Technical Memorandum

Date:	11/22/2021
To:	Larry Walker Associates
From:	Davids Engineering, Inc.
Topic:	**Monitoring Results of Shallow Piezometer Transect Study from May 2020 through November 2021 in the Shasta Valley, Siskiyou County, CA**

Executive Summary

Shallow piezometers were installed in three transects across the Shasta Valley in late April 2020: two transects along different reaches of the Shasta River and one along the Little Shasta River. One of the transects on the Shasta River was upstream of the confluence with the Little Shasta River (SRU), and the other was downstream of the confluence with the Little Shasta River (SRD). The transect along the Little Shasta River (LSR) is within the alluvial portion of the Little Shasta Valley. These piezometers, along with the stilling wells installed in the rivers, were instrumented to continuously monitor water surface elevations and temperatures in and adjacent to surface water features. The goal of monitoring shallow groundwater elevations and temperatures adjacent to surface water features was to identify the direction and gradient of groundwater flow near stream-aquifer boundaries, manifesting as either accretions to or depletions from surface water features. The monitoring results from May 2020 through November 2021 indicated that the Shasta River was primarily gaining in both transect locations during this period, while the Little Shasta River was losing at its transect location during this period. Current funding will allow the study to continue through December 2021, but it is recommended that monitoring continue beyond this date and potentially be expanded to include new areas of the Shasta Valley. Multiple years of data and additional sites will provide useful insights into how changing weather conditions, river stage and flow, water use and water management practices, and water availability (e.g., wet years vs. dry years) influence stream-aquifer interactions in the Shasta Valley.

1 Introduction

Davids Engineering (DE) was subcontracted under Larry Walker Associates (LWA) in an effort for the Shasta Valley Resource Conservation District (SVRCD) to better understand hydrological processes in the Shasta Valley[1]. DE focused primarily on surface water monitoring and focused studies for additional data collection to support Groundwater Sustainability Plan (GSP) development for the Shasta Valley (Valley) groundwater basin under the Sustainable Groundwater Management Act (SGMA). Funding for this project was provided in full or in part from the Water Quality, Supply, and Infrastructure Improvement Act of 2014 and through an agreement with the State Department of Water Resources (DWR). One of the studies by DE included the installation and continuous monitoring of piezometer transects along surface water features in the Shasta Valley to evaluate stream-aquifer interactions over space and time. Despite the diversity of geologic formations in the Shasta Valley and while there are instances of dry wells nearby to productive wells in many parts of the Valley, the valley wide groundwater system

[1] Although this study is currently ongoing, all work in this document is presented in the past tense.

appears to be hydrologically continuous across the extent of the Valley (Mack, 1960; DWR, 2015). Monitoring shallow groundwater elevations and temperatures adjacent to surface water features can help identify the direction and gradient of groundwater flow near stream-aquifer boundaries, manifesting as either accretions to or depletions from surface water features.

Shallow piezometers were installed in three transects across the Shasta Valley: two transects along different reaches of the Shasta River and one along the Little Shasta River (Figure 1). One of the transects on the Shasta River was upstream of the confluence with the Little Shasta River (SRU), and the other was downstream of the confluence with the Little Shasta River (SRD). The transect along the Little Shasta River (LSR) was within the alluvial portion of the Little Shasta Valley. All three transects were located within the boundary of the Shasta Valley groundwater basin. Each transect consisted of five measurement sites: four shallow piezometers and a temporary stilling well in the river; two piezometers were located on each riverbank, with one nearer and one further from the river, and the stilling well in the center of the transect. The five measurement sites were established in a line roughly perpendicular to the flow of the river and were instrumented with pressure transducers to measure temperature and water surface elevation. The piezometer boreholes were drilled, and the sites were instrumented in late April 2020. This TM presents monitoring results for the period from May 2020 through November 2021 along with a discussion of results and recommendations.

2 Methods

2.1 Conceptual Study Design

The installation of piezometer transects to evaluate stream-aquifer interactions was previously identified as a prioritized monitoring activity that would be beneficial for water management in the Shasta Valley (SVRCD, 2013). The measurement of shallow groundwater levels in the aquifer adjacent to a stream, through the installation and instrumentation of piezometers and measured relative to surface water levels in the stream, allows for the determination of hydraulic gradient and whether the stream is gaining or losing at the location of the piezometer transect (Figure 2). If water levels in the aquifer adjacent to the stream are at a higher elevation than stream water levels, it indicates that the stream is gaining at the location of the piezometer transect. Conversely, if water levels in the aquifer adjacent to the stream are at a lower elevation than stream water levels, it indicates that the stream is losing at the location of the piezometer transect. Continuous monitoring of these water levels over time allows for evaluation of seasonal changes or long-term trends.

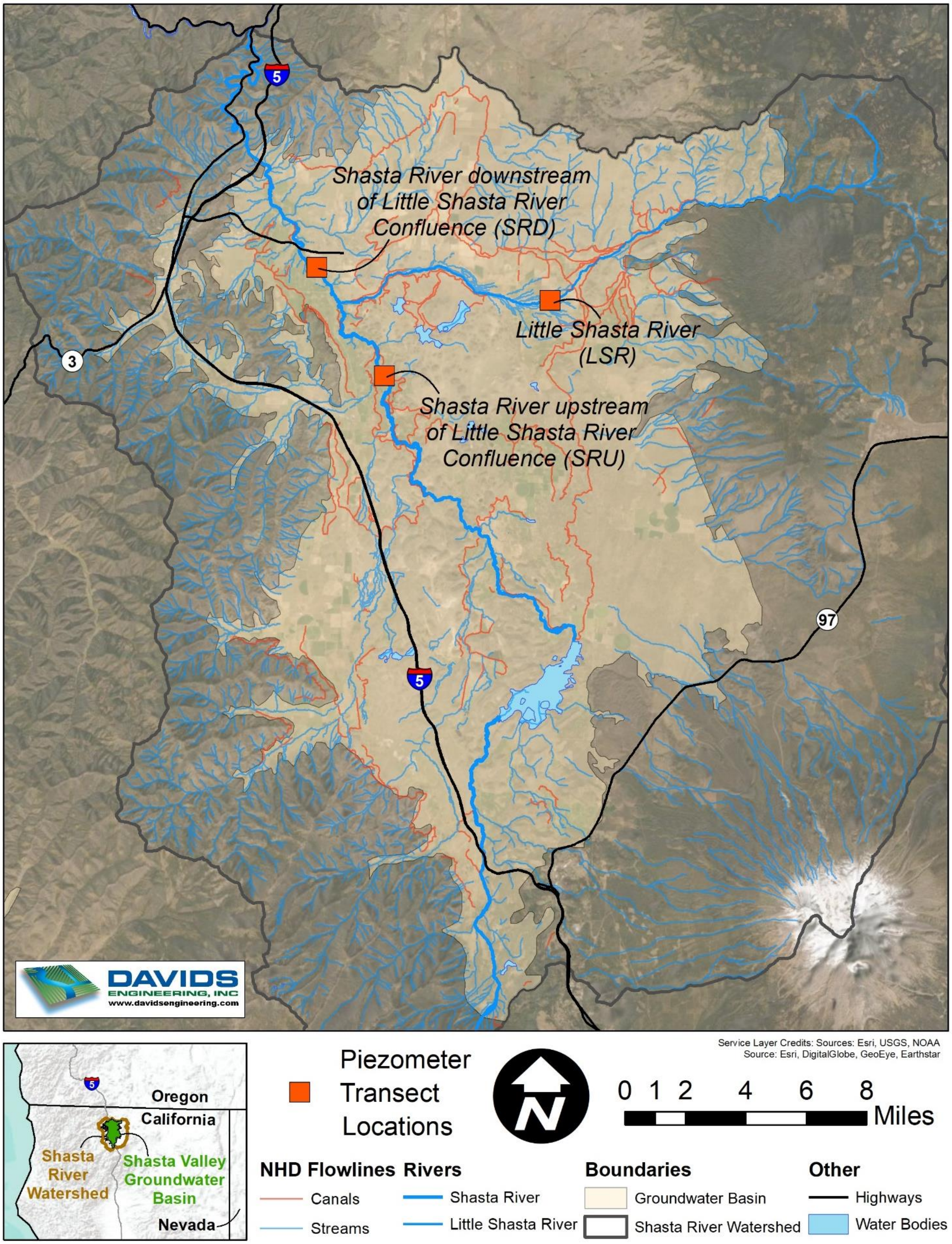

Figure 1. Approximate Location of Piezometer Transects within Shasta Valley.

