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MOUNTAIN FRONT RECHARGE IN A SEMI-ARID CLIMATE, SOUTHWEST MONTANA

Charles Shama
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MOUNTAIN FRONT RECHARGE IN A SEMI-ARID CLIMATE,
SOUTHWEST MONTANA

by
Charles Shama

A thesis submitted in partial fulfillment of the
requirements for the degree of

Master of Science Degree in Geosciences:
Hydrogeology Option

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Abstract

Groundwater recharge to regional valley benches originates largely from adjacent Mountain Front Recharge (MFR). The Madison Valley in Southwest Montana is a semi-arid cold climate that receives 31.75cm annual valley precipitation. In this study, two drainages are characterized and compared, looking at the hydrological processes between the stream and groundwater. North Meadow Creek is a high elevation stream dominated by snowmelt and contains reaches of gaining and losing surface water to groundwater. Daylight Creek is a spring fed disconnected stream. Methods used a surface water balance, temperature as an environmental tracer and two and three component mixing models to investigate groundwater underflow, stream and groundwater fluxes, and source waters for streams. The smaller Daylight Creek watershed is a disconnected stream with a range of specific vertical discharge at 2^{-5} m/s to 8^{-10} m/s. The larger North Meadow Creek watershed contains three unique zones. The upper mountainous reach is a gaining stream, the middle reach is a transition from gaining to losing, and the lower zone is a losing reach. Specific vertical discharge has a range of 5.0^{-5} m/s to 8.0^{-6} m/s. A two and three component mixing model was utilized to fractionate soil water and groundwater. North Meadow Creek has a soil water pulse during the spring melt and a fluctuating fraction groundwater contribution of 10% to 75% throughout the study period. Daylight Creek has no seasonal trend and a constant 40%-50% groundwater contribution during the study period.

Keywords: Mountain Front Recharge Environmental Tracer Hydrogeology Isotope

Dedication

I would like to thank my mother and father for their love and support. And thank my dog, Larry Chubbs, for riding this out with me.

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1. Introduction

Regional Mountain Block Recharge (MBR) is a key component of alluvial basin aquifer systems typical of the western United States. A mountain block includes all the mass composing the mountains, including vegetation, soil, bedrock, and water (Wilson and Guan, 2004). The term Mountain Front Recharge (MFR) is used to describe the contributions of mountainous regions to the recharge of adjacent basin aquifers and MFR is positioned between the mountain block and the basin floor (Wilson and Guan, 2004) (Figure 1). Traditionally modelers of basins treat MFR as a boundary condition (Wilson and Guan, 2004). Historically, MFR estimates have been based on general precipitation characteristics of a mountain or by calibration of a basin groundwater model. Recent advances in landscape-scale ecohydrologic process modeling offer the possibility that meteorological data and land surface physical and vegetative conditions can be used to generate estimates of MFR (Magruder, et al., 2009).

MBR is defined as the surface and subsurface components of mountain front recharge. MFR considers recharge from rainfall, snowmelt, surface runoff, and through fractures and faults. When water is discharged from the mountain block to the adjacent basin it becomes MFR through five distinct components (Figure 1).

- (1) FS.-focused near-surface recharge of shallow groundwater transmitted in the sediments of streams that drain the mountain mass.
- (2) DS-diffuse near-surface recharge that is the infiltration and deep soil drainage occurring during episodic runoff events in ephemeral drainages at the mountain front.
- (3) FR-focused subsurface recharge that follows flow paths within faults and fractures.
- (4) DR-diffuse subsurface recharge through primary permeability in the bedrock matrix.
- (5) RS-recharge from losing stream runoff (Wilson and Guan, 2004).

Figure 1: Schematic diagram illustrating MFR components . FS = focused near-surface recharge, RS = recharge from losing stream runoff, DS = diffuse near-surface recharge, FR = focused subsurface recharge, DR = diffuse subsurface recharge. (Modified from Wilson and Guan 2004)

The focused near surface component (FS) represents MFR contributions at the mountain front from surface stream runoff and shallow subsurface water transmitted by streambed sediments. We emphasize FS here because it is sometimes neglected when MFR is estimated solely from the surface runoff. While the stream channel may be dry, there is often significant subsurface discharge in the sediments underlying the stream and above the bedrock surface. This subsurface flow includes the hyporheic zone beneath the stream, but it can be deeper and wider, especially at the mountain front (Wilson and Guan, 2004). MFR is an important water source to

basin aquifers in semi-arid regions and the least understood component to balancing a groundwater budget (Wilson and Guan, 2004).

Groundwater flow paths in stream valleys where groundwater underflow is focused through coarse sediments in narrow valleys (FS) contributes the most towards MFR (Wilson and Guan, 2004). Focused groundwater flow paths from the mountain to the valley are greatest under mountain streams and are the largest source for MFR (Manning & Solomon, 2003). Existing studies from the Wasatch Mountains of Utah suggest that mountain-front recharge typically accounts for one third to nearly all of the recharge to these aquifers (Manning and Solomon, 2003) which can be FS and RS. Quantifying recharge to an alluvial basin aquifer from streams originating in the mountain block and flowing into and through associated basins generally requires the application of traditional stream gauging techniques and stream channel infiltration characterization (Constantz et al., 2002; Constantz, 2008).

Traditionally in a groundwater basin simulation, the amount of the upstream boundary influx from MBR is estimated in the numerical model calibration stage where the simulated groundwater levels are forced to match the observed groundwater level data by adjusting the hydrogeological parameters and the upstream boundary influx. However, fluxes estimates in this way are plagued by the uncertainty associated with estimating all the other parameters used in the model as well as heads uncertainty used to calibrate the model. Various methods have been developed to improve the estimation boundary influx such as isotopic tracer, heat tracer, chloride mass balance, base flow discharge, and rainfall infiltration methods (Gleeson and Manning, 2008).

Focused recharge in streambeds is measurable using stream gauges and other physical and chemical methods along the stream. MBR distributed over mountain hillslopes cannot to be

directly measured. Another difficulty of quantifying distributed MBR is that the water that percolates below the root-zone at one location may return back the surface or a stream elsewhere, due to the local soil conditions, geologic structures and topographic relief. This water may subsequently re-recharge at a lower location (Earman et al., 2006).

Subsurface temperature is a tracer for detecting water movement because heat in the subsurface is transported by conduction and more importantly advection caused by groundwater movement.

End-member mixing analysis reduces data sets of streamflow chemistry so that the chemical constituents and end-members are identified. No prior information about the end-member population is needed. This is a well-established methodology that has been used to identify sources of water responsible for runoff generation in hillslopes, small catchments (Liu, et al. 2004), and larger watersheds spanning a range of geographic, geologic, climatic, and environmental conditions (Frisbee et al., 2011), or both (Shaw et al., 2014).

2. Purpose

Two watersheds located within the Tobacco Root Mountains are selected for this study. North Meadow Creek and Daylight Creek drainages are analyzed to illustrate the variability of mountain catchments. This study focuses on (1) Focused near-surface recharge of shallow groundwater transmitted in the sediments of streams that drain the mountain mass (FS), and (5) Recharge from losing stream runoff (RS) (Figure 1). Within each watershed, catchment processes and identification of source waters are characterized.

Figure 2: Location and topography of North Meadow Creek and Daylight Creek. Study sites are located at green triangles. SNOTEL and rain stations are located in Ennis, MT and within North Meadow Creek, maroon marks; Irrigation diversions are located along North Meadow Creek, light blue marks, springs are located along Daylight Creek, blue marks.

3. Site Description

Research locations were chosen based on access to the streams for sampling of both the streams and shallow wells; to physically measure stream flow, stilling well level, and groundwater level in shallow wells.

North Meadow Creek watershed (NMC) (11,130 hectares) is located on the southeastern slope of the Tobacco Root Mountains and ranges in elevation from 3050m to about 1525m (Figure 2 and 3). This watershed dominated by snowmelt and the study site consists of a 9.6km reach of North Meadow Creek with four research locations, NMC1, NMC2, NMC3, and NMC4 (Figure 3). NMC drains east into the Madison Valley and Ennis Lake. North Meadow Creek has an elevation difference of 1,600m between NMC1 and NMC4 (Figure 3). The stream slope gradually decreases as the stream exits the mountain front and enters the valley at NMC4.

Figure 3: North Meadow Creek Watershed. NMC1 and NMC2 are located in the upper watershed while NMC3 and NMC4 are located in the lower watershed. Red outline represents watershed boundaries. Cross section and elevation profile is shown with line. Red marker is the location of SNOTEL site 603. Green triangles are study locations. Blue marks are location of irrigation diversions.

Figure 4: Elevation profile of North Meadow Creek. Study locations are marked along the top of elevation profile. This is a section of the creek shown on Figure 3.

The surface geology around North Meadow Creek is mostly made up of metamorphic and igneous rocks of the Aga, Aqfg, and Kgt formations (Figure 8). The rocks weather to sandy/gravelly alluvium in the mountain stream valleys. The regional valley benches are composed of Neogene and Quaternary aged sediments (Tr, Qgr) (Figure 8) and the mountain streams cut through the benches to the Quaternary basin floor. Soils in the catchment range from a sandy loam to a silty loam and are a thin (<1m) and the alluvium is about 7m thick in the high elevations based on cross sections developed from well logs (Figure 5). The soil and alluvium become thicker, greater than 1m for soil and about 30m for alluvium at lower elevations. The geologic cross section of North Meadow Creek were drawn from GWIC well log data along the creek. The cross section reveals a thin layer of alluvium at NMC1 and NMC2. The alluvium consists of sand, gravel and cobble thickens to >30m at NMC3 and NMC4 and includes clay lenses (Figure 5). The bedrock is near surface in the mountain front at NMC1 and deepens in the valley at NMC4.

North Meadow Creek has an average annual precipitation of 99.3 cm (Natural Resources Conservation Service National Water And Climate Center, 2018 (SNOTEL #603)). North

Meadow Creek has an average flow of 0.37 m³/s with peak flows of 2.55 m³/s during spring runoff (Madison Stream Team (MST), 2018).

Figure 5: Geologic profile of North Meadow Creek from GWIC well logs. Dashed line infers bedrock depth. GWIC wells are marked along the top of the cross section. Cross section shown on Figure 3

Daylight Creek watershed (DC) (1,130 hectares) is located on the western slope of a mountain pass at the southern end of the Tobacco Root Mountains and runs through the town of Virginia City, MT. The watershed ranges in elevation from 2,255m to about 1,735m. The watershed is spring-dominated and the study site consists of a 1km reach of Daylight Creek with two research locations DC1, DC2 (Figure 6). Daylight Creek drains west into Alder Creek which flows into the Ruby Valley. Daylight Creek has an elevation difference of 420m from the start of the stream to DC1. The elevation change between DC1 and DC2 is 40m (Figure 7).

Figure 4: Daylight Creek watershed. Green triangles are study locations, blue marks are spring locations, red outline is the watershed boundary, and the line is the elevation profile location.

Figure 5: Elevation profile of Daylight Creek showing study locations. The left side is the upper watershed boundary and the right side is the confluence with Alder Creek.

