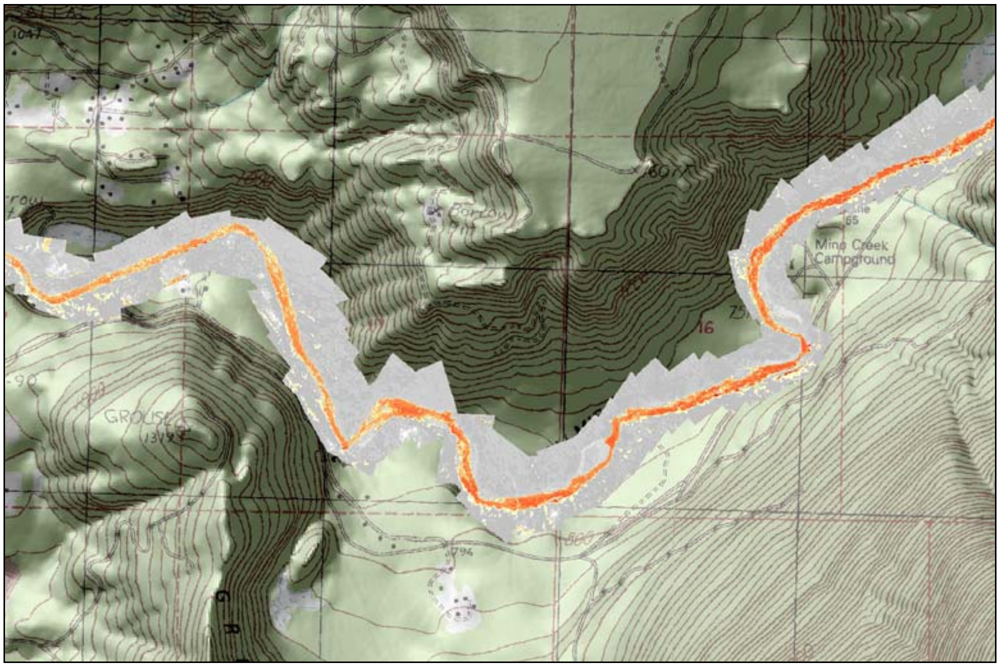
# Airborne Thermal Infrared Remote Sensing

## Snoqualmie River Basin, WA

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Report Date: March 12, 2007

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## Background

On August 13 2006, Watershed Sciences conducted an airborne thermal infrared (TIR) survey along selected reaches of the Snoqualmie River, WA. The project was conducted under contract and in cooperation with Tetra Tech, Inc. and the Washington Department of Ecology. The objective of the survey was to map surface water temperatures to support water quality assessments and temperature TMDL modeling in the basin.

Airborne 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 between 14:14 and 17:42 PM on August 13, 2006. The flight covered the Snoqualmie River (43.2 miles) and a segment of the Middle Fork Snoqualmie River from its mouth upstream to the Taylor River (20.3 miles) (Figure 1).

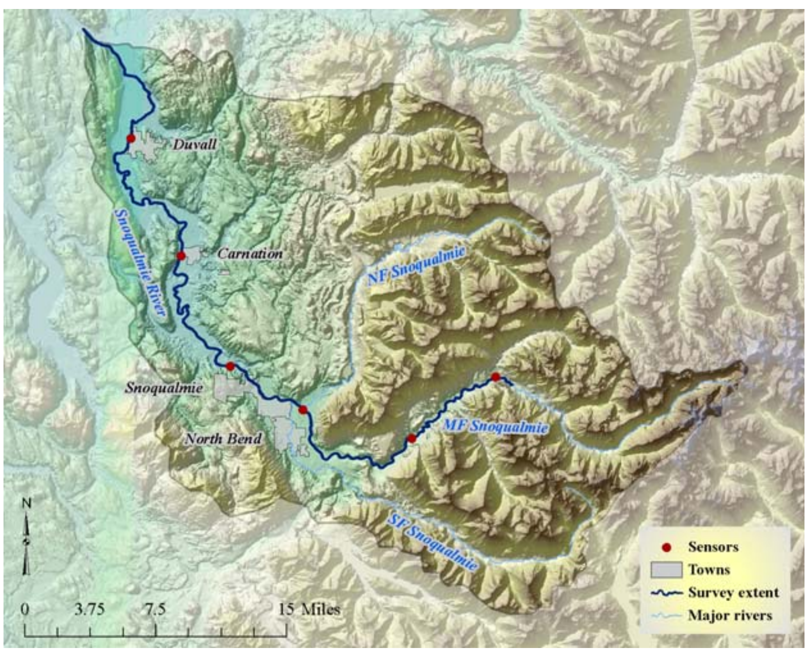


Figure 1 – Extent of the airborne TIR image acquisition on the Snoqualmie River.

# 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). The Firemapper 2.0 is a calibrated radiometer with internal non-uniformity correction and drift compensation. General specifications of the thermal infrared sensor are listed in Table 1.

Thermal infrared images were recorded directly from the sensor to an on-board computer as raw counts, which were than converted to radiant temperatures. The individual images were referenced with time, position, and heading information 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.

Table 1. Summary of TIR sensor specifications.

| | |
|---|---|
| Sensor: | Space Instruments Firemapper 2.0 |
| Wavelength: | 8-12μm |
| Temperature Resolution: | 0.01°C |
| Noise Equivalent Temperature Differences (NETD) | 0.07°C |
| Pixel Array | 320 (H) x 240 (V) |
| Encoding Level: | 16 bit |
| Horizontal Field-of-View: | 44.3° |

Image Characteristics: The aircraft was flown longitudinally along the stream corridor in order to have 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.

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: Prior to the season, the response characteristics of the sensor are measured in a laboratory environment. The response curves related the raw digital numbers recorded by the sensor to emitted radiance from the black body. The raw TIR images collected during the survey initially contain raw digital numbers which are then 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 a reasonably 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 (UTM Zone 10, NAD83) 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).

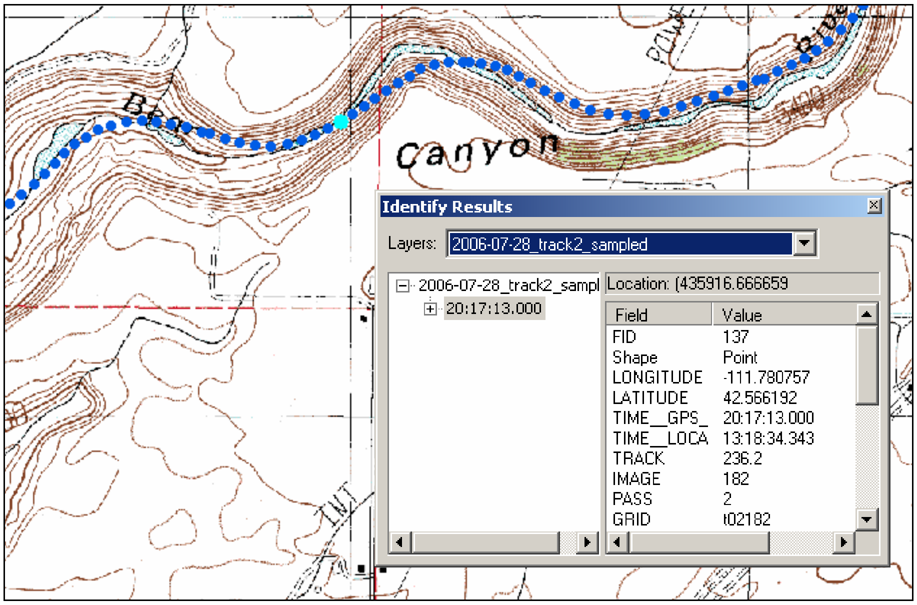


*Figure 3 –Each point on the map represents a thermal image location. The inset box shows the information recorded with each image point during acquisition.*

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: When feasible, Leica Photogrammetry Suite (LPS)[1] was used for automated tie point generation and image ortho-rectification. Using LPS, images were geo-rectified to real world coordinates using the orientation of the imagery, ground control points, and a 10-meter digital elevation model (DEM) of the study area. This produced seamless geo-rectified mosaics of the TIR images. However, this method only worked on stream reaches with minimal sinuosity and accurate control points.

Where automated methods could not be used, individual frames were manually geo-rectified by finding a minimum of six common ground control points (GCP's) between the image frames and existing ortho-photos. The images were then warped using a 1$^{st}$ order polynomial transformation. Due to the low relief along the river bottom, the photos were not corrected for terrain displacement.

[1] Leica Geosystems Photogrammetry Suite (LPS)© is a collection of software tools that operates within ERDAS Imagine Software.

## *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$^{o}$C (Torgersen et al. 2001[2]). 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$^{o}$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.

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

[2] 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.

