Isotopic Characterization of Groundwater and Surface Water in the Billings, Montana Area: Water Budget Estimates Using Strontium and Water Isotopes

Skye Keeshin and Elizabeth Meredith

Ground Water Investigation Program
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Front photo: Hogan's Slough serves as an important drain managing surface and groundwater for the developments west of Billings. Photo by Don Sasse, MBMG.

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PREFACE

The Ground Water Investigation Program (GWIP) at the Montana Bureau of Mines and Geology (MBMG) investigates projects prioritized by the Ground Water Assessment Steering Committee (MCA 2-15-1523). Prioritization is based on factors such as current and anticipated growth of industry, housing, and commercial activity, or changing irrigation practices. Additional program information and project-ranking details are available on the MBMG GWIP website (https://www.mbmg.mtech.edu/waterenvironment/gwip).

Products of the West Billings GWIP project include:

- An environmental tracers report (this report), which uses strontium and water isotopes to quantify contributions of water budget components.
- A water-quality report that presents a characterization of groundwater quality, including nitrate concentrations and sources.
- A groundwater-flow modeling report that presents the terrace-aquifer groundwater budget, model construction, and simulated groundwater responses to residential growth scenarios.
- A GIS web app with surface-water hydrographs, groundwater hydrographs, water chemistry, and water quality results: https://gis-data-hub-mbmg.hub.arcgis.com/apps/52ea3f7210344db98fb5e1a9c9130310/explore
- All data are available on the Ground Water Information Center database (GWIC; MBMG, 2025).

ABSTRACT

The Billings terrace aquifers are the primary source for domestic and stock water outside of city water services. These aquifers are thin, with an average saturated thickness of 15 feet, and are recharged primarily by irrigation water from the Yellowstone River. Other recharge sources include precipitation and inflow from underlying and adjacent shale and sandstone aquifers. Canyon Creek and Hogan's Slough are modified streams that receive inputs from terrace groundwater and irrigation water. We used strontium isotopes ($^{87}Sr/^{86}Sr$) and water isotopes ($\delta^{18}O$ and $\delta^{2}H$) to quantify baseflow to streams and attempt to identify the relative sources of groundwater recharge (irrigation, precipitation, stream loss, and bedrock inflow). Strontium isotopes showed that, during the summer, Canyon Creek and Hogan's Slough function primarily as conduits for irrigation water, while in the spring, they return to being groundwater-fed systems. The observed groundwater strontium isotope ratios suggested an unrecognized strontium source, precluding the use of a simple mixing model to distinguish recharge sources to the terrace aquifer. Low-salinity irrigation water leaking from canals or applied to fields likely leaches strontium from soils derived from the surrounding sedimentary bedrock. The water isotope results showed that irrigation water and precipitation recharge were isotopically indistinguishable. This similarity meant that water isotopes could not be used to quantify relative recharge contributions. These results indicate that physical monitoring methods like lysimeters or soil moisture sensors are better tools to estimate precipitation recharge.

1. INTRODUCTION

Residences and businesses outside of Billings city water services rely on terrace aquifers for domestic water; these aquifers average only 15 ft thick (Olson and Reiten, 2002). Growth outside of city services has been steady; the number of housing units in the study area not served by city services grew from approximately 340 in 1960 to over 3,000 in 2020 (Montana State Library, 2024). This land-use shift from agriculture to residential development has created a dual management challenge: increased demand for groundwater and decreased recharge from canals and applied irrigation. Managing this transition will require an understanding of the interaction between groundwater and surface water. Isotopic tracers offer methods to identify sources of water into and out of the aquifer that are independent of numerical groundwater modeling and physical surface-water and groundwater measurements.

1.1 Purpose and Scope

The MBMG Ground Water Investigation Program (GWIP) Billings project aimed to understand the current terrace groundwater system and use groundwater modeling to predict the effects of future land-use changes. Strontium isotopes ($^{87}Sr/^{86}Sr$) were used to identify sources of gain to Canyon Creek and Hogan's Slough, which are inaccessible for flow measurements due to control structures. Understanding the relative composition of groundwater and direct irrigation-water contributions to stream gain is an important element in quantifying the overall groundwater budget and is critical to groundwater model development. Additionally, we evaluated whether strontium and water isotopes (δ^2H and $\delta^{18}O$) could quantify the proportions of groundwater recharge sources, such as irrigation water and precipitation.

The study area covered 73 mi^2 of the greater Billings area where Yellowstone River terraces dominate the surficial geology and serve as the primary aquifers. The study area extended from 80th Street W. (west) to Highway 87 (east, fig. 1). The northern boundary is delimited by exposed bedrock, while the Yellowstone River marks the southern boundary. Groundwater and surface-water elevations were monitored in 2022 and 2023; 37 samples were collected for strontium analysis and 84 for water isotope analysis. Samples were collected in March/April to represent pre-irrigation low-flow conditions, and August/September to represent peak-irrigation conditions. Samples were collected from surface-water sites (natural and manmade) and from wells completed in the terrace aquifers and the shale below the aquifers.

1.2 Climate

Billings receives an average of 15.1 in of precipitation annually [National Oceanic and Atmospheric Administration (NOAA), 2024], with half typically falling between April and July (fig. 2). The study period captured dry and wet years: 2.3 in below average (2022) and 2.7 in above average (2023). Most notably, June 2023 saw 7.1 in of rain, nearly triple the monthly average, providing a unique opportunity to observe the aquifer response to a spring recharge event.

1.3 Hydrogeologic Setting

The study area is composed primarily of the flat-lying alluvial terraces of the Yellowstone River, which are surrounded and underlain by Cretaceous sedimentary bedrock (fig. 3). There are five terraces and the active floodplain in the Billings area, though only the youngest three terraces and the floodplain are present within the study area. Sand and gravel aquifers that make up the terraces are thin, averaging only 15 ft of saturated thickness (Olson and Reiten, 2002). In the northwest, layers of silty clay colluvium and alluvial fan deposits up to 100 ft thick overlie the gravels, creating confined conditions and increasing the dissolved solids in the water (Olson and Reiten, 2002). This report refers to terrace aquifers or terrace wells even when other sedimentary deposits may overlie them. Beneath these terraces lies approximately 2,000 ft of Cretaceous shale (Lopez, 2000). The shales make poor aquifers due to low transmissivity and high salinity; therefore, the terrace aquifers are the only viable source of potable groundwater.

The natural hydrologic system in Billings has been highly modified by canals, ditches, and drains (fig. 4A). The 63-mi-long Billings Bench Water Association (BBWA) canal, and its 200 mi of laterals, has diverted Yellowstone River water throughout the Billings area for more than 100 years (BBWA, 2025). The BBWA typically operates from April 15th through October 15th. Recharge to the underlying aquifers occurs through leakage from canals, ditches, and laterals and through infiltration of applied flood-irrigation water. This irrigation recharge causes groundwater

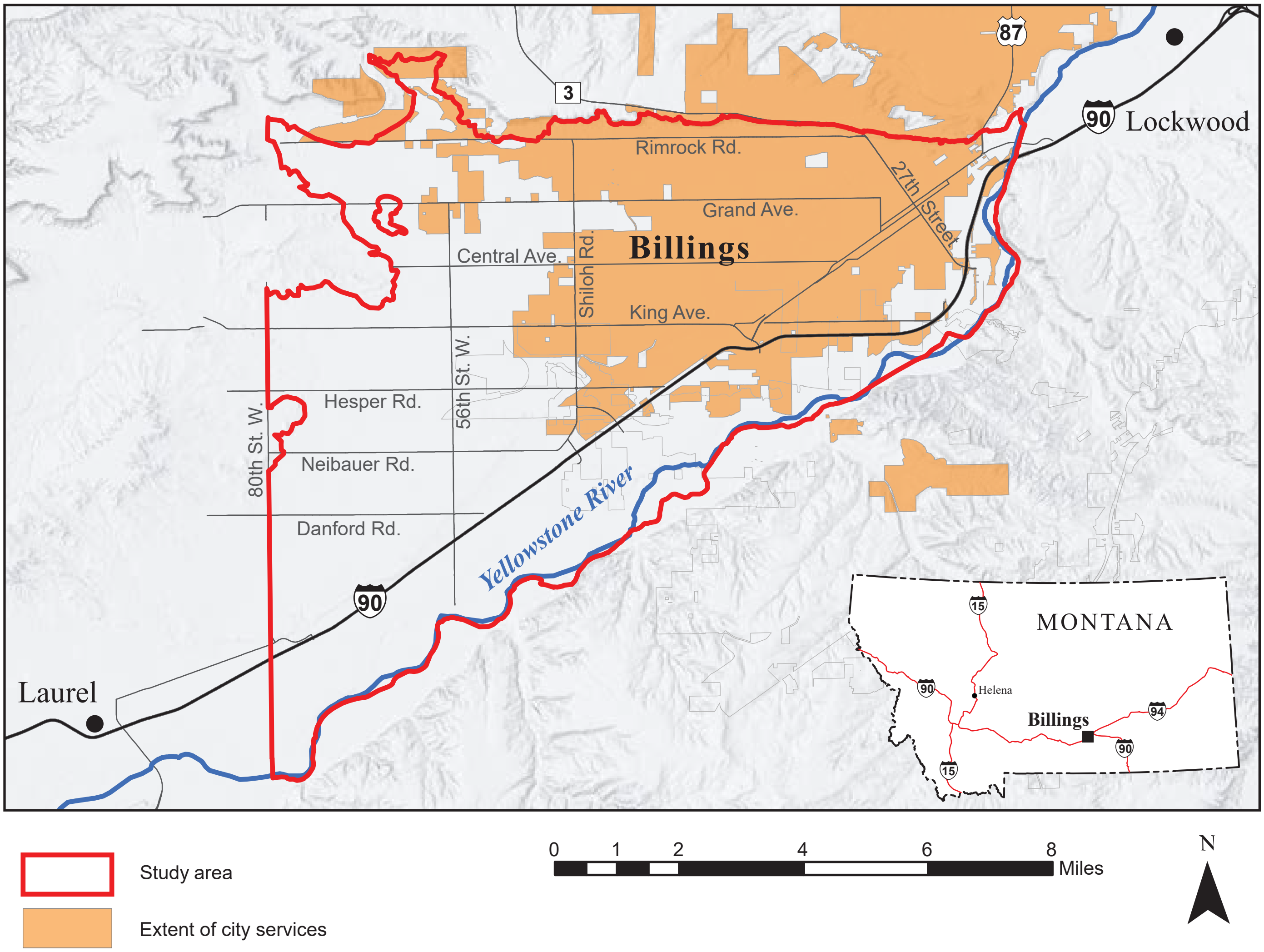

Figure 1. The study area was the extent of the Billings terrace aquifers north of the Yellowstone River from 80th St. West to U.S. Highway 87.

levels to rise as much as 14 ft every spring. Natural and constructed drains move groundwater and surface water to the Yellowstone River. One of the largest is Hogan's Slough, a natural drain, but its location and depth have been modified to accommodate residential and commercial development. Canyon Creek is the only natural, perennial stream in the study area.

There are records of approximately 3,200 wells in the study area; over 1,900 wells were drilled outside the city service area between 1980 and 2024. Of those 1,900 wells, nearly 500 were drilled between 2021 and 2024, primarily (93 percent) for domestic use (MBMG, 2025). The terrace wells typically yield about 30 gpm, and the median well depth is 29 ft. Olson and Reiten (2002) found that hydraulic conductivity in the terrace aquifers ranged from 20 to 200 ft/day, with a mean of 90 ft/day.

1.4 Previous Investigations

1.4.1 Quantifying surface-water and groundwater interaction using strontium isotopes

Strontium isotopes ($^{87}Sr/^{86}Sr$) can be used to distinguish geologically distinct groundwaters, and mixing of groundwater and surface water (Katz and Bullen, 1996; Neumann and Dreiss, 1995; Paces and Wurster, 2014). Strontium isotopes vary in geologic material (including soils, sand and gravel, and bedrock) due to the radioactive decay of ^{87}Rb to the stable ^{87}Sr. The $^{87}Sr/^{86}Sr$ ratio is imparted to the groundwater moving through the geologic material through salt dissolution or cation exchange (McNutt, 2000). The groundwater strontium isotope signature is acquired rapidly, ranging from days to years in both carbonate and siliciclastic sedimentary bedrock (Frost and Toner, 2004). Fractionation of strontium isotopes during mineral precipitation, ion exchange, or biological processes

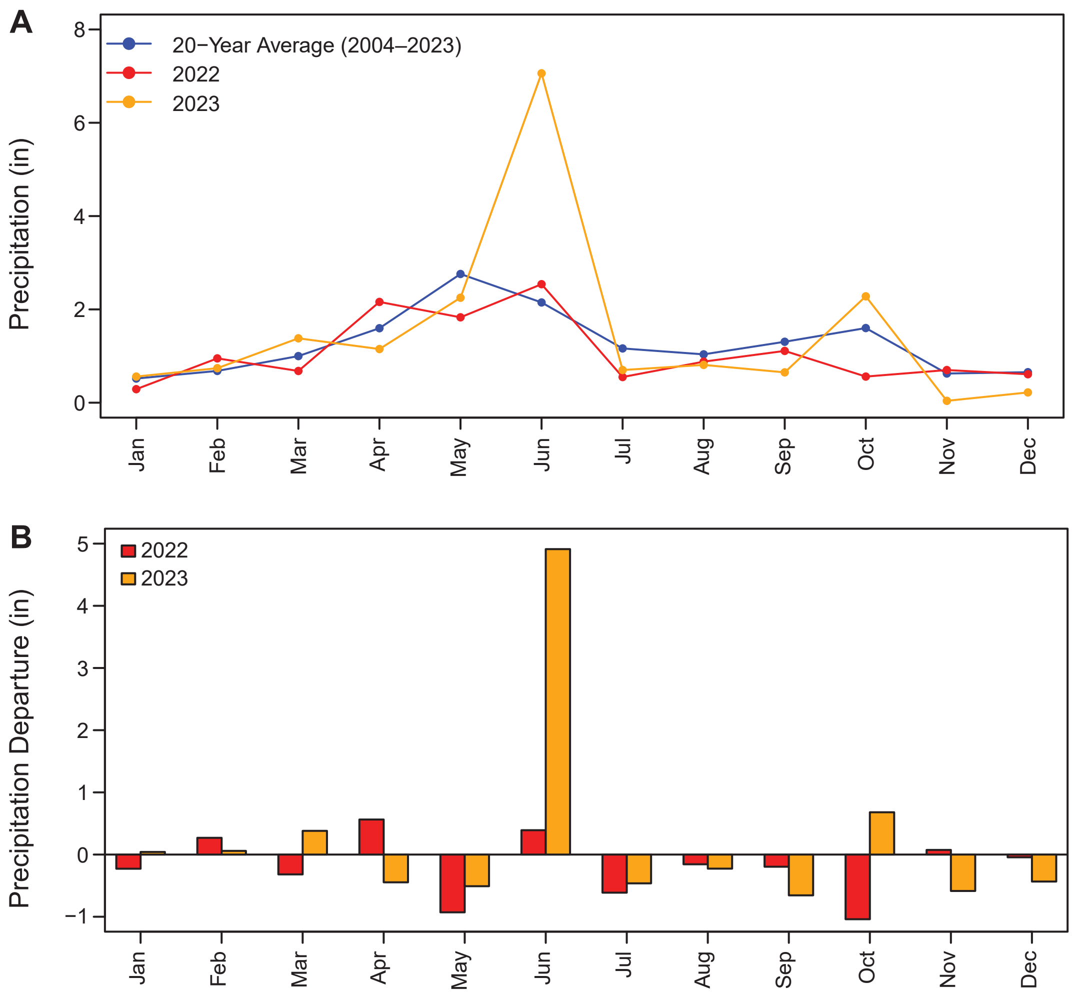

Figure 2. (A) Monthly precipitation totals for 2022 and 2023 and the 20-year average (NOAA, 2024) show the spring and early summer tend to be the wettest months. (B) Monthly precipitation during the study was within 1 inch of the 20-year monthly average with the exception of June 2023, which was 5 inches above average.

is very minor (Faure and Mensing, 2005); therefore, the $^{87}Sr/^{86}Sr$ ratio effectively fingerprints the geologic source of dissolved strontium in groundwater and surface water.

