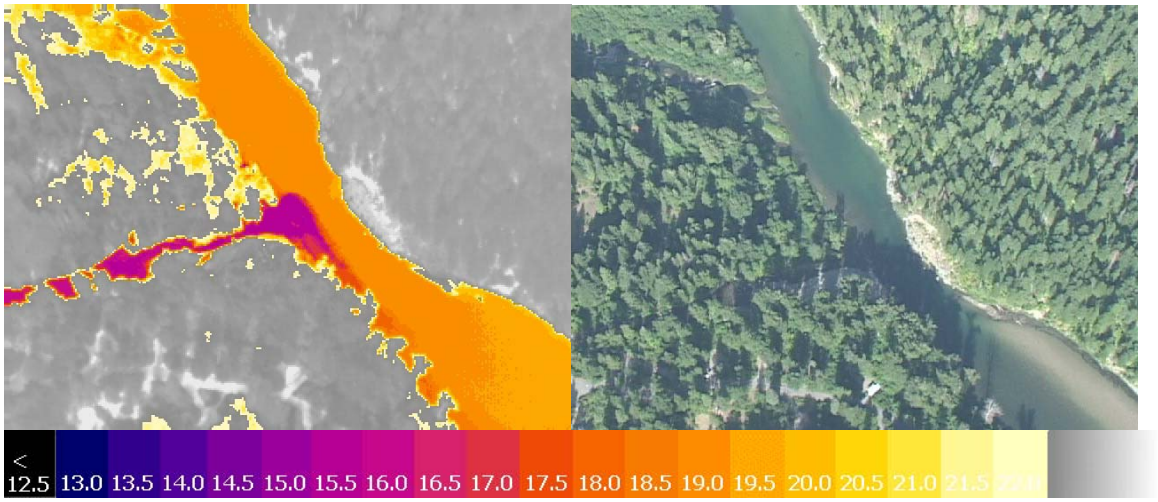
TIR/color video image pair showing an apparent small cool spring (16.2°) on the left bank of the side channel in Wenatchee River (18.4°C) at river mile 23.0 *(frames: Wen20760-0808).*



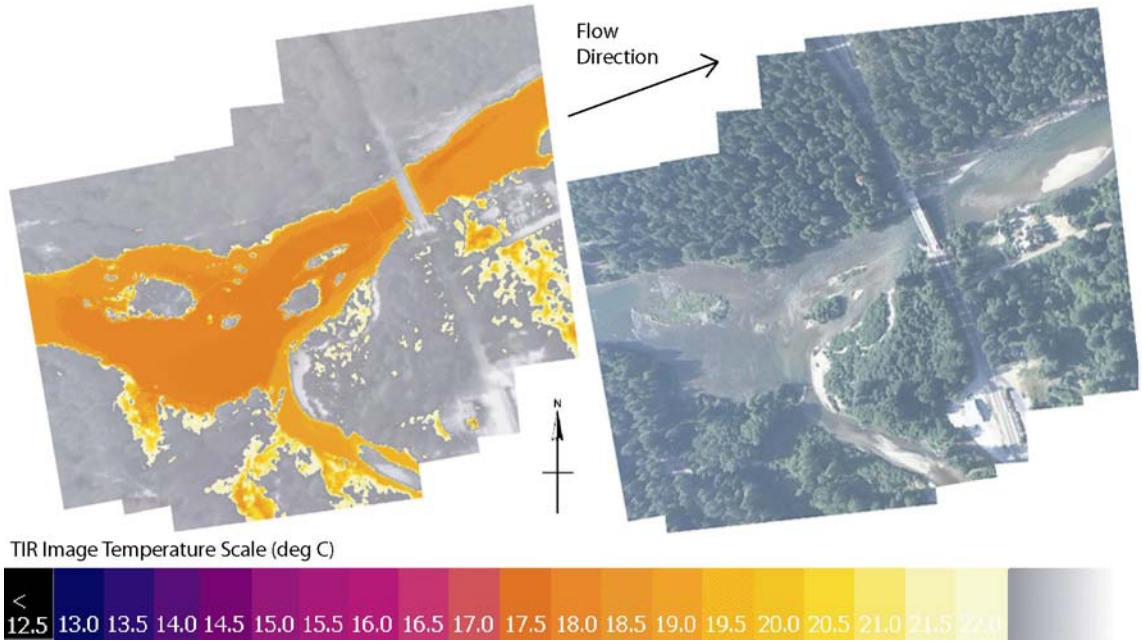
TIR/color video image pair showing the confluence of Cabin Creek (25.6°C) to the right bank of Wenatchee River (18.3°C) at river mile 31.1 *(frame: Wen21041).*



