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HYDROLOGIC RESPONSE OF HEADWATER STREAMS RESTORED WITH BEAVER DAM ANALOGUE STRUCTURES

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HYDROLOGIC RESPONSE OF HEADWATER STREAMS RESTORED WITH BEAVER DAM ANALOGUE STRUCTURES

By

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Abstract

In the semiarid and arid western United States, it is important to understand the potential effects of stream restoration on surface-water and groundwater. In this study, we evaluate the seasonal and annual hydrologic impacts of beaver-dam analogue (BDA) restoration in the Blacktail Creek (BTC) Watershed south of Butte, Montana. We monitored surface water flow, groundwater levels, temperature, and specific conductance primarily using a control-treatment study design. In treated reaches, groundwater levels were closer to the ground surface and showed less seasonal fluctuation. Changes in overall streamflow in the control reaches had stream losses and gains varying from -21.0 to 19.9 % while treatment reaches had stream gains of 12.5 to 17.6 % of water returning to the stream through groundwater discharge. Using specific conductance values and streamflow, the total dissolved load was greater in the treatment reaches compared to the control reach. Two-components mixing model showed that treatment reaches had a greater overall groundwater contribution to the stream during high-flow periods compared to control reaches. Control and treatment late-season vertical hyporheic exchange flows had similar vertical exchange flows but there were greater overall horizontal flows in the treatment reach. BDA implementation creates small off-channel ponds; provides increased groundwater gradients away from the stream during late-season periods, and gradients to the stream during drier years. BDAs increase ecosystem resilience while storing water during reduced snowpack years. Groundwater discharge to streams in treatment reach and groundwater recharge in control reach is evident during high-runoff periods. BDAs can be an effective management tool when applied to the proper setting with a well-defined restoration goal.

Keywords: beaver-dam analogues, restoration, groundwater, surface-water, alpine

Dedication

Thank you to the individuals who have helped shaped me into who I am today.

When you come to a fork in the road, take it. -Yogi Berra

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Glossary of Terms & Acronyms

Term	Definition
Basin01	Basin Creek sub-watershed, north
Basin02	Basin Creek sub-watershed, south
BDA	Beaver-dam analogue (structure)
BTC	Blacktail Creek
Control	Paired or reference reach, unrestored
GW	Groundwater
MASL	Meters above sea level
SC	Specific Conductivity
SM	Snowmelt
SW	Surface Water
PZ	Piezometer
TDS	Total dissolved solids
Transition Reach	BTC reach between control, treatment
Treatment	Reaches restored with BDA structures
USGS	United States Geological Survey
VHG	Vertical hydraulic gradient

1. Introduction

The health of stream, riparian and wetland ecosystems is vulnerable to changes in the overall climate regime, including in mountainous regions across North America (Dwire, 2018), especially at the reach scale (Woznicki et al., 2016). Specifically, areas of the semi-arid mountain west, are projected to see shifts in the timing and type of precipitation, reduced overall river flows, a decline in overall snowpack and longer growing seasons (Mote, 2005; Rood, 2016; Sturrock et al., 2011; Westerling et al., 2006).

Beaver provide ecosystem services as a keystone species, which can reverse or buffer some projected impacts from climate change (Dittbrenner et al., 2018). Beaver activity at the sub-basin scale has shown to decrease the return period of high-intensity floods, reduce and delay peak flows, and increase low flows; however, studies at the reach scale are still needed (Nyssen et al., 2011; Puttock et al., 2017). Beaver activity also increases geomorphic complexity; and encourages sediment deposition, which leads to aggradation of streams and floodplains (Naiman et. al., 1988; Pollock et al., 2007). Storage of water in shallow aquifers from beaver activity has shown to be significant (Puttock et al., 2016), however, during high flow events beaver ponds are limited in their ability to provide surface water storage since they rapidly fill with both sediment and water (Burns and McDonnell, 1998).

There were about 60 million beaver in North America prior to European settlement (White et al., 2015). Beaver population drastically declined during the 1800s due to hunting and trapping pressure (Busher and Lyons, 1999). Since the 1940s, there has been several conservation strategies to retain and encourage beaver populations, however, beaver still require specific conflict mitigation strategies including flood management and tree protection (Castro et al., 2015). Suitable beaver habitat includes existing coniferous-deciduous trees, abundant hardwood vegetation, appropriate watershed size and appropriate stream widths; steep stream gradients and well-drained soils are deterrents to beaver colonization (Howard and Larson, 1985; Macfarlene et al., 2017). Landscape scale models have been developed to assign beaver habitat suitability and conflict avoidances indices to different stream reaches based on land ownership and remote sensing analysis of stream gradient, stream width, valley width, land use and vegetation type (Dittbrenner et al., 2018). These montane ecosystems, with restoration efforts from stakeholder groups, landowners, consultants and government agencies, have potential for improved habitats.

Climate adaptation strategies are primarily focused on increasing dry season stream flows and increasing the extent and vigor of riparian vegetation. BDAs can take a variety of forms and are becoming a popular approach to stream restoration (Lautz et al., 2019; Pilliod et al., 2018) since it is a relatively inexpensive, low-impact, restoration technique that can reverse drying trends, aggrade streams, and provide habitat complexity in headwater streams. This restoration technique from a water rights perspective falls within Montana Department of Natural Resources stream restoration guidelines. Another advantage of BDAs is that they can be used in areas where beaver cannot be introduced due to conflicts. A better understanding of the effectiveness and suitability of BDA restoration design in different hydrogeologic settings is needed (Pilliod, 2008). In this study, we present multiple years of field data on BDA reaches located in on headwater streams in southwest Montana (Fig. 1). Based on these data, we seek to improve the understanding of:

1. How BDAs affect dynamic stream and groundwater elevations.
2. How do BDAs affect interactions between groundwater and surface water.
3. How BDAs affect dry-season streamflow.

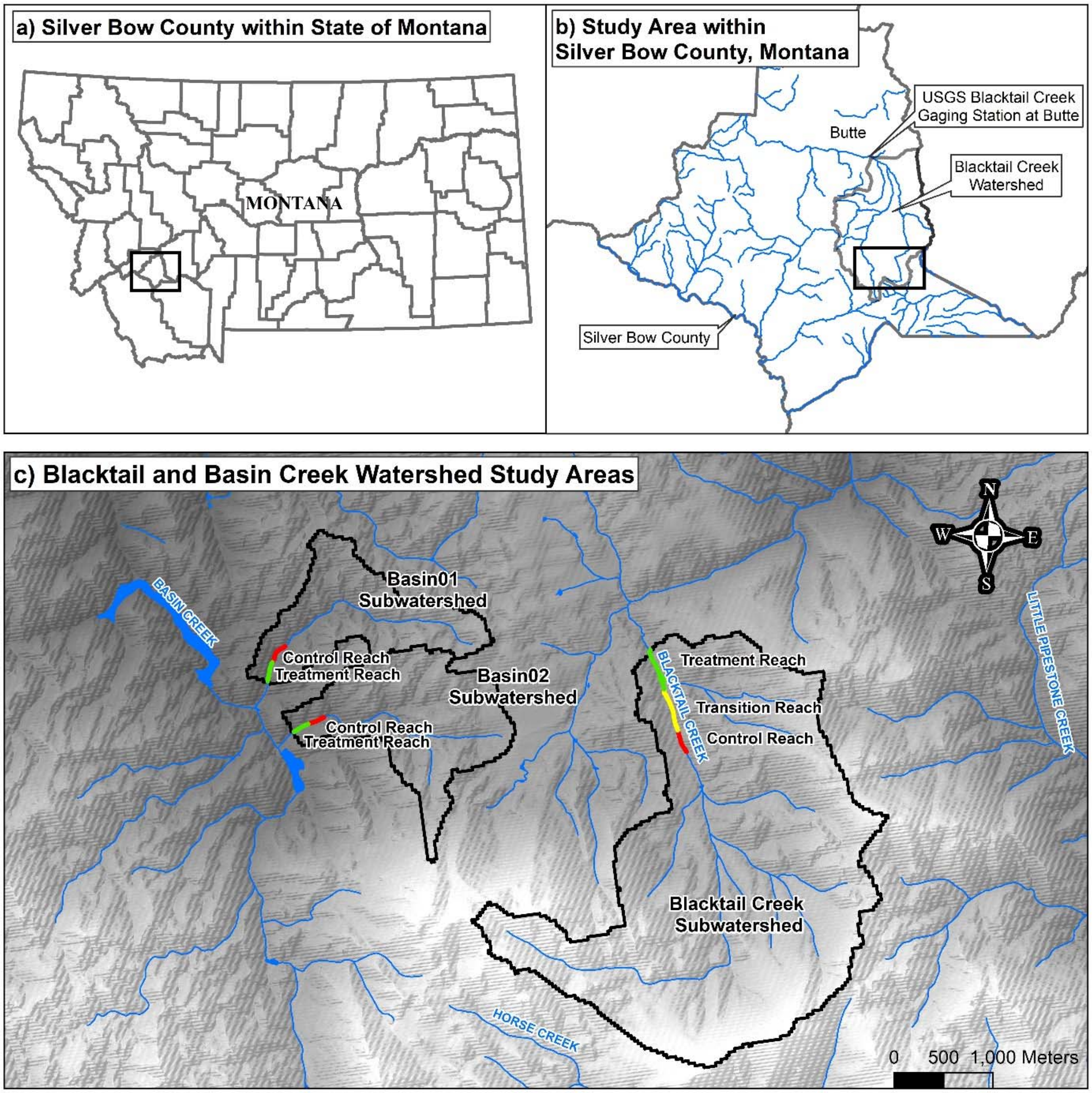

Figure 1: a) Silver Bow County within State of Montana b) Study Area within Blacktail Creek Watershed c) Basin Creek and Blacktail Creek sub-watershed study areas

2. Study Area

The study sites, in the Blacktail Creek (BTC) watershed south of Butte, Montana are in Silver Bow County (Fig. 1a). This watershed is bordered by the Continental Divide and the Highland Mountains, draining a total area of 235 km^2 (Fig. 1b). There is a USGS gage at the mouth of Blacktail Creek: 12323240; Blacktail Creek at Butte, Montana. For the period of record 1989-2017, the BTC peak flow average was 3.81 m^3s^{-1} with a mean flow of 0.31 m^3s^{-1} (USGS, 2020). Of the total drainage area, 46.2% is drained by Basin Creek, a tributary of BTC, impounded by two dams below our Basin01 and Basin02 sites to provide surface water storage and a municipal drinking water source for the City of Butte.

