Airborne Thermal Infrared Remote Sensing
Clakamas River, OR

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REPORT FOR THERMAL INFRARED REMOTE SENSING
CLAKAMAS RIVER, OR

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Background

In 2006, researchers at the Water Resources Graduate Program at Oregon State University contracted with Watershed Sciences, Inc. to acquire thermal infrared (TIR) and true color imagery of the Clakamas River, OR from the River Mill Dam near the town of Estacada, OR to Carver, OR (~15 river miles). The objective of the survey was to map surface temperature patterns during both the minimum and maximum of the diurnal temperatures cycles in the river. Consequently, two flights were conducted. The first was conducted just prior to dawn on August 12th in order to capture daily minimum water temperatures. A second flight was also conducted on August 12th during the mid-afternoon in order to capture heat-of-the-day conditions.

Airborne thermal infrared (TIR) remote sensing has proven 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. This report details the work performed, including methodology and quantitative assessments of data quality. The images contained in this report are not meant to be comprehensive, but provide examples of image scenes and interpretations.

Survey Extent

The TIR data were acquired on August 12, 2006 and consisted of an early morning flight (5:56–6:38) and a mid-afternoon flight (14:26–15:08). Both flights were conducted over the same river extent starting at the River Mill Dam (mile 23.0) and proceeding downstream to the Carver Bridge (mile 8.0). If the river split into multiple channels and the channels were outside of the sensor field of view, then a survey was conducted along each channel resulting in multiple flight lines over some sections of the river (see Figure 1). The map in Figure 1 also shows the location of temperature data loggers deployed by Watershed Sciences prior to the flight and used to calibrate the TIR images.

Methods

Data Collection

Instrumentation: Images were collected with a Space Instruments FireMapper 2.0 sensor (8-12μm) mounted on the underside of a Bell Jet Ranger Helicopter (Figure 2). The TIR sensor was co-mounted with a high-resolution true color digital camera (*Nikon D2X w/ 24mm lens, 6.9 mega-pixels*). Both cameras were positioned to look vertically down from the aircraft (nadir).

