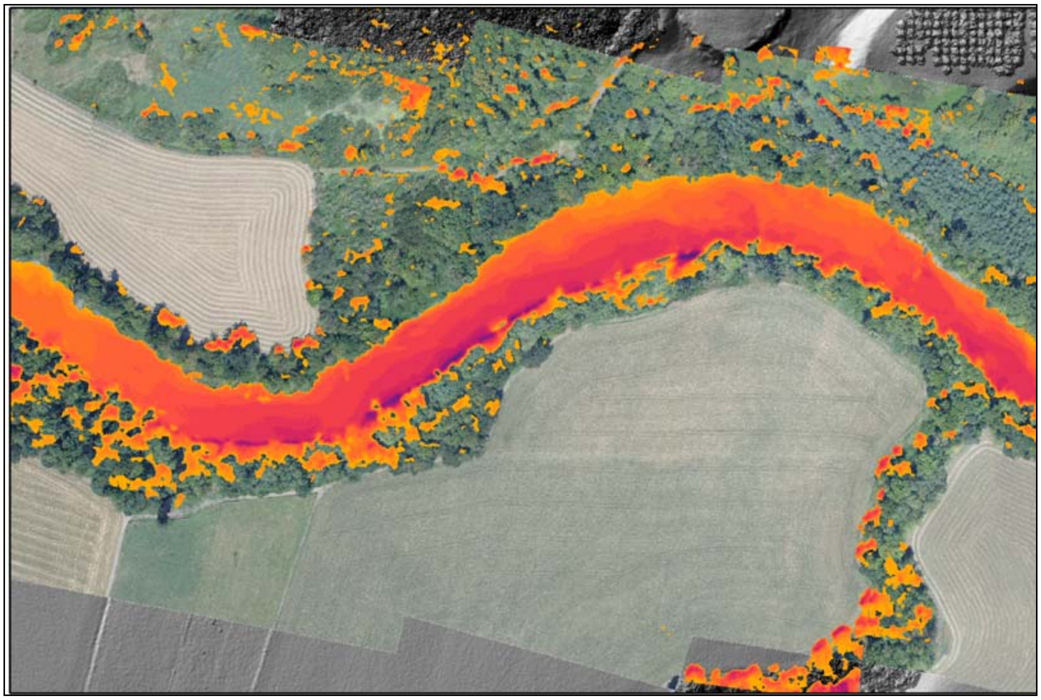
Airborne Thermal Infrared Remote Sensing
Yamhill River, OR



Submitted to:

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Table of Contents

Background

Airborne thermal infrared (TIR) remote sensing has proven to be an effective method for mapping spatial temperature patterns in rivers and streams. These data are used to establish baseline conditions and direct future ground level monitoring. The TIR imagery illustrates the location and thermal influence of point sources, tributaries, and surface springs. When combined with other spatial data sets, the TIR data also illustrate reach-scale thermal responses to changes in morphology, vegetation, and land use. These data have provided the basis for assessing stream temperature dynamics on a number of rivers across the Western United States.

In 2005, the Oregon Department of Environmental Quality (ODEQ) contracted with Watershed Sciences to provide TIR and true color digital imagery of the Yamhill River. The data were acquired on July 27, 2005 during the mid-afternoon hours (1:15 to 3:15 PM). The flight dates were chosen to capture heat of the day, heat of the summer thermal conditions in the river. Prior to the flight, Watershed Sciences' staff distributed in-stream data loggers (Onset Stowaways and Tidbits) in the river in order to provide a quantitative assessment of radiant temperature accuracy (Figure 1).

This report details the work performed, including methodology and quantitative assessments of data quality. In addition, the report presents the spatially continuous longitudinal temperature profile derived from the imagery. These profiles provide a landscape-scale perspective of how temperatures vary along the stream gradient and are the basis for follow-on analysis. Sample images are also contained in this document in order to illustrate some of the thermal features, channel characteristics, and hydrologic processes discussed in the report. The images are not meant to be comprehensive, but to provide examples of image scenes and interpretations contained in the image database.

Survey Extent

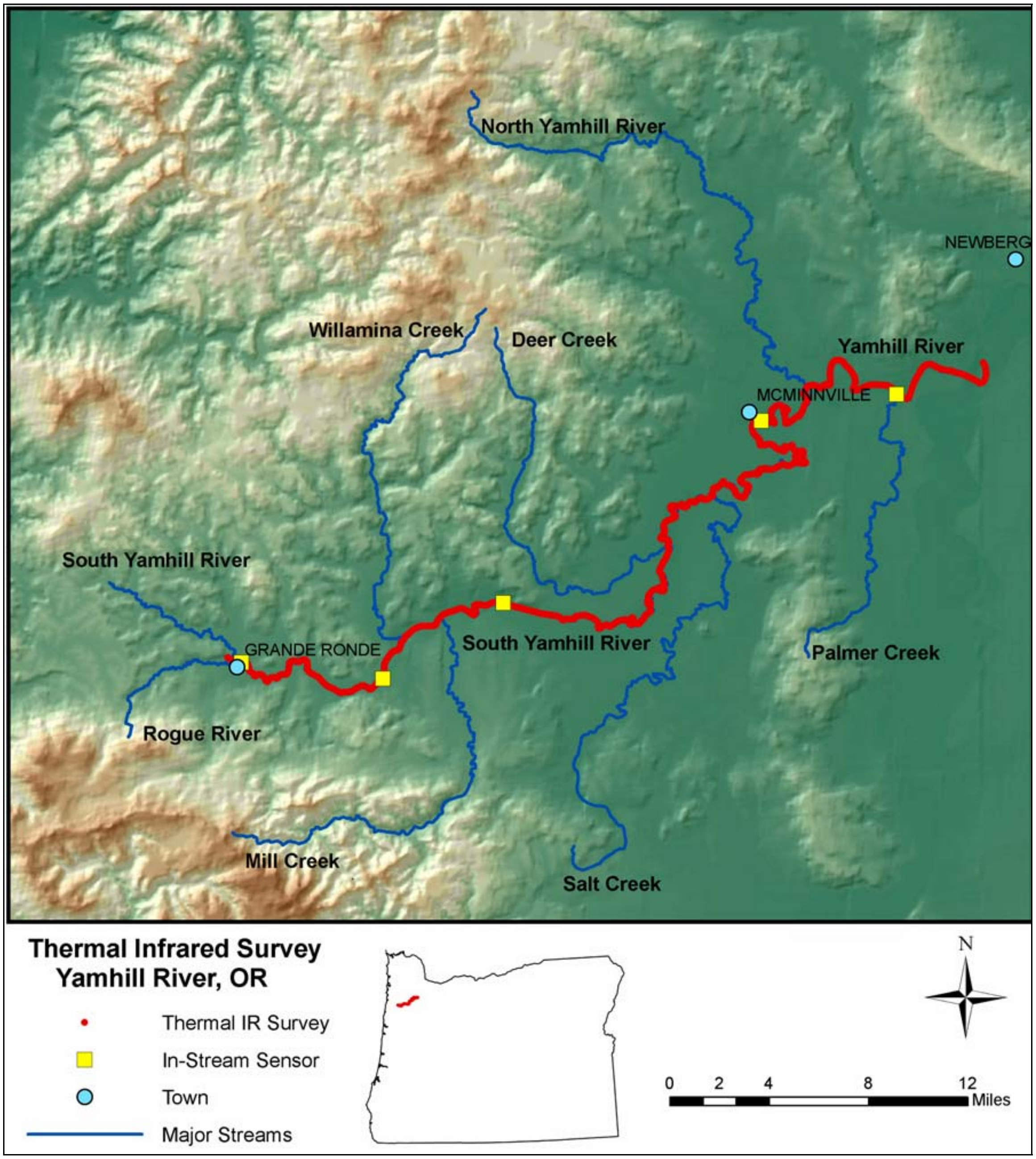


Figure 1 – Map showing the extent of the airborne thermal infrared survey on the Yamhill River on July 27, 2005. The map also shows the location of in-stream temperature monitors.