Because strontium isotopes are conservative, the proportion of two waters in a mixture (endmembers) can be calculated using the measured strontium concentrations and isotope ratios of the two endmembers and of the mixture (eq. 1; Faure and Mensing, 2005):

$$f_x = \frac{R_m C_m - R_y C_y}{R_x C_x - R_y C_y}, \qquad \text{eq. 1}$$

where R is the strontium isotope ratio, C is the strontium concentration (e.g., in mg/L), and f_x is the proportion from 0 to 1 of endmember x. The subscript y denotes the concentration and ratio of the second endmember, while m denotes the concentration and ratio of the mixture of the two endmembers. This equation can be used to plot mixing lines between endmembers and mixtures of three endmembers, creating a ternary-type diagram that comprises all possible mixtures.

Examples of using strontium isotopes to calculate the value of f_x (eq. 1) include: identifying coal aquifer groundwater contributions to Otter Creek and the Powder River in southeastern Montana (Meredith and Kuzara, 2012); calculating the relative contributions to a wetland from three springs with distinct lithologies (Paces and Wurster, 2014); identifying the location of water mains leaking into local groundwater in an urban setting (Leung and Jiao, 2006); calculating contributions to streamflow generation from distinct geologic units (Miller and others, 2021); and tracing inputs of water from coalbed natural gas production to streams (Brinck and Frost, 2007).

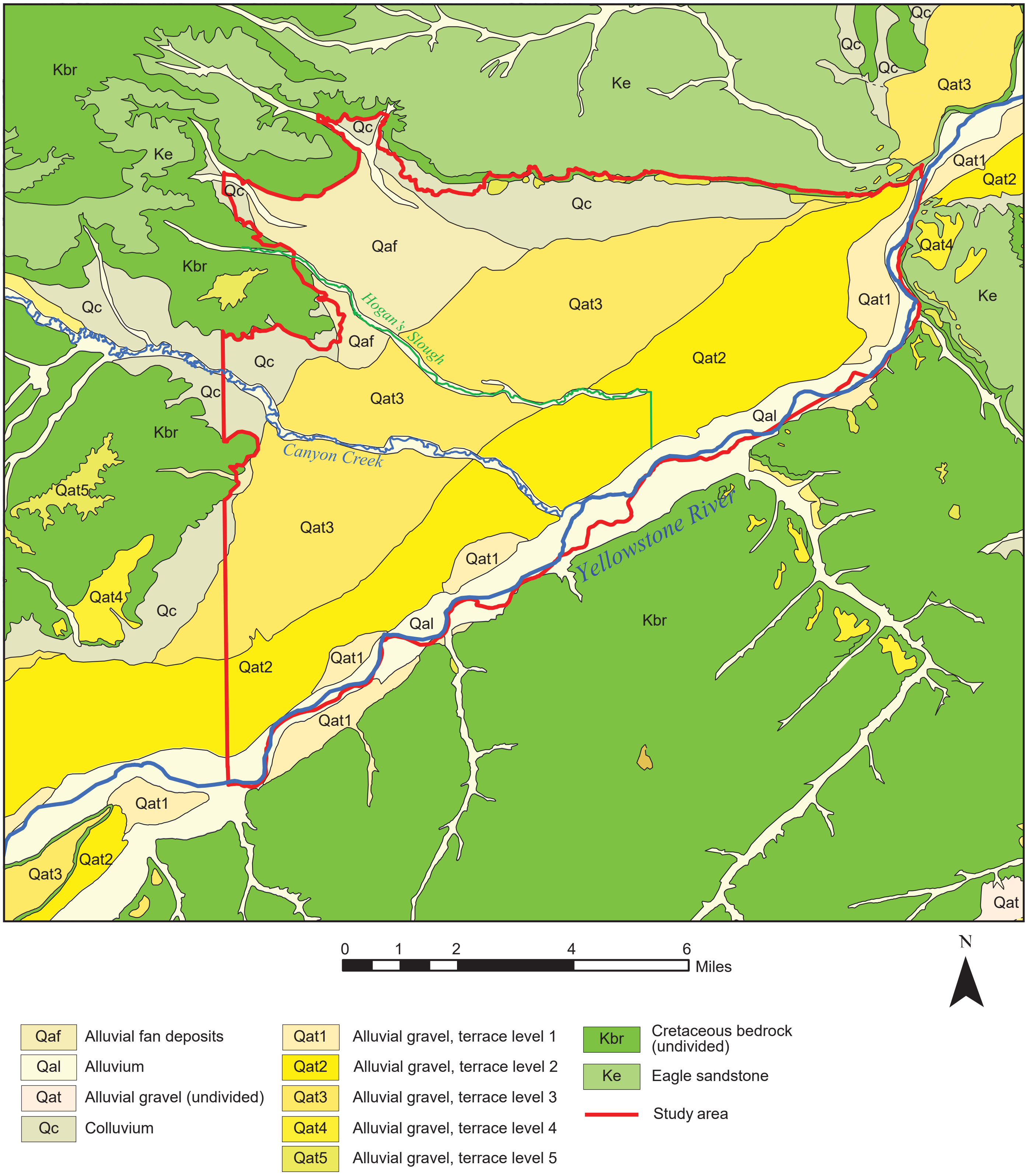

Figure 3. Three Yellowstone River alluvial terraces and alluvial fan deposits comprise the aquifers in the Billings area (modified from Lopez, 2000). Cretaceous bedrock, dominantly shale, underlies the alluvium and makes up the upland areas to the south and west of the study area. The Eagle sandstone rimrocks form the northern border of the study area.

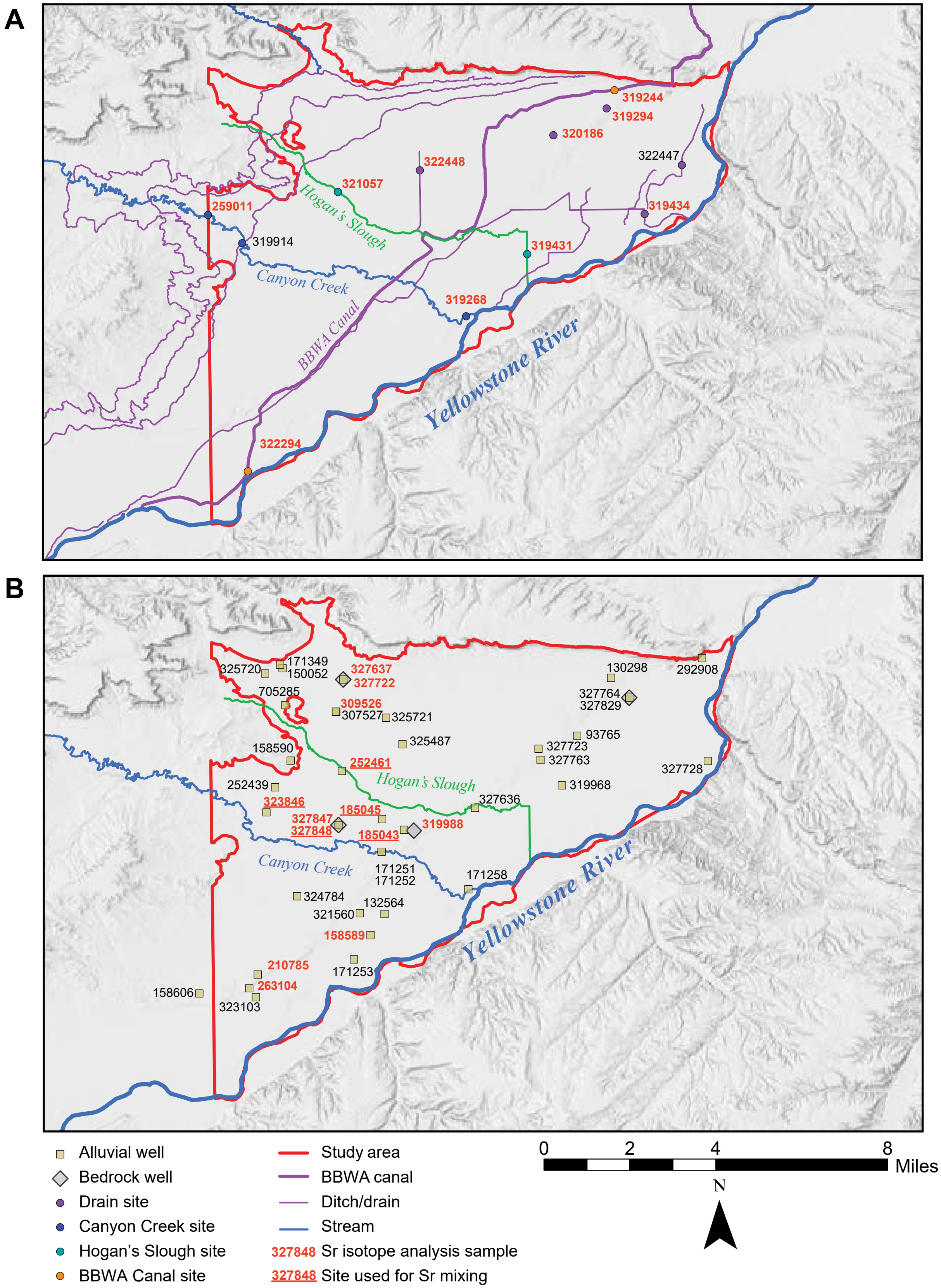

Figure 4. (A) Natural and manmade surface-water features were sampled for isotope chemistry. (B) Groundwater sites sampled for isotope chemistry were chosen to represent major terrace aquifers and land use of the valley. All sites were sampled for water isotopes; red GWIC numbers indicate the site was also sampled for strontium isotopes. Four monitoring wells completed in the underlying shale were paired with nearby terrace aquifer monitoring wells.

1.4.2 Groundwater recharge estimates using water isotopes

Isotope ratios of oxygen ($^{18}O/^{16}O$, reported as $\delta^{18}O$) and hydrogen ($^{2}H/^{1}H$, reported as $\delta^{2}H$) within the water molecule (also called water isotopes) can be used to trace the seasonality and elevation of precipitation and evaporation (Rozanski and others, 1993). Colder temperatures, higher elevations, and more inland locations are associated with lower isotope ratios. Oxygen and hydrogen isotopes in precipitation covary, resulting in the linear relationship of isotopes in precipitation described by the global meteoric water line (eq. 2; Craig, 1961):

$$\delta^2 H = 8 \times \delta^{18} O + 10‰. \qquad \text{eq. 2}$$

The slope and intercept of the precipitation line can vary locally and are defined by a local meteoric water line (LMWL; Putman and others, 2019). The position of the isotopic ratio of surface water and groundwater on the local meteoric water line can illuminate the seasonality of recharge (Abbott and others, 2000; Cole and Boutt, 2021; Jasechko and others, 2014; O'Driscoll and others, 2005) or the relative contribution of potentially isotopically distinct sources like mountain block recharge and irrigation recharge (Bouimouass and others, 2020, 2024; Pierre and others, 2016; Smerdon and others, 2009).

2. METHODS

2.1 Data Management

All site data, including well logs, water-level measurements (groundwater and surface water), surface-water flow measurements, and analytical results (with the exception of strontium isotopes), are stored in the MBMG Ground Water Information Center (GWIC) database (MBMG, 2025). Monitoring sites are identified by a unique GWIC identification number. Site information and GWIC identification numbers are summarized in appendix A. Strontium isotope data can be found in appendix B, table B1.

2.2 Sample Collection and Analysis

Groundwater and surface-water samples were collected in accordance with MBMG Standard Operating Procedures (Gotkowitz, 2023). Thirty-seven samples from 23 sites were analyzed for strontium isotope ratios: 11 terrace wells, 3 bedrock wells, and 9 surface-water sites. Seasonal samples (early spring and late summer) were collected from all but one terrace well and all surface-water sites except the BBWA canal, which does not carry water in early spring (fig. 4, appendix A). Strontium isotopes were analyzed by the University of Waterloo Environmental Isotope Laboratory, Ontario, Canada, on a Thermo-Finnegan Triton thermal ionization mass spectrometer calibrated to National Institute of Standards and Technology (NIST) Standard Reference Material (SRM) 987 strontium carbonate. Results are presented as the ratio of ^{87}Sr to ^{86}Sr (appendix B). Strontium concentrations were measured by inductively coupled plasma atomic emission spectrometry by the MBMG Analytical Laboratory in Butte, Montana.

Eighty-four samples were analyzed for $\delta^{18}O$ and $\delta^{2}H$ of water: 60 terrace groundwater samples from 38 sites; 12 canal/ditch samples from 7 sites; 8 stream samples from 4 sites; and 4 bedrock samples, all from different wells (fig. 4, appendices A, C). Thirty-seven precipitation samples were collected between May 2015 and March 2017 at the MBMG office in downtown Billings. Precipitation samples were collected opportunistically in open containers during rain and snow events, so samples represent individual storms (appendix C). Sample containers were left open to collect the precipitation events for 1 h or the length of the storm, whichever was shorter, and capped immediately upon collection. Some evaporation in the sample collection bottle is possible.

Samples were kept cold until submitted to the laboratory for analysis. Precipitation samples were analyzed by the University of Wyoming Stable Isotope Facility in Laramie, Wyoming by ringdown spectrometry on a Picarro L2130. All other water isotope analyses were performed by cavity ringdown spectrometry on a Picarro L2130 at the MBMG Analytical Laboratory in Butte, Montana. The analytical method is presented in Timmer (2020). Results for both isotopes are presented as per-mil deviation from a VSMOW standard.