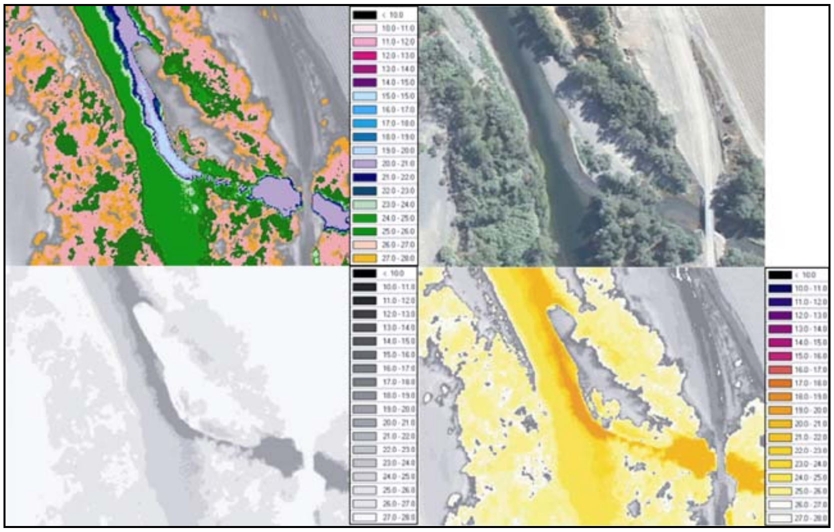


Figure 4 - Example of different color maps applied to the same TIR image.

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. However, slight uniformity differences may be apparent in the thermal mosaics. In order to maintain the integrity of the day, these differences were not smoothed or averaged.

### *Acquisition Parameters*

Table 1. Summary of Thermal Image Acquisition Parameters.

| | |
|---|---|
| Date: | August 13, 2006 |
| Flight Above Ground Level (AGL): | 304 m (1000 ft) |
| Image Footprint Width: | 248 m (814 ft) |
| Pixel Resolution: | 0.78 m (2.5 ft) |

## Weather Conditions

Weather conditions were considered ideal for the survey with warm air temperatures and mostly clear skies (Figure 5). Table 2 summarizes the weather conditions recorded during the time frame of the survey.

Table 2 – Hourly weather conditions observed in Everett, WA on August 13, 2006.

| Time (PDT) | Temp °F | Dew Point °F | Humidity % | Wind Direction | Wind Speed (MPH) | Conditions |
|---|---|---|---|---|---|---|
| 1:53 PM | 72.0 | 52.0 | 49 | Variable | 6.9 | Clear |
| 2:53 PM | 73.9 | 53.1 | 48 | NNW | 8.1 | Clear |
| 3:53 PM | 75.0 | 53.1 | 46 | Variable | 6.9 | Clear |
| 4:53 PM | 75.0 | 52.0 | 44 | NNW | 9.2 | Clear |
| 5:53 PM | 73.9 | 52.0 | 46 | NNW | 10.4 | Clear |
| 6:53 PM | 73.0 | 52.0 | 48 | North | 6.9 | Clear |

Figure 5 – Ground level photo showing the Snoqualmie River on August 13, 2007.

## 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. Since the in-stream data were used to compute an adjustment to the radiant temperatures, they should not be considered an independent check of radiant temperatures. The correction was computed as an average offset from the raw radiant values for all sensor locations. The temperature offsets and resulting accuracies were consistent with other surveys conducted in the Pacific Northwest during

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

| Serial | Stream | mile | Image | Time | Kinetic °T | Radiant °T | Difference °T |
|---|---|---|---|---|---|---|---|
| 1026267 | MF Snoqualmie | 20.1 | t01025 | 14:34 | 16.9 | 16.8 | 0.1 |
| 1026259 | MF Snoqualmie | 11.5 | t02015 | 14:36 | 17.0 | 17.0 | 0.0 |
| 766182 | MF Snoqualmie | 00.4 | t03023 | 14:44 | 18.9 | 18.8 | 0.1 |
| 766181 | Snoqualmie | 37.5 | t04015 | 14:59 | 17.9 | 17.8 | 0.1 |
| 1026264 | Snoqualmie | 24.0 | t08017 | 17:12 | 19.0 | 18.9 | 0.1 |
| 882338 | Snoqualmie | 10.0 | t09011 | 17:28 | 19.0 | 19.0 | 0.1 |

# Results

## *Middle Fork Snoqualmie River*

### Longitudinal Temperature Profile

Median channel temperatures were plotted versus river mile for the Middle Fork Snoqualmie River. The profile also shows the location of sampled tributary and spring inflows with the radiant temperatures for each sampled inflow summarized in Table 4.

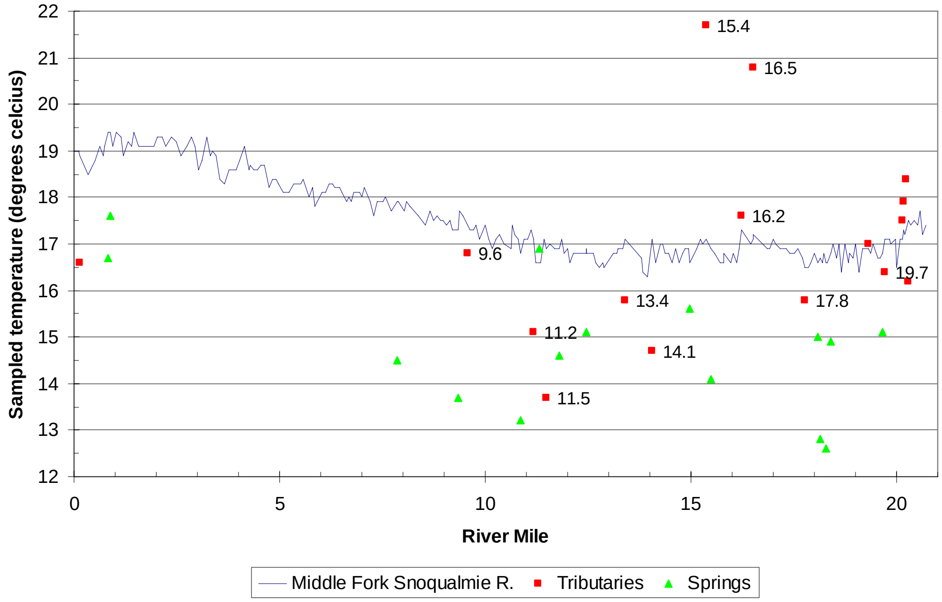



Figure 7 - Median channel temperatures plotted versus river mile for the Middle Fork Snoqualmie River. The locations of detected surface inflows are illustrated on the profile and labeled by river mile.

### Observations and Analysis

The TIR image acquisition on the Middle Fork Snoqualmie River started just upstream of the mouth of the Taylor River (mile 20.3) and proceeded downstream to the North Fork Snoqualmie River. At the start of the survey, radiant water temperatures were ~17.5°C and cooled slighted due to the influence of the Taylor River. Four distinct inflows were detected at the mouth of the Taylor River. The upstream channel contributed cooler water (~16.2°C) to the main-stem and appeared to decrease bulk temperatures in the Middle Fork by ~0.5°C.

Table 4 – Radiant temperatures of sampled tributaries and other surface inflows in the MF Snoqualmie River, WA.

