Ground-Based Monitoring of Carson River Temperature during Airborne Thermal Infrared Survey of August 2006

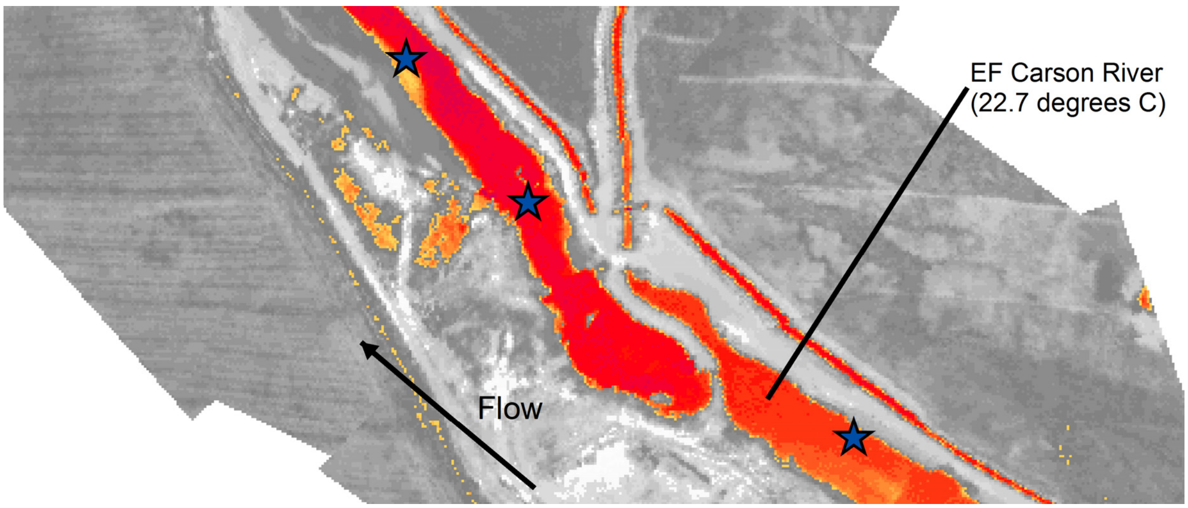

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Table of Contents

Introduction

This report presents results from ground-based water temperature data collected during August 2006 for the Carson River. The ground-based measurements were made to provide a set of independent validation data for comparison with results of an airborne survey that was based on thermal infrared (TIR) remote sensing (Watershed Sciences 2006). The airborne TIR survey was conducted on 8 August 2006 and covered 78.9 miles of the mainstem Carson River and tributaries, including the Carson River's East Fork, West Fork, and Brockliss Slough. The airborne survey and ground-based monitoring reported here were organized by Desert Research Institute (DRI) with cooperation of Nevada Division of Environmental Protection (NDEP). Our goals were to characterize temperature conditions in support of water quality standards assessment, and to promote understanding of hydrologic dynamics within the upper Carson River Basin.

The upper reaches of the Carson River in Nevada are designated to support beneficial use as a coldwater fishery despite frequent exceedances during summer of cold water biota temperature standards (Pahl 2008). Water temperature is directly related to flow and water depth conditions, which are typically highly variable in the Carson River Basin during the irrigation season. Flow monitoring in the Carson Basin upstream from Deer Run Road was limited during 2006 to approximately ten USGS gaging stations none of which featured regular temperature monitoring. Data collected prior to 2006 (summarized by Pahl 2008) indicated instream temperature conditions in the Carson Basin that were highly variable in both space and time, especially during the warm summer months that are critical to aquatic biota.

Although water temperature had been included in many river monitoring activities prior to 2006, prior to this study the Upper Carson Basin lacked a synoptic thermal survey with broad spatial coverage. The current research represented an unprecedented opportunity to improve knowledge of thermal conditions in the Carson River and was the product of a convergence of the following elements:

a) availability of relatively low cost temperature dataloggers,

b) access to airborne survey techniques that were specifically designed for mapping spatial temperature patterns in riverine systems, and

c) interest of the investigators and NDEP in evaluating the effectiveness of using a thermal survey to identify zones of exchange between ground and surface waters.

An airborne thermal survey provides a comprehensive synoptic view of temperature conditions throughout the spatial domain. The resolution of the acquired thermal images is about 0.8 m (2.8 ft), with an accuracy on the order of ±0.3° C. Survey results can be used to identify thermal influences of tributaries, point sources, and surface and subsurface exchange. A shortcoming of the TIR survey is that it only represents a snapshot of conditions for a single point in time (actually a few hours). The thermal survey of the Carson Drainage was planned with the objective of capturing near-maximum summer instream temperature conditions. The survey was conducted during a mid-afternoon of early August, during the period when peak annual temperatures typically occur.

Continuous monitoring of temperature at point stations helps to fill out the picture of thermal conditions within the basin on a space-time continuum. During 2006, continuous measurements of instream temperature were available at two stations in the Carson drainage as part of an NDEP-sponsored turbidity-sediment monitoring study conducted by DRI (Susfalk et al. 2008). Additional instream temperature data from nine locations on the Carson were collected as part of a field effort supporting simulation modeling by Garner (2007) of the potential effects of riparian shading on water temperature. For the study reported herein, instream temperatures were monitored continuously at an additional 20 locations “synoptic sites” during a 12-day period that bracketed the TIR airborne survey. The combined data set provides thermographs for a total of approximately 30 sites.

The objectives of the current research were: a) to monitor instream temperature using ground-based equipment throughout the area of the Carson River Basin covered by the airborne thermal infrared survey, and b) compare TIR survey results with temperature data collected using *in situ* temperature sensors, and c) to provide a preliminary evaluation of the influence of irrigation diversions on the river’s thermal regime.

Study Sites

The spatial extent of the airborne survey included the Carson River from Brunswick Canyon to the confluence of the East and West Forks, the East Fork Carson River from mouth to Nevada-California border, the West Fork Carson River from mouth to Paynseville, California, and the entire length of Brockliss Slough (Figure 1). All told, a total of 78.9 miles (127 km) of river channel were surveyed in the mid-afternoon on 8 August 2006. In stream temperature recorders were installed at the locations listed in Table 1 (also see Figure 1). These sites were selected to provide coverage throughout the area of the airborne survey with placement criteria including accessibility and capturing locations thought to be influenced by groundwater.

Methods

True color and thermal infrared (TIR) images were collected using digital imaging and global positioning systems (GPS) mounted on a helicopter that flew longitudinally 335 m above the stream channel. The approximate image footprint width was 275 m, with an image pixel resolution of 0.86 m (Watershed Sciences (2006).

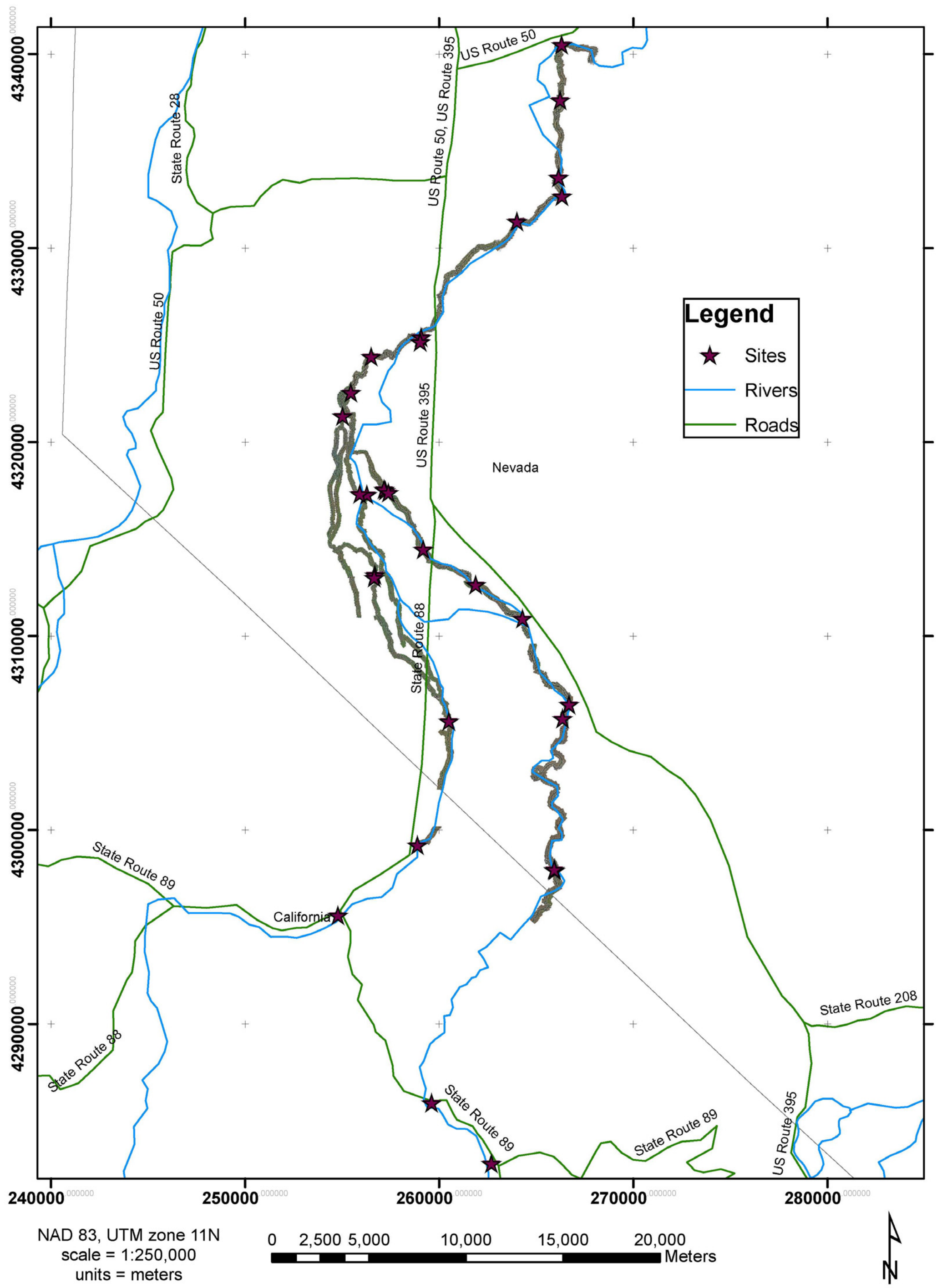


Figure 1. Map of Carson River basin showing locations where in-stream temperature sensors were operated during the TIR survey of August 2006. The area included in the TIR survey within Nevada appears as a gray-orange layer near the blue line that designates rivers.

Table 1. Location of thermograph sites on Upper Carson River and tributaries during August 2006.

Station_ID	West Latitude	North Longitude	Description	Additional_Description
1	38.9304	-119.74711	Lutheran Bridge (2)	Upstream Right bank
2	38.9335	-119.80697	Brockliss Slough at Mottville	Below Scoussa Diversion
3	38.93228	-119.80735	Brockliss Slough at Mottville	Left bank downstream from bridge
4	38.94607	-119.77886	East Fork Carson at Highway 88	Upstream Right bank
5	38.97287	-119.80229	Easf Fork Muller Lane	Below Diversion
6	38.97348	-119.80299	Easf Fork Muller Lane	Below Diversion
7	38.9719	-119.80045	East Fork Muller Lane	Pool above diversion
8	38.91532	-119.71878	East Fork Riverview Bridge	Riffle Downstream
9	38.87611	-119.68971	East Fork Washoe Bridge (Rick's Riverview)	Tied to Turbidity boom
10	38.86955	-119.69331	East Fork Raft Pullout near Washoe Bridge	
11	38.79909	-119.69521	East Fork - Border Ranch	
12	38.79957	-119.69554	East Fork - Border Ranch	
13	38.66218	-119.72757	East Fork - Junction HWY 4 and 89 (2)	
14	38.68954	-119.76403	East Fork - Bridge on Hwy 89 (2)	
15	38.77524	-119.82276	West Fork - Woodford Bridge (2)	
16	38.80881	-119.77713	West Fork – Paynseville	Diamond Valley Rd.
17	38.9708	-119.81315	West Fork Muller Lane	
18	38.97086	-119.8175	East Brockliss	
19	39.55491	-119.75328	West Brockliss on Muller (2)	Beneath upstream side of bridge

20	38.86693	-119.7607	West Fork Dressler Lane	
21	39.00683	-119.8292	Brockliss Slough at Southern Properly Line on Genoa Golf Course	
122	39.0178898	-119.8246241	Genoa Golf Course	
123	39.044503	-119.7840602	Lippincott Ski Ranch	
124	39.04232727	-119.7844517	Ambrosetti Inlet	
125	39.0996663	-119.7290882	McTarnahan	
126	39.11197337	-119.7027804	Foerschler Ranch	
127	39.12061896	-119.7051257	Mexican Dam	Downstream from Dam
128	39.1565741	-119.7055761	Riverview Park (Washoe Bridge)	Attached to Turbidity Probe Boom
129	39.03485509	-119.8132068	Last Low Head dam	
130	39.18222234	-119.7055965	Deer Run Road Gage	
	39.17574	-119.68900	Brunswick Canyon (New Empire Bridge)	Attached to Turbidity Probe Boom

Notes: (1) Geographic coordinates referenced WGS84.

(2) Not retrievable.

