Bonneville Basin Critical Zones: Spring Chemistry and Gastropod Ecology in Playa-Margin Wetlands

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ABSTRACT

Playa margin wetlands in the Bonneville basin are sustained by groundwater-fed brackish springs, which transport salts and other solutes into the playa basin. These wetlands are sensitive to changing water availability and quality, which are impacted by changing climate and land use, and whose sediments also provide important records of changing environmental conditions. Gastropods building their shells in these springs provide important recorders of water chemistry and may reflect changing aqueous conditions. In this paper, we analyze spring water chemistry, gastropod ecology and gastropod shell chemistry of Blue Lake (BL) and Horseshoe Springs (HRS), two groundwater-fed wetlands in the Great Salt Lake watershed. We report the physical parameters including pH, temperature, and specific conductivity across the spring pond at Horseshoe springs. There was a slight but statistically significant variation in these physical characteristics between the deeper and shallower parts of the pool, providing evidence that there are different subsite microclimates, which may impact the populations and the isotopic composition of gastropod shells. We measured gastropod population diversity amongst nearly 12,000 shells sampled at Horseshoe springs, finding low population diversity (Shannon's Diversity Index of 0.432), although the populations of shallow and deep snails are slightly different. The dominant snail at HRS is the *Pyrgulopsis* which is imperiled, and we also note that we did not find living snails here. We evaluated the bulk shell variation of stable carbonate isotopes ($\delta^{13}C$, and $\delta^{18}O$) across sites and genera. We show that there were no significant subsite-level differences in gastropod $\delta^{13}C$ compositions, suggesting that water depth and productivity were not impacting the isotopic signal. We found subsite- and genera-specific differences in snail $\delta^{18}O$ compositions, which we interpret to be more dependent on the geography and microclimate of where the snail lived rather than the genera's physiology (pulmonate versus gil -breathing). We report concentrations of alkali metals (Li, Na, K, Rb, Cs), alkali earth metals (Be, Mg, Ca, Sr, Ba), and metals and metalloids (Al, Sc, Mn, Fe, Cu, Ni, Zn, As) at spring site waters and in bulk shells as potential baseline data for interpreting future or past environmental changes as recorded in shell material. We found trace element concentration and certain elemental ratio differences between genera at the same site (particularly of note were Li, Zn, Mn and Al) that will be important to constrain if these shells are to be applied as a paleoenvironmental proxy and are sometimes attributed to land use change.

Keywords: hydrology, isotopes, carbon, groundwater, gastropod, critical zone

INTRODUCTION

Earth's critical zone encompasses the interactions between the biosphere, atmosphere, hydrosphere, and lithosphere from the top of vegetation to the bedrock (U.S. National Research Council, 2001; Anderson and others, 2007; White and others, 2015). The critical zone is linked to anthropogenic activity, from soil formation's relationship with agricultural production to landscape modifications impacting the hydrologic cycle and water resources (Brantley and others, 2007; Fan and others, 2019; Fovet and others, 2021; Minor and others, 2020). Groundwater-fed wetlands are, like many critical zone ecosystems, susceptible to changes in climate, water quality, air quality, and other effects of human impacts including recreation, agriculture and urbanization (Miguez-Macho & Fan, 2012; Singha & Navarre-Sitchler, 2022; Torgeson and others, 2022). Groundwater-fed wetlands also provide sedimentary records of critical zone (particularly hydrological) processes over time, termed paleo-critical zones by Ashley (2020), which help to calibrate and extend the temporal scales by which we understand the feedbacks between groundwater and climate.

Playa margin wetlands in the Bonneville basin are sustained by brackish to saline springs, transporting salts into the playa basin (Lerback and others, 2019). Louderback and Rhode (2009) estimate the discharge rate of 1.6 cubic meters per second or $5x10^{10}$ L/yr at

Blue Lake (BL), one of the two springs in this study. Lerback and others (2019) reported a slightly lower annual discharge rate of $1.3x10^{10}$ L/yr, and report measured Na concentration ranging between 1400-1600 mg/L from 2016-2018. Using these values, and assuming no recirculation of playa solutes in these springs, we estimate that BL annually brings from 2.0×10^{13} - 7.5×10^{13} mg of sodium to the playa sediments annually (between 22,000-83,000 tons). Considering these salt accumulation rates and long timescales since glacial Lake Bonneville exposed these spring sites, brackish playa margin springs like BL may be an important component of Bonneville basin solute budgets. Thus, understanding the chemical history and sustainability of these spring wetlands is useful in future work describing the dynamic solute and water budgets sustaining the ecosystems and industries of the Bonneville basin.

In this paper, we describe two spring-fed wetlands in the relatively under-studied western side of the Great Salt Lake watershed and describe their spring water chemistry by measuring their physical parameters (total dissolved solids, pH, dissolved oxygen, and temperature) and chemical compositions (alkali metals, alkaline earth metals, select metals and metalloids) (Figure 1). We use these parameters to establish baseline chemistry for future monitoring of spring ecosystem functioning. Importantly, these wetlands foster gastropod (snail) populations, including some endemic genera. Gastropod community diversity can serve as a bioindicator of environmental changes, where an environmental change could lead to inhospitable conditions for a relatively homogenous gastropod population (Magurran, 1988; Hershler and others, 2014). Thus, we survey the gastropod communities in these two springs, and provide a baseline of population composition and diversity. Gastropod shell chemistry has been shown to record groundwater chemistry and changing aqueous conditions in the present, setting the stage for evaluating near-future environmental changes, and in the past to contextualize modern environmental change (Abell, 1985; Abell and Williams, 1989; Rosenthal and Katz, 1989; Ayliffe and others, 1996).

We provide some context for using gastropod shells as proxies for environmental change by investigating the variability of modern shell chemistry, using $\delta^{13}C$ and $\delta^{18}O$ and the trace elemental composition of shells (alkali metals, alkaline earth metals, select metals and metalloids) in comparison to water. $\delta^{13}C$ has been used to reflect changes in the carbon cycle, such as changes in carbon inputs (land-plant versus aquatic humus), photosynthesis, dissolved oxygen content (Keith and others, 1964; Aravena and others, 1992; Jin and others, 2021). $\delta^{18}O$ is often used to interpret the water temperatures at the time of carbonate formation (Anadon and others 2006; Immenhauser and others, 2016). While previous work highlights the complexities of using freshwater gastropods as direct stable isotopic proxies (Shanahan and others, 2005), we provide some additional context of differences by genera to understand differences in shell-building processes and potential disruptions to the isotopic utility as paleoenvironmental indicators. Shell chemical compositions, particularly trace elements, also have potential conservation applications as the rapidly building shells incorporate trace elements being introduced to the environment. If new material (particularly if containing heavy metals) is introduced (deposited and bioavailable) to the springs due to land use change, urbanization, air quality, or industry, the shell chemistry and ecology may record these changes, serving as sentinels of environmental change (Rainbow, 2007; Baroudi and others, 2020). Additionally, recent work highlights the potential for shells from gill-breathing gastropods preserved within spring sediments to record changes in groundwater chemistry through time using radiocarbon isotopes (Lerback and others, 2023).

MATERIALS AND METHODS

Site Description

This study describes two perennial spring wetland sites in northwestern Utah, on traditional and ancestral lands of the Newe/Western Shoshone, Goshute, and Ute peoples. The springs in this study are Blue Lake (BL) springs (40.502, -114.033) and Horseshoe Springs (HRS) (40.614, -112.709) in Toole County, Utah. As reported by Lerback and others (2023), BL and HRS spring systems are brackish (with specific conductance measurements above 7000 µS/cm) and mesothermal, with average temperatures between 20° C and 30°C depending on measurement location within the spring pools. These temperatures are higher than mean annual air temperatures of 12°C (Lerback and others, 2023).

Gastropod Physiology

Gastropod genera sampled in this study include *Melanoides, Pyrgulopsis*, *Physella*, *Tryonia*, *Planorbella*, and *Succineidae* (Figure 2).

Melanoides

M*elanoides* shells found in this study are of the species *tuberculate*. This paper will refer to *Mela-*

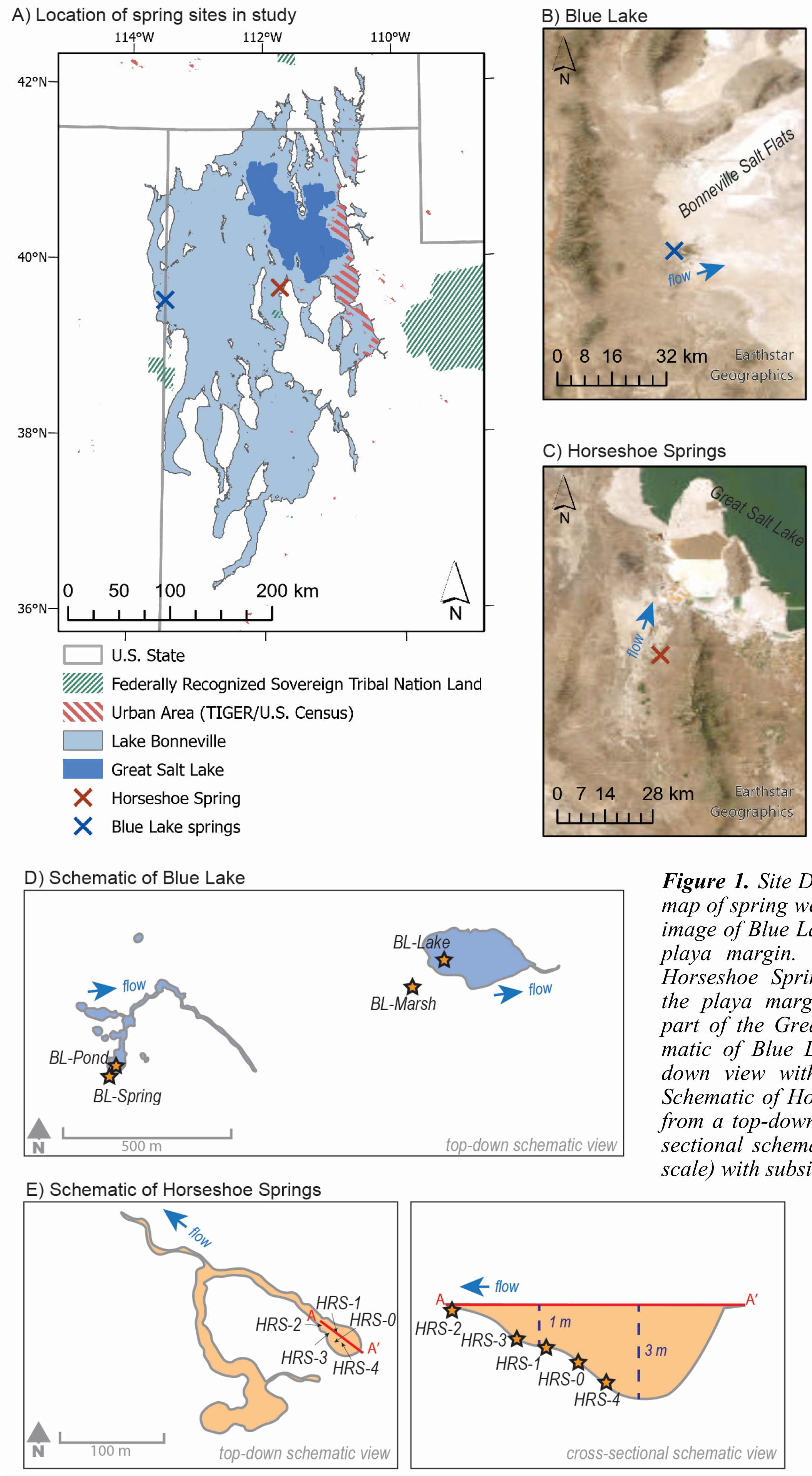

Figure 1. *Site Description. A) Location map of spring wetland sites. B) Satellite image of Blue Lake (BL) wetland at the playa margin. C) Satellite image of Horseshoe Springs (HRS) wetland at the playa margin with the southwest part of the Great Salt Lake. D) Schematic of Blue Lake (BL) from a top-down view with subsites marked. E) Schematic of Horseshoe Springs (HRS) from a top-down view (left) and cross-sectional schematic view (right, not to scale) with subsites marked.*

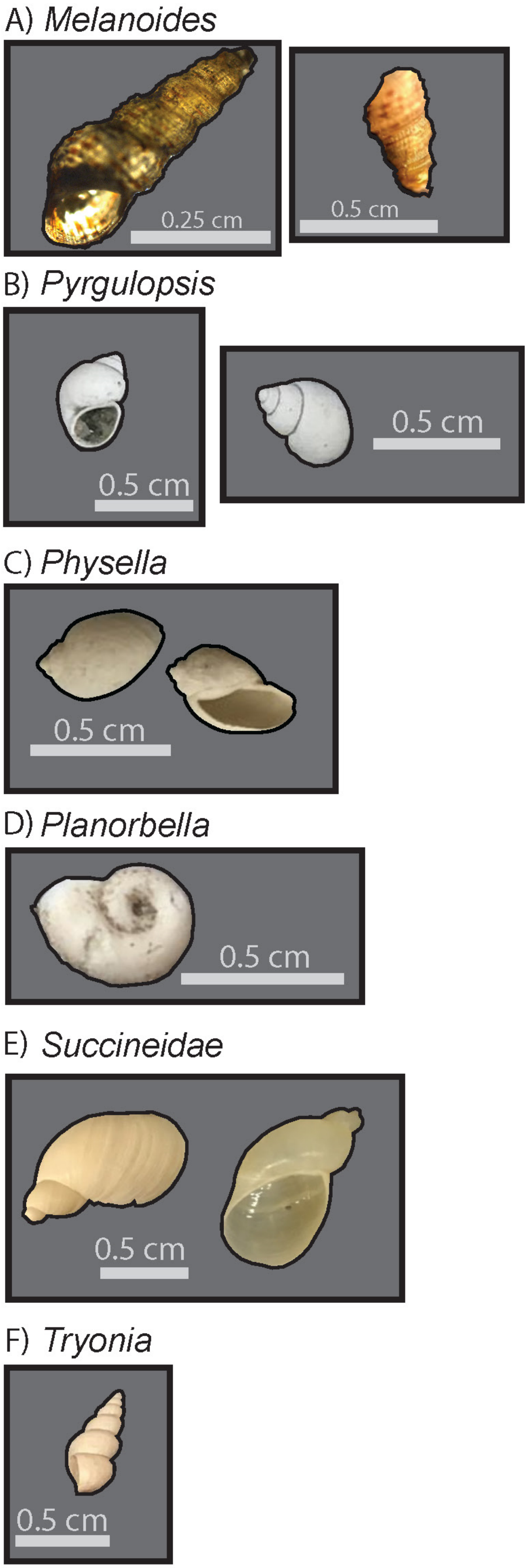

Figure 2. *Gastropod genera found in this study. A) Melanoides, B) Pyrgulopsis, C) Physella, D) Planorbella, E) Succineidae, and F) Tyronia.*

noides tuberculate as the genus only for consistency with the other genera described here. *Melanoides* is a prosobranch (gill-breathing), fully aquatic freshwater spring snail native to tropical Africa and Asia. *Melanoides* was first introduced to North America via the aquatic trade during the 1930s and has continued to spread across the continent into warm regions such as the Great Basin (Murray, 1971). *Melanoides* is an invasive species (Dudgeon, 1986; Facon and others, 2003; Raw and others, 2016). This species likes to burrow into the spring substrate during daylight hours and can therefore be difficult to detect in locations where it has recently been introduced (Subda Rao and Mitra, 1982). They may vary in size from 20 to 40 mm with a lifespan of about 2 – 3.5 years (Berry and Kadri, 1974; Dudgeon, 1982; Livshits and Fishelson, 1983; Pointier, 1989). *Melanoides* is less sensitive to salinity conditions than it is to temperature range, with an optimal growth range of 18 – 31°C (Murray, 1971; Russo, 1973; Roessler and others, 1977; Neck, 1985; Bolaji and others, 2011). When optimal conditions are consistent and abundant, *Melanoides* may reach population densities of up to 6452 m^{-2}, as was found in a study conducted at Fish Springs National Wildlife Refuge by Rader et al. 2003. This is attributed to the species reproducing asexually (parthenogenetic), reproducing more than once in its lifetime as well as early in the life cycle (iteroparous), and by developing offspring internally (viviparous).