Our three sites (Fig. 1c) are located on private parcels and Butte-Silver Bow City property and are bordered by United States Forest Service lands. The BTC, Basin01 and Basin02 sites have upstream drainage areas of approximately 9.4m^2, 1.6 km^2, and 2.1 km^2 respectively (Fig. 1c). At these sites, the streams are perennial with snowmelt driven hydrographs.

The climate, geomorphology, and land cover at the study sites are typical for the northern Rocky Mountains of the United States. The closest meteorological station to the study sites, Basin Creek Snotel (315), is at 2190 MASL. At this station, average precipitation from 1981-2020 was 62.5 cm with an average snow water equivalent maximum values of 22.9 cm in early May (NRCS, 2019). Historic records from 1990-2019 at Basin Creek Snotel indicate July as the warmest month on average reaching 14.7 ºC while the coldest month, December, drops to -6.0 ºC (NRCS, 2020). The BTC site is at an elevation of approximately 1970 MASL while the Basin Creek sites are at approximately 1835 MASL. Valley slopes in the study sites average 2-6 % with the maximum slopes around historic beaver dams and valley crossing access roads. BTC streams flow north-northeast while Basin Creek have southwest orientations. Floodplain width ranges from 40 m to 80 m at the BTC sites and 20 m to 70 m at the Basin Creek sites. Vegetation in the valley bottoms is dominated by wetland grasses, shrubs and willow. Douglas fir, grand fir, western larch and ponderosa pine dominate the uplands (Arno, 1979; MT Field Guide, 2017).

Streamflow, precipitation and snowpack for water years 2016, 2017, 2018 and 2019 were downloaded from the local USGS Streamflow and NRCS Snotel station. The water year 2018 had the highest snowpack and intensity of rain throughout the summer. These data helped to determine qualitative influences of snowpack and precipitation on seasonal and annual streamflow and groundwater at the Blacktail and Basin Creek study sites (Fig. 2; Fig. 3).

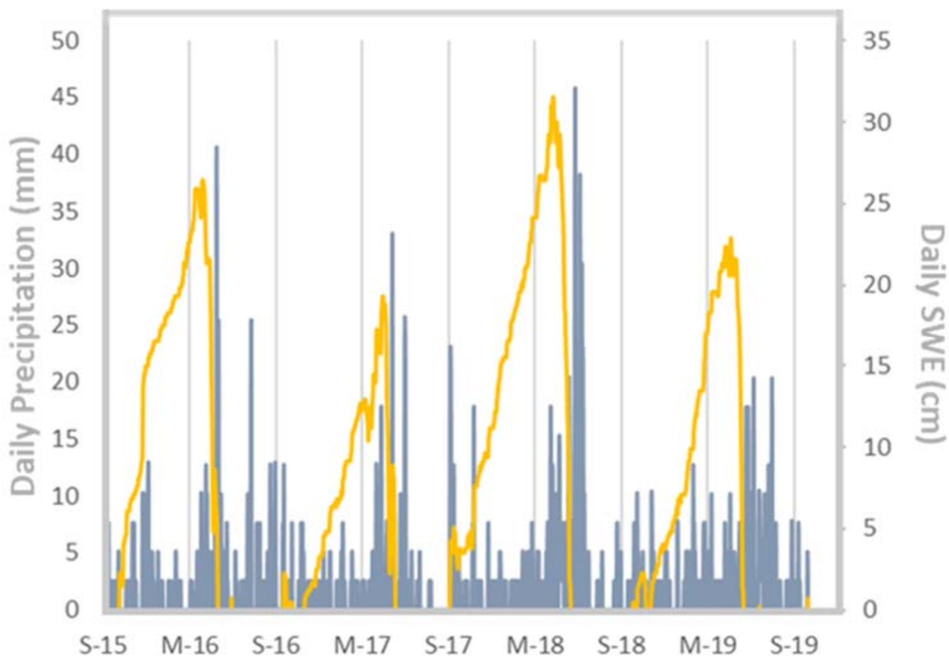

Figure 2: Basin Creek Snotel (315) Hydrology during water years 2016-2019

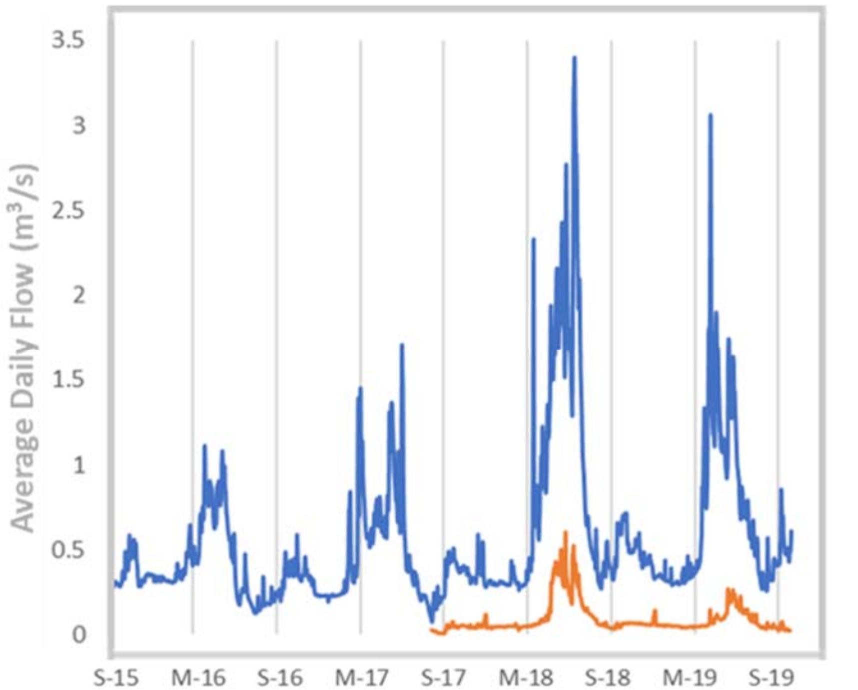

Figure 3: USGS Gaging Station (blue) and Blacktail Creek subwatershed (orange) streamflows

The regional geology is dominated by basin and range faulting with down dropped valleys bounded by mountain blocks. The Highland Mountains plateau to the south of the study sites is at 3116 MASL. The study sites are located within the uplifted mountain block and are underlain by Quaternary alluvium (Qal) and colluvium (Qac) composed unconsolidated gravel, sand, silt and clay with varying depths (McDonald et al., 2012). The Quaternary stream channel alluvium consists of coarse-fine grained silts, sands and some gravels weathered from quartz monzonite and granodiorite of the Boulder Batholith (76.3 ± 0.5 Ma; du Bray et al., 2009; Smedes et al., 1973).

Site specific alluvial thicknesses were determined by seismic refraction and electrical resistivity geophysical methods through the floodplain and on valley benches. Site geophysical surveys shown evidence of graben or half-graben structures with weathered bedrock and a transitional zone of float material consisting of unconsolidated regolith with bedrock as deep as

35 m in locations (Hadley et al., 2019). Depth to bedrock was higher through the floodplain and decreased towards the uplands near conifer stands and large boulder outcrops.

3. Methods

3.1. Site Setup

3.1.1. Groundwater Monitoring

In July 2016, twelve 1.9 cm polyvinyl chloride (PVC) piezometers (PZ) were installed in the BTC treatment site to an average depth of 1.2 m below ground surface (Appendix B.2). PZs in the BTC control reach were installed in June 2017 with twenty-one, 1.9 cm PVC PZs to an average depth of 0.8 m below ground surface. All BTC piezometers had Solinst 601 PVC Standpipe tips with 30 cm lengths of well screen attached to a PVC casing. These piezometers were finished with a silica sand pack at least six inches above the screened interval and a bentonite chip seal to ground surface (Fetter, 1999; Sprecher, 1993).

In June 2019, six 2.5 cm PZs were placed in BTC treatment site with 30.5 cm screened intervals and completed like the other PZs. These PZs were installed within 10 m of the stream and were placed to further understand groundwater flow direction using both vertical and horizontal gradients (Appendices C.1.1-C.1.4; C.2.1).

In August 2019, four 2.5 cm PZs were installed in the streambed at BTC with two in the control reach and two in the treatment reach. These are referred as flux PZs (Appendix B.2). Each flux PZ was equipped with a 0.5 m screen installed below the streambed and a riser that extended above the stream surface.

In June 2017, twenty-four 1.9 cm, PVC PZs were installed at the Basin01 site. These PZs were installed along the upstream control reach and along the downstream treatment reach (Appendix B.4). PZ depths averaged 1.1 m below ground surface and were constructed following similar procedures as the BTC site.

In June 2018, twenty-four, 1.9 cm, PVC PZs were installed in Basin02 site to a depth of 1.0 m with corresponding upstream and downstream locations (Appendix B.5). PZs in Basin02 used saw slots (hacksaw); along the lowest 0.3 m interval and were completed like other sites with silica sand and bentonite.

3.1.2. Surface Water Monitoring

At the BTC site, two staff gages were installed in the planned BDA treatment reach in July 2016. One staff gage was installed at the upstream end of the treatment reach and the other within the reach at the downstream end of the monitoring equipment near a historic beaver-dam. Two staff gages were later installed in 2017 in the BTC control with one upstream and downstream of the twenty-one control PZs. In June 2019, three additional staff gauges and two additional stilling wells were installed on the BTC treatment (Appendix A.1; Appendix B.2).

In June 2017, Basin01 had stilling wells, staff gages and pressure transducers installed at the upstream and downstream extents between PZs (Appendix B.4).

In June 2018, Basin02 had stilling wells, staff gages and temperature probes at the upstream and downstream extents between a PZ transect (Appendix B.5).

3.1.3. BDA Implementation

In October 2016, eighteen BDAs were installed in the BTC treatment reach by Great West Engineering (Helena, Montana) and a restoration crew using techniques based on those described in the Beaver Restoration Guidebook (Bouwes et al., 2018; Castro et al., 2015;) This included the use of site-sourced conifer posts, conifer limbs, and sedge sod mats placed perpendicular to flow. BDA height and structure density per stream length varied according to width to depth ratios, breached dam locations, valley slopes and existing knickpoints such as evolving head cuts. In general, BDA posts extended less than 0.75 m above existing stream surfaces with greater than 50 % of the total post length pounded into the streambed. Primary and secondary BDA structures created step-pool sequences and potential for increased hyporheic flows, especially in porous sediment medium (Fig. 4; Thibodeaux and Boyle, 1987).

In October 2018, the Basin01 and Basin02 downstream treatment reaches had a total of twenty-two and twenty-three BDAs installed by Great West Engineering, a restoration crew and volunteers. A structure on Basin01 and Basin02 was installed every 6.0 m of valley length comparable to natural riffle-pool feature densities (Slocombe and Davis, 2014) above and below the downstream PZ transects.

