Response to Reviewers

Thank you to the reviewers and editor for careful review of our paper "Quantifying Small-scale Temperature Variability using Distributed Temperature Sensing and Thermal Infrared Imaging to Inform River Restoration". We are confident that it will improve the paper.

All reviewers responded positively to using distributed temperature sensing (DTS) and thermal infrared (TIR) sampling to understand spatial stream temperature variability over a range of scales and comparing those data with modeled stream temperatures to identify possible locations and extents of thermal refugia for Lahontan cutthroat trout (LCT). They noted that this is a unique and needed line of research. However, all reviewers recommended further analyses. To address this we:

1) Quantified the percentage of space/time that DTS, TIR, and modeled temperatures exceeded 21 °C (temperatures preferred by adult LCT), 24 °C (chronic 7-day upper thermal limit), and 28 °C (lethal threshold for LCT). We also kept the percentage that the simulation model under-or over-estimates measured temperatures to better understand the times and locations that 1D modeling succeeds of fails for trout (last paragraph in section 4.3). We also show the model performance when measured temperatures are above these thresholds (added a new Figure 7 and Table 5).
2) Compared left and right streambank DTS measurements at 1 m, 10 m, 100 m, and 300 m spatial scales. This evaluated lateral temperature variability with scale and showed that models with larger spatial resolution lose thermal variability (last paragraph in section 4.1).
3) Similarly, we compared TIR measurements at 50 m and 300 m spatial scales. We wanted spatial scales large enough to span the river in all locations, thus we started with 50 m. These results highlighted the minimum temperatures in each reach (last paragraph in section 4.2).
4) We added a new figure showing the TIR imagery (Figure 5).

Below we provide detailed responses to all reviewer comments. Reviewers' recommendations are in black and our responses are in blue.

Authors Response to Reviewer 1

General Comments:

The paper addresses relevant scientific questions focusing on the importance of spatial and temporal fine scale variations in thermal habitat for Pacific salmon. The introduction could focus more on setting up the problem of warming waters for Pacific salmon in the southern extent of their range and on the importance of small scale variability in temperature for fish survival. Examining more recent papers that reference Sutton et al 2007 could help in this effort. Combining DTS, TIR, and one-dimensional temperature modeling in an effort to better manage and restore river systems is unique.

We added the following text and citations to the first paragraph in the 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) and climate change is anticipated to increase stream temperatures in summer, fall, and winter (Isaak et al. 2012). Recent research has quantified when and where cold-water fish need thermal refugia (Brewitt and Danner 2014), estimated the 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). Where stream temperatures are warming or where cold-water fish species are at the southern extent of their range, assessing stream temperatures at small temporal and spatial scales is thus important to quantify stream temperature heterogeneity and best manage complex and variable riverine habitats (Vatland et al. 2015).*"

The methods were outlined reasonably well; however there were some points of confusion. It is possible that a cartoon schematic of the deployment of the DTS could be beneficial.
We show the layout of the fiber optic cable in Figures 3 and 4.

The DTS itself had "two channels"and at times the wording became confusing because the DTS was deployed in a river channel.
We changed the wording to 'instrument channel' when discussing the DTS channels to avoid confusion.

Results largely consisted of summary statistics of the temperature data and modeled temperature. It would be instructive to do more analysis that relates to the Pacific salmon of interest and its 28 degrees C threshold. Additional investigation might be done to research the following
questions: 1) What percentage of the deployment was 28 degrees C exceeded at the mainstem site? 2) When the temperature was exceeded, did the model over or underestimate the actual value and by what percentage? 3) Is there any way to go beyond the summary statistics of the dataset?
The conclusions reached are clear; however, they seem fairly straightforward in that a one-dimensional model would certainly miss fine scale variation that occurs in a real river channel. I think it could be shown more clearly and in further detail the times when the one-dimensional model succeeds or fails for the Pacific salmon.
We added a paragraph in the Results section (last paragraph in section 4.3), Figure 7, and Table 5 to quantify the percentage of time that DTS, TIR, and modeled stream temperatures exceed 21, 24, and 28 degrees C. We also discuss places like the lower Walker River where stream temperatures often near or exceed 28 degrees and that these sections should be restored enough to provide passage. We show the model performance when measured temperatures are above these thresholds (added a new Figure 7). We compared left and right streambank DTS measurements and evaluated TIR data at 50 m and 300 m spatial scales to highlight temperature variability at different spatial scales (e.g., 1 m, 10 m, 100 m, 300 m) (last paragraphs in Sections 4.1 & 4.2).

How certain is that the results presented would not be different for a deployment time later in the summer? How might the results and discussion change for a period later in the summer?
We added the following text to the limitations section to address this comment: "*We deployed the DTS during mid-summer when we anticipated stream temperatures would be warmest (and when the DTS was available) as worst-case scenario for thermal refugia and connectivity. Additional research is needed to quantify how results would change for deployments earlier or later in summer*."

Key numerical results could be added to the abstract.
We added numerical results of model fit with observed data and can add additional numerical results following the addition of new analyses suggested by all reviewers.

At times the writing does not appear to have a singular voice.
We read through the manuscript to improve writing and maintain a singular voice throughout the paper.

Specific Questions:
pg. 3, Line 30: In what way do the diversions and return flows influence the temperature? It could be beneficial to explicitly state they warm the waters.
Diversions and return flows usually warm the river, but do not always warm the river. For example, one of our findings is that water in the Wabuska Drain return flow can be cooler than the rest of the river. For that reason, we left our original sentence unchanged.

pg. 4, Line 10: What percentage of the deployment period did temperatures exceed 28 degrees C? Is this a common problem in the watershed (are there locations where it is always greater than 28 degrees C) or does the problem occur only during discrete heatwave events?
We added a paragraph in the Results section (last paragraph in section 4.3), Figure 7, and Table 5 to quantify the percentage of time that DTS, TIR, and modeled stream temperatures exceed 21, 24, and 28 degrees C. We also discuss places like the lower Walker River where stream temperatures often near or exceed 28 degrees and that these sections should be restored enough to provide passage. We show the model performance when measured temperatures are above these thresholds (added a new Figure 7).

pg. 4, Line 30: Is it necessary to describe how DTS works in this level of detail?
We omitted a couple sentences in this paragraph to remove unneeded details and improve readability.

pg. 8, Line 28: How were key features added to the model output?
We clarified that key features were georeferenced so that the modeled reached that contained the features could be identified. This section now reads:
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 were applied to the model outputs to estimate small-spatial scale variability within each 300 m modeled reach. (starting page 9, line 30).

pg. 9, Line 29: It would be useful to show that there was not a large warming even that occurred between the two deployments at the two sites. Weather conditions should be ruled out as a factor of influence on the two deployments.
Air temperature for the deployments is in Supplemental Figure 2.

Specific Notes:
pg. 2, Line 3: Therefore, assessing stream temperatures...
Text revised to this suggested wording.

pg. 2, Line 9: Stream temperature models are a useful tool for river management because they help...
Text revised to this suggested wording.

pg. 2, Line 23: ...spatially-continuous stream surface temperatures. However, it... What does "it" refer to?
Text revised to this suggested wording. We substituted 'TIR data' in place or 'it'.

pg. 3, Line 31: Interactions between... "between" compares two things while "among" compares more than two things
Thank you. We substituted the word 'among' in place of 'between'.

pg. 4, Line 12: Low instream flows from surface water diversions have also caused the Walker Lake level to decline
We kept our wording for consistency throughout of manuscript. We do not refer to Walker Lake as 'the Walker Lake' elsewhere in the paper.

pg. 5, Line 25: Verb tense was changed to present tense.

We double checked that our methods are described in past tense. Accuracy of data loggers are in present tense because it always holds true.

Authors Response to Reviewer 2

In this manuscript, high spatial resolution temperature observations are used to investigate small scale spatial variability in stream temperatures. These are placed on top of simulated stream temperatures with grid cells of 300m, leading to the conclusion that at moments when the simulated temperature exceeds the critical temperature (for LTC) of 28 C, there are always pockets of water that are cool enough to serve as refuges. Although these findings are potential useful, this manuscripts reads a bit as an engineering report with the focus on 'improving' an existing 1D 300m-resolution temperature model. There is little in-depth science involved: the results section is mainly a summing up of observations at the 300 m scale, while more quantitative assessment of the uncertainties/sensitivities of the used approach is missing.

Because I still think the available data is sufficient to improve the manuscript significantly, I am advising major revisions. What in my opinion is needed is a more in-depth analysis about spatial variability over a whole range of scales. For example: one can compare the left and right bank DTS measurements for each cross section as the smallest scale (_1m). Subsequently, the temperature range for progressively larger scales can be obtained. Finally, the implication for the model scale (300m) can be used as a practical case study. Similar things can be done for the TIR observations. Although it was not clear to me if the 10 points which were used to obtain the summary points were measured in 1 cross section or if they were measured over 300m, with a spatial resolution of 0.6 m, there seems to be enough data to do the same analysis for the TIR data.
We compared left and right streambank DTS measurements at 1 m, 10 m, 100 m, and 300 m spatial scales. This evaluated lateral temperature variability with scale and showed that models with larger spatial resolution lose thermal variability (last paragraph in section 4.1). Similarly, we compared TIR measurements at 50 m and 300 m spatial scales with the raw pixel data rather than the summary points. We wanted spatial scales large enough to span the river in all locations, thus we started with 50 m. These results highlighted the minimum temperatures in each reach (last paragraph in section 4.2).
Line by line comments:

P2,L29: Westhoff et al. (2007) did their research in the Maisbich river in Luxembourg.
We apologize for our error. We have checked our references and revised this sentence to read: "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)."

P3, L3: Neilson et al. (2010) did indeed not use these measurements, but they did model the temperature of transient storage zones.
We do not cite Neilson et al. 2010 on page 3, L3 and the Neilson et al. 2010 paper we cite is a different one from the reference the reviewer provided. We cite:

Neilson, B. T., Hatch, C. E., Ban, H. and Tyler, S. W.: Solar radiative heating of fiber - optic cables used to monitor temperatures in water, Water Resour. Res., 46(July 2009), 1–17, doi:10.1029/2009WR008354, 2010.

P3,L10: isn't spatial variability not the same as temperature range?

We included this phrase to specify that we quantify spatial variability as temperature range rather than other metrics like distributions. We changed the wording to "… evaluate small-scale stream temperature variability, quantified as the range of stream temperatures…," to clarify our intent.

P3, L23: please also indicate stream width and depth estimates.
We added width and depth so this sentence now reads "*The Walker River is a desert stream with mean annual flows of 15.5 – 30 m3/s, width of approximately 7.6 m and depth of about 32.9 cm*."

P4, L31: change to: the majority of the reflected energy has it original wavelength.
Text revised to incorporate reviewer's suggestion.

P6, L25: Are these 10 locations spread over 300 m, or 10 locations covering one crosssection? And why are only values in the centre of the channel taken? Pools etc, are generally located on the sides of the channel. The spatial variability will probably be larger when these values on the side of the channel will be taken into account as well.
The 10 locations were spread over 300 m modeled reaches. We compared estimates of summary points and TIR data using all pixels for the percentage of modeled results that exceeded 21, 24, and 28 degrees, and the results were nearly identical. We analyzed thermal range at multiple spatial scales using TIR data with all pixels (which were 0.6 m).

