Response to Reviewers

Thank you to the reviewers and editor for careful review of our paper. We are confident that it will improve the paper. Below we provide detailed responses to every comment. Reviewers' comments are in black and our responses are in blue.

Authors Response to Reviewer 1

While this paper has made improvements from the previous version, there is still room for further improvements. Most of my line-by-line comments here are on improving comprehension for the reader. One way the authors could do this would be to relate the initial four objectives that are laid out to the methods and results sections. Some clear topic sentences and hand-holding sentences would go a long way in demonstrating how the organization of the paper is related to those topics.

We combined objectives 1 & 3 per your suggestion below. Then we re-organized methods and results and included subheadings that relate to each objective to clarify our work for readers. In doing this, we moved the sections about estimating thermal habitat and refugia connectivity (objective 3) from the discussion to the results. We also gave the paper a detailed read-through, adding segues and topic sentences to improve readability. Finally, we updated the title of the manuscript to reflect that focus changed away from river restoration and toward understanding thermal refugia with DTS, TIR and modeled datasets through the peer-review process.

Similarly, the figure captions could use more detail on which data is being presented, since there are many datasets it is easy to get lost as the reader.

We double checked all figure captions and clarified data sources where needed.

The paper still reads as a report summarizing findings of the methods, without clear hypothesis testing.

We removed extra details regarding DTS and TIR findings, focusing instead on methods and results that tie to our research objectives. We also rewrote the discussion to tie our findings to the literature and discuss thermal refugia in the Walker River for Lahontan cutthroat trout (see next comment).

Lastly, the authors did make an effort to summarize the data for LCT temperature ranges, but I think these analyses could be expanded. Can the authors calculate the spatial extent of different temperatures? How about the connectivity of cold-water patches? How does this build on previous work that has studied thermal refugia – are the features of thermal heterogeneity unique to this system, or have they been observed elsewhere?

We added the connectivity of thermal refugia in this basin (pg 13, ln 19-21): "The shortest distance between refugia, or cooler pockets of water, was 0.3 km, which was the spatial resolution of model reaches. The maximum distance between refugia was 37 km and occurred near Weber Reservoir in the mainstem Walker River. The mean distance between refugia was 2.8 km and the median distance was 0.9 km." We also rewrote the discussion to focus on how our research builds on previous work and highlight how our method quantifies thermal refugia connectivity using modeled and high-resolution measured data.

Abstract

-Could you include some of the results of how temperatures relate to LCT thermal tolerances in the abstract? This might broaden your readership and citations from that audience.

We revised the abstract to highlight LCT thresholds and thermal refugia results to broaden readership.

Introduction

Pg 2 Lines 20-21– Citation for this? Some small scale models do, but perhaps not at a watershed scale?

We added 'watershed-scale models' to qualify the sentence, and cited Null et al. 2017, who discuss these limitations of watershed-scale one-dimensional modeling.

Pg 2 Line 25 – remove 'spatial and' (redundant with point locations)
Done. Thank you.

Pg 3 Lines 13-14 – Can you use data to corroborate a calibration, or do you mean just corroborate the model (drop calibration)?
We removed the word calibration.

Pg 3 Lines 12-15 – As written, it is not clear to the reader at this point what the difference is between Objective 1 and Objective 3.
We combined objectives 1 & 3 into a single objective (#1). Our objectives now read (pg 3, ln 20 – 24): "The objectives of this study were to 1) evaluate stream temperature variability, quantified as the range of stream temperatures, at multiple spatial scales and by river feature using DTS and TIR imagery, 2) use those data to corroborate an existing one-dimensional, 300 m spatial resolution, watershed-scale stream temperature model, and 3) add measured, spatially explicit stream temperature ranges to model results by river feature to estimate thermal habitat and thermal refugia connectivity throughout a watershed."

Pg 3 Line 16 – further (type-o)
Fixed. Thank you.

Pg 3 Line 20 – You may mean barriers to movement or connectivity, rather than migration here ("migration" has very specific implications)
We changed 'migration' to 'movement'.

Pg4 Lines 2-3 –The "Walker River" in the first part of the sentences refers to which part of the river? (At what point in the watershed is the citation referring to/how does it differ from the "mainstem Walker River" in the second part of the sentence?
We omitted this part of the sentence as it is tangential. In general the mainstem Walker River is a losing system.

Pg 4 Lines 11-12 – This sentence might be improved with a little more context – e.g., measure stream temperatures exceeded the 28C threshold (frequently? In many places?) in the 2014-2015 summers, demonstrating that warming stream temperatures are a concern for LCT in the Walker basin.
We rewrote this sentence to read: "Measured mainstem Walker River stream temperatures exceeded the acute 28 °C temperature threshold for LCT throughout summer in 2014 and 2015, demonstrating that warming stream temperatures are a concern for LCT in the Walker Basin". (pg 4, ln 17 – 19)

Pg 4 Line 20 – Improve habitat conditions for who?
We added 'for Lahontan cutthroat trout and other aquatic biota' to this sentence.

Pg 5 Lines 7-9 – If none of your data was from these double-ended set of measurements, do you need to include this in methods?
We removed these sentences.

Fig S2 – Discharge on the Walker doubles from June 26 – June 28 – what was the reason for this change in stream flow?
There was no measurable precipitation during the DTS deployment. The change in streamflow was from upstream reservoir releases, which is described in the supplemental information.

Pg 6 Lines 12-14 – It's not clear what the summary points are, exactly, here. Which surface inflows were

considered, all of the tributary confluences and ditch return points?
We clarified this and it now reads "Watershed Sciences, Inc. also provided summary point data, which are minimum, median, and maximum temperatures of 10 pixels from the middle of the stream." (pg 7, ln 15 – 16)

Pg 7 Line 5-6 The restoration goal of water purchases is well described above, you could exclude it here
We removed this sentence.

Pg 7 Line 12 – details (plural)
Corrected.

Table 2 caption – It's not clear from the caption why data is presented from just afternoon/morning of different days, and what deployment/demobilization days are
We want to highlight that on some days data was not collected for the full day. We changed the caption to read "Daily stream temperatures and ranges for DTS deployments in the East Walker River (11:15 on 6/19/15 to 9:45 on 6/23/15) and mainstem Walker River (14:15 on 6/25/15 to 12:30 on 6/30/19)."

Pg 8 Line 8 – How did the flight times determine which data to use?
We removed that sentence as we think it is clear that modeled and TIR data at corresponding times and locations were compared.

Pg 9 Line 2 – Was percentage evaluated by time or space?
What about the spatial connectivity of suitable temperatures along a stream?
We changed wording to clarify: "The percentage of time that DTS and modeled stream temperatures were below 21 °C, 24 °C, and 28 °C, and the river extent that TIR and modeled stream temperatures were below the same thresholds were also calculated."

