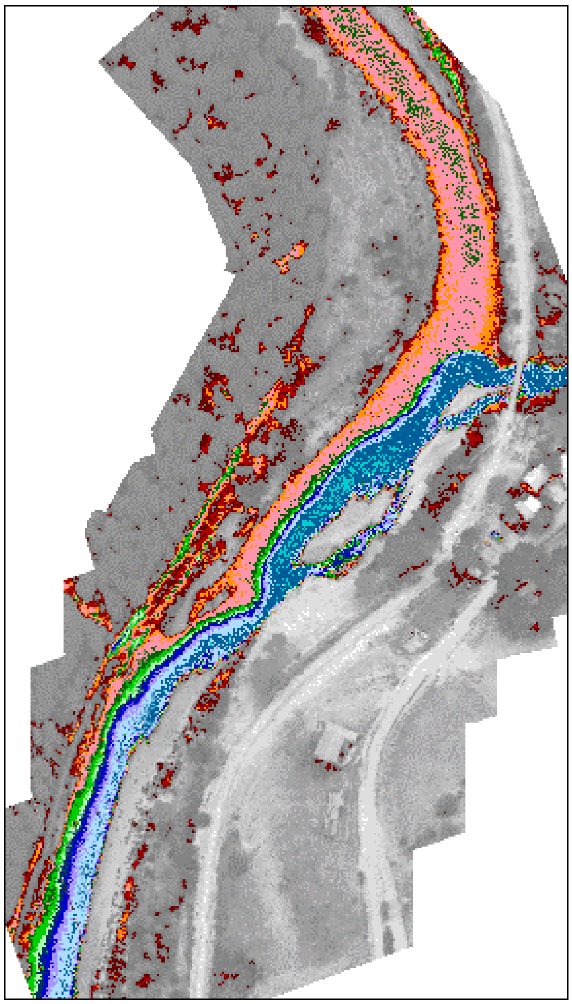
REMOTE SENSING SURVEY OF THE GRANDE RONDE RIVER BASIN

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., 1998; 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 Grande Ronde 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 the project was to collect data for analysis that assists in the development of workable and locally accepted stream temperature best management practices in the Grande Ronde River Basin. FLIR temperature analysis seeks to map cold-water habitats, groundwater influences and temperature profiles across the entire watershed. Ultimately these data will support the development of total daily maximum loads (TMDLs) and water quality management plans (WQMPs) for rural, forested, agricultural and urban lands that address both non-point and point sources of pollution.

This document summarizes the methods and results of the FLIR survey conducted from August 20 – 26, 1999 covering a total of 911 river km (566 river miles) in the Grande Ronde River basin. The data presented in this report are divided into three major sub-basins: a) the Upper Grande Ronde River, b) the Lower Grande Ronde River, and c) the Wallowa River. The "flight" order depended on the stream's priority (*as specified by ODEQ*), the length of the survey, and the geographic location of the stream respectively. 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 Grande Ronde River basin during the summer of 1999. The survey was conducted from August 20 - 26, 1999 and covered a total of 911 river km (566 river miles, Figure 1). Data collection was timed to capture daily stream temperatures, which typically occur between 14:00 and 18:00 hours. Figures 1 thru 3 summarize the date, time, and survey distance for each surveyed stream in the Upper Grande Ronde, Lower Grande Ronde, and the Wallowa sub-basins respectively.

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. FLIR images were 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 Grande Ronde River that was collected at 1 image frame/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).

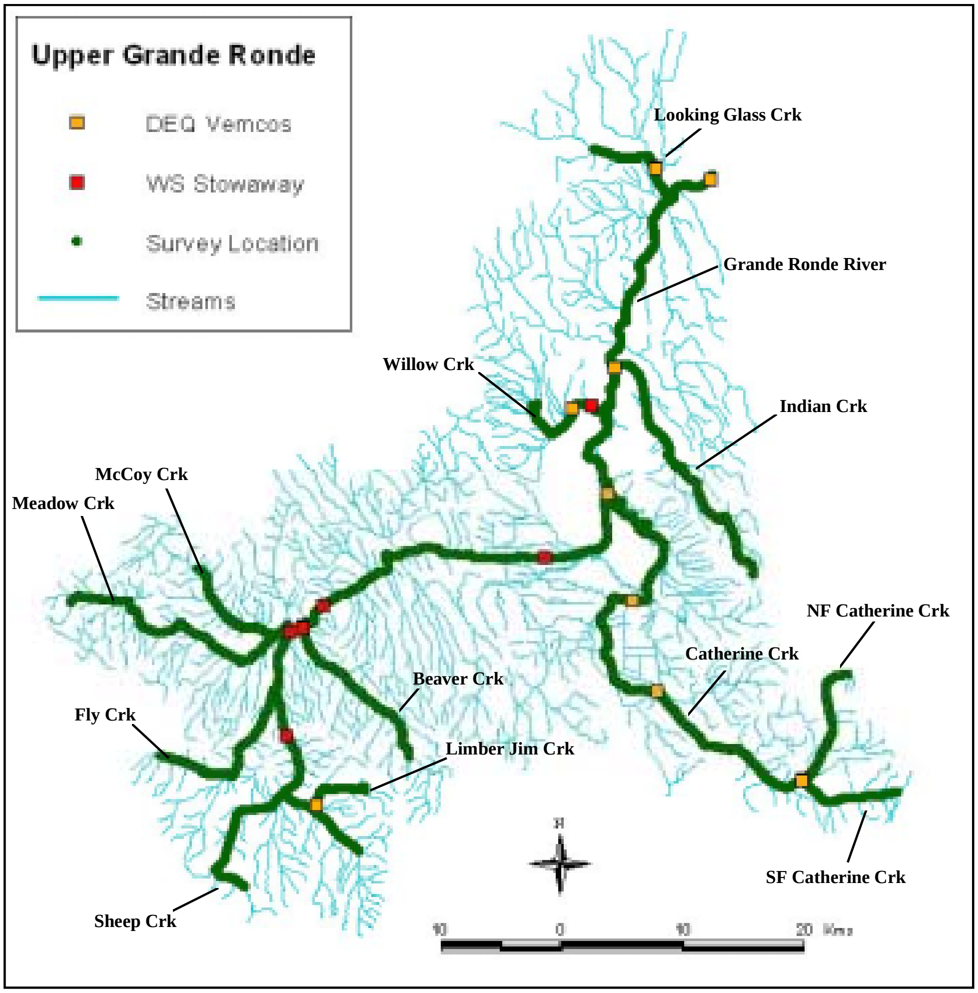
The ground area covered by each thermal image frame depends on the flight altitude used for the stream. In general the flight altitude was selected so that the stream channel occupies approximately 10 to 20% of the image frame. Tributaries were typically flown at an altitude of 1500 ft AGL with the images covering a ground area of approximately 120 x 160 meters (400 x 600 pixel array). For larger channels such as the Lower Grande Ronde 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 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). Figures 1-3 show the location of the Watershed Sciences and ODEQ in-stream data loggers used to ground truth the imagery.