Pyrgulopsis

Pyrgulopsis sp. are one of the largest genera in the family Hydrobiidae, which are a family of prosobranch (gill-breathing) snails. They are the second most common Hydrobiidae genera in North America, specifically in Utah, Nevada, and Idaho, and are typically found in moist wetland areas such as the benthos of lakes and springs (Hershler, 1994). Measuring about 1 – 8 mm in shell length, individuals typically cluster with densities greater than 1000 m^{-2} (Hershler, 1994). They may grow to a length of 2.5 mm (Hershler and Sada, 1987). The temperature range of living specimens falls between 22 – 35°C (Hershler, 1994). Individuals are typically found near spring groundwater discharge areas (Hershler and others, 2014). *Pyrgulopsis* sp. are very sensitive to climatic and environmental changes, which stem from members of this genus diversifying due to their regional separation and isolation; although individual species may live in a range of environments (e.g. temperatures, salinities, CO_2 concentrations), perturbations to these constant conditions can greatly disturb populations (Pearson and others, 2014). They are considered imperiled (Turgeon and others, 1998).

Tyronia

Tyronia sp. is another genera part of the Hydrobiidae family and is restricted to North America. Like its fellow Hydrobiid genera, *Tyronia* sp. are fully aquatic and typically prefer to inhabit thermal springs. Their dispersion is slow and may be linked to drainage history, making them key biogeographical indicator genera (Hershler and others, 1999). Some species may be quite salinity tolerant (Hershler and others, 1999). Shells can range between 1.2 – 7 mm in length (Hershler and Sada, 1987).

Physella

Physella sp. are part of subfamily Physinae, which are pulmonated (lung-breathing) freshwater spring snails. They are difficult to identify based on morphology alone (Young et al., 2021). *Physella* sp. are capable of self-fertilization (parthenogenesis), which may contribute to rapid evolution amplified by isolation or thermally different habitats (Perrin, 1986). They typically reproduce annually (Russell-Hunter, 1978). Observationally, *Physella* sp. have been known to inhabit waters with temperatures of 8 – 35^{o}C. Shell length can grow to 14 mm in very warm water temperatures, indicating that growth is temperature-dependent (McMahon, 1975).

Planorbella

Planorbella sp. are part of family Planorbidae and is a freshwater gastropod genus restricted to North America (Baker, 1945). Members of this genera are hermaphroditic and may rely on self-fertilization for reproduction (Martin and others, 2020). They have been shown in studies to be optimally active between 26 - 28^{o}C, with minimum and maximum optimal thresholds appearing to occur at 18^{o}C and 33^{o}C, respectively. (El-Emam and Madsen, 1982).

Succineidae

Succineidae are a family of minute taxa of pulmonated (lung-breathing) land snails that typically inhabit wetland areas worldwide (Pilsbry, 1948; Patterson, 1971). Genera are typically found on vegetations near streams or marshes, or where dew might be present. There may be extreme differences in morphological features such as size and shell shape, between genera within *Succineidae*. They are hermaphroditic and can reproduce through mutual fertilization or self-fertilization.

Experimental Design

We measured physical and chemical parameters using a multiparameter probe in the spring to understand circulation within the spring pond. We measured probe depth (m), Total Dissolved Solids (TDS in ppt), pH, Dissolved Oxygen (DO in mg/L) and temperature (°C) using an Aqua TROLL 600 Multiparameter Sonde. We recorded these basic physical and chemical parameters of the spring water along a NW-SE transect at HRS to understand the structure of flow and potential circulation within the northern spring pool and stream outlet (Figure 3). The probe recorded the time, which we marked and calibrated to locations marked at 0, 150s, 200s, 250s, 300s, and 345s. Time is used as a proxy for the distance along the transect, as it is not a linear transect. Water samples were collected at the water surface for trace element analyses in High-Density Polyethylene (HDPE) bottles that were washed with 5% HCl and rinsed three times with deionized water. Samples were filtered with a 0.45 µm polypropylene syringe filter and stored with minimal headspace.

At HRS, we sampled bulk sediment at sites HRS-1, HRS-2, HRS-3, and HRS-4 to measure the diversity and density of snail populations. At these four subsites in shallow and deeper waters, we filled one 0.25 L container with bulk sediment. Samples were cleaned at the University of Utah by sieving and rinsing bulk samples with deionized water and soaking the shells in 3% hydrogen peroxide for one hour which served to separate the sediment and organic material from the shells. Snails in sediment samples at each site were identified to the genus level and counted to understand the diversity of taxa across subsites at HRS. Gastropods were collected under a research agreement with the Utah Division of Wildlife Resources (4COLL10642). We used Shannon's Diversity Index to test the diversity of gastropods at HRS, which is a common metric of ecological diversity that takes into consideration the richness and evenness of each of the genera or species collected (Clarke and others, 2014). The equation from Shannon (1948) is

$$H = -\Sigma \frac{number\ of\ individuals\ in\ species}{number\ of\ individuals\ in\ community} \times ln(\frac{number\ of\ individuals\ in\ species}{number\ of\ individuals\ in\ community}) \quad (1)$$

Shells prepared for chemical analysis were cleaned with 3% hydrogen peroxide for one hour to remove organic material, rinsed with deionized water, and then sonicated to further remove organic matter and sediment. Bulk shells were homogenized individually using a mortar and pestle. Four shells were selected to be subsampled along transects from tip to

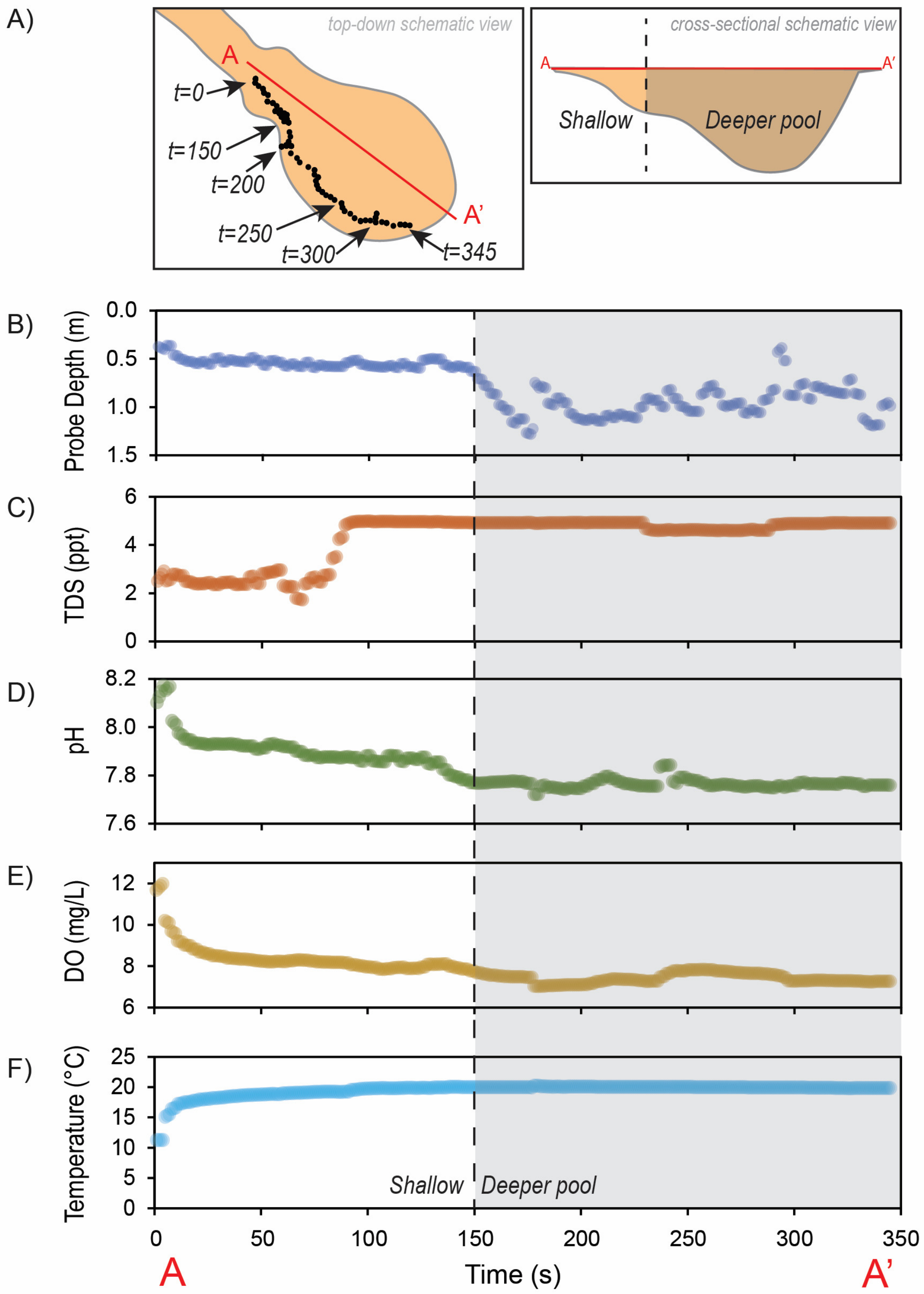

Figure 3. *Physical parameters of water along a transect at HRS. A) Schematic maps of HRS with probe transect locations and select times marked in the left panel, and the bathymetric distinction made between shallow and deep areas of the spring pool on the cross-sectional view in the right panel. B) Probe depth along transect. C) Total Dissolved Solids (TDS) along transect, D) pH along transect. E) Dissolved Oxygen (DO) along transect. F) Water temperature along transect.*

aperture ("intrashell transects") to assess variation in shell chemistry over the snail's lifetime. Intrashell transects were collected at four evenly spaced subsites along the long axis of the shell using a microdrill. *Melanoides* shells from BL-Spring were selected for the intrashell transects due to their relatively larger size.

A total of sixty-four whole gastropod shells (37 from BL and from 27 HRS) and four sub-sampled shells from BL were analyzed at the SIRFER laboratory at the University of Utah. Samples were reacted with orthophosphoric acid and analyzed as CO_2 after cryogenic purification. Samples were analyzed on a Finnigan MAT 252 mass spectrometer. Data are reported using delta notation relative to the Vienna Pee Dee belemnite (VPDB) standard for carbonates and water $\delta^{13}C$ and the Vienna standard mean ocean water (VSMOW) for water $\delta^{18}O$, where analytical precision for $\delta^{13}C$ and $\delta^{18}O$ was ~0.1‰. $\delta^{18}O$-VSMOW values were converted to $\delta^{18}O$-VPDB to directly compare $\delta^{18}O$ of water and shells. An additional 22 shell samples (17 from BL and from five HRS) were added to the dataset here from Lerback and others (2023), where their data were made using the same methods. Analyses including calculation of mean and standard deviations (SD), and statistical tests including analysis of variance (ANOVA) and Tukey's Honestly Significant Difference (HSD) were performed in R v3.6 in RStudio. Comparisons between water and shell isotope values evaluated the fractionation (ε), which is the difference between shell and water isotope values.

Eight shells (four *Succineidae* from BL, three *Pyrgulopsis* and one *Tryonia* from HRS) and four water samples (two from BL and two from HRS) were analyzed for trace element concentrations at the University of Utah's Strontium Isotopes Laboratory using an Agilent 7500ce quadrupole inductively coupled plasma mass spectrometer (ICP-MS).

RESULTS AND DISCUSSION

Spring Water

We evaluated the multiparameter probe data from HRS to understand how the aquatic environment varies within the spring system. We divided the HRS multiparameter probe data from HRS into shallow and deep sections of the pond at time 150s (of a total of 345s recorded) due to the relatively steady depth of the probe measurements (0.5 m depth in the NW section, and 1-1.5 m depth in the SE part of the transect where the shore edge became steep) and the variable depths of the spring pond (Table 1). Over the transect, TDS ranged from 1.7 in the shallow pool to 5.0 ppt in the deeper pool. Average TDS values were 3.6 ppt (SD = 1.2) for the shallow pool and 4.8 ppt (SD = 0.1) for the deeper pool. This difference was significant where (t (151) = 12.6; $p < 0.01$). The decrease in TDS values downstream (from shallower to deeper) within the spring may result from fresh water discharging to the shallower spring pool or evapoconcentration in the deep pool. The water pH increased through the transect, with a total mean of 7.8 (SD = 0.08), ranging from a low of 7.7 in the deep section to a high of 8.2 in the shallow areas. The average of the deep section was 7.8 (SD = 0.01), and the shallow section was 7.9 (SD = 0.07), with a significant difference (t(162) = -22.5; $p < 0.01$). DO content gradually increased from 7.45 mg/L (SD = 0.22) to 8.1 (SD = 0.78) as the water flowed into the shallower region. This difference was significant where (t (170) = -15.5; $p < 0.01$). The temperature was relatively elevated through the transect around 19.5°C (SD = 1.19). The water temperature in the shallow section of the spring was an average of 18.8°C (SD= 1.59. The deep section of the pond water 20.0°C (SD = 0.08), which is warmer than the shallower section (t(148) = 9.0; $p < 0.001$). Data for these measurements are provided in Appendix 1.