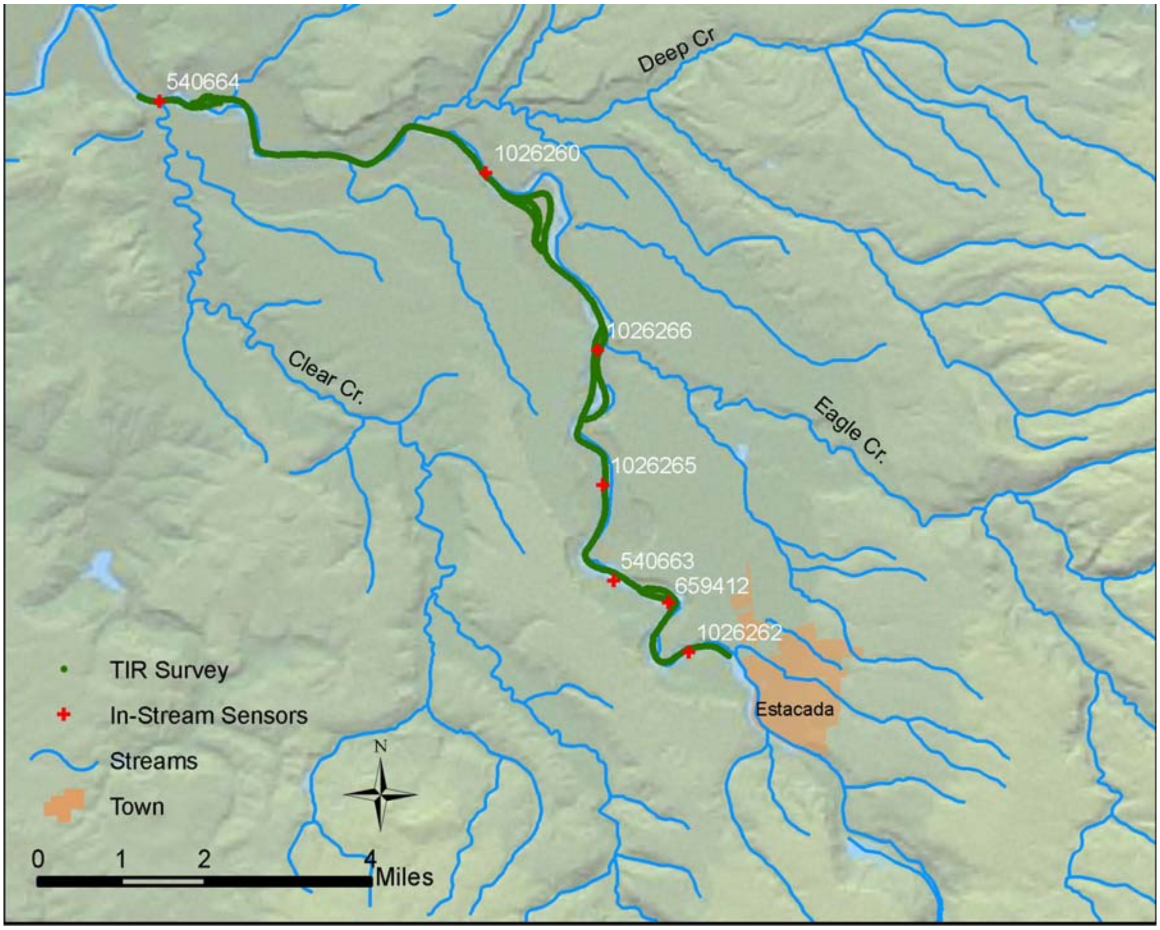


Figure 1 – The extent of the TIR survey conducted on the Clakamas River, OR on August 12, 2006. In-stream sensors used to calibrate the TIR images are shown on the map and labeled by serial number.

The TIR sensor has a horizontal field of view (H-FOV) of 44^{o} and a pixel array of 320 x 240 pixels. The Firemapper 2.0 is a calibrated radiometer with internal non-uniformity correction and drift compensation. Thermal infrared images were recorded directly from the sensor to an on-board computer as raw counts, which were then converted to radiant temperatures. The individual images were referenced with time, position, and heading information provided by a global positioning system (GPS). General specifications of the sensor are listed in Table 1.

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 aircraft was flown longitudinally along the stream corridor in order with the river in the center of the display. The objective was for the stream to occupy 30-60% of the image. The TIR sensor is set to acquire images at its maximum rate (*~1 image/2 seconds*) resulting in considerable vertical overlap between images. The airplane maintained an average flight altitude of 1,200ft (366 m) above ground level (AGL) resulting in a planned image ground footprint width of 977 ft (298 m) and a native pixel resolution of 3.1 ft (0.9 meters).

Table 1. Summary of Thermal Image Acquisition Parameters.

Date:	August 12, 2006
Acquisition Time:	5:56 – 6:38 (AM Flight) 14:26 – 15:08 (PM Flight)
Flight Above Ground Level (AGL):	366 m (1200 ft)
Sensor:	Space Instruments Firemapper 2.0
Wavelength:	8-12µm
Temperature Resolution:	0.01°C
Noise Equivalent Temperature Differences (NETD)	0.07°C
Encoding Level:	16 bit
Horizontal Field-of-View:	44.3°
Image Footprint Width:	298 m (977 ft)
Pixel Resolution:	0.9 m (3.1 ft)

Ground Control: Watershed Sciences deployed in-stream data loggers prior to the flight in order to calibrate and verify the accuracy of the TIR data. The data loggers were distributed at public access points along the survey extent. The sensors were placed on the bottom of the river in locations with good vertical mixing.

Data Processing

Calibration: Calibration of the sensor is performed in the lab using an extended area black body to relate the response characteristics of the sensor to emitted radiance. The raw TIR images collected during the survey contain digital numbers that were converted to radiance ($W/m^2*sr*micron$) values based on the pre-season calibration.

The radiance values were adjusted based on a comparison of the measured radiance to the calculated radiance at each ground truth location. This adjustment was performed to correct for path length attenuation and the emissivity of natural water. 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. The radiance values were then converted to surface temperatures using Planck's Black Body equation.

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 mouths. 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 and heading 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. Due to the relatively small footprint of the imagery and independently stabilized mount, image pixels are not individually registered to real world coordinates. The image index is saved as an ESRI point shapefile containing the image name registered to an X and Y position (Oregon Lambert Projection) of sensor location at time of capture. In order to provide further spatial reference, the TIR images were assigned a river mile based on a routed stream layer (Figure 3).

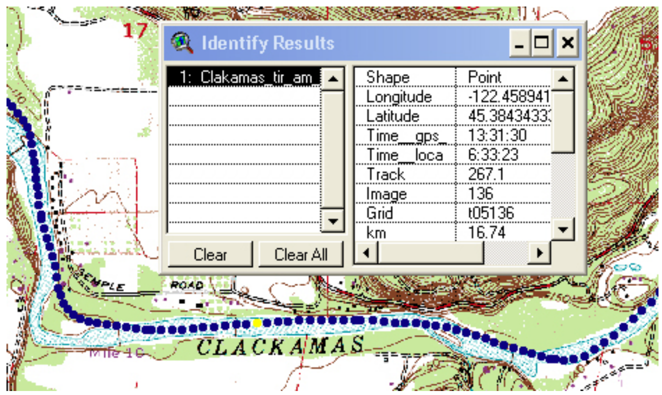


Figure 3 –Each point on the map represents a thermal image location. The inset box shows the information recorded with each image point during acquisition.