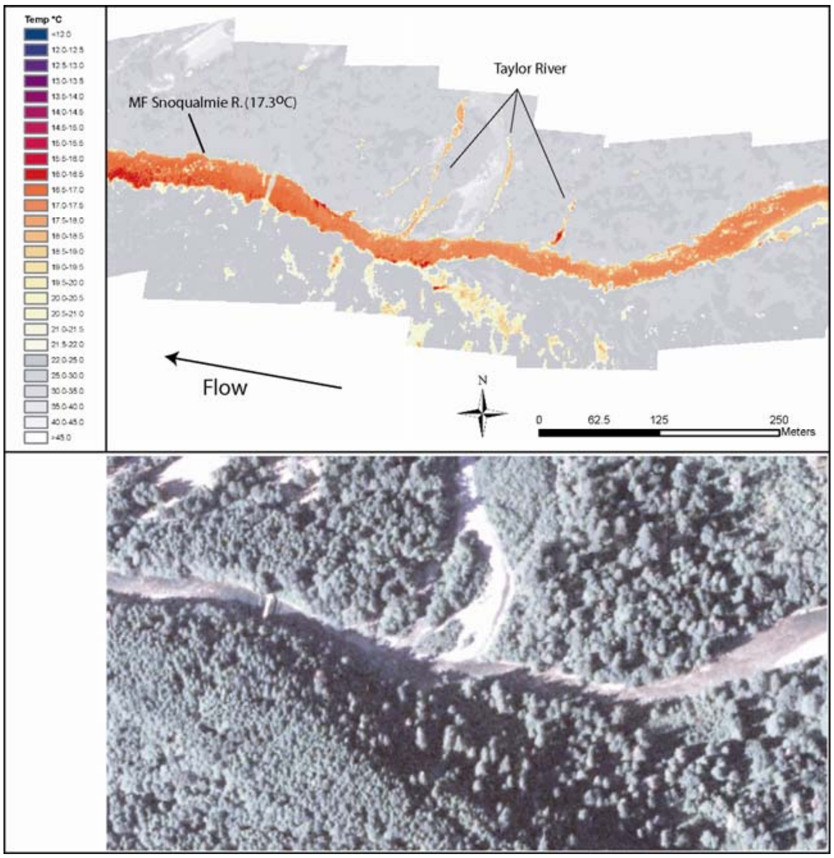
| | Grid | Track | km | mile | Tributary °C | Middle Fork °C | Difference °C |
|---|---|---|---|---|---|---|---|
| **Tributaries** | | | | | | | |
| NF Snoqualmie (R) | t02413 | 2 | 0.21 | 0.13 | 16.6 | 18.9 | -2.3 |
| Unnamed Trib ( R) | t02085 | 2 | 15.41 | 9.58 | 16.8 | 17.4 | -0.6 |
| Unnamed Trib ( R) | t02027 | 2 | 17.97 | 11.17 | 15.1 | 17.1 | -2.0 |
| Granite Creek ( L) | t01330 | 1 | 18.48 | 11.48 | 13.7 | 16.9 | -3.2 |
| Unnamed Trib (R) | t01253 | 1 | 21.57 | 13.40 | 15.8 | 17.1 | -1.3 |
| Unnamed Trib (L) | t01239 | 1 | 22.62 | 14.06 | 14.7 | 17.1 | -2.4 |
| Unnamed Tirb (R) | t01188 | 1 | 24.72 | 15.36 | 21.7 | 17.1 | 4.6 |
| Pratt River (L) | t01151 | 1 | 26.14 | 16.24 | 17.6 | 17.3 | 0.3 |
| Unnamed (R) | t01146 | 1 | 26.55 | 16.50 | 20.8 | 17.1 | 3.7 |
| Unnamed Trib (R) | t01110 | 1 | 28.58 | 17.76 | 15.8 | 16.5 | -0.7 |
| Rainy Creek | t01052 | 1 | 31.09 | 19.32 | 17.0 | 16.9 | 0.1 |
| Backwater (L) | t01038 | 1 | 31.70 | 19.70 | 16.4 | 17.1 | -0.7 |
| Taylor River ( R) | t01023 | 1 | 32.41 | 20.14 | 17.5 | 17.1 | 0.4 |
| Taylor River ( R) | t01022 | 1 | 32.46 | 20.17 | 17.9 | 17.3 | 0.6 |
| Taylor River ( R) | t01020 | 1 | 32.55 | 20.23 | 18.4 | 17.3 | 1.1 |
| Taylor River (R) | t01018 | 1 | 32.65 | 20.29 | 16.2 | 17.5 | -1.3 |
| **Springs** | | | | | | | |
| Spring (L) | t02391 | 2 | 1.36 | 0.84 | 16.7 | 19.4 | -2.7 |
| Spring (R) | t02389 | 2 | 1.43 | 0.89 | 17.6 | 19.4 | -1.8 |
| Spring (L) | t02145 | 2 | 12.66 | 7.87 | 14.5 | 17.9 | -3.4 |
| Spring (L) | t02094 | 2 | 15.03 | 9.34 | 13.7 | 17.3 | -3.6 |
| Spring (R) | t02038 | 2 | 17.49 | 10.87 | 13.2 | 16.8 | -3.6 |
| Spring (R) | t02022 | 2 | 18.21 | 11.31 | 16.9 | 16.6 | 0.3 |
| Spring (L) | t01319 | 1 | 18.97 | 11.79 | 14.6 | 16.9 | -2.3 |
| Small spring (L) | t01295 | 1 | 20.05 | 12.46 | 15.1 | 16.9 | -1.8 |
| Spring (R) | t01203 | 1 | 24.11 | 14.98 | 15.6 | 16.6 | -1.0 |
| Big spring (L) | t01182 | 1 | 24.92 | 15.49 | 14.1 | 16.9 | -2.8 |
| Small spring ( L) | t01097 | 1 | 29.10 | 18.08 | 15.0 | 16.6 | -1.6 |
| Small spring ( L) | t01094 | 1 | 29.21 | 18.15 | 12.8 | 16.7 | -3.9 |
| Big spring (L) | t01088 | 1 | 29.44 | 18.29 | 12.6 | 16.6 | -4.0 |
| Spring (L) | t01084 | 1 | 29.59 | 18.39 | 14.9 | 16.8 | -1.9 |
| Spring (L) | t01039 | 1 | 31.65 | 19.67 | 15.1 | 16.8 | -1.7 |

Stream temperature remained relatively constant over the next ~10.0 miles with radiant temperatures varying between 16.3°C and 17.3°C. This reach was characterized by a relatively confined canyon, forested lands, and a primarily a Northeast/Southwest orientation. In addition, a total of 11 distinct spring discharges and 7 cool water tributaries were detected through this reach. The combination of valley morphology, riparian vegetation, and cool water sources all appear to contribute to maintaining relatively cool water temperatures through this reach. The various springs and cool water tributaries detected in this reach may also represent thermal refugia for cool-water fish species during the summer months.

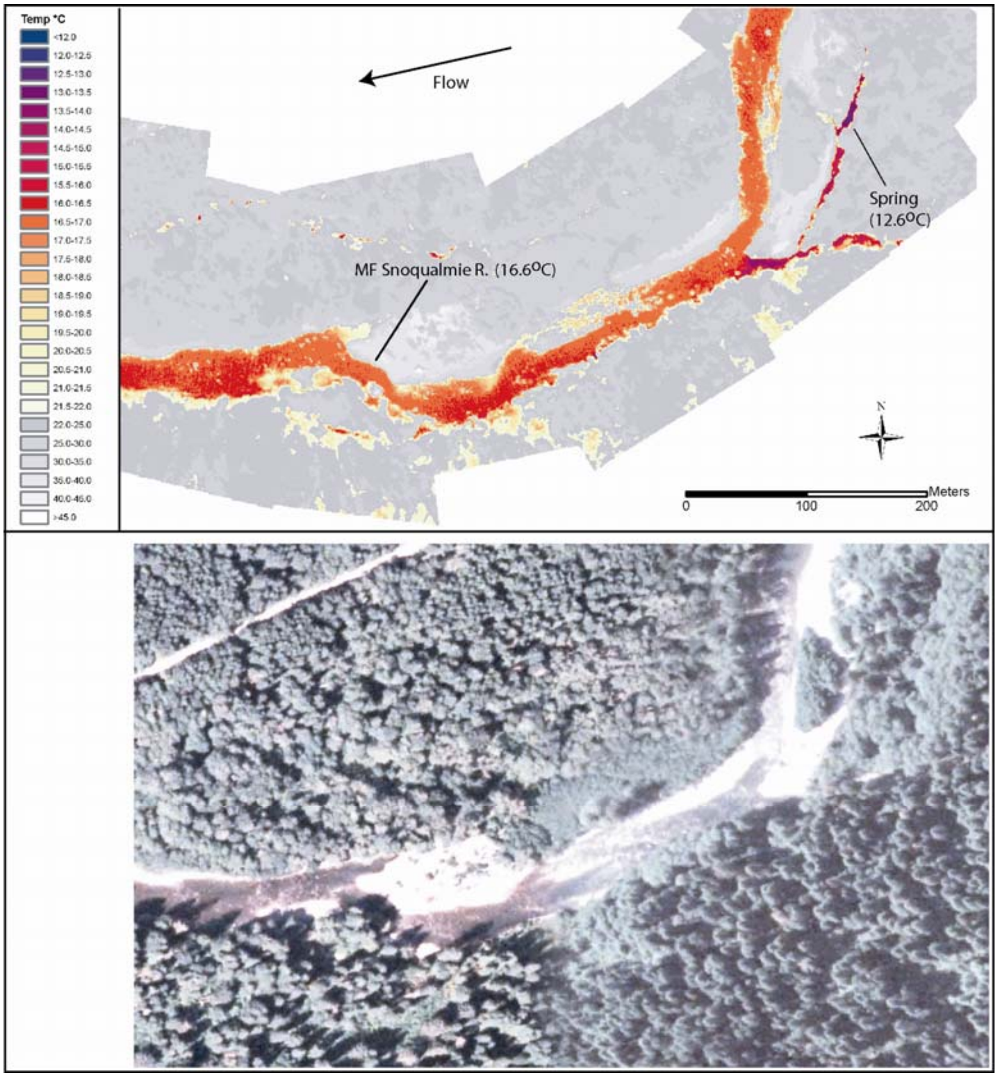
At about river mile 10.6, radiant water temperature exhibited a steady downstream warming trend reaching ~19.2°C at mile 3.3. Inspection of the topographic base maps shows that the change in longitudinal heating rate corresponds to change in stream aspect (East/West) and distinct change in valley form (*reference sampled images*). At mile 10.6, the Middle Fork transitions from a relatively confined forested canyon to the more open valley at the town of North Bend, WA. Three springs were sampled between river miles 7.8 and 10.9; however, fewer inflows were detected compared to the upstream reach. Stream temperature remained relatively constant (~19.3°C) over the lower 3-miles of the Middle Fork.