In the 2nd paragraph of section 4.4, we added results for the spatial connectivity of suitable temperatures along a stream: "Adding observed DTS and TIR temperature ranges from modeled results indicates that cool-water refugia may sometimes exist to support species migration between Walker Lake and tributaries of the Walker River (Fig 9b). The shortest distance between refugia, or cooler pockets of water, was 0.3 km, which was the spatial resolution of model reaches. The maximum distance between refugia was 37 km and occurred near Weber Reservoir in the mainstem Walker River. The mean distance between refugia was 2.8 km and the median distance was 0.9 km." (pg 13, ln 17-21)

Pg 12 Line 11 – Couldn't it be possible to edit out the pixels that contain riparian areas? Clip the buffers to the stream water extent? This would make your comparison of TIR closer to the other stream temp methods
There is substantial uncertainty as to where the water extent is. In other words, it is sometimes unclear whether pixels represent vegetation, shallow water, bare soil, or combinations of all three surfaces. We do not have visible imagery that corresponds to the same time period as the TIR imagery. It is thus a time-consuming exercise that will produce uncertain results. For that reason, we chose not to edit out riparian areas and focused on minimum temperatures instead.

Fig 8 – I find this stacked bar chart to be hard to interpret, personal preference.
We omitted Figure 8. The same information is presented in Table 5.

Pg 13 – Consider adding a section at the beginning of the discussion summarizing your key findings and interpretations, before diving right into limitations.

We moved the summary of our key findings to the first paragraph of the discussion to follow standard paper organization.

Authors Response to Reviewer 2

The authors have improved their manuscript according to all reviews, although I sometimes still have difficulties to distinguish the different statistical measures. Besides that, a couple of new issues have been raised as well, while every now and then I would like to see some more explanation about what exactly is done.

The main 'new' issue comes from the newly mentioned literature listed in the introduction on P2, L4-7. Although I am not familiar with this literature, it is stated here that already a lot is known about how, where and when refugia are needed. This means that this data could be applied to the results presented in this manuscript, but this is unfortunately not done. Instead, the authors state that (p16,L10-13) "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)." While the second part of this statement has apparently being done in the cited literature, the first part ("to validate temperature ranges by river feature at the watershed-scale") is done in this research. By connecting the two, you may get very valuable information about which restoration efforts are required to maintain a save passage for LCT. And such a quantitative analysis is also required to back-up all the suggested efforts listed just below this statement (P16, L14-24).

The literature cited in the introduction is generally species or system specific. We expanded this section of the introduction (4th paragraph of the intro) and clarified which species existing thermal refugia literature refer to. We have also rewritten the discussion to tie our results and findings into the literature. It is not always meaningful to apply existing thermal refugia connectivity (rather than needed thermal refugia connectivity) or assume that thermal refugia needs of Lahontan cutthroat trout are the same as other species studied. We make this clear in our revised discussion by highlighting how our research improves understanding of thermal refugia and how our method is a novel approach to analyze thermal refugia.

A second, slightly minor issue is that the author state that it is not possible to come up with maximum temperatures for the 50 and 300 m reaches of the TIR data due to the fact that part of the TIR data resembles the riparian zone. However, they also have the TIR summary points, which do report a maximum value for the 300 m reaches. So how are these maximum values obtained? At the same time I also wonder what causes the very small range in the TIR data compared to the DTS data (which is clearly visible in Fig. 7).
The summary points are explained page 7 ln 15-17: "Watershed Sciences, Inc. also provided summary point data, which are minimum, median, and maximum temperatures of 10 pixels from the middle of the stream. Flight speed, image overlap, and river features determined which images to sample (Watershed Sciences Inc., 2012)." This summary point method also explains why TIR data showed a smaller range of temperatures than the DTS data in Figure 7.

<u>Line by line comments:</u>
P1, L18: The abbreviation of DTS has not been defined yet
We added the acronym on P1, line 13.

P2, L22: rephrase: you cannot have fine spatial scales at point locations
We removed 'spatial' from this sentence.

P6, L6: How much time did it take to measure the whole stream? And how much would the temperature change over such a time period (you may get such an estimate from the temperature model).
We added another sentence (pg 7, ln 9-10): "Stream temperatures measured with temperature loggers warmed by 1 - 2 oC (average 1.6 oC) between 14:00 to 16:00 when TIR data were collected."

P6, L18: Was the average flow, the average over the TIR collection time?
We revised this sentence to clarify these were the average flows during the TIR data collection period.

P6 L32: Define which boundary conditions are needed
We specified that these are boundary condition streamflows.

P7, L19: Make clear that r refer to a 300m model reach and not to one of the two locations where DTS has been employed.
This refers to the DTS deployment site. To clarify, we changed the subscript for deployment site to s throughout the manuscript.

P8, L1: "One m extends…" ???
This was a typo. We changed it to read "For the 1 m comparison, we …".

P8, L12: I guess you mean the 'mean' instead of 'median'?
This is correct as we have written it. We used TIR summary points, which have data for minimum, median, and maximum stream temperatures. We then averaged the median values for each 300 m reach.

P8, L22-23: Do you mean outside the measured temperature range?
We corrected this sentence to say the 'measured temperature ranges'.

P10,L3: Explain what you mean with 'consistent temperatures'
We reworded this sentence to "Temperatures in the East Walker River changed more over time than over space."

P10,L5-6: This is Ti,r, isn't it? I suggest mentioning these parameters every time you report them, so the reader can easily go back to the methods to see which formula is used. Please do this throughout the manuscript. This will also help to see if all statistics parameters mentioned in section 3 are indeed used. Although I did not double check it, I don't recall to have seen values of Td,r.
We removed equations that were not used and included notation throughout the results section as recommended so that readers can easily go back to methods to see which formula is used.

P10,L25: cooling effect on what? It is indeed cooler in the drain than outside, but due to the limited length of observations downstream of the drain, it is hard to see any cooling effect here.
We changed wording to 'the cooler temperatures in the Wabuska Drain…'.
P11,L9: Do you mean that the temporal (e.g. daily) range of these features were large, or that they are locations with a distinctive lower/higher temperature than the mean spatial temperature of that specific range?

Good question – we meant the latter. We changed this sentence to read (starting pg 10, ln 32) “In the East Walker River site, deep pools and reaches with large wood structures were river features with distinctively lower temperatures than the rest of the river. In the mainstem Walker River, deep pools with riparian vegetation, beaver dams, and islands in the channel were river features that were cooler or warmer than spatially-averaged river temperatures.”

P11,L13: “for one hour”: I guess you mean "for a single point in time"?
We changed wording to ‘a single point in time’.

P11,L24-25: Such a firm statement requires some proof, which is missing here. A few lines before it was stated that it MAY be due to such shallow groundwater contributions.
In fact, don't these shallow groundwater contributions, which are caused by irrigation, consist of the same water as the return flows (and thus with a similar temperature)?
We qualified the statement by saying “ Thus, *monitoring suggests that* large diversions and return flows can create warm water conditions when active…”

Importantly, shallow groundwater and return flow contributions are from irrigation water; however return flow contributions are exposed to atmospheric conditions for longer (or a larger percentage of time once drained from fields) so temperatures may not be similar.