We measured alkali metals (Li, Na, K, Rb, and Cs), alkaline earth metals (Be, Mg, Ca, Sr, and Ba), and select metals and metalloids (Al, Mn, Fe, Zn) in spring waters (Figure 4 and Appendix 2). Overall, alkali metal concentrations were more abundant at BL than at HRS and were highest at the BL-Marsh site, which is likely due to evapoconcentration in the shallow standing water. Al, Mn, and Fe concentrations in HRS and BL were the 0.04 mg/L detection limit. Although this water is not designated for human consumption, it is worth contextualizing these values as below the National Secondary Drinking Water Standards of 0.05-0.2 mg/L, 0.05 and 0.3 mg/L, respectively (U.S. Environmental Protection Agency, 2009). Although these natural brackish springs are not used for drinking water, we note that these analyses did not have high enough resolution to detect whether the concentrations were below the National Primary Drinking Water Regulations maximum contaminant level for As of 0.01 mg/L (U.S. Environmental Protection Agency, 2009).

Gastropods

Ecological Diversity

Biodiversity is important for protecting the stability of the community which can aid in the overall recovery time from ecological harm that may threaten an ecosystem (e.g., natural disasters, famine, and diseases) (Magurran, 1988). We counted nearly 12,000 gastropod shells across four subsites at HRS, and we note that we did not find any living specimens with organic tissues which needed to be cleaned. We believe that the sampled shells are relatively modern

Table 1. *Water Physical Parameters: Probe Transect Data Summary.*

Parameter	Shallow	Deep	Total
Probe Depth (m)	mean = 0.54	mean = 0.95	mean = 0.77
TDS (ppt)	mean = 3.6, SD = 1.21	mean = 4.8, SD = 0.14	mean = 4.3, SD = 1.01
pH	mean = 7.9, SD = 0.07	mean = 7.8, SD = 0.02	mean = 7.8, SD = 0.08
DO (mg/L)	mean = 8.4, SD = 0.73	mean = 7.4, SD = 0.23	mean = 7.8, SD = 0.69
Temperature (°C)	mean = 18.8, SD = 1.59	mean = 20, SD = 0.08	mean = 19.5, SD = 1.2

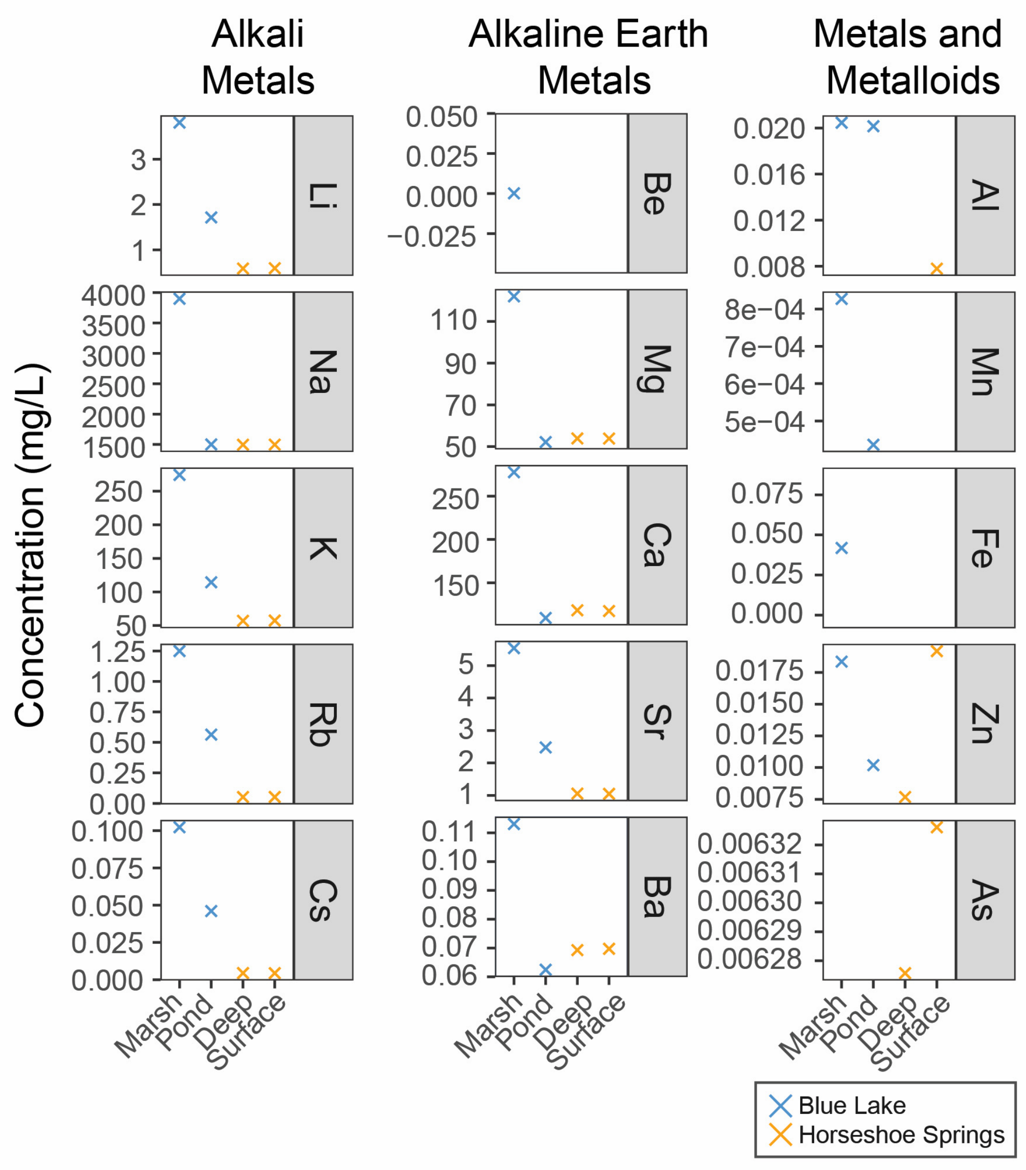

Figure 4. *Trace element concentrations of springwaters. Marsh waters have relatively higher elemental concentrations due to evaporation and relatedly less water input.*

Table 2. *Gastropod Population: Count of Individuals in Sampled Community.*

Genera	**HRS-1 (Deep)**	**HRS-2 (Shallow)**	**HRS-3 (Shallow)**	**HRS-4 (Deep)**
Pyrgulopsis	2404	2149	5253	334
Tyronia	112	72	1596	47
Physella	1	0	17	0

(i.e., not representing shells last alive thousands or hundreds of years ago) based on their sampling location at the surface of the spring sediments but recognize some might represent older shells that could have been brought to the surface by sediment disturbances, e.g., fish burrows in the spring sediments. We counted the number of individuals in each genus to measure the diversity of genera in the ecosystem (Table 2).

The Shannon's Diversity Index at HRS (combining subsites) was 0.432. While the index theoretically ranges from zero to infinity, this value is low compared to other studies where Shannon's Diversity Index often ranges from 1.5-3.5 (Magurran and McGill, 2011; Ifo and others, 2016).

We measured gastropod population diversity differences between the subsites (Figure 1E), which we further grouped into the shallow and deep sections following the distinctions shown in Figure 3A. Subsites HRS-2 and HRS-3 are considered shallow, and subsites HRS-0, HRS-1, and HRS-4 are considered deep (although HRS-0 was not sampled to characterize gastropod diversity). The shallow sediment samples yielded a higher density of shells, where 76% (n = 9087) of individual shells counted were from the shallow samples and both shallow and deep samples had the same volume of sediment collected. *Pyrgulopsis* and *Tyronia* were the most common genera found, with a few *Physella* (n = 18) found in both shallow and deep subsites. While different genera, *Pyrgulopsis* and *Tyronia* are both members of the same gastropod family, and their joint presence may be due to shared preference for similar environmental conditions. A chi-squared (χ^2) analysis of the observed number of *Pyrgulopsis*, *Tyronia*, and *Physella* genera counted from the shallow versus deep subsites resulted in a χ^2 of 219 ($p < 0.05$), thus indicating a statistically significant difference (albeit small) between populations in the small and deep parts of the HRS pond.

δ^{13}C and δ^{18}O

Shells were analyzed for δ^{13}C and δ^{18}O and compared to Total Dissolved Inorganic Carbon (TDIC) δ^{13}C and water δ^{18}O to understand the potential effects of environmentally related and biomediated carbon isotope fractionation (Appendix 3). δ^{13}C and δ^{18}O metrics can be representative of environmental conditions during the time of snail activity and can be used as an indicator of source carbon and source water, useful for evaluating environmental changes in the past (recorded in sedimentary records), and in future collections.

Shell samples were aggregated by subsite at BL and HRS (Figure 5A, Table 3). At BL, the subsite av-

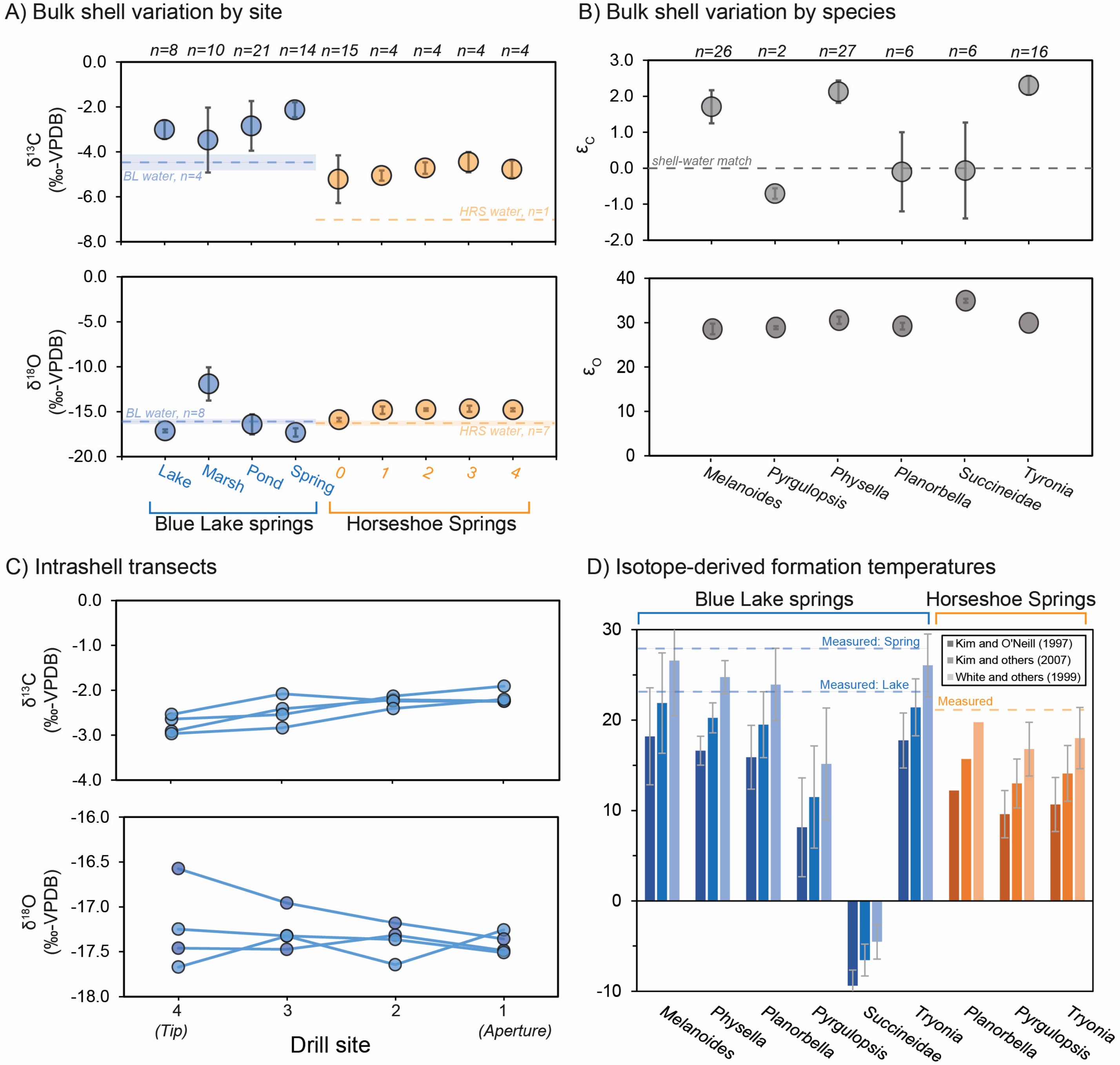

Figure 5. *Stable isotope measurements of gastropod shells. A)* δ^{13}*C and* δ^{18}*O measurements of bulk, homogenized shells by site and subsite. B)* ε_C *and* ε_o *of bulk, homogenized shells by genera. C)* δ^{13}*C and* δ^{18}*O variation within intrashell transects on Melanoides shells. D) Modelled shell formation (ambient water) temperatures based on* δ^{18}*O composition by site and genera.*

Table 3. Gastropod Shell $\delta^{13}C$ and $\delta^{18}O$ Data by Site.

Site	Average of $\delta^{13}C$	SD of $\delta^{13}C$	Count of $\delta^{13}C$	Average of $\delta^{18}O$	SD of $\delta^{18}O$	Count of $\delta^{18}O$
BL-Lake	-3.01	0.41	8	-17.13	0.16	8
BL-Marsh	-3.48	1.44	10	-11.91	1.85	10
BL-Pond	-2.85	1.10	21	-16.41	1.12	21
BL-Spring	-2.13	0.33	14	-17.31	0.46	14
HRS-Subsite-00	-5.22	1.06	15	-15.89	0.20	15
HRS-Subsite-01	-5.06	0.23	4	-14.82	0.41	4
HRS-Subsite-02	-4.72	0.25	4	-14.77	0.14	4
HRS-Subsite-03	-4.46	0.45	4	-14.68	0.35	4
HRS-Subsite-04	-4.77	0.38	4	-14.79	0.17	4

erage $\delta^{13}C$ values of shells ranged from -2.1 to -3.5‰ (a range of by 1.4‰), whereas the $\delta^{13}C_{TDIC}$ values in water samples at BL averaged -4.2‰ (SD = 0.43, n=4) (Lerback and others, 2023). An ANOVA shows that there are no significant differences between subsite $\delta^{13}C_{shell}$ values (F = 0.765, p = 0.519). At BL, the subsite shell averages of $\delta^{18}O$ values ranged from -11.9 to -17.3‰ (a range of by 5.4‰). Subsites had statistically different values (ANOVA F= 36.18, p < 0.01), where a Tukey's HSD test showed that pairwise, the BL-Marsh was different than every other site at p < 0.01 with a difference of more than 4‰). This is likely because the marsh had shallow standing water which may have had significant evaporative effects. Water samples (converted to VPBD from VSMOW) of BL discharge averaged -45.5‰ (SD = 0.1, n=12). Data for water stable isotopes at these sites is provided in Appendix 4.