Temperature Profiles: 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. Radiant temperatures were only sampled along what appeared to be the main flow channel in the river.

Geo-Rectification: The true color images were geo-rectified to real world coordinates using panchromatic ortho-photos (*2000 available on the internet*) as the reference layer. The true color digital images were initially oriented using the position and directional information collected on the aircraft. Individual frames were then geo-rectified by finding a minimum of six common ground control points (GCP's) between the true color images and existing ortho-photos. 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 at an average of twelve ground control points. Due to the low relief along the river bottom, the photos were not corrected for terrain displacement.

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.

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%). 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).

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.

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. This is a consideration when sampling the radiant temperatures at tributary mouths and surface springs.

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

[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.

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.

Image Uniformity: 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. This sensor has an automatic correction scheme which nearly eliminates non-uniformity across the image frame.

Results

Weather Conditions

Weather conditions were considered good for the survey. Table 2 summarizes the weather conditions recorded at the Troutdale, OR Airport during the time frame of the survey.

Table 2. Weather conditions observed at the Troutdale Airport on August 12, 2006.

Time PDT	Temp °F	Temp °C	Humidity %	Wind Direction	Wind Speed MPH	Sky Conditions
4:37 AM	51.8	11.0	82	Calm	Calm	Mostly Cloudy
4:53 AM	51.1	10.6	86	Calm	Calm	Scat. Clouds
5:53 AM	50.0	10.0	89	Calm	Calm	Mostly Cloudy
6:53 AM	51.1	10.6	86	Calm	Calm	Mostly Cloudy
7:04 AM	51.8	11.0	82	Calm	Calm	Overcast
7:53 AM	54.0	12.2	83	Calm	Calm	Overcast
8:53 AM	55.0	12.8	80	Calm	Calm	Overcast
9:53 AM	57.9	14.4	72	Variable	3.5	Overcast
10:53 AM	60.1	15.6	64	Variable	3.5	Overcast
11:53 AM	63.0	17.2	60	Variable	3.5	Scat. Clouds
12:53 PM	66.0	18.9	56	Variable	3.5	Clear
1:53 PM	71.1	21.7	47	NW	4.6	Clear
2:53 PM	73.9	23.3	43	Variable	4.6	Clear
3:53 PM	77.0	25.0	42	Variable	5.8	Clear
4:53 PM	79.0	26.1	39	West	8.1	Clear
5:53 PM	80.1	26.7	38	Variable	5.8	Clear
6:53 PM	79.0	26.1	38	Variable	6.9	Clear

Thermal Accuracy

Table 3 provides a comparison between the kinetic temperatures recorded by the in-stream data loggers and the radiant temperatures derived from the TIR images for both the morning (AM) and afternoon (PM) flights on the Clakamas River. Since the in-stream data were used to compute an adjustment to the radiant temperatures, the table illustrates the range of differences after the images were calibrated. The correction was computed as an average offset from the raw radiant values for all sensor locations. Since the in-stream data are used in the radiant temperature calibration, they should not be considered an independent check of radiant temperatures.

The range of differences between the radiant temperatures and kinetic temperatures were generally within target values (±0.5°C).

Table 3 – Comparison of radiant temperatures derived from the TIR images and kinetic temperatures from the in-stream monitors.

Serial	Image	Local	Kinetic T©	Radiant T©	Difference T©
Morning Flight					
1026262	t01046	5:57	17.1	17.3	-0.2
659412	t02022	6:02	17.0	16.9	0.1
540663	t03018	6:08	16.7	17.1	-0.4
1026265	t03067	6:12	16.4	16.5	-0.1
1026266	t04043	6:19	16.0	16.1	-0.1
1026260	t05006	6:29	16.2	16.5	-0.4
540664	t05271	6:38	16.4	16.2	0.2
Afternoon Flight					
1026262	t06161	14:29	17.8	17.5	0.3
659412	t06008	14:34	18.6	18.8	-0.2
540663	t07045	14:35	18.8	19.3	-0.5
1026265	t08023	14:40	19.7	20.0	-0.3
1026266	t08218	14:46	21.2	21.0	0.1
1026260	t09008	14:59	19.9	20.4	-0.5
540664	t09297	15:08	19.1	19.0	0.1

Longitudinal Profiles

Median sampled temperatures were plotted versus river mile for the Clakamas River from River Mill Dam to the Carver Bridge for both the AM and PM flights (Figures 4 and 5). Tributaries and other sampled surface inflows (i.e. springs/seeps, side channels, off channel) are plotted on the profiles. The profiles were plotted over the same temperature ranges to more easily allow cross comparison.

