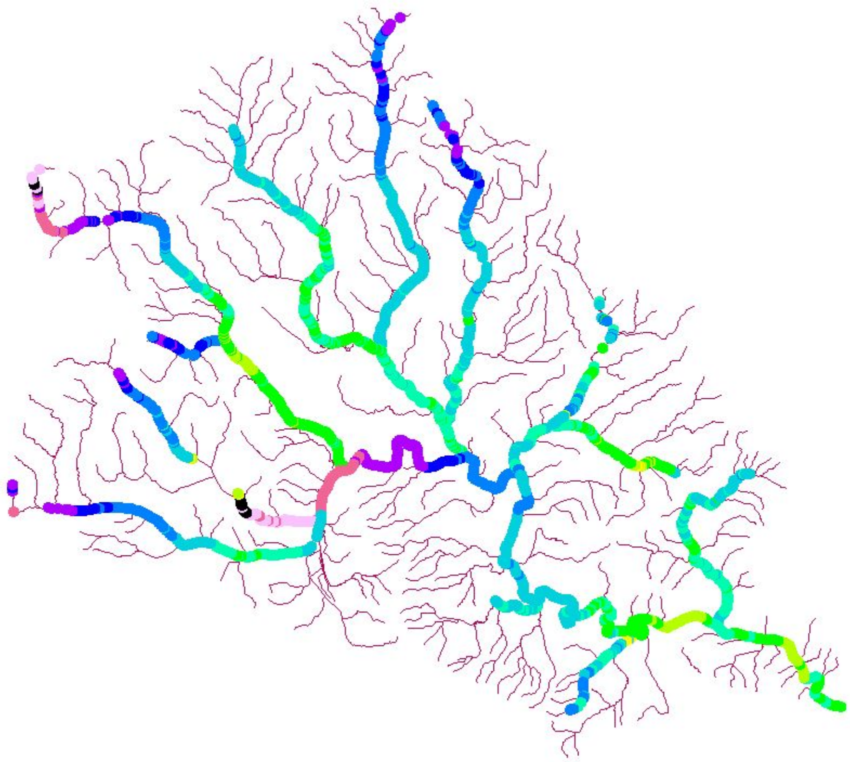
# REMOTE SENSING SURVEY OF THE TUALATIN RIVER BASIN

*Thermal Infrared and Color Videography*



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**FINAL REPORT**

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## Introduction

Forward Looking Infrared (FLIR) has been demonstrated as a reliable, cost-effective, and accessible technology for monitoring and evaluating stream temperatures from the scale of watersheds to individual habitats (Karalus et al., 1996; Norton et al., Faux et al., 1998). In 1999, the Oregon Department of Environmental Quality (ODEQ) contracted with Watershed Sciences, LLC to map and assess stream temperatures in the Tualatin River basin using FLIR.

Traditional methods for monitoring stream temperatures have relied on in-stream temperature monitors to gather data. These monitors provide temporally continuous data, but provide little insight into the spatial variability in temperatures. With the use of remote sensing, we have been able to map stream temperatures across entire stream networks at a point in time. FLIR technology has proven to be a highly portable and cost-effective method to collect very detailed data over large areas in very little time. The combination of temporally and spatially continuous data provides very powerful tools for understanding the dynamics of stream temperature hierarchically across multiple scales (pools → reaches → streams → watersheds). Current research has identified cool versus warm streams within a watershed, cool reaches within a stream, and cool habitats within a reach (McIntosh et al., 1995; Torgerson et al., 1995; Torgerson et al., 1999).

The purpose of this project is to provide spatial temperature data using FLIR thermal imagery. The FLIR data will be used with other data in the development of an assessment to determine the causes of heating and identify cold-water refugia for fish in the Tualatin River basin. Many rivers and streams in this basin are water quality limited for temperature. The assessment will be used to develop Total Maximum Daily Loads (TMDLs) for temperature. The FLIR data will also be used in the development of Water Quality Management Plans (WQMPs) by local management agencies to address causes of heating and to protect coldwater refugia for fish. ODEQ will combine the FLIR temperature data with continuous temperature monitoring and other data (flow, % shading, channel characteristics, etc.) to develop a basin-wide temperature assessment and simulation that would be the basis for a temperature TMDL and for development of temperature management plans.

This document summarizes the methods and results of the FLIR survey conducted from July 27- 30, 1999 covering a total of 395 river km (245 river miles) in the Tualatin River basin. The results and analysis presented here are at the watershed and tributary scales. The data is structured in an ArcView GIS environment to allow further analysis at finer scales.

## Methods

### *Data Collection*

The ODEQ in Portland, Oregon contracted with Watershed Sciences, LLC of Corvallis, Oregon to collect and analyze thermal infrared and visible video imagery in the Tualatin River basin during the summer of 1999. The survey was conducted from July 27- 30, 1999 and covered a total of 395 river km (Figure 1). Data collection was timed to capture daily maximum stream temperatures, which typically occur between 14:00 and 18:00 hours. Table 1 summarizes the date, time, and survey distance for each survey stream.

Data were collected using a FLIR and a Day TV video camera. The two sensors were co-located in a gyro-stabilized mount that attached to the underside of a Bell B3 helicopter. The helicopter was flown longitudinally over the center of the stream channel with the sensors in a vertical (or near vertical) position. All streams except Rock Creek and Beaverton Creek were surveyed upstream starting from the mouth. Rock Creek and Beaverton Creek were surveyed starting headwaters and working downstream due to the proximity of the stream's mouth to the Hillsboro Airport.

Table 1 – Date, time, and distance for streams surveyed in the Tualatin River Basin.

| Stream | Date | Local Time (PM) | kilometer/ mile |
|---|---|---|---|
| Tualatin River<br>Lower (Mouth to Wapato Ck)<br>Upper (Wapato Ck to Headwaters) | 27 July 99 | 14:58 – 16:04<br>17:19 – 17:35 | 130.0/80.7 |
| Scoggins Creek | 28 July 99 | 14:15 – 14:30 | 23.8/14.8 |
| Gales Creek | 28 July 99 | 14:42 – 15:16 | 44.1/27.4 |
| Dairy Creek | 28 July 99 | 16:49 – 17:02 | 16.3/10.1 |
| West Fork Dairy Creek | 28 July 99 | 17:02 – 17:27 | 32.2/20.0 |
| East Fork Dairy Creek | 29 July 99 | 17:00 – 17:23 | 34.6/21.5 |
| McKay Creek | 29 July 99 | 16:16 – 16:48 | 36.1/22.4 |
| Fanno Creek | 29 July 99 | 14:28 – 14:54 | 20.1/12.5 |
| Rock Creek | 30 July 99 | 14:18 – 14:29 | 20.3/12.6 |
| Beaverton Creek | 30 July 99 | 14:38 – 14:47 | 12.6/7.8 |
| Chicken Creek | 30 July 99 | 16:18 – 16:23 | 10.6/6.6 |
| McFee Creek | 30 July 99 | 16:29 – 16:32 | 4.7/2.9 |
| Clear Creek | 30 July 99 | 16:52 – 16:56 | 6.4/4.0 |
| Wapato Creek | 27 July 99 | 16:00 – 16:12 | 2.9/1.8 |
| **Total Kilometers/Miles Surveyed** | | | **394.7/245.1** |

FLIR images were collected digitally and recorded directly from the sensor to an on-board computer. Images were collected at a rate of 1 image frame/second for all streams except the Lower Tualatin River which was collected at 1 image frame every 2 seconds. The FLIR detects emitted radiation at wavelengths from 8-12 microns and records the level of emitted radiation in the form of an image. Each image pixel contains a measured value that can be directly converted to a temperature. The FLIR images represent the full dynamic range of the instrument and were tagged with time and position data provided by a Global Positioning System (GPS).

The ground area covered by each thermal image frame depends on the flight altitude used for the stream. In general the flight altitude was selected so that the stream channel occupies approximately 15 to 20% of the image frame. For surveys near the Hillsboro Airport it was necessary to select a flight altitude that was below the air traffic pattern. This was the case for Rock, Beaverton, and McKay Creek, which were flown at an average altitude of 1100 ft above ground level (AGL). Tributaries were typically flown at an altitude of 1500 ft AGL with the images covering a ground area of approximately 120 x 160 meters (400 x 600 pixel array). For larger channels such as the Tualatin River, the images cover a ground area of approximately 190 x 255 meters (2400 ft AGL).