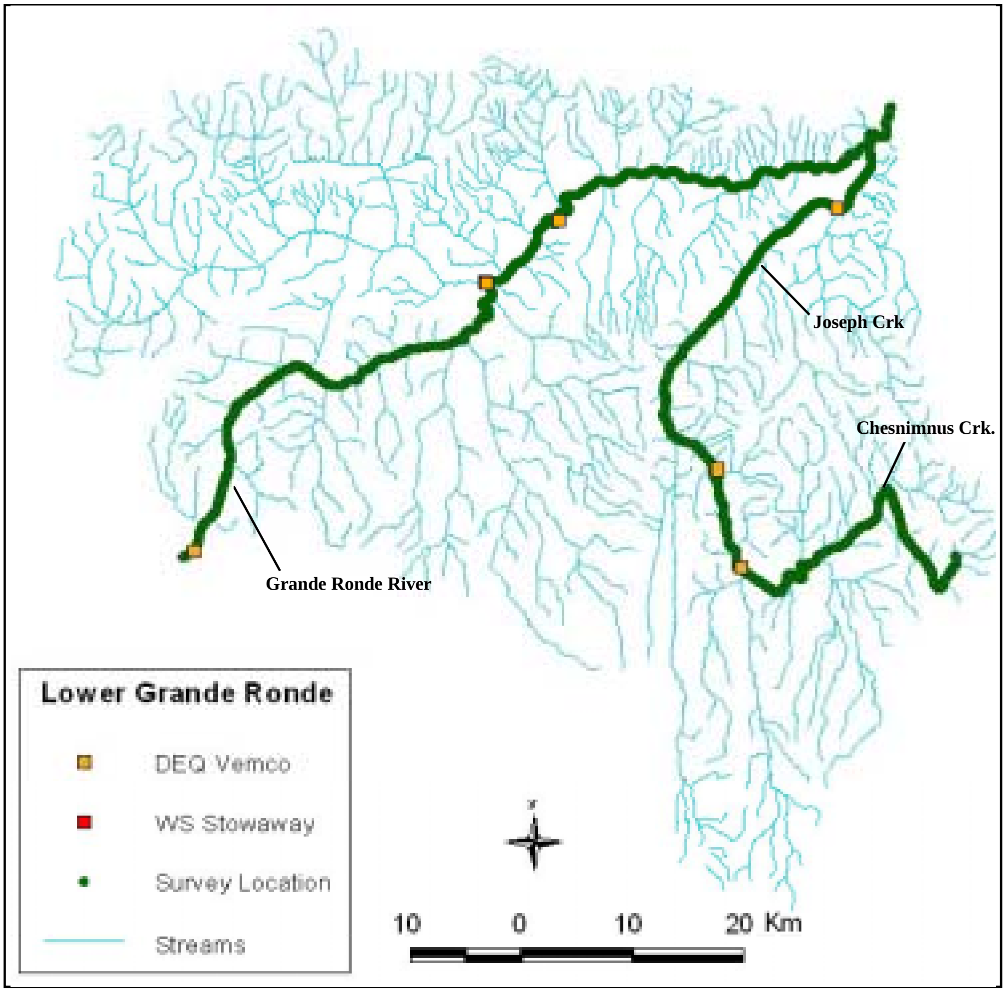
Data Processing

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



Stream	Date	Local Time (PM)	Stream Miles
Upper Grande Ronde (Rondowa to downstream of Tanner Gulch) including the State Ditch	20-August-99	14:51 – 16:12	90.7
South Fork Catherine Creek	21-August-99	13:37 – 13:46	7.8
North Fork Catherine Creek	21-August-99	13:55 – 14:05	9.9
Catherine Creek (Forks to end of the State Ditch)	21-August-99	14:05 – 14:56	53.6
Looking Glass Creek	25-August-99	15:30 – 15:40	8.0
Willow Creek	25-August-99	16:32 – 16:48	10.4
Indian Creek	25-August-99	16:55 – 16:17	21.1
Beaver Creek	26-August-99	14:00 – 14:11	13.5
Meadow Creek	26-August-99	14:22 – 14:44	21.5
McCoy Creek	26-August-99	15:00 – 15:10	9.3
Fly Creek	26-August-99	15:45 – 15:57	13.5
Sheep Creek	26-August-99	16:07 – 16:21	8.0
Limber Jim Creek	26-August-99	16:30 – 16:35	4.6
Total Miles Surveyed			**271.5**

Figure 1 – Date, time, distance, and extent of FLIR surveys in the Upper Grande Ronde River basin and the locations of in-stream data loggers.



Stream	Date	Local Time (PM)	Stream Miles
Lower Grande Ronde (Mouth to Rondowa)	19-August-99	14:33 – 15:38	79.8
Joseph Creek	22-August-99	14:31 – 15:12	48.2
Chesnimnus Creek	22-August-99	15:14 – 15:37	25.6
Total Miles Surveyed			**153.6**

Figure 2 – Date, time, distance, and extent of the FLIR Surveys in the Lower Grande Ronde River Basin and the locations of in-stream data loggers.

Stream	Date	Local Time (PM)	Stream Miles
Wallowa River	23-August-99	13:35 – 14:23	50.1
Lostine River	23-August-99	15:24 – 15:50	25.6
Bear Creek	23-August-99	16:05 – 16:26	19.6
Minam River	21-August-99	15:59 – 16:35	45.3
Total Miles Surveyed			**140.6**

Figure 3 – Date, time, distance, and extent of FLIR Surveys in the Wallowa River Basin and the location of in-stream data loggers.

to the kinetic temperatures from the in-stream data 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 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 30 and 50^{o}C were colored in shades of gray (darker tones to lighter tones), and temperatures > 50^{o}C are white.

Figure 4 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 5 illustrates the temperature GRID displayed in Figure 4 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.

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. 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.

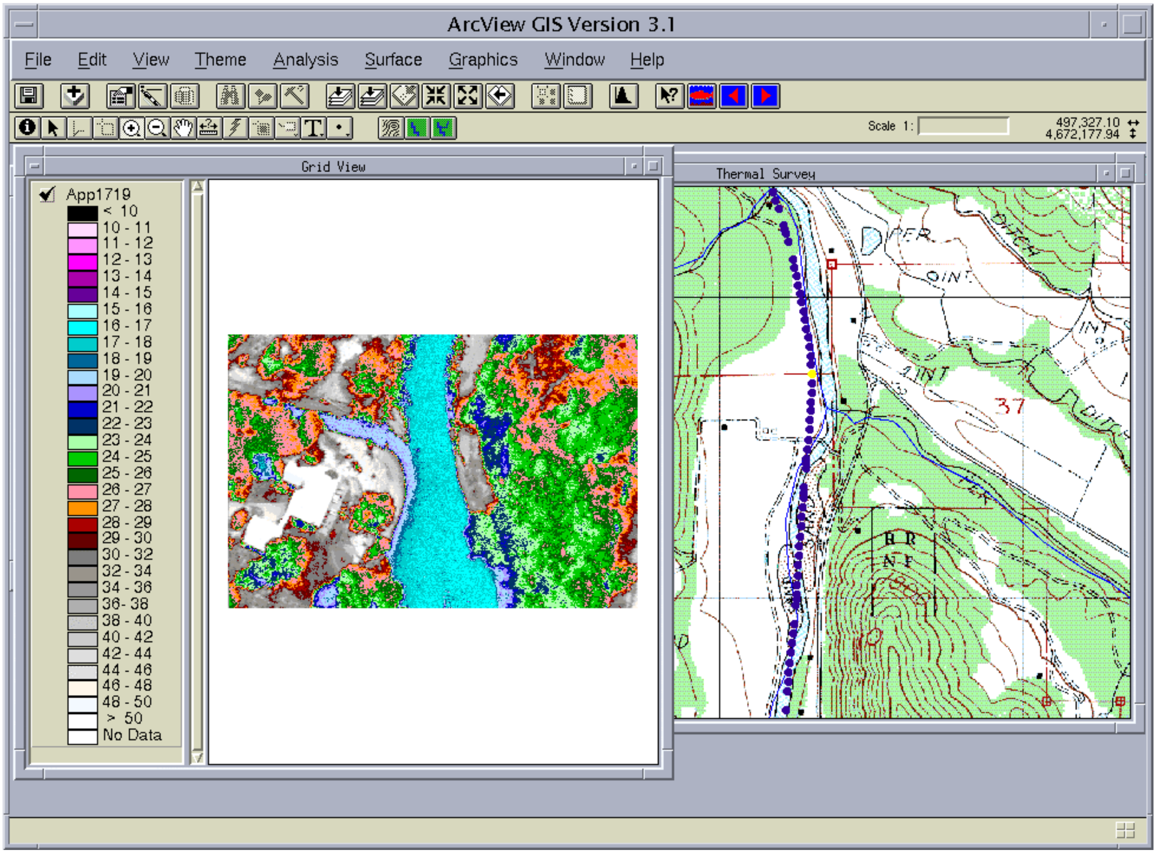


Figure 4 – ArcView display showing a color-coded temperature GRID in one window and the geographic location of the GRID in the other (note that the top of the image is in the flight direction and hence opposite the map).

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.