Figure 4: Example BDA structure on Blacktail Creek. Photo May 2017.

3.1.4. Surface Topography and Surveying

GPS data and drone collected data at the BTC, Basin01 and Basin02 sites assisted in describing study area characteristics including floodplain widths and slopes, stream lengths, PZ distances from stream, horizontal hydraulic gradients, vertical hydraulic gradients and BDA structure locations.

Data from BTC staff gages, stream flow locations and PZs were surveyed using an Emlid Reach RS+ receiver. A digital surface model (DSM) was developed for BTC reaches using areal imagery using a DJI Phantom 4 Pro photography drone in 2019 and analyzed using photogrammetry in Pix4D software.

Basin Creek staff gages and PZs were surveyed using a Trimble R1 GNSS Receiver utilizing Collector for ArcGIS. In 2018, Water and Environmental Technologies (Butte, Montana) developed a LiDAR based digital elevation model (DEM) for the Basin01 and Basin02 sites. 2018. LiDAR data was collected using a WingtraOne VTOL mapping drone.

3.2. Monitoring

3.2.1. Aquifer Properties

Saturated hydraulic conductivity was estimated using slug tests (Fetter, 1994) at four BTC PZs and two Basin PZs. Water slugs were used to raise PZ water levels, 15-20 cm and the falling head values were manually recorded. Slug test data were analyzed following the Hvorselv (1951) method (Baxter et al., 2003), as implemented in AQTESOLV software (Duffield, 2007).

Saturated hydraulic conductivity estimates were also made based on sediment grain size (ASTM D6913). Soil samples from 0 and 2 m below ground surface were removed during PZ installations, oven-dried for 24 hours and homogenized. The Kozeny-Carmen model (Wang et al., 2017) estimates hydraulic conductivity by using the ten-percent finer grain size average (d_{10}) in nine sieved samples and a porosity estimate for unconsolidated alluvial deposits, which was assumed to be 0.3. The Kozeny-Carmen model (Eq. 1) uses several additional variables; C_k as a coefficient ($5.55 \cdot 10^{-3}$), g as the gravitation acceleration ($9.8\ m^2s^{-1}$) and v as the fluid kinematic viscosity of water ($1.2 \cdot 10^{-6}\ m^2s^{-1}$). A uniformity coefficient was determined from the sieve analysis to determine a soil gradation value for the sieved samples using the distribution of the sixty percent (d_{60}) and ten percent (d_{10}) finer particle sizes over the augured depth (Eq. 2; Das, 2010).

$$K = C_k \cdot \frac{g}{v} \cdot \frac{n^3}{(1-n)^3} \cdot d_{10}^2 \qquad \text{Equation 1}$$

$$C_u = \frac{D_{60}}{D_{10}} \qquad \text{Equation 2}$$

3.2.2. Groundwater Measurements

Groundwater level measurements were taken with a Solinst 102M Mini Water Level Meter. Pre-restoration groundwater level measurements were taken in July and October 2016 in the BTC treatment reach. In 2017, 2018 and 2019 monthly water level measurements were collected from the BTC control and treatment reaches. Dry PZ readings were excluded from groundwater level change data. Basin01 had monthly groundwater levels collected in the control and treatment reaches from June to October in 2017, 2018 and 2019. Similarly, Basin02 treatment and control reaches were monitored from June to October in 2018 and 2019.

3.2.3. Transducers and Temperature Loggers

In 2018 and 2019 control and treatment reach stilling wells were installed and equipped with submersible Hobo U20L-01 transducers to record hourly water temperature and pressure from May to September. An hourly recording atmospheric Hobo U20L-01, was air-mounted in the vicinity of the study area to obtain a barometric pressure correction. In June 2018 and 2019 Basin01 had Hobo U20L-01 transducers deployed at the upstream control and downstream reaches recording every hour. In June 2018 and 2019, Basin02 had Hobo U22-001 temperature loggers installed within the stream to record every hour at upstream control and downstream treatment. In October of 2018 and 2019, transducers and temperature loggers were retrieved from the Basin Creek reaches.

3.2.4. Stream Stage

Pre-restoration stream stage readings were taken in the BTC reach in July and October 2016. Stream stage readings in the BTC control and treatment reaches, were taken from May to October in 2017, 2018 and 2019. Stage readings at all BTC sites were taken in conjunction with discharge measurements (see section 3.2.5).

Basin01 control and treatment reach stream stage readings were taken pre-restoration from May to October in 2017 and 2018 and post-restoration from May to October 2019. Basin02 had stream stage measured in September and October 2018 pre-restoration and from June to October in 2019 post-restoration.

3.2.5. Streamflow

Stream flow measurements were taken with a Marsh Birney 2000 Portable Flow Mate utilizing USGS velocity-area methods (Turnipseed and Sauer, 2010). From 2017 to 2019, stream flows were collected at the same interval as groundwater levels in BTC treatment and control reaches and as flow allowed in Basin01 and Basin02 upstream and downstream locations. Flows were difficult to measure at the Basin01 and Basin02 due to the low flow rates.

The rating curves were based on power-law relationships (Eq. 3; Cey et al., 1998) where Q is the stream flow, Z is head above the downstream control structure (a.k.a. G-e; Kennedy, 1984), and a and b are best-fit values. A streamflow hydrograph with hourly intervals was created from streamflow pressure data and the corresponding stage-discharge relationship at that gauging location (Sauer, 2002).

$$Q = aZ^b \qquad \text{Equation 3}$$

Percent average daily streamflow change on BTC reaches were calculated from May to October in 2018 and 2019 (Eq. 4). Subscripts DS and US represent the downstream and upstream gauging locations. Total cumulative surface water volumes were compared to estimate net gains or losses in flow over that study reach (Kalbus et al., 2006).

$$\Delta Q_{reach} = {(Q_{DS} - Q_{US})}/{Q_{DS}} \qquad \text{Equation 4}$$

3.2.6. Groundwater Surface Water Interactions

Instruments were placed in the flux PZs and stream stilling wells for three weeks during a low-flow time period from August to September 2019 recording temperature and pressure data. These data were collected to understand the 1-dimensional vertical flux on BTC reaches (Constantz, 2008). Solinst Pressure transducers were placed near the bottom of the four flux PZ. The transducers record both temperature and pressure. Two Thermochron DS1922L iButtons were installed 30.5 cm and 45.7 cm above each of the four flux PZ transducers recording at thirty-minute intervals. Since these PZs were installed near surface-water stations with stilling wells, temperature and pressure data were also available for the stream. With the boundary conditions (temperature and pressure) from the flux PZ and surface-water transducers, heat advection equations were used to understand stream, groundwater exchanges including flux and flow direction. The observed temperatures from the iButtons were used to calibrate the heat flux models (Constantz, 2008). One-dimensional temperature fluxes were calculated utilizing 1DTempPro software (Koch et al., 2015). These 1DTempPro estimates assisted in the estimation of vertical flux as either groundwater discharge or groundwater recharge in the BTC treatment and control reaches.

BTC horizontal flow direction was compared using groundwater measurements and stream stage readings from June to September 2019. Flow directions utilized a stream stage and a local groundwater elevation value from a piezometer (Appendices C.1.1-C.1.4; Appendix C.2.1). Four monitoring pairs of stream stage and floodplain groundwater levels were compared in the treatment reach. In the control reach, one paired piezometer and staff gage reading were used to determine flow directions.

3.2.7. Percent Change Load and Specific Conductance

Specific conductance (SC) was measured during nine monitoring events at BTC stream gaging locations from June to September 2019 using a WTW Multi340i multimeter. SC was also collected in near-stream flux PZs three times from August to September. Reach specific conductivity was converted to total dissolved solid (TDS) concentration (Atekwana et al., 2004) and multiplied by the streamflow at the time of SC measurement to yield a TDS load in kilograms per day for the gauging location. Percent change TDS load in the control, transition and treatment reaches was calculated to understand either groundwater recharge or groundwater discharge to surface water bodies (Eq. 5). Subscripts, DS and US representing measured SC and flow locations at the downstream and upstream of each the three reaches, respectively.

$$\Delta TDS_{reach} = {(TDS_{DS} - TDS_{US})}/{TDS_{DS}} \qquad \text{Equation 5}$$

Background SC values were used to create a two-component mixing model. The first component was new water (<1 yr old) derived from snowmelt and rain (Q_{SM}) and the second component was old water (>1 yr old) derived from the bedrock aquifer (Q_{GW}). Average snowmelt specific conductance was 3.4 μscm^{-1} near the Basin Creek (315) Snotel Site (Red Mountain Snow Site, Montana; USGS National Water Information System; 2716 MASL). The average specific conductance of nine groundwater samples in the Boulder Batholith Intrusive (211BLDR) near our sites was 353.1 μscm^{-1} (data from 9/2017 and 11/2010; USGS National Water Information System).

The two-component mixing model were used to calculate a flow of each of the components (Q_{GW} and Q_{SM}) in the stream (Q_{SW}) during eight synoptic monitoring events conducted from June to September 2019 (Eq. 6; Eq. 7).

$$F_{GW} + F_{SM} = 1 \qquad \text{Equation 6}$$

$$Q_{SW} = Q_{GW} \cdot F_{GW} + Q_{SM} \cdot (1 - F_{GW}) \qquad \text{Equation 7}$$

For the BTC downstream treatment station, total groundwater flow (Q_{DS}) in m^3day^{-1} required the removal of the fraction of groundwater (F_{GW}) in the surface water tributary flow (Q_{TRIB}). The fraction of groundwater in the tributary and total flow in the downstream treatment area was solved analogous to the other reaches (Eq. 8).

$$Q_{DS} \cdot F_{GW} - Q_{TRIB} \cdot F_{GW} = Q_{GW} \qquad \text{Equation 8}$$

Total groundwater flow (Q_{GW}) at each reach was calculated by taking average surface water flow over the day (Q_{SW}) and multiplying by the fraction of groundwater (F_{GW}) for that gauging location from two-component mixing analysis (Eq. 9).

$$Q_{SW} \cdot F_{GW} = Q_{GW} \qquad \text{Equation 9}$$

3.2.8. Darcy Fluxes and Flows

For PZs near the stream (within <0.5 m), the vertical hydraulic gradient (VHG) was calculated by subtracting the bottom of well and the bottom of the stream bed (dz) and dividing by the differences in pressure head (dh) at each of those points (Eq. 10; Anderson et al., 2005).

