Quantifying Small-scale Temperature Variability using Distributed Temperature Sensing and Thermal Infrared Imaging to Inform River Restoration

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Abstract. Watershed-scale stream temperature models are often one-dimensional because they require less data and are more computationally efficient than two- or three-dimensional models. However, one-dimensional models assume completely mixed reaches and ignore small-scale spatial temperature variability, which may create temperature barriers or refugia for cold water aquatic species. Fine spatial and temporal resolution stream temperature monitoring provides information to identify river features with increased thermal variability. We used a distributed temperature sensing system to observe small-scale stream temperature variability, measured as temperature range through space and time, within two 400 meter reaches in summer 2015 in Nevada's East Walker and mainstem Walker Rivers. In addition, thermal infrared aerial imagery collected in summer 2012 quantified the spatial variability of river temperatures throughout the Walker Basin. Both the distributed temperature sensing data and thermal infrared aerial imagery were used to corroborate temperature model results. Temperature model estimates were within the DTS measured temperature ranges 21% and 70% of the time for the East Walker River and mainstem Walker River, respectively, and within TIR measured temperatures 17%, 5%, and 5% of the time for the East Walker, West Walker, and mainstem Walker Rivers, respectively. Additionally, measured data highlighted that beaver dams and irrigation return flow channels maximize thermal variability and can provide thermal refugia, while groundwater seeps provide small cooler areas and diversion canals often create warm local temperatures downstream. To extend temperature predictions and obtain a better understanding of thermal variability at the watershed-scale, temperature bounds from observations by river features were added to the longitudinal temperature predictions. These results show that while bulk stream temperatures are often too warm to support trout and other cold-water species, thermal refugia may exist to improve habitat connectivity and passage for migratory species. Overall, complementary DTS and TIR measurements identify thermal refugia and augment process-based modeling.

1 Introduction

Trout and salmon avoid heat stress by sheltering in pockets of cold water when stream temperatures are near upper thermal tolerances (Dunham et al. 2003; Sutton et al. 2007). Climate change is anticipated to increase stream temperatures in summer, fall, and winter, thus thermal refugia are often important for trout and salmon (Isaak et al. 2012). Recent research has quantified when and where cold-water fish need thermal refugia (Brewitt and Danner 2014), estimated the required size of thermal refugia and the distance between refugia (Fullerton et al. 2018), demonstrated how fish use thermal refugia (Frechette et al. 2018), and measured the length of time that fish can survive between refugia (Pepino et al. 2015). However, where stream temperatures are warming or where cold-water fish species are at the southern extent of their range, measuring stream temperatures at small temporal and spatial scales is important to quantify stream temperature heterogeneity (Vatland et al. 2015). One-dimensional stream temperature models estimate longitudinal stream temperature changes at the watershed-scale, but are poor predictors of thermal micro-habitats. On the other hand, high resolution temperature monitoring provides micro-habitat information, but is typically conducted over small spatial extents and thus difficult to extrapolate to the watershed scale for management and restoration decisions.

Stream temperature models are a useful tool for river management because they help decision makers understand stream temperature dynamics and the potential impacts of restoration and management. Many one-dimensional temperature models exist, and have been applied to understand temperature effects of dams, reservoir re-operation, climate change, and restoration in systems all over the world (Bond et al., 2015; Elmore et al., 2016; Pelletier et al., 2006). Stream temperature models used in management are often one-dimensional because they are less data intensive and more computationally efficient than two- or three-dimensional models that account for temperature variability over width and depth. However, one-dimensional models do not identify small-scale features like cold water pools, lateral variability, or groundwater influenced areas.

Stream temperature sensors measure temperatures at fine spatial and temporal resolution at point locations. Distributed temperature sensing (DTS) approaches provide near-continuous temperature measurements in both time and space (Selker et al. 2006; Suárez et al. 2011). Raman spectra DTS is capable of measuring temperatures every meter along fiber optic cables with an accuracy of at least ±0.1 ^oC (Tyler et al., 2009), and cables vary between approximately 1 – 10 km. In addition to quantifying thermal dynamics in air, streams, lakes, soil, and snow, DTS has determined zones of groundwater influence (Hare et al. 2015; Selker et al. 2006; Suárez et al. 2011) and hyporheic exchange (Briggs et al., 2012). Thermal infrared (TIR) data have successfully identified spatial heterogeneity (e.g., Bingham et al., 2012) and locate groundwater and tributary inputs (Dugdale et al., 2013; Loheide and Gorelick, 2006; Mundy et al., 2017). TIR imagery similarly captures spatially-continuous stream surface temperatures. However, TIR data are for a single point in time unless acquired on multiple occasions (Dugdale, 2016; Torgersen et al., 2001).

DTS and TIR are sometimes used in conjunction with stream temperature models. DTS data were used to calibrate and validate a 1.3 km physically-based, one-dimensional stream temperature model of the Boiron de Morges River in southwest

Switzerland (Roth et al. 2010) and a 580 m river reach in Luxembourg's Maisbich River (Westhoff et al. 2007). TIR data have been used in conjunction with stationary temperature loggers to calibrate reach- and basin-scale models (Bingham et al., 2012; Cardenas et al., 2014; Carrivick et al., 2012; Deitchman and Loheide, 2012). For example, TIR data were combined with instream temperature loggers to calibrate an 86 km QUAL2Kw water quality model in the Wenatchee River in Washington (Cristea and Burges, 2009) and a 100 km scale statistical model in the Big Hole River, MT (Vatland et al. 2015). In the latter study, Vatland et al. (2015) concluded that single point monitoring sites underestimate the temporal and spatial heterogeneity in stream temperatures and that DTS data provided a promising addition to TIR and stationary loggers. To date, no studies have used DTS and TIR to quantify temperature ranges by river feature within model reaches, and use that information to estimate likely temperature ranges over space and time at the watershed scale. Such insight into small-scale responses allows researchers, managers, and stakeholders to identify thermal micro-habitats and further interpret one-dimensional basin-scale model results.

The objectives of this study were to 1) evaluate small-scale stream temperature variability, quantified as the range of stream temperatures, at multiple spatial scales using DTS data and TIR imagery, 2) use those data to corroborate an existing one-dimensional (300 m spatial resolution) basin-scale stream temperature model calibration, 3) identify river features with greater stream temperature variability, and 4) add measured, spatially explicit stream temperature ranges to model results for appropriate river features to futher interpret temperature variability throughout a watershed. Nevada's Walker Basin was the study watershed and is representative of other arid and semi-arid watersheds in western USA where cold water species like trout and salmon are temperature-limited. River restoration is ongoing in the Walker Basin and there is a clear need to understand small-scale stream temperature ranges in different river features (e.g., beaver ponds, confluences) to identify thermal refugia and barriers to migration.

2 Study Site

The Walker River flows from the east-slope Sierra Nevada Mountains into Walker Lake, a terminal lake in the Great Basin (Fig 1). The lower elevations of the Walker Basin have an arid climate with hot summers, whereas high elevations receive heavy snowfall during cold winters (Sharpe et. al 2008). The Walker River is a desert stream with mean annual flow of 15.5 – 30 m^3/s, mean width of approximately 7.6 m and depth of about 33 cm. The mainstem Walker River is the confluence of two branches, the East Walker River and the West Walker River. In the prolonged drought of 2011-2017, lower portions of the Walker River were dry and disconnected from Walker Lake in fall of 2014 and 2015 (Null et al. 2017).

Figure 1: Walker River modeled extent, June 2015 DTS deployment sites, and July 2012 TIR imagery extent.

Agriculture is the main land use in the basin. Irrigated farmland makes up approximately 450 km^2 of the 10,720 km^2 Walker Basin (Sharpe et. al 2008). Bridgeport Reservoir on the East Walker River, Topaz Reservoir on the West Walker, and Weber Reservoir on the mainstem Walker River regulate water to support agriculture and other human water uses. There are 23 diversions and eight return flows in the East, West, and mainstem Walker Rivers, which influence both streamflows and stream temperatures. Interactions among climate, management actions, surface water, and groundwater are complex in the Walker Basin (Niswonger et al. 2014). The Walker River generally gains water during wet years and loses flow during dry years; however, the mainstem Walker River is almost always a losing reach (Carroll et al., 2010). Agricultural flood irrigation replenishes groundwater levels during the summer months (Carroll et al., 2010; Lopes and Allander, 2009).

Walker Lake once supported healthy populations of Lahontan cutthroat trout (LCT) (*Oncorhynchus clarkii henshawi*), which spawned in the Walker River and tributaries. The historical range of LCT is the Lahontan Basin in eastern California, southeastern Oregon, and northern Nevada, although LCT persist in less than 10% of their historical range because they are limited by warm stream temperatures, low streamflows, and low dissolved oxygen (Coffin and Cowan 1995; USFWS 2003). LCT are now listed as a threatened species under the Endangered Species Act (USFWS 1975). Field studies conducted in Coyote Lake (Oregon), Quinn River (Oregon and Nevada), and Humboldt River (Nevada) indicate LCT occurrence is reduced at stream temperatures above the acute (< 2 hr) threshold of 28 °C (Dunham et al. 2003). Measured stream temperatures exceeded the acute 28 °C temperature threshold for LCT during summer 2014 and 2015 in the Walker River (Null et al., 2017).

Low instream flows from surface water diversions have also caused Walker Lake level to decline, increasing dissolved salts in the lake to concentrations which do not support trout and native benthic insects (Herbst et al., 2013; Wurtsbaugh et al., 2017). To address these problems, an environmental water purchase program acquires natural flow and storage water rights from willing sellers who switch to crops that require less water or improve agricultural water use efficiency (NFWF, 2018; Walker Basin Conservancy, 2018). To date, 2.3 m^3/s of natural flow water rights and 13.3 million m^3 of storage water rights have been purchased, approximately 40% of the water needed to restore Walker Lake salinity to tolerable levels (Walker Basin Conservancy, 2018). Previous modeling has suggested that environmental water purchases intended to increase lake elevation also improve aquatic habitat conditions in the Walker River by increasing streamflows, reducing stream temperatures, and increasing dissolved oxygen concentrations (Elmore et al. 2016; Null et al. 2017).

3 Methods

3.1 Distributed Temperature Sensing (DTS) Data

DTS units measure temperatures by sending a laser pulse down a fiber-optic cable and timing the return signal. Although the majority of the reflected energy has its original wavelength, a portion of the energy is absorbed and re-emitted at both shorter (Anti-Stokes backscatter) and longer (Stokes backscatter) wavelengths. Temperatures along the cable are determined from the Stokes/Anti-Stokes ratio (Selker et al. 2006). A 1 km silver armored DTS cable was deployed to measure diurnal stream temperatures in the mainstem and East Walker Rivers. Data were collected over 400 m in the East Walker River at Rafter 7 Ranch on June 18-23, 2015 and over 450 m in the mainstem Walker River at Stanley Ranch on June 25-30, 2015 (Fig. 1). 2015 was a dry year when snowpack was 5% of normal. The DTS cable was deployed in a U shape at both sites, with approximately 400 m of cable on each side of the stream to capture lateral stream temperature differences. The cable was suspended in the water column approximately 10 cm above the streambed with steel stakes and leashes. Mainstem

Walker River DTS deployment included approximately 20 m of a flood irrigation return flow canal named the Wabuska Drain. The Wabuska Drain was not flowing during the drought when the DTS was deployed, but contained standing water and was connected with the Walker River.

A two-channel Sensornet Orxy DTS unit measured stream temperatures at a spatial resolution of 1 m and temporal resolution of 15 minutes. Each data collection event measured temperatures over 30 seconds and averaged temperature along the 1 m sample interval. Measurement precision from the unit is 0.01 ºC in the -40 to 65 ºC range. The DTS had two co-located fibers within the cable that were connected in a splice box at the end of the cable. This created an internal loop of fiber, producing one double-ended set of temperature measurements (Hausner et al., 2011). However, the splice box was damaged, so two single-ended datasets were evaluated in place of one double-ended dataset.

The DTS was dynamically calibrated during deployment with 10 m of cable placed in three recirculated calibration baths. One ambient and one ice bath were near the DTS unit and one ambient bath was at the end of the cable (Hausner et al., 2011; Tyler et al., 2009). RBRsolo thermocouple temperature sensors that are accurate to 0.002 ºC in the -5 ºC to 35 ºC range measured calibration bath temperatures. Nine Maxim Integrated iButton thermistors provided additional stream temperature measurements along the cable every 15 minutes to verify DTS temperatures. iButton temperature loggers are accurate to 0.5 ºC in the -40 to 85 ºC range. Calibration used a linear transformation to correct the DTS data based on the difference between the DTS and thermocouple temperatures. Post-collection processing used the single-ended explicit calibration method developed by Hausner et al. (2011). Due to cable damage near the splice box prior to the third calibration bath, post processing relied upon iButton data closest to the end of the cable and the two calibration bath thermocouples near the DTS. First, sections of cable that were exposed to air were removed from the dataset. Data points were also removed if the temperature difference between the two instrument channels was >1 ºC because tension on the DTS cable can result in erroneous temperature measurements (Hausner et al., 2011). Temperatures for these points were linearly interpolated between the upstream and downstream cable locations. Root mean square errors (RMSE) were calculated between each thermocouple or iButton and corresponding DTS temperature. We reported the average RMSE of the two thermocouples and iButton to quantify DTS error for the length of the cable for each single-ended dataset. The single-ended dataset with the lowest calibrated RMSE was used for data analysis and results. In addition, RMSE was calculated between georeferenced iButton stream temperature measurements and the corresponding georeferenced DTS stream temperature measurements for the data collection period to provide additional corroboration of the DTS temperatures. iButton residuals were calculated as the difference between iButton temperatures and co-located DTS measured temperatures.