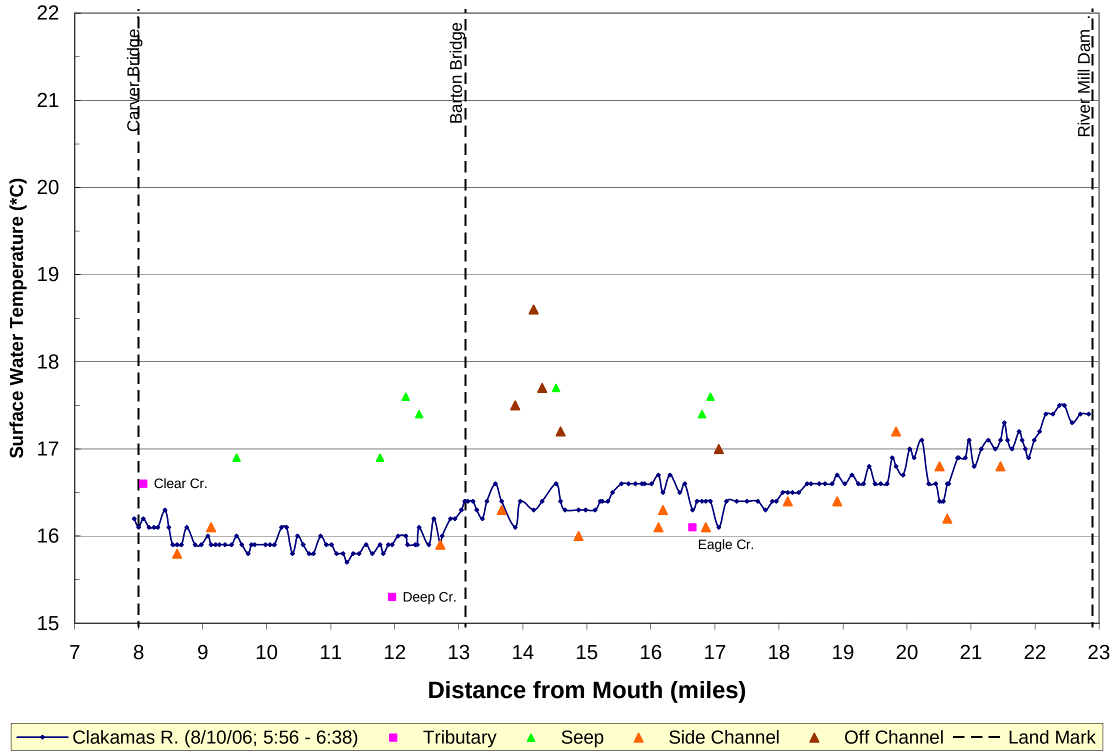


Figure 4 - Median sampled temperatures plotted versus river mile for the Clakamas River during the early morning of August 12, 2006.

