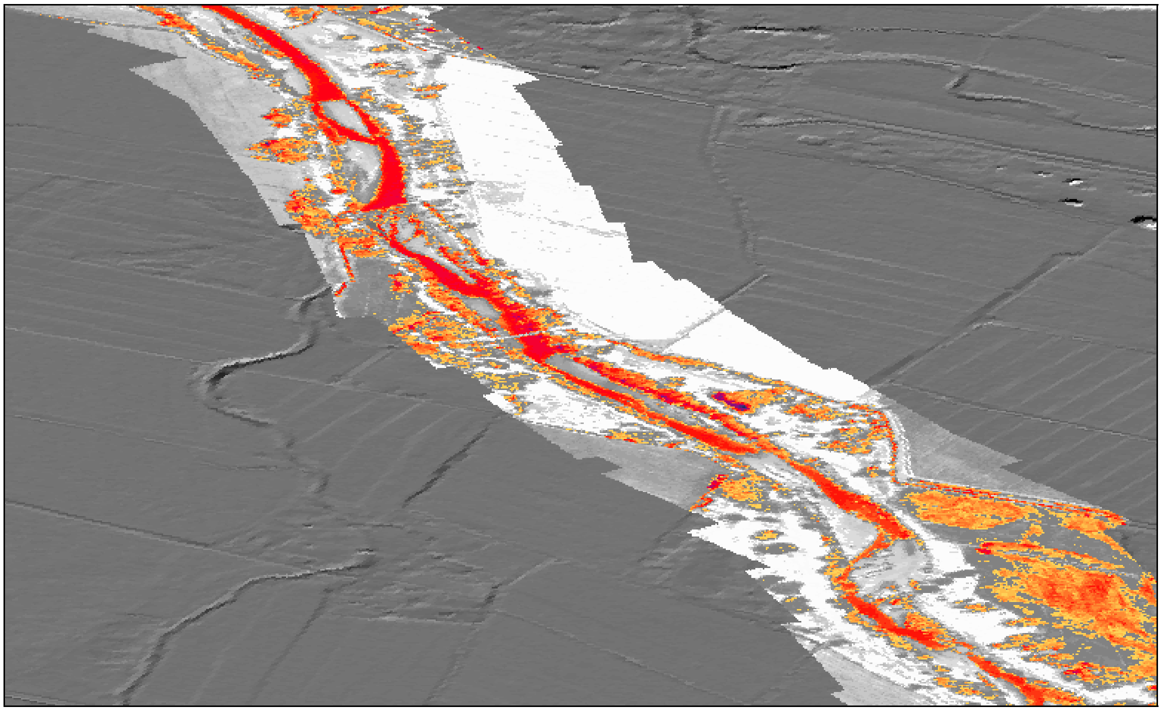
Airborne Thermal Infrared Remote Sensing
Carson River Basin, NV



Submitted to:

Jim Brock
Desert Research Institute
2215 Raggio Parkway
Reno, NV 89512

Submitted by:

Watershed Sciences, Inc.
111 NW 2nd Street, Unit 1
Corvallis, OR 97330

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REPORT FOR THERMAL INFRARED REMOTE SENSING CARSON RIVER, NV

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Background

On August 8 2006, Watershed Sciences conducted an airborne thermal infrared (TIR) survey along selected reaches of the Carson River, NV. The project was conducted under contract and in cooperation with researchers at the Desert Research Institute (DRI), Reno, NV. The TIR image data are intended to support a range of studies in the basin including ground water hydrology and temperature TMDL (total maximum daily load) analysis on the Carson River.

Airborne TIR remote sensing has proven an effective method for mapping spatial temperature patterns in rivers and streams. These data are used to establish baseline conditions and direct future ground level monitoring. The TIR imagery illustrates the location and thermal influence of point sources, tributaries, and surface springs.

The specific objectives of this effort are:

- To spatially characterize surface water temperature patterns and stream flow conditions within the Carson River.
- Combine with other remote sensing and spatial data sets to characterize riparian shading patterns, dynamic surface hydraulics, geomorphology, near-stream land cover, and surface and subsurface water exchange patterns.
- Create GIS compatible data layers that can be used to plan future research, ground based monitoring, and analysis.

This report details the work performed, including methodology and quantitative assessments of data quality. The images contained in this report are not meant to be comprehensive, but provide examples of image scenes and interpretations.

Survey Extent

The TIR survey was conducted in the mid-afternoon on August 8, 2006 and covered the following extents (Figure 1):

<u>Carson River:</u> *21.8 miles (Brunswick Canyon to East/West Fork Confluence).*

<u>East Fork Carson River</u>: *23.5 miles (Mouth to NV/CA Line).*

<u>West Fork Carson River:</u> *17.2 miles (mouth to Paynesville)*

<u>Brockliss Slough:</u> *Entire length of Slough including both East (3.7 miles) and Main (12.7 miles) branches.*

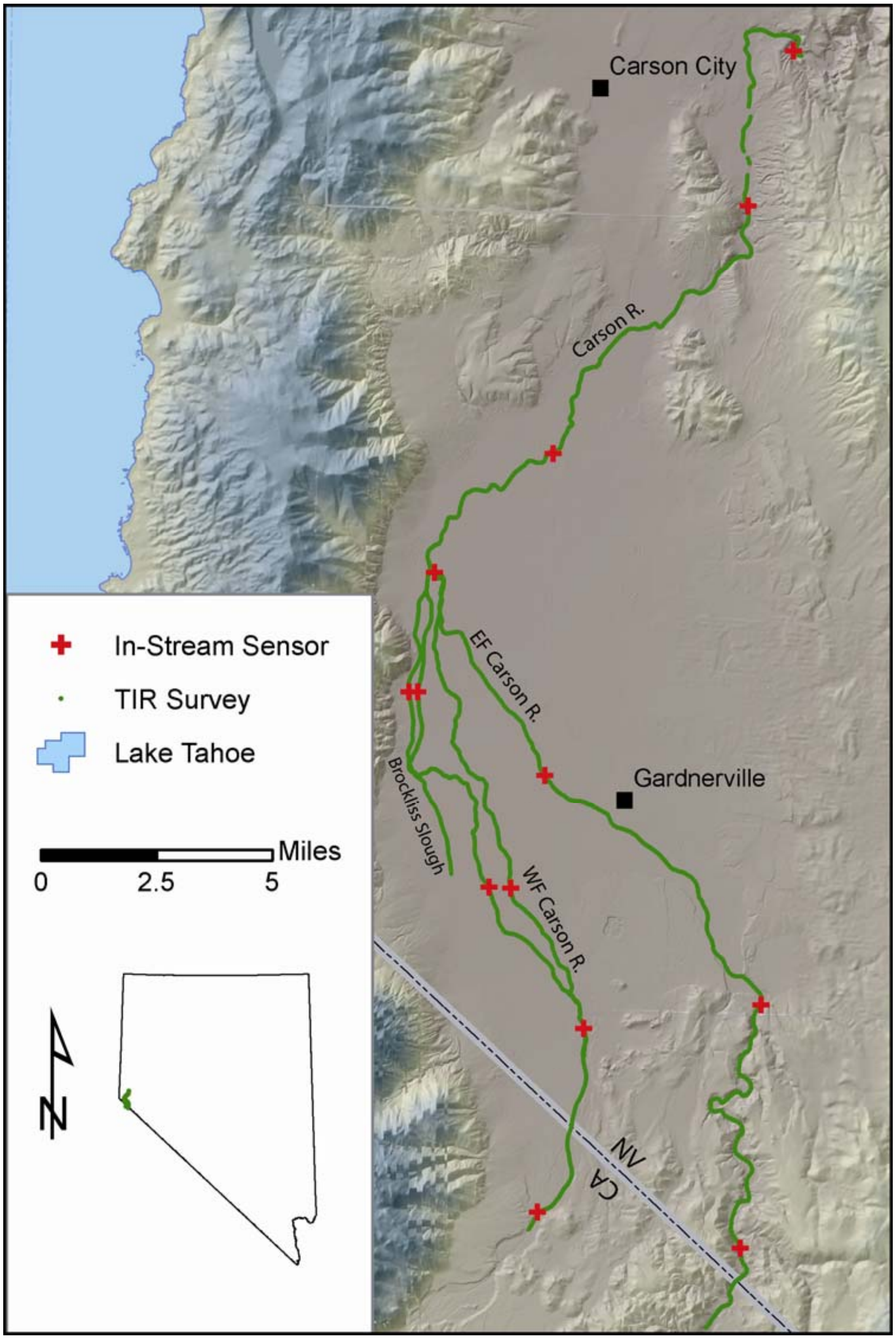


Figure 1 - Map showing the extent of the Carson River TIR survey. The map also shows the general location of in-stream sensors used to calibrate and verify the accuracy of the radiant temperatures derived from the TIR images.

Methods

Data Collection

<u>Instrumentation:</u> Images were collected with a Space Instruments FireMapper 2.0 sensor (8-12µm) mounted on the underside of a Bell Jet Ranger Helicopter (Figure 2). The TIR sensor was co-mounted with a high-resolution true color digital camera (*Nikon D2X w/ 24mm lens, 6.9 mega-pixels*). Both cameras were positioned to look vertically down from the aircraft (nadir). The Firemapper 2.0 is a calibrated radiometer with internal non-uniformity correction and drift compensation. General specifications of the thermal infrared sensor are listed in Table 1.

Thermal infrared images were recorded directly from the sensor to an on-board computer as raw counts, which were than converted to radiant temperatures. The individual images were referenced with time, position, and heading information provided by a global positioning system (GPS).

Figure 2 – Bell Jet Ranger equipped with a thermal infrared radiometer and high resolution digital camera. The sensors are contained in a composite fiber enclosure attached to the underside of the helicopter and flown longitudinally along the stream channel.

Table 1. Summary of TIR sensor specifications.

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

Image Characteristics: The aircraft was flown longitudinally along the stream corridor in order to have the river in the center of the display. The objective was for the stream to occupy 30-60% of the image. The TIR sensor is set to acquire images at its maximum rate (*~1 image/2 seconds*) resulting in considerable vertical overlap between images.

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

Data Processing

Calibration: Prior to the season, the response characteristics of the sensor are measured in a laboratory environment. The response curves related the raw digital numbers recorded by the sensor to emitted radiance from the black body. The raw TIR images collected during the survey initially contain raw digital numbers which are then converted to radiance ($W/m^2*sr*micron$) values based on the pre-season calibration.

The radiance values were adjusted based on a comparison of the measured radiance to the calculated radiance at each ground truth location. This adjustment was performed to correct for path length attenuation and the emissivity of natural water. The in-stream data were assessed at the time the image was acquired, with radiant values representing the median of ten points sampled from the image at the data logger location. The radiance values were then converted to surface temperatures using Planck's Black Body equation.

Interpretation and Sampling: Once calibrated, the images were integrated into a GIS in which an analyst interpreted and sampled stream temperatures. Sampling consisted of querying radiant temperatures (pixel values) from the center of the stream channel and saving the median value of a ten-point sample to a GIS database file. The temperatures of detectable surface inflows (i.e. surface springs, tributaries) were also sampled at their mouths. During sampling, the analyst provided interpretations of the spatial variations in surface temperatures observed in the images.

Geo-referencing: The images are tagged with a GPS position and heading at the time they are acquired. Since the TIR camera is maintained at vertical down-look angles, the geographic coordinates provide a reasonably accurate index to the location of the image scene. Due to the relatively small footprint of the imagery and independently stabilized mount, image pixels are not individually registered to real world coordinates. The image index is saved as an ESRI point shapefile containing the image name registered to an X and Y position (UTM Zone 11, NAD83) of sensor location at time of capture. In order to provide further spatial reference, the TIR images were assigned a river mile based on a routed stream layer (Figure 3).

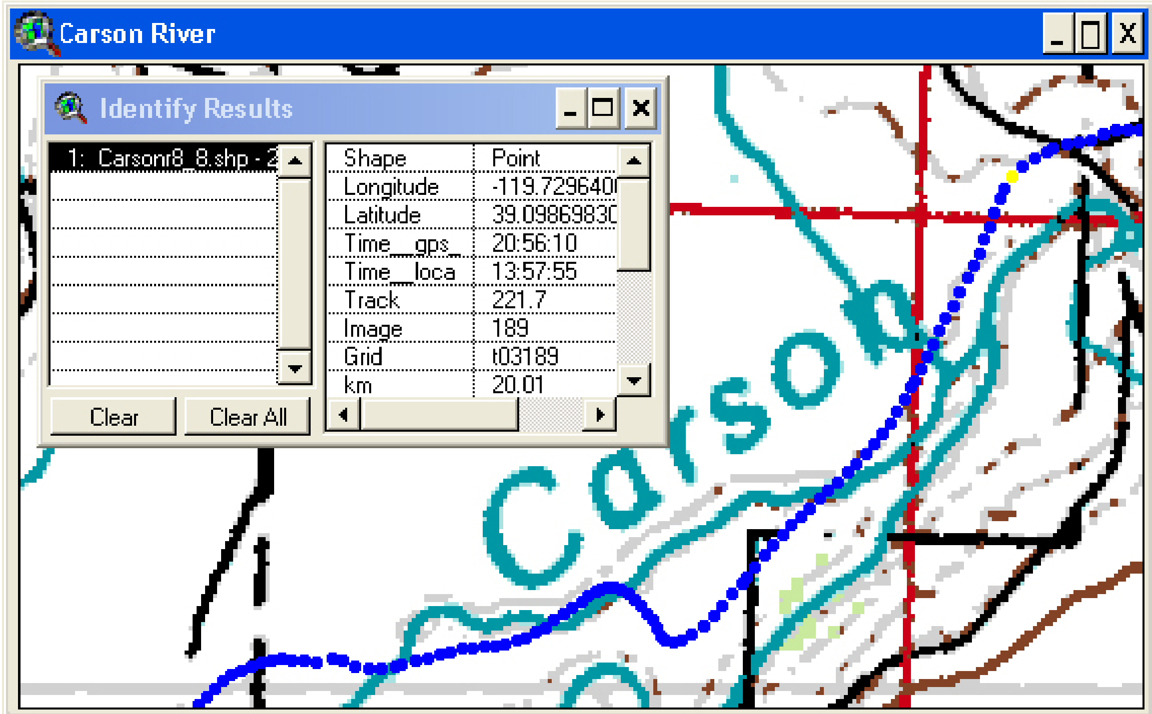


Figure 3 –Each point on the map represents a thermal image location. The inset box shows the information recorded with each image point during acquisition.

Temperature Profiles: The median temperatures for each sampled image were plotted versus the corresponding river mile to develop a longitudinal temperature profile. The profile illustrates how stream temperatures vary spatially along the stream gradient. The location and median temperature of all sampled surface water inflows (e.g. tributaries, surface springs, etc.) are included on the plot to illustrate how these inflows influence the main stem temperature patterns. Radiant temperatures were only sampled along what appeared to be the main flow channel in the river.