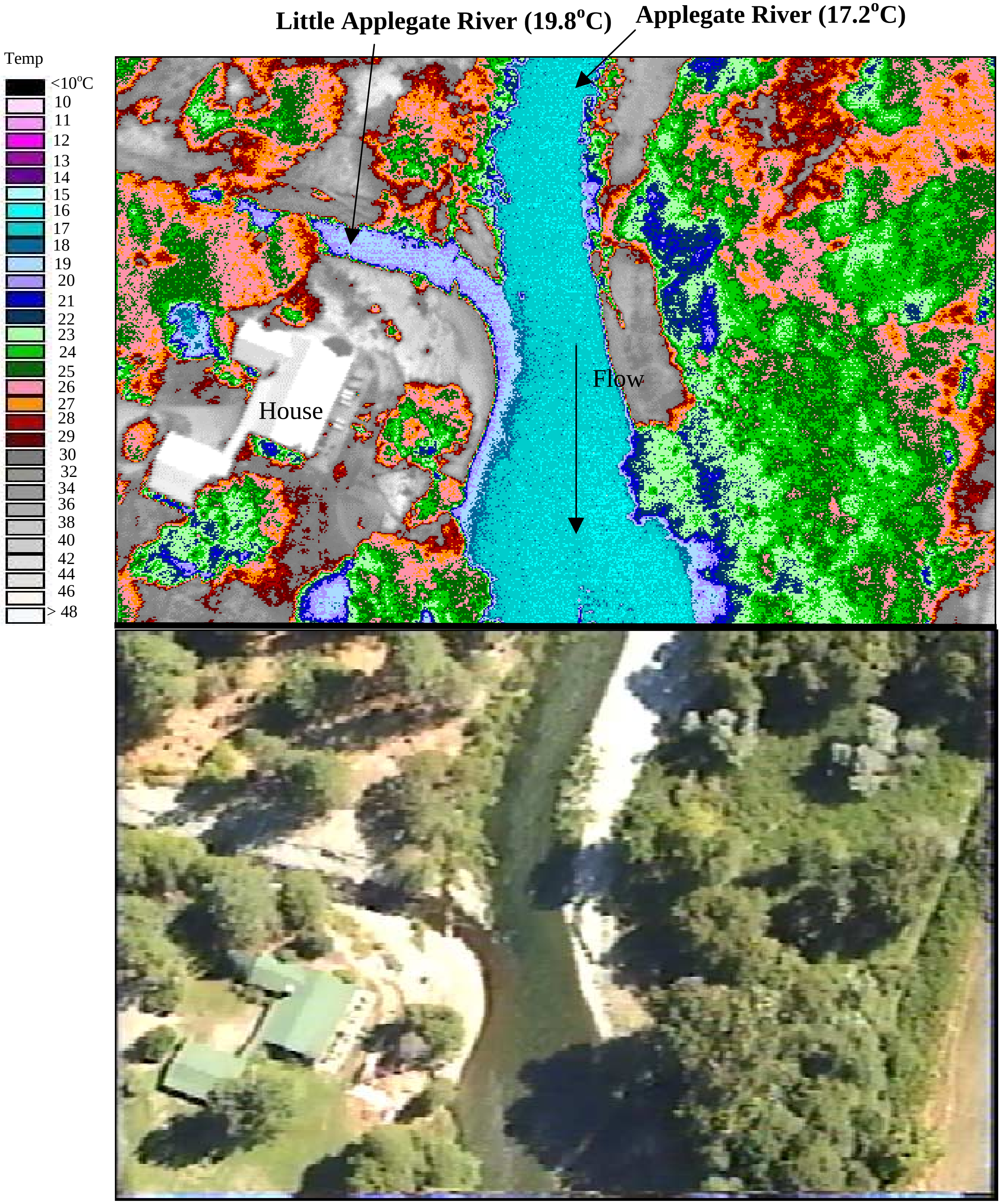


Figure 5 – Temperature Grid (top) and Corresponding Day TV image (bottom) showing the confluence of the Applegate and Little Applegate Rivers. Prominent thermal features are identified on the thermal image.

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 Grande 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. However, some stratified reaches were identified on Catherine Creek and Willow Creek.

Figures 6 and 7 illustrate two cases from Willow Creek where the FLIR image shows evidence of thermal stratification in the stream. Figure 6 shows the confluence of Willow Creek (*1*) and Mill Creek (*2*). The inflow of Mill Creek causes mixing in the downstream direction (*the arrow shows the direction of flow*). The surface temperature variability immediately upstream of the confluence (*location 3*) provides the evidence of thermal stratification. Figure 7 shows Willow Creek (*1*) upstream of Mill Creek. The slight mixing on the bend (*2*) and the magnitude of thermal differences in the surface patterns indicate thermally stratified conditions

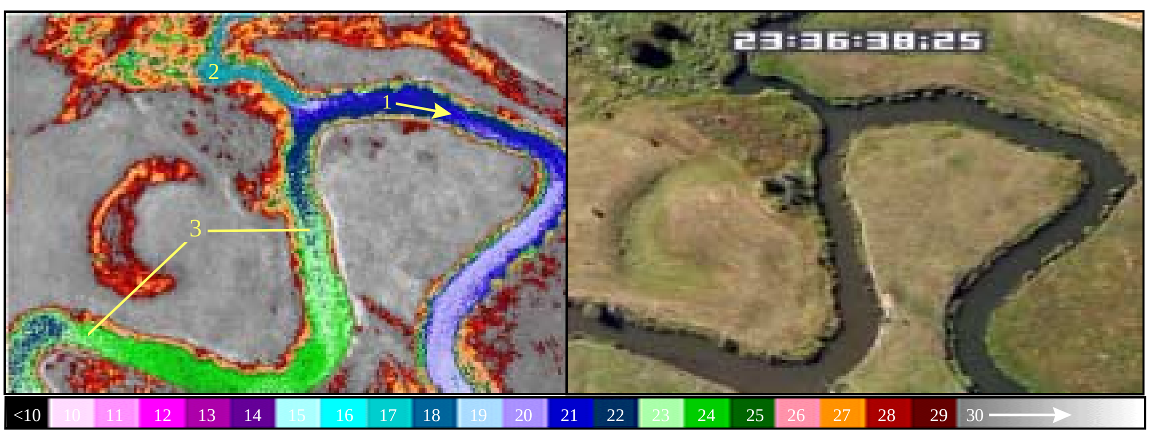


Figure 6 – Thermal image (left) showing evidence of thermal stratification in Willow Creek where mixing is occurring due to a tributary inflow (*frame wil0274*).

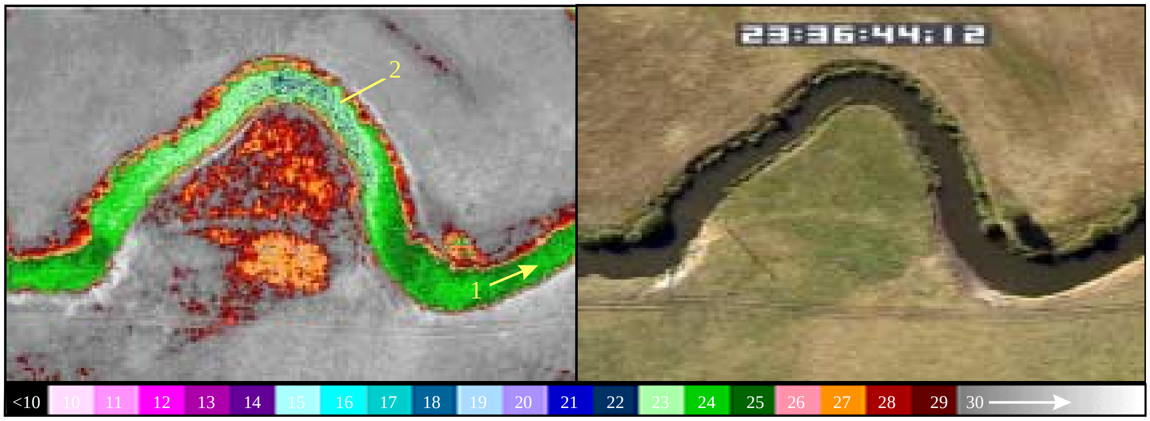


Figure 7 – Thermal image (left) showing evidence of thermal stratification in Willow Creek where there is slight mixing on the stream bends (*frame wil0278*).

Preliminary analysis indicates that Catherine Creek is probably stratified from the mouth upstream to Davis Dam. Willow Creek is stratified intermittently from the mouth to river kilometer 13. The other streams in the basin were considered generally well mixed. However, local areas of thermal stratification may exist. Figure 8 provides an example from Meadow Creek. The image shows Meadow Creek at Camp Elkanah where the surface temperatures upstream of the dam are much warmer then downstream (2) of the dam (*arrow indicates the direction of flow*).

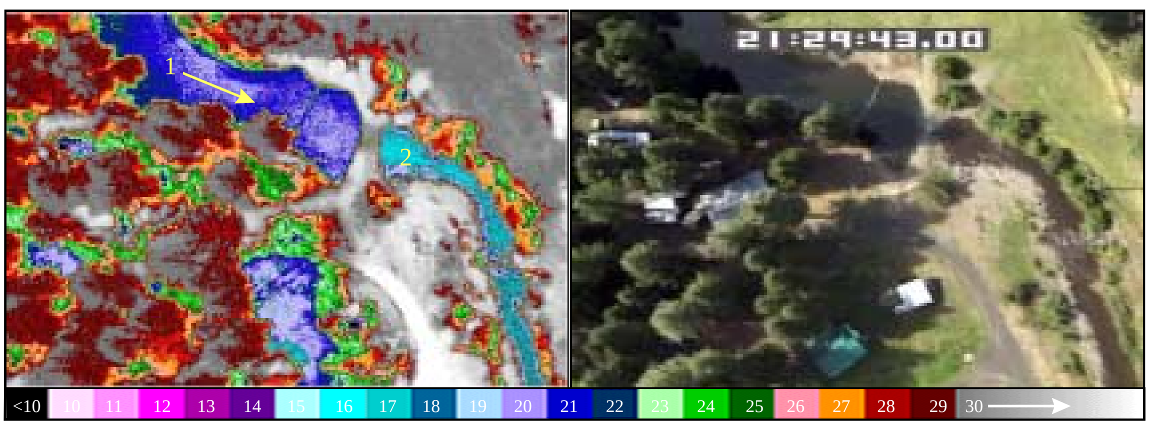


Figure 8 – Meadow Creek at Camp Elkanah showing a thermal stratification upstream (location 1) of a dam (*frame mead0345*).