In-stream temperatures were monitored at synoptic sites using ibutton Thermochron Dataloggers (DS1922L; Maxim Integrated Products, Sunnyvale, CA). These temperature dataloggers were operated at 11-Bit resolution (0.0625°C), with the manufacturer specifying an accuracy of ±0.5°C from -10°C to +65°C. Prior to field deployment, dataloggers were placed into a refrigerated circulation bath (NESLAB RTE 17; Thermo, Newington, NH) for temperature verification of each datalogger. The bath was set to maintain constant temperature at a minimum of two points within the expected range of temperatures and compared to an ASTM certified National Institute of Standards and Technology (NIST) precision thermometer accurate to 0.1ºC. Observed temperatures were compared to actual (NIST) temperatures of the water bath. Differences between the observed and calibrated temperatures averaged 0.1ºC with maximum deviations of 0.2ºC. This procedure was followed for most dataloggers prior to deployment and repeated at one temperature at the end of thermistor deployment to verify proper operation of the temperature data loggers.

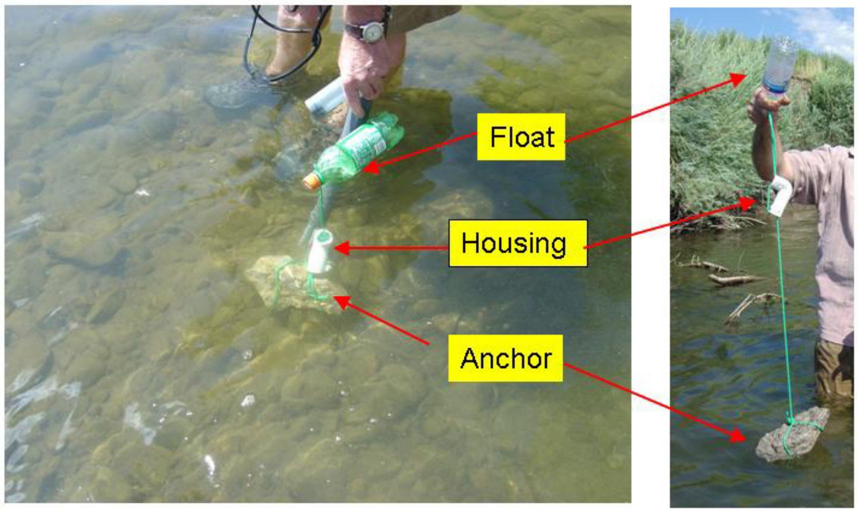
The Thermochron dataloggers were deployed at synoptic sites using a suspension system developed during prior research on the Carson River by Garner (2007). This rigging method is designed to position the device in the water column by use of a float and ballast (Figure 2). The method protected the sensor from direct solar radiation due to the white PVC housing, and maintained an exchange of water through the housing to minimize bias in temperature readings, and thus addressed sampling issues raised by (Dunham et al. 2005). Further, the suspension method kept the sensor from being buried in sandy bottomed channels, and had the added benefit of being inexpensive. The length of rope and position of housing was adjusted to position the sensor at approximately mid depth. Data were logged at either 10 or 30-minute intervals over a period that generally spanned 10-12 days.

Water temperature at turbidity monitoring sites was measured using a CS547A water conductivity-temperature probe (Campbell Scientific Inc., Logan, UT). The probe was suspended at approximately mid-depth in the water column in the channel thalweg. Data were logged at 15 minute intervals using a Campbell Scientific CR10x dataloger (Susfalk et al 2008).

Coordinate data for the sites was collected as waypoints with a Garmin GPS12 (Garmin International, Olathe, KS). Instantaneous measurements of water temperature and specific conductance were taken when the temperature data recorders were deployed (YSI 600XL, Yellow Spring Instrument, Yellow Springs, OH). Water column depth and depth of sensor above river bed were recorded. Discharge data were obtained from USGS gaging stations data using the National Water Information System (http://waterdata.usgs.gov/nv/nwis/).

The time of TIR image acquisition of the frame that corresponded with an instream temperature logger was obtained from the project GIS (Carson_8_8_TIR.xls; Watershed Sciences 2006). The closest data value on the instream temperature record (logged at either 10- or 30-min intervals) to this image acquisition time was selected for the comparison of ground-based and airborne temperature measurements. The coordinates for the instream temperature sites were used to locate the corresponding radiant temperatures. Temperature at the channel thalweg was noted in addition to the TIR-based temperature at the datalogger location. Imagery was processed using ArcGIS 10 (ESRI, Redlands, CA).

Vertical thermal profiles were collected for impounded pools at several low head irrigation diversions using multiple thermochrons attached to a weighted line. Thirteen data recorders were attached to a rope at 20 cm intervals, thus forming a temperature logging chain. The chain was weighted at the bottom and positioned in the channel using a small oar-powered catamaran. The temperature logged by the synchronized thermochrons after they had stabilized was selected for constructing the vertical profiles. The purpose of the vertical profiles was to provide context to the airborne TIR measurements, which detected radiant temperature of the earth's surface skin.



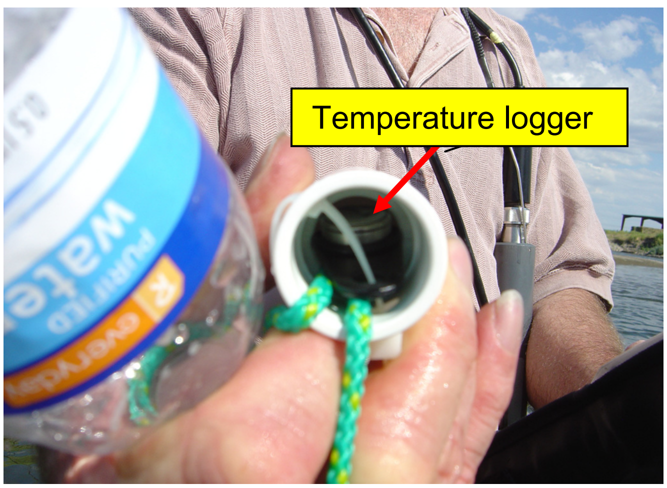


Figure 2. The temperature data loggers were mounted within a housing whose position was secured in the water column using a rock anchor and plastic bottle float connected with a rope. The housing shaded the temperature logger from direct irradiance and allowed for stream flow through the white PVC pipe fitting.

Results and Discussion

Our interest in identifying areas of upwelling groundwater would be best met by selecting conditions during which there were a maximum difference in temperature between the subsurface and surface water, or delta T. Thus, the timing of the airborne TIR survey involved aiming for the period of annual maximum water temperatures, which corresponds with low river flow and maximum air temperature. As the TIR survey involved use of a specially-instrumented aircraft, the flight had to be booked with the contractor months in advance. Early August was selected for scheduling the survey because an above average snowpack was expected to maintain spring runoff flows well into July (Figures 3-4).

The time of the airborne survey on August 8th is shown for reference on the seasonal thermographs for Carson River at the turbidity monitoring stations (Figure 5). Although the synoptic survey did not capture the annual temperature peak, it occurred during the period when surface water temperatures were in excess of 20° C, which provided distinct thermal variation spatially. For example, the longitudinal temperature profile for the Carson River showed a dramatic 6° C temperature decrease as the channel leaves the Carson Valley and enters the canyon east of Prison Hill (Figure 6). Selected results from the airborne survey are discussed here; additional findings are presented in Watershed Sciences (2006).

Temperature data loggers were deployed the week preceding the airborne survey, and collected the following week. These thermographs provided a synoptic view of thermal conditions within the upper Carson Basin. Data collection at the synoptic sites was coordinated with a companion monitoring effort that provided temperature data for validation of a water temperature model in the reach between Genoa Lane and Deer Run Road (Garner 2007). As anticipated, there were several losses or failures of the temperature loggers. Of the 29 devices that were deployed, four were not recovered and one had no data when retrieved. These results confirmed the strategy followed in this campaign of using relatively inexpensive devices and doubling up at important locations. For instance, the temperature logger that failed was at the Border Ranch on the East Fork of the Carson, but results from a second device were available.

Testing in the laboratory water bath demonstrated that the temperature data loggers were well within the accuracy specification of ±0.5°C from -10°C to +65°C. We evaluated the dataloggers at 1°C, 20°C, and 25°C, and the median discrepancy was 0.033 °C. All the residual differences were < 0.10°C except one of 0.152°C, indicating that the accuracy specification provided by the manufacturer for these instruments was conservative.

Results of temperature monitoring at the synoptic sites during 3-15 August 2006 are plotted in Appendix A. The weather was generally clear throughout the period, and the cloudless conditions produced clean diel (24-hour) temperature oscillations at the majority of sites. Water temperature conditions were dynamic, with at-a-station diel swings in temperature variation observed at some locations in excess of 10° C. For example, temperature at three sites within a 10-km segment of the Carson River is shown in Figure 7. This segment spans the river reach between 80 and 70 km (distance from Lahontan Reservoir = rkm) that was revealed by the TIR to have had a pronounced trough of cold temperature (Figure 6) at the time of the flight. Figures 6-7 illustrate the complexity of the thermal regime observed on the Carson River, which varies in both space and time.

Presentation of results from the instream temperature recorders will focus on three locations where the river channel has been altered for irrigation diversion purposes.

Mexican Dam

The temperature recorder at Mexican Dam (rkm 78.7) revealed a distinct change in diel pattern and amplitude beginning on August 10th compared to the trajectories for the other two sites (Figure 7). The amplitude of the diel swing at Mexican Dam decreased from 7° C on August 8th to about 1° C on August 13th, while the swing at Foerschler and Deer Run continued to show a large diel oscillation. Discharge data were not available in close proximity to the reach downstream from Mexican Dam, but the temperature pattern suggests reduced surface water flow conditions after August 10th. The available discharge data at the Carson City and Deer Run Rd gages show that the surface water flow had dropped to approximately 25 cfs from August 12th onward (Figure 8) . An upwelling of groundwater into the river channel would tend to mute the diel temperature swing, as was observed. The pattern of daytime temperature rise and nighttime fall was reestablished at the Deer Run Road monitoring site, only 8 km downstream from Mexican Dam (Figure 7). Garner (2007) provides a detailed analysis of the thermal dynamics associated with riparian shading and flow regime in this reach of the Carson River.

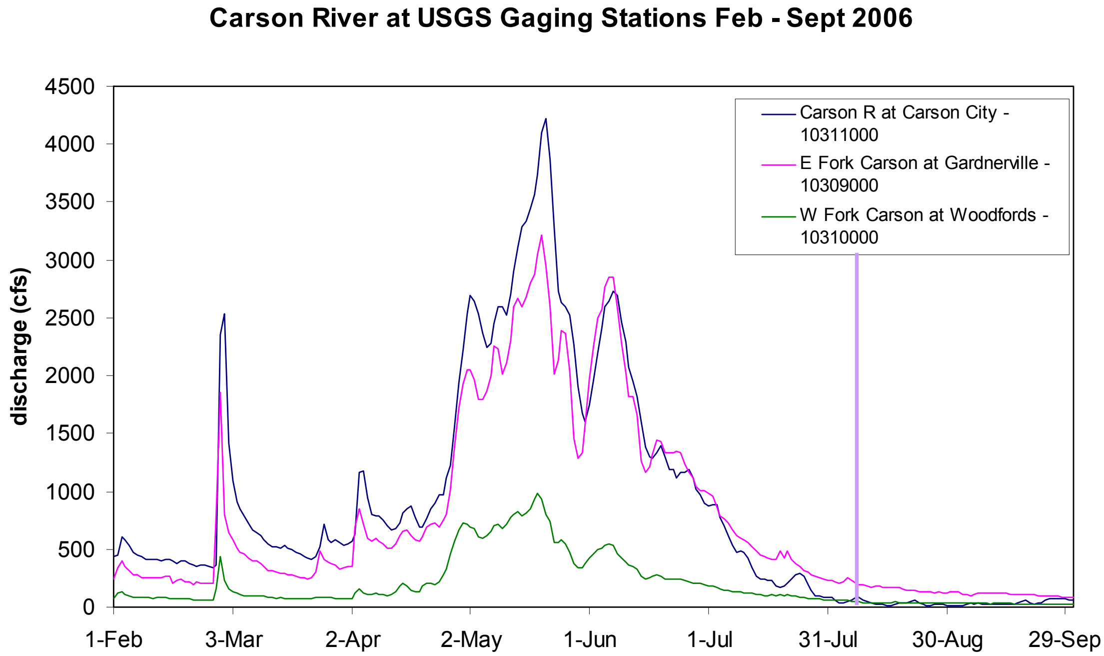


Figure 3. Discharge of mainstem Carson River and its East and West Forks during February through September 2006. August 8th, the date of the airborne survey is shown as a vertical line. (Data Source: USGS).

Carson River at USGS Gaging Stations: 27 July-16 Aug 2006

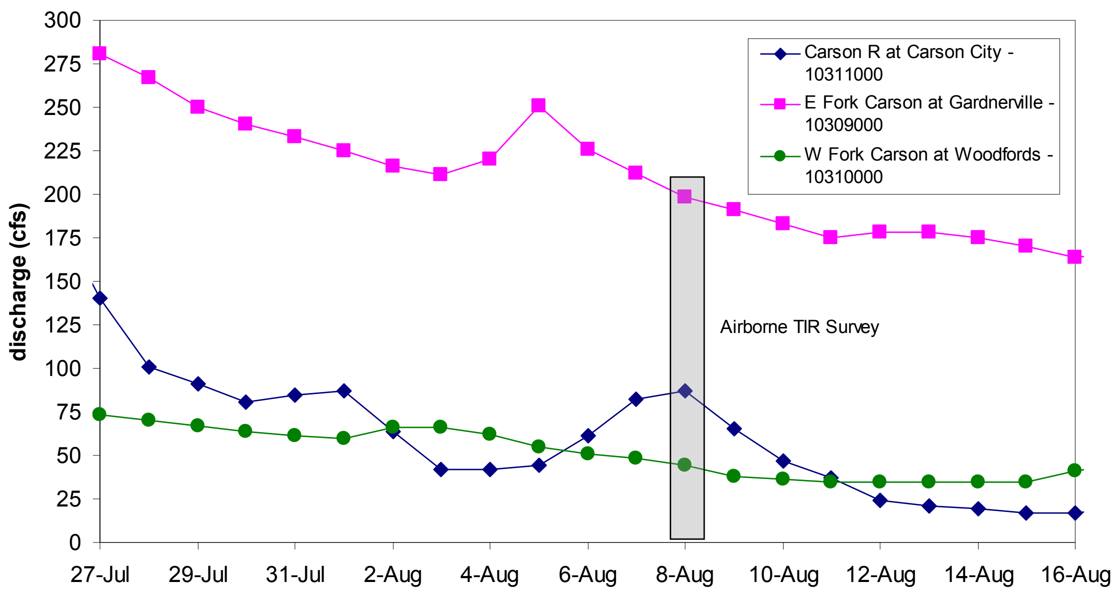


Figure 4. Daily average discharge of Carson River at USGS Carson City, Gardnerville, and Woodfords Gaging stations during 27 July- 16 August. The date of the airborne TIR survey (8 Aug 2006) is depicted with gray shading.

