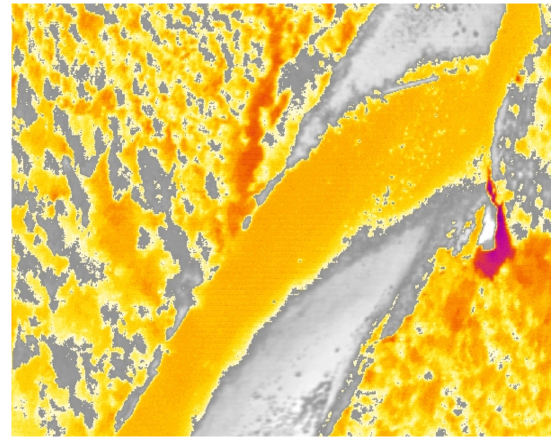
Aerial Survey of Molalla, Pudding Rivers, OR
Thermal Infrared and Color Videography



Report to:

Oregon Department of Environmental Quality
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By:

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Report Date: April 11, 2005
Survey Dates: July 26; August 11-12, 2004

Final Report

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Background

The Oregon Department of Environmental Quality (ODEQ) contracted with Watershed Sciences, Inc. to conduct an airborne thermal infrared (TIR) survey of the Molalla and Pudding Rivers in Oregon. The objective of the project was to exemplify the thermal characteristics of the river and to document surface water inflows and areas of potential sub-surface upwelling. These data directly support the ODEQ's temperature TMDL processes by mapping spatially continuous temperature patterns within the river and locations of surface and subsurface discharges. The airborne TIR surveys were targeted for late July and early August 2004.

Water temperatures vary naturally, due to topography, channel morphology, substrate composition, riparian vegetation, ground water exchanges, and tributary influences. Stream temperatures are also affected by human activities within the watershed. TIR images provide information about spatial stream temperature variability and can illustrate changes in the interacting processes that determine stream temperature. In most cases, these processes are extremely difficult to detect and quantify using traditional ground-based monitoring techniques.

The imagery and derived data are contained in an associated geographic information system (GIS) database. This report provides a detailed description of the work performed, including methodology and quantitative assessments of data quality. In addition, the report presents and discusses the spatially continuous longitudinal temperature profiles derived from the imagery. These profiles provide a landscape scale perspective of how temperatures vary along the stream gradient and are the basis for follow-on analysis.

Methods

Data Collection

Sensor mount used for the TIR and color video surveys.

Instrumentation: 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 individual images were referenced with time and position data provided by a global positioning system (GPS).

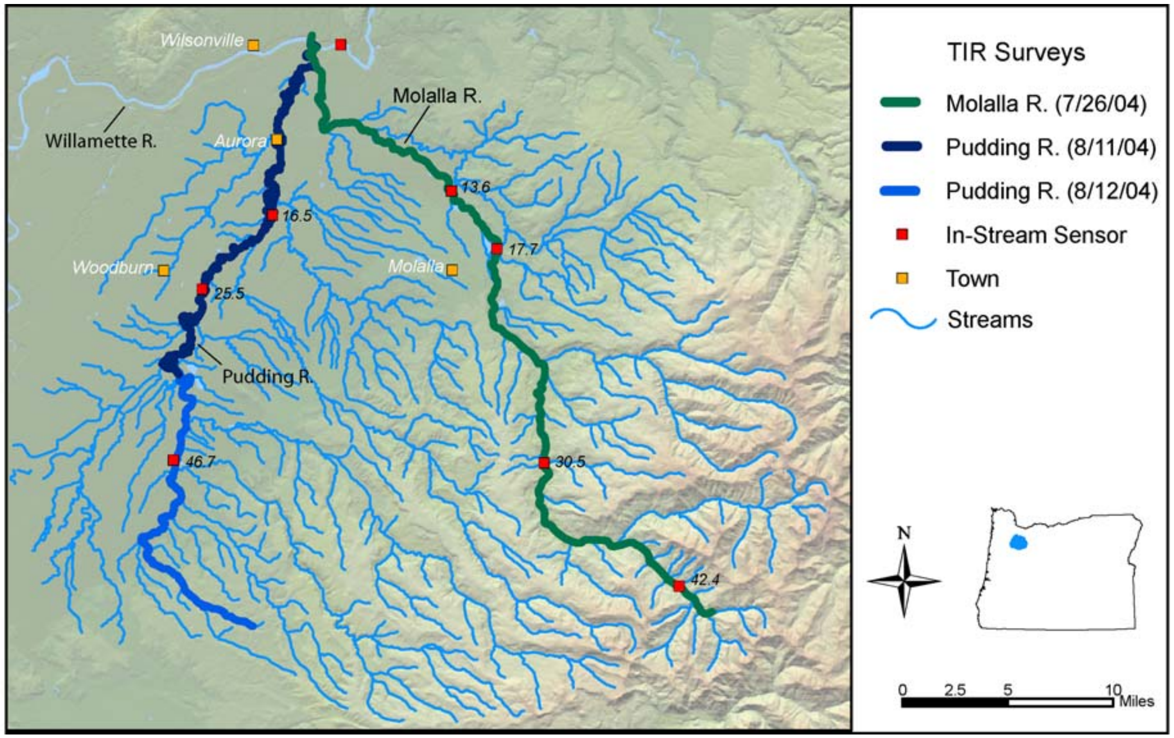
Flight Parameters: The survey of Molalla Creek was conducted in a downstream direction, from its confluence with Henry Creek, near the headwaters, to the mouth at the Willamette River. The Molalla Creek survey was conducted at an average altitude of 1500 ft above ground level (AGL), between 2:36 and 4:23 PM on July 26, 2004. The Pudding River survey was conducted in an upstream direction, from its mouth at Molalla River to its headwaters (river mile 61.2), at an average altitude of 1800 feet. The Pudding River survey was conducted at a higher altitude than that of the Molalla River in order to more efficiently capture the different side and off-channel features associated with the river. Due to the Pudding River's length and sinuosity, the survey was split over two consecutive days. On August 11, 2004, the Pudding River was surveyed between 4:01 and 5:59 PM, from its mouth to the Little Pudding River (river mile 35.2). On August 12, it was surveyed between 2:07 and 3:48 PM, from the confluence of the Little Pudding River to the headwaters.

Image Characteristics: Images were collected sequentially with 40% or greater vertical overlap. On the survey of the Molalla River, the TIR images present a ground width of approximately 160 meters with a spatial resolution of ~0.51 meters. The Pudding River survey yields imagery with a ground width of 193 meters, with a spatial resolution of 0.61 meters.

Ground Control: Watershed Sciences deployed in-stream data loggers prior to the flight in order to ground truth (i.e. verify the accuracy of) the TIR data. The data loggers were placed at access points throughout the watershed with an average of one instrument deployed every 15 river miles. The distribution of the in-stream data loggers allowed for the checking of radiant temperatures at regular intervals over the length of the survey. Meteorological data, including air temperature and relative humidity, were recorded in the basin using a portable weather station (*Onset*), located at Molalla River State Park.

Study Area

The map below illustrates the extent of the airborne TIR surveys conducted on the Molalla and Pudding Rivers in Oregon. The map also shows the location of in-stream sensors used to ground-truth the imagery, labeled by river mile. The Molalla River was surveyed in the afternoon, on July 26, 2004 and the Pudding River was surveyed on August 11 and 12, 2004. The Pudding River survey was split over two days with the first day (8/11/04) covering from the mouth to the Little Pudding River and the second day covering from the Little Pudding River to the headwaters.



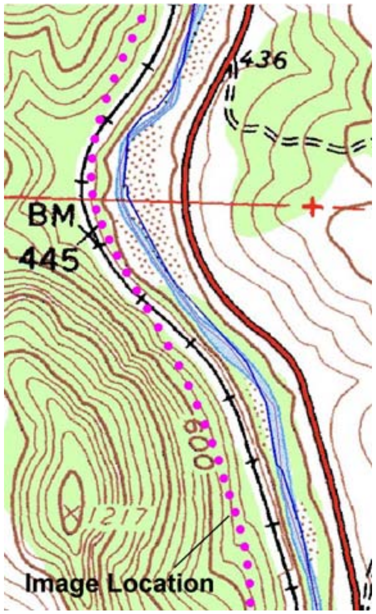
Stream Name - Survey Extent		
Date 2004	**Time (24 hr)**	**River Miles**
Molalla River		
7/26	14:36-16:23	47.1
Pudding River		
8/11	16:01-17:59	36.7
8/12	14:07-15:48	26.8

Data Processing

Calibration: 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's location. Calibration parameters were fine-tuned to provide the most accurate fit between the radiant and kinetic temperatures.

Interpretation and Sampling: Once calibrated, the images were integrated into a GIS in which an analyst interpreted and sampled stream temperatures. Sampling consisted of querying radiant temperatures (pixel values) from the center of the stream channel and saving the median value of a ten-point sample to a GIS database file. The temperatures of detectable surface inflows (i.e. surface springs, tributaries) were also sampled at their mouth. In addition, data processing focused on interpreting spatial variations in surface temperatures observed in the images.

Image showing TIR image points plotted over a USGS 1:24K topographic map. Each point represents a TIR and color video image pair acquired at that location.



Geo-referencing: The images are tagged with a GPS position at the time they are acquired. Since the TIR camera is maintained at vertical down-look angles, the geographic coordinates provide an accurate index to the location of the image scene. In order to provide further spatial reference, the TIR images were assigned a river mile based on a routed stream layer.

Temperature Profiles: The median temperatures for each sampled image were plotted versus the corresponding river mile to develop a longitudinal temperature profile. River miles were derived from the stream center line digitized from USGS 1:24K topographic maps. The profile illustrates how stream temperatures vary spatially along the stream gradient. The location and median temperature of all sampled surface water inflows (e.g. tributaries, surface springs, etc.) are included on the plot to illustrate how those inflows influence the main stem temperature patterns.

Thermal Image Characteristics

Surface Temperatures: Thermal infrared sensors measure TIR energy emitted at the water's surface. Since water is essentially opaque to TIR wavelengths, the sensor is only measuring water surface temperature. Thermal infrared data accurately represents bulk water temperatures where the water column is thoroughly mixed; however, thermal stratification can form in reaches that have little or no mixing. Thermal stratification in a free flowing river is inherently unstable due to variations in channel shape, bed composition, and in-stream objects (i.e. rocks, trees, debris, etc.) that cause turbulent flow and can usually be detected in the imagery. Occurrences of thermal stratification interpreted during analysis are identified in the results section for the survey.

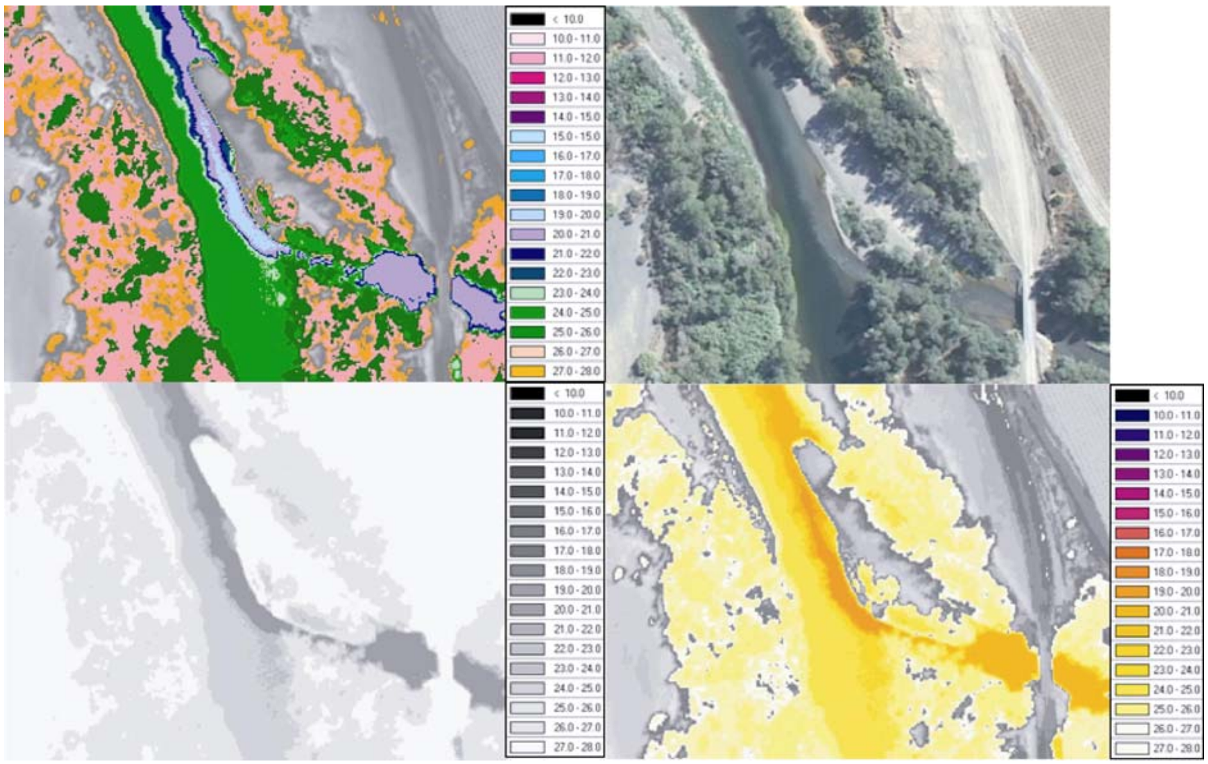
Expected Accuracy: Thermal infrared radiation received at the sensor is a combination of energy emitted from the water's surface, reflected from the water's surface, and absorbed and re-radiated by the intervening atmosphere. Water is a good emitter of TIR radiation and has relatively low reflectivity (~ 4 to 6%). During 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 (e.g. 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[1]). However, the occurrence of reflections as an artifact (or noise) in the TIR images is a consideration during image interpretation and analysis. In general, apparent stream temperature changes of < 0.6^{o}C are not considered significant unless associated with a surface inflow (e.g. tributary).