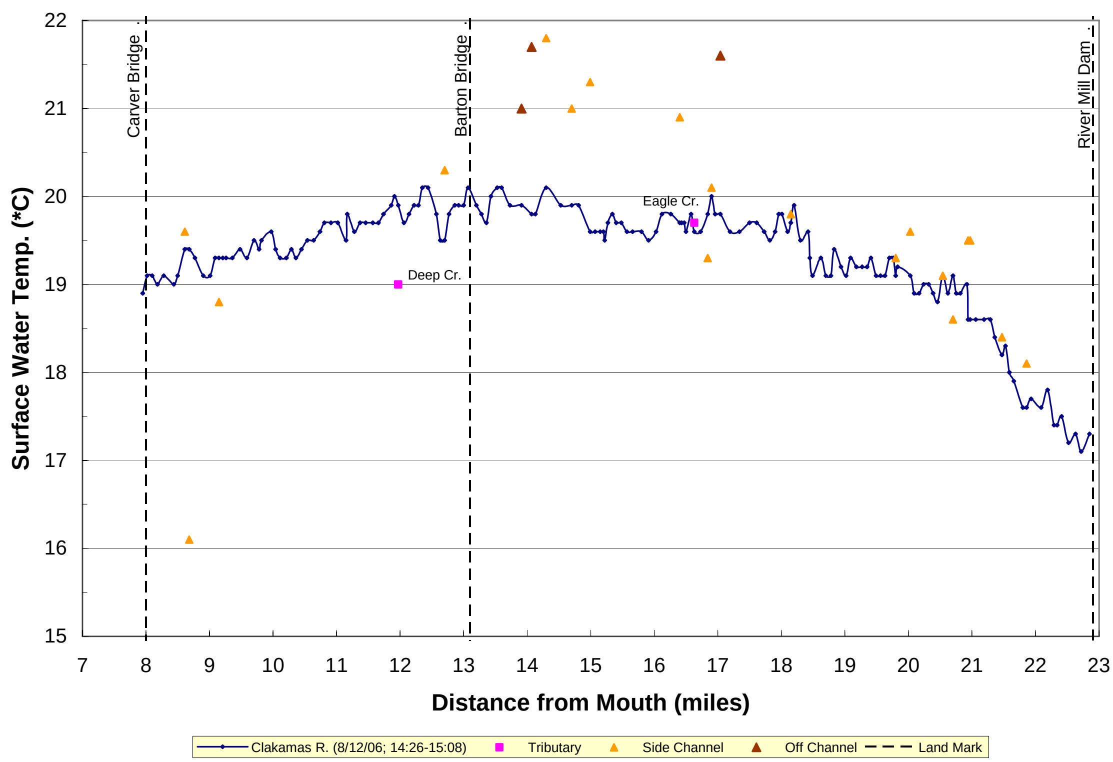


Figure 5 - Median sampled temperatures plotted versus river mile for the Clakamas River during the mid-afternoon on August 12, 2006.

Observation and Analysis

Morning Flight

Radiant water temperatures below River Mill Dam were ~17.4°C at the time of the TIR survey with water temperatures in the main channel getting progressively cooler moving downstream. Over the full 15-mile survey water temperatures ranged from ~17.5°C to a local minimum of 15.7°C (mile 11.3). While the range of sampled temperatures (1.8°C) was relatively small, inspection of the profile shows some apparent spatial trends along the river gradient.

Between river miles 21.0 and 20.6, stream temperatures exhibited a decrease of ~0.7°C before increasing again in the downstream direction. While the magnitude of this decrease is close to the expected frame-to-frame variability (i.e. 0.5°C), this was a notably larger change than observed at other locations along the profile and may warrant further investigation. Radiant water temperatures appeared relatively constant (~16.4°C ±0.3°C) between river mile 19.7 and 13.0 (*near Barton Bridge*). Downstream of Barton Bridge, bulk water temperatures again decreased before leveling off at ~15.8°C.

As mentioned previously, radiant water temperatures were sampled along the main channel as determined based on size (*i.e. channel width*) and apparent flow. Secondary channels were classified as side channels and fourteen were sampled during the early morning flight. The side channels were sampled at the point where they rejoined the main channel. Most of the side channels had water temperatures consistent with water temperatures in the main stem.

Off-Channel features were identified as standing water or ponds that had surface connectivity to the main channel. During the morning flight, five off-channel features were identified and each had warmer radiant temperatures than the main channel. A number of "seeps" were also detected during the morning flight. These features were detected as areas of surface water that had significantly (i.e. >= 0.5°C) different radiant temperatures then the main stem and appeared (*through interpretation of the imagery*) as an area of potential upwelling. The measured radiant temperatures were between 16.9°C and 17.7°C. Examples of both off-channel features and seeps are contained in the Sample Images section of this report.

Afternoon Flight

During the afternoon flights, radiant water temperatures were ~17.4°C and increased steadily downstream of the River Mill Dam (mile 23.0) reaching ~19.6°C at river mile 18.2. Surface water temperatures appeared to increase slightly (19.6°C to 20.1°C) before exhibiting a steady decrease of ~1.0°C between the Barton Bridge (mile 13.0) and the Carver Bridge (mile 8.0).

As with the morning flight, all detected surface water inflows were sampled where they entered the main channel. A total of nineteen side channels were sampled during analysis of the afternoon imagery. Of these, seven side channels had radiant temperatures that were significantly different than the main channel. Three off-channel features were sampled and each had warmer surface temperatures than the main channel.

There we no "seeps" detected during the afternoon flight. Inspection of the TIR imagery showed that there was often little thermal contrast between terrain features and the surface water temperatures. This decreased contrast often made it difficult to detect small features with similar apparent temperatures (i.e. the stream bank and a small seep). Consequently, the seeps were detectable in the morning flight because of the cold back ground temperatures during the morning hours. The lack of detected seeps during the afternoon flight was probably due to the decreased contrast between the land and the water and not due to the absence of the seep.

Comparison AM versus PM

A comparison of longitudinal temperature profiles from the afternoon and morning flight provides additional information on the processes driving spatial temperature patterns in the Clakamas River (Figure 6).