A Decagon eKo Pro Series meteorological station with an eKO ET22 weather sensor collected solar radiation, wind speed and direction, air temperature, humidity, barometric pressure, and precipitation every 15 minutes at the DTS data collection locations for each deployment. Edge of water, DTS cable location, thalweg, and channel cross sections were surveyed with a Leica Viva GS14 GNSS Real Time Kinematic (RTK) GPS and measurements were accurate to approximately 2 cm in the x and y directions. USGS gages 10293500 and 10301500 provided flow data for the East Walker River and mainstem Walker River, respectively. DTS deployments occurred on warm and clear summer days when maximum air temperatures were 34.7 ºC at the East Walker River and 37.9 ºC at the mainstem Walker River DTS sites. Average flow was 1.2 m^3/s (42 ft^3/s) in the East Walker River and 1.0 m^3/s (36 ft^3/s) in the Walker River during deployment (Fig. S2).

3.2 Airborne Thermal Infrared (TIR) Data

TIR imagery of the Walker River was collected by Watershed Sciences Inc. on November 16-17, 2011 (winter flight) and July 18 and 24-26, 2012 (summer flight) (Watershed Sciences Inc., 2011; 2012). 2012 was a dry year when snowpack was 50% of normal. TIR flights measured surface stream temperatures for 240 river km in the East Walker, West Walker, and mainstem Walker Rivers to Weber Reservoir (Fig. 1). A FLIR Systems, Inc. SC6000 sensor (wavelength of 8-9.2 µm, Noise Equivalent Temperature Differences of 0.035 ºC, and pixel array of 640 x 512 at a 14 bit encoding level) mounted on the underside of a Bell Jet Ranger Helicopter collected imagery, and was flown at an altitude of approximately 610 m. Pixel resolution was 0.6 m (Watershed Sciences Inc., 2012). We used summer TIR data for all analyses in this paper, except to identify possible cool-water seeps, which were more apparent with the winter dataset.

Watershed Sciences Inc. calibrated and georeferenced the data, and provided raster layers of the data and interpreted TIR imagery, which we refer to as summary points. Surface inflow temperatures were reported at their confluence with the Walker River. For the summary points, stream channel TIR temperatures were queried at ten locations in the center of the channel and the minimum, median, and maximum values were reported. Flight speed, image overlap, and river features determined which images to sample (Watershed Sciences Inc., 2012). We completed analyses with the georeferenced TIR rasters and the summary points. TIR data were collected on warm summer days with low humidity. Average air temperature during data collection was 33.1 ºC and average wind speed was 11.6 km per hour (kph) in Yerrington, NV. Average flow was 1.0 m^3/s (34 ft^3/s), 1.1 m^3/s (39 ft^3/s), and 2.8 m^3/s (100 ft^3/s) in the mainstem Walker River (USGS gage 10301500), West Walker River (USGS gage 10298600), and East Walker River (USGS gage 10293500), respectively (Watershed Sciences Inc. 2012). Calibrated TIR radiant temperatures were validated with 28 Hobo Pro and iButton sensors. For the river extent used here, TIR data were within 0.5 °C of the instream sensors except for one location in the East Walker River where two instream sensors were 1.7 °C and 3.3 °C cooler than radiant TIR temperature, and one location in the West Walker River where an instream sensor was 1.1 °C cooler than radiant temperature. TIR measured water surface temperatures, so these discrepancies may have occurred where the river was not well mixed. See Watershed Sciences Inc. (2012 and 2011) for additional TIR data collection detail.

3.3 River Modeling System (*RMS*) Modeled Stream Temperatures

Previous research provided modeled streamflows and stream temperatures for one wet (2011) and three dry (2012, 2014, 2015) April 1- October 31 irrigation seasons using *RMS* (Elmore et al. 2016; Null et al. 2017). *RMS* is a 1-dimensional hydrodynamic and water quality model which solves the St. Venant equations for conservation of mass and momentum and the Holly-Priessmann mass transport equation (Hauser and Schohl, 2002). Input requirements for the hydrodynamics module are channel geometry, roughness coefficients, boundary conditions and initial surface water elevations. Outputs are velocity and depth at each model node which are passed to the water quality module. Additional inputs for the water quality module include weather data, riparian shading estimates, boundary temperatures and initial water temperature. Outputs are hourly stream temperatures (Hauser and Schohl, 2002).

The *RMS* model was developed to simulate stream temperatures from environmental water purchases that alter thermal mass. The restoration goal of environmental water purchases is to improve habitat for native organisms and connect Walker River and Walker Lake habitats. Irrigation season was modeled because it is the time period that environmental water purchases occur from irrigators. A total of 305 km of the East Walker, West Walker, and mainstem Walker Rivers were represented in *RMS* at an hourly time step. Model reaches over the model extent were 300 m in length. As a 1-dimensional model, each reach was completely mixed and had a homogenous temperature. Walker River modeled extent included the East Walker River downstream of Bridgeport Reservoir (river km 243 to 117), the West Walker River downstream of Topaz Reservoir (river km 60 to 0) and the mainstem Walker River to Walker Lake (river km 117 to 0) (Fig. 1). For additional model detail see Elmore et al. (2016) and Null et al. (2017).

3.4 Temperature Range Data Analyses

3.4.1 DTS Data Analysis

DTS minimum, maximum, and average stream temperatures were calculated for each 15 minute DTS sample event, day, and for the deployment period for both DTS sites (Table 1). Day and deployment period reach average temperatures were calculated from the 15 minute spatial average following Eq. 1:

$$\bar{T}_{t,r} = \frac{\sum_{i=1}^{t}(\bar{T}_{i,r})}{t} \qquad (1)$$

where $\bar{T}_{t,r}$ is the average temperature for time, t, and $\bar{T}_{i,r}$is the 15 minute event, i, averaged for site, r. Time, t, in Eq. 1 was day, d, or deployment period, p.

Table 1: Description of stream temperature variables.

The temperature range for 15 minute DTS sample event, day, and deployment period was calculated by subtracting the minimum measured temperature from the maximum measured temperature for the 1000 m DTS cable following Eq. 2:

$$R_{t,r} = Ts_{max,i,r} - Ts_{min,i,r} \qquad (2)$$

where $R_{t,r}$ is the temperature range for time, t, and site, r, $Ts_{max,i,r}$ and $Ts_{min,i,r}$ are the maximum and minimum measured temperature for 15 minute events, i, and site, r, *respectively*. Time in Eq. 2 was day, d, or deployment period, p.

The daily and deployment period average DTS stream temperature ranges ($\bar{R}_{t,r}$) were calculated from the 15 minute events for each DTS site following Eq. 3:

$$\bar{R}_{t,r} = \frac{\sum_{i=1}^{t}(Ts_{max,i,r} - Ts_{min,i,r})}{t} \qquad (3)$$

Left and right river bank temperatures measured by the DTS were compared for 1 m, 10 m, 100 m, 300 m extents to quantify thermal variability over multiple spatial scales. Lateral variability was evaluated for the hottest time during each DTS deployment in the mainstem Walker and East Walker Rivers. One m extents used left and right bank measurements perpendicular to the thalweg. At larger spatial scales, we compared the minimum and maximum temperatures for each bank for 10 m, 100 m, and 300 m extents. The range at each scale was then estimated as the maximum absolute value of the difference between the two banks. Wabuska Drain was not included in these analyses.

3.4.2 TIR Data Analysis

To compare measured TIR surface temperatures with model results, TIR summary points provided by Watershed Sciences Inc. (2012) were georeferenced with the 300 m modeled reaches. On average, there were three TIR summary points per 300 m modeled reach. TIR flight times determined which model day and hour to compare with TIR temperatures. The spatial average of minimum, maximum, and average TIR temperature was calculated for the East Walker, West Walker, and mainstem Walker Rivers following Eq. 4:

$$\bar{T}_L = \frac{\sum_{j=1}^{L}(\bar{T}_r)}{L} \quad (4)$$

where $\bar{T}_L$ is average TIR stream temperature for the length of the East, West, or mainstem Walker River, L, and $\bar{T}_r$ is the mean of summary point median TIR stream temperatures for each 300 m reach, r, (i.e., the average 300 m modeled reach temperature) because TIR summary points reported minimum, maximum, and median temperatures only.

The spatial average of the TIR stream temperature range for the East Walker, West Walker, and mainstem Walker Rivers was calculated following Eq. 5:

$$\bar{R}_L = \frac{\sum_{j=1}^{L}(Ts_{max,r} - Ts_{min,r})}{L} \quad (5)$$

where $\bar{R}_L$ is the spatially averaged TIR temperature range for river length, L, $Ts_{max,r}$ is the maximum TIR summary point temperature for the 300 m modeled reach, r, and $Ts_{min,r}$ is the minimum TIR summary point temperature for the 300 m modeled reach, r.

RMSE, MAE, and mean bias were calculated for average 300 m TIR temperatures and the corresponding modeled temperatures to quantify differences. The percentage of time when modeled temperatures were outside of measured temperatures was calculated.

To evaluate TIR temperatures at multiple spatial scales, we clipped the TIR raster to the river channel, generated points at 50 m and 300 m equal intervals along the river centerline, buffered the points and converted the layer to a raster. Then we calculated zonal statistics, including minimum, average, maximum, and temperature range for each 50 m and 300 m extent. TIR pixels that included streambanks or vegetation were warmer than the river and skewed zonal statistics. Thus, we compared minimum pixel temperatures at the 50 m and 300 m scales, rather than temperature range. Extents smaller than 50 m did not always span the river channel laterally.

3.4.3 Comparison to Modeled Data

We evaluated percentage of the DTS, TIR, and modeled datasets for which stream temperatures were below 21 ºC, 24 ºC, and 28 ºC. Temperatures below 21 ºC are optimal for adult LCT (Hickman and Raleigh 1982), temperatures exceeding 24 ºC are stressful for LCT (Dickerson and Vinyard 1999), and temperatures exceeding 28 ºC are lethal for LCT (Dunham et al. 2003). We used hourly DTS measurements so that data were not temporally auto-correlated and did not include Wabuska Drain temperatures in the DTS data so that they could be compared to model results. We calculated the percent of the dataset that DTS and TIR data exceeded temperature thresholds and that the model over-or under-predicted measured temperatures to quantify the thermal range not captured within one-dimensional modeling. RMSE, mean absolute error (MAE), and mean bias between the spatial average for the hourly DTS and modeled temperatures summarized differences between modeled and measured data.

River features like agricultural return flows, diversions, beaver dams, and seeps were georeferenced so that the modeled reach that contained those features could be identified. Measured DTS and TIR temperature ranges provide an estimate of small-spatial scale variability within each 300 m modeled reach. We used this information with the model results to estimate spatial variability missing in model output that is needed to identify potential habitat availability at smaller-spatial scales. Diversion and return flow locations were identified in 2012 by the Walker Basin Project (Tim Minor, pers.comm, 2012). Seeps were identified during TIR surveys from cooler stream temperatures that could not be attributed to shadows, cutbanks, or vegetation (Watershed Sciences Inc. 2012). We used seep locations identified during the winter TIR flight completed on November 16-17, 2011 because temperature differences were more obvious than the summer flight and some of the locations with groundwater seeps in the winter were dry during the summer flight (Watershed Sciences Inc., 2011; 2012). We applied the temperature range observed at seeps during the summer 2012 TIR flight (Watershed Sciences Inc. 2012).

Beaver are native to the Walker Basin (Gibson and Olden, 2014) and beaver dams were identified using 2012 and 2013 Google Earth aerial imagery (Google Earth Pro, 2018). Locations were georeferenced where beaver dams were seen spanning the channel. Often turbulence was observed below the dam and sometimes crowdsourced photos added images of the beaver dams from the ground. We relied primarily on 2012 imagery, unless it was unavailable or of poor quality, when 2013 aerial imagery was used. 2012 and 2013 were dry years, and beaver dams are more abundant in the Walker River during dry years, when high flow events that limit beavers ability to dam across the stream channel are reduced (Nevada Department of Wildlife, 2016).

4 Results

4.1 DTS Measured Stream Temperatures and Ranges

Average RMSE between calibrated DTS data and the three reference temperatures was 0.09 ºC and 0.15 ºC for the East Walker River and mainstem Walker River DTS sites, respectively (Table S1). Average DTS error for both sites was also within the 0.5 ºC precision of the iButtons. There were no significant residual trends in errors for the mainstem Walker River (Table S2 and Fig. S1).