At HRS, the subsite averages of $\delta^{13}C$ ranged from -4.5 to -5.2‰ (a range of 0.8‰), whereas $\delta^{13}C_{TDIC}$ values from water at HRS yielded a value of 7.2‰ (n = 1) (Lerback and others, 2019). The $\delta^{13}C_{TDIC}$ values were not statistically different across sites (ANOVA F = 0.479, p = 0.75). At HRS, the shell subsite averages of $\delta^{18}O$ (VPDB) values ranged from -14.7 to -15.9‰ (a range of 2.6‰). The $\delta^{18}O$ of shells at HRS was statistically different between sites (ANOVA F = 32.28, p < 0.01), where a Tukey's HSD test showed that pairwise, the HRS-0 was different than the other sites at p < 0.01, with a difference of 1‰).Water at HRS had a measured value (converted to VPBD from VSMOW) of -45.5‰ (SD=0.1, n=8).

$\delta^{13}C$ values of bulk sediment were -26.6 and -20.7‰ at BL-pond and HRS-0, respectively (Lerback and others, 2023), which are within the range of values expected of plant material in the region (Hart and others, 2010). Shell $\delta^{13}C$ values are more reflective of water $\delta^{13}C$ (TDIC) than sediment, similar to findings by Fritz and Poplowski (1974).

Stable isotope data of shells were also aggregated by genera (Figure 5B, Table 4) $\delta^{13}C$ (VPDB) values in shells ranged from -1.7‰ of a *Tryonia* at BL to -9.0‰ from a *Planorbella* at HRS. Significant differences existed in $\delta^{13}C$ between genera (ANOVA F = 7.172, p < 0.01), where the Tukey HSD found a difference of greater than 1‰ between *Melanoides* and all other genera (p < 0.1) but no significant differences between the four other genera (p > 0.1). $\delta^{18}O$ (VPDB) values in shells range from -10.0‰ of a *Succineidae* at BL-Marsh at BL to -17.5‰ of a *Melanoides* at BL-Spring. We found differences between the genera $\delta^{18}O$ (ANOVA F = 45.41, p < 0.01), where the Tukey HSD showed a pairwise difference between *Melanoides* and *Tyronia* (difference of 1.3‰, p < 0.01), and between *Melanoides* and *Pyrgulopsis* (difference of 1.9‰, p < 0.01). There was a difference of at least 4‰ between *Succineidae* and all other genera including *Melanoides* (p < 0.01). Lastly, there was also a difference of 1.3‰ between *Planorbella* and *Pyrgulopsis* (p < 0.1).

The fractionation between the measured shell and the spring waters is represented by epsilon (ε) for shell-TDIC in carbon and for shell-H_2O in oxygen stable isotope values (element denoted with a subscript). Water $\delta^{18}O$ for BL and HRS was reported relative to a VSMOW standard, which we convert to the VPDB standard before calculating the fractionation values for oxygen (ε_O). *Planorbella* and *Succineidae* have ε_C near 0, while the other shells (*Melanoides*, *Physella*, and *Tyronia*) show ε_C of greater than 1.5‰. All genera but *Succineidae*, had an average ε_O of 29.6 (SD = 1.2, n = 57). The elevated ε_O of +34‰ (SD = 0.44, n = 6) found in *Succineidae* is unsurprising because *Succineidae* is a genus only found at BL-

Table 4. *Gastropod Shell $\delta^{13}C$ and $\delta^{18}O$ Data by Genera.*

Genera	Average of $\delta^{13}C$	SD of $\delta^{13}C$	Count of $\delta^{13}C$	Average of $\delta^{18}O$	SD of $\delta^{18}O$	Count of $\delta^{18}O$
Melanoides	1.71	0.46	26	-0.95	1.19	15
Physella	-0.70	NA	2	-0.64	NA	2
Pyrgulopsis	2.13	0.31	27	1.03	0.81	19
Planorbella	-0.10	1.10	6	-0.31	0.75	5
Succineidae	-0.06	1.33	6	5.41	0.44	6
Tryonia	2.30	0.26	16	0.41	0.89	16

Marsh, where evaporation is occurring in shallow standing water (Morgan, 1970). Shanahan and others (2005) posit that *Succineidae* and *Physella* are pulmonates (lung-breathing), enabling them to live in these shallow areas where more evaporation is occurring and seasonally changing the water $\delta^{18}O$.

Following the methodologies provided by Shanahan and others (2005), we also evaluated the variation within the whorls of a single shell. The within-shell (intrashell) isotopic variation here may be due to biomediated fractionation or due to seasonal variation in waters during stages of growth. We examined the isotopes in intrashell transects along the long axis of growth from shell aperture to tip (Figure 5C, Appendix 5). These variations are otherwise averaged by homogenizing bulk shells. Variation of $\delta^{13}C$ was less than 1‰ through the shell, where three out of four shells increased by almost 1‰ overall. For $\delta^{18}O$ (VSMOW) values, the maximum variation observed was a linear decrease in one shell from -16.5‰ to -17.5‰ along the transect, whereas the other three shells did not vary more than 0.3‰. The variation within shells indicates that intrashell variation is minimal compared to the variation between bulk shells. This likely reflects the stable conditions provided by the mesothermal, seasonally stable discharge at BL.

We used the measured shell $\delta^{18}O$ values and measured average water $\delta^{18}O$ (which are assumed in paleoclimate studies) to calculate the expected shell formation temperatures (Figure 5D, Appendix 6). Like Shanahan and others (2005), we compare these estimated temperatures to measured temperatures of the springs reported by Lerback and others (2023). The fractionation equation from Kim and O'Neil (1997) estimates temperatures for synthetic calcite, where Kim and others (2007) estimate the formation temperature for synthetic aragonite, and finally, the equation by White and others (1999) estimates the formation temperature for aragonitic molluscs. Each of these equations predicts a temperature lower than the measured discharge temperatures of 28°C at BL and 21°C at HRS, but predicted temperatures for the genera *Melanoides*, *Physella*, *Planorbella*, and *Tyronia* by White and others (1997) are within the range found at BL between the Spring subsite discharge and the Lake subsite, and this equation also is closer to the mesothermal temperatures at HRS as well. Because *Physella, Planorbella* and *Succinidae* are all pulmonates, we might expect these to have more similar predicted temperatures, and different as compared to the gil-breathing genera. However, *Physella* and *Planorbella* predicted temperatures are more closely aligned with the gil-breathing genera, so the $\delta^{18}O$ may be more dependent on the microclimate associated with the location than the genera-specific vital effects that Shanahan and others (2005) discussed.

Trace Elements

We measured alkali metals (Li, Na, K, Rb, and Cs), alkaline earth metals (Be, Mg, Ca, Sr, and Ba), and select metals and metalloids (Al, Mn, Fe, Zn) in gastropod shells from HRS and BL to understand how shell chemistry may represent water or environmental chemistry (Figure 6, Appendix 7). On average, higher concentrations of Li, K, Rb, Be, Sr, Mn, Zn, and As were found in shells from BL than HRS. We provide these data to develop some baseline values as shells can be used as bioindicators of environmental change but note these associations need to be studied in more detail for genera-specific biases. Notably, the single *Tyronia* shell from HRS had concentrations of Na, Rb, Cs, Mg, Ba, Al, and Mn distinctly higher than shells from the same location, although the data are too sparse to draw statistical significance. However, the difference in trace element concentration may indicate there may be phyla- and genera-specific differences in how elements will bioaccumulate in body materials (including shells) (Langston and others, 1998; Rainbow, 2007). Bolotov and others, (2015) showed that freshwater bivalve trace element concentrations are significantly impacted by biological shell-building processes and geography (water elemental concentrations as related to the proximity of chemical sources). Land snail shell incorporation of environmental trace elements have also been discussed as bi-

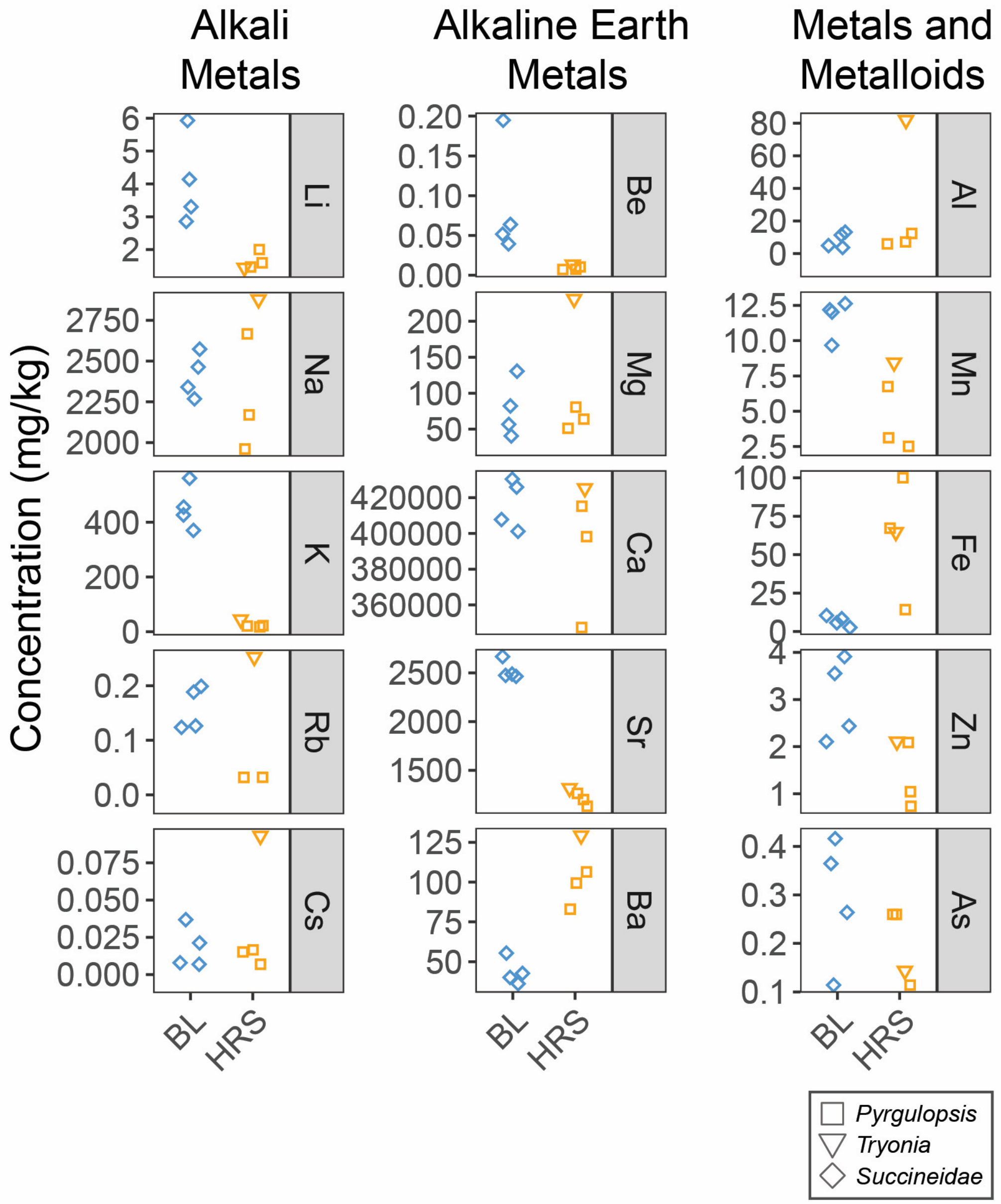

Figure 6. *Trace element concentrations measured in gastropod shells.*

omonitors for changing environmental conditions (de Vaufleury and Pihan, 1999; Madejon and others, 2013; Pauget and others, 2013), but need to be more carefully studied because of high soil variability and complexity of ecosystems. We show that spring snails throughout HRS ponds live in relatively chemically homogeneous environments, and thus we believe aquatic snail shells may be represent more consistent environmental proxies (within same-genera groups) than land snails.

We calculated the elemental ratios (mol/mol) of shells and water that have been evaluated in gastropod shells for paleoclimate reconstructions (Figure 7). These include Mg/Ca which have been used for temperature reconstruction in marine and lake foraminifera collections (Nurenberg and others, 1996; Lea and others, 1999; Elderfield and Ganssen, 2000; Dekens and others, 2002; Anand and others, 2003; Tripati and others, 2003Khider and others, 2015; Gray and Evans, 2019; Saenger and Evans, 2019). The study of Mg/Ca ratios in bivalves and gastropods have been limited and focus primarily on marine systems (Wanamaker and others, 2008; García-Escárzaga and others, 2015). Ulrich and others (2021) found that there was strong association between biomineral elemental chemistry and shell-building genera relatedness and that amongst the marine gastropods that were studied, element incorporation patterns arose at the class level. Our data test whether the Mg/Ca relationship works in the select freshwater gastropod taxa. At BL, waters had higher Mg/Ca ratios than were observed in *Succineidae* shells (approximately 0.8 mmol/mol in water, and 0.0 mmol/mol in shells), whereas in HRS shell the Mg/Ca values were all very low, less than 2.0 mmol/mol. Dellinger and others (2018) show data for marine mollusks that confirm lower Mg/Ca ratios (0.3-8 mmol/mol) than can be expected for more aragonitic materials. Using the calibration equation from Anand and others (2003) (which was derived for marine foraminifera which incorporates source water