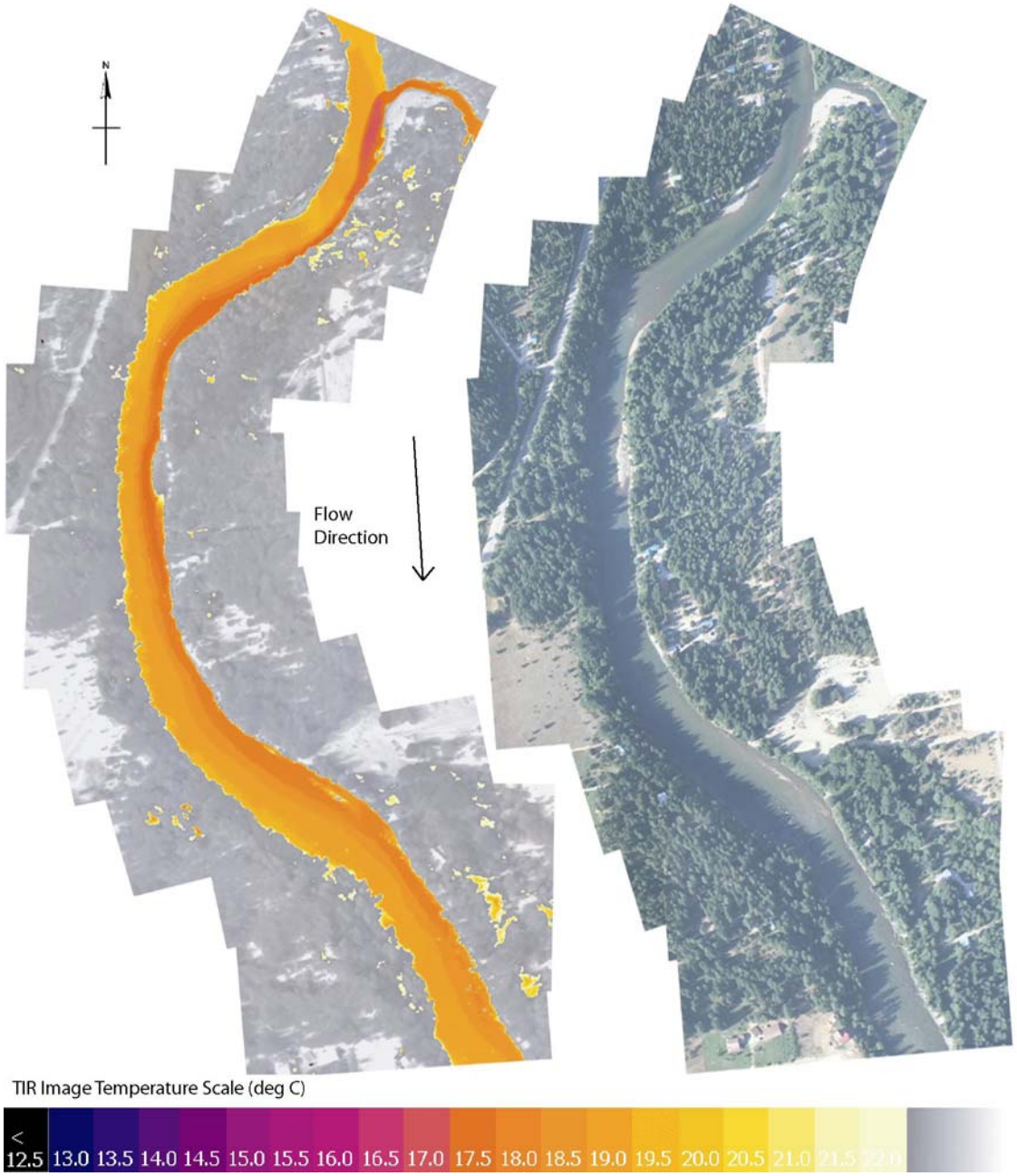
TIR/color video image pair showing a small spring (15.9°C) along the right bank of Wenatchee River (18.6°C) at river mile 32.6 *(frame: Wen21095).*