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

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

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

Thermal Image Characteristics

Surface Temperatures: Thermal infrared sensors measure TIR energy emitted at the water's surface. Since water is essentially opaque to TIR wavelengths, the sensor is only measuring water surface temperature. Thermal infrared data accurately represents bulk water temperatures where the water column is thoroughly mixed; however, thermal stratification can form in reaches that have little or no mixing. Thermal stratification in a free flowing river is inherently unstable due to variations in channel shape, bed composition, and in-stream objects (i.e. rocks, trees, debris, etc.) that cause turbulent flow and can usually be detected in the imagery.

Expected Accuracy: Thermal infrared radiation received at the sensor is a combination of energy emitted from the water's surface, reflected from the water's surface, and absorbed and re-radiated by the intervening atmosphere. Water is a good emitter of TIR radiation and has relatively low reflectivity (~ 4 to 6%). However, variable water surface conditions (i.e. riffle versus pool), slight changes in viewing aspect, and variable background temperatures (i.e. sky versus trees) can result in differences in the calculated radiant temperatures within the same image or between consecutive images. The apparent temperature variability is generally less than 0.5°C (Torgersen et al. 2001[2]). However, the occurrence of reflections as an artifact (or noise) in the TIR images is a consideration during image interpretation and analysis. In general, apparent stream temperature changes of < 0.5°C are not considered significant unless associated with a surface inflow (e.g. tributary).

Differential Heating: In stream segments with flat surface conditions (i.e. pools) and relatively low mixing rates, observed variations in spatial temperature patterns can be the result of differences in the instantaneous heating rate at the water's surface. In the TIR images, indicators of differential surface heating include seemingly cooler radiant temperatures in shaded areas compared to surfaces exposed to direct sunlight.

Feature Size and Resolution: A small stream width logically translates to fewer pixels "in" the stream and greater integration with non-water features such as rocks and vegetation. Consequently, a narrow channel (relative to the pixel size) can result in higher inaccuracies in the measured radiant temperatures. This is a consideration when sampling the radiant temperatures at tributary mouths and surface springs.

Temperatures and Color Maps: The TIR images collected during this survey consist of a single band. As a result, visual representation of the imagery *(in a report or GIS environment*) requires the application of a color map or legend to the pixel values. The selection of a color map should highlight features most relevant to the analysis (i.e. *spatial variability of stream temperatures*). For example, a continuous, gradient style

[2] Torgersen, C.E., R. Faux, B.A. McIntosh, N. Poage, and D.J. Norton. 2001. Airborne thermal remote sensing for water temperature assessment in rivers and streams. *Remote Sensing of Environment* 76(3): 386-398.

color map that incorporates all temperatures in the image frame will provide a smoother transition in colors throughout the entire image, but will not highlight temperature differences in the stream. Conversely, a color map that focuses too narrowly cannot be applied to the entire river and will "washout" terrestrial and vegetation features.

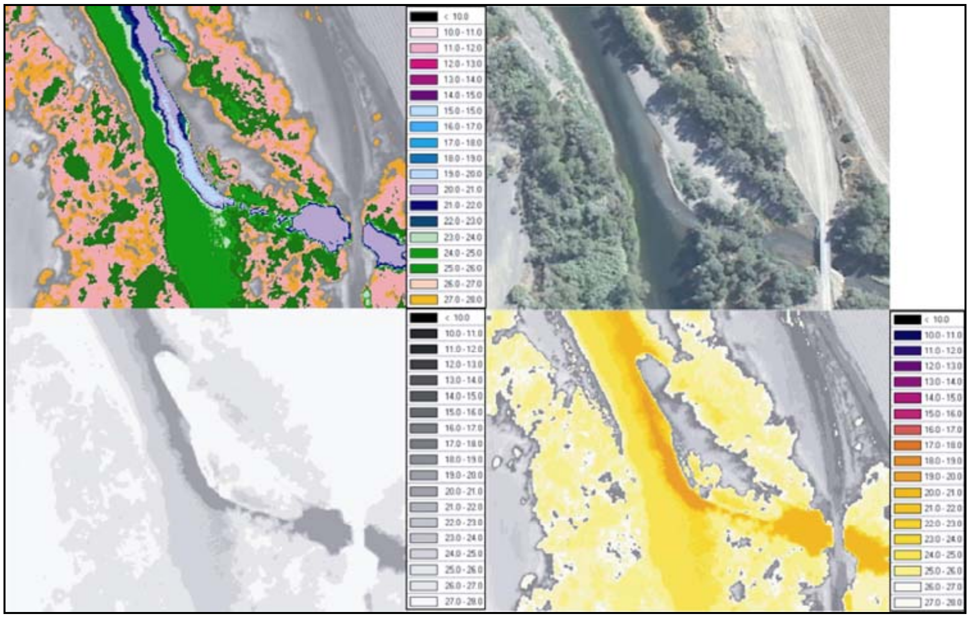


Figure 4 - Example of different color maps applied to the same TIR image.

Image Uniformity: The TIR sensor used for this study uses a focal plane array of detectors to sample incoming radiation. A challenge when using this technology is to achieve uniformity across the detector array. This sensor has an automatic correction scheme which nearly eliminates non-uniformity across the image frame.

Acquisition Parameters

Table 1. Summary of Thermal Image Acquisition Parameters.

Date:	August 8, 2006
Flight Above Ground Level (AGL):	335 m (1100 ft)
Image Footprint Width:	276 m (905 ft)
Pixel Resolution:	0.86 m (2.83 ft)

Weather Conditions

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

Table 2 – Weather conditions in Carson City during the date and time of the TIR survey.

Time PDT	Air Temp °F	Air Temp °C	Humidity %	Wind Direction	Wind Speed MPH	Conditions
Carson City, NV 8-Aug-06						
12:56 PM	81.0	27.2	11.0	Variable	6.9	Clear
1:56 PM	84.9	29.4	8.0	WSW	15.0	Clear
2:25 PM	86.0	30.0	7.0	SW	11.5	Clear
2:56 PM	86.0	30.0	7.0	WNW	16.1	Clear
3:56 PM	84.9	29.4	9.0	NW	13.8	Clear
4:56 PM	86.0	30.0	10.0	WNW	18.4	Clear
5:56 PM	84.0	28.9	13.0	WNW	15.0	Partly Cloudy

Figure 5 – Oblique digital image of the hills outside of Reno taken on August 9, 2006. The weather conditions were considered ideal for TIR surveys on both August 8-9.

Thermal Accuracy

Table 3 provides a comparison between the kinetic temperatures recorded by the in-stream data loggers and the radiant temperatures derived from the TIR images. Since the in-stream data were used to compute an adjustment to the radiant temperatures, they should not be considered an independent check of radiant temperatures. The correction was computed as an average offset from the raw radiant values for all sensor locations.

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

Serial	Pass	Image	Local	Kinetic T©	Radiant T©	Difference T©
Carson R.						
659413	2	IR1-00039	13:40	24.5	24.4	0.1
540663	2	IR1-00296	13:48	19.6	19.9	-0.3
659412	3	IR1-00475	14:07	24.4	24.4	0.0
540664	4	IR1-00254	14:19	24.4	24.7	-0.3
East Fork Carson R.						
1026259	5	IR1-00278	14:32	24.2	24.4	-0.2
1026266	6	IR1-00316	14:46	20.8	20.7	0.1
Border Rd	7	IR1-00328	15:01	19.8	19.0	-0.9
West Fork Carson						
882338	8	IR1-0015	15:08	18.1	18.0	0.1
766181	9	IR1-0040	15:19	20.0	19.7	0.3
882337	9	IR1-0260	15:26	21.3	21.5	-0.2
540664	10	IR1-0385	15:42	25.1	25.0	0.1
Brockliss Slough						
540664	11	IR1-0011	15:48	25.1	25.1	0.0
1026262	11	IR1-0113	15:51	24.3	24.5	-0.2
766181	12	IR1-0018	16:37	20.7	20.5	0.2
766182	12	IR1-0182	16:45	19.3	19.0	0.3
1026265	13	IR1-0303	16:57	20.0	22.4	-2.4

Results

Carson River

Longitudinal Temperature Profile

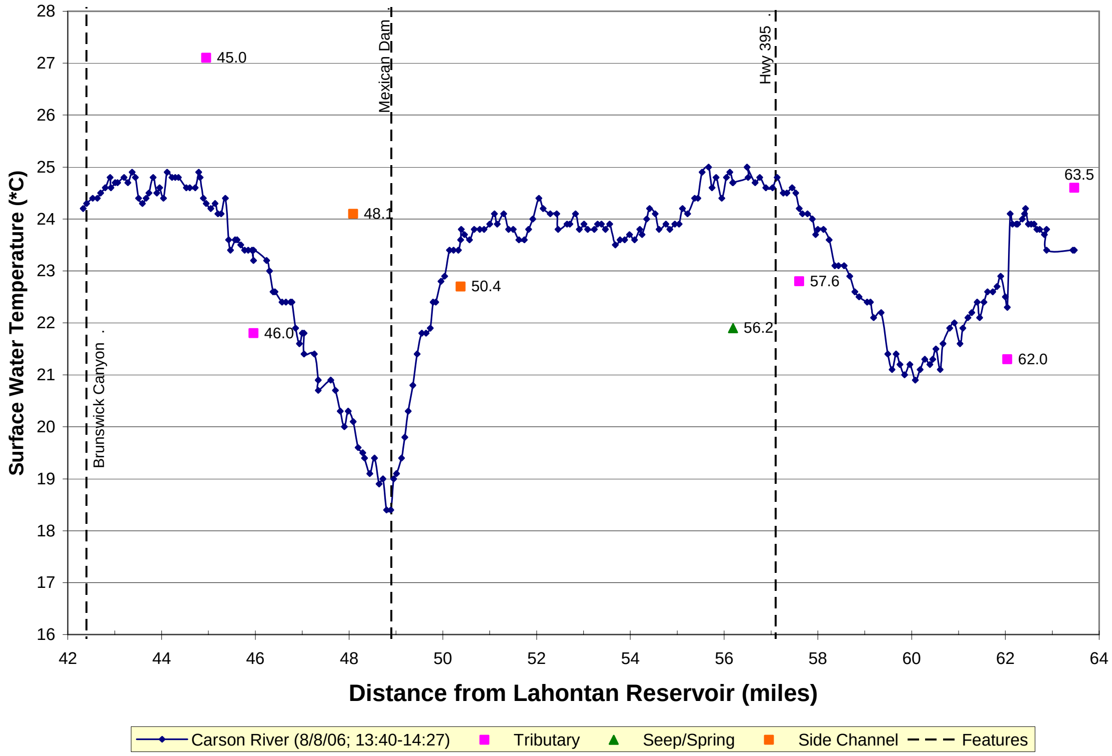


Figure 6 - Median channel temperatures plotted versus river mile for the Carson River. The locations of detected surface inflows are illustrated on the profile and labeled by river mile.

Table 4 - Tributaries and other surface inflows sampled along the Carson River.

Tributary Name	km	mile	Tributary °C	Carson R. °C	Difference °C
Tributary					
Unnamed Inflow (LB)	72.3	45.0	27.1	24.3	2.8
Unnamed Inflow (LB)	74.0	46.0	21.8	23.2	-1.4
Unnamed Inflow (RB)	92.7	57.6	22.8	24.2	-1.4
Brockliss Slough (LB)	99.9	62.0	21.3	24.1	-2.8
WF Carson R. (LB)	102.2	63.5	24.6	23.4	1.2
Seep/Spring					
Seep (RB)	90.4	56.2	21.9	24.7	-2.8
Side Channel					
Side Channel (RB)	77.4	48.1	24.1	20.1	4.0
Side Channel (LB)	81.1	50.4	22.7	23.6	-0.9

Observations and Analysis

The airborne TIR survey of the Carson River extended from Brunswick Canyon upstream to the East Fork Carson River. For the purpose of creating the longitudinal temperature profile, sampled radiant temperatures were assigned a river mile based on the distance from the Lahontan Reservoir. The longitudinal profile illustrates how radiant stream temperatures vary spatially along the stream gradient. Inspection of the profile (Figure 6) in relation to sampled inflows and basin topography can provide indications of the processes that are driving stream temperatures at different spatial scales. The Carson River profile shows a range of radiant temperatures between 18.4°C and 25.0°C with distinct warming and cooling reaches.

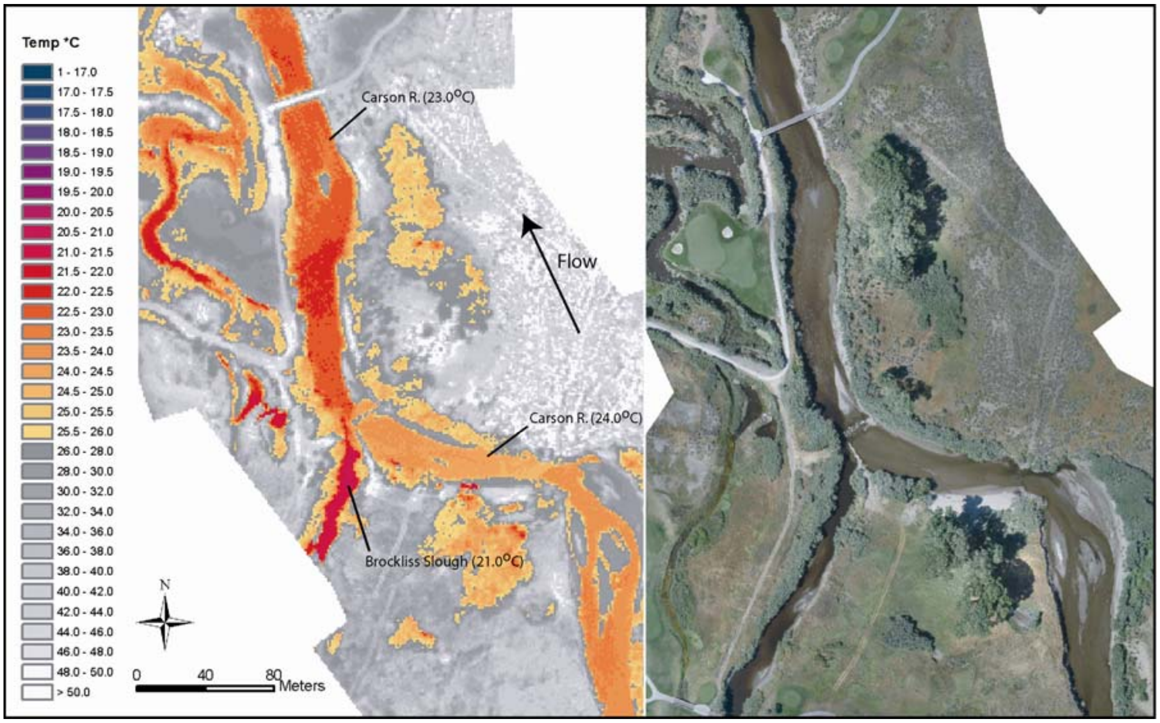
The Brockliss Slough enters the Carson River ~1.5 miles downstream of the West Fork confluence and was observed as a source of cooling to the main stem (*Sample Image Carson1*). Bulk water temperatures in the main stem continued to cool downstream of the Brockliss Slough reaching a local minimum of 20.9°C at mile 60.1. The river transitions along a golf course and several off-channel ponds were observed along this reach, however, the source of cooling could not be determined through further inspection of the imagery. Between mile 60.1 and the Hwy 395 overpass, radiant water temperatures increased rapidly reaching ~24.8°C.