Methods

Data Collection

Instrumentation: Images were collected with TIR (8-12μ) and true color digital cameras mounted on the underside of a helicopter (Figure 2). The helicopter was flown longitudinally along the stream channel with the sensors looking straight down. Thermal infrared images were recorded directly from the sensor to an on-board computer as raw counts, which were then converted to radiance values. The individual images were referenced with time and position data provided by a global positioning system (GPS).

Figure 2 - Bell Jet Ranger equipped with a thermal infrared radiometer and high resolution digital camera. The sensors are contained in a composite fiber enclosure attached to the underside of the helicopter and flown longitudinally along the stream channel.

Image Characteristics: The flight plan was designed to capture the width of the active channel at a high spatial resolution. Images were collected sequentially with 40% or greater vertical overlap. The helicopter maintained a flight altitude of 1200 ft above ground level (AGL), resulting in an image width of 234 meters (768 ft) and a native pixel resolution of 0.37 meters (2.4 ft).

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 along the survey route (Figure 1). The distribution of the in-stream data loggers allowed for the monitoring of radiant temperatures at regular intervals over the extent of the survey. Meteorological data including air temperature and relative humidity were recorded using a portable weather station located at Joe Dancer Park in McMinnville.

Data Processing

Calibration: The raw TIR images contain digital numbers that were converted to radiance values based on the response characteristics of the sensor. These measured radiance values were then adjusted using a version of the radiation transfer equation (listed below). The path length attenuation was calculated empirically by comparing the measured radiance to the calculated radiance at each ground truth location. Given the high emissivity of water, the reflection term $I(T_{reflect})$ was very low and dropped from the equation. The in-stream data were assessed at the time the image was acquired, with radiant values representing the median of ten points sampled from the image at the data logger location.

$$I(T_{measured}) = I(T_{object}) * \varepsilon * \tau + I(T_{reflect}) * (1 - \varepsilon) * \tau$$

I(Tmeasured)	=measured radiance
I(Tobject)	= radiance emitted at the water surface at given temperature
I(Tatmosphere)	= radiance emitted by the intervening atmosphere
I(Treflected)	= radiance reflected by surrounding objects
ε	= emissivity of water
τ	= path length attenuation

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

Geo-referencing: The images are tagged with a GPS position at the time they are acquired. Since the TIR camera is maintained at vertical down-look angles, the geographic coordinates provide an accurate index to the location of the image scene. In order to provide further spatial reference, the TIR images were assigned a river mile based on a routed stream layer (Figure 3).

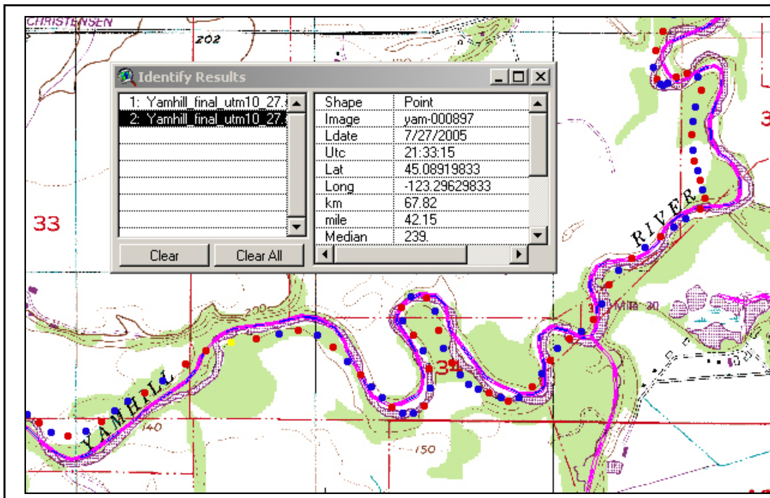


Figure 3 –Each point on the map represents a thermal image location. The inset box shows the information recorded with each image point during acquisition.

<u>Temperature Profiles:</u> The median temperatures for each sampled image were plotted versus the corresponding river mile to develop a longitudinal temperature profile. The profile illustrates how stream temperatures vary spatially along the stream gradient. The location and median temperature of all sampled surface water inflows (e.g. tributaries, surface springs, etc.) are included on the plot to illustrate how these inflows influence the main stem temperature patterns. Where applicable, tributaries or other features that were detected in the imagery, but were not sampled due to their small size (*relative to pixel size*) or the inability to see the stream through riparian vegetation are included on the profile to facilitate the interpretation of the spatial patterns.

<u>Geo-Rectification:</u> The TIR images were geo-rectified to real world coordinates for the first 42.2 river miles using a LiDAR dataset collected by Watershed Sciences on October 12, 2005 (Figure 4). The remaining miles of the survey (to river mile 64.2) were geo-rectified to the most recently available digital orthophoto quads (DOQs). Individual frames were geo-rectified manually by finding a minimum of three common ground control points (GCP's) between the true color images and the base imagery (LiDAR dataset and DOQs). An emphasis was placed on finding control points in or near the river channel, with no points in the upland areas. Control points included fixed features such as vegetation, and channel curvatures. The images were then warped using a 1st order polynomial transformation. TIR images were geo-rectified using the same general methodology with the true color images used as the control layer.

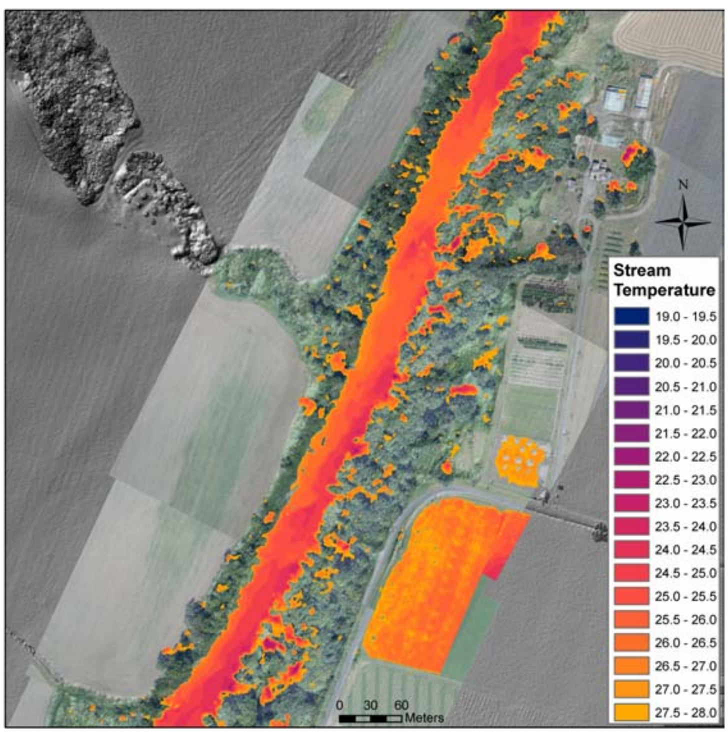


Figure 4 – Thermal mosaic and true-color image mosaics, geo-rectified to a LiDAR bare earth hillshade with a semi-transparent vegetation hillshade (gray base layers), at river mile 2.6 of the Yamhill River.

Thermal Image Characteristics

<u>Surface Temperatures:</u> 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.

<u>Expected Accuracy:</u> Thermal infrared radiation received at the sensor is a combination of energy emitted from the water's surface, reflected from the water's surface, and absorbed and re-radiated by the intervening atmosphere. Water is a good emitter of TIR radiation and has relatively low reflectivity (~ 4 to 6%). However, variable water surface conditions (i.e. riffle versus pool), slight changes in viewing aspect, and variable background temperatures (i.e. sky versus trees) can result in differences in the calculated radiant temperatures within the same image or between consecutive images. The apparent temperature variability is generally less than 0.5°C (Torgersen et al. 2001[1]). However, the occurrence of reflections as an artifact (or noise) in the TIR images is a consideration during image interpretation and analysis. In general, apparent stream temperature changes of < 0.5°C are not considered significant unless associated with a surface inflow (e.g. tributary).

<u>Differential Heating:</u> 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.

<u>Feature Size and Resolution:</u> 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. This was not an issue when sampling radiant temperatures on the Yamhill River, but is a consideration when sampling the radiant temperatures at tributary mouths. In some cases, small tributaries

[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.

were detected in the images, but not sampled due to the inability to obtain a reliable temperature sample.