TIR/color video image pair showing the confluence of Chiwaukum Creek (15.1°C) to the right bank of Wenatchee River (18.8°C) at river mile 35.7 *(frame: Wen21213).*

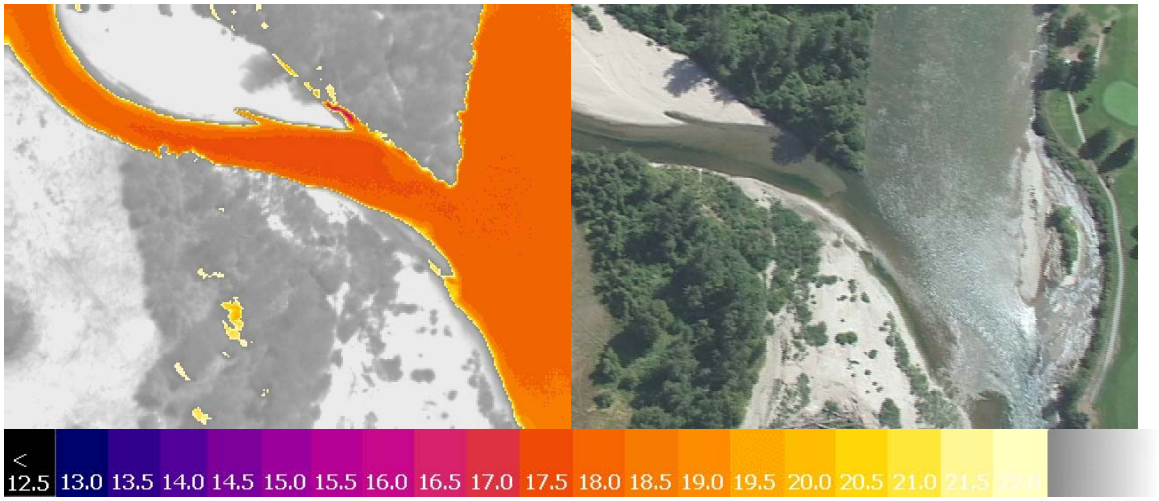


TIR/color video image pair showing how the addition of Nason Creek (18.7°C, right bank) raises mainstream temperatures in Wenatchee River from 17.6 to 18.0°C *(frames: Wen21798-1803).*

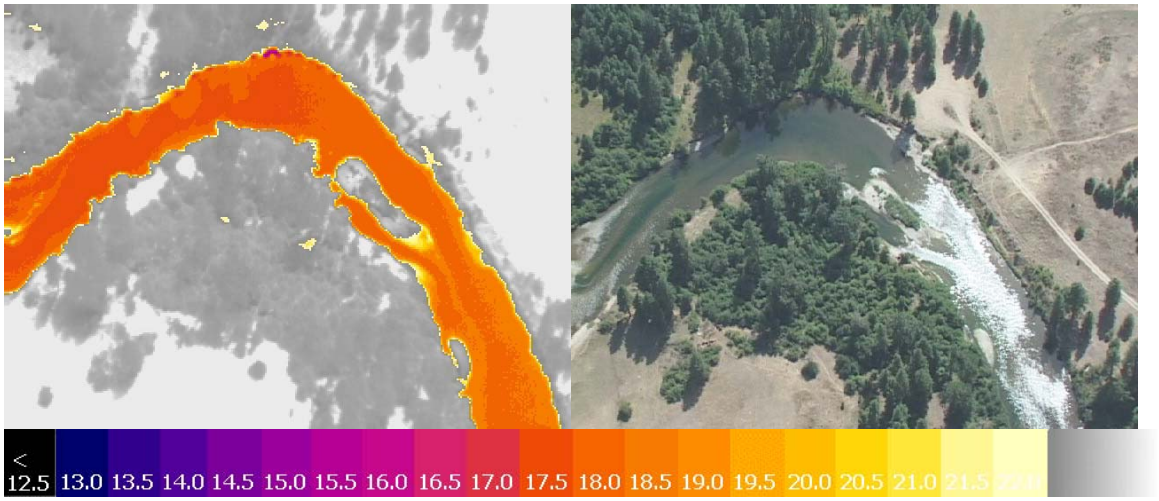


TIR/color video image pair showing the confluence of Chiwawa River (17.0°C) to the left bank of Wenatchee River (19.0°C) at river mile 48.1 *(frames: Wen21621-1646).*