Differential Heating: In stream segments with flat surface conditions (i.e. pools) and relatively low mixing rates, observed variations in spatial temperature patterns can be the result of differences in the instantaneous heating rate at the water's surface. In the TIR images, indicators of differential surface heating include seemingly cooler radiant temperatures in shaded areas compared to surfaces exposed to direct sunlight. Shape and magnitude distinguish spatial temperature patterns caused by tributary or spring inflows from those resulting from differential surface heating. Unlike with thermal stratification, surface temperatures may still represent bulk water conditions if the stream is mixed.

Feature Size and Resolution: A small stream width logically translates to fewer pixels "in" the stream and greater integration with non-water features such as rocks and vegetation. Consequently, a narrow channel (relative to the pixel size) can result in higher inaccuracies in the measured radiant temperatures (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.

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

Temperatures and Color Maps: The TIR images collected during this survey consist of a single band. As a result, visual representation of the imagery *(in a report or GIS environment*) requires the application of a color map or legend to the pixel values. The selection of a color map should highlight features most relevant to the analysis (i.e. *spatial variability of stream temperatures*). For example, a continuous, gradient style color map that incorporates all temperatures in the image frame will provide a smoother transition in colors throughout the entire image, but will not highlight temperature differences in the stream. Conversely, a color map that focuses too narrowly cannot be applied to the entire river and will “washout” terrestrial and vegetation features. The method used to select a color map for the report images attempts to accomplish both. The map is based on using discrete colors to represent the range of water temperatures observed during the analysis, based on 1°C or 0.5°C increments and a linear gray scale to represent temperatures above the maximum observed water temperature. The images below provide an example of three different color maps applied to the same thermal image.



Results

Weather Conditions

The table below summarizes the air temperatures and humidity measured at Molalla River State Park on the Willamette River for July 26 and August 11-12, 2004, during the time frames of the flights.

Time 24 hr.	Air Temp. ^oF	Air Temp. ^oC	RH %
26-Jul-04			
13:00	72.5	22.5	52.8
14:00	76.6	24.8	46.1
15:00	78.7	26.0	41.9
16:00	83.0	28.3	31.5
17:00	84.4	29.1	30.5
11-Aug-04			
13:00	84.4	29.1	43.0
14:00	87.3	30.7	40.4
15:00	90.2	32.3	36.9
16:00	91.7	33.2	34.9
17:00	93.2	34.0	34.4
18:00	91.7	33.2	37.4
12-Aug-04			
13:00	82.2	27.9	45.5
14:00	85.8	29.9	40.4
15:00	88.0	31.1	37.9
16:00	90.2	32.3	35.4
17:00	89.5	31.9	35.9
18:00	94.7	34.9	30.5

The photo of the Molalla River above was taken on July 26, 2004. The image shows the clear sky conditions on the day of the survey. Similar conditions were observed on August 11, and 12.

Thermal Accuracy

The table below summarizes a comparison between the kinetic temperatures recorded by the in-stream data loggers and the radiant temperatures derived from the TIR images. The Pudding River was surveyed over two days (8/11/04 and 8/12/04) with some overlap between days. The in-stream sensors at river miles 16.5 and 25.5 were used to ground truth the measured radiant temperatures on both days. The in-stream sensor that was located at river mile 46.7 on the Pudding River was found out of the water when it was retrieved and consequently was not used to ground truth the TIR imagery. Overall, the observed differences in temperature were consistent with target accuracies (*i.e. average difference* ≤ *0.5^{o}C*).

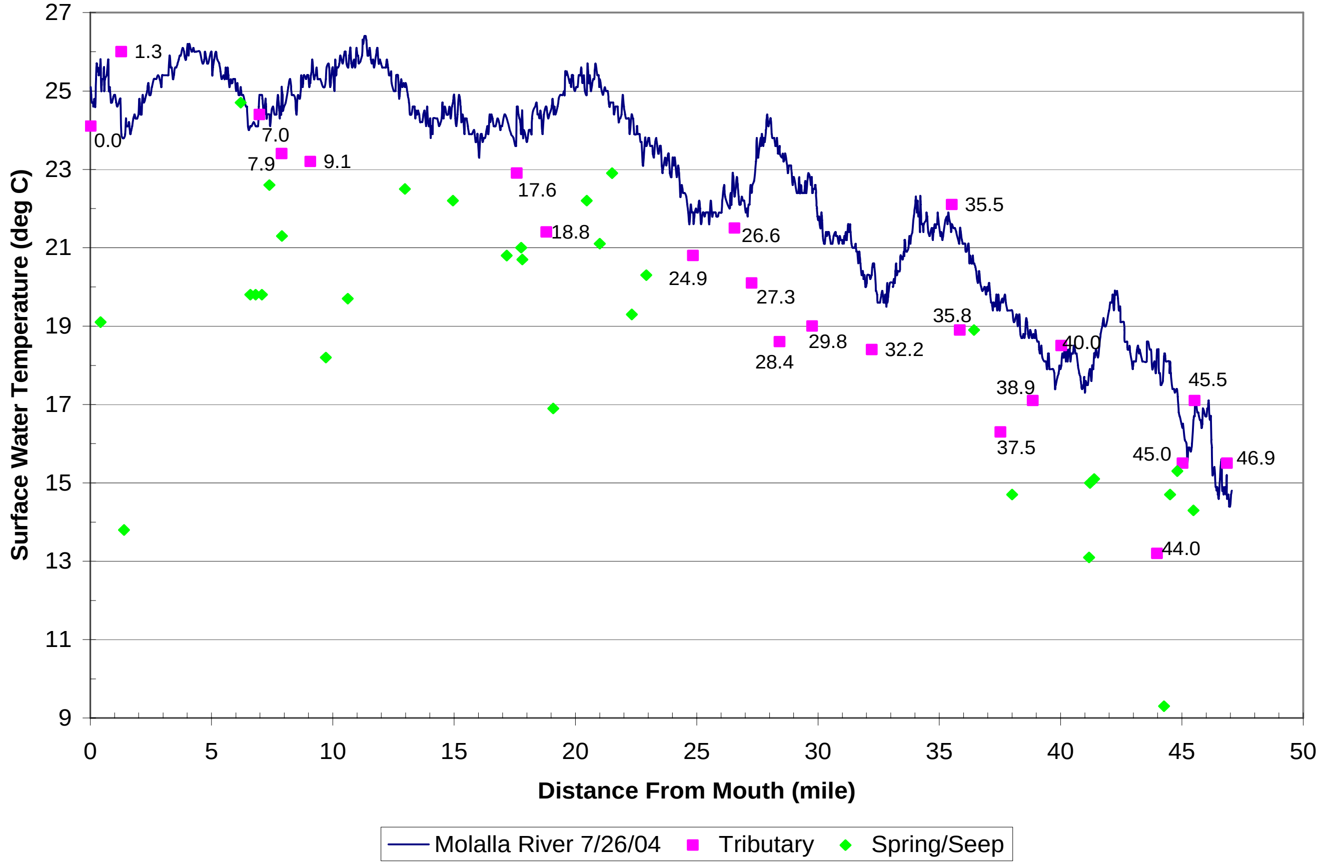
Location	Image	Time	Mile	Kinetic Temp. ^{o}C	Radiant Temp. ^{o}C	Difference ^{o}C
Molalla River 7/26/04 (*avg. absolute = 0.4^{o}C*)						
Molalla R.	mola0284	14:54	42.4	17.6	17.4	0.2
Molalla R.	mola1012	15:20	30.5	19.7	20.3	-0.6
Molalla R.	mola1740	15:44	17.7	24.3	24.5	-0.2
Molalla R.	mola1934	15:51	13.6	25.0	24.6	0.4
Willamette R.	mola2707	16:18	0.0	24.5	23.9	0.6
Pudding River 8/11/04 (*avg. absolute = 0.1^{o}C*)						
Willamette R.	pud0043	16:03	0.0	23.3	23.4	-0.1
Pudding R.	pud1727	16:59	16.5	26.2	26.2	0.0
Pudding R.	pud2416	17:22	25.5	25.4	25.2	0.2
Pudding River 8/12/04 (*avg. absolute = 0.0^{o}C*)						
Pudding R.	pud0020	14:08	16.5	26.2	26.2	0.0
Pudding R.	pud0413	14:21	25.5	25.4	25.3	0.1
Pudding R.*	pud1478	14:57	46.7	n/a	25.8	n/a

*sensor was found out of the water so was not used in the comparison.

Molalla River

Longitudinal Temperature Profile

The figure below illustrates the median sampled temperatures plotted versus river mile for the Molalla River. The locations of sampled tributaries are indicated by river mile in the profile and are listed in the table following. The locations of springs and seeps are also indicated on the profile.



Tributaries and other surface inflows

Name	Image	km	mile	Tributary °C	Molalla R. °C	Difference °C	Name	Image	km	mile	Tributary °C	Molalla R. °C	Difference °C
Tributary							**Spring/Seep**						
Henry Creek (LB)	mola0179	75.4	46.9	15.5	14.6	0.9	Spring (LB)	mola0257	73.2	45.5	14.3	16.6	-2.3
Copper Creek (LB)	mola0254	73.3	45.5	17.1	16.7	0.4	Spring (LB)	mola0283	72.1	44.8	15.3	17.5	-2.2
Unnamed (RB)	mola0274	72.5	45.0	15.5	16.5	-1.0	Spring (LB)	mola0294	71.6	44.5	14.7	17.9	-3.2
Minette Creek (LB)	mola0322	70.8	44.0	13.2	18.4	-5.2	Spring (LB)	mola0305	71.2	44.3	9.3	18.2	-8.9
Table Rock Fork (RB)	mola0564	64.4	40.0	18.5	18.0	0.5	Spring (LB)	mola0504	66.6	41.4	15.1	18.3	-3.2
Horse Creek (LB)	mola0621	62.5	38.9	17.1	18.7	-1.6	Spring (LB)	mola0513	66.3	41.2	15.0	17.9	-2.9
Gawley Creek (LB)	mola0684	60.4	37.5	16.3	19.6	-3.3	Spring (LB)	mola0514	66.3	41.2	13.1	17.8	-4.7
Unnamed (LB)	mola0776	57.7	35.8	18.9	21.4	-2.5	Spring (LB)	mola0661	61.2	38.0	14.7	19.4	-4.7
Unnamed (LB)	mola0794	57.2	35.5	22.1	21.6	0.5	Spring (LB)	mola0741	58.6	36.4	18.9	20.6	-1.7
Pine Creek (RB)	mola1019	51.9	32.2	18.4	20.3	-1.9	Spring (RB)	mola1546	36.9	22.9	20.3	23.9	-3.6
Unnamed (LB)	mola1162	47.9	29.8	19.0	22.4	-3.4	Seep (RB)	mola1576	35.9	22.3	19.3	24.4	-5.1
Unnamed (LB)	mola1292	45.7	28.4	18.6	23.5	-4.9	Seep (RB)	mola1615	34.6	21.5	22.9	24.8	-1.9
Trout Creek (RB)	mola1351	43.9	27.3	20.1	22.4	-2.3	Seep (RB)	mola1638	33.8	21.0	21.1	25.3	-4.2
North Fork (RB)	mola1382	42.8	26.6	21.5	22.3	-0.8	Spring (LB)	mola1662	32.9	20.5	22.2	24.9	-2.7
Russell Creek (LB)	mola1453	40.0	24.9	20.8	21.9	-1.1	Spring (RB)	mola1723	30.7	19.1	16.9	24.6	-7.7
Molalla Braid 2 (LB)	mola1737	30.3	18.8	21.4	24.6	-3.2	Spring (RB)	mola1779	28.7	17.8	20.7	24.4	-3.7
Molalla Braid 1 (LB)	mola1792	28.3	17.6	22.9	24.6	-1.7	Spring (RB)	mola1782	28.6	17.8	21.0	23.9	-2.9
Unnamed (LB)	mola2172	14.6	9.1	23.2	25.2	-2.0	Seep (LB)	mola1805	27.6	17.2	20.8	24.3	-3.5
Milk Creek (RB)	mola2227	12.7	7.9	23.4	25.1	-1.7	Spring (LB)	mola1901	24.1	15.0	22.2	24.7	-2.5
Unnamed (RB)	mola2276	11.2	7.0	24.4	24.9	-0.5	Spring (LB)	mola1991	20.9	13.0	22.5	25.1	-2.6
Pudding River (LB)	mola2562	2.1	1.3	26.0	23.9	2.1	Spring (LB)	mola2102	17.1	10.6	19.7	25.8	-6.1
Willamette River	mola2640	0.0	0.0	24.1	25.1	-1.0	Spring (LB)	mola2144	15.6	9.7	18.2	25.3	-7.1
							Spring (RB)	mola2226	12.7	7.9	21.3	25.0	-3.7
							Spring (RB)	mola2248	11.9	7.4	22.6	24.4	-1.8
							Spring (RB)	mola2269	11.4	7.1	19.8	24.9	-5.1
							Spring (LB)	mola2283	11.0	6.8	19.8	24.1	-4.3
							Spring (LB)	mola2291	10.6	6.6	19.8	24.1	-4.3
							Spring (LB)	mola2308	10.0	6.2	24.7	25.1	-0.4
							Spring (LB)	mola2558	2.2	1.4	13.8	23.8	-10.0
							Spring (RB)	mola2607	0.7	0.4	19.1	25.8	-6.7

Observations and Analysis

The Molalla River was surveyed starting near the headwaters (mile 47.1) and continuing downstream to its confluence with the Willamette River. Radiant water temperatures exhibited an overall pattern of downstream warming, with temperatures increasing from 14.4^{o}C at mile 46.8 to a survey maximum of 26.3^{o}C at mile 11.3. The profile illustrates variable heating rates along the stream gradient and illustrates reaches with localized cooling. A total of 22 tributary inflow and 30 surface springs were sampled during the analysis. Of the 52 inflows sampled, 47 contributed cooler water to the main stem. The following paragraphs provide a more detailed discussion of observed temperatures based on segmentation of the profile into reaches that showed similar thermal response/features. The segmentation is based entirely on visual inspection of the longitudinal profile and is intended to facilitate discussion.