The East Walker River DTS site had consistent temperatures longitudinally (Fig. 2). The deployment period minimum stream temperature was 16.7 ºC and maximum temperature was 24.9 ºC (Table 2). Daily maximum temperatures were measured in a straight, homogenous, unshaded section (Fig. 3). Reach stream temperature range for 15 minute collection events extended from a minimum of 0.5 ºC to a maximum of 2.0 ºC for the deployment period, with an average of 1.0 ºC. A shaded backwater eddy and pools with overhanging shrubs and tall cottonwoods were river features with increased thermal heterogeneity in the East Walker River (Fig. 3).

Figure 2: Stream temperatures measured for the length of the DTS cable at East Walker River (a) and mainstem Walker River (b) DTS sites. Wabuska Drain, which was not flowing but had standing water during sampling, is located at cable distance 110-175 m in the mainstem Walker River site (b).

Table 2: Daily stream temperatures and ranges for DTS deployment reaches in the East Walker and mainstem Walker Rivers. Data collection began in the afternoon on deployment days, June 19th and 25th, and ended in the morning of June 23rd and 30th.

Figure 3: East Walker River daily maximum stream temperatures on June 21, 2015 at 5:30 pm with insets showing details of spatial temperature variability. Modeled reach points represent the division between 300 m modeled reaches.

Stream temperatures varied spatially throughout the mainstem site, visualized as longitudinal color striations at different locations in Figure 2b. Average reach temperature was 25.2 ºC, not including the Wabuska Drain segment (Table 2, excluding distance 110 – 175 m in Fig. 2b). Maximum stream temperature was 32.9 ºC. The average reach temperature range for the deployment was 2.7 ºC, with a minimum reach temperature range of 1.1 ºC and a maximum reach temperature range of 7.0 ºC. When the 20 m section of the Wabuska Drain return flow canal (shown approximately at distance 110 – 175 m in Fig. 2b) was analyzed with the mainstem Walker River, daily minimum and maximum temperatures did not change because reach scale temperature variability was greater than localized variability in areas like the Wabuska Drain. However, the maximum 15 minute reach temperature range for the deployment increased considerably from 7.0 ºC to 10.2 ºC and average reach temperature range for the deployment also increased from 2.7 ºC to 3.6 ºC (Table 2, Fig. 2b). Figure 4 illustrates the cooling effect of the Wabuska Drain and the spatial temperature variability during daily maximum stream temperatures on July 29th.

Figure 4: Mainstem Walker River daily maximum stream temperature on June 29, 2015 at 3:15 pm. Model reach points represent the division between 300 m model reaches.

The coolest temperature at the mainstem Walker River DTS site was 24.4 ºC and occurred approximately 20 m into Wabuska Drain (Fig. 4). Warm stream temperatures of up to 31.8 ºC occurred in the homogeneous mainstem Walker River segment just upstream of the Wabuska Drain along the shallow, right bank. While the Wabuska Drain provided an overall cooling effect on the mainstem Walker River, it was a river feature with increased thermal variability with warm stream temperatures at the mouth and cooler stream temperatures within the Wabuska Drain. The shallow Wabuska Drain also experienced rapid heating and cooling in response to atmospheric conditions. Cool water from the outlet of Wabuska Drain mixed with the mainstem Walker River at hot times of day, expanding the temperature range of the downstream segment as well. In addition to increased temperature ranges in the Wabuska Drain, the mainstem Walker River had more channel and temperature heterogeneity from inactive, breached beaver dams. On June 29th at 3:15 pm, when site average temperature was 29.6 °C, nearly 7 °C of the temperature range observed for this 15 minute sample event occurred at a breached beaver dam (Fig. 4). The warmer temperatures occurred in an unshaded, shallow, backwater location subject to solar warming.

Lateral temperature variability was always greater for the mainstem Walker River than the East Walker River. Thermal ranges increased as the spatial scale increased so that the average lateral range was 0.2 °C, 0.4 °C, 0.7 °C, and 0.9 °C for 1 m, 10 m, 100 m, and 300 m, respectively in the East Walker River, and was 1.3 °C, 2.7 °C, 3.9 °C, and 5.2 °C for 1 m, 10 m, 100 m, and 300 m, respectively in the mainstem Walker River. In the East Walker River deployment site, deep pools and reaches with large wood structures were river features with increased thermal ranges. In the mainstem Walker River, deep pools with riparian vegetation, beaver dams, and islands in the channel were river features with more lateral thermal variability.

4.2 TIR Measured Stream Temperatures and Range

While DTS measurements provided high spatial and temporal stream temperature resolution at two sites, TIR measurements provided continuous surface stream temperatures throughout the Walker River for one hour. Maximum stream temperatures typically occurred in reaches with canal diversions and return flows. The warmest temperature in the East Walker River (Table 3) was 26.5 °C at the Hall Diversion (River km 129) where water ponds at the diversion. Maximum stream temperature in the West Walker was 27.1 °C and occurred upstream of the confluence with the mainstem Walker River. Maximum temperature in the mainstem Walker River was 29.2 °C and occurred at the Wabuska Drain outflow (River km 78). Although Wabuska Drain received agricultural returns during the TIR flight and therefore contributed warm water, rather than the cool water observed during times without agricultural runoff, the 4.5 km stretch of river downstream from the Wabuska Drain was 1 °C cooler than the segment of river upstream of Wabuska Drain (Fig 5). This may be due to groundwater inflows downstream of the Wabuska Drain consistent with valley narrowing (Watershed Sciences Inc., 2012) or shallow groundwater contributions due to irrigation of adjacent fields. While groundwater interactions may be less obvious when the return canal was flowing, DTS results showed evidence of cool water inputs when the canal was not flowing. Thus, large diversions and return flows can create warm water conditions when active, but they also recharge shallow aquifers and increase shallow groundwater contributions and create pockets of cold water.

Table 3: Stream temperatures and temperature ranges within 300 m modeled reaches by river from July 2012 TIR remotely-sensed data.

Figure 5: TIR raster data of the mainstem Walker River near the Wabuska Drain with 50 m and 300 m buffers

The 300 m reaches with the greatest temperature ranges corresponded with locations of canal diversions, return flows, and groundwater seeps (Fig. 6). In the East Walker River, the Fox/Mickey Diversion (River km 126), and Strosnider Diversion (River km 140) had large temperature ranges. In the mainstem Walker River, there was thermal variability at the Spragg-Alcorn-Bewely Diversion (River km 94), the Spragg-Alcorn-Bewely Canal Return (River km 90), and Wabuska Drain (River km 78) (Fig. 6). Maximum 300 m reach temperature range was 1.2 °C in the West Walker River (River km 58), which did not correspond to a diversion, canal return flow, or beaver dam, but is the location of a groundwater seep (Watershed Sciences Inc., 2012). Thus, large diversions and return flows alter river depth and thermal mass while seeps increase temperature ranges by creating a relatively consistent cool water location. TIR surface temperatures are unable to capture thermal stratification of beaver dams and ponds.

Figure 6: Temperature range within each 300 m model reach from July 2012 TIR remotely-sensed data with the upstream-most river km on the left side of the x-axis.

We compared minimum TIR stream temperatures at 50 m and 300 m to improve understanding of thermal refugia at multiple spatial scales. We did not calculate temperature ranges because pixels that contained some water and some riparian area resulted in high maximum temperatures, and thus temperature ranges. We discuss this further in the limitations section. Overall, minimum stream temperatures were nearly identical for 50 m and 300 m reaches. Average minimum temperatures by river were 21 ^{o}C for the East and West Walker Rivers and 22.3 ^{o}C for the mainstem Walker River.

4.3 *RMS* Predictions vs. Measured Temperatures

Model versus DTS data RMSE was 1.1 ^{o}C in the East Walker River and 1.7 ^{o}C in the mainstem Walker River (Table 4). When compared to TIR data, model RMSE and bias were both <1 ^{o}C for the East and West Walker Rivers; however, the RMSE in the mainstem Walker River was 3.4 ^{o}C and the bias was -2.5 ^{o}C (Table 4) where the model performed poorly under low flow conditions. Mainstem Walker River TIR stream temperatures versus modeled stream temperature was the only RMSE value that exceeded the calibrated *RMS* model RMSE. Model bias for the East Walker River indicated the model over estimated stream temperature by 0.2 ^{o}C in the 300 m DTS reach over the five day study period and underestimated temperature by 0.5 ^{o}C for the 77 km TIR extent. The model underestimated stream temperatures by 0.4 ^{o}C from the average DTS values and underestimated stream temperatures by 2.5 ^{o}C when compared to the TIR average temperature in the mainstem Walker River (Table 4).

Table 4: RMSE, MAE, mean bias, and percent of modeled dataset outside of measured values for the East, West, and mainstem Walker Rivers between hourly modeled and DTS and TIR stream temperature measurements.

Modeled temperatures in 2015 were warmer than DTS maximum hourly temperatures 50% of the time in the East Walker River, and 20% of the time in the mainstem Walker River. Conversely, the model under predicted DTS temperatures 29% and 10% of the time in the East Walker and mainstem Walker Rivers, respectively (Table 4, Fig. 7a and b). Temperatures measured in Wabuska Drain were excluded from this analysis because the model estimated temperatures in the main channel only. Modeled temperatures were warmer than the TIR summary point maximum temperatures for 9%, 0%, and 8% of survey extent in the East Walker, West Walker, and mainstem Walker Rivers, respectively. Predicted temperatures were lower than TIR summary point minimum temperatures for 74%, 95%, and 87% of survey extent in the East Walker, West Walker, and mainstem Walker Rivers, respectively (Fig 7c-e, Table 4).

Figure 7: Hourly DTS minimum and maximum temperatures compared to model predictions in the East Walker River (a) and mainstem Walker River (b) DTS sites (Wabuska Drain temperatures are not included as they were not modeled). July 2012 TIR minimum and maximum temperatures compared to modeled temperatures for East Walker (c), West Walker (d), and mainstem

Walker (e) Rivers. The upstream end of Weber Reservoir is at river km 48. The upstream most river km is on the left side of the x-axis in panels c - e. Shaded region shows temperatures exceeding the 28 °C lethal threshold for LCT.

Stream temperatures were rarely cooler than 21 ºC, and this finding was consistent among the DTS, TIR, and modeled data (Fig. 8; Table 5). An exception was during the East Walker River DTS deployment in June 2015, when DTS and modeled results classified nearly 50% of samples below 21 ºC. Stream temperatures were most likely to exceed 28 ºC with the TIR dataset. Nearly all TIR data and model results for West Walker River temperatures were between 24 and 28 ºC in July 2012. The mainstem Walker River nearly always exceeded 21 ºC, usually exceeded 24 ºC, and could exceed 28 ºC with all datasets. TIR stream temperature measurements in the lower reaches of the mainstem Walker River were 4-6 ºC warmer than simulated results and remained near the LCT lethal temperature threshold for an additional 45 km than was previously modeled (Fig. 8).

Figure 8: Model performance when measured temperatures exceed stream temperature thresholds for LCT. The height of each column shows the percentage of data points that DTS (a, b) or TIR (c-e) data exceed 21, 24, and 28 ºC thresholds. Colors within each column shows the extent to which the model over or underestimates stream temperatures compared to measured data.

Table 5: Percentage of DTS, TIR, and modeled stream temperatures that exceed 21 ºC, 24 ºC, and 28 ºC temperature thresholds

5 Discussion

5.1 Limitations

DTS data collection limitations include cable drift, stress, and solar heating, which have been previously described in the literature (Tyler et al., 2009). In our deployments, solar heating of the DTS cable was assumed to be negligible because the cable was silver coated to reflect solar radiation (Tyler et al., 2009) and solar heating of DTS cables would be limited in advection-dominated and turbid rivers (Neilson et al., 2010), such as the Walker River. Field crews used leashes to secure the DTS cable, which was monitored daily to minimize stress and reduce drift. We deployed the DTS during mid-summer when we anticipated stream temperatures would be warmest as a worst-case scenario for thermal refugia and connectivity. Additional research is needed to quantify how results would change when the Wabuska Drain is flowing, or for deployments earlier or later in summer. TIR measures surface water temperatures, which may overestimate water column temperatures from vertical stratification and thermal boundary layer effects (Torgersen et al. 2001). Surface roughness, surface emissivity, surface reflection, variable background temperatures (e.g., sky versus trees), turbidity, changes in viewing aspect, aircraft type, flight speed, wind gusts, and length of time required to collect data all affect TIR image and data quality (Dugdale, 2016). Clipping TIR data to the stream channel was imprecise for datasets collected over large spatial extents. If pixels included streambanks or vegetation, they skewed zonal statistic calculations. For this reason, we did not report maximum temperatures of pixels within 50 m or 300 m reaches, nor could we report temperature ranges which relied upon maximum temperature pixels. We assumed a vertically mixed water column when analyzing the DTS and TIR data. Pools and beaver dams may stratify vertically, increasing the local temperature variability from what was measured or predicted. Quantifying temperature range from vertical stratification was outside the scope of this paper.