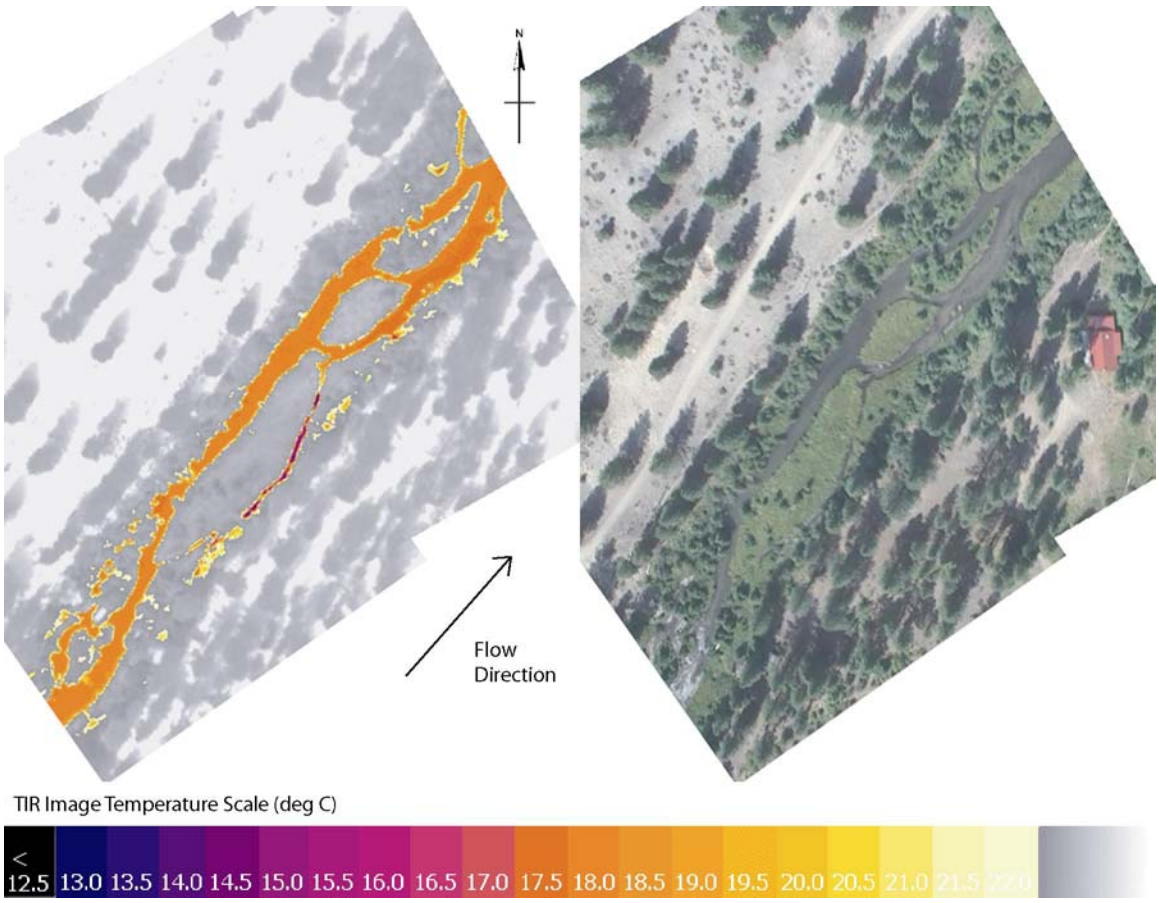
Icicle Creek



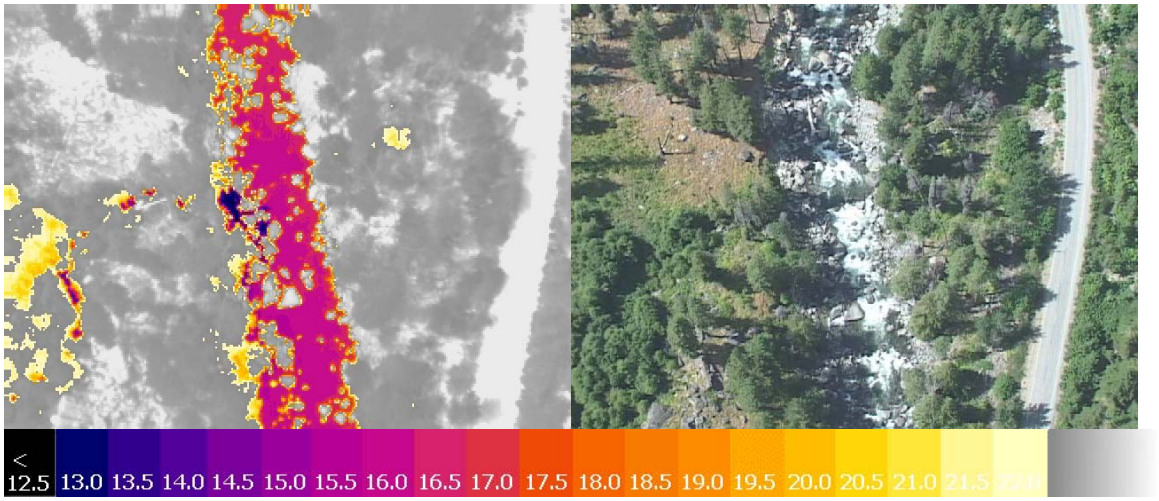
TIR/color video image pair showing the location of what appears to be a spring (16.5°C) on the left bank of Icicle Creek (17.4°C) just upstream of its confluence