Stream temperatures remained relatively warm downstream of the Hwy 395 overpass (above 24.5°C) before decreasing by ~1.2°C at river mile 55.5. A “seep” was sampled at rive mile 56.2, which may provide some indication of the source of cooling (*Sample Image Carson2*). A seep is detected as water that emerges within the alluvial floodplain that has a temperature difference from bulk water temperatures. Seeps are normally small features when compared to other inflows but are often indicators of larger physical processes such as hyporheic flow. Stream temperatures remain relatively constant (~23.9°C, ±0.5°C) over the next five miles.

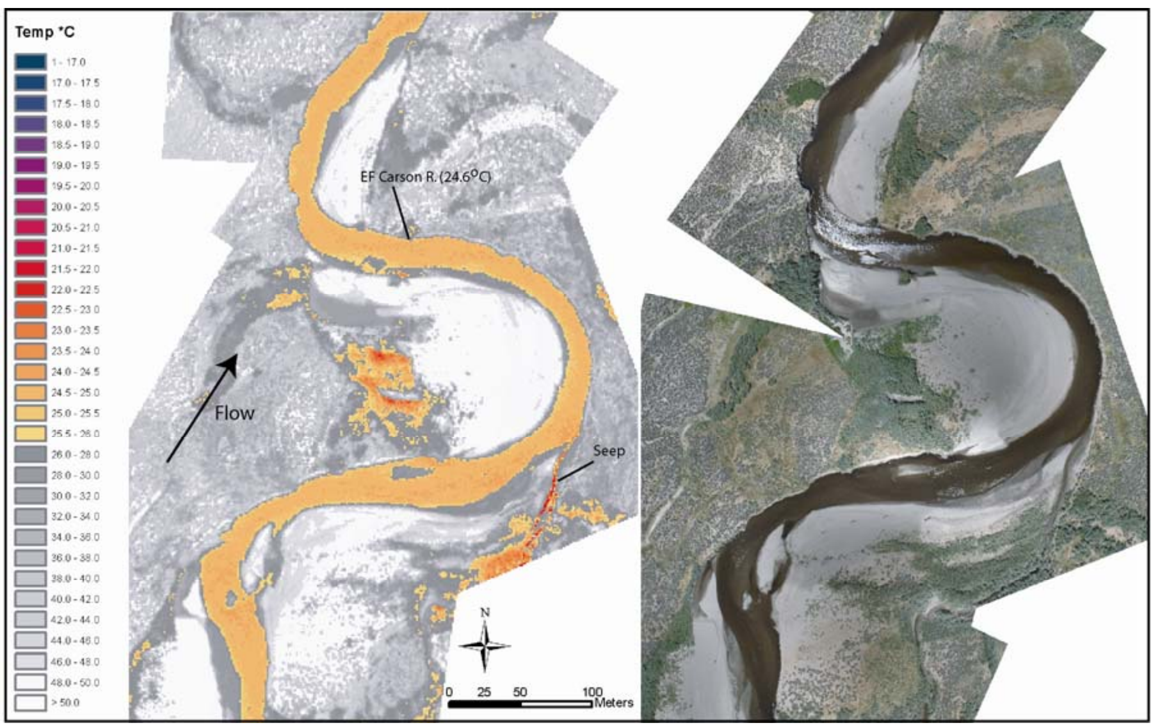
Between river mile 51.1 and 48.9, radiant water temperatures decreased rapidly from 23.1°C to 18.4°C. Inspection of the USGS 1:24K base layers shows that this decrease occurs as the river leaves the Carson Valley and enters the more constricted reach around Prison Hill. Although no surface springs were detected, the 5.4°C water decrease over a 2.2 mile stream segment suggests ground water influence through this reach. The location of this decrease suggests that shallow ground water in the valley is being forced back into the channel by the more confined morphology of the canyon. Moving downstream, stream temperatures increased rapidly again from river mile 48.9 to 44.8 suggesting the absence of the source of cooling was no longer present in this reach.

Overall, the Carson River did not exhibit a high degree of local spatial variability, but showed distinct patterns of warming and cooling at the reach scale. Of the five surface inflows sampled during the analysis, four contributed water that was cooler than the main stem.

Sample Images



Sample image Carson1 – TIR and true color image showing the confluence of the Carson River and Brockliss Slough. The Slough was observed as a cooling source to the Carson River.



Sample Image Carson2 – TIR and true color image showing the Carson River at mile 56.2. The TIR image illustrates a small seep emerging along the right bank of the stream channel.

East Fork Carson River

Longitudinal Temperature Profile

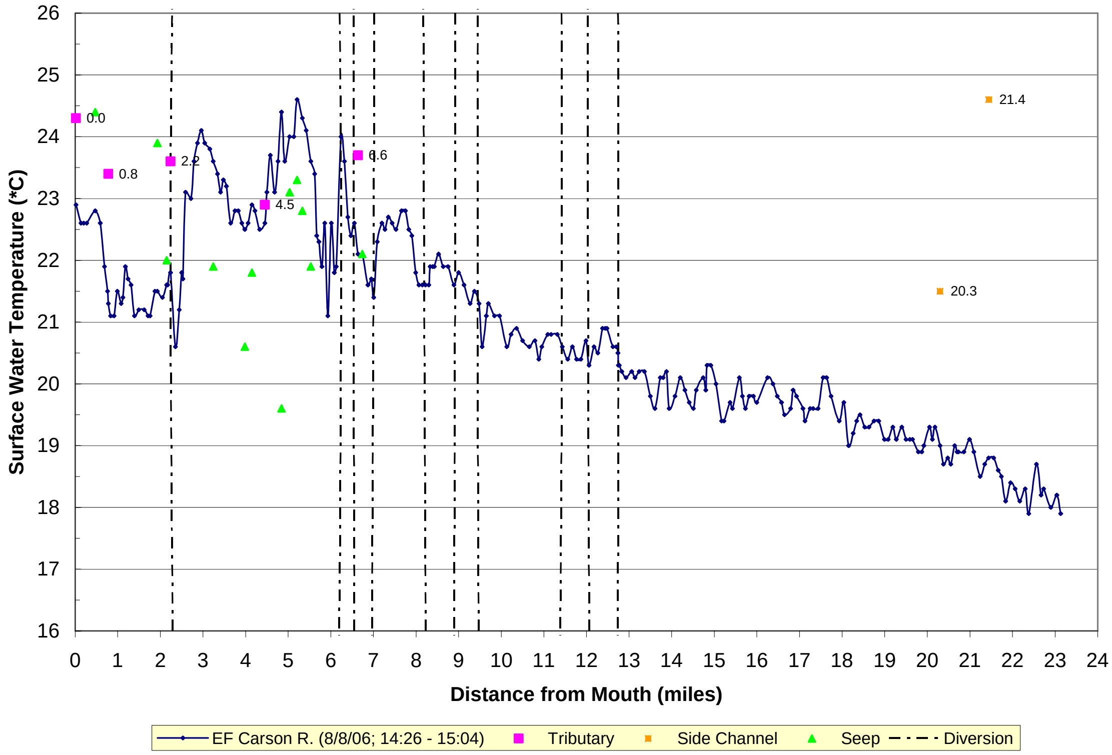


Figure 7 - Median channel temperatures plotted versus river mile for the East Fork Carson River. The locations of detected surface inflows (i.e. tributaries, irrigation returns, and seeps) are illustrated on the profile and summarized in Table 5.

Observations and Analysis

The East Fork Carson River was surveyed from the mouth upstream to ~1.5 miles over the California/Nevada State Line (~23.5 miles). At the upstream end of the survey, radiant water temperatures in the East Fork were ~17.7°C and warmed steadily downstream reaching ~20.1°C at river mile 17.6. Byrant Creek was detected at mile 20.7 but did not have sufficiently visible surface flow to obtain a radiant temperature sample (*sample image EF1*). Two side channels were sampled that had warmer surface temperatures than the main channel.

Table 5 - Tributaries and other surface inflows sampled along the East Fork Carson River.

Tributary Name	km	Mile	Tributary °C	EF Carson R. °C	Difference °C
Tributary					
WF Carson R. (LB)	0.0	0.0	24.3	22.9	1.4
Unnamed Tributary (LB)	1.3	0.8	23.4	21.3	2.1
Off Channel Ponds (LB)	3.6	2.2	23.6	21.8	1.8
Unnamed Inflow (RB)	7.2	4.5	22.9	22.6	0.3
Unnamed Inflow (LB)	10.7	6.6	23.7	22.1	1.6
Side Channel					
Side Channel (RB)	32.7	20.3	21.5	19.0	2.5
Side Channel (RB)	34.5	21.4	24.6	18.8	5.8
Seep					
Seep (LB)	0.8	0.5	24.4	22.8	1.6
Seep (LB)	3.1	1.9	23.9	21.5	2.4
Seep (LB)	3.5	2.2	22.0	21.6	0.4
Seep (LB)	5.2	3.2	21.9	23.6	-1.7
Seep (RB)	6.4	4.0	20.6	22.5	-1.9
Seep (RB)	6.7	4.2	21.8	22.9	-1.1
Seep (LB)	7.8	4.8	19.6	24.4	-4.8
Seep (LB)	8.1	5.0	23.1	24.0	-0.9
Seep (LB)	8.4	5.2	23.3	24.6	-1.3
Seep (RB)	8.6	5.3	22.8	24.3	-1.5
Seep (LB)	8.9	5.5	21.9	23.6	-1.7
Seep (LB)	10.9	6.7	22.1	22.1	0.0

Measured surface temperatures remained relatively constant (~19.8°C) between river mile 17.7 and 12.7 with no definitive patterns of warming/cooling. Inspection of the profile illustrated some local variability where temperatures changed by 0.5-0.9°C over relatively short distances (i.e. miles 17.6 and 15.2). On low flow streams, these patterns of rapid warming and cooling can indicate localized sub-surface exchanges within the active channel. However, no definitive sources were detected through inspection of the imagery and the observed changes in temperatures were just slightly more than expected noise levels.

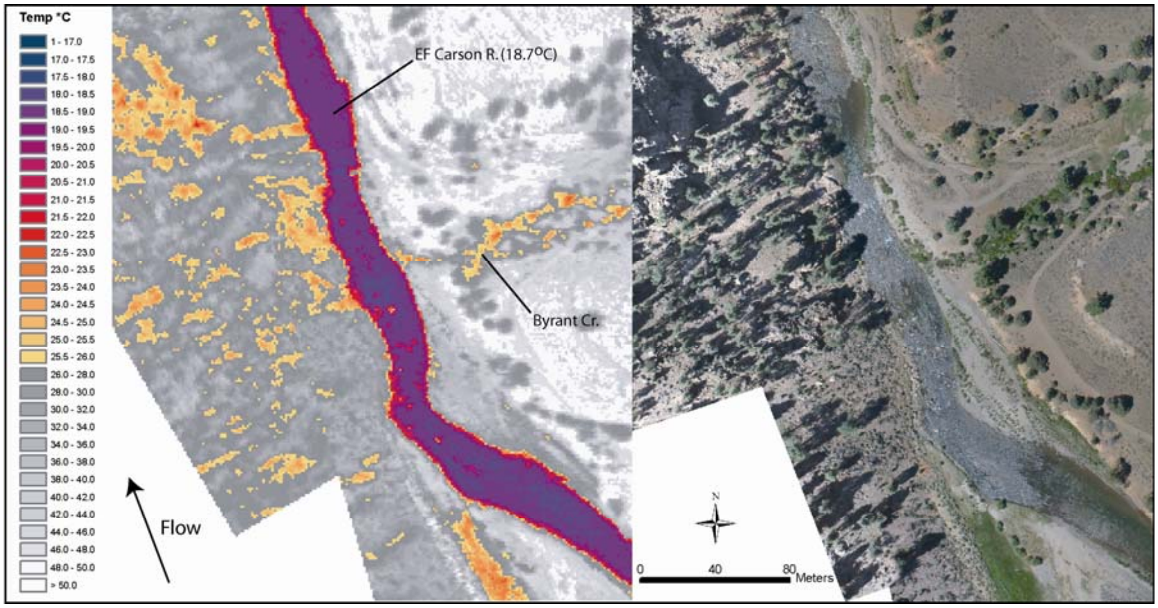
The thermal character of the East Fork changed downstream of river mile 12.7 (*sample image EF2*). There were no flow diversions or significant surface inflows detected from mile 23.5 to mile 12.7. However, from mile 12.7 (approximately Washoe Rd. Bridge) to the mouth, a total of ten flow diversions were noted in the imagery. While the upstream reaches exhibited a modest temperature increase (~2.2°C), the lower 12.7 showed both a high degree of local variability and increased longitudinal heating.

Moving downstream from river mile 12.7, radiant water temperatures in the East Fork increased steadily reaching 22.0°C at mile 8.5. The slight increase in temperatures at river mile 12.5 and the subsequent decrease at river mile 12.3 appeared to be an artifact of the remote sensing (*i.e. slight reflection differences or differential surface heating*) rather than an actual change in bulk temperatures. A decrease in radiant water temperatures was also noted upstream of a diversion dam at river mile 9.6. Surface water behind impoundments are typically the same or warmer than bulk water temperatures due to thermal stratification or differential heating at the stream surface. However, on calm pools the difference between spectral (pool) and diffuse (riffles) reflectance can result in calm pools appearing slight cooler (i.e. 0.5°C) cooler than bulk temperatures.