Date and Time of Day

One of the objectives of the FLIR survey is to capture summer maximum stream temperatures. Figures 9 and 10 show data from seasonal data loggers (DEQ Vemcos) in relation

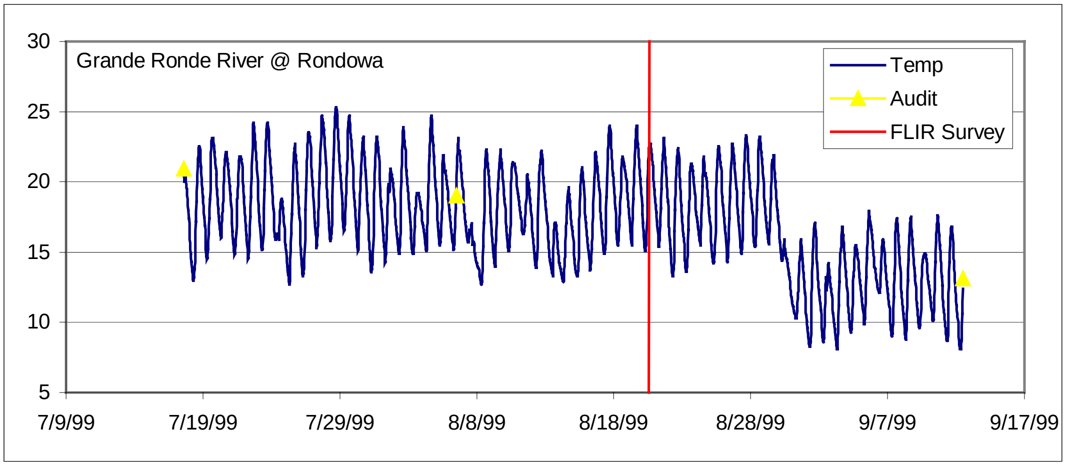


Figure 9 – FLIR Survey in relation to maximum temperatures measured during the summer in the Grande Ronde River (*from DEQ Vemco*).

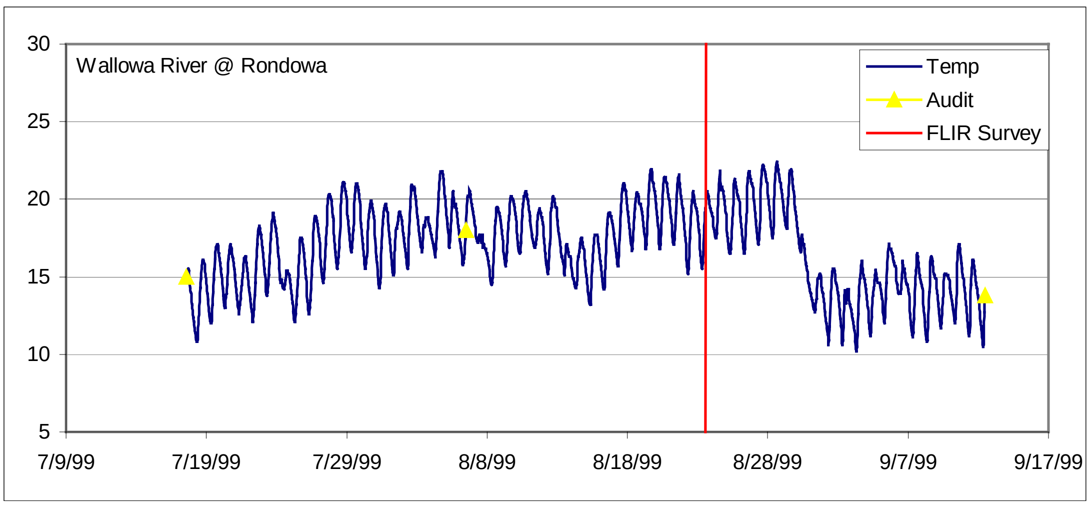


Figure 10 – FLIR Survey in relation to maximum temperatures measured during the summer (*from DEQ Vemco*).

to the date and time of the FLIR survey for the Grande Ronde and Wallowa River Basins. As shown, the FLIR surveys were conducted on days representative of summer maximums.

Figures 11 thru 13 show the duration of time and duration of the FLIR survey in relation to the diurnal temperature cycles recorded by in-stream data loggers. As shown the daily maximum temperatures generally occur between 4:00 pm and 6:00 pm. The temperature changes that occur at each location during the flight were less then 1°C for all points analyzed. The data are only provided for the main channel as they have the longest survey time and therefore the highest potential temperature change from the start to the end of the survey.

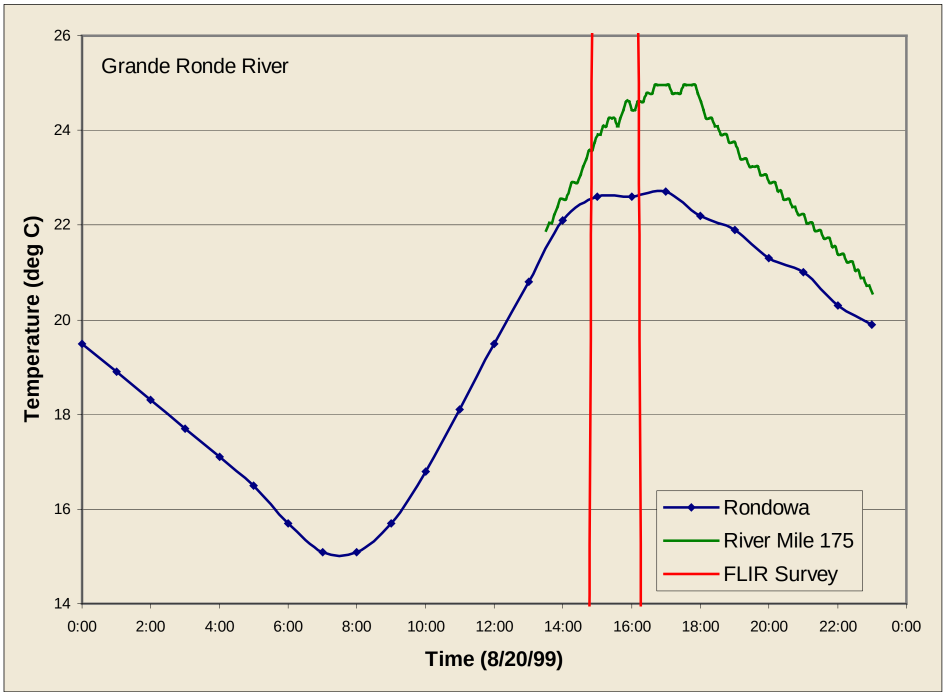


Figure 11 - Time and duration of the FLIR survey on the Upper Grande Ronde River in relation to the daily maximum(s) for two data logger locations.

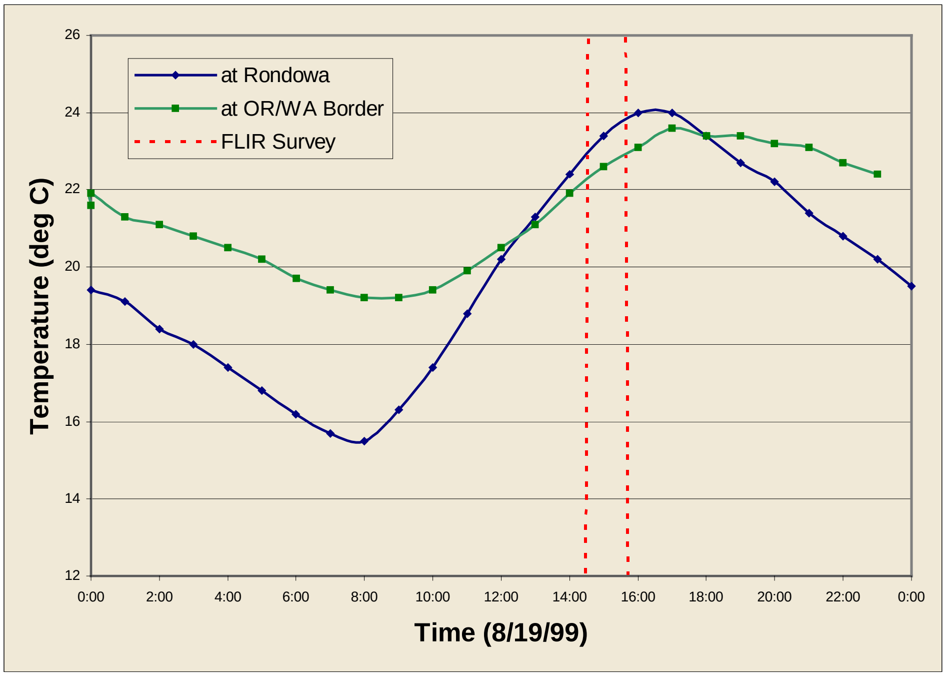


Figure 12 – Time and duration of the FLIR survey on the Lower Grande Ronde River in relation to the daily maximum(s) for two data logger locations.

