Groundwater flux monitoring along streams in the Wood River Valley, Idaho

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1 EXECUTIVE SUMMARY

The scope of this project is to monitor water seepage discharge between the stream and shallow aquifer by using a new passive thermal monitoring approach on two small tributary streams of the Big Wood River near Ketchum, Idaho. The technique employs temperature sensors embedded in the streambed at different depths to resolve vertical fluxes between the stream and groundwater. Results of the new thermal method are compared with seepage survey measurements and the difference in discharge (ΔQ_{USGS}) between U.S. Geological Survey (USGS) gauging stations.

We designed, fabricated, and installed 40 probes along Warm Springs and Trail Creeks during the Fall and Winter of 2018. During data collection in July 2019, it was found that 20 sensors, approximately 10 in each stream, were either broken or removed due to people partially or totally dislodging the sensors from the streambed. An additional 20 probes were fabricated and replaced in Fall 2019 to continue data collection. Similarly, during data collection in July and October 2020 and August and October 2021 we found missing sensors. The locations where sensors were missing are where there is easy public access to the streams.

The quantified vertical fluxes accounts for groundwater recharge or discharge and thus, incrementally summing their values between the two USGS gauging stations quantifies the net amount of water gains/losses occur in that stream section and this value is comparable to ΔQ_{USGS}. Comparison of the three methods show generally similar values. Different behavior and trends between ΔQ_{USGS} and thermal seepage discharge occur during the time when surface water diversions are operational. During the post-irrigation period when diversions are assumed to be negligible, the methods provide similar magnitudes of seepage discharge. The method could be used to constrain the amount of surface water actually extracted from the stream as it accounts for any potential stream gains and/or losses with the aquifer. The new thermal method could be an effective tool to monitor hyporheic exchange of water between the stream and aquifer including the effects of water diversion and possibly nearby wells and provide the input for the previous methods.

2 INTRODUCTION

High-density environmental data acquisition of surface and ground water exchange is vital for informing water management and water balance modeling, validation, and calibration. Such environmental data provide important boundary conditions for numerical modeling of groundwater and surface water for conjunctive management. This information can be used for both calibration and validation of models, as well as iteratively to run different scenarios to predict system behavior. This study addresses these modeling needs and provides the monitoring system of the streambed-aquifer interactions. The method provides a record of both qualitative and quantitative data, including: 1) determination of which reaches are losing and gaining flow at different times of the year, and 2) the intensity of water fluxes. Results of this project provide information at an unprecedented spatial and temporal resolution to guide groundwater model development and management scenarios. This transferable technique can help map and quantify losing and gaining fluxes to and from watercourses across varying spatial scales. For example, the method could be upscaled to a regional program for watershed-scale model improvement or employed as a spatially nested monitoring program for local communities. The technology could further be used to identify which portion of the irrigation canal system in the Treasure Valley or Eastern Snake Plain Aquifer can maximize aquifer recharge during both irrigation and non-irrigation seasons.

The passive thermal method uses the naturally occurring daily fluctuations of water temperature as a tracer to quantify downwelling/upwelling fluxes along the streambed-groundwater interface. The method has been previously applied to provide: 1) local hyporheic fluxes within the first layers of riverbed sediments, 2) scour and deposition of the streambed, as well as 3) the vertical hydraulic conductivity of the streambed, when coupled with vertical pressure measurements. Previous investigations reported very good performance of this method to measure vertical pore-water flux at the local scale. This project upscales the local flux information at the streambed-aquifer interface to quantify gains and losses of water at the reach scale (discharge from and recharge to aquifers). This project also aims to highlight the quantity of sensors that are necessary to provide the spatially averaged recharge/discharge fluxes at the reach scale, which potentially depend on stream morphologic complexity, lithology of the watershed, and geologic characteristic of the reach. The monitoring is performed on two tributaries of the Big Wood River: Warm Springs and Trail Creeks, which are bracketed by USGS gauging stations at either end. Comparison between thermal seepage and discharge difference between the gauging stations (ΔQ_{USGS}) allows quantification of the performance of the model during times when water diversions are inactive. In addition to reach scale values, thermal seepages are compared with measured seepage surveys in order to quantify the performance of the new thermal method in providing spatially distributed hyporheic fluxes.

2.1 *Project objectives*

The project goal is to monitor discharge and recharge along a 1.4-mile reach of Warm Springs Creek and a 5.2-mile reach of Trail Creek, both in the Wood River Valley, Idaho. The streambed-groundwater exchange at the reach scale will be quantified by using a temperature-based methodology proposed by Luce et al. (2013) to capture daily variability in gaining and losing alluvial systems. The method uses the naturally occurring stream water temperature fluctuations as a tracer to detect pore water vertical velocity. It provides local fluxes, q, which are upscaled by averaging them spatially among all m sensors installed in a reach:

$$q_{creek} = \frac{\sum_i^m q_i A_i}{\sum_i^m A_i} = \frac{\sum_i^m Q_{reach,i}}{A_{creek}} \tag{1}$$

where A_i is the area of each sub-reach associated with the i-th sensor. The total recharge/discharge, Q_{creek}, which expresses the total seepage discharge, is quantified by multiplying the reach-scale value by the streambed area, $Q_{creek}=q_{creek}\, A_{creek}=\sum_i^m Q_{reach,i}$. The calculated value, Q_{creek}, is the net loss or gain of water through the streambed for the entire reach, whereas Q_{reach} is the seepage discharge associated with one probe and its associated reach area, A_i.

The seepage discharge Q_{creek} value is compared to seepage surveys coordinated with the USGS and IDWR, which quantify net loss or gain of water by difference between surface water discharge measurements. The comparison is also performed against the calculated difference in discharge between the upstream and downstream USGS gauging stations, ΔQ_{USGS}, on each reach. Estimates from the thermal seepage and ΔQ_{USGS} should have similar values only when there are not surface water losses (e.g., point of water extraction in operation) or gains (e.g., lateral inflows from tributaries or return water).

2.2 *Project Tasks*

The following tasks will be accomplished to reach the project goal:

Year One Tasks (August 6, 2018- June 30, 2019)

Task 1: Construct 40 pore-water flux probes. Each probe will have a datalogger and temperature sensors spaced approximately 15 cm apart.
Task 2: Install 20 flux probes along a 1.5-mile reach of Warm Springs Creek and 20 flux probes along a four-mile reach of Trail Creek. Probes will be installed approximately three feet deep along the stream centerline during low-flow conditions.
Task 3: Compile water temperature and discharge data from USGS gaging stations (WARM SPRINGS CREEK NEAR KETCHUM ID, TRAIL CREEK NR SUN VALLEY ID, TRAIL CREEK AT KETCHUM ID, and WARM SPRINGS CR AT GATES RD NR KETCHUM ID), and water levels from nearby wells. Analyze the compiled data and quantify the existing information on exchange between groundwater and surface water.
Task 4: Collect and analyze temperature data from flux probes. Develop time series of temperature data and quantify local seepage rates. Quantify reach-scale discharge/recharge by upscaling local seepage rates.
Task 5: Meet with the Department's Project Coordinator on a quarterly basis to discuss project status.
Task 6: Submit quarterly status reports to the Department's Project Coordinator.

Year Two Tasks (July 1, 2019- June 30, 2020)

Task 1: Continue to compile and analyze water temperature and discharge data from USGS gaging stations, and water levels from nearby wells. Quantify groundwater recharge from surface water, or discharge to surface water.
Task 2: Continue to collect and analyze temperature data from flux probes. Develop time series of temperature data and quantify local seepage rate. Quantify reach-scale discharge/recharge by scaling up the local seepage rate estimates.
Task 3: Meet with the Department's Project Coordinator on a quarterly basis to discuss project status.
Task 4: Submit quarterly status reports to the Department's Project Coordinator.
Task 5: Submit a Year One Status Report due December 1, 2019, that includes the following:

- Work completed on each task.
- Data collected during first and second year.
- Analysis of recharge/discharge for the first and second year from/to the Wood River tributary streams as a time series, at a daily and monthly time scale.

Year Three Tasks (July 1, 2020- June 30, 2021)

Task 1: Submit a Year Two Status Report due December 1, 2020, that includes the following:

- Work completed on each task.
- Data collected during the first year.
- Analysis of recharge/discharge for the first year from/to the Wood River tributary streams as a time series, at a daily and monthly time scale.

Task 2: Continue to compile and analyze water temperature and discharge data from USGS gaging stations, and water levels from nearby wells. Quantify groundwater recharge from surface water, or discharge to surface water.
Task 3: Continue to collect and analyze temperature data from flux probes. Develop time series of temperature data and quantify local seepage rates. Quantify reach-scale discharge/recharge by scaling up the local seepage rate estimates.
Task 4: Meet with the Department's Project Coordinator on a quarterly basis to discuss project status.
Task 5: Submit quarterly status reports to the Department's Project Coordinator.
Task 6: Submit a Final Report due December 31, 2021, that includes the following:

- Data collected during the second year.
- Analysis of recharge/discharge for the second year from the streams as a time series, at a daily and monthly time scale.
- Overall analysis and quantification of recharge/discharge for Warm Springs Creek and Trail Creek for both study years.
- Analysis of the sensitivity of the flux measurement method to the number and spatial distribution of sensors used to estimate the reach gain/loss estimates.
- Discussion of method assumptions, method accuracy, and future applicability.

