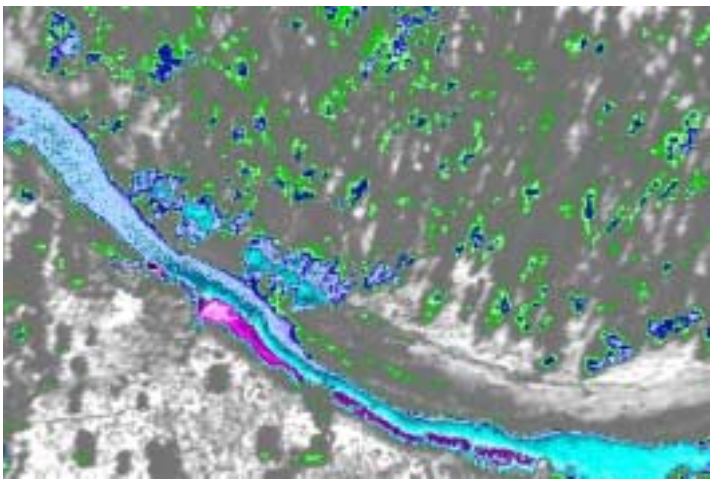
Remote Sensing Survey of the Upper Klamath River Basin

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 Upper Klamath 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 Upper Klamath 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) water quality management plans (WQMPs) for rural, forested, agricultural and urban lands that address both nonpoint and point sources of pollution.

This report summarizes the methods and results of the FLIR survey conducted from August 4-16, 1999 covering a total of 360.7 river miles (580.5 river km) in the Upper Klamath 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

Data were collected in the Upper Klamath River Basin from August 4 – 16, 1999. Data collections were timed to capture daily maximum stream temperatures, which typically occur between 14:00 and 18:00 hours. Figures 1 thru 3 illustrate the extent of the FLIR surveys in the Williamson River, Wood River, and Sprague River sub-basins respectively. Likewise, Tables 1 thru 3 summarize the date, time, and survey distance for

each surveyed stream. The FLIR surveys covered a total of 360.7 river miles (580.5 river km).

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. The FLIR detects emitted radiation at wavelengths from 8-12 microns and records the level of emitted radiation in the form on an image. Each image pixel contains a measured value that can be directly converted to a temperature. The FLIR images 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 flown at an altitude of 1500 ft above ground level (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 Williamson River, the images cover a ground area of approximately 190 x 255 meters (2000 to 2500 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. The advertised accuracy of the Onset Stowaway's is $\pm 0.2^{o}$C. These locations were supplemented by data provided by the Oregon Department of Environmental Quality (ODEQ) and the US Forest Service (USFS) from seasonal in-stream temperature loggers. Figures 1-3 show the location of the in-stream sensors used to ground truth the imagery.

The Klamath Marsh and Sycan Marsh were not included during the FLIR survey because there was no clear channel to follow through these areas. The survey was abandoned when the channel could no longer be detected and then resumed on the upstream side of the marsh. The Sycan River was surveyed in two different legs due to the need to refuel the aircraft. The first leg covered the mouth to the mouth of Paradise Creek. The second leg covers from Paradise Creek to the headwaters. A navigational error resulted in a partial survey of Paradise Creek, which is included in the analysis.

Data collection was postponed several times due to thunderstorms in the region. The bad weather prevented surveying on consecutive days in Sprague River Basin. Table 4 summarizes the meteorological conditions for each of the survey dates. The conditions were recorded hourly at the Klamath Falls and Lakeview Agrimet Stations. The mean temperature and relative humidity were calculated for the times indicated.

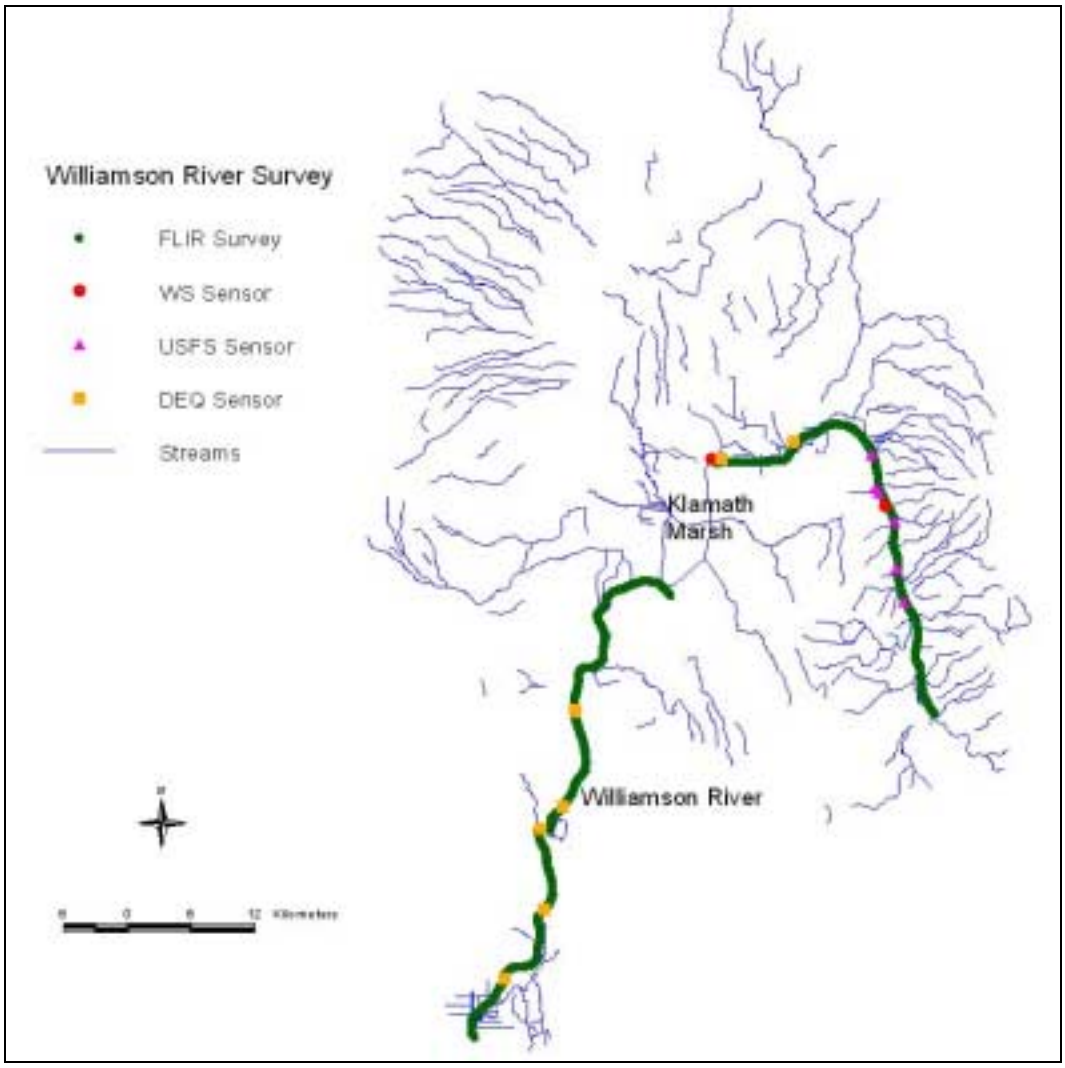


Figure 1- Extent of the FLIR Survey on the Williamson River and the locations of in-stream data loggers.

Table 1 - Date, time, and distance for the Williamson River survey.

Stream	Date	Local Time	Stream Kilometers	Stream Miles
Williamson River	4-August-99	14:19 – 15:25	128.0	77.7

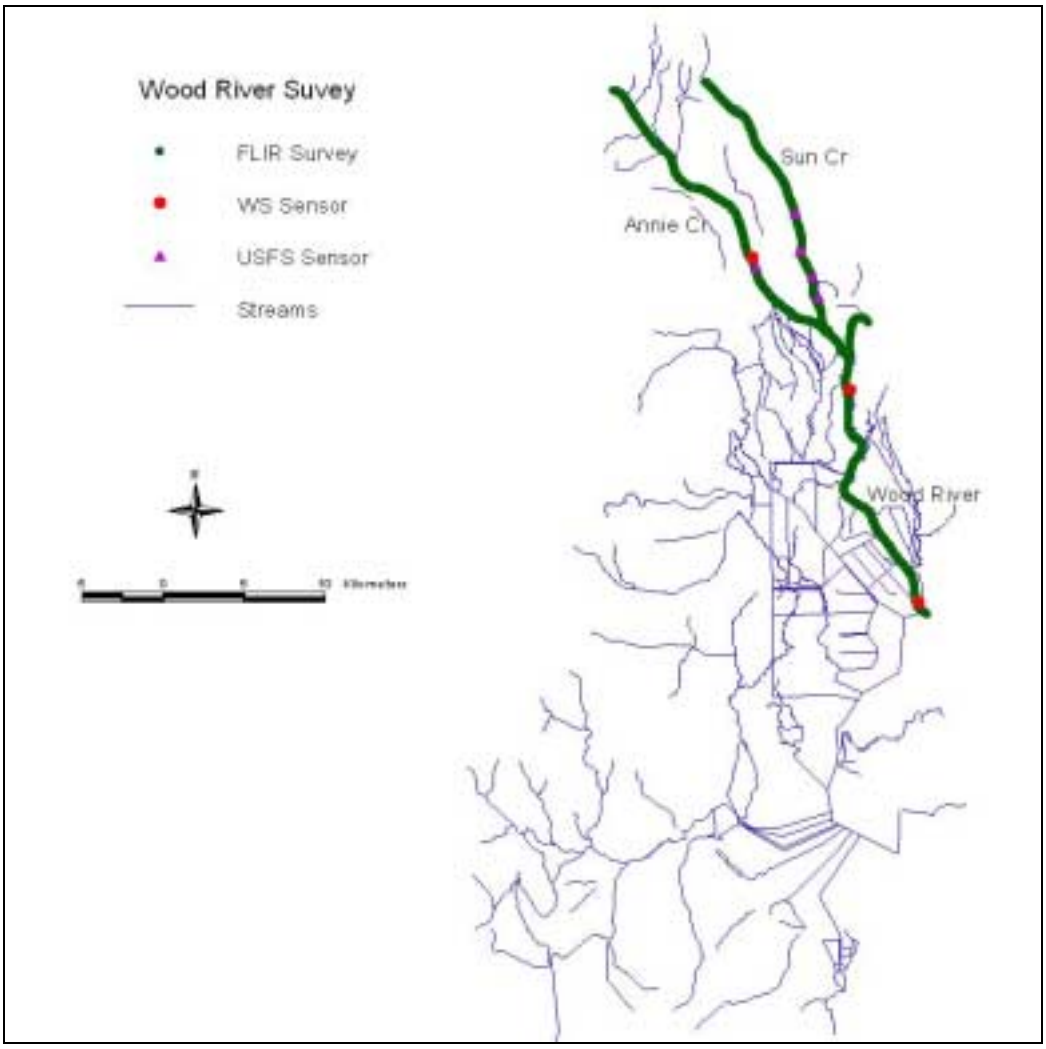


Figure 2 – Extent of the FLIR Surveys on the Wood River and the locations of in-stream data loggers.

Table 2 - Date, time, and distance for streams surveyed in the Wood River basin.

Stream	Date	Local Time	Stream Kilometers	Stream Miles
Wood River	11-August-99	14:08 – 14:22	27.7	17.2
Annie Creek	11-August-99	14:23 – 14:36	24.9	15.5
Sun Creek	11-August-99	14:39 – 15:00	30.1	18.7
Total Miles Surveyed			82.7	51.4

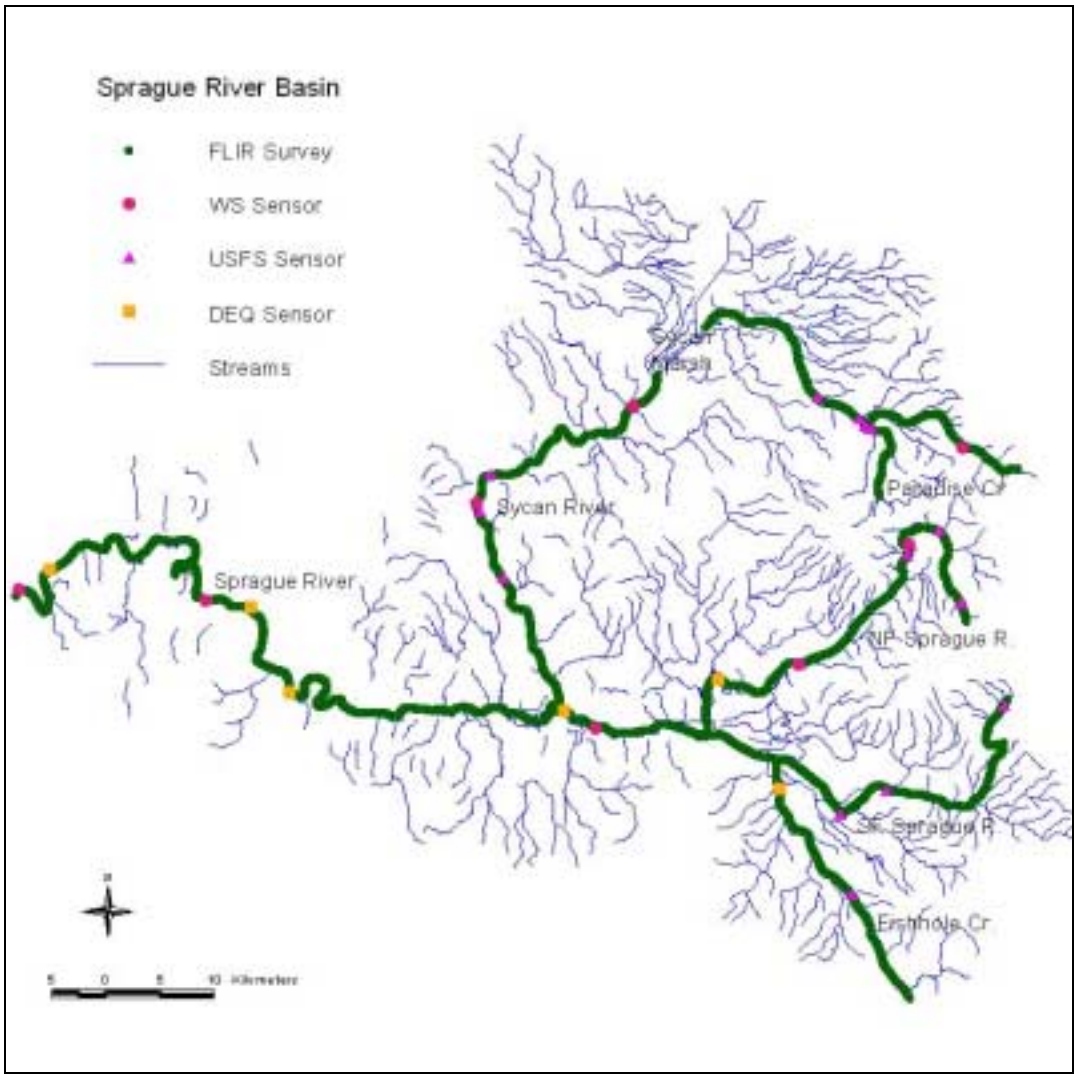


Figure 3 – Extent of FLIR Surveys in the Sprague River Basin and the locations of in-stream data loggers.

Table 3 – Date, time, and distance for streams surveyed in the Sprague River basin.

Stream	Date	Local Time	Stream Kilometers	Stream Miles
Sprague River	12-August-99	14:16 – 15:20	127.4	79.2
SF Sprague River	12-August-99	16:04 – 16:31	47.6	29.6
Fish Hole Creek	12-August-99	16:42 – 16:57	28.6	17.8
Sycan River				
Mouth to Paradise Cr	16-August-99	14:43 – 15:24	85.9	53.4
Paradise Cr to Headwaters	16-August-99	16:53 – 17:02	20.3	12.6
NF Sprague River	16-August-99	16:20 – 16:44	53.8	33.4
Paradise Creek	16-August-99	15:29 – 15:34	9.7	6.0
Total Miles Surveyed			373.3	232.0

Table 4 – Mean meteorological conditions recorded at Oregon Agrimet Stations for each survey date.

Date	Time	Air Temperature	Relative Humidity	Sky Conditions
8/04/99	14:00-15:30	26.5°C (79.6°F)	23%	Clear
8/11/99	13:30-15:00	23.1°C (73.5°F)	35%	Partially Cloudy
8/12/99	14:00-16:00	24.8°C (76.7°F)	33%	Scattered Clouds
8/16/99	1400-15:00	28.9°C (84.0°F)	17%	Clear

Data Processing Methods

An ArcView® GIS point coverage was created for each surveyed stream. The coverage contains the file name, geographic location, date, and time of each image collected during the survey. The coverage provides the basis for assessing the extent of the survey and for integrating with other spatially explicit data layers in the GIS. The image points were then associated with a river kilometer derived from a 1:100k EPA stream coverage of the watershed.

The coverage also allowed us to identify images corresponding to in-stream (temporal) sensors located in the basin. The data collection software was used to extract temperature values from the images at the location of the in-stream recorder. The radiant temperatures were then compared to the kinetic temperatures from the in-stream data loggers to assess the thermal accuracy of the images.

In the laboratory, the FLIR images were converted from their raw format to the Arc/Info GRID format. During the conversion, the minimum and maximum temperatures found in each image were recorded and subsequently recorded back to the point coverage. 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°C. Temperatures < 10°C are black, temperatures between 30 and 50°C were colored in shades of gray (darker tones to lighter tones), and temperatures > 50°C are white.

Figure 4 illustrates a color coded GRID displayed in the ArcView environment. This GRID illustrates the confluence of the Sprague River and the Williamson River. The legend on the left of the "Grid View" specifies the temperature range associated with each color. The other view window shows the point coverage with the displayed GRID location highlighted in yellow. Each blue point in the coverage represents another image location.

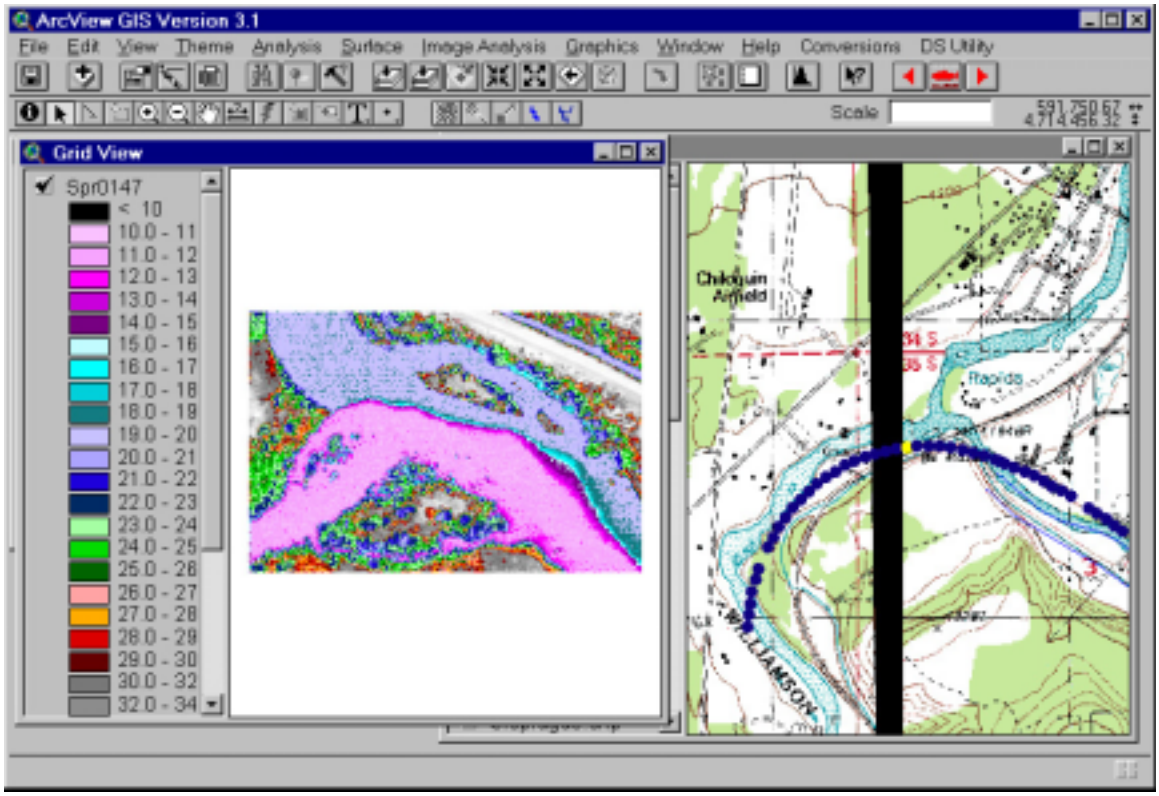


Figure 4 – ArcView display showing a color-coded temperature GRID in one window and the geographic location of the GRID in the other.

Figure 5 illustrates the temperature GRID displayed in Figure 4 with its corresponding Day TV image. The Williamson River and the Sprague 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 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.

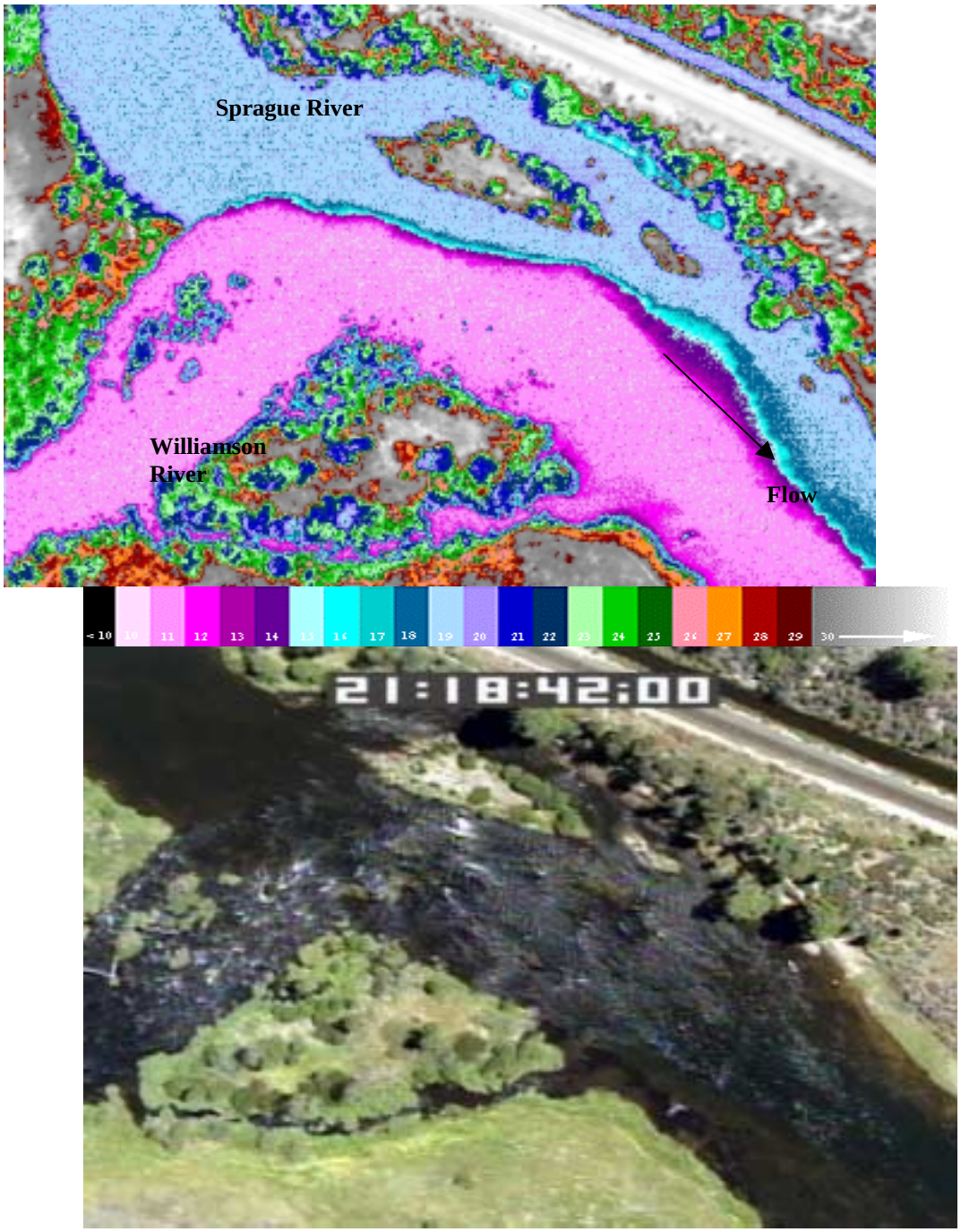


Figure 5 – Thermal image (left) and corresponding Day TV image (right) showing the confluence of the Williamson River (11.2°C) and Sprague River (19.6°C).

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. However, when thermal stratification does occur, the radiant temperatures measured by the FLIR will not necessarily represent bulk water temperature beneath the surface. As a result, it is important to recognize and map locations that show evidence of thermal stratification.

In stream systems, thermal stratification most commonly occurs in behind impoundments or in deep slow moving channels where there is little vertical mixing. Thermal stratification in streams is inherently unstable because the water is moving and mixing will occur due to any number of reasons including in-stream objects, friction with the bank, surface inflow, sub-surface inflow or a change in gradient. As a result, stratified areas can be detected through interpretation of the thermal images. In addition, potential areas of stratification can also be delineated by understanding the physical characteristics of the stream such as depth and gradient and by comparison of the radiant temperatures with in-stream sensors.