with Wenatchee River *(frame: Ice20018).*



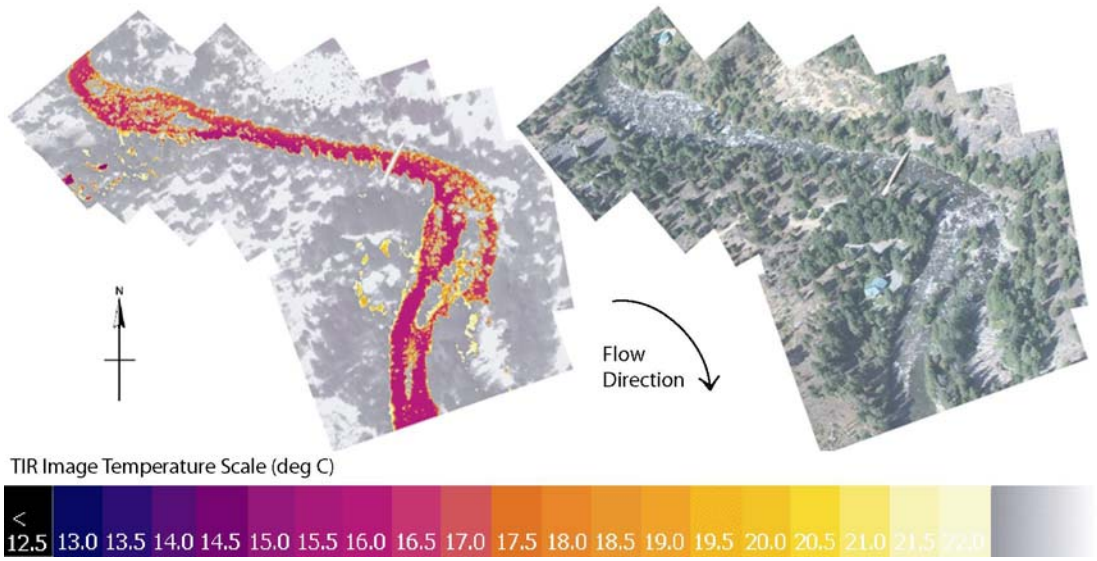
TIR/color video image pair showing a cool region, and therefore a possible spring (~16°C) on the left bank of Icicle Creek (17.4°C) at river mile .5 *(frame: Ice20041).*