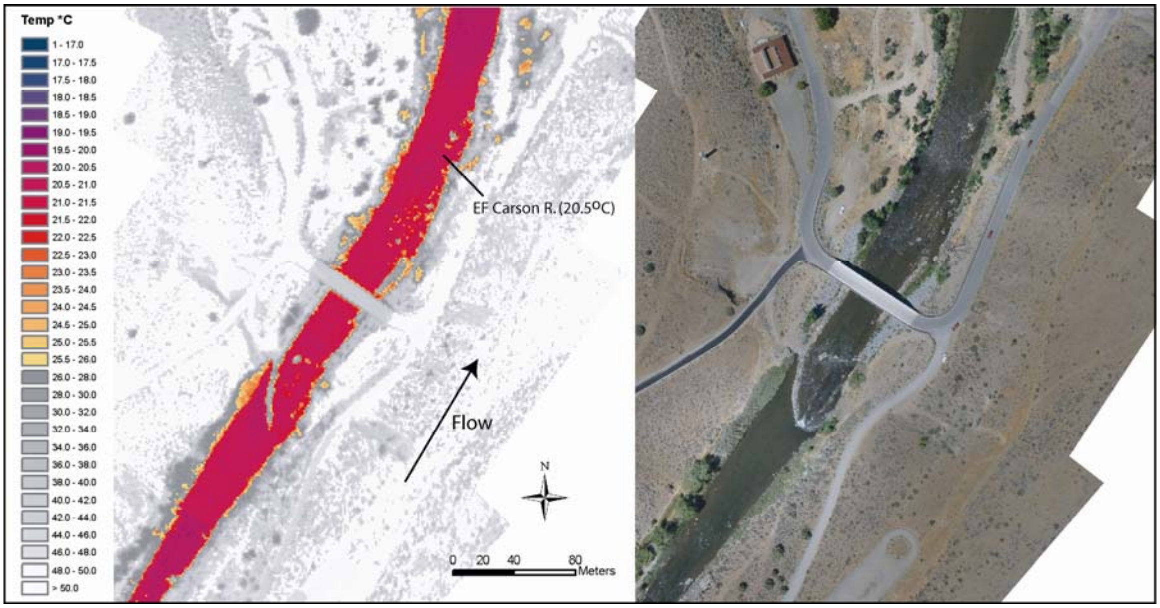
Below river mile 8.5, the East Fork Carson River begins to exhibit both warmer temperatures and considerably more local variability. Stream temperatures ranged from a maximum of 24.6°C (mile 5.2) to a local minimum of 20.6°C at river mile 2.4. The flow diversions appeared to contribute considerably to the observed spatial temperature variability as the apparent level of surface flow changed considerably in the lower reaches (*Sample Image EF3*). In addition, a large number of seeps (12) were detected within the lower reaches. Surface water was considered a seep if it originated from within the alluvial channel. The seeps were sampled where they re-entered the main channel. In most cases, the seep originated cooler than the main stem. The detection of seeps within these reaches indicates hyporheic discharge as a possible source of cooling in the lower East Fork.

The spatial temperature patterns observed in the lower 8.5 river miles are characteristic of low gradient streams in which a combination of physical processes are influencing bulk water temperatures. In the case of the East Fork, flow diversions, shallow sub-surface exchanges within the active channel, and a number of surface inflows combine with normal heating processes to produce a high degree of local spatial temperature variability.

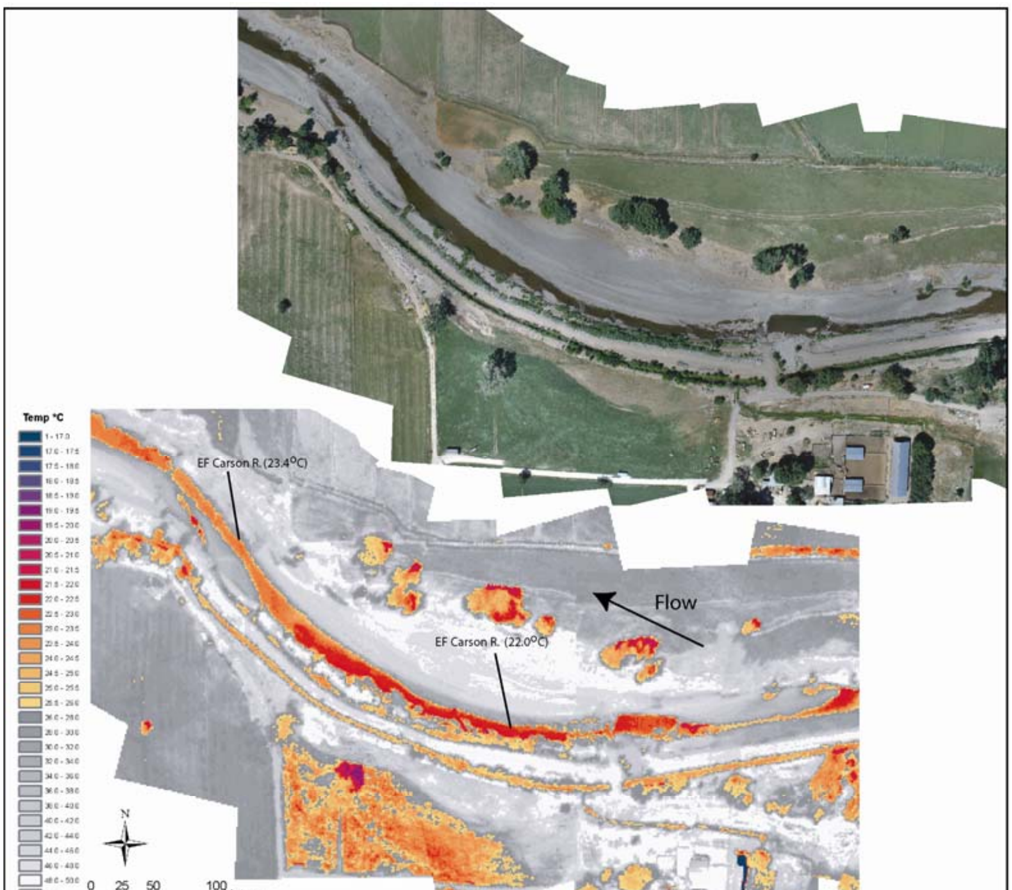
Sample Images



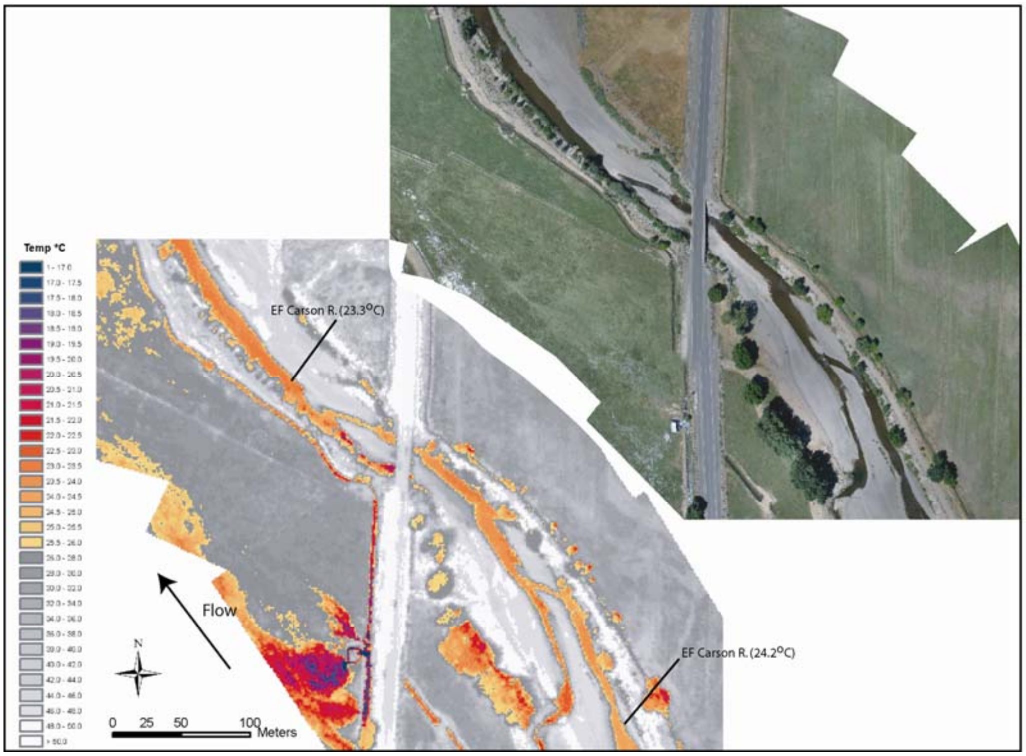
Sample image EF1 – TIR and true color image showing the confluence of the East Fork Carson River and Bryant Creek at mile 20.7. Bryant Creek was detected in the imagery but was considered too small to obtain an accurate radiant temperature sample.



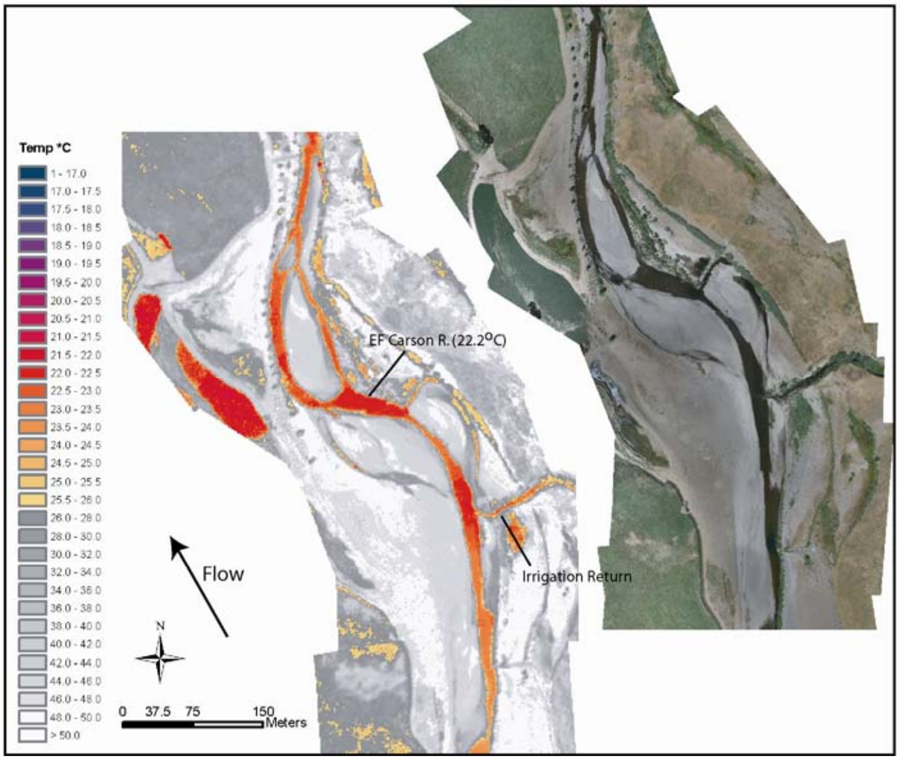
Sample Image EF2 – TIR and true color image showing an impoundment upstream of the Washoe Road Bridge at mile 12.7. The thermal character of the river changed considerably downstream of this location.



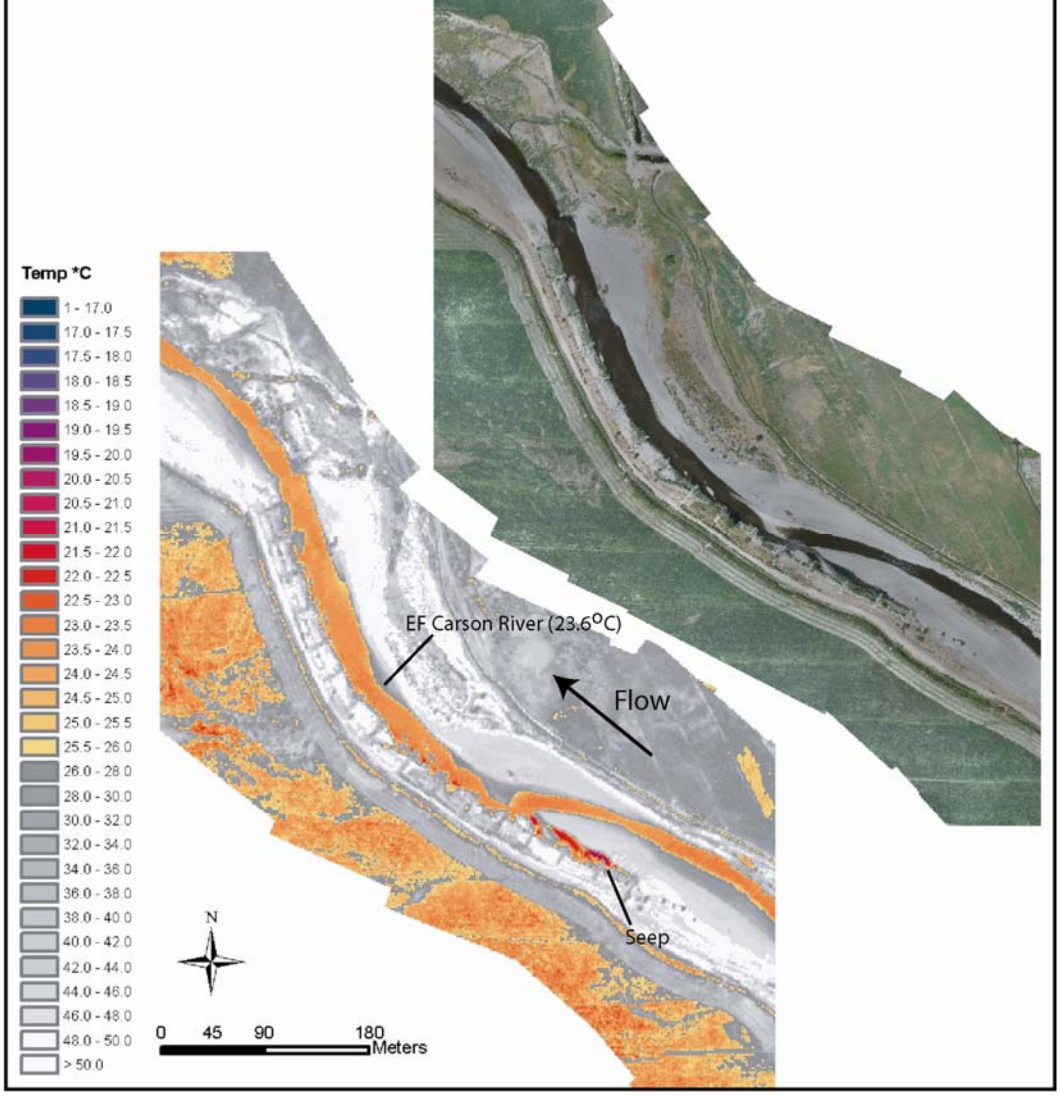
Sample Image EF3 – TIR and true color image showing significant spatial thermal variability between river miles 5.3 and 6.0. The variability appeared to be a combination of the effects of the impoundment/ diversion and shallow sub-surface exchanges.



Sample Image EF4 – TIR and true color image showing the EF Carson River mile 4.9. A seep is visible under the bridge which appears to influence main stem temperatures significantly.



Sample Image EF5 – TIR and true color image showing irrigation return flow to the East Fork Carson River at mile 4.5. The image shows the characteristics of the stream channel within this reach.



Sample Image EF6 – TIR and true color image showing the East Fork Carson River at mile 3.2. The in-channel seep along the left bank is cooler than the mainstem. Detection of similar seeps suggests that hyporheic flow is a process that buffers stream heating in the lower river.