3 Study Site

The study sites include a 1.4 mi (2,247 m) long reach of Warm Springs Creek and a 5.2 mi (8,390 m) long reach of Trail Creek. Both are tributaries of the Big Wood River near the city of Ketchum, Idaho. They are both gravel-bed rivers with median grain sizes of the surface streambed material of 1.15 and 1.5 in (29.2 and 38.3 mm), average channel widths of about 29 and 26 ft (8.83 and 7.92 m) and slopes of 0.0086 and 0.0108 for Warm Spring and Trail Creeks, respectively. Both streams have a USGS gauging station at the upstream and downstream ends that allow monitoring daily differences in discharge (ΔQ_{USGS}) within the two river sections. These differences will be compared to the thermal seepage discharge quantified with vertical fluxes estimated with the new probe exchange method.

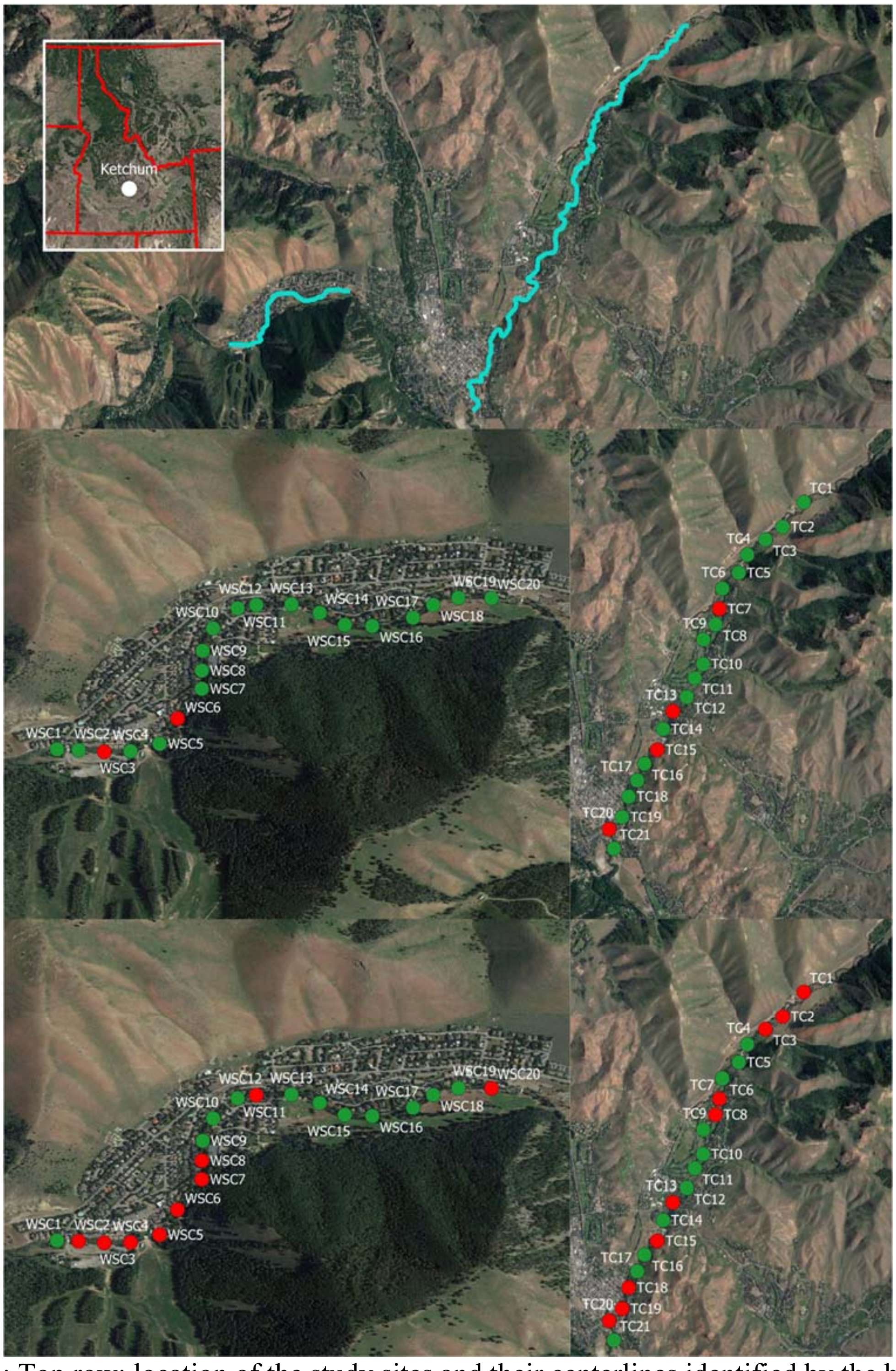

Figure 1: Top row: location of the study sites and their centerlines identified by the blue line, right Trail Creek and left Warm Springs Creek in the top photograph. Left and right pictures show the locations of the thermal probes with circles whose colors indicate damaged and replaced probes (red) and operating (white or green) along Warm Springs and Trail Creeks, respectively in 2019 (middle row) and 2020 (bottom row).

We installed 20 temperature probes approximately equally spaced along both streams: nearly 262 ft (80 m) apart in the shorter Warm Springs Creek and 565 ft (200 m) apart in Trail Creek (Figure 1). Each 4.6 ft-long probe was installed with about 3.3 ft (1 m) in the sediment and about 1.3 ft (0.4 m) above the sediment. The part of the probe in the water column measured stream water temperature, while the buried sensors measured the pore water temperatures at different depths in the streambed.

4 METHODS

This section presents the details on probe design and installation, as well as the analytical methods for analyzing the temperature data to extract flux information.

Figure 2: The first probe on the left has a wire connection, which requires a USB connection to a computer or table, the one in the center is the new wireless version and the download wireless bar on the right.

4.1 ***Thermal probe***

The thermal probe is made of PVC pipe that houses 8 waterproof temperature sensors spaced 5.9 in (15 cm) apart and an Arduino data logger, powered by a high-density battery that can support the system for 2 years. Two generations of probes were produced in response to local stream conditions (Figure 2). The first set of probes had a wire connection to download the data, while the second set that replaced those removed or broken during the first year had a wireless connection. The latter has the practical advantage that avoids working under the water to open the probe and download the data. This facilitates data collection by reducing field service time and potential for disturbing the apparatus. To minimize power consumption, the wireless connection is activated with a magnetic switch that powers up the system for data transfer and then goes into standby mode. Data transfer occurs through a local Wi-Fi connection that can connect to a smartphone, tablet, or laptop computer.

High spatial density application of this type of data collection system has been hindered by installation difficulties within gravel-bed rivers. The current system was developed through an iterative approach that incorporates many generations of installers. Penetrating coarse bed materials like gravel and cobbles requires locally loosening of the bed and installation of a driver sleeve (Figure 3). Bed loosening occurs with a 3.2 ft (1 m) long hardened steel auger bit mounted on a portable hammer drill that can break large cobbles that would otherwise prohibit further vertical progress. The driving sleeve is a two-part system with a hardened internal driving tip and a steel casing sleeve. They are collectively driven into the bed with a gas-powered post pounder directly after loosening the soil. The internal driving tip is removed, and the probe is inserted into the sleeve. Once the probe is in place, the sleeve is removed leaving only the probe.

Figure 3: A) loosening the bed sediments with the hammer drill, B) installing the driver sleeve with the post driver.

4.2 *Data Analysis Techniques*

Data analysis uses two techniques based on the thermal conditions of the water column. A steady-state technique (Bredehoeft and Papadopulos, 1965) is applied when temperature fluctuations are low, for example during winter when diel thermal changes are limited. The other technique is appropriate for unsteady thermal conditions when oscillations of the temperature signal is present at a frequency that could be daily or larger (Luce *et al.*, 2013). Both methods are based on the governing equation for one-dimensional advection-diffusion that can be expressed as (Bredehoeft and Papadopulos, 1965; Stallman, 1965; Goto *et al.*, 2005; Hatch *et al.*, 2006; Keery *et al.*, 2007):

$$\frac{\partial T}{\partial t} = \kappa_e \frac{\partial^2 T}{\partial z^2} - \frac{q}{\gamma}\frac{\partial T}{\partial z} \quad (1)$$

where T is temperature (°C), t is time (s), κ_e is the effective thermal diffusivity (m^2 s^{-1}), z is depth into the streambed (m) (positive downward), q is the Darcy flux (m s^{-1}) and $\gamma = \rho c/\rho_f c_f$ with ρc is the heat capacity of the sediment-water matrix and $\rho_f c_f$ is the heat capacity of water. The Darcian flux q is related to the pore water velocity, u, by $u = q/n$, where n is the sediment porosity (-) and to the thermal front velocity, v_t, by $v_t = q/\gamma$. Two important solutions are available: for steady-state thermal conditions ($\partial T/\partial t \rightarrow 0$) and those for unsteady conditions that typically are governed by daily or larger periodic signals. The former is used during the winter or when daily fluctuations are subdued, while the latter is used for all other cases.