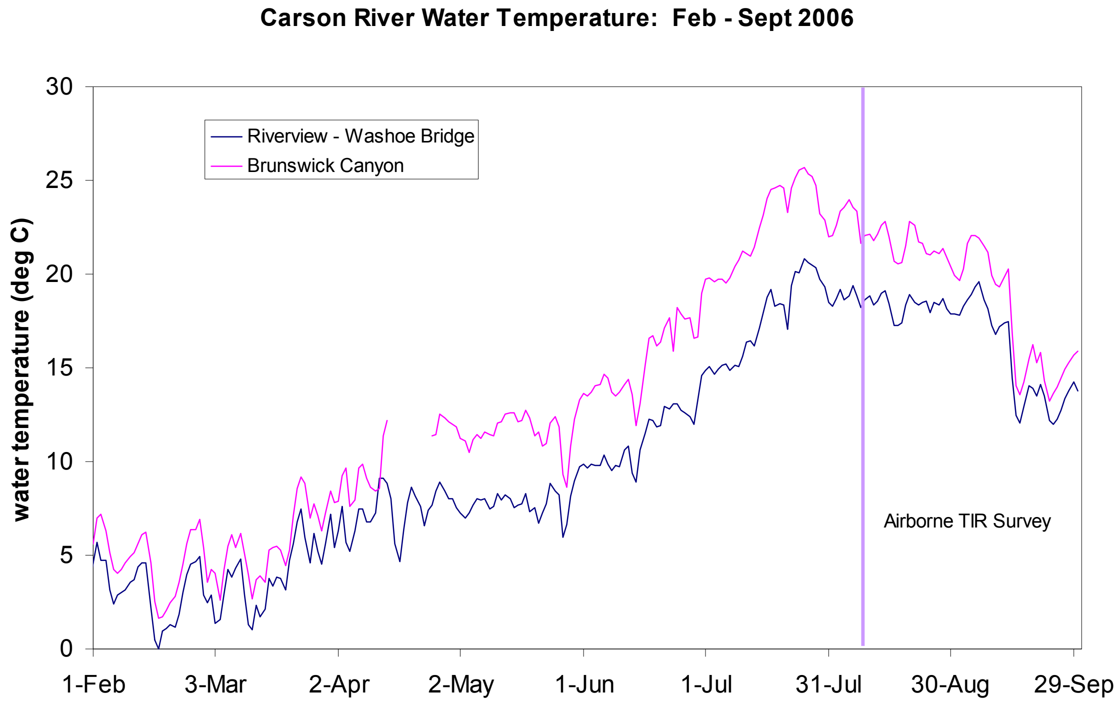


Figure 5. Daily average water temperature of Carson River at Washoe Bridge and Brunswick Canyon turbidity monitoring stations (Data Source: Susfalk et al. 2008)

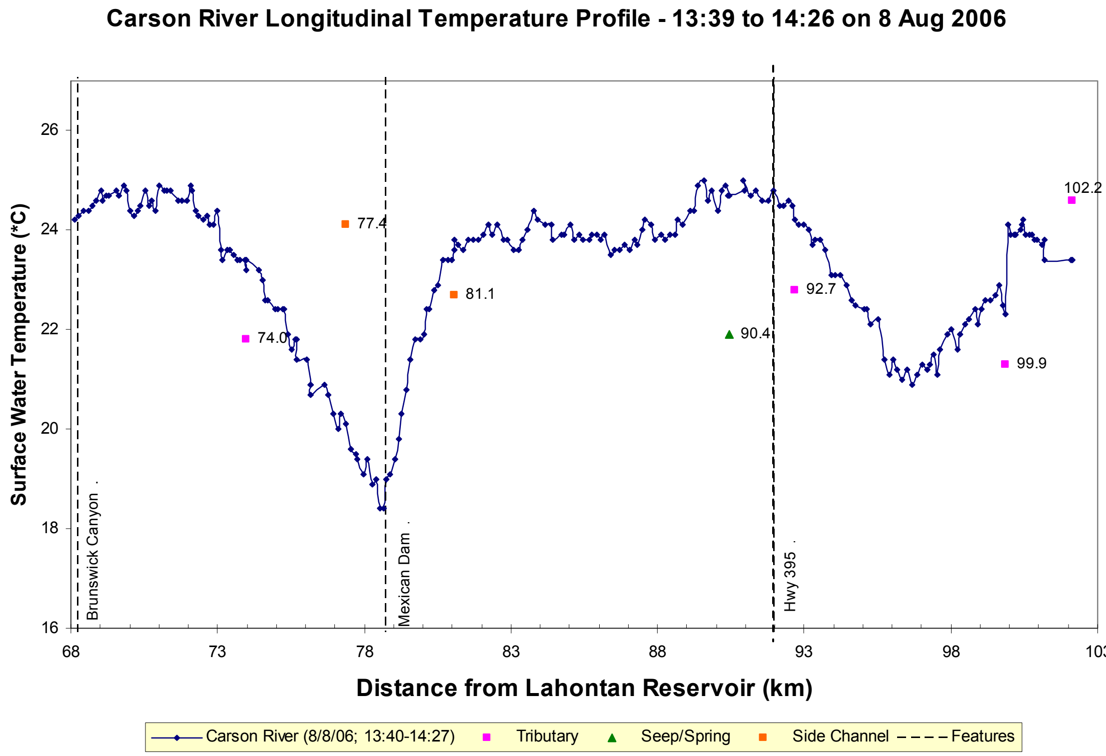


Figure 6. Longitudinal profile of surface water temperature for Carson River on 8 Aug 2006 13:40-14:27. (Data Source: Watershed Sciences 2006).

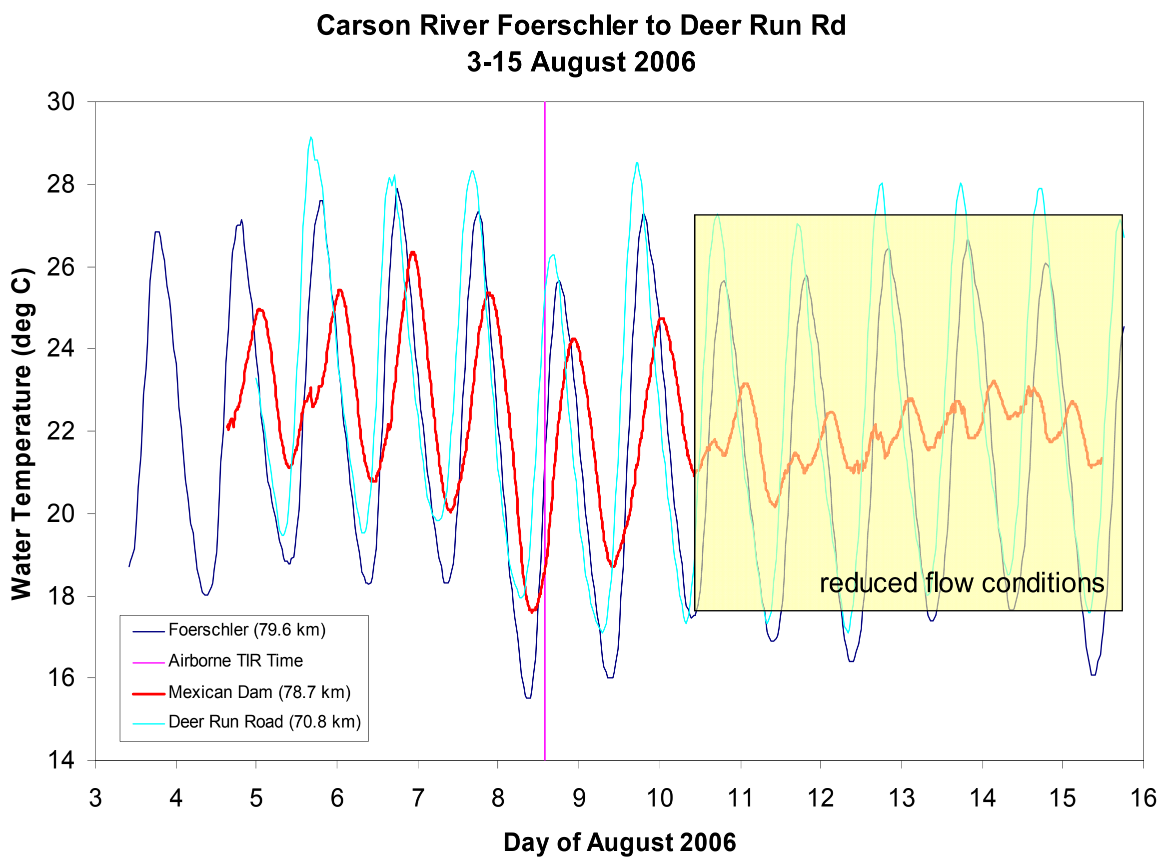


Figure 7. Carson River Temperature 3-15 Aug 2006 at Foerschler, Mexican Dam, and Deer Run Road Sites. The time of aerial TIR survey is indicated with vertical violet line. Distance from Lahontan Reservoir is given in parentheses.

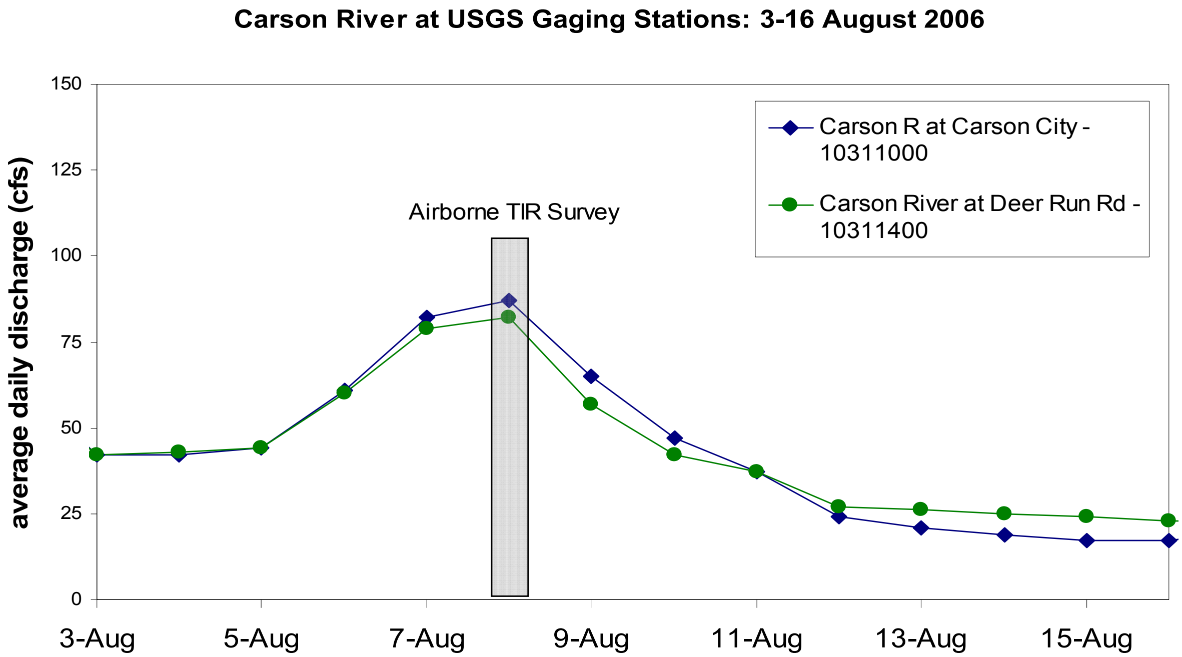


Figure 8. Discharge of Carson River at Carson City and Deer Run Rd USGS Gages during 3-16 August 2006.

Scoussa Diversion on Brockliss Slough

The Scoussa Diversion is located 100 m downstream from the Mottsville Lane bridge over Brockliss slough (Figure 9). Temperature recorder Site 2 was located in mid-channel 30 m downstream from the diversion. Water temperature was stratified vertically at the site, with a temperature gradient of 3.72°C (Table 2). The physical habitat where the temperature recorder was installed had a current velocity estimated visually to be about 25 cm/s, i.e., this site was not standing water. Surface water characteristics at Site 2 were suggestive of local groundwater influence. We noted the water had a distinct brown stain compared with the channel above the diversion.

Table 2. Water temperature at Site 2 on 2 Aug 2006 14:26 PDT

Location	Depth from Bed(m)	Temperature (°C)
Surface	0.6	20.70
Sensor	0.4	18.07
Bottom	0.0	16.98

Table 3. Characteristics of water measured for vertical profile of Brockliss Slough at the Mottsville Lane Bridge 14:52 PDT. -119.8068133 38.93205000. Site 3 sensor was tethered to concrete wall on west side of channel downstream from bridge (Figure 10). Surface and bottom temperatures were measured from center of bridge on downstream side (see Figure 11).