<u>Temperatures and Color Maps:</u> 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. Figure 5 provides an example of three different color maps applied to the same thermal image.

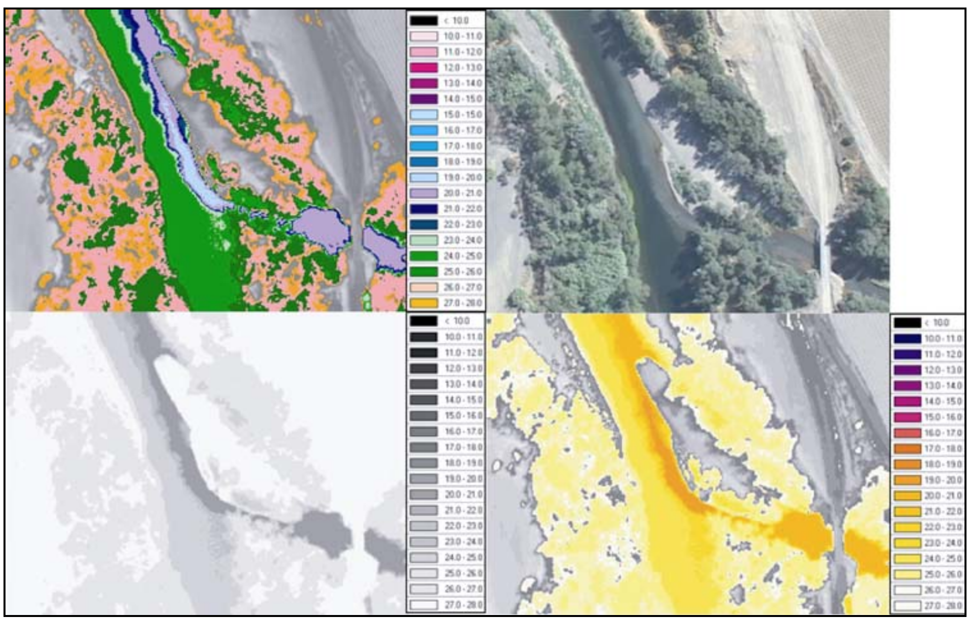


Figure 5 - Example of different color maps applied to the same TIR image.

<u>Image Uniformity:</u> The TIR sensor used for this study uses a focal plane array of detectors to sample incoming radiation. A challenge when using this technology is to achieve uniformity across the detector array. A calibration is performed on the ground, which provides a uniformity correction. However, due to lens distortion and variable transmission effects, slight radiometric differences can exist between the center and edge of the images. These differences are typically small, with resulting temperature variations ranging from 0.2 to 0.4°C. These differences are not normally an issue, but are noticeable when multiple frames are mosaicked.

Results

Weather Conditions

Table 1 - Weather conditions recorded at Joe Dancer Park in McMinnville during the time of the survey on July 27, 2005.

Time	Air Temp °F	Air Temp °C	Dew Point °F	RH %
12:00	85.8	29.9	48.7	27.7
12:30	87.3	30.7	46.5	24.4
13:00	88.7	31.5	45.7	22.6
13:30	90.2	32.3	49.0	24.4
14:00	91.7	33.2	48.8	23.1
14:30	92.5	33.6	47.2	21.3
15:00	94.0	34.4	43.9	17.9
15:30	94.7	34.9	43.9	17.5
16:00	94.7	34.9	43.9	17.5
16:30	95.5	35.3	40.7	15.1
17:00	94.7	34.9	42.7	16.7

Weather conditions were considered ideal with clear skies, air temperatures in the mid 90's (°F), low humidity, and calm winds.

Thermal Accuracy

Table 2 summarizes a comparison between the kinetic temperatures recorded by the in-stream data loggers and the radiant temperatures derived from the TIR images. The average absolute temperature accuracies were within the desired accuracy of ±0.5°C. The range of temperature differences was generally consistent with those observed during other surveys conducted over the past six years.

Table 2 - Comparison of in-stream (kinetic) temperatures and radiant temperatures derived from the TIR imagery.

Image Frame	River Mile	Time 24 hr	Kinetic °C	Radiant °C	Difference °C
27-July-05 (avg. abs. difference = 0.4°C)					
yam-000083*	4.3	13:22	20.7	21.1	-0.4
yam-000318	16.2	13:43	24.0	23.3	0.8
yam-001001	48.0	14:42	24.5	24.5	0.0
yam-001143	55.2	14:54	23.6	23.3	0.3
yam-001318	63.7	15:10	20.0	20.4	-0.4

**Located in mouth of Palmer Creek.*

Longitudinal Temperature Profile

Median sampled temperatures were plotted versus river mile for the Yamhill River from its mouth at the Willamette River to the confluence of the Rogue River, for a total of 64.2 river miles. Tributaries and other sampled inflows (e.g. springs/seeps) are labeled on the profile by river mile and summarized in the associated table (Table 3).

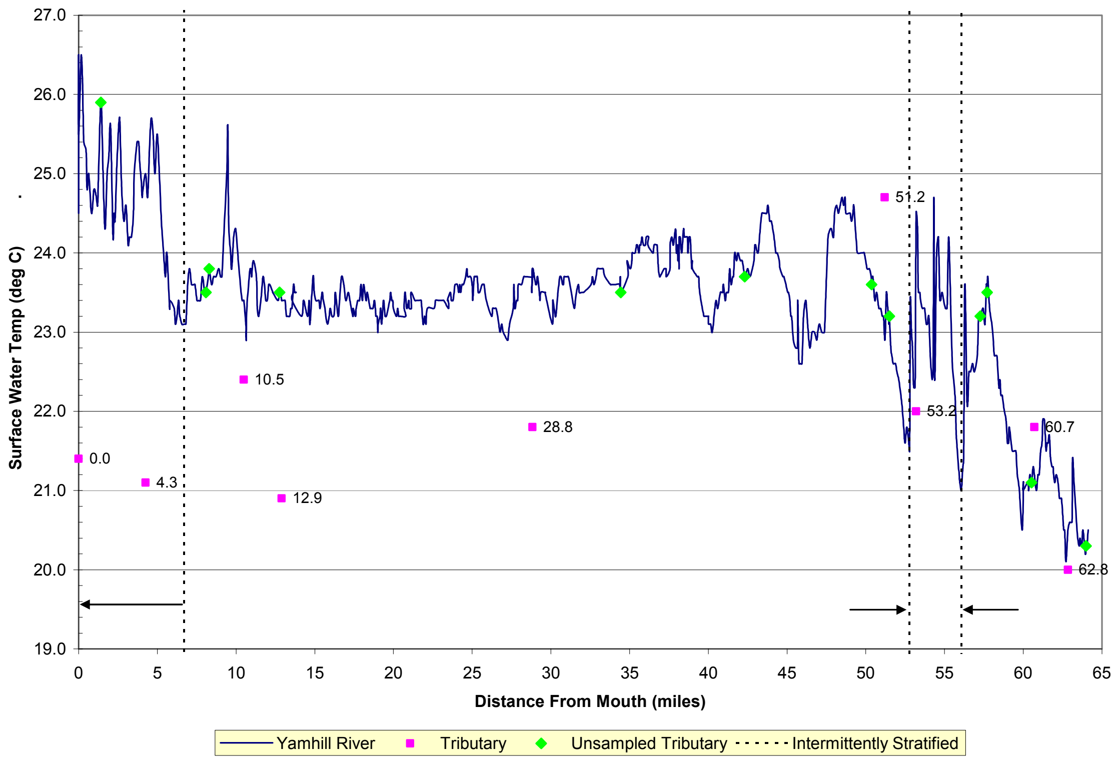


Figure 6 - Median sampled temperatures plotted versus river mile for the Yamhill River. Tributaries and other sampled inflows (e.g. springs/seeps) are labeled on the profile by river mile.

Table 3 – Location and radiant temperature of tributaries sampled during the Yamhill River survey on July 27, 2005.