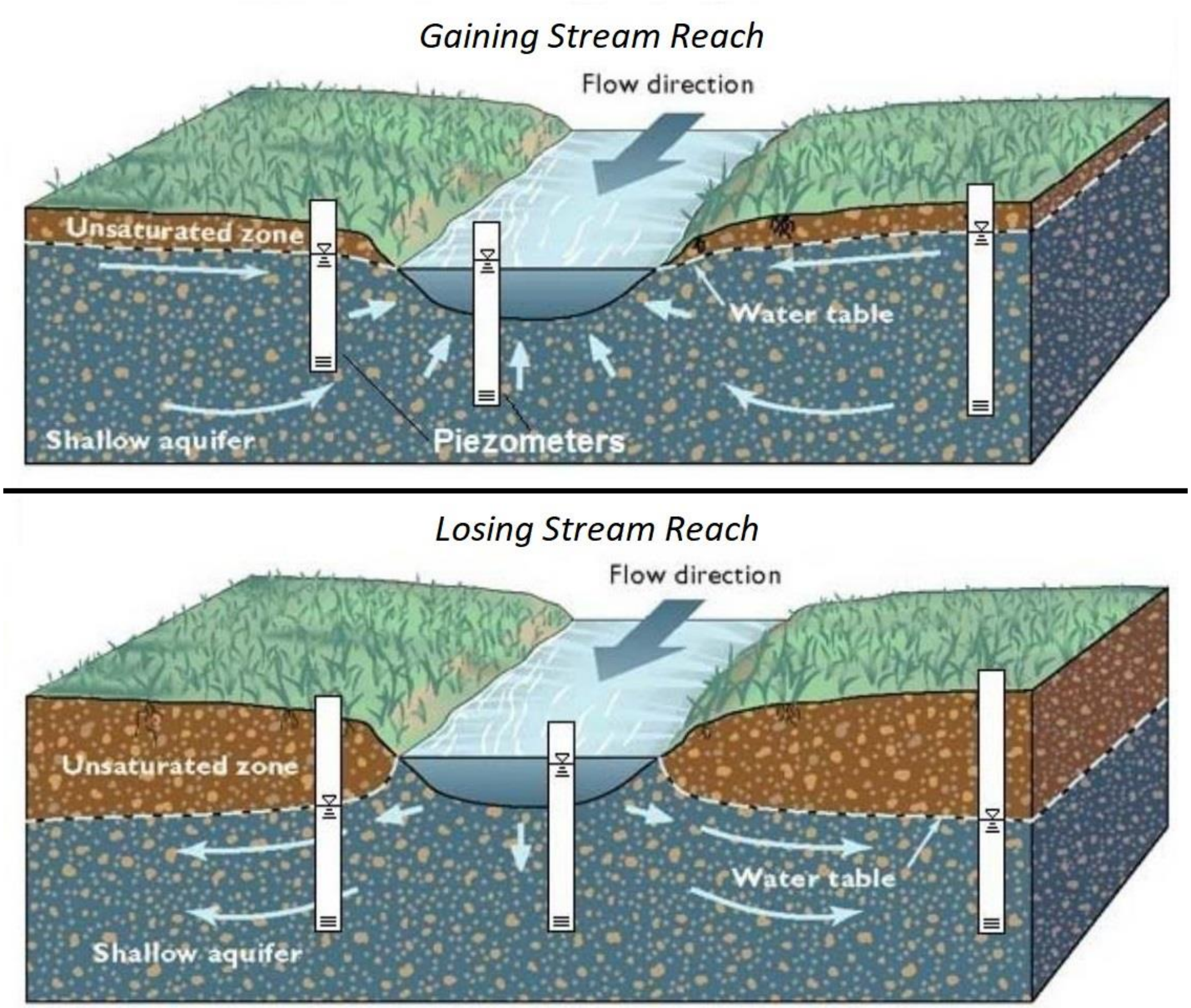

Figure 2. Conceptual Diagram of Piezometers in Gaining and Losing Stream Reaches (Modified from Winter et al., 1999).

Also, temperatures can be measured and monitored in the aquifer and stream to provide additional insight into stream-aquifer interactions (Constantz, 2008). Surface water is exposed to four heat-transfer mechanisms, most notably radiative heat input from the sun and convective heat transfer as water flows downstream and mixes. Although the influence of these is highly dependent on location, riparian conditions, and weather conditions, these typically lead to both higher temperatures in surface water than groundwater in summer months and more fluctuation in surface water temperature than groundwater temperature as the conditions influencing heat-transfer change. In a losing reach, the temperature in the shallow aquifer adjacent to the stream will more closely mirror surface water temperatures in the stream as surface water flows from the stream into the adjacent groundwater system. Conversely, in a gaining reach, the temperature in the shallow aquifer adjacent to the stream will remain more constant, not following surface water temperature trends as closely, as groundwater flows from the aquifer into the stream.

Both water levels, or water surface elevations, and temperature were contrasted and compared between shallow groundwater in piezometers and surface water features to evaluate stream-aquifer interactions at the three transects.

2.2 Study Design, Initiation, and Implementation

2.2.1 Piezometer Construction, Equipment Installation, Site Commissioning and Maintenance

The piezometer transect locations were determined through coordination between DE, LWA, and SVRCD staff and local stakeholders and landowners. A total of 12 piezometer boreholes were drilled, along with installation of screens, standpipes, filter pack, surface seals, and well caps, by Lawrence & Associates during April 2020. Each transect consists of four shallow piezometers and a temporary stilling well installed in the river in the center of the transect to measure surface water elevations. All piezometers and stilling wells were instrumented with Onset pressure transducers (Part # U20-001-04), and each transect has an additional pressure transducer installed in the open air to measure and account for atmospheric pressure, for a total of 18 pressure transducers. Measurement of water levels with these pressure transducers has a typical error of 0.01 ft and a maximum error of 0.02 ft (Onset, 2020). Pressure transducers were configured to log data on a 15-minute timestep. Following the installation of instrumentation, elevation surveys of each transect site were completed to determine water surface elevations relative to other locations in the transect[2]. These data were compiled and reviewed to determine site characteristics at the outset of the study at the beginning of May 2020.

After study initiation, SVRCD staff completed monthly site visits for data download and site maintenance activities. Data were organized, compiled, and processed using Onset's Hoboware Pro software, Python scripting, and a custom-built Microsoft Access database. The dataset presented in this TM from the start of the study through early November 2021 also underwent additional review and QA/QC measures.

2.2.2 Site Naming Convention

The naming convention used for this study was comprised of a Transect ID used to designate the transect, followed by a Pressure Transducer Location Code used to designate the location within the transect. The Transect ID used to distinguish each of the three transect locations is shown below in Table 1.

[2] During the elevation survey, elevation at the top of each piezometer was surveyed relative to a local benchmark and the depth-to-water in each piezometer standpipe was measured using a well sounder to determine relative water surface elevations for each piezometer transect.

A Leica Disto 20x automatic optical level and 16 ft aluminum telescoping Philadelphia rod were used by a two-man team to survey the well cap elevations and water surface elevation in the river at each transect; the elevation of the north rim of the well cap at the Left Bank Near (LBN) location was used as the local benchmark. The distance from the well cap to the top of the piezometer standpipe was measured using a tape measure, and the depth-to-water from the top of the piezometer standpipe was measured using a Global Water WL500-100M water level sounder to determine water surface elevations relative to other locations in the transect. Latitude and longitude for each transect location were recorded using a GPS-enabled device, and the water surface elevation above mean sea level at the local benchmark was determined by entering the coordinates into Google Earth Pro.

Table 1. Transect Name and ID.

Transect ID	Transect Name
SRU	Shasta River upstream of the Little Shasta River confluence
SRD	Shasta River downstream of the Little Shasta River confluence
LSR	Little Shasta River in Little Shasta Valley

Each transect includes six pressure transducers: one measuring atmospheric pressure[3], one installed in a temporary stilling well in the river to measure surface water levels, and four installed in piezometers (two on each bank of the river) to measure shallow groundwater levels. The codes shown below in Table 2 are descriptors to uniquely identify each pressure transducer at each transect site. The codes below (individually or combined) are added to the right of the Transect ID to create a SiteID to uniquely identify each pressure transducer of the 18 total installed as part of the study (Table 3).

Table 2. Pressure Transducer Location Codes.

Code	Description
LB	Left bank, looking D/S
RB	Right bank, looking D/S
N	Near, Closer to stream/river
F	Far, Further to stream/river
SWE	Surface Water Elevation
ATC	Atmospheric Compensation

[3] The pressure transducer measuring atmospheric pressure was installed in the open air just beneath the well cap in the Left Bank Near (LBN) piezometer standpipe.

Table 3. SiteID, Site Description, Associated Atmospheric Compensation Site (i.e. ATC SiteID).

SiteID	Site Description	ATC SiteID
SRU-LBN	Shasta River upstream of the Little Shasta River confluence, Left Bank near River	SRU-ATC
SRU-LBF	Shasta River upstream of the Little Shasta River confluence, Left Bank further from River	SRU-ATC
SRU-RBN	Shasta River upstream of the Little Shasta River confluence, Right Bank near River	SRU-ATC
SRU-RBF	Shasta River upstream of the Little Shasta River confluence, Right Bank further from River	SRU-ATC
SRU-SWE	Shasta River upstream of the Little Shasta River confluence, Surface Water Elevation	SRU-ATC
SRU-ATC	Shasta River upstream of the Little Shasta River confluence, Atmospheric Pressure Compensation	SRU-ATC
SRD-LBN	Shasta River downstream of the Little Shasta River confluence, Left Bank near River	SRD-ATC
SRD-LBF	Shasta River downstream of the Little Shasta River confluence, Left Bank further from River	SRD-ATC
SRD-RBN	Shasta River downstream of the Little Shasta River confluence, Right Bank near River	SRD-ATC
SRD-RBF	Shasta River downstream of the Little Shasta River confluence, Right Bank further from River	SRD-ATC
SRD-SWE	Shasta River downstream of the Little Shasta River confluence, Surface Water Elevation	SRD-ATC
SRD-ATC	Shasta River downstream of the Little Shasta River confluence, Atmospheric Pressure Compensation	SRD-ATC
LSR-LBN	Little Shasta River in Little Shasta Valley, Left Bank near River	LSR-ATC
LSR-LBF	Little Shasta River in Little Shasta Valley, Left Bank further from River	LSR-ATC
LSR-RBN	Little Shasta River in Little Shasta Valley, Right Bank near River	LSR-ATC
LSR-RBF	Little Shasta River in Little Shasta Valley, Right Bank further from River	LSR-ATC
LSR-SWE	Little Shasta River in Little Shasta Valley, Surface Water Elevation	LSR-ATC
LSR-ATC	Little Shasta River in Little Shasta Valley, Atmospheric Pressure Compensation	LSR-ATC

3 Results

This section presents the results of monitoring water surface elevations and temperature at each of the transect locations, along with some observations and a discussion of the results. Finally, a comparison of the results at the different transects is included. Attachment A includes a spreadsheet with daily average water surface elevations and temperatures for all 15 measurement sites.

3.1 Shasta River Upstream of Little Shasta River Confluence (SRU)

Figure 3 is a heatmap depicting the daily average values of water surface elevation and temperature for the five monitoring sites at the SRU transect. Figure 4 is a heatmap depicting the daily average difference between the water surface elevation and temperature for each of the shallow piezometers in reference to the surface water location (calculated as surface water subtracted from groundwater)[4]. Although the heatmaps depict transect location results directly alongside one another, the distances between piezometers varies. For this transect, the Right Bank Near (RBN) piezometer was located roughly 160 feet from the river edge and located within an inside bend of the river, and the Right Bank Far (RBF) piezometer was located roughly 520 feet from the river edge (e.g., roughly 360 feet further from the river than RBN location). The LBN piezometer was located roughly 140 feet from the river edge, and the LBF piezometer was located roughly 510 feet from the river edge. The Shasta River had continuous flow past the transect location throughout the study period from May 2020 through November 2021. The text below includes observations based on the study results seen in Figures 3 and 4.

The river stage remained relatively stable during the monitoring period, with total fluctuations in stage of typically less than two feet. River stage remained steady from May through September 2020, after which there was an increase in stage from late September 2020 through mid-November 2020. This increase coincides with the end of the irrigation season and cessation of upstream diversions and pumping and the beginning of the winter season with increased precipitation. The river stage remained steady from mid-November 2020 through April 2021, when it decreased to and remained at levels similar to the 2020 spring and summer. This decrease coincided the start of the 2021 irrigation season. The river stage in November 2021 was the highest during the entire monitoring period.