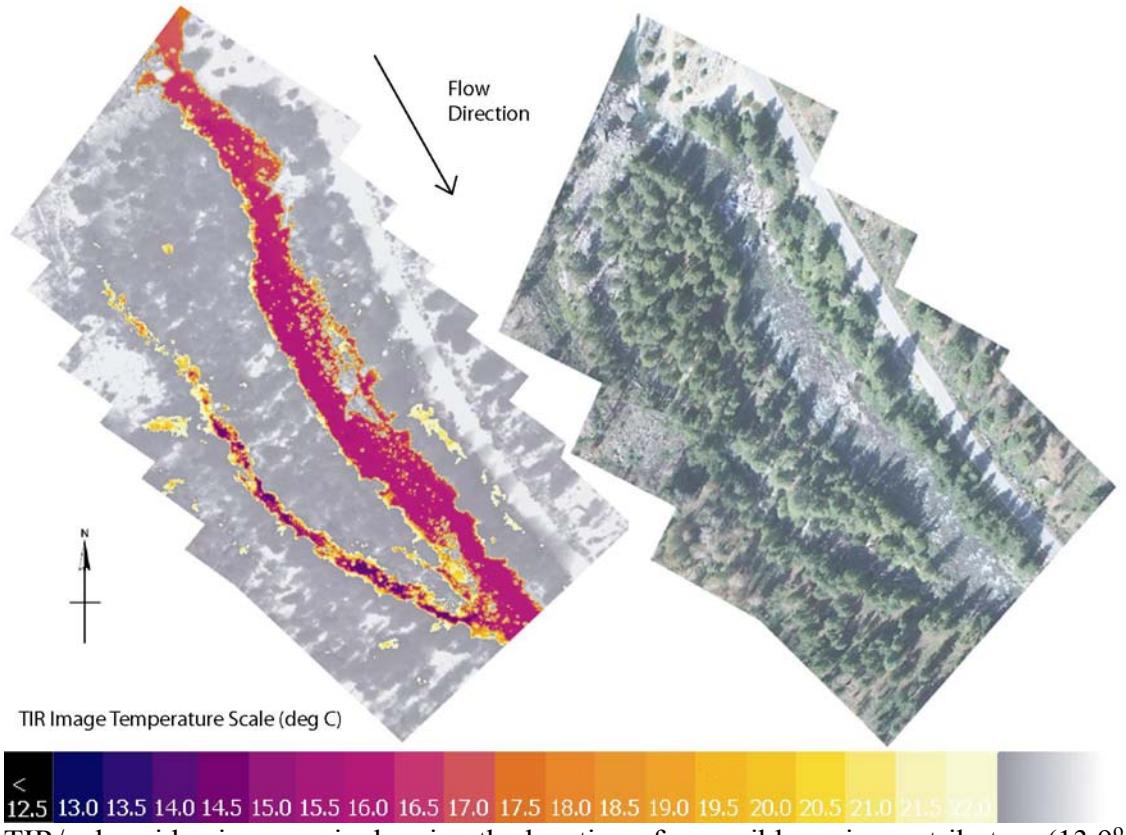
TIR/color video image pair showing a cool source (~14°C) along the right bank of Icicle Creek (17.5°C) at river mile 3.2 *(frames: Ice20167-0169)*.



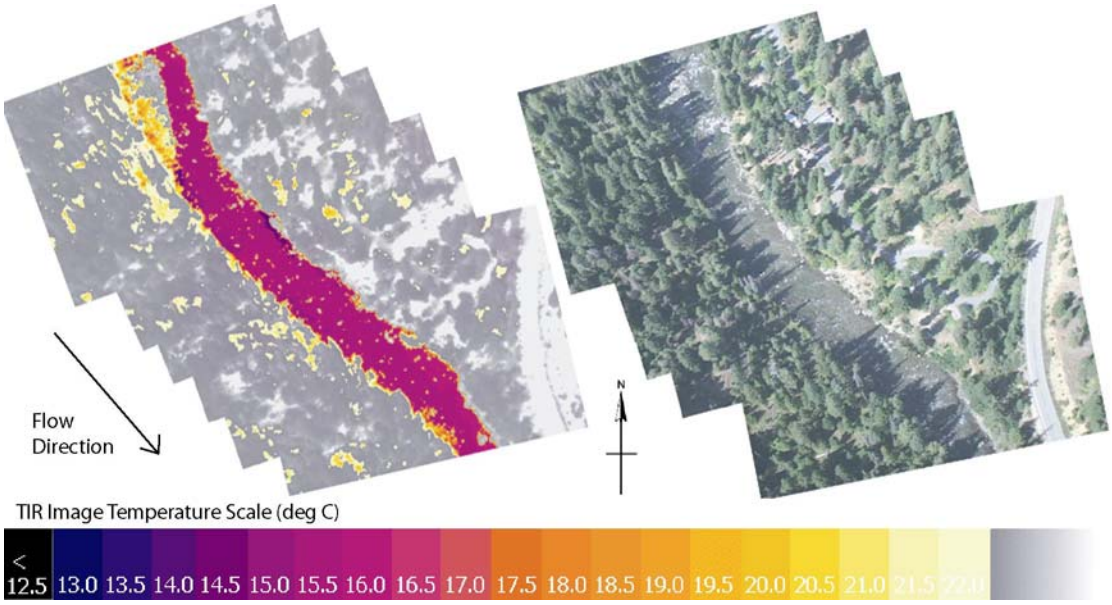
TIR/color video image pair showing the confluence of Rat Creek (12.5°C) to the right bank of Icicle Creek (15.8°C) at river mile 7.6 *(frame: Ice20379)*.