Day TV images were recorded to an on-board digital videocassette recorder at a rate of 30 frames/second. GPS time and position were encoded on the recorded video. The Day TV sensor was aligned to present the same ground area as the thermal infrared sensor. The GPS time coding provides a means to correlate Day TV images with the FLIR images during post-processing.

Watershed Sciences (WS) distributed in-stream temperature data loggers (Onset Stowaways) in the basin prior to the survey in order to ground truth (i.e. verify the accuracy of) the radiant temperatures measured by the FLIR. At least one data logger was placed in each of the “primary” streams surveyed. The advertised accuracy of the Onset Stowaway’s is $\pm 0.2^{o}$C. These locations were supplemented by data provided by ODEQ from seasonal in-stream temperature loggers (Vemcos). A USGS site on the Tualatin River near the mouth of Fanno Creek was also included in the comparison. Figure 1 shows the location of the Watershed Sciences and ODEQ in-stream data loggers used to ground truth the imagery. The meteorological conditions were recorded before the flight and are summarized in Table 2.

### *Data Processing*

A computer program was used to scan the FLIR imagery and create a text file containing the image name, time, and location it was acquired. The text file was then converted to an ArcView GIS point coverage. This coverage shows the spatial extent of the survey and allows for the integration of the FLIR with other spatially explicit data layers in the GIS. In addition, we identified the FLIR images associated with the ground truth locations from this coverage. The data collection software was used to extract radiant temperature values from the associated images at the location of the in-stream recorder. The radiant temperatures were then compared to the kinetic temperatures from the in-stream loggers to assess the accuracy of the FLIR data.

The image points were associated with a river kilometer using the dynamic segmentation features of Arc/Info GIS software. The river kilometers were derived from 1:100K “routed” stream covers from the Environmental Protection Agency (EPA). The route measures provide a spatial context for developing longitudinal temperature profiles of stream temperature.

In the laboratory, a computer algorithm was used to convert the raw thermal images (radiance values) to ARC/INFO GRIDS where each GRID cell contained a temperature value. During the conversion, the program recorded the minimum and maximum temperature value found in each image. An ArcView Extension was used to display the GRID associated with an image location selected in the point coverage. The GRID was color-coded to visually enhance

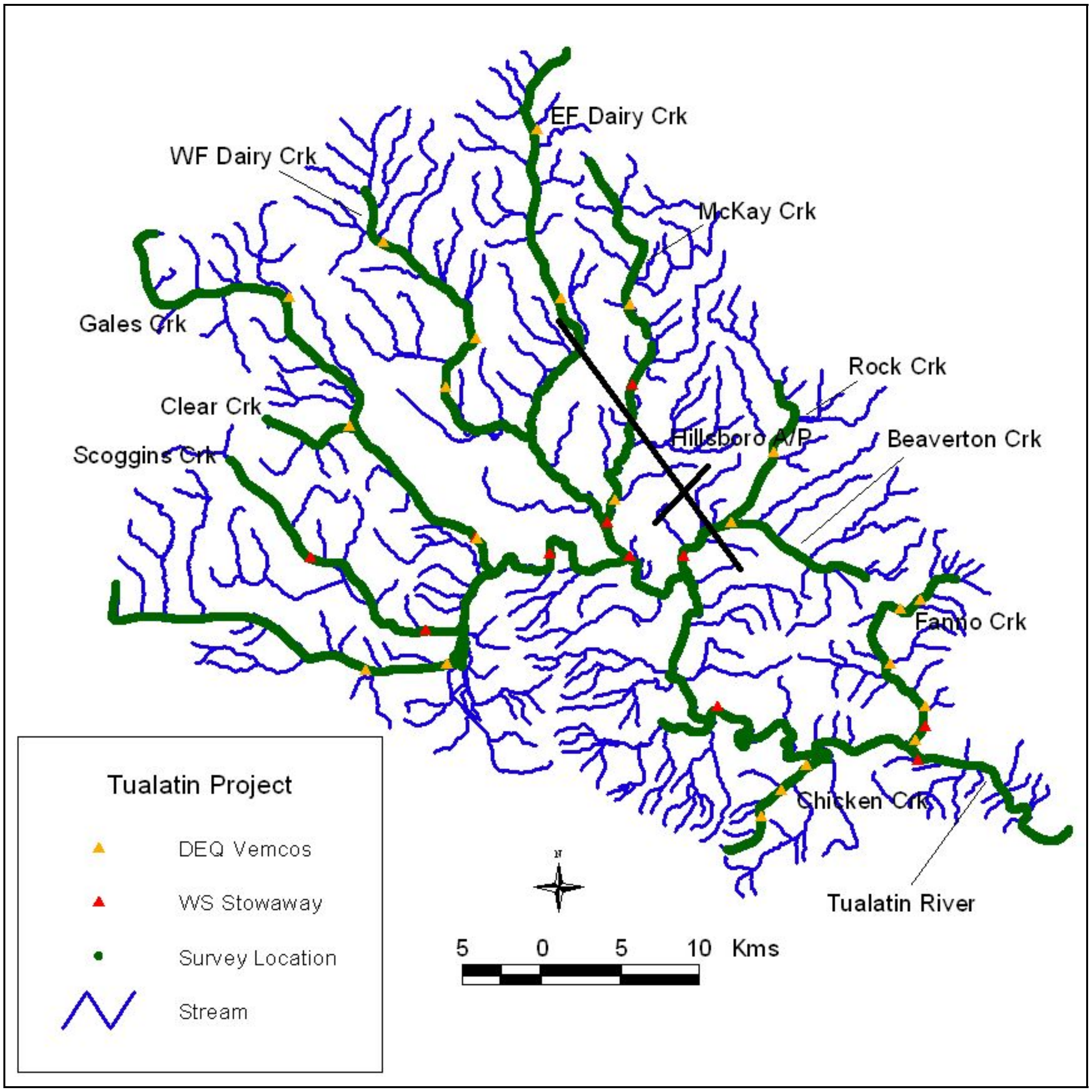



Figure 1 – Extent of the FLIR Surveys in the Tualatin River Basin and the location of in-stream data loggers.

Table 2. Meteorological conditions for Tualatin River basin flights from the National Weather Service, Portland, Oregon.

| Day, Time | Temperature | Relative Humidity | Sky Conditions |
|---|---|---|---|
| 7/27/99, 16:30 | 31.0°C | 32% | Clear, scattered clouds |
| 7/27/99, 18:00 | 31.1°C | | Clear, scattered clouds |
| 7/28/99, 13:00 | 27.8°C | 40% | Clear, scattered clouds |
| 7/28/99, 17:00 | 31.1°C | 40% | Clear, scattered clouds |
| 7/29/99, 13:00 | 27.8°C | 40% | Clear, scattered clouds |
| 7/29/99, 17:00 | 31.1°C | 40% | Clear, scattered clouds |
| 7/30/99, 13:00 | 22.8°C | 57% | Clear, scattered clouds |
| 7/30/99, 14:00 | 23.9°C | 54% | Clear, scattered clouds |