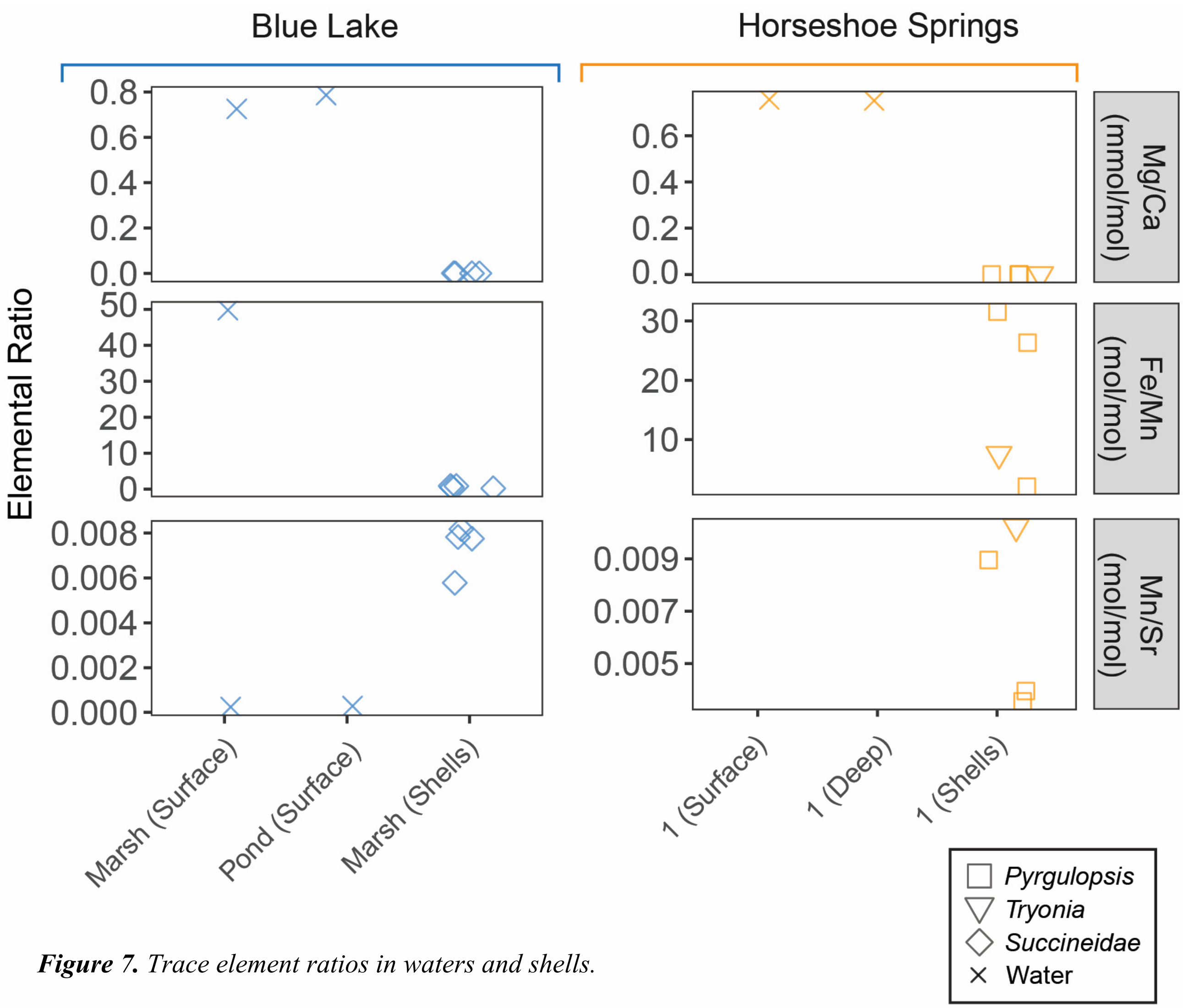

Figure 7. *Trace element ratios in waters and shells.*

Mg/Ca geochemistry), the expected Mg/Ca ratio for these shells is 3.011 and 2.515 mmol/mol, respectively (using the water temperatures of 23°C at BL and 21°C at HRS reported by Lerback and others, 2023). Given the measured ratios of 3.1 and 4.3 mmol/mol for BL and HRS, these spring water gastropod genera record very different Mg/Ca ratios that may reflect the gastropod shell-building processes partitioning of elemental species, especially in comparison to the marine foraminiferal calibrations that have been previously reported. Therefore, freshwater gastropods are likely unsuitable for temperature reconstruction with the Mg/Ca paleothermometer without further study.

Gastropod elemental ratios of Fe/Mn and Mn/Sr have been used as a proxy for a variety of processes, such as changes in water chemistry including sediment input, redox conditions, and water balance fluctuations (Rosenthal and Katz, 1989; Wanamaker Jr and others, 2008; Korponai and others, 2010). More specifically, Fe/Mn and Mn/Sr have been used in sedimentary records as indicators of redox conditions at the time of deposition and may also indicate potential alteration via diagenesis (Templeton and others, 2000). Examples of such factors affecting Fe/Mn and Mn/Sr ratios are changing mixing regimes, erosional input of sediment, aquatic productivity, soil leaching, and eutrophication. Water Fe/Mn ratios were not reported because concentrations were below the instrument detection limit. The Fe/Mn values of *Succineidae* shells found at BL range from 0.21 to 0.85 mol/mol, whereas the Fe/Mn values of *Pyrgulopsis* and single *Tryonia* collected at HRS range from 2.08 to 31.56 mol/mol (Figure 7, Table 8). We observed within-genera variability even within the same site; one *Pyrgulopsis* shell from HRS has Fe/Mn and Mn/Sr values that show an elevated signal compared to the two other *Pyrgulopsis* samples, falling nearer that *Tryonia* sample from the same site. We also observed some subsite variation; the *Succineidae* samples from BL show a depleted Fe/Mn signal relative to sampled marsh surface water, and an elevated Mn/Sr signal when compared to both marsh surface and pond surface water. This elevated Mn/Sr may reflect preferential uptake or more bioavailability of the trace element Mn as compared to the more abundant elements.

CONCLUSIONS

Wetland critical zones are important sites to monitor for changes to water resources and biodiversity and are sites for sedimentological preservation of wetland critical zone processes. The water chemistry shapes wetland critical zones over long time periods, and the chemistry provides solutes that contribute to the saline ecosystems of the Bonneville basin. Aspects of the water chemistry are preserved in gastropod shells, which can (1) provide an ongoing observational metric as "sentinel" organisms, rapidly capturing chemical changes to the system, and (2) also which are preserved in sediments, providing historical records of the magnitude of change in spring chemistries which contextualize modern environmental changes. We provide chemical characteristics of modern water from two mesothermal, playa-margin springs in the western Bonneville basin, and evaluate gastropod chemistry as providing potential records of spring chemistry changes through time.

The Shannon's Diversity Index at four HRS subsites indicates that the ecological diversity is low, with one snail genera, *Pyrgulopsis* (an imperiled genera) being the dominant shell found (Magurran, 1988; Magurran and McGill, 2011). While more research (particularly into paleoenvironmental conditions and past population distributions) can clarify a baseline diversity in these springs, the low diversity index reported here may reflect that the ecosystem's overall stability may be sensitive to environmental changes, including land use change that impacts the geochemical profile of the water. The modern chemistry of the shells can also be used as a baseline to compare with sedimentary shell records or future shell collections as bioindicators of environmental change. We present isotopic and trace element data among subsites and genera to constrain the variables relevant to scientists interested in using shells as proxies for spring water changes through time. We found genera and subsite differences in δ^{13}C and δ^{18}O variations and trace element chemistry of modern water and shells, which will need to be better constrained in order to effectively use these chemical relationships to interpret past environments. Our data did not find evidence for significant physiological differences based on pulmonate versus gil-breathing genera in the stable isotope data.

Overall, this paper describes wetland critical zone chemistry and metrics of biodiversity in a system of ecological importance in the Great Salt Lake watershed. As gastropods deposited in spring sediments can be used as recorders of environmental change, we evaluate the factors that may impact geochemical preservation and thus environmental reconstructions.

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Appendix 1. *Water physical parameter data from probe transect.*

Time	Group	Depth (m)	Temperature (°C)	Total Dissolved Solids (ppt)	pH	RDO Concentration (mg/L)	Specific Conductivity (µS/cm)
1	Shallow	0.373	11.27	2.5	8.1	11.68	3852.72
2	Shallow	0.383	11.27	2.64	8.13	11.78	4067.68
3	Shallow	0.393	11.28	2.78	8.15	11.88	4282.65
4	Shallow	0.403	11.28	2.92	8.17	11.99	4497.62
5	Shallow	0.362	15.12	2.52	8.15	10.2	3869.74
6	Shallow	0.363	15.32	2.55	8.16	10.14	3916.6
7	Shallow	0.365	15.53	2.58	8.17	10.08	3963.46
8	Shallow	0.461	16.38	2.79	8.03	9.7	4286.13
9	Shallow	0.465	16.5	2.78	8.02	9.64	4282.09
10	Shallow	0.469	16.62	2.78	8.01	9.58	4278.05
11	Shallow	0.5	17.22	2.73	7.98	9.21	4197.18
12	Shallow	0.504	17.26	2.73	7.97	9.19	4199.55
13	Shallow	0.508	17.3	2.73	7.97	9.17	4201.92
14	Shallow	0.526	17.5	2.5	7.95	9.03	3849.93
15	Shallow	0.527	17.52	2.49	7.95	9.01	3828.27
16	Shallow	0.528	17.54	2.47	7.95	9	3806.61
17	Shallow	0.53	17.55	2.46	7.95	8.99	3784.95
18	Shallow	0.546	17.76	2.41	7.93	8.83	3700.48
19	Shallow	0.547	17.77	2.4	7.93	8.82	3688.59
20	Shallow	0.548	17.78	2.39	7.93	8.81	3676.71
21	Shallow	0.53	17.95	2.39	7.93	8.69	3684.06
22	Shallow	0.529	17.97	2.39	7.93	8.68	3683.68
23	Shallow	0.528	17.98	2.39	7.93	8.67	3683.31
24	Shallow	0.554	18.06	2.44	7.93	8.61	3746.17
25	Shallow	0.555	18.07	2.44	7.93	8.6	3750.11
26	Shallow	0.555	18.07	2.44	7.93	8.6	3754.06
27	Shallow	0.497	18.2	2.37	7.93	8.51	3643.82
28	Shallow	0.494	18.21	2.37	7.93	8.51	3638.84
29	Shallow	0.491	18.22	2.36	7.93	8.5	3633.87
30	Shallow	0.488	18.23	2.36	7.93	8.5	3628.89
31	Shallow	0.532	18.3	2.44	7.93	8.48	3758.54
32	Shallow	0.533	18.31	2.45	7.93	8.48	3763
33	Shallow	0.534	18.32	2.45	7.93	8.47	3767.47
34	Shallow	0.511	18.44	2.46	7.93	8.4	3780
35	Shallow	0.511	18.45	2.46	7.93	8.39	3783.48
36	Shallow	0.511	18.46	2.46	7.93	8.39	3786.96
37	Shallow	0.524	18.53	2.37	7.93	8.37	3649.47
38	Shallow	0.524	18.54	2.37	7.93	8.37	3641.83
39	Shallow	0.524	18.54	2.36	7.93	8.37	3634.18
40	Shallow	0.531	18.63	2.38	7.92	8.35	3661.48
41	Shallow	0.531	18.63	2.38	7.92	8.34	3660.27
42	Shallow	0.532	18.64	2.38	7.92	8.34	3659.06

43	Shallow	0.533	18.65	2.38	7.92	8.34	3657.85
44	Shallow	0.49	18.69	2.68	7.92	8.31	4119
45	Shallow	0.488	18.7	2.69	7.92	8.31	4144.63
46	Shallow	0.486	18.7	2.71	7.92	8.31	4170.27
47	Shallow	0.516	18.74	2.43	7.91	8.27	3738.22
48	Shallow	0.516	18.74	2.42	7.91	8.27	3723.76
49	Shallow	0.517	18.75	2.41	7.91	8.27	3709.3
50	Shallow	0.563	18.78	2.8	7.91	8.24	4312.73
51	Shallow	0.566	18.79	2.82	7.91	8.24	4336.27
52	Shallow	0.569	18.79	2.83	7.91	8.24	4359.8
53	Shallow	0.522	18.86	2.86	7.93	8.21	4407.27
54	Shallow	0.52	18.87	2.87	7.93	8.21	4422.75
55	Shallow	0.518	18.87	2.88	7.93	8.21	4438.23
56	Shallow	0.516	18.87	2.89	7.93	8.21	4453.71
57	Shallow	0.535	18.82	2.96	7.92	8.24	4550.99
58	Shallow	0.535	18.82	2.96	7.92	8.24	4555.91
59	Shallow	0.534	18.82	2.96	7.92	8.24	4560.83
60	Shallow	0.572	18.96	2.32	7.92	8.22	3570.09
61	Shallow	0.574	18.97	2.29	7.92	8.22	3517.96
62	Shallow	0.577	18.97	2.25	7.92	8.22	3465.82
63	Shallow	0.554	19.02	2.28	7.92	8.26	3510.2
64	Shallow	0.553	19.03	2.27	7.92	8.26	3493.2
65	Shallow	0.553	19.03	2.26	7.92	8.26	3476.19
66	Shallow	0.577	19.06	1.8	7.9	8.29	2773.32
67	Shallow	0.578	19.06	1.78	7.9	8.3	2738.19
68	Shallow	0.579	19.07	1.76	7.9	8.3	2703.05
69	Shallow	0.579	19.07	1.73	7.9	8.3	2667.92
70	Shallow	0.538	19.13	2.38	7.88	8.29	3666.19
71	Shallow	0.536	19.13	2.41	7.88	8.29	3705.42
72	Shallow	0.535	19.13	2.43	7.88	8.29	3744.64
73	Shallow	0.586	19.19	2.63	7.88	8.25	4041.07
74	Shallow	0.588	19.19	2.65	7.88	8.25	4078.32
75	Shallow	0.59	19.19	2.68	7.88	8.25	4115.56
76	Shallow	0.565	19.23	2.48	7.87	8.22	3819.99
77	Shallow	0.565	19.23	2.47	7.87	8.21	3806.91
78	Shallow	0.565	19.23	2.47	7.87	8.21	3793.82
79	Shallow	0.577	19.25	2.74	7.88	8.2	4218.14
80	Shallow	0.577	19.25	2.75	7.88	8.2	4234.77
81	Shallow	0.577	19.25	2.76	7.88	8.2	4251.4
82	Shallow	0.577	19.25	2.77	7.88	8.2	4268.03
83	Shallow	0.58	19.27	3.44	7.88	8.19	5288.08
84	Shallow	0.58	19.27	3.48	7.88	8.19	5352.31
85	Shallow	0.581	19.27	3.52	7.88	8.19	5416.53
86	Shallow	0.581	19.22	4.24	7.87	8.19	6517.24
87	Shallow	0.581	19.22	4.29	7.87	8.19	6596.06
88	Shallow	0.581	19.21	4.34	7.87	8.19	6674.87
89	Shallow	0.54	19.26	4.82	7.88	8.17	7421.89