P12,L10: Maybe I misunderstood what has been compared here, but this statement implies that the minimum temperatures for all six 50 m reaches within a 300m reach should be the same. When looking at Fig. 5, this seems not to be the case with differences in minimum temperatures between the six 50m reaches of 1 or maybe 2 degrees C
The absolute minimum temperatures for the mainstem, East Walker, and West Walker Rivers do not change if lateral comparisons are for 50 m reaches or 300 m reaches. We have revised wording of this section to clarify this point. However, you bring up a good point that the average of the minimum temperatures vary for 50 m versus 300 m reaches. We added a sentence to highlight how this differs based on scale of analysis (pg 12, ln 6-9): “However, minimum temperatures varied among 50 m river segments than made up each 300 m river segment (Fig. 5). Thus, average minimum temperatures were 0.8 oC warmer when analyzing data at the 50 m scale than the 300 m scale. This highlights the extent to which spatial temperature variability varies by the scale of analysis.”

P13,L24-26: Please quantify this effect! In other words: what is the accuracy of this method?
The accuracy of our TIR data compared to temperature loggers was already included. We moved it to the first paragraph of TIR stream temperature results to highlight it (P11, ln 4-7): “*TIR data were within 0.5 °C of iButton sensors, except for one location in the East Walker River where redundant sensors were 1.7 °C and 3.3 °C cooler than radiant TIR temperature, and one location in the West Walker River where an iButton was 1.1 °C cooler than radiant TIR temperature. TIR measures water surface temperatures, so these discrepancies may have occurred where the river was not well mixed*.” It is outside the scope of this paper to quantify the effect of surface roughness, surface emissivity, surface reflection, variable background temperatures, turbidity, changes in viewing aspect, aircraft type, flight speed, wind gusts, and data collection time on TIR image and quality, but we would be remiss to not succinctly describe sources of data error in the limitations section.

P13,L31-32: I understand that this is outside the scope of this paper, but with some simple back-of-the-envelope calculations (e.g. a simple diffusion equation) it is possible to give an estimate or an upper limit of this stratification. This may also help to get an idea about the accuracy of the TIR data.

We disagree with this comment. Stratification is complex as it is a function of inflow velocities, orientation, slope, channel/pool geometry, as well as atmospheric influences including wind speed, air temperature, radiation penetration to the bed, bed conduction, groundwater inflows… To double check, we estimated stratification using pool geometry, thermocline heat transfer, and vertical diffusion. However, we had to make so many assumptions that stratification patterns and temperatures were not reliable estimates. Although we can come up with values, we have no reason to believe them and including them detracts rather than improves the paper.

P14,L7: "Future studies could collect data specifically to overlap in time and space": Please make clear what the gain is of doing so!
We changed this sentence to read (pg 14, ln 16-18): "Future studies could collect data specifically to overlap in time and space so that temperature distributions along the river are not affected by different years and sample periods."

P14,L18-19: "indicating that these methods complement each other": But it could also be that different periods result in different temperature distributions along the complete stream...
We added this thought to the manuscript. This sentence now reads (pg 14, ln 28-29): "… indicating that these methods complement each other, but also suggesting that different years may result in alternate temperature distributions along the river (Tables 2 and 3)."

P14,L32: "has poor aquatic habitat as a function of streamflow and stream temperature": What do you mean with this statement?
We revised this sentence to read (pg 15, ln 12-13): "Previous research has shown that the mainstem Walker River has low streamflows and warm stream temperatures that do not support LCT or other cold-water species …".

P15,L1-2: I am not familiar with those studies, but does this conclusion arises from results presented in this manuscript?
Or stated differently: Your results show that although the modelled stream water temperature may be too high, there are still places within each model reach that are colder (or cold enough). Can you subsequently use the findings of the studies listed here or in Line 4-7 of the introduction to indicate if these location for refugia are sufficient for LCT to survive?
We added the connectivity of thermal refugia in this basin (pg 13, ln 19-21): "The shortest distance between refugia, or cooler pockets of water, was 0.3 km, which was the spatial resolution of model reaches. The maximum distance between refugia was 37 km and occurred near Weber Reservoir in the mainstem Walker River. The mean distance between refugia was 2.8 km and the median distance was 0.9 km." We also rewrote the discussion to focus on how our research builds on previous work and highlight how our method quantifies thermal refugia connectivity using modeled and high-resolution measured data.

We also added a new 3rd paragraph to the discussion synthesizing temperature and thermal refugia needs for LCT.

P15,L11-12: Also here: Is it possible to connect your quantitative results with the studies described in L4-7 of the introduction. The same for L23-24 of this page
We have rewritten the discussion section and have done this. In particular, see the 3rd paragraph of the discussion.

P15,L19-20: I still don't understand what you mean: Is it a spatial temperature range that covers a 300 m modelling grid cell or is it a temporal range comparing day and night temperatures of the specific beaver dam?

We mean temperature variability over sampling event which were collected every 15 minutes. We reworded this section to read (pg 15, ln 5-7): “Beaver dams had especially high temperature variability, consistent with findings from Majerova et al. (2015) and Weber et al. (2017). A 7 oC temperature range was observed within a beaver dam in the mainstem Walker River during a DTS sampling event.”

P15,L30-32: Are these values compared to the mean temperature of the 300m reach, or do they reflect the maximum range? In case of the latter you cannot simply say that the coldest temperature within a model reach is this much colder, while in case of the former you have to make explicit that in Fig. 9 you assume that the modelled temperature is the 'correct' average of the whole stream segment.

These values are added to the simulated temperature of the 300 m modeled reach. We clarified this on pg 13, ln 11-12: “Measured DTS and TIR temperature ranges from return flows, diversions, beaver dams, and seeps were added or subtracted to perfectly-mixed, 300 m modeled reach stream temperatures to estimate thermal refugia connectivity.”

P16,L10-13: I don’t understand why future research is needed for this: In the introduction you stated that this literature studied this effect. So why can you not use their results to say something about the survival changes of LCT for the Walker stream. Eventually you may come up with advice on where extra refugia are needed.

And to be more strict: such a quantitative analysis should be done first before you can suggest the list of restoration efforts listed in the next paragraph (P16,L14-24)

We revised this section to be more specific about future research needs. It now reads (pg 15, ln 32-34): “Additional work is needed to understand the resiliency of streamflows and thermal refugia with interannual variability and with anticipated climate change.”

Fig. 2: In section 3.1, it is stated that ~400 m of cable is situated on either side of the river. So that means that the upper half of the plot should be more or less a mirror image of the lower half. So I think it is helpful if the flow direction is indicated in the graph, where the water is flowing to (or from) ~550m.

We added the flow direction to Figure 2 and labelled it as river right or river left.

Fig. 3: The purple dots indicate the borders of the 300m model reaches. However, the reach covered by the DTS cable is 400 (or 450). I understand there can be some kind of sinuosity in the cable, but a difference of 100 or 150 m seems rather large to me. To me it seems that the modelled stream reaches are too short and I am wondering which effect this has on the simulated stream water temperature.