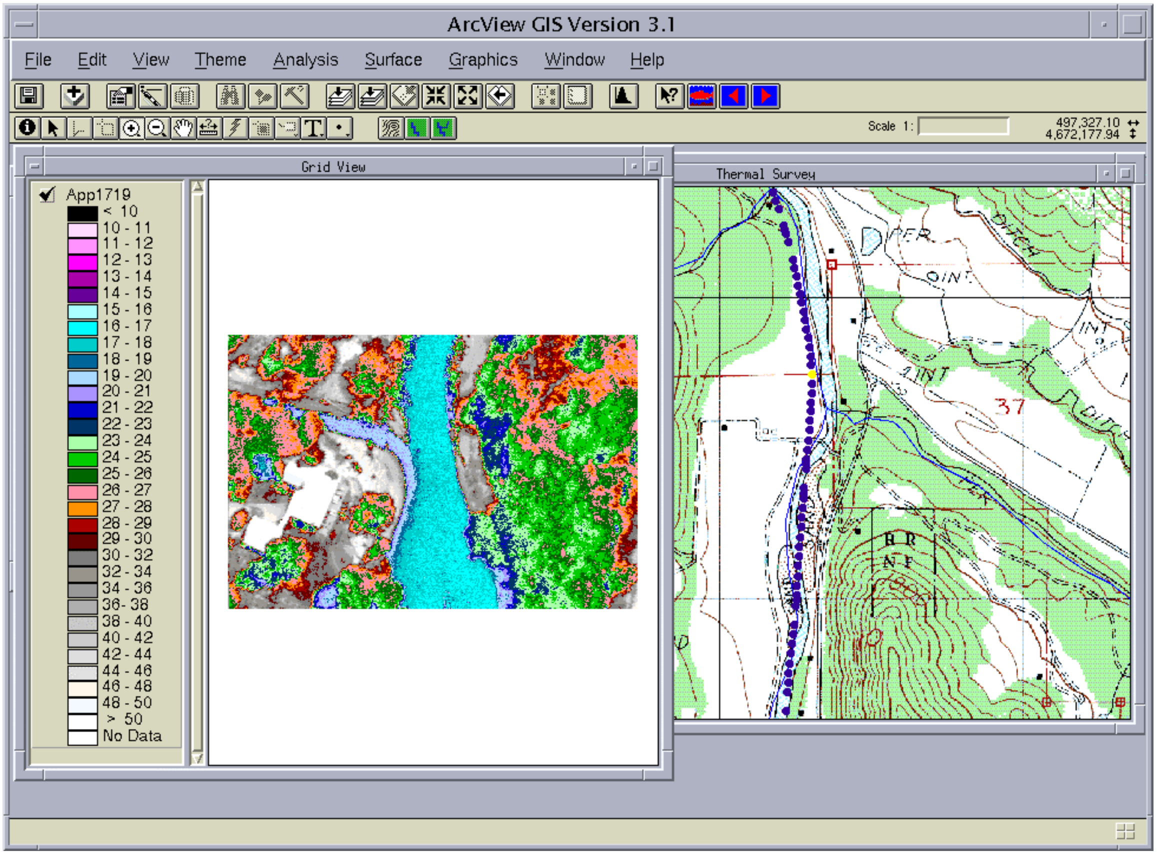



Figure 2 – ArcView display showing a color-coded temperature GRID in one window and the geographic location of the GRID in the other (note that the top of the image is in the flight direction and hence opposite the map).

temperature differences, enabling the user to extract temperature data. The GRIDS were classified in one-degree increments over the temperature range of 10 to 50$^{o}$C. Temperatures < 10$^{o}$C are black, temperatures between 10 and 30$^{o}$C are color, temperatures between 30 and 50$^{o}$C were colored in shades of gray (darker tones to lighter tones), and temperatures > 50$^{o}$C are white.

Figure 2 illustrates a color coded GRID displayed in the ArcView environment. This GRID illustrates the confluence of the Applegate River and the Little Applegate River in southwest Oregon. The legend on the left of the "Grid View" specifies the temperature range associated with each color. The other view window, "Thermal Survey", shows the point coverage with the displayed GRID location highlighted in yellow. Each blue point in the "Thermal Survey" view represents another image location.

Figure 3 illustrates the temperature GRID displayed in Figure 2 with its corresponding Day TV image. Prominent thermal features are identified in each image. The Applegate River and the Little Applegate River are clearly visible in the image due to the high thermal contrast with the warmer terrain features. This is the standard format currently used to interpret and analyze the thermal image data.

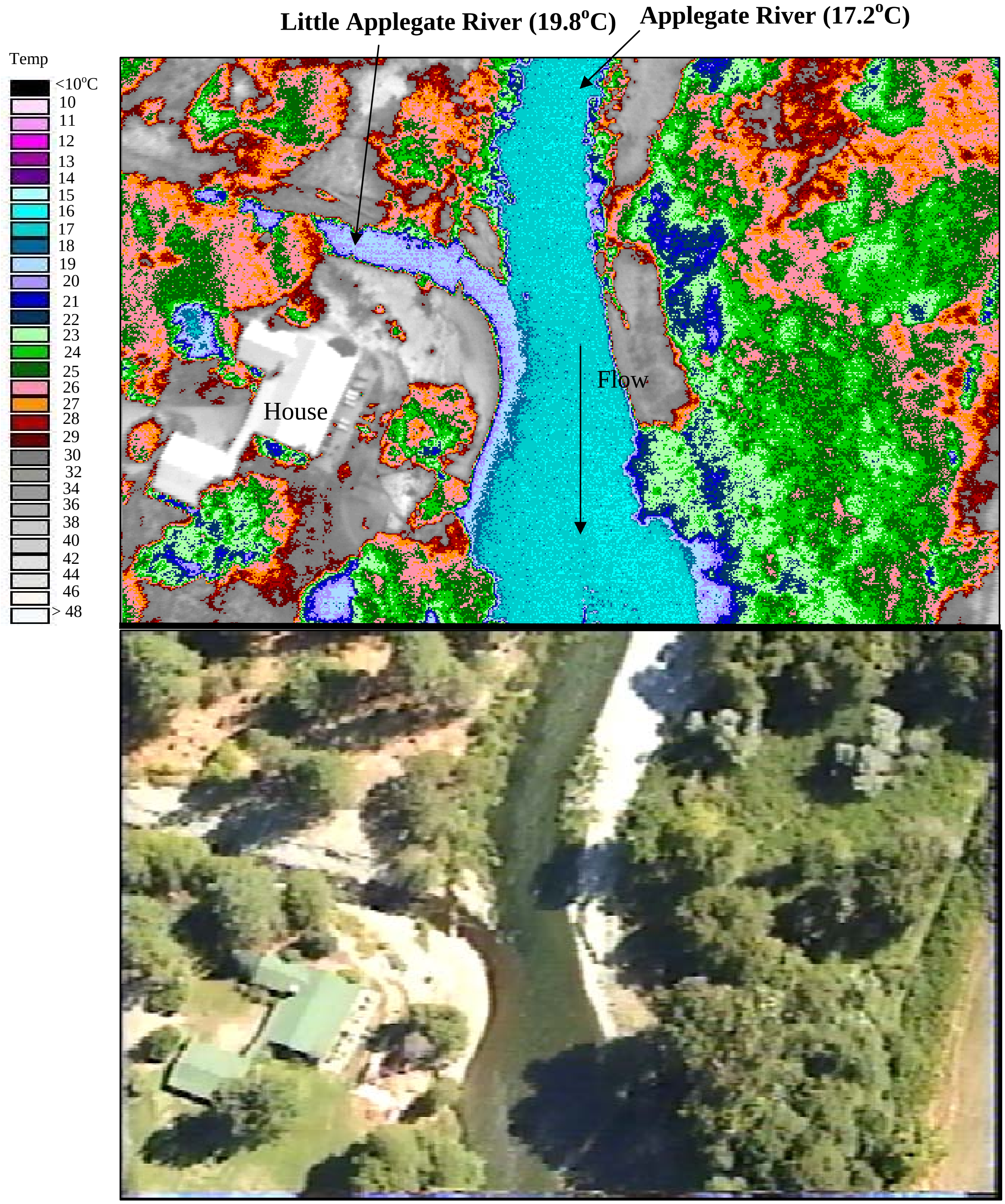



Figure 3 – Temperature Grid (top) and Corresponding Day TV image (bottom) showing the confluence of the Applegate and Little Applegate Rivers. Prominent thermal features are identified on the thermal image.

Once in the GRID format, the images were analyzed to derive the minimum, maximum, and median stream temperatures. To derive these measures, an ArcView program was used to sample the GRID cell (temperature) values in the stream channel. Ten sample points were taken longitudinally in the center of the stream channel (Figure 4). Samples were taken on every 4th image to provide complete coverage without sampling the same water twice (there is approximately 40-60% overlap between images). Where there were multiple channels, only the main channel (as determined by width and continuity) was sampled. In cases where the channel was obscured by vegetation the next image where the stream channel was clearly visible was sampled. For each sampled image, the sample minimum, maximum, median, and standard deviation was recorded directly to the point coverage attribute file. We have found the median value to be the most useful measure of stream temperatures because it minimizes the effect of extreme values.