Tributary Name	Image	km	mile	Tributary	Yamhill River	Difference
Willamette River (RB)	yam-000011	0.0	0.0	21.4	24.5	3.1
Palmer Creek (RB)	yam-000083	6.8	4.3	21.1	25.0	3.9
North Yamhill River (LB)	yam-000201	16.9	10.5	22.4	23.4	1.0
Unnamed Tributary (RB)	yam-000255	20.8	12.9	20.9	23.4	2.5
Salt Creek (RB)	yam-000598	46.4	28.8	21.8	23.8	2.0
Mill Creek (RB)	yam-001063	82.4	51.2	24.7	22.9	-1.8
Willamina Creek (LB)	yam-001105	85.6	53.2	22.0	24.5	2.5
Rowell Creek (RB)	yam-001242	97.7	60.7	21.8	21.2	-0.6
Rock Creek (RB)	yam-001296	101.1	62.8	20.0	20.5	0.5

Observations and Analysis

The Yamhill River was surveyed from its mouth at the Willamette River upstream to its confluence with the Rogue River, at river mile 64.2. Over the course of the survey, 9 tributaries were sampled; more were identified in the imagery, but due to the inability to clearly see the mouth of these tributaries, they remained unsampled. Of the 9 sampled tributaries, 7 contributed water which was cooler than that of the main stem.

Visual inspection of the TIR images show areas of intermittent thermal stratification (illustrated on longitudinal profile) and possibly differential surface heating. In river systems, thermal stratification is inherently unstable, resulting in rapid local shifts in measured surface temperatures. In some cases, observed temperature responses are due to a discharge into the river (i.e. surface or subsurface inflow), while in other cases, the response is due to a transition between a stratified and mixed condition. In a stratified reach, a more detailed analysis of in-stream data, morphology, and flow conditions should supplement direct interpretation of the imagery.

A trend line based on the sampled data (*described by a 2nd order polynomial*) was plotted over the longitudinal temperature profile to illustrate the general basin-scale temperature patterns (Figure 7). At the upstream end of the survey, radiant water temperatures exhibited a rapid downstream warming trend with noted stratification, before leveling off at about mile 44.0. Moving downstream, the profile shows a slight cooling trend with less local variability between miles 44.0 and 23.0. Surface temperature remained relatively constant (~23.4^{o}C) to river mile 12.0, with local variability, consistent with expected sampling noise (i.e. ±0.5^{o}C). Between river mile 12.0 and the mouth, surface water temperatures again showed a rapid warming trend and increased local variability.

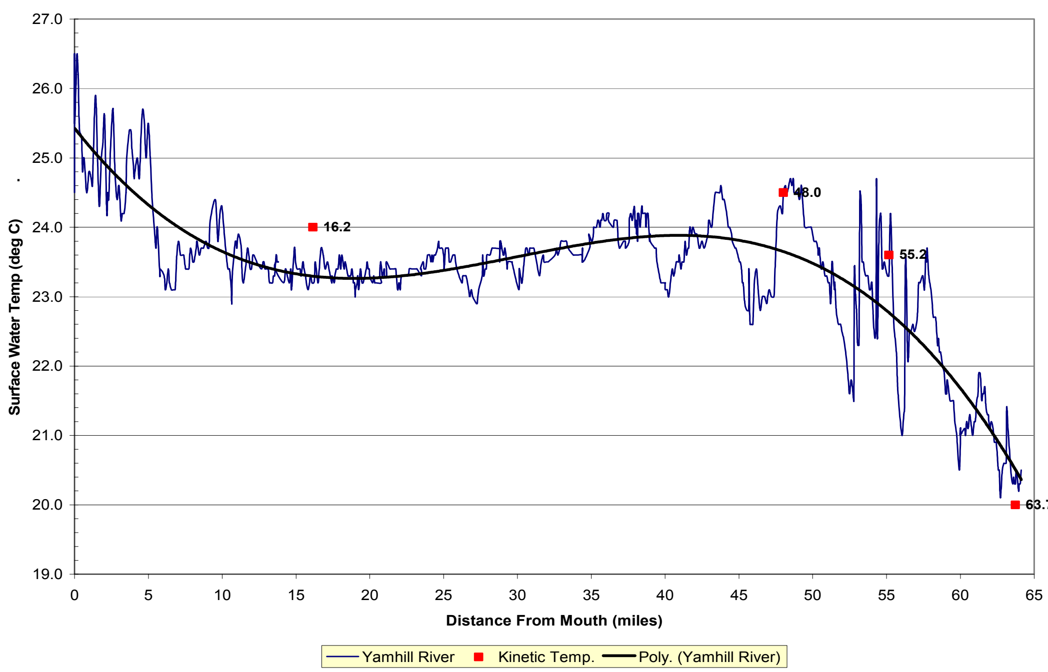
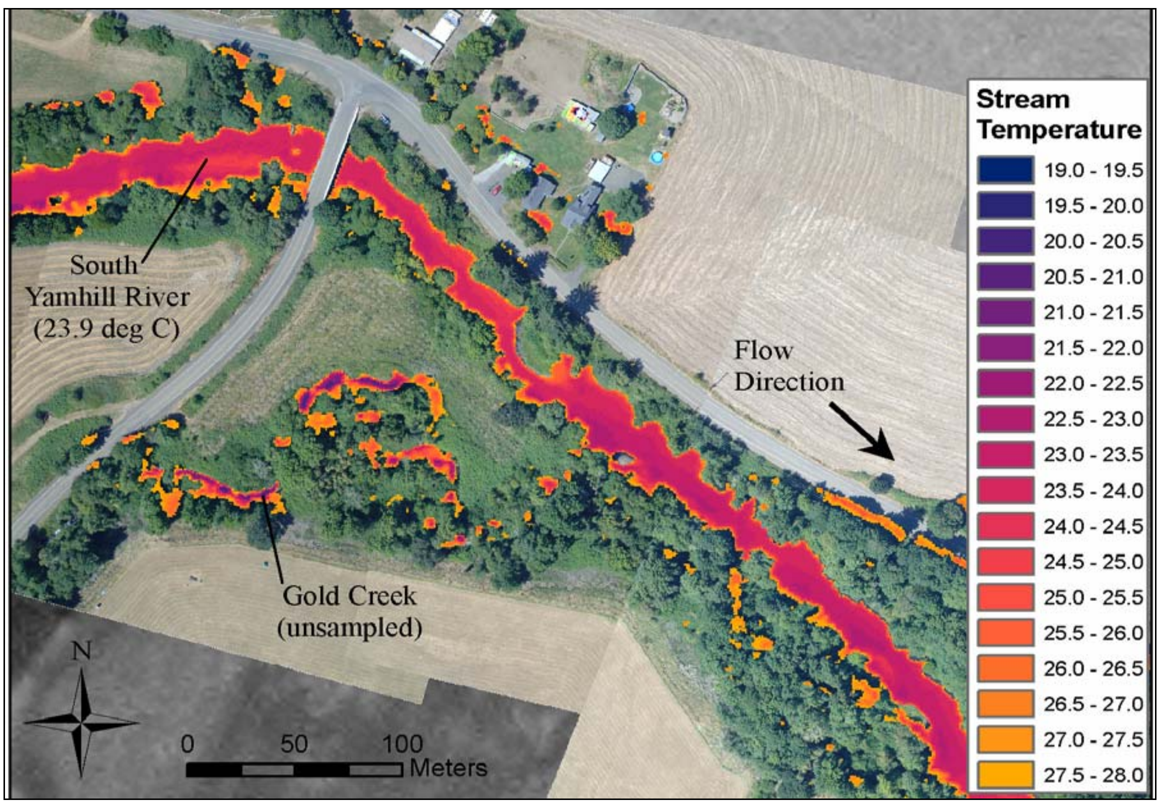


Figure 7 – Longitudinal profile for the Yamhill River with a general trend line for the radiant temperatures (2nd order polynomial) and the kinetic temperatures taken during the survey.

The following paragraphs describe some of the thermal features and local temperature patterns observed in the longitudinal profile:

- At the upstream end of the survey, the South Yamhill River was 20.5°C. Downstream of the Rogue River (which was too small to sample), the South Yamhill River rose to 21.4°C in one mile, then dropped to a survey minimum of 20.1°C at river mile 62.7 near the inflow of Rock Creek (20.0°C). Rowell Creek (mile 60.7) contributed 21.8°C water to the main stem (21.0°C) and appeared to contribute to an apparent decrease in main stem temperatures at this location. Cosper Creek was detected just downstream of Rowell Creek; however Cosper Creek was too small in the imagery to allow for an accurate temperature sample.