2.3 Surface-Water Flow Measurement

Discharge, stage, specific conductance (SC), and temperature were measured approximately monthly through 2023 at upstream and downstream sites on Canyon Creek (sites 259011 and 319268, fig. 4A, table 1) and on Hogan's Slough (sites 321057 and 319431, fig. 4A). The upstream site marks where Canyon Creek enters the study area at 80th St. W. and King Avenue. The downstream site was established at a private bridge where Canyon Creek meets the Yellowstone River. The Hogan's Slough upstream site marks the most accessible perennial location, near 56th St. W. between Central Avenue and King Avenue. The downstream site was established at a footbridge near where Hogan's Slough meets the Yellowstone River (fig. 4). On Canyon Creek, a site 1-mi straight-line distance downstream of the upgradient site (319914, fig. 4A) was used for analysis of SC, as SC was not recorded consistently at the upgradient site (259011).

An OTT MF pro (an electromagnetic current meter) with reported accuracy of ±2 percent of the velocity reading from 0 to 10 ft/s was used for the discharge measurements. All velocity readings were within this range. A 5-percent error of the total discharge measurement was assumed (Sauer and Meyer, 1992). Rating curves were established for these sites using power regression and were used to calculate streamflow from measured stage readings.

3. RESULTS

3.1 Surface-Water Specific Conductance

The water levels (stage) in Canyon Creek and Hogan's Slough follow the irrigation season (figs. 5, 6). In a typical Montana stream, flow peaks during spring snowmelt and returns to low baseflow by fall. In Canyon Creek and Hogan's Slough, however, flows remain artificially high from April to October. These streams function as drains, collecting groundwater, irrigation return flows, and direct discharge from irrigation canals and ditches. Stage in Billings canals and ditches is controlled by directing excess flow at stage-control weirs into natural drainages. Because of the influence of direct discharge of irrigation water, stage in Canyon Creek and Hogan's Slough dropped rapidly at the end of the irrigation season in mid-October of both 2022 and 2023.

Specific conductance (SC) reveals how irrigation water controls the water chemistry in Canyon Creek and Hogan's Slough. The SC of these streams shifts abruptly at the start and end of the irrigation season, acting as a chemical marker for water source (fig. 5). The contrast between upstream and downstream sites highlights the dilution process. Upstream, the water is dominated by baseflow from the marine-bedrock uplands, resulting in high SC levels (4,000–5,000 µS/cm) due to high dissolved solids. As this water moves downstream, it is diluted by increasing volumes of low-salinity Yellowstone River water and terrace-aquifer groundwater.

This dilution is most visible outside of the irrigation season. During these baseflow periods, SC drops from 5,000 µS/cm upstream to 2,000 µS/cm downstream (figs. 5, 6), driven primarily by groundwater gains from the terrace aquifers. However, once the canals begin diverting river water, this gap shrinks to less than 1,000 µS/cm. This uniformity suggests that low-salinity irrigation water overwhelms the system, making up the majority of the flow at both sampling points. While these SC patterns track the input of irrigation water, they fail to separate out the relative contributions to these streams of irrigation water and groundwater within and outside of irrigation season.

3.2 Strontium Isotopes

Strontium concentrations and strontium isotope ratios ($^{87}Sr/^{86}Sr$) reveal a clear contrast between two endmember water sources: the BBWA Canal (high ratio, low concentration; sites 322294 and 319244) and the Niobrara shale bedrock (low ratio, high concentration; well 327637; fig. 7). Results from all other samples plot above the two-endmember mixing line indicating that a third, mid-to-high isotope ratio and mid-to-high concentration endmember is present. This third source is likely from dissolution of soil salts, minerals within the fine-grained sediment overlying the terrace aquifer, or the aquifer matrix itself. Given one or more unidentified sources of strontium, the relative composition of the terrace groundwater from bedrock groundwater and irrigation recharge could not be calculated.

Strontium signatures in two terrace wells (210785, 263104; fig. 7), located within 0.2 mi of the BBWA canal (fig. 4B), reveal the influence of irrigation. The isotope ratio of samples collected from these wells is very similar to the isotope ratio of the canal water. The similar isotopic ratios, combined with low specific conductance, strongly suggest that irrigation water is the primary source of recharge in this area.

Table 1. Stream and drain discharge measurements.

Canyon Creek											
Site 259011 (upstream)					Site 319268 (downstream)						
Date	Flow (cfs)	Stage (ft)	SC (µS/cm)	Temp (°C)	Date	Flow (cfs)	Stage (ft)	SC (µS/cm)	Temp (°C)	Gain (cfs)	% Gain
10/20/22 12:30	43.3	2.80	479	10.4	10/19/22 12:45	132	3.38	425	11.1	88.7	205%
2/28/23 16:00	1.1	0.69	6,447	1.6	2/28/23 11:40	***frozen***				–	–
3/28/23 12:45	**1.2**	**0.74**	**4,308**	**4.1**	**3/28/23 13:15**	**5.1**	**2.14**	**1,944**	**5.0**	**3.9**	326%
4/24/23 15:15	0.5*	0.66	4,564	13.2	4/25/23 16:45	10.9*	2.19			10.4*	2080%
5/22/23 13:05	42.1*	2.80			5/25/23 9:40	236.0	6.17	1,458	15.7	193.9*	461%
6/19/23 14:35	41.2*	2.76	888	17.0	6/21/23 9:40	151.2	4.84	488	14.3	110.0*	267%
7/26/23 10:30	9.9	1.30	1,655	21.6	7/25/23 8:25	59.1	2.89	801	21.5	49.2	497%
8/30/23 10:30	**34.8***	**2.47**	**508**	**20.2**	**8/29/23 9:15**	**166.5**	**3.54**	**409**	**19.2**	**131.7***	378%
9/13/23 10:30	25.8	1.95	728	17.7	9/12/23 9:20	152.3*	3.59			126.5*	491%
10/3/23 13:30	37.6*	2.60	566	12.4	10/5/23 9:10	159.2*	3.75	385	11.3	121.6*	323%
Hogan's Slough											
Site 321057 (upstream)					Site 319431 (downstream)						
Date	Flow (cfs)	Stage (ft)	SC (µS/cm)	Temp (°C)	Date	Flow (cfs)	Stage (ft)	SC (µS/cm)	Temp (°C)	Gain (cfs)	% Gain
10/20/22 11:00	1.4	0.48	2,562	8.8	10/18/22 15:15	64.6	1.50	473	11.5	63.3	4653%
2/28/23 15:05	0.6	0.92	4,763	1.8	2/28/23 13:45	4.4	0.50	2,106	4.6	3.8	691%
3/29/23 11:30	**0.5***	**0.89**	**2,930**	**2.6**	**3/28/23 15:15**	**4.0**	**0.49**	**1,825**	**8.7**	**3.5***	700%
4/24/23 15:45	0.5*	0.89	4,564	13.2	4/25/23 10:45	6.6*	0.57	1,423	10.7	6.1*	1220%
5/22/23 13:05	4.5	1.29	898	19.5	5/23/23 16:30	23.1	0.97	758	20.0	18.6	418%
6/20/23 17:00	3.3	0.70	2,296	15.9	6/19/23 16:45	30.5	1.07	678	16.0	27.2	821%
7/25/23 12:45	5.1	0.92	95	21.6	7/27/23 9:30	50.8	1.23	534	21.0	45.8	905%
8/30/23 13:15	**2.0***	**0.68**	**1,836**	**19.6**	**8/28/23 15:50**	**56.7**	**1.40**	**470**	**21.5**	**54.8***	2740%
9/12/23 15:15	6.5	1.00	848	17.6	9/11/23 16:50	45.0*	1.25	530	18.7	38.5*	589%
10/4/23 14:15	4.3	0.80	1,158	12.2	10/2/23 17:50	60.9*	1.45	524	13.9	56.6*	1329%

*Discharge estimated from stage.

Note. Bolded rows indicate measurements that correspond to dates of strontium isotope mixing analysis.

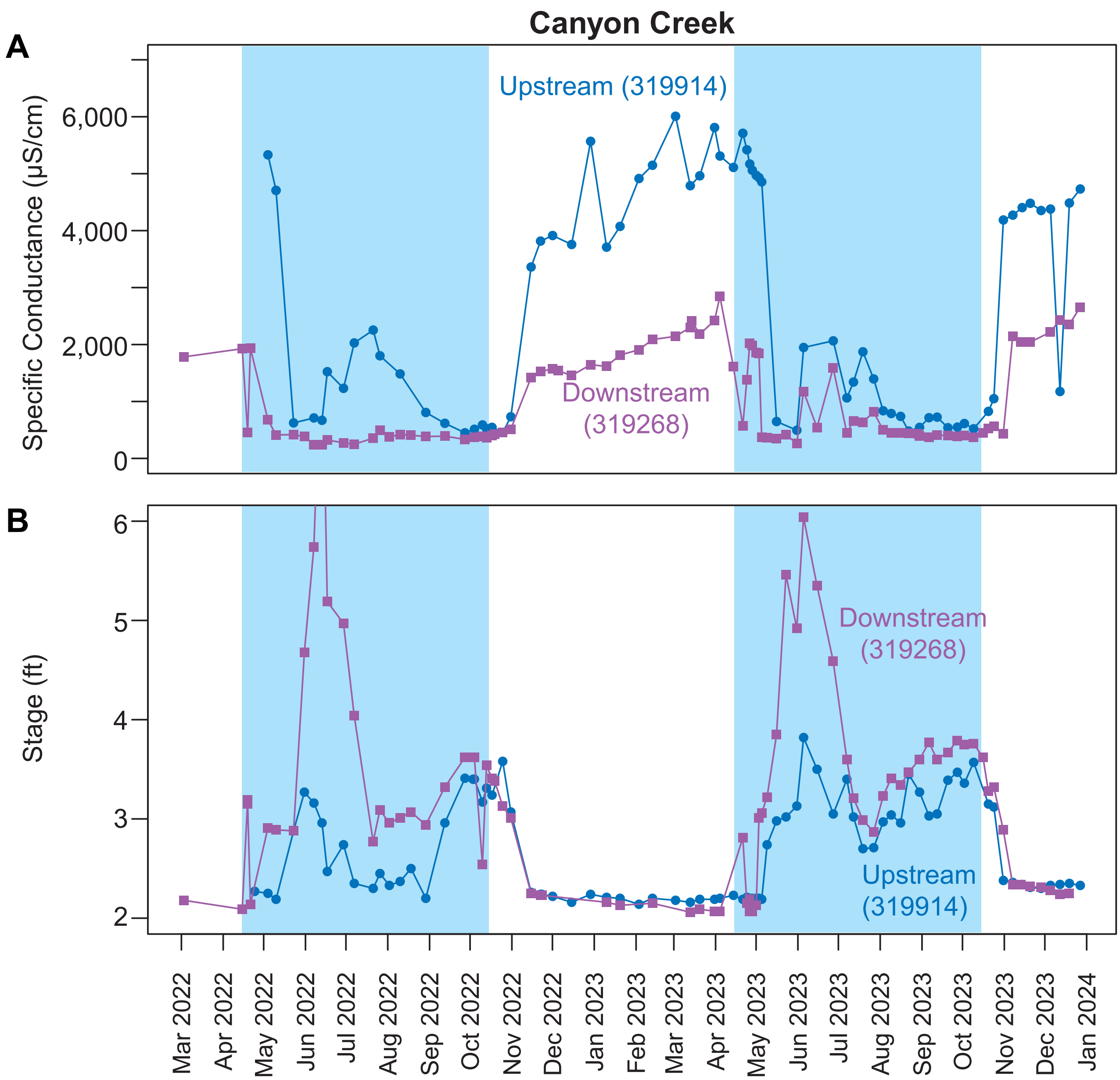

Figure 5. Specific conductance (A) at upstream and downstream sites on Canyon Creek is highest in the late winter and spring and lowest during irrigation season. Stage (B) at the downstream site on Canyon Creek is affected by the Yellowstone River during high flows in May, June, and July. A stage measurement of 8.0 ft at site 319268 during flooding in June 2022 is omitted to preserve the resolution of lower stage measurements. Blue shading indicates the approximate irrigation season from April 15th to October 15th when canals and ditches are transporting water from the Yellowstone River.

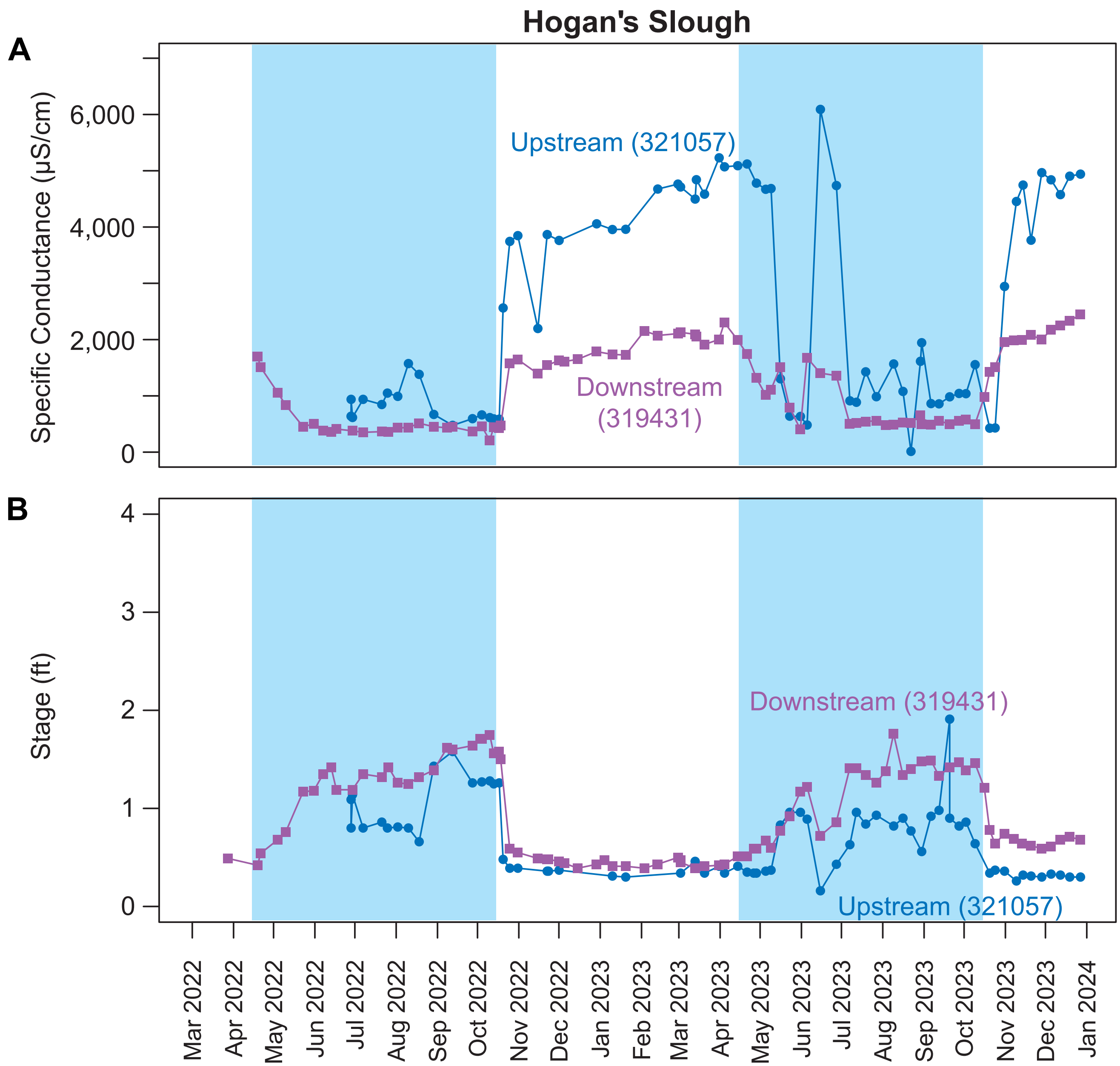

Figure 6. Specific conductance (A) of upstream and downstream sites on Hogan's Slough is highest in the late winter and spring and lowest during irrigation season. Stage (B) shows generally gaining conditions all year. Blue shading indicates the approximate irrigation season from April 15th to October 15th when canals and ditches are transporting water from the Yellowstone River.