Section 3.4: Here, many statistical parameters are explained. As a reader I found it difficult to remember what the meaning is of each statistic. Furthermore, the symbols defined here hardly ever comes back in the results section. My suggestion here is to only define a few of them, and in the results section clearly state if a spatial or temporal range is discussed.
We followed your suggestion to remove many parameters. We clarified the statistical parameters that we kept. Overall this should clarify this section and remove some redundancy and unneeded detail.

P7, L16: use subscripts for TSavg: now it reads as T*S*a*v*g (the same for all other equations). Instead of 'avg' one can also use a bar on top of T
We have removed avg in the notation and use bars over the top of the variable instead.

P8, L1: what does "top of hour" mean?
We changed text to say 'hourly' instead of 'top of the hour' throughout the manuscript.

P8, L10: If I understood it correctly, these summary points were the mean, min and max. So why are there "on average" 3 summary points? This implies that at some location you have less and at others you have more summary points.
Model spatial extent and the summary points were developed independently. Thus sometimes 4 or 5 happened to be located within a model reach. On average there were 3 summary points per modeled reach.

P8, L15: L is river length, isn't it?
Yes. We clarified the text to read "*where $\overline{T}_L$ is average stream temperature for the length of the East, West, or mainstem Walker River, L*".

P8, L28: What do you mean with "extrapolate model outputs"?
We re-wrote that section to clarify our meaning. It now reads "*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 were applied to the model outputs to estimate small-spatial scale variability within each 300 m modeled reach."

P8, L31: the key features are the same as the river features discussed in the previous lines, aren't they?
We changed 'key features' to 'river features' to clarify our meaning.

P11, L15: I guess you mean that the backwater location is subject to a higher thermal mass (or lower heat capacity)?
We revised this sentence to read "*The warmer temperatures occurred in an unshaded, shallow, backwater location subject to lower heat capacity*".

P11, L33: with a single snapshot in time one cannot conclude that the stream is cooling. One can only see that it is cooler downstream, but this can also be caused by warm water that only travels slowly downstream.
We revised this text to read "*Although Wabuska Drain was receiving agricultural returns and therefore contributing warm water, rather than the cool water observed during times with limited agricultural returns, a 4.5 km stretch of river downstream from the Wabuska Drain was 1 ^{o}C cooler than the segment of river upstream of Wabuska Drain*".

Section 5: Discussion: I miss a discussion on the difference between TIR and DTS measured ranges: which one has the largest range and highest temperature, and why? Although both methods measured at different periods in time, it must be possible to say something about it.
We added the following text to address this concern "*Overall, DTS measured a larger temperature range than TIR imagery in both the East Walker River and mainstem river (Tables 2 and 3) because the fine DTS spatial resolution 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, but by DTS in the mainstem, indicating that both methods are useful, and more widespread data collection of longer DTS deployments or repeated TIR collection would further improve results.*" (starting page 16, line 9)

P14, L4-5: Why is the change in temperature over time minimized on warm days? I would presume that on such days the rate of change is at its maximum, since also the daily amplitude is the largest on these days
We omitted to words 'warm, clear' to clarify that we minimized stream temperature changes through time by collected TIR imagery on days with similar weather conditions.

P14, L8-9: Can you quantify the effect of stratification?
We noted that quantifying temperature range from vertical stratification is outside the scope of this paper.

P15, L6: The definition of temperature range is defined as Tmax-Tmin, so it can never be a negative value.
We changed '*temperature range'* to '*temperatures'* to distinguish meaning from our earlier definition.

Section 5.4: this belongs in the conclusion (or summary) section.
We moved this section to the summary section.

Figures, general comment: add the caption of the figures also right below the figures: I know this will happen once the manuscript is published, but as a reviewer, I found it annoying that these captions were only listed in the text.
We added captions to the figures.

Fig. 3b: reduce the scale on the vertical axis to max 2 C?
We kept the scale on the y-axis to max 8 C so the figure is comparable with Figure 4b. We felt that different scales between Figures 3b and 4b would be misleading to readers.

Fig.5: In my opinion, there is little added value to the panels b-d. I also wouldn't call them "summaries" anyway: it is just a different way of plotting the same results.
We removed panels b-d from this figure.

Fig.7: What was the time for the simulated temperature? I am also wondering how variable the range over time is. This is especially interesting since the TIR data is from a completely different year than the DTS measurements. The legend of panel b can also be improved: What is the dark blue line, how are the average temperatures obtained?
We added the time for the simulated temperature to the caption and reworded it so it now reads "*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)*." We removed the average temperatures to simplify the figure.

The DTS measurements give spatio-temporal ranges and the TIR measurements give spatial variability for one time period. TIR and DTS data were acquired at different times. We have overlain both DTS and TIR onto the same model run because it reduced data/complexity and led to largely the same results. We could overlay these data onto the RMS model output for matching time periods (i.e., TIR for 2012 model run and DTS for 2015 model run) and separate Figure 7b into 2 figures if this is misleading. We like this figure because it is our perception that managers make decisions as new data is analyzed and shared without always developing contracts for additional model runs.

Authors Response to Reviewer 3

Hydrology and Earth System Sciences manuscript HESS-2018-441 describes the result of a study to quantify small-scale temperature variability in the Walker River, Nevada, using a combined approach leveraging DTS, thermal infrared (TIR) remote sensing and one-dimensional river temperature modelling. DTS and TIR data were incorporated with coarser temperature model predictions to identify potential thermal refugia habitat that may otherwise be missed from lower-resolution temperature model outputs. While the general idea of combining TIR, DTS and model predictions is laudable (and there is definitely a need for this type of research), I felt that the manuscript was generally too descriptive, with a lack of formal hypothesis testing or deeper analysis. Furthermore, the method by which the TIR/DTS data was combined with the temperature model predictions (through simple addition of temperature ranges to the temperature model-derived thermal long profiles) was rather simplistic and does not appear to offer a substantial benefit over the use of the DTS/TIR data alone. Despite these issues, I support the general concept of the manuscript and believe that the idea of combining DTS, TIR and model predictions has merit, but I feel that significant revisions (including a much more in-depth

treatment/analysis of the data beyond the scope of what would normally be considered 'major revisions') is needed prior to publication.
Please see summary of additional analyses at the beginning of this document.

—General comments—
-In section 3.4 (and table 1), it is quite difficult to remember/follow the names of the different variables. Is there any way of streamlining/simplifying this?
We removed many parameters and clarified the statistical parameters that we kept. Overall this should clarify this section and remove some redundancy and unneeded detail.

-It's probably not necessary to give all of the detail about the DTS system (ie. 2 channels, cable stress, etc) in the methods and results sections. Consider removing all superfluous information to streamline the manuscript.
We removed unneeded DTS details and text to streamline the manuscript.

-It would be nice to see some of the TIR imagery to allow for comparison with the DTS data; given the large time difference between the TIR and DTS data, the information in table 3 is of limited use.
We kept Table 3 since it provides a succinct summary of max, min, and average TIR measured temperatures and ranges. We added a new figure 5 of TIR imagery to the revised manuscript.

-Use of the word 'RMS' (ie. the name of the model) is confusing in places when you are also talking about RMSE. Consider putting 'RMS' in italics or similar to avoid confusion.
We italicized 'RMS' throughout the manuscript to avoid confusion with RMSE.

-There is very little information about the RMS model in terms of inputs, implementation, etc. I appreciate that this information is already given in the other references provided, but it would nonetheless be useful for see it outlined in this MS (maybe a short paragraph explaining model function, input data, etc).
We improved the description of the RMS model to include description of inputs, model function, and implementation. Section 3.3 now reads:

"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). RMS has a hydrodynamic module and a water quality module, which are run sequentially (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 input into 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.

Previous research provided modeled streamflows and stream temperatures for one wet (2011) and three dry (2012, 2014, 2015) irrigation seasons (April 1-October 31) (Elmore et al. 2016; Null et al. 2017). The model was developed to simulate stream temperatures from environmental water purchases that alter thermal mass to improve habitat for native organisms and connect Walker River and Lake. Irrigation season (April 1–October 31) was modeled because that 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 and 300 m modeled reach spatial resolution. As a 1-dimensional model, each reach has a homogenous temperature throughout the reach. Walker River modeled extent includes 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)."*

-It's not immediately clear in the manuscript how you 'apply' the DTS/TIR temperature data to the model. From my reading, you simply add/subtract the temperature range to the model outputs. Is this correct? If so, I would have thought that this process (ie. calculating temperature variability from DTS and TIR and simply adding/subtracting to/from the model outputs) is accompanied by a range of issues given that the DTS data is essentially a measure of spatio-temporal temperature range, whereas the TIR data only gives spatial variability. Also, given that the TIR data and DTS data were acquired at different times, it does not seem appropriate to overlay these data onto the RMS model output for the same point in time (eg. fig 7).
We changed this wording to "*Measured DTS and TIR temperature ranges were added to model outputs to estimate small-spatial scale variability within each 300 m modeled reach. This provided an estimate of spatial variability missing in the model output that is needed to gain insight into potential habitat availability at smaller-spatial scales*." The DTS measurements give spatio-temporal ranges and the TIR measurements give spatial variability for one time period. TIR and DTS data were acquired at different times. We have overlain both DTS and TIR onto the same model run because it reduced data/complexity and led to largely the same results. We could overlay these data onto the RMS model output for matching time periods (i.e., TIR for 2012 model run and DTS for 2015 model run) and separate Figure 7b into 2 figures if this is misleading.

-What is the reason for the large temperature discrepancy between the two river banks? This kind of information is quite interesting and could benefit from a thorough treatment in the manuscript.
We compared left and right streambank DTS measurements at 1 m, 10 m, 100 m, and 300 m spatial scales. This evaluated lateral temperature variability with scale and showed that models with larger spatial resolution lose thermal variability (last paragraph in section 4.1).

-Section 3.4 of the methodology is difficult to follow. Given that this section contains the majority of the analyses covered in the results and discussion sections, it would be beneficial to restructure this section to make the subsequent results and discussion easier to follow.
We completed a major revision of this section, removing redundancy and unnecessary detail.

—Introduction—
P2 L1: Would be good to have 1-2 sentences of more general information on the importance of river temperature in the context of climate change.
We added the following phrase to the 1st sentence: "…and climate change is anticipated to increase stream temperatures in summer, fall, and winter (Isaak et al. 2012)."

P2 L24: It would be a good idea here to qualify the point about TIR only providing a single snapshot in time by saying something along the lines of 'unless acquired multiple occasions'.
We added this phrase.

—Methods—
P4 L22-28: These lines are potentially redundant and could be moved or redistributed elsewhere in the methods section.
We omitted these lines and added the pertinent information that was not redundant elsewhere in the methods.

P4 L30-31 and P5 L1-5: I'm not sure that a description of how DTS works is necessary; consider removing this paragraph (or at least, shortening it to one sentence)

We shortened this section so it is now 2 sentences: "*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)*."

P5 L6-13: Consider adding a figure to illustrate the deployment of the DTS. I appreciate that this is partially covered in fig 1 (large scale) and fig 3/4, but it would be nice to see a full resolution map showing the DTS installation.