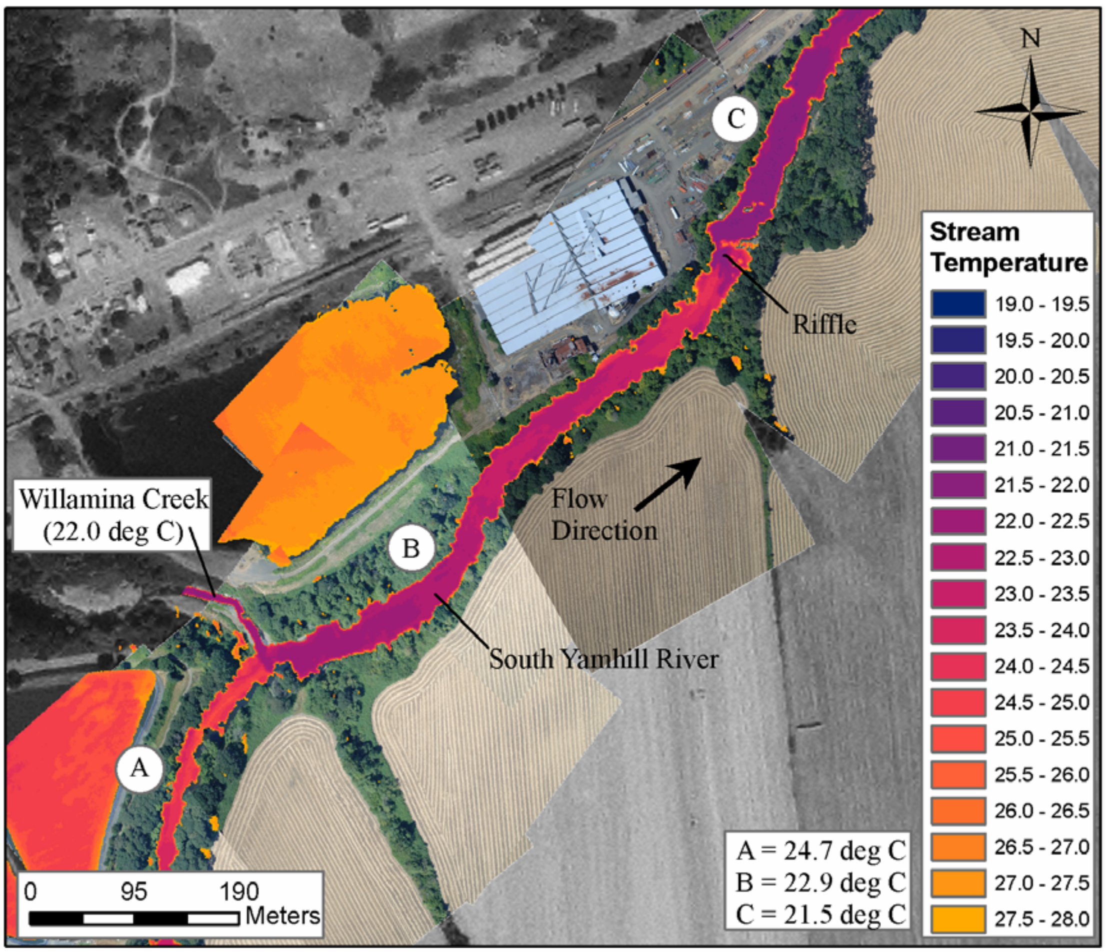
- From river mile 59.9, the temperature of the South Yamhill River slowly increased over the next 2 miles to reach 23.7°C at river mile 57.8. Downstream of river mile 57.8, the addition of both Gold and Lady Creeks (river miles 57.7, 57.3 respectively) helped to lower the main stem temperature to 21.0°C by river mile 56.1 (see figure below).



This image scene shows the confluence of Gold Creek and the South Yamhill River (23.9°C) at river mile 57.7. Gold Creek contributed visibly colder water to the South Yamhill River; however, due to the inability to see its mouth in the imagery, Gold Creek remained unsampled.

- From mile 56.1 to mile 52.1, the South Yamhill River experienced differing degrees of stratification, interspersed with riffles. Within this reach, the temperature varied between 24.7°C and 21.6°C in a relatively short distance, aided in part by the contribution of 22.0°C water from Willamina Creek at river mile 53.2 near the end of this reach (see figure below).

- Mill Creek (river mile 51.2) added water which was 1.8°C warmer than the main stem, contributing to the overall warming trend observed in this reach. Radiant water temperatures in the South Yamhill River reached 24.0°C at river mile 48.7, downstream of Ash and Rock Creeks (both unsampled due to size). From river mile 48.7 to 43.8, the temperature of the main stem dropped from 24.7°C to 22.6°C, and rose again to 24.6°C. The factors contributing to this drop in temperature were not apparent from the imagery; however, the apparent cooling reach (from mile 48.7 to 45.9) started at the town of Sheridan and continued on a relatively straight path with a narrow, tree-lined channel.

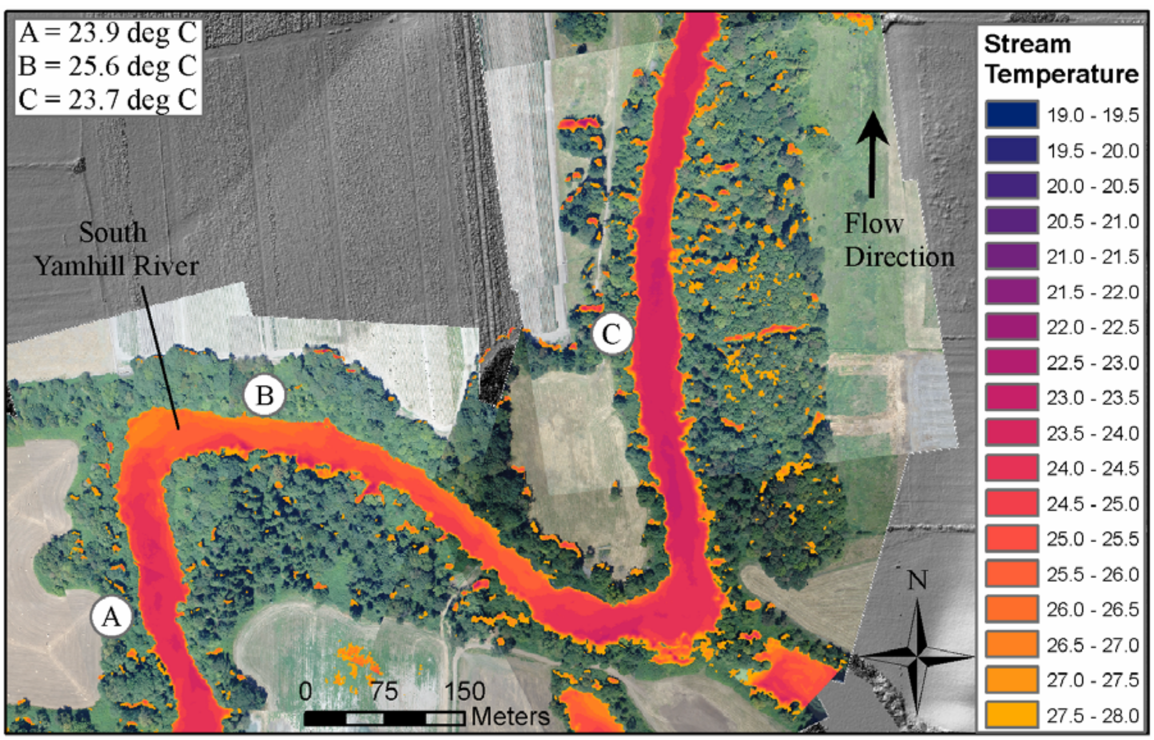


*This image scene shows the confluence of Willamina Creek to the left bank of the South Yamhill River at river mile 53.2. The flow from Willamina Creek enters the South Yamhill at 22.0°C and cools the temperature from 24.7°C (**A**) to 22.9°C (**B**); however, the flow becomes stratified, and the full mixing of Willamina Creek doesn't occur until the flow of the South Yamhill River passes a riffle at river mile 52.8, where the temperature drops to 21.5°C (**C**).*

- From mile 43.8 to 10.7, the South Yamhill River temperature fluctuated between 24.6°C and 22.9°C for approximately 33 miles. In this reach, both Salt Creek (21.8°C) and an unnamed tributary (20.9°C) contributed cooler water than the mainstream South Yamhill River (~23.5°C). Three additional tributaries were identified; however none were sampled due to their small sizes.