Groundwater elevations in the piezometers on both sides of the river tended to be higher than the surface water elevation, or stage, in the river, with elevations increasing with distance from the river. In the further piezometers on both sides of the river, there were sharp increases in water surface elevation periodically during the 2020 and 2021 irrigation seasons. At the RBF location, there was a similar sharp decrease shortly after the increase; at the LBF location, there was a decrease immediately after the increase peaked, but it tended to be a more gradual decrease than seen at the RBF location. At the nearer piezometers on both sides of the river, similar increase/decrease trends were seen with smaller changes in water surface elevation, although the connection is more obviously seen along the left bank. The temporal trends in water surface elevations for LBF and LBN were closely correlated (i.e., when one when up or down, the other did as well), while the correlation between RBF and RBN was less

[4] Roughly one month of data was lost due to equipment failure during February 2021 at the LBN site, and two months of data were lost due to equipment malfunction from August through October 2021 at all transect sites.

pronounced. The lands on either side of the river in this transect location were irrigated, and these periodic pulses of water observed in piezometers were likely reflective of deep percolation from irrigation events reaching the water table. Because the groundwater elevations are higher than the stream during these periods, recharge from applied irrigation water appears to be returning to the Shasta River. Additionally, there is the potential for surface and subsurface inflows along Julien Creek as it flows east towards its confluence with the Shasta River corridor to influence the higher groundwater elevations seen along the left bank in the vicinity of this transect location.

As expected, the surface water temperature in the Shasta River showed the greatest fluctuations with seasonal highs and lows that are more extreme than seen in the adjacent shallow groundwater system. Although fluctuating with weather conditions, sun exposure, and ambient air temperature, it generally increased to a seasonal peak around 70˚F in July 2020, and then decreased to a seasonal low around 45˚F in December 2020. The seasonal peak temperature in July 2021 was around 65˚F, noticeably cooler than July 2020. Groundwater temperatures were more stable, with seasonal lows of around 50˚F in May 2020 and 2021 and seasonal peaks of around 60˚F in October and November 2020 and 2021. The piezometers along the left bank of the river showed more minimal temperature fluctuations than those along the right bank of the river. The RBN temperature was noticeably different than other piezometer sites, with relatively higher temperatures. This may be due to its location on an inside bend of the Shasta River, where it may be more influenced by surface water conditions than the other piezometers. During the irrigation season, periodic increases in temperature are also observed, which may be indicative of relatively warmer irrigation water moving through the shallow groundwater system.

With the exception of the RBN piezometer in late July and early August in 2020 and sporadic intervals during the 2021 irrigation season, all piezometers showed higher groundwater elevations than surface water elevations during the study period. Groundwater temperatures also did not show strong responses or similarities to surface water temperatures. These results indicate that the Shasta River was gaining in the transect location over the study period.

Interestingly, changes in groundwater levels due to irrigation events on the left bank do not seem to correlate strongly with changes in groundwater temperatures as might be expected due to relatively warm irrigation-related deep percolation reaching the water table. This may be due to the integrated pressure and temperature sensors being installed at a depth that did not experience the thermal changes from deep percolation that the top of the water table may have experienced.

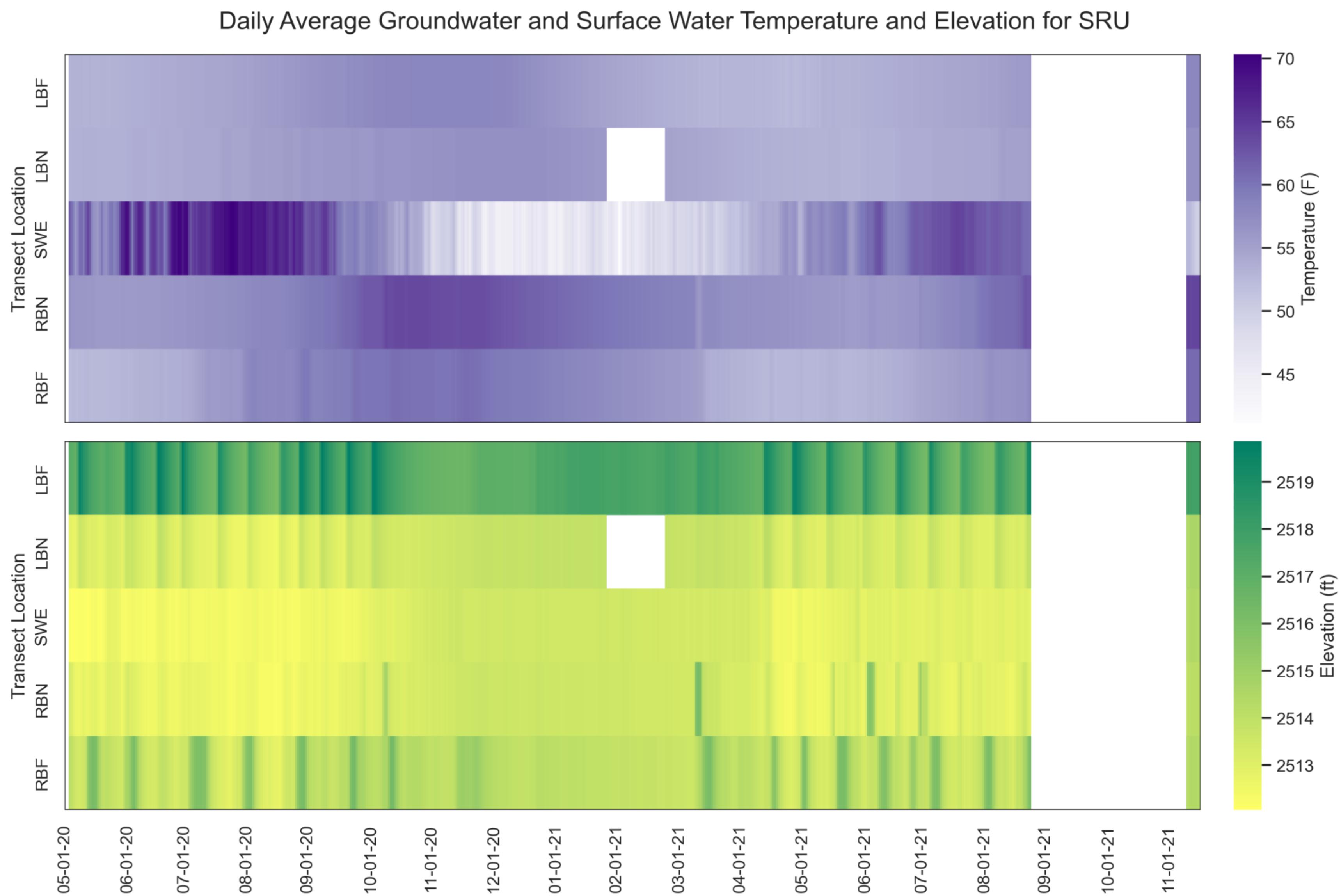

Figure 3. Daily average groundwater and surface water elevations and temperatures for the Shasta River Upstream (SRU) transect; monitoring locations are the left bank far (LBF), left bank near (LBN), surface water elevation (SWE), right bank near (RBN), and right bank far (RBF).

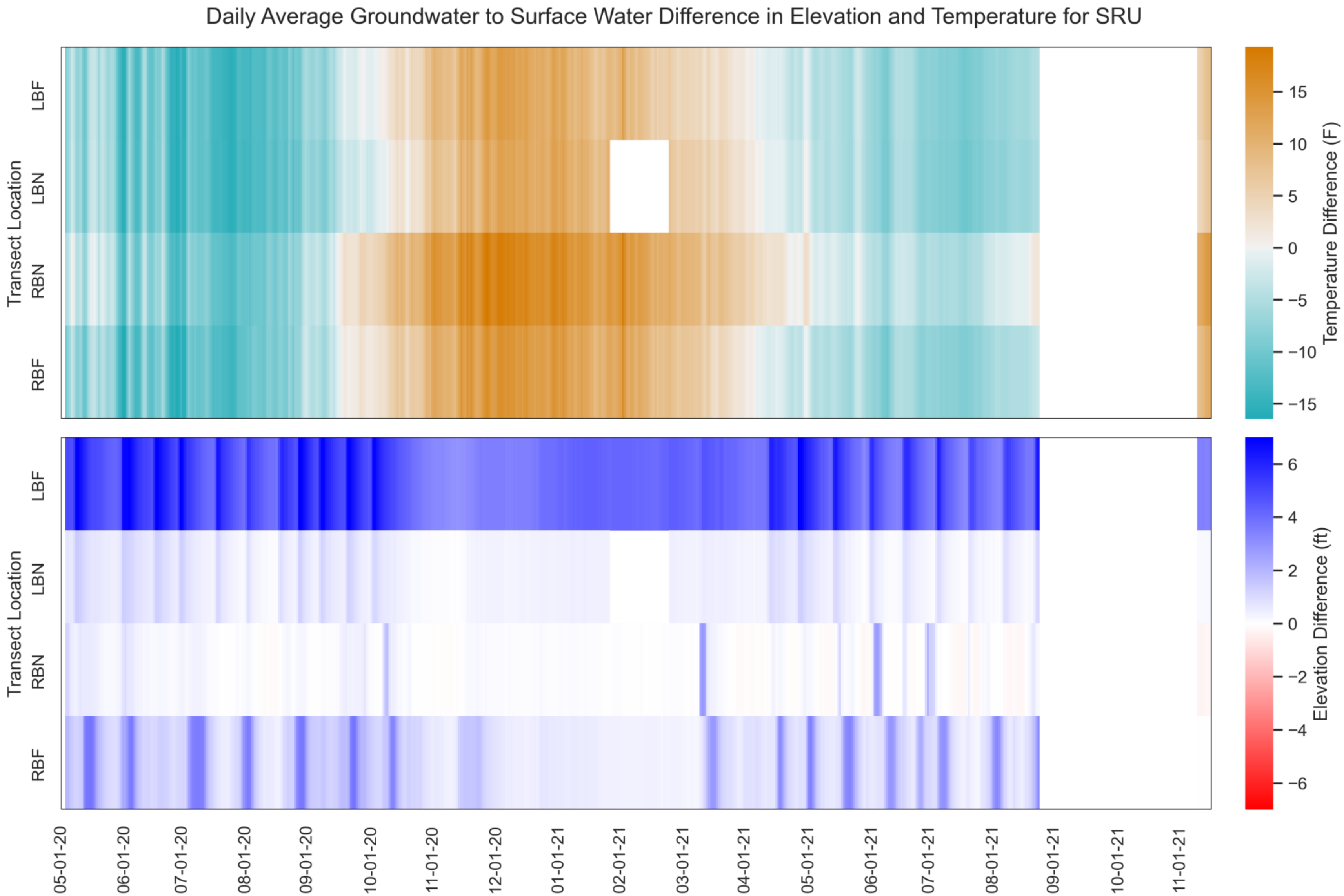

Figure 4. Daily average difference in groundwater and surface elevations and temperatures (Groundwater – Surface Water) for the Shasta River Upstream (SRU) piezometers installed at left bank far (LBF), left bank near (LBN), right bank near (RBN), and right bank far (RBF).