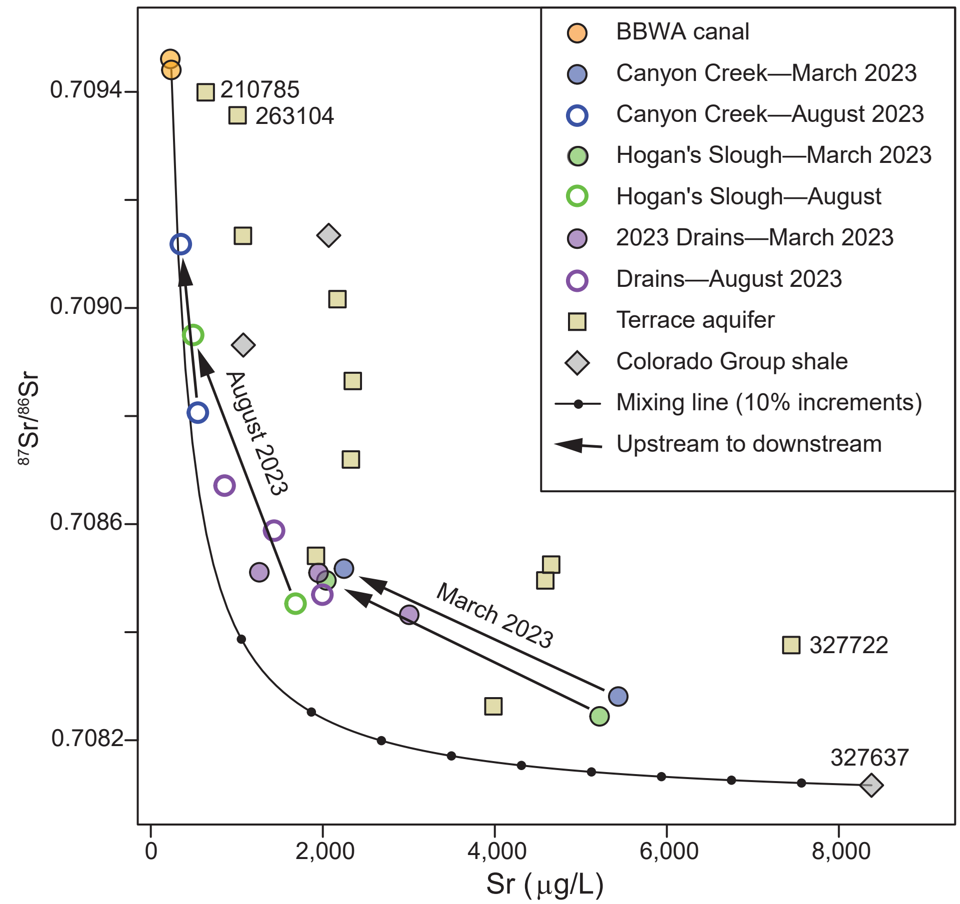

Figure 7. Strontium concentration and $^{87}Sr/^{86}Sr$ isotopic ratios for groundwater and surface-water samples from the study area generally align along a mixing line of irrigation water and shale-bedrock groundwater. A third source of strontium must be present to account for the samples from terrace wells and surface water not falling along this mixing line. The black line represents a two-endmember mixture between the BBWA canal (322294) and a high-salinity shale well (327637). Black dots represent 10 percent increments along the mixing line.

Conversely, in the northwest of the study area, terrace groundwater shows a bedrock influence. One well (327722) had the highest strontium concentration of any terrace groundwater well (7,450 µg/L) and a low strontium ratio, similar to the results from the shale bedrock endmember well (327637). This similarity likely stems from infiltration through alluvial fan deposits composed of sediment eroded directly from the surrounding bedrock.

The pre-irrigation (March) samples from upstream sites on Canyon Creek and Hogan's Slough had the highest strontium concentrations and lowest strontium isotope ratios of the surface-water samples (figs. 8A, 8C). The values were similar to those of the bedrock endmember well (327637, figs. 4B, 7), likely reflecting the bedrock influence on water quality in the upland tributary reaches of the streams. The strontium results from the Canyon Creek and Hogan's Slough samples plot close to, but not on, the two-endmember mixing line between bedrock groundwater and irrigation water (fig. 7). This deviation indicates that downgradient samples collected from Canyon Creek and Hogan's Slough are likely a mix of three sources: upstream flow, irrigation water, and terrace groundwater. A three-endmember mixing diagram was used to estimate the relative contribution of sources of stream gain between upstream and downstream sample points (fig. 8, appendix B). Due to the spatial variability in terrace groundwater strontium concentrations and isotope ratios, multiple endmembers from nearby sampled wells were used to represent the groundwater in the mixing calculations (appendix B). The results of the mixing diagrams can be used to estimate both the source of gain and the magnitude of gain in Canyon Creek and Hogan's Slough. Streamflow gain is expressed as percent increase in discharge, calculated as the increase in flow between the upstream and downstream sites divided by the upstream flow. The gain calculated from isotope mixing was compared to measured streamflow gain as a check to the assumptions of the endmember mixing analysis.

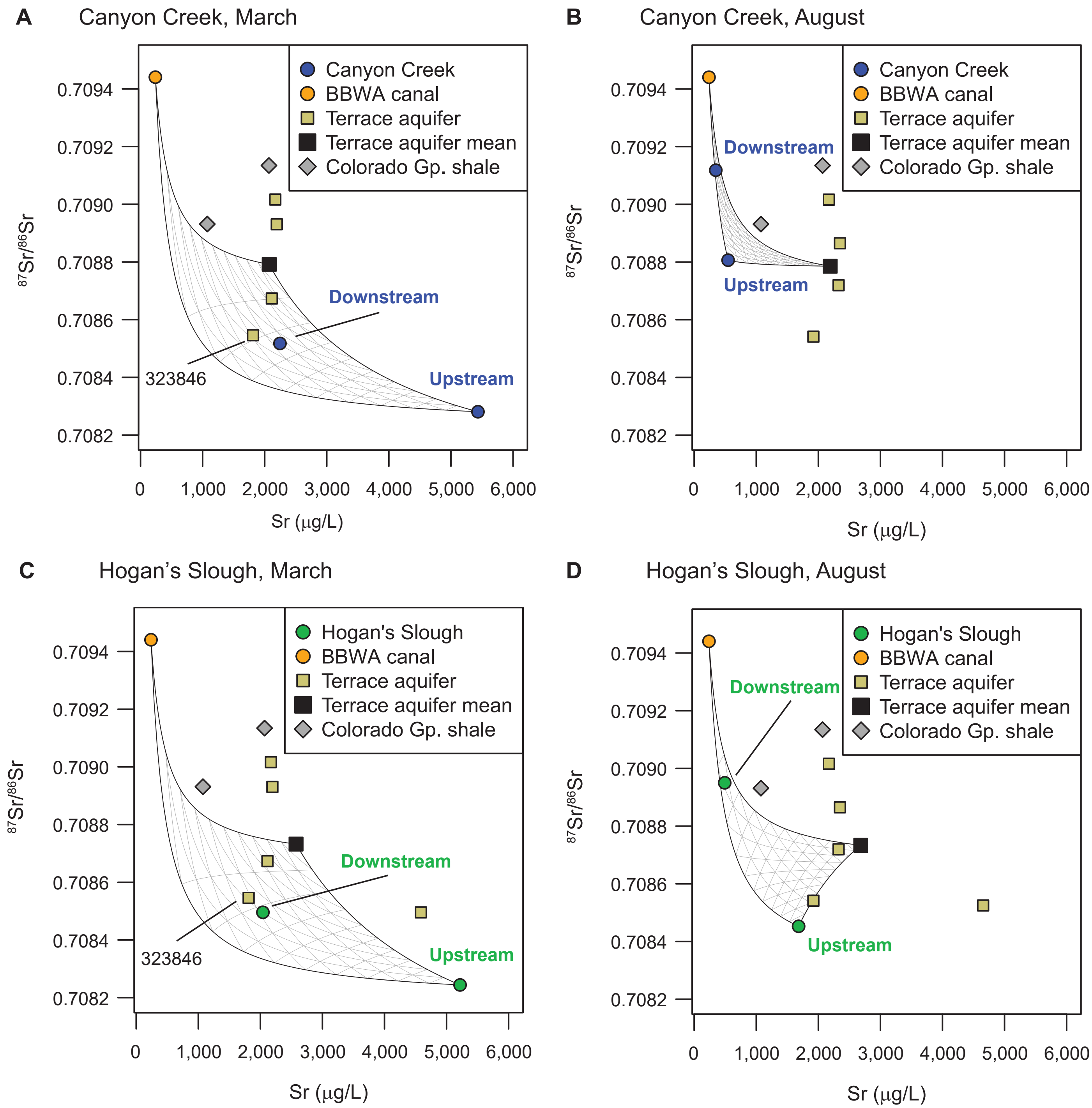

Figure 8. Three-endmember mixing webs for Canyon Creek and Hogan's Slough in March (A, C) and August of 2023 (B, D) provide an estimate of irrigation water and groundwater contributions to stream discharge. The upstream BBWA site (322294) in August 2023 represents the irrigation water endmember in all analyses, the upstream surface-water site from Canyon Creek or Hogan's Slough is the stream endmember, and four (Canyon Creek) or five (Hogan's Slough) nearby terrace wells represent the groundwater endmember. A mean of the four or five terrace wells is also used. Two-endmember mixing curves among canal water, surface water, and terrace groundwater make up the outside of the web, while intermediate 10% mixtures constitute the web. These plots can be read as ternary diagrams to discern the percentage of each endmember in the downstream site. Terrace groundwater well 323846 is labeled in the March 2023 plots as an example of how groundwater inputs can fully account for stream gains.

3.2.1 Magnitude of streamflow gain from isotope mixing and direct measurement

In March 2023, isotope mixing indicated that streamflow in Canyon Creek increased by 300 percent when using the mean terrace groundwater strontium concentration and isotope ratio, with a range of 233 to 400 percent. These estimates are closely in line with the measured streamflow gain, which increased from 1.2 cfs to 5.1 cfs, a gain of 326 percent (table 1). In Hogan's Slough in March 2023, isotope mixing indicated an increase in flow of 355 percent using the mean terrace groundwater composition, with a range of 270 to 1,150 percent. The measured streamflow increased from 0.5 to 4.0 cfs, a gain of 700 percent, which falls within the admittedly broad range from isotope mixing. These results suggest that the selected terrace aquifer samples represent a reasonable estimate of the geochemical nature of streamflow gains.

In August 2023, when canals were in full operation, isotope mixing indicated that streamflow in Canyon Creek increased by 285 percent based on the mean terrace groundwater composition; the range was 233 to 1,900 percent. The anomalously high value was due to the endmembers and mixture forming a single mixing-line curve, which makes small changes in concentration and ratio result in large changes in calculated percentages (appendix B, table B2, GWIC ID 323846). Measured streamflow increased from 34.8 to 166.5 cfs, a gain of 378 percent. In Hogan's Slough in August 2023, isotope mixing indicated an increase in flow of 1,011 percent using the mean terrace groundwater composition, with a range of 669 to 1,011 percent. Measured streamflow in Hogan's Slough increased from 2.0 to 56.7 cfs, a gain of 2,740 percent. The much larger observed increase in flow in Hogan's Slough than estimated from isotope mixing could be the result of high flow measurement error caused by vegetation growth in the streambed in August. Flow measurement error with heavy vegetation can be as high as 20 percent (Sauer and Meyer, 1992). The minimum increase in streamflow given this larger error is still 1,790 percent, though closer to the expected gain based on isotope mixing.

3.2.2 Source of streamflow gain from isotope mixing

Mixing analysis for Canyon Creek and Hogan's Slough showed that in March 2023, downstream increases in discharge could be explained almost entirely (up to 100 percent) by terrace groundwater inputs (figs. 8A, 8C). Terrace well 323846 had a strontium concentration and isotope ratio similar to the downstream samples in March 2023, an example of how terrace groundwater may fully account for stream gain outside of irrigation season (fig. 8, appendix B, table B2). Conversely, during irrigation season in August 2023, downstream increases in discharge can be explained almost entirely by additions of irrigation water; the stream chemistry shifts once water is running in the canals. In August, the downstream gain in both streams was composed almost entirely (87 to 100 percent) of water isotopically similar to that in the BBWA canal (figs. 8B, 8D). The remaining portion was sourced from terrace groundwater. Inspection of the August 2023 mixing diagrams suggests that Canyon Creek and Hogan's Slough can be adequately described as a two-member mixture between the upstream water and irrigation water from the canals and ditches during irrigation season. This suggests that nearly all summer gains are the result of direct canal overflows or short-path irrigation returns through the soil with minimal chemical alteration, rather than terrace groundwater discharge.

3.3 Water Isotopes

To evaluate recharge sources using $\delta^{18}O$ and $\delta^{2}H$, we approximated a Local Meteoric Water Line (LMWL) using three data sources as no published LMWL exists for the Billings area: MBMG storm-event samples from 2015–2017 (site 284061; appendix C); monthly composite precipitation samples from nearby Roundup, MT (Carstarphen and others, 2024; site 326630; appendix C); and modeled values for Billings from the Online Isotopes in Precipitation Calculator (OIPC; Bowen and others, 2005; Bowen, 2017; Bowen and Revenaugh, 2003; Bowen and Wilkinson, 2002; appendix C). After removing results from samples impacted by evaporation, the resulting regression lines' slopes and intercepts were remarkably consistent (fig. 9A). The approximated Billings LMWLs are similar to the LMWL calculated for western Montana by Carstarphen and others (2024).