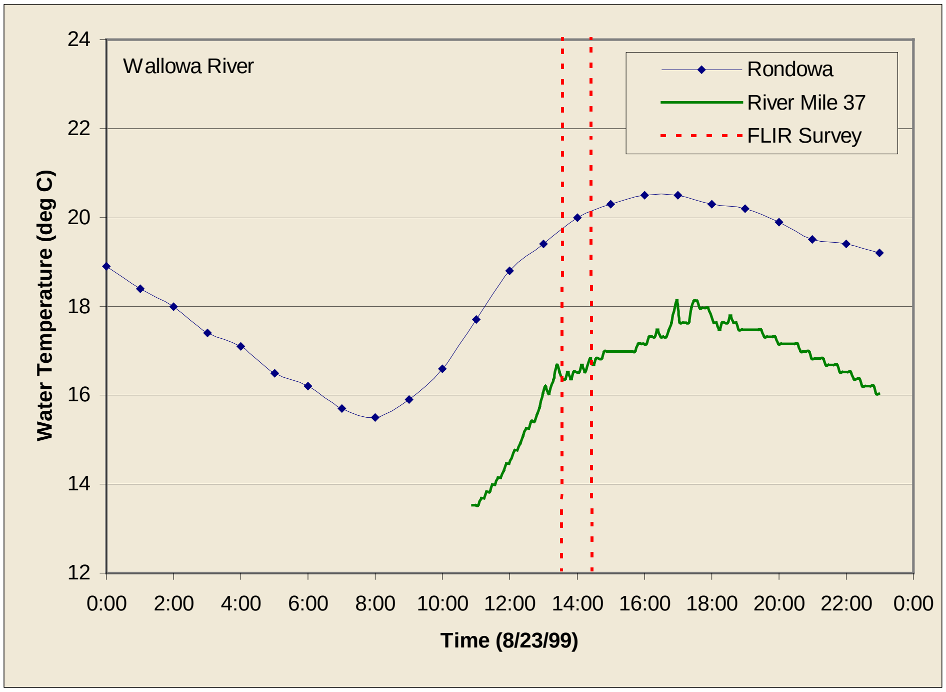


Figure 13 – Time and duration of the FLIR survey on the Wallowa River in relation to the daily maximum(s) for two data logger locations.

Results

Thermal Accuracy

Watershed Sciences 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. The advertised accuracy of the Onset Stowaway's is $\pm 0.2^{o}$C. These locations were supplemented by data provided by OR DEQ from seasonal in-stream temperature loggers (Vemcos). Figures 1-3 show the locations of the Watershed Sciences and ODEQ in-stream data loggers used to ground truth the imagery for each sub-basin. At least two data loggers were "flown over" during each survey.

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 at least 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. This process is known as ground-truthing.

Tables 4 thru 6 provide a comparison of the in-stream and radiant temperatures for the Upper Grande Ronde, Lower Grande Ronde, and Wallowa River Basins, respectively. The Delta ^{o}C column represents the difference between the in-stream temperature and the radiant temperature at that location. A negative number in this column means the radiant temperature was higher than the measured in-stream temperature. Yellow shaded cells represent differences of less then or equal to ±0.5^{o}C. Orange shaded cells show examples of a thermally stratified condition where the surface temperatures measured by the FLIR are higher (*greater then 0.5^{o}C*) then the water temperatures measured by the in-stream data loggers. Red shaded cells represent differences of greater then ±0.5^{o}C that were not attributed to thermal stratification.

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, the radiant temperatures were consistent with the measured in-stream temperatures.

Upper Grande Ronde

There were a total of 19 data sites used to verify the accuracy of the FLIR imagery in this sub-basin. Three of these sensors were located in thermally stratified reaches of the stream. Thermal stratification was determined based both on the differences between the temperatures given by the in-stream data logger and a review of the FLIR imagery near the data logger location. Thermally stratified conditions are discussed in more detail in the next section.

There were three locations where the differences between the in-stream data loggers and the radiant temperatures exceeded ±0.5^{o}C (*red shaded cells*). The Limber Jim Creek location showed the largest difference with the radiant temperature 3^{o}C warmer then the DEQ Vemco located at river mile 0.4. There is no conclusive reason given for this difference. Limber Jim Creek was surveyed in the same "flight" as Fly Creek and Sheep Creek. The ground truth locations in the mouth of Fly Creek and in the Upper Grande Ronde River near Fly Ridge Rd matched closely to the imagery. A plausible explanation is that there is some uncertainty in the location of this in-stream data logger. A review of the longitudinal temperature profile for Limber Jim Creek shows rapidly decreasing temperatures as one moves up-stream from the mouth.

The DEQ Vemco in the mouth of the SF Catherine Creek recorded a temperature 1.6^{o}C higher then the radiant temperature measured by the FLIR. Again, there is no definite reason given for this temperature difference. However, the FLIR image showing the confluence of the NF and SF Catherine Creek shows only slight temperature difference between the two streams.

Lower Grande Ronde Basin

Table 5 shows a comparison of in-stream temperatures to radiant temperatures derived from the thermal infrared images in the Lower Grande Ronde Basin. There were 8 in-stream data loggers used to ground truth the FLIR imagery. The in-stream and radiant temperatures were within ±1.0^{o}C for all ground truth locations.

Table 1 – Comparison of in-stream temperatures to radiant temperatures derived from the thermal infrared images in the Upper Grande Ronde Basin.

Stream	Site	Owner	Image Name	Time	In-Stream OC	Radiant OC	Delta OC
Grande Ronde	Pierce Lane Bridge	WS	ugr2328	15:32	25.4	25.8	-0.4
	Red Bridge CG	WS	ugr3400	15:55	24.6	24.1	0.5
	Indian Creek (mouth)	DEQ	ugr1099	15:09	26.8	27.2	-0.4
	Rondowa	DEQ	ugr0022	15:01	22.2	23	-0.4
Catherine Creek	Goodly Rd Bridge	DEQ	cath2454	14:47	20.5	23.4	-2.9
	Catherine Mouth	DEQ	cath3433	15:05	22.2	24.6	-2.4
	Upstream of Union	DEQ	cath1680	14:34	21.5	21.2	0.3
	NF Catherine Mouth	DEQ	cath0524	14:14	15.5	15.9	-0.4
SF Catherine Creek	Mouth	DEQ	sfca0510	13:57	17.7	16.1	1.6
Looking Glass Creek	Upstream of Hatchery	DEQ	look0195	15:43	16.2	16.4	-0.2
Indian Creek	Mouth	DEQ	ind0085	16:05	27.1	26.9	0.2
Willow Creek	Courtney Rd Bridge	WS	wil0112	16:33	20	21.8	-1.8
	Courtney Lane	DEQ	wil0212	16:35	19.9	20.4	-0.5
Beaver Creek	Mouth	WS	beav0029	14:00	23.2	22.5	0.7
	Mouth	OSU*	beav0029	14:00	22.0	22.5	-0.5
Meadow Creek	Mouth	WS	mead0020	14:23	22.8	22.7	0.1
Fly Creek	Mouth	OSU*	fly0016	15:45	24.1	23.5	0.5
Sheep Creek	UGR @ Fly Ridge Rd.	WS	shp0014	16:17	23.1	23.4	-0.3
Limber Jim Creek	Meadow at RM 0.4	DEQ	lj0064	16:30	18.2	21.2	-3.0

Delta within ±0.5°C, Delta outside ±0.5°C, Orange = Example of Thermal Stratification
*Onset Stowaway Locations provided by the Department of Fish and Wildlife, Oregon State University.

Table 2 – Comparison of in-stream temperatures to radiant temperatures derived from the thermal infrared images in the Lower Grande Ronde Basin.