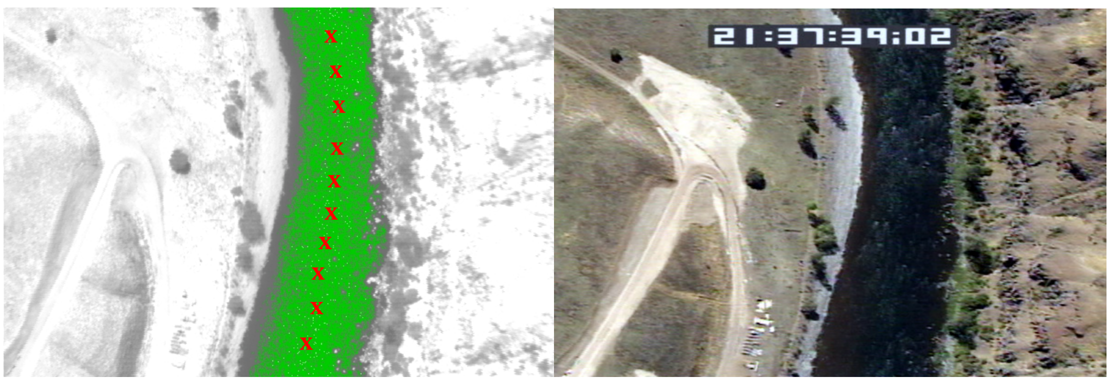



Figure 4 – Thermal/Day TV image pair showing typical temperature sampling locations (red x's). These samples determine the median stream temperature for this image frame.

The temperature of tributaries and other detectable surface inflows were also sampled from images. These inflows were sampled at their mouth using the same techniques described for sampling the mainstem channel. If possible, the surface inflows were identified on the USGS 24K base maps. The inflow name and median temperature were then entered into the point coverage attribute file.

Day TV images corresponding to the FLIR images were extracted from the database using a computer-based frame grabber. The images were captured to correspond to the thermal infrared images and provide a complete coverage of the stream. The video images were "linked" to the corresponding thermal image frame in the ArcView GIS environment.

*Data Limitations*

**Thermal Stratification**

FLIR systems measure thermal infrared energy emitted at the water surface. Since water is essentially opaque to thermal infrared wavelengths (8 - 12μm), the sensor is only measuring the water surface temperature. This is typically not an issue on streams where the water column is thoroughly mixed. Field measurements conducted by Oregon State University on the Middle Fork of the John Day River, OR and on the Klamath River, CA confirmed that thermal stratification was insignificant or not present even in the deepest pools. The majority of stream miles surveyed in the Tualatin basin are probably not stratified. This is evidenced by the comparison of the image temperature measurements to the in-stream temperature measurements at locations throughout the basin (Table 4). However, field measurements showed some level of stratification in the Lower Tualatin River and several tributaries. This was supported by initial review of the FLIR imagery.

Figure 5 illustrates a thermal image that shows evidence of thermal stratification. The same image is presented using two different color schemes. The image on the left is in gray scale, where lighter tones represent warm temperatures and dark tones represent cooler temperatures. The gray scale image has a consistent gradient throughout the full range of temperatures and it is somewhat easier to identify common features such as trees and houses. On the right is a pseudo-color version of the same image where temperatures normally associated with natural water are assigned a color to emphasize in-stream differences. The Tualatin River (location 1) runs in the direction of the arrow and cool water streaks (location 2) are noticeable behind in-stream objects. These streaks indicate areas of mixing downstream of the objects and are 1.5 to 2°C cooler then the measured surface temperature.

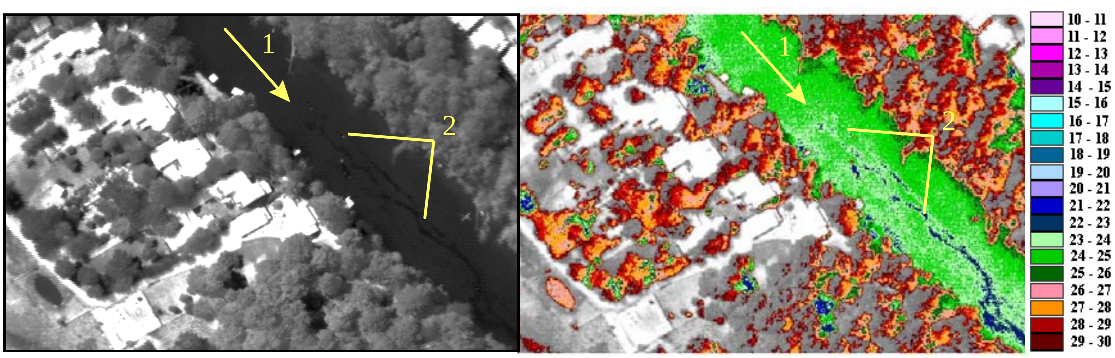



Figure 5 - The same thermal image (gray scale/pseudo-color) of the Tualatin River showing an area of probable stratification (*image frame: dms0313, river km 17.2 (mile 10.7)*) as evidenced by the cool water streaks behind in-stream objects.

Figure 6 shows an area where the surface temperature of the Tualatin River (location 1) changes fairly drastically. This area is located 1.3 km (0.8 miles) downstream of the image in Figure 4. The 2.6°C drop in surface temperature seems to be due to a change from a stratified condition to a well-mixed condition, although the reason for this change is not apparent from the image. Figure 7 shows a similar drop in surface temperature in the Tualatin River (location 1) immediately downstream of a dam (location 2). Direction of flow in indicated by the arrow at location 2 and a cable crossing the river is noticeable at location 3. According to the Unified Sewerage Agency this is the site of a diversion dam near Cook Park. In the summertime when the diversion is not in place, shallow rapids form. While there is evidence of mixing in both Figures 6 and 7, it is difficult to determine if the mixing is occurs throughout the water column.

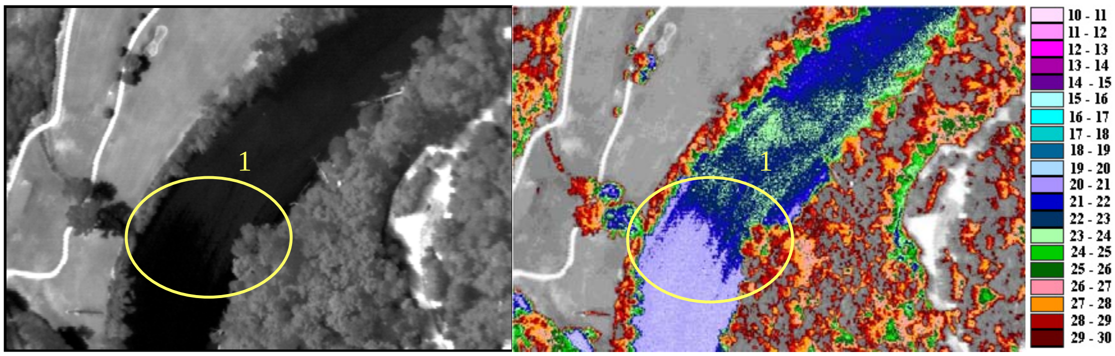



Figure 6 – The same thermal image (gray scale/pseudo-color) showing a 2.6°C drop in median surface temperature (*image frame: dms0291, river km 15.9 (mile 9.9)*) in the downstream direction (location 1). This is the site of a diversion dam near Cook Park.

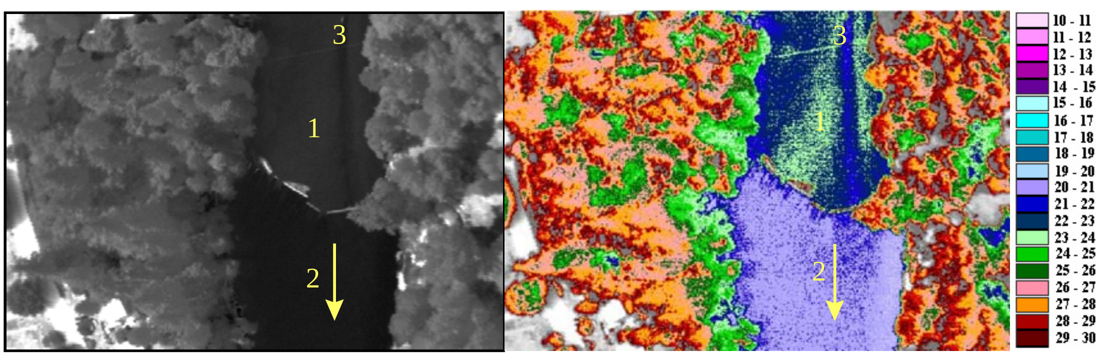



Figure 7 – The same thermal image (gray scale/psuedo-color) showing a 2.7 °C drop in median surface temperature (*image frame: dms0116, river km 5.6 (mile 3.5))* immediately downstream of a dam.