90	Shallow	0.538	19.26	4.86	7.88	8.16	7481.36
91	Shallow	0.535	19.26	4.9	7.88	8.16	7540.84
92	Shallow	0.519	19.54	4.95	7.87	8.07	7613.5
93	Shallow	0.517	19.56	4.96	7.87	8.07	7627.92
94	Shallow	0.515	19.57	4.97	7.87	8.06	7642.34
95	Shallow	0.514	19.59	4.98	7.87	8.06	7656.77
96	Shallow	0.554	19.7	4.98	7.86	8.02	7661.11
97	Shallow	0.556	19.71	4.98	7.86	8.01	7660.43
98	Shallow	0.558	19.72	4.98	7.86	8.01	7659.74
99	Shallow	0.571	19.77	4.99	7.88	7.97	7680.29
100	Shallow	0.573	19.77	4.99	7.88	7.97	7681.31
101	Shallow	0.574	19.78	4.99	7.88	7.96	7682.32
102	Shallow	0.578	19.8	4.97	7.86	7.94	7650.34
103	Shallow	0.579	19.81	4.97	7.86	7.94	7649.01
104	Shallow	0.579	19.81	4.97	7.86	7.94	7647.67
105	Shallow	0.585	19.84	4.98	7.86	7.86	7658.82
106	Shallow	0.586	19.84	4.98	7.86	7.86	7658.77
107	Shallow	0.586	19.84	4.98	7.86	7.85	7658.71
108	Shallow	0.587	19.84	4.98	7.86	7.85	7658.65
109	Shallow	0.571	19.83	4.98	7.88	7.87	7657.5
110	Shallow	0.57	19.83	4.98	7.88	7.87	7657.75
111	Shallow	0.57	19.83	4.98	7.88	7.87	7657.99
112	Shallow	0.589	19.81	4.97	7.88	7.93	7648.08
113	Shallow	0.59	19.81	4.97	7.88	7.93	7647.5
114	Shallow	0.59	19.8	4.97	7.88	7.94	7646.92
115	Shallow	0.55	19.84	4.97	7.86	7.94	7647.9
116	Shallow	0.548	19.85	4.97	7.86	7.94	7647.75
117	Shallow	0.547	19.85	4.97	7.86	7.95	7647.61
118	Shallow	0.58	19.89	4.97	7.87	7.89	7643.28
119	Shallow	0.581	19.89	4.97	7.87	7.89	7643.09
120	Shallow	0.582	19.89	4.97	7.87	7.89	7642.9
121	Shallow	0.583	19.9	4.97	7.87	7.89	7642.71
122	Shallow	0.594	19.87	4.97	7.87	7.89	7642.89
123	Shallow	0.595	19.87	4.97	7.87	7.89	7642.82
124	Shallow	0.596	19.87	4.97	7.87	7.89	7642.74
125	Shallow	0.517	19.92	4.97	7.87	7.95	7639.41
126	Shallow	0.513	19.93	4.97	7.87	7.96	7639.25
127	Shallow	0.509	19.93	4.97	7.87	7.96	7639.08
128	Shallow	0.502	19.85	4.96	7.85	8.08	7632.75
129	Shallow	0.5	19.85	4.96	7.85	8.09	7632.33
130	Shallow	0.498	19.85	4.96	7.85	8.1	7631.92
131	Shallow	0.502	19.94	4.96	7.85	8.09	7636.98
132	Shallow	0.502	19.95	4.96	7.85	8.09	7637.16
133	Shallow	0.503	19.95	4.96	7.85	8.09	7637.33
134	Shallow	0.503	19.96	4.96	7.85	8.09	7637.5
135	Shallow	0.559	19.94	4.95	7.83	8.1	7608.89
136	Shallow	0.562	19.95	4.94	7.82	8.1	7607.48

137	Shallow	0.565	19.95	4.94	7.82	8.1	7606.07
138	Shallow	0.587	20.04	4.94	7.8	8	7601.13
139	Shallow	0.59	20.04	4.94	7.8	8	7600.29
140	Shallow	0.592	20.04	4.94	7.8	7.99	7599.45
141	Shallow	0.576	20.03	4.94	7.79	7.93	7592.73
142	Shallow	0.575	20.03	4.94	7.79	7.92	7592.35
143	Shallow	0.574	20.03	4.93	7.79	7.91	7591.96
144	Shallow	0.588	20.02	4.93	7.78	7.86	7586.62
145	Shallow	0.588	20.02	4.93	7.78	7.86	7586.22
146	Shallow	0.588	20.01	4.93	7.78	7.86	7585.82
147	Shallow	0.589	20.01	4.93	7.78	7.85	7585.42
148	Shallow	0.629	20.01	4.93	7.77	7.77	7578.26
149	Shallow	0.631	20.01	4.93	7.77	7.77	7577.78
150	Deep	0.634	20.01	4.93	7.77	7.76	7577.3
151	Deep	0.704	20.02	4.93	7.77	7.69	7576.95
152	Deep	0.708	20.02	4.92	7.77	7.68	7576.81
153	Deep	0.713	20.02	4.92	7.77	7.67	7576.66
154	Deep	0.774	20	4.92	7.77	7.62	7576.71
155	Deep	0.779	19.99	4.92	7.77	7.62	7576.73
156	Deep	0.784	19.99	4.92	7.77	7.62	7576.75
157	Deep	0.856	19.99	4.92	7.77	7.57	7572.97
158	Deep	0.861	19.99	4.92	7.77	7.57	7572.77
159	Deep	0.866	19.99	4.92	7.77	7.56	7572.56
160	Deep	0.871	19.98	4.92	7.77	7.56	7572.35
161	Deep	0.977	19.98	4.92	7.77	7.52	7569.69
162	Deep	0.984	19.98	4.92	7.77	7.52	7569.47
163	Deep	0.991	19.98	4.92	7.77	7.52	7569.25
164	Deep	1.028	19.99	4.92	7.77	7.5	7567.25
165	Deep	1.032	19.99	4.92	7.77	7.5	7567.09
166	Deep	1.035	19.99	4.92	7.77	7.5	7566.94
167	Deep	1.154	19.98	4.92	7.78	7.49	7572.95
168	Deep	1.161	19.98	4.92	7.78	7.49	7573.25
169	Deep	1.167	19.98	4.92	7.78	7.49	7573.55
170	Deep	1.123	19.98	4.92	7.77	7.49	7572.76
171	Deep	1.123	19.98	4.92	7.77	7.49	7572.84
172	Deep	1.123	19.98	4.92	7.77	7.48	7572.92
173	Deep	1.122	19.98	4.92	7.77	7.48	7572.99
174	Deep	1.268	19.98	4.93	7.77	7.46	7583.29
175	Deep	1.275	19.98	4.93	7.77	7.46	7583.81
176	Deep	1.281	19.98	4.93	7.77	7.45	7584.33
177	Deep	1.225	19.97	4.93	7.77	7.46	7581.18
178	Deep	0.745	20.23	4.91	7.72	7.04	7546.57
179	Deep	0.773	20.24	4.9	7.72	7.03	7545.79
180	Deep	0.802	20.24	4.9	7.72	7.02	7545.01
181	Deep	0.784	20.14	4.91	7.76	7.03	7551.84
182	Deep	0.793	20.13	4.91	7.76	7.03	7552.02
183	Deep	0.802	20.12	4.91	7.76	7.03	7552.19

184	Deep	0.959	20.08	4.92	7.75	7.06	7570.66
185	Deep	0.966	20.08	4.92	7.75	7.06	7571.86
186	Deep	0.973	20.07	4.92	7.75	7.06	7573.06
187	Deep	0.979	20.07	4.92	7.75	7.07	7574.27
188	Deep	0.908	20.07	4.93	7.75	7.07	7578.24
189	Deep	0.907	20.07	4.93	7.75	7.07	7578.83
190	Deep	0.906	20.07	4.93	7.75	7.07	7579.42
191	Deep	0.954	20.05	4.92	7.74	7.09	7576.65
192	Deep	0.955	20.05	4.92	7.74	7.09	7576.53
193	Deep	0.956	20.05	4.92	7.74	7.09	7576.41
194	Deep	1.06	20.08	4.94	7.75	7.1	7594.5
195	Deep	1.067	20.08	4.94	7.75	7.1	7595.42
196	Deep	1.074	20.08	4.94	7.75	7.1	7596.35
197	Deep	1.112	20.1	4.93	7.75	7.1	7590.61
198	Deep	1.116	20.1	4.93	7.75	7.1	7590.65
199	Deep	1.12	20.1	4.93	7.74	7.1	7590.69
200	Deep	1.124	20.1	4.93	7.74	7.1	7590.72
201	Deep	1.135	20.11	4.92	7.75	7.11	7572.66
202	Deep	1.136	20.11	4.92	7.76	7.11	7571.53
203	Deep	1.138	20.11	4.92	7.76	7.11	7570.39
204	Deep	1.121	20.08	4.93	7.77	7.17	7583.62
205	Deep	1.121	20.08	4.93	7.77	7.17	7584
206	Deep	1.12	20.08	4.93	7.77	7.17	7584.38
207	Deep	1.143	20.07	4.93	7.78	7.25	7584.39
208	Deep	1.144	20.06	4.93	7.78	7.26	7584.7
209	Deep	1.145	20.06	4.93	7.78	7.26	7585.02
210	Deep	1.146	20.06	4.93	7.78	7.27	7585.33
211	Deep	1.088	20.04	4.93	7.79	7.32	7583.78
212	Deep	1.086	20.04	4.93	7.8	7.32	7583.68
213	Deep	1.083	20.04	4.93	7.8	7.33	7583.58
214	Deep	1.108	20.03	4.93	7.79	7.38	7588.5
215	Deep	1.108	20.03	4.93	7.79	7.38	7588.74
216	Deep	1.109	20.03	4.93	7.79	7.38	7588.97
217	Deep	1.075	20.04	4.93	7.77	7.37	7590.77
218	Deep	1.074	20.04	4.93	7.77	7.38	7590.97
219	Deep	1.073	20.04	4.93	7.77	7.38	7591.17
220	Deep	1.095	20.06	4.93	7.77	7.36	7590.4
221	Deep	1.095	20.06	4.93	7.77	7.36	7590.37
222	Deep	1.096	20.06	4.93	7.76	7.36	7590.35
223	Deep	1.096	20.07	4.93	7.76	7.36	7590.33
224	Deep	1.11	20.05	4.94	7.76	7.34	7592.75
225	Deep	1.111	20.05	4.94	7.76	7.34	7592.85
226	Deep	1.113	20.05	4.94	7.76	7.34	7592.96
227	Deep	1.008	20.05	4.94	7.76	7.31	7595.79
228	Deep	1.002	20.05	4.94	7.76	7.3	7595.99
229	Deep	0.997	20.05	4.94	7.76	7.3	7596.19
230	Deep	0.919	20.05	4.68	7.76	7.27	7197.13

231	Deep	0.912	20.05	4.66	7.76	7.27	7175.5
232	Deep	0.906	20.05	4.65	7.76	7.27	7153.87
233	Deep	0.928	20.05	4.62	7.76	7.27	7114.05
234	Deep	0.928	20.05	4.62	7.76	7.27	7104.11
235	Deep	0.928	20.05	4.61	7.76	7.27	7094.18
236	Deep	0.928	20.05	4.6	7.76	7.27	7084.24
237	Deep	0.99	20.05	4.61	7.83	7.47	7099.62
238	Deep	0.994	20.05	4.62	7.84	7.48	7100.44
239	Deep	0.998	20.05	4.62	7.84	7.49	7101.27
240	Deep	0.833	20.04	4.63	7.84	7.64	7130.42
241	Deep	0.825	20.04	4.64	7.84	7.65	7132.41
242	Deep	0.817	20.04	4.64	7.84	7.66	7134.39
243	Deep	0.909	20.03	4.62	7.78	7.76	7105.67
244	Deep	0.911	20.03	4.62	7.77	7.77	7104.64
245	Deep	0.912	20.03	4.62	7.77	7.78	7103.6
246	Deep	0.987	20.03	4.63	7.79	7.77	7116.45
247	Deep	0.993	20.03	4.63	7.79	7.77	7116.51
248	Deep	0.999	20.03	4.63	7.79	7.77	7116.57
249	Deep	1.006	20.03	4.63	7.79	7.77	7116.64
250	Deep	1.04	20.03	4.64	7.78	7.82	7131.62
251	Deep	1.043	20.02	4.64	7.78	7.82	7132.73
252	Deep	1.046	20.02	4.64	7.78	7.82	7133.84
253	Deep	1.044	20.02	4.64	7.78	7.82	7136.56
254	Deep	1.044	20.01	4.64	7.78	7.82	7136.98
255	Deep	1.044	20.01	4.64	7.78	7.82	7137.4
256	Deep	0.87	20.01	4.63	7.77	7.84	7121.68
257	Deep	0.86	20.01	4.63	7.77	7.84	7120.84
258	Deep	0.85	20.01	4.63	7.77	7.84	7120
259	Deep	0.792	20	4.61	7.76	7.82	7094.36
260	Deep	0.786	20	4.61	7.76	7.82	7092.63
261	Deep	0.779	20	4.61	7.76	7.82	7090.9
262	Deep	0.773	20	4.61	7.76	7.82	7089.17
263	Deep	0.85	20.01	4.6	7.76	7.77	7078.52
264	Deep	0.853	20.01	4.6	7.76	7.77	7077.45
265	Deep	0.856	20.01	4.6	7.76	7.77	7076.38
266	Deep	0.979	20.01	4.61	7.76	7.76	7099.24
267	Deep	0.988	20.01	4.62	7.76	7.76	7100.3
268	Deep	0.996	20.01	4.62	7.76	7.75	7101.37
269	Deep	0.981	20.01	4.6	7.76	7.73	7081.11
270	Deep	0.982	20.01	4.6	7.76	7.73	7080.49
271	Deep	0.984	20.01	4.6	7.76	7.73	7079.86
272	Deep	0.963	20	4.6	7.76	7.69	7077.37
273	Deep	0.961	20	4.6	7.76	7.69	7076.78
274	Deep	0.959	20	4.6	7.76	7.69	7076.19
275	Deep	0.957	20	4.6	7.76	7.68	7075.59
276	Deep	1.056	19.98	4.62	7.75	7.67	7104.38
277	Deep	1.061	19.98	4.62	7.75	7.66	7105.89