$$VHG = -\frac{dh}{dz} \qquad \text{Equation 10}$$

Stream and nearby PZ specific discharge (q), estimates were determined from the product of VHG and average hydraulic conductivity (K) from the sieve tests (Eq. 11; Darcy, 1856). Hydraulic conductivity values from slug tests were not used to calculate specific discharge values due to the imposed hydraulic stress on a small portion of the aquifer material near the PZ screen.

$$q = -\left(k \cdot \frac{dh}{dz}\right) \qquad \text{Equation 11}$$

To calculate an area of groundwater recharge or discharge or surface water discharge, the longitudinal stream lengths along the control and treatment reaches were measured in ESRI ArcMap and multiplied by the average wetted perimeter during streamflow measurements in 2018 and 2019. With the reach length (L_R), wetted perimeter (W_P) and average vertical flux value (q) calculated via 1DTempPro and VHGs, a net vertical flow volume was then estimated from August to September 2019 (Eq. 12; Fig. 5).

$$Q = -\left(q \cdot L_R \cdot W_P\right) \qquad \text{Equation 12}$$

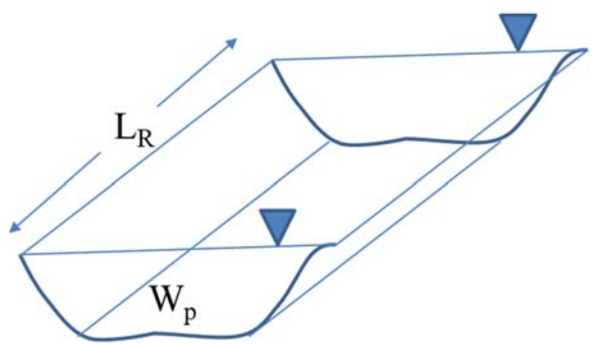

Figure 5: Conceptual diagram of stream area calculated for groundwater recharge or groundwater discharge.

Surface water net gains or losses (Eq. 4) through control and treatment reaches were compared to estimates of vertical gains or losses to estimate horizontal gains or losses.

4. Results

4.1. Annual Hydrology

Water year 2018 had the greatest average flow during this study at the USGS Blacktail Creek Stream gage (Fig. 3), and the greatest accumulated precipitation and maximum water volume in snow from any of the years 2016-2019 (Fig. 2). The 2017 water year had the least amount of snow water equivalent and the second lowest flow and accumulated precipitation. Water years 2016 and 2017 from the USGS and Basin Creek Snotel Data were drier compared to 2018 and 2019.

4.2. Aquifer Properties

Slug tests (n=6) performed using the Hvsorlev method (Baxter et al., 2003) in wells across the BTC study area were used to estimate an average hydraulic conductivity of 0.32 $mday^{-1}$. Values of hydraulic conductivity were estimated to be 1.79 $mday^{-1}$ with sieve tests utilizing the Kozeny-Carmen method (Eq. 1). Sieve samples (n=9) average D_{10} particle size were 0.056 mm with a range from 0.025 and 0.079 mm. The sieve samples had a particle uniformity coefficient (D_{60}/D_{10}) of 27.5 (Eq. 2). The particle size distribution and soil cores verify a poorly sorted alluvium comprised of primarily coarse to fine sand layers interbedded with varying amounts of silts and clays.

4.3. Groundwater Measurements & Gradients

Seasonal groundwater level changes at the BTC control and treatment reaches between June to August 2019 were mapped with relative spatial distance from stream (Fig. 6). BTC treatment PZs shows an average groundwater drop of 12.8 cm ± 9.2 across 17 non-dry PZs; two dry PZ decreased an average of at least 25.7 cm ± 0.7 from June to August 2019. Control groundwater levels showed a decrease averaging 31.9 cm ± 12.3 in seven non-dry PZs; and 12 dry PZ dropped an average of at least 32.1 cm ± 11.7. Water level measurements in June and August 2019 show that for non-dry PZs groundwater levels in the treatment reach dropped 19.1 cm less than the control reach. Also, 89% of wells in the treatment reach contained water in August while 37% of the wells in the control reach remained wet.

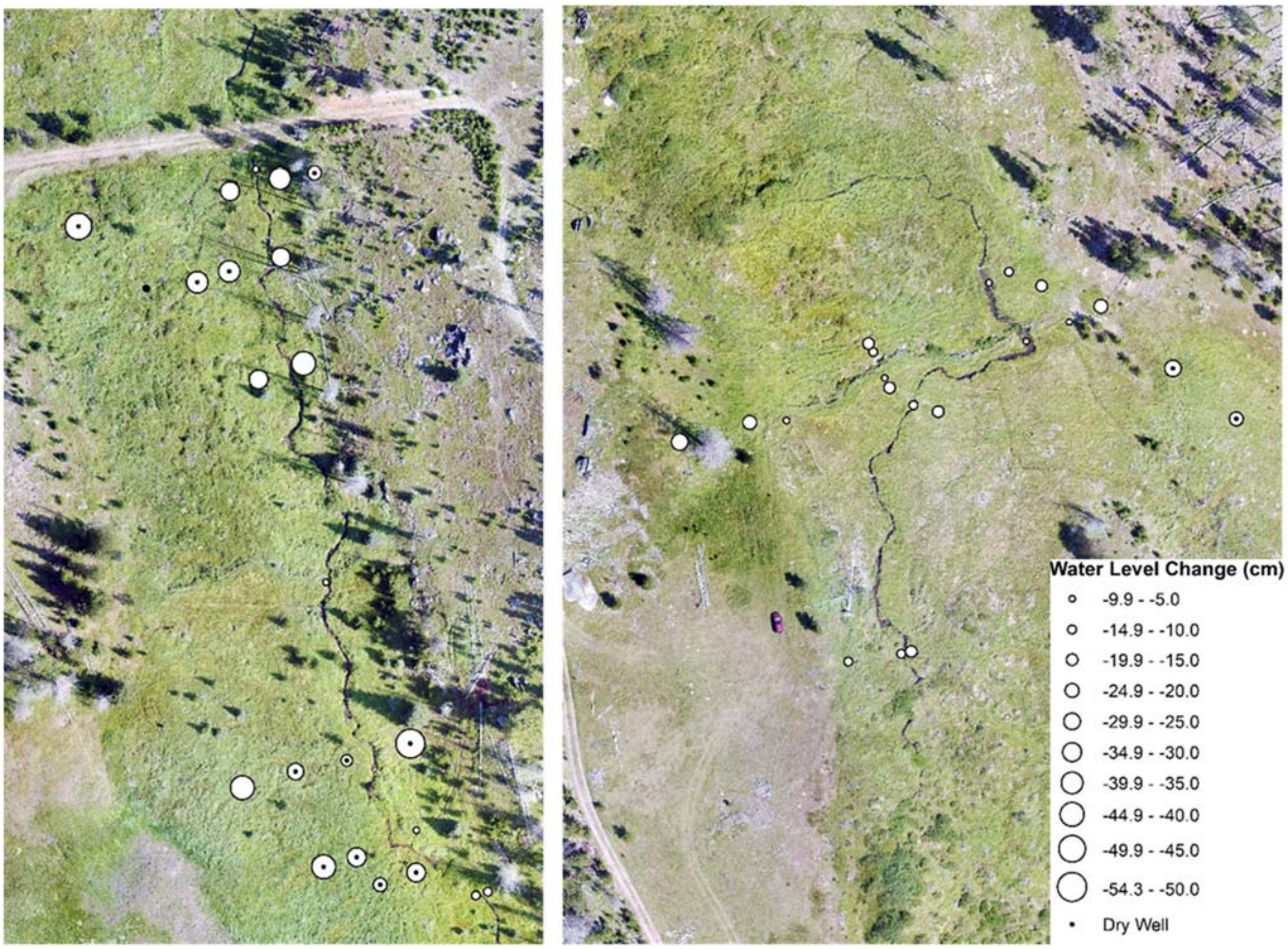

Figure 6: Blacktail Creek June-August 2019 groundwater level change on control reach (left) and treatment reach (right)

Multi-year responses to restoration were observed in the Basin02 treatment reach PZs, with the Basin01 control reach PZs as reference. The BDAs were installed in the treatment reach in October 2018. Groundwater level measurements in June 2018 and June 2019 (Fig. 7) at the control reach had an average drop of 15.0 cm ± 0.14, with the PZs with higher 2018 groundwater elevations systematically dropping by more than the lower elevation PZs. Groundwater elevations in the Basin02 treatment reach had little change from 2018 to 2019, with an average increase of 0.01 cm ± 0.09.

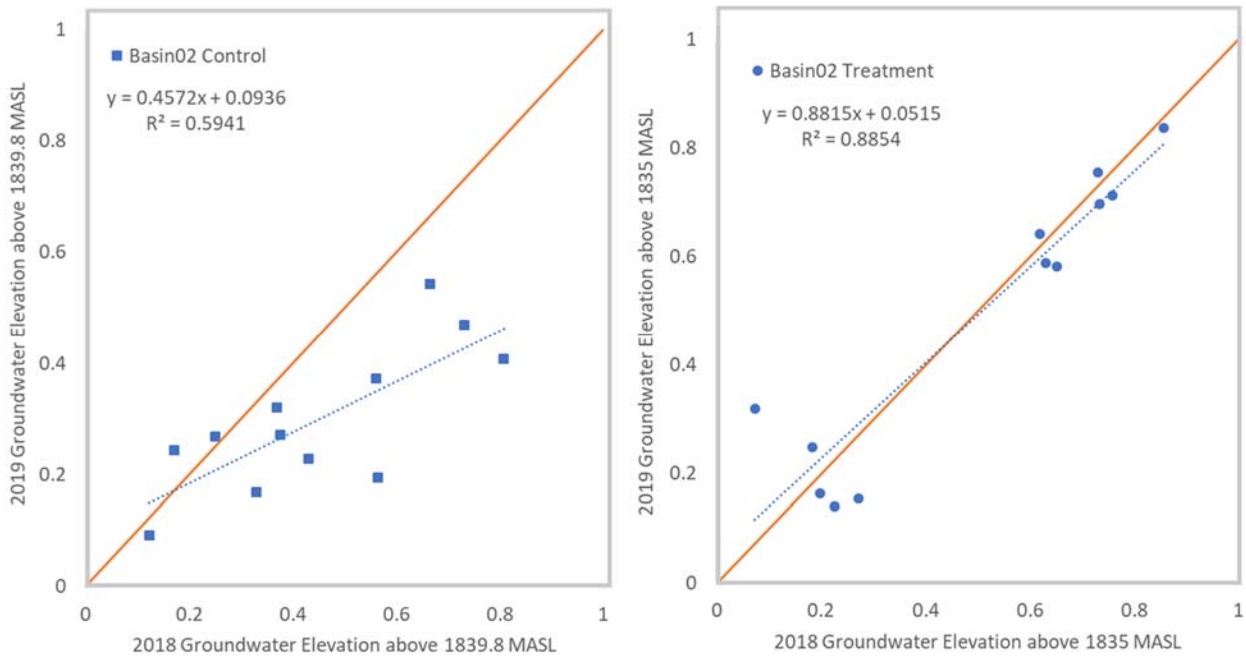

Figure 7: Basin02 June 2018 (pre-treatment) groundwater elevations in treated and control reaches compared to June 2019 (post-treatment) groundwater elevations. Relationships were evaluated by fitting a least square trendline (dashed blue).