4.3 ***Quasi-steady state thermal regime***

The Bredehoeft and Papadopulos (1965) method was applied with the following boundary conditions:

$$T_z = T_0 \quad at \quad z = 0 \quad (2)$$

$$T_z = T_L \quad at \quad z = L \quad (3)$$

where T_z is the temperature (°C) at depth, z, T_0 is the temperature at the upper boundary (°C) and T_L is the lowermost temperature measurement (°C). The solution to equation (1) with boundary conditions (2) and (3) is:

$$\frac{(T_z - T_0)}{(T_L - T_0)} = \frac{exp\left(\frac{\beta z}{L} - 1\right)}{[exp(\beta) - 1]} \quad (4)$$

where $\beta = c_f \rho_f q L/\lambda_0$, The dimensionless parameter β, is positive when q is positive (i.e., downward flow) and negative when q is negative (i.e., upward flow) and λ_0 is the thermal conductivity of the sediment-fluid matrix (W m^{-1} °C^{-1}). A solver is used to quantify the value of β that minimizes the difference between the temperature profile predicted with equation (4) and that observed by the field sensors. Once β is known the seepage velocity can be quantified from the thermal properties of the water and the sediment fluid matrix:

$$q = \frac{\beta \, \lambda_0}{L \, c_f \rho_f} \tag{5}$$

Daily average temperatures for each monitoring location and depth were calculated during the entire period of record. The lower limit of accepted velocities was taken as:

$$|q| = \frac{0.5\lambda_0}{c_f \rho_f L} \tag{6}$$

Velocities with a magnitude less than that predicted from equation (6) are considered 0.

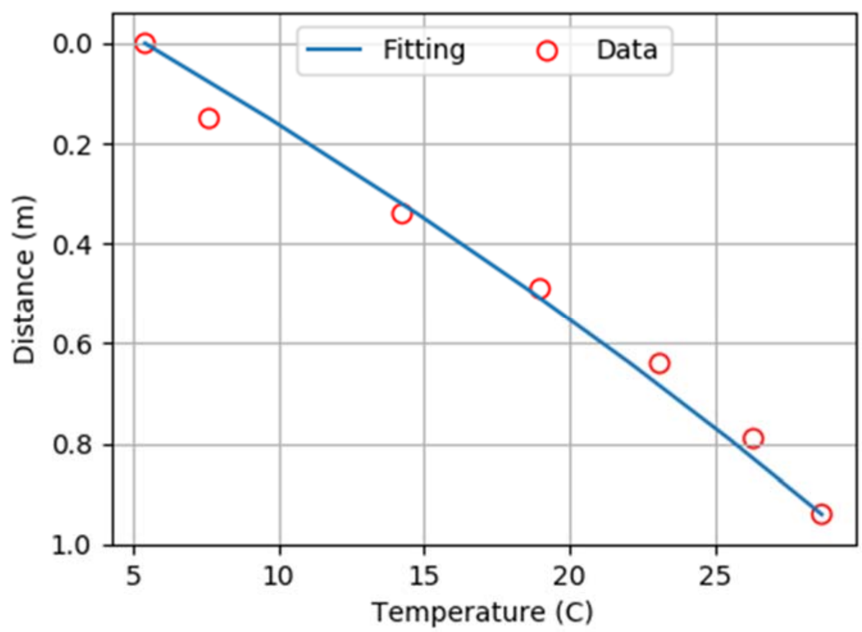

Figure 4: Example of Bredehoeft model (1965); red circles are observed data and blue line is the temperature reconstruction done with the calibrated parameter β. Data are from the upstream most probe of Warm Spring Creek during a winter day.

4.4 ***Unsteady thermal regime***

Bed seepage velocity for unsteady temperature signals is derived by analyzing the phase, φ, and amplitude, A, of the temperature signals, extracted using the Fast Fourier Transform (FFT), of two paired sensors separated by a sediment thickness Δz, with one in the water column (subscript w) and one buried in the sediment (subscript s) following the method of Luce et al. (2013).

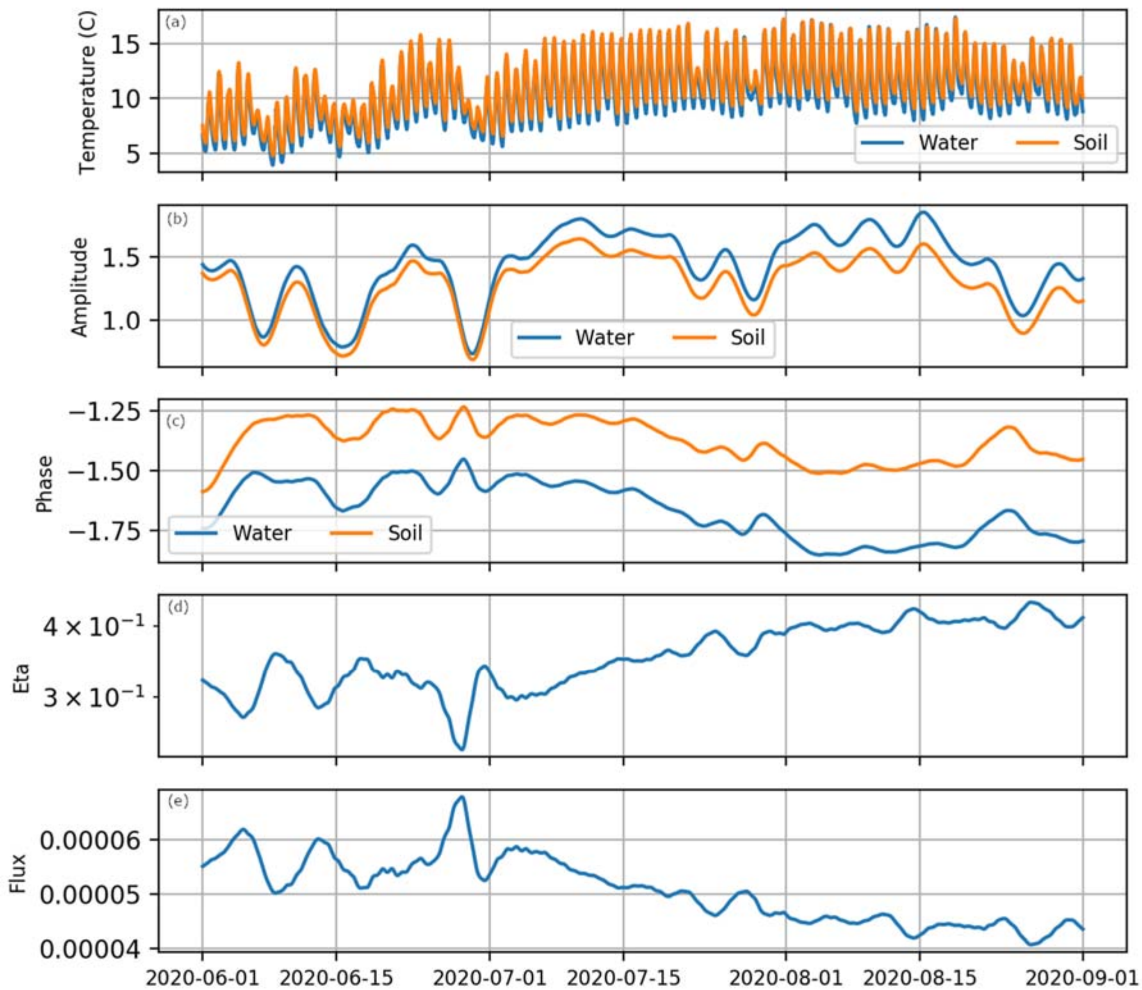

Figure 5: (a) Example of measured temperature, FFT extracted (b) phase and (c) amplitude, (d) quantified η, (e) flux over time at Trail Creek probe 9.