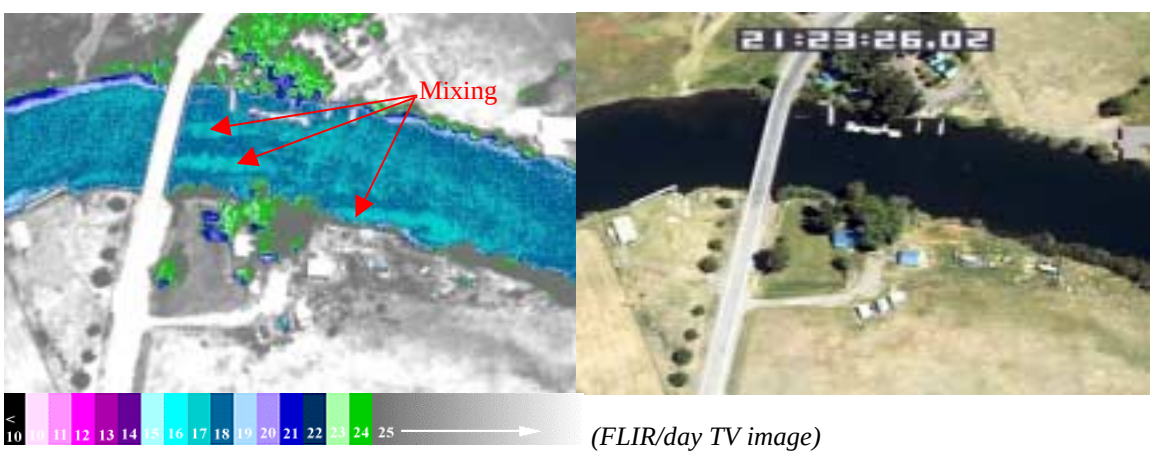
The majority of stream miles surveyed in the Upper Klamath Basin were not stratified. However, there was evidence of some thermal stratification in reaches of the Williamson River and in isolated areas in the Sprague River basin. Table 5 provides a summary of the thermally stratified locations detected during analysis of the thermal imagery.

Table 5 – Summary of potentially thermally stratified areas in the Upper Klamath River.

Stream	Stratified Areas	Comments
Williamson River	wil0022 – wil0135 (0.0 – 11.0 km) wil0464 – wil0895 (35.7 - 68.0 km)	Lake Influence? Intermittent
Sycan River	syc1490 – syc1641 (67.8 – 75.0 km)	Intermittent
SF Sprague	Sf0031 (1.1 km)	Canal Location

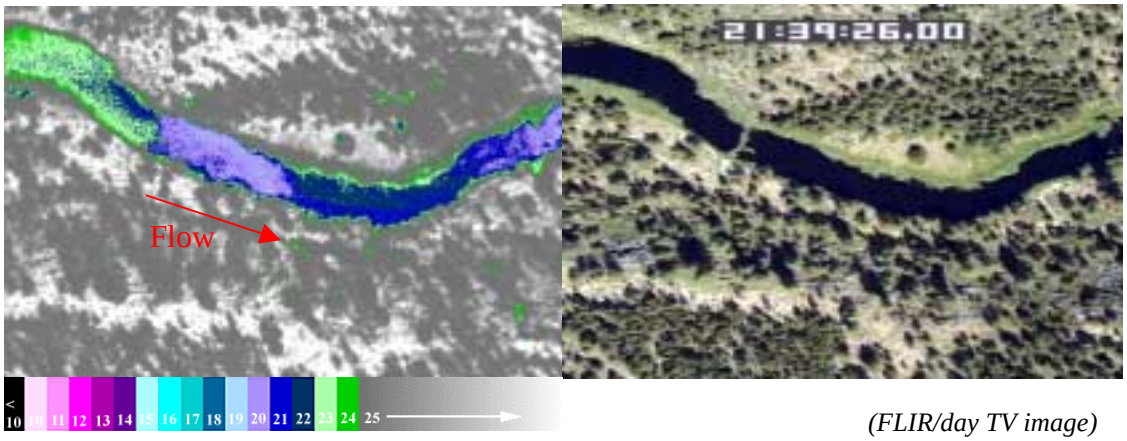
The Williamson River had two reaches where thermal stratification was evident. The first reach was the Lower Williamson River from the mouth to river mile 6.8 (km 11.0). Figure 6 shows an example from this reach where thermal stratification is evident. The Williamson River flows from left to right in the image. The arrows point to areas of mixing behind the bridge pylons that indicate cooler water below the surface. The median radiant temperature at this location is 18.2^{o}C and the kinetic temperature from an in-stream data logger at this location was 17.3^{o}C. Lower terrain gradient, deeper channel, and the lake influence near the mouth contribute to a decrease in the rate of vertical mixing in this reach.

The Williamson River also shows evidence of thermal stratification upstream from the Williamson River Campground to the Klamath Marsh. Figure 7 shows an example of thermal stratification upstream of Buckeroo Spring (river mile 26.4, km 42.5). The thermal stratification is evidenced by the variation and patchiness of the surface temperatures. Stratification in this reach is intermittent with mixing due to both surface and sub-surface inflows.



(FLIR/day TV image)

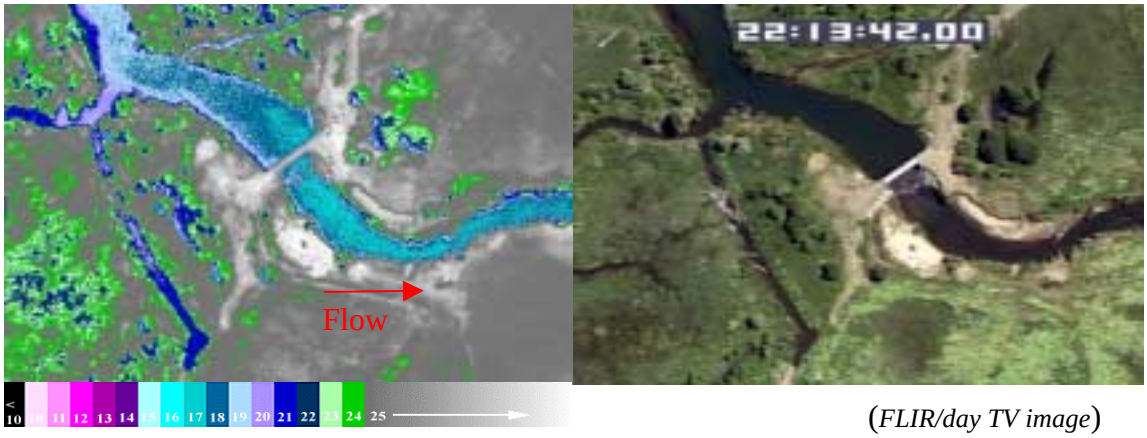
Figure 6 – Pseudo-color thermal image of the Williamson River at Modoc Road showing evidence of thermal stratification in this reach. The arrows point to areas of mixing.



(FLIR/day TV image)

Figure 7 – Pseudo-color thermal image of the Williamson River at river mile 68.5 (km 42.5). The thermal patchiness at the surface is a sign of thermal stratification.

Areas of thermal stratification also were detected in the Sycan River upstream of the Sycan Marsh. Figure 8 shows an image example of evidence of thermal stratification upstream of a weir (river mile 43.6, km 70.1). The thermal image shows surface variability upstream of the weir. In addition, there is a 1.2^{o}C water temperature difference between the upstream and downstream side of the weir. The mixed areas downstream of the weir are more representative of bulk water temperatures in this reach.



(*FLIR/day TV image*)

Figure 8 – Pseudo-color thermal image of the Sycan River (river mile 43.6, km 70.1). The surface water temperature downstream of the weir is 17.8^{o}C while the surface water temperature upstream of the diversion is 19.0^{o}C.

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 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. We use this process to calibrate ground-truth the imagery.

Tables 6 thru 9 provide a comparison of the in-stream and radiant temperatures for the Williamson River, the Wood River, and Sprague 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.

Williamson River

A total of 16 data loggers were used to verify the accuracy of the FLIR imagery in this sub-basin. Eight of the locations recorded temperature differences (kinetic versus radiant) of less then ±0.5^{o}C. Of the eight locations that recorded higher temperature differences, six had radiant temperatures less then those recorded by the in-stream data logger.

The in-stream data logger located at the Mouth of the Spraque River read approximately 1°C warm for both this survey and the Sprague River survey that was conducted on 12 August 1999. The data logger located at the Williamson Campground showed a 0.9^{o}C difference from the measured radiant temperature. There is no definitive reason for this difference. However, there was some uncertainty on the exact location of this sensor. Review of the imagery showed a lot of surface temperature variability in this

reach and it is possible that the sensor was in a locally warm area (backwater or side-channel).

The FLIR survey resumed up-stream of Klamath Marsh at Military Road Crossing. There were two in-stream data loggers located in the canal at this location. The Watershed Sciences Onset Stowaway recorded temperatures slightly cooler then the radiant temperature. However, the ODEQ sensor located approximately 150 meters upstream recorded a temperature 1.5^{o}C warmer then the radiant temperatures.

At Modoc Rd. Bridge, the radiant temperature was warmer then the in-stream data logger. A review of the imagery shows evidence of thermal stratification at this location. Thermal stratification is discussed later in this report. The difference between the in-stream data logger and the radiant temperature suggests that difference between surface temperatures and sub-surface temperatures at this location are less then 1°C.

The other location in which the radiant temperature was warmer then the in-stream data was upstream of the Williamson Canal. The imagery does not show evidence of thermal stratification in this reach.

Table 6 – Comparison of in-stream temperatures to radiant temperatures derived from the thermal infrared images for the Williamson River.

Stream	Site	Owner	Image	Time	In-Stream ^{o}C	Radiant ^{o}C	Delta ^{o}C
Williamson	Modoc Rd Bridge	DEQ	Wil0125	14:23	17.3	18.1	-0.8
	U/s of Spraque River	DEQ	Wil0257	14:27	11.9	12.1	-0.2
	Sprague River Mouth	DEQ	Wil0255	14:27	22.2	21.2	1
	Spring Cr	DEQ	Wil0396	14:34	9.3	9.8	-0.5
	Williamson CG	DEQ	Wil0449	14:35	21.1	20.2	0.9
	Kirk Bridge	DEQ	Wil0596	14:40	24.9	24.4	0.5
	Kirk Bridge	DEQ	Wil0596	14:40	25.1	24.4	0.7
	Military Crossing	WS	Will0092	15:03	22.8	23.0	-0.2
	Military Crossing	DEQ	Will0095	15:03	23.9	22.4	1.5
	Silver Lake Rd	DEQ	Will0206	15:07	23.9	23.3	0.6
	U/S of Canal	WNF	Will0338	15:11	20.5	21.5	-1.0
	Lower Royce Tract	WNF	Will0390	15:13	20.8	20.7	0.1
	Upper Royce Tract	WNF	Will0396	15:13	21.3	20.9	0.4
	Rd49 Bridge Gauge	WS	Will0414	15:14	21.3	20.4	0.9
	Near Rocky Ford	WNF	Will0442	15:15	20.4	20.7	-0.3
	Deep Cr Ranch	WNF	Will0504	15:22	18.4	18.9	-0.5

Delta outside ±0.5^{o}C, Orange = Thermal Stratification

Wood River

The surveys in the Wood River Basin were all conducted on the same day. A total of 8 in-stream data loggers were used to ground truth the imagery. All eight locations recorded temperatures within ±0.5°C of the measured radiant temperatures.

Table 7 – Comparison of in-stream temperatures to radiant temperatures derived from the thermal infrared images for the Wood River Basin.

Stream	Site	Owner	Image Name	Time	In-Stream °C	Radiant °C	Delta °C
Wood	Mouth	WS	Wd0027	14:08	12.0	11.5	0.5
	Ft. Klamath Bridge	WS	Wd0568	14:19	10.2	10.3	-0.1
Annie Cr	NP Boundary	WNF	Ann0286	14:28	9.1	9.4	-0.3
	Pondersosa picnic	WS	Ann0308	14:29	10.5	10.0	0.5
Sun Cr	State Forest Bnd.	WNF	Sun0108	14:51	11.4	11.9	-0.5
	Above bridge	WNF	Sun0147	14:52	11.2	11.3	-0.1
	WNF #3 Road	WNF	Sun0207	14:53	9.9	10.4	-0.5
	NP Boundary	WNF	Sun0283	14:54	9.7	9.5	0.2

Sprague River

There were a total of 30 in-stream data loggers used to ground truth the imagery in this basin. Overall, 23 of the 30 recorded temperature differences (kinetic versus radiant) of within ±0.5°C.

The Sprague River had 8 in-stream data loggers and all of the ground truth locations recorded differences ≤ 1.0°C. The data logger in the mouth of the Sprague River recorded a temperature almost 1°C warmer then the measured radiant temperature. This data logger recorded approximately the same difference during the Williamson River survey on 4 August 1999.

There were two ground truth locations on the SF Sprague River and both were within ±0.5°C of the radiant temperatures. Fish Hole Creek also had two ground truth points and both matched closely with the FLIR.

The NF Sprague River had the largest temperature differences recorded during the 1999 data collection season. Two in-stream data loggers (1 Watershed Sciences and 1 USFS) were located at the FS3411 Bridge Crossing. Both of these sensors recorded exactly the same water temperatures. The radiant temperature at this location was 0.5°C higher then the in-stream temperatures. However, using the same conversion parameters, the three in-stream data loggers located up-stream all registered temperatures of approximately 1.1°C higher then the radiant temperature. There is no reason to suspect that any of the in-stream data loggers are in error. A possible explanation is that the atmospheric conditions changed from the start to the end of the survey. However, there is no recorded data to verify this theory. As a result, the calibration parameters that

matched the sensors at the FS3411 Bridge were used since they result in the "cooler" profile. Interpretation of the longitudinal profile should consider an increased error on this stream.

All eight in-stream data loggers on the Sycan River (including Paradise Creek mouth) recorded temperatures within ±0.5°C of the FLIR. Paradise Creek was surveyed from its mouth to the confluence of Watson Creek. The in-stream data loggers at the mouth of Paradise Creek and the mouth of Crazy Creek both recorded temperatures consistent with the radiant temperatures.

Table 8 – Comparison of in-stream temperatures to radiant temperatures derived from the thermal infrared images for the Sprague River Sub-Basin.

Stream	Site	Owner	Image	Time	In-Stream °C	Radiant °C	Delta °C
Sprague	Williamson Park	WS	Spr0110	14:18	14.5	14.0	0.5
	Mouth	DEQ	Spr0152	14:19	20.7	19.8	0.9
	Sub-station	DEQ	Spr0394	14:25	21.1	20.3	0.8
	Road Mile 12	WS	Spr1307	14:46	20.9	21.1	-0.2
	Saddle Mtn Pit Rd.	DEQ	Spr1446	14:49	20.6	21.5	-0.9
	Rabe Ranch	DEQ	Spr1787	14:54	21.6	22.4	-0.8
	Godowa Spring Rd.	DEQ	Spr2761	15:13	20.3	20.3	0.0
	Beatty Gap Gauge	WS	Spr2868	15:15	19.6	19.9	-0.3
SF Sprague	SF Picnic Area	WNF	Sf0482	16:12	20.3	20.7	-0.4
	U/s Brownsworth Cr	WNF	Sf0631	16:14	19.9	20.4	-0.5
	U/s Corral Cr	WNF	Sf1229	16:31	10.4	10.3	0.1
NF Sprague	Ivory Pine Rd	DEQ	Nfs0225	16:24	20.7	20.2	-0.5
	FS3411 Bridge	WS	Nfs0501	16:30	13.3	13.8	-0.5
	FS3411 Bridge	WNF	Nfs0505	16:30	13.3	13.8	-0.5
	Sandhill C.G.	WNF	Nfs0958	16:36	19.7	18.6	1.1
	U/S Sandhill C.G.	WS	Nfs0962	16:36	19.9	18.6	1.3
	Lee Thomas Crossing	WNF	Nfs1100	16:39	18.1	16.9	1.2
Fishhole Cr	Bly Bridge Hwy 140	DEQ	Fh0093	16:43	22.4	22.3	0.1
	U/S of Biggs Springs	WNF	Fh0814	16:55	23.4	23.5	-0.1
Sycan	Coyote Bucket	WNF	Syc0486	14:50	21.1	20.6	0.5
	D/S Teddy Meadows	WNF	Syc0690	14:55	20.6	20.7	-0.1
	Rt44 and FS4466	WS	Syc0710	14:55	20.6	20.3	0.3
	U/S Teddy Meadows	WNF	Syc0809	15:05	18.7	18.8	-0.1
	Rt27 Bridge	WS	Syc1349	15:09	21.7	21.4	0.3
	Emigrant Crossing	WNF	Syc1956	15:20	16.4	16.7	-0.3
	Pike's Crossing	WNF	Syc2108	15:23	16.4	16.9	-0.5
Paradise Cr.	Paradise Cr Mouth	WNF	Syc2132	15:28	15.5	15.9	-0.4
	Crazy Cr Mouth	WNF	Syc2276	15:29	15.1	15.6	-0.5
Sycan (2nd)	FS3380 Bridge	WS	Sycb0348	16:58	15.6	15.1	0.5

Date and Time of Day

One of the objectives of the FLIR survey is to capture summer maximum stream temperatures. Figures 9-12 show data from a seasonal data logger in relation to the date and time of the FLIR survey on the Williamson River, Sun Creek, the Sprague River, and the Sycan River respectively. As shown in Figure 9, the Williamson River was surveyed on a day (8/4/99) that was representative of summer daily maximums. Several storms and cooler weather moved in after the Williamson River flight. FLIR surveys were postponed and then resumed again on 11 August 1999.

Figure 10 shows water temperatures recorded in Sun Creek in the Wood River Basin. The maximum temperatures recorded during the survey date were about 1.5^{o}C cooler then the maximums recorded during the end of August. Figure 11 shows a similar plot for the Sprague River. As shown, the maximum temperatures on the day of the FLIR survey were approximately 2°C cooler then the summer maximum temperatures recorded on 4 August 99 and then again at the end of August. Bad weather again delayed the FLIR surveys, which were resumed on 16 August 1999.

Figure 12 shows the recorded summer temperatures on the Sycan River (surveyed 8/16/99). As with the Sprague River, the maximum daily temperatures on the day of the FLIR survey were approximately 2°C cooler then the summer maximums.

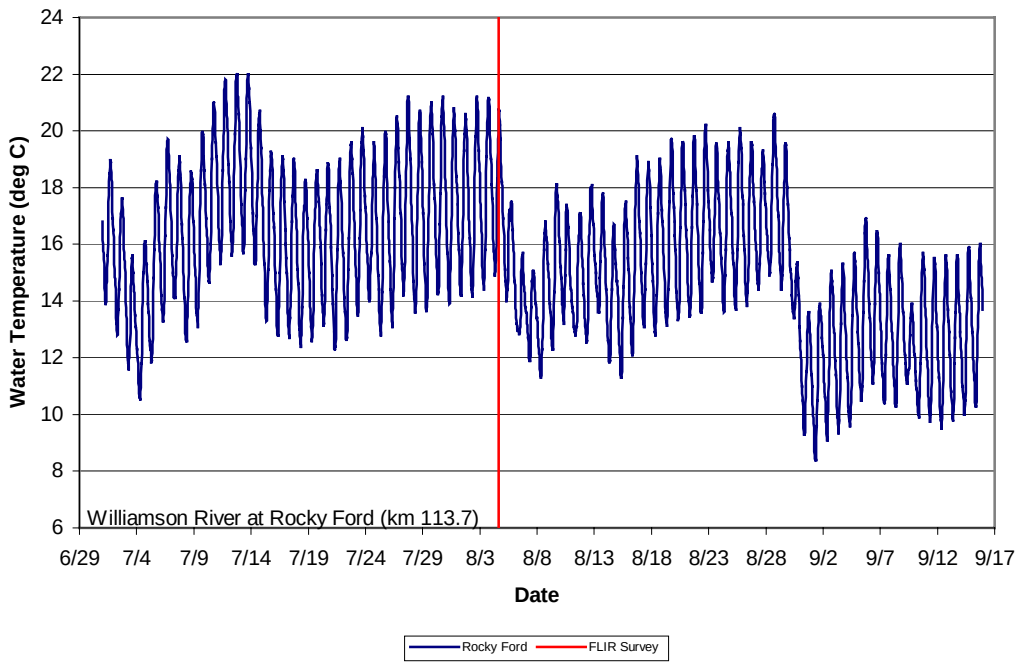


Figure 9 – FLIR survey in relation to water temperatures measured during the summer in the Williamson River at Rocky Ford (river mile 70.6).

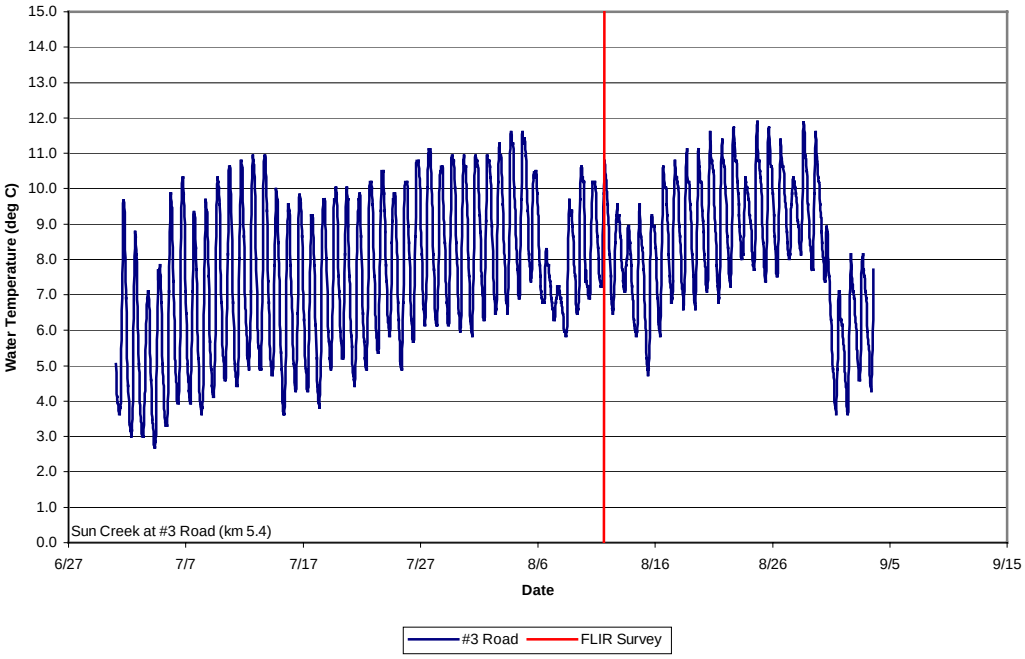


Figure 10 – FLIR survey in relation to water temperatures measured during the summer in Sun Creek at #3 Road (river mile 3.3).

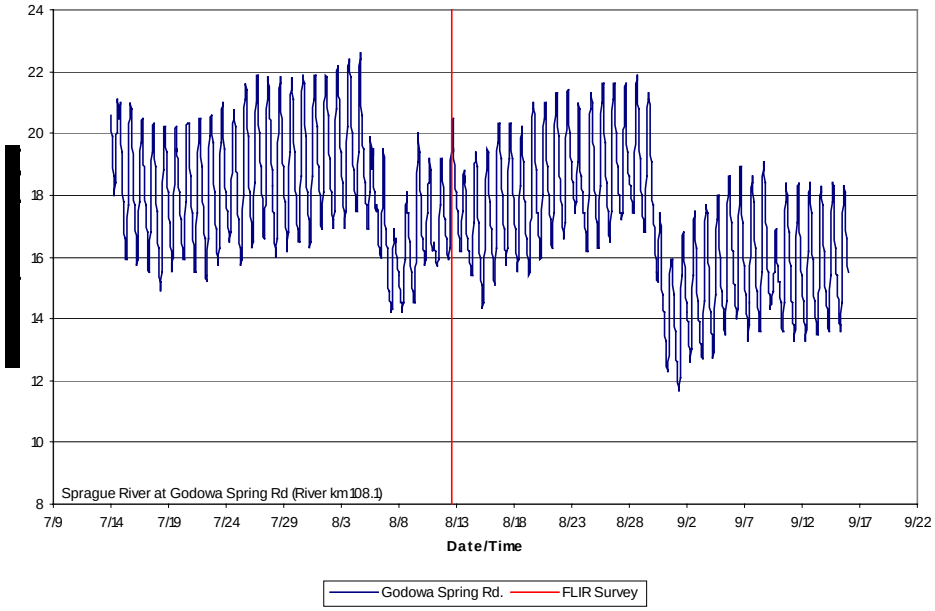


Figure 11 – FLIR survey in relation to water temperatures measured during the summer in the Sprague River at Godowa Spring Rd (river mile 67.2).

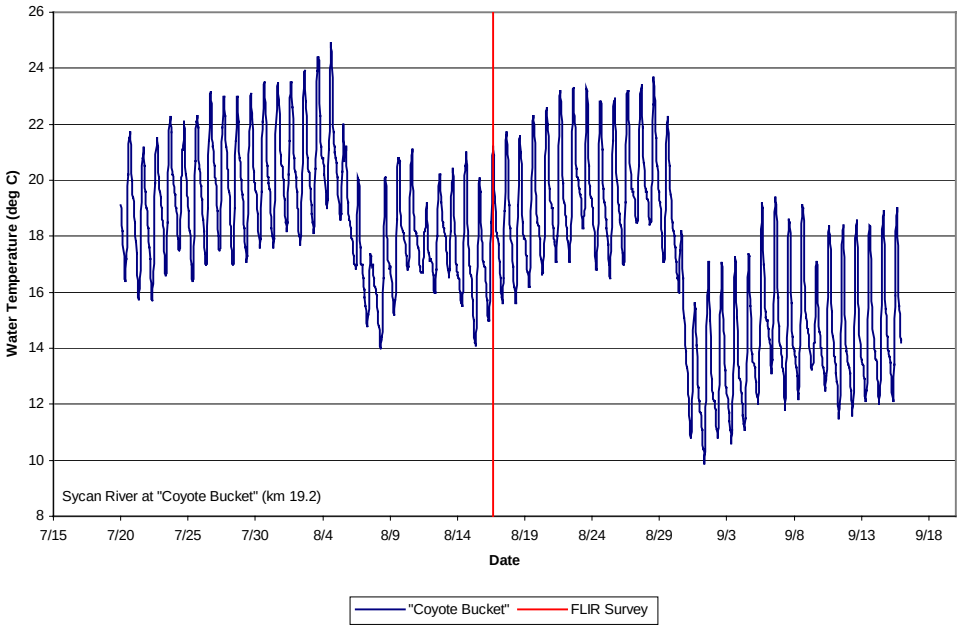


Figure 12 – FLIR survey in relation to water temperatures measured during the summer in the Sycan River at "Coyote Bucket" (river mile 11.9).