Mile 47.2 to 39.8 (local spatial variability) - Radiant water temperatures in the first six miles of the TIR survey were characterized by local thermal variability with distinct areas of relatively rapid heating/cooling. Downstream of the Ogle Creek confluence (mile 46.4), stream temperatures increased rapidly by ~2.8^{o}C from mile 46.4 to 46.0. Upstream of Ogle Creek, the river flowed in a generally west/southwest direction, but transitioned to a north/northwest direction near the Ogle Creek confluence, and this change in aspect may have altered the level of direct solar radiation incident on the stream's surface. Ogle Creek was visible in the imagery, but did not have sufficient visible surface water to obtain a radiant temperature sample.

Just downstream of the Copper Creek confluence (mile 45.5), stream temperatures decreased by ~1.5^{o}C (15.5^{o}C). This reach segment includes the location of Mining Iron Creek (*not sampled*) and a small, apparent spring along the left bank. Copper Creek had temperatures similar to the Molalla River, and the other detected inflows did not appear to contribute sufficient flow to create a thermal response in the main stem. The magnitude of the temperature decrease suggests possible ground water upwelling at this location.

Moving downstream, radiant water temperatures increased rapidly from ~15.5^{o}C at mile 45.2 to ~18.2^{o}C at mile 44.3. Temperatures remained near 18.2^{o}C to mile 42.9 before heating again to ~19.9^{o}C at mile 42.2. Minette Creek (13.2^{o}C) joins the Molalla River at mile 44.0 and is a source of cooling. However, other processes that contributed to the differences in heating rates within this reach segment were not apparent from the imagery.

Radiant water temperatures in the Molalla River decreased from ~19.9^{o}C to ~17.4^{o}C between miles 42.2 and 40.9. Three apparent springs were detected (mile 41.4 and 41.2), indicating possible sub-surface discharge in this reach. The apparent springs were within the visible shadows along the left bank and were classified based on their surface temperature, both absolute and compared to the surroundings. However, the shadows made it difficult to verify the source in the true color imagery (*reference sample imagery*). Inspection of the imagery and topographic base maps did not reveal other sources of cooling within this reach.

Mile 39.8 to Mile 21.4 *(downstream heating with distinct areas of cooling):* This segment is characterized by steady downstream warming interrupted by two distinct cooling reaches. Overall, radiant water temperatures increased from ~17.4°C at mile 39.8 to ~21.8°C at mile 27.1. Five tributaries were sampled, and five springs/seeps were detected.

The first cooling trend was observed between river miles 34.0 and 32.7, where temperatures decreased from a local maximum of ~22.3°C to ~19.6°C. Inspection of the topographic base maps shows that, although the terrain in the upper river is relatively steep, there is a distinct constriction of the channel at river mile 34.0. Past TIR surveys have shown that transitions in morphology are often areas where sub-surface flow is forced into the active channel, resulting in changes in prevailing temperature trends. In addition, the topographic base map shows a general change in orientation from primarily a north flow direction to a north/northeast orientation, which suggests differences in topographic and vegetative shading conditions compared to upstream reaches.

The second cooling trend occurs between river miles 27.9 and 24.7, with temperatures decreasing from ~24.4°C to ~21.6°C. Trout Creek (mile 27.3) was observed as a cooling source to the river. However, the contribution of Trout Creek did not account for the full decrease in main stem temperatures. Visual inspection of the topographic base maps shows that the river make transitions to a lower gradient, less confined reach between the mouths of Trout Creek (mile 27.3) and the North Fork Molalla River (mile 26.6).

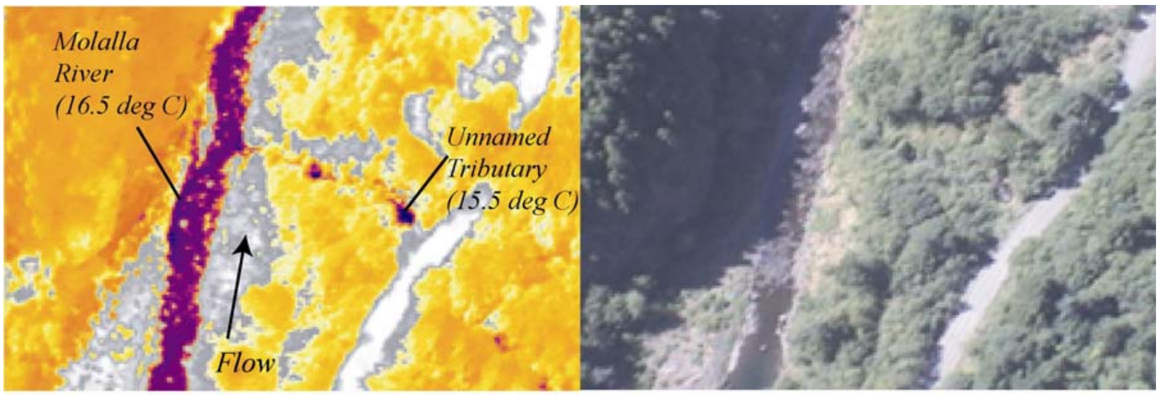
Downstream of the North Fork, radiant water temperatures decreased slightly, falling from ~22.3°C to ~21.6°C at the mouth of Russell Creek (mile 24.9). Russell Creek contributed water that was ~1.1°C cooler than the main stem, but was also relatively small and only partially visible through the riparian canopy. Downstream of the Russell Creek confluence, stream temperatures again showed a pattern of downstream warming, with temperatures reaching 24.7°C at mile 21.4.

Mile 21.4 to Mile 0.0 (*warmer temperatures*): In the lower 20 miles of the Molalla River, water temperatures were relatively warm, ranging between 23.4°C and 26.4°C. A notable characteristic of this reach was a number small springs and seeps, which emerged from within the floodplain (*see sample images*). A total of 18 springs/seeps were sampled in the lower 21 miles. All cool water sources not identified as surface flow (tributaries, irrigation returns, etc.) were classified as springs or seeps. The detection of the springs/seeps suggests that hyporheic exchange may help buffer temperatures in the lower river and potentially create localized thermal refuge for cold-water fish species.

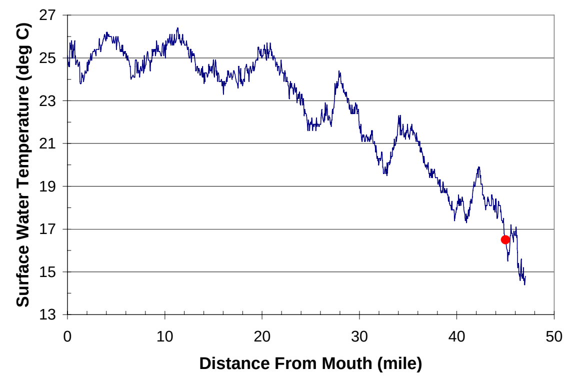
Sample Images

The following pages contain sample images from the TIR survey of the Molalla River, which provide samples of thermal features and channel conditions observed during the survey.

Unnamed Tributary (mile 45.0)

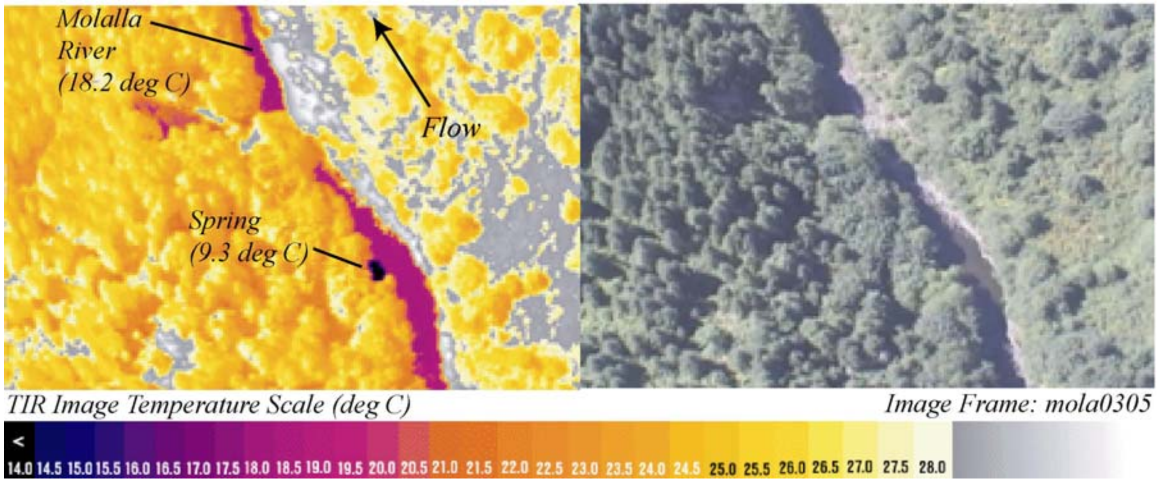


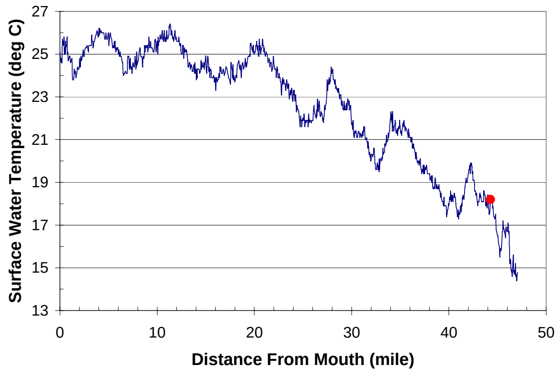
TIR Image Temperature Scale (deg C) *Image Frame: mola0274*



The image pair above shows the confluence of an unnamed tributary at river mile 45.0, just 0.2 miles upstream of the mapped confluence of Lake Creek. This tributary contributes water that is 1^0C cooler than the Molalla River (16.5^{o}C) at this point. The plot above shows the location of this image (red dot) along the longitudinal profile.

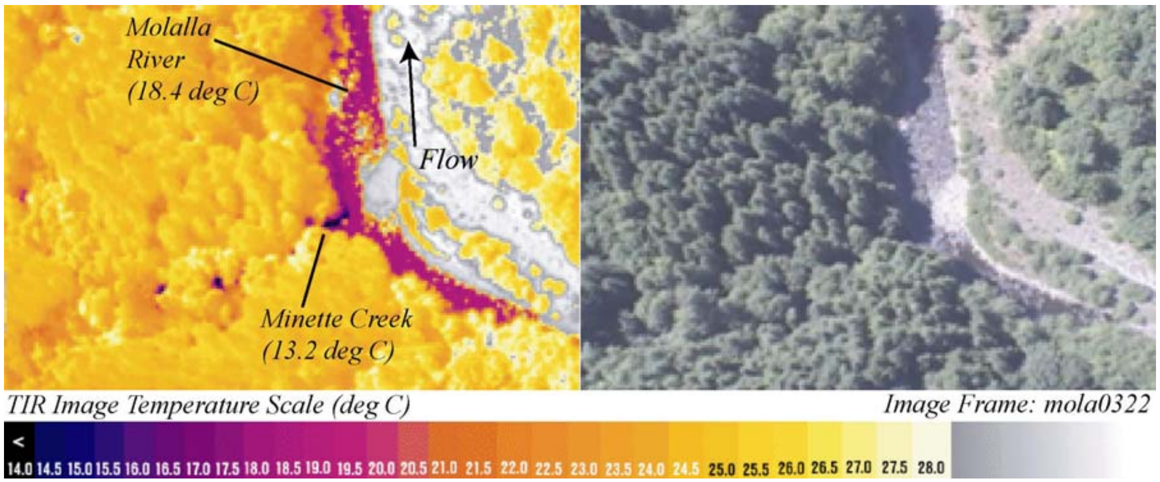
Spring (mile 44.3)

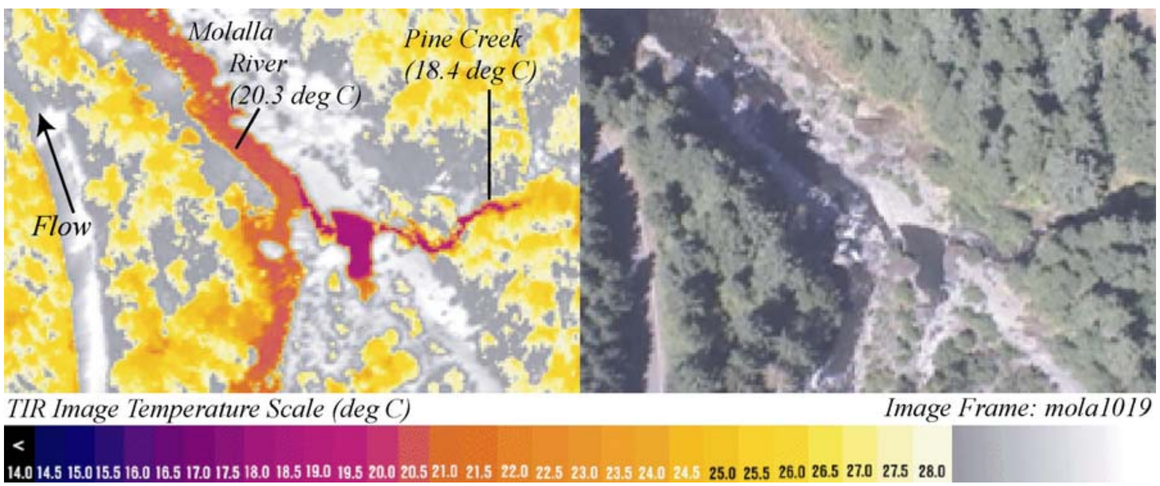




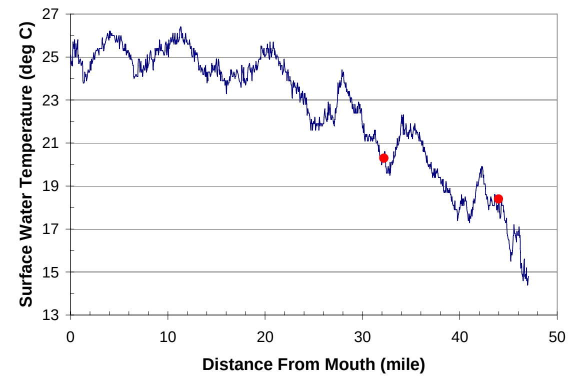
The image pair above shows the location of an apparent spring (9.3°C) on the left bank of the Molalla River (18.2°C) at river mile 44.3. The visible shadows (reference the true color imagery on the right) often made it difficult to identify the source of cold water. Detection and classification of this springs and others like it were based primarily on location, temperature, and thermal contrast within the scene. The plot above shows the location of this image (red dot) along the longitudinal profile.