Obtaining small-scale spatial and temporal stream temperatures and comparing them to model results has a number of limitations. First, resolution of information varied between DTS data, TIR data, and modeled results, reducing the number of comparable observations. TIR imagery represents a single point in time unless flights are repeated. DTS measurements were dense (1 m in these deployments) with a 15 minute temporal resolution, but were limited by cable length and field crews to monitor the deployment. Second, DTS and TIR measurements were collected in different years because we used existing TIR imagery collected as part of the Walker Basin Project, a multi-partner comprehensive effort to sustain the basin's economy, ecosystem, and lake. Future studies could collect data specifically to overlap in time and space; however, opportunistically using existing data for re-analysis and to improve model result interpretation and river management is a laudable goal that may reduce the cost of river science and management. Multi-year, multi-partner river monitoring, modeling, and management is common in large, important, or complex river basins. This research highlights the differences in temperature variability given alternative sampling and modeling methods.

5.2 Walker River Habitat Implications from DTS and TIR Stream Temperature Measurements

Warm stream temperatures and low flows threaten native trout and other cold water species in the Walker River. This research measured the range of stream temperatures that was unquantified and underrepresented in existing basin-scale modeling. Overall, DTS measured a larger temperature range than TIR imagery in the East Walker River (2.0 °C and 1.1 °C, respectively) and mainstem river (10.2 °C and 1.0 °C, respectively) (Tables 2 and 3) because DTS could measure temperatures that varied spatially over short distances where beaver dams or return flows existed. The warmest temperatures were measured by TIR imagery in the East Walker River (26.5 °C), but by DTS in the mainstem (32.9 °C), indicating that these methods complement each other (Tables 2 and 3). More widespread data collection with more extensive DTS deployments or repeated TIR collection would further improve results.

Our results confirm those of other studies showing that stream temperatures warm longitudinally during summer (Elmore et al. 2016). TIR temperatures showed a general longitudinal warming trend, with stream temperatures increasing 9 °C from Bridgeport Dam to Weber Reservoir. Consistent with model results (Elmore et al. 2016), the coolest observed temperature, 20.1 °C, occurred in the East Walker River and the warmest observed temperature, 29.2 °C, occurred in the mainstem Walker River (Table 3). Average DTS stream temperatures in East Walker River were approximately 4 °C cooler and less variable than the mainstem Walker River (Fig. 2). Average DTS temperature ranges were nearly 2 °C greater in the mainstem Walker River than the East Walker River. The East Walker River DTS site is farther upstream and close to Bridgeport Reservoir, a bottom release dam. The mainstem Walker River DTS site is 92 km downstream from the East Walker River DTS site and also receives contributions from the West Walker River, fed by surface water releases from Topaz Reservoir. TIR data showed that stream temperatures in the lower Walker River were 4 – 6 °C warmer than simulated results estimated. That reach has challenging conditions for simulation models with a wide channel and low flow conditions. Previous research has shown that the Walker River has poor aquatic habitat as a function of streamflow and stream temperature from the confluence of the East and West Walker Rivers to Walker Lake for LCT and other cold water species (Elmore et al., 2016;

Hogle et al., 2014; Mehler et al., 2015; Null et al., 2017). Those studies suggest that the East and West Walker Rivers are likely to support native aquatic species. Water purchases and other restoration actions that prioritize passage through the lower Walker River to re-connect river and lake ecosystems are likely to be more effective than actions to restore suitable habitat in the lower Walker River (Hogle et al., 2014).

Although Wabuska Drain was receiving agricultural returns during the TIR flight and therefore contributing warm water, a 4.5 km stretch of river downstream from the Wabuska Drain was 1 ºC cooler than the river segment at the Wabuska Drain. Lopes and Allander (2009) identified local streamflow gains near the Wabuska gage, hypothesizing they originated from groundwater to Wabuska Drain. However, shallow subsurface water, or interflow contributions to Wabuska Drain may not occur when groundwater levels decline outside of irrigation season or during droughts (Naranjo and Smith, 2016). Thus, large diversions and return flows can create warm water conditions when active, but irrigation practices may also recharge shallow aquifers and create pockets of cold water in return flow canals. However, it may be difficult for LCT to reach these refuges or they may be insufficient for cold water habitat. Stream temperatures measured by the DTS in the shallow water at the mouth of Wabuska Drain and in the mainstem Walker River upstream of the Wabuska Drain exceeded LCT acute temperature threshold of 28 ºC. Similarly, maximum TIR temperature in the mainstem Walker River was 29.2 ºC at the Wabuska Drain return flow (River km 78), which may create temperature barriers for cold water species like LCT at some times.

The greatest temperature variability in the Walker River DTS sites occurred in the early afternoon of summer days and at canal diversions, return flows, beaver ponds, and backwater eddies. Beaver dams had high spatial and temporal temperature ranges, consistent with findings from Majerova et al. (2015) and Weber et al. (2017). 15-minute temperature range of 7 ºC was observed in a beaver dam in the mainstem Walker River. Cristea and Burges (2009) observed 2 - 3 ºC temperature range due to cold water seeps or channel braiding in the Pacific Northwest, which is comparable to the 1 – 2 ºC temperature range observed in the East Walker River in the DTS data and TIR imagery. Cooler temperatures in the pool created by the beaver dam may be a potential temperature refuge for fish. Return flow channels, beaver dams, and seeps likely create thermal refugia during some time periods, improving aquatic habitat connectivity for cold water species.

5.3 One-Dimensional Model Result Interpretation

To provide greater insight into watershed-scale responses, measured DTS and TIR temperature ranges from return flows, diversions, beaver dams, and seeps were added or subtracted to one-dimensional stream temperature predictions to identify potential micro-habitats, temperature barriers, and temperature refugia in the basin. Overall, we identified 23 diversions, 8 return flows, 53 possible seeps, and 42 beaver dams throughout the modeled reach of the West Walker, East Walker, and mainstem Walker Rivers (Fig 9a). Average temperature change was -2.5 °C for return flows, +1.2 °C for diversions, -3.2 °C for beaver dams, and -1.9 for groundwater seeps, although observed temperatures varied from -10.1 to +2.3 °C for return flows, -1.2 to +4 °C for diversions, -5.1 to +2 °C for beaver dams, -4.2 to 0 °C for seeps. Adding and subtracting observed DTS and TIR temperature ranges from modeled results suggests that cool-water refugia may sometimes exist to support species migration between Walker Lake and upper tributaries of the Walker River (Fig 9b).

Figure 9: Locations of river features that affect stream temperatures in the Walker Basin (a). Warmest predicted *RMS* stream temperatures for June 29, 2015 (6:00 pm) with estimated temperature ranges by river feature using DTS data from June 29, 2015 at the warmest observed time (3:15 pm) and TIR data from July 18 and 24 - 26, 2012) (b).

Results show specific river features like diversions, return flows, beaver dams, and large eddies provide small-scale temperature variability. Cold-water refugia potentially allow trout populations to persist where surrounding stream temperatures exceed thermal tolerance limits (Brewitt and Danner 2014; Sutton et al., 2007). However, trout use of thermal refugia may vary, as availability of refugia change with streamflow and weather conditions, and as trout habitat needs vary with life stage (Frechette et al. 2018; Dugdale et al. 2013). Future research is needed to validate temperature ranges by river feature at the watershed-scale, evaluate how fish use thermal refugia, and improve understanding of the resiliency of thermal refugia with anticipated climate change (Fullerton et al. 2018; Frechette et al. 2018; Ficklin et al. 2018; Stevens and DuPont 2011; McCullough et al. 2009).

Augmenting environmental water purchases with secondary restoration efforts at canal return flows and beaver dams could further preserve cold water observed in both DTS and TIR datasets. Secondary restoration efforts should focus on minimizing thermal barriers and enhancing cold water refugia to improve habitat connectivity and mitigate warm stream temperatures in the Walker River. Results identified warm water segments that may act as thermal barriers to fish passage in shallow, unshaded reaches at the mouth of irrigation structures and return flow outlets, stagnant edges of beaver dam pools, and in homogenous, unshaded habitat segments. Promising secondary restoration efforts include native riparian vegetation restoration to reduce heating due to solar radiation, creating channel complexity to increase habitat quality, and increasing thermal variability by re-introducing beaver, designing beaver dam analogs restoration efforts, or adding large wood to the river (Bond et al., 2015; Poole and Berman, 2001; Weber et al., 2017). While restoration is ongoing to preserve the riparian corridor and promote native habitat by reducing grazing and removing invasive plants (USFWS, 2017), other secondary restoration projects depend on the extent to which stakeholders want to manage habitat and restoration.

6 Summary

This is the first study using both DTS and TIR to quantify small-scale temperature range within one-dimensional stream temperature model reaches. Overall, modeled temperature estimates were within the DTS measured temperature ranges 21% and 70% of the time for the East Walker River and mainstem Walker River, respectively, and within TIR measured temperatures 17%, 5%, and 5% of the time for the East Walker, West Walker, and mainstem Walker Rivers, respectively. DTS measured larger temperature ranges than TIR imagery and captured lateral temperature variability more effectively than TIR data. DTS data showed that lateral temperature range increases as it is calculated for larger spatial scales, although models with coarser spatial resolution (larger nodes or cells) erroneously reduce the thermal range of the rivers and habitats they represent.

We show the utility of DTS and TIR data for one-dimensional model validation, but also extend their use to further quantify the possible spatial variability occurring within model reaches containing key features that create thermal heterogeneity not captured by one-dimensional models. In other words, complementary DTS, TIR, or temperature sensor observations are necessary to understand the extent and spatial locations of thermal refugia, and augment process-based modeling. Our results contribute to literature describing thermal refugia networks and how they may be considered and maintained with reservoir releases, riparian restoration, or other river restoration approaches (Isaak et al., 2010; Seavy et al., 2009; Sutton et al., 2007). By coupling high resolution stream temperature monitoring with process-based modelling, simulations can help identify temperature barriers, refuges, and promising restoration strategies. This provides a more realistic stream temperature range than one-dimensional modeling alone, especially when model results assess habitat suitability or evaluate watershed-scale river management and restoration alternatives. Our approach may also be applied by stakeholders who do not have the funding or background to conduct additional model simulations, but prefer to post-process results with observations. Comparing DTS and TIR stream temperature measurements to predicted stream temperatures helps to bound spatial temperature ranges and can be applied in other watersheds to identify habitat features that are important for understanding small-scale temperature ranges and restoration management.

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Table 1: Description of stream temperature variables.

Variable	Metric	Temporal Extent	Spatial Extent
		DTS	
$T_{min,t,r}$	Minimum Temperature	15 minute (i), Hourly (h), Day (d), Deployment Period (p)	300m
$T_{max,t,r}$	Maximum Temperature		
$\bar{T}_{t,r}$	Average Temperature		
$R_{i,r}$	Temperature Range $Ts_{max,i,r}$ -$Ts_{min,i,r}$	15 minute	
$R_{min,t}$	Minimum of $R_{i,r}$	Day (d), Deployment Period (p)	
$R_{max,t}$	Minimum of $R_{i,r}$		
$\bar{R}_{i,r}$	Average of $R_{i,r}$		
$T_{mod,h,r}$	Modeled Stream Temperatures	Hourly (h)	
		TIR	
$T_{min,r}$	Minimum of Summary Points	Hour of Flight Collection	300 m
$T_{max,r}$	Maximum of Summary Points		
$\bar{T}_{s,r}$	Average of Summary Point Medians		
R_r	Temperature Range $Ts_{max,r}$ -$Ts_{min,r}$		
$T_{min,L}$	Minimum of $Ts_{min,r}$		East, West, or mainstem Walker River
$T_{max,L}$	Maximum of $Ts_{max,r}$		
$\bar{T}_L$	Average $Ts_{avg,r}$		
$R_{max,L}$	Maximum of R_r		
$\bar{R}_L$	Average of R_r		
$T_{mod,h,r}$	Modeled Stream Temperatures	Hourly (h)	300 m

Table 2: Daily stream temperatures and ranges for DTS deployment reaches in the East Walker and mainstem Walker Rivers. Data was only collected in the afternoon on deployment days, June 19th and 25th, and only in the morning of demobilization days, June 23rd and 30th.