Figures 8 thru 11 provide the field measurements taken in the Tualatin River on July 27, 1999 during the time of the FLIR survey. The ODEQ took the temperatures at different depths in the water column. Of the four locations, the measurements at Stafford Rd. (river km 8.7 (mile 5.4)) and Shamberg Rd. (river km 26.1 (mile 16.2)) showed some level of stratification. The locations at Boone's Ferry Rd. (river km 13.9 (mile 8.6)) and Hwy 219 (river km 71.5 (mile 44.4)) show well-mixed conditions. A pseudo-color FLIR image of the location is provided in each figure as well as the median water surface temperature derived from the image. A visual comparison of these images indicates that there is considerably more unexplained temperature variation at the water surface for the stratified locations. One should note that the image acquisition time and the time of the field measurements are different.

In-stream Measurement
7/27/99, 15:20
**Tualatin River @ Stratford Rd.**
River Mile: 5.38

| Temp (deg C) | Depth |
|---|---|
| 21.5 | 1’ |
| 20.7 | 3’ |
| 20.5 | 5’ |
| 20.3 | 7’ |
| 19.8 | 9’ |
| 19.7 | 11’ |
| 19.7 | 13’ bottom |

FLIR Image: dms0169
7/27/99, 15:03
Median Surface Temperature: 22.7 deg C

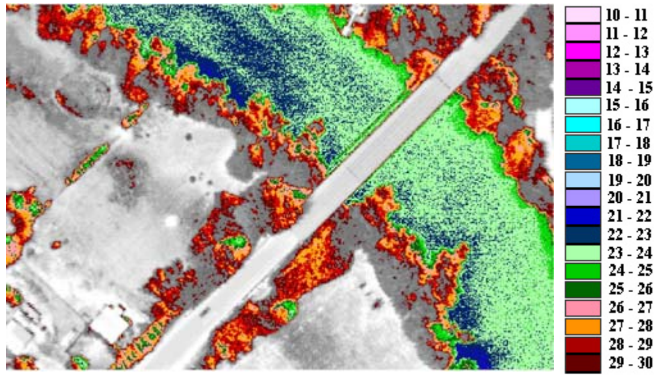



Figure 8 – In-stream temperature measurements taken at Stafford Road are shown on the left. A pseudo-color FLIR image at this location is shown on the right.

In-stream Measurement
7/27/99, 15:40
**Tualatin River @ Boones Ferry Rd**
River Mile: 8.60

| Temp (deg C) | Depth |
|---|---|
| 21.5 | 1’ |
| 21.5 | 3’ |
| 21.3 | 5’ bottom |

FLIR Image: dms0256
7/27/99, 15:06
Median Surface Temperature: 20.5

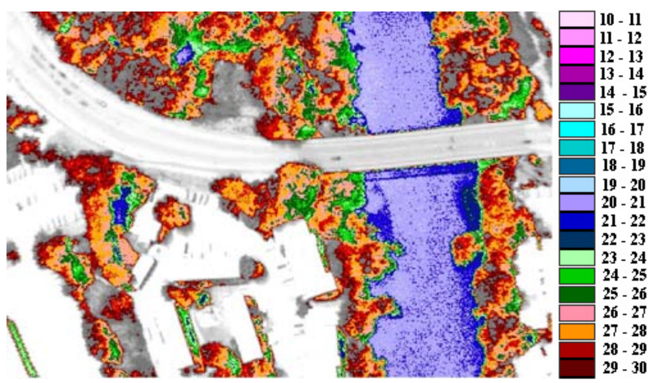



Figure 9 - In-stream temperature measurements taken at Boone’s Ferry Road are shown on the left. A pseudo-color FLIR image at this location is shown on the right.

In-stream Measurement
7/27/99, 16:20
**Tualatin River @ Shamberg Bridge**
River Mile: 16.2

| Temp (deg C) | Depth |
|---|---|
| 21.2 | 1’ |
| 20.6 | 3’ |
| 20.3 | 6’ |
| 20.1 | 9’ |
| 20.1 | 11’ bottom |

FLIR Image: dms0460
7/27/99, 15:13
Median Surface Temperature: 21.7

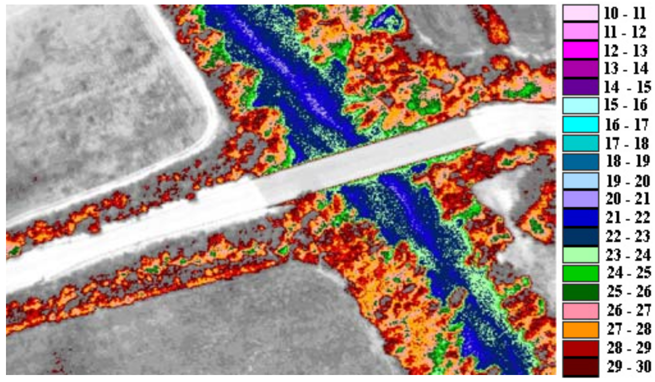



Figure 10 - In-stream temperature measurements taken at Shamberg Bridge are shown on the left. A pseudo-color FLIR image at this location is shown on the right.

In-stream Measurement
7/27/99, 16:50
**Tualatin River @ Hwy 219**
River Mile: 44.4

| Temp (deg C) | Depth |
|---|---|
| 16.5 | 1’ |
| 16.5 | 2’ bottom |

FLIR Image: dms1161
7/27/99, 15:39
Median Surface Temperature: 16.6

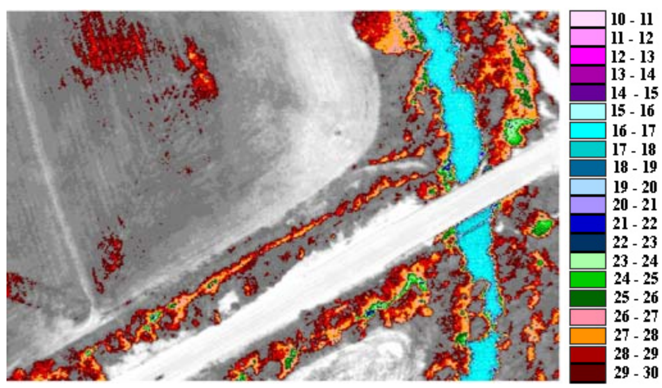



Figure 11 - In-stream temperature measurements taken at Hwy 219 are shown on the left. A pseudo-color FLIR image at this location is shown on the right.

Our review of the FLIR data for the Tualatin River basin indicates thermal stratification was found in the following water bodies. The lower 26 km (16.2 miles) of the Tualatin River was intermittently stratified as indicated by the FLIR imagery and ODEQ field surveys. The entire length of Wapato Creek was stratified due to low flow, stagnant water conditions. There is evidence of thermal stratification upstream of the dam on Gales Creek; we estimate this extends upstream 2-3 km above the dam. Beaverton Creek had one image (#285) where thermal stratification was evident. The lower 2.5 km of Chicken Creek appear stratified as evidenced by low flows and the extreme temperature variation in the reach. There is evidence of thermal stratification from river km 9-10 in Fanno Creek and river km 12-14 in Rock Creek. These results mean that the temperatures derived from the FLIR in these reaches are not representative of the water column and cannot reliably be used to assess stream temperatures.

### Flight Paths

The standard protocol for surveying streams with the FLIR is fly upstream directly over the stream channel. The pilot maneuvers the aircraft so that the stream is maintained in the sensor's field-of-view. Sometimes it is difficult to follow the stream if there are numerous meander bends, human alterations (such as canals), and/or significant canopy combined with a lack of terrain relief. The agricultural reaches in the Tualatin Basin had several combinations of these factors. If the stream goes outside the sensor field-of-view, the missed section of stream is immediately resurveyed.

The proximity of the Hillsboro Airport to many of the surveyed streams confounded the problems of maintaining a consistent flight path. The main approach to the Hillsboro Airport is illustrated in Figure 1 as a solid black line. As shown, the paths of Rock Creek, McKay Creek, East Fork Dairy Creek, and Beaverton Creek cross the main approach path. For safety reasons, missed sections of stream along this line were not resurveyed. In addition, the very upper end of Fanno Creek was not surveyed due to air space constraints due to Portland International Airport.