West Fork Carson River

Longitudinal Temperature Profile

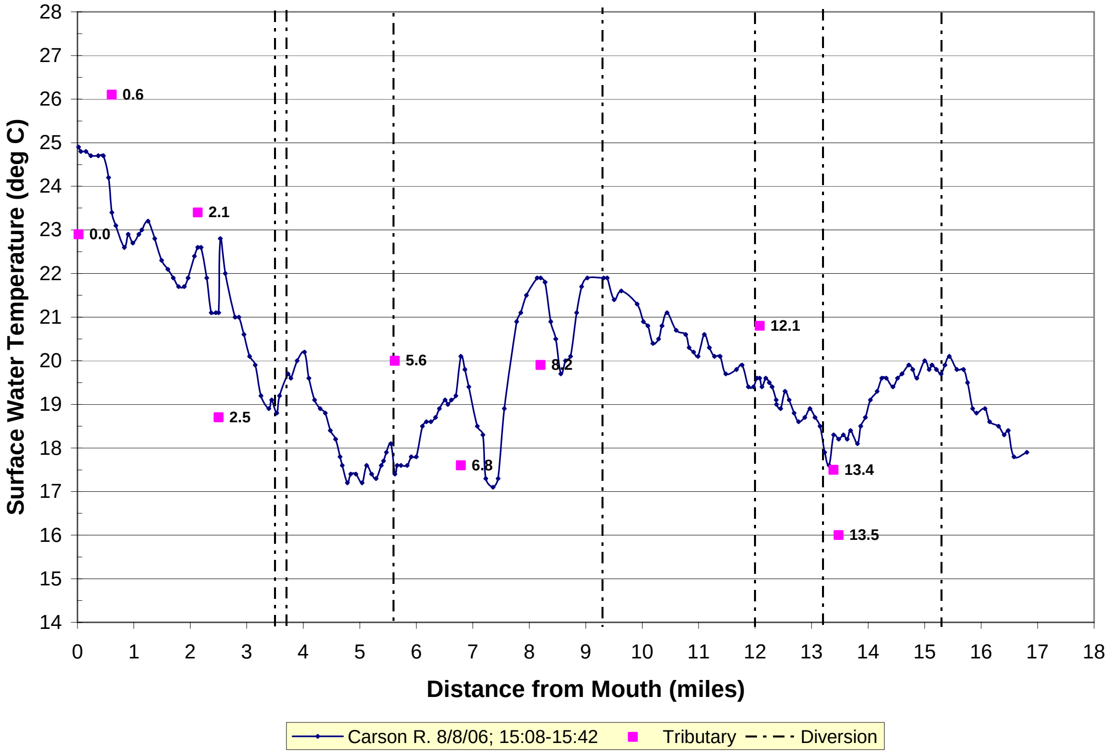


Figure 8 - Median stream temperatures plotted versus river mile for the West Fork Carson River. The tributary temperatures are labeled on the profile by river mile. The locations of major diversions are also shown on the profile to add additional context to the spatial temperature patterns.

Table 6 - Tributaries and other surface inflows sampled along the West Fork Carson River.

Tributary Name	Image	km	mile	Tributary °C	WF Carson R. °C	Difference °C
Unnamed Inflow (RB)	134	21.7	13.5	16.0	18.2	-2.2
Unnamed Inflow (RB)	137	21.6	13.4	17.5	18.3	-0.8
Unnamed Inflow (LB)	35	19.5	12.1	20.8	19.6	1.2
Unnamed Inflow (LB)	243	13.2	8.2	19.9	21.9	-2.0
Rocky Creek (RB)	55	10.9	6.8	17.6	20.1	-2.5
Unnamed Inflow (RB)	104	9.1	5.6	20.0	17.4	2.6
Unnamed Inflow (RB)	240	4.0	2.5	18.7	21.1	-2.4
Irrigation Return (RB)	255	3.4	2.1	23.4	22.6	0.8
Home Slough (RB)	314	1.0	0.6	26.1	23.4	2.7
EF Carson River (RB)	334	0.0	0.0	22.9	24.9	-2.0

Observations and Analysis

Radiant temperatures in the West Fork Carson River exhibited considerable spatial variability along the stream gradient. The West Fork was characterized by a number of diversions, sloughs, and surface inflows that influenced the width and (presumably) flow levels within the stream. Several inflows observed in the imagery were not identified on the 1:24K USGS topographic maps used as reference. These mass transfers (both gaining/losing) resulted in often dramatic changes in stream temperatures and seemed to govern the thermal structure of the West Fork Carson River.

At Paynesville (mile 17.0), radiant water temperatures were ~17.8°C and increased rapidly to ~20.0°C at river mile 15.4. Radiant water temperatures stayed relatively constant downstream of a diversion at mile 15.4 before exhibiting a decrease of ~2.0°C between miles 14.2 and 13.4. The source of cooling through this reach was not directly apparent from the imagery. However, an apparent surface spring was detected along the right bank at river mile 13.5 (*Sample Images; Figure WF1*). This spring combined with the rate of cooling suggests a ground water influence through this reach.

From the diversion at mile 13.2, radiant water temperatures warmed consistently in the downstream direction reaching a local maximum of 21.9°C at river mile 9.3. At mile 10.9, the Brockliss Slough splits from the WF Carson River (*Sample Images: WF2*) and appears to divert the majority of flow from the West Fork. Below the split, the WF Carson River has a considerably narrow wetted width and resembles a canal. Water temperatures continued to increase steadily, reaching a local maximum of 21.9°C at mile 9.3. The West Fork Carson is again diverted at mile 9.3 resulting in a wetted channel of ~10 ft. Due to the small channel size, radiant temperature samples were only taken in the wider parts of the channel to avoid hybrid pixels.

Moving downstream of mile 9.3, radiant temperatures in the West Fork exhibited two relatively sharp decreases at river miles 8.6 (-2.2°C) and 7.3 (-4.8°C) (*Sample Image: WF3*). Visual inspection of the imagery did not reveal any surface inflows at these locations. Consequently, the rapid decrease in temperatures were likely due to localized subsurface discharges into the stream channel. The small size of the West Fork at river mile 8.6 and the subsequent increase in temperatures downstream, suggests that a relatively small sub-surface discharge at this location had a dramatic effect on in-stream temperatures. Water temperatures downstream of river mile 7.3 increased to a local maximum of 20.1°C (mile 6.8) before exhibiting a consistent cooling trend to river mile 4.8.

In the lower 4.8 miles of the West Fork, radiant water temperatures showed a steady increase reaching a survey maximum of ~24.9°C at the East Fork confluence. An unnamed inflow at river mile 2.5 was observed as a source of cooling and had a local cooling influence on bulk water temperatures. Home Slough and an irrigation return flow were also observed in the lower 4 miles of the WF Carson. Inspection of both the TIR and true color imagery also illustrated a considerable amount of algae on the stream survey in the lower 4.8 miles (*Sample Images WF6*) which resulted in variable surface temperature patterns. At the confluences, water temperatures in the West Fork were ~2.0°C warmer than in the East Fork.

Sample Images

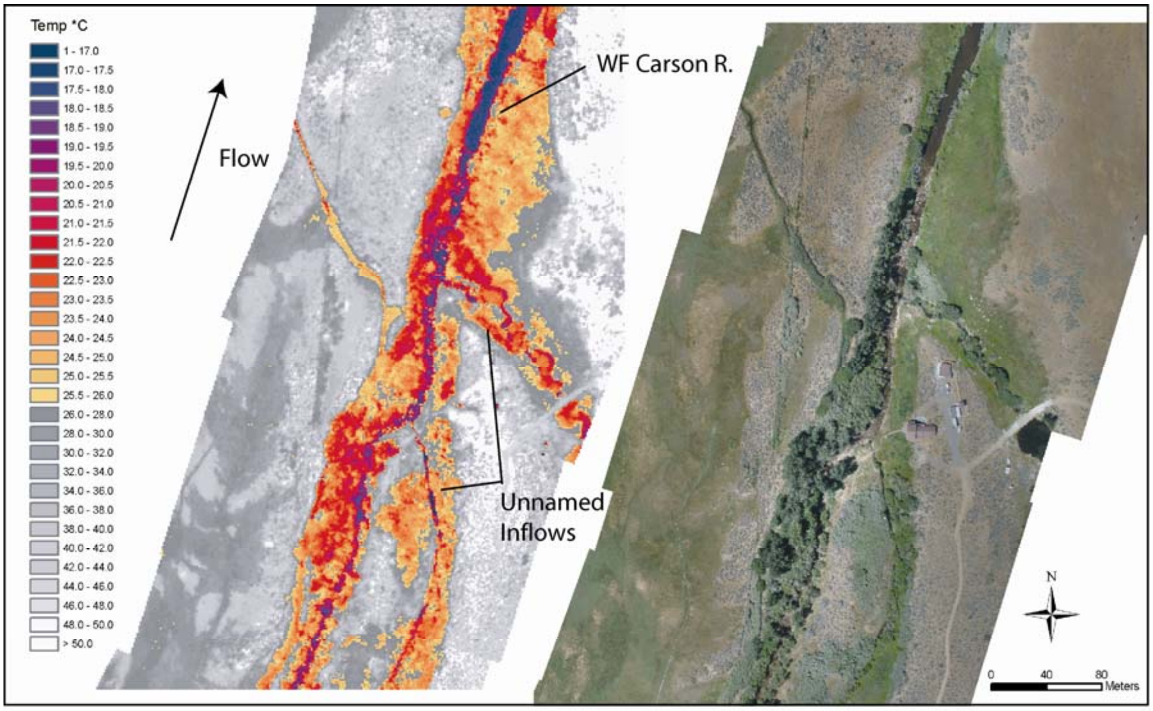


Figure WF1 – TIR and true color image showing an apparent surface spring along the right bank of the WF Carson River at mile 13.4. The West Fork exhibited a ~2.0°C decrease in temperature just upstream of this point, suggesting a ground water influence.

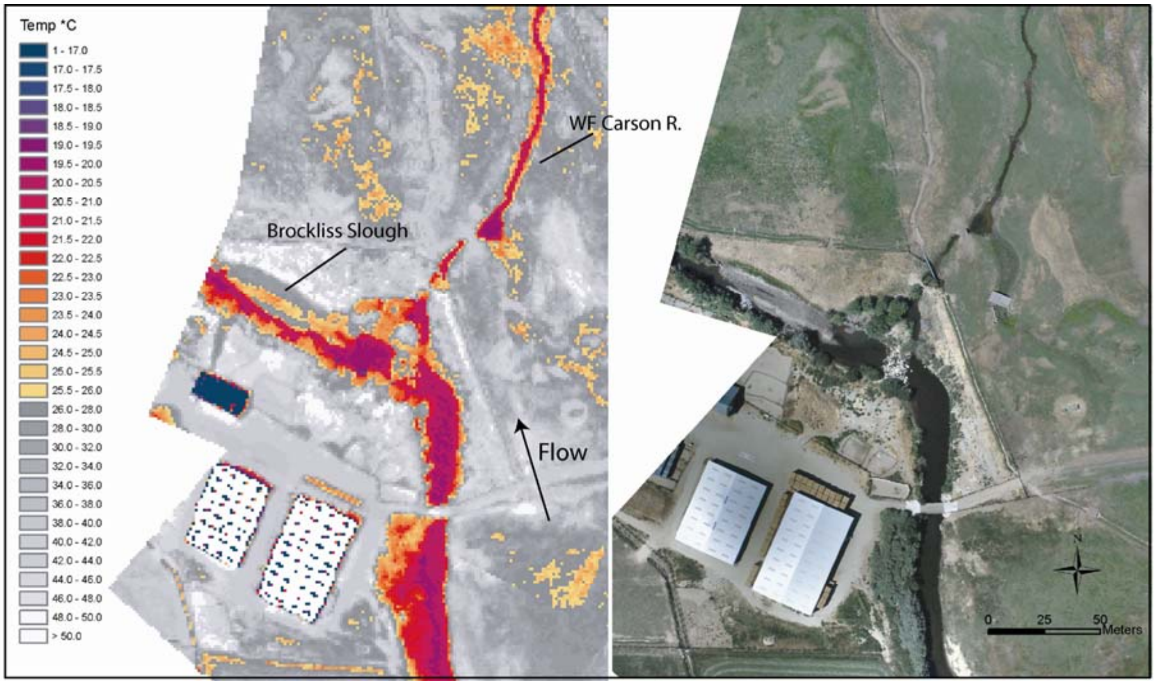


Figure WF2 – TIR and true color image showing the split of the West Fork Carson River and the Brockliss Slough. The Brockliss Slough appears to carry most of the flow from the river.

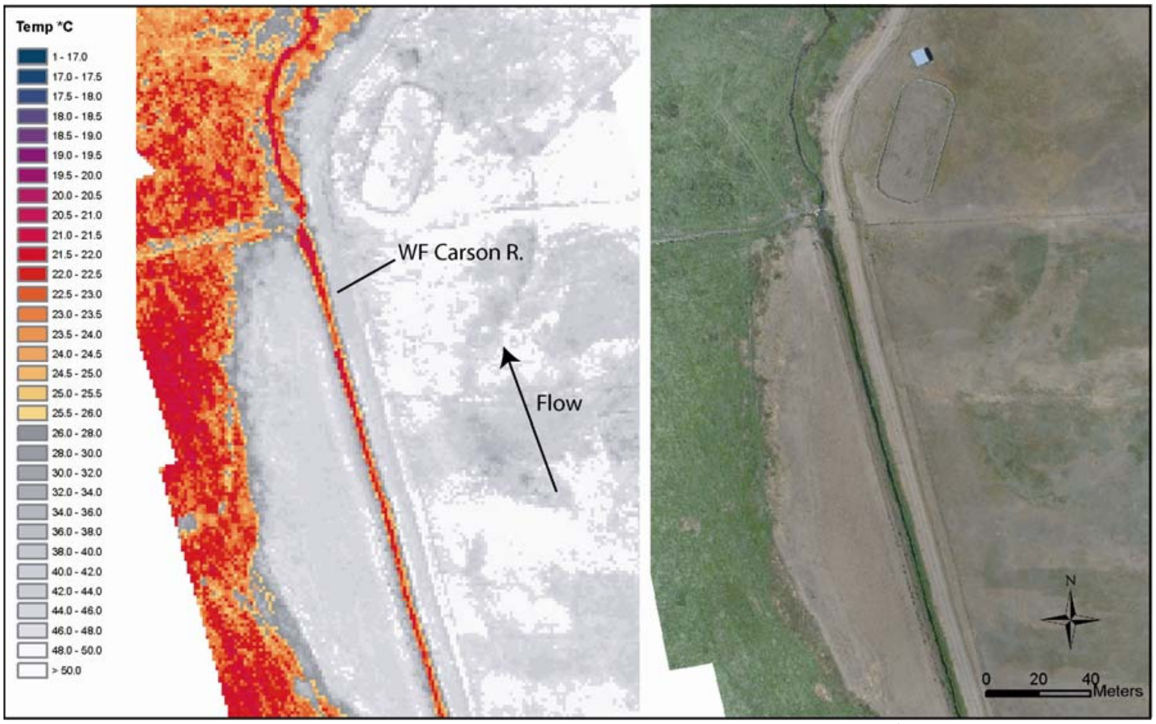


Figure WF3 – TIR and true color image showing the West Fork Carson River (21.1°C) at mile 10.4. The river is straightened and has very narrow wetted width (~6 ft).