We show the layout of the fiber optic cable in Figures 3 and 4.

P5 L18-22: Is this information necessary? Consider removing.

We omitted lines 19-22 (line numbering from original document).

P5 L28: This sentence formulation is slightly difficult to follow. Do you mean to say that the calibration process consisted of using a linear transform to correct the DTS based on the difference between the DTS and thermocouple temperatures in the ice bath?

We revised this sentence to read: "Calibration used a linear transformation to correct the DTS data based on the difference between the DTS and thermocouple temperatures."

P6 L18-32: There isn't any mention here of the winter TIR data collection flights which you subsequently refer to later on in the manuscript. The manuscript only appears to have dates and hydrometeorology information for the summer flights. I appreciate that the winter data is only used for locating seeps, but it would be good to talk about the winter flights here first.

We discuss the winter and summer flights in the first sentence of Section 3.2.

P6 L32: Although I managed to find the Watershed Sciences documents online, they were quite difficult to track down. It would therefore be good to give some further brief details of the flights, for example RMSE or R2 of TIR data vs. logger values, etc.

We added the following sentences to describe TIR validation. "*TIR radiant temperatures were validated with 28 Hobo Pro and iButton kinetic 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*."

P7 L7: Sentence ('each reach [: : :] throughout the reach') is a little clunky – consider rewriting.

We revised this sentence to read: "As a 1-dimensional model, each reach has a homogenous temperature."

P8 L28: This sentence ('To extrapolate model outputs: : :') is difficult to follow; it is difficult to understand exactly what you are doing here. Can you think of a different way to explain this step in the methodology?

We've revised this sentence to read "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."

P8 L32 and P9 L1: What do you mean by ‘were developed in 2012’? Do you mean that diversions/return flows were implemented in 2012 in the model, or in reality? Or just that they were mapped/identified?
We changed wording from ‘developed in 2012’ to ‘identified in 2012’.

P8 L2-4: If you wanted to exhaustively identify all seeps, I wonder if a better practice would have been to combine data from the winter and summer survey flights? Also, please give some detail about how the seeps were identified. Was it from manual photo interpretation? Were aerial photos acquired simultaneously to aid the interpretation process?
Due to the low water in July, the majority of locations on the Walker that showed groundwater activity in the winter were dry at the time of the summer flight. Seeps were identified from cooler stream temperatures that could not be attributed to shadows, cutbanks, or vegetation. We added text describing this to Section 3.4.

—Results—
P9 L26-30: These sentences would be better suited to the discussion section.
We moved the last sentence to the Discussion (section 5.2). We left the sentences about the dam releases so the results make sense to readers unfamiliar with this system.

P10 L20: I’m not sure what you mean here when you say that the daily max/minimum temperature changed little when analysed with the Walker River. Do you mean to say that a lack of large-scale temperature variability in the study reach masks considerable localised variability in areas like the Wabuska drain?
Yes. We revised the sentence to reflect your suggested wording. “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 masks localized variability in areas like the Wabuska Drain.”

P10 L25-30: Some of this material might be better suited to the discussion section.
We moved this text to Section 5.2 in the Discussion.

P11 L32-33 and P12 L1-5: This would also be more suitable to the discussion.
We moved this text to the discussion.

—Discussion—
P13 L23-31 and P14 L1-9: I’m not really sure what information this ‘limitations’ section adds to the manuscript. There are clearly limitations when conducting an approach such as this combining TIR, DTS and modelling. However, this section reads more like a list of problems associated with TIR and DTS data collection (which have already been well established in the literature) rather than a critical appraisal of the inherent difficulties of combining and comparing these types of data with 1D temperature models, which would be much more interesting (and potentially useful for the reader).
We largely rewrote the limitations section. We briefly summarized problems associated with TIR and DTS data collection which have been previously discussed in the literature. Then we highlighted the difficulties of comparing datasets with different spatial and temporal resolutions and that were collected in different years.

We added the following text: “*Obtaining small-scale spatial and temporal stream temperatures and comparing them to model results has a number of limitations. First, the spatial and temporal resolution vary between DTS and TIR datasets and with simulated model results. TIR imagery represents a single* *point in time unless costly flights are repeated. DTS measurements are dense (1 meter in these deployments) with a 15 minute temporal resolution, but are limited by cable length and field crews to monitor the deployment. Comparing measured data to hourly model results with 300 m spatial resolution further reduces the number of comparable observations. 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, modelling, and management is common in large, important, or complex river basins. This research highlights the differences in temperature variability given alternative sampling methods*."

—Figures—
Figure 7(b). As discussed above, it is not clear how you combine the RMS stream temperature data with DTS data from June 2015 and TIR data from July 2012. Surely this mixing up of different dates and times means that the temperature ranges from the DTS cannot be comparable to those from the TIR? Also, to what does the 'average temperature' refer? Is it from the DTS data (temporal) or is it average temperature (spatial) calculated as the mean of all pixels covering the refugia/beaver dam, etc?
The DTS measurements give spatio-temporal ranges and the TIR measurements give spatial variability for one time period. TIR and DTS data were acquired at different times. We have overlain both DTS and TIR onto the same model run because it reduced data/complexity and led to largely the same results. We could overlay these data onto the RMS model output for matching time periods (i.e., TIR for 2012 model run and DTS for 2015 model run) and separate Figure 7b into 2 figures if this is misleading. We removed the average temperature to clarify the figure.

Authors Response to Reviewer 4

The article compares temperature data from DTS and thermal imagery within a stream reach where one-dimensional temperature modelling was conducted. The study takes place in the Walker Basin, NV, where stream temperatures can exceed thermal tolerance for native, threatened trout. This study provides a unique combination of methods and is useful in understanding the pros and cons of each. The study is relevant for work that seeks to restore habitat for fish in streams where temperatures rise above the thermal tolerance of threatened cold-water species.

There are a few places where the manuscript could be improved. The authors generally summarize the differences between the methods, but they could take it to the next level with doing a more quantitative analysis comparing the different methods. At the end, there is not a strong conclusion, or list of pros and cons, comparing DTS vs TIR methods for validating or contributing to stream modelling efforts. What would the authors decide to use - DTS or TIR - based on the results of this paper? Second this paper has the data to conduct analyses that look at the availability of different water temperatures that are relevant for trout. For example, the authors focus on 28C as a thermal cut off for LCT, but these fish may become thermally stressed at much lower temperatures (e.g., 21 or 22C). Additionally, very cold temperatures in the summer may not be ideal for growth. The authors could consider adding an analysis that describes the area of stream that is available to LCT below different cut offs, e.g., below 18C, below 21C, below 25C, and below 28C, and the distance between those areas. The DTS and TIR methods identify river features that the one dimensional model doesn't, but how important/large/cold

is the water provided by these features? The authors could also compare how the different methods perform in quantifying the amount and connectivity of thermal refugia.
We added a paragraph in the Results section (last paragraph in section 4.3 and Table 5) to quantify the percentage of time that DTS, TIR, and modeled stream temperatures exceed 21, 24, and 28 degrees C. We also discuss places like the lower Walker River where stream temperatures often near or exceed 28 degrees and that these sections should be restored enough to provide passage. We show the model performance when measured temperatures are above these thresholds (added a new Figure 7).

We also rewrote much of the Summary section to directly compare DTS, TIR and modeled data, describing DTS better quantify temperature range at many river features and across lateral streambanks, although multiple types of measure data complement each other.

One way that could improve the flow of the results section would be to put the comparison of all three methods up front, and then describe the results of how temperatures differ in the basin second. These are currently split into different sections, with the temperatures differences in the basin described following each method.
We reorganized the results section so that we discuss temperature maximums and ranges for the DTS and TIR, as well as new analyses comparing the results at different spatial scales. We moved all text about how temperature differ throughout the basin and those implications to the discussion section.

Additionally, the description of the DTS channels can be a bit confusing because there are river channels and DTS channels – is there another descriptor that could be used in place? The focus on the Wabuska diversion can also be confusing, because it was flowing during the time window of one method and not flowing for the time window of the other method.
We changed the wording to 'instrument channel' when discussing the DTS channels to avoid confusion. The Wabuska Drain is important to our findings, so we left it in the manuscript. We have tried to be clear about when it was flowing and when it was not flowing, but had standing water.

Finally, the introduction and discussion could use more context for why micro thermal regufia is important for cold water fish and trout. The author should look for more recent citations of Sutton et al. 2007, Brewitt and Danner 2014, etc.
We added the following text and citations to the 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) and climate change is anticipated to increase stream temperatures in summer, fall, and winter (Isaak et al. 2012). Recent research has quantified when and where cold-water fish need thermal refugia (Brewitt and Danner 2014), estimated the 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). Where stream temperatures are warming or where cold-water fish species are at the southern extent of their range, assessing stream temperatures at small temporal and spatial scales is thus important to quantify stream temperature heterogeneity and best manage complex and variable riverine habitats (Vatland et al. 2015)*."

We also added the following citations to the discussion: "*Future research is needed to validate temperature ranges by river feature at the watershed-scale, evaluate how fish use thermal refugia, and to improve understanding of the resiliency of thermal refugia with anticipated climate change (Fullerton et al. 2018; Frechette et al. 2018; Stevens and DuPont 2011; McCullough et al. 2009).*"

Specific Comments:

Pg 2 Line 5. It could be useful to explain here explicitly what you mean by one dimension. (Obvious to stream temp. modelers but less intuitive to managers). Do you mean longitudinal interpolations along the stream?

We changed this sentence to "However, one-dimensional stream temperature models *that estimate longitudinal stream temperature changes and* that are applied at the watershed-scale are poor predictors of thermal micro-habitats" to describe one-dimensional stream models for readers unfamiliar with modeling.

Pg 2 Line 13-15. Similar comment as above – what does 2, vs 3 dimensions mean for streams? Length, width, depth, and in that order?

1-, 2-, and 3-dimensional stream temperature models typically represent longitudinal, lateral, and depth dimensions, in that order. To clarify, we revised the sentence to "… one-dimensional because they are less data intensive and more computationally efficient than two- or three-dimensional models *that also vary by width and depth*…".

Pg 2 Lines 23-25. Switch the order of these sentences. Describe how TIR has been used to locate various stream features, but then the downside is that it is a single snapshot in time.

Done.

Pg 3 Lines 2-5: This sentence is key in setting up what your study contributes to the ones that you cite, but it isn't clear. These methods have been used to calibrate reach scale models but hasn't been used to quantify temperature ranges within model reaches? The difference in the wording is very slight, and needs to be clarified.

Yes, we mean that DTS and TIR have been used to calibrate models, but haven't been used to quantify temperature ranges within the model reaches. We have rephrased the sentence to clarify our meaning: "*While DTS and TIR have been used to calibrate reach-scale models, no studies have used DTS and TIR to quantify temperature ranges by river feature within model reaches, and use to that information to estimate likely temperature ranges at the watershed scale*."

Pg 3 Lines 9 – 10 Objective #3 is has circular wording, it's not clear what the objective is. Is the goal to identify features with greater temperature ranges because they have variable temperatures? Maybe the objective is just to identify those features?