	Minimum				Maximum				Average	
	Min. Temp. (ºC)	Min. Temp. Time	Min. Range (ºC)	Min. Range Time	Max. Temp. (ºC)	Max. Temp. Time	Max. Range (ºC)	Max. Range Time	Avg. Temp (ºC)	Avg. Range (ºC)
East Walker River										
6/19/15	19.8	11:15	0.6	19:45	24.9	17:00	1.4	13:00	23.1	1.0
6/20/15	18.0	6:15	0.5	8:30	24.9	17:30	2.0	13:00	21.3	1.1
6/21/15	18.0	6:15	0.5	23:30	24.4	17:30	1.5	13:45	21.2	0.9
6/22/15	16.7	8:30	0.5	0:30	24.0	17:30	1.7	14:45	20.3	1.0
6/23/15	17.3	8:00	0.5	8:15	21.0	0:15	1.1	9:45	18.9	0.7
Overall	**16.7**	**8:30**	**0.5**	**8:15**	**24.9**	**17:00**	**2.0**	**13:00**	**21.0**	**1.0**
Mainstem Walker River including Wabuska Drain										
6/25/15	22.0	14:15	3.6	23:45	32.9	16:15	10.2	16:00	28.6	7.1
6/26/15	21.0	6:30	1.6	23:00	29.9	14:15	6.5	14:15	25.0	3.8
6/27/15	21.8	7:00	1.4	9:15	31.0	15:45	6.7	15:45	25.8	3.0
6/28/15	21.8	8:00	1.4	9:30	26.9	16:30	3.2	16:30	24.3	2.2
6/29/15	21.0	6:00	2.0	8:30	31.9	15:15	7.5	15:15	25.2	3.7
6/30/15	20.0	6:45	2.4	10:00	29.5	12:30	6.3	12:30	23.1	3.5
Overall	**20.0**	**6:45**	**1.4**	**9:30**	**32.9**	**16:15**	**10.2**	**16:00**	**25.2**	**3.6**
Mainstem Walker River excluding Wabuska Drain										
6/25/15	23.7	23:45	2.2	19:15	32.5	16:15	7.0	15:30	28.8	3.9
6/26/15	20.0	6:30	1.2	21:00	29.9	14:15	4.5	14:00	25.1	2.5
6/27/15	21.8	7:00	1.1	9:30	31.0	15:45	3.4	15:45	25.8	1.8
6/28/15	21.8	8:00	1.2	9:30	26.9	16:30	3.1	15:45	24.4	2.0
6/29/15	21.0	6:00	1.8	9:45	31.9	15:15	7.0	14:00	25.3	3.5
6/30/15	20.0	6:45	2.3	10:00	29.5	12:30	5.7	12:30	23.1	3.4
Overall	**20.0**	**6:45**	**1.1**	**9:30**	**32.5**	**16:15**	**7.0**	**15:30**	**25.2**	**2.7**

Table 3: Stream temperatures and temperature range within 300 m modeled reaches by river from July 2012 TIR remotely-sensed data.

	Minimum Temperature (ºC)	Maximum Temperature (ºC)	Average Temperature (ºC)	Maximum Range (ºC)	Average Range (ºC)
East Walker River	20.1	26.5	24.7	1.1	0.3
West Walker River	24.1	27.1	25.6	1.2	0.4
Mainstem Walker River	22.9	29.2	27.3	1.0	0.3

Table 4: RMSE, MAE, mean bias, and percent of modeled dataset outside of measured values for the East, West, and mainstem Walker Rivers between hourly modeled and measured DTS and TIR stream temperatures.

	RMSE (ºC)	MAE (ºC)	Mod. – Meas. Bias (ºC)	Mod. > Meas. (%)	Mod. < Meas. (%)	n (hrs)
East Walker River DTS	1.1	0.9	0.2	50	29	94
mainstem Walker River DTS	1.7	1.3	-0.4	20	10	118
East Walker River TIR	0.8	0.6	-0.5	9	74	2
West Walker River TIR	0.9	0.8	-0.8	0	95	1
mainstem Walker River TIR	3.4	2.7	-2.5	8	87	3
Walker River Overall TIR	1.9	1.2	-1.1	7	83	6

Table 5: Percentage of DTS, TIR, and modeled stream temperatures that exceed 21 ºC, 24 ºC, and 28 ºC temperature thresholds

	Mainstem Walker River		
	>21 ºC	>24 ºC	>28 ºC
DTS	98.6	62.4	17.3
Modeled DTS collection period	100	64.4	6.8
TIR	100	98.7	47.2
Modeled TIR collection period	100	77.1	0
	East Walker River		
DTS	51.0	7.3	0
Modeled DTS collection period	54.3	13.8	0
TIR	99.2	93.7	23.5
Modeled TIR collection period	99.0	54.6	0
	West Walker River		
TIR	100	99.9	24.7
Modeled TIR collection period	100	100	0

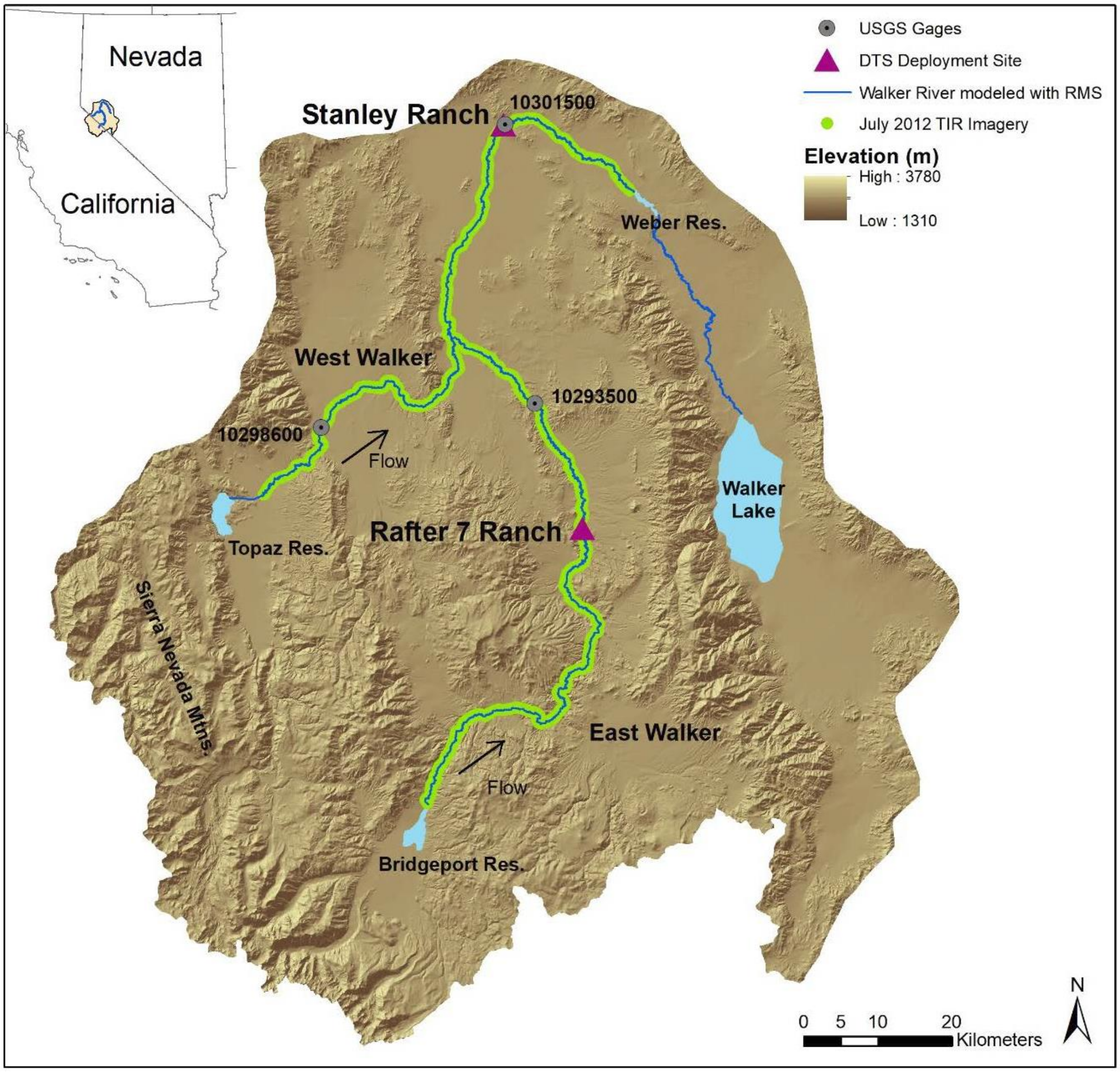
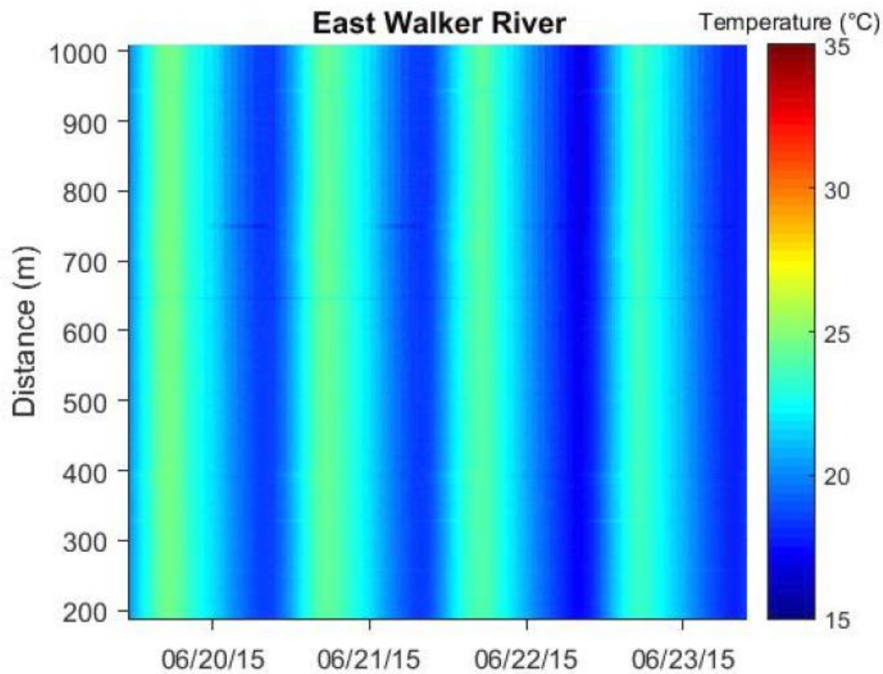


Figure 1: Walker River modeled extent, June 2015 DTS deployment sites, and July 2012 TIR imagery extent.

(a)



(b)

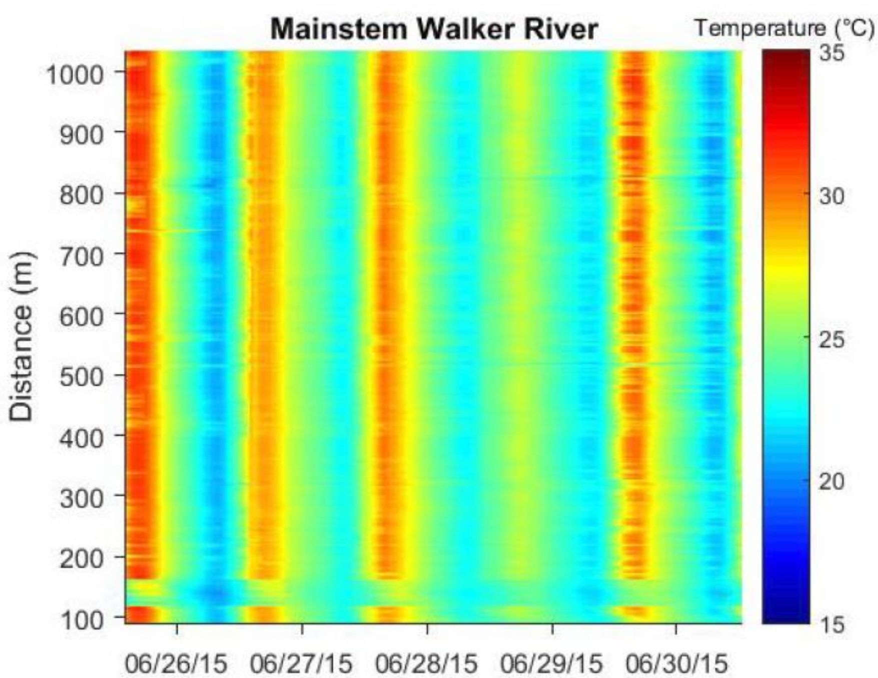


Figure 2: Stream temperatures measured for the length of the DTS cable at East Walker River (a) and mainstem Walker River (b) DTS sites. Wabuska Drain, which was not flowing but had standing water during sampling, is located at cable distance 110-175 m in the mainstem Walker River site (b).