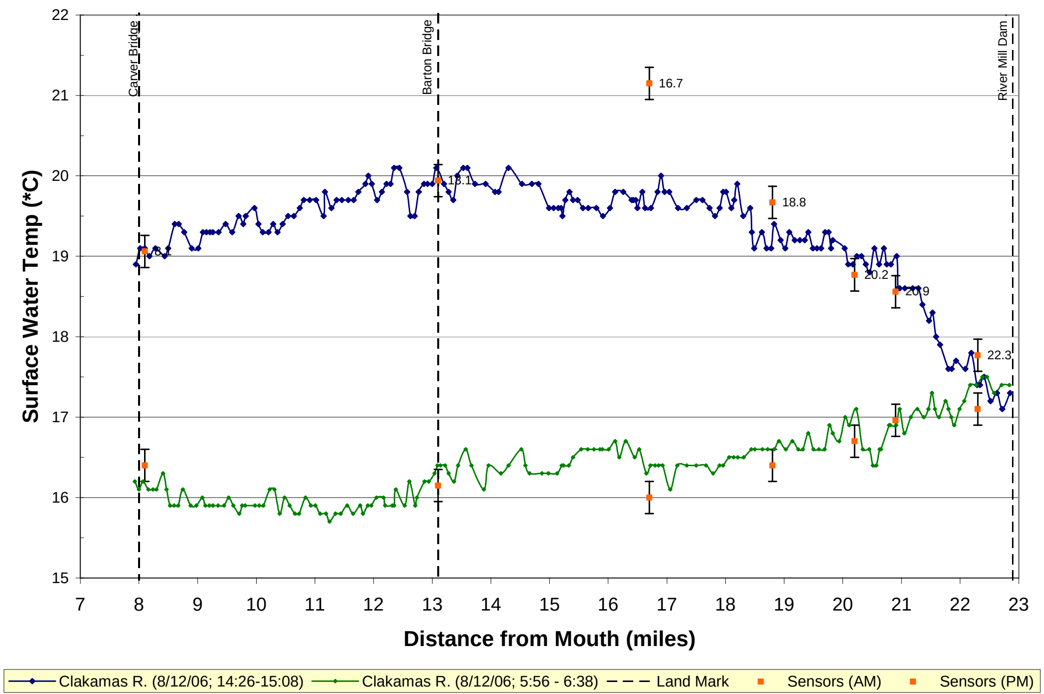


Figure 6 – Comparison of the longitudinal temperature profiles for the morning and afternoon flights on the Clakamas River. The plot also shows the location and recorded temperatures from the in-stream data loggers. The in-streams sensor temperatures at the time of the overflight are shown on the profiles. Note that the sensor at river mile 16.7 was not located within the main flow and therefore not representative of the bulk water temperatures during the afternoon flight.

While temperatures at the outlet of the dam were very similar between the morning and afternoon flights, the downstream spatial temperature patterns were almost mirror images. Both profiles show consistent temperature patterns over similar reaches. For example, both patterns showed a decrease in longitudinal heating (PM) or cooling (AM) between river miles 18 and 19. The warming (PM) (or cooling (AM)) continued at a lower rate in both profiles until approximately Barton Bridge (mile 13). In both profiles, the reach between Barton and Carver Bridges showed a distinct change in the downstream temperature pattern.

Over the surveyed reach, the Clakamas River was characterized by multiple channels, large gravel bars, and a number of off-channel ponds. This channel complexity combined with the observed spatial temperature patterns and evidence of “seeps” in the TIR imagery, suggests that hyporheic flow paths may have a regulating influence on in-stream temperature patterns. This is particularly true in the reach between Barton and Carver Bridges, which showed downstream cooling during heat-of the day conditions and almost constant temperatures in the early morning profile.