To estimate the relative recharge to the terrace aquifers, we focused on "non-growing season" precipitation (October to April), as summer rain in semi-arid regions like Billings rarely infiltrates deep enough to recharge the aquifer (Jasechko and others, 2014). This is confirmed by long-term monitoring water-level

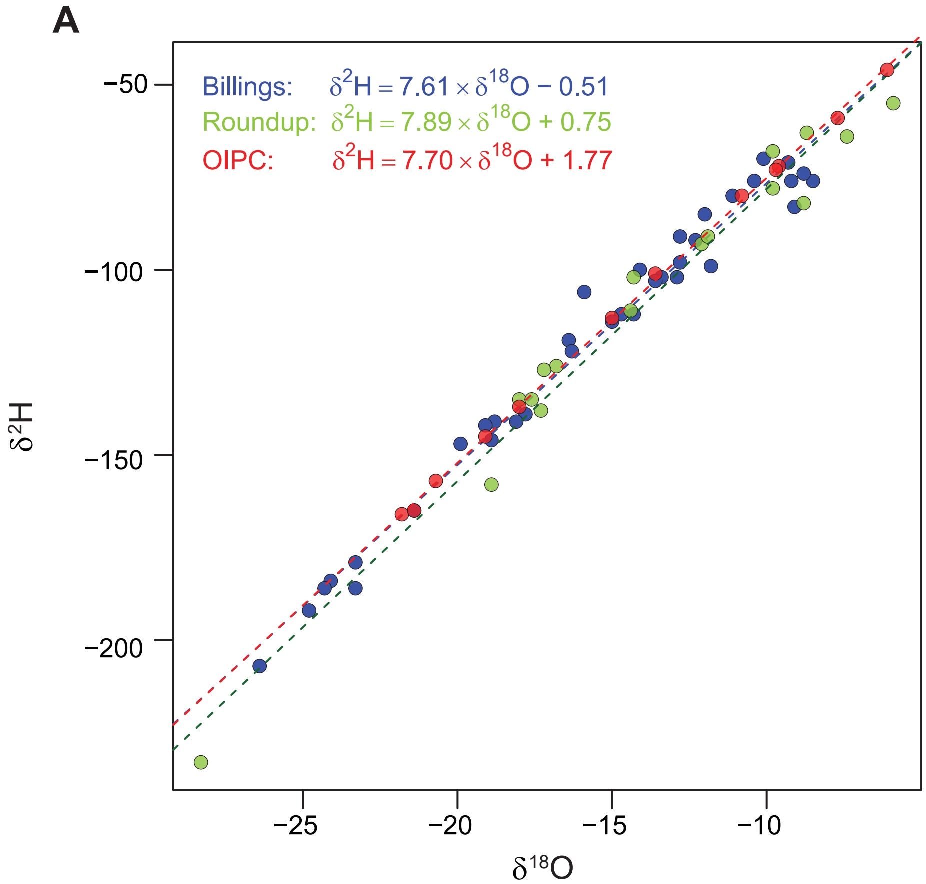

Figure 9. (A) The local meteoric water line for Billings was estimated using precipitation isotope values from three sources: Billings precipitation events from 2015 to 2016, monthly composites from Roundup, MT (Carstarphen and others, 2024), and modeled monthly values from the OIPC (Bowen and others, 2005; Bowen and Revenaugh, 2003; Bowen and Wilkinson, 2002)

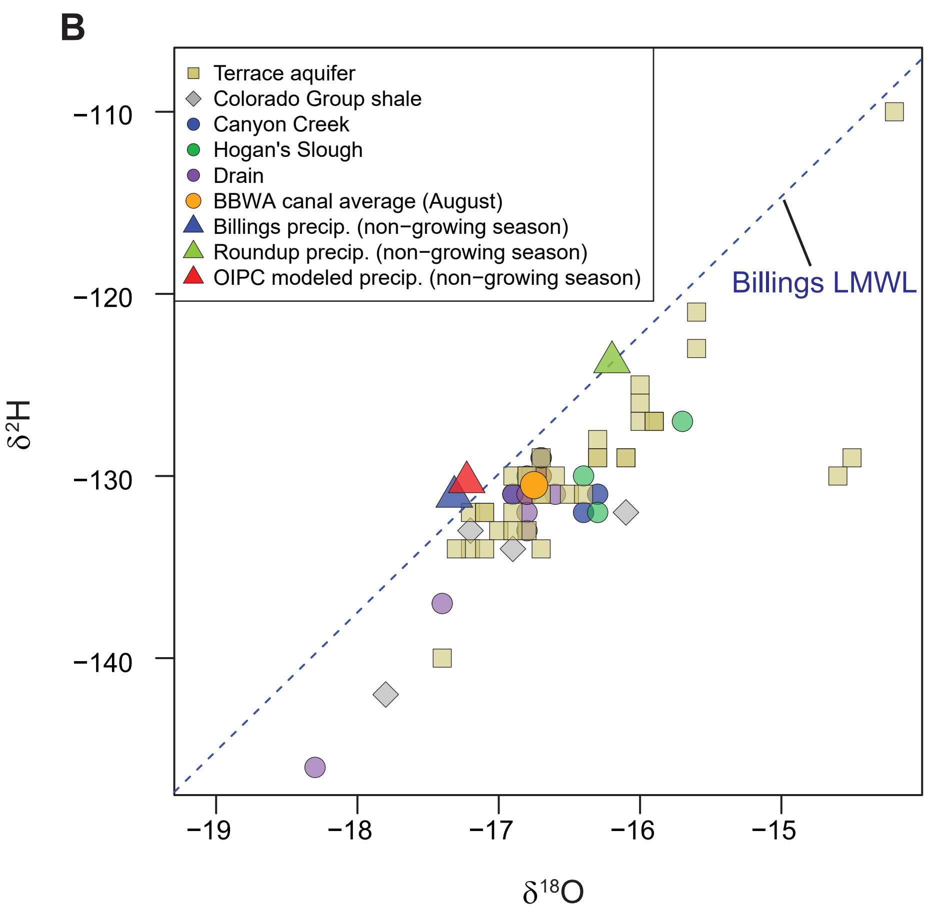

Figure 9. (B) Groundwater and surface-water samples from this study are isotopically similar to irrigation water sourced from the Yellowstone River. Estimated non-growing season (October–April) precipitation from three sources was also isotopically similar to irrigation water (the mean of the August BBWA samples). Each terrace well is plotted only once, with preference given for irrigation season samples when available; however, 5 of the 37 terrace groundwater samples were sampled in March or April. All surface-water samples are shown.

data that show few examples of the sharp water-level rise during high groundwater levels that would indicate recharge from summer precipitation (fig. 10). While these rare summer recharge events are present, recharge is dominated by irrigation recharge over seasonal timescales. By using the three different LMWL datasets described above and weighting the data for monthly precipitation averages (PRISM, 2024), we estimate the $\delta^{18}O$ of non-growing season precipitation (recharge) to be -17.3‰ in Billings, -16.2‰ in Roundup, and -17.2‰ for the OIPC dataset.

The stream and canal isotope values ranged from -16.4‰ at Canyon Creek (site 259011, fig. 9B) in March 2023 to -16.75‰ from the BBWA canal in August 2023 (average from sites: 322294 and 319244; fig. 9B). Values of $\delta^{18}O$ in the terrace groundwater ranged from -17.4‰ to -14.2‰ (fig. 9B, appendix C). Seasonal $\delta^{18}O$ variation from samples collected from individual wells was minimal in the terrace aquifers, with a mean range of 0.16‰.

Using published isotope data for Yellowstone River water near Livingston and summer precipitation data (April through October) from southern Canada, Olson and Reiten (2002) estimated the relative contributions of groundwater recharge from precipitation versus irrigation water (applied irrigation water and canal losses). Their estimate indicated that on average, 84 percent of the Billings terrace groundwater is composed of irrigation water. This study sought to update the Olson and Reiten (2002) study with the new understanding of recharge mechanics from Jasechko and others (2014) by only considering the isotope signature of precipitation that falls outside of the growing season. The $\delta^{18}O$ signatures of the revised precipitation recharge, stream/canal water, and groundwater are indistinguishable. For this mixing analysis to work, the two sources must be isotopically distinct (Rozanski and others, 1993). We expected a contrast: the Yellowstone River (irrigation source) starts in high mountains over 11,000 ft, while the elevation of local Billings rain falls at 3,000 ft. The isotopic overlap between endmembers means that the relative recharge contributions from these two recharge sources—the Yellowstone River and Billings precipitation—cannot be calculated for the terrace aquifers. Thus, we were unable to verify or update the relative recharge calculations presented in Olson and Reiten (2002).

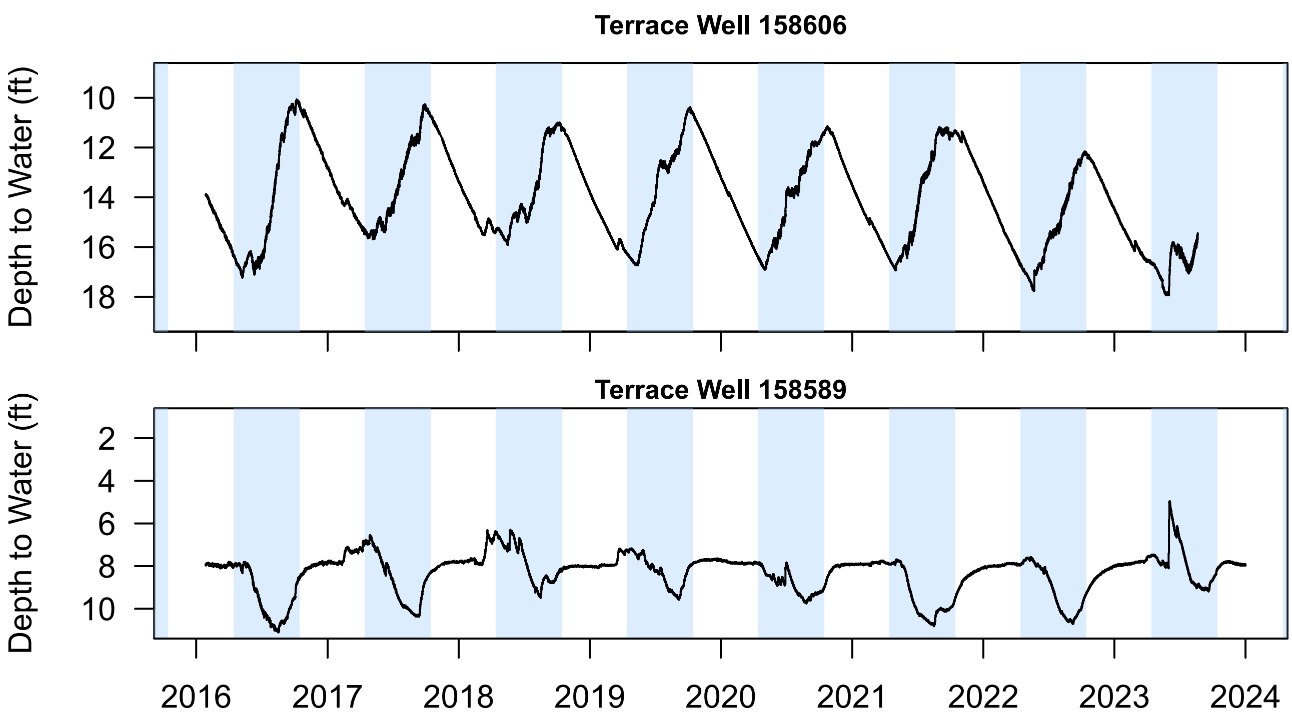

Figure 10. Long-term monitoring well static water levels show annual cycles of drawdown and recharge. Year markers indicate the start of each calendar year; blue shading indicates the typical irrigation season of May 15th to October 15th when canals and ditches are operating. Well 158606 exhibits a rising limb from June to October, while well 158589 generally exhibits a rising limb from August to November. These wells show some flashy rises during the summer in some years, indicating summer recharge from rain. These summer recharge events are small in comparison to seasonal variation driven by irrigation recharge and drawdown from pumping for lawn irrigation.

4. DISCUSSION

The means and timing by which groundwater moves out of the study area is an important aspect of understanding the hydrogeologic system in the Billings area. While Canyon Creek and Hogan's Slough clearly gain water as they flow downstream, interpreting these gains solely as groundwater discharge would overestimate the volume of groundwater baseflow. The strontium isotope mixing models reveal that during peak summer, nearly all stream gain (87–100 percent) comes from irrigation water as canal discharges, irrigation overflow, and possibly short-path irrigation returns through soils. Only 0–13 percent of streamflow gain is from groundwater. In contrast, during the March baseflow period, the streams are fed almost entirely by the terrace aquifers. This is an important distinction and insight borne out by isotopic tracing when physical measurements were not possible.

While strontium isotopes were successful in identifying sources of stream gain, they failed to quantify the proportions of terrace groundwater recharge. Terrace groundwater cannot be characterized by a three-endmember mixing model of irrigation water, bedrock groundwater, and stream loss. The uncharacterized source of strontium likely comes from the dissolution of soil salts or the aquifer matrix. In the semi-arid, high-salinity environment of Billings, where groundwater specific conductance can exceed 5,000 µS/cm, the original isotopic signature of the recharge water is rapidly overwhelmed by local mineral dissolution. Consequently, characterization and quantification of recharge sources using strontium isotopes is better suited for lower-salinity environments where the strontium contributed by recharge sources will not be overwhelmed by local salt dissolution.

Water isotopes ($\delta^{18}O$ and $\delta^{2}H$) proved ineffective for estimating the proportion of terrace groundwater contributed by precipitation and irrigation-water recharge. The isotopic signatures of recharge from non-irrigation season precipitation and irrigation water were indistinguishable, which precludes calculating mixing ratios. Using the local precipitation isotopic signature to estimate recharge is difficult in an arid environment like Montana. A very small proportion of precipitation becomes groundwater, with studies in southeastern Montana placing the range from 1 percent (Miller, 1979) to 4 percent (Meredith and others, 2009; Meredith and Blais, 2019). This small proportion makes well-defined and distinct isotopic signatures critical for accurate mixing calculations. The irrigation water isotope signature was based on two samples collected in August and may not accurately represent recharge from irrigation. While the water isotope signature of irrigation water could be better refined through more frequent measurements, the signature of precipitation that results in recharge is difficult to measure. Additionally, assuming that no recharge occurs in the summer is an oversimplification as summer recharge events can be seen in some hydrographs that responded to an unusually large 5-in storm event in June 2023 (fig. 10). These summer recharge events are infrequent but can be large when they do occur. Physical measurements via lysimeters or soil moisture sensors are likely to be better tools for estimates of precipitation recharge than water isotopes in this semi-arid region.

5. CONCLUSIONS

Isotopic characterization and mixing models successfully identified the sources of streamflow gains to two perennial channels in the Billings area: Canyon Creek and Hogan's Slough. The stream reaches and irrigation-overflow structures are largely inaccessible or dangerous to access for discharge measurements. Isotopic tracing provided a way to estimate sources of gain in the streams with minimal stream access. Strontium isotopes were used to determine that, during the irrigation season (May–October), these natural channels function primarily as irrigation-water drains, while outside of irrigation season (November–April), they return to being groundwater-fed systems.