Location	Depth from bed (m)	Temperature (°C)
Surface	1.0	22.24
Sensor	0.4	22.03
Bottom	0.0	19.88

The TIR results for Brockliss Slough revealed a relatively cool ~1-km long segment of channel in the vicinity of Mottsville Lane (11.7-12.6 km; see Figure 12). Radiant surface temperature in this segment was coldest (19.4° C) immediately downstream from the Scoussa Diversion near Site 2. The thermographs for Site 2 and Site 3 tracked each other closely during 4-8 August. The temperature at the two sites showed a divergent pattern from August 8th onward, presumably due to reduced flow conditions (see yellow highlight on Figure 11). Results from the Mottsville Lane TIR and instream temperature data during the August 2006 illustrated the following:

a) Variation of instream water temperature occurred in the vicinity of irrigation diversions, with cooler conditions prevailing down gradient apparently due to groundwater influences.

b) The extent to which instream temperatures were altered above and below irrigation withdrawals was affected by discharge conditions.

c) Vertical gradients of water temperature occurred in the water column of the river with temperature at the surface cooler than at the river bed.

d) Data interpretation would be enhanced in future similar studies to augment temperature recorders with water depth sensors.

East Fork Carson River Diversion 250 m Downstream from Muller Lane

A low head irrigation diversion is located downstream from Muller Lane that extended across the entire channel. This dam is constructed of local alluvium from the channel and is rebuilt annually to convey irrigation water to the cultivated fields north of the East Fork of the Carson River. Three temperature recorders were deployed at the diversion, one in the pool upgradient from the diversion (Site 7) and two in the tailwater reach (Site 5 and Site 6; See Figure 12-15). The thermographs at these three locations during 3-15 August 2006 are plotted in Figure 21. Note that the amplitude of the diel oscillation was attenuated at down gradient Sites 5 and 6 from August 9th onward (Figure 14). Although stream gaging data are not available close by, the hydrograph at the Carson City USGS gage (10311400) on the mainstem showed a downward trend beginning on August 9th (Figure 8).

During the six days prior to August 9th, the daily maximum water temperature at the pool Site 7 was 26.40° C, compared to 25.65° C and 25.43° C at down gradient Sites 5 and 6, respectively. This amounted to a temperature difference above and below the diversion of -0.76° C to -0.97° C prior to August 9th. For the reduced flows observed during the six-day period following the ninth, the temperature difference above and below the diversion was in the range -3.63° C to -3.78° C (Table 4). Thus, results from the instream sensors showed that the diversion dam had a net cooling effect with respect to maximum temperature. This cooling effect was enhanced during reduced flow conditions.

The temperature decrease detected with the instream sensors was also evident in the airborne TIR results in the vicinity of the diversion. Over a 100 m , distance the temperature decreased from 23.1° C to 20.6° C, a net chance of minus 2.5° C. The temperature of the instream sensors at the time of the TIR survey are plotted on the longitudinal profile of radiant temperature in Figure 15. The fit between the airborne temperature measurements and the instream sensors is remarkably close.

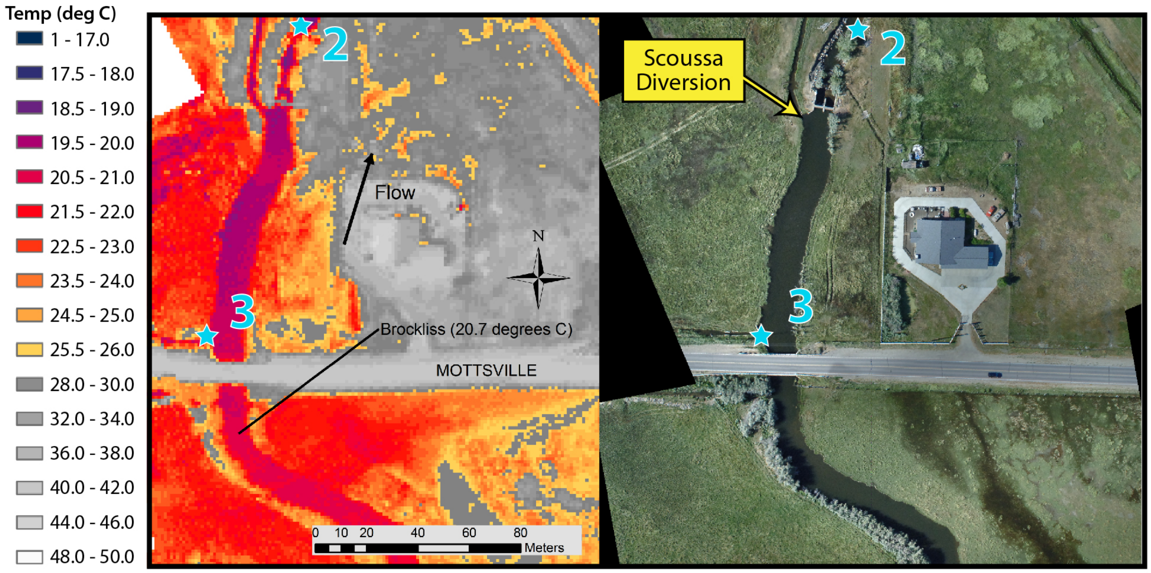


Figure 9. TIR (left) and true color (right) image of Brockliss Slough at Mottsville Lane. Location of in stream temperature data logger site indicated with blue stars. 8 Aug 2006 Imagery source: Watershed Sciences (2006).

Figure 10. Brockliss Slough at Mottsville. P. Pugsley points to thermochron secured to post and A. Ball records notes. 2 Aug 2006

Figure 11. Brockliss Slough at Mottsville Lane. J. Brock measures water temperature at surface 22.24 deg C, at bottom 19.88 deg C. 2 Aug 2006

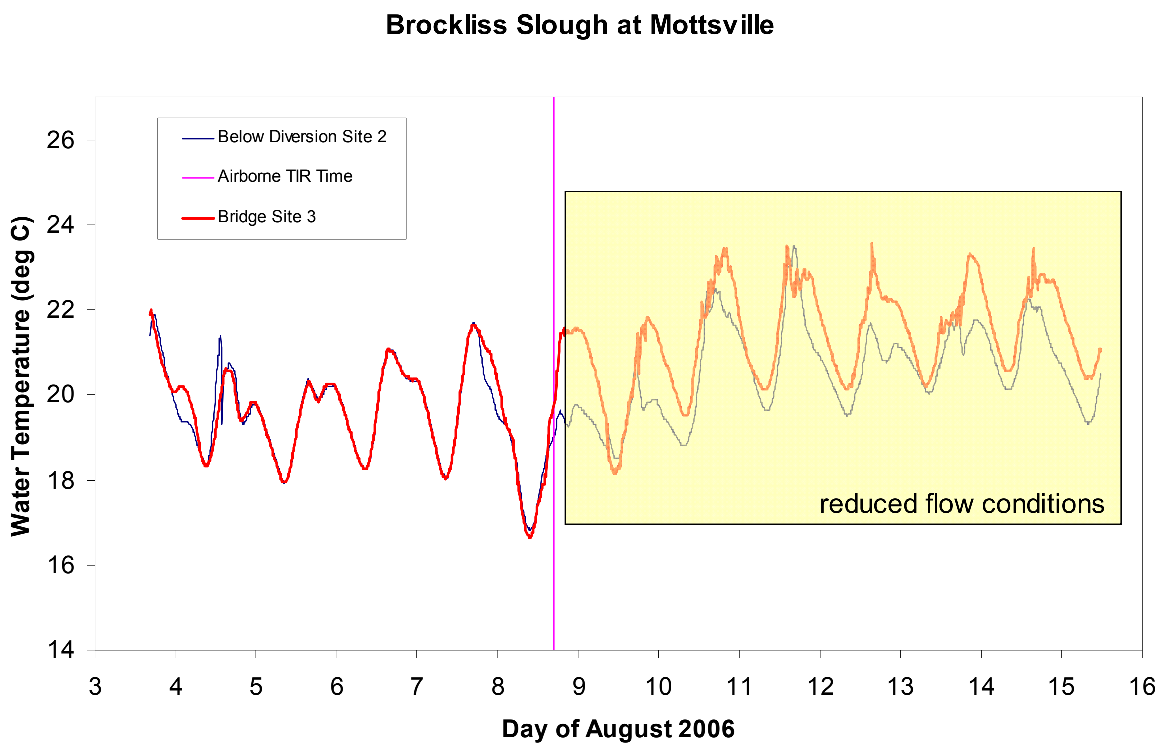


Figure 12. Water temperature measured with instream temperature logger in Brockliss Slough above and below Scoussa Diversion. 3-15 August 2006. Period of apparent reduced flow conditions highlighted in yellow.

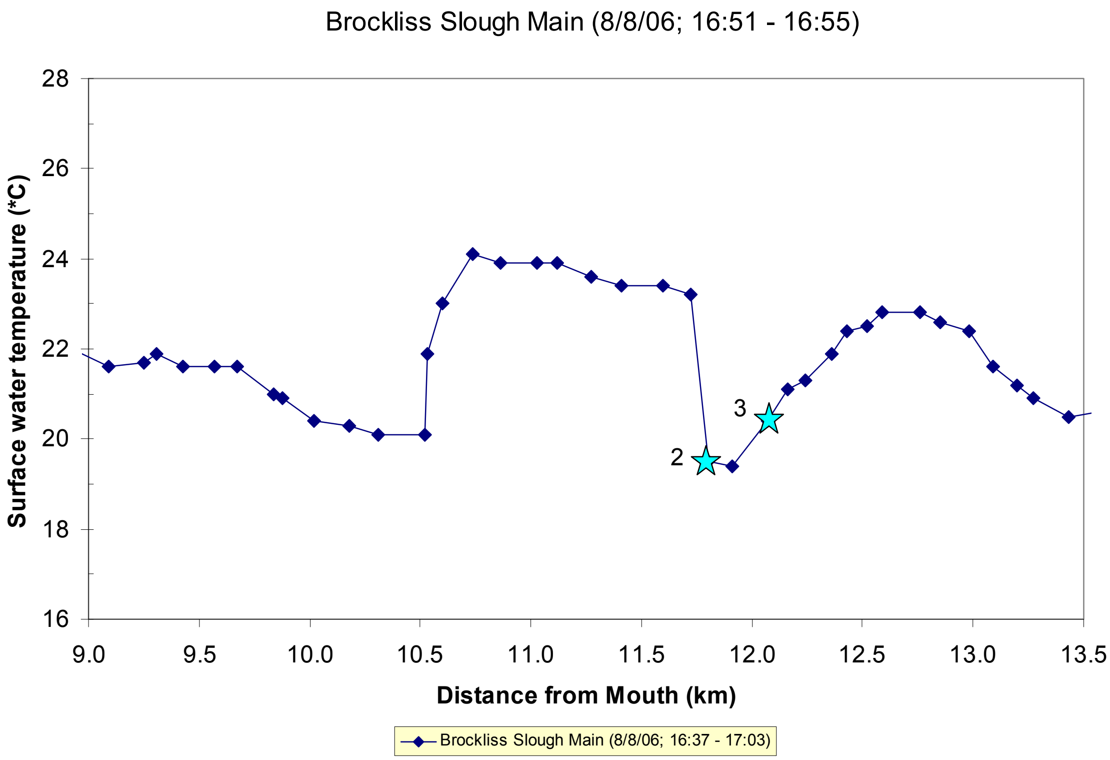


Figure 13. Airborne TIR and instream temperature recorder location for Sites 2,3 on Brockliss Slough 8 August 2006. TIR data source: Watershed Sciences 2006.