## Results

### *Thermal Accuracy*

Temperature values from the in-stream data loggers were downloaded to a computer and formatted in an Excel Spreadsheet. The radiant temperature derived from the imagery represents the average of 10 points sampled from the image at the data logger location. The in-stream temperature at the date and time the image was acquired was then compared to the radiant temperature derived from the image. If a consistent difference was observed for all the in-stream sensors in given stream, the parameters used to convert radiant values to temperatures were adjusted to provide a better fit to the in-stream sensors.

Table 3 provides a comparison of the in-stream and radiant temperatures. A total of 33 points were used to assess the temperature accuracy of the imagery. Of the 33 locations, 28 showed a difference of less then $\pm 0.5^{o}$C (contract specifications) between the FLIR image and the in-stream data logger. The factors that influence the accuracy of the radiant temperature calculations are spatial. Therefore, it is important to consider accuracy on a stream-by-stream basis. In general, we considered the accuracies for each stream to be very good. The exception is Chicken Creek, which had two of the five points greater then $\pm 0.5^{o}$C. While no definite answers are provided for these differences, the FLIR would not have these differences (i.e. $3.5^{o}$C and $1.1^{o}$C) without relatively large changes in the recording conditions, which would not exist within 11 km of stream. Therefore we can speculate that these differences are the result of uncertainties in the location of the in-stream temperature logger relative to the survey, stratification, or physical characteristics of the stream channel.

A logical explanation for the 3.5$^o$C temperature difference at the "Edy Tualatin" location on Chicken Creek was the stream channel was very narrow at this point. For stream channel widths less then 0.8 meters, the radiance value recorded in the image may be an integration of the water surface and the bank vegetation resulting in an inaccurate water surface temperature. This was the only reach where we found this to be a problem.

***Analysis of Thermal Imagery***

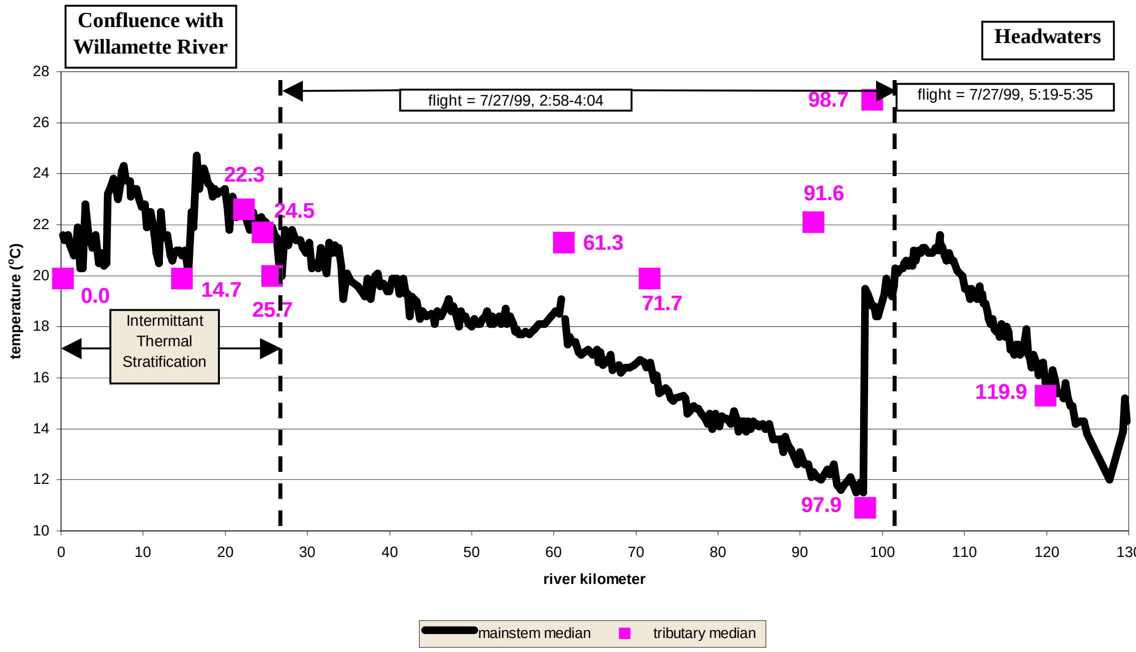
## Tualatin River

The median temperatures for each sampled image for the Tualatin River from the confluence with the Willamette River to the headwaters was plotted versus the corresponding river kilometer (Figure 12). The plot also contains the median temperature of all surface water inflows (e.g., tributaries, canals) that were visible in the imagery where they input into the Tualatin River. Tributaries are labeled in Figure 12 by river kilometer with their name and temperature listed in the associated table. Only the surface water inflows that could be positively identified in the imagery were included. In some cases, tributaries and other surface water inputs were obscured by riparian vegetation or outside the sensor field of view and their image location could not be accurately determined.

Figure 12 shows how stream temperatures vary longitudinally along the Tualatin River and the influence of select tributaries. Temperatures are relatively cool in the headwaters and increase steadily in a downstream direction to river km 107 (mile 66.5) where median temperatures reach 21.6$^o$C. From river km 107 (mile 66.5) downstream temperatures decrease slowly to river km 98 (mile 60.9) where mainstem temperatures decrease almost 9$^o$C at the confluence with Scoggins Creek (Figure B-7). Mainstem temperatures reach their lowest point at the confluence with Scoggins Creek. From river km 98 (mile 60.9) to river km 16.5 (mile 10.3) mainstem temperatures increase linearly in a downstream direction, reaching the maximum-recorded temperatures at river km 16.5 (24.7 $^o$C). Only two tributaries, Rock Creek (Figure B-3 to B-4) and Dairy Creek (Figure B-5) seem to have a noticeable effect on mainstem temperatures in this reach, increasing mainstem temperatures for a short distance downstream of their inputs. From river km 16.5 (mile 10.3) to the confluence with the Willamette River mainstem temperatures fluctuate between 20 and 24$^o$C. In the lower 26 km (mile 16.2) of the Tualatin river there was evidence of intermittent thermal stratification as evidenced from the FLIR imagery and ODEQ field measurements. From our sampling of mainstem temperatures we were able to detect inflow from 10 different tributaries. Five tributaries were contributing warmer water (range of the difference = +0.2 to + 9.8$^o$C) and five were contributing cooler water (range of the difference = -0.5 to -8.6$^o$C).

Table 3 – Comparison of in-stream temperatures and radiant temperatures derived from thermal infrared images, Tualatin Basin 27-30 July 1999. The Delta$^{o}$C column represents the in-stream temperature minus the radiant temperature.