## Sample Images

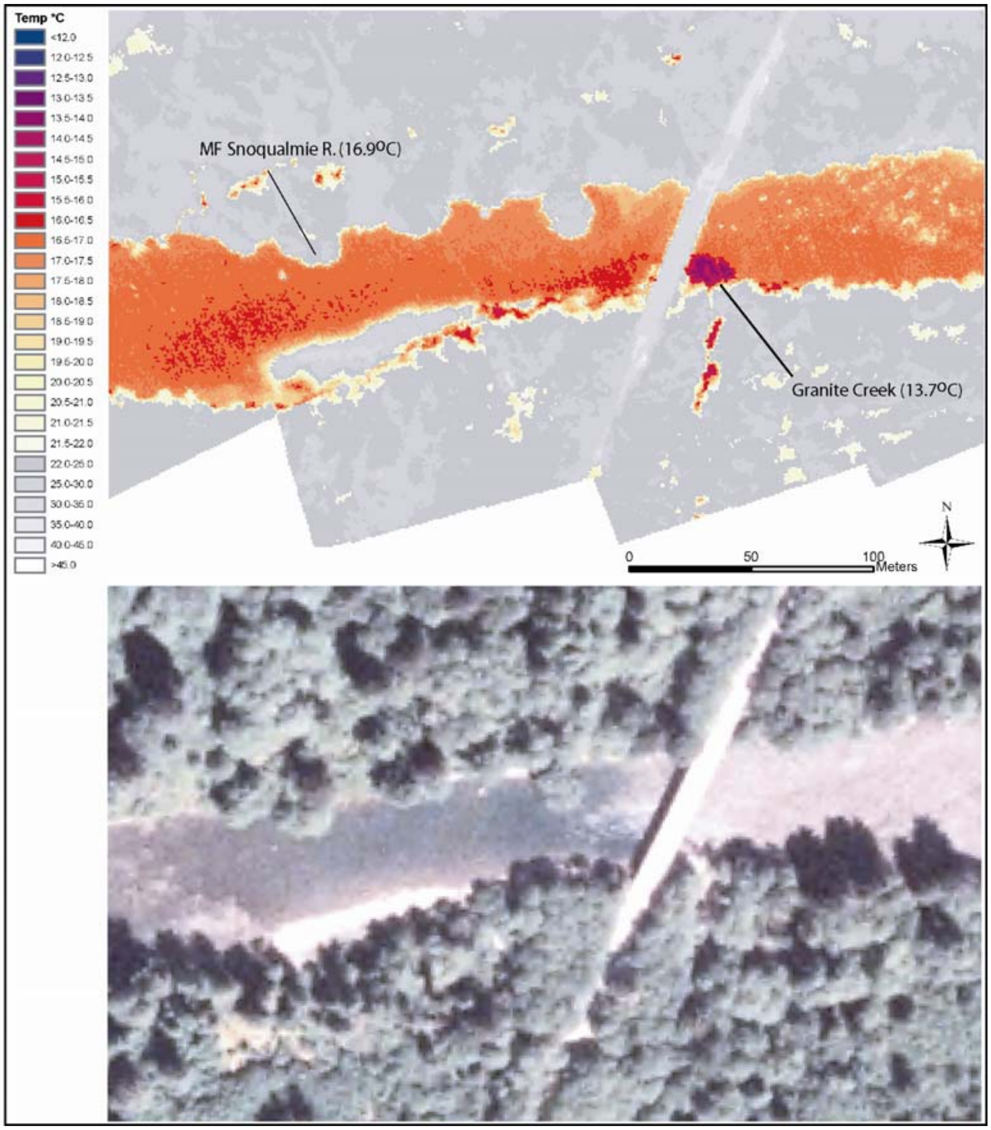
The images in this section highlight thermal features and/or channel conditions. The true color imagery is primarily from publicly available NAIP 1-meter color ortho-photos.



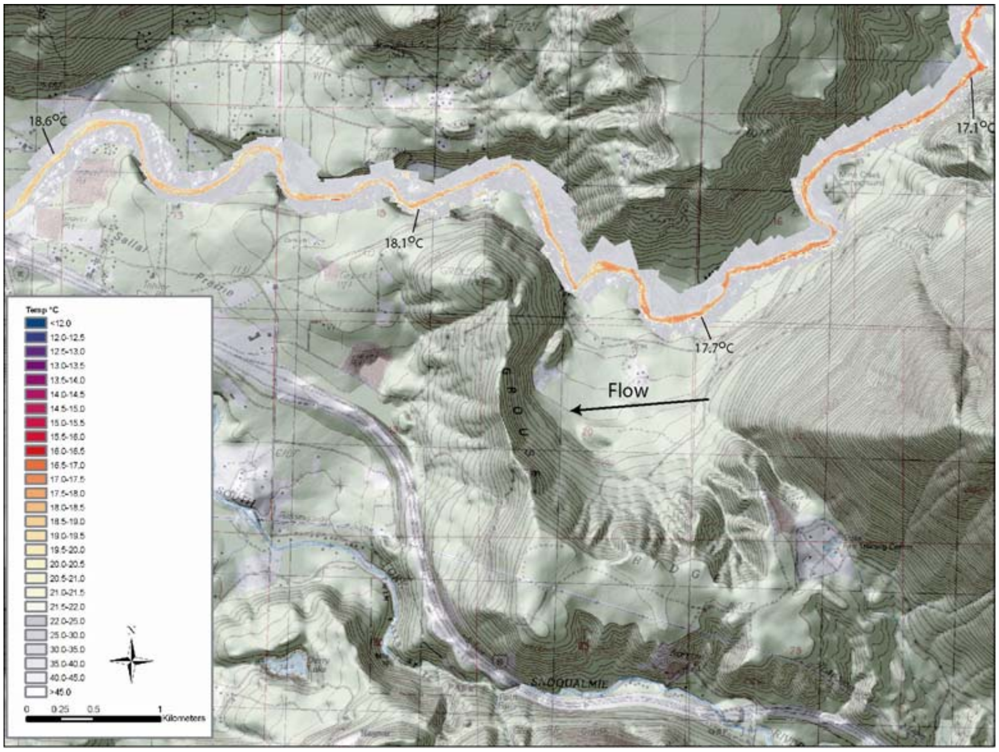

*Sample Image Middle Fork* – TIR (top) and true color image showing the confluence of the Middle Fork Snoqualmie River and the Taylor River at mile 20.3. The airborne survey started just upstream of the Taylor River, which had multiple inflows into the Snoqualmie River.



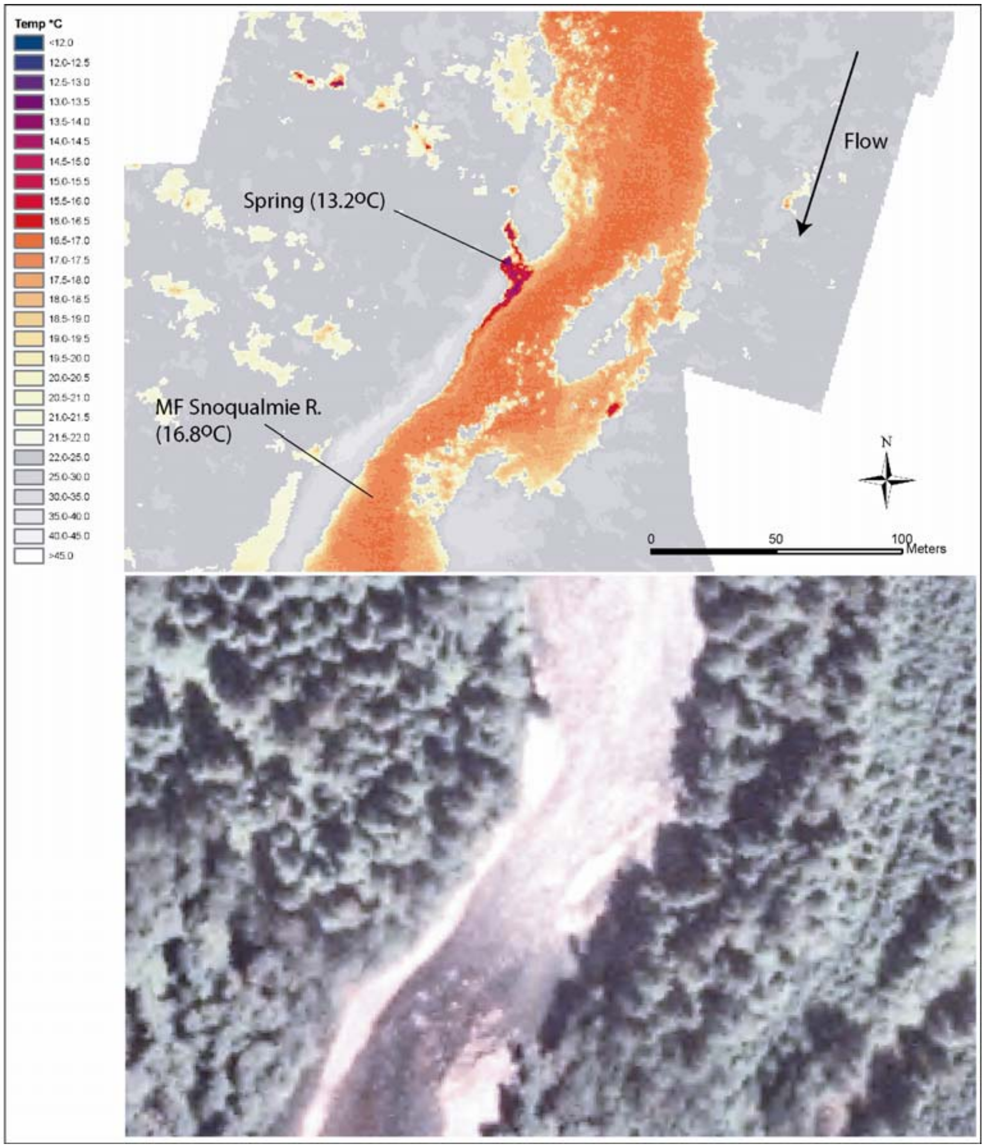

*Sample Image Middle Fork* – TIR (top) and true color (bottom) image showing a spring along the left bank of the Middle Fork Snoqualmie River at mile 18.3. A total of 11 separate sub-surfaces discharges were sampled between river mile 20.3 and 10.8, which probably helps buffer longitudinal heating through this reach.