Modeled stream reaches were delineated using 2011 river centerline. ArcGIS’ split command was used to split the line into segments of equal length (Elmore et al. 2016; Elmore 2015). The RMS model represents 300 km of river with 999 nodes, thus each modeled reach is 300.3 meters. It is possible that the channel shifted between the 2011 channel layer used in the model and the 2015 channel observed during the DTS deployment. However, the suggestion that modeled reaches were too short or that modeling was sloppy is baseless.

Fig. 6: I don’t understand the phrase “with the upstream-most river km on the left side of the x-axis”. The same phrase is present in the caption of Fig. 7, and there I have the feeling that the authors mean that in the graphs the water is flowing from left to right.

We changed the caption to read “Temperature range within each 300 m model reach from July 2012 TIR summary point data.”

Quantifying Thermal Refugia Connectivity by Combining Temperature Modeling, ~~Small-scale Temperature Variability using~~ Distributed Temperature Sensing, and Thermal Infrared Imaging ~~to Inform River Restoration~~

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Abstract. Watershed-scale stream temperature models are often one-dimensional because they require less data and are more computationally efficient than two- or three-dimensional models. However, one-dimensional models assume completely mixed reaches and ignore small-scale spatial temperature variability, which may create temperature barriers or refugia for cold water aquatic species. Fine spatial and temporal resolution stream temperature monitoring provides information to identify river features with increased thermal variability. We used ~~a~~ distributed temperature sensing (DTS) ~~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, t~~Thermal infrared (TIR) aerial imagery collected in summer 2012 quantified the spatial temperature variability ~~of river temperatures~~ throughout the Walker Basin. We coupled high resolution measured data with simulated stream temperatures to corroborate model results and estimate the spatial distribution of thermal refugia for Lahontan cutthroat trout. ~~Both the distributed temperature sensing data and thermal infrared aerial imagery were used to corroborate temperature model results.~~ Temperature model estimates were within the DTS measured temperature ranges 21% and 70% of the time for the East Walker River and mainstem Walker River, respectively, and within TIR measured temperatures 17%, 5%, and 5% of the time for the East Walker, West Walker, and mainstem Walker Rivers, respectively. DTS, TIR, and modeled stream temperatures in the mainstem Walker River nearly always exceeded the 21°C optimal temperature threshold for adult trout, usually exceeded the 24 ºC stress threshold, and could exceed the 28 ºC lethal threshold for Lahontan cutthroat trout. ~~Additionally, m~~Measured ~~data~~stream temperature ranges varied from -10.1 to +2.3 °C for agricultural return flows, -1.2 to +4 °C for diversions, -5.1 to +2 °C for beaver dams, -4.2 to 0 °C for seeps. ~~highlighted that b~~T~~eaver 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, t~~emperature ~~bounds from observations~~ranges ~~by river features~~ were added to ~~the longitudinal~~simulated stream temperatures ~~predictions~~at known river features. The average

distance between thermal refugia in this system was 2.8 km. W~~These results show that w~~hile ~~bulk~~ simulated stream temperatures are often too warm to support Lahontan cutthroat trout and other cold-water species, thermal refugia may exist to improve habitat connectivity and ~~passage for migratory species~~facilitate trout movement between spawning and summer habitats. Overall, ~~complementary~~ high resolution DTS and TIR measurements ~~identify~~ quantify temperature ranges of ~~thermal~~ refugia and augment process-based modeling.

1 Introduction

Trout and salmon avoid heat stress by sheltering in thermal refugia, or 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, w~~Where stream temperatures are warming or where cold-water fish species are at the southern extent of their range, measuring stream temperatures at small temporal and spatial scales is important to quantify thermal refugia and stream temperature heterogeneity (Vatland et al. 2015). One-dimensional stream temperature models estimate longitudinal stream temperature changes at the watershed-scale, but are poor predictors of thermal micro-habitats. On the other hand, high resolution temperature monitoring provides micro-habitat information, but is typically conducted over small spatial extents and thus difficult to extrapolate to the watershed scale for management and restoration decisions.

Stream temperature models are useful for river management because they help decision makers understand stream temperature dynamics and the potential impacts of restoration and management. Many one-dimensional temperature models exist, and have been applied to understand temperature effects of dams, reservoir re-operation, climate change, and restoration in systems all over the world (e.g., Bond et al., 2015; Elmore et al., 2016; Pelletier et al., 2006). Stream temperature models used in management are often one-dimensional because they are less data intensive and more computationally efficient than two- or three-dimensional models that account for temperature variability over channel width and depth. However, one-dimensional watershed-scale models do not identify ~~small-scale~~river features like cold water pools, lateral variability, or groundwater seeps that are smaller than model spatial resolution ~~like cold water pools, lateral variability, or groundwater influenced areas~~ (Null et al. 2017).

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

~~2017). TIR imagery similarly captures spatially-continuous stream surface temperatures. However, TIR data are for a single point in time unless acquired on multiple occasions (Dugdale, 2016; Torgersen et al., 2001).~~

DTS) and thermal infrared (TIR) are sometimes used in conjunction with stream temperature models. DTS provides near-continuous temperature measurements in both time and space (Selker et al. 2006; Suárez et al. 2011). Raman spectra DTS is capable of measuring temperatures every meter along fiber-optic cables with an accuracy of at least ±0.1 ºC (Tyler et al., 2009), and cables vary between approximately 1 – 10 km. 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). DTS data were used to calibrate and validate a 1.3 km physically-based, one-dimensional stream temperature model of the Boiron de Morges River in southwest Switzerland (Roth et al. 2010) and a 580 m river reach in Luxembourg's Maisbich River (Westhoff et al. 2007). TIR imagery ~~similarly~~ capture spatially-continuous stream surface temperatures and ~~.~~ have successfully identified spatial heterogeneity (Bingham et al., 2012; Fullerton et al. 2018) and located groundwater and tributary inputs (Dugdale et al., 2013; Loheide and Gorelick, 2006; Mundy et al., 2017). However, TIR data are for a single time unless acquired on multiple occasions (Dugdale, 2016; Torgersen et al., 2001). 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.