3.2 Shasta River Downstream of Little Shasta River Confluence (SRD)

Figure 5 is a heatmap depicting the daily average values of water surface elevation and temperature for the five monitoring sites at the SRD transect, and Figure 6 is a heatmap depicting the daily average difference between the water surface elevation and temperature for each of the shallow piezometers in reference to the surface water location (calculated as surface water subtracted from groundwater)[5]. Although the heatmaps depict transect location results directly alongside one another, the distances between piezometers varies. For this transect the Right Bank Near (RBN) piezometer was located roughly 170 feet from the river edge, and the Right Bank Far (RBF) piezometer was located roughly 360 feet from the river edge (e.g. roughly 190 feet further from the river than RBN location). The LBN piezometer was located roughly 70 feet from the river edge, and the LBF piezometer was located roughly 260 feet from the river edge. The Shasta River had continuous flow past the transect location throughout the study period from May 2020 through November 2021. The text below includes observations based on the study results seen in Figures 5 and 6.

The river stage remained relatively stable during the monitoring period, with total fluctuations in stage of less than two feet. Apart from fluctuations in late May 2020, river stage remained steady from May through mid-September 2020. The second half of September showed increasing stage, culminating in a roughly 6 inch increase from September 30th to October 1st. This final increase coincides with the end of the irrigation season and cessation of upstream diversions and pumping. The river stage remained relatively steady from October 2020 through April 2021, when it decreased to and remained at levels similar, but slightly lower, than to the spring and summer of 2020. This decrease coincided with the start of the 2021 irrigation season. The river stage in November 2021 was at a similar elevation as in November 2020.

Groundwater elevations in the piezometers on both sides of the river tended to be higher than the surface water elevation, or stage, in the river through most of the study period, with elevations increasing with distance from the river. At the LBF location, there were periodic sharp increases in water surface elevation followed by a more gradual decrease after the increase peaked during the 2020 and 2021 irrigation seasons. During the late summer in 2020 and 2021, the left bank also had periods with groundwater elevations similar to or slightly lower than surface water elevations. Groundwater levels along the right bank tended to be higher in elevation than along the left bank and had fewer and less extreme fluctuations both day-to-day and seasonally. Groundwater elevations increased on both sides of the river from late September through December 2020, similar to surface water elevation trends, and elevations in November 2021 were similar to those in November 2020 at all transect locations. At the nearer piezometers on both sides of the river, the fluctuations seen appeared to align with fluctuations at the further piezometers, indicating a strong hydrological connection. Although lands directly adjacent to the river and immediately surrounding the piezometers were not irrigated on either bank, there was irrigation of upgradient lands resulting in periodic tailwater or seepage inflows towards the river in the vicinity in this transect location; increases in groundwater levels observed in piezometers were likely reflective of irrigation events on these upgradient lands. Additionally, there is the potential for surface

[5] Two months of data were lost due to equipment malfunction from August through October 2021 at all transect sites.

and subsurface inflows along the Little Shasta River corridor to influence higher groundwater elevations seen along the right bank in this transect location.

As expected, the surface water temperature in the Shasta River showed the greatest fluctuations with seasonal highs and lows that are more extreme than seen in the adjacent shallow groundwater system. Although fluctuating with weather conditions, sun exposure, and ambient air temperature, it generally increased to seasonal peaks around 75˚F in July 2020 and 2021, and decreased to a seasonal low temperature around 40 ˚F in December 2020 and January 2021. Groundwater temperatures were more stable but showed differences between the right and left banks. The temperatures at the two piezometer locations along the right bank were very similar to one another and noticeably higher than along the left bank; the right bank piezometers increased to seasonal peaks around 60˚F from September through November and seasonal lows between 50˚F and 55˚F from March through May in 2020 and 2021. Along the left bank, the two piezometers showed different seasonal trends. Although both had seasonal lows between 45˚F and 50˚F from January through May, the LBF temperature increased more rapidly and has a higher seasonal peak around 60˚F in August while the LBN temperature increased more slowly and had a seasonal peak around 55˚F from September through November. The differences in temperature along each bank of the river in this location are indicative of different sources and influences.

With the exception of groundwater elevations along the left bank during the late summer period, piezometers showed higher groundwater elevations than surface water elevations during the study period. Groundwater temperatures also did not show strong responses or similarities to surface water temperatures, although differences are seen between the piezometer locations within the transect. These results indicate that the Shasta River was generally gaining in the transect location over the study period, with some potential losses to the shallow groundwater system adjacent to the left bank in the late summer.

Interestingly, changes in groundwater levels due to irrigation events do not seem to correlate with changes in groundwater temperatures as might be expected due to relatively warm irrigation-related deep percolation reaching the water table. This may be due to the integrated pressure and temperature sensors being installed at a depth that did not experience the thermal changes from deep percolation that the top of the water table may have experienced.

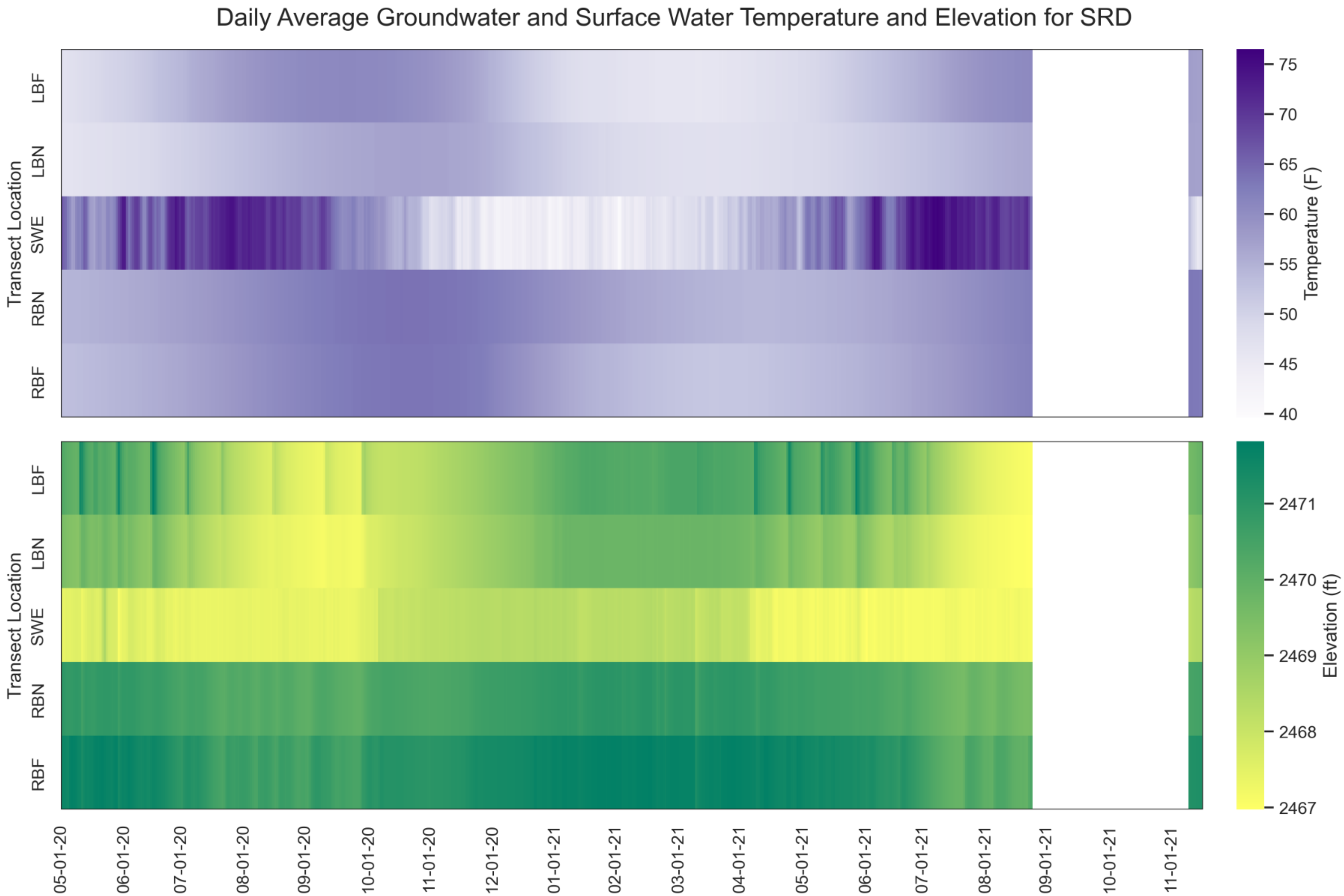

Figure 5. Daily average groundwater and surface water elevations and temperatures for the Shasta River Downstream (SRD) transect; monitoring locations are the left bank far (LBF), left bank near (LBN), surface water elevation (SWE), right bank near (RBN), and right bank far (RBF).