278	Deep	1.066	19.97	4.62	7.75	7.66	7107.39
279	Deep	1.029	19.96	4.65	7.76	7.66	7147.6
280	Deep	1.029	19.96	4.65	7.76	7.66	7150.33
281	Deep	1.029	19.96	4.65	7.76	7.65	7153.06
282	Deep	1.057	19.95	4.61	7.76	7.65	7098.87
283	Deep	1.057	19.95	4.61	7.76	7.65	7096.65
284	Deep	1.058	19.95	4.61	7.76	7.65	7094.42
285	Deep	0.932	19.95	4.62	7.75	7.63	7101.76
286	Deep	0.926	19.95	4.62	7.75	7.62	7100.99
287	Deep	0.92	19.95	4.62	7.75	7.62	7100.22
288	Deep	0.913	19.95	4.61	7.75	7.62	7099.45
289	Deep	0.83	19.95	4.83	7.75	7.59	7426.1
290	Deep	0.823	19.95	4.84	7.75	7.59	7443.64
291	Deep	0.816	19.95	4.85	7.75	7.58	7461.18
292	Deep	0.431	19.95	4.85	7.76	7.54	7465.86
293	Deep	0.409	19.95	4.86	7.76	7.53	7472.57
294	Deep	0.387	19.95	4.86	7.76	7.53	7479.27
295	Deep	0.519	19.95	4.88	7.75	7.46	7502.56
296	Deep	0.519	19.95	4.88	7.75	7.45	7503.16
297	Deep	0.871	19.95	4.89	7.76	7.29	7522.43
298	Deep	0.879	19.95	4.89	7.76	7.29	7522.81
299	Deep	0.879	19.94	4.89	7.76	7.28	7524.61
300	Deep	0.879	19.94	4.89	7.76	7.28	7524.72
301	Deep	0.879	19.94	4.89	7.76	7.28	7524.82
302	Deep	0.776	19.94	4.89	7.77	7.29	7520.93
303	Deep	0.768	19.94	4.89	7.77	7.29	7520.66
304	Deep	0.761	19.94	4.89	7.77	7.29	7520.39
305	Deep	0.754	19.94	4.89	7.77	7.29	7520.13
306	Deep	0.907	19.91	4.89	7.77	7.3	7527.86
307	Deep	0.913	19.91	4.89	7.77	7.3	7528.18
308	Deep	0.919	19.91	4.89	7.76	7.3	7528.49
309	Deep	0.791	19.91	4.89	7.77	7.32	7528.08
310	Deep	0.787	19.9	4.89	7.77	7.32	7528.22
311	Deep	0.783	19.9	4.89	7.77	7.32	7528.36
312	Deep	0.805	19.9	4.89	7.76	7.32	7523.26
313	Deep	0.803	19.9	4.89	7.76	7.32	7522.95
314	Deep	0.802	19.9	4.89	7.76	7.32	7522.63
315	Deep	0.829	19.89	4.92	7.76	7.31	7563.5
316	Deep	0.831	19.89	4.92	7.76	7.3	7565.7
317	Deep	0.834	19.88	4.92	7.76	7.3	7567.89
318	Deep	0.836	19.88	4.92	7.76	7.3	7570.08
319	Deep	0.85	19.86	4.92	7.76	7.29	7569.92
320	Deep	0.851	19.86	4.92	7.76	7.29	7570.78
321	Deep	0.853	19.86	4.92	7.76	7.29	7571.64
322	Deep	0.859	19.84	4.92	7.77	7.29	7573.14
323	Deep	0.86	19.84	4.92	7.77	7.29	7573.11
324	Deep	0.861	19.84	4.92	7.77	7.29	7573.08

325	Deep	0.726	19.82	4.91	7.77	7.29	7558.29
326	Deep	0.718	19.82	4.91	7.77	7.29	7557.48
327	Deep	0.711	19.82	4.91	7.77	7.29	7556.68
328	Deep	0.858	19.84	4.91	7.76	7.28	7558.94
329	Deep	0.863	19.84	4.91	7.76	7.28	7558.79
330	Deep	0.869	19.85	4.91	7.76	7.28	7558.63
331	Deep	0.874	19.85	4.91	7.76	7.28	7558.48
332	Deep	1.114	19.86	4.91	7.75	7.26	7556.52
333	Deep	1.13	19.86	4.91	7.75	7.26	7556.5
334	Deep	1.146	19.86	4.91	7.75	7.26	7556.49
335	Deep	1.182	19.87	4.92	7.76	7.25	7563.37
336	Deep	1.188	19.88	4.92	7.76	7.25	7563.71
337	Deep	1.194	19.88	4.92	7.76	7.25	7564.04
338	Deep	1.184	19.87	4.91	7.76	7.27	7561.04
339	Deep	1.183	19.87	4.91	7.76	7.27	7561.01
340	Deep	1.182	19.87	4.91	7.76	7.27	7560.98
341	Deep	0.987	19.87	4.91	7.76	7.26	7559.3
342	Deep	0.976	19.87	4.91	7.76	7.26	7559.13
343	Deep	0.964	19.87	4.91	7.76	7.26	7558.95
344	Deep	0.953	19.87	4.91	7.76	7.26	7558.78
345	Deep	0.988	19.86	4.91	7.76	7.27	7557.15

Appendix 2. *Water Trace Element Data (mg/L).*

Site	subsite	Li	Na	K	Rb	Cs	Be	Mg	Ca	Sr	Ba	Al	Sc	Mn	Fe	Cu	Ni	Zn	As
BL	Marsh	3.81	3897	274	1.25	0.102	0.0002	122.1	278	5.5	0.11	0.02	<0.0002	0	0.042	<0.5	0	0.02	<0.04
BL	Pond	1.71	1501	114	0.56	0.046	<0.000006	52.1	109	2.5	0.06	0.02	0.0002	0	<0.008	<0.5	0	0.01	<0.04
HRS	Deep	0.59	1496	57	0.05	0.004	<0.00005	53.9	118	1.1	0.07	<0.005	<0.0004	<0.003	<0.04	<0.0007	<0.0002	0.01	<0.04
HRS	Surface	0.59	1498	58	0.05	0.004	<0.00005	53.8	117	1	0.07	0.01	<0.0004	<0.003	<0.04	0	<0.0002	0.02	<0.04

Appendix 3. *Bulk shell stable isotope data.*

Sample Name	Site	Sample Type	Genera	Sub-site	δ^{13}C (‰-VPDB)	δ^{18}O (‰-VSMOW)	Data Source	Lab
BL-M-T6-1	BL	Shell	*Succineidae*	BL-Marsh	-3.4	-10.017	this study	SIRFER
BL-M-T6-2	BL	Shell	*Succineidae*	BL-Marsh	-3.33	-10.017	this study	SIRFER
BL-M-T6-6	BL	Shell	*Succineidae*	BL-Marsh	-4.23	-10.546	this study	SIRFER
BL-M-T6-3	BL	Shell	*Succineidae*	BL-Marsh	-3.07	-10.703	this study	SIRFER
BL-M-T6-4	BL	Shell	*Succineidae*	BL-Marsh	-5.18	-10.812	this study	SIRFER
BL-M-T6-5	BL	Shell	*Succineidae*	BL-Marsh	-6.49	-11.096	this study	SIRFER
BL-P-T5-8	BL	Shell	*Melanoides*	BL-Pond	-1.84	-12.646	this study	SIRFER
BL-M-T2-1	BL	Shell	*Pyrgulopsis*	BL-Marsh	-2.34	-13.182	this study	SIRFER
BL-M-T2-3	BL	Shell	*Pyrgulopsis*	BL-Marsh	-2.52	-13.894	this study	SIRFER
BL-M-T2-4	BL	Shell	*Pyrgulopsis*	BL-Marsh	-2.14	-14.243	this study	SIRFER
HRS-01-PP-O1	HRS	Shell	*Pyrgulopsis*	HRS-Subsite-01	-5.24	-14.343	this study	SIRFER
HRS-03-PP-O1	HRS	Shell	*Pyrgulopsis*	HRS-Subsite-03	-4.85	-14.361	this study	SIRFER
HRS-03-PP-O2	HRS	Shell	*Pyrgulopsis*	HRS-Subsite-03	-3.95	-14.406	this study	SIRFER
HRS-02-TP-O2	HRS	Shell	*Tryonia*	HRS-Subsite-02	-4.39	-14.568	this study	SIRFER
HRS-04-TP-O1	HRS	Shell	*Tryonia*	HRS-Subsite-04	-4.42	-14.578	this study	SIRFER
BL-M-T2-2	BL	Shell	*Pyrgulopsis*	BL-Marsh	-2.09	-14.634	this study	SIRFER
HRS-04-TP-O2	HRS	Shell	*Tryonia*	HRS-Subsite-04	-4.48	-14.733	this study	SIRFER
HRS-01-TP-O2	HRS	Shell	*Tryonia*	HRS-Subsite-01	-4.76	-14.776	this study	SIRFER
HRS-02-PP-O1	HRS	Shell	*Pyrgulopsis*	HRS-Subsite-02	-4.67	-14.795	this study	SIRFER
HRS-01-PP-O2	HRS	Shell	*Pyrgulopsis*	HRS-Subsite-01	-5.23	-14.83	this study	SIRFER
HRS-02-PP-O2	HRS	Shell	*Pyrgulopsis*	HRS-Subsite-02	-4.86	-14.851	this study	SIRFER
HRS-02-TP-O1	HRS	Shell	*Tryonia*	HRS-Subsite-02	-4.97	-14.858	this study	SIRFER
HRS-04-PP-O1	HRS	Shell	*Pyrgulopsis*	HRS-Subsite-04	-5	-14.879	this study	SIRFER
HRS-03-TP-O1	HRS	Shell	*Tryonia*	HRS-Subsite-03	-4.82	-14.88	this study	SIRFER
HRS-04-PP-O2	HRS	Shell	*Pyrgulopsis*	HRS-Subsite-04	-5.18	-14.959	this study	SIRFER
HRS-03-TP-O2	HRS	Shell	*Tryonia*	HRS-Subsite-03	-4.2	-15.059	this study	SIRFER
BL-P-T4-2	BL	Shell	*Planorbella*	BL-Pond	-4.82	-15.295	this study	SIRFER
HRS-01-TP-O1	HRS	Shell	*Tryonia*	HRS-Subsite-01	-5.01	-15.349	this study	SIRFER
HRS-T2-4	HRS	Shell	*Pyrgulopsis*	HRS-Subsite-00	-5.14	-15.565	this study	SIRFER
HRS-T4-1	HRS	Shell	*Planorbella*	HRS-Subsite-00	-8.96	-15.67	this study	SIRFER
HRS-T2-1	HRS	Shell	*Pyrgulopsis*	HRS-Subsite-00	-5.19	-15.718	this study	SIRFER
HRS-T2-5	HRS	Shell	*Pyrgulopsis*	HRS-Subsite-00	-5.19	-15.778	this study	SIRFER
HRS-T2-2	HRS	Shell	*Pyrgulopsis*	HRS-Subsite-00	-5.08	-15.788	this study	SIRFER
HRS-T2-3	HRS	Shell	*Pyrgulopsis*	HRS-Subsite-00	-5.03	-15.883	this study	SIRFER
HRS-T1-3	HRS	Shell	*Tryonia*	HRS-Subsite-00	-4.95	-15.98	this study	SIRFER
BL-P-T2-2	BL	Shell	*Pyrgulopsis*	BL-Pond	-1.92	-16.045	this study	SIRFER
HRS-T1-4	HRS	Shell	*Tryonia*	HRS-Subsite-00	-4.98	-16.068	this study	SIRFER
HRS-T1-1	HRS	Shell	*Tryonia*	HRS-Subsite-00	-4.57	-16.085	this study	SIRFER
HRS-T1-5	HRS	Shell	*Tryonia*	HRS-Subsite-00	-5.02	-16.131	this study	SIRFER
HRS-T1-2	HRS	Shell	*Tryonia*	HRS-Subsite-00	-4.96	-16.158	this study	SIRFER
BL-P-T2-1	BL	Shell	*Pyrgulopsis*	BL-Pond	-1.72	-16.282	this study	SIRFER
BL-P-T3-2	BL	Shell	*Physella*	BL-Pond	-5.02	-16.341	this study	SIRFER
BL-S-T1-1	BL	Shell	*Tryonia*	BL-Spring	-1.92	-16.374	this study	SIRFER
BL-P-T1-1	BL	Shell	*Tryonia*	BL-Pond	-1.71	-16.524	this study	SIRFER
BL-P-T4-5	BL	Shell	*Planorbella*	BL-Pond	-4.5	-16.641	this study	SIRFER
BL-P-T3-1	BL	Shell	*Physella*	BL-Pond	-4.82	-16.819	this study	SIRFER
BL-P-T4-1	BL	Shell	*Planorbella*	BL-Pond	-3.65	-16.823	this study	SIRFER
BL-P-T5-6	BL	Shell	*Melanoides*	BL-Pond	-2.24	-16.858	this study	SIRFER
BL-L-T5-4	BL	Shell	*Melanoides*	BL-Lake	-2.93	-16.893	this study	SIRFER
BL-P-T4-4	BL	Shell	*Planorbella*	BL-Pond	-3.71	-16.916	this study	SIRFER
BL-P-T5-3	BL	Shell	*Melanoides*	BL-Pond	-2.48	-17.015	this study	SIRFER
BL-P-T5-4	BL	Shell	*Melanoides*	BL-Pond	-2.15	-17.058	this study	SIRFER
BL-P-T5-1	BL	Shell	*Melanoides*	BL-Pond	-2.44	-17.084	this study	SIRFER
BL-P-T5-7	BL	Shell	*Melanoides*	BL-Pond	-2.49	-17.125	this study	SIRFER
BL-P-T5-2	BL	Shell	*Melanoides*	BL-Pond	-2.46	-17.135	this study	SIRFER
BL-L-T5-3	BL	Shell	*Melanoides*	BL-Lake	-2.99	-17.162	this study	SIRFER
BL-L-T5-1	BL	Shell	*Melanoides*	BL-Lake	-3.02	-17.238	this study	SIRFER
BL-L-T5-2	BL	Shell	*Melanoides*	BL-Lake	-2.38	-17.238	this study	SIRFER
BL-S-T5-4	BL	Shell	*Melanoides*	BL-Spring	-2.23	-17.343	this study	SIRFER
BL-S-T5-1	BL	Shell	*Melanoides*	BL-Spring	-2.1	-17.516	this study	SIRFER
BL-S-T5-5	BL	Shell	*Melanoides*	BL-Spring	-2.29	-17.519	this study	SIRFER
BL-S-T1-2	BL	Shell	*Tryonia*	BL-Spring	-1.91	-17.541	this study	SIRFER
BL-S-T5-2	BL	Shell	*Melanoides*	BL-Spring	-2.13	-17.549	this study	SIRFER
BL-P-T4-3	BL	Shell	*Planorbella*	BL-Pond	-3.08	-	this study	SIRFER
BL-Spring-Shell-2019-1	BL	Shell	*Melanoides*	BL-Spring	-2.21	-	Lerback and others, 2023	NOSAMS
BL-Spring-Shell-2019-2	BL	Shell	*Melanoides*	BL-Spring	-2.26	-	Lerback and others, 2023	NOSAMS
BL-Spring-Shell-2019-3	BL	Shell	*Melanoides*	BL-Spring	-	-	Lerback and others, 2023	NOSAMS
BL-Spring-Shell-2019-4	BL	Shell	*Melanoides*	BL-Spring	-3.08	-	Lerback and others, 2023	NOSAMS
BL-Pond-Shell-2019-1	BL	Shell	*Melanoides*	BL-Pond	-2.17	-	Lerback and others, 2023	NOSAMS
BL-Pond-Shell-2019-2	BL	Shell	*Melanoides*	BL-Pond	-2.09	-	Lerback and others, 2023	NOSAMS
BL-Pond-Shell-2019-3	BL	Shell	*Melanoides*	BL-Pond	-2.37	-	Lerback and others, 2023	NOSAMS
BL-Pond-Shell-2019-4	BL	Shell	*Melanoides*	BL-Pond	-2.14	-	Lerback and others, 2023	NOSAMS
BL-Lake-Shell-2018-1	BL	Shell	*Melanoides*	BL-Lake	-3.06	-	Lerback and others, 2023	NOSAMS
BL-Lake-Shell-2018-2	BL	Shell	*Melanoides*	BL-Lake	-2.85	-	Lerback and others, 2023	NOSAMS
BL-Lake-Shell-2018-3	BL	Shell	*Melanoides*	BL-Lake	-2.98	-	Lerback and others, 2023	NOSAMS