The objective is simply to identify the features. We omitted the phrase "…*due to spatially variable temperatures*" to clarify meaning.

Pg 3, Lines 11-18 I suggest reducing this description of theWalker Basin to 1 sentence, maybe 2 sentences here. You get into more detailed description in the next section. For example, environmental water purchases seem relatively uncommon, and you do them more justice in the next section.

We omitted 2 of the sentences so now we have 2 sentences here: "*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., pools, confluences) to identify temperature barriers to migration and better interpret watershed-scale model results.*"

Pg 4 Second paragraph – It would be nice to include some description about how narrow the range of LCT is. It makes your study more special.

We added the historical range of LCT. This sentence now reads: "*The historical range of LCT is the Lahontan Basin in eastern California, southeastern Oregon, and northern Nevada*, although LCT are limited in their native range by warm stream temperatures, low streamflows, and low dissolved oxygen in the Walker River (Coffin and Cowan 1995; USFWS 2003)."

Pg 4 Line 8 – Are all these study sites in CA? For a European journal, the places should be better located.
These sites are in Nevada and Oregon. We've added the state in which they're located to the text.

Pg 4 Line 14 - This sentence is a little unclear as to what it means in context of the previous sentence. Because the lake is inhabitable, it means the lake and stream systems are disconnected?
We deleted this sentence.

Pg 4 Line 17 – Restore to tolerable salinity ranges? Restore is a broad word. The discussion of salinity is really interesting, but perhaps not relevant to your stream temperature focus.
We revised the sentence to "to restore Walker Lake salinity to tolerable levels". We kept the discussion of salinity and Walker Lake to add context to the research.

Pg 4 Line 22 – Can you be more specific about what a 'dry year' means in this basin? I.e., received <25% of historical rainfall, or stream base flows were at XX% of the average flows for that time of year? (Especially since you do have USGS gauge data)
We removed this section following the recommendation of another reviewer. However, we added that in dry year 2012 snowpack was 50% of normal and in dry year 2015 snowpack was 5% of normal to the DTS and TIR subsections.

Pg 4 Line 26 – Comparing measured and modeled data? (rather than between)
We changed "between" to "comparing".

Pg 6 Line 31 – the East Walker has more flow than the mainstem – presumably because of diversions? Remind the reader of that again
Diversions vary streamflows in both the East and West Walker Rivers so that some days flows are higher in the East Walker River and some days they are higher in the West Walker River. We do not want to imply that West Walker flows are always lower than East Walker flows, so we made no changes to the text.

Pg 9 Line 30 – was the Elmore et al. 2015 study also conducted in the Walker R basin? This point may be better situated in the discussion.
We moved this sentence to the Discussion (section 5.2).

Pg 9 – Fig 2 caption – A reminder of what is the Wabuska Drain (not-flowing, but standing water from an ag ditch) would help the reader in the caption.
We added a description of Wabuska Drain, so the caption now reads: "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)."

Pg 10 – Fig 3 – The sub-panels in Fig 3 should be labelled. In looking at the figure, it's not clear why these two features are called out. It looks like there is more variation between river left and river right than anything else. Fig 3 b could probably be moved to supplemental.

We amended Figure 3 caption to include that insets show details of spatial temperature variability. We removed figure 3b.

Pg 10 – Why do Fig 3 and Fig 4 visualize different times, 5:30 pm vs 3:15 pm?
Figures 3 and 4 visualize each reach at their maximum daily temperature. We felt this was more representative and comparable than picking an arbitrary time that is the same for both reaches.

Pg 10 Lines 19-31 – How different would this look if the Wabuska drain was flowing? Is it more often flowing or not flowing in the summer months?
We do not know how different results would be if the Wabuska Drain were flowing. Thus we added a line to the limitations section: "*Additional research is needed to quantify how results would change when the Wabuska Drain is flowing, or for deployments earlier or later in summer*." The Wabuska Drain is usually flowing during summer, except during dry/very dry years when irrigators use more groundwater than surface diversions. The majority of years in the past decade have been dry/very dry years.

Pg 10 – Fig 4 – It would be nice to add a line or circle indicating where the beaver dam is on that reach of stream. Fig 4 b could also be moved to supplemental. However it might be worth exploring why there is day-to-day variation in the temperature ranges – could plot the data against air temperature range for the day?
The beaver dam locations are shown in the insets of Figure 4. We removed figure 4b.

Pg 11 Lines 10 – 11 Have LCT been observed using the Wabuska drain when it is flowing, or when stream temps aren't so high at the mouth?
LCT have not been observed near the Wabuska Drain that we are aware of.

Pg 11 Lines 31-32 Are there studies that show that LCT cannot move through warm temperatures? Maybe save the temperature implications for fish for the discussion, when you can do a more thorough review of studies on LCT (and related salmonids) and their thermal tolerance. They may be able to move through a small area of warm temperatures. What may be more important is the extent of cold water refuges, which could be quantified with the given data.
We moved all implications for fish to the discussion so that we could put the findings into context with the literature.

Pg 11 – Lines 33-34 – Make it clear that the cool water from Wabuska was observed with the other method/time window when stream temps were monitored.
We added 'during the TIR flight' to the sentence to clarify.

Pg 12 – Fig 5 – Similarly to the other figures, the sub-panels b,c,d could be moved to supplemental since they are redundant with the main figure. Alternatively, they may be a better way to present the data in the main figure, so you could consider dropping panel a.
We removed panels b-d from this figure.

Pg 13 – Lines 16-19 – Model estimated within 1C – that's pretty good! But under estimating by 2.5C is less desirable – could be a point to discuss.
We discuss this in section 5.3 where we add "*TIR stream temperature measurements in the lower reaches of the mainstem Walker River were considerably warmer than simulated results and remain near LCT lethal thermal threshold for an additional 45 km than was previously estimated*."

Pg 14 – Lines 13-15, Maybe it didn't exceed 28C, but trout can be thermally stressed at much lower temperatures.
We added that trout can be thermally stressed at lower temperatures to the sentence.

Pg 14 Line 23 – Is this study from the Walker R Basin, or generally citing groundwater depletion from drought?
This study is from the Walker Basin. We made no change since the sentence specifically discusses interflow to the Wabuska Drain.

Pg 14 Line 30 – How migratory are LCT? Would they historically migrate between lakes and streams, and was that during the summer? If not, then you could shift your focus to movement and opportunities for longitudinal connectivity rather than migration.
LCT historically migrated between Walker River and Lake. However, we changed this sentence to focus on aquatic habitat longitudinal connectivity because it is more broadly applicable for cold water habitat and species.

Pg 15 Lines 9-10 Describing that there is a range in temperatures doesn't necessarily mean that there is thermal refugia. How cold is the water around these features? If it has high variability but it still warm, then it may not provide refuge for LCT.
We added and subtracted the temperature ranges that we measured from the modeled values. It doesn't mean there is always thermal refugia, but is suggests there may sometimes be refugia. We modified our wording to "*suggests that cool-water refugia may sometimes exist*" so that we do not oversell our findings.

Pg 15 Lines 27-29 This would be a good place to give a nod to the work that has evaluated how fish use thermal refugia (do a forward search on Sutton et al 2007).
We added 4 references (Fullerton et al. 2018; Frechette et al. 2018; Stevens and DuPont 2011; McCullough et al. 2009) to give a nod to current research on how fish use thermal refugia.

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

Jessica R. Dzara[1], Bethany T. Neilson[1], Sarah E. Null[2],

[1]Department of Civil & Environmental Engineering, Utah State University, 8200 Old Main Hill, Logan, Utah, 84321-8200, USA
[2]Department of Watershed Sciences, Utah State University, 8200 Old Main Hill, Logan, Utah, 84321-8200, USA

Correspondence to: Sarah E. Null (sarah.null@usu.edu)

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 ~~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. 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, ~~Assessing~~ measuring stream temperatures at small temporal and spatial scales is ~~thus~~ important to quantify stream temperature heterogeneity ~~and best manage or restore complex and variable riverine habitats~~ (Vatland et al. 2015). ~~However, o~~One-dimensional stream temperature models estimate longitudinal stream temperature changes ~~are applied~~ at the watershed-scale, but are poor predictors of thermal micro-habitats. On the other hand, h~~H~~igh 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~~, helping~~ decision makers ~~to~~ 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 ~~also vary~~ account for temperature variability ~~by~~ over width and depth. ~~; however, one-dimensional models assume perfectly mixed reaches. Thus~~However, one-dimensional models do not identify small-scale features like cold water pools, ~~cool margins,~~ lateral variability, or groundwater influenced areas~~, and reaches that are incompletely mixed laterally~~.

Stream temperature sensors ~~estimate~~ measure ~~stream~~ temperatures at fine spatial and temporal resolution at point locations. ~~However, d~~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 ~~a~~ 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 ~~been~~ successfully ~~used to~~ identified~~y~~ 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 ~~remotely sensed~~ imagery similarly captures spatially-continuous stream surface temperatures. ~~; h~~However, TIR data are~~it is~~ for a single point in time unless acquired on multiple occasions (Dugdale, 2016; Torgersen et al., 2001). ~~TIR data have been successfully~~

~~used to identify 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).~~

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~~; Westhoff et al., 2007~~) 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. ~~While DTS and TIR have been applied~~ used ~~to calibrate reach-scale models, n~~To date, no studies have used ~~both~~ DTS and TIR to quantify ~~observed~~ temperature ranges by river feature within model reaches, and ~~more importantly,~~ use ~~to~~ that~~is~~ information to~~to extend model predictions for key river features~~ estimate likely temperature ranges over space and time at the watershed scale~~ that create highly variable temperatures over small spatial scales~~. Such insight into small-scale responses allows researchers, managers, and stakeholders to identify thermal micro-habitats and further interpret ~~1D~~one-dimensional basin-scale model results.

The objectives of this study were to 1) evaluate small-scale stream temperature variability, ~~or~~quantified as the range of stream temperatures, at multiple spatial scales using DTS data and TIR imagery, 2) use tho~~e~~se 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~~ ranges due to spatially variable temperatures~~, 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, focusing on environmental water purchases to improve habitat connectivity between Walker River and Lake (National Fish and Wildlife Foundation, 2011; Walker Basin Conservancy, 2017). An existing hydrodynamic streamflow and temperature model has evaluated restoration alternatives (Elmore et al. 2015; Null et al. 2017). However, to assist in prioritizing restoration efforts,~~ River restoration is ongoing in the Walker Basin and there is a clear need to understand small-scale stream temperature ranges in ~~various~~ different river features (e.g., beaver ponds~~pools~~, confluences)~~,~~ to identify thermal refugia and ~~temperature~~ barriers to migration~~, and to better interpret reach or watershed-scale model results~~.