The surface geology of Daylight Creek is volcanic tuff weathered to clays (Figure 8). This tuff is greater than 150m thick (GWIC id 294418 (Table I)). The volcanic tuff weathers into clay, resulting in landslides that dominate the topography. Springs emerge from the past landslides, forming Daylight Creek. Soils in the catchment are silty clay with depths from 1-3m. Daylight Creek and Virginia City have few well logs. There is not enough information to develop a cross section. The few well logs in GWIC reveals that there is a thick clay layer near the surface, a basalt layer below the clay followed by a very thick layer of volcanic tuff, which is similar to clay.

Virginia City has an average annual precipitation of 31.75 cm (Western Regional Climate Center (WRCC), 2018). Daylight Creek has an average flow of 0.02 m³/s.

Table I: Well logs near Daylight Creek (m).

GWIC id	latitude	longitude		GWIC id	latitude	longitude	
294418	45.3	-111.92		153479	45.4	-111.98	
	from (m)	to (m)	description		from (m)	to (m)	description
	0	0.6	topsoil		0	0.8	firm clay bedrock
	0.6	4.6	clay		0.8	0.9	bedrock
	4.6	22.8	basalt bedrock				
	22.8	33.5	sticky clay				
	33.5	185.9	volcanic tuff

Figure 6: Surface geology map USGS 500k (MBMG). Qal, QTs Qgr are Quaternary age alluvium and basin fill sediments. Tr and Ts are Neogene age rhyolite volcanic rocks. Tanb is Neogene age basalt volcanic rocks. Kgt is Cretaceous age granite rocks. Aga and Aqfg are Archean age gneiss and amphibolite rocks.

4. Methods

4.1. Vertical GW/SW fluxes for recharge/discharge (RS)

Groundwater/surface water fluxes highlight variations in stream dynamics at each study site. Stream reaches can be gaining from groundwater and/or losing to groundwater at different times of the year.

Shallow wells were installed at each research site. Each well was instrumented with a Solinst Levelogger pressure transducer which records pressure and temperature and DS1922L Thermochron temperature loggers set at middle and upper heights relative to each water column. Another Solinst Levelogger pressure transducer was set on the stream bed (Figure 9). These instruments created a temperature profile from the stream down to the bottom of the well. At NMC3 a Barologger was installed at the top of the well to record air pressure.

Figure 7: Schematic of site equipment setup for all study sites, showing relative depth and location of piezometer, staff gauge, transducers, and temperature buttons.

All wells are constructed of 3.81cm diameter galvanized steel pipe and a 0.6m steel mesh screen on the bottom. The wells were manually pounded into the ground using a fence post pounder. NMC 1 well depth is 2.04m; NMC2 well depth is 1.64m; NMC3 well depth is 1.71m; NMC4 well depth is 2.18m; DC 1 well depth is 1.45m; DC 2 well depth is 2.98m.

4.1.1. Darcy's physical flux

Flux estimates are based on both Darcy's law (equation 3) and temperature flux calculations from variations of stream and groundwater temperatures.

$$q = -K \frac{dh}{dl} \quad (1)$$

where q is specific discharge; K is hydraulic permeability; dh/dl is the change in hydraulic head.

Slug tests were performed to estimate hydraulic permeability. On select sites a permeameter test was conducted to find the saturated hydraulic conductivity of the soil. Difference in water head (dh) is calculated by calculating the vertical elevation difference of the stream water elevation and the well water elevation. Difference in vertical length (dl) is the elevation difference between the streambed and bottom of the well. Dividing the water head by the vertical length to calculate hydraulic head (dh/dl). At each site the staff gauge and well were surveyed with GPS using a Trimble Geo 7X handheld data collector paired with a Trimble Zephyr 3 antenna.

Slug tests were performed at two sites (NMC1, NMC3) on North Meadow Creek to estimate hydraulic conductivity of the sand and gravel subsurface using the Hvorslev method (Fetter 2014).

$$K = \frac{r^2 \ln \frac{R}{r}}{2LT_0} \quad (2)$$

where K is hydraulic conductivity (m/s); r is radius of well casing (m); R is radius of well screen (m); L is length of well screen (m); T₀ is time it takes for water level to rise or fall 37% of initial change (s).

Slug test used a measured volume of water for the slug injected at both sites. The slug test performed at Daylight Creek failed because the slug did not fall quick enough for the Hvorslev method. Instead a constant head permeameter test was conducted using the Guelph Permeameter model 2800 to test the saturated hydraulic permeability of the soil at Daylight Creek.

$$K_s = [(0.0041)(R_c)(R_2)] - [(0.0054)(R_c)(R_1)] \quad (3)$$

where K_s is field saturated hydraulic conductivity; R_c is a reservoir constant; R₁ and R₂ are steady state rate of flow (cm/s).

4.1.2. Temperature profile method

Using 1DTempProV2 groundwater software developed by USGS (<http://water.usgs.gov/ogw/bgas/1dtemppro/>) is a graphical user interface that numerically solves the flow and heat-transport equations (Voytek, E., et al. 2013).

Figure 8: Thermal and hydraulic conditions in streambeds under the influence of streamflow for (a) gaining, (b) losing, (c) disconnected, and (d) ephemeral stream settings. The two temperature boxes are stream temperature and well temperature (Modified from Constantz 2008).

The surface water temperature (Figure 10, A-D) will typically reflect diurnal temperature changes. At a gaining stream (A), the groundwater temperature is constant; the temperature buttons in between the GW and SW will be a muted surface water signal. The temperature signal in a losing stream (B), show the groundwater temperature as a muted surface water signal and the temperature buttons in between the GW and SW will be a muted SW and an enhanced GW. The temperature signal of a disconnected stream (C), the groundwater temperature is not affected

by the surface water temperature. The temperature signal of an ephemeral stream (D) will show no pattern between the groundwater and surface water.

4.2. Surface water balance

North Meadow Creek and Daylight Creek were manually measured for discharge at each study locations monthly using a March Mcbirney Flo-Mate 2000 flow meter. Irrigation diversions (D1-D7) at North Meadow Creek were measured when the stream sites were measured. At NMC1, NMC2 and DC1 and DC2, total discharge was the same as the manual measurements because there are no irrigation diversions between these reaches. NMC3 total discharge was the stream discharge with the addition of diversions D1-D6. NMC4 total discharge was the stream discharge with the addition of diversions of D1-D7.

4.3. Mixing Models to determine source waters for catchment GW/SW

The δD and $\delta^{18}O$ values for precipitation worldwide behave predictably, falling along the global meteoric water line (GMWL) as defined by Craig (1961), who expresses the relationship between ^{18}O and 2H in meteoric waters as follows:

$$\delta^2H = 8\delta^{18}O + 10\text{‰} \quad (4)$$

This relationship for ^{18}O and 2H isotopes is primarily a reflection of differences in their equilibrium fractionation factors. The slope of the GMWL expresses this ratio, which is eight times greater for oxygen than hydrogen. Local meteoric water lines in arid environments will exhibit the same slope, but plot higher in relation to 2H because of increased evaporation. In precipitation, the initial liquid phase of rain is enriched in ^{18}O and 2H as compared to the later precipitation. Consequently, in rain events, the precipitation is depleted in ^{18}O and 2H as the rain continues, a phenomenon known as "rainout effect" (Clark & Fritz, 1997). The fundamental control on the isotopic composition of precipitation is temperature. With increasing temperature,

precipitation becomes enriched in the heavier isotopes, ^{18}O and ^2H , in a linear relationship. Temperature affects oxygen fractionation at a rate of approximately 0.5‰ for every °C. Similar effects are shown with increasing elevation and increased distance from the equator (both of which correspond to lower temperature) (Clark & Fritz, 1997).

Sample bottles were rinsed three times in sample water before sample collection. The water samples are analyzed for specific conductivity in the Montana Bureau of Mines and Geology (MBMG) lab using a VWR Scientific E. C. Meter Model 1054. Water samples for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ were collected and analyzed at the MBMG lab using a Picarro L2130-i Cavity Ring-Down Spectroscopy. Isotopic compositions are expressed as a δ (per mil) ratio of the sample to the Vienna Standard Mean Ocean Water (VSMOW) standard, where R is the ratio of $^{18}\text{O}/^{16}\text{O}$.

$$\Delta^{18}\text{O}_{\text{sample}} = [(R_{\text{sample}}/R_{\text{VSMOW}}) - 1] \times 10^3 \quad (5)$$

A three component endmember mixing model can be established if two or more environmental tracers are used. Specific conductivity (Sc) $\mu\text{S}/\text{cm}$ was used for the first tracer, and $\delta^{18}\text{O}$ was used for the second tracer. δD was used for model verification.

$$F_1 + F_2 + F_3 = 1 \quad (6)$$

$$A_1 F_1 + A_2 F_2 + A_3 F_3 = A_s \quad (7)$$

$$B_1 F_1 + B_2 F_2 + B_3 F_3 = B_s \quad (8)$$

where F is the fraction of total streamflow from an end-member contribution; A and B represent compositions of tracers A and B; subscripts 1, 2, 3 represent end members 1, 2, 3, subscript s represents sample. A matrix is used to calculate solutions using $\delta^{18}\text{O}$ and Sc.

$$D = \begin{bmatrix} 1 & 1 & 1 \\ A_1 & A_2 & A_3 \\ B_1 & B_2 & B_3 \end{bmatrix} \quad (9)$$

The determinant is

$$|D| = -A_2B_1 + A_3B_1 + A_1B_2 - A_3B_2 - A_1B_3 - A_2B_3 \quad (10)$$

Solutions for endmember contributions are

$$F_1 = \frac{1}{|D|} [(A_2B_3 - A_3B_2) + (B_2 - B_3)A_s + (A_3 - A_2)B_s] \quad (11)$$

$$F_2 = \frac{1}{|D|} [(A_3B_1 - A_1B_3) + (B_3 - B_1)A_s + (A_1 - A_3)B_s] \quad (12)$$

$$F_3 = \frac{1}{|D|} [(A_1B_2 - A_2B_1) + (B_1 - B_2)A_s + (A_2 - A_1)B_s] \quad (13)$$

John Anderson (2015) hypothesized that the rain and snow were actually a soil water signature. The end-member was relabeled as ‘Soil-Water’, to represent the shallow subsurface flow from the current water year’s source. A two-component end-member mixing model was established with soil water being one end-member and groundwater from a deeper well is the other end-member. The mathematical development for a two end-member mixing model, based

on the mass balance for water and tracers are as follows, using the fraction of streamflow discharge:

$$F_1 + F_2 = 1 \quad (14)$$

where: F_s the sample; F_1 is the percentage of end-member 1 (groundwater) in the sample; F_2 is the percentage of end-member 2 (soil water) in the sample;

$$C_1 F_1 + C_2 F_2 = C_s \quad (15)$$

where C_1 is concentration of end-member 1; C_2 is concentration of end-member 2; C_s is concentration of the sample. Specific conductivity (Sc) $\mu S/cm$ is used for the concentration.

Validation of both two and three component mixing models was performed using a third independent tracer, δD . The tracers of the end-members $\delta^{18}O$ and Sc were used to predict δD values. Those predicted δD values were plotted vs the observed sample δD values.

5. Results

5.1. Vertical GW/SW fluxes for recharge/discharge (RS)

5.1.1. Darcy flux

Specific discharge is one to two orders of magnitude larger at North Meadow Creek sites than Daylight Creek, which is appropriate based on the lithology of each site. North Meadow Creek is underlain with sands and gravels (Figure 5) where Daylight Creek is underlain by silts and clays (Table 1).

Figure 9: Slug test data from DC1. The blue line is the depth of water during the slug test August 15th. Notice that the water level remains constant for 40min.