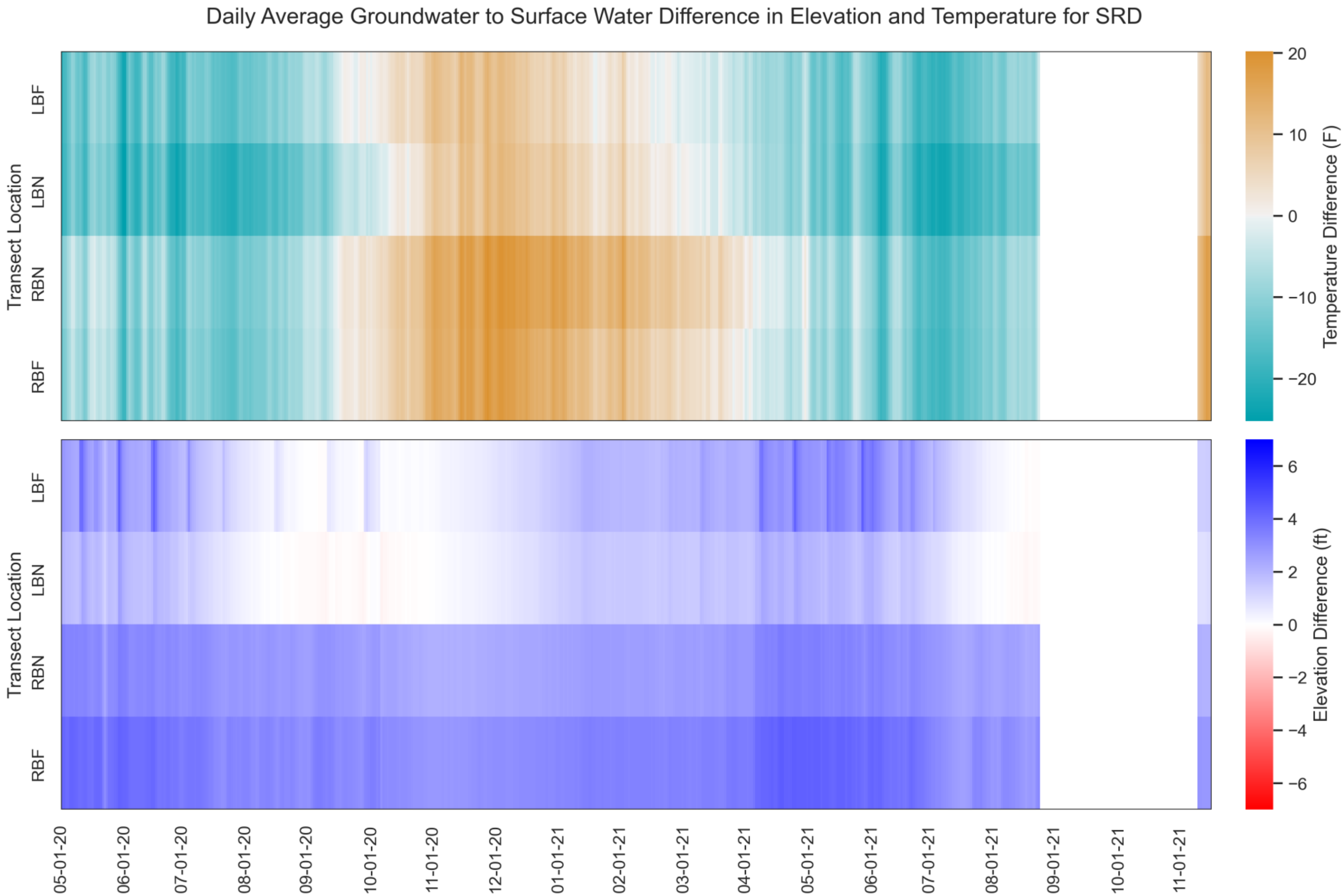

Figure 6. Daily average difference in groundwater and surface elevations and temperatures (Groundwater – Surface Water) for the Shasta River Downstream (SRD) piezometers installed at left bank far (LBF), left bank near (LBN), right bank near (RBN), and right bank far (RBF).

3.3 Little Shasta River in the Little Shasta Valley (LSR)

Figure 7 is a heatmap depicting the daily average values of water surface elevation and temperature for the five monitoring sites at the LSR transect, and Figure 8 is a heatmap depicting the daily average difference between the water surface elevation and temperature for each of the shallow piezometers in reference to the surface water location (calculated as surface water subtracted from groundwater)[6]. Although the heatmaps depict transect location results directly alongside one another, the distances between piezometers varies. For this transect the Right Bank Near (RBN) piezometer was located roughly 120 feet from the river edge, and the Right Bank Far (RBF) piezometer was located roughly 520 feet from the river edge (e.g., roughly 400 feet further from the river than RBN location). The LBN piezometer was located roughly 70 feet from the river edge, and the LBF piezometer was located roughly 420 feet from the river edge. The Little Shasta River did not have continuous flow throughout the study period. The text below includes observations based on the results seen in Figures 7 and 8.

Apart from a few spikes in stage likely associated with precipitation events, the river stage remained relatively steady from the start of the study in May 2020 until beginning to decline in late June 2020. During a monthly site visit on 6/16/20 the river was noted to have continuous flow, but during the next site visit on 7/17/20 it was noted that surface water was only present in isolated pools. On 8/22/20 the water level in the isolated pool where surface water elevations were monitored fell below the level where the pressure transducer was installed, making further data collection at this site impossible until levels rise. This was a decline in stage of roughly three feet. Water level increased above the pressure transducer again in mid-October 2020, and in early November the river stage rapidly increased more than three feet as winter flows returned to the Little Shasta River. River stage remained relatively stable from November 2020 through late June 2021, although a modest decrease is seen in February and March 2021. After late June 2021, the stage in the river steadily declines at a similar rate to that seen during the same period in 2020. An equipment malfunction in mid-August stopped the data record, although water levels were close to dropping below the pressure transducer elevation. The river stage in November 2021 was at a similar elevation as in November 2020, having increased over three feet in elevation from the prior measurement in August 2021.

Unfortunately, due to underlying geological conditions (primarily the presence of large cobbles) the piezometer boreholes were not able to be drilled as deeply in this transect as the other two transects. Groundwater levels in three of the four piezometers dropped below the level where the pressure transducer was installed at the bottom of the standpipe during the study period:

- At LBF (the shallowest piezometer borehole) this occurred on 6/19/20 and the only period where groundwater levels were higher than the pressure transducer again was during March and April 2021 at the seasonal high.
- At RBN this occurred on 9/12/20, but levels increased above the pressure transducer elevation again in late October 2020.
- At LBN this occurred on 10/10/20. but levels increased above the pressure transducer elevation again in late October 2020.

[6] Two months of data were lost due to equipment malfunction from August through October 2021 at all transect sites.

Data collection at these sites was not possible while groundwater levels were lower than the pressure transducer elevations, and these transect locations would benefit from deepened boreholes, which would allow pressure transducers to be installed at a greater depth and lower elevation.

Groundwater elevations in the piezometers on both sides of the river were consistently lower than the surface water elevation throughout the study period, with elevations decreasing with distance from the river. In contrast to the other two transects along the Shasta River, the lands on either side of the river in this transect location were not irrigated. During May and early June 2020, there were short periods of increased stage in the Little Shasta River, and the groundwater levels in the piezometers (at lower elevation than river stage) also showed increased water levels following increased stage in the Little Shasta River. This was potentially reflective of water flow from the river into the adjacent groundwater system on either bank in the location of the transect. Generally, groundwater levels at each piezometer all roughly followed the seasonal trends seen in surface water elevation in the Little Shasta River. Seasonal declines in shallow groundwater elevation began in late spring 2020 and 2021 (preceding declines in river stage, which began in late June) and continued until fall or early winter, when they began to increase as or after stage increased in the Little Shasta River. Although the general trends at each location are similar, there are still noticeable differences in groundwater elevations and trends between piezometers in the transect. The LBN location typically most closely parallels the surface water elevation in the Little Shasta River, both in changes over time and in elevation, suggesting a closer hydrological connection than other transect locations. The RBN location was typically to be lower in elevation than LBN, although it has similar seasonal high and low elevations; its elevations changes tend to be more gradual than the LBN location. The LBF location had a similar groundwater elevation to the other transect sites in May 2020, but did not recover to the same seasonal high in the spring of 2021. Finally, the RBF location showed the least decline and overall fluctuation of all measurement sites in the transect. For the several days in mid-August 2020 and 2021 prior to the end of the SWE data record, the RBF site showed higher water level than the SWE location. This indicates potential groundwater inflows from upgradient sources to the RBF transect location that were not present at other piezometer locations in this transect.

As expected, the surface water temperature in the Little Shasta River showed the greatest fluctuations with seasonal highs and lows that are more extreme than seen in the adjacent shallow groundwater system. Although fluctuating with weather conditions, sun exposure, and ambient air temperature, it generally increased to seasonal peaks between 70˚F and 75˚F in July and August 2020 and 2021, and decreased to a seasonal low temperature around 40 ˚F from December 2020 through February 2021. Groundwater temperatures were more stable, with seasonal lows of around 50˚F in March and April and seasonal peaks of around 60˚F in September and October. The trends at each site were similar, although the RBF temperature was slightly higher than the other locations. Groundwater temperatures tended to be higher than the surface water temperature in the winter months and lower in the summer months.

Piezometers consistently showed lower groundwater elevations than surface water elevations during the study period; these results indicate that the Little Shasta River was losing in the transect location during the study period.

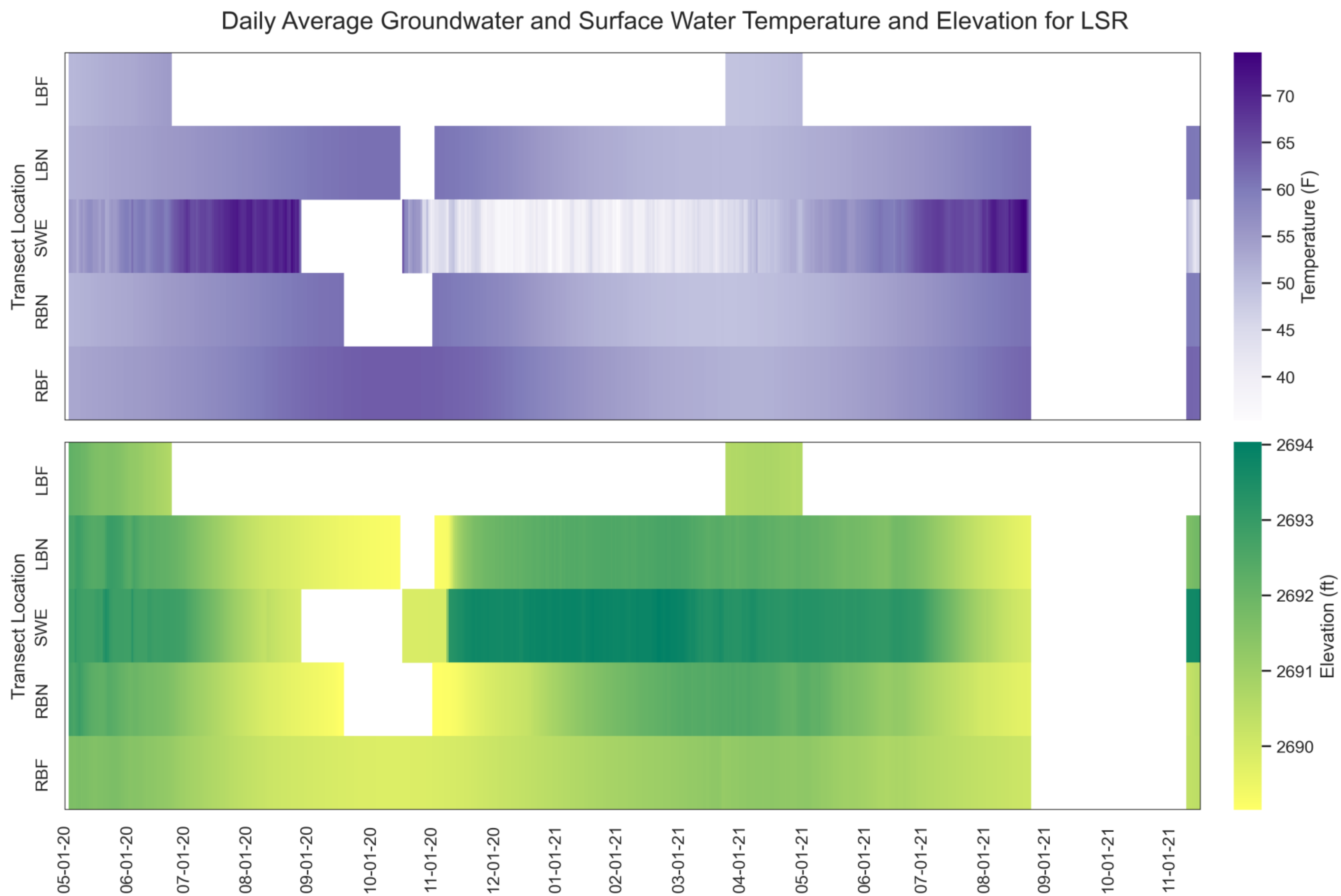

Figure 7. Daily average groundwater and surface water elevations and temperatures for the Little Shasta River (LSR) transect; monitoring locations are the left bank far (LBF), left bank near (LBN), surface water elevation (SWE), right bank near (RBN), and right bank far (RBF).