Figures 13 thru 14 show the 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 typically occur between 14:00 and 18:00. These data are provided for the three longest FLIR surveys conducted in the Upper Klamath Basin.

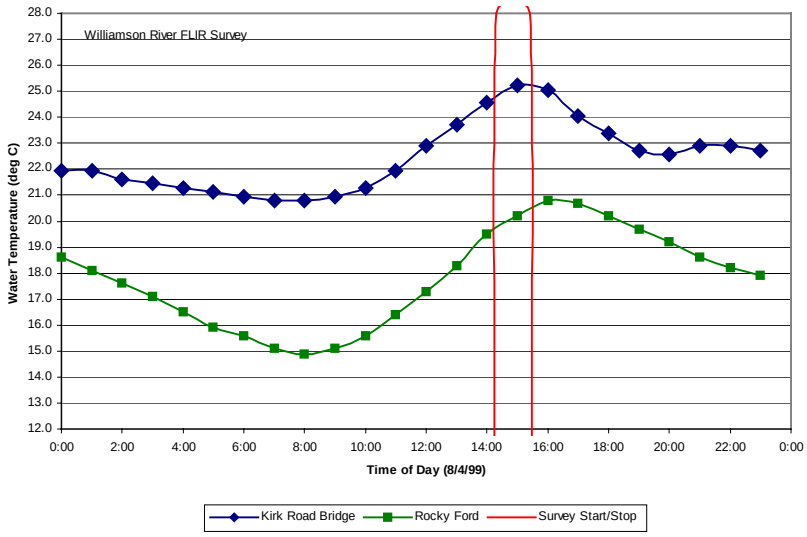


Figure 13 – Time and duration of the FLIR survey on the Williamson River in relation to daily maximum(s) for two data logger locations.

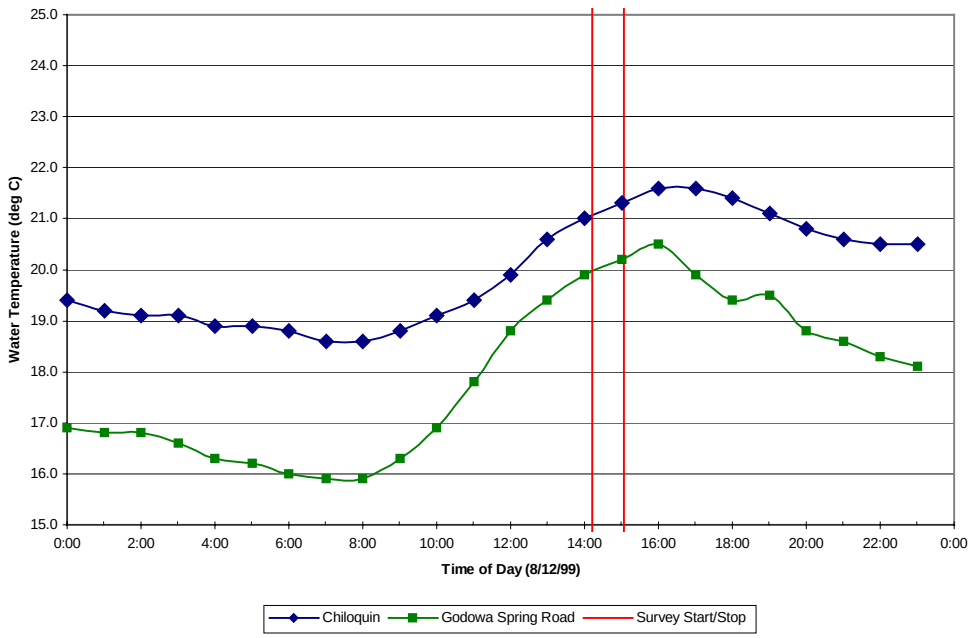


Figure 14 – Time and duration of the FLIR survey on the Sprague River in relation to daily maximum(s) for two data logger locations.

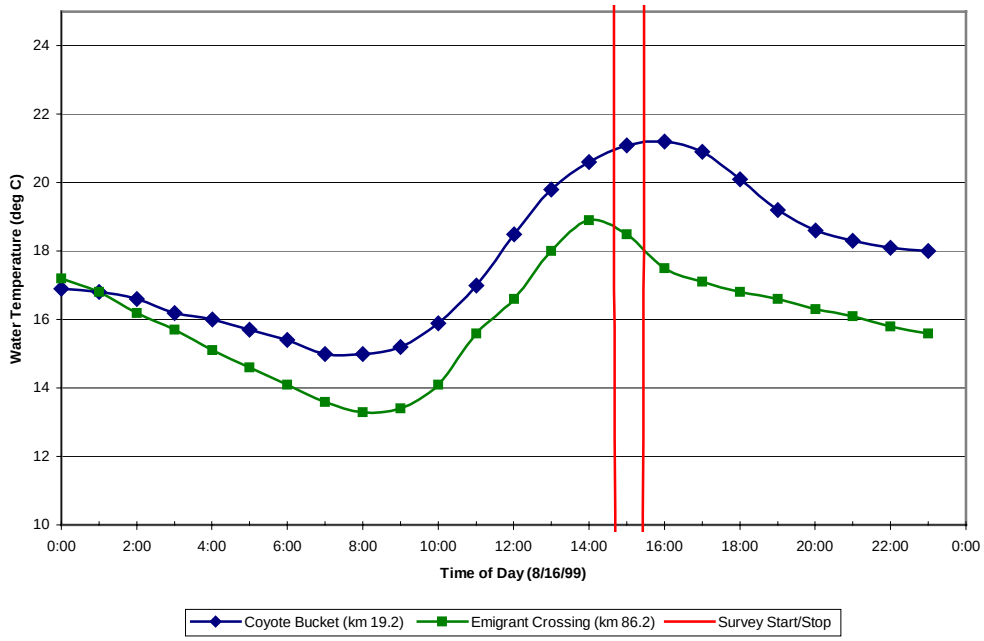


Figure 15 – Time and duration of the FLIR survey on the Sycan River in relation to daily maximum(s) for two data logger locations.

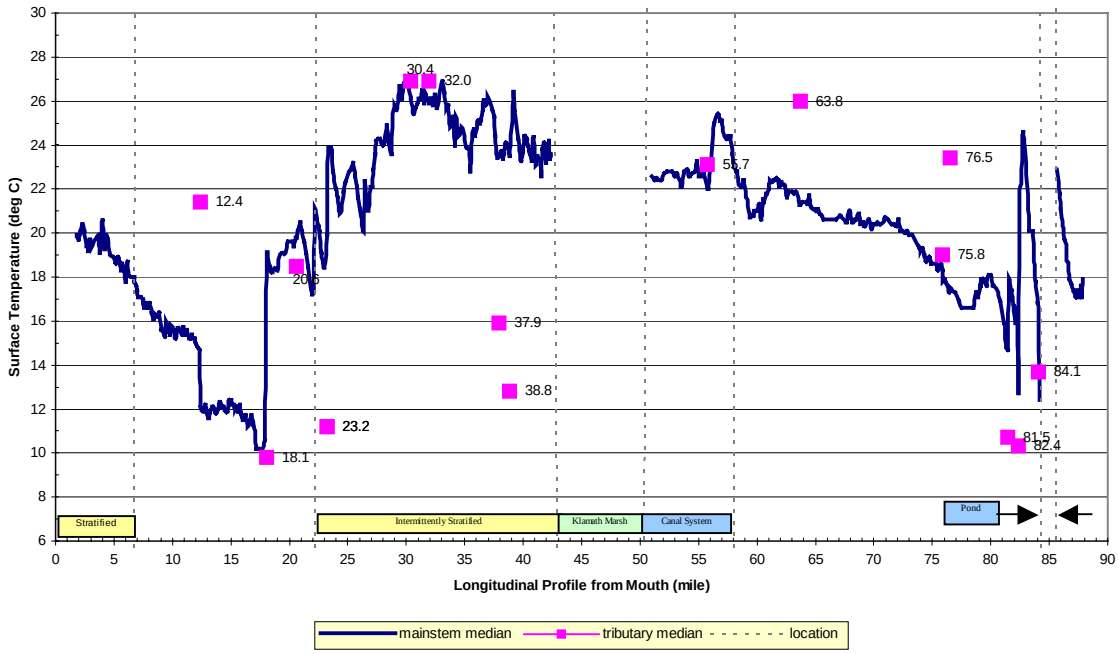
Analysis of Thermal Imagery

Williamson River

The median temperatures for each sampled image for the Williamson River from Agency Lake to the headwaters was plotted versus the corresponding river mile (Figure 16). The Klamath Marsh divided the survey since there was no clear, single channel through the marsh. 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 Williamson River. Tributaries are labeled in Figure 16 by river mile 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.

Figure 16 shows how stream temperatures vary longitudinally along the Williamson River and the influence of tributaries. The survey concluded just upstream of a pond (river mile 87.6) near the headwaters. Three springs downstream of the pond outlet (river mile 84.1, 82.4, and 81.5) have a strong cooling influence on mainstem water temperatures (Appendix Images A.20, A.21, A.23). Two of the three springs (river mile 84.1 and 82.4) were not identified on the USGS 1:24K topographic maps. In addition, there is a cooling influence evident at river mile 82.6 that appears due to sub-surface inputs (Appendix Image A.22). The Williamson River temperature drops from 17.9^{o}C to 16.6^{o}C between river mile 79.1 and 78.4 with no apparent point source inflows detected in this reach. The water temperature then steadily rises from 16.6^{o}C to 22.4^{o}C between river mile 78.5 and 60.9. The three point sources detected in this area are all warmer than the mainstem temperatures. Flow from each of these streams is low compared to the mainstem and no immediate impact is detectable in mainstem temperatures. The water temperatures are more variable in the canal area upstream of the Klamath Marsh. However, water temperatures through this reach remain above 22.4^{o}C.

The surface water temperatures of the Williamson River downstream of the Klamath Marsh to river mile 27.3 are generally between 23.0^{o}C and 26°C. There is evidence of thermal stratification throughout this reach. As a result, surface temperatures may not represent bulk water temperatures. There are two sources of thermal cooling between river miles 38.8 to 38.0. A cooling trend is observed between river miles 27.3 to 23.0 that is not associated with any detectable point sources. The stream gradient increases through this reach and the apparent temperature drop may be the result of a transition from an intermittently stratified to a mixed condition. An unnamed spring and an unnamed tributary contribute cold water to the mainstem at river mile 23.2 causing a drop in the mainstem water temperatures (Appendix Image A.16). Two point sources between river mile 18.6 and 6.8 influence water temperatures dramatically. Spring Creek decreases the mainstem temperatures by 9.3^{o}C at river mile 18.1 (Appendix Image A.14). At the confluence of the Sprague River, Williamson River temperatures increase 2.6^{o}C (Appendix Image A.13). The Williamson River surface water temperature shows a general warming trend from the Sprague River to the mouth. There is evidence of thermal stratification in the lower 6.8 miles of the river (Appendix Image A.12).



Tributary	River mile	River km	Tributary Temp (°C)	Mainstem Temp (°C)	Difference (Trib-mainstem)	FLIR Image
Sprague River (RB)	12.4	20.0	21.4	12.1	9.3	wil0255
Spring Creek (LB)	18.1	29.1	9.8	19.1	-9.3	wil0397
Larkin Creek (RB)	20.6	33.2	18.5	19.8	-1.3	wil0434
No Name (RB)	23.2	37.3	11.2	19.9	-8.7	wil0485
Spring (RB)	23.2	37.4	11.2	22.2	-11.0	wil0486
No Name (RB)	30.4	48.9	26.9	26.1	0.8	wil0640
Gerwick Ditch (RB)	32.0	51.5	26.9	25.9	1.0	wil0675
Spring? (LB)	37.9	61.1	15.9	23.5	-7.6	wil0787
Springs (LB)	38.8	62.4	12.8	23.5	-10.7	wil0805
Canal (LB)	55.7	89.7	23.1	22.1	1.0	will0164
Irving Creek (LB)	63.8	102.6	26.0	21.3	4.7	will0329
Deep Creek (LB)	75.8	122.0	19.0	18.3	0.7	will0520
No Name - Small (LB)	76.5	123.1	23.4	17.5	5.9	will0530
Wickiup Spring (LB)	81.5	131.1	10.7	14.7	-4.0	will0606
Springs (LB)	82.4	132.6	10.3	12.7	-2.4	will0620
Spring (LB)	84.1	135.3	13.7	16.4	-2.7	will0658

Figure 16 – Median water temperature versus river kilometer for the Williamson River. Tributaries are described in the table (LB/RB = left and right bank looking upstream) (flight: 8/4/99, 14:19 – 15:25)

Wood River

The median temperatures for each sampled image for the Wood River from Agency Lake to the Wood River Springs was plotted versus the corresponding river mile (Figure 17). 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 Wood River. Only the surface water inflows that could be positively identified in the imagery were included.

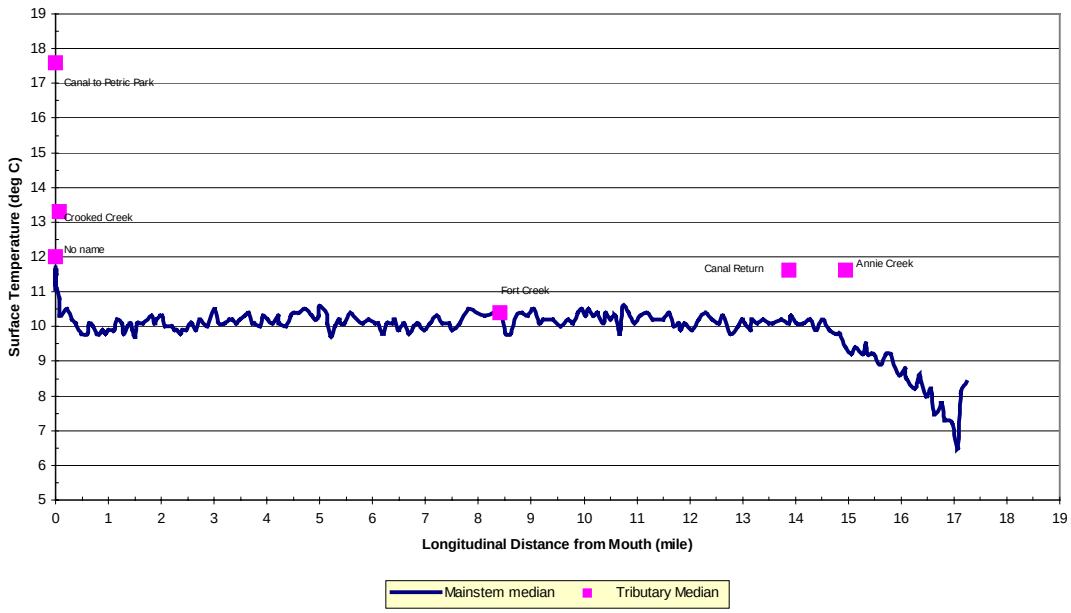


Figure 17 – Median stream temperature versus river mile for the Wood River. Tributaries are labeled on profile (flight: 8/12/99, 14:08 – 14:22).

The Wood River emerges cold (8.4^{o}C) from Wood River Springs (mile 17.0) and then warms steadily to the confluence of Annie Creek at river mile 15.0 (Appendix Image A.5). The water temperatures remain constant at approximately 10°C for the next 14.6 miles with variations less then ±0.5^{o}C. The ±0.5^{o}C variation is typical of observed noise between thermal images. All five detected point sources contributed water warmer then the then median temperature of the Wood River. The warmest of these inflows was Crooked Creek at 13.5^{o}C (Appendix Image A.3). The slight rise in temperature in the lower 0.3 miles of the river is probably due to the influence of Agency Lake.

Sun Creek

Sun Creek in the Wood River Basin was surveyed from the confluence of Annie Creek to the headwaters. The median water temperature sampled from each image was plotted versus the corresponding river mile (Figure 18). Sun Creek started at about 6.0°C near the headwaters, which is consistent with groundwater temperatures. The stream temperature rises steadily (5.3°C) from river mile 10.6 to 1.1. There was one surface water inflow detected at river mile 10.8. Sun Creek is partially diverted into several canals after it leaves the Winema National Forest (Appendix Image A.7). Stream temperatures increased 1.7°C between the Winema National Forest boundary and the confluence with Annie Creek (Appendix Image A.6).

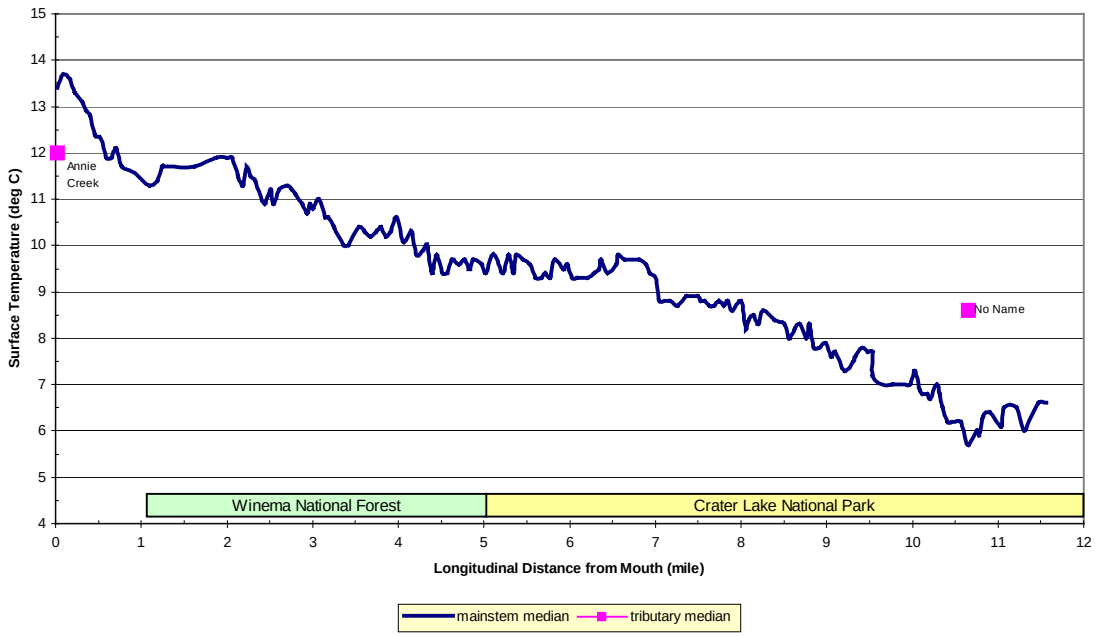


Figure 18 – Median stream temperature versus river mile for Sun Creek. Tributaries are labeled on the profile (flight: 8/11/99, 14:39 – 15:00).

Annie Creek

Annie Creek in the Wood River Basin was surveyed from the mouth to the headwaters. The median temperature sampled from each image was plotted versus the corresponding river mile (Figure 19). Annie Creek starts at about 4.0^{o}C, which is consistent with groundwater temperatures. The stream temperatures rise to about 7.0^{o}C at mile 14.7. Annie Creek combines with Goodbye Cr., Munson Cr., and another unnamed tributary between mile 14.3 and 14.7. Each of these tributaries contributes flow that is less then 8.0^{o}C. Pole Bridge Creek enters Annie Creek at 5.2^{o}C and slightly reduces the temperature of Annie Creek. Stream temperatures show a consistent 5.6^{o}C rise throughout the rest of its length. Annie Creek was approximately 12.4^{o}C at the mouth at the time of the survey, which was 3.1^{o}C warmer then the Wood River (Appendix Image A.11).

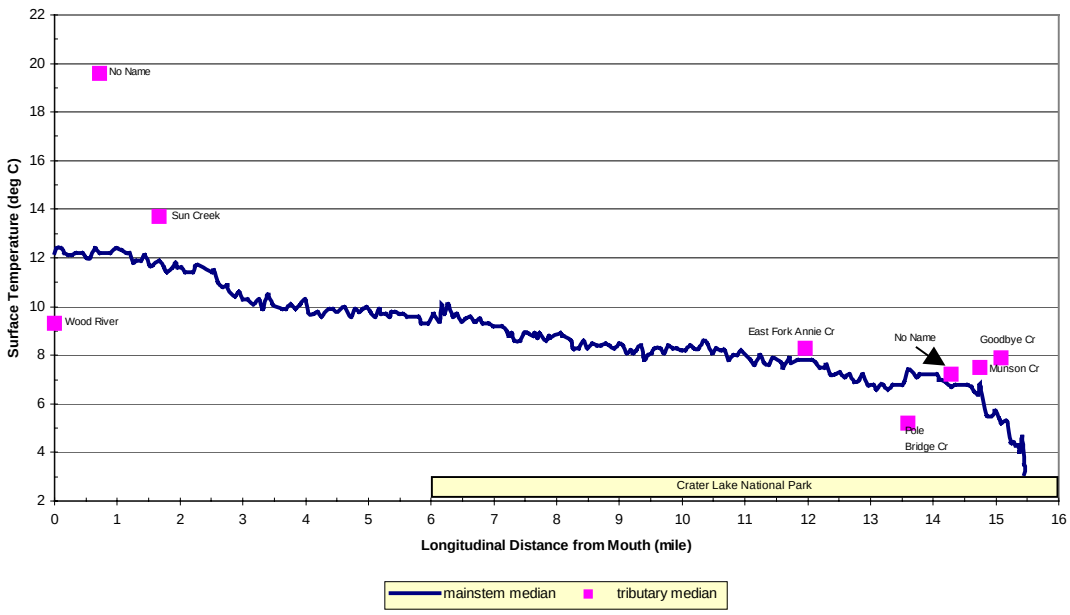


Figure 19 - Median stream temperature versus river mile for Annie Creek. Tributaries are labeled on the profile (flight: 8/11/99, 14:23 – 14:36).

Sprague River

The median temperature for each sampled image for the Sprague River from the confluence with the Williamson River to the confluence of the North Fork and South Fork Sprague River was plotted versus the corresponding river mile (Figure 20). The plot also contains the median temperature of all surface inflows (e.g. tributaries, canals) that were visible in the imagery where they input into the Sprague River. Tributaries are labeled in Figure 20 by river mile with their name and temperature listed in Table 9. Only the surface inflows that could be positively identified in the imagery were included. In some cases, tributaries and other surface inputs were obscured by vegetation or outside the sensor field of view and their image location could not be accurately determined.

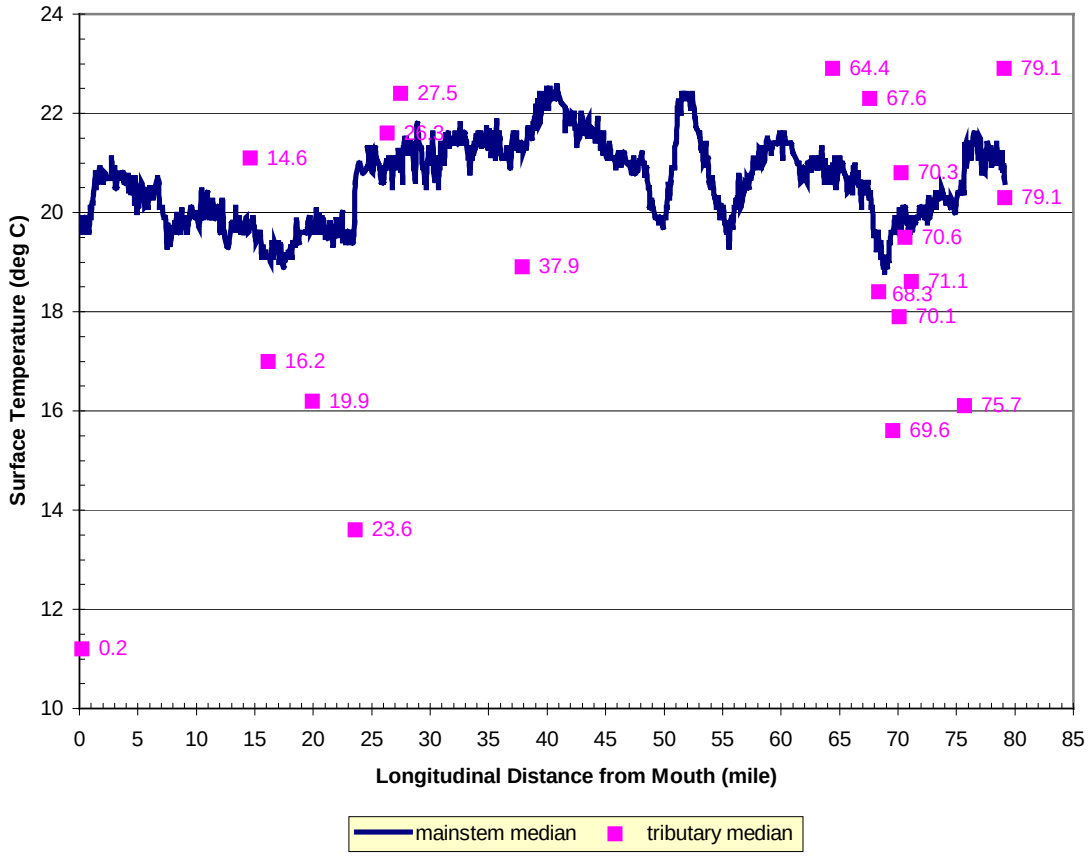


Figure 20 – Median Stream temperature versus river mile for the Sprague River (flight: 8/12/99, 14:16 – 15:20).