The slug test at DC1 was conducted by pouring a volume of water at 15:00:10 (Figure 11). Results show that the water level held constant during the entire test time (Figure 11). The Hvorslev method failed at the DC1 site since the injected slug did not drop and for this method to

work, there needs to be a measurable drop. Permeameter results were used to estimate hydraulic conductivity for Daylight Creek. Results from constant head permeameter tests and K value obtained from equation 3 displayed on Table 2.

Table II: Hydraulic conductivity from slug tests and permeameter tests. K values are m/s.

site	K
	m/s
NMC1	1.6E-04
NMC2	1.6E-04
NMC3	2.2E-05
NMC4	2.2E-05
DC1	2.1E-07
DC2	2.1E-07

For NMC1 and NMC2 hydraulic conductivity value came from NMC1 slug tests. For NMC3 and NMC4 hydraulic conductivity came from NMC3 slug test. For DC1 and DC2 hydraulic conductivity came from DC2 permeameter test (Table III). These values were assigned based upon sediment types. Specific discharge (m/s) results are displayed in Table VII.

Figure 10: NMC1 slug test. The water injection for the slug occurred at 13:26:29 and the water level dropped to background levels by 13:26:59.

Figure 11: NMC3 slug test. The water injection for the slug occurred at 11:44:53 and the water level dropped to background levels by 11:48:29.

Table III: Specific Discharge (q) from manual water level measurements, positive values downward flow (losing stream), negative values upward flow (gaining stream).

	Specific Discharge (m/s)					
Date	NMC1	NMC2	NMC3	NMC4	DC1	DC2
May	4.2E-06	-6.9E-05	3.2E-06	2.2E-05	5.4E-08	2.4E-08
July	-1.6E-05	-6.7E-05	3.8E-06	-1.5E-06	6.3E-08	3.7E-08
October	-1.3E-05	-6.4E-05	4.4E-06	-1.3E-06	1.0E-08	2.5E-08
November	-1.2E-05	-6.5E-05	4.0E-06	7.4E-07	-6.3E-10	2.2E-08

5.1.2. Temperature flux

Results of the temperature profiles provide direction of groundwater flow and specific discharge between each study site separated into monthly values. The temperature profiles at each study site are plotted to visually show gaining, losing and disconnected reaches in streams relating back to Figure 9.

NMC1 and NMC2 are show of a gaining stream because the temperature line at the bottom of the well is unaffected by the stream water line (Figure 12 & 13). NMC3 and NMC4 show the groundwater temperature lines are responding closely to the stream temperature

changes indicating a losing stream (Figure 14 & 15). DC1 and DC2 show the groundwater line responding with a muted signal to the stream temperature lines indicating a disconnected stream (Figure 16 & 17).

Figure 12: Temperature profile at NMC1. Temperature was recorded in the stream (blue line), at a shallow well depth (green line), at a deeper well depth (orange line), and at the bottom of the well (black line). This profile is representative of a gaining stream.

Figure 13: Temperature profile at NMC2. Temperature was recorded in the stream (blue line), at a shallow well depth (green line), at a deeper well depth (orange line), and at the bottom of the well (black line). This temperature profile represents a gaining stream.

Figure 14: Temperature profile at NMC3. Temperature was recorded in the stream (blue line), at a depth in the middle of the well (orange line), and at the bottom of the well (black line). This temperature profile represents a losing stream.

Figure 15: Temperature profile at NMC4. Temperature was recorded in the stream (blue line), at a depth in the middle of the well (orange line), and at the bottom of the well (black line). The stream temperature data was lost due to floodwaters in June. A new temperature sensor was placed July 2nd. This temperature profile represents a losing stream.

Figure 16: Temperature profile at DC1. Temperature was recorded in the stream (blue line), at a shallow well depth (green line), at a deeper well depth (orange line), and at the bottom of the well (black line). The intermediate depth temper sensors record the same temperature, overlapping each other. This temperature profile represents a losing or disconnected stream.

Figure 17: Temperature profile at DC2. Temperature was recorded in the stream (blue line), at a shallow well depth (green line), at a deeper well depth (orange line), and at the bottom of the well (black line). The deep well temperature sensor malfunctioned in June. This temperature profile represents a losing or disconnected stream.

Table IV: Specific vertical discharge (m/s) estimation. Positive values represent a downward flow (losing stream) and negative values represent an upward flow (gaining stream) N/A represents not enough data to estimate q . NMC1 and NMC2 are upstream locations above the valley bench. NMC3 and NMC4 are downstream locations below the valley bench. DC1 is upstream of DC2.

	upstream		downstream		upstream	downstream
Month	NMC1	NMC2	NMC3	NMC4	DC1	DC2
April	-8.10E-06	-3.23E-06	2.86E-05	N/A	2.41E-05	5.88E-06
May	-1.74E-06	-3.20E-06	-1.32E-05	N/A	-2.06E-08	-1.58E-06
June	-2.89E-07	-1.45E-06	-2.89E-07	N/A	-3.36E-09	-5.09E-07
July	-5.54E-07	-5.10E-07	4.32E-06	-1.88E-05	1.80E-06	8.64E-10
August	-2.14E-07	-6.15E-09	8.32E-06	-4.42E-07	6.83E-06	4.62E-07
September	N/A	N/A	4.77E-07	N/A	-1.51E-06	3.18E-08
October	N/A	N/A	N/A	N/A	-1.72E-06	-2.82E-05

NMC1 and NMC2 show a constantly gaining stream throughout the study period. NMC3 shows a transition from a gaining stream during the spring runoff months and a losing stream during the dry summer months. NMC4 shows a gaining stream during the summer. DC1 and DC2 show a gaining stream in the spring months and a losing stream in the summer months and a gaining stream in the autumn months. Months with no data are a result of not having enough temperature data to run the vertical discharge estimate program 1DTempProV2 (Table 4). General trends of vertical fluxes match within one to two orders of magnitude with Darcy's Law of specific vertical discharge (Table III).

5.2. Surface water balance

Total discharge for North Meadow Creek changes between reaches, illustrating gaining and losing reaches between study locations (Table V). Between NMC1 and NMC2, the stream is gaining. Between NMC2 and NMC3, the stream is gaining. Between NMC3 and NMC4 the

stream is losing. Shown are the dates when all the study locations and diversions were measured in the same day (Table V).

Table V: Surface water discharge at North Meadow Creek in m³/sec. Total discharge for for NMC3 is the stream and diversions 1-6. Total discharge for for NMC4 is the stream and diversions 1-7.

Date	NMC 1	NMC 2	NMC 3; D1-D6	NMC 4;D1- D7
4/2/2017	0.39	0.39	0.63	0.36
4/8/2017	0.14	0.25	0.52	0.32
4/21/2017	0.14	0.38	0.65	0.42
5/10/2017	0.87	1.18	1.37	1.08
7/30/2017	0.65	0.76	0.87	0.68
9/9/2017	0.30	0.53	0.87	0.59

Table VI: Surface water discharge at North Meadow Creek in m³/sec.

Date	DC1	DC2
4/16/2017	0.02	0.02
4/21/2017	0.03	0.04
5/3/2017	0.02	0.01
5/10/2017	0.02	0.03
5/27/2017	0.02	0.03
6/10/2017	0.03	0.03
6/24/2017	0.02	0.02
7/30/2017	0.02	0.01
9/9/2017	0.02	0.02

Daylight Creek has a constant stream flow and there is no gaining or losing of stream water between DC1 and DC2 (Table VI).

5.3. Mixing models to determine source waters for catchment GW/SW

The precise relationship between the δD and $\delta^{18}O$ of precipitation can vary from geographic region to region. It is important to establish a local meteoric water line (LMWL) for any detailed field investigation using stable isotopes of water samples (Craig, 1961).

Figure 18: Plot of precipitation samples, $\delta D\text{‰}$ on the y-axis and $\delta^{18}O\text{‰}$ on the x-axis. The Global Meteoric Water Line is (GMWL) is plotted for reference. Snow samples are an 'x' and rain samples are green marks. Snow and rain isotope results form a Local Meteoric Water Line (LMWL).

North Meadow Creek isotope samples plot along the local meteoric water line (LMWL) established from snow and rain samples collected in the Daylight Creek area by the MBMG during this study (Figure 18). This LMWL is used for both North Meadow Creek and Daylight Creek area because the watersheds are close by and snow samples came from NMC while rain samples came from DC. This LMWL at $y = 6.6974x - 17.28$ is comparable to Gammons et al. (2006) who established a LMWL for Butte, MT at $y = 7.3227x - 7.3445$. The LMWL developed from rain and snow samples has a lesser slope than the GMWL (Craig, 1961) (Figure 18). This is due to the study area being near the center of the North American continent and is located at high elevations. As rain clouds travel from the ocean across the continent, the heavier isotopes rain out first leaving the lighter isotopes to rain out in the interior of continents. At high elevations when air masses are orographically uplifted, they cool and precipitate preferentially the heavier isotopes, leaving the lighter isotopes to be precipitated in the high elevation mountains.

Figure 19: Stream and well samples from NMC and DC are plotted with the precipitation samples. NMC samples are blue squares plotted along the LMWL. DC samples are black triangles plotted below the LMWL. The GMWL is shown for reference.

Stream and well isotope samples from both NMC and DC plot lighter along the LMWL (Figure 19). The surface and groundwater isotope samples from North Meadow Creek and Daylight Creek plot in two distinct groupings. North Meadow Creek plots along the Local Meteoric Water Line (LMWL). Daylight Creek plots below the LMWL indicating evaporation and/or a colder, higher elevation water recharge source than NMC.

Figure 20: NMC groundwater and stream isotope samples. The blue squares are stream samples and the orange circles are the well samples. The GMWL is plotted for reference.

Figure 20 illustrates that the groundwater samples plot slightly lighter and in a tighter grouping than the stream samples. Mixing between the stream and the shallow subsurface is occurring shown by the overlapping grouping of stream and groundwater samples.

Figure 21: Daylight Creek groundwater and stream isotope samples. The blue squares are stream samples and the orange circles are the well samples. The GMWL is plotted for reference.

Figure 21 illustrates that the stream samples are lighter than the groundwater samples and that the stream and groundwater are from the same source shown by the overlapping of each grouping. This trend is apparent for all of NMC sites, see appendix E for complete isotope and Sc data.

Figure 22: NMC Sc seasonal trend. Specific conductivity is on the y-axis and the date when samples were collected on the x-axis. A third-order polynomial trend line is applied to the data. Sc ranges from 50 -270 $\mu\text{S}/\text{cm}$.

North Meadow Creek exhibits a specific conductivity seasonal trend. During spring runoff, high melt rates are the cause for the drop in Sc during April and May suggesting fresh snowmelt with lower Sc. (Figure 22).

Figure 23: NMC $\delta^{18}\text{O}$ seasonal trends. $\delta^{18}\text{O}$ ‰ is on the y-axis and the date when samples were collected on the x-axis. A third-order polynomial trend line is applied to the data. $\delta^{18}\text{O}$ ‰ ranges from -17.5 to -18.5‰.

North Meadow Creek exhibits a trend of $\delta^{18}\text{O}$ shows some enrichment during the summer from warmer temperatures and a depression in the fall from September snowstorms (Figure 23).