The dimensionless number η, which indicates downwelling for values less than 1 and upwelling for larger than 1, is first quantified from the comparison of the signal from the paired sensors:

$$\eta = \frac{-\ln\left(\frac{A_s}{A_w}\right)}{\varphi_s - \varphi_w} = \frac{-\ln(A_r)}{\Delta\varphi} \tag{7}$$

The average effective thermal diffusivity, $\overline{\kappa}_e$, expresses the thermal property of the sediment and pore-water matrix between the paired sensors, separated by a sediment thickness, Δz, and, once it is quantified, is considered a constant in time. It is quantified from the temperature time series obtained during a period, t_p, of steady-state elevation of the streambed, e_{bed}, when Δz is constant during the time t_p and known, Δz_c,

$$\bar{\kappa}_e = \int_{t_p} \kappa_e dt\,; with\ \kappa_e = \frac{\omega \Delta z_c^2}{\Delta\varphi^2}\frac{\eta}{1+\eta^2} \tag{8}$$

where $\omega = 2\pi / P$ is the expected angular frequency at the analyzed period, P, of the temperature signal. The method quantifies the Darcian seepage flux, q:

$$q = \gamma \sqrt{\omega \bar{\kappa}_e \left(\eta + \frac{1}{\eta}\right)} \frac{1-\eta^2}{1+\eta^2} \qquad or \qquad q = \gamma\omega \frac{\Delta z}{\Delta\varphi}\frac{1-\eta^2}{1+\eta^2} \tag{9}$$

The change in sediment thickness between the paired sensors can be also monitored over time with the following equation:

$$\Delta z = \Delta\varphi \sqrt{\frac{\bar{\kappa}_e}{\omega}\left(\eta + \frac{1}{\eta}\right)} \tag{10}$$

and thus, the streambed elevation changes

$$e_{streambed} = e_{sensor} + \Delta z \tag{11}$$

where e_{sensor} is the elevation of the buried sensor.

The unsteady thermal regime uses the stream water temperature oscillations, which can occur at different frequencies from the daily to the weekly and seasonal. One of the strongest frequencies is the daily cycle, which is typically strong in the summer and weak in the winter. The method uses the temperature signal of one sensor in the surface water and another in the sediment as exemplified in Figure 5. Then from both signals the method extracts their phase and amplitude from which η is quantified and the flux determined.

4.5 *Data Analysis*

Once the vertical fluxes are quantified at each probe, a specific streambed area, A, is associated to each one to quantify the thermal seepage discharge of a reach, Q_{reach}. We define a reach as the area bounded by half the distance to the upstream and half the distance to downstream nearest probes. The sum of these two distances identifies the length, L, of each reach.

$$Q_{reach} = q_i A_i = q_i W_i L_i \tag{12}$$

where W is the representative stream water surface width of each reach. At each probe, we surveyed the cross-section and the edge of water at installation from which W is extracted. While L does not change with discharge, W might. However, because the stream banks are quite steep in both creeks, we assumed that change in W is negligible with discharge as long as the stream discharge is below bankfull.

The total seepage discharge, Q_{creek}, is then quantified by summing all the reach discharges. A incremental Q_{creek} can be quantified by integrating the effect along the stream reach as

$$Q(x)_{Creek} = \int_0^x q(x)W(x)dx \tag{13}$$

with the total seepage with x=L_{stream} where L_{stream} is the total length of the study site between the USGS gauging station.

$$Q_{Creek} = \int_0^L q(x)W(x)dx \tag{14}$$

This value, Q_{creek}, accounts for all gains and losses and is compared with the difference in discharge between the upstream and downstream USGS gauging stations, ΔQ_{USGS}, at each creek. A negative value of ΔQ_{USGS} or Q_{creek} means the stream is losing and positive indicates it is gaining. Difference in surface water are due to different factors including: water management (diversions, pond operation), tributary and geothermal inflows and surface-subsurface water interactions, whereas the seepage discharge is governed by fluxes from and to the aquifer.

5 RESULTS AND DISCUSSION

The thermal regime differs between creeks and along them (Figure 6). The upstream section of Warm Springs Creek shows the strong influence of geothermal water with temperature as high as 28 °C, which decreases during the summer (Figure 6 top left panel). Additional analysis is required, but the decrease could be due to snowmelt (increased volume of cold water), pumping (removal of the hot water) and/or a reversal from upwelling flows during the winter to downwelling during the summer (Figure 10). The geothermal effect decreases with distance downstream and by the middle of the study reach it is no longer detectable (Figure 6, left panel). Daily temperature oscillations of the surface water reduce with depth and are almost undetectable at 3.2 ft (1 m) depth, especially in the summer period. Trail Creek shows a constant groundwater temperature, which is only impacted by seasonal variations in the upstream sections (Figure 6, top right panel). The middle and lower sections show thermal regimes in the sediment following the stream water thermal oscillations both at daily and larger frequencies. This is very evident in TC12 which is a strong downwelling location (losing section of the stream), while TC5 is predominantly upwelling (see constant temperature of the groundwater). These observations will be confirmed by data analysis later in the report (see Figure 11). Several days show very low temperatures near freezing in the middle section and constant freezing temperatures for most of the winter in the lower section (Figure 6, lower left panel). Both techniques do not work in some winter periods when temperature do not have oscillations for two different reasons. The unsteady technique does not work because of the lack of oscillations. The steady-state technique does not work either because of too small pore water temperature vertical gradients, i.e., pore water temperatures at daily and even weekly time scale are very similar (within 3°C over 3.2 ft, 1 m, depth) and does not allow for the accurate application of the Bredehoeft and Papadopulos (1965) model.

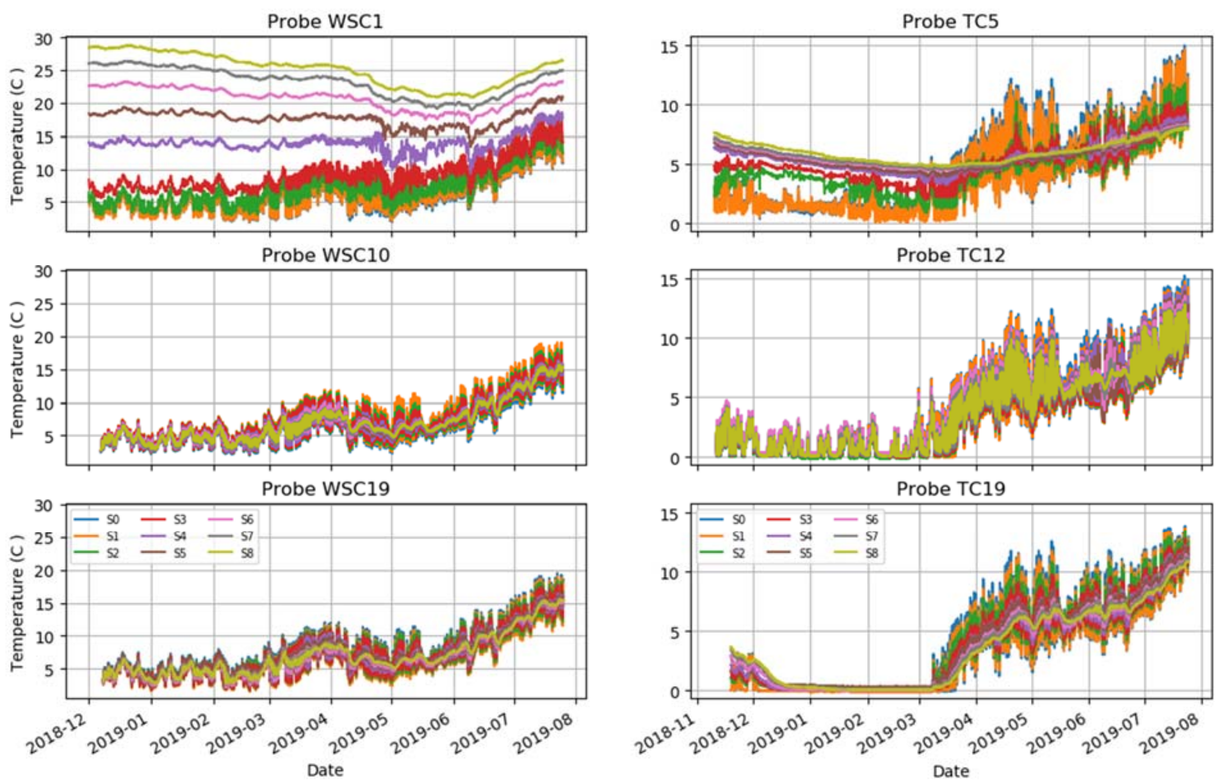

Figure 6: Example of data recorded at an upstream (top row), middle (center row) and downstream (bottom row) probes along Warm Spring (left panels) and Trail (right panels) Creeks. Colored lines indicate temperature at different depths with deeper sensors with higher numbers. Sensors are 5.9 in (15 cm) spaced, so sensor S8 is 3.9 ft (1.2 m) below sensor S0 in the surface water.

5.1 *Model testing*

The U.S. Geological Survey and our team performed seepage surveys at the end of October and first days in November in 2019 and 2020. During the seepage surveys we also downloaded the probe data. To test the accuracy of the method, a comparison of the 2019 seepage survey shows very good matches with the predicted probe exchange method along Warm Spring Creek (Figure 7). The thermal method accurately captures the increases and decreases in discharge along the stream besides the downstream net gain or loss.