The short-term groundwater level response to treatment was measured at the Basin01 treatment reach. Groundwater levels measured two-weeks before restoration were compared to groundwater level measured two weeks post-restoration (Fig. 8). The BDAs were installed on Basin01 in October 2018. Groundwater levels rose a maximum of 14.0 cm in a well 1.2 m from the stream after BDA implementation, and groundwater levels showed little to no changes more than 6 m from the creek. This illustrates either a lag in the travel of the stored water near the stream across the floodplain reflecting the silty sand hydraulic conductivity, or that the BDAs are only influencing sediments in the nearby aquifer around the streambed.

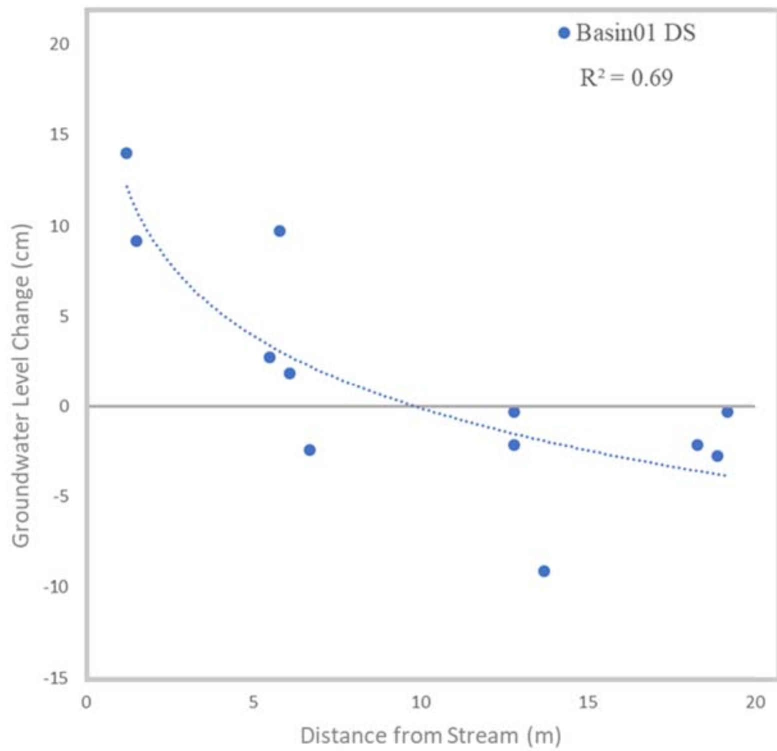

Figure 8: Basin01 downstream treatment October 2018 two weeks pre-post restoration groundwater response with distance from stream.

4.4. Staff Gage Readings

BTC treatment reach surface-water elevations were read at the upstream staff gage and downstream staff gage. Pre-restoration values were measured in July and October 2016. Post-Restoration values were measured during the snow free period (May-October) in 2017, 2018 and 2019 (Fig. 9). The pre-restoration measurements were the lowest values at both gages in the restored reach. Post-restoration stream stage at the upstream and downstream gages remained at least 12 cm and 16 cm above pre-restoration data, respectively.

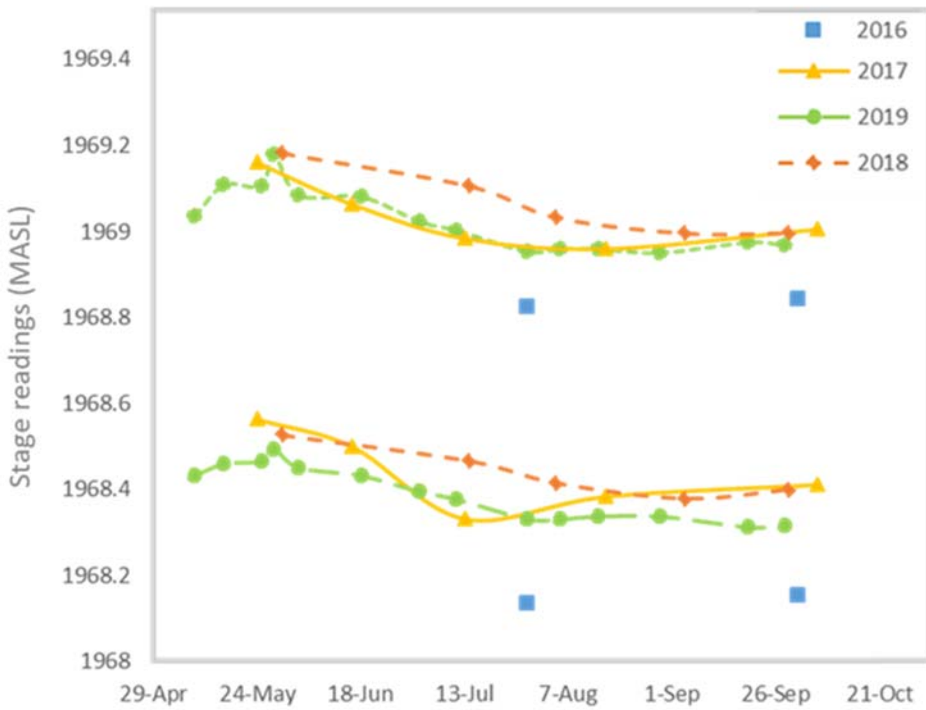

Figure 9: Blacktail Creek 2016 stream stage in the treatment reach pre-restoration and post restoration 2017-2019 steam stage. The two datasets represent staff gages placed at the upstream (top) and downstream (bottom) extents of BDAs.

4.5. Surface-Water Measurements

Daily surface water balances gain or loss in streamflow was compared on the BTC control, transition and treatment reaches in 2018 and 2019 (Fig. 10). The cumulative volumetric change in the BTC control, transition and treatment reaches was also compared from May to September 2018 and 2019 (Fig. 11). The control reach had net groundwater recharges of 21.0 and 12.5 % of stream flows in 2018 and 2019. The transition reach showed a 3.5 and 19.9 % of groundwater discharge to the stream. In the treatment reach, 17.6 and 12.5% of the flow, returned to the stream. Surface water flow differences during 2018 and 2019 exhibit a net loss within the control reach, a slight net gain of flow in 2018 and a substantial net gain in 2019 along the transition reach and a net gain within the treatment reach.

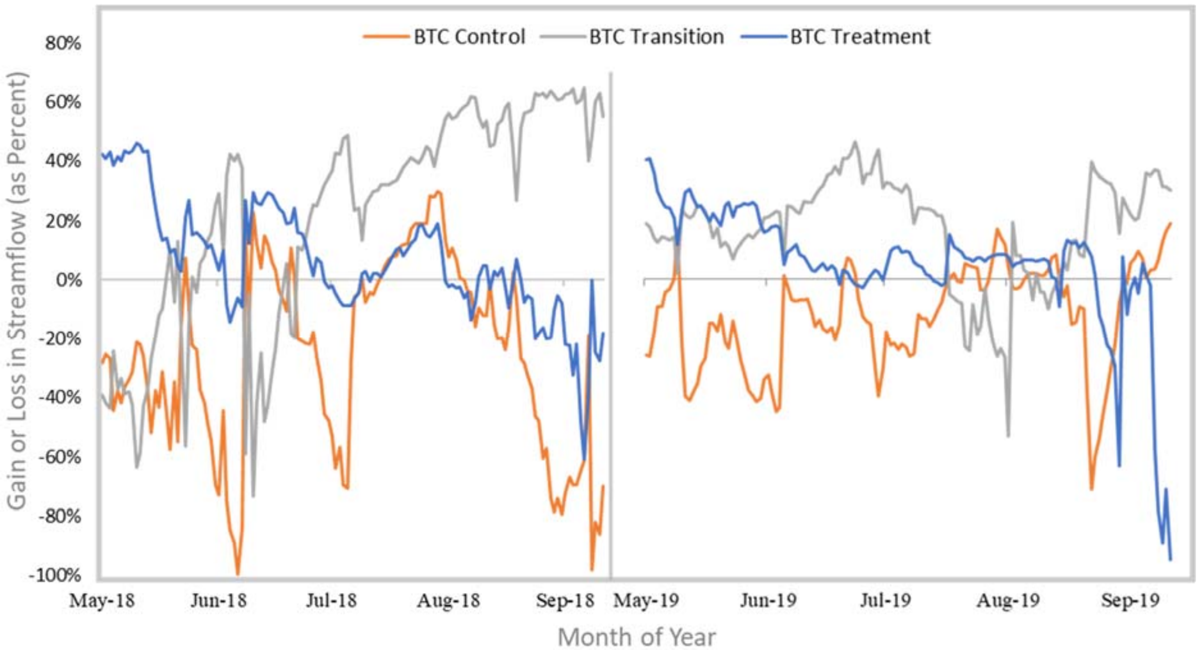

Figure 10: Blacktail Creek 2018 and 2019 average daily streamflow percent change between upstream and downstream monitoring locations in the BTC control reach, transition reach, and treatment reach. Percentage are based on the change in flow and the measured flow at the downstream station.

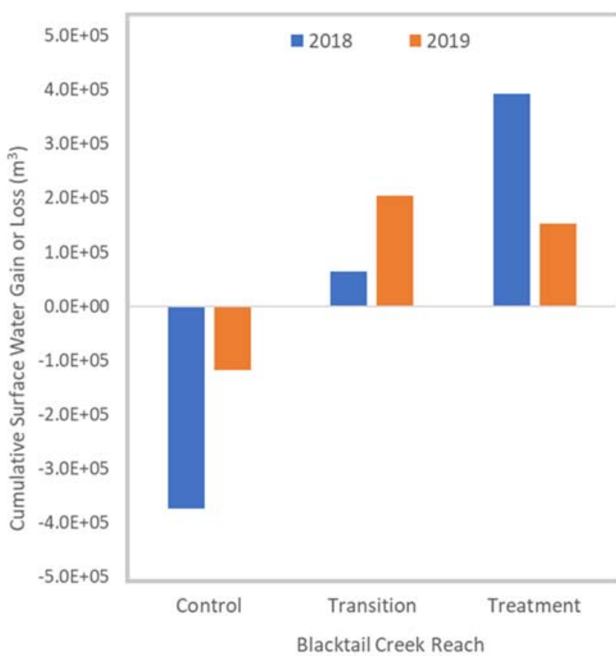

Figure 11: Blacktail Creek 2018 and 2019 cumulative volumetric gain or loss (m^3) between upstream and downstream monitoring locations in the control, transition and treatment reaches.