Figure 24: DC Sc and seasonal trend. Specific conductivity is on the y-axis and the date when samples were collected on the x-axis. A third-order polynomial trend line is applied to the data. Sc ranges from 340 - 460 $\mu\text{S/cm}$.

Figure 25: DC $\delta^{18}\text{O}$ seasonal trends. $\delta^{18}\text{O}\text{‰}$ is on the y-axis and the date when samples were collected on the x-axis. A third-order polynomial trend line is applied to the data. $\delta^{18}\text{O}\text{‰}$ ranges from -18.1 to -18.7‰.

Figure 24 shows that Daylight Creek show no seasonal trend. Spring creeks usually have consistent water chemistry if the flow is from non-fractured bedrock. DC2 exhibits similar results.

Figure 26: North Meadow Creek $\delta^{18}\text{O}$ vs Sc three-component model, groundwater, rain, and snow. End-members (EM) were chosen to encompass most of the stream and well data.

Figure 27: Daylight Creek $\delta^{18}\text{O}$ vs Sc three-component model, groundwater, rain, and snow. End-members (EM) were chosen to encompass most of the stream and well data.

5.4. Mixing Models

A three-component mixing model (Figures 26 and 27) separates groundwater, snow, and rain end-members. Rain and snow end-members were chosen based on the furthest value out on the triangle. Groundwater end-member was chosen from a single deep well sample. After reviewing the mixing model data, it has come to the attention that the rain and snow are not the true end-members. The $\delta^{18}\text{O}$ for rain and snow are different but the Sc is similar indicating a different end-member. All the surface and groundwater samples trend to be a line. When the rain and snow end-member $\delta^{18}\text{O}$ samples are averaged, they fall along the trend line. A simpler approach would be a two-member mixing model (Figures 28 and 29) where the end-members rain and snow are combined and averaged to become soil water as one end-member and groundwater as the other end-member. The $\delta^{18}\text{O}$ data for the stream and well samples are close together between -18‰ and -19‰ while the Sc is a range from 250 – 800 $\mu\text{S}/\text{cm}$. Rain and snow may not be true end-members, but shallow soil water consisting of mixtures of rain and snow. This would make a two-component mixing model based on Sc since the Sc of rain and snow is essentially the same. This study will present results of both three and two component mixing models.

Figure 28: North Meadow Creek $\delta^{18}\text{O}$ vs Sc two-component model groundwater and soil water. The soil-water endmember is an average of the rain and snow samples.

Figure 29: Daylight Creek $\delta^{18}\text{O}$ vs Sc two-component model groundwater and soil water. The soil-water endmember is an average of the rain and snow samples.

Sc and $\delta^{18}\text{O}$ were used in three-member and two-member mixing analysis to determine source waters of North Meadow Creek and Daylight Creek. Equations 8-18 results in fractions of each end-member plotted in Figures 31 and 33. Rain and snow $\delta^{18}\text{O}\text{‰}$ and Sc were averaged to create the soil water end-member. At NMC, the stream and well samples plot closer to the soil water end-member than the groundwater end-member. At DC the stream plots closer to the soil water end-member while the well samples range from groundwater to soil water.

Figure 30: Fractionation of three end-members groundwater (EM1), rain (EM2), and snow (EM3) at North Meadow Creek. The fraction of the end-members is on the y-axis and the date is on the x-axis.

The three-component mixing model shows the groundwater end-member with a decline during the spring and steadily increases through the summer and fall (Figure 30). The downstream locations (NMC3, NMC4) have a much larger fraction of groundwater than the upstream locations (NMC1, NMC2). The rain end-member shows an increase during the spring, than all locations converge at about 30% by late summer (Figure 30). The snow end-member has a consistent high fraction in the upstream locations and a low fraction in the downstream locations (Figure 30). See appendix H for complete end-member mixing data.

There was little to no precipitation in the form of rain or snow during July and August, yet the three member mixing model shows 30%-40% fraction of rain and upwards of 45% snow during those months. Shallow subsurface residence time could explain the snow-like signature shown in upstream locations NMC1 and NMC2 during late summer.

Figure 31: Fractionation of two end-members groundwater (EM1) and soil water (EM2) at North Meadow Creek. The fraction of the end-members is on the y-axis and the date is on the x-axis.

The two-component mixing model (Figure 31) has the groundwater end-member at 30%-50% during early spring. During the spring melt, there is a small fraction of groundwater and a large fraction of soil water, which is the previous winters snowpack entering the stream (Figure 31). The soil water fraction stays at about 70% or more in the upstream locations. The downstream locations have a higher groundwater fraction 35-65% than the upstream locations

10-30% during the late summer months. This two-component model shows a similar trend as the three-component model.

Figure 32: Fractionation of three end-members groundwater (EM1), rain (EM2), and snow (EM3) at Daylight Creek. The fraction of the end-members is on the y-axis and the date is on the x-axis.

The three-component mixing model for Daylight Creek (Figure 32) has the groundwater end-member at 35%-50%. During the snowmelt period usually May through June, when there is frequent rain, the rain end-member is at 40% and the snow end-member is down to 15%-20%. During the months of July and August there was very little precipitation but this mixing model is showing 25% snow and 35% rain.

Figure 33: Fractionation of two end-members groundwater (EM1) and soil water (EM2) at Daylight Creek. The fraction of the end-members is on the y-axis and the date is on the x-axis.

The two-component mixing model of Daylight Creek (Figure 33) has a consistent mix between the two end-members, groundwater, and soil water. Daylight Creek is a spring fed creek where during the summer months all of its flow originates from springs. A constant mix validates a spring fed stream with little to no inputs from snow melt in lower elevations. Both the three-component and two-component model show similar groundwater patterns.

5.5. Discharge based on source

Discharge components are calculated by multiplying the fractions of each endmember by the total discharge from manual measurements. At North Meadow Creek, irrigation diversions are between NMC2 and NMC3. Flow is greatly reduced from the diversions and at NMC4 removes all the flow from the stream in the month of August (Figure 34).

Figure 34: Three-component discharge at North Meadow Creek. The fractionation of the end-members rain (EM1), snow (EM2), and groundwater (EM3) are multiplied by the monthly stream discharge.

Figure 35: Two-component discharge at North Meadow Creek. The fractionation of the end-members soil-water (EM1) and groundwater (EM2) are multiplied by the monthly stream discharge.

The two-component discharge at North Meadow Creek (Figure 35) shows that groundwater is a steady contributor throughout the year. The soil water has a spring melt pulse that gradually tapers off in the summer months, indicating a 1-3 month travel time and a slower melt of high elevation snowfields. Similar to the three-component discharge (Figure 34), the two-component discharge (Figure 35) has a soil water discharge in the upper reaches and a groundwater discharge in the lower reaches.

Figure 36: Three-component discharge at Daylight Creek. The fractionation of the end-members rain (EM1), snow (EM2), and groundwater (EM3) are multiplied by the monthly stream discharge.

Figure 37: Two-component discharge at Daylight Creek. The fractionation of the end-members soil-water (EM1) and groundwater (EM2) are multiplied by the monthly stream discharge.

The two and three component discharge (Figures 36 and 37) shows that groundwater is 30% of the total flow. Discharge is constant with a slight decrease in late summer.

Figure 38: validation of end-members on NMC2. The model predicted values are on the y-axis and the observed values are on the x-axis. The observed vs predicted values are near a 1:1 relationship.

Validation of both two and three component mixing models was performed using a third independent tracer, δD . The tracers of the end-members $\delta^{18}O$ and Sc were used to predict δD values. Those predicted δD values were plotted vs the observed sample δD values. The results of are near the 1:1 line with R^2 values at 0.94. Both the two and three component models can be validated with these results. In addition, the groundwater results of the three and two component mixing are similar. Therefore, the three component mixing model may not be the best, and the two component mixing model would be best to characterize catchment processes, but both models support each other. See appendix H for complete end member mixing data and validation.

6. Summary

6.1. Vertical GW/SW fluxes for recharge/discharge (RS).

The physical hydraulic properties of the streams, wells, and sediments permit groundwater flux estimates using the Darcy equation (equation 4). North Meadow Creek has a high hydraulic conductivity (Table II) and groundwater fluxes vary through the season (Table III & IV). At NMC2 the stream transitions from point A to point B (Figure 3). This reach has groundwater gaining until after B where the stream transitions to a constant losing reach. Daylight Creek has a low hydraulic conductivity (Table II) and groundwater fluxes stay relatively constant (Table III & IV).

Observations of changes in groundwater temperature profiles enabled an estimate of downward and upward fluxes (Table IV). The Darcy fluxes also provide estimates of groundwater fluxes and compliment the temperature results (Table III). The temperature profiles reveal that North Meadow Creek is a stream that has a snowmelt runoff with gaining and losing segments transitioning throughout the study. In April, the gaining section of the stream ends at NMC2 and transitions to a losing stream by NMC3. During snowmelt runoff, May through June, the gaining section pulses downstream to NMC3. In July through October, the gaining reaches recedes upstream to NMC2, and NMC3 transitions back to a losing stream. At Daylight Creek the flux estimates are small magnitude and do not change through the season. Daylight Creek is a losing stream throughout the study.

The specific vertical discharge estimates from the temperature profiles (Table 4) match close to the estimates from the Darcy equation (Table 3). The flux estimates are within one to two orders of magnitude and agree on direction of either upward or downward groundwater flow.

The surface water balance reveals that North Meadow Creek is a gaining stream between NMC1 and NMC3 and a losing stream between NMC3 and NMC4 (Table V). At NMC3, this location is not losing during the entire study and the reach above NMC3 may be only partially gaining during the wet months of May and June and losing during the dry months of July, August, and September. This reinforces the GW/SW fluxes the Darcy and temperature profile methods.

6.2. Mixing models to determine source waters for catchment GW/SW.

The relative fraction of groundwater in North Meadow Creek is 10-30% during the snowmelt runoff and 25-65% during the late summer months when the creek is near base flow (Figure 31). Identification and characterization of water sources to North Meadow Creek and Daylight Creek and water mixing in these watersheds are addressed by examining variations of specific conductivity (Figures 26-29). These mixing fractions show that groundwater is similar in both three-member and two-member mixing models (Figures 30-33). In the months of July and August a precipitation signature is seen even though there was very little rain events during those months (Figures 30 & 32). This signature may be incorrectly assigned to precipitation end-members (rain and snow). Soil water is the shallow near-surface water entering the streams. This soil water has a short residence time and is younger than the groundwater end-member. The water samples do not show a variation with $\delta^{18}\text{O}$ as much as Sc between precipitation and groundwater (Figures 31 & 33). The soil water is water directly flowing from the spring into the creek, not collecting many salts from the soils and having a low specific conductivity. The groundwater is underground seeps that are in contact with the soils and are increasing specific conductivity.

6.3. Stream Processes

North Meadow Creek is a stream with gaining and losing segments that cycle through the year. Early spring the gaining section of the stream ends at NMC2 and transitions to a losing stream by NMC3. During spring runoff the gaining section pulses downstream to NMC3. After the spring runoff and through the summer the gaining section recedes upstream to NMC2 and NMC3 transitions back to a losing stream. The relative fraction of groundwater in North Meadow Creek is low during the spring runoff and high during the late summer months. In the months of July and August shallow near-surface water dominates the upstream sections at NMC2 and NMC1 while groundwater dominates the lower stream sections of NMC3 and NMC4. The bedrock is fractured and has weathered to sandy/gravelly alluvium in the stream valley resulting in a good connection between groundwater and surface water. This enhanced groundwater underflow and stream connectivity is shown with a gaining reach in the high elevations. As the stream flows out of the mountains it becomes a losing reach as seen in both the Darcy and temperature flux estimates (Tables 3 and 4).