Recent research has quantified when and where fish use thermal refugia, although results are system or species specific. For example, in the Pacific Northwest and northern California, thermal refugia are generally 2.7 – 13 km long and are spaced approximately 5.7 – 49.4 km apart using TIR data with spatial resolution of at least 250 m (Fullerton et al., 2018). Authors emphasized that this is the existing refugia distribution, not necessarily the distribution that is needed to support migratory fish. Doubling the frequency of thermal refugia increased the abundance of rainbow trout and Chinook salmon, while doubling refuge area had only minor improvements for rainbow trout abundance (Ebersol et al., 2003). Brewitt and Danner (2014) showed that 80 % of juvenile steelhead move into refuges when stream temperatures are 22 – 23 °C, and all move when stream temperatures exceed 25 °C. Similarly, adult Atlantic salmon thermoregulate body temperature by using large, stratified pools with temperatures of 17 – 19 °C (Frechette et al., 2018). Westslope cutthroat trout that were larger than 300 mm used side channels that were cooler than 20 °C and deeper than 2 m, although smaller fish were less likely to use thermal refugia (Stevens and DuPont, 2011). Brook char that leave cool water refugia for less than 60 minutes to forage maintained body temperatures below critical thresholds. Thus, short excursions allowed fish to forage during long periods of unfavourable stream temperatures (Pepino et al., 2015). To date, no studies have used DTS and TIR to quantify temperature ranges by river feature within model reaches, and use that information to estimate likely temperature ranges over space and time at the watershed scale. Such insight into ~~small-scale responses~~micro-habitats allows researchers, managers, and stakeholders to identify thermal refugia and estimate potenital temperature range by river feature. ~~micro-habitats and further interpret one-dimensional basin-scale model results.~~

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

2 Study Site

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

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

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

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

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

3 Methods

3.1 Distributed Temperature Sensing (DTS) Data

3.1.1 DTS Data Collection

DTS units measure temperatures by sending a laser pulse down a fiber-optic cable and timing the return signal. Although most of the reflected energy has its original wavelength, a portion of the energy is absorbed and re-emitted at both shorter (Anti-Stokes backscatter) and longer (Stokes backscatter) wavelengths. Temperatures along the cable are determined from the Stokes/Anti-Stokes ratio (Selker et al. 2006). A 1 km silver armored DTS cable was deployed to measure diurnal stream temperatures in the mainstem and East Walker Rivers. Data were collected over 400 m in the East Walker River at Rafter 7 Ranch on June 18-23, 2015 and over 450 m in the mainstem Walker River at Stanley Ranch on June 25-30, 2015 (Fig. 1). 2015 was a dry year when snowpack was 5% of normal. The DTS cable was deployed in a U shape at both sites, with approximately 400 m of cable on each side of the stream to capture lateral stream temperature differences. The cable was suspended in the water column approximately 10 cm above the streambed with steel stakes and leashes. Mainstem Walker River DTS deployment included approximately 20 m of a flood irrigation return flow canal named the Wabuska

Drain. The Wabuska Drain was not flowing during the drought when the DTS was deployed, but contained standing water and was connected with the Walker River.

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

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

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

3.1.2 DTS Data Analysis

DTS minimum ($Tmin_{i,s}$), maximum ($Tmax_{i,s}$), and site-averaged stream temperatures ($TBAR_{i,s}$) were calculated for each 15 minute DTS sample event, *i*, at each DTS site, *s* (Table 1). Deployment period average temperatures were calculated from the 15 minute spatial average following Eq. 1:

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

where $\bar{T}_{p,s}$ is the average temperature for deployment period, *p*, at deployment site, *s*.

Table 1: Description of stream temperature variables.

The temperature range of each DTS deployment site for a 15 minute DTS sample event ($R_{i,s}$), and deployment period ($R_{p,s}$) was calculated by subtracting the minimum measured temperature ($Ts_{min,i,s}$) from the maximum measured temperature ($Ts_{max,i,s}$) for the 1000 m DTS cable. The minimum 15 minute temperature range for each site ($R_{min,i,s}$) and maximum temperature range for each site ($R_{max,i,s}$) were also calculated. The deployment period average DTS stream temperature ranges ($\bar{R}_{p,s}$) were calculated from the 15 minute events for each DTS site following Eq. 2:

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

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

3.2 Airborne Thermal Infrared (TIR) Data

3.2.1 TIR Data Collection

TIR imagery of the Walker River was collected by Watershed Sciences Inc. on November 16-17, 2011 (winter flight) and July 18 and 24-26, 2012 (summer flight) (Watershed Sciences Inc., 2011; 2012). 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. TIR flights measured surface stream temperatures for 240 river km in the East Walker, West Walker, and mainstem Walker Rivers to Weber Reservoir (Fig. 1). Stream temperatures warmed by 1 to 2 ºC (average 1.6 ºC) between 14:00 to 16:00 when TIR data were collected. A FLIR Systems, Inc. SC6000 sensor (wavelength of 8-9.2 µm, Noise Equivalent Temperature Differences of 0.035 ºC, and pixel array of 640 x 512 at a 14 bit encoding level) mounted on the underside of a Bell Jet Ranger Helicopter collected imagery, and was flown at an altitude of approximately 610 m. Pixel resolution was 0.6 m (Watershed Sciences Inc., 2012). ~~We used summer TIR data for all analyses in this paper, except to identify possible cool-water seeps, which were more apparent with the winter dataset.~~

Watershed Sciences Inc. calibrated and georeferenced the data, and provided raster layers of the data. Surface inflow temperatures were reported at their confluence with the Walker River. Watershed Sciences, Inc. also provided ~~and interpreted TIR imagery, which we refer to as~~ summary point datas, which are minimum, median, and maximum temperatures of 10 pixels from the middle of the stream. ~~Surface inflow temperatures were reported at their confluence with the Walker River. For the summary points, stream channel TIR temperatures were queried at ten locations in the center of the channel and the minimum, median, and maximum values were reported.~~ Flight speed, image overlap, and river features determined which images to sample (Watershed Sciences Inc., 2012). We ~~completed analyses with the~~used georeferenced TIR rasters and ~~the~~ summary points for analyses. TIR data were collected on warm summer days with low humidity. Average air temperature during data collection was 33.1 ºC and average wind speed was 11.6 km per hour (kph) in Yerrington, NV. Average flow during data collection 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 details.

3.2.2 TIR Data Analysis

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

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. TIR pixels that included streambanks or vegetation were warmer than the river and skewed temperature range, average temperature, and maximum temperature zonal statistics. Thus, we compared zonal statistics for minimum pixel temperatures at the 50 m and 300 m scales. Extents smaller than 50 m did not always span the river channel laterally.

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 River Modeling System (*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 condition streamflows 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. Water quality o~~O~~utputs 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 river km ~~of the East Walker, West Walker, and mainstem Walker Rivers~~ were represented in *RMS* at an hourly time step. Model reaches over the model extent were 300 m ~~in length~~long. As a 1-dimensional model, each reach was completely mixed and had a homogenous temperature. Walker River modeled extent included the East Walker River downstream of Bridgeport Reservoir (river km 243 to 117), the West Walker River downstream of Topaz Reservoir (river km 60 to 0) and the mainstem Walker River to Walker Lake (river km 117 to 0) (Fig. 1). For additional model details see Elmore et al. (2016) and Null et al. (2017).