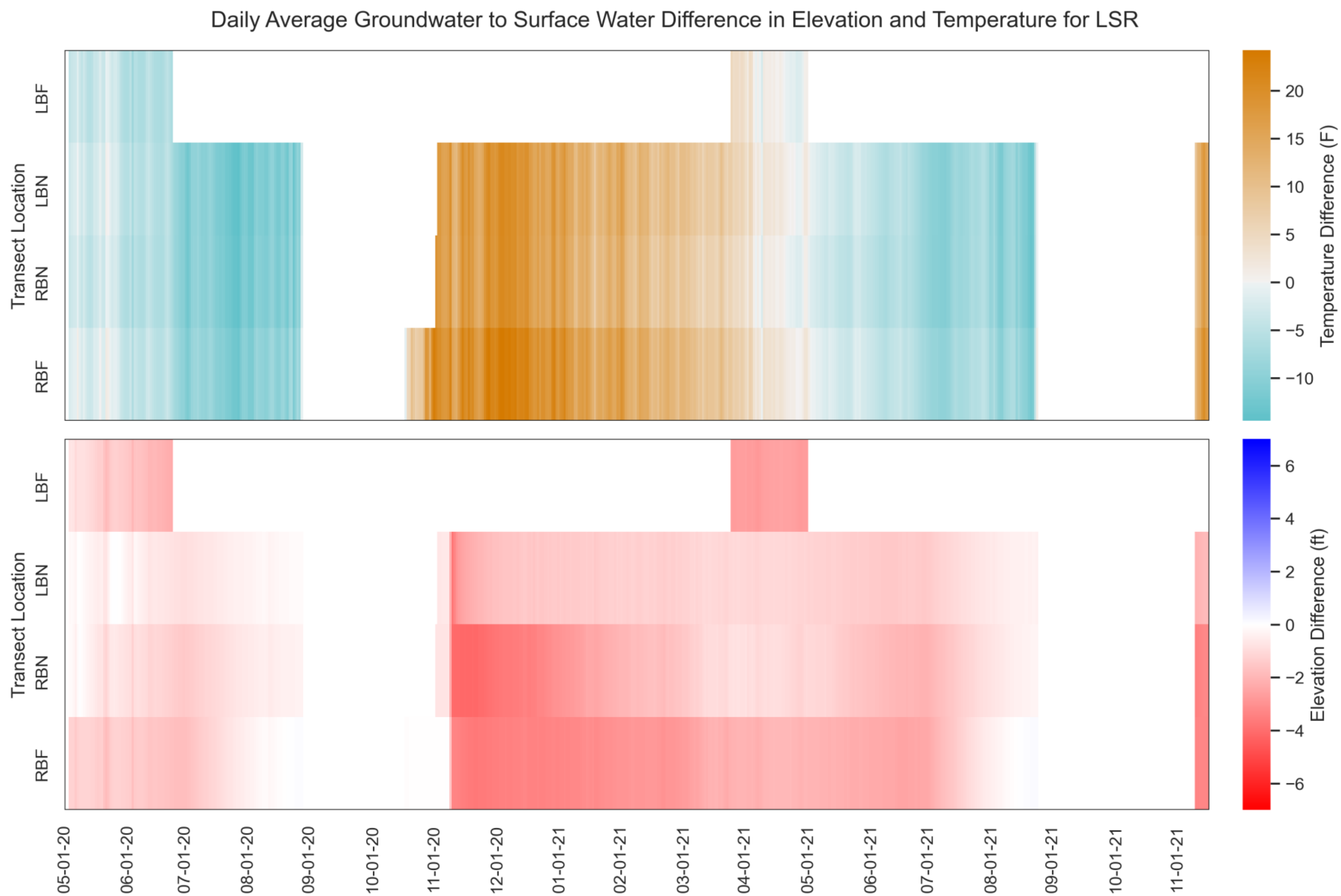

Figure 8. Daily average difference in groundwater and surface elevations and temperatures (Groundwater – Surface Water) for the Little Shasta River (LSR) piezometers installed at left bank far (LBF), left bank near (LBN), right bank near (RBN), and right bank far (RBF).

3.4 Average Monthly Water Elevations

Figure 9 is a heatmap showing average monthly water elevations for the three piezometer transects using data from both 2020 and 2021, which provides a sense of monthly trends at each site. The monitoring locations within each transect are shown equally spaced in the figures, which is not representative of actual distances between locations in the field. The results show that the surface water elevations for the two Shasta River transects (SRU and SRD) were generally lower than the shallow groundwater elevations on either bank of the river, indicating potential gains in the transect location. In contrast, the Little Shasta River transect (LSR) show that surface water elevations were generally higher than the shallow groundwater elevations on either bank of the river, indicating potential losses in the transect location. The blank, white values for the LSR transect are months during which data are unavailable due to water levels dropping below the elevation of the pressure transducers for those transect locations.

3.5 Summary of Average Stream-Aquifer Differences and Comparison of Transects

Figure 10 is a heatmap depicting the daily average water surface elevations for the five monitoring sites at each of the three transects, and Figure 11 is a heatmap depicting the daily average difference between the water surface elevations for each of the shallow piezometers in reference to the surface water location (calculated as surface water subtracted from groundwater)[7]. Figures 12 and 13 are similar heatmaps to Figures 10 and 11 that depict the daily average temperature values instead of water surface elevations. The difference calculations for Figures 11 and 13 mean that a positive water surface elevation or temperature difference indicates a higher average water surface elevation or temperature in the piezometers than in the surface water, and vice versa. These results were shown in Sections 3.1 through 3.3 for each individual transect but are included here for ease of comparison between transects to review overall trends and results across the monitoring locations.

Overall, shallow groundwater levels relative to surface water showed relatively consistent trends during the study period, and the 2021 irrigation season results were similar to the 2020 irrigation season results. The shallow groundwater levels in the two transects along the Shasta River tended to be higher in elevation and have a hydraulic gradient towards the river, while in the Little Shasta River they tend to be lower in elevation and have a hydraulic gradient away from the river. While these trends were influenced by a variety of factors, one that may contribute to differences is the irrigation of lands on either side of the river, as the lands along the Shasta River in the vicinity of or upgradient of the transect were irrigated while lands along the Little Shasta River were unirrigated for a larger area around and upgradient of the transect. For the two transects along the Shasta River, the effects of irrigation are clearly seen through periodic spikes in shallow groundwater elevations during the irrigation season.

[7] Two months of data were lost due to equipment malfunction from August through October 2021 at all transect sites.

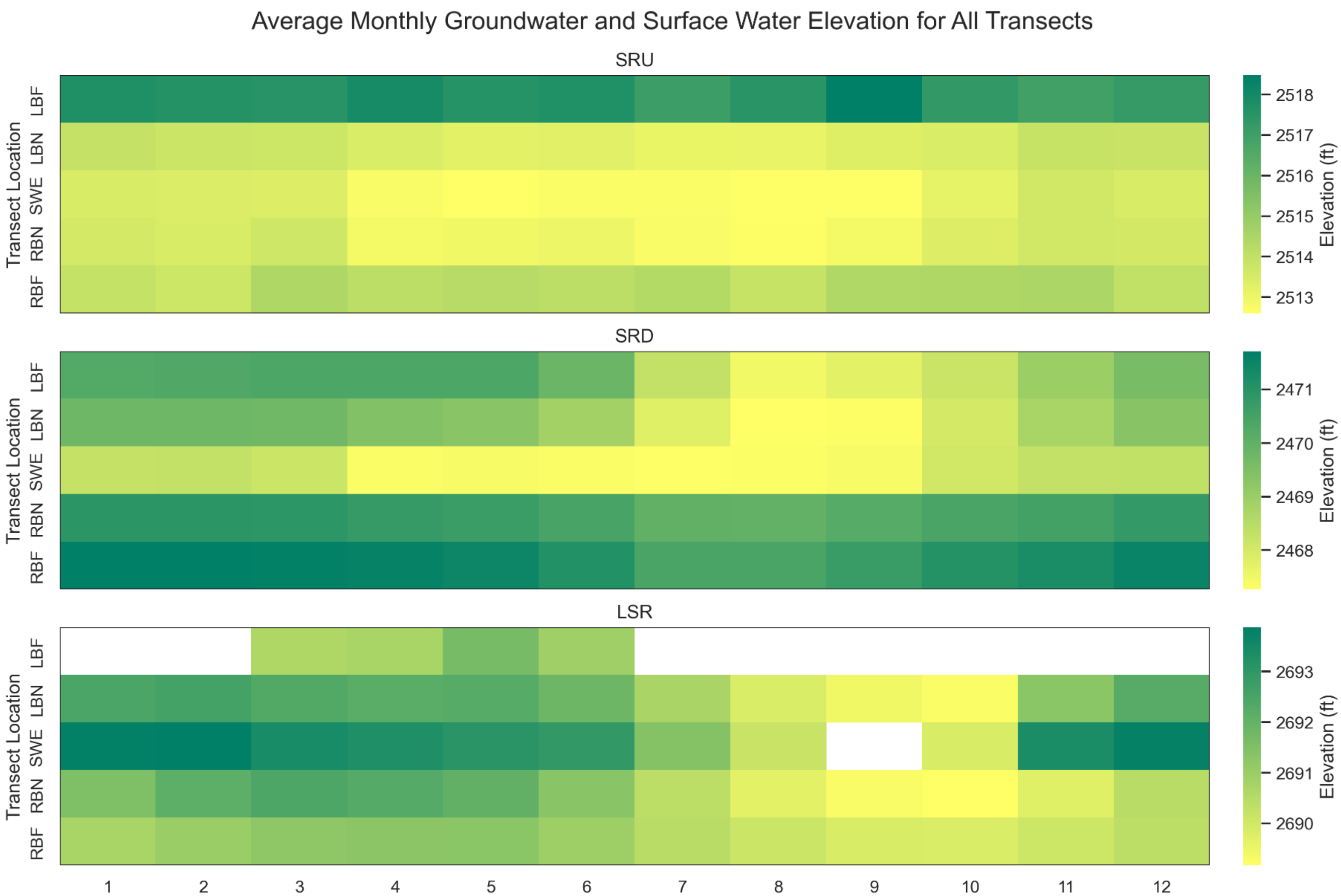

Figure 9. Average monthly groundwater and surface water elevations for the Shasta River Upstream (SRU), Shasta River Downstream (SRD) and Little Shasta River (LSR) transects. Monitoring locations are left bank far (LBF), left bank near (LBN), surface water elevation (SWE), right bank near (RBN), and right bank far (RBF). Months are represented by numbers 1 through 12 (i.e. January through December).