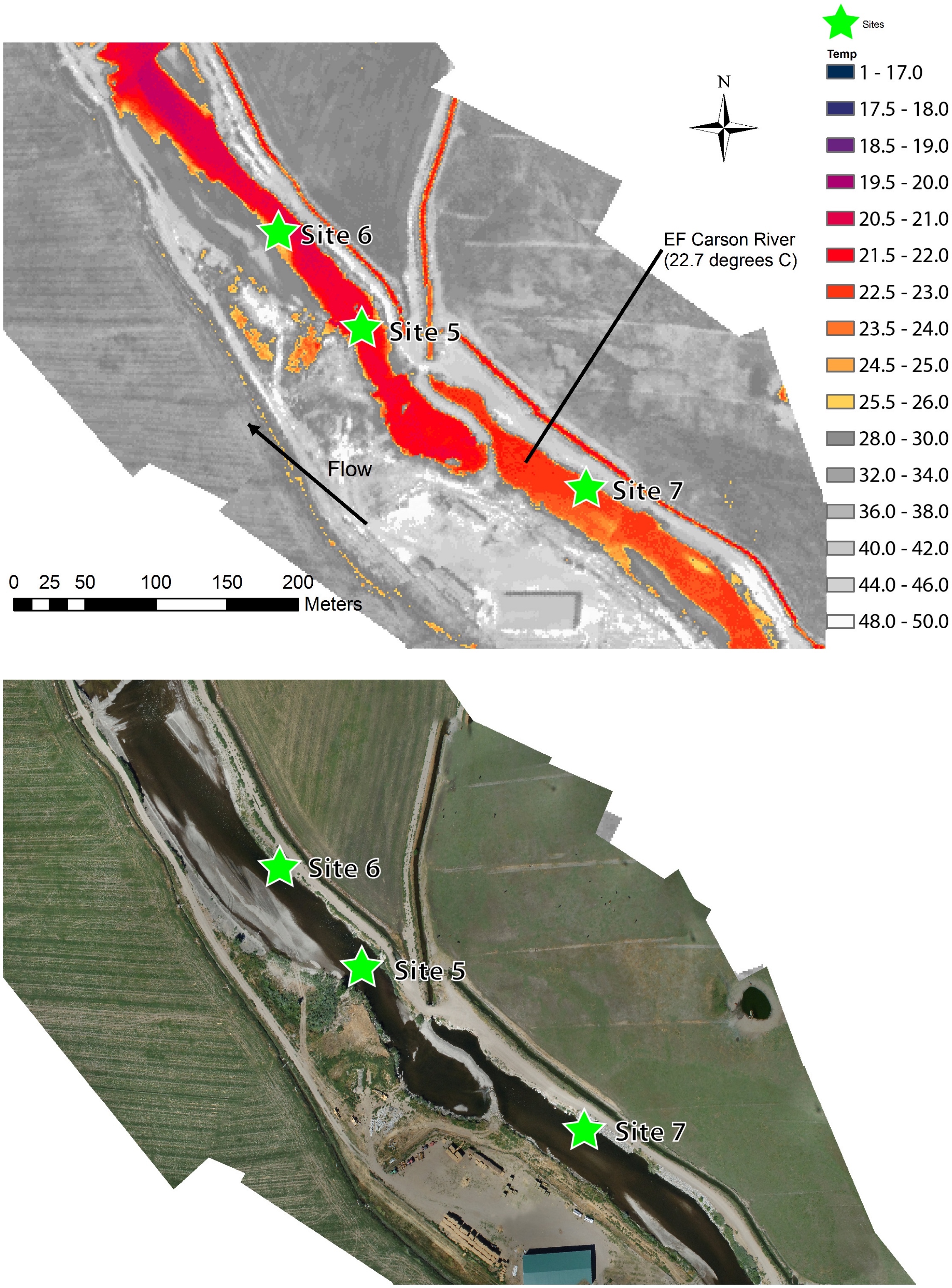


Figure 14. TIR (above) and true color (below) image of East Fork of Carson River downstream from Muller Lane. Location of temperature logger sites indicated with stars. Imagery source: Watershed Sciences (2006)

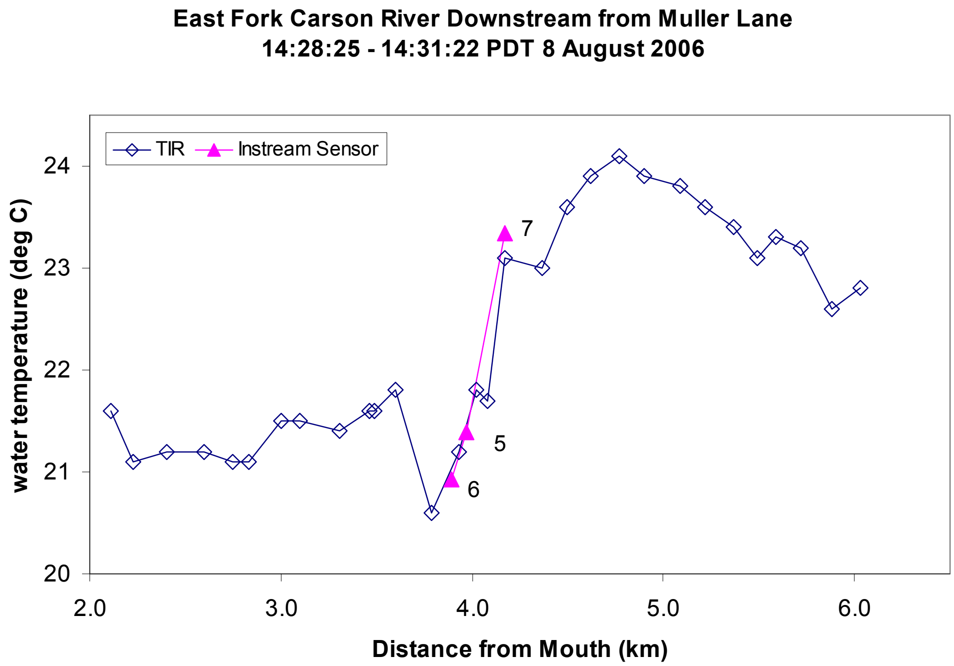


Figure 15. Airborne TIR and instream temperature at Sites 5, 6, and 7 of East Fork Carson River downstream from Muller Lane. 8 August 2006. TIR data source: Watershed Sciences 2006

Figure 16. River level view looking upstream towards Site 5 from gravel bar below diversion. 2 August 2006.

Figure 17. East Fork Carson downstream from Muller Lane below diversion. Site 6 shown in red circle. 2 Aug 2006

Figure 18. East Fork Carson R downstream from Muller Lane above diversion. Site 7 shown in red circle. 2 Aug 2006

Figure 19. East Fork Carson downstream from Muller Lane below diversion. Site 5 shown in red circle. 2 Aug 2006

Figure 20. East Fork Carson below diversion looking downstream from point located between Sites 5 and 6. 2 Aug 2006

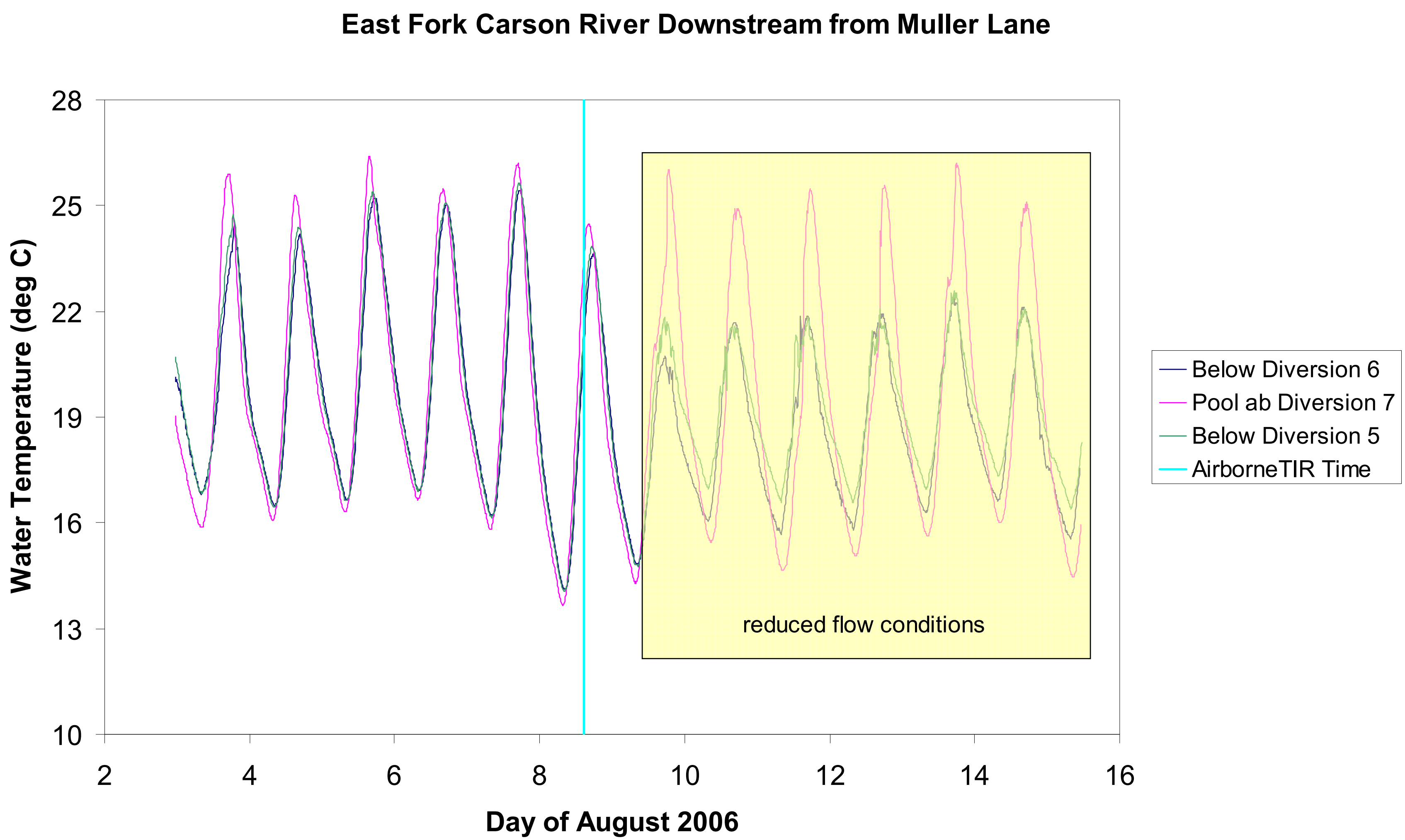


Figure 21. Water temperature at East Fork Carson River downstream from Muller Lane during 3-15 August 2006. The time of aerial TIR survey is indicated with vertical turquoise line.

Table 4. Instream water temperature statistics (degrees C) for Sites 5, 6, and 7 on East Fork of Carson River downstream from Muller Lane during periods preceding and following the August 2006 airborne thermal survey.

Site	Statistic	Period (2006)	
	six day	3-8 Aug	9-15 Aug
5	max	25.65	22.58
	mean	19.94	18.96
	min	14.07	14.76
6	max	25.43	22.43
	mean	19.89	18.45
	min	14.11	14.86
7	max	26.40	26.22
	mean	19.88	19.25
	min	13.64	14.27

The time series from the instream sensors in the vicinity of diversions suggests that the magnitude of temperature differences detected during the TIR survey of the Carson River represent a conservative view as the survey took place at a time with relatively higher flows than present only a few days later.

Vertical Temperature Profiles

The TIR survey approach provided a comprehensive view of radiant surface temperature. Supplemental measurements of temperature on vertical profiles were made to assess the extent to which temperature at positions deeper in the water column differed from surface temperature. Under the low flow conditions prevalent during the August 2006 synoptic survey the upper Carson River did not have many pools in excess of 1 m. We made measurements on 23 August 2006 at three vertical profiles, one at Mexican Dam, and two at Last Low Head Diversion. Results of the vertical profiles are plotted in Figures 22 and 23. At Mexican Dam, there was a vertical temperature gradient of 1.3° C over a 2.0 m depth, with cooler conditions prevailing near the bed. At Last Low Head Diversion, we detected a zone in the impounded pool that was 2° C cooler than the surface.

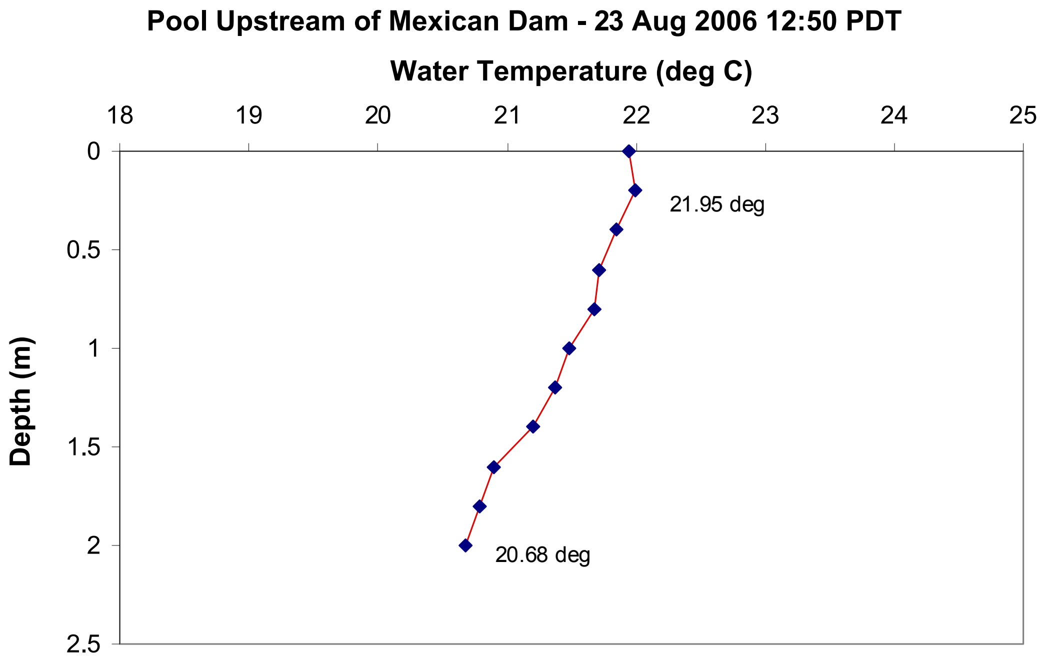


Figure 22. Vertical profile of temperature in pool upstream of Mexican Dam on Carson River on 23 Aug 2006.