Tributaries (miles 44.0; 32.2)

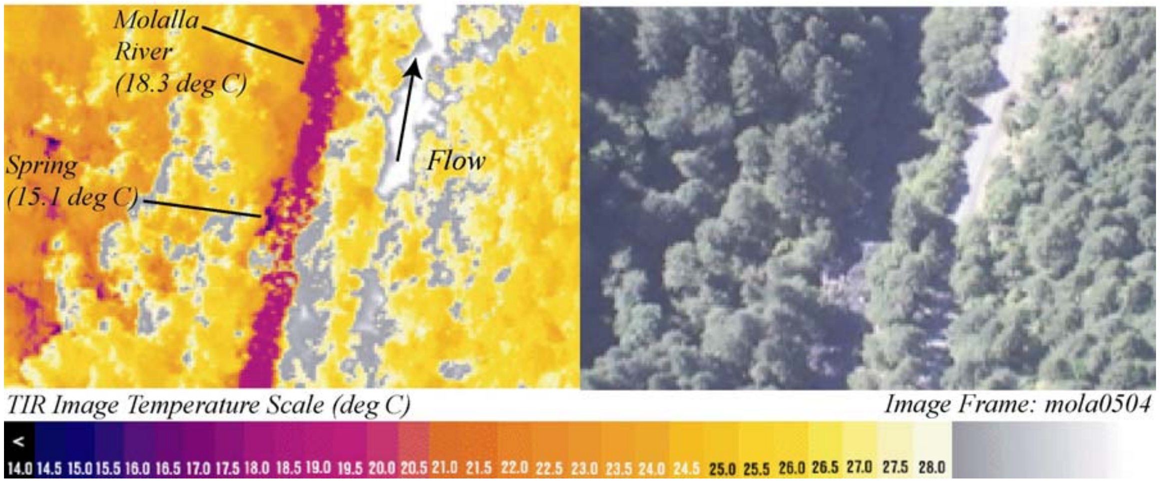




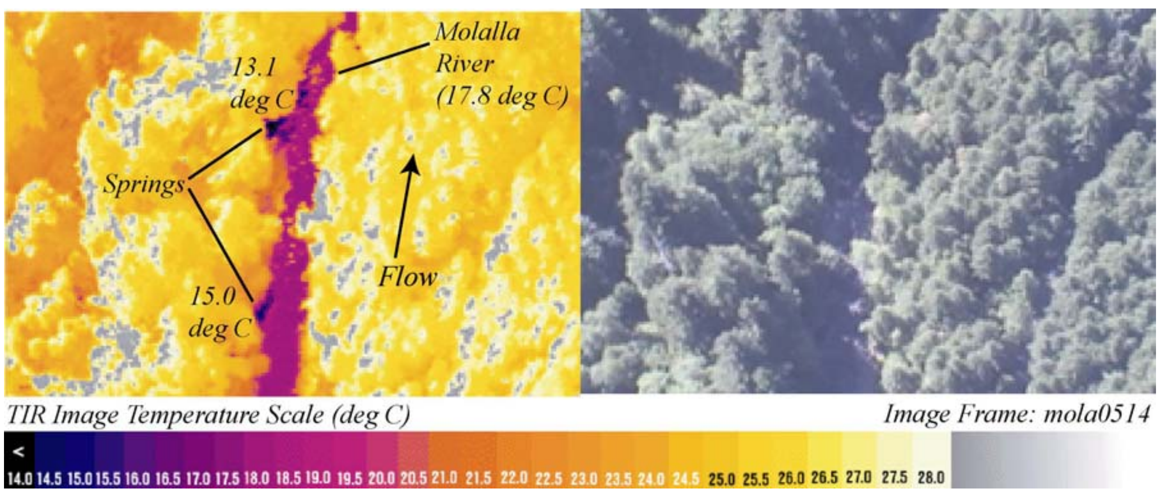
The image pairs on the left show the confluences of two tributaries to the Molalla River. The image pair on top shows the confluence of Minette Creek (13.2°C) and the Molalla River (18.4°C) at river mile 44.0. The image pair on the bottom shows the confluence of Pine Creek (18.4°C) and the Molalla River (20.3°C) at river mile 32.2. The plot below shows the locations of these tributary confluence images (red dots) along the longitudinal profile.

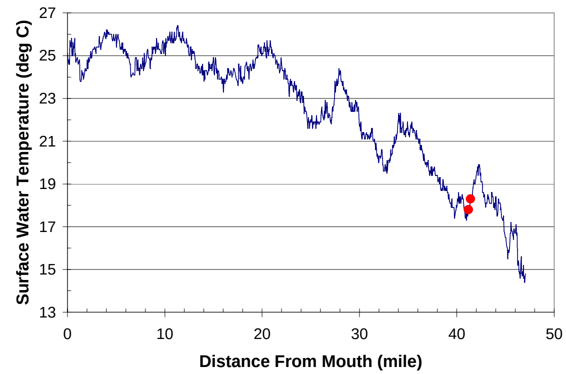


Springs (miles 41.4; 41.2)

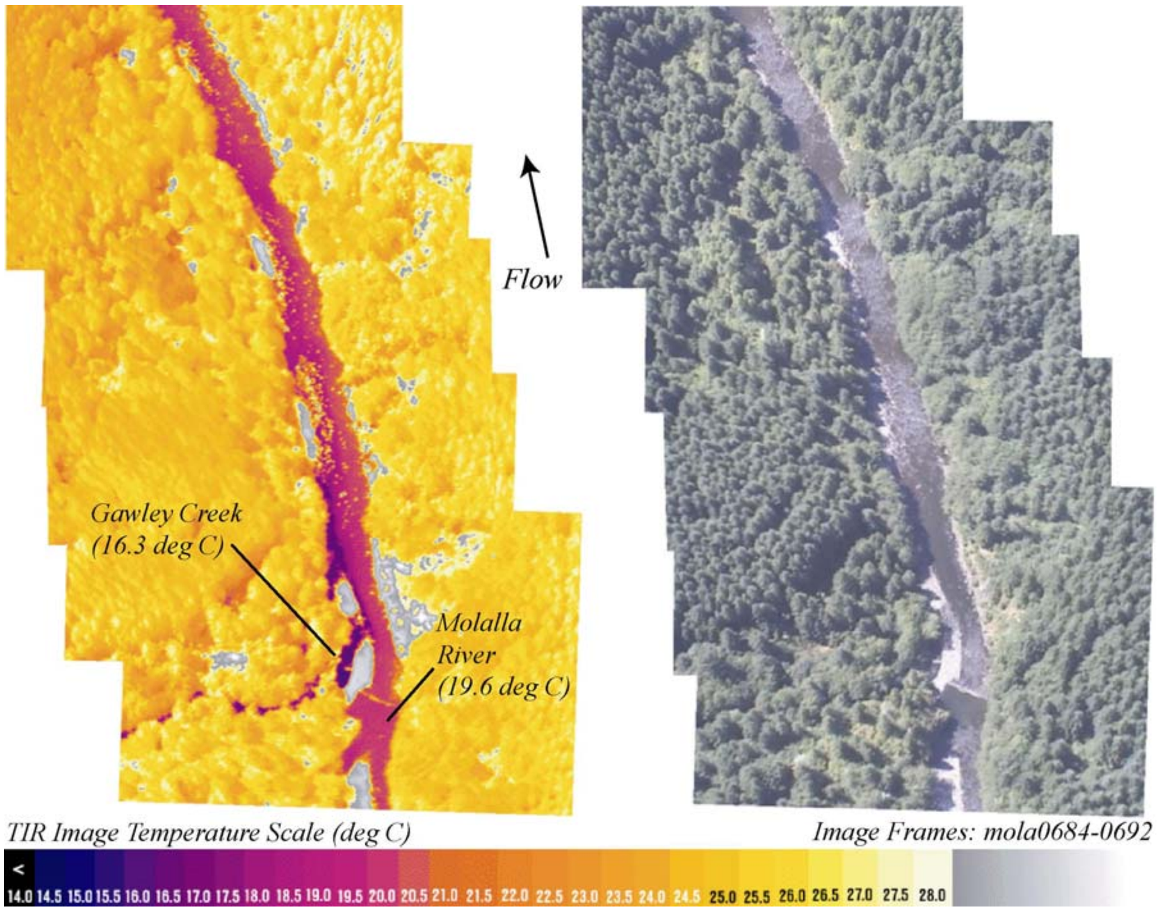


The image pairs on the left show a series of cool regions along the left bank of the Molalla River which were classified as springs. The image pair on the top shows a spring (15.1°C) along the left bank of the Molalla River (18.3°C) at river mile 41.4. The image pair on the bottom shows two springs along the left bank of the Molalla River (17.8°C) at river mile 41.2. The upstream spring (in the bottom half of the image) was 15.0°C while the spring just downstream (in the top half of the image) was 13.1°C. The plot below shows the locations of these spring images (red dots) along the longitudinal profile.

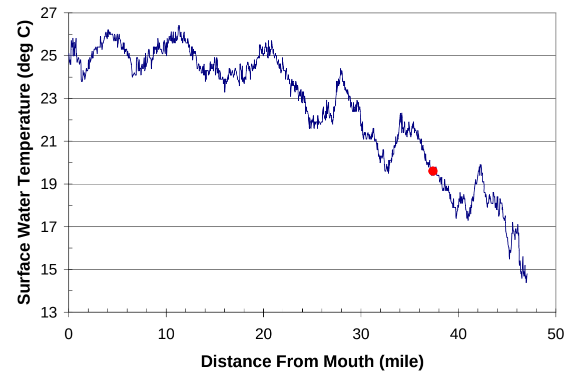




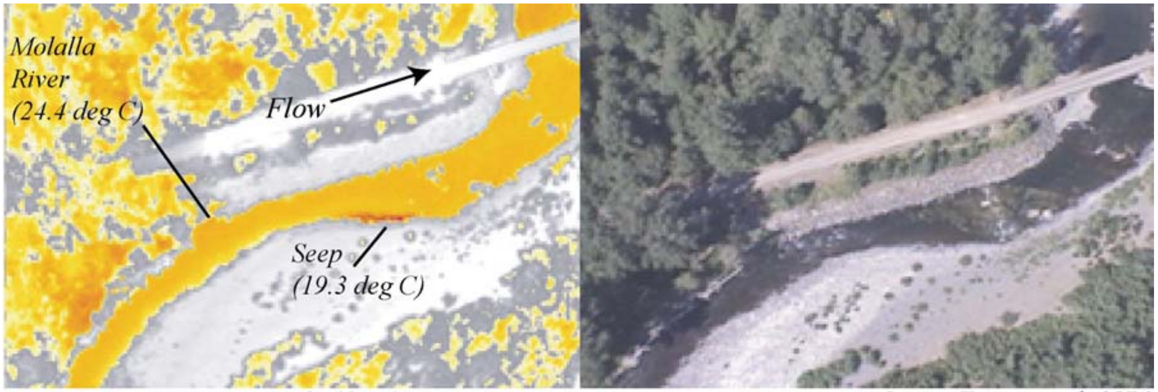
Gawley Creek (mile 37.4)



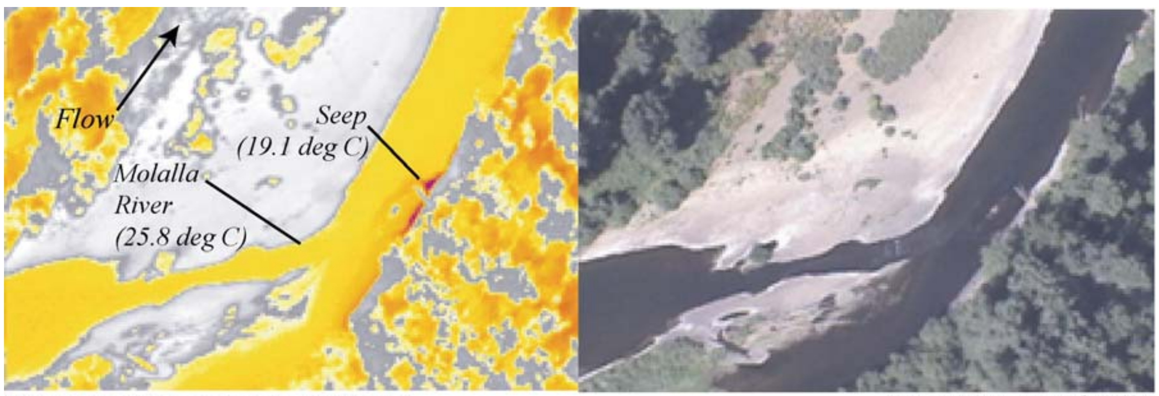
The image pair on the left shows the confluence of Gawley Creek (16.3°C) and the Molalla River (19.6°C) at river mile 37.4. The plot below shows the location of this image (red dot) along the longitudinal profile.