- The North Yamhill River joined the South Yamhill River at river mile 10.5. From this point, the water surface temperature of the Yamhill River increased rapidly, with a higher degree of spatial variability due to intermittent stratification around a large bend at river mile 9.5. The temperature quickly dropped back down to 23.7°C by river mile 9.1, as the river shifted through another bend, changing directions and yielding a more mixed condition in the channel (see figure below).

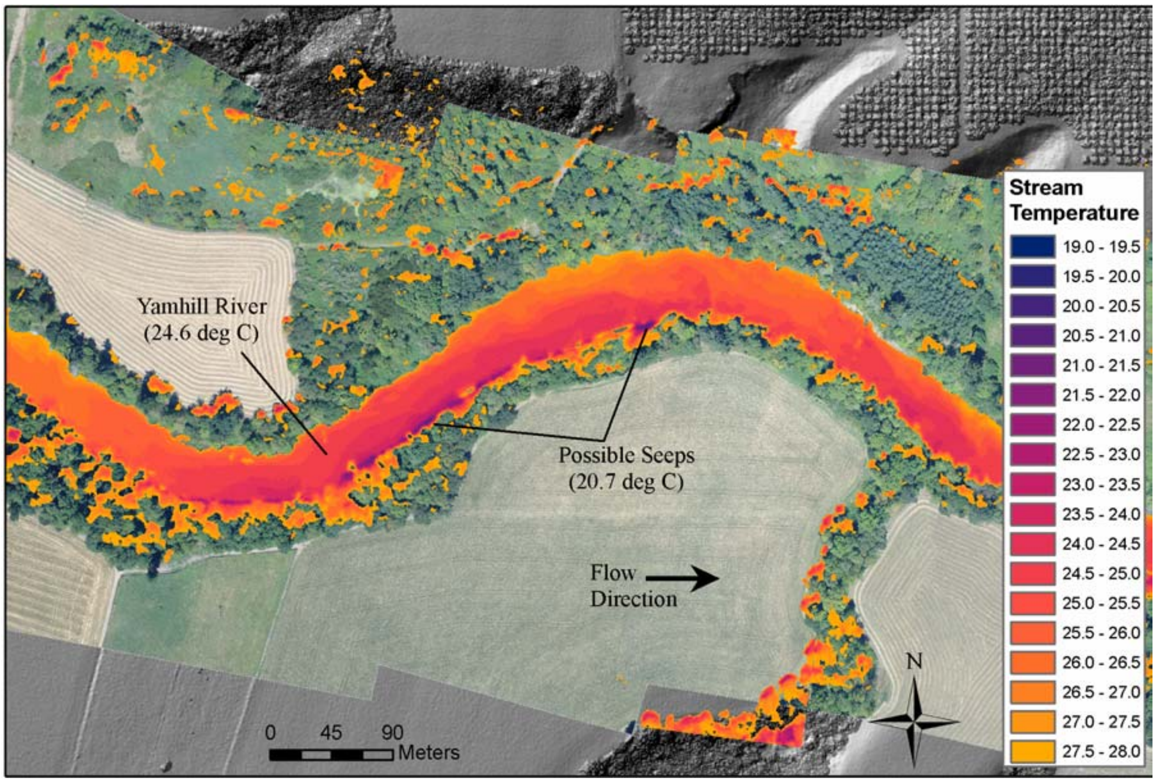
- From this point, with the addition of Millican and Hawn Creeks (both unsampled), the temperature in the Yamhill River dropped to 23.1°C at river mile 6.7. Moving downstream, the river experienced more stratification, resulting in variations in temperature from 23.1°C to 26.5°C continuing downstream to the mouth. In this stratified reach, Palmer Creek contributed water that was 3.9°C cooler than the main stem, at river mile 4.3. At the mouth, surface temperatures in the Yamhill River reached a survey maximum of 26.5°C before mixing with the Willamette River (21.4°C).



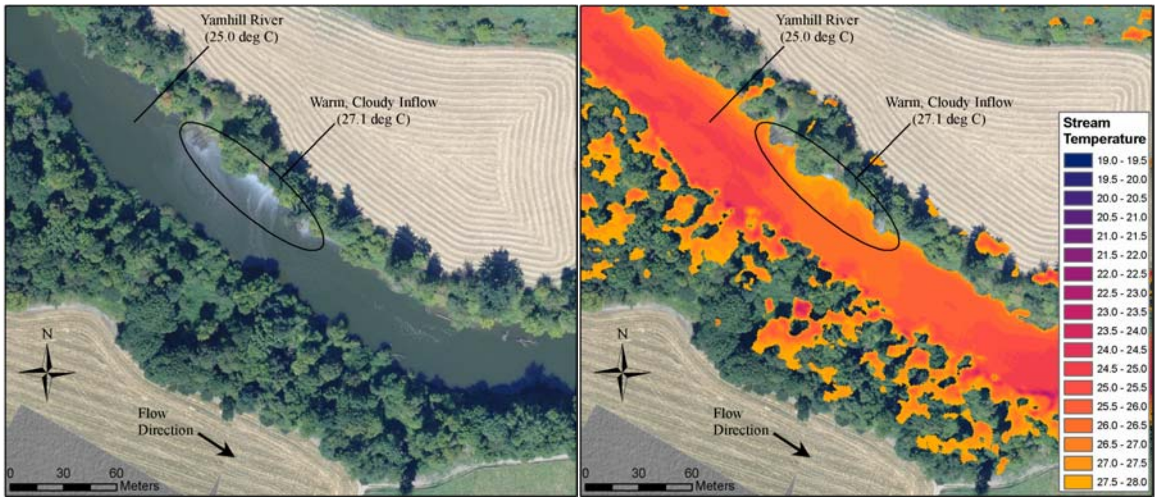
*This image scene shows a stratified condition in the South Yamhill River at river mile 9.5. The temperature of the main stem rises from 23.9°C (**A**) to 25.6°C (**B**) in the stratified bend before mixing and dropping to 23.7°C (**C**).*