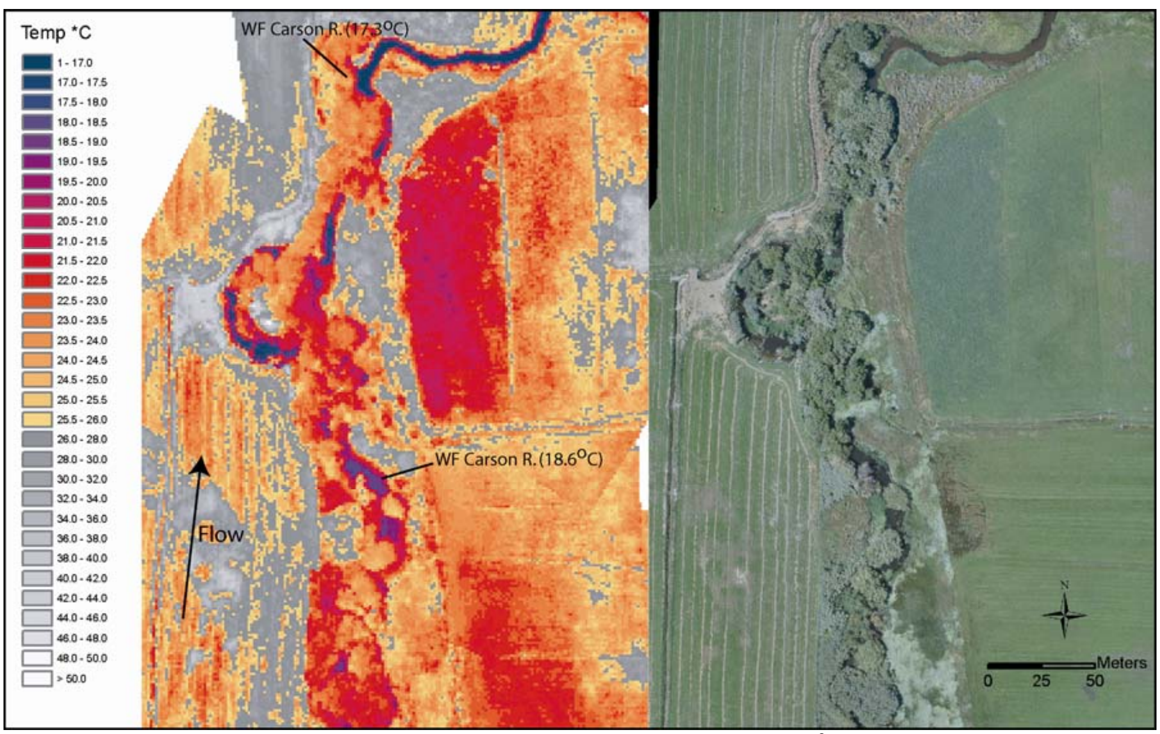


Figure WF 4 – TIR and true color image showing the location of a sharp 1.3°C decrease in surface temperatures in the West Fork Carson River at mile 7.5. The source of cooling was not directly apparent through inspection of the imagery. However, a decrease of 1.3°C in bulk water temperatures over such a longitudinal distance suggests a ground water influence.

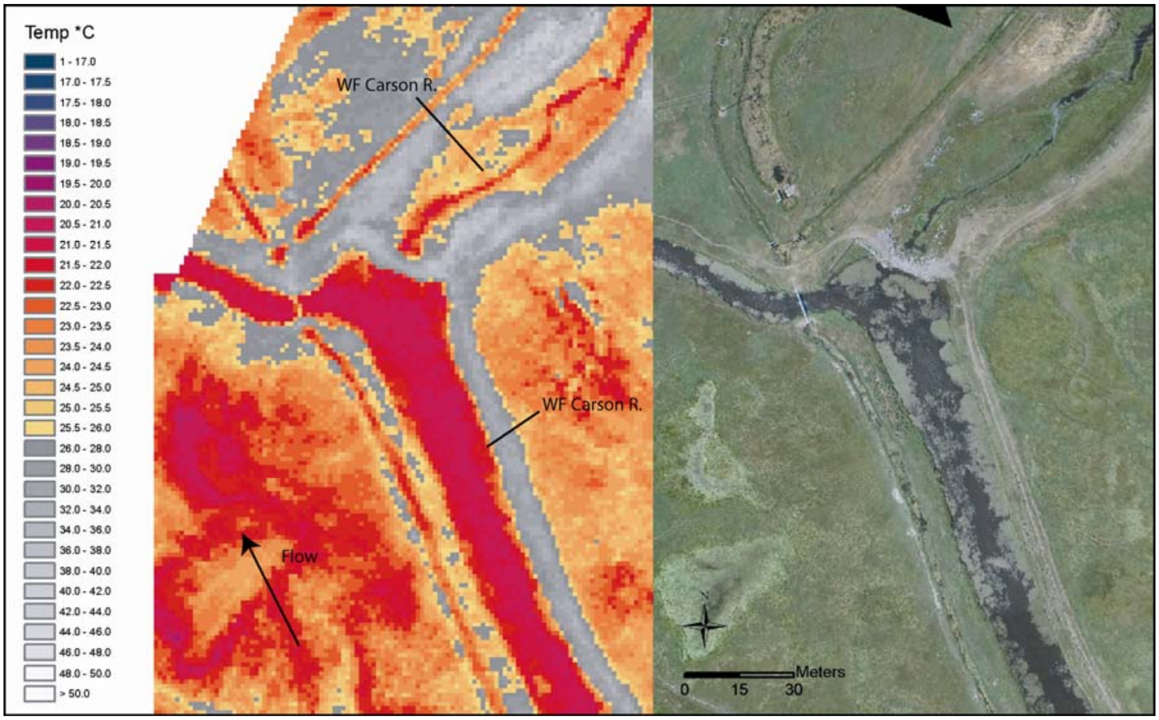


Figure WF 5 – TIR and true color image showing a diversion at river mile 2.8 that appears to divert most of the surface flow in the West Fork Carson River (21.0°C).

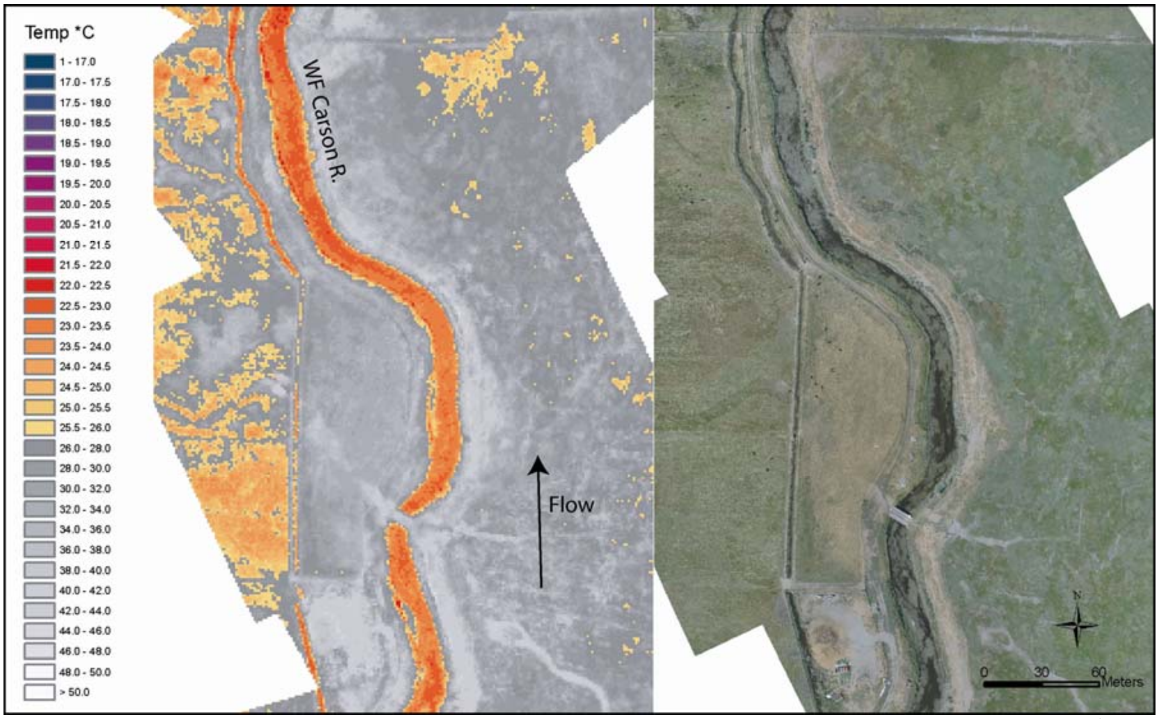


Figure WF6 – TIR and true color image showing flow conditions in the West Fork Carson River (23.0°C) at mile 1.1. Algae were observed on the water's surface along much of the lower 4.8 river miles.

Brockliss Slough

Brockliss Slough was surveyed as two separate branches which ultimately joined together ~0.5 miles upstream of the Carson River confluence. Both branches were distinguished on the UGSS 7.5' topographic base maps and available GIS stream layers. The longest branch split from the West Fork Carson River at mile 10.9 and joined Johnson Slough at mile 4.9 before traveling down the far left side of the valley. The smaller branch originated just downstream of Johnson Slough and traveled between the main branch and the West Fork Carson River.

Longitudinal Temperature Profile

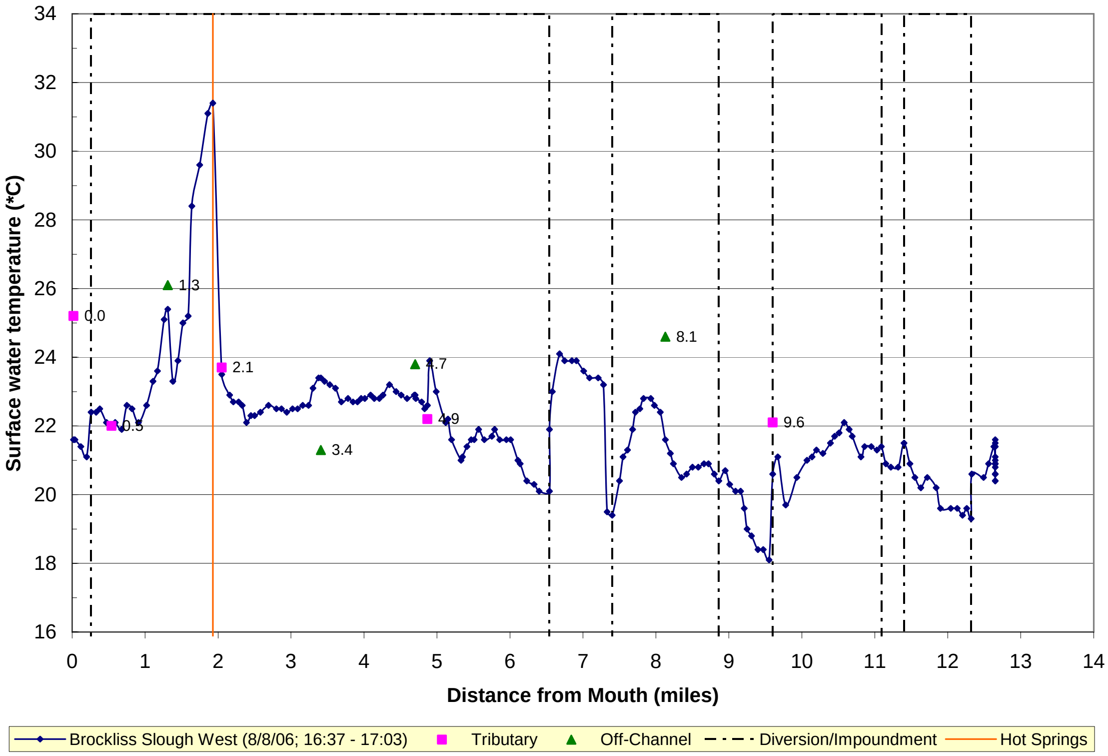


Figure 9 - Median surface water temperatures plotted versus river mile for the main channel of Brockliss Slough. The locations of diversions are illustrated on the plot to provide additional context.

Table 7 - Temperature and location of surface water inflows sampled during analysis of Brockliss Slough.

Tributary Name	km	mile	Tributary °C	Brockliss Slough °C	Difference °C
Unnamed Inflow (LB)	15.5	9.6	22.1	20.6	1.5
Johnson Slough (LB)	7.8	4.9	22.2	22.6	-0.4
Brockliss Slough (RB)	3.3	2.1	23.7	23.5	0.2
Brockliss Slough (RB)	0.9	0.5	22.0	22.0	0.0
Carson River (RB)	0.0	0.0	25.2	21.6	3.6
			Off-Channel		
Off Channel (RB)	13.1	8.1	24.6	21.6	3.0
Off Channel (LB)	7.6	4.7	23.8	22.9	0.9
Off Channel (LB)	5.5	3.4	21.3	23.4	-2.1
Off Channel (RB)	2.1	1.3	26.1	25.4	0.7

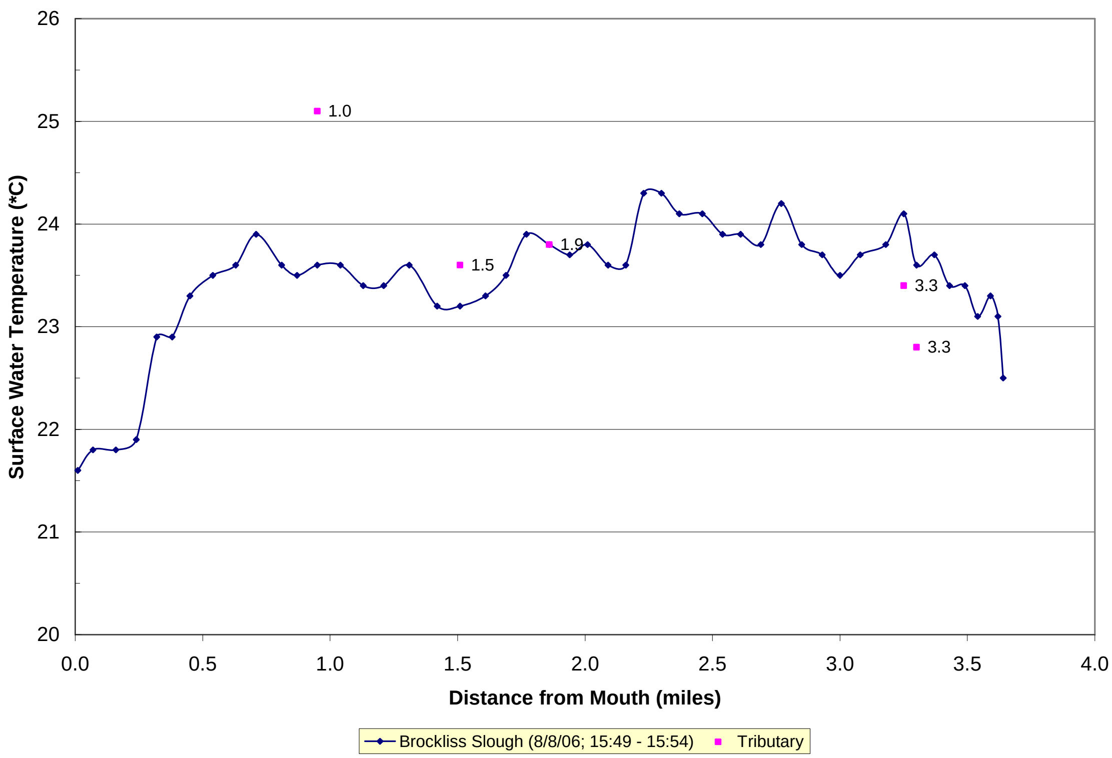


Figure 10 - Median surface water temperatures plotted versus river mile for the main channel of Brockliss Slough. This part of the slough was the smaller Branch of the Slough that started 0.5miles from the Carson River and terminated at an irrigation ditch near the confluence of Johnson Slough.