Follow-On

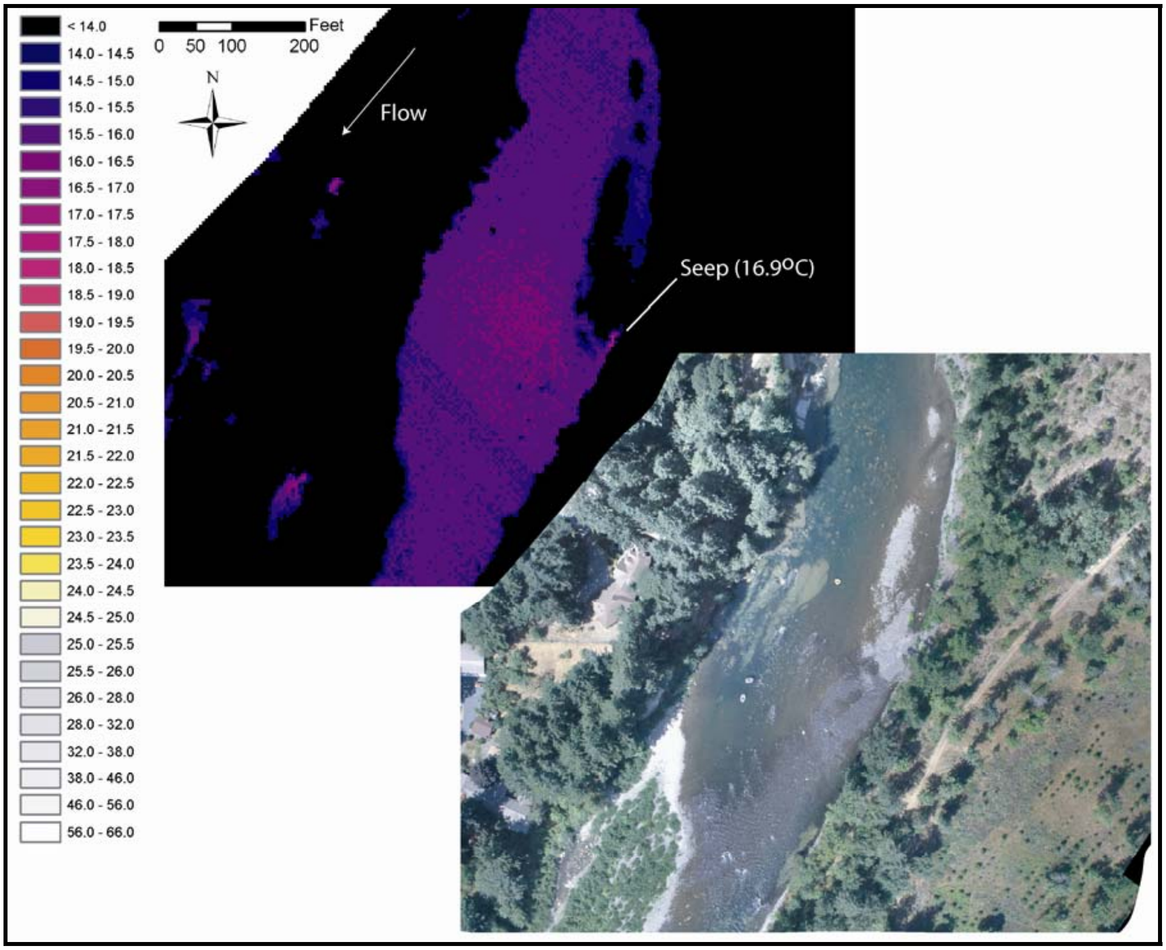
This report provides some hypotheses on the processes influencing spatial temperature patterns at this scale based on analysis of the TIR imagery. These hypotheses and observations are considered to be a starting point for more rigorous spatial analysis and fieldwork. Follow-on analysis may include:

- Since the seeps detected in the imagery are small, they should be considered detection of a process within a given reach and provide information on the type of channel and geomorphoric conditions under which that process occurs in the Clakamas River. Follow on analysis may look at the significance of these seeps to temperatures at different spatial scale and localize thermal habitat for cold water fish.

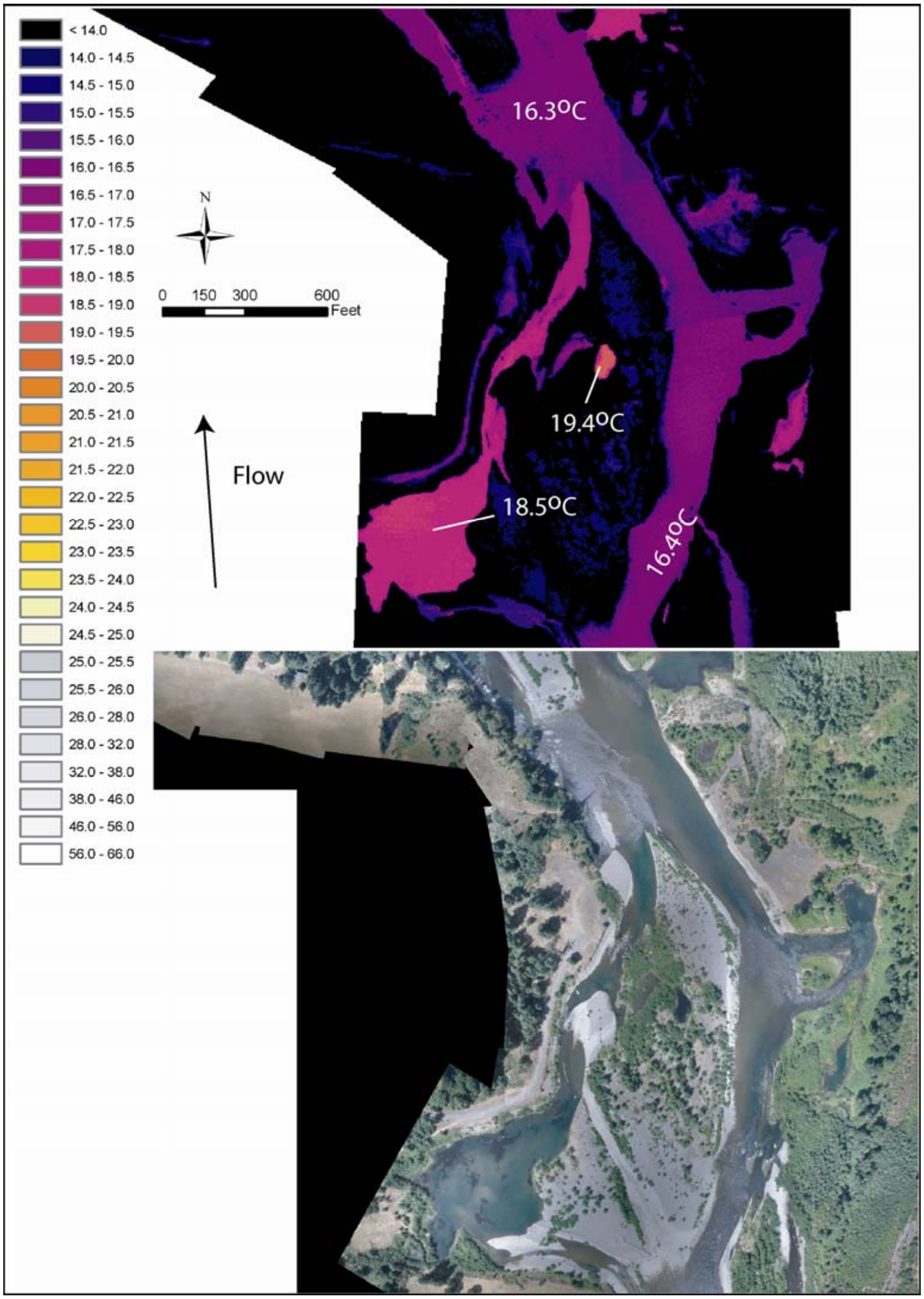
- The TIR imagery and derived data sets provide a spatial context for analysis of seasonal temperature data from in-stream data loggers and for future deployment and distribution of in-stream monitoring stations.