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~~, which flows into Walker Lake~~. 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 ~~between~~ 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~~water~~ (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 ~~The abundance and distribution of native~~ LCT persist in less than 10% of their historical range because they are limited by warm stream temperatures, low streamflows, and low dissolved oxygen ~~in the Walker River~~ (Coffin and Cowan 1995; USFWS 2003). ~~Historically, the Walker River contained healthy populations of LCT (Coffin and Cowan 1995); however,~~ now ~~they persist in less than 10% of their historical range of the Walker River~~ 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 ~~(> 28 °C)~~ 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). ~~This has largely disconnected river and lake ecosystems.~~ 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~~research~~ 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

~~DTS and TIR field measurements estimated stream temperature ranges for various river reaches and features within these reaches at small-spatial scales in the Walker River during dry years. Measured data were 1) compared to River Modeling System v4 (*RMS*) modeled temperature estimates to corroborate model results and 2) used to highlight river features and locations that provided thermal barriers or refugia for native aquatic species like LCT. This section describes DTS and TIR data collection, the *RMS* streamflow and temperature model, statistical analyses between measured and modeled data, and methods applied to upscale model results to measured data by identifying river features like diversions, return flows, seeps, and beaver dams throughout the modeled reach.~~

3.1 Distributed Temperature Sensing (DTS) Data

DTS units measure temperatures ~~throughout a fiber optic cable~~ by sending a laser pulse down a fiber-optic~~the~~ cable and timing the return signal. Although the majority of the reflected energy ~~sent into the cable is reflected back at the~~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. ~~These changes in the back-reflected wavelength frequency are Raman-backscatter. Raman-backscatter is further split into two categories, Stokes backscatter, the longer wavelength reflection, and Anti-Stokes backscatter, the shorter wavelength reflection.~~ Temperatures along the cable are determined from the Stokes/Anti-Stokes ratio ~~, with changing wavelength amplitude depending on temperatures~~ (Selker et al. 2006).

A ~~silver~~ 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~~toward the downstream end of the DTS cable~~. 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. ~~In this installation, the DTS measured temperatures on Channel 1 that covered the length of fiber from the instrument to the damaged splice; and then Channel 2 measured temperatures for the same length, on the other fiber. This resulted in two temperature measurements at each data collection point along the cable.~~

The DTS was dynamically calibrated during deployment with 10 m of cable placed in three recirculated calibration baths. ~~, o~~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 ~~measured temperatures in calibration baths~~ 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 ~~compared the DTS data against thermocouple data and adjusted~~correct the DTS data based on the difference between the DTS and thermocouple temperatures~~to match the thermocouple data using a linear transformation~~. Post-collection processing used the single-ended explicit calibration method developed by Hausner et al. (2011). ~~First, sections of cable that were exposed to air were removed from the dataset.~~ 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. ~~Because tension on the DTS cable can result in erroneous temperature measurements (Hausner et al., 2011),~~ D~~d~~ata points were also removed if the temperature difference between the two instrument channels was >1 ºC b~~B~~ecause 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~~s~~) 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 ~~channel~~single-ended dataset. The single-ended dataset ~~channel~~ with the lowest calibrated RMSE was used for data analysis and results. In addition, RMSE was~~s were~~ calculated between ~~the~~ georeferenced iButton stream temperature measurements and the corresponding georeferenced DTS stream temperature measurements for the ~~entire~~ 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. ~~Survey data georeferenced the DTS cable and estimated 10 cm contours of streambed~~

~~bathymetry.~~ 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 °C at the East Walker River and 37.9 °C 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. ~~(2012)~~ 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 ~~and~~ measured surface stream temperatures for 240 river km in the East Walker, West Walker, and mainstem Walker Rivers to Weber Reservoir ~~on July 18 and 24 - 26, 2012~~ (Fig. 1). A FLIR Systems, Inc. SC6000 sensor (wavelength of 8-9.2 µm, Noise Equivalent Temperature Differences of 0.035 °C, 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. ~~2012 was a dry year when snowpack was 50% of normal.~~

Watershed Sciences Inc. ~~(2012)~~ calibrated and~~,~~ georeferenced the data, and provided ~~it with~~raster layers of the data ~~summary points of TIR data,~~ and interpreted ~~the~~ 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, s~~S~~tream channel TIR temperatures were ~~summarized by~~ quer~~y~~ied~~ng temperature~~ at ten locations in the center of the channel and ~~reporting~~ the minimum, median, and maximum values were reported. ~~We refer to these interpreted temperatures as summary points throughout this paper. We completed analyses with both the georeferenced TIR data with all pixels and the summary points and the results. They were nearly identical.~~ 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. ~~Watershed Sciences Inc. (2012) reported stream temperature accuracy of 0.5 °C or better for TIR imagery.~~ TIR data were collected on warm summer days with low humidity. Average air temperature during data collection was 33.1 °C 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 ~~that make up~~over the model extent were 300 m ~~modeled reach spatial resolution~~in length. ~~Based on underlying modeling assumptions~~As a 1-dimensional model, each reach wa~~i~~s completely mixed and had~~s~~ a homogenous temperature~~ throughout the reach~~. Walker River modeled extent included~~s~~ 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 ~~and Comparison to *RMS* Outputs~~Data Analyses

3.4.1 DTS Data Analysis

DTS ~~each~~ minimum, maximum, and average stream temperatures were calculated for each 15 minute DTS sample event, day, and for the ~~entire~~ deployment period for both DTS sites (Table 1). ~~The 15 minute reach average temperature was calculated as the spatial average of the temperature measured at each 1 m DTS sampling point.~~ Day and deployment period reach average temperatures were calculated from the 15 minute spatial average following Eq. 1:

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

where $\bar{T}_{t,r}$ $\cancel{TSavg_{t,r}}$ is the ~~reach~~ average temperature for time, t, and $\bar{T}_{i,r}$ $\cancel{TS_{avg,i,r}}$ is the 15 minute event, i, ~~spatial~~ average~~d~~ for ~~reach~~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 ~~reach~~site, r, $Ts_{max,i,r}$ ~~is maximum measured temperature for 15 minute events, i,~~ and $Ts_{min,i,r}$ are the maximum and ~~is~~ minimum measured temperature for 15 minute events, i, and ~~reach~~site, r, *respectively*. Time in Eq. 2 was day, d, or deployment period, p.

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

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

~~where $Ravg_{t,r}$ is the average reach temperature range for time, t, $Ts_{max,i,r}$ is maximum measured temperature for 15 minute events, i, and $Ts_{min,i,r}$ is minimum measured temperature for 15 minute events, i, and reach, r. Time in Eq. 3 was day, d, or deployment period, p.~~

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. ~~Lateral~~ One m ~~reache~~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 extent~~reache~~s. 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~~is~~ analyse~~i~~s.

3.4.2 TIR Data Analysis

~~TIR temperature measurements were also compared with modeled temperatures for the Walker River from Bridgeport and Topaz Reservoirs to Weber Reservoir over three days in July 2012 when TIR data was collected.~~ 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~~3~~ 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 ~~for each 300 m modeled reach~~ was calculated for the East Walker, West Walker, and mainstem Walker Rivers following Eq. 4:

$$\bar{T}\cancel{TSavg}_{L} = \frac{\sum_{j=1}^{L}(\cancel{T}\bar{T}\cancel{s_{avg}}_{,r})}{L} \qquad (4)$$

where $\bar{T}\cancel{TSavg}_{L}$ is average TIR stream temperature for the length of the East, West, or mainstem Walker River, L, ~~spatially averaged temperature~~ and $\bar{T}\cancel{Ts_{avg}}_{,r}$ is the mean of summary point median TIR stream temperatures for ~~the~~each 300 m ~~model~~ed reach, r, (i.e., the average 300 m modeled reach temperature) because TIR summary points reported minimum, maximum, and median temperatures only. ~~River length, L, in Eq. 4 was the East Walker, West Walker, and mainstem Walker Rivers.~~

The spatial average of the TIR stream temperature range ~~within each 300 m modeled reach~~ for the East Walker, West Walker, and mainstem Walker Rivers was calculated following Eq. 5:

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

where $\bar{R}\cancel{Ravg}_L$ is the ~~river, L,~~ spatially averaged TIR~~?~~ temperature range for river length ~~of river~~, 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 ~~between~~ for ~~the~~ average 300 m ~~modeled reach~~TIR temperatures~~,~~ ~~$\bar{T}_r$ $Ts_{avg,r}$,~~ and the corresponding modeled temperatures to quantify differences. The percentage of time when modeled temperatures ~~, $T_{mod,toh,r}$,~~ were outside of measured temperatures~~, $T_{mod,toh,r} < Ts_{min,r}$ and $T_{mod,toh,r} > Ts_{max,r}$,~~ 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

~~In addition, hourly reach minimum and maximum top of the hour DTS temperatures, $Ts_{min,toh,r}$ and $Ts_{max,toh,r}$, respectively, were compared to hourly modeled Walker River stream temperatures, $T_{mod,toh,r}$, to quantify the thermal range not captured within the one-dimensional modeling. The percentage of time when modeled temperatures were outside of measured temperatures, $T_{mod,toh,r} < Ts_{min,toh,r}$ and $T_{mod,toh,r} > Ts_{max,toh,r}$, was also calculated. RMSE, mean absolute error (MAE), and mean bias between the spatial average for the top of the hourly DTS temperatures and hourly modeled temperatures summarized differences between modeled and measured 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. ~~To assess model performance during these critical temperatures for trout w~~We calculated the percent of the dataset ~~when~~that DTS and TIR data exceeded temperature thresholds ~~are exceeded~~ and that the model ~~is~~ over-or under-predicted~~ing~~ 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.

~~To extrapolate model outputs that provide a uniform estimate of stream temperature for each 300 m modeled reach, measured DTS and TIR temperature ranges at r~~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 ~~were applied to the~~~~compared to~~ ~~model outputs~~ ~~to~~ provide an estimate of small-spatial scale variability within each 300 m modeled reach. We used this information with the model results ~~for each reach to This provided an~~to estimate ~~of~~ spatial variability missing in ~~the~~ model output that is needed to ~~gain insight into~~identify potential habitat availability at smaller-spatial scales. ~~However,~~ river~~key features must be identified throughout the area of interest to determine where to apply the estimated variability.~~ Diversion and return flow locations were ~~developed~~ 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 ~~larger and thus~~ 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). ~~; however, w~~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 a~~we~~re more abundant in the Walker River during dry years, when high flow events that limit beavers ability to dam across the stream channel a~~we~~re reduced (Nevada Department of Wildlife, 2016).

4 Results

4.1 DTS Measured Stream Temperatures and Ranges

~~Temperature differences were observed between DTS channels, potentially from stress on the cable.~~ DTS ~~Channel 2 had the lowest RMSE values, with a~~Average RMSE between calibrated DTS data and the three reference temperatures was~~of~~ 0.09 ºC and 0.15 ºC for~~at~~ the East Walker River and mainstem Walker River DTS sites, respectively (Table S1). ~~iButton stream temperature measurements provided an additional test of DTS measurements.~~ Average DTS error for both sites was also within the 0.5 ºC precision of the iButtons. ~~iButton residuals vs. DTS temperatures showed that iButtons measured warmer temperatures than the DTS for the East Walker River, although the average bias for all iButtons was 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 ~~data show consistent colors longitudinally, indicating more~~had consistent temperatures ~~through the length of the reach for sampled time periods~~longitudinally (Fig. 2). The deployment period minimum stream temperature was 16.7 °C and maximum temperature was 24.9 °C ~~and occurred between 6:15 and 8:30 am~~(Table 2). ~~Deployment period maximum temperature was 24.9 °C and occurred between 5:00 and 5:30 pm.~~ Daily maximum temperatures were measured in a straight, homogenous, unshaded section (Fig. 3~~a~~). ~~The daily minimum reach temperature range occurred between midnight and 8:15 am, while daily maximum reach temperature range occurred between 1:00 and 3:00 pm (Table 2).~~ Reach stream temperature range for~~of~~ 15 minute collection events extended from a minimum of 0.5 °C to a maximum of 2.0 °C for the deployment period, with an average of 1.0 °C. 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~~a~~).