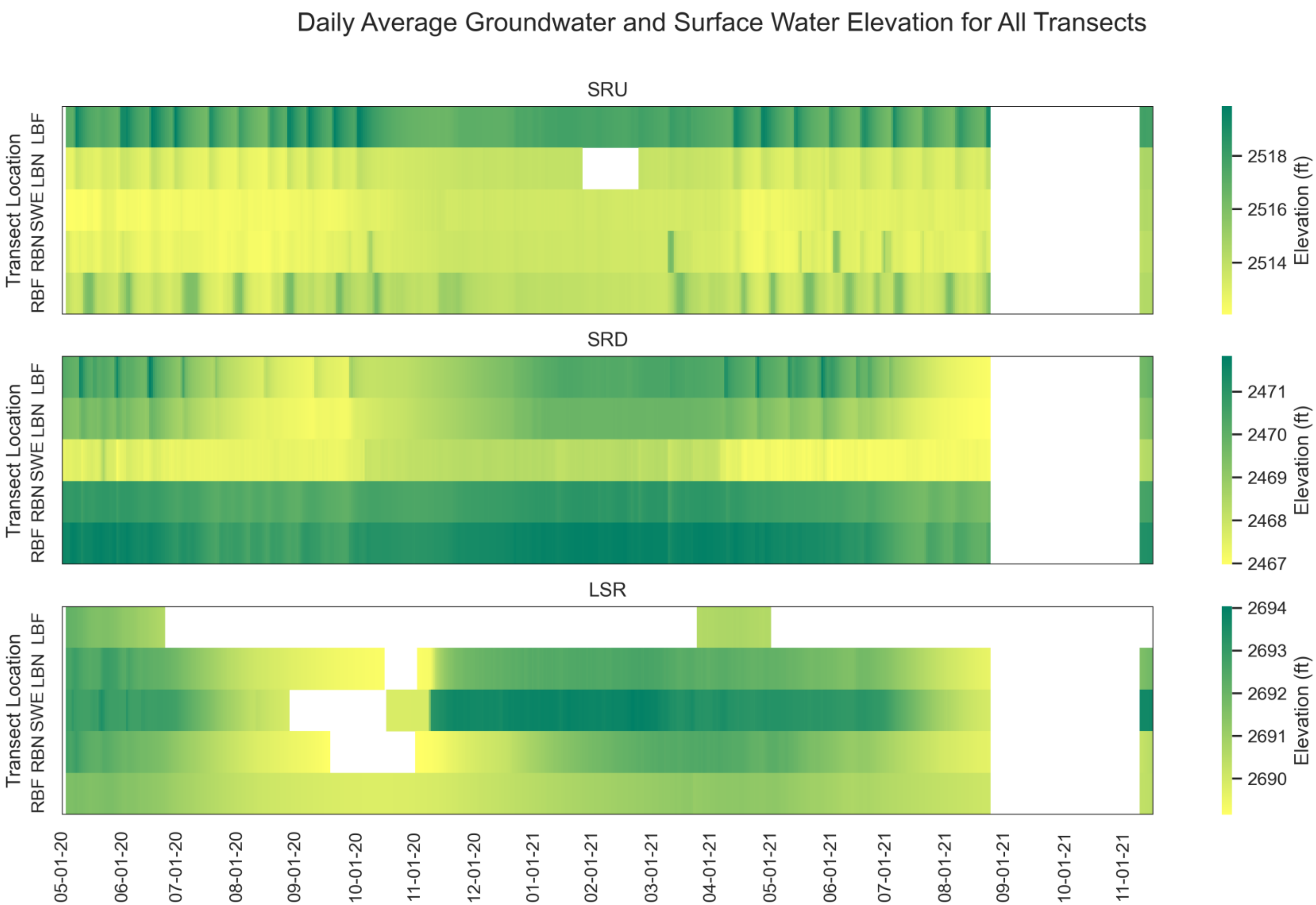

Figure 10. Daily average groundwater and surface water elevations for the Shasta River Upstream (SRU), Shasta River Downstream (SRD) and Little Shasta River (LSR) transects. Monitoring locations are left bank far (LBF), left bank near (LBN), surface water elevation (SWE), right bank near (RBN), and right bank far (RBF).

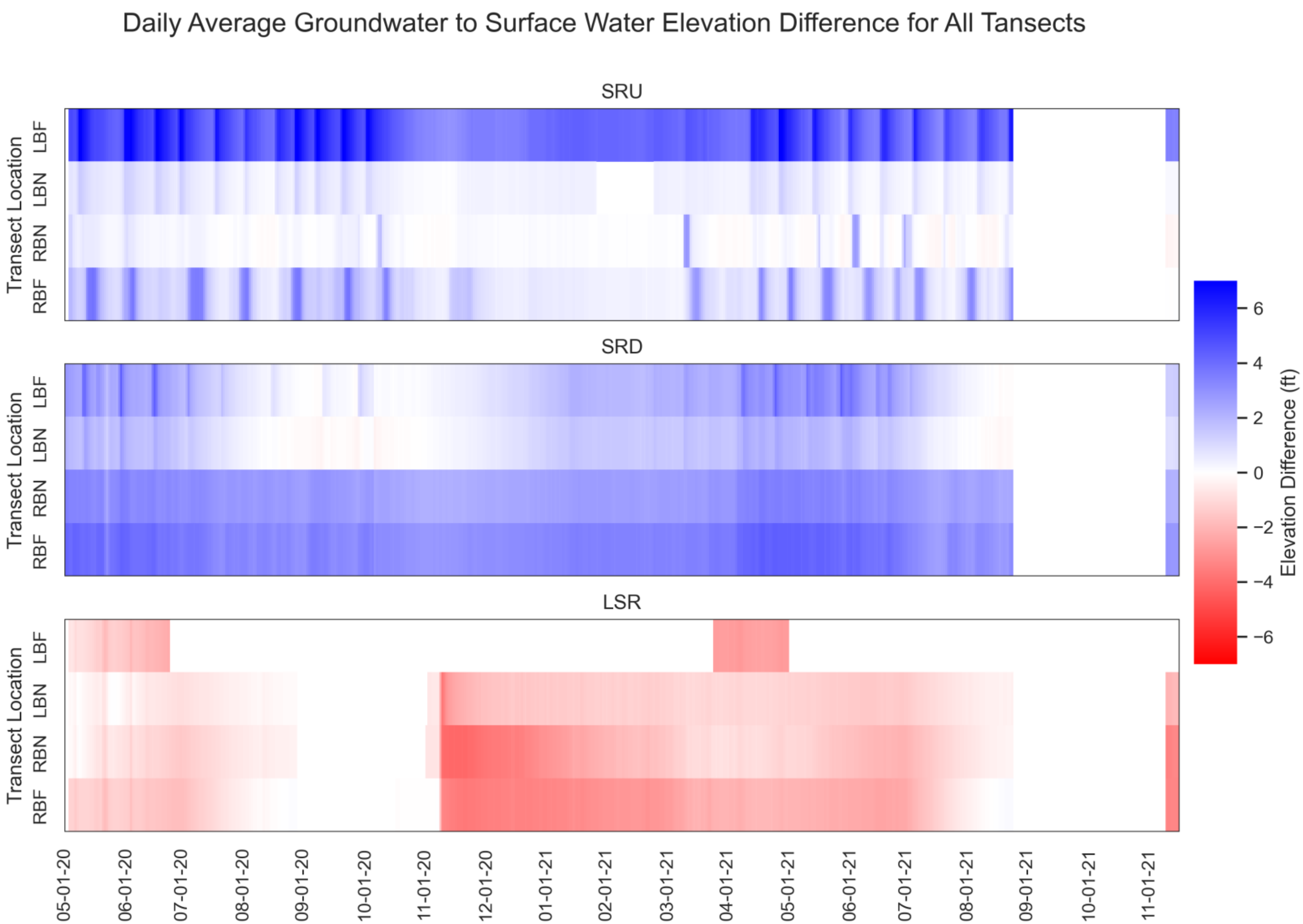

Figure 11. Daily average difference in groundwater and surface elevations (Groundwater – Surface Water) for the Shasta River Upstream (SRU), Shasta River Downstream (SRD) and Little Shasta River (LSR) transects. Monitoring locations are left bank far (LBF), left bank near (LBN), surface water elevation (SWE), right bank near (RBN), and right bank far (RBF).