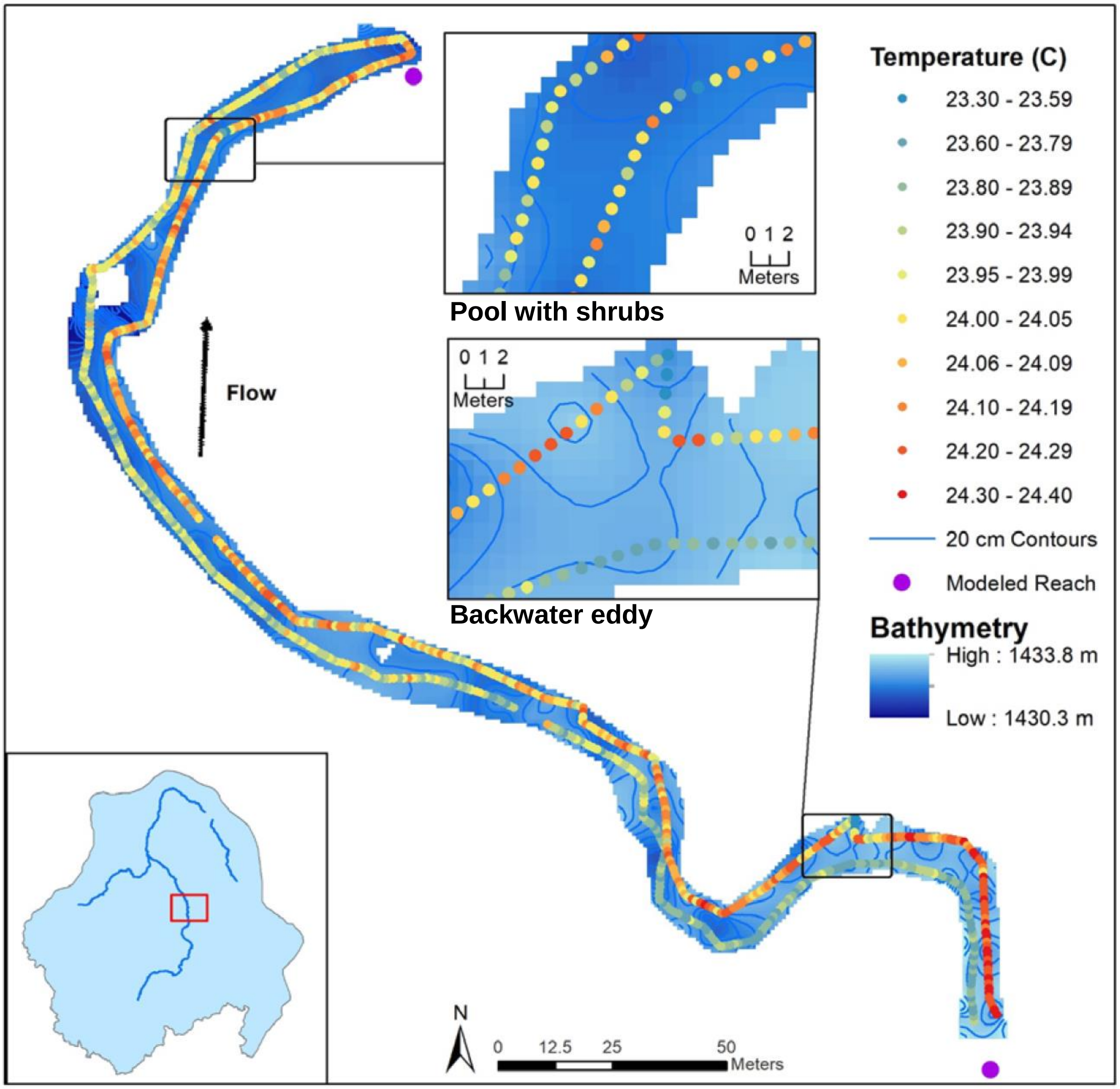


Figure 3: East Walker River daily maximum stream temperatures on June 21, 2015 at 5:30 pm with insets showing details of spatial temperature variability. Modeled reach points represent the division between 300 m modeled reaches.

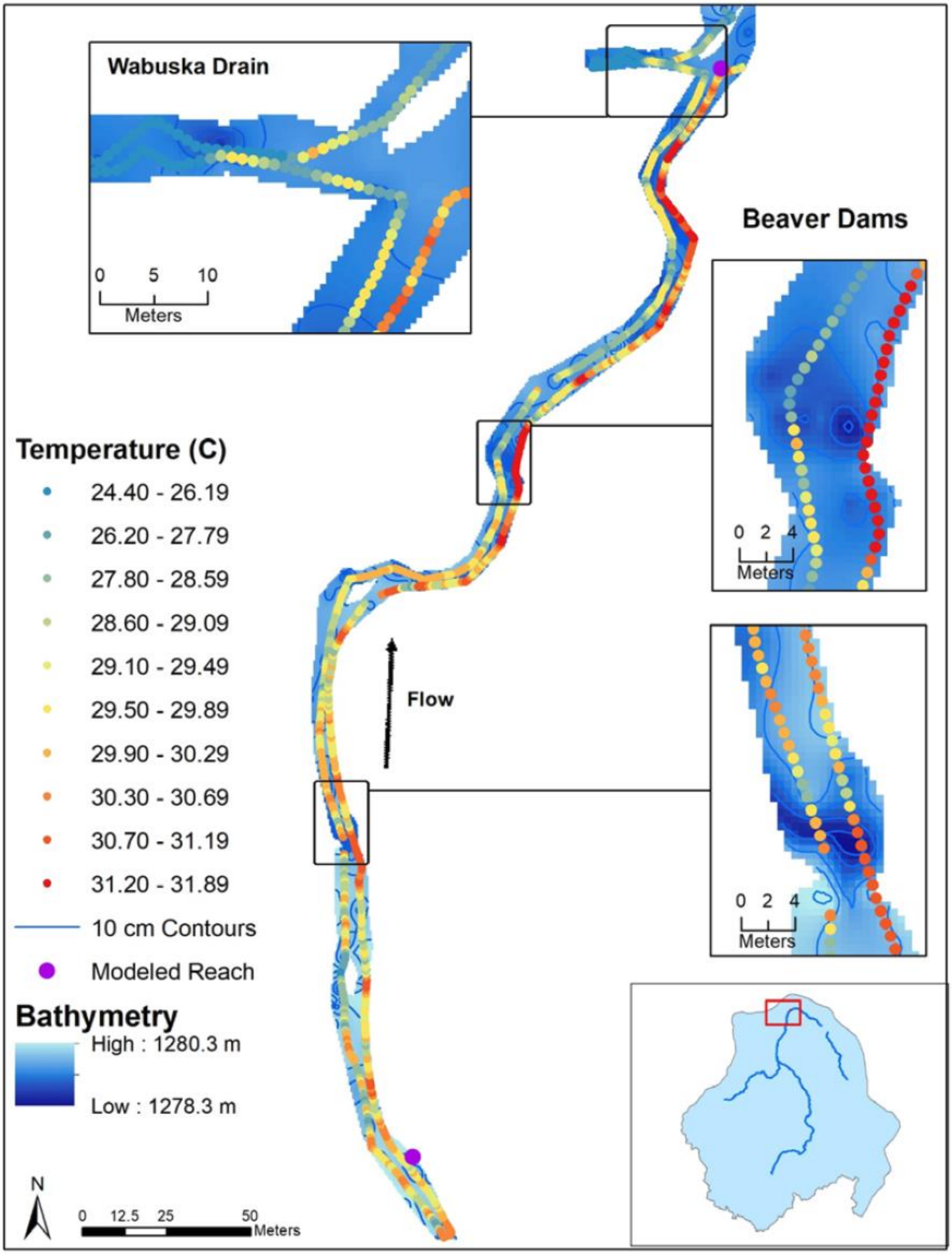


Figure 4: Mainstem Walker River daily maximum stream temperature on June 29, 2015 at 3:15 pm. Model reach points represent the division between 300 m model reaches.

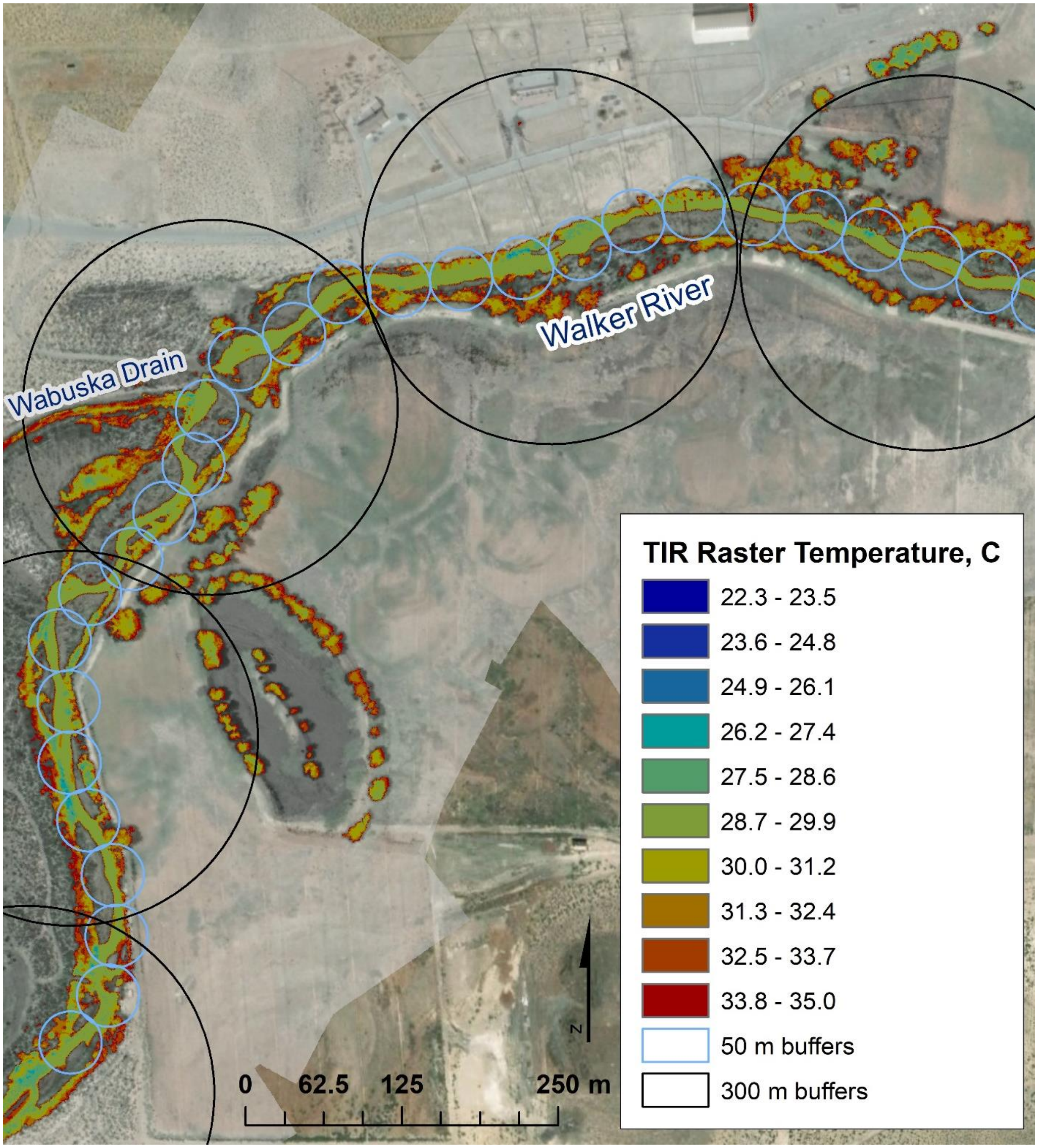


Figure 5: TIR raster data of the mainstem Walker River near the Wabuska Drain with 50 m and 300 m buffers

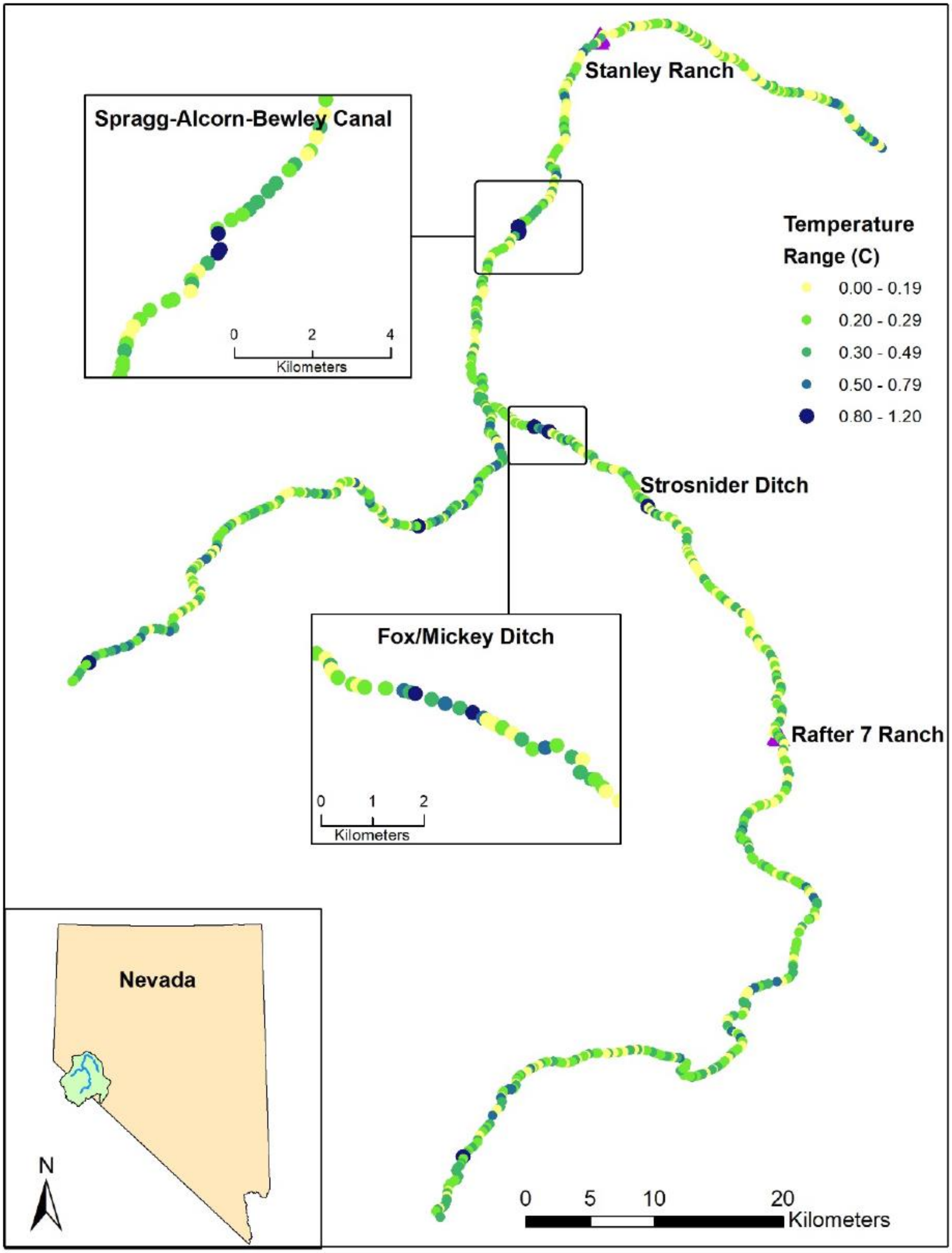


Figure 6: Temperature range within each 300 m model reach from July 2012 TIR remotely-sensed data with the upstream-most river km on the left side of the x-axis.