4.6. Groundwater Surface-Water Interactions using Specific Conductance

BTC specific conductivity (SC) measurements during June to September 2019 in BTC treatment and control reaches (Appendix F.1; Appendix F.2) varied between 191.0 μscm^{-1} ± 22.74 and 203.88 μscm^{-1} ± 25.2 respectively. The incoming tributary in the treatment contributes water with an average SC value of 70.7 μscm^{-1} ± 6.7, lowered the overall SC of BTC. The highest stream SC values occur during late-August at low flow time periods with peaks of 237 μscm^{-1} in the control and 223 μscm^{-1} in the treatment below the tributary inflow.

BTC percent change in TDS load (Fig. 12) was compared from June to September in 2019. The control reach recharges 9 % of TDS to groundwater, the transition reach discharges 9 % of TDS to surface water bodies and the treatment discharges 4 % of TDS to surface water bodies. Groundwater discharge or load increases are from higher groundwater and SC to the stream, while losses are from increased groundwater recharge and losses in overall streamflow. Each reach, wavers between groundwater discharge and groundwater recharge of TDS load over the duration of the falling limb of hydrograph, baseflow and event hydrographs.

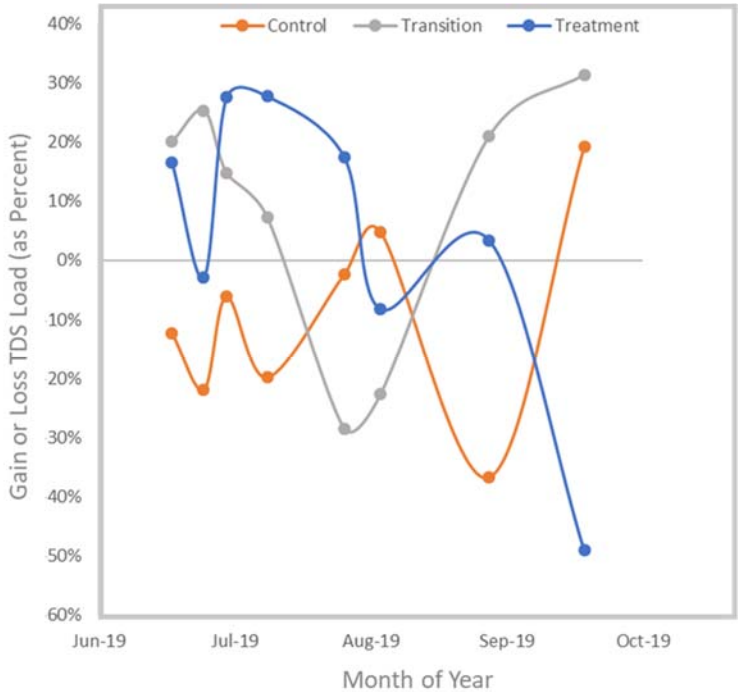

Figure 12: Blacktail Creek June to September 2019 total dissolved solids (TDS) load percent gain or loss through the control, transition and treatment reach

BTC specific conductivity in the control and treatment reaches was used with snowmelt, and groundwater end members to develop a two-component mixing model. At each reach, total source water shifts from snowmelt to deep groundwater from June to September 2019 (Fig. 13). The BTC control reach has a slightly larger fraction of groundwater component over the season compared to the treatment reach (Fig. 13). The BTC control reach had less overall inflow and fluctuation of groundwater with a geometric mean of 2556 m^3day^{-1} ± 567 while the treatment had a geometric mean of 3034 m^3day^{-1} ± 1276.

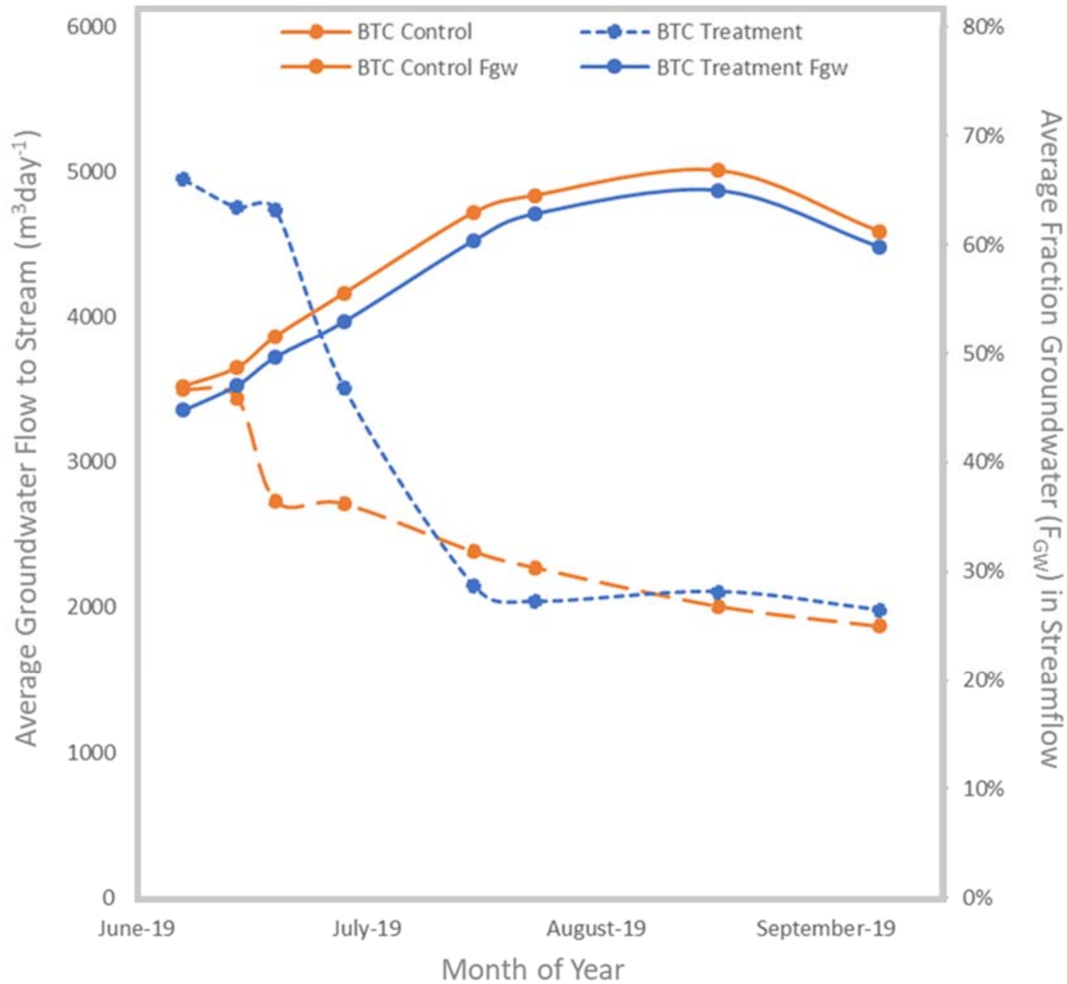

Figure 13: Blacktail Creek control and treatment 2019 average groundwater flow and to stream and average fraction of groundwater in streamflow from two-component mixing analysis.

4.7. Horizontal Hydraulic Gradients

BTC upstream treatment and downstream treatment pre and post-restoration groundwater flow direction in July and October were compared using stream stage and nearby groundwater elevations (Appendix C.1; Fig. 14). BTC upstream treatment 2016 pre-restoration groundwater flow was directed toward the creek. BTC upstream treatment post-restoration gained during 2017 to 2019. In the BTC downstream, 2016 treatment pre-restoration groundwater flow direction indicated an overall gain of water. In 2017, flow continued to the creek while in 2018 and 2019 surface-water recharged the aquifer with a return to groundwater discharge in October 2019. The change in gradient in the upstream treatment was less than the downstream treatment from 2016-2019. BTC upstream and downstream treatment show groundwater recharge and groundwater discharge variations throughout entire reach.

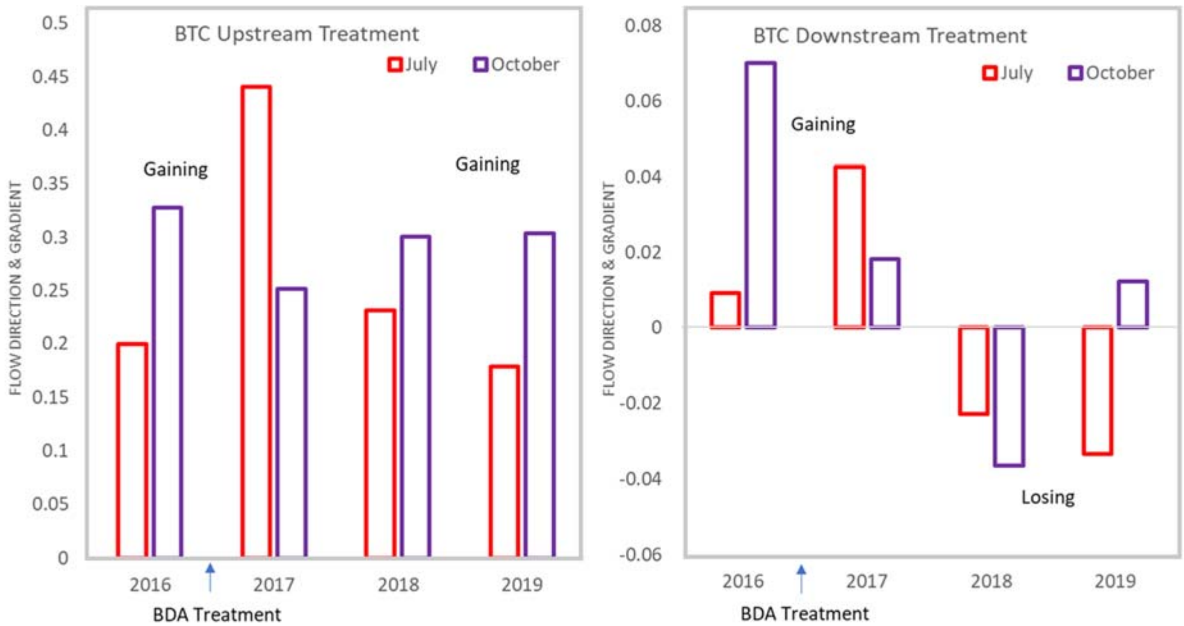

Figure 14: Blacktail Creek July and October 2016 (pre-treatment) upstream and downstream groundwater and stream stage gradients compared to July and October 2017-2019 (post-treatment) gradients.