Observations and Analysis

Over its length, Brockliss Slough was characterized by changes in wetted channel width and flow characteristics. In some places, the Slough appeared to have very little flow and temperature patterns suggested some level of thermal stratification or differential surface heating. The slough was further distinguished by a significant amount of standing surface water and marsh areas. In some cases these features had direct surface connectivity to the main channel and other areas the standing surface water was observed as off-channel ponds or marches. The characteristics of the slough (both natural and man made) resulted in considerable thermal spatial variability along the channel.

A total of eight impoundments and irrigation diversions were noted during inspection of the imagery. The features often marked changes in the channel and flow characteristics and the longitudinal temperature profile shows that many of the dramatic shifts in surface water temperatures are spatially associated with the location of a diversion or impoundment. The following paragraphs further explore the longitudinal profile.

On the main branch, surface temperatures were ~21.4 at the split from the West Fork Carson River (mile 12.7). Based on the wetted width of the channel visible, it appears that Brockliss Slough takes the majority of flow from the West Fork. Approximately 0.4 miles downstream of the split, surface water temperatures exhibited a ~1.3°C decrease at an impoundment. In past TIR surveys, water temperatures decreases have been observed downstream of impoundments due to the water taking sub-surface pathways around or under the dam and emerging cooler on the downstream end. Another possibility is that the water upstream of the dam is thermally stratified (or differentially heating) with more well mixed conditions occurring downstream of the dam. However, the TIR imagery did not show any indicators of thermal stratification upstream of the impoundment at this location.

Moving downstream from mile12.3, radiant water temperatures increased to approximately 21.5°C just upstream of another impoundment at mile 11.4. Some variability in surface temperatures was observed in this segment and inspection of the imagery suggests some differential surface heating. These areas are characterized by water that is out of the main flow or areas in visible shade. While these surface temperature differences are typically small (i.e. < 1.0°C), they often confound interpretation of the temperature patterns (*sample images BS1*).

Radiant water temperatures in Brockliss Slough exhibited a slight cooling trend downstream of mile 10.6, before dropping to a survey low of 18.1°C at an impoundment at river mile 9.6 (*sample image BS3*). Inspection of the imagery upstream of the impoundment shows algae on the water surface and no obvious mixing (i.e. riffles). The flow conditions suggest the potential for thermal stratification or differential surface heating. However, no indicators of thermal stratification (i.e. wind mixing, mixing on corners) were present in the imagery. The cooling downstream of the dam was presumably due to the bottom release of cooler water from the upstream pool and the possibility of ground water upwelling from below and around the dam.

Radiant water temperatures increased steadily between river miles 9.6 (18.1°C) and 7.8 (22.8°C) before decreasing to 19.4°C upstream of an impoundment at mile7.3 (*sample image BS4*). As observed in other locations, surface water temperatures are often highest upstream of impoundments due to slow flow velocities and the higher potential for stratification. The source of cooling upstream was not directly apparent from the imagery; however the imagery shows a considerable quantity of off channel surface water through this reach suggesting at least the possibility of shallow sub-surface exchange. Surface temperatures were the same immediately above and below the impoundment.

The longitudinal temperature profile illustrates a dramatic increase in surface temperatures just downstream of the impoundment at river mile 7.3. The imagery shows a warmer irrigation return at this location, but it does not appear to have enough flow to cause such a dramatic change in the slough temperatures. Surface water temperatures remained high (23.2°C – 24.1°C) before showing a decrease downstream of another impoundment at mile 6.5. Stream temperatures again increased before reaching the confluence of Johnson Slough at river mile 4.9. A slight increase in temperatures was observed just upstream of the confluence. However, this apparent increase appeared due to some thermal stratification in the slough at this location.

Between the confluence of Johnson Slough and river mile 2.4 (*sample image BS5*), surface temperatures in Brockliss Slough remained between 23.3°C and 22.0°C. It is important to note that an in-stream sensor at river mile 2.9 recorded kinetic water temperatures of 20.0°C at the time of the over flight while radiant surface temperatures were 22.5°C (*re: Table 3*). The reason for this discrepancy was not known. The sensor was located on the bottom of the river and may have registered cooler sub-surface flow than was measured at the surface by the TIR sensor.

At mile 2.4, Walley's Hot Springs were visible in the imagery off the left bank (*sample image BS6*). The hot springs had a direct influence on the surface temperatures in Brockliss Slough downstream at mile 1.9 which is obvious in the longitudinal temperature profile. Stream temperatures decreased rapidly downstream of the hot springs and was ultimately cooler than the Carson River at the confluence.

Inspection of the longitudinal profile illustrates in-flow diversions have a significant influence in defining the spatial temperature patterns in Brockliss Slough. Overall surface temperatures were relatively cool compared to air temperatures and maximum temperatures observed in the Carson River. This was true even though there were large sections of the slough that had very little riparian vegetation and the channel was exposed to direct solar radiation. The cooler bulk temperatures suggest areas of diffuse sub-surface exchanges throughout the slough that buffer temperature increases due to physical heating processes. Figure 11 illustrates the combined longitudinal temperature profile for both branches of Brockliss Slough.

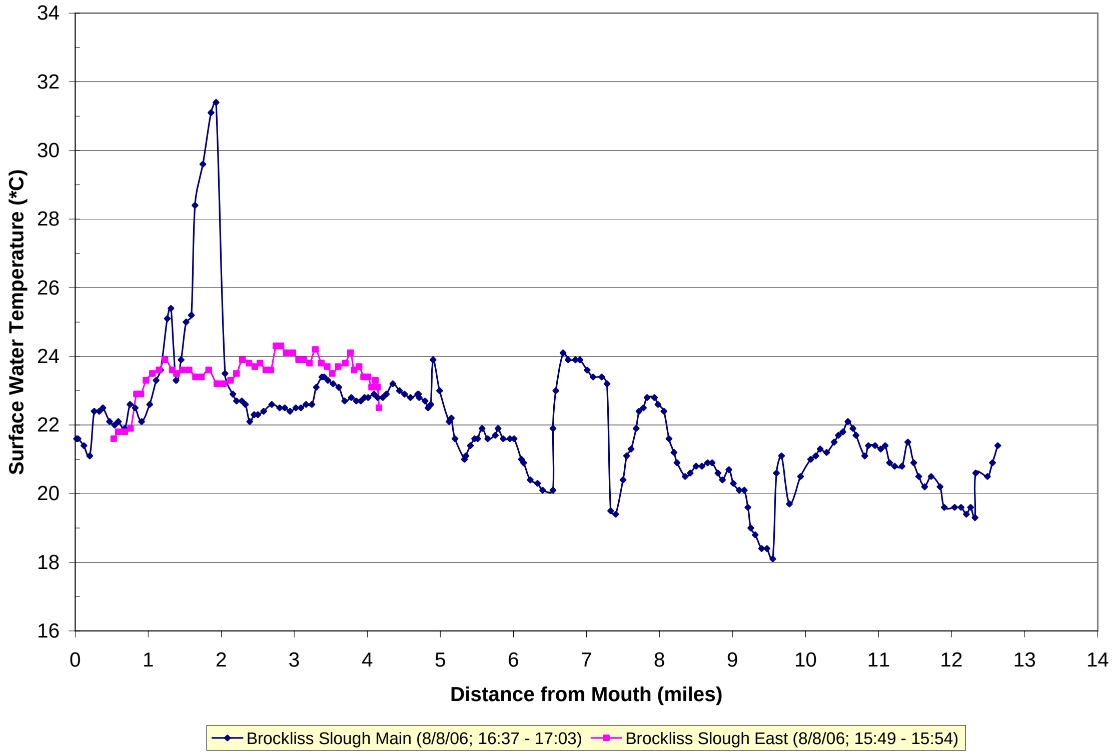
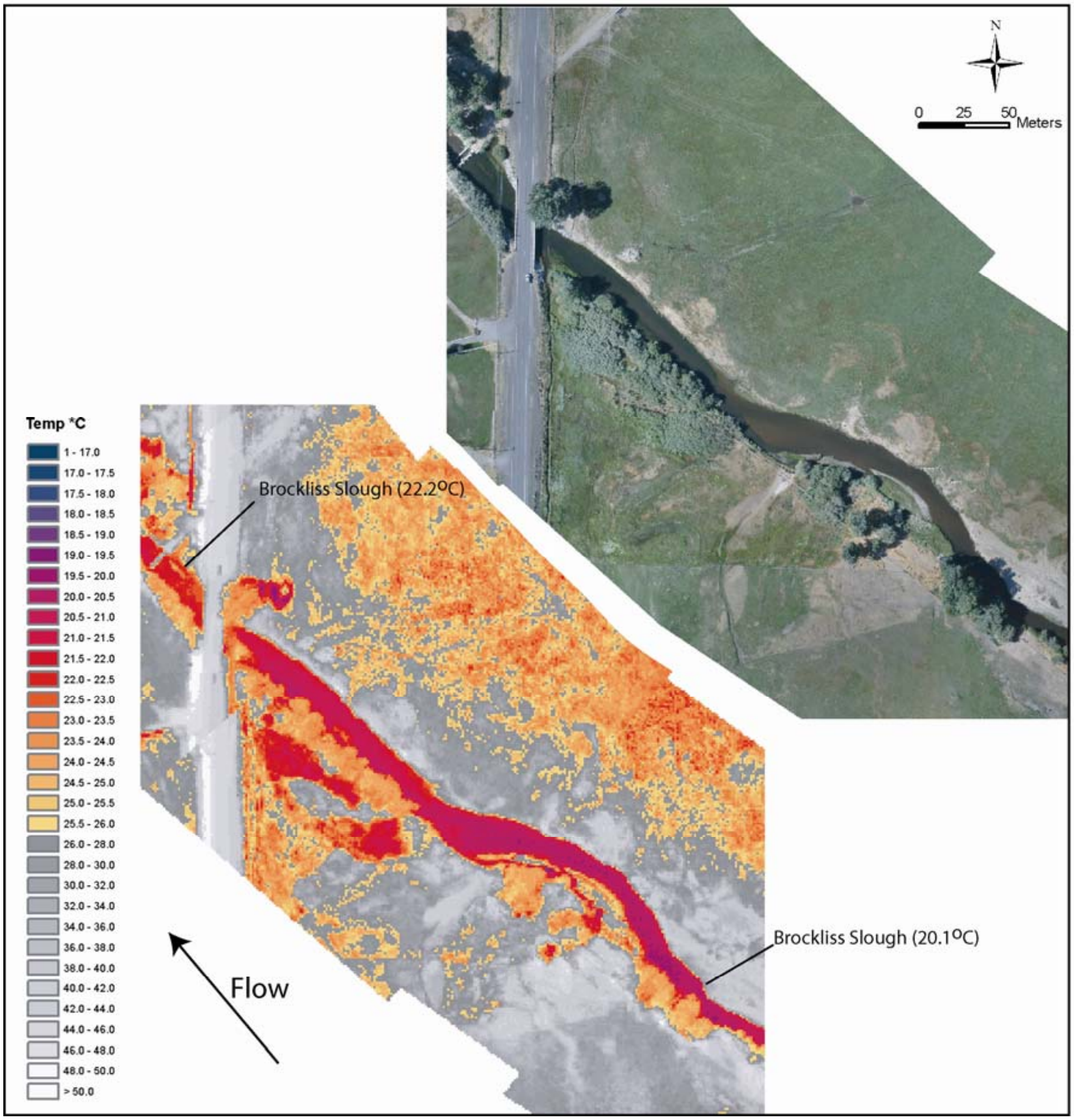
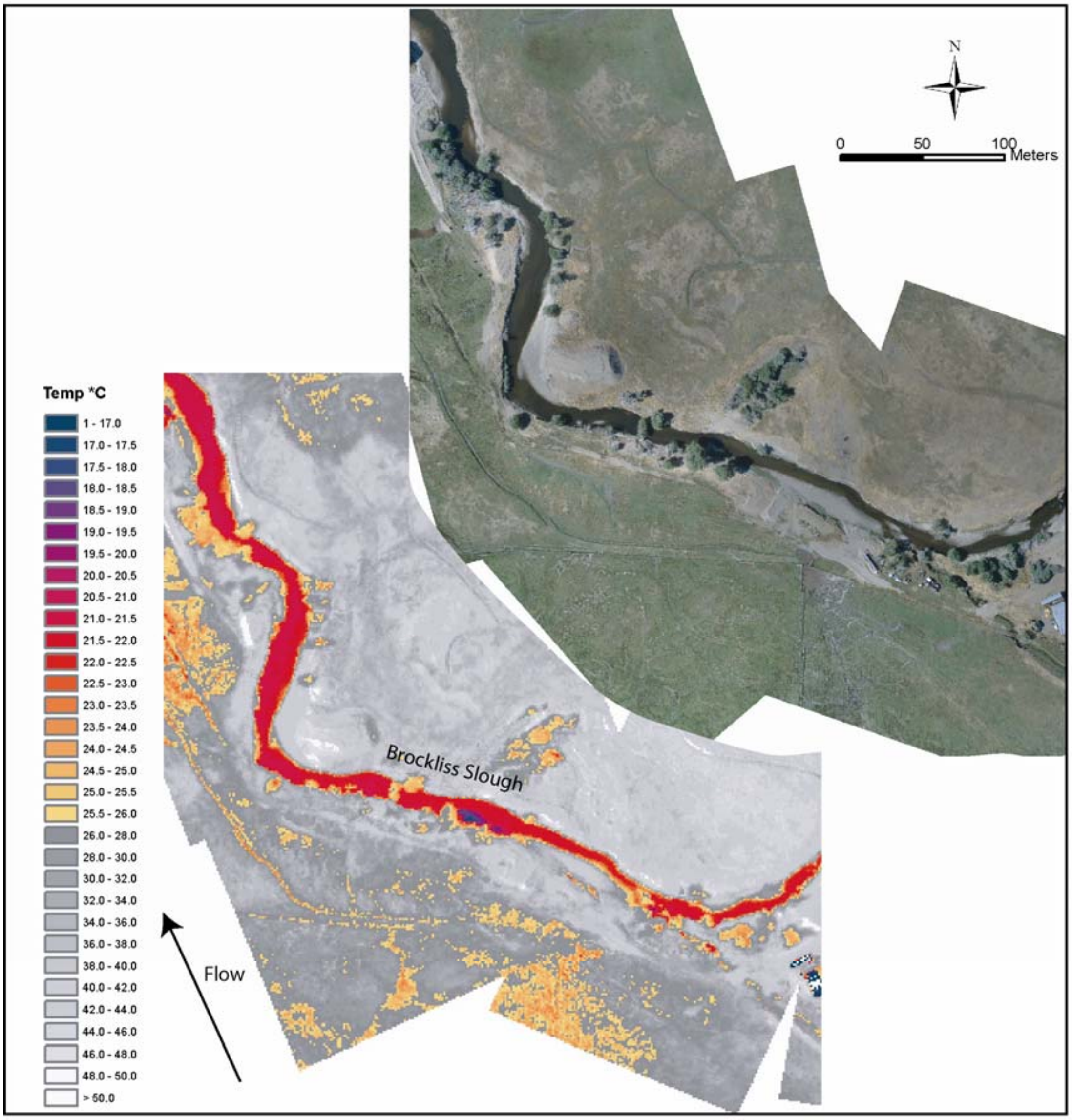


Figure 11 - Combined median temperature profiles for both the main branch and East Branch of Brockliss Slough.