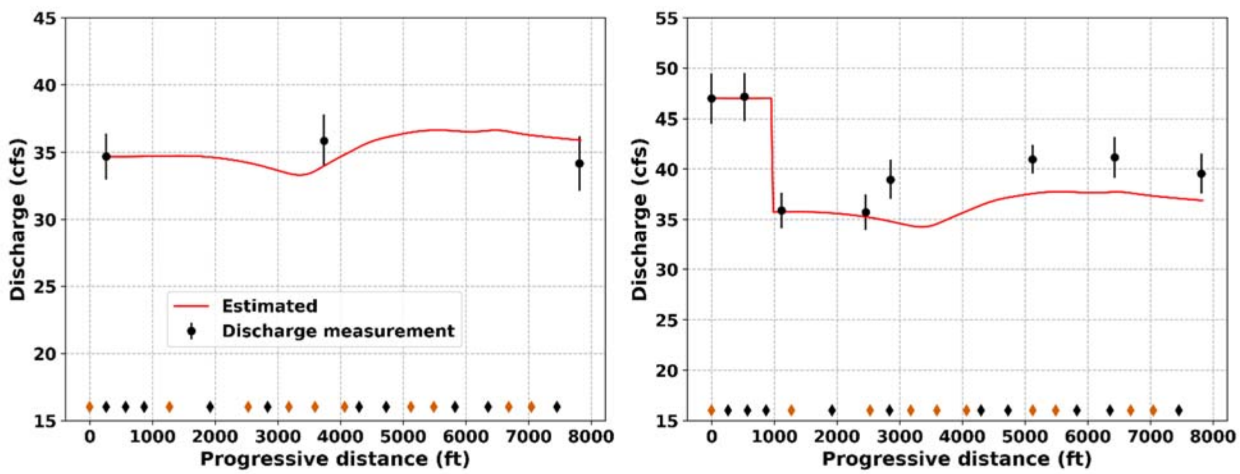

Figure 7: Comparison between thermal seepage solid lines and seepage survey black markers (left USGS seepage run on October 30th, 2019) and (right UI seepage run on October 31st, 2019). The diamonds represent the position of the probes, red vermilion and black color indicate probes with and without useful data at the time of the seepage, respectively.

The sudden drop in discharge, an effect of surface water extraction for snowmaking, is captured during the seepage survey (right panel in Figure 7). By correcting for the water extracted by the surface pump, the thermal method matches the seepage survey results well. Comparison between the seepage survey and the thermal seepage in 2020 in Warm Springs Creek (left panel in Figure 8) is affected by the loss of many probes, limiting the comparison to only the central part of the stream.

The Trail Creek seepage survey in 2019 was too late in the season when stream water temperatures showed little or no fluctuations and temperature differentials between the stream and the deepest sensors were already within a 3 °C range, such that even the steady-state method could not be used. Consequently, we could not compare some seepage survey results in this creek. We can compare the seepage survey made in May 2021, which is affected by two surface water management components: (1) the surface diversion upstream the Hemingway Memorial and (2) the Sun Valley Lake. The diversion dam near the Sun Valley Community School was not diverting water on the day of the survey. Adjusting the for those two water management components, the comparison shows a good match between the exchange predicted and measured discharges (Figure 8 right panel).

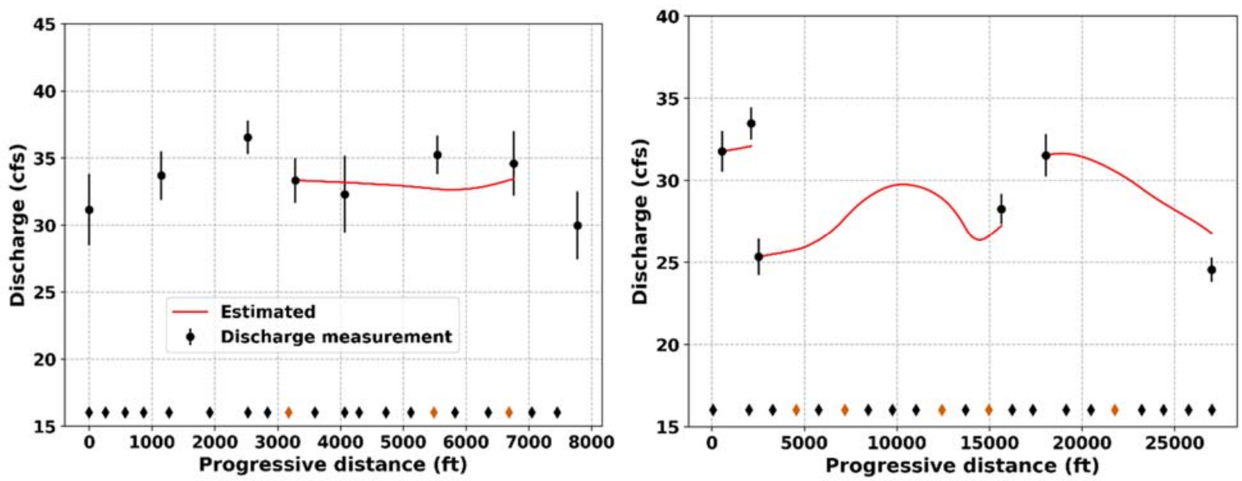

Figure 8: Comparison between thermal seepage solid lines and seepage survey black markers (left UI seepage run on October 22nd, 2020) on the Warm Springs and (right UI seepage run on May 11th, 2021) on Trail Creek. The diamonds represent the probe position and red vermilion and black colors indicate probes with and without useful data at the time of the seepage, respectively.

Comparisons between the difference in discharge between the downstream and the upstream USGS stations, ΔQ_{USGS}, and the total seepage discharge, Q_{Creek}, also show good agreement in periods when surface diversions and water retention and release from Sun Valley Lake on Trail Creek are not operational (Figure 9). Warm Springs Creek has most water diverted during the snowmaking period and Q_{Creek} is above ΔQ_{USGS} between the end of October and December in 2019. During the rest of the winter, ΔQ_{USGS} and Q_{Creek} agree showing a losing stream.

In Trail Creek, values of ΔQ_{USGS} and Q_{Creek} show the same behavior, which is an almost neutral stream during the end of October when surface diversions are closed and the reservoir is open, such that there is little water diversion or storage occurring. ΔQ_{USGS} and Q_{Creek} have large differences the rest of the year due to active surface water diversions. This is exemplified by the May to August period in Trail Creek. During the spring and early summer, Q_{Creek} quantifies a gaining stream of almost 17.65 cfs (0.5 $m^3 \cdot s^{-1}$), whereas the ΔQ_{USGS} analysis shows a losing stream of about 17.65 cfs (0.5 $m^3 \cdot s^{-1}$). The sum of these two values provides the real amount of water removed from the stream for that period of nearly 35.3 cfs (1 $m^3 \cdot s^{-1}$). During the late spring the reservoir fills up and upstream discharge is reduced through the dam owing to storage. During that period, the value of ΔQ_{USGS} chiefly quantify the reservoir storage. However, once the water level in the dam stabilizes and the discharges in and out the reservoirs are similar, ΔQ_{USGS} and Q_{Creek} have similar values.

The net seepage discharge from the probe exchange method, Q_{creek}, indicates the loss or gain of water through the streambed interface with the groundwater over the course of the year. Conversely, the reach discharge difference between USGS gages, Q_{USGS}, accounts for the total loss or gain of water due to both surface and subsurface processes which include in-stream water extraction and tributary inflows, evapotranspiration, and groundwater exchange. Whereas Q_{creek} quantified only the last process, groundwater exchange. Comparison between Q_{creek} and ΔQ_{USGS} should be similar when only groundwater exchange is the primary contributor to changes in surface discharge, i.e., no surface water extraction in operation and low tributary inflows. When Q_{creek} and ΔQ_{USGS} are different, this difference should quantify the net surface water extractions/withdrawals. Thus, the method helps to better constrain the amount of surface water actually extracted from the stream as it accounts for any potential stream gains and/or losses.

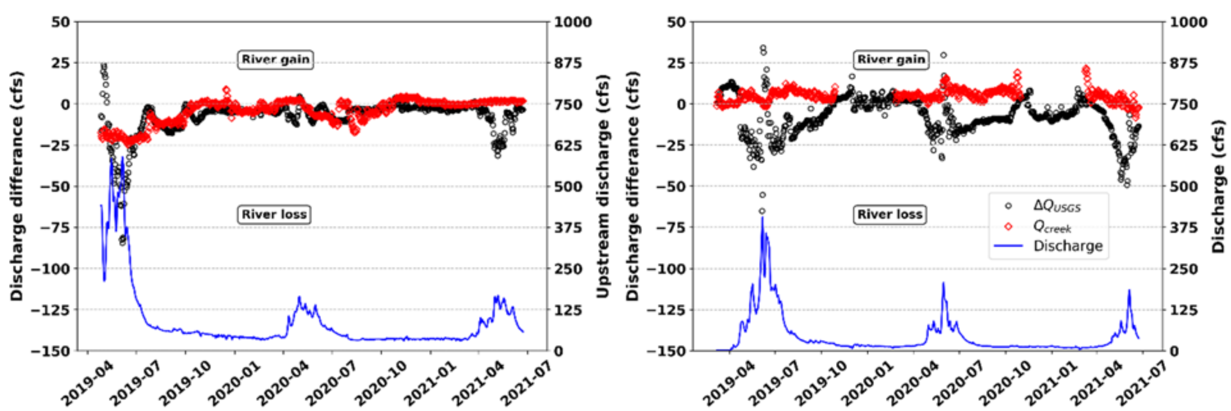

Figure 9: Daily total seepage discharge, Q_{creek}, ($m^3 \cdot s^{-1}$) (red diamonds, estimated seepage), USGS discharge difference, ΔQ_{USGS}, (black circles, measured seepage) and the upstream discharge recorded at the USGS station (13136550 for Warm Springs Creek and 13137300 for Trail Creek) at Warm Springs Creek (left) and Trail Creek (right).