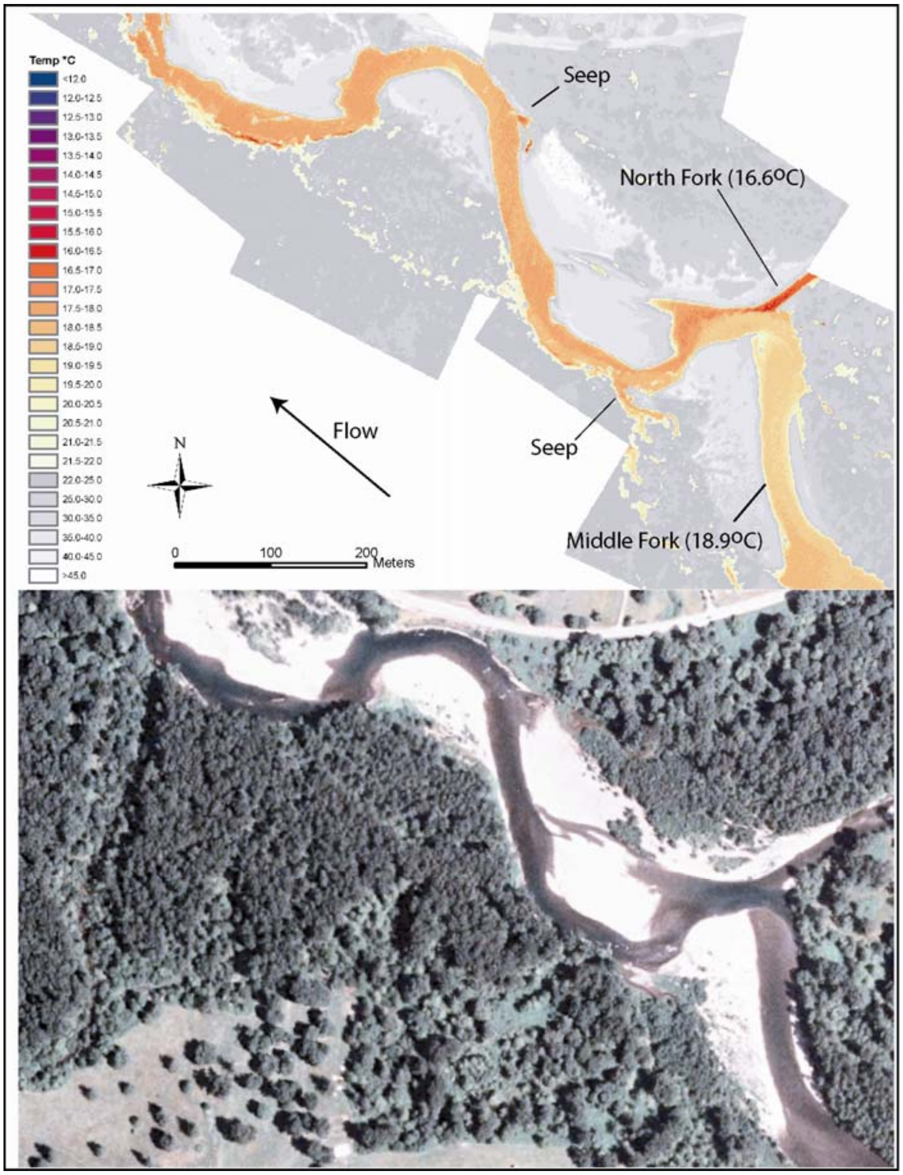

*Sample Image Middle Fork* – TIR (top) and true color (bottom) image showing the confluence of Granite Creek (13.7°C) and the Middle Fork Snoqualmie River at mile 11.5. Granite Creek was one of nine cool water tributaries sampled during the analysis of the Middle Fork imagery.




*Sample Image Middle Fork* – The map above shows the TIR mosaic plotted over the 1:24K topographic base map between river miles 10.4 and 4.2. Radiant temperatures are labeled along the stream gradient and show a downstream warming trend that occurs as the Middle Fork transitions from the confined canyon to the more open valley reach. Radiant temperatures in the Middle Fork were relatively constant upstream of mile 10.4




*Sample Image Middle Fork* – TIR (top) and true color (bottom) image showing an apparent cold water spring discharge (13.2°C) in the Middle Fork Snoqualmie River at mile 10.9. The spring was not identified on the USGS 1:24K topographic maps.




*Sample Image Middle Fork* – TIR (top) and true color (bottom) image showing the confluence of the North and Middle Fork Snoqualmie River. Seeps are visible along both the left and right bank of the Snoqualmie River suggesting that some level of hyporheic flow.

## *Snoqualmie River*

### Longitudinal Temperature Profile

Median channel temperatures were plotted versus river mile for the Snoqualmie River. The profile also shows the location of sampled tributary and spring inflows with the radiant temperatures for each sampled inflow summarized in Table 5. The Snoqualmie River survey was suspended at 15:12 at mile 24.2 in order to address a technical issue on the aircraft. The survey was resumed at the same location at 17:13.

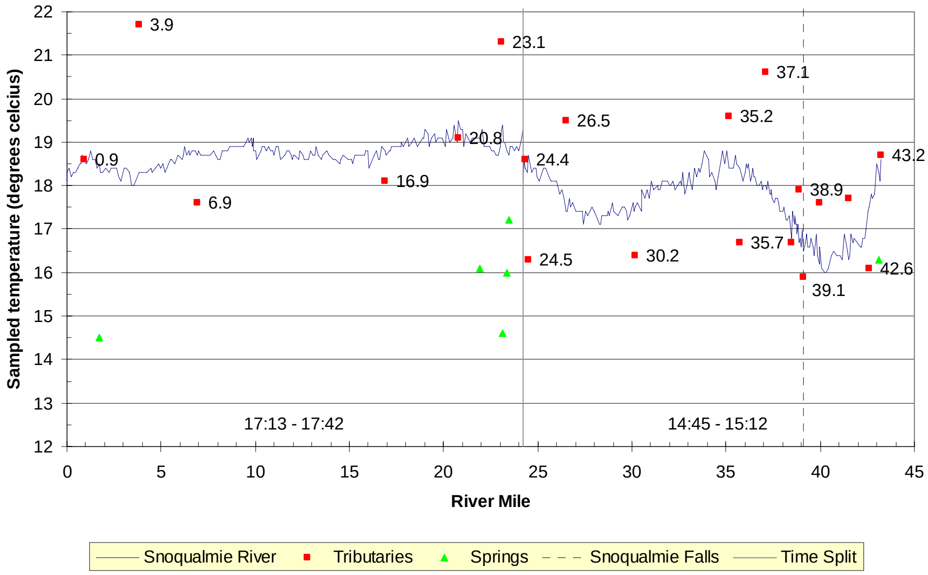



Figure 7 - Median channel temperatures plotted versus river mile for the Snoqualmie River. River miles were routed upstream from the mouth. The locations of detected surface inflows (i.e. tributaries, irrigation returns, and seeps) are illustrated on the profile and summarized in Table 5.

### Observations and Analysis

Downstream of the Middle Fork confluence, the radiant water temperatures in the Snoqualmie River decreased rapidly from ~18.6$^{o}$C at mile 43.2 to ~16.6$^{o}$C at mile 42.2. The decrease appeared primarily due to the cooling influence of the North Fork and South Fork Snoqualmie Rivers. The cooling continued downstream reaching a local minimum of 16.1$^{o}$C at mile 40.4 near the town of Snoqualmie, WA. Inspection of the topographic maps (*reference sample imagery*) shows that the valley bottom constricts significantly at Snoqualmie Falls (mile 39.12). The valley form and the continued cooling downstream of the South Fork confluence suggests some sub-surface influence through this reach.