However, the application of strontium isotopes to identify groundwater recharge sources to the terrace aquifers was hampered by strontium from outside the measured endmembers of irrigation water, bedrock inflows, and stream losses. Soil salts, minerals within the fine-grained sediment overlying the terrace aquifer, and/or the aquifer matrix itself are the likely sources of the uncharacterized strontium. Strontium isotopes may not be useful in semi-arid settings like Billings where the isotopic signature of the groundwater recharge from low-salinity streams or irrigation water is quickly overwhelmed by dissolution of salts present in soils or aquifer materials. Rapid equilibration with aquifer materials makes strontium a useful tracer (Frost and Toner, 2004) but also means that the signature of recharge water can be lost rapidly. Strontium isotope fingerprinting of recharge sources to groundwater may be successfully applied in lower-salinity settings.

Similarly, the water isotope signatures failed to distinguish between local precipitation and irrigation water. The expected isotopic contrast between high-altitude mountain snowmelt and lower-altitude, non-growing season precipitation was not observed in the Billings area. The isotopic character of precipitation-derived recharge in Billings remains uncertain, but is likely variable between years depending on the timing of sporadic recharge. For example, a series of May rainstorms in one year may dominate recharge with relatively enriched water isotope ratios, whereas another year could see isotopically depleted recharge from melting after a February snowstorm. Recharge from precipitation in semi-arid settings like Billings is therefore likely to be spatially and temporally variable and dependent on antecedent soil moisture conditions. Modeling or direct observation of infiltration and recharge are likely to be more effective approaches for quantifying precipitation recharge in Billings and similar areas.

ACKNOWLEDGMENTS

This work would not have been possible without the Billings area well owners who allowed us to collect samples. The City of Billings Public Schools and Parks Department allowed access to key wells throughout the city and provided insight into how groundwater, irrigation canals, and drains are used by the city. The Billings Public Works Water Quality Division, under the direction of Chief Chemist Jeanne Haupt, provided anion analyses as an in-kind contribution to the study. Field measurements and data management were done by MBMG staff Don Sasse, Matt Smith, Todd Myse, Shawn Kuzara, and student research assistants Preston Webster and Emily Routen.

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APPENDIX A

SAMPLED SITE SUMMARY

Table A1. Isotope sampling locations.

GWIC ID	Site	Latitude	Longitude	Aquifer / Type	Well Depth (ft)	Strontium Isotopes	Water Isotopes
Groundwater Sites							
327728	Monitoring Well*	45.76249	-108.48075	Terrace 1	15		x
171253	Monitoring Well	45.69699	-108.65226	Terrace 1	13		x
171258	Monitoring Well	45.72025	-108.5968	Terrace 2	25		x
319968	Billings Parks Well	45.75491	-108.55115	Terrace 2			x
158589	Monitoring Well	45.705102	-108.644155	Terrace 2	25	x	x
321560	Private Well	45.71258	-108.64915	Terrace 2	26		x
327829	Monitoring Well*	45.78418	-108.51817	Terrace 2	24		x
323103	Private Well	45.68458	-108.69959	Terrace 2	18		x
263104	Private Well	45.68762	-108.70275	Terrace 2	28	x	x
171251	Monitoring Well	45.73322	-108.63839	Terrace 2	37		x
292908	Monitoring Well	45.79723	-108.48286	Terrace 2	25		x
93765	School District Well	45.77156584	-108.5435206	Terrace 2	27		x
327636	Monitoring Well*	45.74766	-108.59313	Terrace 2	59		x
132564	School District Well	45.7122	-108.6373	Terrace 2	28		x
319527	Private Well	45.76067	-108.65598	Terrace 3	44	x	x
171252	Monitoring Well	45.73322	-108.63837	Terrace 3	15		x
158606	Monitoring Well	45.68604991	-108.726798	Terrace 3	33		x
325487	Private Well	45.76942	-108.627735	Terrace 3			x
309526	School District Well	45.78055	-108.65951	Terrace 3	90	x	x
327763	Billings Parks Well*	45.76357	-108.56131	Terrace 3	18		x
327723	Monitoring Well*	45.76732	-108.56222	Terrace 3	18		x
158590	Private Well	45.76429	-108.68169	Terrace 3	38		x
252461	Private Well	45.75878	-108.65837	Terrace 3	40	x	x
185045	Monitoring Well	45.74418	-108.63793	Terrace 3	29	x	x
324784	Private Well	45.71849	-108.67925	Terrace 3			x
130298	Monitoring Well	45.791	-108.52684	Terrace 3	15		x
323846	Private Well	45.746913	-108.693614	Terrace 3	57	x	x
307527	School District Well	45.780639	-108.659667	Terrace 3	50		x
185043	Monitoring Well	45.7405	-108.62747	Terrace 3	29	x	x
210785	Monitoring Well	45.69224	-108.69862	Terrace 3	12	x	x
252439	Private Well	45.75534	-108.68933	Terrace 3	60		x
327848	Monitoring Well*	45.74237	-108.65896	Terrace 3	27	x	x
325721	Private Well	45.778387	-108.63552	Terrace 3			x
325720	Private Well	45.793743	-108.6936	Alluvial Fan			x
150052	Private Well	45.7955	-108.68514	Alluvial Fan	85		x
171349	Private Well	45.796677	-108.6863012	Alluvial Fan	54		x
327722	Billings Parks Well*	45.79145	-108.65589	Alluvial Fan	35	x	x
705285	Private Well	45.78301	-108.68404	Alluvial Fan	16		x
327764	Monitoring Well*	45.78418	-108.51822	Carlile Shale	33		x
319988	Monitoring Well	45.7402	-108.62276	Niobrara Shale	120	x	x
327637	Billings Parks Well*	45.79144	-108.65595	Niobrara Shale	70	x	x
327847	Monitoring Well*	45.74237	-108.65899	Niobrara Shale	40	x	x

Table A1—*Continued*.

GWIC ID	Site	Latitude	Longitude	Aquifer / Type	Well Depth (ft)	Strontium Isotopes	Water Isotopes
Surface-Water Sites							
322294	BBWA Canal at Allendale Rd.	45.66825	-108.70229	Canal		x	x
319244	BBWA Canal at MSU Billings W.	45.79543	-108.52366	Canal		x	x
321057	Hogan's Slough at 56th St.	45.76213	-108.65747	Drain		x	x
319431	Hogan's Slough at Elysian Rd.	45.7405	-108.56667	Drain		x	x
319434	City County Drain	45.75354	-108.5099	Drain		x	x
322448	Shiloh Drain at Central Ave.	45.76918	-108.61791	Drain			x
322447	Yegen Drain at 27th St. S.	45.76987	-108.49165	Drain			x
259011	Canyon Creek at 80th St.	45.75489	-108.72027	Stream		x	x
319914	Canyon Creek at Big Ditch	45.74523	-108.70387	Stream			x
319268	Canyon Creek at Goodman Rd.	45.71976	-108.59643	Stream		x	x
319294	Pioneer Creek at Pioneer Park	45.78931	-108.52755	Stream		x	x
320186	Spring Creek at Lewis Ave.	45.78051	-108.55337	Stream		x	x

* Monitoring well installed for this project.

APPENDIX B

STRONTIUM ISOTOPE RATIOS AND CONCENTRATIONS

Table B1. Strontium isotope and concentration results.

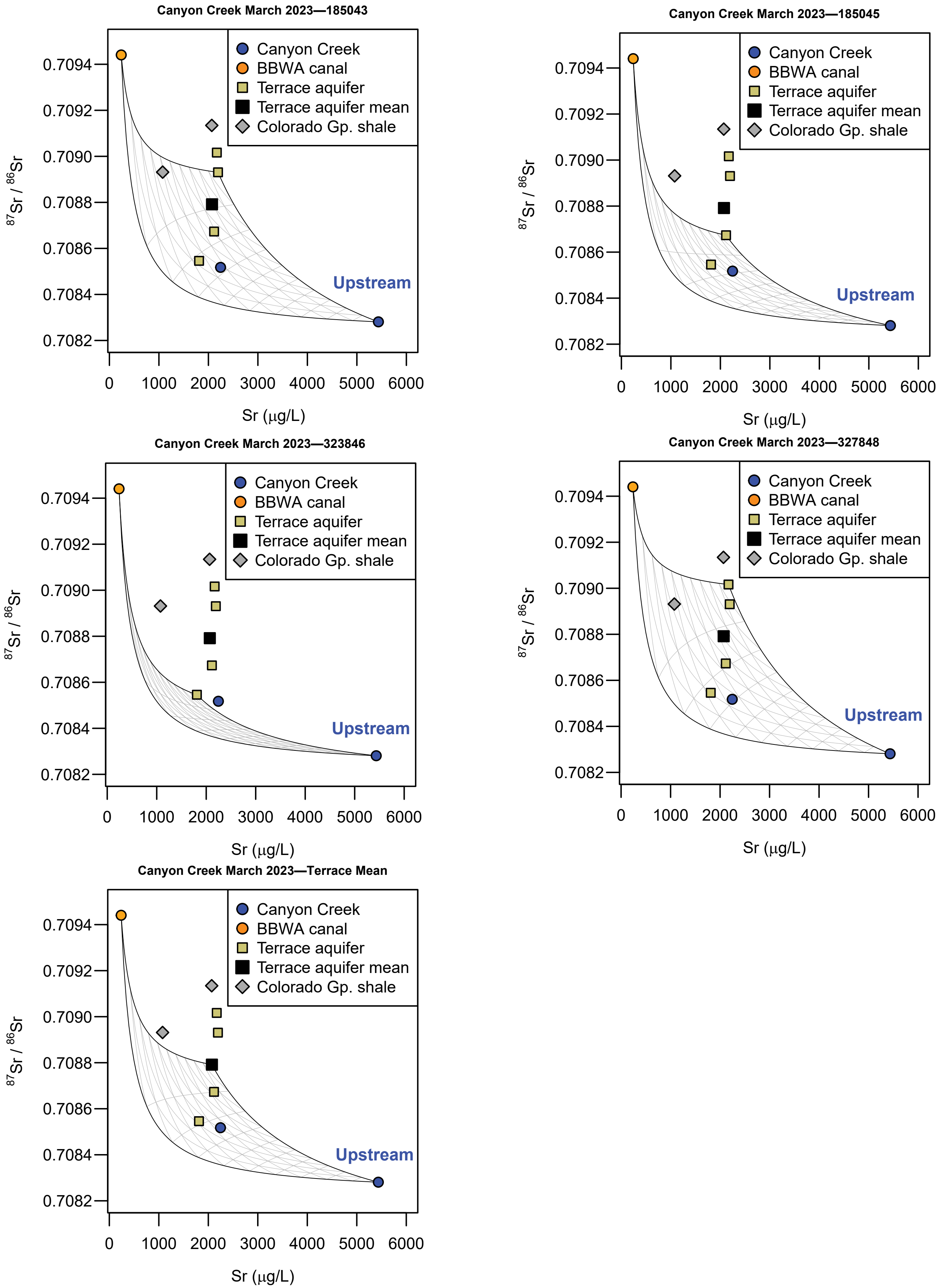
GWIC ID	Latitude	Longitude	Site	Aquifer/Type	Sample Date	$^{87}Sr/^{86}Sr$	Sr (µg/L)
Groundwater Sites							
158589	45.705102	-108.644155	Monitoring Well	Terrace 2	3/24/2023	0.70912105	931.49
					8/31/2023	0.70913357	1,071.17
263104	45.68762	-108.70275	Private Well	Terrace 2	3/24/2023	0.70934783	874.77
					8/30/2023	0.70935659	1,009.14
309526	45.78055	-108.65951	School District Well	Terrace 3	3/29/2023	0.70827589	3,670.73
					9/7/2023	0.70826273	3,983.71
252461	45.75878	-108.65837	Private Well	Terrace 3	3/23/2023	0.70849575	4,586.79
					9/7/2023	0.70852504	4,655.05
185045	45.74418	-108.63793	Monitoring Well	Terrace 3	3/29/2023	0.70867337	2,114.85
					9/7/2023	0.70871959	2,326.47
323846	45.746913	-108.693614	Private Well	Terrace 3	3/23/2023	0.70854589	1,811.44
					8/30/2023	0.70854132	1,920.54
185043	45.7405	-108.62747	Monitoring Well	Terrace 3	3/29/2023	0.70893062	2,194.10
					9/7/2023	0.70886490	2,348.40
210785	45.69224	-108.69862	Monitoring Well	Terrace 3	3/24/2023	0.70939389	965.64
					8/30/2023	0.70939919	638.34
327848	45.74237	-108.65896	Monitoring Well	Terrace 3	9/8/2023	0.70901633	2,170.22
327722	45.79145	-108.65589	Billings Parks Well	Alluvial Fan	9/7/2023	0.70837610	7,447.39
319988	45.7402	-108.62276	Monitoring Well	Niobrara Shale	3/29/2023	0.70893138	1,075.62
327637	45.79144	-108.65595	Billings Parks Well	Niobrara Shale	9/7/2023	0.70811665	8,379.58
327847	45.74237	-108.65899	Monitoring Well	Niobrara Shale	9/8/2023	0.70913439	2,068.39
Surface-Water Sites							
322294	45.66825	-108.70229	BBWA Canal at Allendale Rd.	Canal	8/31/2023	0.70944058	238.91
319244	45.79543	-108.52366	BBWA Canal at MSU Billings W.	Canal	8/31/2023	0.70946096	226.57
319434	45.75354	-108.5099	City County Drain	Drain	3/14/2023	0.70850992	1,949.91
					8/29/2023	0.70858791	1,433.11
321057	45.76213	-108.65747	Hogan's Slough at 56th St.	Drain	3/14/2023	0.70824420	5,217.63
					8/29/2023	0.70845278	1,682.95
319431	45.7405	-108.56667	Hogan's Slough at Elysian Rd.	Drain	3/14/2023	0.70849579	2,041.58
					8/29/2023	0.70895004	492.11
320186	45.78051	-108.55337	Spring Creek at Lewis Ave.	Drain	3/14/2023	0.70843215	3,004.69
					8/29/2023	0.70846946	1,994.68
259011	45.75489	-108.72027	Canyon Creek at 80th St.	Stream	3/14/2023	0.70828089	5,435.11
					8/29/2023	0.70880632	547.00
319268	45.71976	-108.59643	Canyon Creek at Goodman Rd.	Stream	3/14/2023	0.70851760	2,245.84
					8/29/2023	0.70911820	348.52
319294	45.78931	-108.52755	Pioneer Creek at Pioneer Park	Stream	3/14/2023	0.70851084	1,261.52
					8/29/2023	0.70867129	858.06