~~3.4 Temperature Range Data Analyses~~

~~3.4.1 DTS Data Analysis~~

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

~~(1)~~

~~where~~

~~is the average temperature for time, *t*, and~~

~~is the 15 minute event, i, averaged for site, *r*. Time, *t*, in Eq. 1 was day, *d*, or deployment period, *p*.~~

~~Table 1: Description of stream temperature variables.~~

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

~~(2)~~

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

~~The daily and deployment period average DTS stream temperature ranges (~~

~~) were calculated from the 15 minute events for each DTS site following Eq. 3:~~

~~(3)~~

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

~~*3.4.2 TIR Data Analysis*~~

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

~~(4)~~

~~where~~

~~$_L$ is average TIR stream temperature for the length of the East, West, or mainstem Walker River, L, and~~

~~$_r$ is the mean of summary point median TIR stream temperatures for each 300 m reach, r, (i.e., the average 300 m modeled reach temperature) because TIR summary points reported minimum, maximum, and median temperatures only.~~

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

~~(5)~~

~~where~~

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

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

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

3.~~4.~~3 Comparison of Measured and~~to~~ Modeled Data

We calculated the percentage of time that the model over- or under-predicted DTS temperatures and the percentage of space that the model over- or under-predicted TIR temperatures to quantify the thermal range not captured within one-dimensional modeling. We used hourly DTS measurements so that data were not temporally auto-correlated and omitted Wabuska Drain temperatures so DTS data were comparable to model results. TIR data were averaged for 300 m reaches to compare to modeled results. RMSE, mean absolute error (MAE), and mean bias summarized differences between modeled and measured data.

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

~~RMSE, mean absolute error (MAE), and mean bias between the spatial average for the hourly DTS and modeled temperatures summarized differences between modeled and measured data.~~

Measured DTS and TIR temperature ranges for river features like return flows, diversion, beaver dams, and seeps provided estimates of small-spatial scale variability. ~~River features like a~~Agricultural return flows, diversions, beaver dams, and seeps were georeferenced ~~so that~~and the modeled reach that contained those features ~~could be~~was identified. ~~Measured DTS and TIR temperature ranges provide an estimate of small-spatial scale variability within each 300 m modeled reach.~~ W~~W~~e ~~used this information with~~added or subtracted measured temperature ranges to~~ the~~ modeled temperatures~~ results~~ at georeferenced river features to estimate spatial variability missing in model output~~ that is needed to identify potential habitat availability at smaller spatial scales~~. Diversion and return flow locations were identified in 2012 by the Walker Basin Project (Tim Minor, pers.comm, 2012). Seeps were identified during TIR surveys from cooler stream temperatures that could not be attributed to shadows, cutbanks, or vegetation (Watershed Sciences Inc. 201~~2~~1). We used seep locations identified during the winter TIR flight completed on November 16-17, 2011 because temperature differences were more obvious than the summer flight and some of the locations with groundwater seeps in the winter were dry during the summer flight (Watershed Sciences Inc., 2011; 2012). We applied the temperature range observed at seeps during the summer 2012 TIR flight (Watershed Sciences Inc. 2012).

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

4 Results

4.1 DTS Measured Stream Temperatures and Ranges

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

Temperatures in the~~he~~ East Walker River ~~DTS site had consistent temperatures longitudinally~~changed more through time than through space (Fig. 2). The deployment period minimum stream temperature (Tmin_i) was 16.7 ºC and maximum temperature (Tmax_i) was 24.9 ºC (Table 2). ~~Daily m~~Maximum temperatures were measured in a straight, homogenous, unshaded section (Fig. 3). ~~Reach s~~Stream temperature range for 15 minute collection events (R_i) ~~extend~~varied from a minimum of 0.5 °C to a maximum of 2.0 °C for the deployment period, with an average (RBAR$_{p,s}$) 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).

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 deployments in the East Walker River (11:15 on 6/19/15 to 9:45 on 6/23/15) and mainstem Walker River (14:15 on 6/25/15 to 12:30 on 6/30/19). ~~Daily stream temperatures and ranges for DTS deployment reaches in the East Walker and mainstem Walker Rivers. Data collection began in the afternoon on deployment days, June 19th and 25th, and ended in the morning of June 23rd and 30th.~~

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

Stream temperatures varied spatially throughout the mainstem DTS site, visualized as longitudinal color striations ~~at different locations~~ in Figure 2b. Average ~~reach~~ deployment site temperature (TBAR$_{p,s}$) was 25.2 °C, not including the Wabuska Drain segment (Table 2, excluding distance 110 – 175 m in Fig. 2b). Maximum stream temperature (Tmax$_i$) was 32.9 °C. The average ~~reach~~ temperature range for the deployment (RBAR$_{p,s}$) was 2.7 °C, with a minimum deployment site ~~reach~~ temperature range (Rmin$_i$) of 1.1 °C and a maximum site ~~reach~~ temperature range (Rmax$_i$) of 7.0 °C. Average DTS stream temperatures (TBAR$_{p,s}$) in the East Walker River were approximately 4 °C cooler and less variable than the mainstem Walker River (Fig. 2). Average DTS temperature ranges (RBAR$_{p,s}$) were nearly 2 °C greater in the mainstem Walker River than the East Walker River. The East Walker River DTS site is farther upstream and close to Bridgeport Reservoir, a bottom release dam. The mainstem Walker River DTS site is 92 km downstream from the East Walker River DTS site and receives contributions from the West Walker River, fed by surface water releases from Topaz Reservoir.

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 across the deployment site was greater than localized variability in areas like the Wabuska Drain. However, the maximum 15 minute ~~reach~~ temperature range for the deployment (Rmax$_{i,s}$) increased considerably from 7.0 °C to 10.2 °C and average ~~reach~~ temperature range for the deployment (RBAR$_{p,s}$) also increased from 2.7 °C to 3.6 °C (Table 2, Fig. 2b). Figure 4 illustrates ~~the cooling effect of the~~cooler temperatures in the Wabuska Drain and ~~the~~ spatial temperature variability during daily maximum stream temperatures (Tmax$_{d,s}$) on July 29th. The coolest temperature (Tmin$_i$) in~~at~~ the mainstem Walker River DTS site was 24.4 °C and occurred approximately 20 m into Wabuska Drain (Fig. 4). S~~Warm s~~tream temperatures of up to 31.8 °C occurred in the homogeneous mainstem Walker River segment just upstream of the Wabuska Drain along the shallow, right bank and at the mouth of the drain. The shallow Wabuska Drain also experienced rapid heating and cooling in response to atmospheric conditions. Cool water from the outlet of the Wabuska Drain mixed with the mainstem Walker River at hot times of day, expanding the temperature range ~~of the~~ downstream ~~segment~~ of the drain as well. In addition to ~~increased~~ wider temperature ranges in the Wabuska Drain, the mainstem Walker River had ~~more~~ greater ~~channel and~~ temperature heterogeneity from inactive, breached beaver dams. On June 29th at 3:15

pm, when ~~site~~ average site temperature (TBAR$_{i,s}$) was 29.6 ºC, nearly 7 ºC of the temperature range observed for this 15 minute ~~sample~~ event occurred at a breached beaver dam (Fig. 4). ~~The warmer temperatures occurred in an unshaded, shallow, backwater location subject to solar warming.~~

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

Lateral temperature variability was always greater ~~for~~ in the mainstem Walker River than the East Walker River. ~~Thermal~~ Temperature ranges increased as ~~the~~ spatial scale increased, so that the average lateral range was 0.2 ºC, 0.4 ºC, 0.7 ºC, and 0.9 ºC for 1 m, 10 m, 100 m, and 300 m spatial scales, respectively, in the East Walker River, and was 1.3 ºC, 2.7 ºC, 3.9 ºC, and 5.2 ºC 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 distinctively lower temperatures than the rest of the river ~~with increased thermal ranges~~. In the mainstem Walker River, deep pools with riparian vegetation, beaver dams, and islands in the channel were river features that were cooler or warmer than spatially-averaged river temperatures~~with more lateral thermal variability~~.