Table 9 – Sprague River Tributaries identified by river mile (LB/RB = left and right bank looking upstream).

Tributary	River Mile	River Km	Tributary Temp (°C)	Mainstem Temp (°C)	Difference (Trib – mainstem)	FLIR Image
Williamson River	0.0	0.0	11.2	19.6	-8.4	spr0147
Copperfield Creek	14.6	23.5	21.1	19.8	1.3	spr0693
Spring	16.2	26.0	17.0	19.1	-2.1	spr0735
Spring	19.9	32.1	16.2	19.8	-3.6	spr0846
Kamkaun Spring	23.6	38.0	13.6	20.6	-7.0	spr1000
No Name	26.3	42.4	21.6	21.0	0.6	spr1086
No Name	27.5	44.2	22.4	20.8	1.6	spr1146
Trout Creek	37.9	60.9	18.9	21.4	-2.5	spr1685
No Name	41.9	67.5	23.6	22.2	1.4	spr1848
Canal or Side Channel	64.4	103.7	22.9	21.0	1.9	spr2635
No Name	67.6	108.8	22.3	20.4	1.9	spr2777
Side Channel	68.3	110.0	18.4	19.4	-1.0	spr2807
Spring	69.6	111.9	15.6	19.6	-4.0	spr2851
No Name	70.1	112.9	17.9	19.6	-1.7	spr2870
No Name	70.3	113.1	20.8	19.6	1.2	spr2876
No Name	70.6	113.6	19.5	20.1	-0.6	spr2888
No Name	71.1	114.5	18.6	19.9	-1.3	spr2913
Side Channel	72.8	117.2	18.4	20.0	-1.6	spr2963
No Name	75.7	121.8	16.1	21.4	-5.3	spr3049
SF Sprague	79.1	127.3	22.9	20.7	2.2	spr3188
NF Sprague	79.1	127.3	20.3	20.6	-0.3	spr3189

A notable feature of the Sprague River temperature profile is that the water temperature varies from a maximum temperature of 22.6°C at mile 48.8 to a minimum of 18.8°C at mile 68.8. While there are identifiable areas of warming and cooling, the temperature profiles changes within a 3.7°C range for the entire 79.1-mile survey.

The median water temperature downstream of the confluence of the NF Sprague and the SF Sprague is 20.6°C (Appendix Image A.29). The Sprague River rises to 21.4°C at mile 75.8 before dropping to 20.0°C due to a surface water inflow (Appendix Image A.28). The Sprague River continues to cool between mile 75.8 and 68.6 before reaching a local minimum of 18.8°C. Six surface water inputs were detected through this reach that contributed cooler water to the mainstem including a spring at mile 69.6. The Sprague River warms approximately 2.8°C from mile 68.8 to 59.9. There were two surface water inflows identified through this reach that contribute warmer water. The stream then cools again between mile 60.3 and 55.6. There were no point sources detected in this reach that contribute to this cooling trend. The cooling trend is presumed due to sub-surface inflows. Over the next 5.6 miles stream temperatures warms rapidly to about 22.4°C and then rapidly cools again to 19.7°C. There were no point sources

detected through this reach and a review of the imagery does not show any evidence of thermal stratification. The Sprague River warms again between mile 49.9 and 40.8 from 19.7^{o}C to 22.6^{o}C. There is a general cooling trend between mile 40.8 and 17.5. The Sprague River is influenced through this reach by the Kamkaun Spring, which contributes water that is 7.0^{o}C cooler then the mainstem (Appendix Image A.27). The Sprague River water temperatures rise by approximately 2.0^{o}C from mile 17.5 to mile 1.5. Finally, an apparent 1°C decrease in temperature is observed between river mile 1.5 and its confluence with the Williamson River (Appendix Image A.24). The reason for this temperature decrease is not apparent from the imagery.

The Sprague River is very sinuous and there are numerous side channels and canals which often made it difficult to identify the main river channel (Appendix Image A.25). In the case where there were two large channels, the survey followed the one that appeared to carry the most flow. As a result, it is possible to miss surface water inflows that enter on a secondary channel. The mouth of the Sycan River was missed for this reason.

Sycan River

The median temperatures for each sampled image for the Sycan River from the confluence with the Sprague River to the headwaters was plotted versus the corresponding river mile (Figure 21). The Sycan Marsh divided the survey since there was no clear, single channel through the marsh. 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 Sycan River. Tributaries are labeled in Table 10 by river mile with their name and temperature. 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 21 shows how stream temperatures vary longitudinally along the Sycan River and the influence of select tributaries.

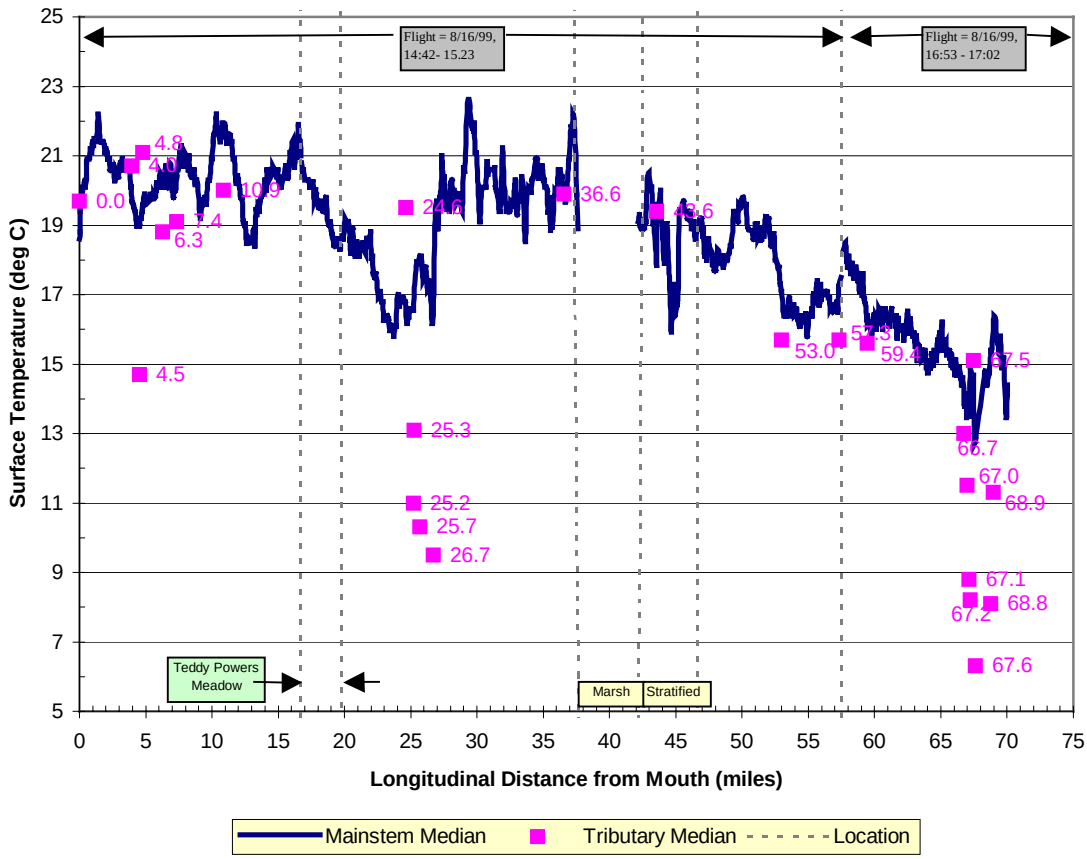


Figure 21 – Median stream temperatures versus river mile for the Sycan River (flight: 8/16/99).

Stream temperatures in the Sycan River started at about 13.4°C near mile 70.0. The South Fork Sycan River along with numerous surface inflows between mile 67.1 and 67.7 drop the stream temperature to below 13.0°C (Appendix Images A63, A.64). The Sycan River then warms to the confluence of Paradise Creek at mile 57.3 (Appendix Image A.61) with some local cooling due to the inflow of Skull Creek. The Sycan River cools approximately 1.5°C between Paradise Creek and mile 54.2. Stream temperatures warm over the next 7.5 miles to about 19.0°C. The Sycan River upstream of the Sycan Marsh has several weirs and irrigation canals. Review of the thermal imagery shows evidence of thermal stratification in this reach (Appendix Images A.59, A60).

Stream temperatures downstream of the Sycan Marsh generally stay at around 20°C until mile 26.7. There is some variability noted in this reach with stream temperatures ranging from 18.5°C to 22.7°C. The temperature changes are at a local scale with no prevailing warming or cooling trends. There was no evidence of thermal stratification detected in the imagery, however, the stream is small in this reach and temperatures may change on a local scale in response to relatively small inputs. In addition, aquatic vegetation was noted on the stream surface that will influence the apparent temperatures.

Tarrent spring and three other unnamed springs were detected between mile 25.2 and 26.7 (Appendix Images A.55 – A.57). The cold water contributions from these springs drop the mainstem temperature by 3.7°C. The spring influence continues to mile 23.7 where temperatures reach a local minimum of 15.8°C. Stream temperatures raise 6.1°C between mile 23.7 and mile 16.5 where they reach a local maximum of 21.9°C at the downstream end of Teddy Powers Meadows. The stream cools again between river mile 16.5 and mile 12.8. There were no surface water inflows detected through this reach. Stream temperatures show local scale temperature changes in the lower 12.8 miles of stream. Three surface water inflows contribute to the cooling trend observed between mile 7.7 and mile 4.5 (km 12.4 and km 7.3)

Table 10 – Sycan River Tributaries identified by river mile (LB/RB = left and right bank looking upstream).

Tributary	**River mile**	**River km**	**Tributary Temp (°C)**	**Mainstem Temp (°C)**	**Difference (trib-mainstem)**	**FLIR Image**
Sprague River	0.0	0.0	19.7	18.6	1.1	syc0010
No Name	4.0	6.4	20.7	19.7	1.0	syc0160
No Name	4.5	7.3	14.7	19.0	-4.3	syc0187
No Name	4.8	7.7	21.1	19.6	1.5	syc0199
No Name	6.3	10.1	18.8	20.1	-1.3	syc0253
Pond Outlet	7.4	11.8	19.1	20.4	-1.3	syc0294
Blue Creek	10.9	17.5	20.0	21.9	-1.9	syc0439
Pond Outlet	24.6	39.7	19.5	16.5	3.0	syc1000
Spring	25.2	40.5	11.0	16.5	-5.5	syc1034
Spring	25.3	40.6	13.1	17.1	-4.0	syc1037
Spring	25.4	40.8	9.8	0.0	9.8	syc1040
Springs	25.7	41.3	10.3	18.1	-7.8	syc1049
Tarrent Spring	26.7	43.0	9.5	16.6	-7.1	syc1079
Long Creek	36.6	58.9	19.9	20.1	-0.2	syc1432
Canal (Return)	43.6	70.1	19.4	19.1	0.3	syc1541
Spring (unmapped)	53.0	85.3	15.7	17.1	-1.4	syc1926
Paradise Creek	57.3	92.3	15.7	17.3	-1.6	syc2132
Skull Creek	59.4	95.7	15.6	16.4	-0.8	sycb0085
No Name	66.7	107.4	13.0	14.2	-1.2	sycb0381
No Name	67.0	107.8	11.5	13.6	-2.1	sycb0393
No Name	67.1	108.0	8.8	13.6	-4.8	sycb0400
No Name	67.2	108.2	8.3	0.0	8.3	sycb0401
No Name	67.2	108.2	8.2	14.9	-6.7	sycb0402
No Name	67.5	108.6	15.1	14.7	0.4	sycb0414
South Fork Sycan	67.6	108.8	6.3	12.8	-6.5	sycb0418
No Name	68.8	110.7	8.1	15.4	-7.3	sycb0469
No Name	68.9	111.0	11.3	16.1	-4.8	sycb0475

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North Fork Sprague River

The median temperatures for each sampled image for the North Fork Sprague River from the confluence with the Sprague River to the headwaters was plotted versus the corresponding river mile (Figure 22). 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 Sycan River. Tributaries are labeled in Table 11 by river mile with their name and temperature.

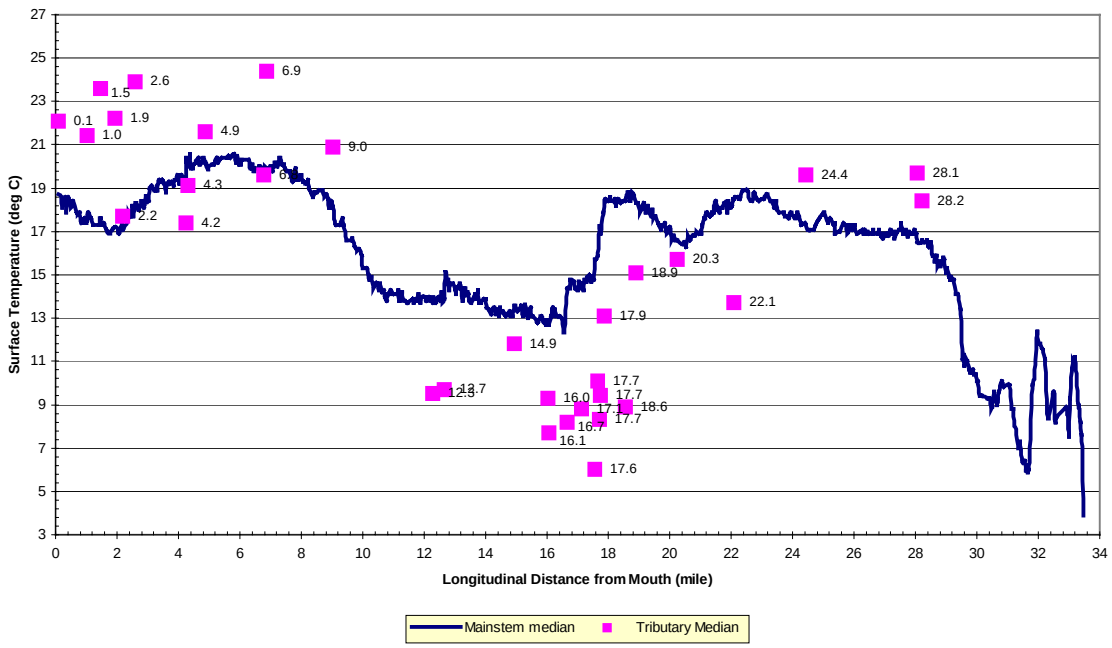

Figure 22 – Median stream temperatures versus river mile for the NF Sprague River (flight: 8/16/99, 4:20 – 4:44).

Stream temperatures in the NF Sprague River start at less then 5°C at the headwater springs (mile 33.5) (Appendix Image A.41). Temperatures are variable in the first three miles between river mile 33.5 and 30.1, but remain less then 12.5°C and generally less then 10.0°C. Stream temperatures climb from 9.4°C at mile 30.1 to 16.9°C at mile 28.0. The stream temperatures show little variation between mile 28.0 and mile 24.6. A 2°C temperature rise (17.0°C to 19.0°C) is observed between mile 24.6 and 22.4. Subsequently there is an approximately 2.7°C cooling trend observed between mile 22.4 and mile 20.5. Cold Creek (mile 22.1) contributes significantly to this cooling trend. Seven spring inflows were detected between mile 17.1 and 18.6 that were not shown on the USGS 1:24K topographic maps (Appendix Images A.32, A.33, A.35). The springs are sources of thermal cooling and drop the mainstem temperature by about 3.8°C. Sheepy Creek, Boulder Creek, and four more springs also are sources of thermal cooling between

Table 11 – NF Sprague River Tributaries identified by river mile (LB/RB = left and right bank looking upstream).

Tributary	River Mile	River Km	Tributary Temp. (°C)	Mainstem Temp (°C)	Difference (Trib-mainstem)	FLIR Image
SF Sprague	0.0	0.0	22.1	18.7	3.4	nfsp0025
No Name	1.0	1.6	21.4	17.6	3.8	nfsp0065
No Name (small)	1.5	2.3	23.6	17.3	6.3	nfsp0086
No Name	1.9	3.1	22.2	17.2	5.0	nfsp0101
Five Mile Creek	2.2	3.5	17.7	17.1	0.6	nfsp0116
No Name	2.6	4.2	23.9	18.3	5.6	nfsp0131
Meryl Creek	4.2	6.8	17.4	20.5	-3.1	nfsp0198
No Name	4.3	6.9	19.1	20.0	-0.9	nfsp0201
Canal	4.9	7.8	21.6	20.2	1.4	nfsp0227
No Name	6.8	10.9	19.6	19.9	-0.3	nfsp0305
No Name	6.9	11.1	24.4	19.9	4.5	nfsp0311
No Name	9.0	14.5	20.9	18.1	2.8	nfsp0397
Spring	12.3	19.8	9.5	14.0	-4.5	nfsp0533
Spring	12.7	20.4	9.7	13.9	-4.2	nfsp0549
Boulder Creek	14.9	24.0	11.8	13.6	-1.8	nfsp0649
Spring	16.0	25.8	9.3	12.9	-3.6	nfsp0697
Springs	16.1	25.9	7.7	12.7	-5.0	nfsp0699
Sheepy Creek	16.7	26.8	8.2	14.4	-6.2	nfsp0723
Springs	17.1	27.6	8.8	14.6	-5.8	nfsp0743
No Name	17.6	28.3	6.0	15.8	-9.8	nfsp0765
Springs	17.7	28.4	10.1	15.9	-5.8	nfsp0769
Springs	17.7	28.5	8.3	17.3	-9.0	nfsp0771
Springs	17.7	28.5	9.4	16.9	-7.5	nfsp0773
Springs	17.9	28.8	13.1	18.3	-5.2	nfsp0779
Springs	18.6	29.9	8.9	18.4	-9.5	nfsp0807
No Name	18.9	30.4	15.1	18.3	-3.2	nfsp0819
Gearhart Creek	20.3	32.6	15.7	16.6	-0.9	nfsp0867
Cold Creek	22.1	35.6	13.7	18.5	-4.8	nfsp0937
No Name	24.4	39.3	19.6	17.3	2.3	nfsp1005
No Name	28.1	45.2	19.7	16.5	3.2	nfsp1161
Dead Cow Creek	28.2	45.4	18.4	16.6	1.8	nfsp1165

mile 16.7 and mile 12.3 (Appendix Images A.36-A.37). In this reach, the stream temperatures reach a local minimum of 12.4°C at river mile 16.5. The stream temperatures warm steadily from mile 10.7 to about river mile 7.3. Stream temperatures gain 6.6°C through this reach and there were no point sources detected through this reach. A final cooling trend is detected between mile 4.3 and mile 2.1. There are two sources of thermal cooling in this reach including Meryl Creek.

South Fork Sprague River

The median temperatures for each sampled image for the South Fork Sprague River from the confluence with the Sprague River to the headwaters was plotted versus the corresponding river mile (Figure 23). 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 SF Sprague River. Tributaries are labeled in Table 12 by river mile with their name and temperature.

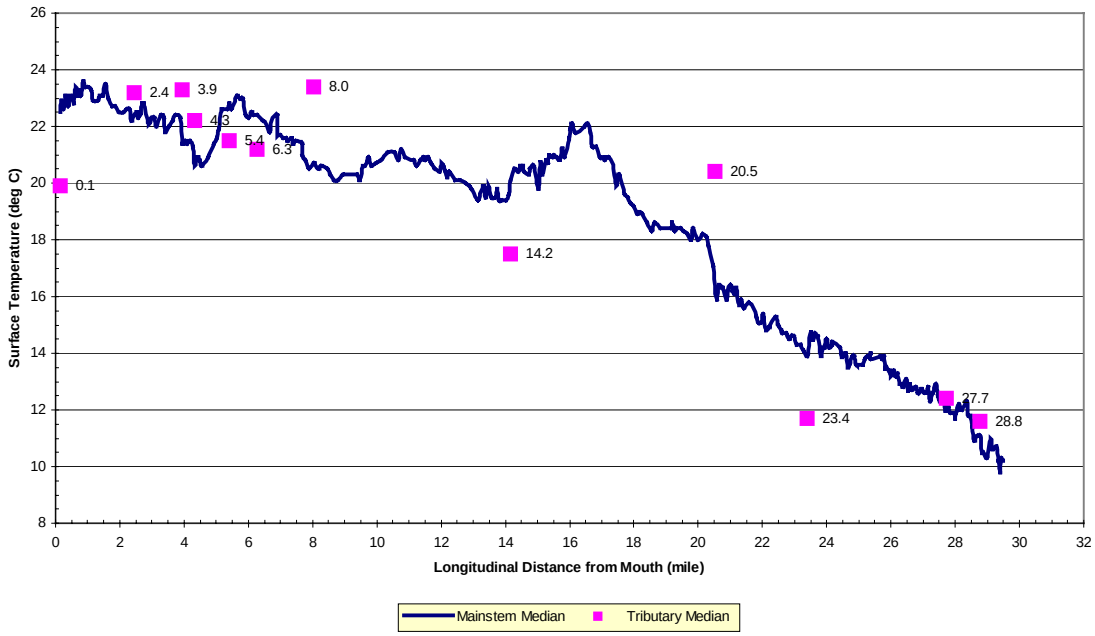

Figure 23 - Median stream temperatures versus river mile for the SF Sprague River (flight: 8/16/99, 16:04 – 16:31).

Stream temperatures start at about 10°C near the headwaters and warms steadily in the downstream direction to 16°C at river mile 20.5. At river mile 20.5, Whitworth Creek contributes water that is 4.2^{o}C warmer then the mainstem water temperatures and raises the mainstem temperatures to about 18.0^{o}C (Appendix Image A.45). The river continues to warm between river mile 20.5 and river mile 16.1 reaching a local maximum of 22.1^{o}C. Stream temperatures cool between river mile 16.1 and river mile 14.0. Brownsworth Creek (river mile 14.2) is a source of thermal cooling. There was no other surface inflows detected in this reach. Stream temperatures warm to 23.1^{o}C at river mile 5.6. There is a local cooling trend between river mile 5.6 and river mile 4.6. Two surface inflows were detected in this reach that contribute cooler water to the mainstem. The SF Sprague River warmed 3.0^{o}C between river mile 4.6 and its confluence with the NF Sprague River. The tributary inflows in this reach all entered warmer then the mainstem (Appendix Images A.42-A.44). The SF Sprague River was 2.4^{o}C warmer then the NF Sprague River at the confluence.

Table 12 - SF Sprague River Tributaries identified by river mile (LB/RB = left and right bank looking upstream).

Tributary	River mile	River km	Tributary Temp	Mainstem Temp	Difference (trib-mainstem)	FLIR Image
NF Sprague	0.1	0.2	20.1	22.5	-2.4	sf0009
Canal	2.4	3.9	23.2	22.4	0.8	sf0123
Canal Return	3.9	6.3	23.3	21.4	1.9	sf0201
Fishhole Creek (canal)	4.3	7.0	22.2	20.6	1.6	sf0218
Canal	5.4	8.7	21.5	22.8	-1.3	sf0272
No Name	6.3	10.1	21.2	22.4	-1.2	sf0314
No Name	8.0	12.9	23.4	20.7	2.7	sf0396
Brownsworth Creek	14.2	22.8	17.5	20.1	-2.6	sf0624
Whitworth Creek	20.5	33.0	20.4	16.2	4.2	sf0903
No Name	23.4	37.6	11.7	13.9	-2.2	sf1026
Camp Creek	27.7	44.6	12.4	12.1	0.3	sf1180
Corral Creek	28.8	46.3	11.6	11.1	0.5	sf1216

FishHole Creek

The median temperatures for each sampled image for Fishhole Creek from the confluence with the SF Sprague River to river mile 17.6 was plotted versus the corresponding river mile (Figure 24). 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 Fishhole Creek. Tributaries are labeled in Table 13 by river mile with their name and temperature.

The Fishhole Creek survey concluded at a pond near river mile 17.6. The pond outflow was a source of thermal loading and raised the water temperature of Fishhole Creek from 22.2^{o}C to 25.5^{o}C. From this point, stream temperatures cool to river mile 16.0. At river mile 16.0, the stream enters a wetland area and splits into several channels. This is also an area of low thermal contrast between the stream and the surrounding environment, which makes detection of the stream more difficult (Appendix ImageA.51). The wetland area continues to about river mile 14.0 and a general cooling trend was observed through this reach. Stream temperatures are 20°C at river mile 14.0 and generally increase the downstream direction before reaching 24.9^{o}C at river mile 4.0. A local cooling trend is observed between river mile 9.1 and mile 7.8. Robinson Spring Creek is a source of thermal cooling in this reach (Appendix Image A.50). Fishhole creek splits into multiple channels between river mile 4.0 and the route 140 bridge at river mile 1.9 (Appendix Image A.49). The survey followed a continuous channel through this reach, however, the main stream channel was not clearly defined. The longitudinal temperature profile is highly variable in this area, which is most likely due to the inter-mixing of the different channels. Fishhole Creek is part of the canal system

downstream of route 140 and contributes warmer water to the SF Sprague River (Appendix Image A.47).