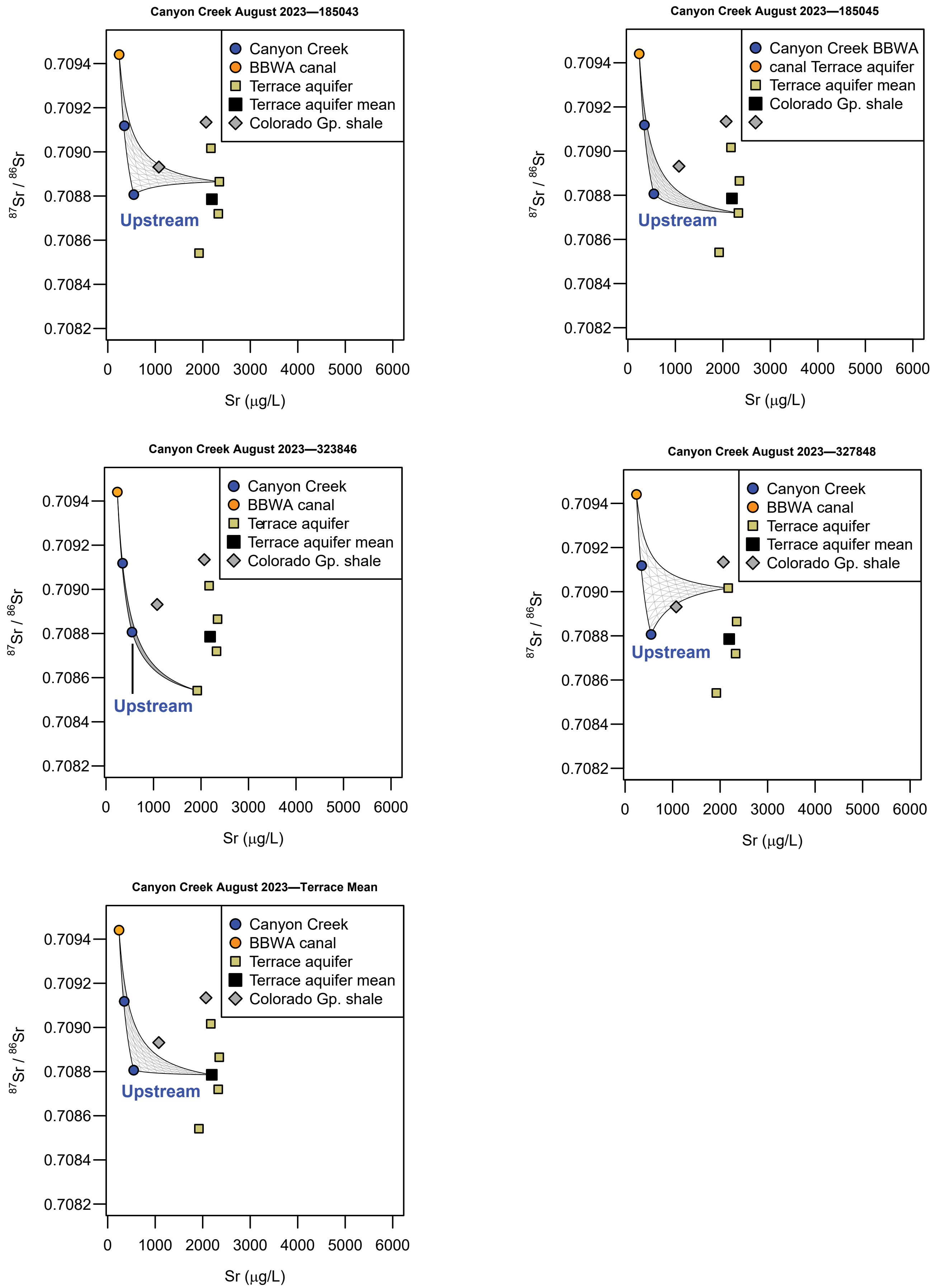
Table B2. Three-endmember strontium mixing calculations.

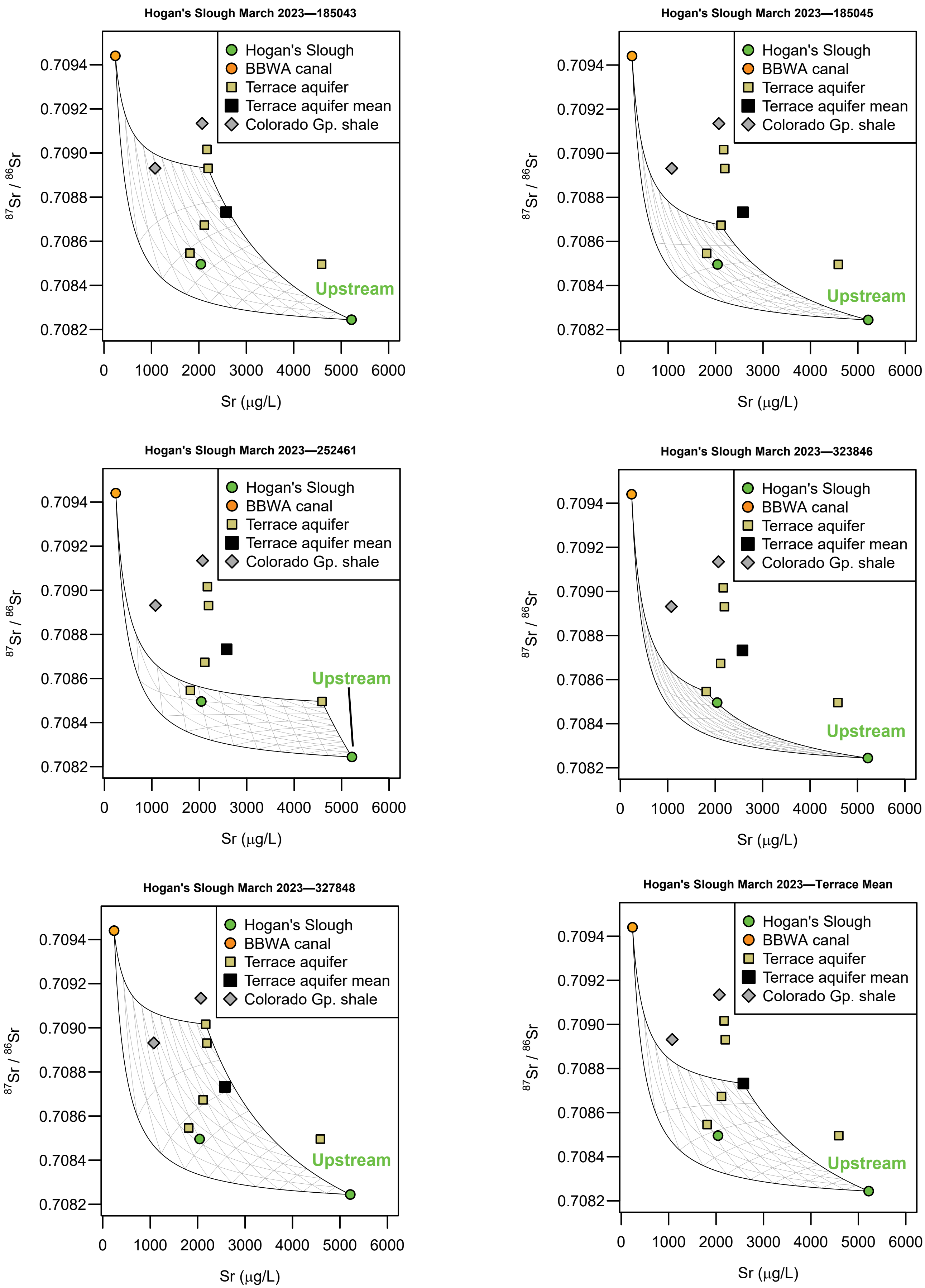
Sample Date	Terrace Groundwater Endmember GWIC ID	Terrace Groundwater Endmember Name	Upstream Endmember GWIC ID	Upstream Endmember Name	Upstream %	BBWA %	Terrace GW %	% Gain
March 2023	185043	Monitoring Well	321057	Hogan's Slough at 56th St.	27	50	23	270
	185045	Monitoring Well			20	35	45	400
	252461	Private Well			10	60	30	900
	323846	Private Well			8	0	92	1,150
	327848	Monitoring Well			27	51	22	270
		MEAN			**22**	**48**	**30**	**355**
March 2023	185043	Monitoring Well	259011	Canyon Creek at 80th St.	30	39	31	233
	185045	Monitoring Well			20	25	55	400
	323846	Private Well			NA	NA	NA	NA
	327848	Monitoring Well			30	45	25	233
		MEAN			**25**	**35**	**40**	**300**
August 2023	185043	Monitoring Well	321057	Hogan's Slough at 56th St.	11	84	5	809
	185045	Monitoring Well			9	85	6	1,011
	252461	Private Well			0	92	8	NA
	323846	Private Well			0	87	13	NA
	327848	Monitoring Well			13	84	3	669
		MEAN			**9**	**85**	**6**	**1,011**
August 2023	185043	Monitoring Well	259011	Canyon Creek at 80th St.	30	70	0	233
	185045	Monitoring Well			30	70	0	233
	323846*	Private Well			36	64		178
	327848	Monitoring Well			30	70	0	233
		MEAN			**26**	**72**	**2**	**285**

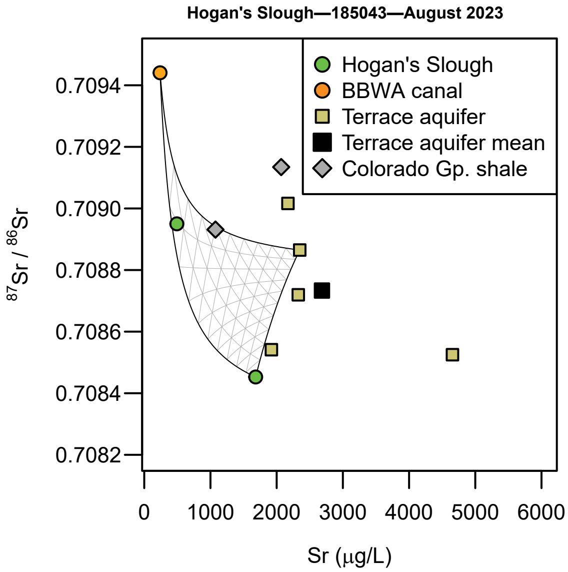
*Calculated as a two-endmember mix between the BBWA and upstream endmembers.

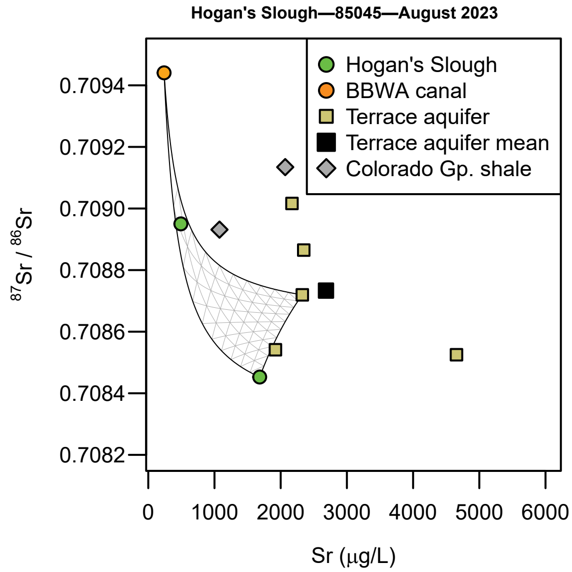
Three-Endmember Mixing Webs

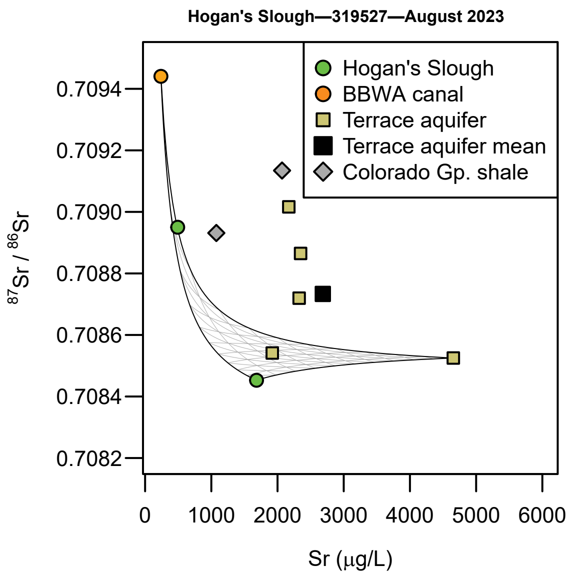


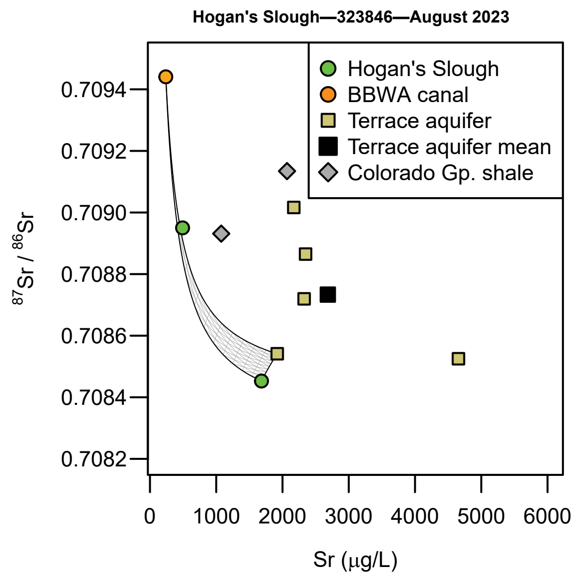

Canyon Creek August 2023—185043
Canyon Creek
BBWA canal
Terrace aquifer
Terrace aquifer mean
Colorado Gp. shale
Upstream
0.7094
0.7092
0.7090
0.7088
0.7086
0.7084
0.7082
$^{87}Sr / ^{86}Sr$
0 1000 2000 3000 4000 5000 6000
Sr (µg/L)
Canyon Creek August 2023—185045
Canyon Creek BBWA
canal Terrace aquifer
Terrace aquifer mean
Colorado Gp. shale
Upstream
0.7094
0.7092
0.7090
0.7088
0.7086
0.7084
0.7082
$^{87}Sr / ^{86}Sr$
0 1000 2000 3000 4000 5000 6000
Sr (µg/L)
Canyon Creek August 2023—323846
Canyon Creek
BBWA canal
Terrace aquifer
Terrace aquifer mean
Colorado Gp. shale
Upstream
0.7094
0.7092
0.7090
0.7088
0.7086
0.7084
0.7082
$^{87}Sr / ^{86}Sr$
0 1000 2000 3000 4000 5000 6000
Sr (µg/L)
Canyon Creek August 2023—327848
Canyon Creek
BBWA canal
Terrace aquifer
Terrace aquifer mean
Colorado Gp. shale
Upstream
0.7094
0.7092
0.7090
0.7088
0.7086
0.7084
0.7082
$^{87}Sr / ^{86}Sr$
0 1000 2000 3000 4000 5000 6000
Sr (µg/L)
Canyon Creek August 2023—Terrace Mean
Canyon Creek
BBWA canal
Terrace aquifer
Terrace aquifer mean
Colorado Gp. shale
Upstream
0.7094
0.7092
0.7090
0.7088
0.7086
0.7084
0.7082
$^{87}Sr / ^{86}Sr$
0 1000 2000 3000 4000 5000 6000
Sr (µg/L)