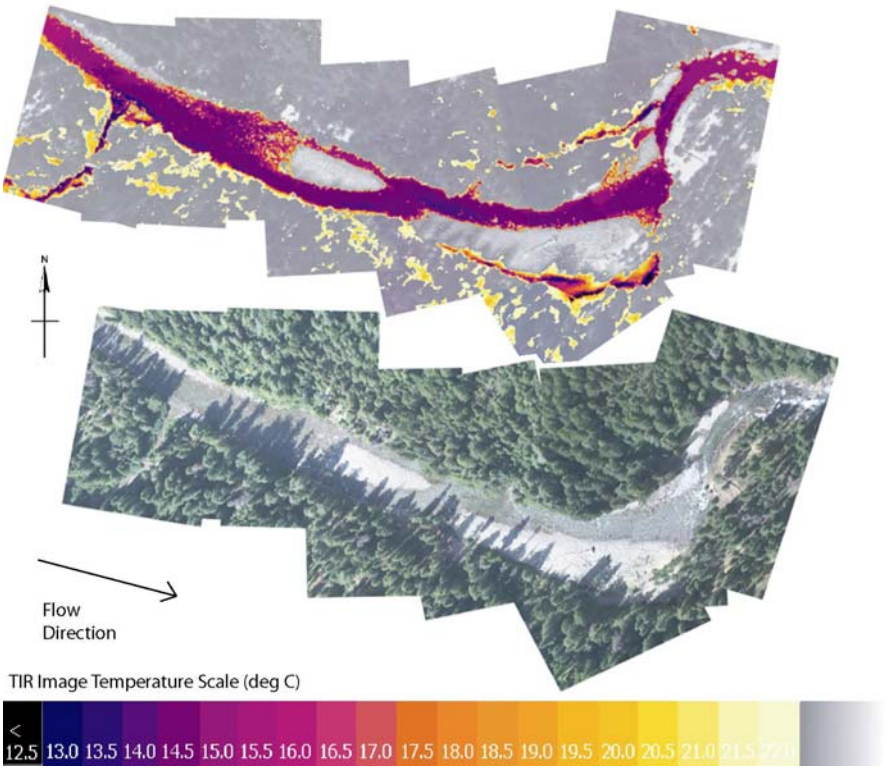
TIR/color video image pair showing the confluence of Eightmile Creek (15°C) to the right bank of Icicle Creek (16.6°C) at river mile 8.7 *(frames: Ice20418-0432).*



TIR/color video image pair showing the location of a possible spring or tributary (13.9°C) on the right bank of Icicle Creek (15.7°C) at river mile 10.3 *(frames: Ice20502-0508).*



TIR/color video image pair showing two springs at river mile 12.5 of Icicle Creek (15.2°C). The spring on the left bank measures 13.3°C while the right bank spring is 13.8°C *(frames: Ice20606-0611).*



TIR/color video image pair showing the confluence of Trout and Chatter Creeks to Icicle Creek (14.2°C) at river mile 16.5. Trout Creek enters on the right bank at the left edge of the images and is 13.2°C. Chatter Creek enters the left bank at the top of the images and measures 12.9°C. The cooler region on the right bank downstream from Trout Creek measures 12.3°C *(frames: Ice20814-0828).*