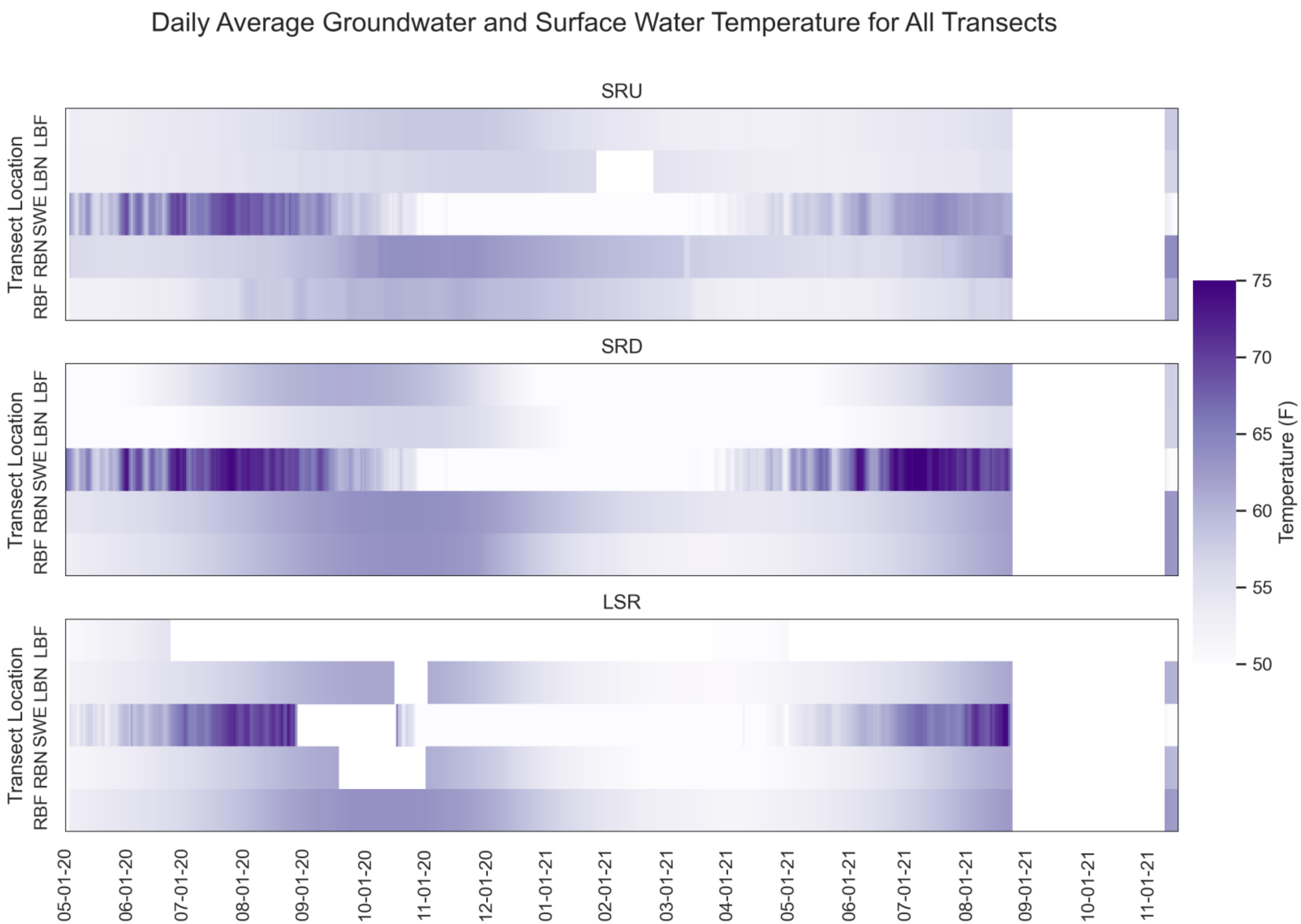

Figure 12. Daily average groundwater and surface water temperatures for the Shasta River Upstream (SRU), Shasta River Downstream (SRD) and Little Shasta River (LSR) transects. Monitoring locations are left bank far (LBF), left bank near (LBN), surface water elevation (SWE), right bank near (RBN), and right bank far (RBF).

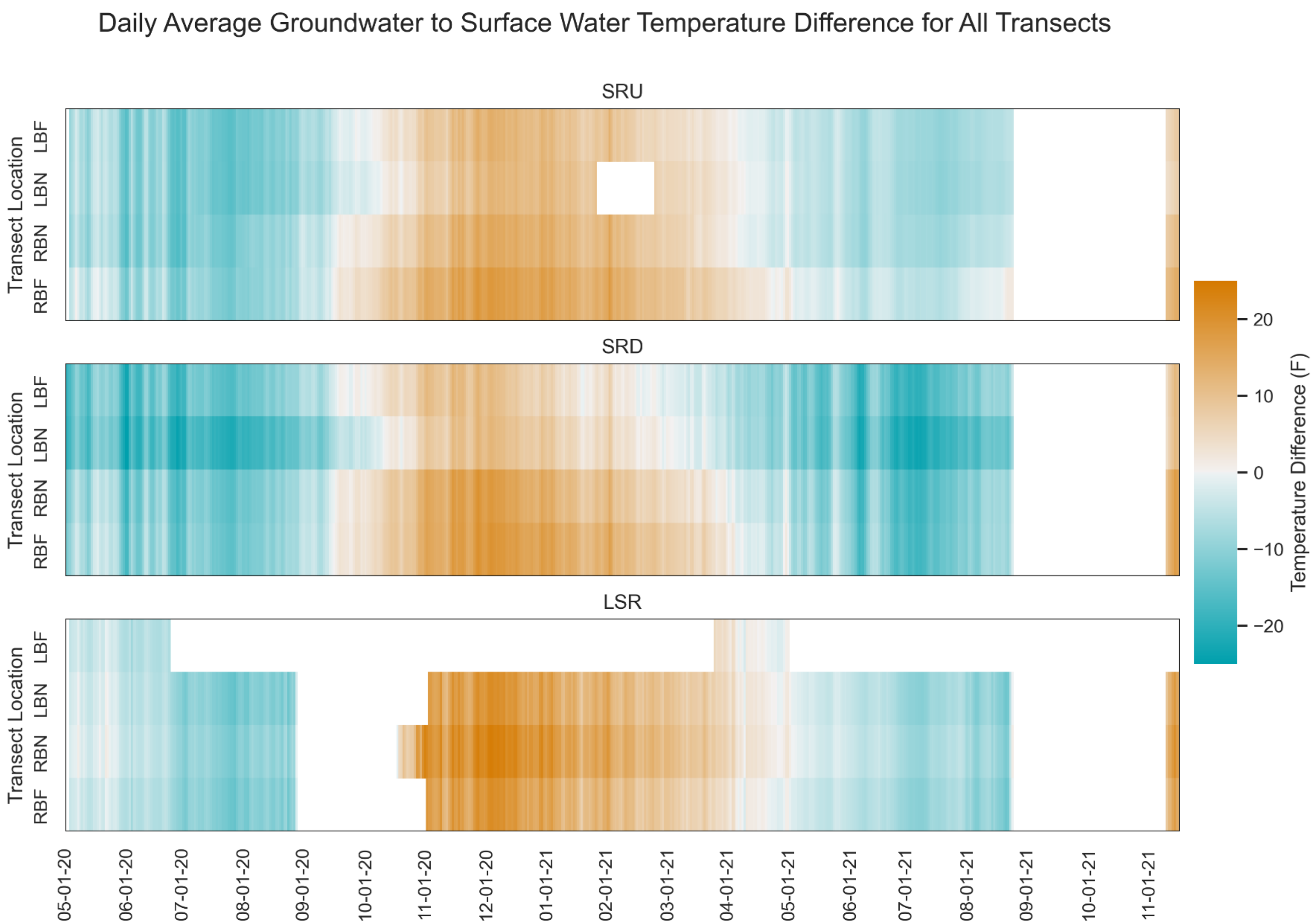

Figure 13. Daily average difference in groundwater and surface temperatures (Groundwater – Surface Water) for the Shasta River Upstream (SRU), Shasta River Downstream (SRD) and Little Shasta River (LSR) transects. Monitoring locations are left bank far (LBF), left bank near (LBN), surface water elevation (SWE), right bank near (RBN), and right bank far (RBF).

Temperatures differed across the transects, but overall showed the same general trends. The shallow groundwater was lower in temperature at the start of the study in May 2020 (e.g., negative values) with greater differences from surface water temperatures at the SRU and SRD transects than at the LSR transect. Initially, the differences increased into the summer months of 2020 as surface water temperatures increased more rapidly than groundwater temperatures. However, in late summer and early fall, as groundwater temperatures continued to slowly rise and surface water temperatures began falling, the trend reversed. The differences decreased and then became positive in September or October 2020 for all the piezometers; this is reflective of surface water temperatures decreasing below shallow groundwater temperatures. This trend continued into the winter and spring of 2021, until decreasing groundwater temperatures and increasing surface water temperatures again cause the trend to reverse. Temperature trends during the 2021 irrigation season were similar to those observed during the 2020 irrigation season.

Surface water temperatures during the spring and summer months were greater at the SRD transect than the SRU transect, which was potentially caused by surface warming in the Shasta River as it flowed downstream. With relatively similar groundwater temperatures in each transect location, this resulted in greater temperature differences observed at the SRD transect than the SRU transect. Interestingly, the surface water temperatures in the in the SRU transect during the 2021 irrigation season were not as high as during the 2020 irrigation season, although they were similar during both irrigation seasons at the SRD transect. The temperature difference comparison at all transects reflected the slower changes in shallow groundwater temperatures relative to changes in surface water temperatures.

4 Discussion and Conclusions

The study provides valuable information about stream-aquifer interactions in the Shasta Valley along the Shasta River and Little Shasta River. Monitoring results indicating the Shasta River was primarily gaining in both transect locations during this period, while the Little Shasta River was losing at its transect location during this period. Current funding allows the study to continue through December 2021. Included below are recommendations based on the data collected thus far over the study period from May 2020 through November 2021:

- The study and data collection should continue beyond December 2021 for as long as possible. Multiple years of data will provide useful insight into how changing weather conditions, river stage and flow, water use and water management practices, and water availability (e.g., wet years vs. dry years) influence stream-aquifer interactions in the Shasta Valley. As the GSP is implemented between 2022 and 2042, these data also have potential to reveal responses of stream-aquifer interactions to GSP implementation.
- Additionally, if possible or feasible due to funding and other water monitoring or management priorities in the basin, it is recommended that the piezometer boreholes in the transect along the Little Shasta River be deepened so that the pressure transducers can be installed further below ground to record data on changing water surface elevations and temperatures in case groundwater levels continue to consistently drop below the current bottom of the piezometer borehole and elevation where the pressure transducers are installed.

- Additionally, depending on funding and other priorities, further evaluation of the piezometer transects could be completed through additional data collection and data analysis. This includes, but is not limited to, the following:
    - Quantification of accretions or depletions in stream reaches that include the piezometer transects through flow measurements of upstream and downstream surface water flow.
    - Addition of a floating temperature sensor in each piezometer so that the temperature records are reflective of first encountered groundwater, instead of deeper groundwater that might not be influenced by deep percolation from applied water.
    - Water quality sampling of shallow groundwater and surface water.
    - Analysis of flow gradients, saturated flow thickness, and hydraulic conductivity and detailed investigation into the groundwater and surface water conditions in the vicinity of the piezometer transects.
- Finally, depending on funding and other priorities, it is recommended that additional piezometer transects be installed, commissioned, and monitored in other locations distributed across the Shasta Valley to provide additional insight into stream-aquifer interactions. High priority locations for additional transects include:
    - Shasta River downstream of the confluence with Big Springs Creek.
    - Shasta River near the confluence with Parks Creek.
    - Shasta River downstream of Lake Shastina.
    - Shasta River upstream of Lake Shastina.

5 References

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6 Attachments

- SV_Shallow_Piezometer_Transect_Study_Daily_Avg_May_20_Nov_21.xlsx
    - Spreadsheet with daily averages for water surface elevation and temperature at all sites.

7 Acknowledgements

This project would not have been possible without the facilitation, technical expertise, and leadership of SVRCD and the voluntary partnership and participation of private landowners.

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