BL-Lake-Shell-2018-4	BL	Shell	*Melanoides*	BL-Lake	-3.89	-	Lerback and others, 2023	NOSAMS
HRS-Pond-Shell-2020-1	HRS	Shell	*Pyrgulopsis*	HRS-Subsite-00	-5.18	-	Lerback and others, 2023	NOSAMS
HRS-Pond-Shell-2020-2	HRS	Shell	*Pyrgulopsis*	HRS-Subsite-00	-4.43	-	Lerback and others, 2023	NOSAMS
HRS-Pond-Shell-2020-3	HRS	Shell	*Pyrgulopsis*	HRS-Subsite-00	-4.77	-	Lerback and others, 2023	NOSAMS
HRS-Pond-Shell-2020-4	HRS	Shell	*Pyrgulopsis*	HRS-Subsite-00	-4.79	-	Lerback and others, 2023	NOSAMS
BL-Spring-Shell-2020-5	BL	Shell	*Pyrgulopsis*	BL-Spring	-1.82	-	Lerback and others, 2023	NOSAMS
BL-Spring-Shell-2020-6	BL	Shell	*Pyrgulopsis*	BL-Spring	-1.97	-	Lerback and others, 2023	NOSAMS
BL-Spring-Shell-2020-7	BL	Shell	*Pyrgulopsis*	BL-Spring	-1.94	-	Lerback and others, 2023	NOSAMS
BL-Spring-Shell-2020-8	BL	Shell	*Pyrgulopsis*	BL-Spring	-1.83	-	Lerback and others, 2023	NOSAMS
BL-Pond-Sediment-2020-1	BL	Sediment	-	BL-Pond	-26.61	-	Lerback and others, 2023	NOSAMS
HRS-Pond-Sediment-2020-1	HRS	Sediment	-	HRS-Subsite-00	-20.65	-	Lerback and others, 2023	NOSAMS

Appendix 4 . *Water stable isotope data.*

Site	Type	δ^{18}O (‰-VSMOW)	δ^{18}O (‰-VPDB converted)	δ^{13}C (‰-VPDB)	δ^{13}C Source	Lab	Source	Subsite
BL	Water	-	-	-3.73	Measured	NOSAMS	Lerback and others, 2023	BL-Lake
BL	Water	-	-	-4	Measured	NOSAMS	Lerback and others, 2023	BL-Pond
BL	Water	-	-	-4.5	Measured	NOSAMS	Lerback and others, 2019 Supplementary Data. "Lookout Point, 6/2/2017"	BL-Spring
BL	Water	-	-	-4.65	Measured	NOSAMS	Lerback and others, 2023	BL-Spring
HRS	Water	-	-	-7.02	Measured	NOSAMS	Lerback and others, 2023	HRS-Subsite-00
BL	Water	-15.9	-45.42	-		SIRFER	Lerback and others, 2019	BL-Spring
BL	Water	-16.05	-45.56	-		SIRFER	Lerback and others, 2019	BL-Spring
BL	Water	-15.92	-45.43	-		SIRFER	Lerback and others, 2019	BL-Spring
BL	Water	-15.99	-45.5	-		SIRFER	Lerback and others, 2019	BL-Spring
BL	Water	-16	-45.51	-		SIRFER	Lerback and others, 2019	BL-Spring
BL	Water	-16.1	-45.61	-		SIRFER	Lerback and others, 2019	BL-Spring
BL	Water	-15.86	-45.37	-		SIRFER	Lerback and others, 2019	BL-Lake
BL	Water	-15.74	-45.26	-		SIRFER	Lerback and others, 2019	BL-Lake
HRS	Water	-16.23	-45.73	-		SIRFER	Lerback and others, 2023	HRS-Subsite-00
HRS	Water	-16.06	-45.57	-		SIRFER	Lerback and others, 2023	HRS-Subsite-00
HRS	Water	-15.98	-45.49	-		SIRFER	Lerback and others, 2023	HRS-Subsite-00
HRS	Water	-16.04	-45.55	-		SIRFER	Lerback and others, 2023	HRS-Subsite-00
HRS	Water	-16	-45.51	-		SIRFER	Lerback and others, 2023	HRS-Subsite-00
HRS	Water	-15.89	-45.41	-		SIRFER	Lerback and others, 2023	HRS-Subsite-00
HRS	Water	-16.01	-45.52	-		SIRFER	Lerback and others, 2023	HRS-Subsite-00

Appendix 5. *Gastropod Intrashell $\delta^{13}C$ and $\delta^{18}O$ Transect Data.*

Sample Name	Drill site Number	$\delta^{13}C$	$\delta^{18}O$
BL-S-T5-9-4	4	-2.91	-17.46
BL-S-T5-9-3	3	-2.41	-17.48
BL-S-T5-9-2	2	-2.21	-17.32
BL-S-T5-9-1	1	-2.24	-17.49
BL-S-T5-8-4	4	-2.64	-17.25
BL-S-T5-8-3	3	-2.54	-17.33
BL-S-T5-8-2	2	-2.13	-17.37
BL-S-T5-8-1	1	-1.91	-17.51
BL-S-T5-7-4	4	-2.54	-17.67
BL-S-T5-7-3	3	-2.08	-17.33
BL-S-T5-7-2	2	-2.24	-17.65
BL-S-T5-7-1	1	-2.25	-17.26
BL-S-T5-6-4	4	-2.97	-16.57
BL-S-T5-6-3	3	-2.84	-16.96
BL-S-T5-6-2	2	-2.41	-17.18
BL-S-T5-6-1	1	-2.2	-17.36

Appendix 6. *Calculated formation temperatures of gastropod shells*

Sample Name	**Genera**	**Sub-site**	**T (℃; Kim and O'Neill, 1997)**	**T (℃; Kim and others, 2007)**	**T (℃; White and others, 1999)**
BL-M-T6-1	*Succineidae*	BL-Marsh	-11.4	-8.6	-6.8
BL-M-T6-2	*Succineidae*	BL-Marsh	-11.4	-8.6	-6.8
BL-M-T6-6	*Succineidae*	BL-Marsh	-9.3	-6.5	-4.5
BL-M-T6-3	*Succineidae*	BL-Marsh	-8.7	-5.9	-3.8
BL-M-T6-4	*Succineidae*	BL-Marsh	-8.3	-5.4	-3.3
BL-M-T6-5	*Succineidae*	BL-Marsh	-7.2	-4.3	-2.1
BL-P-T5-8	*Melanoides*	BL-Pond	-0.8	2.2	5
BL-M-T2-1	*Pyrgulopsis*	BL-Marsh	1.4	4.5	7.5
BL-M-T2-3	*Pyrgulopsis*	BL-Marsh	4.5	7.7	11
BL-M-T2-4	*Pyrgulopsis*	BL-Marsh	6	9.2	12.7
BL-M-T2-2	*Pyrgulopsis*	BL-Marsh	7.7	11	14.6
BL-P-T4-2	*Planorbella*	BL-Pond	10.7	14.1	18
BL-P-T2-2	*Pyrgulopsis*	BL-Pond	14.1	17.7	21.9
BL-P-T2-1	*Pyrgulopsis*	BL-Pond	15.2	18.8	23.2
BL-P-T3-2	*Physella*	BL-Pond	15.5	19.1	23.5
BL-S-T1-1	*Tryonia*	BL-Spring	15.7	19.2	23.7
BL-P-T1-1	*Tryonia*	BL-Pond	16.4	20	24.5
BL-P-T4-5	*Planorbella*	BL-Pond	16.9	20.5	25.1
BL-P-T3-1	*Physella*	BL-Pond	17.8	21.4	26.1
BL-P-T4-1	*Planorbella*	BL-Pond	17.8	21.4	26.1
BL-P-T5-6	*Melanoides*	BL-Pond	17.9	21.6	26.3
BL-L-T5-4	*Melanoides*	BL-Lake	18.1	21.8	26.5
BL-P-T4-4	*Planorbella*	BL-Pond	18.2	21.9	26.6
BL-P-T5-3	*Melanoides*	BL-Pond	18.7	22.4	27.1
BL-P-T5-4	*Melanoides*	BL-Pond	18.9	22.6	27.4
BL-P-T5-1	*Melanoides*	BL-Pond	19	22.7	27.5
BL-P-T5-7	*Melanoides*	BL-Pond	19.2	22.9	27.7
BL-P-T5-2	*Melanoides*	BL-Pond	19.3	23	27.8
BL-L-T5-3	*Melanoides*	BL-Lake	19.4	23.1	27.9
BL-L-T5-1	*Melanoides*	BL-Lake	19.8	23.5	28.4
BL-L-T5-2	*Melanoides*	BL-Lake	19.8	23.5	28.4
BL-S-T5-4	*Melanoides*	BL-Spring	20.3	24	28.9
BL-S-T5-1	*Melanoides*	BL-Spring	21.1	24.9	29.9
BL-S-T5-5	*Melanoides*	BL-Spring	21.1	24.9	29.9
BL-S-T1-2	*Tryonia*	BL-Spring	21.2	25	30
BL-S-T5-2	*Melanoides*	BL-Spring	21.3	25.1	30.1
HRS-01-PP-O1	*Pyrgulopsis*	HRS-Subsite-01	6.3	9.5	13
HRS-03-PP-O1	*Pyrgulopsis*	HRS-Subsite-03	6.3	9.6	13.1
HRS-03-PP-O2	*Pyrgulopsis*	HRS-Subsite-03	6.5	9.8	13.3
HRS-02-TP-O2	*Tryonia*	HRS-Subsite-02	7.3	10.6	14.1
HRS-04-TP-O1	*Tryonia*	HRS-Subsite-04	7.3	10.6	14.2
HRS-04-TP-O2	*Tryonia*	HRS-Subsite-04	8	11.3	15
HRS-01-TP-O2	*Tryonia*	HRS-Subsite-01	8.2	11.5	15.2
HRS-02-PP-O1	*Pyrgulopsis*	HRS-Subsite-02	8.3	11.6	15.3
HRS-01-PP-O2	*Pyrgulopsis*	HRS-Subsite-01	8.4	11.8	15.4
HRS-02-PP-O2	*Pyrgulopsis*	HRS-Subsite-02	8.5	11.9	15.6
HRS-02-TP-O1	*Tryonia*	HRS-Subsite-02	8.5	11.9	15.6
HRS-04-PP-O1	*Pyrgulopsis*	HRS-Subsite-04	8.6	12	15.7
HRS-03-TP-O1	*Tryonia*	HRS-Subsite-03	8.6	12	15.7
HRS-04-PP-O2	*Pyrgulopsis*	HRS-Subsite-04	9	12.4	16.1
HRS-03-TP-O2	*Tryonia*	HRS-Subsite-03	9.4	12.8	16.6
HRS-01-TP-O1	*Tryonia*	HRS-Subsite-01	10.8	14.2	18.1
HRS-T2-4	*Pyrgulopsis*	HRS-Subsite-00	11.7	15.2	19.2
HRS-T4-1	*Planorbella*	HRS-Subsite-00	12.2	15.7	19.8
HRS-T2-1	*Pyrgulopsis*	HRS-Subsite-00	12.4	15.9	20
HRS-T2-5	*Pyrgulopsis*	HRS-Subsite-00	12.7	16.2	20.3
HRS-T2-2	*Pyrgulopsis*	HRS-Subsite-00	12.8	16.3	20.4
HRS-T2-3	*Pyrgulopsis*	HRS-Subsite-00	13.2	16.7	20.9
HRS-T1-3	*Tryonia*	HRS-Subsite-00	13.6	17.2	21.4
HRS-T1-4	*Tryonia*	HRS-Subsite-00	14.1	17.6	21.8
HRS-T1-1	*Tryonia*	HRS-Subsite-00	14.1	17.7	21.9
HRS-T1-5	*Tryonia*	HRS-Subsite-00	14.4	17.9	22.2
HRS-T1-2	*Tryonia*	HRS-Subsite-00	14.5	18	22.3

Appendix 7. *Gastropod Shell Trace Element Data (mg/kg)*

Site	Taxa	Li	Na	K	Rb	Cs	Be	Mg	Ca	Sr	Ba	Al	Sc	Mn	Fe	Cu	Ni	Zn	As
BL	*Succineidae*	3.3	2573	370	0.12	0.008	0.0392	56.7	407754	2486.8	40.07	4.86	0.0268	12.19	2.611	5.4	0.21	2.44	0.11
BL	*Succineidae*	5.93	2268	456	0.19	0.037	0.195	130.5	425888	2666.1	55.38	13.16	0.032	9.67	8.333	3.7	0.22	3.91	0.36
BL	*Succineidae*	2.86	2464	561	0.2	0.021	0.0516	82.2	430344	2473.6	42.62	11.31	0.0398	12.02	10.424	3.4	0.15	2.11	0.42
BL	*Succineidae*	4.14	2340	427	0.13	0.007	0.064	40.6	401159	2463.8	36.12	3.7	0.0271	12.63	5.667	11.2	0.35	3.55	0.26
HRS	*Pyrgulopsis*	1.6	2170	21	0.03	0.017	0.007	80.6	398182	1263.9	99.39	5.95	0.09	3.12	100.026	<11	1.9	2.09	0.26
HRS	*Pyrgulopsis*	2	2667	22	<0.03	0.007	0.0105	51.1	415211	1200.8	106.43	7.12	0.0949	6.75	14.235	<11	2.2	1.05	0.11
HRS	*Pyrgulopsis*	1.47	1960	18	0.03	0.015	0.0077	63.9	347402	1131.3	83.02	12.29	0.0812	2.51	67.234	<9	1.67	0.74	0.26
HRS	*Tryonia*	1.44	2879	45	0.25	0.093	0.0134	230.9	425229	1317.5	129.36	81.88	0.1146	8.45	64.693	<20	2.25	2.11	0.14