NMC1 and NMC2 show a constantly gaining stream throughout the study period. NMC3 shows a transition from a gaining stream during the spring runoff months and a losing stream during the dry summer months. NMC4 shows a losing stream during the summer. Shallow subsurface residence time could explain the snow-like signature shown in upstream locations NMC1 and NMC2 during late summer. The source of the water is from high elevation mountains and is mostly meteoric and does not have an evaporation signal (Figure 20).

Daylight Creek is a spring creek with little to no variation in stream flow or stream chemistry. The surface geology of Daylight Creek is volcanic tuff weathered to clays; this clay has poor hydraulic conductivity 2^{-7} m/s (Table II) and may be a losing and disconnected stream.

Isotope samples show the source of the spring is snowmelt from high elevations. At the high elevation there is a permeable layer of bedrock (Table 1), where the source water enters the ground. At lower elevations, the volcanic tuff weathers into clay and becomes unsTable resulting in landslides that dominate the topography. Groundwater flow must be blocked and springs emerge from past landslides that form Daylight Creek.

During the summer months there is no snowpack or much rainfall, therefore all of the stream flow originates from springs. The source of water for the springs comes from a higher elevation than the lower elevation watershed (Figure 21). The soil water could be the water directly flowing from the spring into the creek, collecting many salts from the soils and having a low specific conductivity, while the groundwater can be underground seeps that are in contact with the soils and are collecting more dissolved constituents while moving through the soil profile.

7. Conclusion

Isotope and water chemistry analysis indicate that direct infiltration by precipitation and mountain front recharge are the two main recharge sources in the study area. End-member mixing analysis using stable isotopes and specific conductivity as tracers was shown useful for estimating the contribution of the different recharge sources.

Local and regional geology of the catchment might have the largest control on the timing and amount of groundwater that contributes to streamflow in North Meadow Creek and Daylight Creek. The use of $\delta^{18}\text{O}$, δD , Sc , and temperature as environmental tracers in groundwater and surface water in North Meadow Creek and Daylight Creek drainages provide a good method for characterizing how precipitation and groundwater partitions through mountain catchments. These tracers reveal complex spatial and temporal mixing between recent precipitation and deeper groundwater.

7.1. Future research

Further research would include water sampling at spring locations and along both mountain ranges to the south and north of Daylight Creek to determine source waters for the springs. Water sampling at smaller tributaries and more rain and snow sampling within the higher elevations at North Meadow Creek would establish a more accurate mixing model. Geophysical methods to determine the cross sections of the stream valleys such as electrical resistivity can better estimate the surface to bedrock depth and can be used with the Darcy equation to determine groundwater underflow (FS). Residential wells within each drainage should be sampled and have their water level monitored to get a better understanding of the groundwater processes.

These methods are inexpensive, easy to implement and can be reproduced in other mountain catchments providing a useful contribution by demonstrating methods to improve the understanding of groundwater dynamics within the mountain front.

Mountain Front Recharge is an important component of the basin groundwater balance in a semi-arid area. Improving the understanding and estimation of MFR is critical for effective basin water management.

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9. Appendix A: Well logs

North Meadow Creek							
GWIC id	latitude	longitude		GWIC id	latitude	longitude	
125136	45.44	-111.71		153479	45.29	-111.93	
	from (m)	to (m)	description		from (m)	to (m)	description
	0	6.1	cobblestone		0	2.4	clay bedrock
	6.1	24.4	sand & gravel		2.4	3.1	bedrock
	24.4	42.7	sand & gravel				
GWIC id	latitude	longitude		GWIC id	latitude	longitude	
135218	45.52	-111.84		153479	45.29	-111.93	
	from (m)	to (m)	description		from (m)	to (m)	description
	0	0.9	topsoil		0	0.9	topsoil
	0.9	9.1	granite boulders		0.9	28.9	boulders
	9.1	92.6	granite		28.9	51.2	granite
GWIC id	latitude	longitude		GWIC id	latitude	longitude	
195839	45.44	-111.73		197618	45.51	-111.82	
	from (m)	to (m)	description		from (m)	to (m)	description
	0	0.6	topsoil		0	0.9	topsoil
	0.6	3	sand		0.9	6.4	gravel sand
	3	22.8	grey clay		6.4	48.8	granite
	22.8	24.4	gravel				
GWIC id	latitude	longitude		GWIC id	latitude	longitude	
276809	45.46	-111.76		290425	45.43	-111.78	
	from (m)	to (m)	description		from (m)	to (m)	description
	0	1.5	topsoil		0	1.8	sand & gravel
	1.5	17.7	gravel		1.8	6.7	sand & gravel
					6.7	15.2	clay
					15.2	22.8	soft sandstone
					22.8	27.4	hard sandstone

Appendix B: Equations

9.1. Slug and permeameter

$$K = \frac{r^2 \ln \frac{L}{R}}{2 * L * T_0} \quad (1)$$

$$K_s = [(0.0041)(R_c)(R_2)] - [(0.0054)(R_c)(R_1)] \quad (2)$$

9.2. Isotope and end member mixing model

$$\delta^2H = 8\delta^{18}O + 10\text{‰} \quad (3)$$

$$\Delta^{18}O_{\text{sample}} = [(R_{\text{sample}}/R_{\text{VSMOW}}) - 1] \times 10^3 \quad (4)$$

$$F_1 + F_2 + F_3 = 1 \quad (5)$$

$$A_1F_1 + A_2F_2 + A_3F_3 = A_s \quad (6)$$

$$B_1F_1 + B_2F_2 + B_3F_3 = B_s \quad (7)$$

$$D = \begin{bmatrix} 1 & 1 & 1 \\ A_1 & A_2 & A_3 \\ B_1 & B_2 & B_3 \end{bmatrix} \quad (8)$$

$$|D| = -A_2B_1 + A_3B_1 + A_1B_2 - A_3B_2 - A_1B_3 - A_2B_3 \quad (9)$$

$$F_1 = \frac{1}{|D|} [(A_2B_3 - A_3B_2) + (B_2 - B_3)A_s + (A_3 - A_2)B_s] \quad (10)$$

$$F_2 = \frac{1}{|D|} [(A_3 B_1 - A_1 B_3) + (B_3 - B_1) A_s + (A_1 - A_3) B_s] \quad (11)$$

$$F_3 = \frac{1}{|D|} [(A_1 B_2 - A_2 B_1) + (B_1 - B_2) A_s + (A_2 - A_1) B_s] \quad (12)$$

$$F_1 + F_2 = 1 \quad (13)$$

$$F_1 = (C_s - C_2) / (C_1 - C_2) * 100 \quad (14)$$

site	K
	m/s
NMC1	1.6E-04
NMC2	1.6E-04
NMC3	2.2E-05
NMC4	2.2E-05
DC1	2.1E-07
DC2	2.1E-07

9/9/2017					
site	q	k	dh/dl	dl	dh
	m/s	m/s			
NMC1	1.4E-05	1.6E-04	-0.085918854	4.19	-0.36
NMC2	6.5E-05	1.6E-04	-0.408163265	5.39	-2.2
NMC3	3.7E-06	2.2E-05	-0.168975069	3.61	-0.61
NMC4	4.3E-06	2.2E-05	-0.195180723	4.15	-0.81
DC1	4.4E-08	2.1E-07	-0.21021021	3.33	-0.7
DC2	-3.3E-08	2.1E-07	0.159178434	7.79	1.24
5/3/2017					
site	q	k	dh/dl	dl	dh
	m/s	m/s			
NMC1	-4.2E-06	0.00016	0.026252983	4.19	0.11
NMC2	6.9E-05	0.00016	-0.432282004	5.39	-2.33
NMC3	3.2E-06	0.000022	-0.144044321	3.61	-0.52
NMC4	-2.2E-05	0.000022	0.997590361	4.15	4.14
DC1	-5.4E-08	0.00000021	0.258258258	3.33	0.86
DC2	-2.4E-08	0.00000021	0.114249037	7.79	0.89
7/30/2017					
site	q	k	dh/dl	dl	dh
	m/s	m/s			
NMC1	1.6E-05	0.00016	-0.097852029	4.19	-0.41
NMC2	6.7E-05	0.00016	-0.419294991	5.39	-2.26
NMC3	3.8E-06	0.000022	-0.171745152	3.61	-0.62
NMC4	1.5E-06	0.000022	-0.06746988	4.15	-0.28
DC1	-6.3E-08	0.00000021	0.3003003	3.33	1
DC2	-3.7E-08	0.00000021	0.175866496	7.79	1.37
10/5/2017					
site	q	k	dh/dl	dl	dh
	m/s	m/s			
NMC1	1.3E-05	0.00016	-0.08353222	4.19	-0.35
NMC2	6.4E-05	0.00016	-0.400742115	5.39	-2.16
NMC3	4.4E-06	0.000022	-0.199445983	3.61	-0.72
NMC4	1.3E-06	0.000022	-0.057831325	4.15	-0.24
DC1	-1E-08	0.00000021	0.048048048	3.33	0.16
DC2	-2.5E-08	0.00000021	0.118100128	7.79	0.92
11/3/2017					
site	q	k	dh/dl	dl	dh
	m/s	m/s			
NMC1	1.2E-05	0.00016	-0.07398568	4.19	-0.31
NMC2	6.5E-05	0.00016	-0.40445269	5.39	-2.18
NMC3	4E-06	0.000022	-0.180055402	3.61	-0.65
NMC4	-7.4E-07	0.000022	0.03373494	4.15	0.14
DC1	6.3E-10	0.00000021	-0.003003003	3.33	-0.01
DC2	-2.2E-08	0.00000021	0.105263158	7.79	0.82

site:DC2	8/14/2017	depth of well: 32cm	combined reservoir				
R1 reading #	time (min)	time interval (min)	water level (cm)	water level change (cm)			
1	0	1	0				
2	1	1	0.5	0.5			
3	2	1	1.5	1			
4	3	1	2.3	0.8			
5	4	1	3	0.7			
6	5	1	3.7	0.7			
7	6	1	4.4	0.7			
8	7	1	5	0.6			
9	8	1	5.7	0.7			
R1(cm/s)		0.001166667					
R2 reading #	time (min)	time interval (min)	water level (cm)	water level change (cm)			
1	0	1	6.7				
2	1	1	7.5	0.8			
3	2	1	9.5	2			
4	3	1	11.5	2			
5	4	1	13.5	2			
6	5	1	15.3	1.8			
7	6	1	16.6	1.3			
8	7	1	18.4	1.8			
9	8	1	20.3	1.9			
10	9	1	22	1.7			
11	10	1	24	2			
12	11	1	25.6	1.6			
13	12	1	27.2	1.6			
14	13	1	28.7	1.5			
15	14	1	30.5	1.8			
R2(cm/s)		0.0029			K	0.00019688 cm/s	
						1.9688E-06 m/s	
						0.170104147 m/d	

site: NMC1	8/12/2017	depth of well: 25cm	combined reservoir	
R1 reading #	time (min)	time interval (min)	water level (cm)	water level change (cm)
1	0	1	0	
2	1	1	1	1
3	2	1	2	1
4	3	1	5.5	3.5
5	4	1	8.1	2.6
6	5	1	11	2.9
7	6	1	14.2	3.2
8	7	1	17	2.8
9	8	1	20.1	3.1
10	9	1	23	2.9
11	10	1	26.1	3.1
			average	3
	R1 (cm/min)	0.05000		
R2 reading #	time (min)	time interval (min)	water level (cm)	water level change (cm)
1	0	1	28.5	
2	1	1	35	6.5
3	2	1	49.5	14.5
4	3	1	68.5	19
refilled				
1	0	1	0	
2	1	1	6	6
3	2	1	13	7
4	3	1	28	15
5	4	1	42.5	14.5
6	5	1	60	17.5
7	6	1	74	14
			average	15.25
	R2 (cm/min)	0.25417		

site: NMC3	8/12/2017	depth of well: 15cm	combined reservoir	
R1 reading #	time (min)	time interval (min)	water level (cm)	water level change (cm)
1	0	1	0	
2	1	1	0.5	0.5
3	2	1	1.4	0.9
4	3	1	1.7	0.3
5	4	1	2.1	0.4
6	5	1	2.5	0.4
7	6	1	3	0.5
8	7	1	3.4	0.4
9	8	1	3.8	0.4
	R1 (cm/min)	0.00667		
R2 reading #	time (min)	time interval (min)	water level (cm)	water level change (cm)
1	0	1	4.5	
2	1	1	5	0.5
3	2	1	5.5	0.5
4	3	1	6	0.5
5	4	1	6.5	0.5
	R2 (cm/min)	0.00833		