Table 5 – Radiant temperatures of sampled tributaries and other surface inflows in the Snoqualmie River, WA.

| Tributary Name | Grid | Track | km | mile | Tributary °C | Snoqualmie R. °C | Difference °C |
|---|---|---|---|---|---|---|---|
| **Tributaries** | | | | | | | |
| Skykomish River (R) | t09348 | 9 | 1.49 | 0.93 | 18.6 | 18.6 | 0.0 |
| Holding Pond (L ) | t09259 | 9 | 6.20 | 3.85 | 21.7 | 18.3 | 3.4 |
| Cherry Creek ( R) | t09119 | 9 | 11.13 | 6.91 | 17.6 | 18.7 | -1.1 |
| Unnamed Trib (L) | t08215 | 8 | 27.21 | 16.91 | 18.1 | 18.8 | -0.7 |
| Harris Creek (R) | t08106 | 8 | 33.49 | 20.81 | 19.1 | 19.5 | -0.4 |
| Unnamed trib ( L) | t08043 | 8 | 37.18 | 23.10 | 21.3 | 19.3 | 2.0 |
| Tolt River ( R) | t04405 | 4 | 39.20 | 24.36 | 18.6 | 18.4 | 0.2 |
| Canal (R) | t04400 | 4 | 39.44 | 24.51 | 16.3 | 18.7 | -2.4 |
| Griffin Creek (R) | t04340 | 4 | 42.67 | 26.51 | 19.5 | 17.4 | 2.1 |
| Patterson Creek (L) | t04244 | 4 | 48.60 | 30.20 | 16.4 | 17.5 | -1.1 |
| Raging River (L) | t04099 | 4 | 56.57 | 35.15 | 19.6 | 18.4 | 1.2 |
| Unnamed Trib (R) | t04082 | 4 | 57.52 | 35.74 | 16.7 | 18.4 | -1.7 |
| Unnamed Trib (R) | t04027 | 4 | 59.71 | 37.10 | 20.6 | 18.0 | 2.6 |
| Tokul Creek (R) | t03233 | 3 | 61.91 | 38.47 | 16.7 | 16.8 | -0.1 |
| Power Plant ( R) | t03207 | 3 | 62.60 | 38.90 | 17.9 | 16.7 | 1.2 |
| Spring/waterfall (L) | t03198 | 3 | 62.96 | 39.12 | 15.9 | 16.5 | -0.6 |
| Kimball Creek (L) | t03158 | 3 | 64.28 | 39.94 | 17.6 | 16.2 | 1.4 |
| Brockway Creek | t03105 | 3 | 66.76 | 41.48 | 17.7 | 16.3 | 1.4 |
| SF Snoqualmie (L) | T03065 | 3 | 68.56 | 42.60 | 16.1 | 17.5 | -1.4 |
| Unnamed Trib ( L) | t03040 | 3 | 69.58 | 43.24 | 18.7 | 18.4 | 0.3 |
| **Springs** | | | | | | | |
| Small Spring ( R) | t09322 | 9 | 2.79 | 1.73 | 14.5 | 18.5 | -4.0 |
| Spring (L) | t08077 | 8 | 35.29 | 21.93 | 16.1 | 19.1 | -3.0 |
| Spring? (L) | t08042 | 8 | 37.24 | 23.14 | 14.6 | 19.4 | -4.8 |
| Spring (R) | t08036 | 8 | 37.58 | 23.35 | 16.0 | 18.8 | -2.8 |
| Spring (R) | t08033 | 8 | 37.75 | 23.46 | 17.2 | 18.7 | -1.5 |
| Spring (R) | t03046 | 3 | 69.40 | 43.12 | 16.3 | 18.3 | -2.0 |

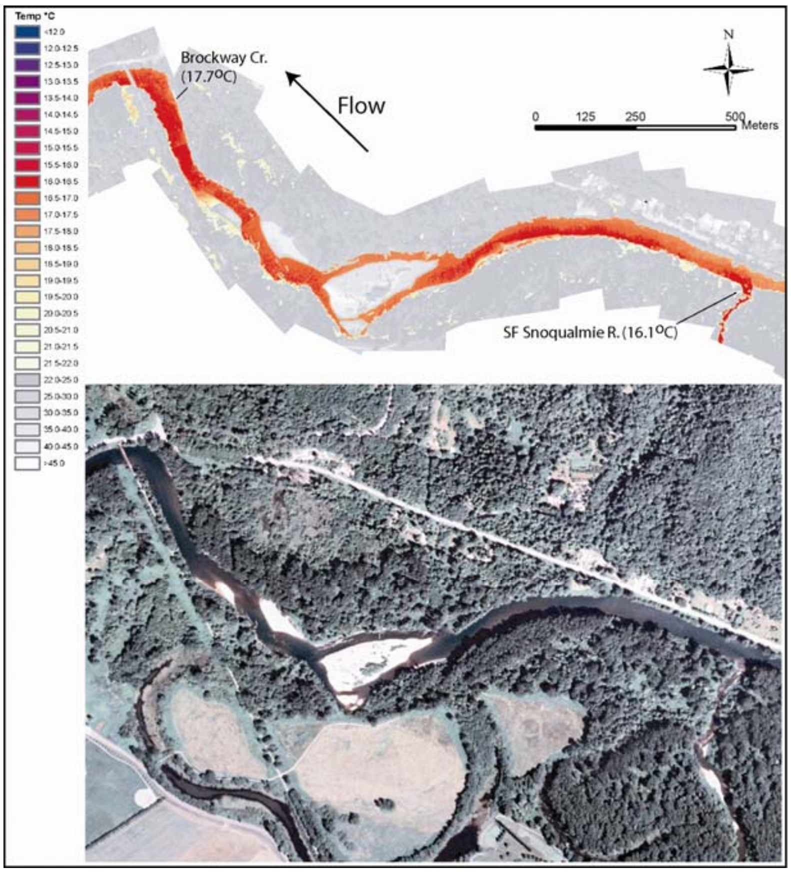
Radiant water temperatures in the Snoqualmie River showed a consistent longitudinal heating trend below Snoqualmie Falls reaching a local maximum of 18.8°C at mile 35.0. The profile shows some local temperature variability near river mile 35.0, but inspection of the TIR imagery and topographic base maps do not indicate the source.

Moving downstream, stream temperatures showed a slight cooling trend (~1.5°C) between miles 33.9 (18.7°C) and miles 28.3 (17.1°C). Patterson Creek (mile 30.2) was observed as a cooling source within this reach, but appeared relatively small compared to the flow in the main stem (*reference sample imagery*). Although the source of the cooling could not be positively determined through inspection of the imagery, the Snoqualmie River exhibited increased in sinuosity with a number of mapped wetlands and sloughs through this reach. Past TIR surveys have shown that these features provide conduits for sub-surface exchange and are often associated with reaches with little or no longitudinal heating.

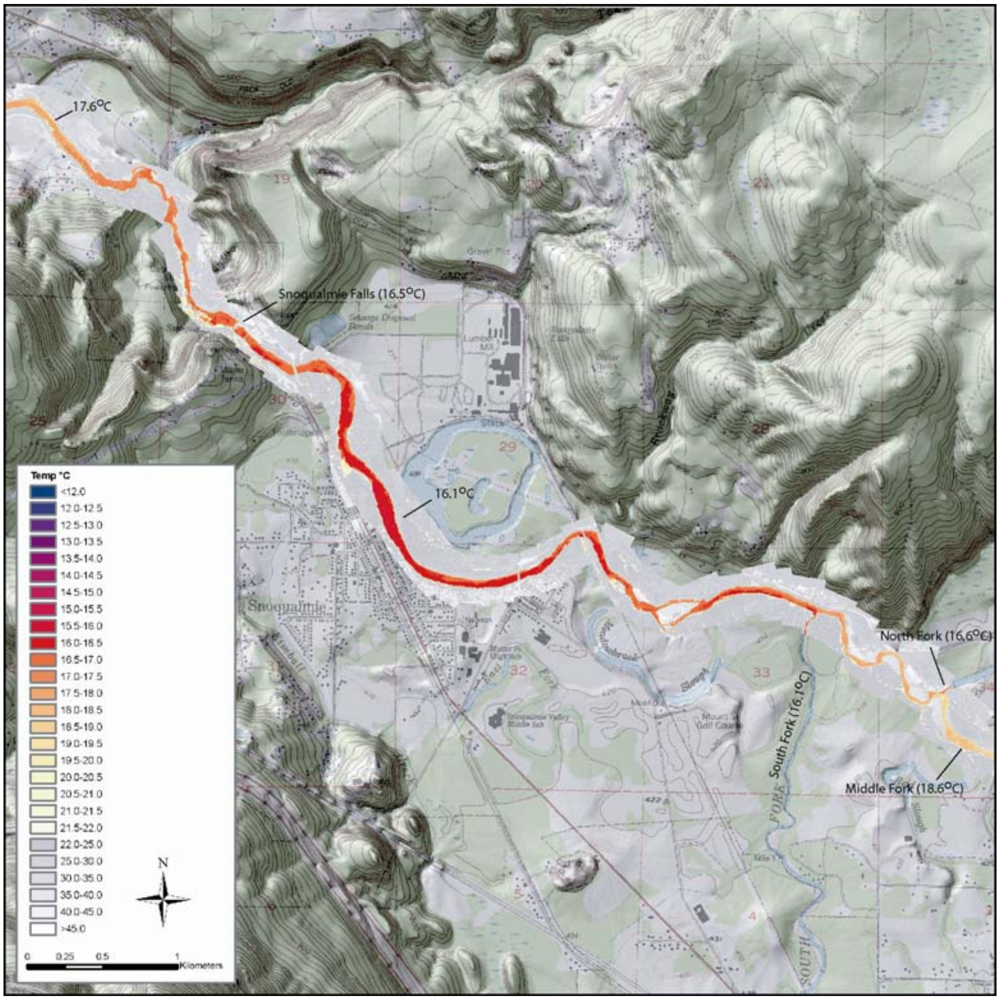
Radiant water temperatures increased steadily from 17.1°C to 19.3°C between river mile 27.3 and river mile 24.4. As mentioned previously, the flight was suspended between 3:12 PM and 5:13 PM to fix a technical problem on the aircraft. The slight increase in stream temperature at mile 24.2 represents the change in water temperature during this time delay. A cluster of 4 springs were detected between river miles 23.5 and 21.9, which contributed to some local variability within this reach.