Seeps (miles 22.3; 0.4)

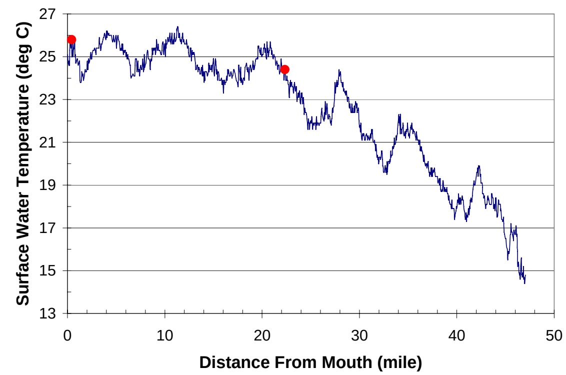


TIR Image Temperature Scale (deg C) *Image Frame: mola1576*

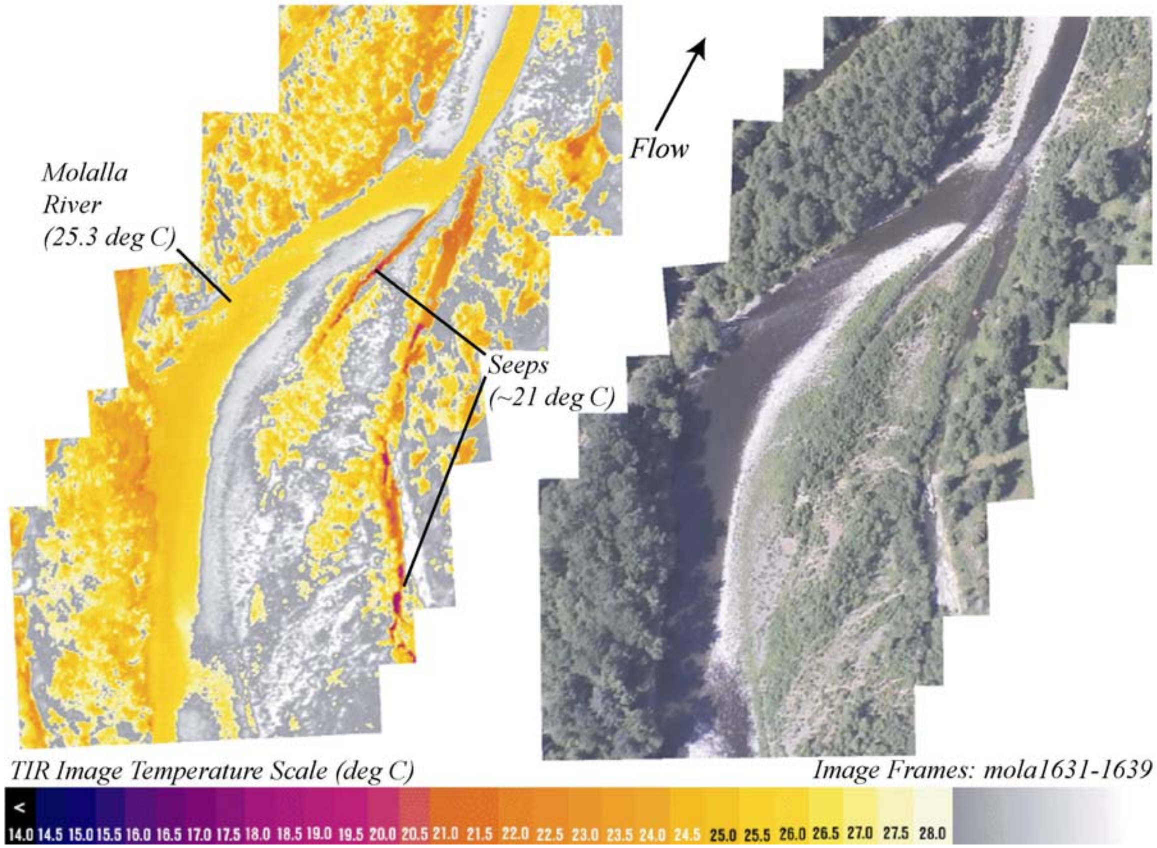


TIR Image Temperature Scale (deg C) *Image Frame: mola2607*

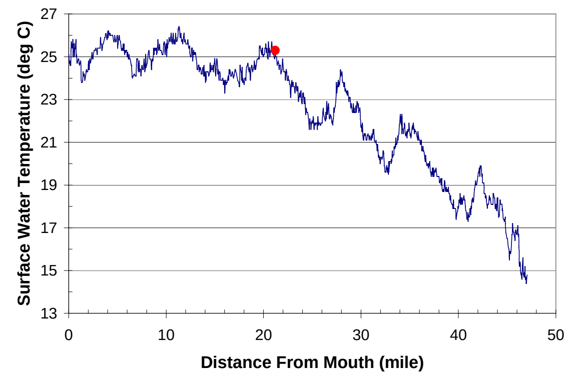
The image pairs on the left show two seeps along the right bank of the Molalla River. The image pair on the top shows a seep (19.3°C) at river mile 22.3 of the Molalla River (24.4°C). The image pair on the bottom shows the location of a seep (19.1°C) on the right bank of the Molalla River (25.8°C) at river mile 0.4. The plot below shows the locations of these images (red dot) along the longitudinal profile.



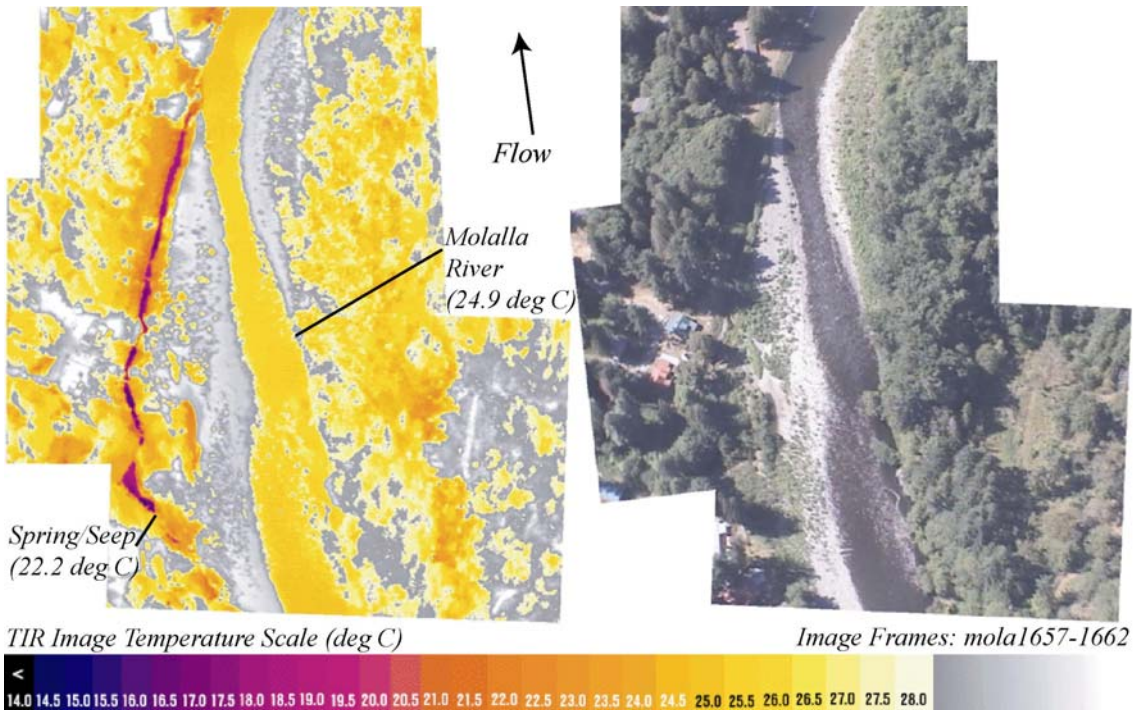
Seeps (mile 21.2)

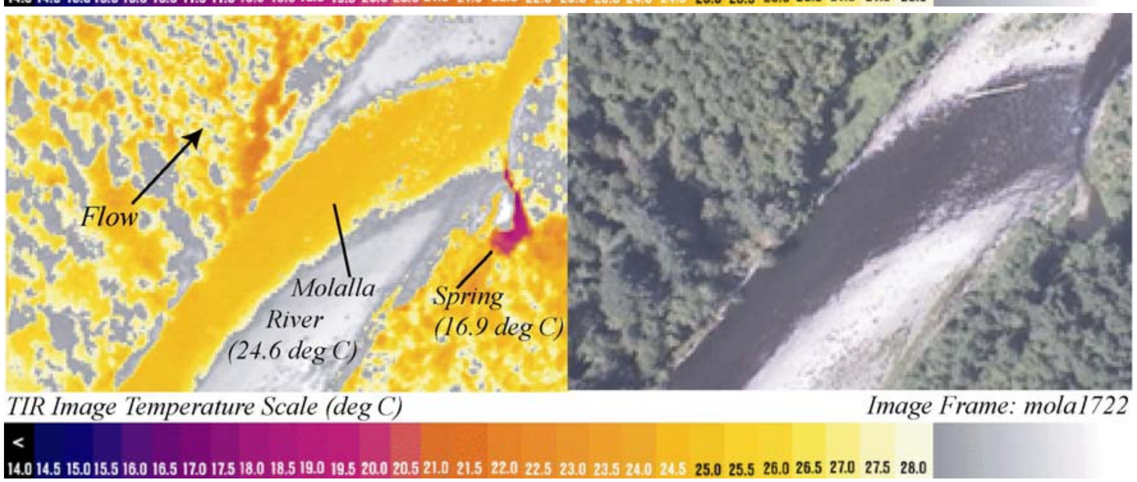


The image pair on the left shows two seeps (approximately 21^{o}C) along the right bank of the Molalla River (25.3^{o}C) at river mile 21.2. The plot above shows the location of this image (red dot) along the longitudinal profile.

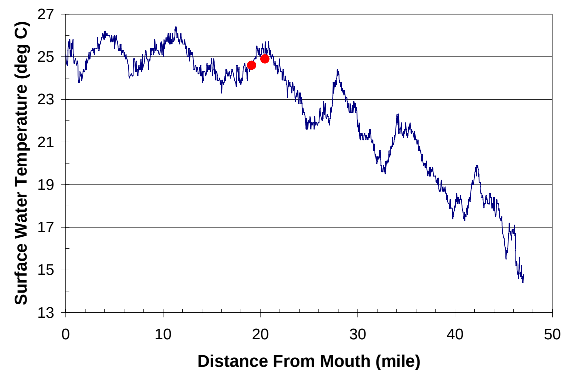


Springs (miles 20.5; 19.1)

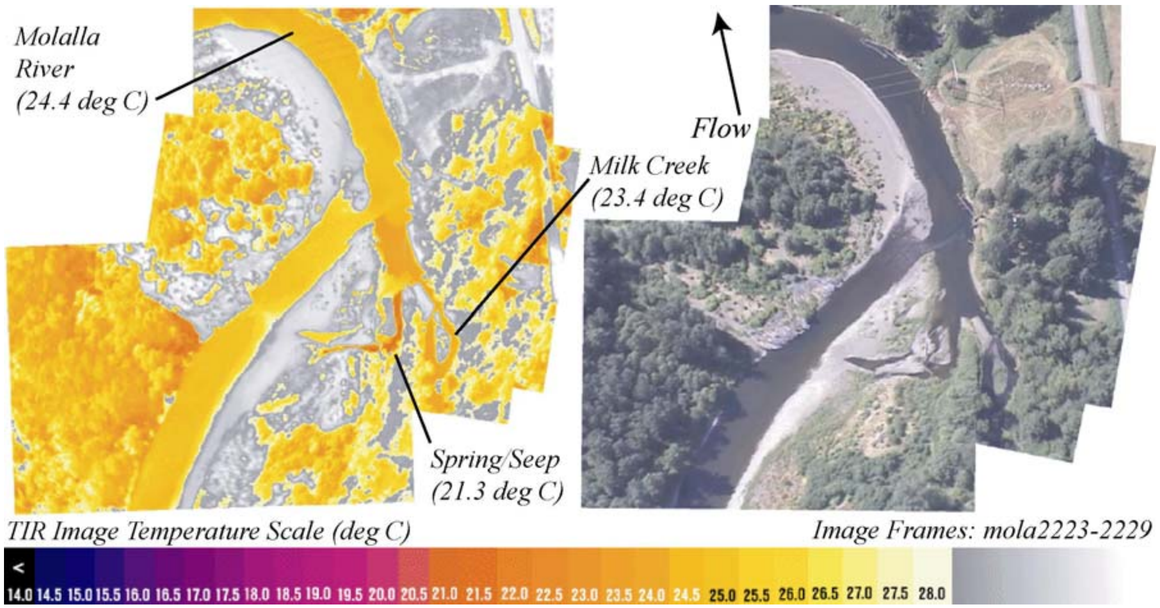


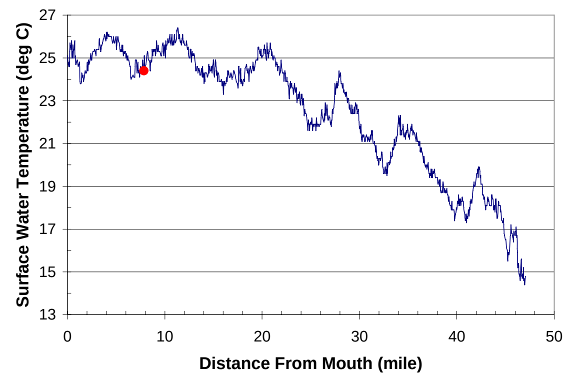


The image pairs on the left show the locations of two springs on the Molalla River. The image on the top shows a spring (22.2°C) along the left bank of the Molalla River (24.9°C) at river mile 20.5. The image pair on the bottom shows a spring (16.9°C) on the right bank of the Molalla River (24.6°C) at river mile 19.1. The plot below shows the locations of these images (red dots) along the longitudinal profile.