- The rectified true color images provide a good data source evaluation of other physical habitat characteristics within the stream. These images may provide information at a spatial resolution and temporal significance that are not available from other sources.

Sample Images



Example: TIR (top) and true color image (bottom) showing the Clakamas River (15.9°C) at mile 11.8. The image pair shows an example the detection of apparent seep at the downstream end of the gravel bar along the left bank. The seeps were detectable in the early morning flight due to the large thermal contrast been the cold bank and terrain features and the water surface. The illustrated TIR image is from the geo-rectified mosaic and illustrates some of the slight uniformity and frame-to-frame differences in the thermal imagery. The color map used to display the images exaggerates these differences. These artifacts can reduced in the mosaic by using smoothing or averaging options available in most mosaicing programs. However, averaging can also result in the loss of small features such as the seeps due to small differences in pixel registration between frames.



Example: The TIR image (top) and true color image (bottom) shows the Clakamas River between miles 14.0 and 15.0. While bulk temperatures in the main channel are relatively constant, the side-channels and off-channel ponds show considerable variability in the surface temperatures. A number of seeps are also visible along the islands and gravel bars.

Deliverables

The TIR imagery is provided in two forms: 1) individual un-rectified frames and 2) 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.

Deliverables are provided on DVD:

Geo-Corrected Imagery is stored as: **Oregon Lambert, NAD83, Units = Int. Feet.**

- Unrectified – contains un-rectified single frame images.
    - Clakamas AM – calibrated, but un-rectified TIR image frames from the morning flight in ESRI GRID Format. These images retain the native resolution of the sensor. GRID cell value = radiant temp. (^{o}C) * 10.
    - Clakamas PM – calibrated, but un-rectified TIR image frames from the morning flight in ESRI GRID Format. These images retain the native resolution of the sensor. GRID cell value = radiant temp. (^{o}C) * 10.
    - TrueColor – un-rectified true color images (jpg).
    - Indices – ESRI shapefile (points) showing image locations for both TIR and true color image files.
- Rectified – contains geo-rectified images.
    - Clakamas AM – calibrated, but un-rectified TIR image frames from the morning flight in ESRI GRID Format. These images retain the native resolution of the sensor. GRID cell value = radiant temp. (^{o}C) * 10.
    - Clakamas PM – calibrated and rectified TIR image frames from the morning flight in ESRI GRID Format. These images retain the native resolution of the sensor. GRID cell value = radiant temp. (^{o}C) * 10.
    - Mosaics – Geo-rectified images mosaics for both the true color and thermal IR images in geo-tiff format.
- Report – Copy of this report.
- Longitudinal Profile – Excel File containing the longitudinal temperature profiles.
- Project – ArcGIS project illustrating the mosaic and the photo_index for the rectified images.

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