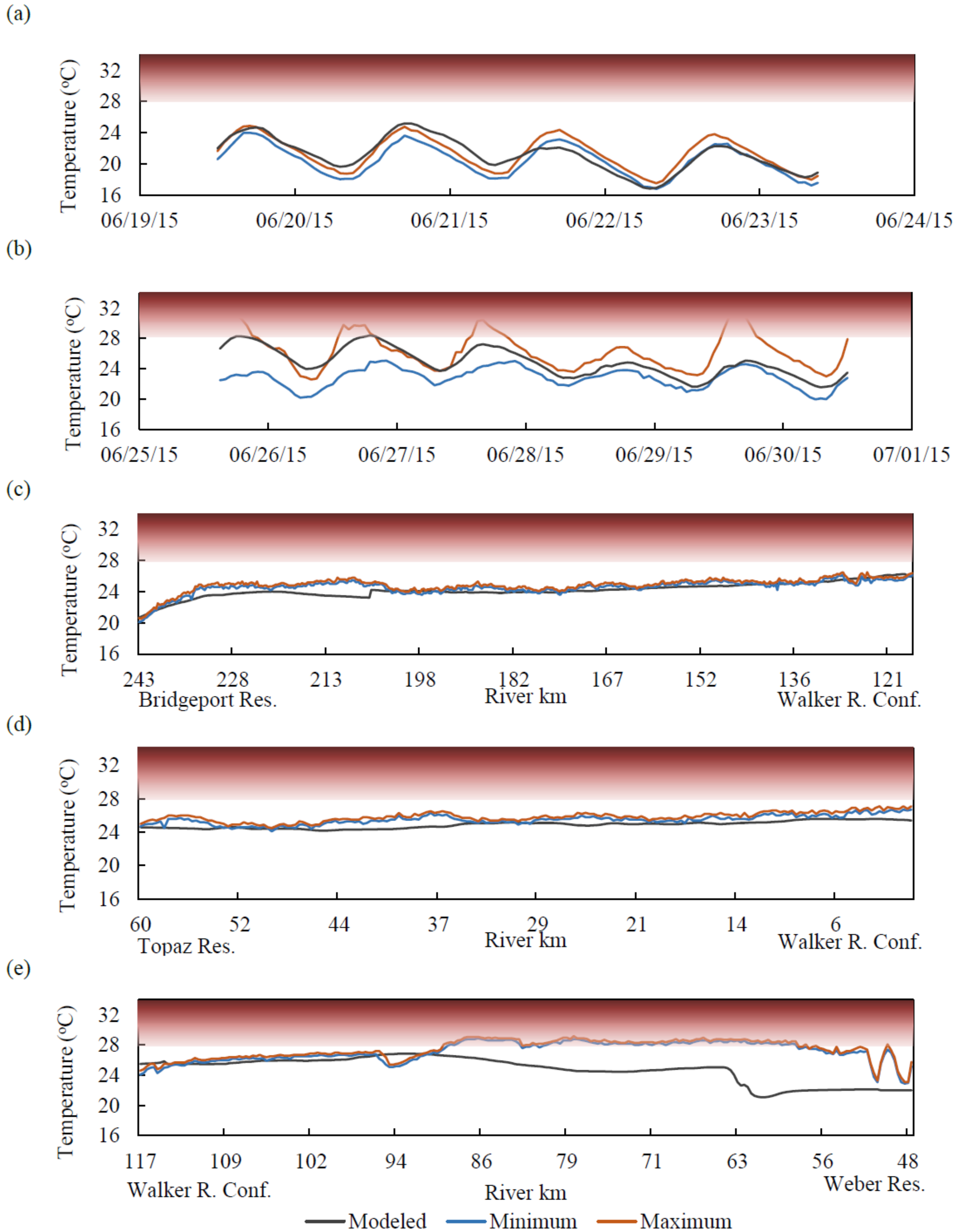


Figure 7: Hourly DTS minimum and maximum temperatures compared to model predictions in the East Walker River (a) and mainstem Walker River (b) DTS sites (Wabuska Drain temperatures are not included as they were not modeled). July 2012 TIR minimum and maximum temperatures compared to modeled temperatures for East Walker (c), West Walker (d), and mainstem Walker (e) Rivers. The upstream end of Weber Reservoir is at river km 48. The upstream most river km is on the left side of the x-axis in panels c - e. Shaded region shows temperatures exceeding the 28 °C lethal threshold for LCT.

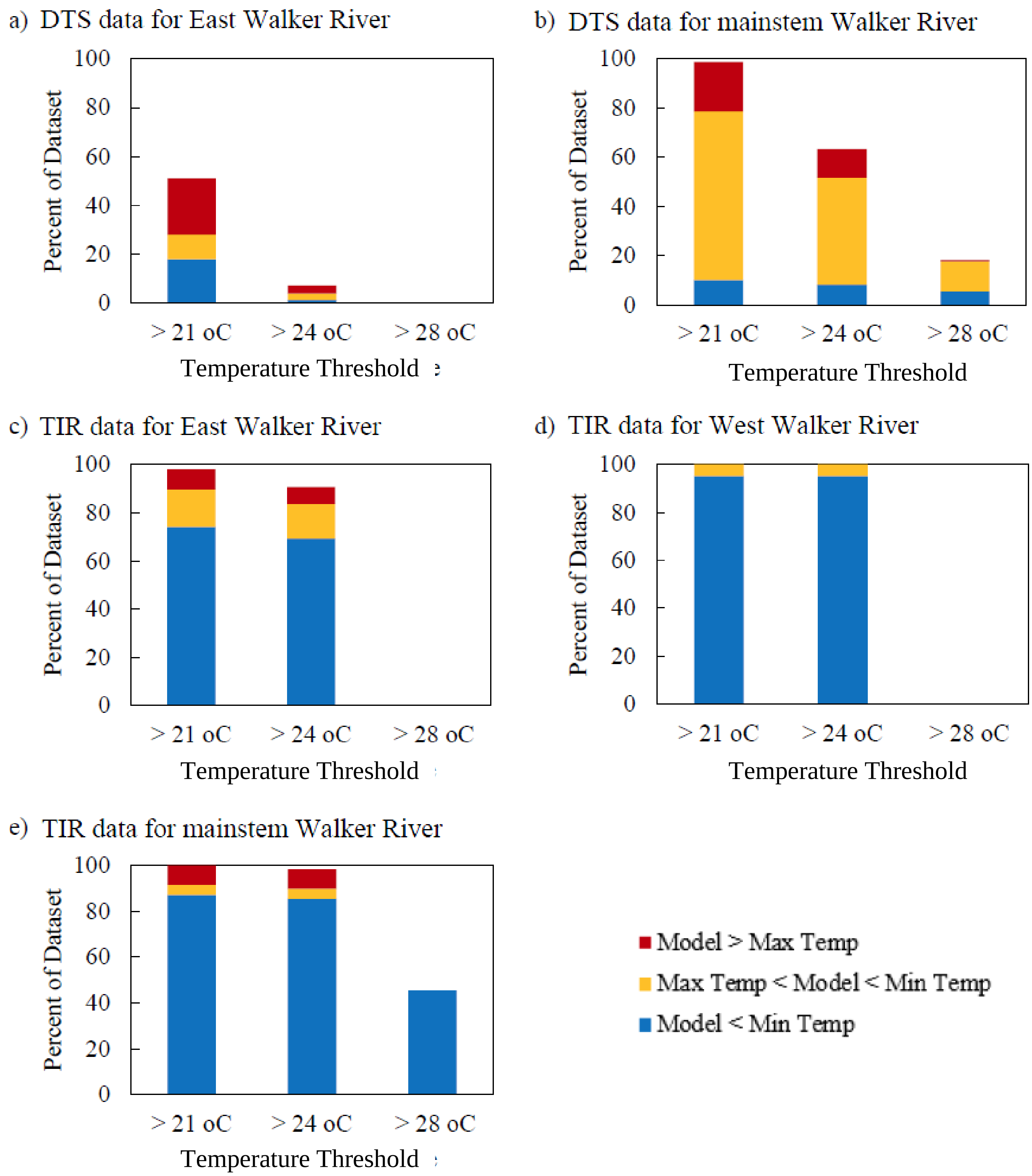


Figure 8: Model performance when measured temperatures exceed stream temperature thresholds for LCT. The height of each column shows the percentage of data points that DTS (a, b) or TIR (c-e) data exceed 21, 24, and 28 ºC thresholds. Colors within each column shows the extent to which the model over or underestimates stream temperatures compared to measured data.