Stream	Site	Owner	Image Name	Time	In-Stream °C	Radiant °C	Delta °C
Grande Ronde	Wenaha River Mouth	DEQ	lgr0890	15:03	18.9	19.8	-0.9
	Upstream of Wenaha Mouth	DEQ	lgr0891	15:03	24.2	23.9	0.3
	OR/WA State Line	DEQ	lgr0719	14:57	22.6	22.1	0.5
	Grande Ronde River @ Rondowa	DEQ	lgr1778	15:37	22.9	22.6	0.3
	Wallowa River Mouth	DEQ	lgr1777	15:37	21.9	21.3	0.6
Joseph Creek	Upstream of Cottonwood Creek	DEQ	joe0241	14:35	24.4	24.6	-0.2
	FS Road 190	DEQ	joe1555	15:00	25.4	24.6	0.8
	Chesnimnus Creek Mouth	DEQ	joe1924	15:12	26.4	26.2	0.2

Delta within ±0.5°C, Delta outside ±0.5°C

Wallowa Basin

Table 6 shows a comparison of in-stream temperatures to radiant temperatures derived from the thermal infrared images in the Lower Grande Ronde Basin. There were 9 in-stream data loggers and one field measurement used to ground truth the FLIR imagery. Of the 9 ground truth points, 7 points showed a temperature difference of less then ±0.5°C between the FLIR image and the in-stream data loggers. In general, we considered these accuracies to be good. The data logger near the mouth of the Minam River was in very shallow water and it may not provide an accurate representation of the water temperature of the main channel.

One of the two data loggers in the Lostine River also recorded temperatures greater then the radiant temperatures. While this data logger passed preseason accuracy checks, it consistently read high when deployed in the field during other surveys (*Fanno Creek, Tualatin Basin and Beaver Creek, Grande Ronde Basin*).

Table 3 – Comparison of in-stream temperatures to radiant temperatures derived from the thermal infrared images in the Wallowa River Basin.

Stream	***Site***	***Owner***	***Image Name***	***Time***	***In-Stream °C***	***Radiant °C***	***Delta °C***
Wallowa River	Mouth	DEQ	wal0033	13:45	19.8	19.3	0.5
	River Mile 16.5	WS	wal0794	13:58	18.2	18.1	0.1
	River Mile 35.6	WS	wal1840	14:15	16.6	16.9	-0.3
	downstream of Wallowa Lake	DEQ	wal2700	14:33	18.7	18.6	0.1
Lostine River	Pole Bridge	WS	lost0798	15:50	13.5	13.7	-0.2
	Williamson CG	WS	lost1008	15:53	13.8	12.4	1.4
Bear Creek	upstream of Chamberlain Ditch	WS	bear0255	16:08	18	18.5	-0.5
	gauging station	DEQ	bear0179	16:19	17.6	17.9	-0.3
Minam River	Mouth	WS	min0045	16:10	24.3	23	1.3
	Red Point Ranch*	Field	min1133	16.8	16.8	17	-0.2

Delta within ±0.5°C, Delta outside ±0.5°C.

**This in-stream measurement was taken 40 minutes after fly over*.

Analysis of Thermal Imagery

Grande Ronde River

Data collection for the Grande Ronde River was conducted on two consecutive days. The reach from the mouth to the Wallowa River was flown on August 19 from 14:34 to 15:37 and the reach from the Wallowa River to the headwaters was flown on August 20 from 14:51 to 16:12, a total distance of 272 km (169 miles). We terminated the flight just above the East Fork of the Grande Ronde approximately 9.7 km (6 miles) from the watershed divide. The flight was terminated due to the channel being completely obscured by canopy cover. While the timing of the two flights was different, we examined overlapping images from the two flights and found only a 0.3^{o}C between common images. Based on these small differences, we concluded that analyzing the data cumulatively was appropriate. The median temperatures for each sampled image for the Grande Ronde River from the confluence with the Snake River to the headwaters was plotted versus the corresponding river kilometer (Appendix Figure A1). 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 Grande Ronde River. Tributaries are labeled in Figure A1 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.

The longitudinal temperature profile in Appendix Figure A1 shows how stream temperatures vary along the length of the Grande Ronde River and the influence of select tributaries. At the upstream end of the survey, median stream temperatures were about 14^{o}C. From here downstream 15.5 km (9.6 miles) to the old splash dam at the outlet of Vey Meadows stream temperatures increase rapidly at the rate of 0.6^{o}C/km in a near linear progression. At the outlet of Vey Meadows median temperatures reach a local maximum of 22.9^{o}C. Temperatures decrease about 1.8^{o}C over the next 5.5 km (3.4 miles), reaching a local minimum of 21.0^{o}C near a spring at river kilometer 251 (river mile 156). From river kilometer 251 downstream to Meadow Creek temperatures increase at a rate of 0.26^{o}C/km reaching a local maximum of 24.9^{o}C just above Meadow Creek. The reaches from Meadow Creek to the town of Island City (river kilometer 198) stream temperatures fluctuate between 23.8 and 25.7^{o}C with a slight warming trend in the downstream direction. From Island City downstream to the confluence with Lookingglass Creek, stream temperatures range between 23.8 and 28.6^{o}C, changing rapidly over relatively short distances (< 1.0 km). Our review of the imagery and stagnant low flow conditions within this reach suggest indicate thermal stratification may be a significant factor in the widely fluctuating stream temperatures.

At the confluence with Lookingglass Creek, Grande Ronde River temperatures drop 4.4^{o}C to 21.9^{o}C due to the cold input from Lookingglass Creek (18.3^{o}C, Appendix Figure B15). Below Lookingglass Creek, temperatures increase to about 23^{o}C until the confluence with the Wallowa River (20.9^{o}C) where stream temperatures are decreased by 2^{o}C to 21^{o}C. From the Wallowa River to the Wenaha River stream temperatures increase steadily to a local maximum of 24.4^{o}C. The input from the Wenaha River (19.9^{o}C) decreases the Grande Ronde River by 2.6^{o}C to 21.8^{o}C (Appendix Figure B5). From the confluence with the Wenaha to the Snake River the Grande Ronde increases to a maximum of 24.5^{o}C at the mouth. The Snake River is 22.4^{o}C at the confluence with the Grande Ronde River.

From our sampling of mainstem temperatures we were able to detect inflow from 50 different tributaries. Thirty-two tributaries were contributing cooler water (range = +0.2 to + 9.8^{o}C) and five were contributing cooler water (range = -0.5 to –8.6^{o}C).

Lower Grande Ronde River Basin

In addition to the mainstem flight, Joseph and Chesnimnus Creeks were surveyed with FLIR in the Lower Grande Ronde River basin (Table 2, Appendix Figure A2). Joseph and Chesnimnus Creeks were surveyed continuously from the confluence with the Grande Ronde upstream 188.5 km (73.6 miles) to about 7.0 km (4.3 miles) from the watershed divide of Chesnimnus Creek on August 22, 1999 from 14:31 – 15:36. Near the headwaters stream temperatures ranged between 19.2 and 22.4°C for the first 8.5 km. From river km 109.8 (river mile 68.2) to river kilometer 108.1 (river mile 67.2) stream temperatures decrease 5.0°C. There are no obvious point source inputs in this reach but the imagery indicates a very clear drop in stream temperatures. We attribute this decrease to groundwater inputs, although we have no ground data to support this conclusion. From river kilometer 108.1 (river mile 67.2) to the confluence with Joseph Creek (river kilometer 77.6/river mile 48.2) Chesnimnus Creek warms progressively in the downstream direction reaching a maximum of 26.2°C at the mouth (Appendix Figure B4). At the confluence with Joseph Creek, Crow Creek also inputs to Joseph Creek, decreasing stream temperatures by 2.7°C to 23.6°C. Stream temperature decrease in the downstream direction to river kilometer 37.0 (river mile 23.6) where they reach a local minimum of 20.7°C. From river kilometer 37.0 to the confluence with the Grande Ronde River, Joseph Creek warms slowly in the downstream direction reaching a local maximum of 24.9°C near the mouth (Appendix Figure B1). Thirteen tributary or off-channel features were detected over the survey reach and are summarized in Appendix Figure A2. Twelve of the thirteen tributaries detected were contributing cooler inflows to the mainstem.

Wallowa River Basin

Four streams in the Wallowa River basin were flown in 1999 to collect FLIR data. The Minam River was flown on August 21 and the Wallowa River, Lostine River, and Bear Creek were flown on August 23rd (Figure 3). The Wallowa River was flown from the mouth to Wallowa Lake a distance of 80.3 km (49.9 miles, Appendix Figure A3). At the outlet to Wallowa Lake, stream temperatures were 18.7°C and increased rapidly over the next 3.5 km reaching the maximum for the survey of 20.1°C. Over the next 3.5 km stream temperatures decrease rapidly reaching the minimum for the survey of 15.9°C at river km 73.6 (river mile 45.7). This decrease was caused by large inputs of groundwater throughout this reach (Appendix Figures B8-B9). Over the next 32 km to the confluence with the Lostine River, stream temperatures remained relatively constant. From the Lostine River to the confluence with the Grande Ronde stream temperatures increased steadily in the downstream direction inputting to the Grande Ronde at 18.6°C (Appendix Figure B6). While the longitudinal profile for the Wallowa River is representative of thermal conditions, absolute temperatures do not represent daily maximum as the data was collected in the early afternoon (13:35 – 14:23). We were able to detect 12 tributaries and 28 off-channel features (side-channels, springs) with the FLIR. The majority of the tributaries (7/12) and off-channel features (17/28) were contributing warmer inflows to the Wallowa River. The only area contributing significant cool inputs was the reach below the Wallowa Lake where cold springs were very evident.