Appendix D: Temperature profiles

NMC1-4; DC1,2

Appendix E: Isotope and Specific conductivity results

MBMG North Meadow Creek					Lab Sc 12/1/17
Sample ID	$\delta^{18}\text{O}$	$\delta^2\text{H}$	Location	Date	Scp S/cm
SHAMA-1	-18.3	-141	NMC 4	5/23/2017	130
SHAMA-2	-18.3	-140	NMC 3	5/23/2017	130
SHAMA-3	-18.3	-139	NMC 2	5/23/2017	77
SHAMA-4	-18.2	-139	NMC 1	5/23/2017	59
SHAMA-7	-18.2	-140	NMC 4 well	5/23/2017	137
SHAMA-8	-18.6	-142	NMC 3 well	5/23/2017	173
SHAMA-9	-18.6	-143	NMC 2 well	5/23/2017	145
SHAMA-10	-18.2	-139	NMC 1 well	5/23/2017	121
SHAMA-13	-18.2	-141	NMC 4 well	5/3/2017	209
SHAMA-14	-18.5	-142	NMC 3 well	5/3/2017	212
SHAMA-15	-18.5	-143	NMC 2 well	5/3/2017	160
SHAMA-16	-18.3	-141	NMC 1 well	5/3/2017	126
SHAMA-19	-18.3	-141	NMC 4	5/3/2017	175
SHAMA-20	-18.3	-141	NMC 3	5/3/2017	182
SHAMA-21	-18.3	-141	NMC 2	5/3/2017	126
SHAMA-22	-18.5	-141	NMC 1	5/3/2017	123
SHAMA-25	-18.4	-140	NMC 4	5/10/2017	167
SHAMA-26	-18.5	-140	NMC 3	5/10/2017	137
SHAMA-27	-18.4	-140	NMC 2	5/10/2017	115
SHAMA-28	-18.2	-139	NMC 1	5/10/2017	103
SHAMA-31	-18.3	-142	NMC 4	4/21/2017	
SHAMA-32	-18.3	-141	NMC 3	4/21/2017	145
SHAMA-33	-18.3	-141	NMC 2	4/21/2017	161
SHAMA-34	-18.3	-140	NMC 1	4/21/2017	121
SHAMA-41	-18.4	-142	NMC 1	3/28/2017	126
SHAMA-42	-18.4	-141	NMC 2	3/28/2017	136
SHAMA-43	-18.3	-141	NMC 3	3/28/2017	146
SHAMA-44	-18.4	-142	NMC 4	3/28/2017	160
3	-18.1	-136	NMC 1	6/10/2017	61
4	-17.6	-135	NMC 2	6/10/2017	62
5	-18.1	-136	NMC 3	6/10/2017	69
6	-17.9	-136	NMC 4	6/10/2017	83
11	-18.2	-137	NMC 1	7/29/2017	100
13	-18.2	-137	NMC 2	7/29/2017	95
15	-18.2	-138	NMC 3	7/29/2017	197
17	-18.1	-137	NMC 4	7/29/2017	205
12	-18.2	-136	NMC 1 well	7/29/2017	106
14	-18.6	-141	NMC 2 well	7/29/2017	146
16	-18.5	-140	NMC 3 well	7/29/2017	129
18	-18.0	-137	NMC 4 well	7/29/2017	105
19	-18.0	-136	NMC 1	8/11/2017	138
22	-18.1	-138	NMC 2	8/11/2017	112
24	-15.6	-131	NMC 3	8/11/2017	274
23	-18.6	-141	NMC 2 well	8/11/2017	181
25	-18.4	-139	NMC 3 well	8/11/2017	
30	-18.3	-138	NMC 1	9/9/2017	113
32	-18.2	-138	NMC 2	9/9/2017	123
34	-18.2	-139	NMC 3	9/9/2017	212
36	-18.2	-138	NMC 4	9/9/2017	216
31	-18.3	-137	NMC 1 well	9/9/2017	121
33	-18.6	-142	NMC 2 well	9/9/2017	156
35	-18.4	-140	NMC 3 well	9/9/2017	187
37	-18.0	-137	NMC 4 well	9/9/2017	207
CS_10	-18.3	-138	NMC 1 well	10/5/2017	117
CS_11	-18.2	-139	NMC 1	10/5/2017	107
CS_12	-16.8	-131	NMC 2 well	10/5/2017	40
CS_13	-18.1	-139	NMC 3 well	10/5/2017	234
CS_14	-18.2	-139	NMC 3	10/5/2017	220
CS_15	-18.0	-137	NMC 4 well	10/5/2017	199
CS_16	-17.4	-138	NMC 4	10/5/2017	228
CS_5	-18.2	-139	NMC 1	11/3/2017	116
CS_6	-18.2	-139	NMC 2	11/3/2017	131
CS_7	-18.2	-139	NMC 3	11/3/2017	172
CS_8	-18.2	-139	NMC 4	11/3/2017	182

MBMG Daylight Creek					lab Sc 12/1/17
Sample ID	$\delta^{18}\text{O}$	$\delta^2\text{H}$	Location	Date	Sc $\mu\text{S/cm}$
SHAMA-5	-18.4	-145	VC 2	5/23/2017	451
SHAMA-6	-18.5	-146	VC 1	5/23/2017	356
SHAMA-11	-18.5	-145	VC 2 well	5/23/2017	800
SHAMA-12	-18.4	-146	VC 1 well	5/23/2017	500
SHAMA-17	-18.4	-145	VC 2 well	5/3/2017	893
SHAMA-18	-18.4	-145	VC 1 well	5/3/2017	630
SHAMA-23	-18.7	-146	VC 2	5/3/2017	458
SHAMA-24	-18.6	-146	VC 1	5/3/2017	455
SHAMA-29	-18.6	-147	VC 2	5/10/2017	445
SHAMA-30	-18.7	-147	VC 1	5/10/2017	390
SHAMA-35	-18.5	-146	VC 2	4/21/2017	460
SHAMA-36	-18.7	-147	VC 1	4/21/2017	408
SHAMA-37	-18.5	-146	VC 2	4/16/2017	466
SHAMA-38	-18.5	-147	VC 1	4/16/2017	403
1	-18.3	-142	VC 1	6/10/2017	379
2	-18.1	-140	VC 2	6/10/2017	410
7	-18.5	-145	VC 1	7/29/2017	350
8	-18.4	-144	VC 1 well	7/29/2017	430
9	-18.5	-144	VC 2	7/29/2017	401
10	-18.3	-143	VC 2 well	7/29/2017	576
20	-18.6	-145	VC 2	8/11/2017	370
21	-18.5	-143	VC 2 well	8/11/2017	754
26	-18.5	-145	VC 1	9/9/2017	345
27	-18.4	-144	VC 1 well	9/9/2017	321
28	-18.6	-145	VC 2	9/9/2017	409
29	-18.4	-143	VC 2 well	9/9/2017	680
CS_17	-17.9	-143	VC 1 well	10/5/2017	364
CS_18	-18.6	-146	VC 1	10/5/2017	386
CS_19	-18.2	-143	VC 2 well	10/5/2017	690
CS_20	-18.5	-145	VC 2	10/5/2017	415
CS_3	-18.5	-146	VC 1	11/3/2017	354
CS_4	-18.6	-146	VC 2	11/3/2017	382
CS_9	-18.2	-139	VC 2	11/3/2017	

Precip at Upper Northmeadow Creek				lab Sc 12/1/17	
Sample ID	$\delta^{18}\text{O}$	$\delta^2\text{H}$	Location	Date	Sc $\mu\text{S/cm}$
SHAMA-39	-21.9	-170	SNOW	3/28/2017	33
SHAMA-40	-22.0	-170	SNOW	3/28/2017	52
CS_2	-19.4	-143	NMC 1 snow	11/3/2017	29
CS_1	-19.4	-143	VC 1 snow	11/3/2017	42
MBMG Precip at Virginia City upper gauge					
Sample ID	$\delta^{18}\text{O}$	$\delta^2\text{H}$	Location	Mean Date	Sc $\mu\text{S/cm}$
	-18.2	-140	upper	4/18/2017	39.00
	-14.9	-112	upper	5/17/2017	39.00
	-16.4	-124	upper	6/16/2017	39.00
	-8.9	-65	upper	7/16/2017	39.00
	-13.1	-116	upper	8/16/2017	39.00
	-19.9	-150	upper	9/16/2017	39.00
	-17	-127	upper	10/16/2017	39.00
MBMG Precip at Virginia City lower gauge					
Sample ID	$\delta^{18}\text{O}$	$\delta^2\text{H}$	Location	Mean Date	Sc $\mu\text{S/cm}$
	-18.7	-147	lower	3/17/2017	39.00
	-17.5	-134	lower	4/16/2017	39.00
	-13.5	-101	lower	5/17/2017	39.00
	-12.1	-93	lower	6/16/2017	39.00
	-3.3	-49	lower	7/16/2017	39.00
	-12.4	-105	lower	8/16/2017	39.00
	-16.3	-127	lower	9/16/2017	39.00
	-16	-128	lower	10/16/2017	39.00
MBMG madison valley ennis gravel pit shallow well					
$\delta^{18}\text{O}$	$\delta^2\text{H}$	Sc $\mu\text{S/cm}$			
-18.752	-137.73	307

Appendix F: Endmember mixing results

Definition of symbols									
As = the sample concentration for tracer A									
Bs = the sample concentration for tracer B									
A1 = The 1st endmember concentration of tracer A									
B1 = The 1st endmember concentration of tracer B									
A2 = The 2nd endmember concentration of tracer A									
B2 = The 2nd endmember concentration of tracer B									
A3 = The 3rd endmember concentration of tracer A									
B3 = The 3rd endmember concentration of tracer B									
f1 = the fraction of the 1st endmember in the sample									
f2 = the fraction of the 2nd endmember in the sample									
f3 = the fraction of the 3rd endmember in the sample									
C1 = The chemistry value of the first endmember for a solute not used in the Endmember mixing analysis									
C2 = The chemistry value of the second endmember for a solute not used in the Endmember mixing analysis									
C3 = The chemistry value of the third endmember for a solute not used in the Endmember mixing analysis									
Cobserved = the observed value of tracer C for the sample									
Cpredicted = the predicted value of tracer C for the given sample									