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 ~~(a) and 15 minute temperature range during DTS deployment (b)~~. Modeled reach points represent the division between 300 m modeled reaches.

Stream temperatures varied spatially throughout the mainstem ~~Walker River~~site, ~~which are apparent~~visualized as longitudinal color striations at different locations ~~longitudinally~~ in Figure 2b. Average reach temperature ~~for 6/25/15 – 6/30/15~~ was 25.2 °C, not including the Wabuska Drain segment (Table 2, excluding distance 110 – 175 m in Fig. 2b). ~~Deployment m~~Maximum stream temperature was 32.9 °C ~~and daily maximum stream temperatures occurred between 2:15 and 4:30 pm~~. ~~The daily maximum reach temperature range occurred between 2:00 to 3:45 pm, roughly the same time as daily maximum stream temperatures were observed.~~ The average reach temperature range for the deployment was 2.7 °C, with a minimum reach temperature range of 1.1 °C and a maximum reach temperature range of 7.0 °C. ~~Daily minimum reach temperature ranges occurred around 9:30 am.~~

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~~d~~ because reach scale temperature variability was greater than localized variability in areas like the Wabuska Drain. ~~little because they occurred in the mainstem Walker River.~~ However, the maximum 15 minute reach temperature range for the deployment increased considerably from 7.0 °C to 10.2 °C and average reach temperature range for the deployment also increased from 2.7 °C to 3.6 °C (Table 2, Fig. 2b). ~~Temperature range increase~~d~~s with the inclusion of the Wabuska Drain because it contained cooler water during hot times of the day, providing a lower~~ cooler ~~minimum temperature than observed in the mainstem Walker River.~~ Figure 4 illustrates the cooling effect of the Wabuska Drain and the spatial temperature variability during daily maximum stream temperatures on July 29th ~~at 3:15 pm.~~ ~~Because daily minimum and maximum temperatures did not change, but the reach temperature range increased with the inclusion of the Wabuska Drain, the Wabuska Drain likely receives cool groundwater inputs which pool in the canal without lateral mixing with warmer water in the mainstem river (Fig. 2b and Fig. 4a). This allows Wabuska Drain to provide a cool water refuge from the hot temperatures in the mainstem during the day when agricultural return flows are limited and water in the drain is likely dominated by groundwater inflow. The cool water preserved in Wabuska Drain increased reach temperature range during hot times of the day, driving the increase in observed daily maximum reach temperature range and daily average reach temperature range.~~

Figure 4: Mainstem Walker River daily maximum stream temperature on June 29, 2015 at 3:15 pm ~~(a) and 15 minute temperature range during DTS deployment (Wabuska Drain temperatures are not included) (b)~~. Model reach points represent the division between 300 m model reaches.

~~Figure 4 illustrates the cooling effect of the Wabuska Drain and the spatial temperature variability during daily maximum stream temperatures on July 29th at 3:15 pm.~~ The coolest temperature at~~in~~ the mainstem Walker River DTS site was 24.4 °C and occurred approximately 20 m into Wabuska Drain (Fig. 4~~a~~). Warm stream temperatures of up to 31.8 °C occurred in the homogeneous mainstem Walker River segment just upstream of the Wabuska Drain ~~outlet~~ 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. ~~In addition, c~~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. ~~Stream temperatures 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 °C and thus may be thermal barriers to fish passage during summer afternoons.~~

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 ~~reach~~ 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~~a~~). The warmer temperatures occurred in an unshaded, shallow, backwater location subject to ~~lower heat capacity~~ ~~increased~~ solar warming ~~increased solar heating~~. ~~Cooler temperatures occurred in the pool created by the dam, making the deeper pool a potential temperature refuge for fish.~~

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 ~~improved~~ continuous ~~spatial resolution at one hour for~~ surface stream temperatures throughout~~in~~ the Walker River for one hour. Maximum stream temperatures typically occurred in reaches with canal diversions and return flows. ~~Maximum~~ The warmest ~~reach~~ temperature in the East Walker River ~~of 26.5 ºC~~ (Table 3) ~~occurred~~ was 26.5 ºC at the Hall Diversion (River km 129) where water ponds at the diversion. ~~The m~~Maximum stream temperature ~~of 27.1 ºC~~ in the West Walker was 27.1 ºC and occurred upstream of the confluence with the mainstem Walker River. Maximum temperature in the mainstem Walker River was~~of~~ 29.2 ºC and occurred ~~in the reach immediately downstream of~~at the Wabuska Drain out~~return~~ flow (River km 78)~~, which may create temperature barriers for cold water species like LCT at some times~~. Although Wabuska Drain ~~was~~ received~~ing~~ agricultural returns during the TIR flight and therefore contributed~~ing~~ warm water, rather than the cool water observed during times ~~with limited~~without agricultural ~~returns~~runoff, ~~cooling of 1 ºC~~ the~~a~~ ~~over~~ 4.5 ~~river~~ km stretch of river downstream from the Wabuska Drain was 1 ºC cooler than the segment of river upstream of Wabuska Drain (Fig 5)~~observed downstream of the Wabuska Drain~~. This ~~response~~ may be due to ~~additional increased~~ 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 ~~increased~~ groundwater ~~influence~~ interactions may be less obvious when the return canal wa~~i~~s flowing, ~~the~~ 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 ~~that can~~and increase shallow groundwater contributions~~, and~~ and create~~ing~~ 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 ~~to~~ with locations ~~with~~ of canal diversions, return flows, and groundwater seeps (Fig. 6~~a~~). ~~TIR results at the basin-scale support DTS findings of increased temperature range at Wabuska Drain measured at the Stanley Ranch DTS deployment site (River km 78) (Fig. 5). 300 m reach temperature range was also larger i~~In the East Walker River, ~~at~~ the Fox/Mickey Diversion (River km 126), and Strosnider Diversion (River km 140) had large temperature ranges ~~(Fig. 5b)~~. In the mainstem Walker River, there was ~~more~~ 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). ~~TIR summary reports did not include the locations of beaver dams, and TIR surface temperatures are unable to capture thermal stratification of beaver dams and ponds. The m~~Maximum 300 m reach temperature range was 1.2 ºC 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 ~~(a) and summarized by river section (b, c, and d)~~ 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 refugiae at multiple spatial scales. We did not ~~use~~ calculate temperature ranges because pixels that contained some water and some riparian area ~~of the terrestrial environment~~ 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 ºC for the East and West Walker Rivers and 22.3 ºC for the mainstem Walker River.

4.3 *RMS* Predictions vs. Measured Temperatures

Model versus DTS data RMSE was 1.1 ºC in the East Walker River and 1.7 ºC in the mainstem Walker River (Table 4). When compared to TIR data, model RMSE and bias were both <1 ºC for the East and West Walker Rivers; however, the RMSE in the mainstem Walker River was 3.4 ºC and the bias was -2.5 ºC (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 ºC in the 300 m DTS reach over the five day study period and underestimated temperature by 0.5 ºC for the 77 km TIR extent. The model underestimated stream temperatures by 0.4 ºC from the average DTS values and underestimated stream temperatures by 2.5 ºC 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 ~~top of the hour~~ DTS and TIR stream temperature measurements.

~~Overall, *RMS* 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 (Table 4). TIR stream temperature measurements in the lower reaches of the mainstem Walker River were considerably warmer than simulated results and remain near LCT lethal thermal threshold for an additional 45 km than was previously estimated. The model performed similarly at measured temperatures above biologically significant temperature thresholds (Fig. 7). However, it is important to note that some of this error is due to measurement errors within the DTS and TIR observations. In particular, TIR data capture surface water temperatures, which may overestimate water column temperatures from vertical stratification and thermal boundary layer effects (Torgerson et al. 2001) and DTS data in shallow areas may be influenced by solar radiation penetration in the water column (Neilson et al. 2010).Predicted~~ Modeled temperatures in 2015 were warmer than DTS maximum ~~top of the~~ 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 ~~within a 300 m modeled reach~~ 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: ~~Top of the h~~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.

~~The RMSE for the DTS deployment length was 1.1 °C in the East Walker River and 1.7 °C in the mainstem Walker River (Table 4). Predicted temperatures were lower than TIR minimum temperatures within a 300 m modeled reach for 74%, 95%, and 87% of survey extent in the East Walker, West Walker, and mainstem Walker Rivers, respectively (Fig 6c-e, Table 4). Modeled temperatures were greater than the TIR maximum temperatures within a reach for 9%, 0%, and 8% of survey extent in the East Walker, West Walker, and mainstem Walker Rivers, respectively. The~~ a~~RMSE and bias were both <1 °C for the East and West Walker Rivers; however,~~ the ~~the RMSE in the mainstem Walker River was 3.4 °C and~~ the ~~bias was -2.5 °C (Table 4) where the model performed poorly under low flow conditions (Fig 6e). *RMS* temperature predictions were within the DTS measured temperature ranges 21% and 70% of the time for the East Walker River and mainstem Walker River, respectively. Predicted temperatures were within TIR measured temperatures 17%, 5%, and 5% of the time for the East Walker, West Walker, and mainstem Walker Rivers, respectively (Table 4). However, m~~M~~ainstem Walker River TIR stream temperatures versus modeled stream temperature is the only RMSE value that exceeded the calibrated *RMS* model RMSE (Table 5). Model bias for the East Walker River indicated the model over estimated stream temperature by 0.2 °C in the 300 m DTS reach over the five day study period and underestimated temperature by 0.5 °C for the 77 km TIR extent. The model underestimated stream temperatures by 0.4 °C from the average DTS valuesmeasured at the top of the hour and underestimated stream temperatures by 2.5 °C when compared to the TIR average temperature in the mainstem Walker River (Table 4).~~ 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

~~Interestingly, the model over estimated temperatures in the East Walker River with a bias of 0.2 ºC for the deployment period, but under estimated temperatures in the mainstem Walker River with a bias of -0.4 ºC for the deployment period (Table 4).~~

5 Discussion

5.1 Limitations

~~Obtaining small-scale spatial and temporal stream temperatures and comparing them to model results has a number of limitations. –~~DTS data collection limitations include cable drift, stress, and solar heating, which have been previously described in the literature ~~DTS data quality can be impacted by instrument drift during multi-day deployments and drift can be as large as 1-2 ºC from cable stress and rapid fluctuations in internal DTS temperature~~ (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~~hold~~ the DTS cable~~ in place and~~ ~~monitored DTS cables~~ ~~were~~ , which was monitored daily to minimize stress and reduce drift~~ and it was assumed that the DTS cable did not move during deployments~~. 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). ~~Deployments used leashes to hold the cable in place and minimize cable stress as much as possible; however, evidence of minimal cable stress was observed from different temperatures of the two DTS channels (Table S1). In addition,~~