BTC treatment horizontal hydraulic gradients at the upstream, midstream and downstream staff gages were compared from May to September 2019 (Appendices C.1.1; C.1.2; C.1.3). Stream stage and groundwater elevation comparisons showed groundwater recharge at the upstream staff gage, groundwater discharge at the midstream staff gage and varying groundwater discharge and groundwater recharge at the downstream staff gage throughout the summer.

BTC control horizontal gradients at the downstream gauging station were compared from May to September 2019 (Appendix C.2.1). The stream had an overall groundwater discharge and transitioned to a groundwater recharge mid-July before returning to a slight groundwater discharge in late-September.

Stream gain or stream loss direction and magnitude (Table I) is compared across the BTC control and treatment reaches in both the horizontal and vertical directions (Table II; Table III).

Table I.: Magnitude and Directions of Horizontal and Vertical Gaining or Losing Stream:

SYMBOL:	↑	↑	=	↓	↓
STREAM:	GAINING	WEAK GAIN	NEUTRAL	WEAK LOSS	LOSING
GRADIENT:	> 0.025	< 0.025	-0.025 < 0 > 0.025	> -0.025	> -0.025

Table II.: Blacktail Creek Control and Treatment Horizontal Groundwater Flow Directions:

Blacktail Creek	Control	Treatment		
Horizontal Gradient	Downstream	Upstream	Midstream	Downstream
6/7/2019	↑	↓	↑	↓
6/18/2019	↑	↓	↑	↑
6/27/2019	↑	↓	↑	↑
7/2/2019	↑	↑	↑	↑
7/11/2019	↑	↓	↑	↑
7/28/2019	↓	↓	↑	↓
8/5/2019	↓	↓	↑	↓
8/14/2019	↓	↓	↑	=
8/19/2020	↓	↓	↑	↓
8/29/2019	↓	↓	↑	↓
9/19/2019	=	↓	↑	↑
9/28/2019	=	↓	↑	↑
Groundwater:	Discharge/ Recharge/ Neutral	Recharge	Discharge	Discharge/ Recharge/ Discharge

4.8. Vertical Hydraulic Gradients and Fluxes

Thirty-minute recording iButtons and transducers along with physical measurements calculated an average BTC vertical hydraulic gradient during late-season flow periods from

August to September in 2019 (Fig. 15). The average vertical gradient for each of the three segments on the BTC treatment noted as upstream, mid-stream and downstream staff gages were -0.11, -0.037, and -0.038, respectively. The BTC upstream and downstream treatment recharge groundwater while the midstream discharges to surface water during this late summer season period. In the BTC control, the average vertical gradient at the upstream reach was -0.030, recharging to groundwater. Simulations via 1DTempPro show similar flux direction and magnitude at the BTC upstream treatment (Fig. 16). The upstream control is recharging groundwater in the vertical direction. The upstream treatment is recharging groundwater, midstream treatment is discharging to surface water and the downstream treatment is recharging and discharging (Table III).

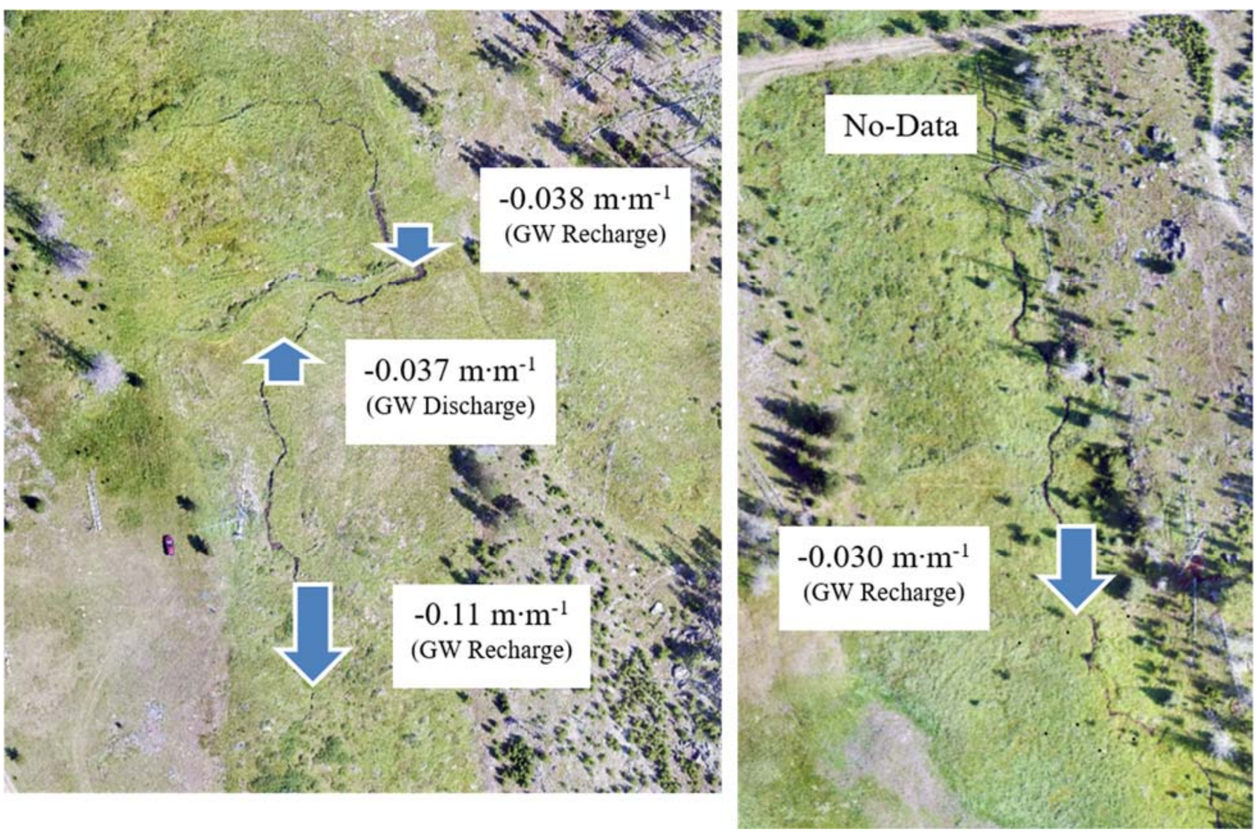

Figure 15: Blacktail Creek August-September 2019 upstream, midstream and downstream treatment gradients and flow direction and upstream control gradient and flow direction.

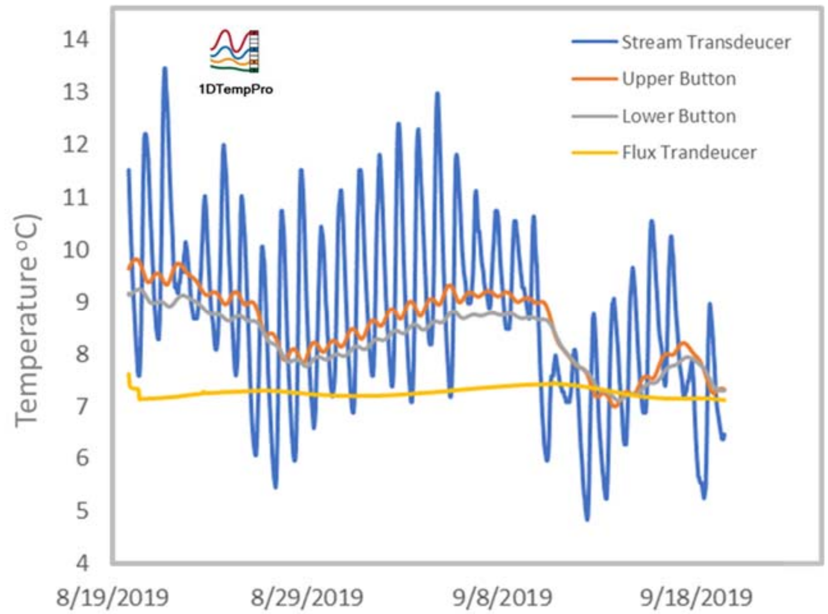

Figure 16: Blacktail Creek August-September 2019 upstream treatment 1DTempPro modeled output showing a losing stream.

Table III.: Blacktail Creek Control and Treatment Vertical Flow Directions:

Blacktail Creek	Control	Treatment		
Vertical Gradient	Upstream	Upstream	Midstream	Downstream
8/14/2019		↓	↑	↓
8/19/2020	↓	↓	↑	↓
8/29/2019	↓	↓	↑	↓
9/19/2019	↓	↓	↑	↑
9/28/2019	↓	↓	↑	↑
GROUNDWATER:	Recharge	Recharge	Discharge	Recharge/ Discharge

4.9. Groundwater and Surface-Water Exchange Flows

BTC treatment and control total vertical flow (m^3day^{-1}) values were calculated (Table IV). Three BTC treatment vertical gradients (Fig. 15) were used to calculate total vertical flow in 40 m intervals of stream length with 2.5 m wetted perimeters, and vertical estimates of hydraulic conductivity of 1.8 $mday^{-1}$. The BTC control reach vertical flow was calculated with one vertical gradient (Fig. 15) along a 175 m stream reach with a 2.25 m wetted perimeter, and 1.8 $mday^{-1}$ estimated hydraulic conductivity.

Table IV.: Blacktail Creek Treatment and Control Vertical Flow Estimates and Surface Water Balances:

Blacktail Creek (08/19-09/19)	Upstream Treatment	Midstream Treatment	Downstream Treatment	Treatment (sum)	Control (sum)
$dh \cdot dl^{-1}$ (VHG)	-0.110	-0.037	-0.038	---	-0.03
Stream Length (m)	40	40	40	---	175
Wetted Perimeter (m)	2.5	2.5	2.5	---	2.25
Vertical Flow (m^3day^{-1})	19.7	-6.62	6.80	19.9	20.8
GROUNDWATER	Recharge	Discharge	Recharge	Recharge	Recharge
Surface Water Balance (m^3day^{-1})	---	---	---	359 (Recharge)	187 (Recharge)
Flow per Stream Length (m^3day^{-1})(m^{-1})	0.49	-0.17	0.17	0.17	0.12

BTC control and treatment total vertical groundwater recharge from August to September 2019 was 20.8 and 19.9 m^3day^{-1}, respectively. BTC control and treatment surface water balances had a 187 and 359 m^3day^{-1} groundwater recharge during the same period. The average flow per meter stream length in the control reach was 0.12 m^3day^{-1} of groundwater recharge compared to the treatment reach of 0.17 m^3day^{-1} per meter stream length.