| ***Stream*** | ***Site*** | ***Owner*** | ***km/mile*** | ***Image Name*** | ***Time*** | ***InStream $^{o}C$*** | ***Radiant $^{o}C$*** | ***Delta $^{o}C$*** |
|---|---|---|---|---|---|---|---|---|
| **Tualatin** | Tualatin Park | WS | 13.9/8.6 | dms0264 | 15:16 | 21.7 | 21.7 | 0.0 |
| | RR Bridge@Fanno Ck | USGS | 23.5/14.6 | dms0277 | 15:07 | 19.8 | 20.5 | -0.7 |
| | D/S of Scholls Bridge | WS | 42.8/26.6 | dms0702 | 15:31 | 19.6 | 19.4 | 0.2 |
| | Rt. 219 Bridge | WS | 71.3/44.3 | dms1160 | 15:49 | 17.2 | 16.7 | 0.5 |
| | Golf Course Rd. | WS | 82.8/51.4 | dms1431 | 16:02 | 14.0 | 14.4 | -0.4 |
| | Mt. Richmond | DEQ | 107.2/66.6 | ums0122 | 17:32 | 21.3 | 21.5 | -0.2 |
| **Scoggins** | Patton Valley Rd. | WS | 2.6/1.6 | scog0150 | 14:26 | 10.6 | 10.6 | 0.0 |
| | West Shore Drive | WS | 13.5/8.4 | scog0538 | 14:34 | 18.4 | 18.0 | 0.4 |
| **Gales** | Route 47 | DEQ | 3.5/2.2 | gld0163 | 14:54 | 21.4 | 21.0 | 0.4 |
| | Beaver Ck @ Gales | DEQ | 29.6/18.4 | gld1137 | 15:16 | 17.6 | 18.0 | -0.4 |
| | Clear Ck @ Mouth | DEQ | 17.7/11.0 | gld0742 | 15:10 | 17.0 | 17.4 | -0.4 |
| **Dairy** | Tualatin River at Rt.219 | WS | 71.3/44.3 | wda0056 | 16:58 | 18.3 | 18.0 | 0.3 |
| | Rt 8 Bridge | WS | 3.2/2.0 | wda0181 | 17:04 | 20.7 | 21.0 | -0.3 |
| **WF Dairy** | Greenville Rd | DEQ | 11.1/6.9 | wda1065 | 17:21 | 20.3 | 20.8 | -0.5 |
| | HWY 47 Banks | DEQ | 15.9/9.9 | wda1295 | 17:25 | 20.0 | 19.8 | 0.2 |
| | Fisher Rd | DEQ | 27.4/17.0 | wda1756 | 17:33 | 19.9 | 19.5 | 0.4 |
| **Fanno** | Footbridge@Durham Pk | DEQ | 0.3/0.2 | fan0067 | 14:38 | 20.2 | 19.7 | 0.5 |
| | Durham Road | WS | 1.8/1.1 | fan0159 | 14:41 | 21.7 | 20.4 | 1.3 |
| | Bonita Road | DEQ | 3.4/2.1 | fan0223 | 14:42 | 20.6 | 20.6 | 0.0 |
| | N Dakotaus Ash | DEQ | 8.5/5.3 | fan0460 | 14:48 | 21.4 | 21.5 | -0.1 |
| | Scholls Ferry | DEQ | 14.7/9.1 | fan0691 | 14:55 | 18.9 | 18.9 | 0.0 |
| | Nicol | DEQ | 16.6/10.3 | fan0781 | 14:58 | 19.1 | 19.5 | -0.4 |
| **McKay** | 20' D/S of Union Rd. | WS | 14.3/8.9 | mcf0538 | 16:41 | 18.6 | 18.2 | 0.4 |
| | McKay at Pudgett Rd | DEQ | 1.9/1.2 | mcf0074 | 16:26 | 19.9 | 19.7 | 0.2 |
| | Collins @ Rm16 | DEQ | 23.7/14.7 | mcf0837 | 16:48 | 18.4 | 18.4 | 0.0 |
| **EF Dairy** | Uble Rd | DEQ | 15.5/9.6 | ed469 | 17:18 | 18.8 | 19.3 | -0.5 |
| | Fern Flat | DEQ | 28.2/17.5 | ed952 | 17:26 | 14.8 | 14.8 | 0.0 |
| **Rock** | Hwy 8 | WS | 1.9/1.2 | rock0566 | 14:37 | 20.3 | 19.9 | 0.4 |
| | West Union Rd | DEQ | 14.0/8.7 | rock0205 | 14:31 | 18.0 | 18.9 | -0.9 |
| **Beaverton** | BaseLine | DEQ | 0.5/0.3 | beav435 | 14:55 | 21.3 | 21.4 | -0.1 |
| **Chicken** | Edy Tualatin | DEQ | 4.5/2.8 | chik0153 | 16:30 | 17.1 | 20.6 | -3.5 |
| | Kruger Rd | DEQ | 6.9/4.3 | chik0235 | 16:31 | 17.8 | 17.5 | 0.3 |
| | Le Bueau | DEQ | 2.4/1.5 | chik0085 | 16:28 | 18.8 | 19.9 | -1.1 |




| Tributary | River km/mile | Tributary Temp ($^o$C) | Tualatin Temp ($^o$C) | Difference (trib-mainstem) | FLIR image |
|---|---|---|---|---|---|
| Willamette River | 0.0/0.0 | 19.9 | 21.6 | -1.7 | dms0011 |
| Fanno Ck | 14.7/9.1 | 19.9 | 20.8 | -0.9 | dms0277 |
| Unnamed Ck (RB) | 22.3/13.9 | 22.6 | 22.4 | +0.2 | dms0401 |
| Chicken Ck | 24.5/15.2 | 21.7 | 22.2 | -0.5 | dms0436 |
| Chicken Ck canal | 25.7/16.0 | 20.0 | 21.9 | -1.9 | dms0456 |
| Rock Ck | 61.3/38.1 | 21.3 | 18.3 | +3.0 | dms1011 |
| Dairy Ck | 71.7/44.5 | 19.9 | 16.6 | +3.3 | dms1164 |
| Gales Ck | 91.6/56.9 | 22.1 | 12.3 | +9.8 | dms1554 |
| Scoggins Ck | 97.9/60.8 | 10.9 | 19.5 | -8.6 | dms1636 |
| Wapato Ck | 98.7/61.3 | 26.9 | 18.8 | +8.1 | dms1691 |
| Hillsboro Reservoir | 119.9/74.5 | 15.3 | 15.8 | -0.5 | ums0344 |

Figure 12 – Median stream temperature versus river kilometer for the Tualatin River. Tributaries are described in the table (LB/RB = left and right bank looking upstream).

## Tributaries

In addition to the mainstem flight, thirteen tributaries were surveyed with FLIR (Table 1). Longitudinal temperature profiles were developed for each of the surveyed streams (Appendix Figures 1-13). Collecting FLIR data on the tributaries presented different challenges than the mainstem Tualatin River. Narrower channels, canopy cover, irrigation diversions, and low flow conditions confound the limitations of thermal remote sensing (*reference the data limitations section*). We will discuss our analysis of the FLIR data for tributaries in the upstream order that the tributaries occur.

Fanno Creek was surveyed from the mouth upstream for about 19 km (11.8 miles)(Appendix Figure 1). Stream temperatures started at about 17.5$^{o}$C in the headwaters and increased slowly to about river km 10.5 (mile 6.5) despite considerable variation in temperatures from image-to-image. The upper reach is highly developed with the Portland Country Club (Figure B-17) running through portions of the area. Many portions of the stream were channelized and had low streamflows. At river km 10.5 (mile 6.5) stream temperatures increased rapidly for the next couple of kilometers to the maximum for the survey of 23$^{o}$C. Temperatures then decreased back to about 20.5$^{o}$C within 2 km (1.2 miles) of the maximum. This rapid change in stream temperatures appears to be due to thermal stratification in this reach. Over the next 8 km (5 miles) temperatures decrease slightly in a downstream direction, reaching about 19.5$^{o}$C at the mouth (Figure B-10). Temperatures in the lower 8 km (5 miles) were also much less variable then the upper reach. No tributaries to Fanno Creek were detected with the FLIR due low flows or views being obscured by riparian vegetation.

Chicken Creek was surveyed from the mouth to a distance of about 9.5 km (5.9 miles) upstream (Appendix Figure 2). Temperatures were about 17$^{o}$C in the headwaters and fluctuated between 17 and 21$^{o}$C to about river km 2.5 (mile 1.6). From here to the confluence with the Tualatin River stream temperatures increased rapidly to a maximums of 27 to 33$^{o}$C. There was evidence of thermal stratification due to low flows in the lower 2.5 km (1.6 miles). Most of the flow in this lower reach is diverted into a canal that was not surveyed. The stream channel was blocked by riparian vegetation throughout much of the flight. No tributaries to Chicken Creek were detected with the FLIR. In addition our ground-truthing of the imagery was poor for 2 of the 3 in-stream data loggers in Chicken Creek (see section on thermal accuracy). We found no apparent reason for these discrepancies but recommend that the data from Chicken Creek be used conservatively.

McFee Creek was surveyed from the mouth to a distance of about 4.5 km (2.8 miles) upstream (Appendix Figure 3). The survey was terminated a considerable distance from the headwaters due to complete canopy closure with much of the surveyed reach being partially or completely obscured by riparian vegetation. For the surveyed reach, stream temperatures generally increased in a downstream direction but there was considerable variation in temperatures. No tributaries were detected in the surveyed reach.