Surface roughness, surface emissivity, surface reflection, variable background temperatures (e.g., sky versus trees), turbidity, changes in viewing aspect, aircraft type, flight speed, ~~and~~ 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. - ~~The length of time required to collect TIR imagery can also impact the quality of data because stream temperatures change during the course of the survey (Dugdale, 2016); this was minimized in this study by collecting all TIR imagery on warm, clear days with similar weather conditions.~~ W~~Unless noted, w~~e assumed a vertically mixed water column when analyzing the DTS and TIR data~~, which is again reasonable for advection-dominated streams~~. ~~However, the skin of the water surface can be a different temperature than the water column, potentially creating a source of error in TIR data . Additionally, p~~Pools and beaver dams may stratify vertically, increasing the local temperature variability from what was measured or predicted. Quantifying temperature range from vertical stratification wa~~i~~s 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, ~~the data spatial and temporal~~ resolution of information -varied~~s~~ between ~~y betweenamong~~ DTS data~~, and~~

TIR data, ~~datasets~~ and ~~with simulated model results~~modeled ~~data~~results, reducing the number of comparable observations. TIR imagery represents a single point in time unless flights are repeated~~.~~. DTS measurements we~~a~~re dense (1 m~~eter~~ in these deployments) with a 15 minute temporal resolution, but we~~a~~re 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 ~~small-scale thermal variability, or~~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 ~~longer~~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 ~~hott~~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 ~~within model reaches for the deployment~~ were nearly 2 °C greater in the mainstem Walker River than the East Walker River. ~~The East Walker River did not exceed the acute 28 °C temperature threshold for LCT and~~ 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. ~~These results confirm those of other studies showing that stream temperatures warm longitudinally during summer (Elmore et al. 2015).~~ 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). ~~Maximum DTS temperatures in the mainstem Walker River were 4.5 ºC warmer than the acute temperature threshold of 28 ºC for LCT (Dunham et al. 2003).~~

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 ~~during the entire year, particularly~~ outside of irrigation season ~~as groundwater levels decline~~ or ~~with groundwater depletion from~~during drought~~ condition~~s (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~~these~~ may be difficult for LCT to reach these refuges or they may be insufficient for cold water habitat. S~~S~~tream 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~~ and thus may be thermal barriers to fish passage during summer afternoons~~. 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 ~~study reaches~~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 ~~between Walker Lake and River~~ for cold water~~, migratory~~ 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 add~~ppli~~ed 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 ~~7~~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~~ranges~~ 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~~pplying~~ observed DTS and TIR temperature ranges from ~~DTS and TIR observations~~ 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 9~~7~~b).

Figure ~~7~~9: Locations of river features that affect stream temperatures in the Walker Basin (a). Warmest p~~P~~redicted *RMS* stream temperatures for June 29, 2015 (6:00 pm) with ~~average temperature change and~~ 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).

~~Previous research has shown that the Walker River has poor aquatic habitat as a function of streamflow, stream temperature, dissolved oxygen concentrations, food abundance, and substrate from the confluence of the East and West Walker Rivers to Walker Lake for LCT and other cold water species (Elmore et al., 2015; Hogle et al., 2014; Mehler et al., 2015; Null et al., 2017). However, those studies show 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 restoring suitable habitat in the lower Walker River (Hogle et al., 2014; Null et al., 2016, 2017).~~

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). ~~for whichwere24 °C, and 28 °C. Sededcould The model performed poorly in the wide channel and low flow conditions of the lower mainstem Walker River.~~ 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

~~5.4 Complementing Process-based Modeling with DTS and TIR Measurements~~

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 ~~R~~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 ~~C~~coupling high resolution stream temperature monitoring with process-based ~~modeling~~modelling, ~~makes~~s ~~model~~ simulations can help ~~more useful for~~ identify~~ing~~ 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 ~~measurement data~~observations. ~~Using DTS and TIR to~~ C~~c~~omparing DTS and TIR~~e~~ 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. ~~This research uses the Walker River to demonstrate how an~~

~~increased understanding of the temperature ranges present within modeled reaches can be used to interpret model results, supplying vital information for restoration decision makers.~~

~~6 Summary~~

~~Small-scale (micro-habitat) stream temperature ranges and timing were measured using DTS and TIR. Observations were coupled with an existing one-dimensional (300 m resolution) stream temperature model to identify temperature barriers and refuges at the watershed-scale. Stream restoration that maximizes cold water refugia mitigates warm stream temperatures to increase habitat quality and connectivity for native fishes. Understanding small-scale temperature ranges is useful to re-interpret watershed-scale stream temperature results and identify river features that provide thermal refugia or thermal barriers to migration. Beaver dams and return flow channels maximize temperature ranges and may mitigate warm stream temperatures. Restoration should maintain and enhance these features to improve aquatic habitat connectivity.~~

Acknowledgements:

This research was funded by the National Fish and Wildlife Foundation (grant number 2010-0059-201). The DTS was provided by the Center for Transformative Environmental Monitoring Programs (CTEMPs), funded by the National Science Foundation (award EAR 0930061). Thank you to Scott Tyler and Scott Kobs at the University of Nevada, Reno and Mark Hausner at the Desert Research Institute for DTS expertise and guidance. Thank you also to Nathaniel Mouzon, Kelley Sterle, Zack Arno, Hannah Friedrich, and Curtis Gray for field assistance, and to Brett Roper for feedback on an early version of this paper.

References

Bingham, Q. G., Neilson, B. T., Neale, C. M. U. and Cardenas, M. B.: Application of high-resolution, remotely sensed data for transient storage modeling parameter estimation, Water Resour. Res., 48(8), 1–15, doi:10.1029/2011WR011594, 2012.

Bond, R. M., Stubblefield, A. P. and Kirk, R. W. Van: Sensitivity of summer stream temperatures to climate variability and riparian reforestation strategies, J. Hydrol. Reg. Stud. J. Hydrol., 4, 267–279, doi:10.1016/j.ejrh.2015.07.002, 2015.

Brewitt, K. S., & Danner, E. M. (2014). Spatio-temporal temperature variation influences juvenile steelhead (Oncorhynchus mykiss) use of thermal refuges. Ecosphere, 5(7), 1-26.

Briggs, M. A., Lautz, L. K., McKenzie, J. M., Gordon, R. P. and Hare, D. K.: Using high-resolution distributed temperature sensing to quantify spatial and temporal variability in vertical hyporheic flux, Water Resour. Res., 48(2), 1–16, doi:10.1029/2011WR011227, 2012.

Cardenas, M. B., Doering, M., Rivas, D. S., Galdeano, C., Neilson, B. T. and Robinson, C. T.: Analysis of the temperature dynamics of a proglacial river using time-lapse thermal imaging and energy balance modeling, J. Hydrol., 519(PB), 1963–1973, doi:10.1016/j.jhydrol.2014.09.079, 2014.

Carrivick, J. L., Brown, L. E., Hannah, D. M. and Turner, A. G. D.: Numerical modelling of spatio-temporal thermal heterogeneity in a complex river system, J. Hydrol., 414–415(February), 491–502, doi:10.1016/j.jhydrol.2011.11.026, 2012.

Carroll, R. W. H., Pohll, G., McGraw, D., Garner, C., Knust, A., Boyle, D., Minor, T., Bassett, S. and Pohlmann, K.: Mason valley groundwater model: Linking surface water and groundwater in the walker river Basin, Nevada1, J. Am. Water Resour. Assoc., 46(3), 554–573, doi:10.1111/j.1752-1688.2010.00434.x, 2010.

Coffin, P. D. and Cowan, W. F.: Lahontan Cutthroat Trout Recovery Plan., 1995.

Cristea, N. C. and Burges, S. J.: Use of Thermal Infrared Imagery to Complement Monitoring and Modeling of Spatial Stream Temperatures, J. Hydrol. Eng., 14(10), 1080–1090, doi:10.1061/(ASCE)HE.1943-5584.0000072, 2009.

Deitchman, R. and Loheide, S. P.: Sensitivity of Thermal Habitat of a Trout Stream to Potential Climate Change, Wisconsin, United States, J. Am. Water Resour. Assoc., 48(6), 1091–1103, doi:10.1111/j.1752-1688.2012.00673.x, 2012.

Dickerson, B.R., Vinyard, G.L.: Effects of high chronic termperatures and diel temperature cycles on the survival and growth of Lahontan cutthroat trout. Transactions of the American Fisheries Society 128: 516-521, 2003.

Dugdale, S. J.: A practitioner's guide to thermal infrared remote sensing of rivers and streams: recent advances, precautions and considerations, Wiley Interdiscip. Rev. Water, 3(April), 251–268, doi:10.1002/wat2.1135, 2016.

Dugdale, S. J., Bergeron, N. E. and St-Hilaire, A.: Temporal variability of thermal refuges and water temperature patterns in an Atlantic salmon river, Remote Sens. Environ., 136(October 2014), 358–373, doi:10.1016/j.rse.2013.05.018, 2013.

Dunham, J., Schroeter, R. and Rieman, B.: Influence of Maximum Water Temperature on Occurrence of Lahontan Cutthroat Trout within Streams, North Am. J. Fish. Manag., 23, 1042–1049 [online] Available from: https://www.fs.fed.us/rm/pubs_other/rmrs_2003_dunham_j001.pdf (Accessed 20 July 2017), 2003.

Elmore, L. R., Null, S. E. and Mouzon, N. R.: Effects of Environmental Water Transfers on Stream Temperatures, River Res. Applic., 32(7), doi:10.1002/rra.2994, 2016.

Ficklin, D.L., Abatzoglou, J.T., Robeson, S.M., Null, S.E., Knouft, J.H. (2018). Naturla and managed watersheds show similar responses to recent climate change. PNAS, 115(34).

Frechette, D. M., Dugdale, S. J., Dodson, J. J., & Bergeron, N. E. (2018). Understanding summertime thermal refuge use by adult Atlantic salmon using remote sensing, river temperature monitoring, and acoustic telemetry. Canadian Journal of Fisheries and Aquatic Sciences, 75(11), 1999-2010.

Fullerton, A. H., Torgersen, C. E., Lawler, J. J., Steel, E. A., Ebersole, J. L., & Lee, S. Y. (2018). Longitudinal thermal heterogeneity in rivers and refugia for coldwater species: effects of scale and climate change. Aquatic sciences, 80(1), 3.

Gibson, P. P. and Olden, J. D.: Ecology, management, and conservation implications of North American beaver (Castor canadensis) in dryland streams, Aquat. Conserv. Mar. Freshw. Ecosyst., 24(3), 391–409, doi:10.1002/aqc.2432, 2014.

Google Earth Pro: Google Earth Pro (Version 7.3.1.4507), 2018.

Hare, D. K., Briggs, M. A., Rosenberry, D. O., Boutt, D. F. and Lane, J. W.: A comparison of thermal infrared to fiber-optic distributed temperature sensing for evaluation of groundwater discharge to surface water, J. Hydrol., 530, 153–166, doi:10.1016/j.jhydrol.2015.09.059, 2015.

Hauser, G. E. and Schohl, G. A.: River Modeling System v4-User Guide and Technical Reference, Norris, Tennessee., 2002.