4.2 TIR Measured Stream Temperatures and Ranges

TIR data were within 0.5 °C of iButton sensors, except for one location in the East Walker River where redundant sensors were 1.7 °C and 3.3 °C cooler than radiant TIR temperature, and one location in the West Walker River where an iButton was 1.1 °C cooler than radiant TIR temperature. TIR measures water surface temperatures, so these discrepancies may have occurred where the river was not well mixed.

While DTS measurements provided high spatial and temporal stream temperature resolution at two sites, TIR measurements provided continuous ~~surface~~ stream surface temperatures throughout the Walker River for ~~one hour~~a single time. Maximum stream temperatures typically occurred in reaches with canal diversions and return flows. The warmest temperature in the East Walker River (Table 3) was 26.5 ºC ~~at the Hall Diversion (River km 129)~~ where water ponds at a~~the~~ diversion (river km 129). Maximum stream temperature in the West Walker River was 27.1 ºC and occurred upstream of the confluence with the mainstem Walker River. Maximum temperature in the mainstem Walker River was 29.2 ºC and occurred at the Wabuska Drain outflow (River km 78). Although the Wabuska Drain received agricultural returns during the TIR flight and therefore contributed warm water, ~~rather than the cool water observed during times without agricultural runoff,~~ the 4.5 km stretch of river downstream from the Wabuska Drain was 1 ºC cooler than the segment of river upstream of the Wabuska Drain (Fig 5). This may be due to groundwater inflows downstream of the Wabuska Drain consistent with valley narrowing (Watershed Sciences Inc., 2012) or shallow groundwater contributions due to irrigation of adjacent fields. While groundwater interactions may be less obvious when the return canal was flowing, DTS results showed evidence of cool water inputs when the canal was not flowing. Thus, monitoring suggests that large diversions and return flows can create warm water conditions when active, but they may also recharge shallow aquifers, ~~and~~ increase shallow groundwater contributions, and create pockets of cold water. Shallow subsurface contributions to Wabuska Drain may not occur when groundwater levels decline outside of irrigation season or during droughts (Naranjo and Smith, 2016).

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

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

The 300 m reaches with the greatest temperature ranges corresponded ~~with~~ to locations of canal diversions, return flows, and groundwater seeps (Fig. 6). In the East Walker River, the Fox/Mickey Diversion (r~~R~~iver km 126)~~,~~ and Strosnider Diversion (r~~R~~iver km 140) had large temperature ranges. In the mainstem Walker River, ~~there was~~ thermal variability occurred at the Spragg-Alcorn-Bewle~~l~~y Diversion (r~~R~~iver km 94), the Spragg-Alcorn-Bewle~~l~~y Canal Return (r~~R~~iver km 90), and Wabuska Drain (r~~R~~iver km 78) (Fig. 6). Maximum 300 m reach temperature range was 1.2 °C in the West Walker River (r~~R~~iver 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~~data are unable to capture thermal stratification of beaver dams and ponds.

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

We compared minimum TIR stream temperatures at 50 m and 300 m to improve understanding of thermal refugia at multiple spatial scales. We did not calculate temperature ranges because mixed pixels that contained ~~some~~ water and ~~some~~ land ~~riparian~~ areas 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~~($Tmin_L$) were 21 °C for the East and West Walker Rivers and 22.3 °C for the mainstem Walker River.

4.3 *RMS* Predictions vs. Measured Temperatures

Modeled versus DTS stream temperature ~~data~~ RMSE was 1.1 °C in the East Walker River and 1.7 °C in the mainstem Walker River (Table 4). When compared to TIR data, ~~model~~ RMSE and bias were both <1 °C for the East and West Walker Rivers. ~~; h~~However, ~~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 (Table 4). Mainstem Walker River TIR ~~stream temperatures~~ versus modeled stream temperature was the only RMSE value that exceeded the calibrated *RMS* model RMSE of 2.5 °C (Null et al., 2017). Model bias for the East Walker River indicated the model over-estimated stream temperature by 0.2 °C in the ~~300 m~~ DTS ~~reach~~ site over the five day study period and underestimated temperature by 0.5 °C for the 77 km TIR extent. In the mainstem Walker River, t~~T~~he model underestimated stream temperatures by 0.4 °C from the average DTS values and underestimated stream temperatures by 2.5 °C when compared to the TIR data ~~average temperature in the mainstem Walker River~~ (Table 4).

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

Modeled temperatures in 2015 were warmer than DTS maximum hourly temperatures 50% of the time in the East Walker River~~,~~ and 20% of the time in the mainstem Walker River. Conversely, the model under-~~-~~predicted DTS temperatures 29% and 10% of the time in the East Walker and mainstem Walker Rivers, respectively (Table 4, Fig. 7a and b). Temperatures measured in Wabuska Drain were excluded from this analysis because the model ~~estimated~~ simulated 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.~~ Simulated temperatures were cold~~low~~er than TIR summary point minimum temperatures for 74%, 95%, and 87% of survey extent in the East Walker, West Walker, and mainstem Walker Rivers, respectively (Fig 7c-e, Table 4). Stream temperatures in the lower Walker River could be 4 – 6 ºC warmer than simulated results estimated. That reach has challenging conditions for simulation models with a wide channel and low flow conditions.

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

4.4 Thermal Habitat and Thermal Refugia Connectivity for LCT

Stream temperatures were rarely cooler than 21 ºC, and this finding was consistent among the DTS, TIR, and modeled data (Fig. 8; Table 5). An exception was during the East Walker River DTS deployment in June 2015, when nearly 50% of DTS samples and modeled results ~~classified nearly 50% of samples~~were below 21 ºC. Stream temperatures were most likely to exceed 28 ºC with the TIR dataset. Nearly all TIR ~~data~~ and model ~~results~~ temperatures 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

Measured DTS and TIR temperature ranges from return flows, diversions, beaver dams, and seeps were added or subtracted to perfectly-mixed, 300 m modeled reach stream temperatures to estimate thermal refugia connectivity. We identified 23 diversions, 8 return flows, 53 possible seeps, and 42 beaver dams throughout the modeled reach (Fig 9a). We used average temperature changes of -2.5 °C for return flows, +1.2 °C for diversions, -3.2 °C for beaver dams, and -1.9 for groundwater seeps, although observed temperatures varied from -10.1 to +2.3 °C for return flows, -1.2 to +4 °C for diversions, -5.1 to +2 °C for beaver dams, -4.2 to 0 °C for seeps. Adding observed DTS and TIR temperature ranges from modeled results indicates that cool-water refugia may sometimes exist to support species migration between Walker Lake and tributaries of the Walker River (Fig 9b). The shortest distance between refugia was 0.3 km, the spatial resolution of model reaches, and maximum distance was 37 km and near Weber Reservoir on the mainstem Walker River. The mean distance between refugia was 2.8 km and the median distance was 0.9 km.