FLIR data was collected on three tributaries to the Wallowa River: the Minam and Lostine River and Bear Creek. The Minam River survey was flown from the mouth to an area about 4 km above Lowry Gulch, a distance of 72.8 km (45.2 miles) and 6.7 km (4.2 miles) from the watershed divide (Appendix Figure A4). Stream temperatures in the headwaters were about 12.0^{o}C and increased progressively to the confluence with the Wallowa River, imputing to the Wallowa at 22.9^{o}C. The only significant deviation from the overall warming trend was below river km 20 (river mile 12.4) where an unnamed tributary and Trout Creek contributed cooler flows to the Minam River, decreasing the mainstem temperature about 1.0^{o}C to river km 14. From river km 14 (river mile 9) to the mouth, stream temperatures increased slowly in the downstream direction. We detected 16 tributaries with the FLIR; the majority (11/16) were contributing cooler flows to the Minam River.

The Lostine River was flown from the mouth upstream 41.2 km (25.6 miles), concluding about 7 km (4 miles) from the watershed divide (Appendix Figure A5). Stream temperatures in the headwaters were about 9.3^{o}C and increased slowly downstream to river km 24 (river mile 15) where temperatures remained steady for the next 6 km. The upper end of this reach happens to coincide with the Eagle Cap Wilderness Boundary. At river km 18.1 (river mile 11.3), there is a diversion from the Lostine River that feeds a large pond. The pond returns warm water (21.1^{o}C) flow to the Lostine River at river km 16.7 (river mile 10.3) that elevates Lostine River temperatures about 2.0^{o}C. From river km 16.7 to the confluence with the Wallowa River stream temperatures warm slowly in the downstream direction, reaching about 19.0^{o}C at the mouth (Appendix Figure B7). We detected 27 tributaries and off-channel features contributed input to the Lostine River. The majority of tributaries (9/17) were contributing warmer flows, although most of them were quite cold (< 15.0^{o}C). Most off channel features (6/10) were contributing cooler flows (Appendix Figures B12-14). Overall stream temperatures and thermal features were very cold.

We surveyed Bear Creek from the mouth upstream 31.6 km (19.6 km) to about 1.5 km above Granite Creek (Appendix Figure A6), a distance of about 7 km below the watershed divide. Near the headwaters stream temperatures are 10-11^{o}C, but warm relatively fast reaching a local maximum of 16.1^{o}C at river km 23.2 (river mile 14.0). At river km 23.2 stream temperatures decrease almost instantaneously to about 10.0^{o}C. This appears to be due to inputs from several springs in this reach. Temperatures range between 10 and 11^{o}C over the next 1.5 km and then begin to warm slowly in the downstream direction reaching the maximum (20.8^{o}C) at the confluence with the Wallowa River (Appendix Figure B10). We were able to detect 4 tributaries with the FLIR with 3 out of 4 contributing warmer flows, although all four tributaries were less then 15.3^{o}C.

Upper Grande Ronde River Basin

The FLIR survey of the Upper Grande Ronde River basin included the mainstem river and twelve tributaries (Figure 1). Lookingglass Creek was flown from the mouth upstream a distance of 12.8 km (8 miles, Appendix Figure A7). The flight was terminated about 11.6 km (7.2 miles) below the watershed divide due to canopy closure over the stream. Stream temperatures in the headwaters were 9.3^{o}C and increase slowly in the downstream direction reaching the maximum (17.0^{o}C) for the survey at the confluence with the Grande Ronde River (24.2^{o}C). The cool input from Lookingglass creek has a significant cooling effect on the Grande

Ronde River (Appendix Figure B15). We were able to detect four tributaries contributing flow to Lookingglass Creek and all were contributing warmer water.

Indian Creek was flown from the mouth a distance of 34 km (21.1 miles) and terminated about 1.5 km from the watershed divide (Appendix Figure A8). In the headwaters, stream temperatures were 10.3°C and increase slowly over the next 1.8 km to 12.4°C. At river km 32.2 (river mile 20), temperatures decrease abruptly to 8.9°C for no apparent reason. From river km 32.2 to the confluence with the Grande Ronde, stream temperatures increase progressively in the downstream direction reaching the maximum (26.6°C) for the survey at the confluence with the Grande Ronde River (24.6°C, Appendix Figure B16). We detected 5 tributaries contributing flow to Indian Creek with four of the five imputing cooler streamflows.

Willow Creek was flown from the mouth upstream a distance of 16.4 km (10.2 miles) and ended just above Dry Creek (Appendix Figure A9). Stream temperatures at the upstream end of the survey were warm (20.2°C) and increased progressively downstream to river km 8.9 (river mile 5.5) where the maximum temperatures (24.5°C) for the survey were recorded. From river km 8.9 downstream there was considerable evidence of thermal stratification throughout the river rendering interpretation of the imagery of minimal use. At the confluence with the Grande Ronde River, Willow Creek was contributing cooler (24.3°C) flows to the mainstem (26.3°C, Appendix Figure B16).

In the Catherine Creek sub-basin, the flights were conducted in the downstream direction. The South Fork Catherine Creek was flown first from the headwaters downstream to the confluence with the North Fork and Catherine Creek, a distance of about 12 km (7.5 miles). The North Fork Catherine Creek was flown from the headwaters to the confluence with Catherine Creek, a distance of about 16 km (9.9 mile). The last portion of the flight was the Catherine Creek, which was flown from the North/South Fork confluence to the confluence with the Grande Ronde River, a distance of 86.3 km (53.6 miles). Both the North Fork and South Fork were very cold (<10.0°C) in the headwaters (Appendix Figure A10). The South Fork warmed steadily in the downstream direction reaching a maximum of 16.3°C at the confluence with Catherine Creek and the North Fork. We were unable to detect any tributary inputs to the South Fork. The North Fork warmed relatively quickly in the first 3.6 km, reaching a local maximum of 14.0°C at river km 98.6 (river mile 61.2). At river km 98.6 a cold spring inputs into the North Fork at 9.1°C and cools the North Fork by about 2.0°C. Below the spring the North Fork slowly warms in the downstream direction reaching a maximum of 16.4°C at the confluence with Catherine Creek and the South Fork. We were able to detect seven tributaries and one spring in the North Fork, all were contributing cooler inflows to the North Fork.

From the confluence with the North and South Forks, Catherine Creek warms steadily in the downstream direction to Little Catherine Creek at river km 79 (river mile 49, Appendix Figure A10). From river kilometer 79 to 75, stream temperatures are relatively constant at just under 20.0°C. At river kilometer 75, stream temperatures are cooler (1.0+°C) over the next several kilometers for no apparent reason. From river km 72 (river mile 44.7) downstream stream temperatures increase slowly to about river km 67 (river mile 41.6) where they reach a local maximum of 21.0°C. From river kilometer 67 to Davis Dam (river km 54.5/river mile 33.8) stream temperatures are relatively constant, fluctuating between 19.6 and 21.6°C. Below

Davis Dam, we documented that thermal stratification of the water column was a common feature due to low, stagnant streamflows (see previous section on *Data Limitation*, Thermal Stratification). Surface water temperatures below Davis Dam always exceeded the maximums recorded above the dam reaching a maximum of 26.9^{o}C at river km 14.5 (river mile 9.0). We were able to detect ten tributaries contributing flow to the mainstem of Catherine Creek. Four were contributing warmer flow, four were cooler and two were the same as the mainstem.

Beaver Creek was surveyed from the mouth a distance of 21.5 km (13.4 miles) upstream, approximately 10.0 km (6.3 miles) below the watershed divide (Appendix Figure A11). At the upstream end of the survey, Beaver Creek was about 12.0^{o}C and remained cool for the next 0.6 km to the confluence with Cove Creek. Although Cove Creek (9.7^{o}C) was cooler then Beaver Creek (11.9^{o}C), stream temperatures warmed rapidly in the downstream direction over the next 3.4 km reaching a local maximum of 18.6^{o}C at river km 17.2 (river mile 10.8), just below Hoodoo Creek (Appendix Figure B19). From river km 17.2 to 13.7 stream temperatures decrease by 4.0^{o}C reaching a local minimum of 14.6^{o}C at river km 13.7 (river mile 8.5). Proceeding downstream from river km 13.7, stream temperatures increase steadily reaching a local maximum of 22.1^{o}C at river km 3.5 (river mile 2.2). Below River km 3.5 stream temperatures cool rapidly to 18.0^{o}C in the vicinity of Little Beaver Creek (16.6^{o}C), which inputs to Beaver Creek 1.4^{o}C cooler. This reach of Beaver Creek is unconstrained and contains multiple channels and some evidence of springs. From Little Beaver Creek to the confluence with the Grande Ronde, Beaver Creek warms rapidly reaching the maximum for the survey of 22.3^{o}C (Appendix Figure B18). Beaver Creek inputs to the Grande Ronde River 0.9^{o}C cooler then the mainstem. We were able to detect six tributary inputs to Beaver Creek with all contributing cooler flows.