NMC1 3 component

Sample ID	Sample Date	As		Bs		A1		B1		A2		B2		A3		B3		[D]	f		
		$\delta^{18}\text{O}$	Sc uS/cm	$\delta^{18}\text{O}$	Sc uS/cm	$\delta^{18}\text{O}$	Sc uS/cm	$\delta^{18}\text{O}$	Sc uS/cm	$\delta^{18}\text{O}$	Sc uS/cm	$\delta^{18}\text{O}$	Sc uS/cm	$\delta^{18}\text{O}$	Sc uS/cm	$\delta^{18}\text{O}$	Sc uS/cm		GW	rain	snow
SHAMA-4	5/23/2017	-18.2	59	-18.2	121	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.075	0.379	0.546						
SHAMA-10	5/23/2017	-18.2	121	-18.2	121	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.306	0.310	0.384						
SHAMA-16	5/3/2017	-18.3	126	-18.3	126	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.325	0.286	0.390						
SHAMA-22	5/3/2017	-18.5	123	-18.5	123	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.313	0.257	0.429						
SHAMA-28	5/10/2017	-18.2	103	-18.2	103	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.239	0.324	0.437						
SHAMA-34	4/21/2017	-18.3	121	-18.3	121	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.306	0.291	0.403						
SHAMA-41	3/28/2017	-18.4	126	-18.4	126	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.325	0.263	0.412						
3	6/10/2017	-18.1	61	-18.1	61	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.082	0.390	0.528						
11	7/29/2017	-18.2	100	-18.2	100	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.228	0.338	0.434						
12	7/29/2017	-18.2	106	-18.2	106	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.250	0.325	0.425						
19	8/11/2017	-18.0	138	-18.0	138	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.369	0.316	0.315						
30	9/9/2017	-18.3	113	-18.3	113	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.276	0.296	0.428						
31	9/9/2017	-18.3	121	-18.3	121	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.306	0.299	0.396						
CS_10	10/5/2017	-18.3	117	-18.3	117	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.291	0.303	0.406						
CS_11	10/5/2017	-18.2	107	-18.2	107	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.254	0.316	0.430						
CS_5	11/3/2017	-18.2	116	-18.2	116	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.287	0.311	0.402						

C1	C2	C3	f1*C1	f2*C2	f3*C3	Cobserved	Cpredicted
-137.7	-114.5	-156.0	-10.276	-43.420	-85.201	-138.9	-138.9
-137.7	-114.5	-156.0	-42.132	-35.454	-59.964	-142.9	-137.6
-137.7	-114.5	-156.0	-44.701	-32.720	-60.779	-142.7	-138.2
-137.7	-114.5	-156.0	-43.160	-29.443	-66.990	-140.7	-139.6
-137.7	-114.5	-156.0	-32.884	-37.145	-68.139	-139.5	-138.2
-137.7	-114.5	-156.0	-42.132	-33.345	-62.838	-140.7	-138.3
-137.7	-114.5	-156.0	-44.701	-30.141	-64.293	-141.4	-139.1
-137.7	-114.5	-156.0	-11.304	-44.610	-82.416	-134.8	-138.3
-137.7	-114.5	-156.0	-31.342	-38.724	-67.733	-136.8	-137.8
-137.7	-114.5	-156.0	-34.425	-37.254	-66.243	-141.2	-137.9
-137.7	-114.5	-156.0	-50.867	-36.128	-49.151	-137.5	-136.1
-137.7	-114.5	-156.0	-38.022	-33.873	-66.775	-140.8	-138.7
-137.7	-114.5	-156.0	-42.132	-34.181	-61.699	-138.3	-138.0
-137.7	-114.5	-156.0	-40.077	-34.693	-63.330	-141.7	-138.1
-137.7	-114.5	-156.0	-34.939	-36.199	-67.099	-130.5	-138.2
-137.7	-114.5	-156.0	-39.563	-35.617	-62.653	-138.9228	-137.8

NMC2 3 component

Sample ID	Sample Date	As $\delta^{18}\text{O}$	Bs Sc uS/cm	A1 $\delta^{18}\text{O}$	B1 Sc uS/cm	A2 $\delta^{18}\text{O}$	B2 Sc uS/cm	A3 $\delta^{18}\text{O}$	B3 Sc uS/cm	D	f1 GW	f2 rain	f3 snow
SHAMA-3	5/23/2017	-18.3	77	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.142	0.350	0.508
SHAMA-9	5/23/2017	-18.6	145	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.396	0.220	0.385
SHAMA-15	5/3/2017	-18.5	160	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.451	0.206	0.342
SHAMA-21	5/3/2017	-18.3	126	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.325	0.290	0.386
SHAMA-27	5/10/2017	-18.4	115	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.284	0.290	0.427
SHAMA-33	4/21/2017	-18.3	161	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.455	0.245	0.300
SHAMA-42	3/28/2017	-18.4	136	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.362	0.258	0.380
4	6/10/2017	-17.6	62	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.086	0.468	0.446
13	7/29/2017	-18.2	95	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.209	0.331	0.461
14	7/29/2017	-18.6	146	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.399	0.217	0.383
22	8/11/2017	-18.1	112	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.272	0.331	0.397
23	8/11/2017	-18.6	181	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.530	0.176	0.294
32	9/9/2017	-18.2	123	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.313	0.299	0.388
33	9/9/2017	-18.6	156	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.437	0.199	0.364
CS_12	10/5/2017	-16.8	40	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.004	0.636	0.360
CS_6	11/3/2017	-18.2	131	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.343	0.289	0.368

C1	C2	C3	f1*C1	f2*C2	f3*C3	Cobserved	Cpredicted
-137.7	-114.5	-156.0	-19.525	-40.109	-79.234	-138.9	-138.9
-137.7	-114.5	-156.0	-54.463	-25.152	-60.030	-142.9	-139.6
-137.7	-114.5	-156.0	-62.171	-23.603	-53.410	-142.7	-139.2
-137.7	-114.5	-156.0	-44.701	-33.165	-60.173	-140.7	-138.0
-137.7	-114.5	-156.0	-39.049	-33.195	-66.535	-139.5	-138.8
-137.7	-114.5	-156.0	-62.684	-28.075	-46.734	-140.7	-137.5
-137.7	-114.5	-156.0	-49.839	-29.565	-59.256	-141.4	-138.7
-137.7	-114.5	-156.0	-11.818	-53.586	-69.603	-134.8	-135.0
-137.7	-114.5	-156.0	-28.773	-37.847	-71.839	-136.8	-138.5
-137.7	-114.5	-156.0	-54.977	-24.899	-59.793	-141.2	-139.7
-137.7	-114.5	-156.0	-37.508	-37.848	-61.942	-137.5	-137.3
-137.7	-114.5	-156.0	-72.960	-20.197	-45.826	-140.8	-139.0
-137.7	-114.5	-156.0	-43.160	-34.225	-60.475	-138.3	-137.9
-137.7	-114.5	-156.0	-60.115	-22.794	-56.840	-141.7	-139.7
-137.7	-114.5	-156.0	-0.514	-72.857	-56.155	-130.5	-129.5
-137.7	-114.5	-156.0	-47.270	-33.100	-57.351	-138.9228	-137.7

NMC3 3 component

Sample ID	Sample Date	As $\delta^{18}\text{O}$	Bs Sc uS/cm	A1 $\delta^{18}\text{O}$	B1 Sc uS/cm	A2 $\delta^{18}\text{O}$	B2 Sc uS/cm	A3 $\delta^{18}\text{O}$	B3 Sc uS/cm	D	f1 GW	f2 rain	f3 snow
SHAMA-2	5/23/2017	-18.3	130	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.340	0.288	0.373
SHAMA-8	5/23/2017	-18.6	173	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.500	0.188	0.312
SHAMA-14	5/3/2017	-18.5	212	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.646	0.154	0.201
SHAMA-20	5/3/2017	-18.3	182	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.534	0.221	0.246
SHAMA-26	5/10/2017	-18.5	137	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.366	0.239	0.395
SHAMA-32	4/21/2017	-18.3	145	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.396	0.259	0.345
SHAMA-43	3/28/2017	-18.3	146	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.399	0.264	0.336
5	6/10/2017	-18.1	69	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.112	0.381	0.507
15	7/29/2017	-18.2	197	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.590	0.211	0.200
16	7/29/2017	-18.5	129	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.336	0.250	0.414
24	8/11/2017	-15.6	274	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.877	0.553	-0.430
25	8/11/2017	-18.4		-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	-0.146	0.411	0.734
34	9/9/2017	-18.2	212	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.646	0.203	0.151
35	9/9/2017	-18.4	187	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.552	0.200	0.248
CS_13	10/5/2017	-18.1	234	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.728	0.196	0.076
CS_14	10/5/2017	-18.2	220	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.675	0.193	0.132
CS_7	11/3/2017	-18.2	172	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.496	0.243	0.261

NMC4 3 component

Sample ID	Sample Date	As $\delta^{18}\text{O}$	Bs Sc uS/cm	A1 $\delta^{18}\text{O}$	B1 Sc uS/cm	A2 $\delta^{18}\text{O}$	B2 Sc uS/cm	A3 $\delta^{18}\text{O}$	B3 Sc uS/cm	[D]	f1 GW	f2 rain	f3 snow
SHAMA-1	5/23/2017	-18.3	130	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.340	0.284	0.376
SHAMA-7	5/23/2017	-18.2	137	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.366	0.285	0.349
SHAMA-13	5/3/2017	-18.2	209	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.634	0.208	0.158
SHAMA-19	5/3/2017	-18.3	175	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.507	0.220	0.272
SHAMA-25	5/10/2017	-18.4	167	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.478	0.224	0.299
SHAMA-31	4/21/2017	-18.3		-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	-0.146	0.428	0.717
SHAMA-44	3/28/2017	-18.4	160	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.451	0.233	0.315
6	6/10/2017	-17.9	83	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.164	0.404	0.432
17	7/29/2017	-18.1	205	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.619	0.225	0.156
18	7/29/2017	-18.0	105	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.246	0.356	0.398
36	9/9/2017	-18.2	216	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.660	0.199	0.141
37	9/9/2017	-18.0	207	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.627	0.233	0.140
CS_15	10/5/2017	-18.0	199	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.597	0.246	0.157
CS_16	10/5/2017	-17.4	228	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.705	0.309	-0.014
CS_8	11/3/2017	-18.2	182	-18.752	307	-14.54667	39.00	-20.7	39	-1640.94	0.534	0.229	0.238