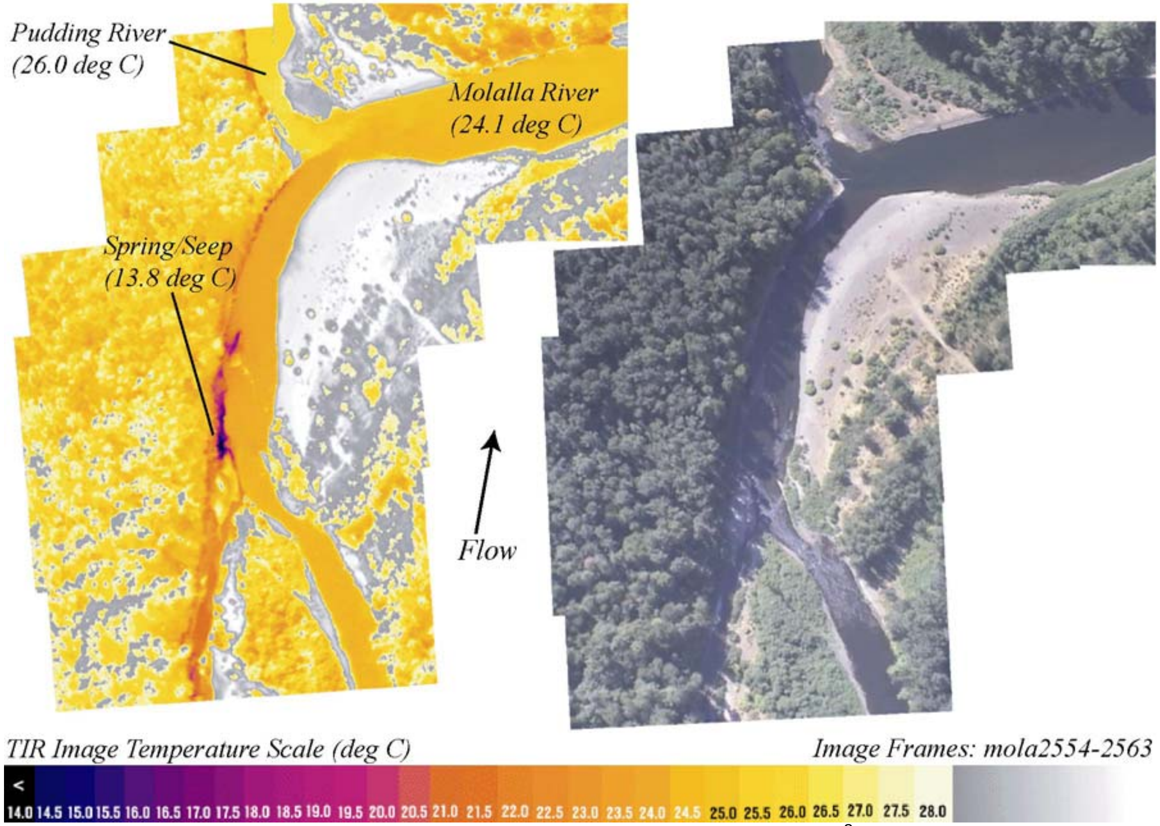
Milk Creek (mile 7.9)

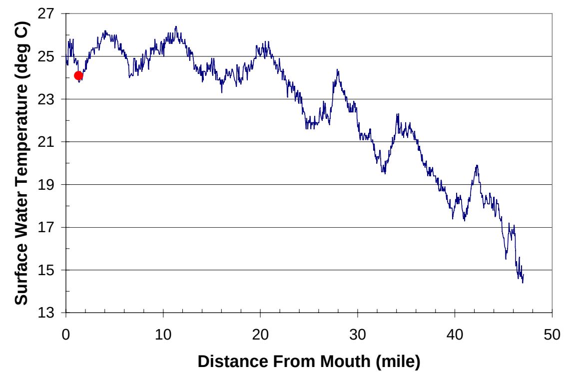




The image pair above shows the confluence of Milk Creek (23.4^{o}C) and the Molalla River (24.4^{o}C) at river mile 7.9. This image also shows a spring/seep (21.3^{o}C) entering the Molalla River near the mouth of Milk Creek. The plot above shows the location of this image (red dot) along the longitudinal profile.

Pudding River Confluence (mile 1.3)



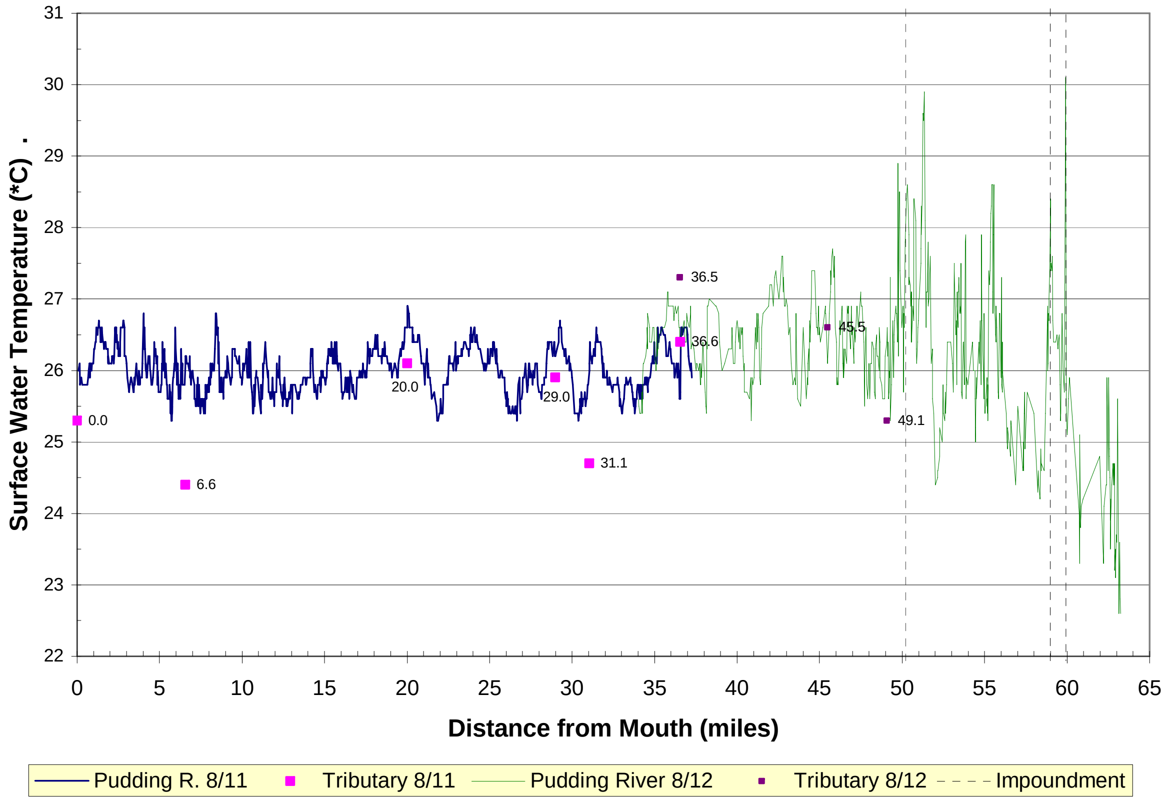


The image pair above shows the confluence of the Pudding River (26.0°C) and the Molalla River (24.1°C) at river mile 1.3. Also shown in the image is a spring (13.8°C) along the left bank upstream of the Pudding confluence. The plot above shows the location of this image (red dot) along the longitudinal profile.

Pudding River

Longitudinal Temperature Profile

The figure below illustrates the median sampled temperatures plotted versus river mile for the Pudding River. The location of tributaries and other surface inflows (e.g. springs) detected during the analysis are also illustrated on the plot and labeled by river mile. The table on the next page provides a summary of sampled inflows.



Tributaries, surface springs, and other detected surface inflows

Tributary Name	Image	km	mile	Tributary °C	Pudding R. °C	Difference °C
Aug. 11, 2004						
Molalla River (LB)	puda0166	0.0	0.0	25.3	26.0	-0.7
Mill Creek (LB)	puda0765	10.6	6.6	24.4	26.1	-1.7
Butte Creek (RB)	puda1927	32.2	20.0	26.1	26.7	-0.6
Zollner Creek (RB)	puda2672	46.7	29.0	25.9	26.2	-0.3
Unnamed Tributary (LB)	puda2814	50.0	31.1	24.7	26.1	-1.4
Little Pudding River (LB)	puda3183	58.9	36.6	26.4	25.7	0.7
Aug. 12, 2004						
Little Pudding River (LB)	pudb0932	58.8	36.5	27.3	26.4	0.9
Abiqua Creek (RB)	pudb1304	73.2	45.5	26.6	26.1	0.5
Silver Creek (RB)	pudb1610	79.0	49.1	25.3	26.4	-1.1

Observations and Analysis

The Pudding River presented some unique operational challenges. In the upper reaches (*headwaters to about mile 50*), the Pudding River was small and partially canopied by riparian vegetation. Surface temperatures were generally warm (e.g. greater than 22.6°C), which resulted in areas of decreased thermal contrast between the stream surface and terrestrial features. This combination of conditions made it difficult to continuously detect the stream's surface through the canopy from normal operating altitudes (i.e. above ground level). In the lower reaches, the river became progressively more sinuous with an almost constant series of large oxbows and meander bends. The desire to maintain high spatial resolution in the imagery required following the channel at slow speeds and precluded capturing the extent of the meander bends in single image frames.

Overall, radiant water temperatures in the Pudding River were warm, with measured temperatures exceeding 24°C over the lower 60 miles of river. Tributaries and other detected surface inflows were similarly warm, with radiant temperatures ranging between 24.4°C and 27.3°C. The following paragraphs provide a more detailed discussion of observed temperatures based on segmentation of the profile into reaches that showed similar thermal response/features. The segmentation is based entirely on visual inspection of the longitudinal profile and review of the TIR imagery and is intended to facilitate discussion.

Mile 63.2 – 49.1: The Pudding River showed an overall pattern of downstream warming with radiant water temperatures increasing from a survey low of 22.6°C at mile 63.2. Within this general trend, radiant water temperatures exhibited a high degree of spatial thermal variability. A number of different factors potentially contributed to the observed variability. First, the imagery shows a narrow stream channel (relative to pixel size) with considerable riparian vegetation. Some areas were not sampled due to the inability to detect the stream's surface through the riparian canopy. Under these conditions, one would expect a higher number of hybrid pixels (*reference the chapter regarding thermal image characteristics*) and hence increased sampling noise. However, since the temperature sampling is supervised, the "noise" due to hybrid pixels is considered minor and would not account for the level of local variability in the longitudinal temperature profile. The observed thermal variability is more likely attributable to the interaction of thermodynamic processes along the stream gradient. Due to the small size of the stream, water temperatures can respond dramatically to any mass balance change (e.g. sub-surface exchange, water withdrawals, etc.) in the river. Likewise, stream temperatures will also respond more rapidly to changes in micro-climates and exposure to direct solar radiation. The degree of local spatial thermal variability observed in this reach segment was similar to past surveys on small streams in the Willamette Valley, Oregon.[2] Three impoundments were detected within this reach segment, and high surface temperatures were measured just upstream of each impoundment. Review of the imagery suggests some level of thermal stratification within this reach. This was particularly true for the largest impoundment, located at river mile 50.2, where radiant surface temperatures approached recorded air temperatures.

Mile 49.1 to 36.5: Downstream of the Silver Creek confluence (mile 49.1), the Pudding River appeared to have increased surface flow compared to upstream reaches and was more continuously visible in the imagery. At the confluence of Silver Creek, the Pudding River is still confined by the terrain. However, as the river moves downstream to the confluence of the Little Pudding River (mile 36.5), it becomes progressively more sinuous and characteristic of the lower river. Radiant water temperatures were relatively warm, ranging between 25.4°C and 27.7°C and continued to exhibit some local spatial variability. Inspection of the TIR imagery shows evidence of differential heating at the water's surface, which contributes to variability in the profile. Normal indicators of differential heating are slightly warmer (e.g. 1 °C) radiant temperatures in calm, exposed pools and slightly cooler temperatures in shaded areas.

Mile 36.5 to 0.0: Between the Little Pudding River and the mouth of the Pudding River, radiant water temperatures ranged between 25.3 and 26.9°C. Measured temperatures were less variable locally than observed in the upper reaches. Five tributaries were sampled in the lower river. While water temperatures in the tributaries exceeded 24.4°C at the time of the survey, they still contributed cooler water than the main stem Pudding River. Inspection of the TIR imagery of this reach segment shows locations of differential heating at the water's surface, but no thermally stratified areas that were clearly stratified.

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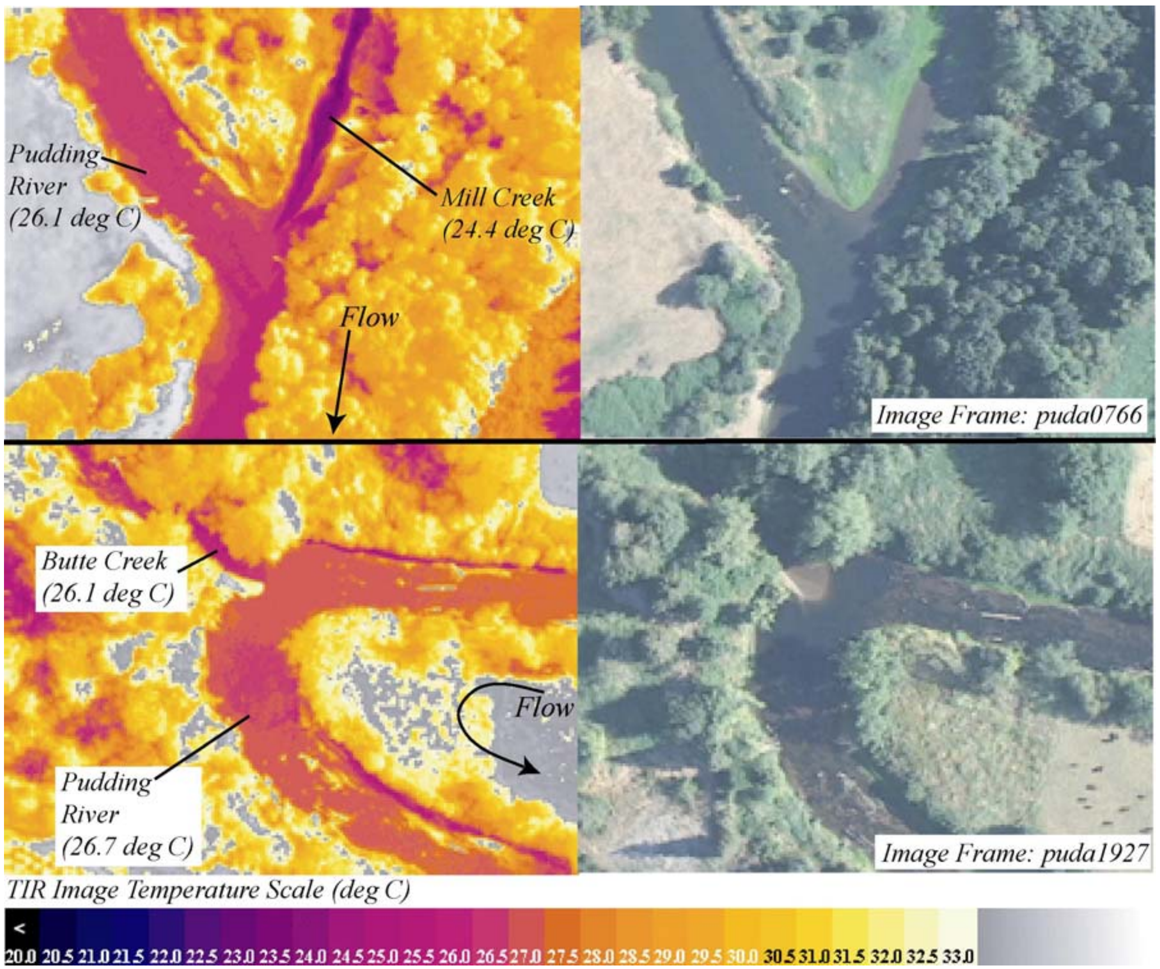
[2] Watershed Sciences, LLC. 2002. "Airborne Thermal Infrared and Color Videography of Johnson Creek, OR". Report to the Oregon Department of Environmental Quality.