Rock Creek was surveyed from the mouth to about 20 km upstream where canopy closure ended data collection (Appendix Figure 4). From the headwaters to the confluence with Beaverton Creek (river km 6.9, mile 4.3), temperatures in Rock Creek were highly variable with temperatures ranging widely between 17 and 23°C. This appeared to be due to very low flows and small, shallow channels in some sections. It was also very difficult to detect the stream in many parts of the upper section due to the density of the riparian canopy. There was also evidence of thermal stratification from river kilometer 12-14. From the confluence with Beaverton Creek to the confluence of the Tualatin River, Rock Creek temperatures were much less variable from image to image due to increased flows and larger channels. Temperatures in this reach ranged between 18 and 20.6°C, reaching there lowest temperatures below Beaverton Creek at the confluence with the Tualatin River. The lower temperatures at the mouth of Rock Creek may be due to cooler Tualatin River flows backing up into Rock Creek. No tributaries were detected with the FLIR along Rock Creek. Beaverton Creek, a major tributary to Rock Creek was also sampled for about 12.5 km (7.8 miles)(Appendix Figure 5, Figures B-46 to B-48). In the headwaters stream temperatures were quite warm (19°C). Temperatures climb slowly in the downstream direction reaching a maximum of 25.8°C at river km 9.4 (mile 5.8). From river km 9.4 (mile 5.8) to the confluence with Rock Creek temperatures decrease slowly to about 21°C. The rise in temperatures in the headwaters and then the subsequent downstream cooling were not the result of thermal stratification. Further field investigation is warranted in this reach. One image at about river km 5 (mile 3.1) indicated thermal stratification in the image, accounting for the rise in temperature. We identified four tributary or off-channel features in the Beaverton survey. They are indicated on the graph and described in the accompanying table. None of these features seemed to have a significant effect on mainstem temperatures.

In the Dairy Creek watershed the mainstem of Dairy Creek was flown along with the West and East Forks and McKay Creek (Table 1, Appendix Figures 6-9). Temperatures for Dairy Creek (Appendix Figure 6) were relatively constant from the confluence of the East and West Forks (Figure B-21) to the confluence with the Tualatin River (Figure B-18), ranging from 20-22°C. No tributaries or off-channel features were detected in this reach. McKay Creek was sampled from the mouth to the headwaters, a distance of about 36 km (22.4 miles)(Appendix Figure 7, Figure B-19, Figures B-49 to B-51). Temperatures were generally cool in the headwaters and progressively warmed in a downstream direction, reaching 20°C at the mouth. One tributary, Waible Gulch, was visible in the FLIR imagery and was contributing flows about the same temperature as McKay Creek. The East Fork of Dairy Creek was flown from the mouth to the headwaters, a distance of about 35 km (21.7 miles)(Figures B-26 to B-28). Stream temperatures in the headwaters were generally cool (14°C) and increased incrementally in a downstream direction reaching maximums of 20°C at the mouth (Appendix Figure 8). Four tributaries were detected with the FLIR, with two contributing warmer flows (river km 3.0 (mile 1.9) and 20.2(mile 12.5)) and two being similar temperatures as the mainstem (river km 24.3 (mile 15.1) and 29.7(mile 18.4)). All of the tributaries sampled seemed to have minimal effects on mainstem temperatures. At river km 18.6 (mile 11.6) we detected a warmer off-channel pond. The West Fork Dairy Creek was flown from the mouth to the headwaters (Figures B-22 to B-25), a distance of about 32 km (19.9). Temperatures started very warm in the headwaters (18+°C) and warmed slowly downstream reaching maximums of 22°C near the mouth (Appendix Figure 9). One tributary, Cedar Canyon Creek (river km 13.1 (mile 8.1)), was detected with the FLIR and was contributing significantly warmer flow to the West Fork (25.2°C).

Gales Creek was flown from the mouth to the headwaters, a distance of about 44 km (27.3 miles)(Appendix Figure 10, Figures B-30 to B-40). Temperatures were very cold in the headwaters (10$^{o}$C) and increased progressively to about river km 14.5 (mile 9.0) where they reach the maximum for Gales Creek of 24.4$^{o}$C. At river km 20.8 (mile 12.9), there is some evidence of thermal stratification due to a dam (Figure B-36). From river km 14.5 to the mouth stream temperatures are generally lower cycling between 21 and 23$^{o}$C (Figure B-30). We were able to detect the inputs from three tributaries using the FLIR, Prickett, Roderick, and Beaver Creeks. None of the tributaries seemed to have a significant effect on mainstem temperatures. FLIR data was collected on one tributary, Clear Creek. Clear Creek was flown from the mouth to the headwaters, a distance of about 6 km (3.7 mile)(Appendix Figure 11). Temperatures were cooler in the headwaters (14-15$^{o}$C) and increased in a downstream direction reaching their maximums at the mouth (17$^{o}$C). Two tributaries to Clear Creek were detected with the FLIR. Roaring Creek (river km 3.9, mile 2.4) contributed cooler flows while one unnamed tributary (river km 5.5, mile 3.4) contributed warmer flows. The tributary at river km 5.5 (mile 3.4) seemed to warm Clear Creek while Roaring Creek seemed to have little effect on Clear Creek.

Scoggins Creek was surveyed from the mouth to the headwaters, a distance of about 24 km (14.9 miles)(Appendix Figure 12). Data was collected on the entire stream except for the reach that contained Henry Hagg Lake (river km 7.9-12.9). Stream temperatures were cooler in the headwaters (14$^{o}$C) and warmed slowly in a downstream direction until the inlet with Henry Hagg Lake where temperatures reached their maximum for the survey (25.3$^{o}$C, Figure B-44). At the outlet to the lake (river km 7.9, mile 4.9) the lake temperatures were unchanged from the inlet. Temperatures at both these points were taken on the lake surface. Below Scoggins Dam (river km 16, mile 9.9) stream temperatures drop to the lowest levels of the survey, ranging between 9.3 and 11.2$^{o}$C (Figure B-41). The low temperatures are due to bottom release from the reservoir (Figure B-43). One tributary, Parsons Creek (river km 16, mile 9.9), was detected with FLIR and was contributing warmer flow (19.4$^{o}$C) to Scoggins Creek with little apparent effect on the mainstem.

Wapato Creek was flown from the mouth upstream about 3 km (1.9 miles)(Figures B-52 to B-53). The creek was extremely warm in this reach ranging between 26.3 and 28.2$^{o}$C (Appendix Figure 13). Due to its slough-like condition the imagery indicated Wapato Creek was probably stratified.

## Discussion

FLIR was used to map stream temperatures for the Tualatin River and all major tributaries in the basin, a distance of 395 km (245 miles). The data was collected in late July 1999 to assess low flow high summer temperatures in support of the ODEQs TMDL development in the Tualatin River basin. Working in a watershed with urban streams and a busy airport posed significant operational challenges but overall data quality remained high. Analysis of the thermal accuracy of the FLIR compared to in-stream sensors was well within the specified tolerance of $\pm 0.5^{o}$C.

Assessment of the stream temperature patterns in the Tualatin River basin indicated that stream temperatures tended to increase in a downstream direction, but the pattern of this change varied among streams. In addition, the analysis showed the influences of tributary inputs on stream temperature. Tributaries influenced the receiving streams locally, but generally did not alter the prevailing temperature trend. The one prominent exception to this pattern was Scoggins Creek, a major tributary located near the headwaters of the Tualatin River. Scoggins Creek forces a major reset of thermal conditions in the Tualatin River due to cold water releases from Henry Hagg Reservoir. The inflow from Scoggins Creek lowered mainstem temperatures by almost 9$^{o}$C. The temperature of the Tualatin River did not return to levels recorded immediately upstream of Scoggins Creek until 56 km (34.8 miles) below the Scoggins Creek confluence. Of the eleven tributaries that were detected with the FLIR while collecting on the Tualatin River, five were contributing warmer inflows and six were contributing cooler inflows. While several tributaries, such as Rock and Dairy Creek, had local effects on mainstem temperatures, Scoggins Creek was clearly the dominant tributary influence in the watershed.

In addition, our analysis indicated thermal stratification was an intermittent process in the Tualatin River and several tributaries. Thermal stratification seems to be the result of relatively deep-water columns with very low flows in the lower mainstem, and low flow conditions in the tributaries. There was evidence of thermal stratification in the lower 26 km of the Tualatin River, a reach extending 2-3 km upstream of the dam on Gales Creek, the lower 2.5 km of Chicken Creek, and short reaches of Fanno and Rock Creek.

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