Selected Images

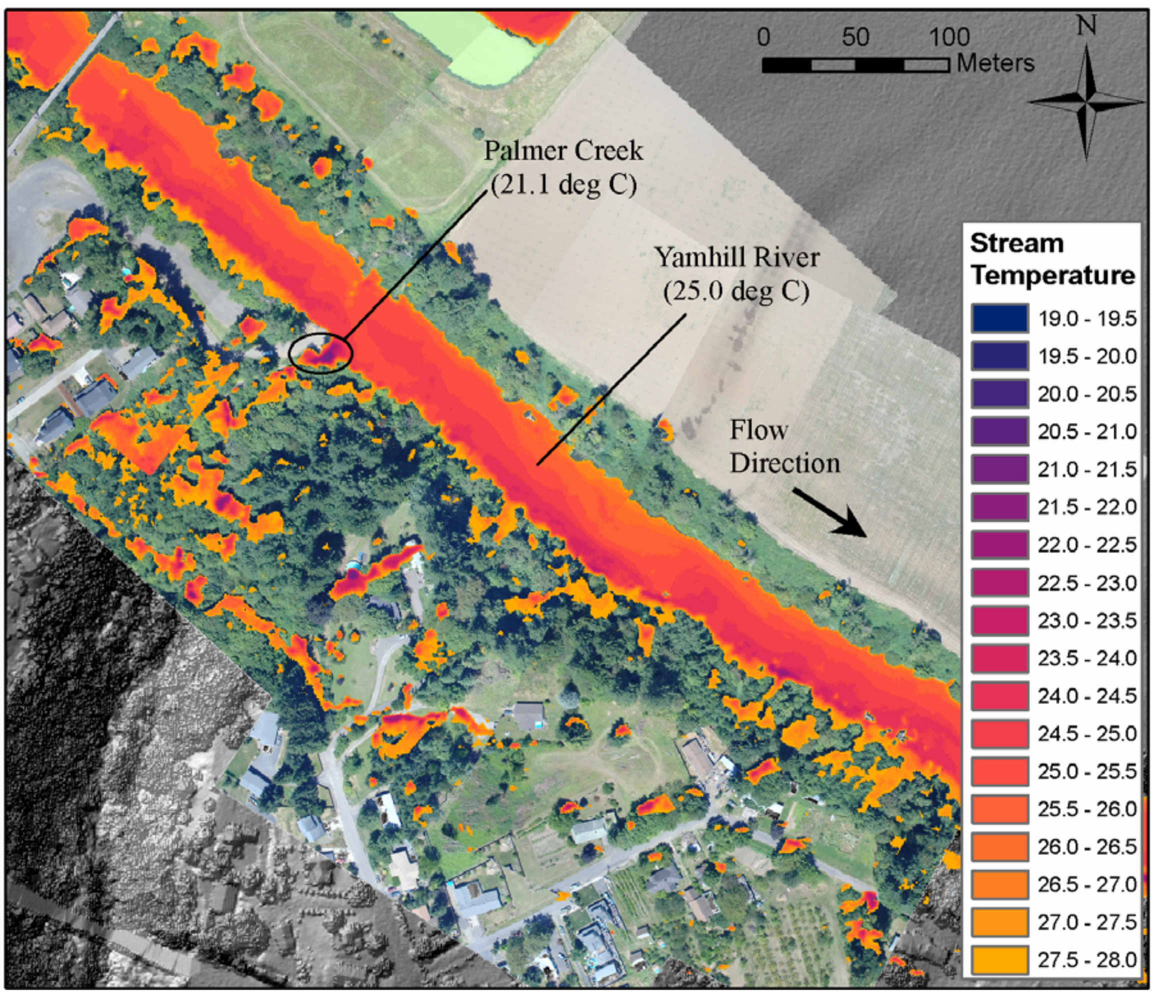
The following pages contain examples of imagery that show features and processes discussed in the previous section. Radiant water temperatures in the TIR images are color coded with the scale displayed on the right of each image. The TIR images are displayed over the true color digital images, then over LiDAR derived bare-earth and vegetation hillshades (river miles 0 – 42.2), and over DOQs (river mile 42.2 – 64.2). Values above the maximum observed water temperatures are transparent.



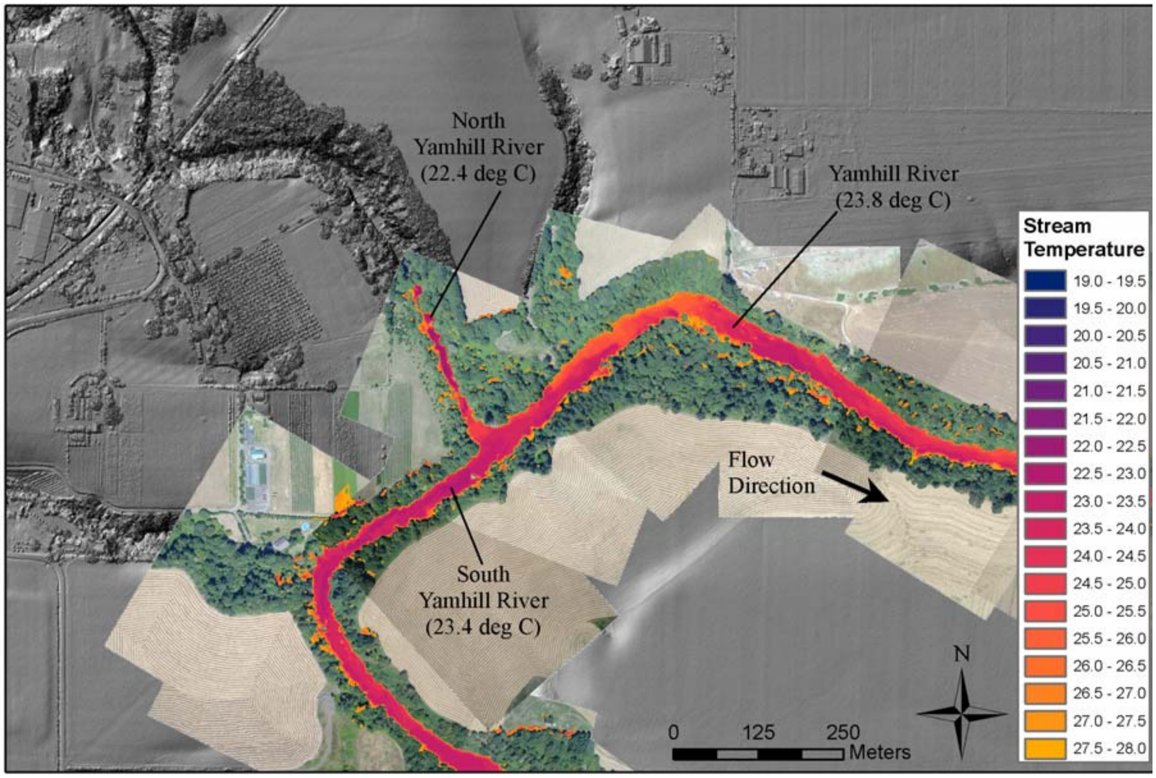
The image scene above shows a series of cool regions along the right bank of the Yamhill River at river mile 1.2. The main stem Yamhill was 24.6°C while the cool regions were approximately 20.7°C; however, the classification of these cool regions as seeps was made difficult by the inability to see the bank below the vegetation cover and shadows.



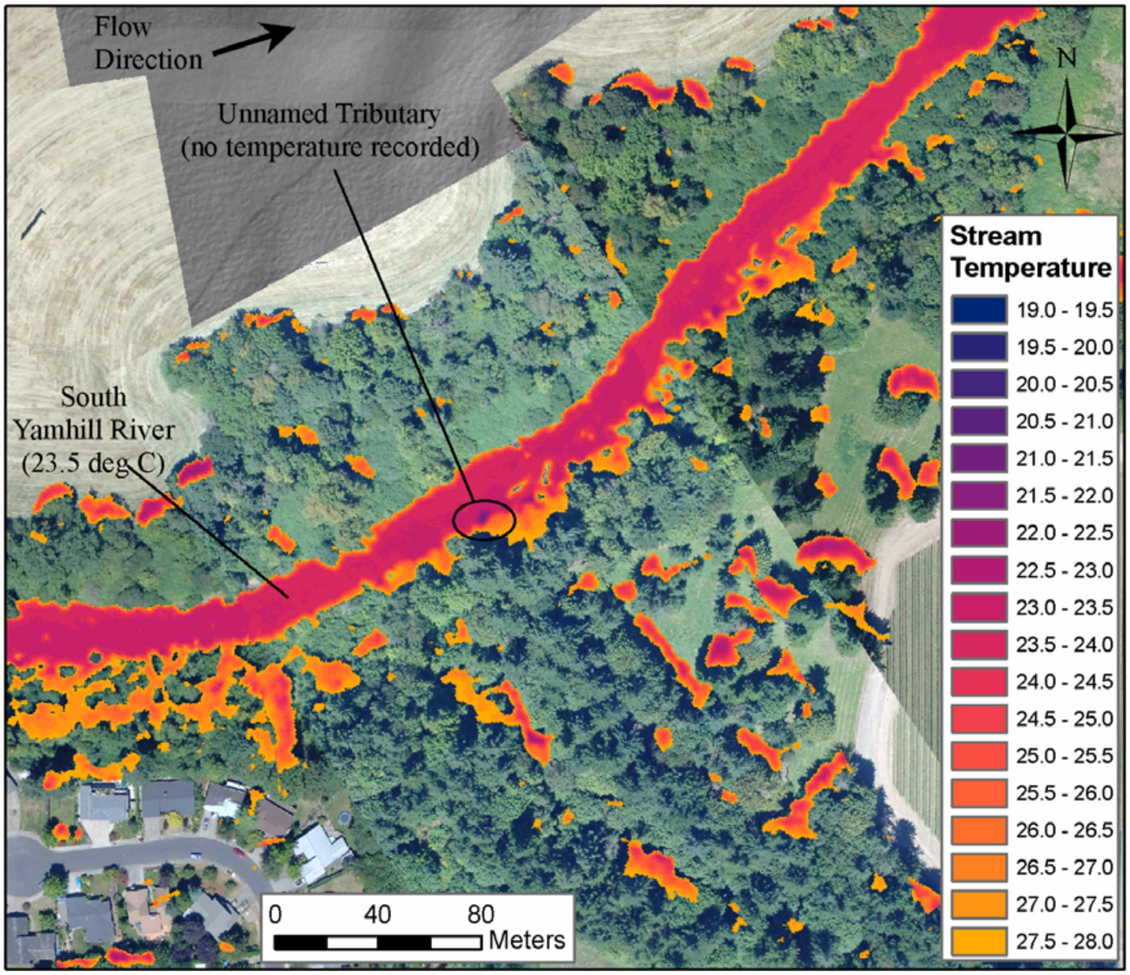
This pair of image scenes shows a region of the Yamhill River at river mile 1.5 with a warm, cloudy inflow on the left bank, contributing water at 27.1°C while the mainstream Yamhill is 25.0°C.