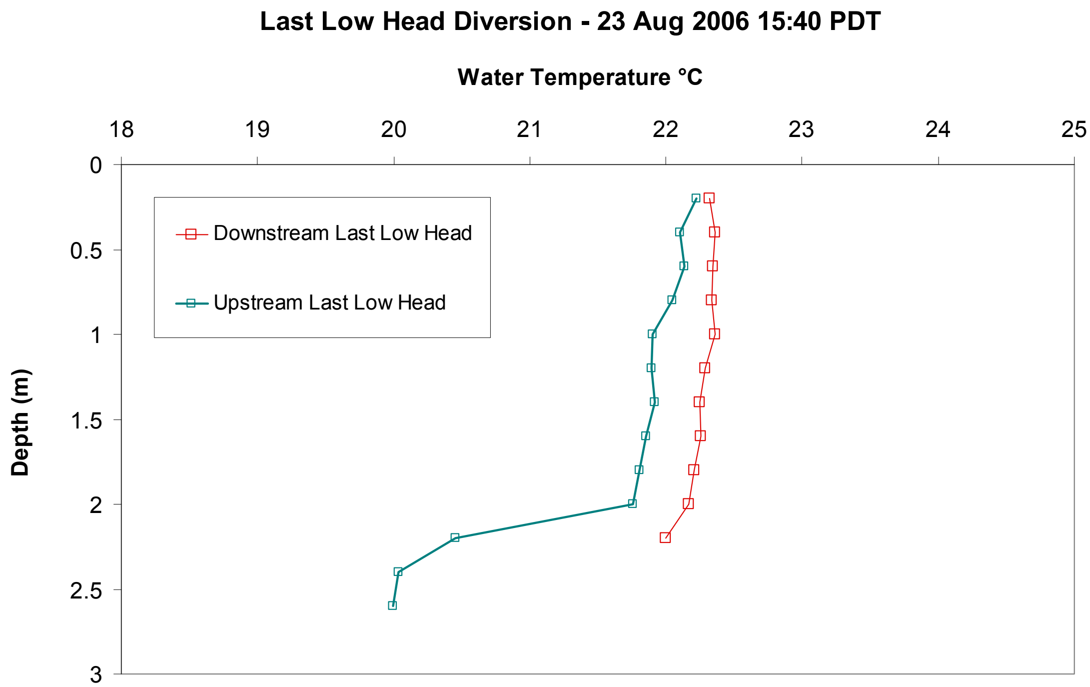


Figure 23. Vertical profile of temperature in pools above and below Last Low Head Diversion on East Fork of Carson River on 23 Aug 2006.

Comparison of AirborneTIR and Instream Measured Temperature

The instream measured temperatures are compared against the TIR Survey-derived radiant temperatures in Figure 24. With an r^2 of 0.74, the fit is reasonably good, with 17 of the 22 residuals within 1° C. The thermal accuracy for 16 points reported by Watershed Sciences (2006) had 15 points within ±1°C with one having a difference of -2.4° C. Residual analysis (Figure 25) reveals three points with a differential of 1-2° C and two points with residuals that are close to 3° C. Large residuals may be caused by poor mixing (could be either in x, y, or z direction) at a site, or a location with high spatial variability where the error in GPS coordinates for the instream data recorders was significant.

The two outliers with a residual > 2° C were West Fork at Paynesville (-2.7° C) and Carson River at Ambrosetti (-2.8° C). The Ambosetti site (AMB) was at the outlet of the drain from a pond area that is fed predominantly by groundwater. This location is suspected to have a large groundwater influence as suggested by the shape of the diel temperature trajectories, especially after flows began to decrease from August 9th onward (Appendix A). The West Fork at Paynseville site (WFPAYN) is located in a reach with large cobbles and riparian shading from cottonwood trees extending over the channel. The GPS coordinates for the instream sensor were on a tree crown, so we used a point in the thalweg of the stream channel to select the TIR temperature. We have no further information on spatial distribution of instream temperatures at the Paynesville site to explain the relatively large residual. The Carson River at McTarnahan site (McT) had its instream sensor located at the warmest site on the River, and was 1.35° C higher than the radiant temperature derived from the TIR image.

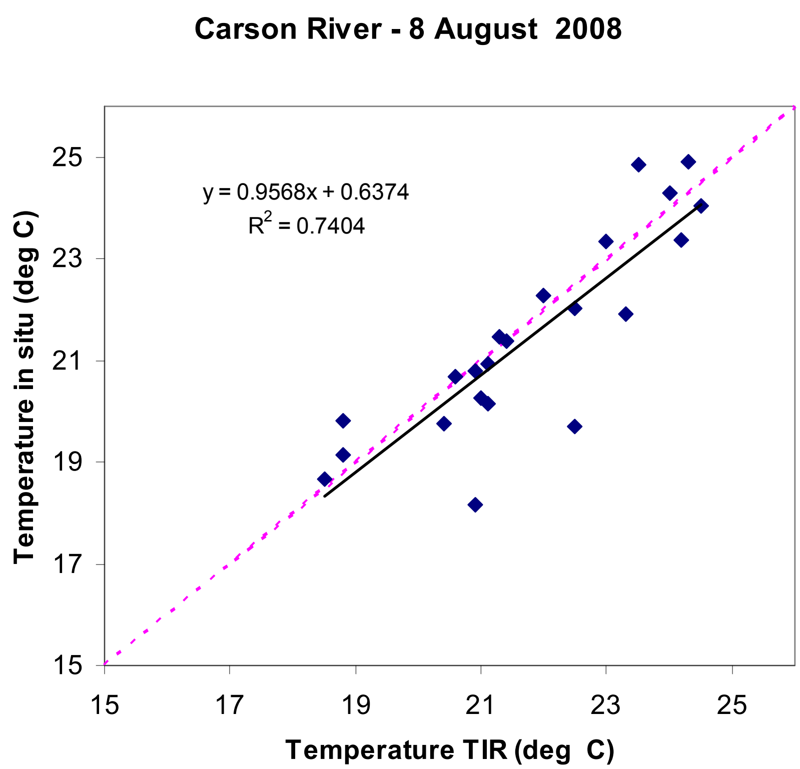


Figure 24. Correlation between water temperature measured by TIR Survey with corresponding instream data recorder for 8 Aug 2006. n=22. Equality line shown in violet.

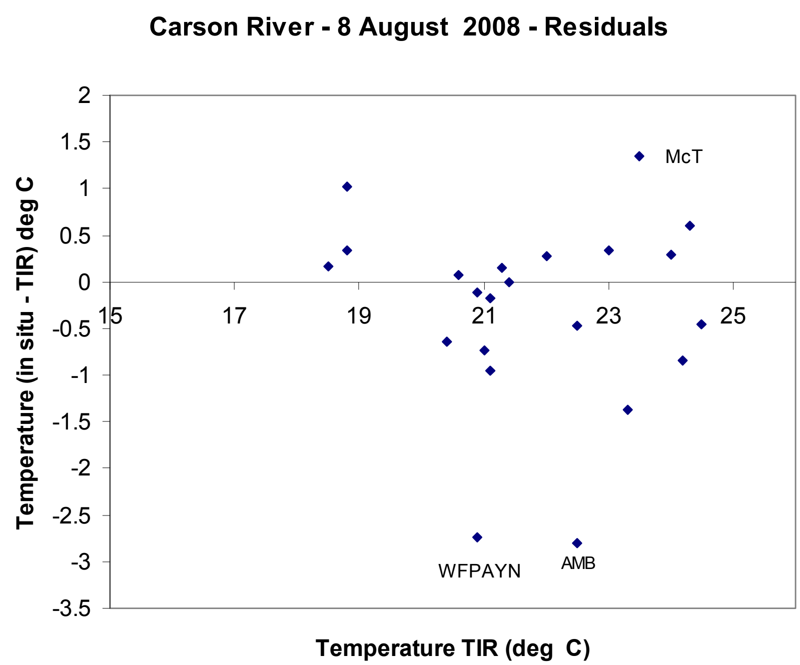


Figure 25. Plot of residuals between TIR survey temperature and instream measurement for correlation shown in Figure 24. Positive residuals indicate instream values are warmer than TIR.

Conclusions

1. As expected, water temperatures varied greatly in space and time during August in the upper Carson River basin.
2. The temperature measured by instream sensors matched the temperature derived from TIR survey images reasonably well, with a goodness of fit (R^2 = 0.74; n = 22).
3. The technique for deployment of the temperature recorders using a float, string, and weight worked well. The accuracy of the GPS used to obtain instream coordinates was a limitation for the analysis. A mapping grade field GPS unit with sub meter accuracy is recommended to match the resolution of the thermal imagery.
4. Discharge influenced the temperature regime on a daily basis. Augmenting the instream temperature recorders with level sensors would enhance understanding of thermal dynamics.
5. The three irrigation diversions that were evaluated had cooler mid-day temperatures in their tailwaters than in the impounded pools.

Acknowledgements

I thank Jeramie Memmott, Chris Garner, Andrew Ball, and Ryan Shearer for assistance with field work and data analysis. Jeramie created the map of sample sites, as well. Paul Pugsley (Carson Valley Conservation District) contributed valuable information on the hydrologic setting of the Carson Valley and helped arrange for access permission from private landowners. Randy Pahl of NDEP provided guidance, assistance, and helpful suggestions throughout the project. Randy and Chris Garner assisted with the vertical thermal profiling of pools. Lisa Wable improved the clarity of the images. Alan McKay helped secure funding for the airborne thermal survey. I extend special thanks to Russ Faux of Watershed Sciences who assisted with coordination and implementation of the airborne thermal survey. The research was funded partially by Nevada Department of Environmental Protection (NDEP) and the US Environmental Protection Agency by Assistance Agreement No. X-83277801 awarded to Desert Research Institute.

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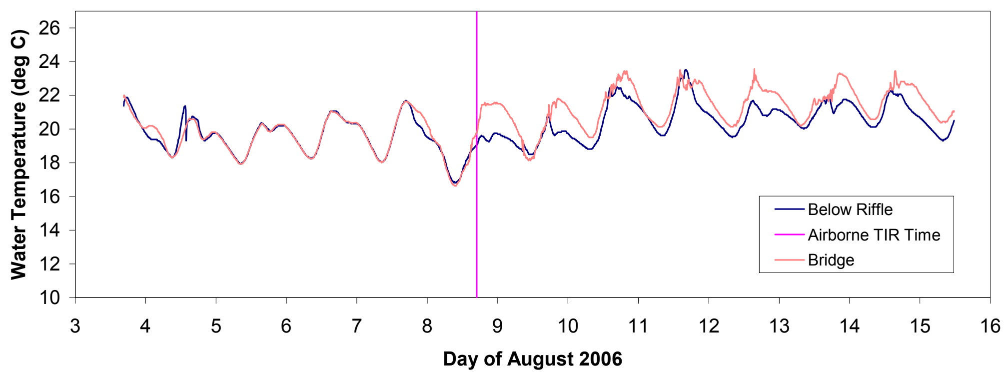
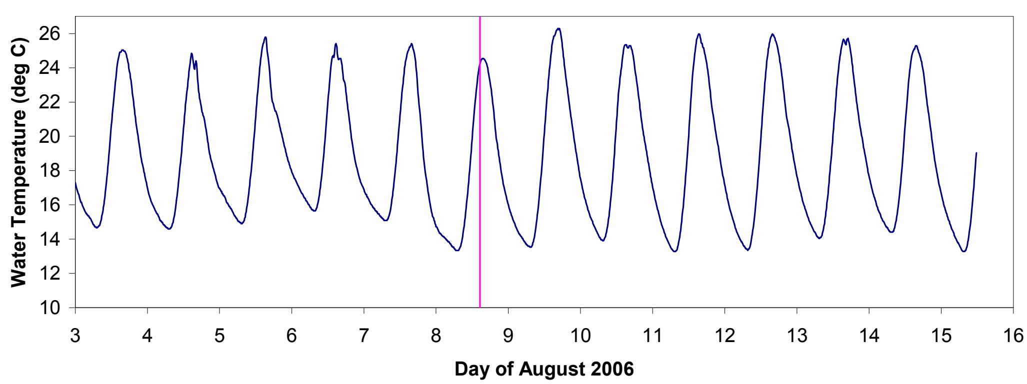
Appendix A

Plots of water temperature during August 2006
at sites where temperature data loggers were deployed