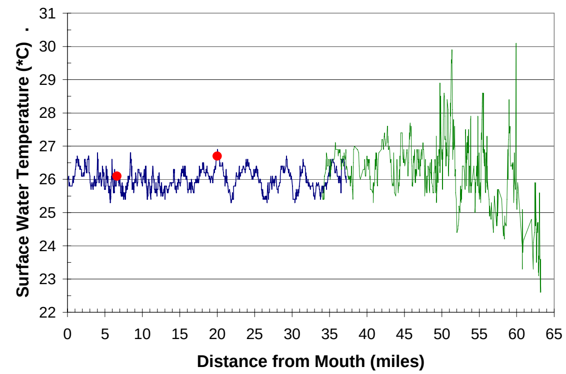
Sample Images

The following pages contain sample images from the TIR survey of the Pudding River, which provide samples of thermal features and channel conditions observed during the survey.

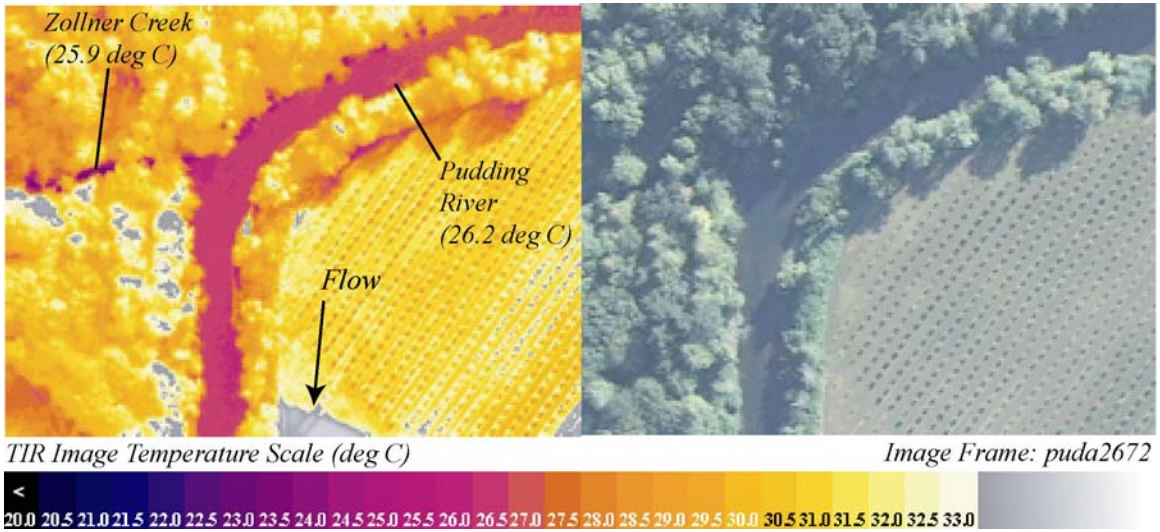
Mill Creek and Butte Creek (miles 6.6; 20.0)

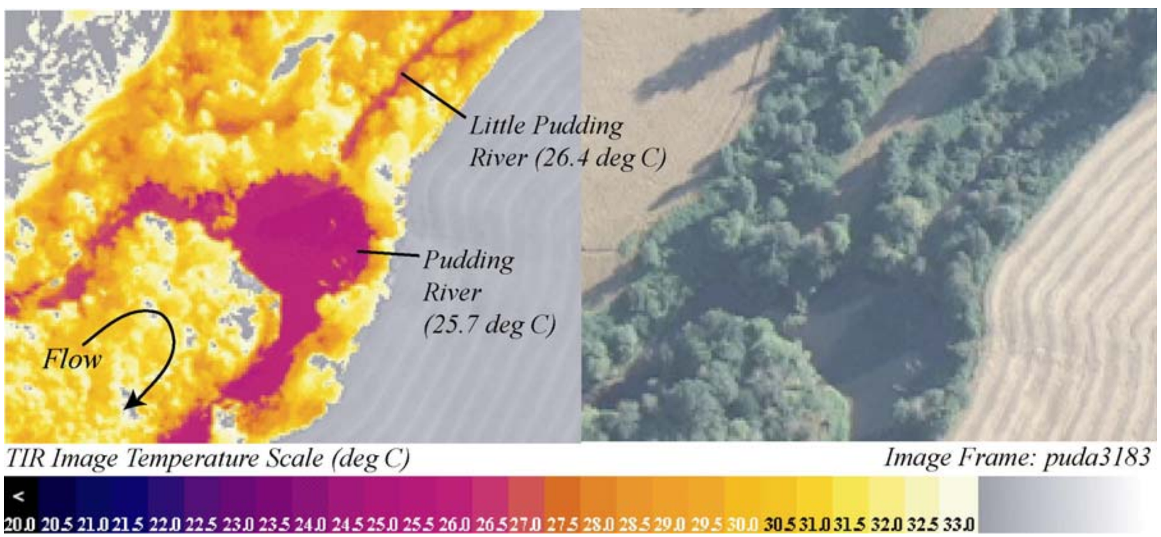


The image pairs on the left show the confluences of two tributaries to the Pudding River which contribute colder water than the main stem. The image pair on the top shows the confluence of Mill Creek (24.4°C) and the Pudding River (26.1°C) at river mile 6.6. The bottom pair shows the confluence of Butte Creek (26.1°C) and the Pudding River (26.7°C) at river mile 20.0. The plot below shows the locations of these images (red dots) along the longitudinal profile.

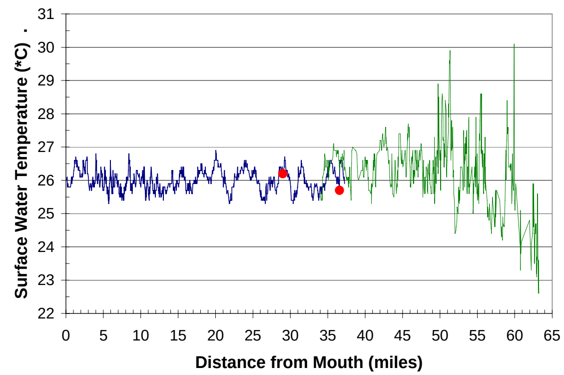


Zollner Creek and the Little Pudding River (miles 29.0; 36.6)

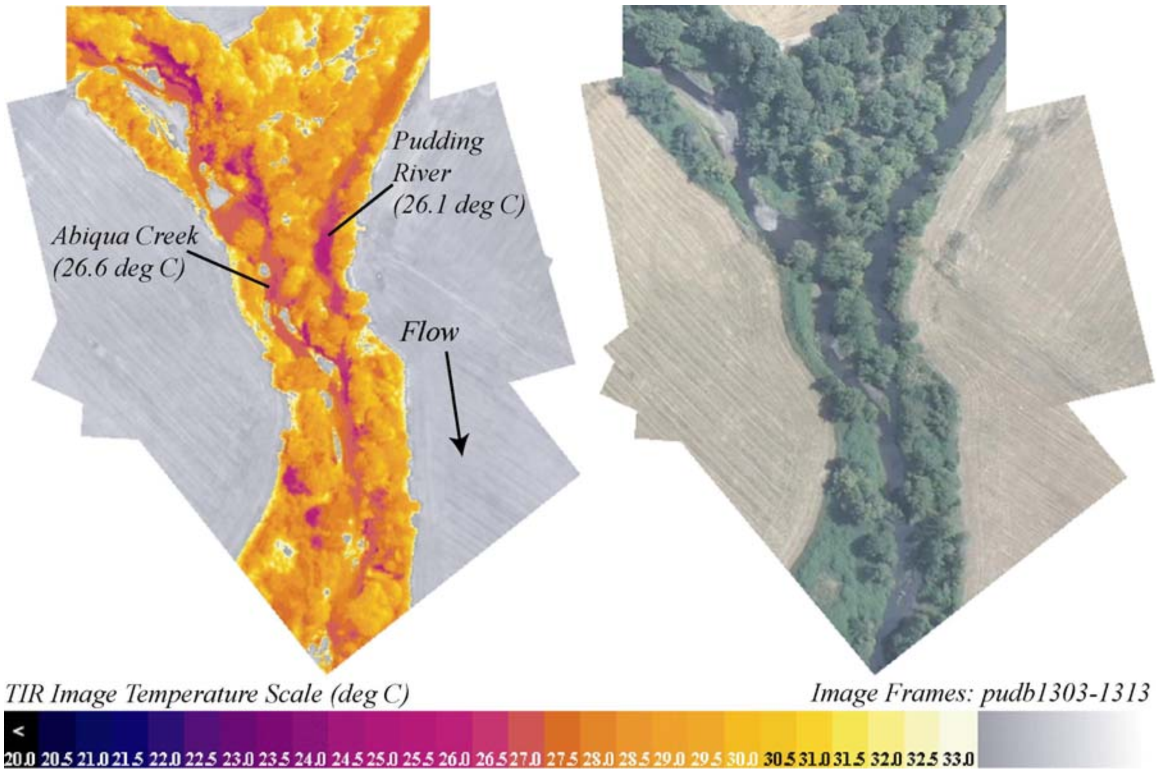


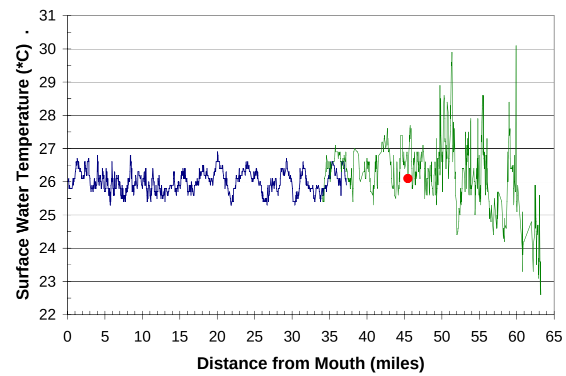


The image pairs on the left show the confluence of two tributaries to the Pudding River. The pair on the top shows the confluence of Zollner Creek (25.9°C) and the Pudding River (26.2°C) at river mile 29.0, and the pair on the bottom shows the confluence of the Little Pudding River (26.4°C) and the Pudding River (25.7°C) at river mile 36.6. The plot below shows the locations of these images (red dots) along the longitudinal profile.



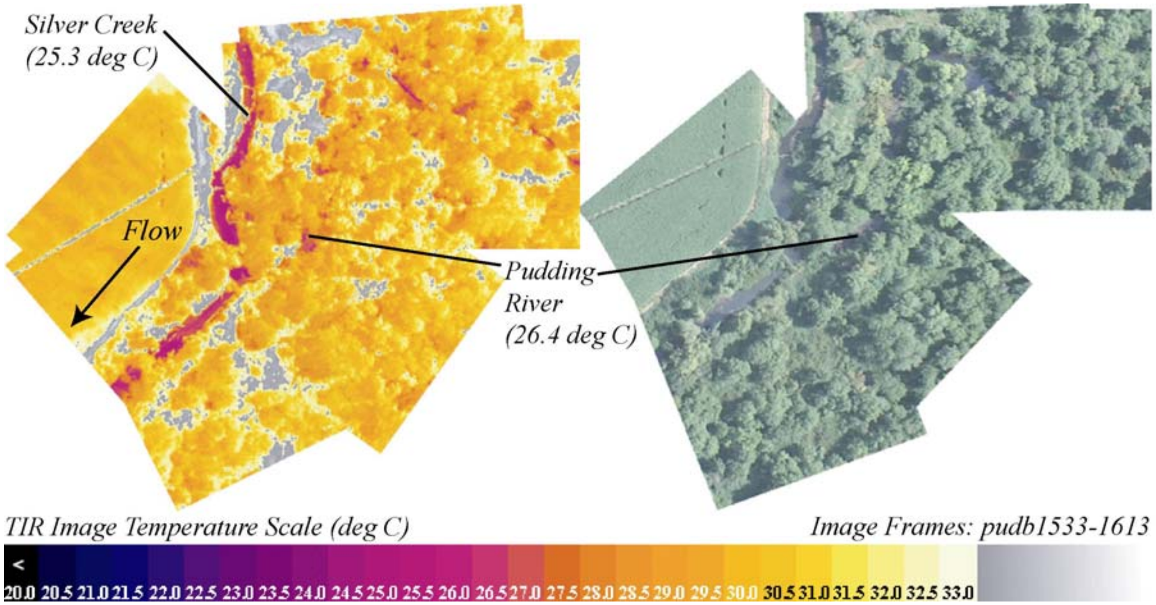
Abiqua Creek (mile 45.5)

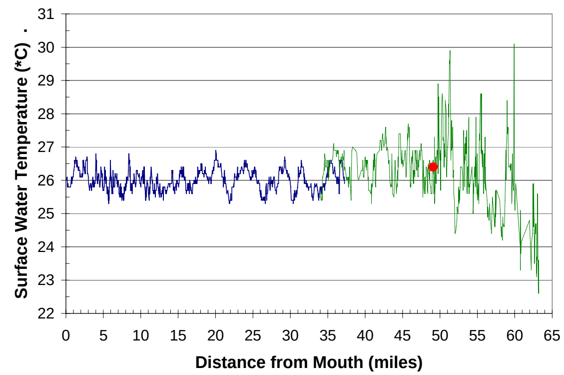




The image pair above shows the confluence of Abiqua Creek (26.6°C) and the Pudding River (26.1°C) at river mile 45.5. The plot above shows the location of this image (red dot) along the longitudinal profile.