Between mile 21.9 and the mouth of the Snoqualmie River, radiant water temperatures ranged from 19.1°C and 18.0°C. Inspection of the profile shows a slight overall cooling trend in the lower 20 river miles. Of the five tributaries sampled within this reach, two contributed cooler water to the mainstem.

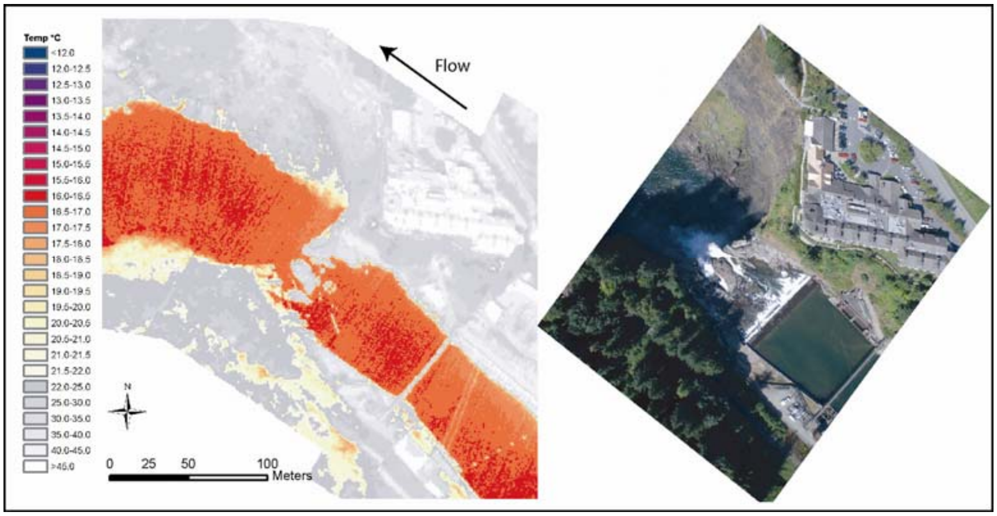
## Sample Images



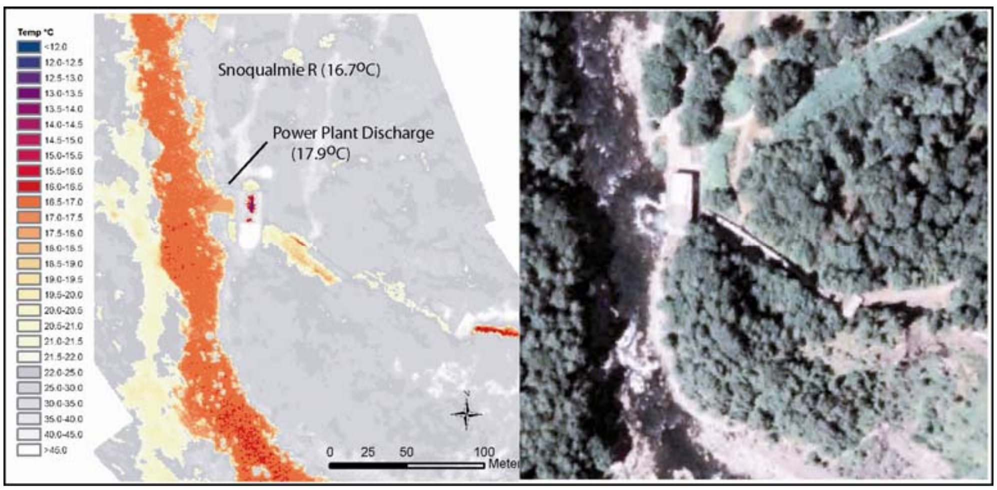

*Sample image Snoqualmie River* – TIR (top) and true color (bottom) image showing the inflow of the SF Snoqualmie River to the Snoqualmie River at mile 42.6. The inflow of the North and South Forks helped lower bulk water temperatures by ~2.0°C. Brockway Creek was detected at mile 41.5 but was barely visible through the riparian canopy.



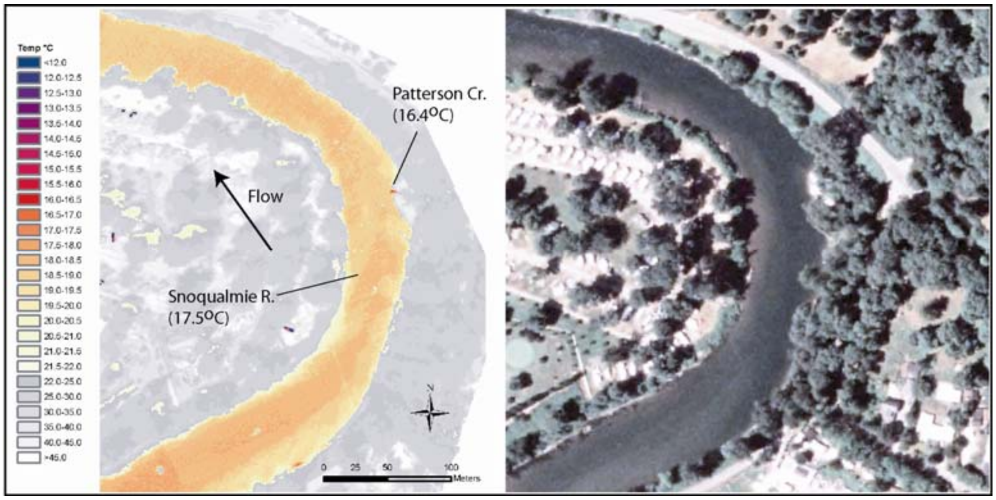

*Sample Image Snoqualmie River* – The image above shows the TIR image mosaic of the Snoqualmie River from mile 37.8 to the Middle Fork Confluence (mile 43.3) plotted over the 1:24K USGS topographic maps. Radiant temperatures are labeled to illustrate the longitudinal temperature pattern through this reach. The North Fork and South Fork Snoqualmie River both have a cooling influence on the river. However, the river does not reach a local minimum of 16.1°C until river mile 40.4. The continued cooling combined with the valley morphology suggests some sub-surface influence between the South Fork (mile 42.6) and the town of Snoqualmie (mile 40.4). Stream temperatures increased slightly (~0.5°C) to Snoqualmie Falls, before exhibiting steady and consistent downstream warming.



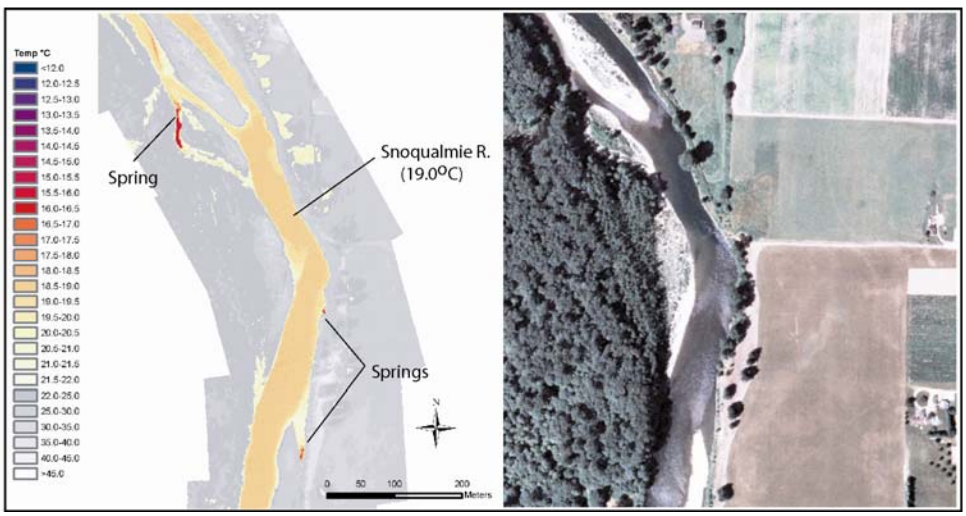
*Sample Image Snoqualmie River* – The TIR (left) and true color image (right) above show the Snoqualmie Falls at river mile 39.1. The falls are a prominent feature on the river and the true color image illustrated above is from the high resolution digital camera that was co-mounted with the thermal IR camera.