5.2 ***Temporal and spatial analysis of stream exchange***

High temporal and spatial resolutions of the thermal method allow mapping the seepage discharges temporally and spatially along Warm Springs Creek (Figure 10) and Trail Creek (Figure

11). This analysis shows that Warm Springs Creek generally loses water to the aquifer (aquifer is recharged by the stream) over its entire length. An exception is noticeable during the winter 2019-2020 when the middle section of the stream gains water. During the same period, the upper portion of the creek becomes nearly neutral.

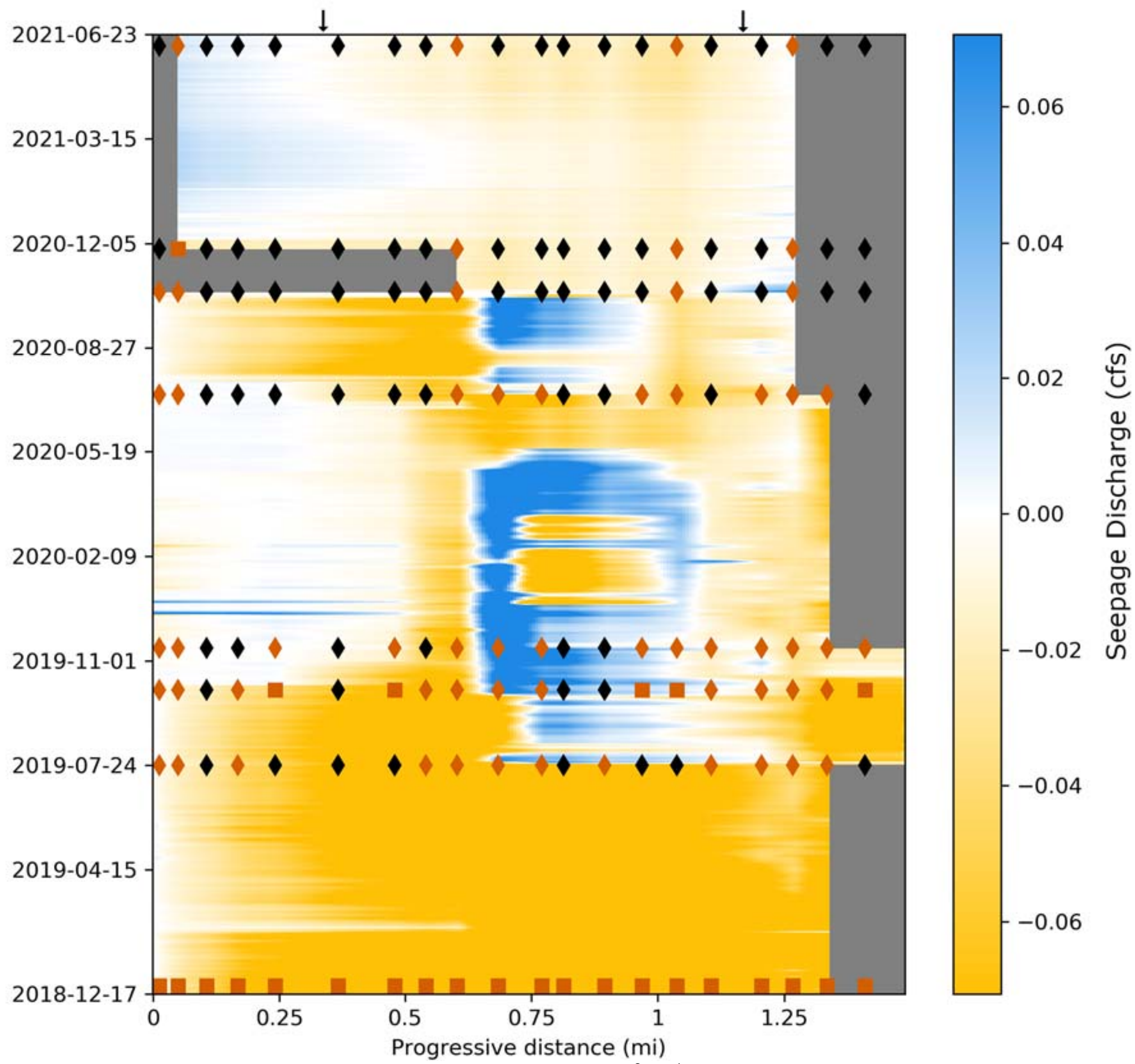

Figure 10: Daily reach seepage discharge, $Q_{reach}(x)$, ($ft^3 \cdot s^{-1}$) along Warm Springs Creek (horizontal axis from upstream, 0 to downstream, 1.48 mi (2,392 m)) for each day (vertical axis). Diamonds and square indicate location of probes (red vermilion data available and black data not-available) and installation or replacement of a probe, respectively.

Conversely, Trail Creek is chiefly a gaining stream with some losses in the middle portion of the study reach (Figure 11). The Trail Creek pattern is quite stable through the entire year. Both steady-state and unsteady methods could not resolve the seepage discharge during the winter due to constant temperature and negligible thermal vertical gradients in Trail Creek. It is interesting to note that the losing section is where most wells (black arrows in Figure 11) are located. Additional analysis is needed to link the losing pattern with the well operations.

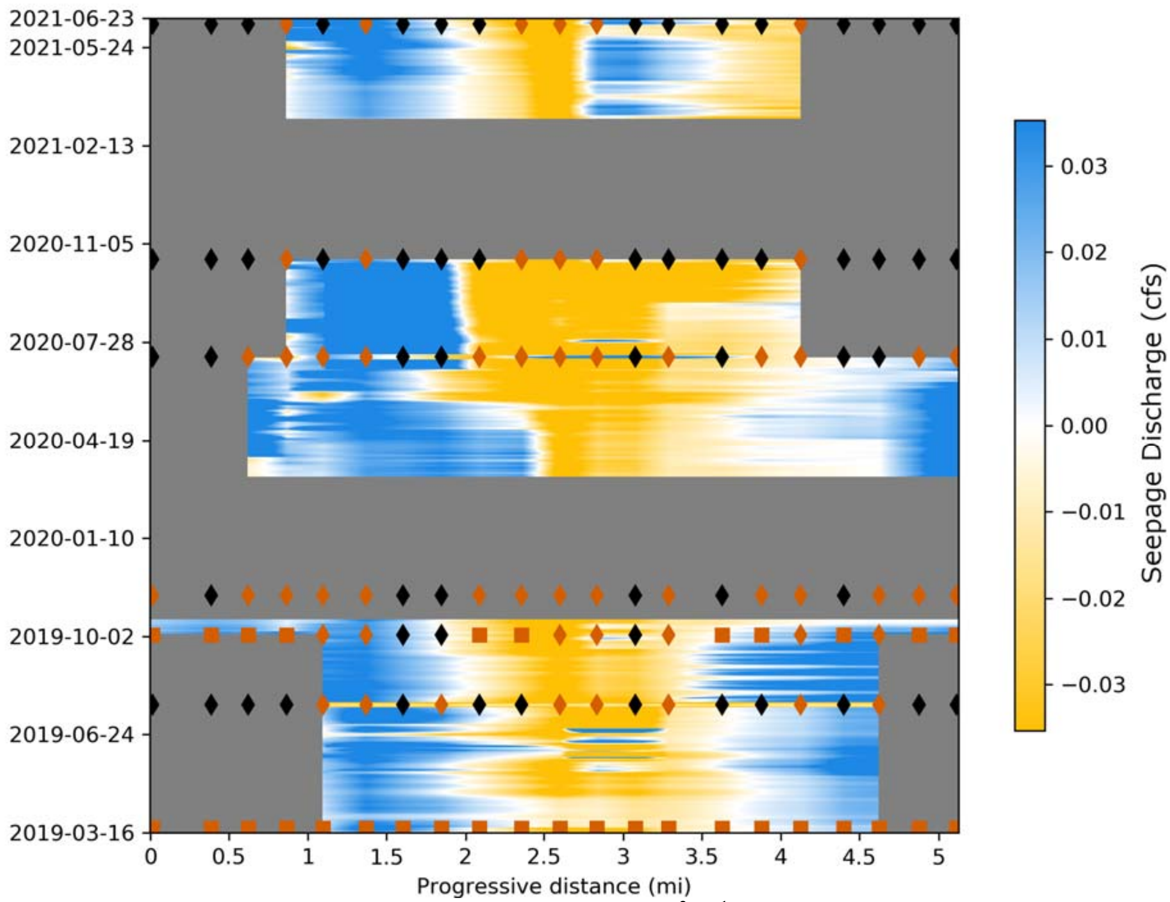

Figure 11: Daily reach seepage discharge, $Q_{reach}(x)$, ($ft^3 \cdot s^{-1}$) along Trail Creek (horizontal axis from upstream, 0 to downstream, 8,300 m) for each day (vertical axis from starting of the study top to last data collection bottom). Diamonds and square indicate location of probes (vermilion data available and black data not-available) and installation or replacement of a probe, respectively.