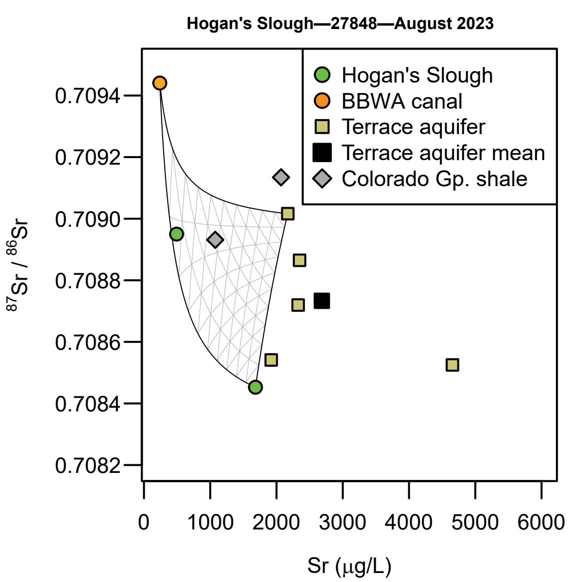

Hogan's Slough March 2023—185043
Hogan's Slough March 2023—185045
Hogan's Slough March 2023—252461
Hogan's Slough March 2023—323846
Hogan's Slough March 2023—327848
Hogan's Slough March 2023—Terrace Mean
Hogan's Slough
BBWA canal
Terrace aquifer
Terrace aquifer mean
Colorado Gp. shale
Upstream
87Sr / 86Sr
Sr (µg/L)
0.7082
0.7084
0.7086
0.7088
0.7090
0.7092
0.7094
0
1000
2000
3000
4000
5000
6000

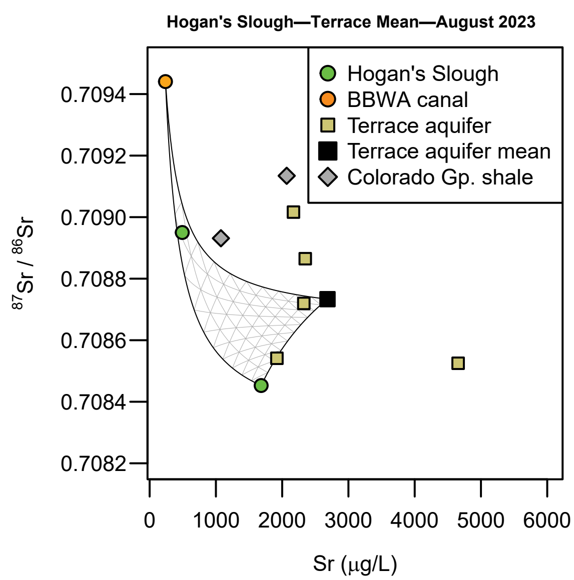

Hogan's Slough—185043—August 2023
Hogan's Slough
BBWA canal
Terrace aquifer
Terrace aquifer mean
Colorado Gp. shale
$^{87}Sr / ^{86}Sr$
0.7094
0.7092
0.7090
0.7088
0.7086
0.7084
0.7082
0 1000 2000 3000 4000 5000 6000
Sr (µg/L)


Hogan's Slough—85045—August 2023
Hogan's Slough
BBWA canal
Terrace aquifer
Terrace aquifer mean
Colorado Gp. shale
$^{87}Sr / ^{86}Sr$
0.7094
0.7092
0.7090
0.7088
0.7086
0.7084
0.7082
0 1000 2000 3000 4000 5000 6000
Sr (µg/L)


Hogan's Slough—319527—August 2023
Hogan's Slough
BBWA canal
Terrace aquifer
Terrace aquifer mean
Colorado Gp. shale
$^{87}Sr / ^{86}Sr$
0.7094
0.7092
0.7090
0.7088
0.7086
0.7084
0.7082
0 1000 2000 3000 4000 5000 6000
Sr (µg/L)


Hogan's Slough—323846—August 2023
Hogan's Slough
BBWA canal
Terrace aquifer
Terrace aquifer mean
Colorado Gp. shale
$^{87}Sr / ^{86}Sr$
0.7094
0.7092
0.7090
0.7088
0.7086
0.7084
0.7082
0 1000 2000 3000 4000 5000 6000
Sr (µg/L)


Hogan's Slough—27848—August 2023
Hogan's Slough
BBWA canal
Terrace aquifer
Terrace aquifer mean
Colorado Gp. shale
$^{87}Sr / ^{86}Sr$
0.7094
0.7092
0.7090
0.7088
0.7086
0.7084
0.7082
0 1000 2000 3000 4000 5000 6000
Sr (µg/L)


Hogan's Slough—Terrace Mean—August 2023
Hogan's Slough
BBWA canal
Terrace aquifer
Terrace aquifer mean
Colorado Gp. shale
$^{87}Sr / ^{86}Sr$
0.7094
0.7092
0.7090
0.7088
0.7086
0.7084
0.7082
0 1000 2000 3000 4000 5000 6000
Sr (µg/L)

APPENDIX C

WATER ISOTOPE RESULTS

Table C1. Water isotope results.

GWIC ID	Site	Latitude	Longitude	Aquifer / Type	Sample Date	$\delta^{18}O$	$\delta^{2}H$
Groundwater Sites							
327728	Monitoring Well*	45.76249	-108.48075	Terrace 1	9/8/2023	-15.9	-127
171253	Monitoring Well	45.69699	-108.65226	Terrace 1	3/24/2023	-16.9	-134
					8/31/2023	-17.0	-133
171258	Monitoring Well	45.72025	-108.59680	Terrace 2	8/31/2023	-16.3	-129
319968	Billings Parks Well	45.75491	-108.55115	Terrace 2	3/24/2023	-15.9	-127
158589	Monitoring Well	45.70510	-108.64416	Terrace 2	3/24/2023	-15.9	-128
					8/31/2023	-16.0	-125
321560	Private Well	45.71258	-108.64915	Terrace 2	4/10/2023	-15.7	-129
					9/7/2023	-16.0	-127
327829	Monitoring Well*	45.78418	-108.51817	Terrace 2	9/1/2023	-16.7	-129
323103	Private Well	45.68458	-108.69959	Terrace 2	3/24/2023	-16.9	-134
					8/30/2023	-14.5	-129
263104	Private Well	45.68762	-108.70275	Terrace 2	3/24/2023	-16.4	-131
					8/30/2023	-15.6	-121
171251	Monitoring Well	45.73322	-108.63839	Terrace 2	4/10/2023	-16.1	-131
					9/7/2023	-16.8	-130
292908	Monitoring Well	45.79723	-108.48286	Terrace 2	4/10/2023	-17.1	-142
					9/8/2023	-16.0	-126
93765	School District Well	45.77157	-108.54352	Terrace 2	9/13/2023	-15.6	-123
327636	Monitoring Well*	45.74766	-108.59313	Terrace 2	9/8/2023	-16.7	-131
132564	School District Well	45.71220	-108.63730	Terrace 2	9/13/2023	-16.6	-130
319527	Private Well	45.76067	-108.65598	Terrace 3	9/7/2023	-17.3	-134
171252	Monitoring Well	45.73322	-108.63837	Terrace 3	4/10/2023	-16.0	-130
					9/7/2023	-16.3	-128
158606	Monitoring Well	45.68605	-108.72680	Terrace 3	4/11/2023	-16.8	-133
325487	Private Well	45.76942	-108.62774	Terrace 3	3/23/2023	-16.6	-134
					9/7/2023	-17.1	-132
309526	School District Well	45.78055	-108.65951	Terrace 3	3/29/2023	-16.4	-134
					9/7/2023	-17.1	-134
327763	Billings Parks Well*	45.76357	-108.56131	Terrace 3	9/8/2023	-15.9	-127
327723	Monitoring Well*	45.76732	-108.56222	Terrace 3	9/11/2023	-16.1	-129
158590	Private Well	45.76429	-108.68169	Terrace 3	3/23/2023	-16.5	-132
					8/30/2023	-16.9	-130
252461	Private Well	45.75878	-108.65837	Terrace 3	3/23/2023	-16.7	-134
185045	Monitoring Well	45.74418	-108.63793	Terrace 3	3/29/2023	-16.4	-132
					9/7/2023	-16.8	-130
324784	Private Well	45.71849	-108.67925	Terrace 3	3/23/2023	-16.4	-131
130298	Monitoring Well	45.79100	-108.52684	Terrace 3	3/22/2023	-16.6	-133
					8/30/2023	-16.1	-129
323846	Private Well	45.74691	-108.69361	Terrace 3	3/23/2023	-16.8	-133
					8/30/2023	-17.2	-132
307527	School District Well	45.78064	-108.65967	Terrace 3	3/29/2023	-16.7	-134
					9/7/2023	-17.2	-134

Table C1—*Continued.*

GWIC ID	Site	Latitude	Longitude	Aquifer / Type	Sample Date	$\delta^{18}O$	$\delta^{2}H$
185043	Monitoring Well	45.74050	-108.62747	Terrace 3	3/29/2023	-11.5	-110
					9/7/2023	-4.7	-69
210785	Monitoring Well	45.69224	-108.69862	Terrace 3	3/24/2023	-16.6	-133
					8/30/2023	-14.2	-110
252439	Private Well	45.75534	-108.68933	Terrace 3	4/10/2023	-16.4	-133
					8/30/2023	-16.9	-132
327848	Monitoring Well*	45.74237	-108.65896	Terrace 3	9/8/2023	-17.1	-132
325721	Private Well	45.77839	-108.63552	Terrace 3	3/22/2023	-16.9	-133
325720	Private Well	45.79374	-108.69360	Alluvial Fan	3/22/2023	-16.8	-140
					8/31/2023	-17.4	-140
150052	Private Well	45.79550	-108.68514	Alluvial Fan	3/22/2023	-16.6	-132
					8/30/2023	-16.5	-131
171349	Private Well	45.79668	-108.68630	Alluvial Fan	3/22/2023	-16.0	-130
					8/30/2023	-16.3	-129
327722	Billings Parks Well*	45.79145	-108.65589	Alluvial Fan	9/7/2023	-16.7	-131
705285	Private Well	45.78301	-108.68404	Alluvial Fan	3/23/2023	-16.5	-132
					8/30/2023	-14.6	-130
327764	Monitoring Well*	45.78418	-108.51822	Carlile Shale	9/1/2023	-16.9	-134
319988	Monitoring Well	45.74020	-108.62276	Niobrara Shale	3/29/2023	-16.1	-132
327637	Billings Parks Well*	45.79144	-108.65595	Niobrara Shale	9/7/2023	-17.8	-142
327847	Monitoring Well*	45.74237	-108.65899	Niobrara Shale	9/8/2023	-17.2	-133
	Surface-Water Sites						
322294	BBWA Canal at Allendale Rd.	45.66825	-108.70229	Canal	8/31/2023	-16.8	-131
319244	BBWA Canal at MSU Billings W.	45.79543	-108.52366	Canal	8/31/2023	-16.7	-130
319434	City County Drain	45.75354	-108.50990	Drain	3/14/2023	-16.8	-133
					8/29/2023	-16.7	-129
321057	Hogan's Slough at 56th St.	45.76213	-108.65747	Drain	3/14/2023	-16.3	-132
					8/29/2023	-15.7	-127
319431	Hogan's Slough at Elysian Rd.	45.74050	-108.56667	Drain	3/14/2023	-16.4	-130
					8/29/2023	-16.7	-129
322448	Shiloh Drain at Central Ave.	45.76918	-108.61791	Drain	3/14/2023	-16.8	-132
					8/29/2023	-16.8	-131
322447	Yegen Drain at 27th St. S.	45.76987	-108.49165	Drain	3/14/2023	-18.3	-146
					8/29/2023	-16.9	-131
320186	Spring Creek at Lewis Ave.	45.78051	-108.55337	Drain	3/14/2023	-16.6	-131
					8/29/2023	-16.8	-130
259011	Canyon Creek at 80th St.	45.75489	-108.72027	Stream	3/14/2023	-16.4	-132
					8/29/2023	-16.7	-130
319268	Canyon Creek at Goodman Rd.	45.71976	-108.59643	Stream	3/14/2023	-16.3	-131
					8/29/2023	-16.9	-131
319294	Pioneer Creek at Pioneer Park	45.78931	-108.52755	Stream	3/14/2023	-17.4	-137
					8/29/2023	-16.8	-131

Table C2. Local meteoric water line precipitation results.

Billings Precipitation (site 28406)		
Sample Date	$\delta^{18}O$	$\delta^{2}H$
5/28/2015	-13.4	-102
5/29/2015	-9.1	-83
6/1/2015	-8.5	-76
6/19/2015	-9.3	-71
7/19/2015	-12	-85
8/4/2015	-8.8	-74
8/18/2015	-14.3	-112
9/17/2015	-11.8	-99
10/3/2015	-12.3	-92
10/19/2015	-9.2	-76
10/27/2015	-12.8	-98
11/2/2015	-11.1	-80
11/20/2015	-15.9	-106
12/14/2015	-18.8	-141
2/15/2016	-14.7	-112
3/22/2016	-17.8	-139
3/23/2016	-18.9	-146
3/29/2016	-19.1	-142
4/14/2016	-15	-114
4/18/2016	-12.9	-102
4/27/2016	-16.4	-119
4/28/2016	-19.9	-147
5/9/2016	-12.8	-91
5/10/2016	-24.1	-184
5/21/2016	-16.3	-122
6/13/2016	-13.6	-103
8/18/2016	-10.4	-76
9/12/2016	-23.3	-179
10/2/2016	-10.1	-70
10/3/2016	-14.1	-100
10/4/2016	-18.1	-141
12/15/2016	-26.4	-207
1/31/2017	-24.8	-192
2/6/2017	-24.3	-186
2/22/2017	-23.3	-186
3/8/2017	-21.4	-165

Roundup Precipitation (site 326630)		
Composite Month	$\delta^{18}O$	$\delta^{2}H$
July 2023	-9.8	-78
August 2023	-7.4	-64
September 2023	-8.7	-63
October 2023	-9.8	-68
November 2023	-16.8	-126
December 2023	-18.9	-158
January 2024	-28.3	-233
February 2024	-17.3	-138
March 2024	-18	-135
April 2024	-14.3	-102
May 2024	-14.4	-111
June 2024	-17.2	-127
July 2024	-8.8	-82
August 2024	-5.9	-55
September 2024	-12.1	-93
October 2024	-11.9	-91
November 2024	-17.6	-135

Online Isotopes in Precipitation Calculator* (OIPC)		
Modelled Month	$\delta^{18}O$	$\delta^{2}H$
January	-20.7	-157
February	-21.8	-166
March	-19.1	-145
April	-15	-113
May	-10.8	-80
June	-9.6	-72
July	-7.7	-59
August	-6.1	-46
September	-9.7	-73
October	-13.6	-101
November	-18	-137
December	-21.4	-165

*Database available online: https://wateriso.utah.edu/waterisotopes/pages/data_access/oipc.html