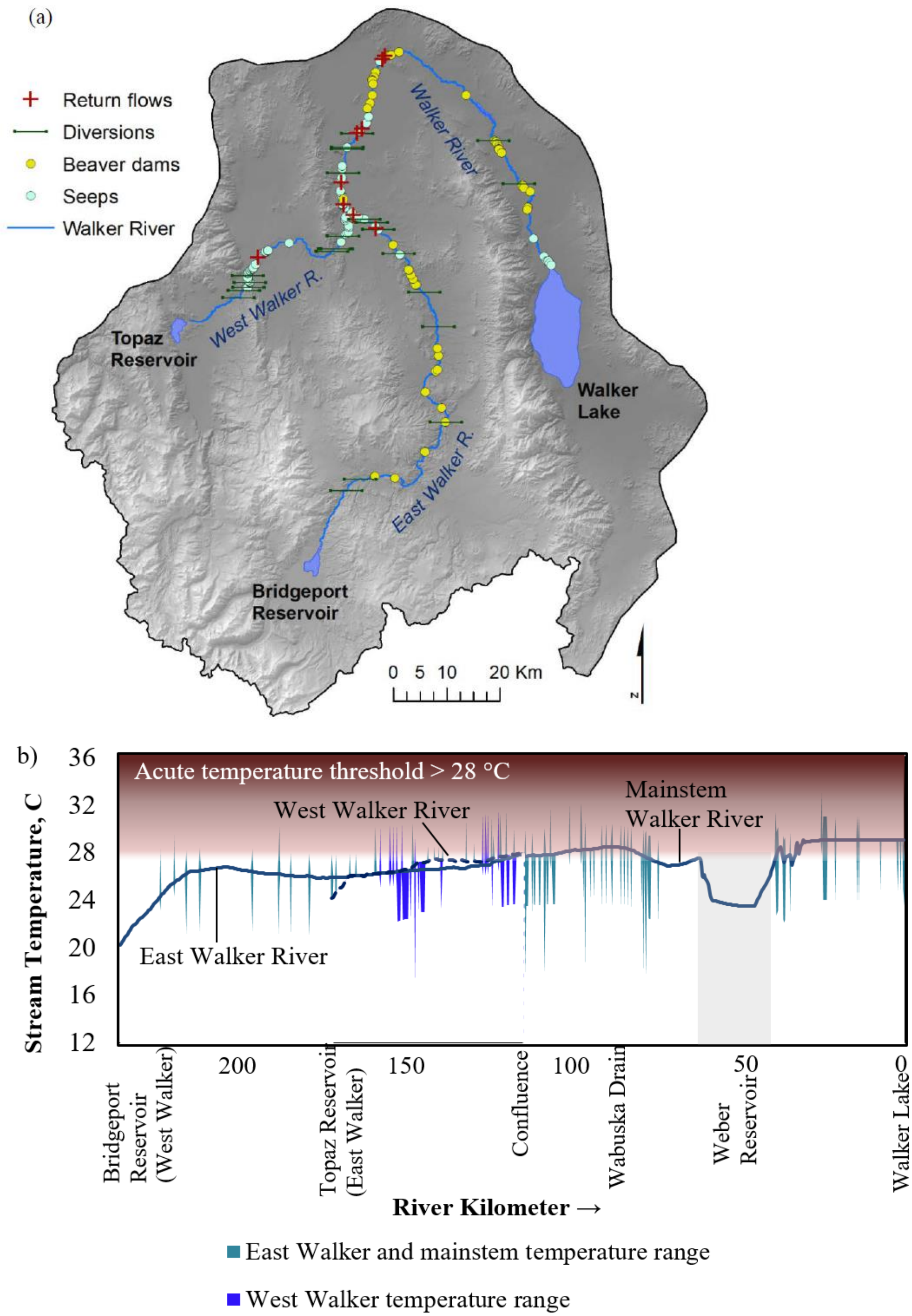


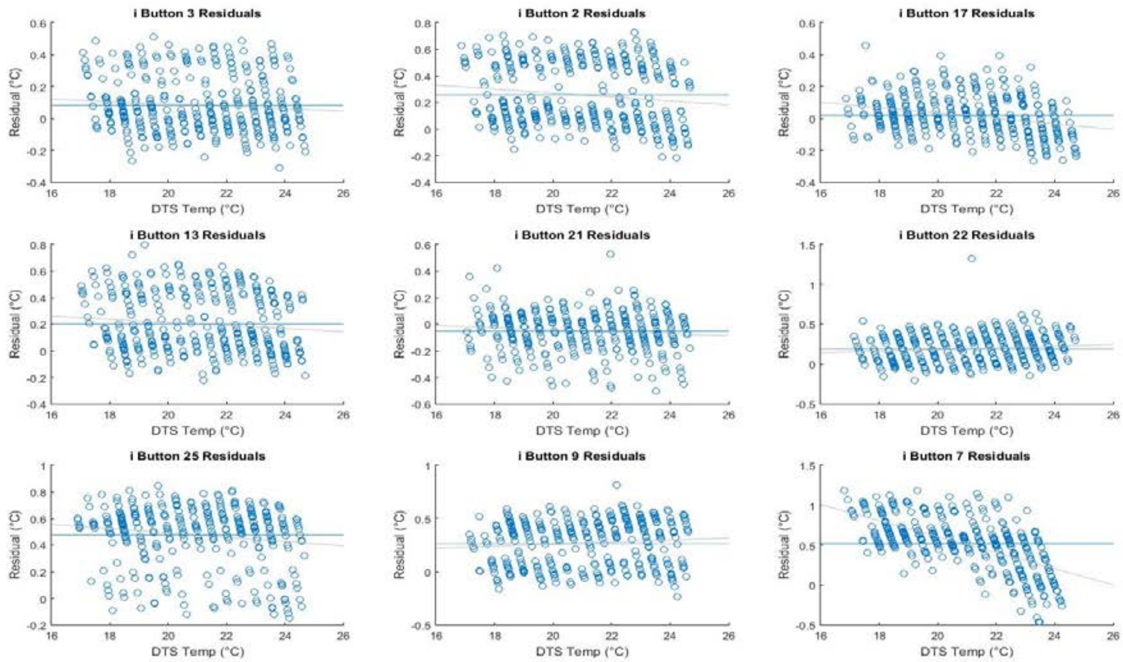
Figure 9: Locations of river features that affect stream temperatures in the Walker Basin (a). Warmest predicted *RMS* stream temperatures for June 29, 2015 (6:00 pm) with estimated temperature ranges by river feature using DTS data from June 29, 2015 at the warmest observed time (3:15 pm) and TIR data from July 18 and 24 - 26, 2012) (b).

Table S1: Mean RMSE and bias of DTS stream temperature compared to three reference temperatures for each DTS channel.

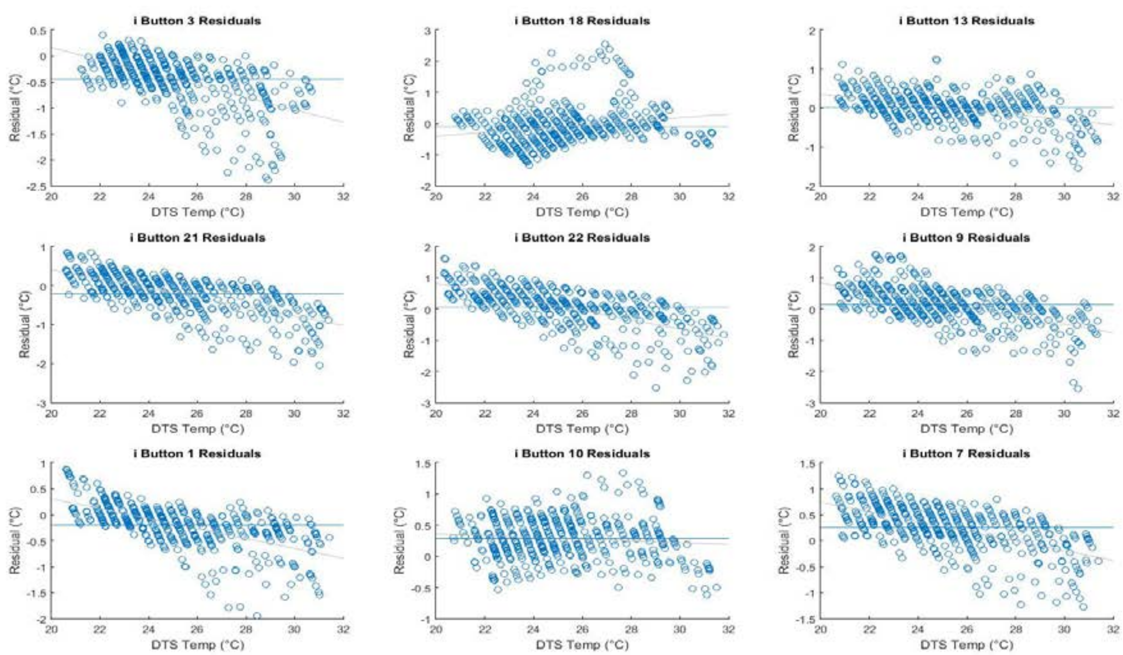
	RMSE (°C)	Mean Bias (°C)
East Walker River Ch. 1	0.12	0.00
East Walker River Ch. 2	0.09	0.00
Mainstem Walker River Ch. 1	0.15	0.00
Mainstem Walker River Ch. 2	0.15	0.00

Table S2: RMSE and Bias between DTS and iButton stream temperature measurements at the East Walker River and Mainstem Walker River DTS sites.

	East Walker River			Mainstem Walker River		
iButton Number	Cable Distance (m)	RMSE (°C)	Bias (°C)	Cable Distance (m)	RMSE (°C)	Bias (°C)
3	509.883	0.0	0.0	162.892	0.5	-0.5
2	777.736	0.0	0.0	calibration bath	--	--
17	975.582	0.0	0.0	buried in sediment	--	--
18	buried in sediment	--	--	325.227	0.5	0.0
13	691.495	0.5	0.0	748.313	0.5	0.0
21	482.489	0.0	0.0	725.992	0.5	-0.5
22	278.555	0.5	0.5	872.093	0.5	0.0
25	890.356	0.5	0.5	calibration bath	--	--
9	601.196	0.5	0.5	buried in sediment	--	--
1	calibration bath	--	--	941.086	0.5	0.0
10	calibration bath	--	--	498.722	0.5	0.5
7	941.086	0.5	0.5	609.313	0.5	0.5
Average		**0.5**	**0.5**		**0.5**	**0.0**


i Button 3 Residuals
i Button 2 Residuals
i Button 17 Residuals
i Button 13 Residuals
i Button 21 Residuals
i Button 22 Residuals
i Button 25 Residuals
i Button 9 Residuals
i Button 7 Residuals
Residual (°C)
DTS Temp (°C)

(a)

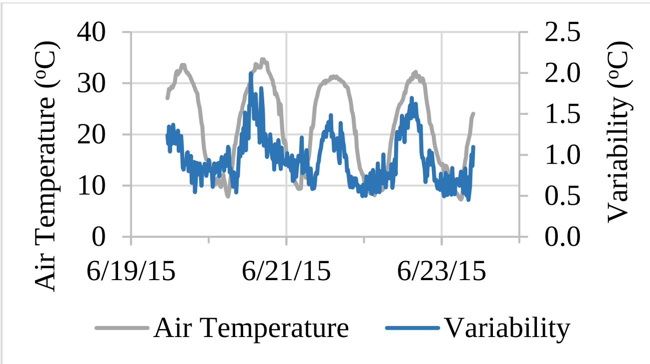

i Button 3 Residuals
i Button 18 Residuals
i Button 13 Residuals
i Button 21 Residuals
i Button 22 Residuals
i Button 9 Residuals
i Button 1 Residuals
i Button 10 Residuals
i Button 7 Residuals
Residual (°C)
DTS Temp (°C)

(b)

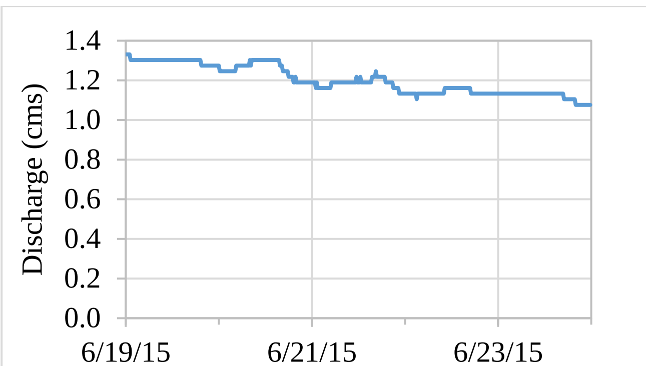
Figure S1: I Button Residuals vs. DTS data for the East Walker River (a) and Mainstem Walker River (b) DTS sites. Residual is defined as I Button temperature – DTS temperature. The best fit line (grey) represents the i Button residual. Bias is shown as the reference line (blue).

S1.0 Measure Flow and Weather Data

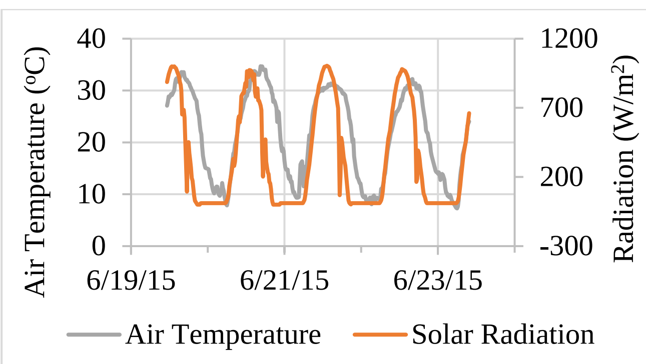
Stream flow and weather were fairly consistent during the study period at the East Walker River DTS site. Flow was initially near 1.4 cms (50 cfs) and dropped about 0.2 cms (5 cfs) during deployment. Initial streamflow was just over 0.6 cms (20 cfs) and increased over 0.6 cms (25 cfs) during the deployment at the mainstem Walker River DTS site. No rain events occurred during this time and flow changes were due to reservoir release magnitudes. The peaks in variability at the mainstem Walker River DTS site on the 25th and 29th do not correlate with changes in flow or weather (Fig. S2).



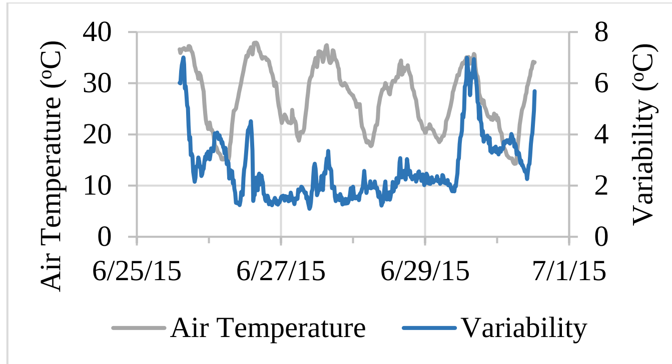
(a)



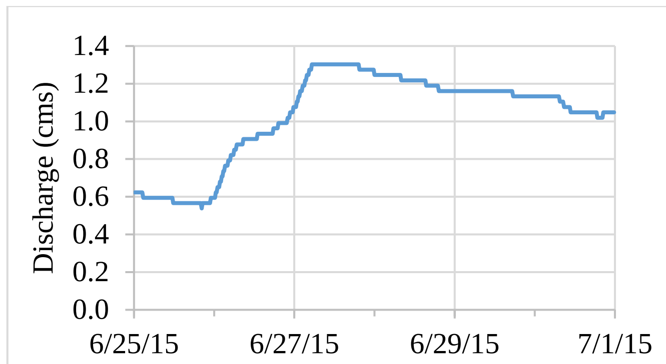
(b)



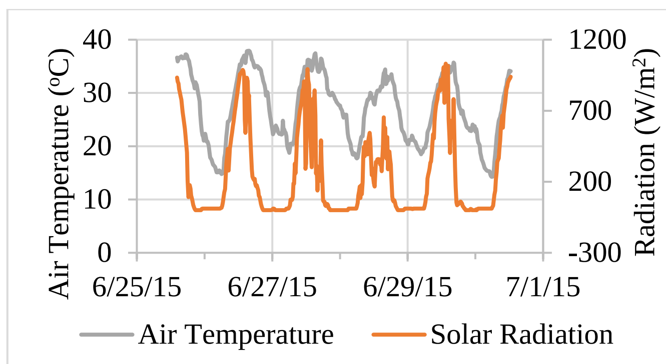
(c)



(d)



(e)



(f)

Figure S2: Stream temperature variability, flow, air temperature, and solar radiation measured every 15 minutes at the East Walker River (a, b, and c) and mainstem Walker River (d, e, and f) DTS sites. Stream temperature variability is calculated for the length of the study reach, not including Wabuska Drain at the mainstem Walker River DTS site.