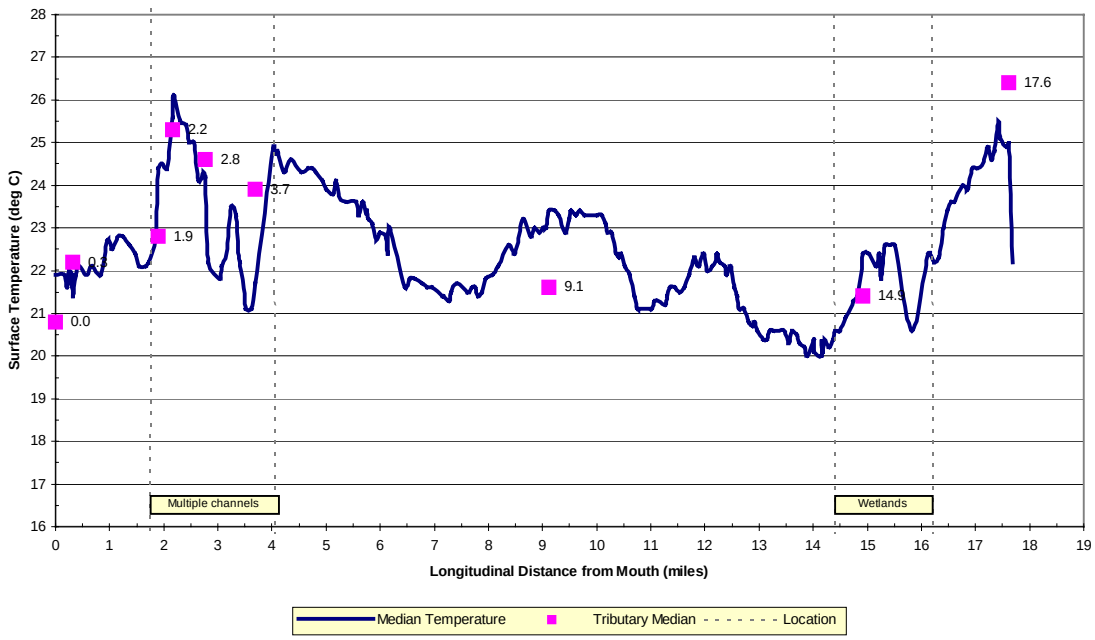

Figure 24 - Median stream temperatures versus river mile for the Fishhole Creek (flight: 8/12/99, 16:42 – 16:57).

Table 13 – Fishhole Creek tributaries identified by river mile (LB/RB = left and right bank looking upstream).

Tributary	mile	km	Tributary Temp (°C)	Mainstem Temp (°C)	Difference (trib – mainstem)	FLIR Image
SF Sprague	0.0	0.0	20.8	21.9	-1.1	fh0013
Canal	0.3	0.5	22.2	21.4	0.8	fh0023
Side Channel	1.9	3.0	22.8	24.4	-1.6	fh0103
Side Channel	2.2	3.5	25.3	25.6	-0.3	fh0117
from Skeddadal Spring	2.8	4.5	24.6	24.2	0.4	fh0149
Pole Creek	3.7	5.9	23.9	21.7	2.2	fh0193
Robinson Spring Creek	9.1	14.7	21.6	23.4	-1.8	fh0441
Side Channel	14.9	24.0	21.4	22.4	-1.0	fh0735
No Name	17.6	28.3	26.4	25.0	1.4	fh0867

Paradise Creek

The median temperatures for each sampled image for Paradise Creek from the confluence with the Sycan River to the confluence of Watson Creek was plotted versus the corresponding river mile (Figure 25). The location and temperature of tributaries are labeled on Figure 25.

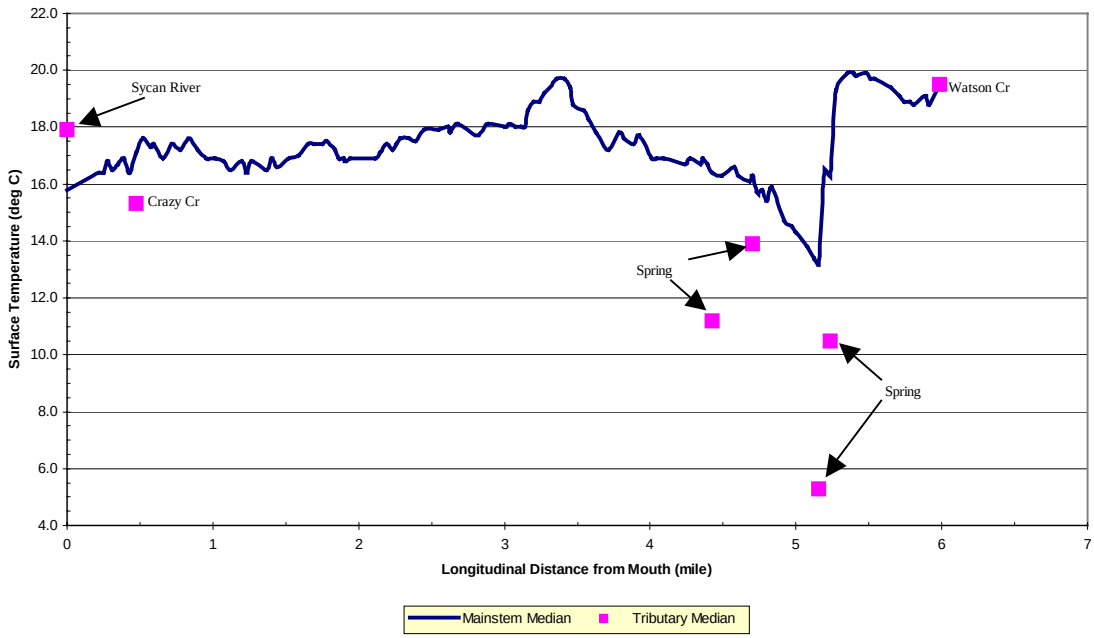

Figure 25 - Median stream temperatures versus river mile for the Paradise Creek (flight: 8/16/99, 15:29 – 15:34).

Paradise Creek and Watson Creek have almost equal water temperatures (19.5^{o}C) at their confluence. Two springs near river mile 5.3 dramatically drop the temperature of Paradise Creek from 20.0^{o}C to 13.2^{o}C (Appendix Images A.68-A.67). These springs were not mapped on the USGS 1:24K topographic maps. Stream temperatures warm in the downstream direction between river mile 5.3 and river mile 3.4 from 13.2^{o}C to 19.7^{o}C. Downstream of river mile 3.4, the stream cools reaching 15.8^{o}C at its confluence with the Sycan River. Crazy Creek was the only surface inflow detected through this reach and is a source of thermal cooling (Appendix Image A.65).

Discussion

FLIR was used to map stream temperatures in the Wood River, Williamson River, and Sprague River basins, a distance of 360.7 miles (580 km). The data were collected in early August 1999 to assess low-flow high summer temperatures in support of ODEQs TMDL development in the Upper Klamath basin. Bad weather interrupted the surveys on several occasions. The Williamson River was surveyed at temperatures representative of highs observed during the summer. However, the storms decreased water temperatures to below their mid-summer highs for the remaining surveys. 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 pattern of the Williamson River showed high thermal complexity at the watershed scale. The analysis showed the influence of tributary inputs on the river temperature. In addition, several springs were detected that altered the overall temperature pattern. Three springs were detected near the headwaters that set the temperature in the upper river. From these springs, the temperatures tended to increase in a downstream direction to the Klamath Marsh. Maximum apparent temperatures were observed immediately downstream of Klamath Marsh. The temperatures in the lower river were strongly influenced by two major tributaries. The inflow of Spring Creek lowered the mainstem temperature by 9.3^{o}C. The Sprague River, a major tributary located six miles downstream of Spring Creek, subsequently raised the temperature by 2.6^{o}C.

The streams surveyed in the Wood River basin showed less complex temperature patterns. The Wood River stayed at an almost constant temperature (10°C) after initially warming up downstream of the headwater springs. Tributary inflows did not alter this trend. Sun Creek and Annie Creek temperatures both generally increased in the downstream direction. Both of these streams started high in Crater Lake National Park and stayed cold through much of their length.

Like the Williamson River, assessment of the temperatures patterns in the Sprague River Basin indicated generally high thermal complexity at the watershed scale. Spring inflows were detected on the North Fork Sprague River, the Sycan River, and Paradise Creek that altered the overall temperature pattern by lowering mainstem temperatures. Large spring inflows were also detected on the Sprague River although the influence on the mainstem was less dramatic. In addition, the analysis showed the influence of tributary inputs on the stream temperatures.

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Torgerson, C.E., D.M. Price, H.W. Li, and B.A. McIntosh. 1999. Multiscale thermal refugia and stream habitat associates of chinook salmon in Northeastern Oregon. Ecological Applications. 9(1), pp 301 – 319.

Appendix A – Selected Images

Wood River

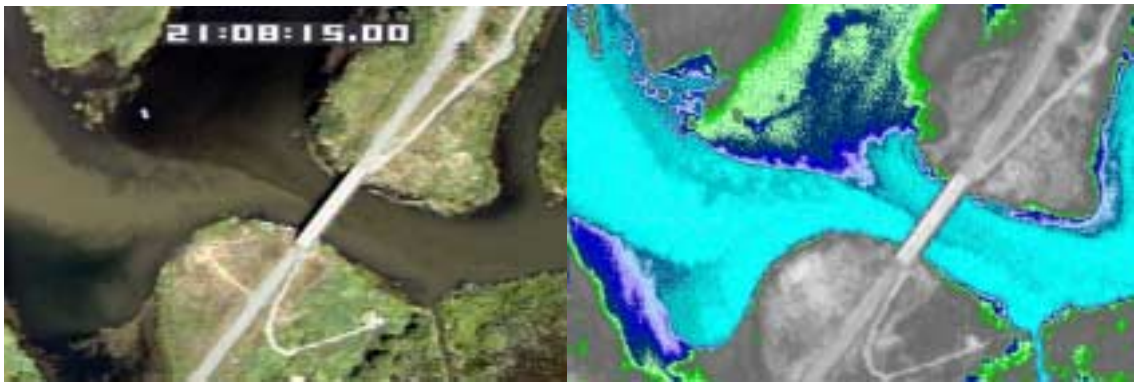

Figure A.1 - Thermal/Day TV image pair of the Wood River (11.4^{o}C) near the mouth. The canal to Petric Park is in the top of the image on the left side of the road. The thermal mixing behind the boat in the upper left is evidence of thermal stratification in the canal (*frame: wd0028*).

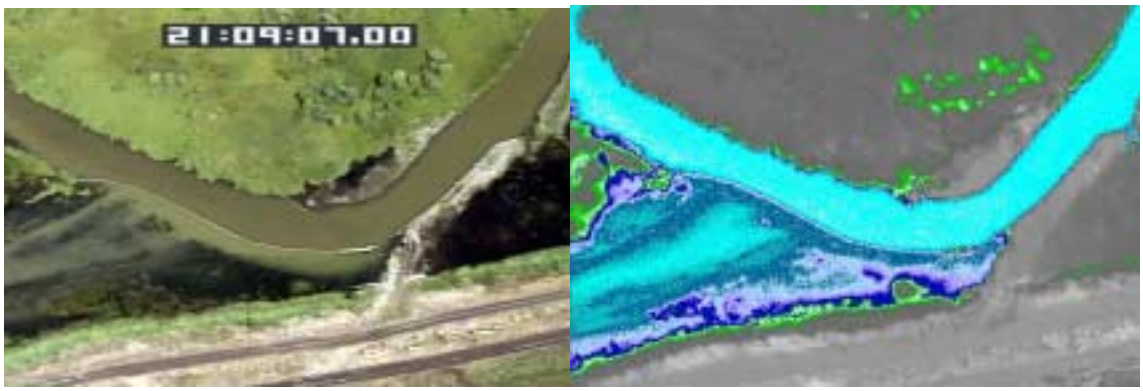

Figure A.2 - Thermal/Day TV image pair of the Wood River (11.2^{o}C). The river flows from left to right in the image and surface inflow is visible from the left bank. The surface inflow originates from upstream on the Wood River. Buoys or a filter is visible in both images indicating that this may be part of wetland reconstruction (*frame: wd0089*).

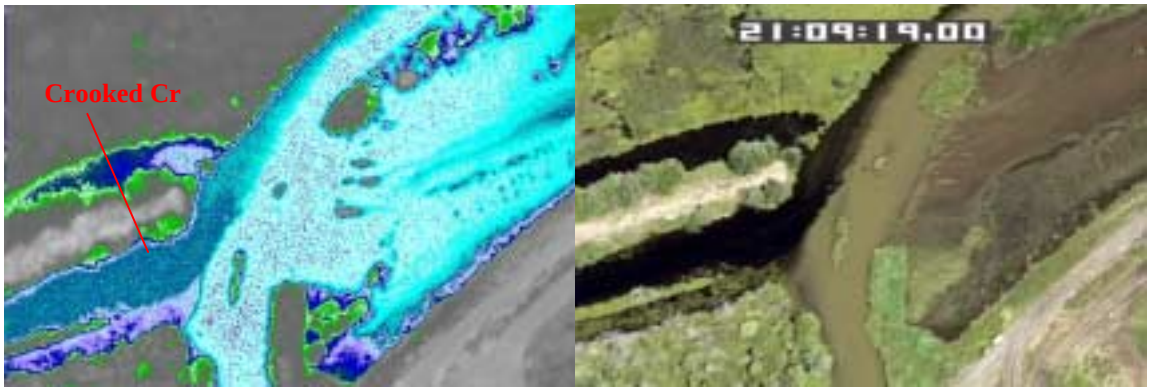

Figure A.3 - Thermal/Day TV image pair of the confluence of the Wood River (10.3°C) and Crooked Creek (13.3°C). The flow direction is from the bottom to the top of the image (*frame: wd0091*).

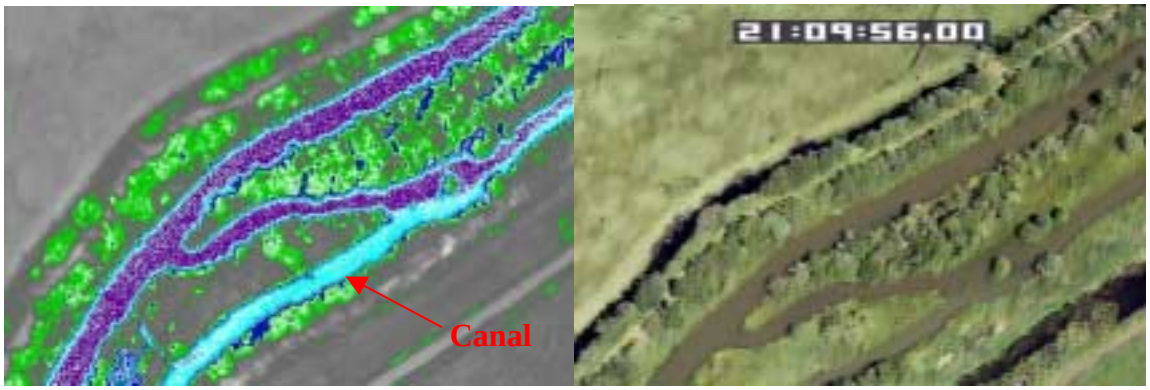

Figure A.4 - Thermal/Day TV image pair showing the Wood River (9.8°C) and the Wood River Canal. The Wood River flows from the bottom left to the top right of the image (*frame: wd0127*).

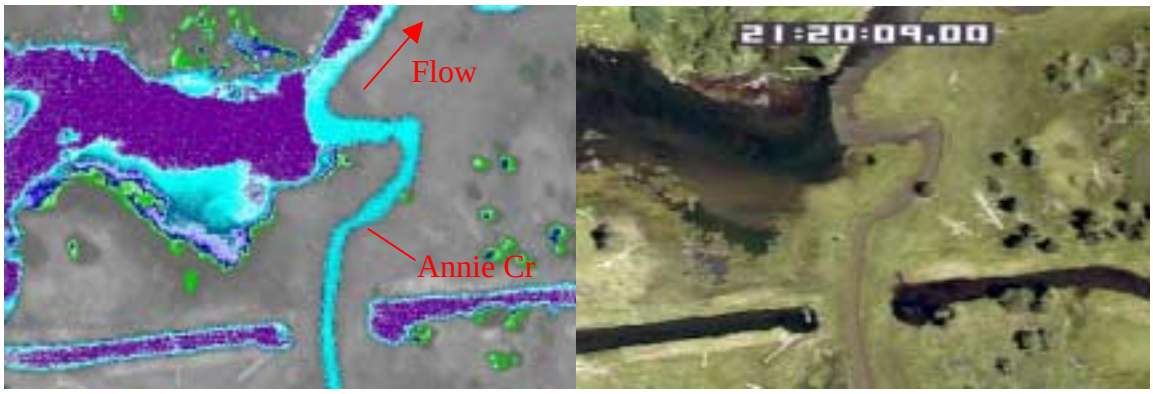

Figure A.5 - Thermal/Day TV image pair of the confluence of the Wood River (9.5°C) and Annie Creek (11.6°C). Annie Creek flows from the bottom to the top of the image. The Wood River flows from left to right in the image (*frame: wd0648*).

Sun Creek

Figure A.6 - Thermal/Day TV image pair of the confluence of Sun Creek (13.5°C) and Annie Creek (12°C). Annie Creek flows from left to right in the image. Sun Creek flows in from the top left of the image (*frame: sun0044*).

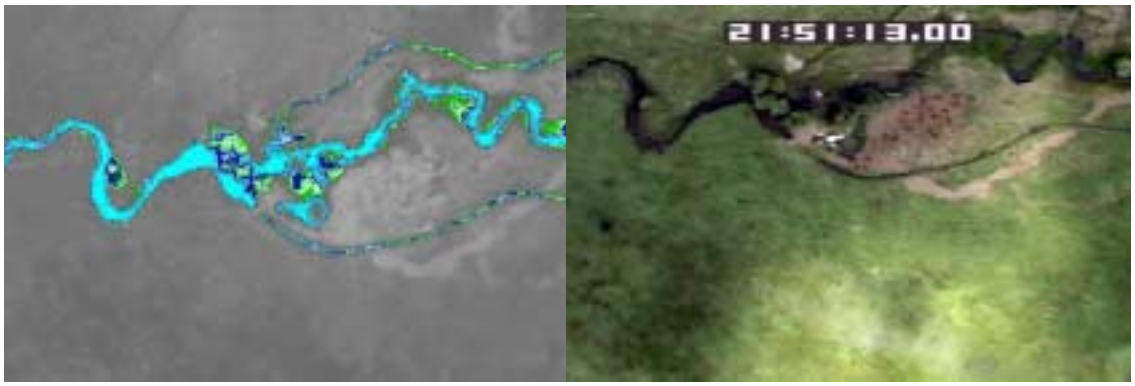

Figure A.7 - Thermal/Day TV image pair of Sun Creek (11.6°C) showing a dam that diverts water to two different canals. The flow direction is from left to right in the image (*frame: sun0083*).

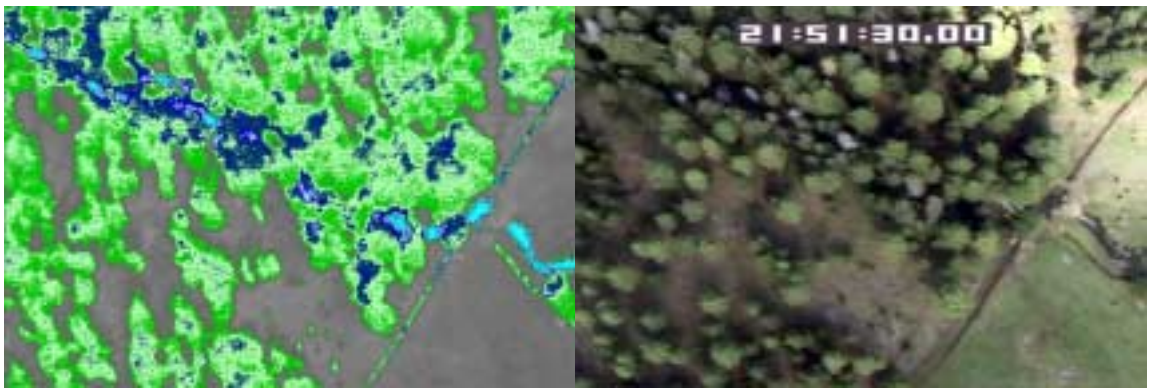

Figure A.8 - Thermal/Day TV image pair of Sun Creek (11.4^{o}C) at the Forest Boundary (*frame: sun0098*). Sun Creek flows from left to right in the image.

Figure A.9 - Thermal/Day TV image pair of Sun Creek (6.7^{o}C) near the end of the survey. The flow direction is from the top to the bottom of the image (*frame: sun0536*).

Annie Creek

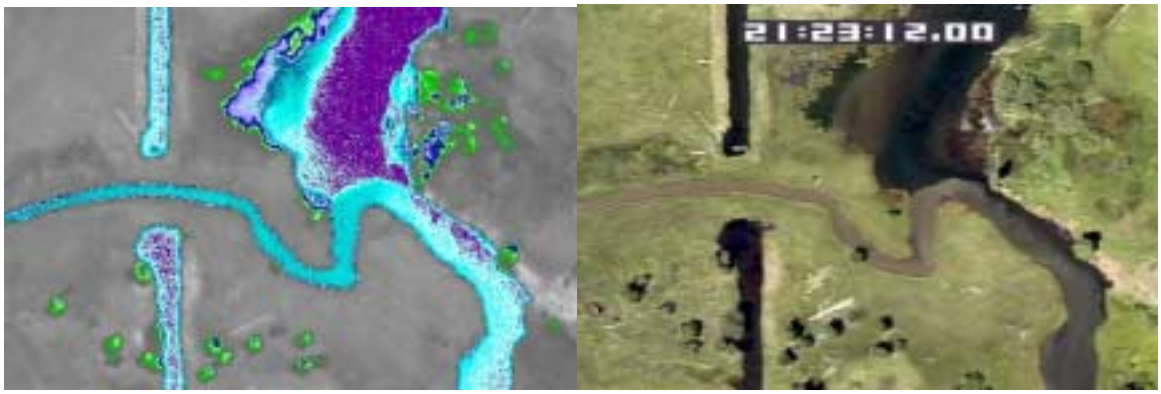

Figure A.10 - Thermal/Day TV image pair of the confluence of Annie Creek (12.2^{o}C) and Wood River (9.3^{o}C) (*frame: ann0012*).

Figure A.11 - Thermal/Day TV image pair of the confluence of Annie Creek (11.9^{o}C) and Sun Creek (13.7^{o}C) (*frame: ann0084*).

Williamson River

Downstream of Klamath Marsh

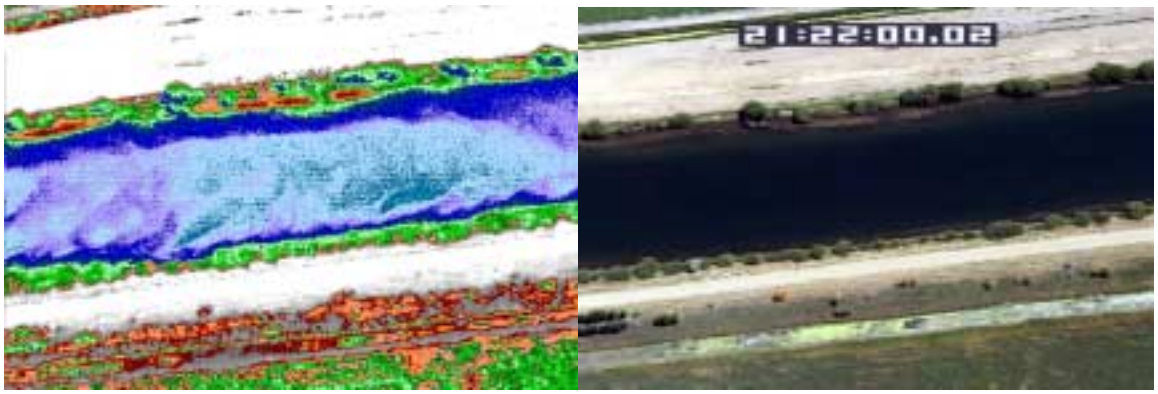

Figure A.12 - Williamson River (river mile 4.2) showing evidence of thermal stratification in the lower river. The mixing patterns and patchiness observed in the surface temperatures are signs of stratification (*frame: wil0081*).

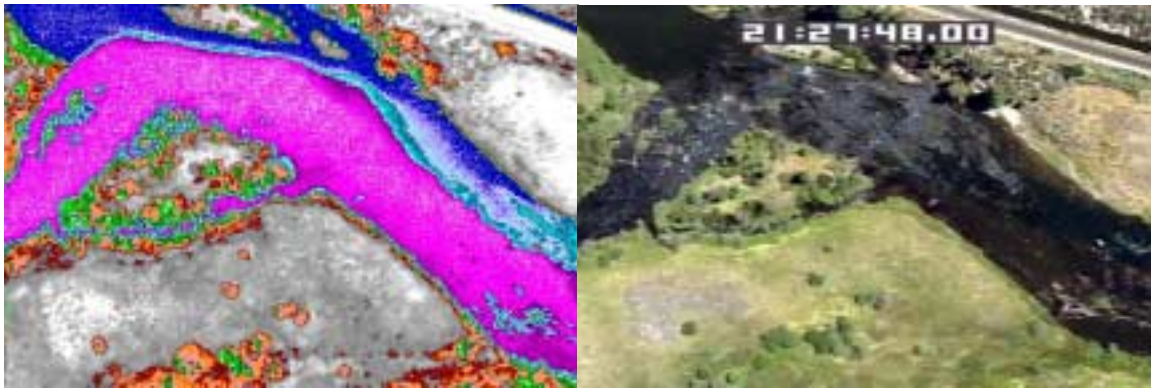

Figure A.13 - Confluence of the Williamson River (12.1^{o}C) (river mile 12.4) and the Sprague River (21.4^{o}C) (*frame: wil0255*).

Figure A.14 - Confluence of the Williamson River (19.1°C) and Spring Creek (9.8°C) (river mile 18.1) (*frame: wil0380*).