Meadow Creek was surveyed from the mouth upstream 34.4 km (21.4 miles), a distance of about 4.0 km (2.5 miles) from the watershed divide (Appendix Figure A12). At the upstream end of the survey Meadow Creek was 14.8^{o}C and warmed to 18-20^{o}C over the next 2 km. Temperatures tended to increase over the next 10 km, reaching a local maximum of 24.4^{o}C at river km 24.3 (river mile 15.1). Over the next 4 km there is a general cooling trend as Meadow Creek moves through the canyon reach known as “The Narrows” reaching a local minimum of 19.1^{o}C at river km 20.8 (river mile 13.0). From river km 20.8 to 10.5 there is a general warming trend, reaching a local maximum of 26.1^{o}C at river km 10.5 (river mile 6.5). This reach exhibited wide swings in temperature of short distances suggesting the potential for thermal stratification. Closer examination indicated that the exchange of sub-surface flows with in-channel flows was creating local areas of thermal refugia (Appendix Figures B24-25). From river km 10.5 to 5.1 there was a general cooling trend in Meadow Creek, reaching a local minimum of 22.6^{o}C at the lower end. At river km 9 (river mile 5.6) stream temperatures dropped rapidly below a small gravel push-up dam at Camp Elkanah (Figure 8). The temperature decrease was simply a surface phenomenon due to stratification below the dam. Within a short distance downstream stream temperatures returned to the level recorded above the dam. Below river km 5.1 stream temperatures again varied considerably over short distances, with limited evidence of sub-surface cooling (Appendix Figures B22-23). The maximum temperatures (27.0^{o}C) for the survey were recorded at river km 1.4 (river mile 0.9), just upstream of Dark Canyon Creek. Meadow Creek contributes stream flow at 24.4^{o}C at the confluence with the Grande Ronde River (Appendix Figure B21). We were able to detect three tributaries with the

FLIR, two were contributing cooler temperatures (Dark Canyon and Cougar Creeks) and one was contributing warmer flows (McCoy Creek). Dark Canyon Creek caused a 2.5+^{o}C drop in mainstem temperatures for a short distance while McCoy Creek caused a small increase.

McCoy Creek, a major tributary to Meadow Creek was surveyed from the mouth upstream a distance of 14.8 km (9.2 miles, Appendix Figure A13). The survey was stopped due to the stream going dry. At the upper end of the survey McCoy Creek was 16.9^{o}C. Over the next 2 km, stream temperatures increase to a local maximum of 21.3^{o}C followed by a rapid decrease in temperatures to 16.3^{o}C at river km 12.1 (river mile 7.5). This local decrease seems to be due to the influence of an unnamed tributary or cooler inflows from a secondary channel although the cause is difficult to determine from the imagery due to shading (Appendix Figure B29). Stream temperatures increase to 20.1^{o}C immediately below this area and increase slowly in the downstream direction, reaching a local maximum of 26.3^{o}C at river km 4.7 (river mile 2.9). From river km 4.0 (river mile 2.5) to the confluence with Meadow Creek, McCoy Creek exhibits considerable thermal heterogeneity (Appendix Figures B26-28) in the form of springs, secondary channels, and sub-surface inputs. Stream temperatures reach a local minimum of 22.1^{o}C at river km 2.8 (river mile 1.7) and then increase downstream reaching the maximum for the survey (27.6^{o}C) just above the confluence with Meadow Creek. McCoy Creek inputs warmer streamflow (26.2^{o}C) to Meadow Creek (24.9^{o}C).

Fly Creek was flown from the mouth upstream 21.6 km (13.4 miles) and stopped about 4.0 km from the watershed divide (Appendix Figure A14). At the upstream end of the survey, stream temperatures were relatively warm (17.9^{o}C) and proceeded to increase in the downstream direction reaching a local maximum of 24.9^{o}C at river km 15.5 (river mile 9.6). Over the next 1.8 km stream temperatures are relatively constant, ranging between 22.9 and 24.4^{o}C, until the confluence with Little Fly Creek (river km 13.7). Little Fly Creek inputs 22.9^{o}C water, decreasing Fly Creek temperatures to 22.9^{o}C (Appendix Figure B31). Below Little Fly Creek, temperatures again increase in the downstream direction, reaching a local maximum of 24.4^{o}C at river km 11.0 (river mile 6.8). From river km 11 to 7, temperatures slowly decrease in the downstream direction, reaching a local minimum of 21.4^{o}C at river km 7 and remain relatively constant to river km 4.5 (river mile 2.8). At river km 4.5, temperatures again increase in the downstream direction reaching the maximum (24.9^{o}C) for the survey just above the confluence with the Grande Ronde (Appendix Figure B30). Above Little Fly Creek Fly Creek is a small meadow stream with little shade, below Little Fly Creek Fly Creek is in a forested canyon where exposure to solar radiation is greatly reduced.

Sheep Creek was surveyed from the mouth upstream 12.4 km (7.7 miles) and stopped about 6 km from the watershed divide (Appendix Figure A15). At the terminus of the survey temperatures were 14.9^{o}C and increased steadily in the downstream direction reaching the maximum (24.5^{o}C) for the survey near the confluence with the Grande Ronde (Appendix Figure B35). The shape of the longitudinal temperature profile for Sheep Creek is a classic asymptotic curve used to describe the typical pattern of increase in the downstream direction.

Limber Jim Creek was flown from the mouth upstream 7.4 km (4.6 miles) concluding about 5.6 km (3.5 miles) from the watershed divide (Appendix Figure A16). At the end of the survey Limber Jim Creek is 15.5^{o}C and cools to about 14.0^{o}C over the next 2 km. At river km

5.8, stream temperatures begin to increase and continue increasing to the confluence with the Grande Ronde River. Limber Jim Creek reaches the maximum stream temperature at the mouth (21.9^{o}C, Appendix Figure B36). Only one tributary was detected in the survey, the North Fork of Limber Jim Creek enters Limber Jim Creek at 20.4^{o}C, 4.4^{o}C warmer then Limber Jim.

Discussion

FLIR was used to map stream temperatures for the Grande Ronde River and most major tributaries in the basin, a distance of 911 km (561 miles). The data was collected in August 1999 to assess low flow high summer temperatures in support of the ODEQs TMDL development in the Grande Ronde River basin. The Grande Ronde Basin involved the most extensive FLIR data collection to date; with the data collection on the Grande Ronde River being the longest longitudinal temperature we've ever developed (275 km, 171 miles). Unlike the challenges of working in the Tualatin Basin (urban streams and a busy airport) or the Klamath Basin (persistent bad weather) the Grande Ronde portion of the project was not encumbered by weather or logistics. Analysis of the thermal accuracy of the FLIR compared to in-stream sensors was on average within the specified tolerance of $\pm 0.5^o$C.

Assessment of the stream temperature patterns in the Grande Ronde River basin indicated that stream temperatures tended to increase in a downstream direction, but the pattern of this change varied among streams. Our analysis showed the influences of tributary inputs on stream temperature, particularly along the Grande Ronde. Stream temperatures increased along an asymptotic curve for the Grande Ronde River until the confluence with Lookingglass Creek. Lookingglass Creek, Wallowa, and Wenaha Rivers had significant cooling effect on the mainstem for relatively long distances. Below Lookingglass Creek the Grande Ronde River never approached the maximum temperatures recorded in the Grande Ronde valley. This was largely due to the low flows above Lookingglass Creek and the cool temperatures and higher flows from these three tributaries. In effect, these three tributaries reset stream temperatures in the lower 135 km (84 miles) of the basin.

In addition, our analysis indicated thermal stratification was an intermittent process in the Grande Ronde River and several tributaries. These conditions were found in the Grande Ronde River from La Grande downstream to Lookingglass Creek, Catherine Creek from Davis Dam to the mouth, the lower reaches of Willow Creek, and a small section of Meadow Creek. These conditions seemed to be the result of low stagnant flows in the above reaches. In Catherine and Meadow Creeks these conditions were due to the impounding of water by dams, while the mainstem and Willow Creek were due to low flow conditions. These conditions represented a very small percentage of the stream miles flown.

We also found evidence of thermal refugia in the Wallowa River immediately downstream of Wallowa Lake and in portions of the Lostine River, Meadow Creek, McCoy Creek, and Fly Creek. While we did not do a field evaluation of these sites, it was apparent from the imagery that these conditions were associated with springs and sub-surface inflow at the downstream end of secondary channels. We found no evidence of thermal refugia in the mainstem Grande Ronde River.

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