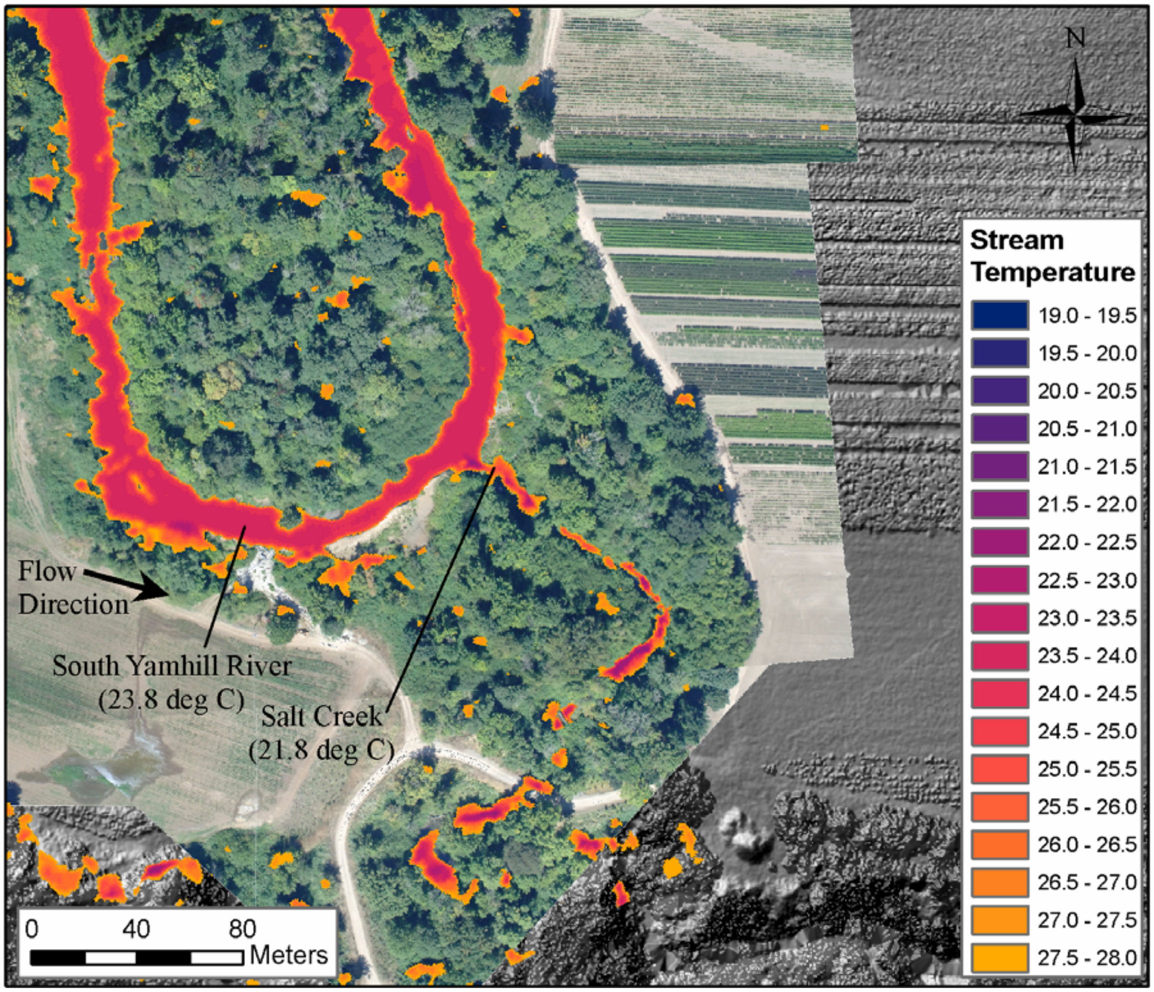
This image scene shows the confluence of Palmer Creek (21.1°C) and the Yamhill River (25.0°C) at river mile 4.3.



This image scene shows the confluence of the North Yamhill River (22.4^{o}C) and the South Yamhill River (23.4^{o}C) at river mile 10.5. Differences in surface temperatures are obvious downstream of the confluence which are presumably due to differential surface heating or thermal stratification. These short scale differences in surface temperatures contributed to the high degree of local thermal variability observed in the longitudinal profile.



This image scene shows the confluence of an unnamed tributary to the right bank of the South Yamhill River at river mile 12.8. The temperature of the main stem was recorded at 23.5^{o}C, but the temperature of the tributary was not recorded, due to the inability to see the mouth through the vegetation.



This image scene shows the confluence of Salt Creek (21.8°C) to the right bank of the South Yamhill River (23.8°C) at river mile 28.8.

Summary

A TIR survey was successfully conducted on the Yamhill River. A total of 5 in-stream data loggers were used to calibrate and verify the accuracy of the radiant temperatures. The results showed the average absolute difference between kinetic and radiant temperatures was within the desired accuracy of ±0.4°C, with the differences ranging between -0.4°C and 0.8°C. A longitudinal temperature profile was developed by sampling radiant temperatures along the stream gradient. Interpretation of the TIR imagery in relation to the longitudinal profile can provide insight into the physical processes driving the observed temperature patterns.

The TIR imagery is provided in three forms: 1) individual un-rectified frames, 2) individual geo-rectified frames, and 3) a continuous geo-rectified mosaic. The mosaic allows for easy viewing of the continuum of temperatures along the stream gradient, but also shows edge match differences and geometric transformation effects. The un-rectified frames are useful for viewing images at their native resolutions. The native resolution is often better for detecting smaller thermal features. A GIS point layer is included which provides an index of image locations, the results of temperature sampling, and interpretations made during the analysis. The true color digital images are provided as 2-mile geo-rectified mosaics.

Deliverables

Deliverables are provided on a set of DVD's:

All Geo-Corrected Imagery are stored as: UTM Zone 10; NAD83

DVD-1

TIR Images (Un-rectified) - Calibrated TIR images in ESRI GRID Format. GRID cell value = radiant temperature * 100. Radiant temperatures are calibrated for the emissive characteristics of water and may not be accurate for terrestrial features. These images retain the native resolution of the sensor.

TIR Images (Geo-rectified) – Calibrated TIR images in ESRI GRID Format. These images were rectified to real world coordinates.

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

Colormap – A color map for displaying water temperatures in the TIR imagery.

Longprofile - Excel spreadsheet containing the longitudinal temperature profile.

Coverages – Point layer showing image locations, sampled temperatures, and image interpretations.

Report - This report.

TrueColor – Geo-Rectified true color imagery from river mile 00 to 20.

DVD-2

TrueColor – Geo-Rectified true color imagery from river mile 20 to 64.