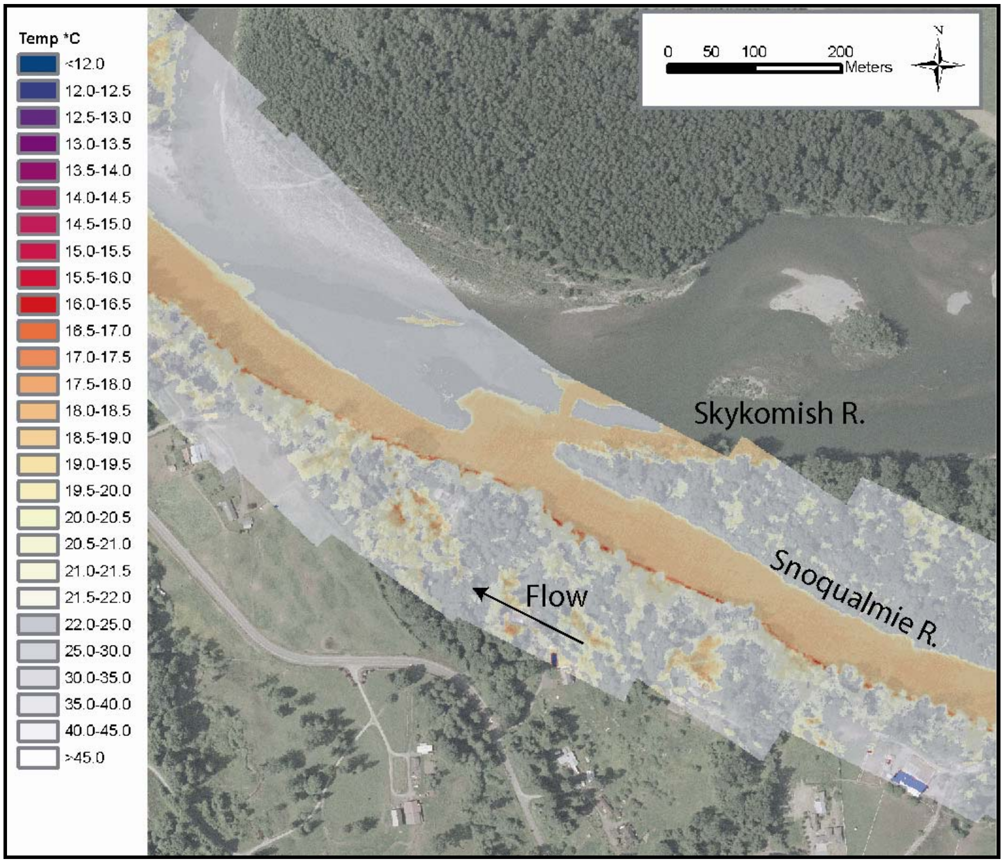
*Sample Image Snoqualmie River* – TIR (left) and true color image (right) showing the Power Plant outflow at river mile 38.9.




*Sample Image Snoqualmie Rive* – The TIR (left) and true color image (right) above show the confluence of Patterson Creek (16.4°C) and the Snoqualmie River (17.5°C). Patterson Creek was 1.1°C cooler than the main river, but also appeared relatively small with no visible thermal mixing plume. Small inflows were sampled during the analysis to illustrate the frequency and temperatures of mass transfer locations along the river.




*Sample Image Snoqualmie Rive* – The TIR (left) and true color image (right) above show a series of apparent springs on the Snoqualmie River from river mile 23.1 to 23.5. The springs suggest the presence of hyporheic flow within this reach.




*Sample Image Snoqualmie River* – The image above shows the confluence of the Snoqualmie River (18.6°C) and the Skykomish River (18.6°C). The TIR image is illustrated with partial transparency over the 1-ft true color ortho-photos obtained from King County. The surface temperatures in the Skykomish River were similar the Snoqualmie River in the main flow, but was warmer out of the main flow.

## Combined Profile

The median temperatures for the Middle Fork and mainstem Snoqualmie River were combined to create a spatially continuous longitudinal temperature profile (Figure 8).

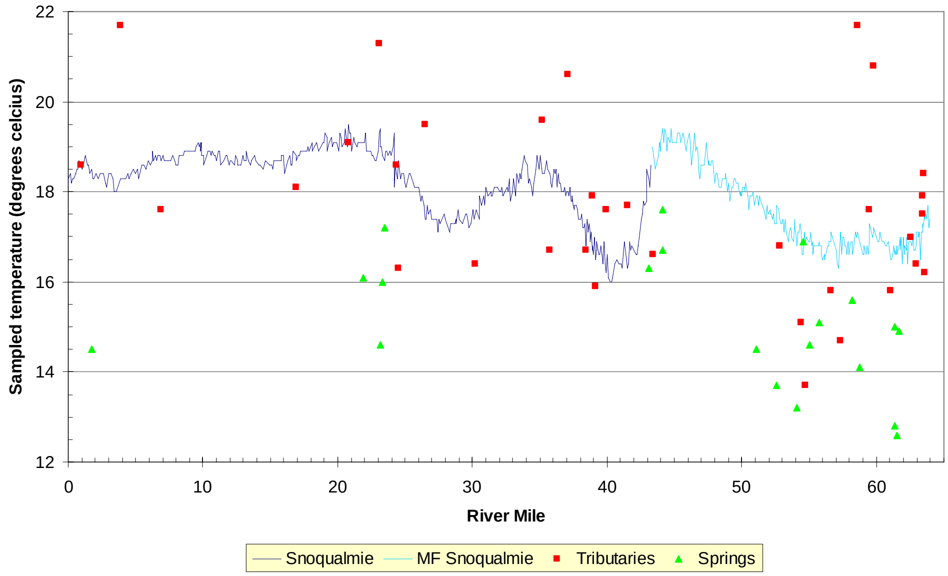



Figure 8 – Median water temperatures versus river mile for both the Snoqualmie and Middle Fork Snoqualmie Rivers. The plot also shows the location of tributary and springs inflows sampled during the analysis.

## Summary

An airborne thermal infrared survey was successfully conducted on Snoqualmie River and Middle Fork Snoqualmie River, WA on August 13, 2006. The flight date and specifications were coordinated with Tetra Tech Inc. and Washington Dept. of Ecology.

Watershed Sciences deployed in-stream sensors which were used to calibrate and verify the accuracy of the radiant temperatures. The results showed that the radiant temperature accuracies were consistent with previous surveys conducted on other streams in the Western United States. Since these in-stream sensors were used to calibrate the imagery, independent checks using other sensors are warranted.

Overall, the TIR data showed how temperatures varied spatially along the stream gradient. The Middle Fork results suggested that the bulk water temperatures at the basin scale were driven by valley morphology. A number of cold water spring and tributaries also helped moderate stream heating and created area of local refugia. The mainstem Snoqualmie River also exhibited variations in reach scale longitudinal heating (and cooling) rates over the upper 20 river miles.

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. 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 field work.

## Contact Information

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## Deliverables

The TIR imagery is provided in two forms: 1) individual un-rectified frames and 2) a continuous geo-rectified mosaic at 2.5 ft (0.74) m resolution. 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 and are often better for detecting smaller thermal features. A GIS point layer is included which provides an index of TIR image locations, the results of temperature sampling, and interpretations made during the analysis. The true color digital images are provided as individual un-rectified frames with separate index for identifying individual frames.

Deliverables are provided on two DVD's:

Geo-Corrected Imagery and index files are stored in the following projections:

**1. UTM Zone 10, NAD83, Units = Meters.**
**2. Washington State Plane North, Units = Feet**

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DVD 1 - Snoqualmie_1

a. Thermal_Mosaic: Continuous image mosaic of the geo-rectified TIR image frames at 2.5 ft resolution in geo-tiff format. GRID cell value = radiant temperature * 10.
b. Longprofile: Longitudinal temperature profile showing median temperatures versus river mile.
c. Surveys: Point layer showing acquired image points with sampled radiant temperatures.
d. Hydrography: Streams layer for the Snoqualmie River Basin.
e. Report: A copy of this report.

DVD 2 - Snoqualmie_2

f. Thermal Unrectified - Calibrated TIR images in ESRI GRID Format. GRID cell value = radiant temperature * 10. 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.
g. TC_Unrectified – Unrectified true color images in jpg format. An index is provided to show the geographic location of the aircraft at the time the image was acquired.
h. Surveys - Point layers showing image locations for both the thermal and true color images.