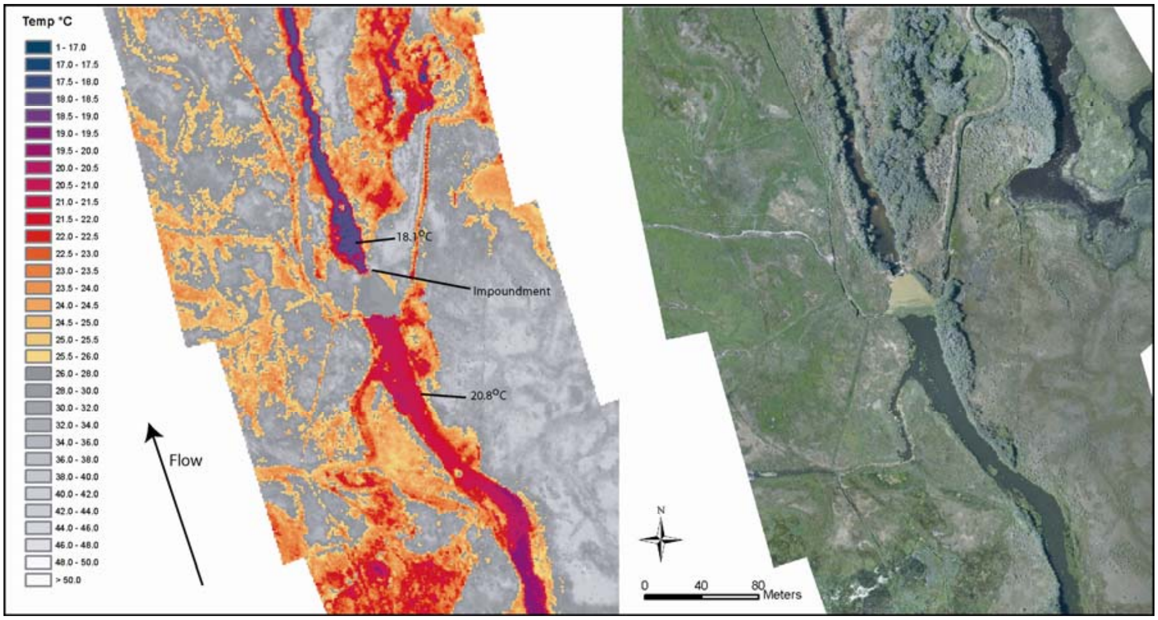
Sample Images



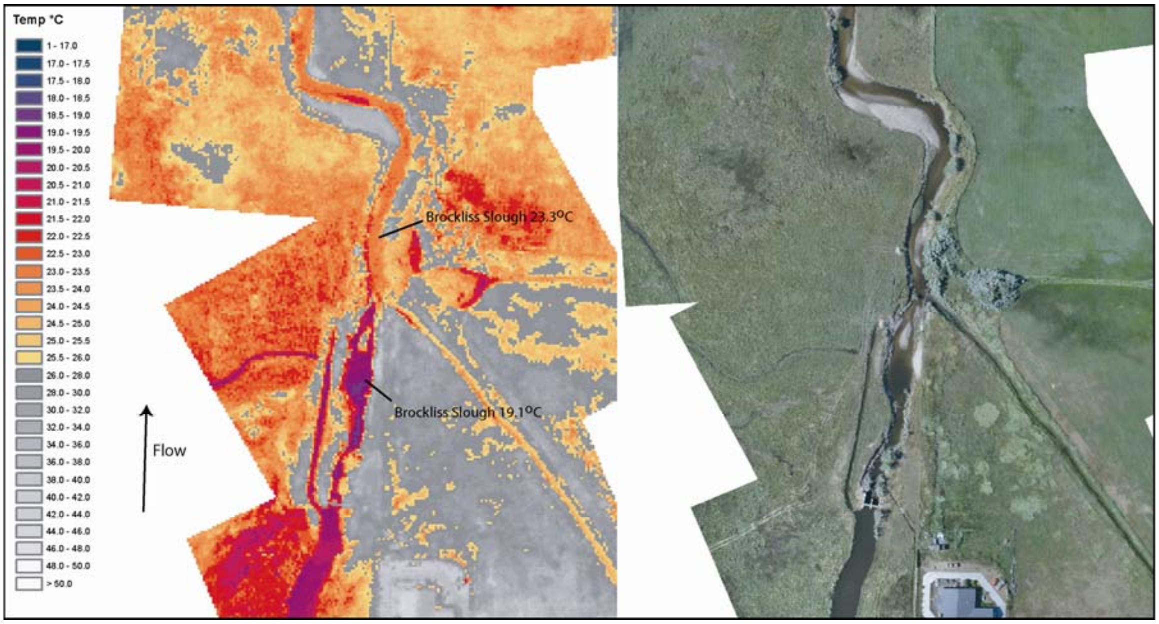
BS1 – TIR and true color image showing Brockliss Slough at river mile 11.6. The image shows a rapid 2.1^{o}C temperature increase in surface temperatures in the downstream direction. This apparent increase is presumably due to differential heating at the stream surface through this segment.



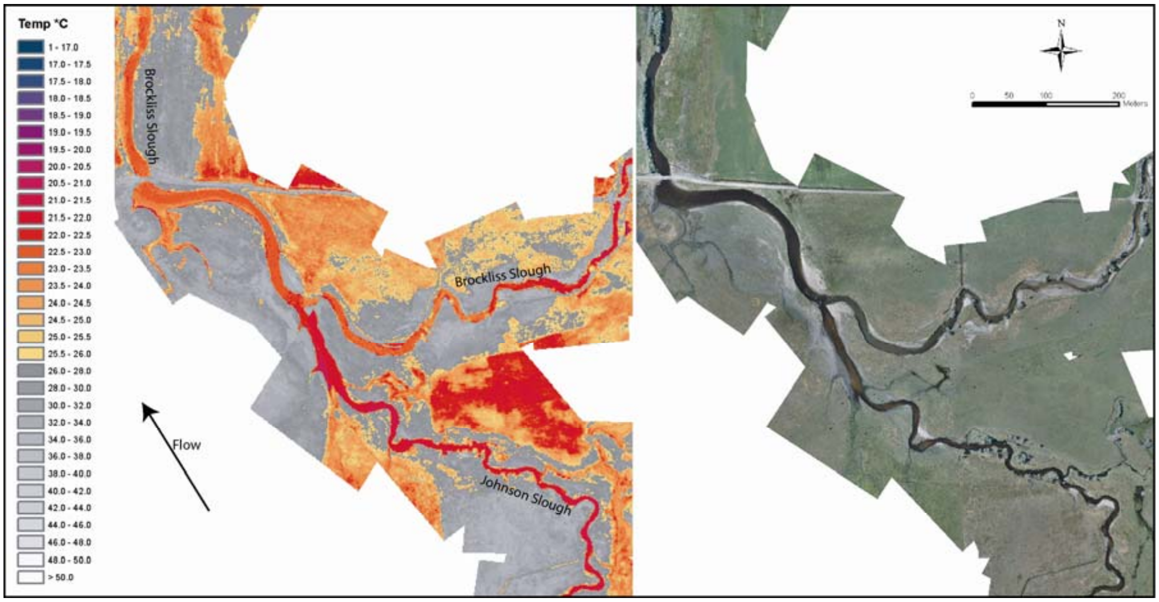
BS2 – TIR and true color image showing an example of channel conditions in Brockliss Slough at river mile 10.5. The image shows cooler shadows along the left bank that appears due to the visual shadows on a small gravel bar. The true color imagery is used as an aid in helping to identify the source of surface temperature variability.



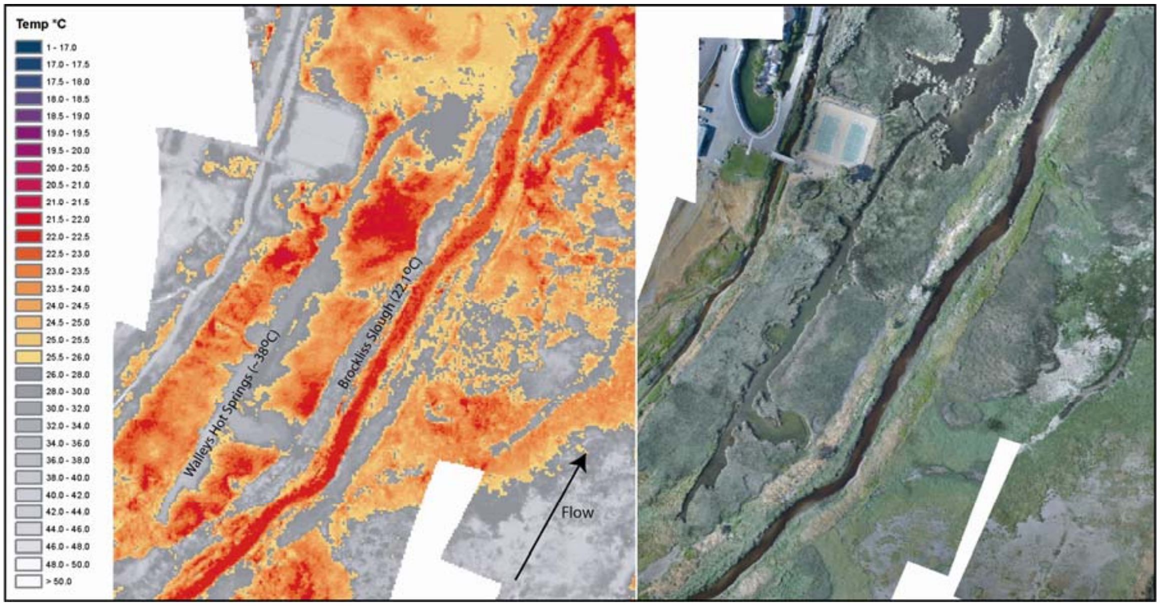
BS3 – TIR and true color image showing an impoundment in Brockliss Slough at mile 9.6. A decrease in in-stream temperatures was observed immediately downstream of the impoundment. An irrigation return is visible upstream of the impoundment.



BS4 – TIR and true color image showing an impoundment in Brockliss Slough at mile 7.3. Surface water temperatures decreased upstream of the impoundment and showed a significant increase just downstream.



BS5 – TIR and true color image showing the confluence of Johnson and Brockliss Slough at mile 4.9. Johnson Slough appears to dominate the thermal characteristics of the stream at this point.



BS6 – TIR and true color image showing Walley's Hot Springs off the left bank. The surface temperature is ~38^{o}C and higher then the color slice used for the TIR imagery.

Summary

Airborne thermal infrared surveys were successfully conducted on selected streams in the Carson River Basin, NV on August 8, 2006. The flight was coordinated with researchers at the Desert Research Institute who performed ground level monitoring (i.e. continuous temperatures and flow) during the time frame of the survey.

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

Overall, the TIR data showed how temperatures varied spatially over the survey extents. On the East Fork, West Fork, and Brockliss Slough, spatial variability in the temperature patterns were often directly associated with impoundments and flow diversions located along the stream gradient. The East Fork was characterized by large gravel bars with numerous seeps and side-channels. The detected seeps and apparent changes in surface flow suggest areas of sub-surface exchange within the river channel. Theses exchanges were suspected sources of local variability observed in the lower river. By contrast, the West Fork and Brockliss Slough did not have large gravel bars and in some areas resembled canals. In some areas, the flow conditions were conducive to thermal stratification and formation of algae on the stream surface.

A 1-meter digital elevation model (DEM) derived from LiDAR data exists for the Carson Valley. The 1-meter DEM provides a context for analyzing the thermal image in relation to the geomorphology of the valley and channel. A follow-on analysis may include examining the spatial temperature patterns in relation to stream gradient, channel complexity, and valley form.

The TIR imagery and derived data sets provide a spatial context for analysis of seasonal temperature data from in-stream data loggers and for future deployment and distribution of in-stream monitoring stations. This report provides some hypotheses on the processes influencing spatial temperature patterns at this scale based on analysis of the TIR imagery. These hypotheses and observations are considered to be a starting point for more rigorous spatial analysis and field work.

Deliverables

The TIR imagery is provided in three forms: 1) individual un-rectified frames and 2) a continuous geo-rectified mosaic at 1.2 m resolution. The mosaic allows for easy viewing of the continuum of temperatures along the stream gradient, but also shows edge match differences and geometric transformation effects. The un-rectified frames are useful for viewing images at their native resolutions and are often better for detecting smaller thermal features. A GIS point layer is included which provides an index of image locations, the results of temperature sampling, and interpretations made during the analysis. The true color digital images are provided as geo-rectified mosaics at 20-cm resolution.

Deliverables are provided on a set of DVD's:

Geo-Corrected Imagery are stored as: **UTM Zone 11, NAD83, Units = Meters.**

1. Rectified_Images
    a. TC_Mosaic - Geo-Rectified true color imagery mosaics at 20-centimeter resolution in geo-tiff format. An index is provided that shows the location of each mosaic segment.
    b. TIR_Mosaic - Continuous image mosaic of the geo-rectified TIR image frames at 1.2 meter resolution in geo-tiff format. GRID cell value = radiant temperature * 10.

2. Unrectified_Images.
    a. TIR_Frames - Calibrated TIR images in ESRI GRID Format. GRID cell value = radiant temperature * 10. Radiant temperatures are calibrated for the emissive characteristics of water and may not be accurate for terrestrial features. These images retain the native resolution of the sensor.
    b. TC_Frames – Unrectified true color images in jpg format. An index is provided to show the geographic location of the aircraft at the time the image was acquired.
    c. Indices - Point layers showing image locations, sampled temperatures, and image interpretations.

3. Longprofile - Excel spreadsheet containing the longitudinal temperature profiles.

4. Report - A copy of this report.