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

5~~.1~~ Limitations

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

Obtaining small-scale spatial and temporal stream temperatures and comparing them to model results has several limitations. First, resolution ~~of information~~ varied between DTS~~ data~~, TIR~~ data~~, and modeled data~~results~~, reducing the number of comparable observations. TIR imagery represents a single point in time unless flights are repeated. DTS measurements were dense (1 m in these deployments) with a 15 minute temporal resolution, but were limited by cable length and field crews to monitor the deployment. Second, DTS and TIR measurements were collected in different years because we used existing TIR imagery collected as part of the Walker Basin Project, a multi-partner ~~comprehensive~~ effort to sustain the basin's economy, ecosystem, and lake. Future studies could collect data specifically to overlap in time and space so that temperature distributions along the river are not affected by different years and sample periods. ~~; h~~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.

6~~5~~ Discussion

~~Warm stream temperatures and low flows threaten native trout and other cold water species. This research~~We measured the range of stream temperatures that was unquantified ~~and underrepresented~~ in existing one-dimensional, basin-scale models~~ing~~. Overall, DTS measured a larger maximum 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, but also suggesting that different years may result in alternate temperature distributions along the river (Tables 2 and 3). DTS and TIR augment process-based modeling by identifying river features that may provide thermal refugia. The range of temperatures in river features like seeps, beaver dams, and return flows were added to simulated temperatures to estimate temperature barrier and thermal refuge distribution throughout a watershed. Coupling high resolution stream temperature monitoring with process-based modelling results in a more realistic stream temperature range than one-dimensional modeling alone, especially when model results assess habitat suitability to identify promising restoration strategies and watershed-scale management.

Temperature ranges reported here are comparable to those previously reported in the literature. Cristea and Burges (2009) observed 2 - 3 ºC temperature range due to cold water seeps or channel braiding in the Pacific Northwest, which is near the 1 – 2 ºC temperature range observed in the East Walker River in the DTS data and TIR imagery. Beaver dams had especially high temperature ranges, consistent with findings from Majerova et al. (2015) and Weber et al. (2017). A 7 ºC temperature range was observed within a beaver dam in the mainstem Walker River during a 15 minute sampling event.

Thermal refugia are likely needed for species to persist near the margins of their distributions (Brewitt and Danner, 2014). Previous research has shown that the confluence of the East and West Walker Rivers to Walker Lake has low streamflows and warm stream temperatures that do not support LCT or other cold water species, but that the East and West Walker Rivers are likely to support native aquatic species (Elmore et al., 2016; Hogle et al., 2014; Mehler et al., 2015; Null et al., 2017). Our work nuanced those findings by highlighting the distribution and temperature ranges of likely thermal refugia from the confluence of the East and West Walker Rivers to Walker Lake.

Although detailed movement and summer home range data are unavailable for LCT, movement patterns have been described for Bonneville cutthroat trout (Schrank and Rahel, 2004) and Colorado River cutthroat trout (Young, 1996).

Bonneville cutthroat trout move up to 82 km between spawning and over-summer habitats, with farther movements positively correlated to fish length (Schrank and Rahel, 2004). However, movement declines through summer. Summer home ranges of Colorado River cutthroat trout have a median of 0.2 km (Young, 2004) and Bonneville cutthroat trout do not move more than 0.5 km during summer. This suggests that the existing network of thermal refugia in the lower Walker river may be adequate for LCT to move between spawning and lake habitats (following lake restoration), but are unlikely to provide refugia necessary for summer habitat.

From a broader perspective, this~~Our~~ research contributes to literature describing thermal refugia networks and how they may be included for watershed management (Isaak et al., 2012; Sutton et al., 2007). River features like diversions, return flows, and beaver dams provide temperature variability, and often, thermal refugia for cold water species like LCT. Fine spatial and temporal resolution stream temperature monitoring paired with watershed-scale modelling indicates that the distance between refugia varied from 0.3 to 37 km, closer together than the 5.7 to 49.4 km demonstrated by Fullerton et al. (2018) in the Pacific Northwest. Stream temperatures suggest that if LCT and other native fish have not migrated through warm reaches by summer, they must shelter in refuges to thermoregulate body temperature (Frechette et al., 2018). Since stream temperatures neared or exceeded LCT temperature thresholds for extended periods, foraging habitat near to thermal refugia are likely needed to maintain body temperatures (Pepino et al., 2015). 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 reduce uncertainty and validate the large temperature ranges observed for return flows, diversions, beaver dams, and seeps. Additional work is also needed to quantify the distance between thermal refugia and foraging habitats in this system (Pepino et al., 2015), the maximum distance between refugia for LCT to move between spawning and summer habitats (Shrank and Rahel, 2004), and to improve understanding of the resiliency of streamflows and thermal refugia with anticipated climate change (McCullough et al. 2009; Ficklin et al., 2018; Null and Prudencio, 2016). DTS and TIR stream temperature measurements bound temperature variability and can be used with simulation models in other watersheds to identify river features that provide thermal refugia, create temperature barriers, and inform restoration. Our approach may also be used by stakeholders who do not have the funding or background to conduct additional model simulations, but prefer to improve interpretation of model results with observations.

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

~~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 °C cooler than the river segment at the Wabuska Drain. identified local streamflow gains near the Wabuska gage, hypothesizing they originated from groundwater to Wabuska Drain. However, shallow subsurface water, or interflow contributions to Wabuska Drain may not occur when groundwater levels decline outside of irrigation season or during droughts (Naranjo and Smith, 2016). Thus, large diversions and return flows can create warm water conditions when active, but irrigation practices may also recharge shallow aquifers~~

~~and create pockets of cold water in return flow canals. However, it may be difficult for LCT to reach these refuges or they may be insufficient for cold water habitat. Stream temperatures measured by the DTS in the shallow water at the mouth of Wabuska Drain and in the mainstem Walker River upstream of the Wabuska Drain exceeded LCT acute temperature threshold of 28 °C. Similarly, maximum TIR temperature in the mainstem Walker River was 29.2 °C at the Wabuska Drain return flow (River km 78), which may create temperature barriers for cold water species like LCT at some times.~~

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

~~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.~~

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Table 1: Description of stream temperature variables.

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

Table 2: Daily stream temperatures and ranges for DTS deployment~~ reache~~s in the East Walker River (11:15 on 6/19/15 to 9:45 on 6/23/15) and mainstem Walker Rivers (14:15 on 6/25/15 to 12:30 on 6/30/19). ~~**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 (°C)	Maximum Temperature (°C)	Average Temperature (°C)	Maximum Range (°C)	Average Range (°C)
East Walker River	20.1	26.5	24.7	1.1	0.3
West Walker River	24.1	27.1	25.6	1.2	0.4
Mainstem Walker River	22.9	29.2	27.3	1.0	0.3

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

	RMSE (°C)	MAE (°C)	Mod. – Meas. Bias (°C)	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