This monitoring project spanned almost 3 water years, one wet water year (2019) followed by 2 extremely dry water years (2020 and 2021). The results show some interesting interaction between stream and its aquifer and the role of the aquifer in maintaining surface water. Warm Springs Creek, which is generally a losing stream, loses less water as the climate get drier (Figure 9 and Figure 10). Its yearly seepage volume was -6,420,00 m^3 in 2019 and -1,197,00 m^3 in 2020, where the negative sign means water recharging the aquifer. By contrast, Trail Creek, which is typically a gaining stream, gains more water in the dry than wet water year (Figure 9 and Figure 11). Its yearly seepage volume was 4,661,000 m^3 in 2019 and 7,359,660 m^3 in 2020. These two behaviors may indicate that the stream-aquifer relationship maintains a stable stream discharge during variable climatic conditions, by reducing losses in a losing stream and increasing gains in a gaining stream. Whereas the stream piezometric head quickly responds to discharge changes that of the aquifer is lagged. Thus, reduced discharge in the stream leads to lower water surface elevation and thus less heads while the groundwater table may remain with similar head. The reduced stream head may result in smaller head difference between stream and aquifer in the dry than wet water years in Warms Springs. This causes less loses from the stream. Conversely, reduced stream head may result in larger head difference between stream and aquifer in the dry than wet water years in Trail Creek. This causes an increase groundwater discharge to the stream. Information from well installation in the area suggest the presence of two aquifers: one shallow (phreatic, unconfined) and one deep (confined) with an impervious layer between the two aquifers. It is the deep aquifer which recharge the shallow aquifer. However, further data collection and analysis is required to understand it.

5.3 *Probe site selection*

We suggest that the number of probes required to quantify the seepage at the reach scale is a function of (1) geology of the valley, (2) valley confinement, and (3) aquifer interaction at river confluences (e.g., Trail Creek with Big Wood River). Following these hydrogeomorphological characteristics, we dived each creek into separate zones for analysis. Trail Creek can be separated into 4 zones: the upstream end segment is characterized by a narrow valley with some exposed bedrock, the second segment is characterized by a progressive widening of the valley width, the third segment shows a narrowing of the valley width, and the last downstream segment widening within the Big Wood River valley with a possible interaction with the Big Wood River aquifer (Figure 12 left). Within each zone, we selected one probe at the beginning, center, and end for analysis. For a sequence of zone one the same probe may serve as the downstream end probe of the upstream zone and the upstream end probe for the downstream zone. Thus, for Trail Creek we suggest 9 probes may be sufficient and 5 for Warms Spring Creek (Figure 12 right).

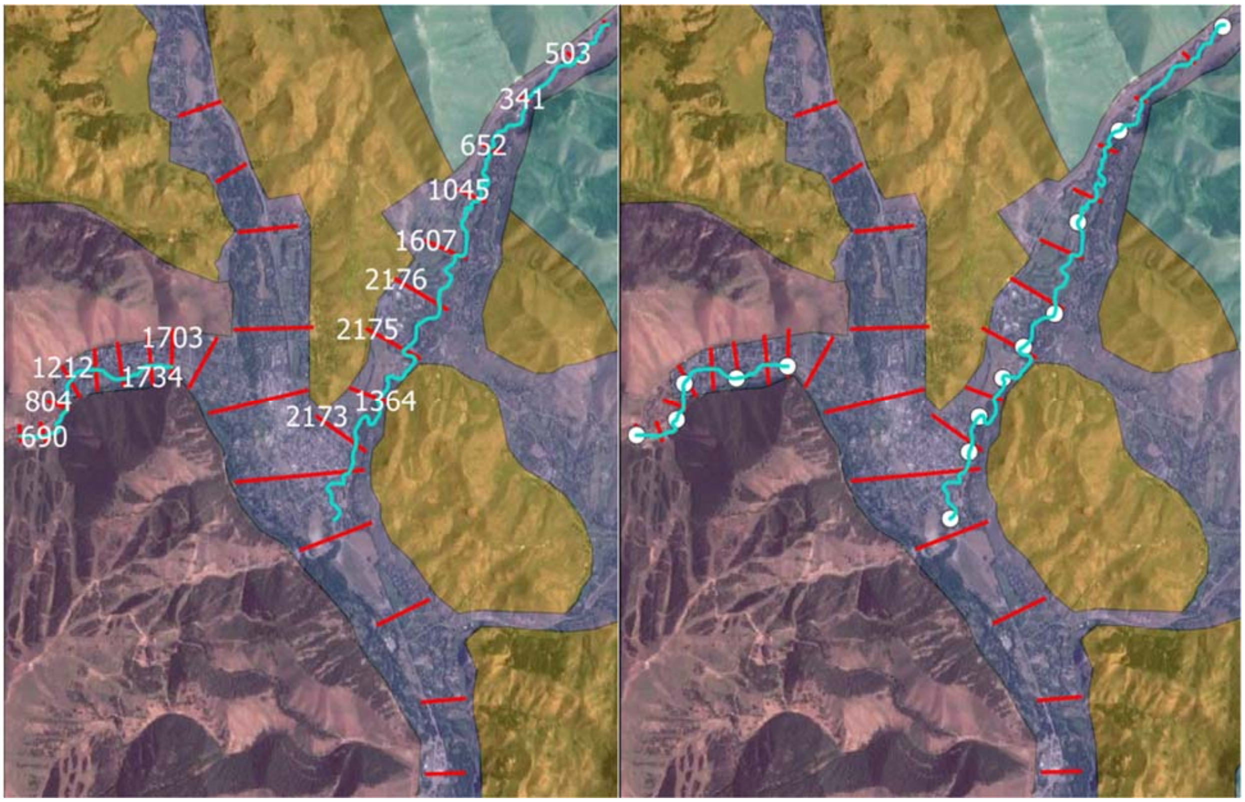

Figure 12: Changes in valley width reported in ft (red lines, left panel) and suggested locations (white solid circles) of subset of probes within each hydrogeomorphological segment (right figure). Geological (color coded shade) and valley confinement (red lines) along the Warm Springs (left blue line) and Trail Creek (right blue line).

We removed the probe in the middle of zone 2 for Trail Creek, because of the presence of the artificial reservoir, we used only 1 probe in Zone 1 and Zone 4 because probes were missing. This reduced the system to 5 probes that are identified with blue dots in Figure 13 from which quantifying the exchange between the river and the ground water. Similarly, we divided Warm Springs Creek into 2 zones: an upstream segment characterized by narrow valley width with sedimentary rocks and the second downstream segment with widening valley and alluvial deposit.

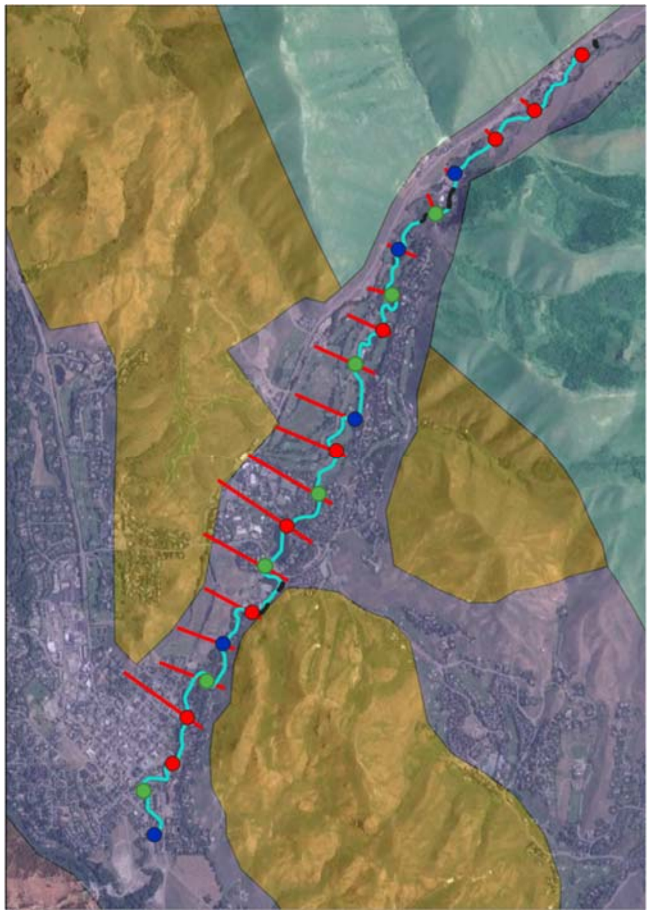

Figure 13: Trail Creek. Red lines are the estimated width of the aquifer/valley, dots are the probes (red without data, green and blue with data on June 30th, 2020)