Hausner, M. B., Suárez, F., Glander, K. E., Giesen, N. van de, Selker, J. S. and Tyler, S. W.: Calibrating Single-Ended Fiber-Optic Raman Spectra Distributed Temperature Sensing Data, Sensors, 11(12), 10859–10879, doi:10.3390/s111110859, 2011.

Herbst, D. B., Roberts, S. W. and Medhurst, R. B.: Defining salinity limits on the survival and growth of benthic insects for the conservation management of saline Walker Lake , , doi:10.1007/s10841-013-9568-6, 2013.

Hickman, T., Raleigh R.F. Habitat suitability index models: cutthroat trout. USDA Fish and Wildlife Service. (1982).

Hogle, C., Sada, D. and Rosamond, C.: Using Benthic Indicator Species and Communit Gradients to Optimize Restoration in the Arid, Endorheic Walker River Watershed, Western USA, River Res. Appl., 31(712–727), doi:10.1002/rra.2765, 2014.

Isaak, D. J., Luce, C. H., Rieman, B. E., Nagel, D. E., Peterson, E. E., Horan, D. L., Parkes, S. and Chandler, G. L.: Effects of climate change and wildfire on stream temperatures and salmonid thermal habitat in a mountain river network, Ecol. Appl., 20(5), 1350–1371, doi:10.1890/09-0822.1, 2010.

Isaak, D. J., S. Wollrab, D. Horan, and G. Chandler. "Climate change effects on stream and river temperatures across the northwest US from 1980–2009 and implications for salmonid fishes." Climatic Change 113, no. 2 (2012): 499-524.

Loheide, S. P. and Gorelick, S. M.: Quantifying Stream−Aquifer Interactions through the Analysis of Remotely Sensed Thermographic Profiles and In Situ Temperature Histories, Environ. Sci. Technol., 40(10), 3336–3341, doi:10.1021/ES0522074, 2006.

Lopes, T. J. and Allander, K. K.: Hydrologic Setting and Conceptual Hydrologic Model of the Walker River Basin, West-Central Nevada. [online] Available from: https://pubs.usgs.gov/sir/2009/5155/pdf/sir20095155.pdf (Accessed 19 May 2017), 2009.

Majerova, M., Neilson, B. T., Schmadel, N. M., Wheaton, J. M. and Snow, C. J.: Impacts of beaver dams on hydrologic and temperature regimes in a mountain stream, Hydrol. Earth Syst. Sci, 19, 3541–3556, doi:10.5194/hess-19-3541-2015, 2015.

McCullough, Dale A., John M. Bartholow, Henriëtte I. Jager, Robert L. Beschta, Edward F. Cheslak, Michael L. Deas, Joseph L. Ebersole et al. "Research in thermal biology: burning questions for coldwater stream fishes." Reviews in Fisheries Science 17, no. 1 (2009): 90-115.

Mehler, K., Acharya, K., Sada, D. and Yu, Z.: Factors affecting spatiotemporal benthic macroinvertebrate diversity and secondary production in a semi-arid watershed, J. Freshw. Ecol., 30(2), 197–214, doi:10.1080/02705060.2014.974225, 2015.

Mundy, E., Gleeson, T., Roberts, M., Baraer, M. and McKenzie, J. M.: Thermal Imagery of Groundwater Seeps: Possibilities and Limitations, Groundwater, 55(2), 160–170, doi:10.1111/gwat.12451, 2017.

Naranjo, R. C. and Smith, D. W.: Quantifying seepage using heat as a tracer in selected irrigation canals, Walker River Basin, Nevada, 2012 and 2013., 2016.

Neilson, B. T., Hatch, C. E., Ban, H. and Tyler, S. W.: Solar radiative heating of fiber - optic cables used to monitor temperatures in water, Water Resour. Res., 46(July 2009), 1–17, doi:10.1029/2009WR008354, 2010.

Nevada Department of Wildlife: Nevada Department of Wildlife Statewide Fisheries Management Federal Aid Job Progress Reports F-20-52 Western Region. [online] Available from: http://www.ndow.org/uploadedFiles/ndoworg/Content/Our_Agency/Divisions/Fisheries/East Walker River JPR 2016.pdf, 2016.

NFWF: Walker Basin Restoration Program, [online] Available from: http://www.nfwf.org/walkerbasin/Pages/home.aspx (Accessed 16 May 2018), 2018.

Niswonger, R. G., Allander, K. K. and Jeton, A. E.: Collaborative modelling and integrated decision support system analysis of a developed terminal lake basin, J. Hydrol., 517, doi:10.1016/j.jhydrol.2014.05.043, 2014.

Null, S. E., Mouzon, N. R. and Elmore, L. R.: Dissolved oxygen, stream temperature, and fish habitat response to environmental water purchases, J. Environ. Manage., 197, 559–570, doi:10.1016/j.jenvman.2017.04.016, 2017.

Pelletier, G. J., Chapra, S. C. and Tao, H.: QUAL2Kw – A framework for modeling water quality in streams and rivers using a genetic algorithm for calibration, Environ. Model. Softw., 21(3), 419–425, doi:10.1016/j.envsoft.2005.07.002, 2006.

Pépino, Marc, Katerine Goyer, and Pierre Magnan. "Heat transfer in fish: are short excursions between habitats a thermoregulatory behaviour to exploit resources in an unfavourable thermal environment?." Journal of Experimental Biology (2015): jeb-126466.

Poole, G. C. and Berman, C. H.: An ecological perspective on in-stream temperature: Natural heat dynamics and mechanisms of human-caused thermal degradation, Environ. Manage., 27(6), 787–802, doi:10.1007/s002670010188, 2001.

Roth, T. R., Westhoff, M. C., Huwald, H., Huff, J. A., Rubin, J. F., Barrenetxea, G., Vetterli, M., Parriaux, A., Selker, J. S. and Parlange, M. B.: Stream Temperature Response to Three Riparian Vegetation Scenarios by Use of a Distributed Temperature Validated Model, Environ. Sci. Technol., 44(6), 2072–2078, doi:10.1021/es902654f, 2010.

Seavy, N. E., Garadali, T., Golet, G. H., Griggs, T., Howell, C. A., Kelsey, R., Small, S. L., Viers, J. H. and Weigand, J. F.: Why Climate Change Makes Riparian Restoration More Important than Ever: Recommendatios for Practice and Research, Ecol. Restor., 27(3), 9, doi:10.3368/er.27.3.330, 2009.

Selker, J., Thévenaz, L., Huwald, H., Mallet, A., Luxemburg, W., Van De Giesen, N., Stejskal, M., Zeman, J., Westhoff, M. and Parlange, M. B.: Distributed fiber-optic temperature sensing for hydrologic systems, Water Resour. Res., 42(12), 1–8, doi:10.1029/2006WR005326, 2006a.

Selker, J., Giesen, N. Van De, Westhoff, M., Luxemburg, W. and Parlange, M. B.: Fiber optics opens window on stream dynamics, Geophys. Res. Lett., 33(December), 27–30, doi:10.1029/2006GL027979, 2006b.

Sharpe, S. E., Cablk, M. E. and Thomas, J. M.: The Walker Basin, Nevada and California: Physical Environment, Hydrology, and Biology. [online] Available from: https://www.dri.edu/images/publications/2007_sharpes_cablkm_etal_wbncpehb.pdf (Accessed 22 June 2016), 2008.

Stevens, B. S., & DuPont, J. M. (2011). Summer use of side-channel thermal refugia by salmonids in the North Fork Coeur d'Alene River, Idaho. North American Journal of Fisheries Management, 31(4), 683-692.

Suárez, F., Hausner, M., Dozier, J., Selker, J. and Tyler, S.: Heat Transfer in the Environment: Development and Use of Fiber-Optic Distributed Temperature Sensing, Dev. Heat Transf. [online] Available from: http://fiesta.bren.ucsb.edu/~dozier/Pubs/Heat-transfer-in-the-environment--development-and-use-of-fiber-optic-distributed-temperature-sensing.pdf, 2011.

Sutton, R. J., Deas, M. L., Tanaka, S. K., Soto, T. and Corum, R. A.: Salmonid Obersvations at a Klamath River Thermal Refuge Under Various Hydrological and Meteorological Conditions, River Res. Appl., 23(775–785), doi:10.1002/rra.1026, 2007.

Torgersen, C. E., Faux, R. N., McIntosh, B. A., Poage, N. J. and Norton, D. J.: Airborne thermal remote sensing for water temperature assessment in rivers and streams, Remote Sens. Environ., 76(3), 386–398, doi:10.1016/S0034-4257(01)00186-9, 2001.

Tyler, S. W., Selker, J. S., Hausner, M. B., Hatch, C. E., Torgersen, T., Thodal, C. E. and Schladow, S. G.: Environmental temperature sensing using Raman spectra DTS fiber-optic methods, Water Resour. Res., 45, 1–11, doi:10.1029/2008WR007052, 2009.

U.S. Fish and Wildlife Service (USFWS): Threatened Status for Three Species of Trout. [online] Available from: https://ecos.fws.gov/docs/federal_register/fr64.pdf (Accessed 20 July 2017), 1975.

U.S. Fish and Wildlife Service (USFWS): Short-term action plan for Lahontan cutthroat trout (Oncorhynchus clarki henshawi) in the Walker River Basin, Reno, NV., 2003.

U.S. Fish and Wildlife Service (USFWS): River Restoration Program, [online] Available from: https://www.fws.gov/lahontannfhc/dtlp/river-restore.html (Accessed 16 May 2018), 2017.

Vatland, S. J., Gresswell, R. E. and Poole, G. C.: Quantifying stream thermal regimes at multiple scales: Combining thermal infrared imagery and stationary stream temperature data in a novel modeling framework, Water Resour. Res., 51(1), 31–46, doi:10.1002/2014WR015588, 2015.

Walker Basin Conservancy: Walker Basin Conservancy, [online] Available from: http://www.walkerbasin.org/ (Accessed 16 May 2018), 2018.

Watershed Sciences Inc.: Airborne Thermal Infrared Remote Sensing Walker River Basin (Winter)., 2011.

Watershed Sciences Inc.: Airborne Thermal Infrared Remote Sensing Walker River Basin (Summer)., 2012.

Weber, N., Bouwes, N., Pollock, M. M., Volk, C., Wheaton, J. M., Wathen, G., Wirtz, J. and Jordan, C. E.: Alteration of stream temperature by natural and artificial beaver dams, edited by U. G. Munderloh, PLoS One, 12(5), e0176313, doi:10.1371/journal.pone.0176313, 2017.

Westhoff, M. C., Savenije, H. H. G., Luxemburg, W. M. J. ., Stelling, G. S., van de Giesen, N. C., Selker, J. S., Pfister, L. and Uhlenbrook, S.: A distributed stream temperature model using high resolution temperature observations, Hydrol. Earth Syst. Sci., 11(4), 1469–1480, doi:10.5194/hess-11-1469-2007, 2007.

Wurtsbaugh, W. A., Miller, C., Null, S. E., Derose, R. J., Wilcock, P., Hahnenberger, M., Howe, F. and Moore, J.: Decline of the world ' s saline lakes, , (October), doi:10.1038/NGEO3052, 2017.

Table 1: Description of stream temperature variables.

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