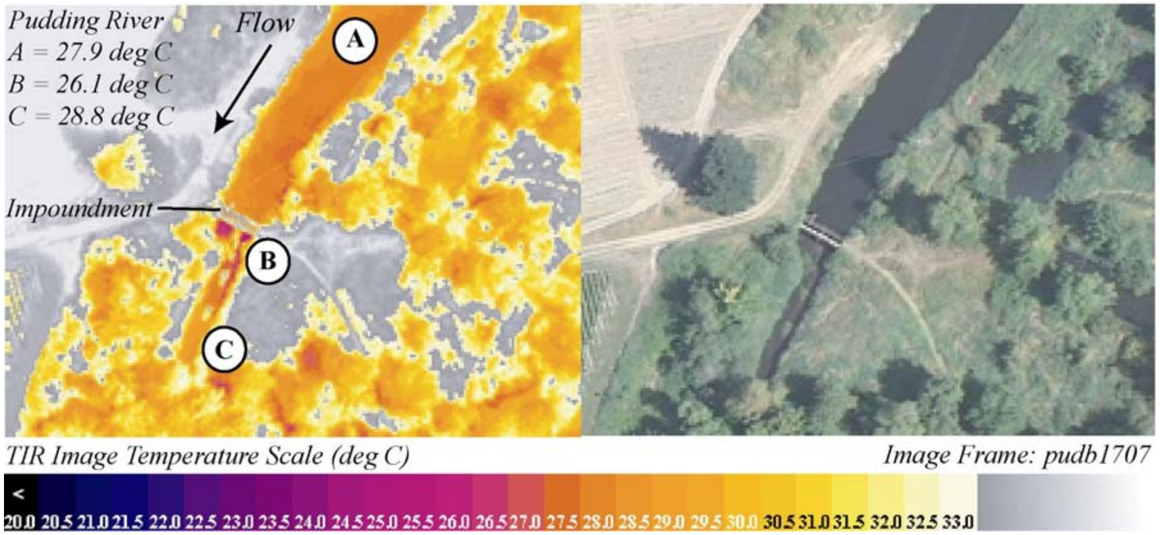
Silver Creek (mile 49.1)

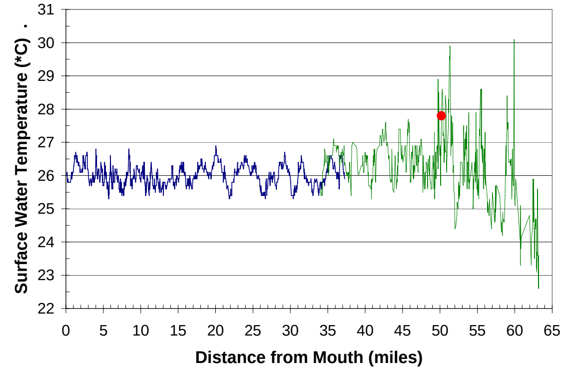




The image pair above shows the confluence of Silver Creek (25.3°C) and the Pudding River (26.4°C) at river mile 49.1. Downstream of the addition of the Silver Creek flow to the Pudding River, the main stem becomes continuously visible, with more surface flow. The plot above shows the location of this image (red dot) along the longitudinal profile.

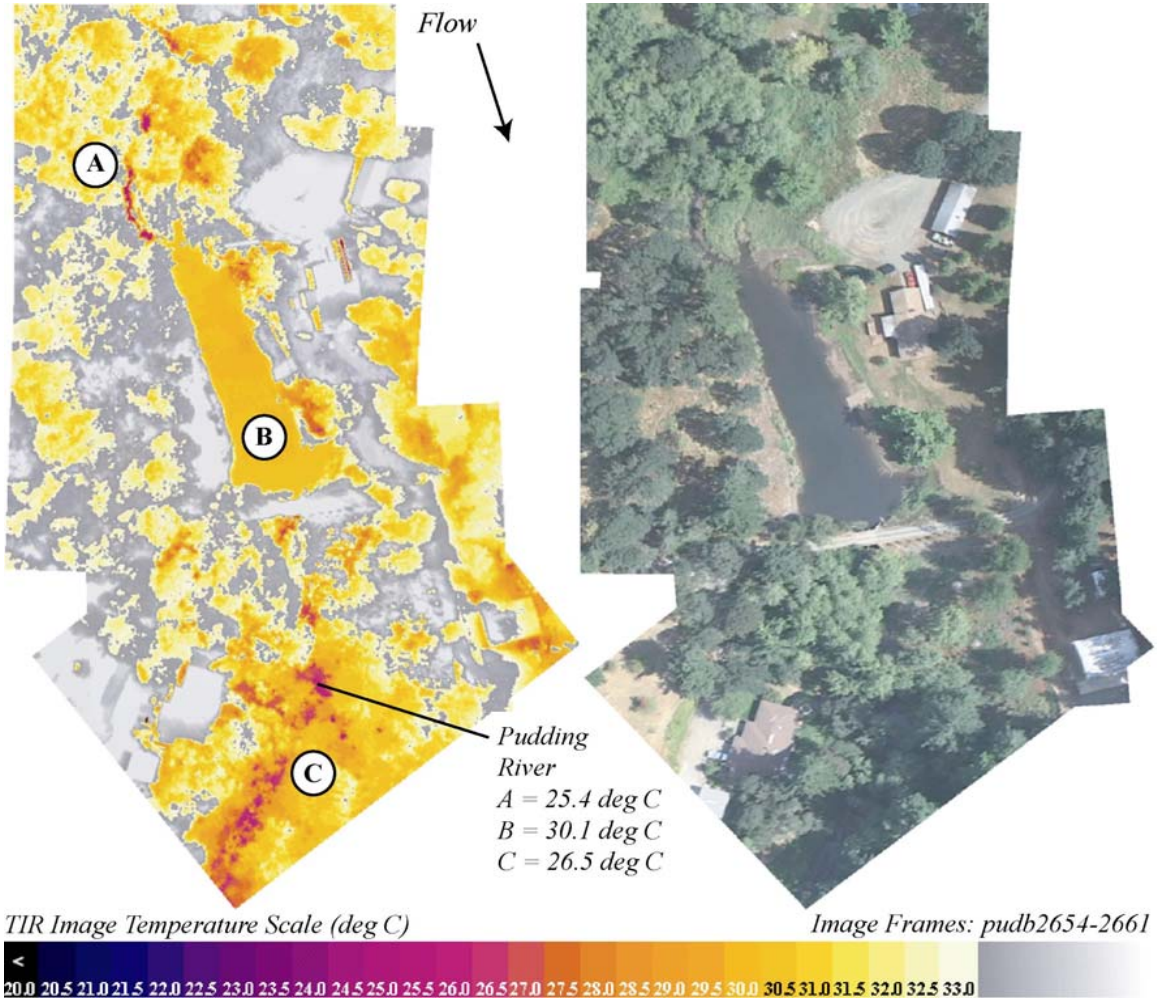
Impoundment (mile 50.2)



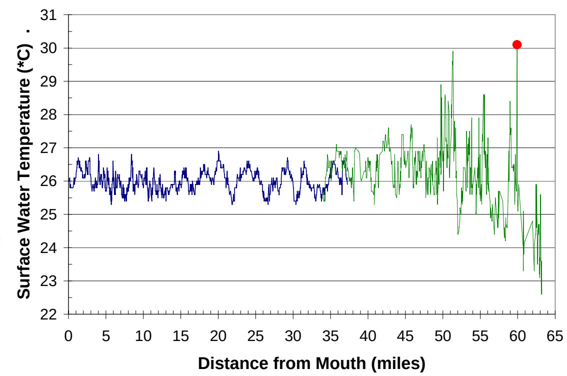


The image pair above shows an impoundment at river mile 50.2 of the Pudding River. Upstream of the impoundment (point A), the Pudding River main stem was 27.9°C, and showed cooler temperatures of 26.1°C at the outlet (point B). The cooler temperatures at the outlet suggest some level of thermal stratification upstream of the impoundment. However, radiant water temperatures increased rapidly again downstream, reaching 28.8°C just downstream of the outlet (point C). The plot above shows the location of this image (red dot) along the longitudinal profile.

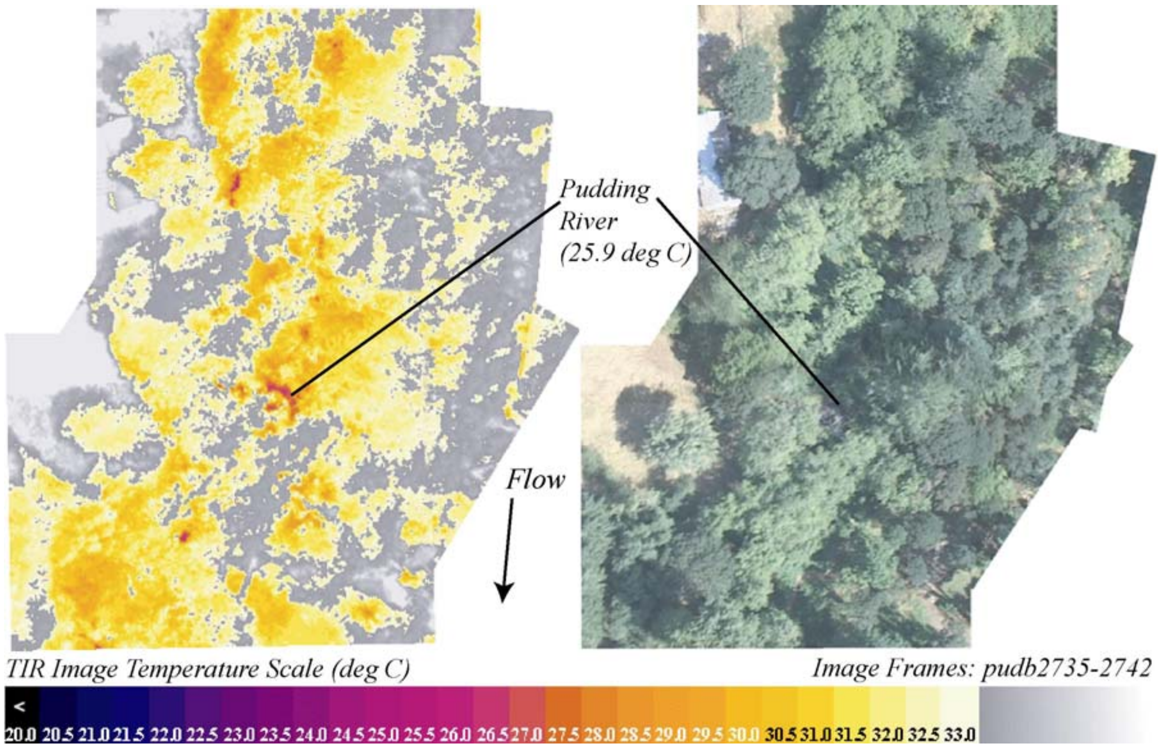
Impoundment (mile 59.9)

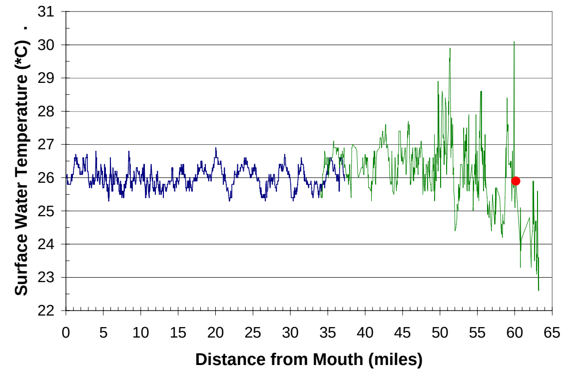


The image pair on the left shows an impoundment at river mile 59.9 of the Pudding River. The temperature at point A was 25.4°C, with the temperature increasing to 30.1°C just upstream of the road crossing (point B) and decreasing again, reaching 26.5°C at point C. The high surface temperatures at point B suggest that the pond behind the impoundment is thermally stratified. The plot below shows the location of this image (red dot) along the longitudinal profile.



Heavily Canopied Conditions (mile 60.2)





The image pair above shows the Pudding River at river mile 60.2. Canopy masking in this and other reaches resulted in intermittent sampling of main stem temperatures in the upper river. The plot above shows the location of this image (red dot) along the longitudinal profile.

Summary of Survey Results

TIR images of the Molalla and Pudding Rivers were successfully collected during mid-summer of 2004. The accuracy of the radiant temperatures was within specified values (i.e. ±0.5^{o}C) when compared to kinetic temperatures recorded by in-stream data loggers deployed prior to the flight. Weather conditions were considered good on the days of the survey.

Longitudinal temperature profiles were developed for both the Pudding and Molalla Rivers. The profile illustrates how heating (*and cooling*) rates vary along the stream gradient and identifies the locations where temperatures exhibit a high degree of local spatial variability. A more detailed analysis of the imagery, vegetation, and morphology is warranted to understand the observed spatial temperature patterns. The hypotheses and observations contained in this report 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 for the viewing of temperature patterns and channel characteristics at finer spatial scales.

The spatially explicit temperature data generated by this survey provide a compliment to temporally continuous in-stream data collected using more traditional monitoring methods. In the context of this effort, the spatial data will provide a calibration source for physically based, basin scale stream temperature models used in ODEQ's TMDL process. In addition, the TIR imagery is a powerful tool for illustrating and communicating thermal processes in the watershed. Further analysis might include:

1. <u>Molalla River</u>: What role does sub-surface exchange play in defining spatial temperature patterns in the river? Do detected areas of localized hyporheic discharge represent thermal refuge for cold water fish species?

2. <u>Pudding River:</u> Image mosaics (and possibly geo-rectification) of large meander bends will facilitate interpretation of temperature patterns in the lower river. How variable are temperature vertically in the lower river (e.g. do low stream gradients and variable mixing rates result in cooler temperatures near the bottom of deep pools?)? What are the thermal processes driving spatial temperature variability in the upper river?