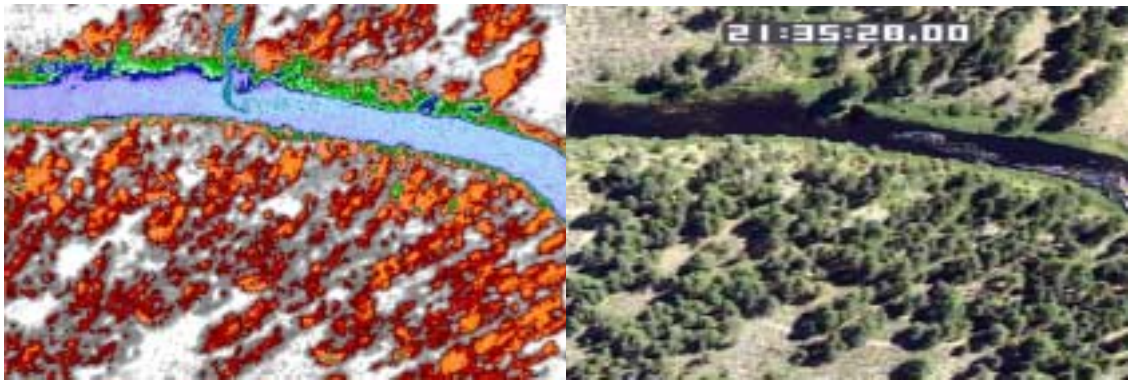

Figure A.15 - Confluence of the Williamson River (19.8°C) (river mile 20.6) and Larkin Creek (18.5°C). The Williamson River shows some signs of thermal stratification in this reach (frame: wil0434).

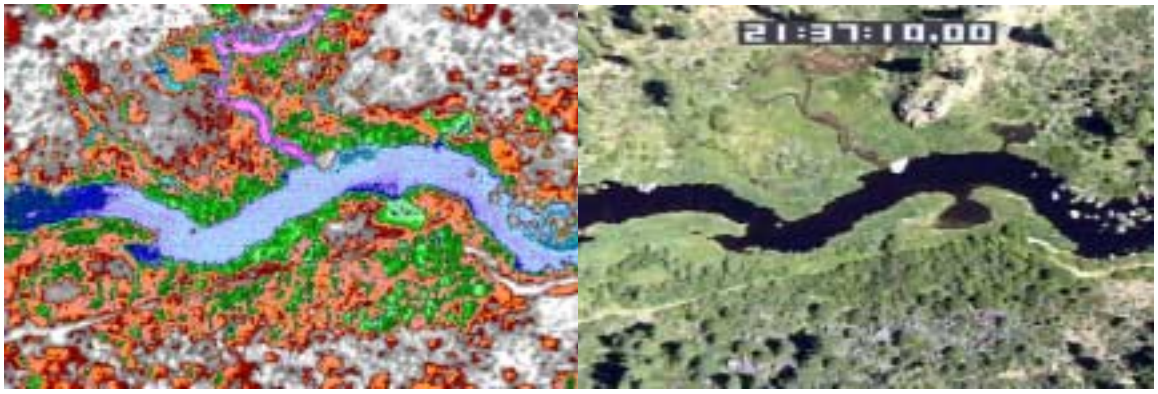

Figure A.16 - Williamson River at (river mile 23.2) flows from right to left in this image. The river has a surface temperature of 19.8°C and an non-named stream (11.2°C) flows in from the top of the image. The temperature shift upstream of the inflow is often associated with thermal stratification (frame: wil0485).

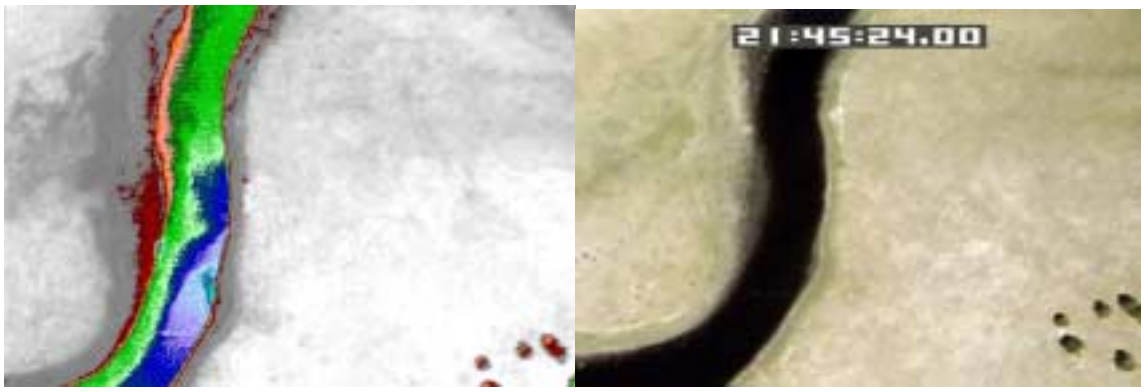

Figure A.17 - Williamson River (river mile 35.4) showing an area of mixing on the LB. The river shows evidence of stratification through this reach. As a result, interpretation of the surface temperature patterns is difficult. However, areas of mixing such as this one on the left bank suggest possible sub-surface inflow (*frame: vwil0732*)

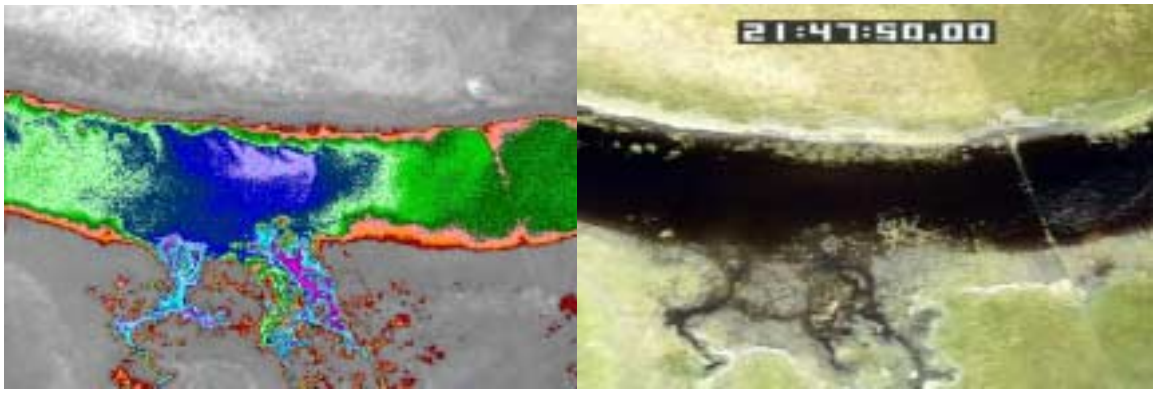

Figure A.18 - Williamson River (river mile 38.8) at spring inflow from the left bank. The Williamson River is thermally stratified in this reach. The spring inflow (12.8^{o}C) causes mixing in the Williamson River. (*frame: wil0805*).

Upstream of Klamath Marsh

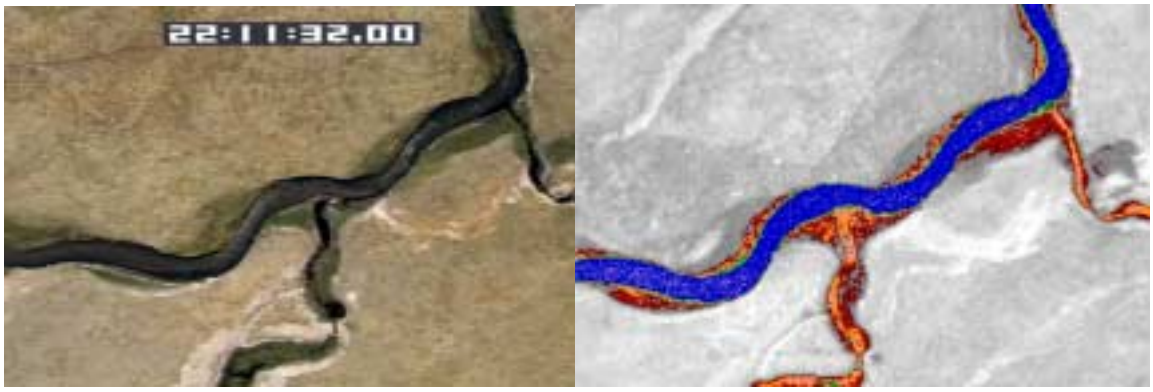

Figure A.19 - Confluence of the Williamson River (21.3°C) and Irving Creek (26°C). Irving Creek appears to have very little flow (*frame: will0329*).

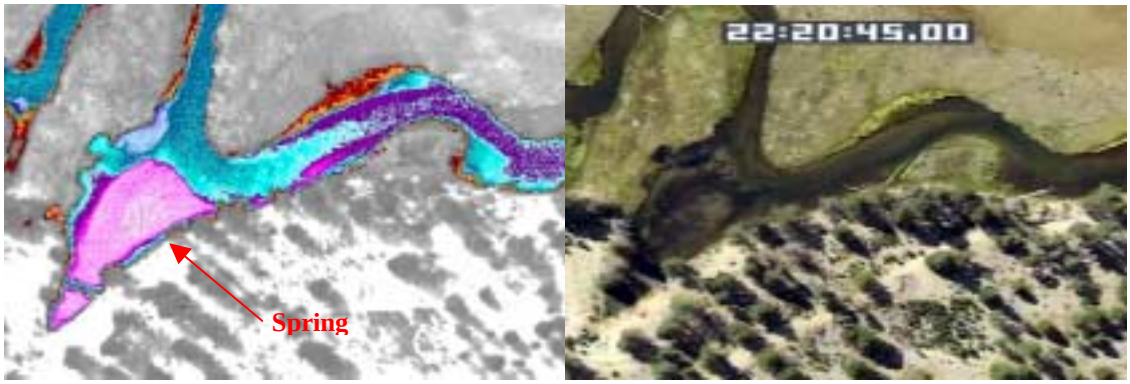

Figure A.20 - Williamson River (river mile 81.5) at Wickiup Spring. Flow direction is from left to right in the image (*frame: will606*).

Figure A.21 - Williamson River (river mile 82.2) at spring inflow from the left bank. The spring is not identified on the USGS 1:24k topographic map (*frame: will0620*).

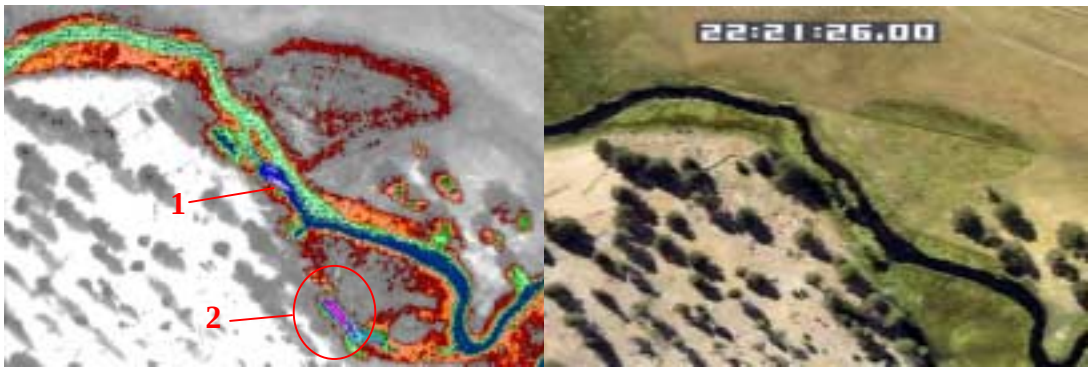

Figure A.22 - The water surface temperature (river mile 82.2) changes in this reach. There is mixing at location 1 (23.1^{o}C upstream) that results in cooler downstream temperatures (22.3^{o}C). However, it is not obvious from the imagery if the mixing is due some small spring inflows or if the upstream sections are thermally stratified. The cold area at location 2 is due to shadows on moist vegetation (*frame: will0626*).

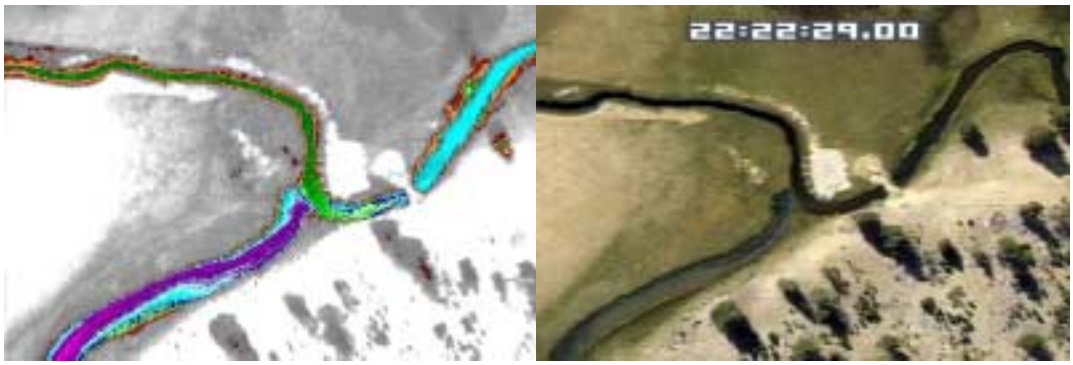

Figure A.23 - Confluence of the Williamson River (river mile 84.0) and what appears to be a spring near "Bull Pasture". Flow direction is from left to right in the image (*frame: will0658*).

Sprague River

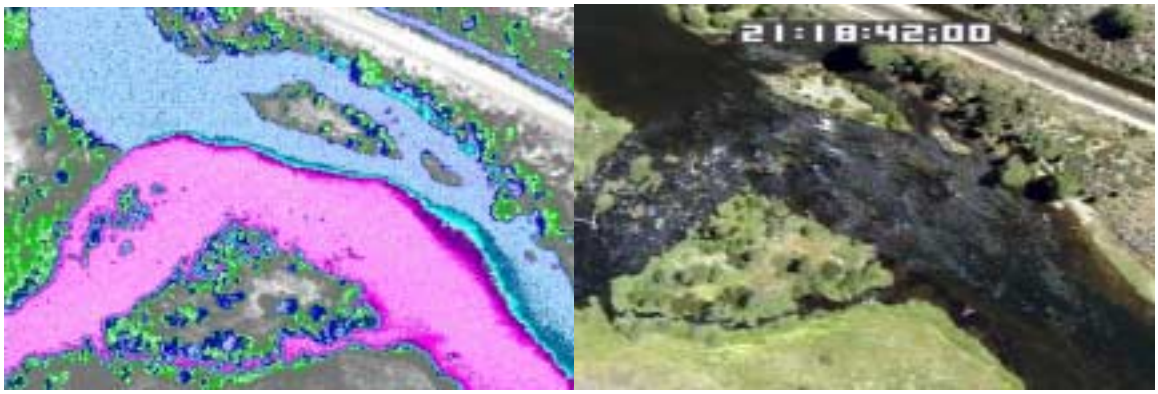

Figure A.24 Confluence of the Sprague River (19.6°C) and the Williamson River (11.2°C) (*frame: spr0147*).

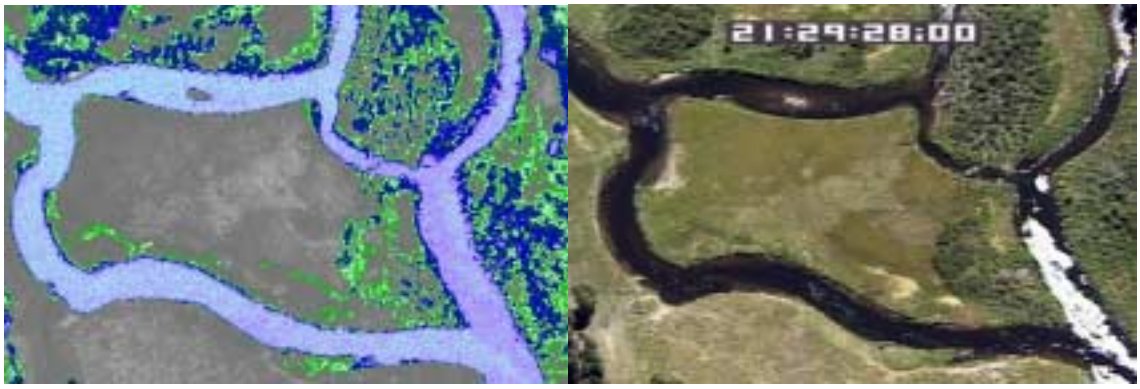

Figure A.25 - There are a lot of braided channels in the Sprague River (20.0°C) (river mile 11.9) (*frame: spr0628*).

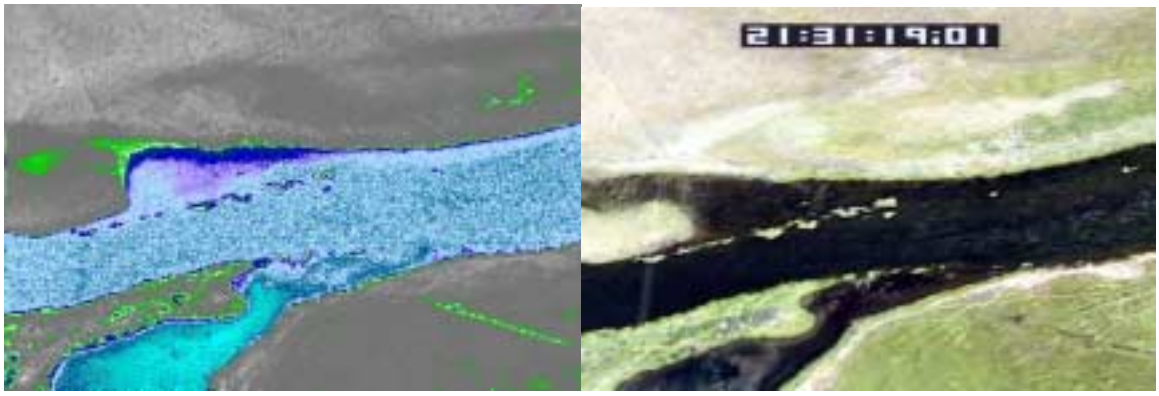

Figure A.26 - Spring (17.0°C) on the LB of the Sprague River (19.1°C) at river mile 16.2 mile (*frame: spr0735*).

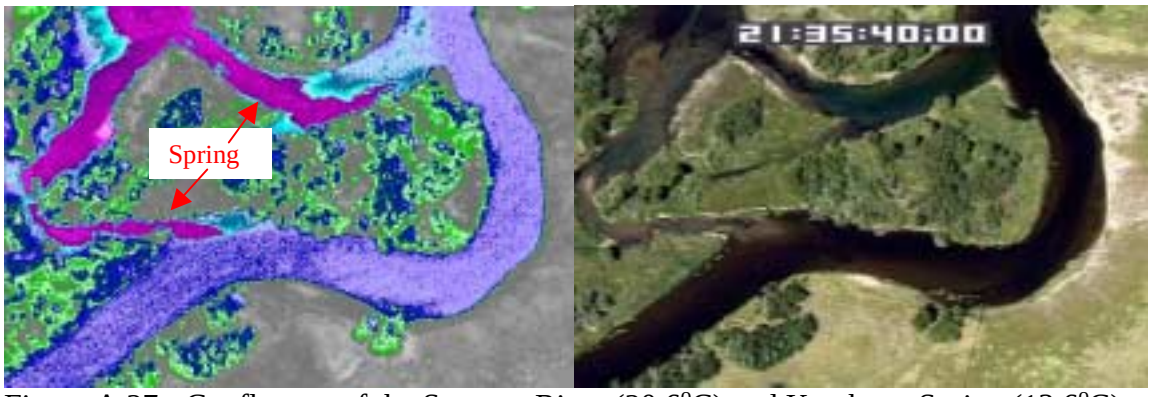

Figure A.27 - Confluence of the Sprague River (20.6°C) and Kamkaun Spring (13.6°C) at river mile 23.6 The flow direction is from the bottom to the top of the image (*frame: spr1000*).

Figure A.28 - Cold surface inflow (16.1°C) on the Sprague River at river mile 75.7 (*frame: spr3049*)

Figure A.29 - Confluence of the NF Sprague (23°C) and SF Sprague (20.6°C). The SF Sprague flows in from the bottom left of the image. The NF Sprague flows in from the bottom right of the image (*frame: spr3188*).

North Fork Sprague River

Figure A.30 - Small surface inflows like this one at river mile 2.6 are common on the lower NF Sprague River (frame: nfs0131).

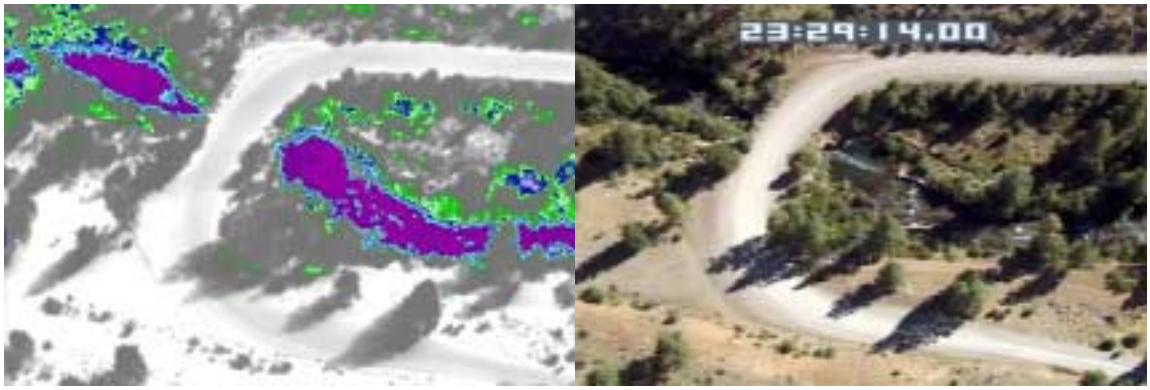

Figure A.31 - Forest Service Road 3411 Bridge at river mile 11.5. The NF Sprague River (13.7°C) flows from left to right in the image (*frame: nfsp0501*).

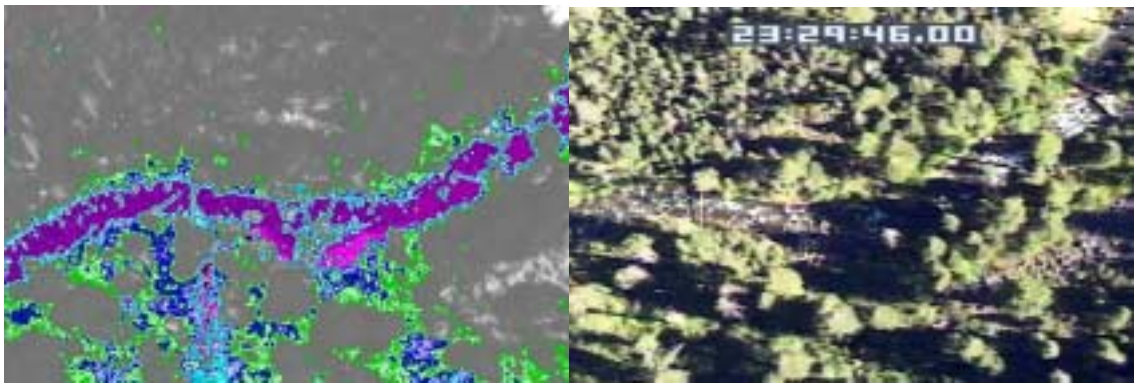

Figure A.32 - Spring inflow (9.5°C) is visible on the LB of the NF Sprague River (14°C) at river mile 12.3. The spring is not mapped on the USGS 1:24 Topographic maps (*frame: nfsp0533*).

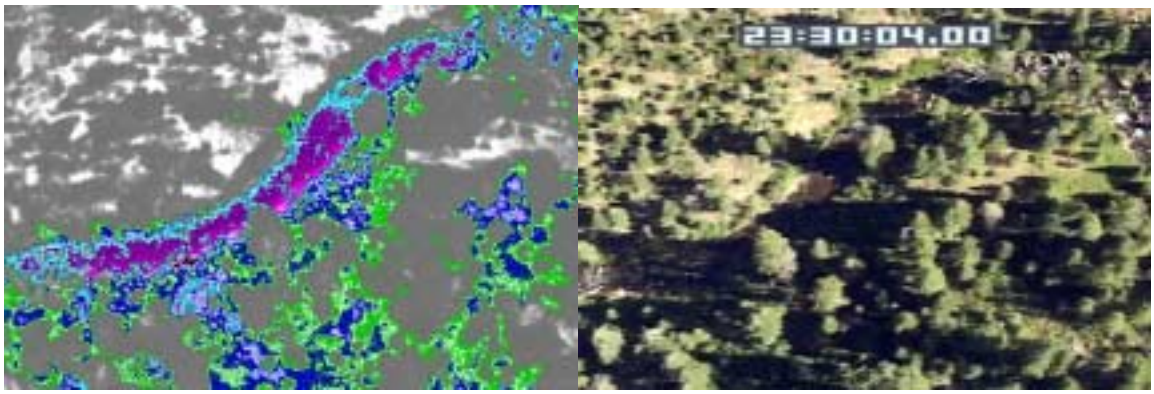

Figure A.33 - Spring inflow (9.7°C) is just visible of the LB of NF Sprague River (13.9°C) at river mile 12.7. This spring is not mapped on the USGS 1:24K Topographic maps (*frame: nfsp0549*).