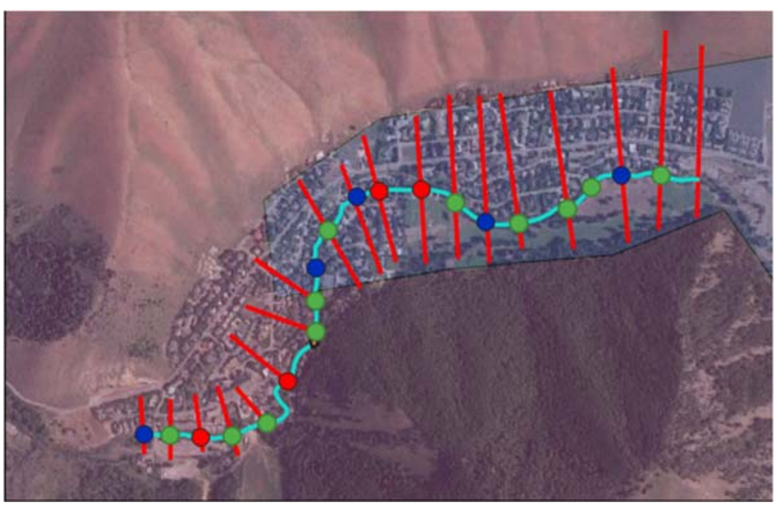

Figure 14: Warm Springs Creek. Red lines are the estimated width of the aquifer/valley, dots are the probes (red without data, green and blue with data on October 31st, 2019).

We have compared the thermal seepage calculated with all the probes active with the one calculated with a subset of probes chosen upon the previous consideration. For Trail Creek (Figure 15 left panel), we can notice that the thermal seepage calculated with the subset of probes match very well the seepage calculated with all the active probes. For Warm Springs Creek (Figure 15 right panel), the comparison between the in-stream discharge influenced by the thermal seepage discharges show similar values which matched the measured discharge.

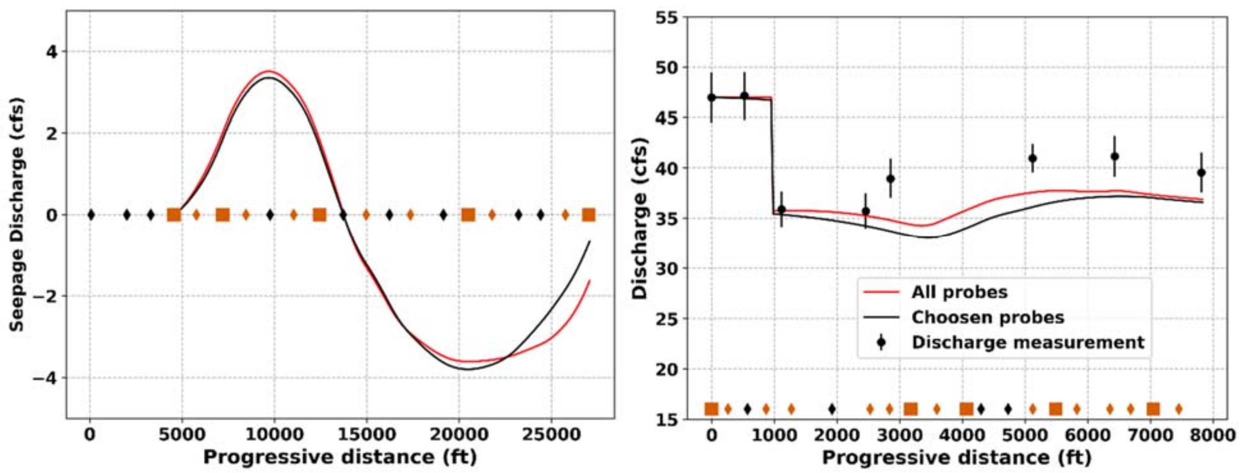

Figure 15: Trail Creek exchange (left panel) comparison on June 30th, 2020. Warm Springs Creek discharge (right panel) comparison on October 31st, 2019. Symbols (diamonds and square) indicate probes location with square the subset selected based on hydrogeomorphological characteristics. Black and vermilion colors indicate probes without and with data, respectively.

6 LIMITATIONS, CONCLUSIONS, AND NEXT STEPS

The data show that the vertical fluxes estimated with the thermal method provides good agreement with both the seepage surveys and difference in discharge between upstream and downstream gauging stations (ΔQ_{USGS}) during times with limited surface water extraction in both creeks. The method has the advantage to provide high-resolution temporal and spatial values, which can better characterize the aquifer-stream water exchange. Longitudinal summation of each reach exchange provides the total seepage discharge, Q_{creek}, that indicates the loss or gain of water through the streambed interface with the groundwater at daily or longer time scales. Conversely, the difference between surface discharge measurements, like ΔQ_{USGS}, accounts for the total loss or gain of water through surface water extraction, tributary inflows, evapotranspiration, and groundwater exchange (the last is ΔQ_{creek}). The values of ΔQ_{creek} and ΔQ_{USGS} are similar only when groundwater exchange occurs, i.e., no surface water surface extraction and negligible tributary inflows. Otherwise, the difference in values between the two methods quantify the net surface water extractions/withdrawals. For instance, in a losing stream ΔQ_{USGS} may overestimate the surface water withdrawn (some water is “lost” to the aquifer) while in a gaining reach it may underestimate them (as water is added by the groundwater). Thus, the thermal method helps constrain the amount of surface water actually extracted from the stream, as it accounts for any potential stream gains and/or losses.

This monitoring project spanned almost 3 water years, one wet water year (2019) that was followed by 2 extremely dry water years (2020 and 2021). The results show some very interesting interaction between stream and its aquifer and the role of the aquifer in maintaining surface water. Warm Springs Creek, which is generally a losing stream, loses less water as the climate get drier. By contrast, Trail Creek is a typically gaining stream that gains more water as in the dry water year. These two behaviors may indicate that the stream-aquifer relationship is to maintain a stable stream discharge during variable climatic conditions, by reducing losses in a losing stream and increasing gains in a gaining stream. Further data collection and analysis is required to understand it.

The two streams are very popular recreational areas where people float, fish, or walk, such that many probes have been removed. Even the latest probe design that had a smaller protruding profile in the water and was painted black to minimize visual identification experienced some vandalism, although much less than the original design. This is especially true for Trail Creek, where most of the probes near the campground and outside the golf course have been damaged or removed. Thus, we had to interpolate linearly to fill the gap generated by the lost probes. With all the consequent uncertainty insert into the calculation of the thermal seepages.

Further, we were expecting to see a greater relationship between streambed fluxes and local geologic constraints. For example, we expected upwelling and downwelling to occur upstream and downstream of exposed bedrock areas, but this was not noticeable from the data. This could be due to fractured bedrock in the region that lets the groundwater freely pass through.

For future directions and applications, we suggest that an important application of the probe exchange method adopted in this project would be to detect losing sections of irrigation canals, stream and well operations. Detection of losing sections can help in prioritizing area to reduce canal losses or increase groundwater recharge in designated areas. This method could inform which canal sections have the highest potential for recharging the groundwater and be locally optimized for that purpose. Alternatively, leaky sections of a canal can be spatially identified that may require further maintenance or lining to reduce seepage losses in specific areas. The method could be used also to better inform conjunctive use of surface and subsurface flows as their interaction can be better constrained.

7 References

Bredehoeft JD, Papadopulos IS. 1965. Rates of vertical groundwater movement estimated from the earth's thermal profile. *Water Resources Research* **1** (2): 325–328

Goto S, Yamano M, Kinoshita M. 2005. Thermal response of sediment with vertical fluid flow to periodic temperature variation at the surface. *Journal of Geophysical Research* **110**: B01106

Hatch C, Fisher AT, Revenaugh JS, Constantz J, Ruehl C. 2006. Quantifying surface water–groundwater interactions using time series analysis of streambed thermal records: Method development. *Water Resources Research* **42**: W10410

Keery J, Binley A, Crook N, Smith JWN. 2007. Temporal and spatial variability of groundwater–surface water fluxes: Development and application of an analytical method using temperature time series. *Journal of Hydrology* **336**: 1–16

Luce CH, Tonina D, Gariglio F, Applebee R. 2013. Solutions for the diurnally forced advection-diffusion equation to estimate bulk fluid velocity and diffusivity in streambeds from temperature time series. *Water Resources Research* **49** (1): 488–506 DOI: 10.1029/2012WR012380

Stallman RW. 1965. Steady 1 – dimensional fluid flow in a semi-infinite porous medium with sinusoidal surface temperature. *Journal of Geophysical Research* **70** (12): 282102827