DC1 3 component

Sample ID	Sample Date	As $\delta^{18}\text{O}$	Bs Sc uS/cm	A1 $\delta^{18}\text{O}$	B1 Sc uS/cm	A2 $\delta^{18}\text{O}$	B2 Sc uS/cm	A3 $\delta^{18}\text{O}$	B3 Sc uS/cm	D	f1 GW	f2 rain	f3 snow
SHAMA-6	5/23/2017	-18.5	356	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.371	0.216	0.412
SHAMA-12	5/23/2017	-18.4	500	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.540	0.166	0.294
SHAMA-18	5/3/2017	-18.4	630	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.692	0.118	0.190
SHAMA-24	5/3/2017	-18.6	455	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.487	0.164	0.349
SHAMA-30	5/10/2017	-18.7	390	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.411	0.166	0.423
SHAMA-36	4/21/2017	-18.7	408	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.432	0.166	0.402
SHAMA-38	4/16/2017	-18.5	403	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.426	0.196	0.378
1	6/10/2017	-18.3	379	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.398	0.248	0.354
7	7/29/2017	-18.5	350	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.364	0.217	0.419
8	7/29/2017	-18.4	430	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.458	0.209	0.333
26	9/9/2017	-18.5	345	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.358	0.218	0.424
27	9/9/2017	-18.4	321	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.330	0.246	0.424
CS_17	10/5/2017	-17.9	364	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.381	0.321	0.299
CS_18	10/5/2017	-18.6	386	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.406	0.194	0.400
CS_3	11/3/2017	-18.5	354	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.369	0.217	0.414

C1	C2	C3	f1*C1	f2*C2	f3*C3	Cobserved	Cpredicted
-145.0	-114.5	-156.0	-53.823	-24.781	-64.330	-146.2	-142.9
-145.0	-114.5	-156.0	-78.273	-18.981	-45.928	-146.0	-143.2
-145.0	-114.5	-156.0	-100.345	-13.474	-29.684	-145.4	-143.5
-145.0	-114.5	-156.0	-70.632	-18.775	-54.430	-145.9	-143.8
-145.0	-114.5	-156.0	-59.596	-19.034	-65.950	-147.1	-144.6
-145.0	-114.5	-156.0	-62.652	-18.952	-62.774	-147.0	-144.4
-145.0	-114.5	-156.0	-61.803	-22.406	-58.982	-146.9	-143.2
-145.0	-114.5	-156.0	-57.728	-28.404	-55.193	-142.2	-141.3
-145.0	-114.5	-156.0	-52.804	-24.825	-65.366	-144.7	-143.0
-145.0	-114.5	-156.0	-66.388	-23.944	-51.954	-143.8	-142.3
-145.0	-114.5	-156.0	-51.956	-24.946	-66.115	-144.5	-143.0
-145.0	-114.5	-156.0	-47.881	-28.175	-66.100	-144.1	-142.2
-145.0	-114.5	-156.0	-55.181	-36.743	-46.571	-143.1	-138.5
-145.0	-114.5	-156.0	-58.917	-22.222	-62.337	-145.6	-143.5
-145.0	-114.5	-156.0	-53.484	-24.862	-64.586	-145.7	-142.9

DC2 3 component

Sample ID	Sample Date	As $\delta^{18}\text{O}$	Bs Sc uS/cm	A1 $\delta^{18}\text{O}$	B1 Sc uS/cm	A2 $\delta^{18}\text{O}$	B2 Sc uS/cm	A3 $\delta^{18}\text{O}$	B3 Sc uS/cm	D	f1 GW	f2 rain	f3 snow
SHAMA-5	5/23/2017	-18.4	451	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.482	0.194	0.323
SHAMA-11	5/23/2017	-18.5	800	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.891	0.032	0.077
SHAMA-17	5/3/2017	-18.4	893	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	1.000	0.000	0.000
SHAMA-23	5/3/2017	-18.7	458	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.491	0.138	0.372
SHAMA-29	5/10/2017	-18.6	445	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.475	0.166	0.358
SHAMA-35	4/21/2017	-18.5	460	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.493	0.172	0.335
SHAMA-37	4/16/2017	-18.5	466	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.500	0.177	0.323
2	6/10/2017	-18.1	410	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.434	0.264	0.302
9	7/29/2017	-18.5	401	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.424	0.205	0.371
10	7/29/2017	-18.3	576	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.629	0.150	0.221
20	8/11/2017	-18.6	370	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.388	0.192	0.421
21	8/11/2017	-18.5	754	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.837	0.054	0.108
28	9/9/2017	-18.6	409	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.433	0.184	0.383
29	9/9/2017	-18.4	680	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.751	0.104	0.146
CS_19	10/5/2017	-18.2	690	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.762	0.118	0.120
CS_20	10/5/2017	-18.5	415	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.440	0.196	0.364
CS_4	11/3/2017	-18.6	382	-18.4	893	-14.54667	39.00	-20.7	39	-5228.96	0.402	0.199	0.399

NMC1 2 component

						fraction of		two member mixing model					
						fs	groundwater	1		Soil water			
Sample ID	$\delta^{18}\text{O}$	$\delta^2\text{H}$	Location	Date	Sc $\mu\text{S/cm}$		1.00	2.00	groundwater	1	end member		
SHAMA-4	-18.2	-139	NMC 1	5/23/2017	59		0.07	0.93			$\delta^{18}\text{O}$	$\delta^2\text{H}$	Sc $\mu\text{S/cm}$
SHAMA-10	-18.2	-139	NMC 1 well	5/23/2017	121		0.31	0.69			-18.752	-137.73	307
SHAMA-16	-18.3	-141	NMC 1 well	5/3/2017	126		0.32	0.68			-15.8	-123	39.00
SHAMA-22	-18.5	-141	NMC 1	5/3/2017	123		0.31	0.69					
SHAMA-28	-18.2	-139	NMC 1	5/10/2017	103		0.24	0.76					
SHAMA-34	-18.3	-140	NMC 1	4/21/2017	121		0.31	0.69					
SHAMA-41	-18.4	-142	NMC 1	3/28/2017	126		0.32	0.68					
3	-18.1	-136	NMC 1	6/10/2017	61		0.08	0.92					
11	-18.2	-137	NMC 1	7/29/2017	100		0.23	0.77					
12	-18.2	-136	NMC 1 well	7/29/2017	106		0.25	0.75					
19	-18.0	-136	NMC 1	8/11/2017	138		0.37	0.63					
30	-18.3	-138	NMC 1	9/9/2017	113		0.28	0.72					
31	-18.3	-137	NMC 1 well	9/9/2017	121		0.31	0.69					
CS_10	-18.3	-138	NMC 1 well	10/5/2017	117		0.29	0.71					
CS_11	-18.2	-139	NMC 1	10/5/2017	107		0.25	0.75					
CS_5	-18.2	-139	NMC 1	11/3/2017	116		0.29	0.71					

NMC2 2 component

						fraction of		two member mixing model					
						fs	groundwater	1		soil water			
Sample ID	$\delta^{18}\text{O}$	$\delta^2\text{H}$	Location	Date	Sc $\mu\text{S/cm}$		1.00	2.00	groundwater	1	end member		
SHAMA-3	-18.3	-139	NMC 2	5/23/2017	77		0.14	0.86			$\delta^{18}\text{O}$	$\delta^2\text{H}$	Sc $\mu\text{S/cm}$
SHAMA-9	-18.6	-143	NMC 2 well	5/23/2017	145		0.39	0.61			-18.4	-137.73	307
SHAMA-11	-18.5	-143	NMC 2 well	5/3/2017	160		0.45	0.55			-15.1	-118	39.38
SHAMA-2	-18.3	-141	NMC 2	5/3/2017	126		0.32	0.68					
SHAMA-2	-18.4	-140	NMC 2	5/10/2017	115		0.28	0.72					
SHAMA-3	-18.3	-141	NMC 2	4/21/2017	161		0.45	0.55					
SHAMA-4	-18.4	-141	NMC 2	3/28/2017	136		0.36	0.64					
4	-17.6	-135	NMC 2	6/10/2017	62		0.08	0.92					
13	-18.2	-137	NMC 2	7/29/2017	95		0.21	0.79					
14	-18.6	-141	NMC 2 well	7/29/2017	146		0.40	0.60					
22	-18.1	-138	NMC 2	8/11/2017	112		0.27	0.73					
23	-18.6	-141	NMC 2 well	8/11/2017	181		0.53	0.47					
32	-18.2	-138	NMC 2	9/9/2017	123		0.31	0.69					
33	-18.6	-142	NMC 2 well	9/9/2017	156		0.44	0.56					
CS_12	-16.8	-131	NMC 2 well	10/5/2017	40		0.00	1.00					
CS_6	-18.2	-139	NMC 2	11/3/2017	131		0.34	0.66					

NMC3 2 component

					fs	fraction of fraction of groundwa soil water		two member mixing model						
Sample ID	$\delta^{18}\text{O}$	$\delta^2\text{H}$	Location	Date	Sc $\mu\text{S/cm}$	1.00	2.00	groundwa 1			soil water 2			
SHAMA-6	-18.5	-146	VC 1	5/23/2017	356	0.37	0.63	end member			end member			
SHAMA-12	-18.4	-146	VC 1 well	5/23/2017	500	0.54	0.46	$\delta^{18}\text{O}$	$\delta^2\text{H}$	Sc $\mu\text{S/cm}$	$\delta^{18}\text{O}$	$\delta^2\text{H}$	Sc $\mu\text{S/cm}$	
SHAMA-18	-18.4	-145	VC 1 well	5/3/2017	630	0.69	0.31	-18.4	-145	893	-15.8	-123	39.00	
SHAMA-24	-18.6	-146	VC 1	5/3/2017	455	0.49	0.51							
SHAMA-30	-18.7	-147	VC 1	5/10/2017	390	0.41	0.59							
SHAMA-36	-18.7	-147	VC 1	4/21/2017	408	0.43	0.57							
SHAMA-38	-18.5	-147	VC 1	4/16/2017	403	0.43	0.57							
1	-18.3	-142	VC 1	6/10/2017	379	0.40	0.60							
7	-18.5	-145	VC 1	7/29/2017	350	0.36	0.64							
8	-18.4	-144	VC 1 well	7/29/2017	430	0.46	0.54							
26	-18.5	-145	VC 1	9/9/2017	345	0.36	0.64							
27	-18.4	-144	VC 1 well	9/9/2017	321	0.33	0.67							
CS_17	-17.9	-143	VC 1 well	10/5/2017	364	0.38	0.62							
CS_18	-18.6	-146	VC 1	10/5/2017	386	0.41	0.59							
CS_3	-18.5	-146	VC 1	11/3/2017	354	0.37	0.63							

DC2 2 component

[illegible]

Appendix G: Surface Water

Date	NMC 1	NMC 2	NMC 3; D1-D6	NMC 4;D1- D7
4/2/2017	0.39	0.39	0.63	0.36
4/8/2017	0.14	0.25	0.52	0.32
4/21/2017	0.14	0.38	0.65	0.42
5/10/2017	0.87	1.18	1.37	1.08
7/30/2017	0.65	0.76	0.87	0.68
9/9/2017	0.30	0.53	0.87	0.59

Date	DC1	DC2
4/16/2017	0.02	0.02
4/21/2017	0.03	0.04
5/3/2017	0.02	0.01
5/10/2017	0.02	0.03
5/27/2017	0.02	0.03
6/10/2017	0.03	0.03
6/24/2017	0.02	0.02
7/30/2017	0.02	0.01
9/9/2017	0.02	0.02

SIGNATURE PAGE

This is to certify that the thesis prepared by Charles Shama entitled "Mountain Front Recharge in a Semi-Arid Climate, Southwest Montana" has been examined and approved for acceptance by the Department of Geological Engineering, Montana Tech of The University of Montana, on this 20th day of April, 2018.

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