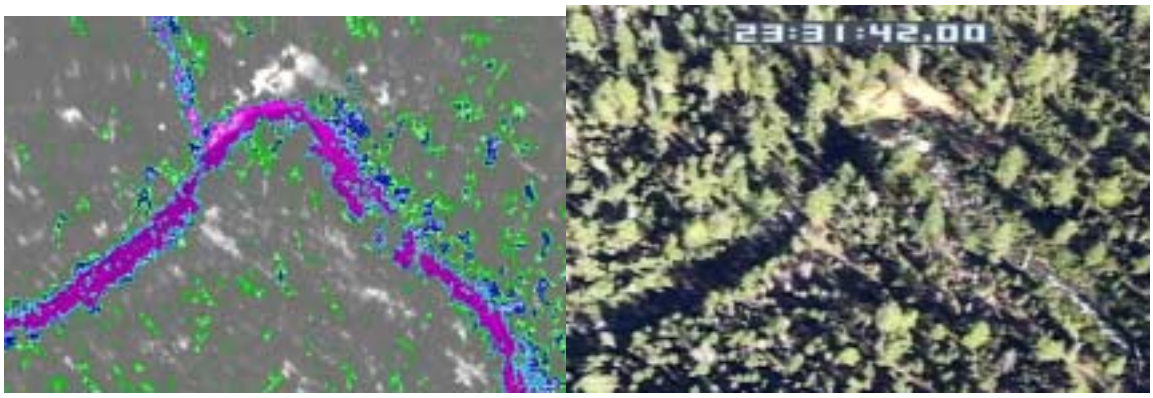

Figure A.34 - Confluence of Boulder Creek (11.8^{o}C) and the NF Sprague River (13.6^{o}C) at river mile 14.9 (*frame: nfsp0649*).

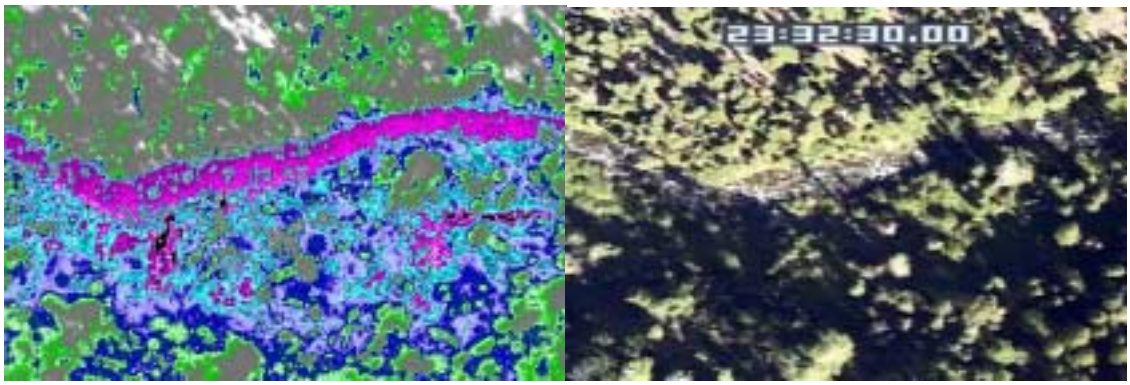

Figure A.35 - Springs (7.7^{o}C) along the left bank of the NF Sprague River (12.7^{o}C) at river mile 16.1 (*frame: nfsp0699*).

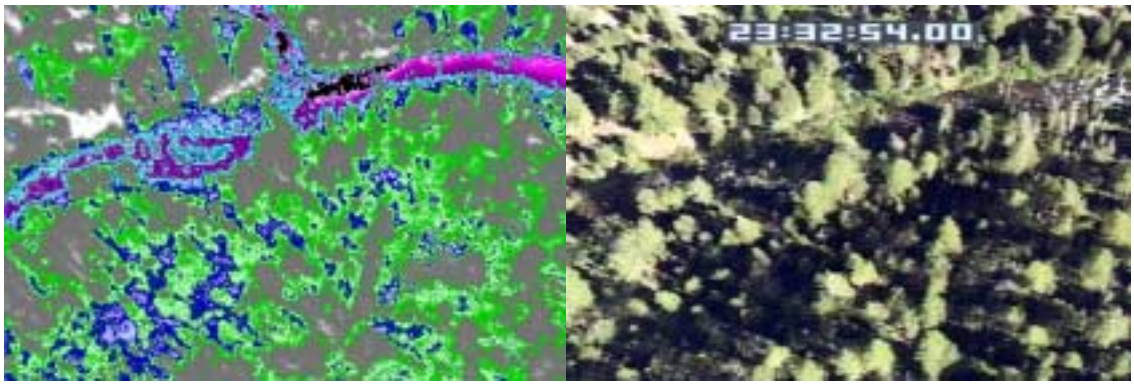

Figure A.36 - Confluence of the NF Sprague River (14.4^{o}C) and Sheepy Creek (8.4^{o}C) at river mile 16.7 (*frame: nfsp0723*).

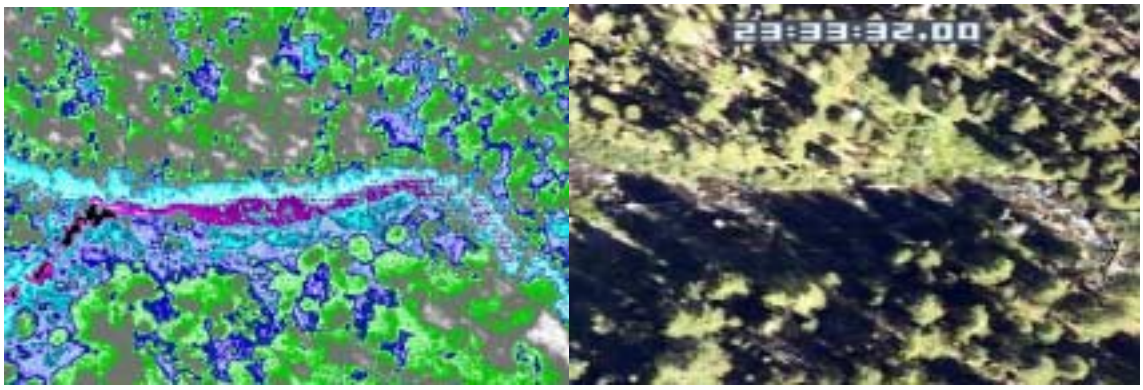

Figure A.37 - Confluence of the NF Sprague River and an unnamed tributary at river mile 17.6. The surface water temperature of the tributary is 6.0°C and the temperature of the NF Sprague upstream of the confluence is 15.8°C (*frame: nfsp0765*).

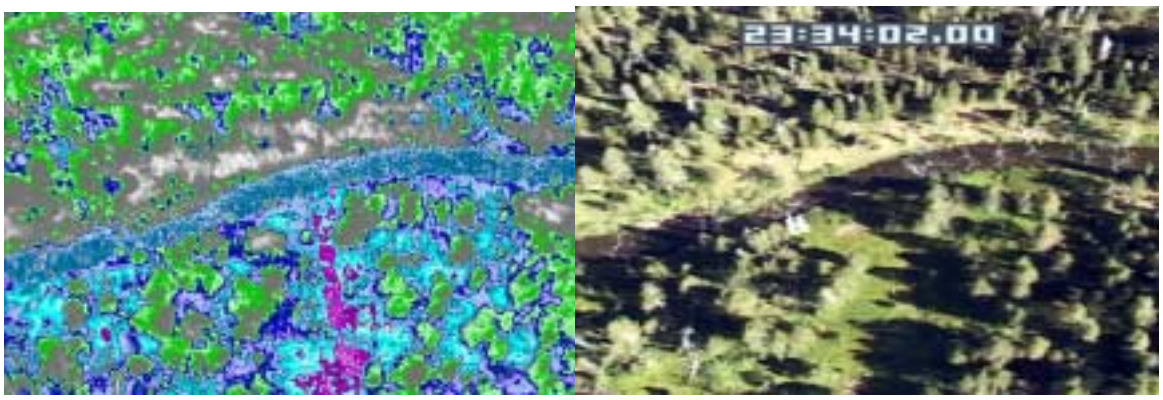

Figure A.38 - The NF Sprague River flows from left to right in this image. The cold area on the left bank suggests cold water inflow (river mile 18.3). The solar shading on the day video image makes it difficult to determine if there is any surface water. However, the cooler surface temperatures along this line compared to other parts of the meadow is an indicator of sub-surface flow (frame: *nfsp0797*).

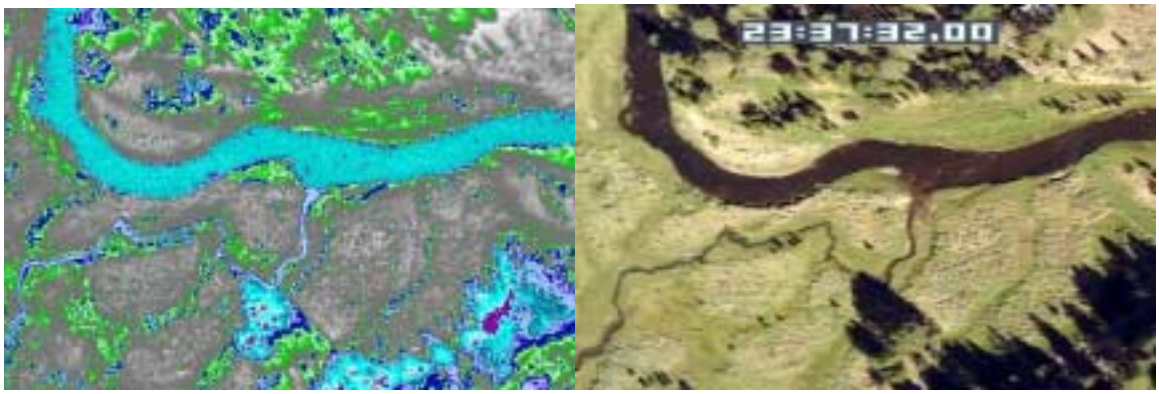

Figure A.39 - Confluence of the Sprague River (17.3°C) and an unnamed tributary (19.6°C) at river mile 24.4 (*frame: nfsp1005*).

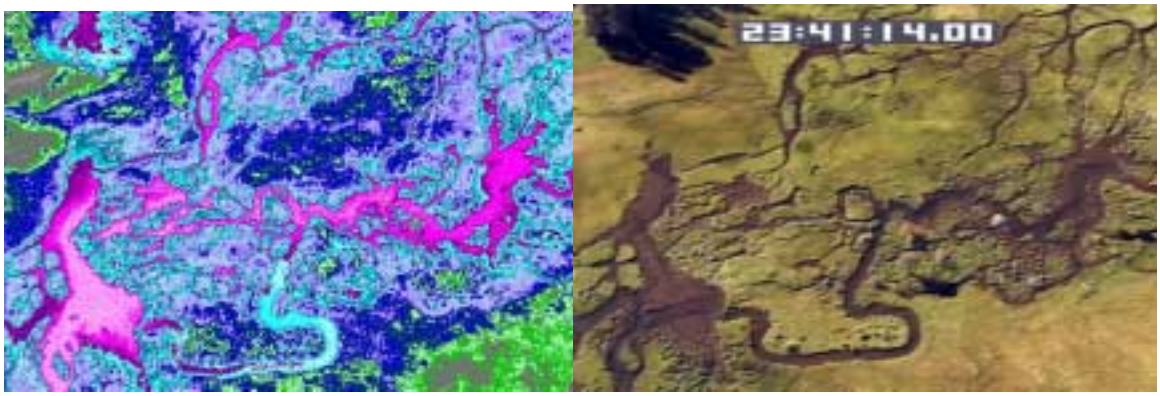

Figure A.40 - Braided Channel (river mile 29.5) in Lee Thomas Meadow (*frame: nfsp1229*).

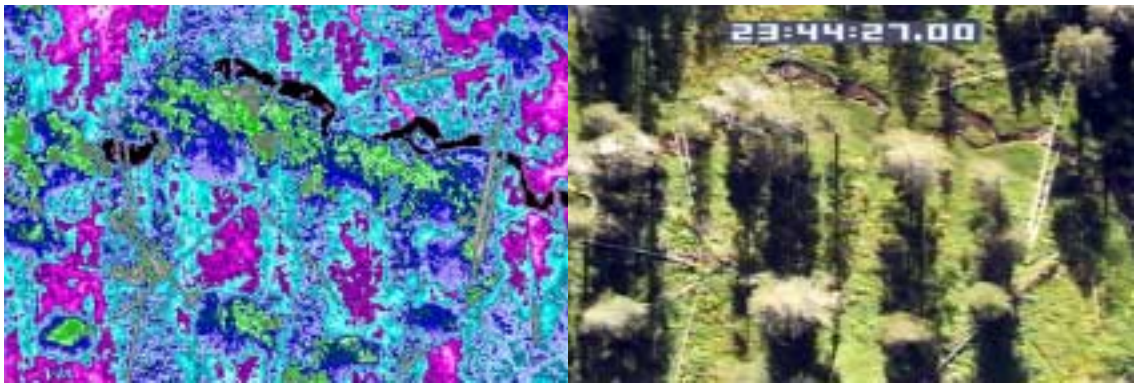

Figure A.41 - Spring at the Head of the NF Sprague River at river mile 33.5 (*frame: 1421*).

South Fork Sprague River

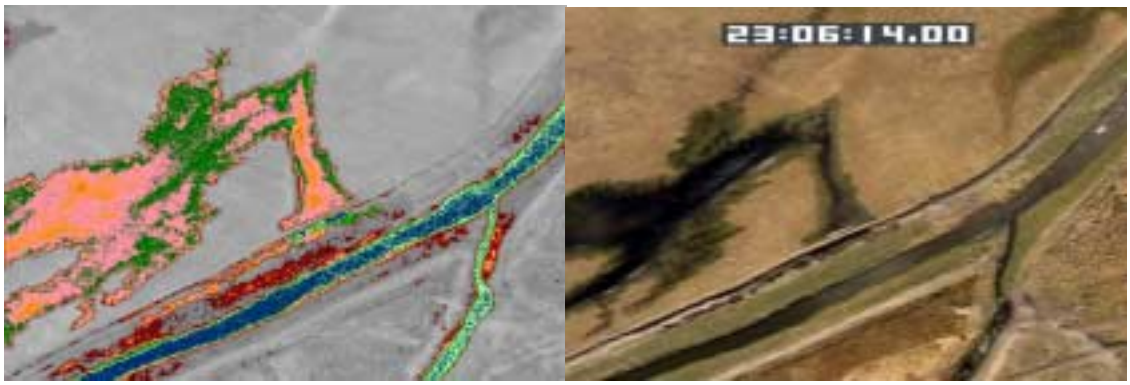

Figure A.42 - Canal Return on the SF Sprague River at river mile 2.4. The SF Sprague flows from the bottom left of the image. The canal flows in from the bottom of the image (*frame: sf0123*).

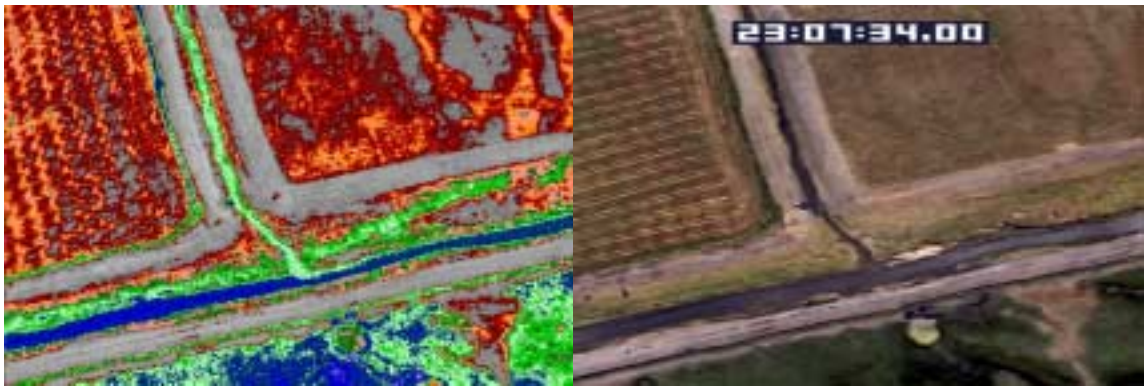

Figure A.43 - Canal Return (23.3^{o}C) on the SF Sprague River (21.4^{o}C) a river mile 3.9. The SF Sprague River flows from left to right in the image (*frame: sf202*)

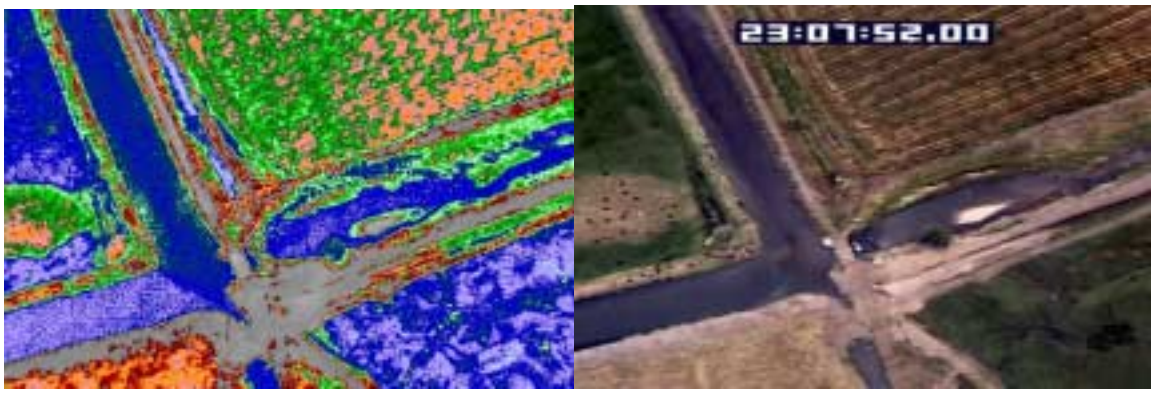

Figure A.44 - Confluence of Fishhole Creek (22.2°C) and SF Sprague River (20.6°C) at river mile 4.3. The SF Sprague River flows from left to right in the image. Fishhole Creek flows from the top to the bottom of the image (*frame: sf0218*).

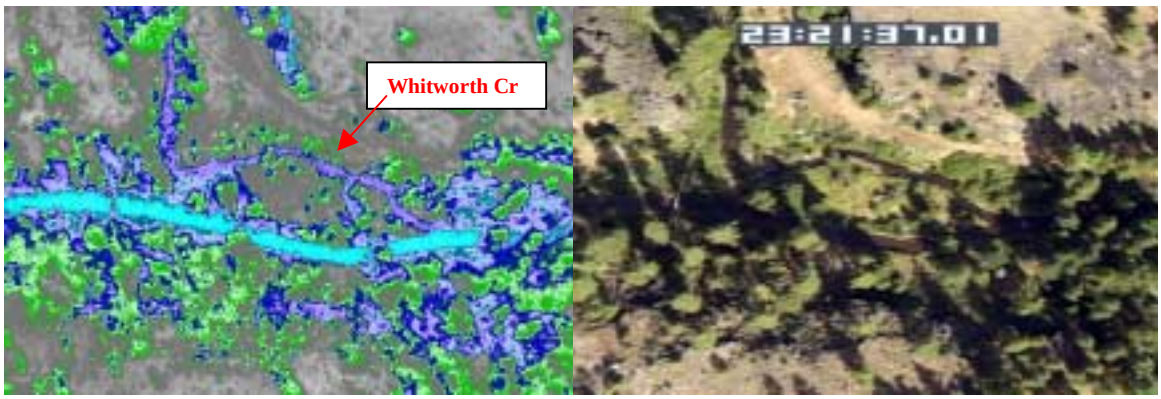

Figure A.45 - Confluence of Whitworth Creek (20.4°C) and SF Sprague River (16.2°C) at river mile 20.5. The SF Sprague River flows from left to the right in the image (frame: sf0903).

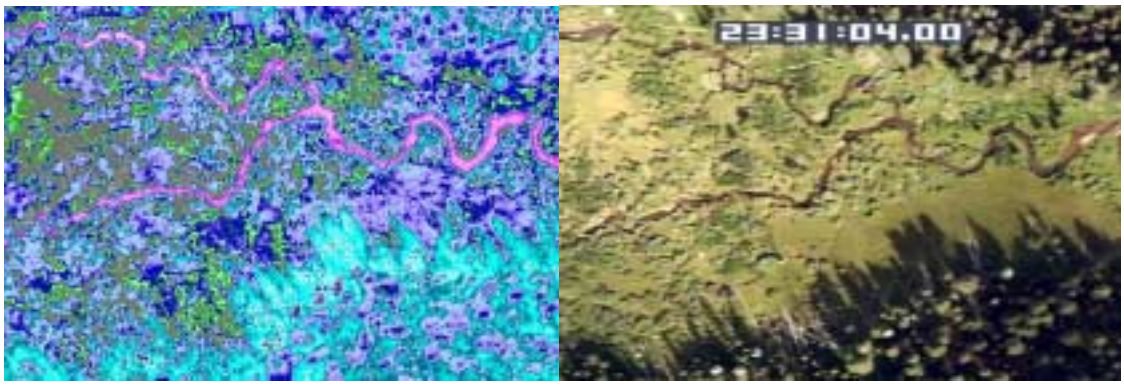

Figure A.46 - Confluence of the SF Sprague River (11.1°C) and Corral Creek (11.6°C). Corral Creek flows in from the bottom left of the image and the SF Sprague flows in from the top left of the image (*frame: sf1216*).

Fishhole Creek

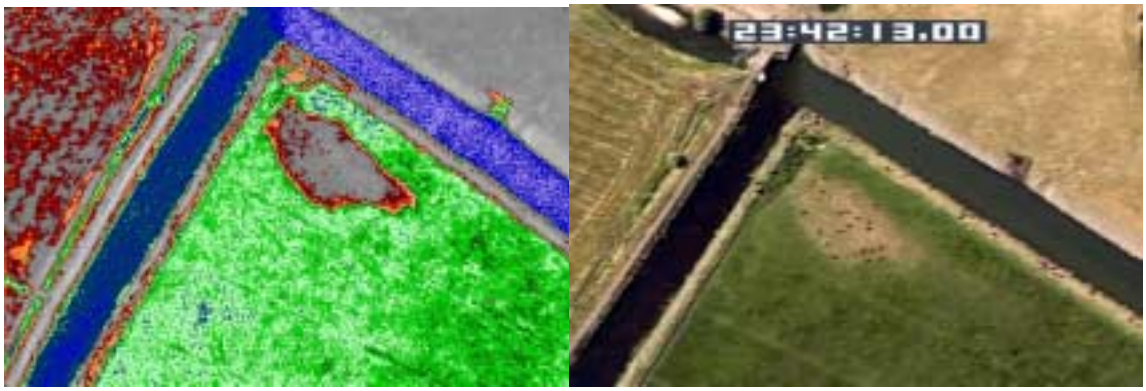

Figure A.47 - Confluence of Fishhole Creek (21.9°C) and the SF Sprague River 20.8°C). Fishhole Creek flows from the bottom to the top of the image and SF Sprague River flows from right to left in the image (*frame: fh0013*).

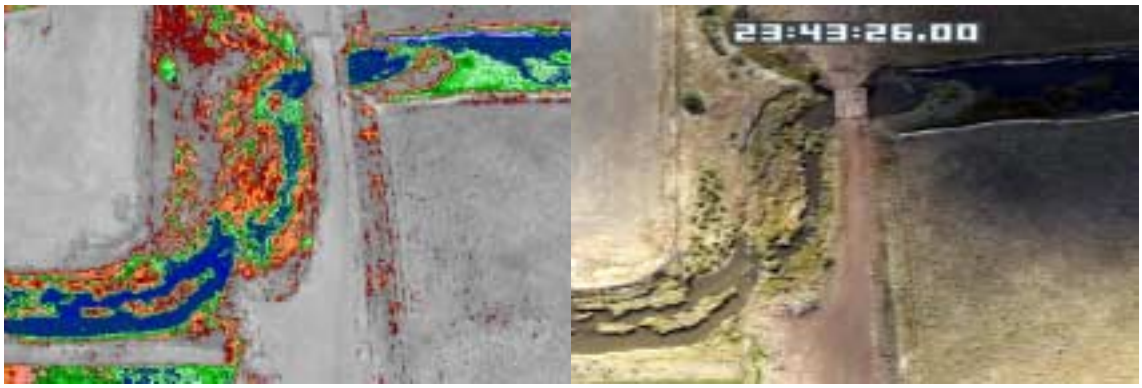

Figure A.48 - Fishhole Creek (22.1°C) (river mile 1.5) flows from left to right in the image. Vegetation is visible on the stream surface that causes apparent variability in surface temperatures (*frame: fh0085*).

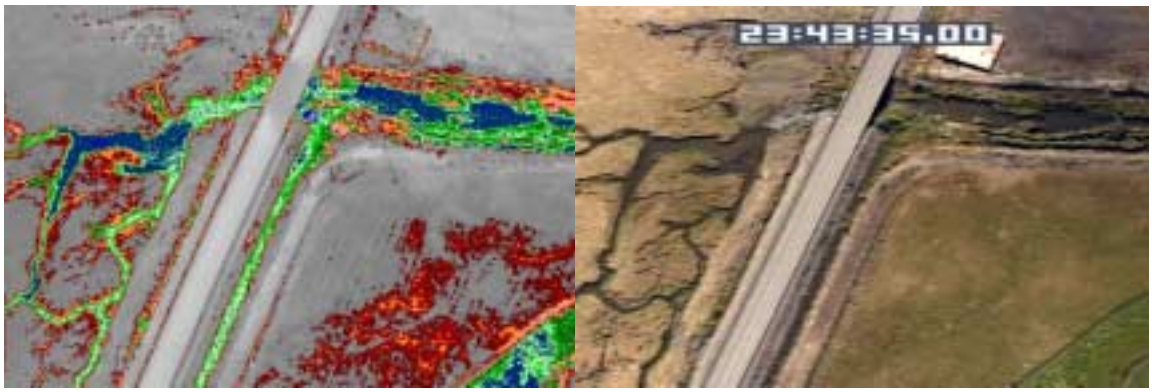

Figure A.49 - Fishhole Creek (22.2°C) flows from left to right in the image under route 140 near Bly. As suggested by the image, Fishhole creek has multiple channels upstream of this location, which made following the stream difficult (*frame: fh0093*).