Brockliss Slough at Mottsville



East Fork Carson at Highway 88



East Fork Carson at Riverview Bridge

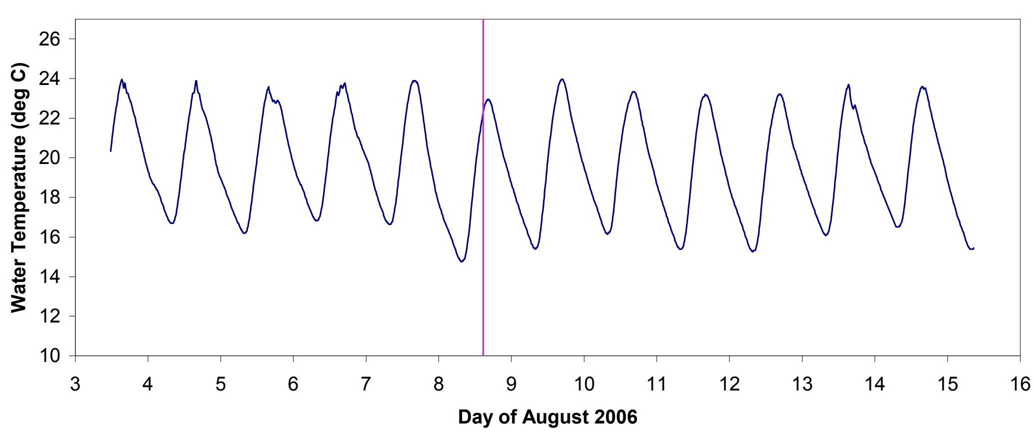


Figure 4

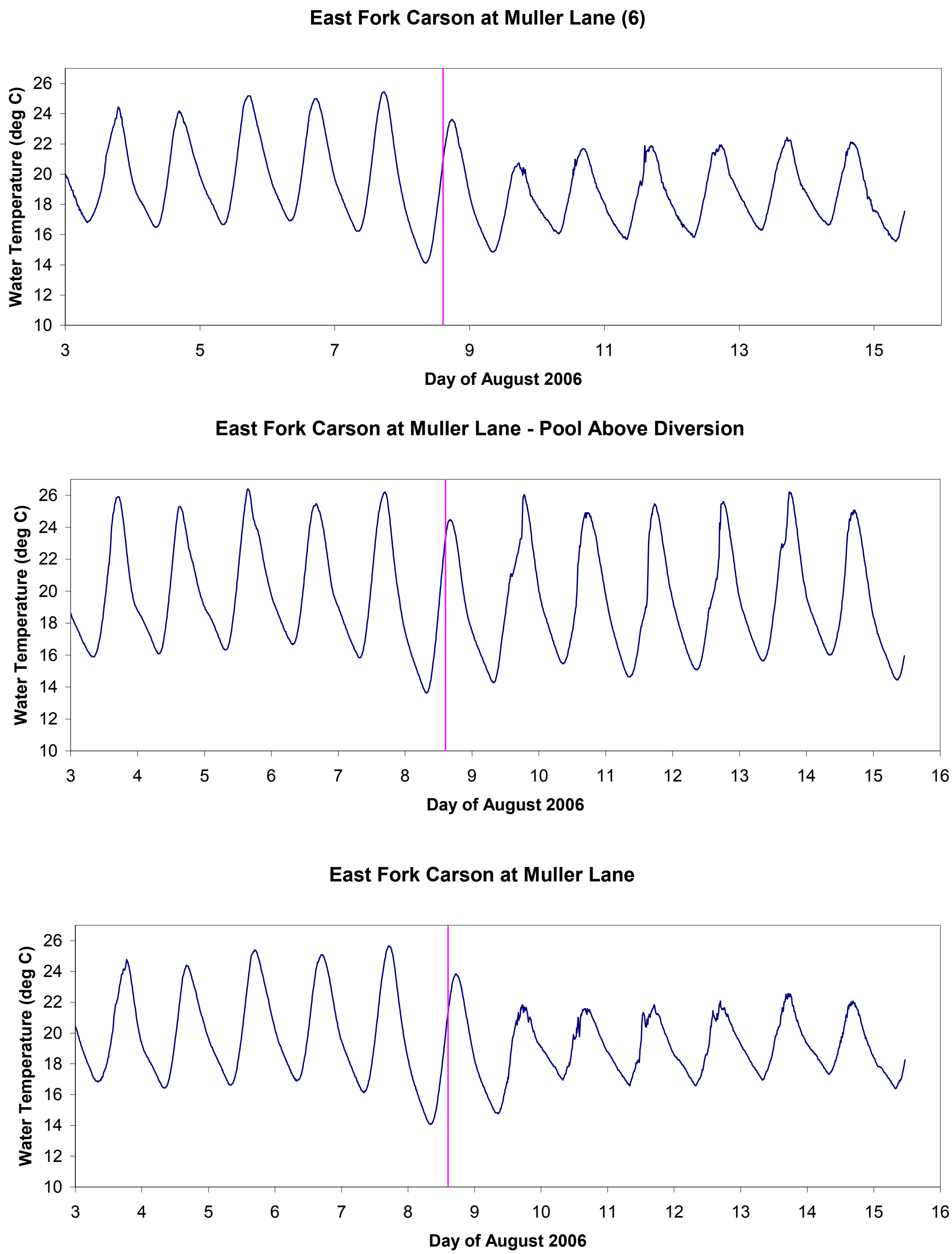
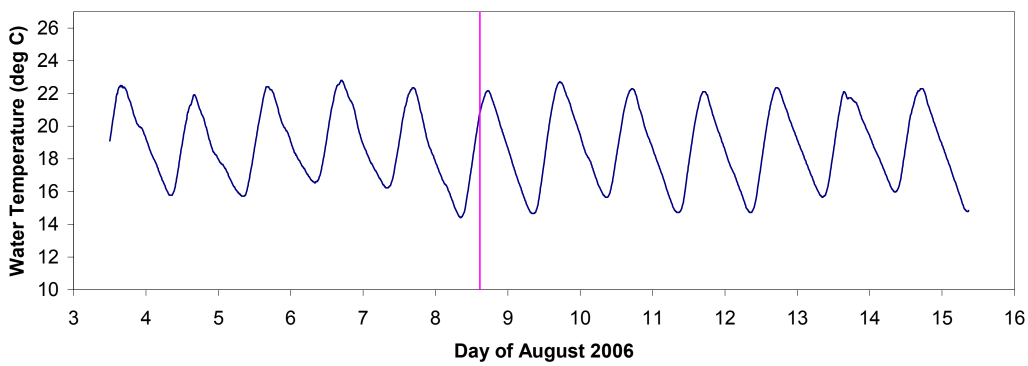
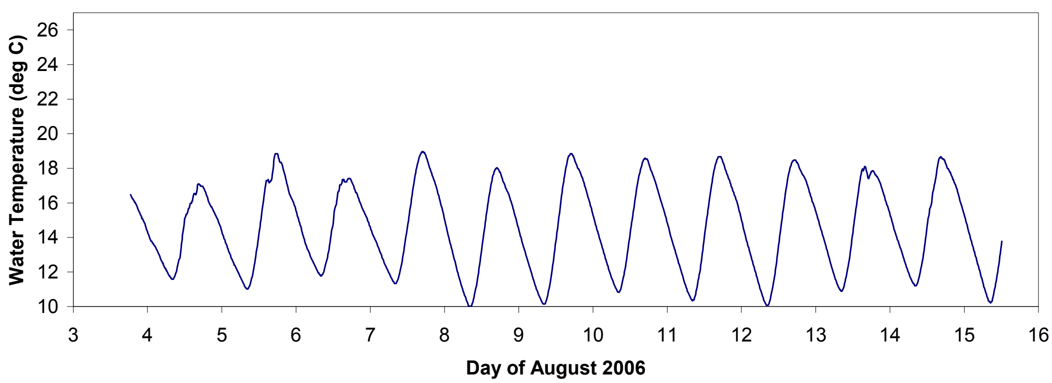

East Fork Carson at Muller Lane (6)
Water Temperature (deg C)
26
24
22
20
18
16
14
12
10
3
5
7
9
11
13
15
Day of August 2006
East Fork Carson at Muller Lane - Pool Above Diversion
Water Temperature (deg C)
26
24
22
20
18
16
14
12
10
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Day of August 2006
East Fork Carson at Muller Lane
Water Temperature (deg C)
26
24
22
20
18
16
14
12
10
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Day of August 2006

Figure 5

East Fork Carson at Washoe Bridge



East Fork Carson at Junction HWY 4 and 89



East Brockliss

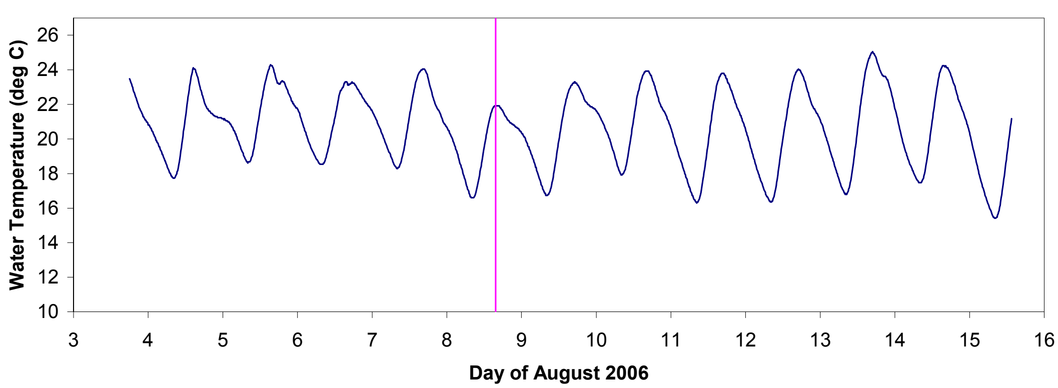


Figure 6

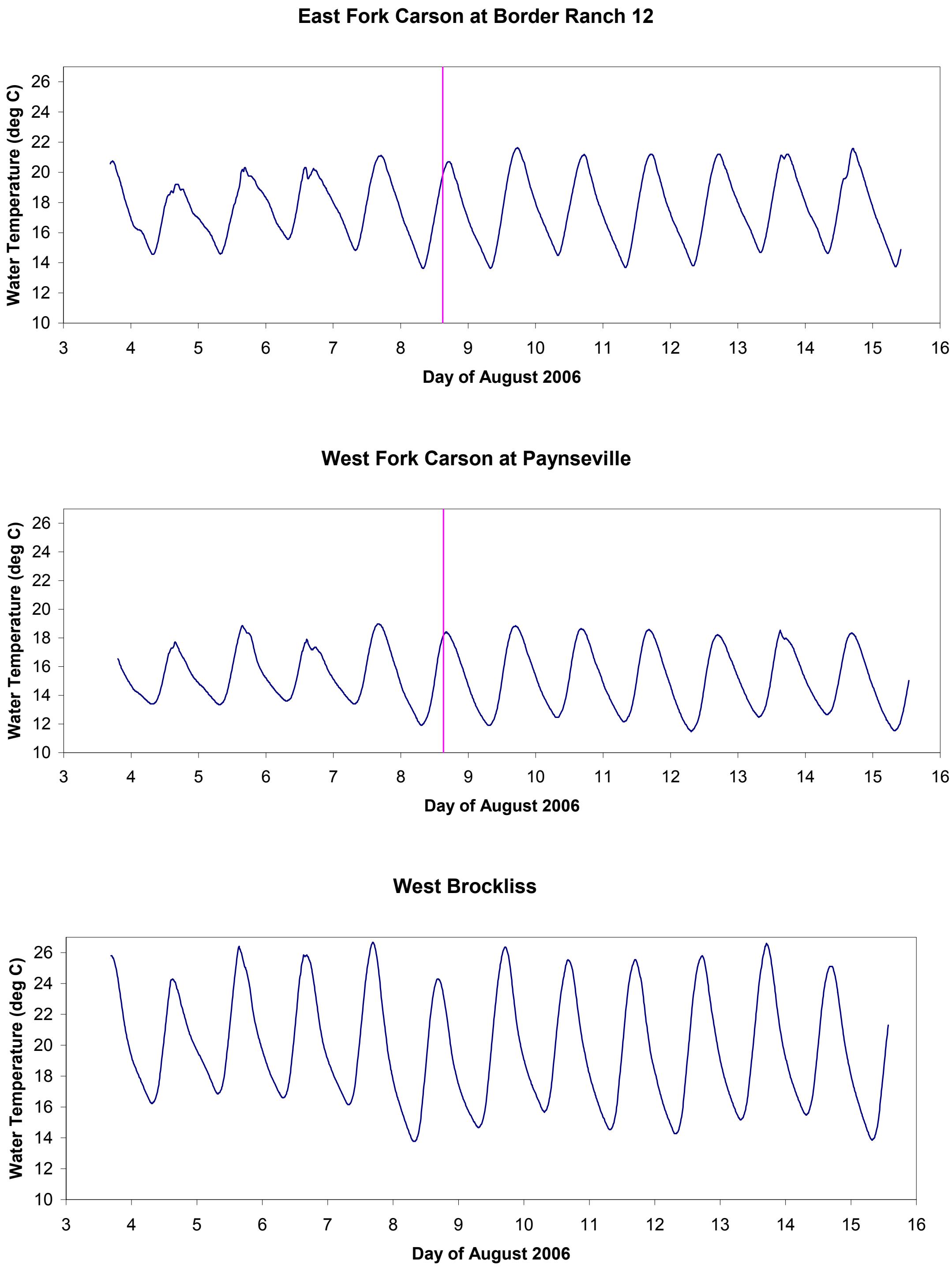

East Fork Carson at Border Ranch 12
Water Temperature (deg C)
26
24
22
20
18
16
14
12
10
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Day of August 2006
West Fork Carson at Paynseville
Water Temperature (deg C)
26
24
22
20
18
16
14
12
10
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Day of August 2006
West Brockliss
Water Temperature (deg C)
26
24
22
20
18
16
14
12
10
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Day of August 2006

Figure 7

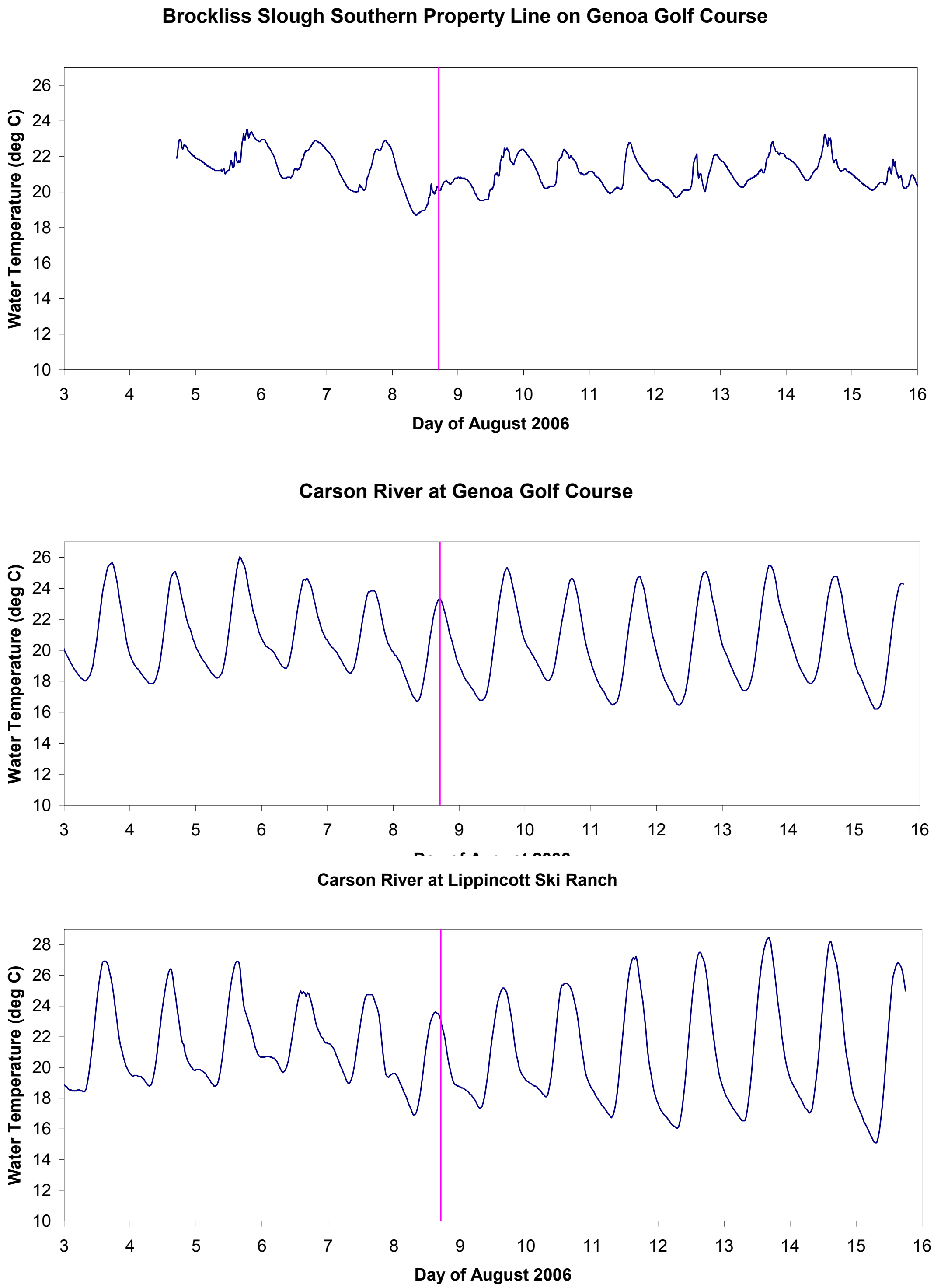
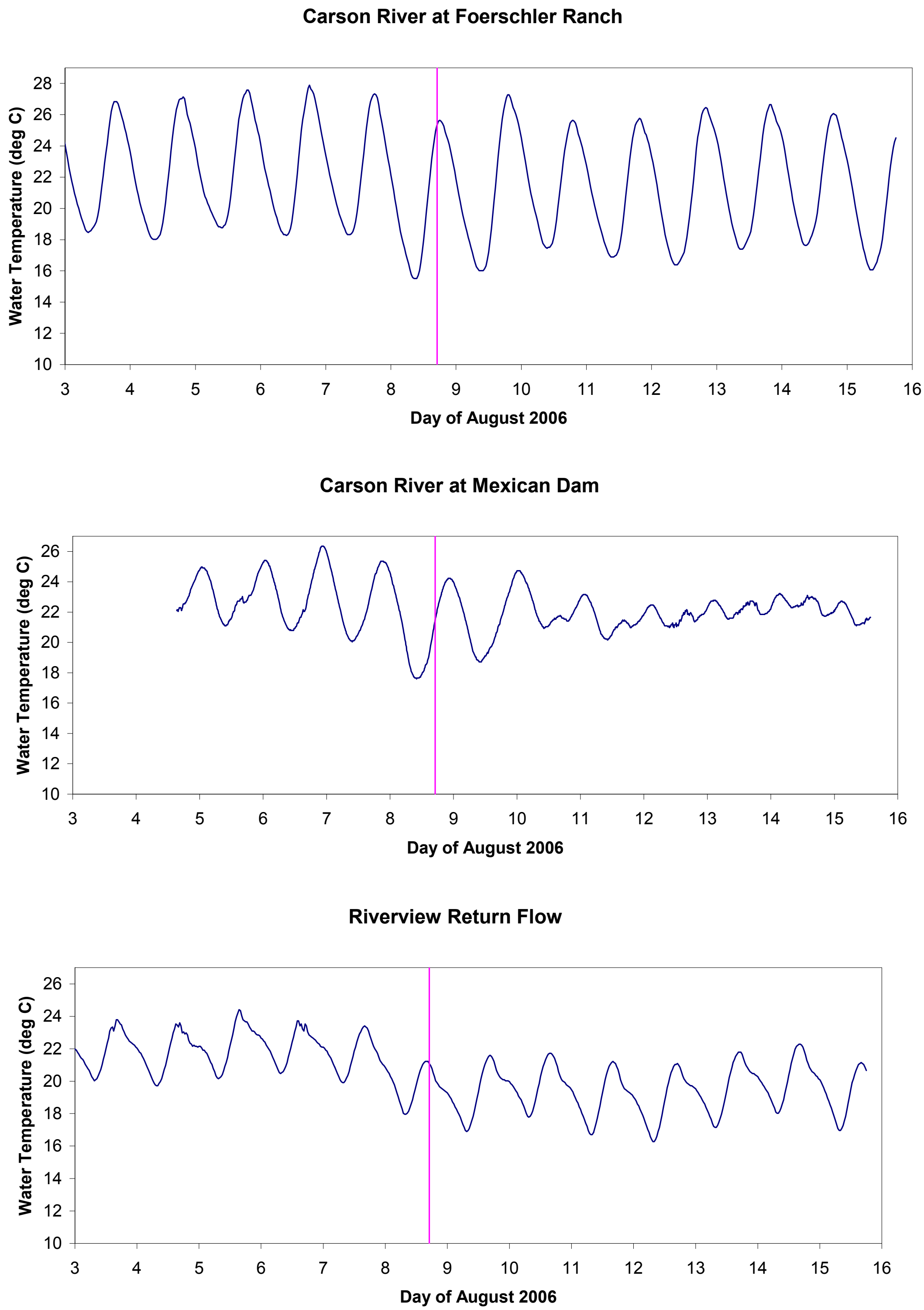

Brockliss Slough Southern Property Line on Genoa Golf Course
Water Temperature (deg C)
10
12
14
16
18
20
22
24
26
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Day of August 2006
Carson River at Genoa Golf Course
Water Temperature (deg C)
10
12
14
16
18
20
22
24
26
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Carson River at Lippincott Ski Ranch
Water Temperature (deg C)
10
12
14
16
18
20
22
24
26
28
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Day of August 2006

Figure 8



Carson River at Foerschler Ranch
Water Temperature (deg C)
28
26
24
22
20
18
16
14
12
10
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Day of August 2006
Carson River at Mexican Dam
Water Temperature (deg C)
26
24
22
20
18
16
14
12
10
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Day of August 2006
Riverview Return Flow
Water Temperature (deg C)
26
24
22
20
18
16
14
12
10
3
4
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6
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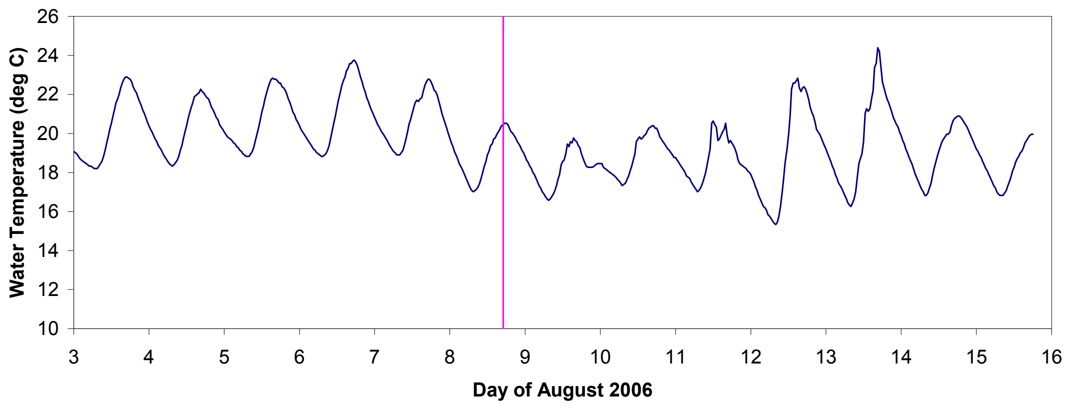
8
9
10
11
12
13
14
15
16
Day of August 2006

Figure 9

Carson River at Ambrosetti



Carson River at McTarnahan

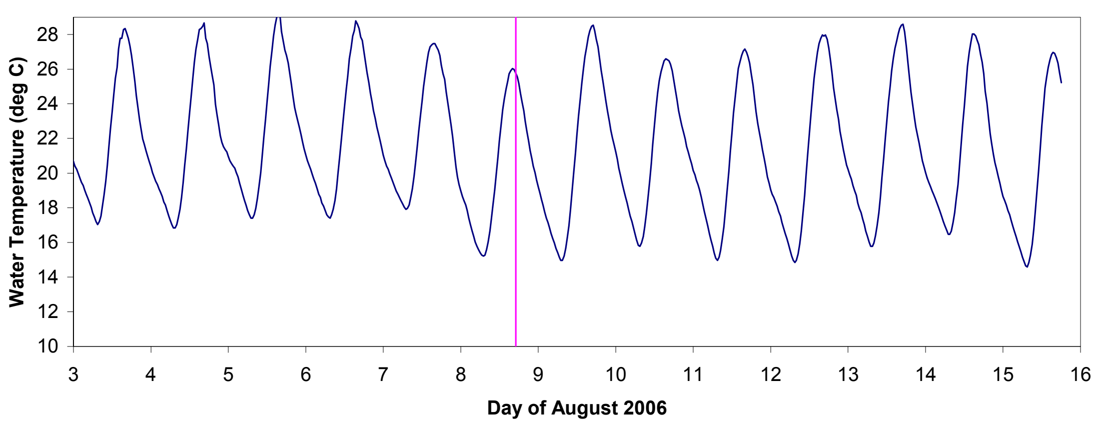
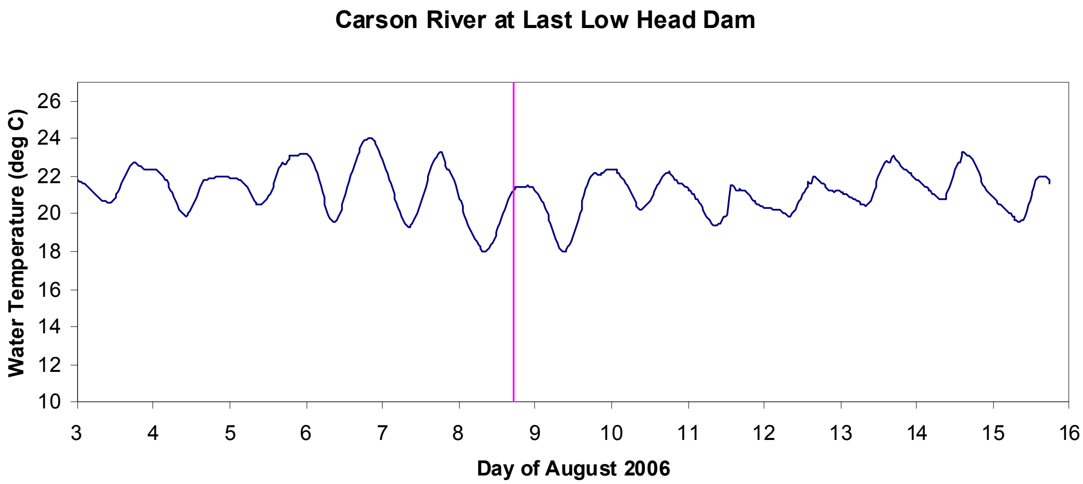


Figure 10


Carson River at Last Low Head Dam
Water Temperature (deg C)
26
24
22
20
18
16
14
12
10
3
4
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6
7
8
9
10
11
12
13
14
15
16
Day of August 2006

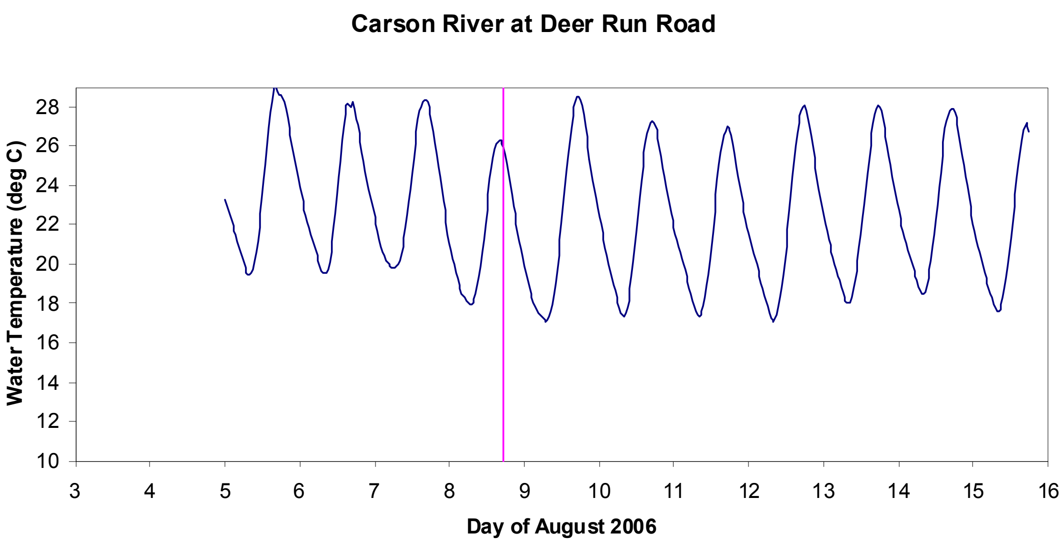
Carson River at Deer Run Road
Water Temperature (deg C)
28
26
24
22
20
18
16
14
12
10
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Day of August 2006

Figure 11