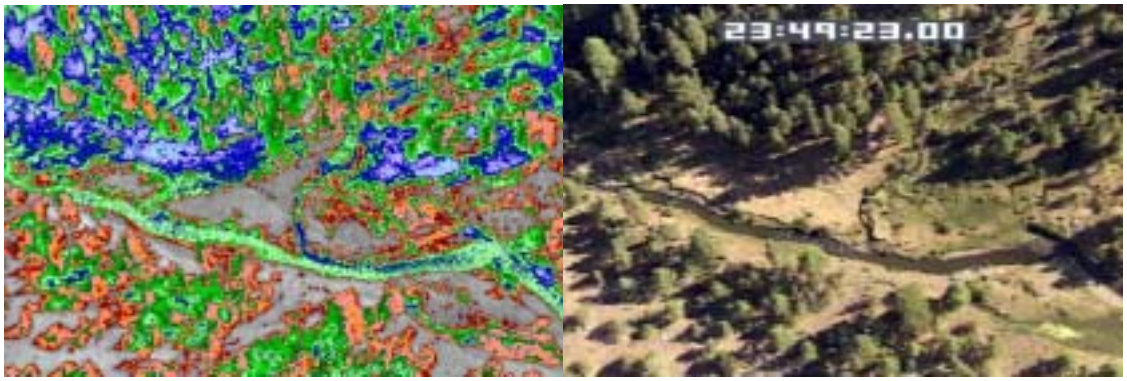

Figure A.50 - Fishhole Creek (23.4) flows from left to right in the image (river mile 9.1). Robinson Spring Creek (21. 6°C) from to the bottom of the image (*frame: fh0441*).

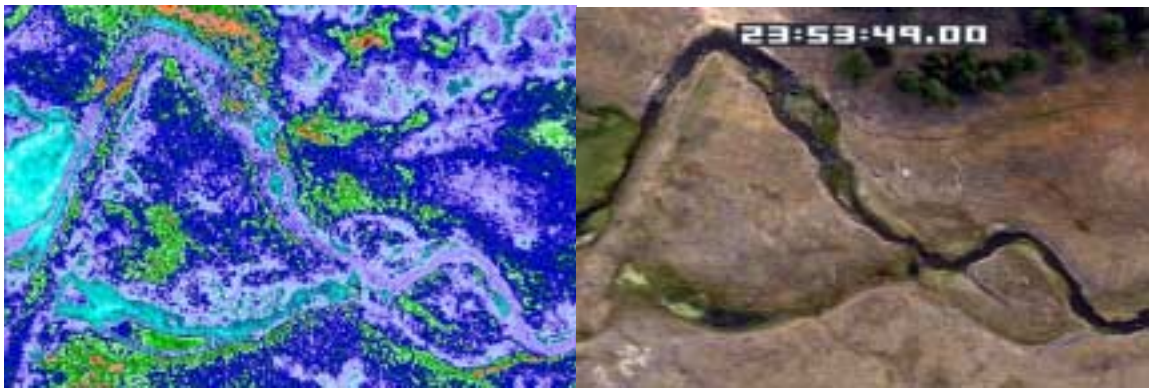

Figure A.51 - Fishhole Creek (21.1^{o}C) flows from left to right in the image (river mile 14.4). There is very low thermal contrast in this reach, which makes detection of the stream difficult in the thermal image.

Sycan River

Figure A.52 - Confluence of the Sycan River (18.7°C) and the Sprague River (19.7°C). The Sycan River flows in from the bottom left of the image and the Sprague River flows from the top to the bottom of the image (*frame: syc0010*).

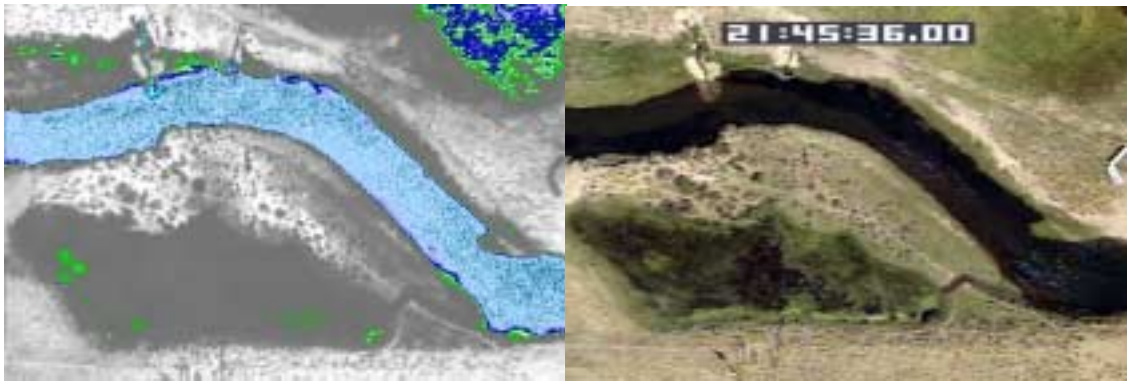

Figure A.53 - A surface inflow (14.7°C) is detectable at river mile 4.5 of the Sycan River (19.0°C) . The source of the inflow could not be determined (*frame: syc0187*)

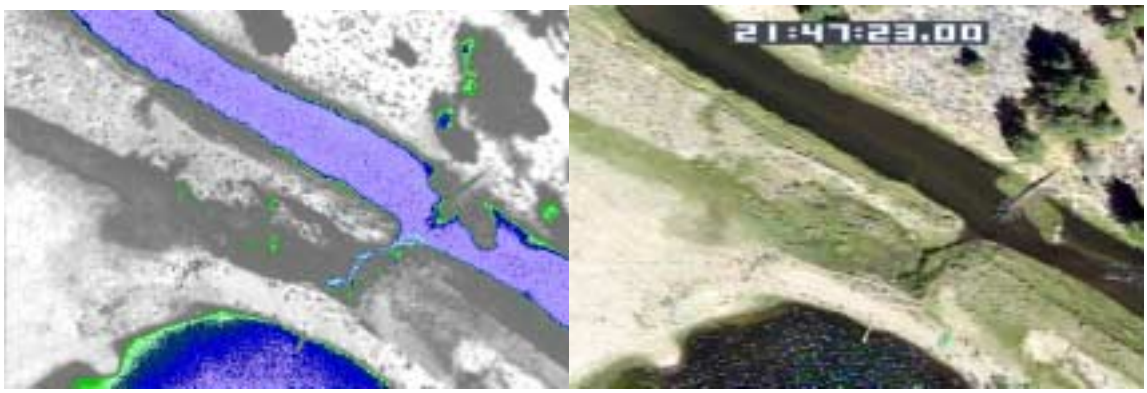

Figure A.54 - Outlet of a pond (19.1°C) entering the Sycan River (20.4°C) at river mile 7.4 (*frame: syc0294*).

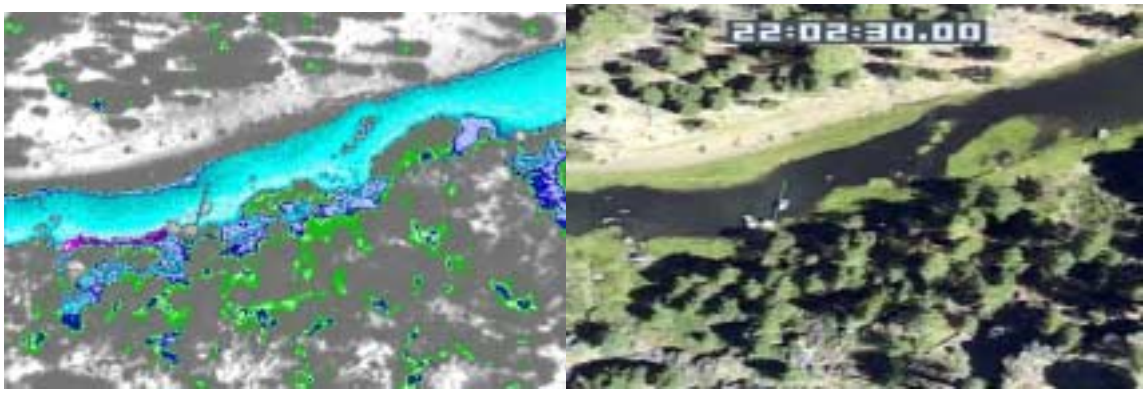

Figure A.55 – This Spring input at river mile 25.2 was not mapped on the USGS 1:24k topographic maps (*frame: syc1034*).

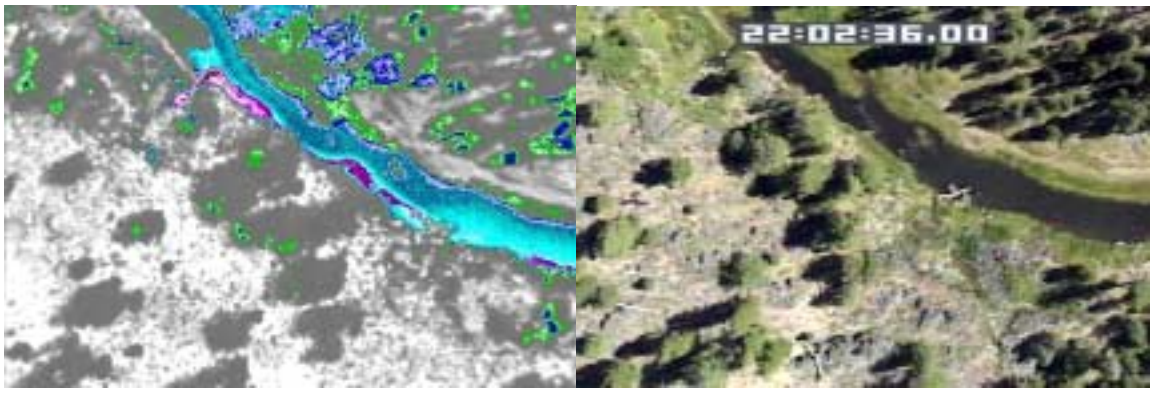

Figure A.56 - This spring at river mile 25.4 lowers the water temperature in the Sycan River. This spring was not mapped on USGS 1:24k topographic maps (*frame: syc1040*).

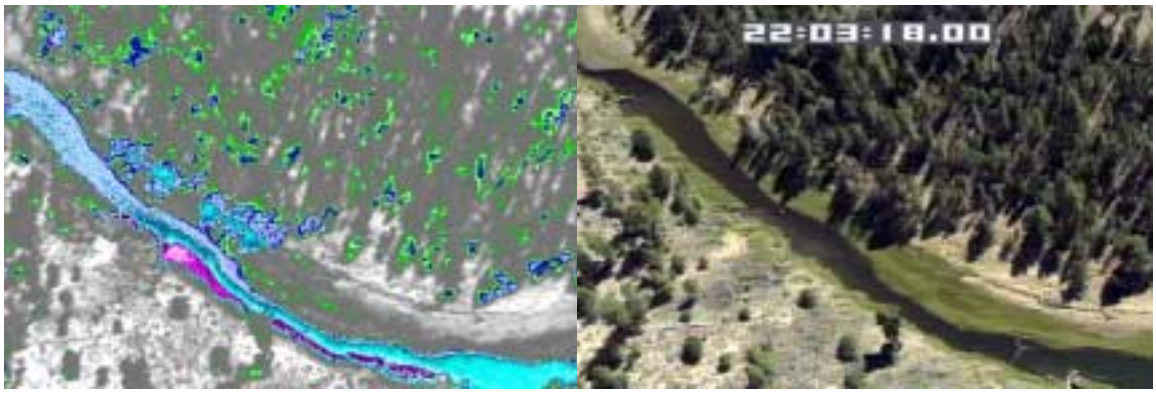

Figure A.57 - Tarrent Spring dramatically lowers the water temperature in the Sycan River at mile 26.7 (*frame: 1082*).

Figure A.58 - Sycan River at the downstream end of the Sycan Marsh. Cooler water temperatures just downstream of the impoundment indicate thermal stratification upstream. Variations in the surface temperatures are also due to vegetation at the waters surface (*frame: syc1474*).

Figure A.59 - Weir at river mile 43.6. The surface water temperature downstream of the weir is 17.8°C while the surface water temperature upstream of the diversion is 19.0°C. The temperature difference is an indication of thermal stratification upstream of the weir (*frame: syc1540*).

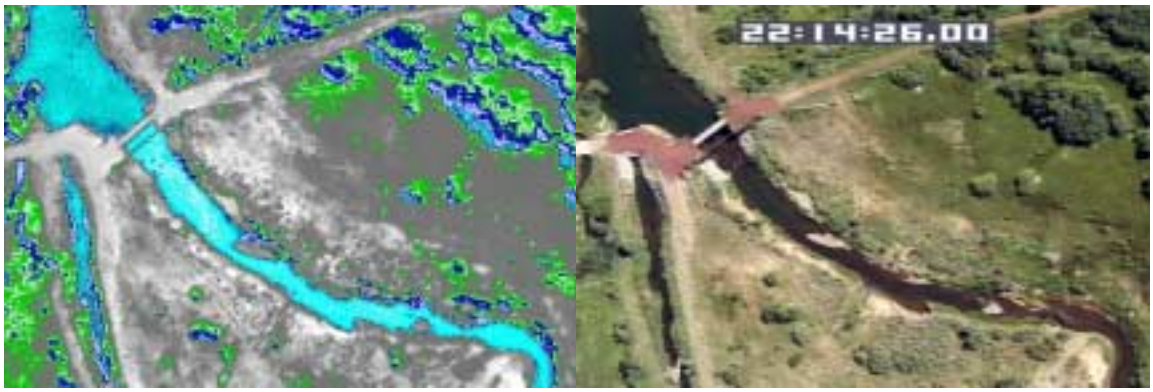

Figure A.60 - Diversion at river mile 44.7 on the Sycan River. The surface water temperature downstream of the diversion is 16.0°C and 17.2°C upstream of the diversion. The temperature difference is evidence of thermal stratification upstream of the diversion. Thermal stratification is common immediately upstream of impoundments (*frame: syc1586*).

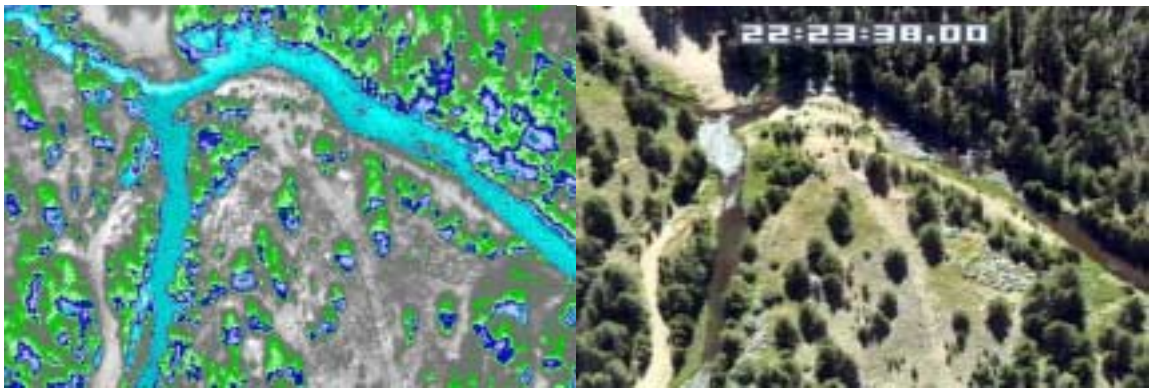

Figure A.61 - Confluence of Paradise Creek (15.7^{o}C) and the Sycan River (17.0^{o}C) at river mile 57.3 (*frame: syc2132*)

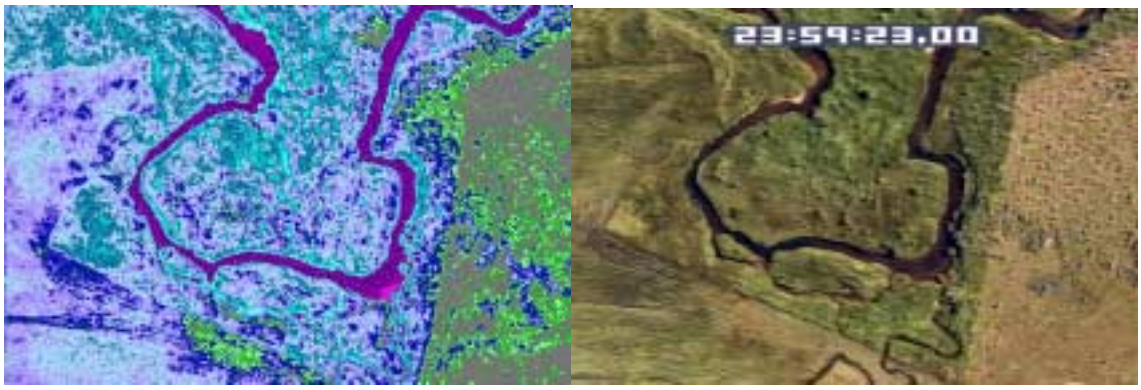

Figure A.62 - Small tributary or Spring inflow (13.0^{o}C) to the Upper Sycan River (14.2^{o}C) at river mile 66.7. The Sycan River flows from left to right in the image and the spring flows in from the bottom of the image. This inflow was not mapped on the USGS 1:24 topographic maps (*frame: sycb0381*)

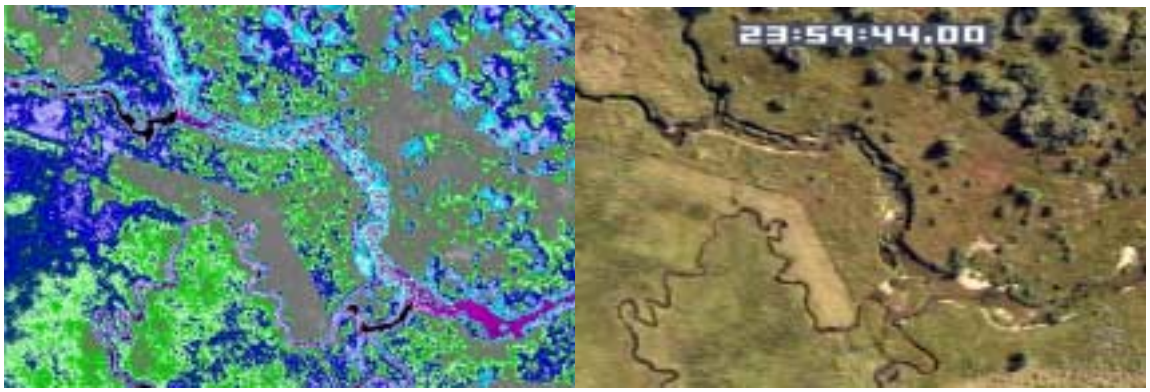

Figure A.63 - Tributary or spring inflows to the upper Sycan River at river mile 67.2. These inflows are not shown on the USGS 1:24k topographic maps, but change the water temperature in the Upper Sycan. The water temperature of the downstream inflow is 9.2°C and the upstream inflow is 8.4°C. The Sycan River water temperature is 15.3°C upstream of these inflows and 13.4°C after the inflows (*frame: sycb0401*).

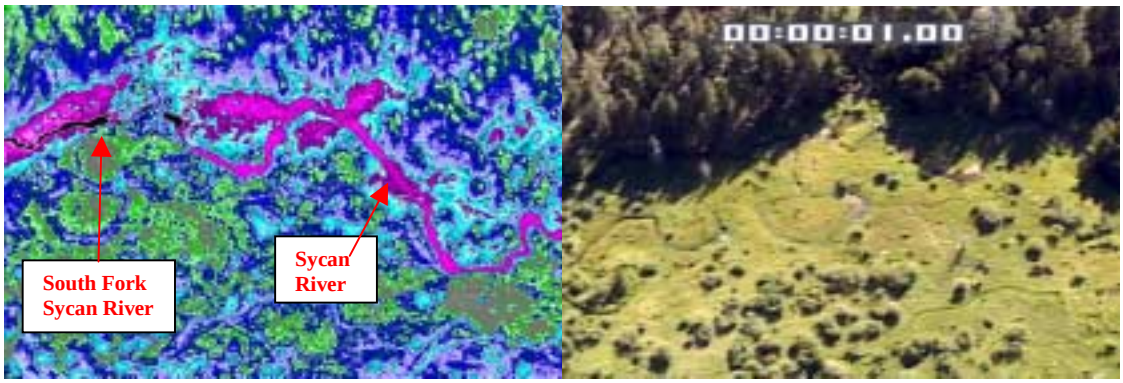

Figure A.64 - Confluence of the South Fork Sycan and the Sycan River at river mile 67.6. The Sycan River upstream of the confluence is almost impossible to detect (*frame: sycb0418*).

Paradise Creek

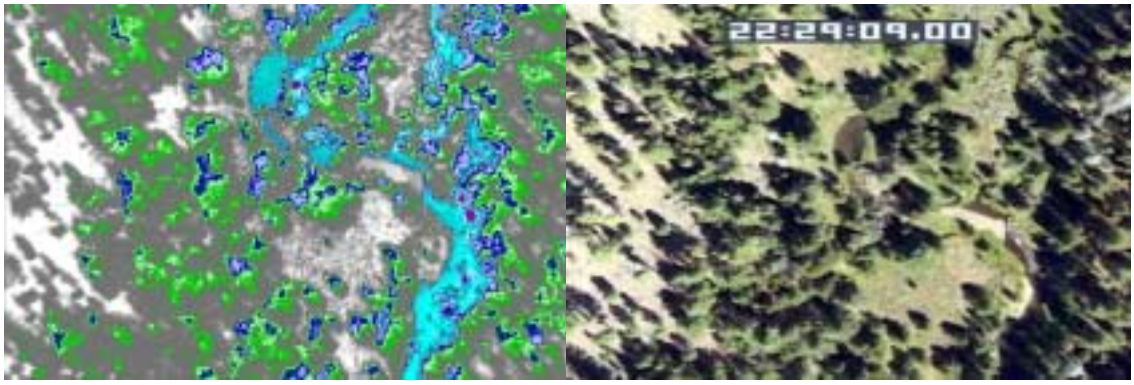

Figure A.65 - Confluence of the Paradise Creek (17.1°C) and Crazy Creek (15.3°C) at river mile 0.5. Paradise Creek flows from the top to the bottom of the image. Crazy Creek is visible on the right bank (*frame: syc2276*).

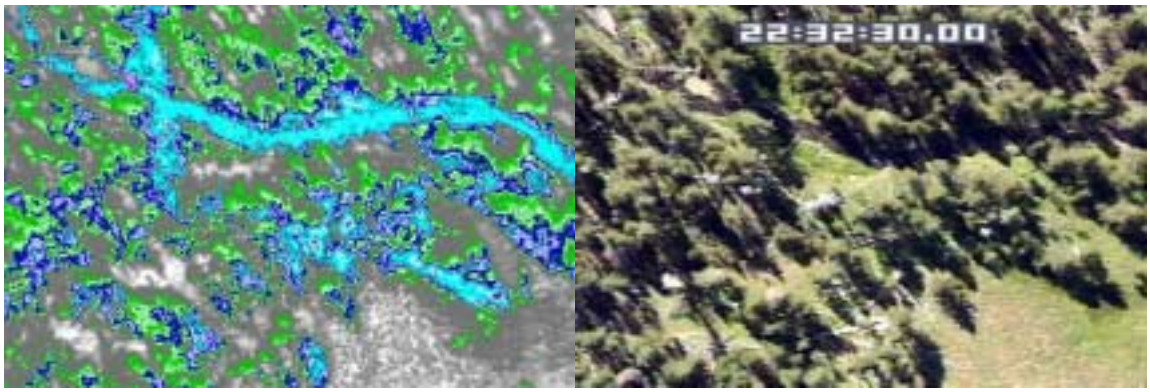

Figure A.66 - Detection of sub-surface input on Paradise Creek at river mile 4.4. Paradise Creek flows from left to right in the image (*frame: syc2471*).

Figure A.67 - Detection of a large spring (5.3°C) on Paradise Creek (13.2°C) at river mile 5.2. Paradise Creek flows from left to right in the imagery. The spring was not mapped on the USGS 1:24k topographic map (*frame: syc2511*).

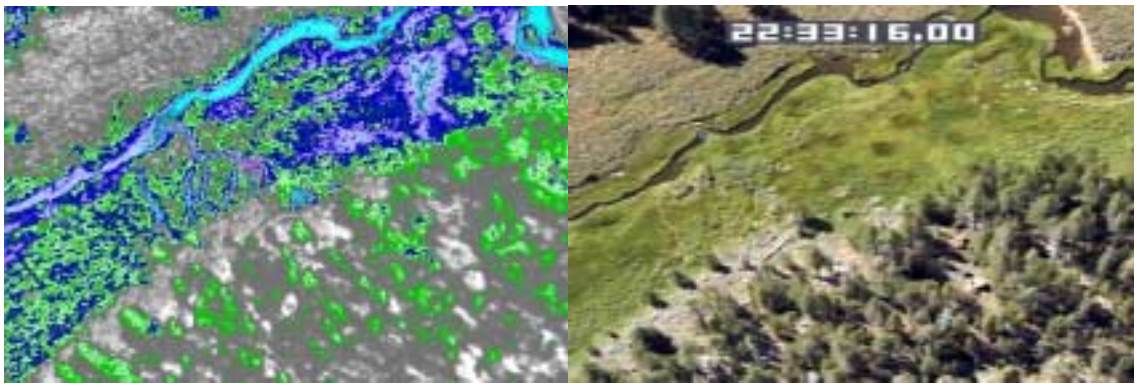

Figure A.68 - Detection of a spring (10.5°C) on Paradise Creek (16.3°C) at river mile 5.2. Paradise Creek flows from left to right in the imagery. The spring was not mapped on the USGS 1:24k topographic map (*frame: syc2515*).