5. Discussion

5.1. BDA impact on dynamic stream and groundwater elevations:

5.1.1. Blacktail Creek sub-watershed

The BTC treatment reach showed lower overall percent increases of flow in 2018 and 2019, compared to the transition and control reaches (Fig. 10; Fig. 11). This is indicative of streamflow attenuation like natural beaver dams (Nyssen et al., 2011), and forcing of water into the aquifer via a losing stream.

The BTC treatment shows elevated stages in 2017, 2018 and 2019 compared to pre-restoration data in 2016 (Fig. 9). As the BDAs increase deposition of sediment, the height and extent of the streambed increases, creating a better connection to the floodplain and the surrounding aquifer near the stream. BTC treatment groundwater data in 2019 has sustained groundwater elevations compared to the control site, evidence of a greater stream-groundwater connectivity from increased stage (Fig. 6).

5.1.2. Basin Creek sub-watershed

In the Basin02 treatment reach, groundwater levels were less sensitive to overall wetter years (2018) and dryer conditions (2019) than the control reach (Fig. 7). BDAs in the Basin02 treatment reach inundated an area of 250 m^2 utilizing a relic beaver dam. This BDA created pond in Basin02, closely resembles a beaver pond and the ability to increase surface and groundwater storage across a greater width of the floodplain. In the Basin01 treatment reach, post-restoration groundwater levels increased up to 6.0 m from the stream compared to pre-restoration (Fig. 8). Time post-restoration may have limited the aquifers ability to increase storage across the entire floodplain. In contrast, BDA restoration in this single threaded channel on Basin01 may have increased horizontal and vertical groundwater discharge toward the creek through direct hyporheic exchange flows. Basin01 and Basin02 are examples of BDA effect on groundwater storage with small localized ponds behind each structure. Basin02 shows the impact of BDA restoration utilizing the existing topography to create a larger ponds and expanded groundwater storage (Fig 7).

Basin01 stream stage was impacted by BDAs especially in the reach of high-density dam installations, thus resulting in small pools. A stream length of 40m in this DS reach, was left undisturbed immediately above the staff gage and PZ location (B.4). These riffle-run sequences between BDAs, providing step-pool features, are important habitat and increase overall stream heterogeneity including thermal refuge locations. These small voids in restoration may have exacerbated groundwater flow direction toward the stream.

5.2. BDA impact on Groundwater and Surface-Water Interactions:

5.2.1. Hyporheic Exchange Flows

Step-pool sequences like the BDA structures within this study area (Fig. 4) on BTC, affect ground and surface-water interactions. Previous modeling shows that step-pool features decrease groundwater residence time in unconstrained systems, drive significant hyporheic exchange flows and create more heterogeneities in flow to and from the stream (Kasahara and Wondzell, 2003; Lautz et al., 2016). Modeling studies have additionally emphasized higher discharge conditions increase the variability of hyporheic exchange flow residence times and depth to which hyporheic flows are reached (Mojarrad et al., 2019). The BTC treatment site shows variation in horizontal and vertical flow directions (Table II; Table III) as well as increased hyporheic exchange flows during high-flow periods (Fig. 13). The BTC control, a reach with fewer geomorphic features, has an overall losing signature from surface water balances, horizontal gradients away from the stream and downward vertical exchange flows. The lack of complexity in the BTC control reach through an incised channel and low sinuosity, greatly reduces hyporheic exchange flows.

Impacts to groundwater on the BTC treatment reach is most related to pond and plug examples and relates to the sponge model (Rodrigeuz et al., 2017). The sponge model demonstrates that high-montane meadows, (i.e. BTC control, transition and treatment reaches) may act as a source of recharge during snowmelt or precipitation through bank storage or surface infiltration (Fig. 5; Fig. 11; Fig. 12;). Water recharged to the aquifer in the control and transition reaches continues to return to the treatment reach during high flow with greater stream-aquifer connectivity (Fig. 13; Fig. 17). The BTC treatment groundwater contributes a greater overall flow during high-runoff periods compared to the control site. As the BTC control and treatment reaches approach baseflow conditions, both reaches recharge groundwater overall.

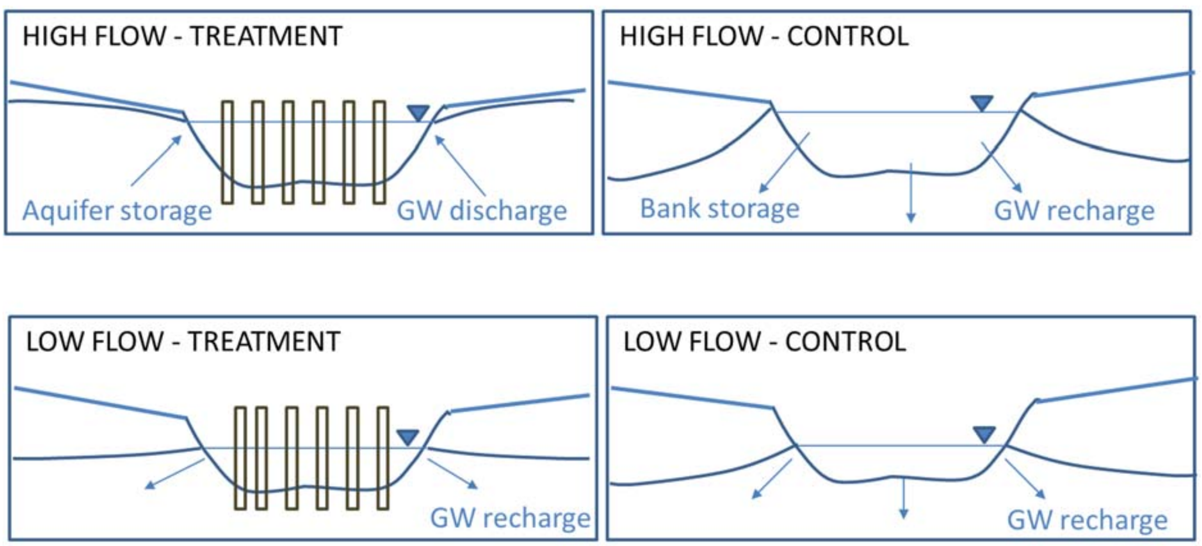

Figure 17: Conceptual groundwater flow direction in high flow and low flow scenarios at treatment and control sites.

Return flows in the transition and treatment site are seen during high-flow periods and reduce during baseflow conditions. Typically, bedrock constraints create potential for groundwater discharge and reduced hyporheic exchange flows (Kasahara and Wondzell, 2003). In the BTC transition reach, sinuosity and relatively deep bedrock depth are major influences on high hyporheic exchange flows (Cardenas, 2009) including groundwater discharge. At the BTC treatment reach, step-pool features create potential for groundwater discharge and unconstrained bedrock system create the potential for increased hyporheic exchange flows. The volume and percent of return flow in the BTC transition reach is evidence of a natural stream gain without assistance from BDA restoration.

5.2.2. Groundwater and Surface-Water Gradients

Qualitative changes in bank storage via gaining reaches or return flow in losing reaches can be determined by the magnitude and direction of horizontal gradients (Fig 14). Increased horizontal gradients toward the stream, decrease the amount of bank storage in a gaining reach. Similarly, increased horizontal gradients from the stream decreases the amount of return flow in a losing reach (Cook, 2015).

BTC upstream treatment pre-restoration and post-restoration gradients were positive toward the stream in July and October from 2016 to 2019 (Fig. 14). Post-restoration gradients had an increased gradient toward the stream in July 2017 (reduced bank storage) and a decreased gradient toward the stream in October 2018 (increased bank storage). Post-restoration groundwater surface water comparisons had fewer overall gains in July compared to October (Fig. 14). This evidence of a general increase of bank storage during lower flows at the upstream treatment site.

BTC downstream treatment 2016 pre-restoration and 2017 post-restoration gradients were positive toward the stream during these relatively dry periods. In July 2017 the BTC downstream treatment had increased positive gradients in July 2017 (reduced bank storage) thus a reduction in total stream gains later in the season (Fig. 14). In October 2017 the BTC downstream October gradients were decreased positive gradients (increased bank storage) thus increases in overall stream gains (Fig. 14). At the downstream treatment in July 2018, October 2018 and July 2019, the gradient was negative away from the stream with an overall stream loss during these wetter periods where the reach had sustained groundwater levels. In October 2019, the gradient reversed again returning to a slight gain (increased bank storage) and increased bank storages.

BTC upstream treatment gradients in 2019 showed little impact of BDA structures as the reach was losing overall for the summer (Appendix C.1.1). In the midstream treatment, the stream was strongly gaining and losing to gaining on each reach bank (Appendices C.1.2; C.1.3). At the downstream treatment staff gage, gradients tended to be between gaining and losing throughout the summer (Appendix C.1.4). Without BDA structures, the BTC treatment horizontal and vertical flow directions would likely be away from the stream.

5.3. BDA impact on dry-season streamflow:

Late-season BTC treatment vertical hydraulic gradients at the treatment showed an overall stream loss at the upstream treatment, a gain in the mid-stream and an overall loss in the downstream stream. The BTC downstream treatment location, showed an overall groundwater discharge during drought conditions in July 2017, increasing overall stream flows as the stage had dropped lower than the groundwater elevation. Monitoring in the wetter years of 2018 and 2019 show overall groundwater recharge and a loss of overall streamflow as the stream stage is higher than the local groundwater elevation. BTC upstream control vertical gradients and downstream control horizontal gradients during late-season flows show an overall losing reach (Fig. 15; Fig 16; Table III).

Flow estimations at the BTC control and treatment reaches show similar overall vertical discharges to groundwater and distinct losses of total flow in each reach from August to September 2019 (Table IV). The horizontal component of groundwater discharge in the treatment is greater than the control from the increased depth of streambed sediments. This increased depth of more transmissive streambed sediments has increased horizontal connectivity to the aquifer. The BTC treatment flow loss per stream length is greater compared to the control site, likely due to the increased aquifer connectivity. During groundwater recharge periods, the horizontal component of groundwater flow may also dominate the flow rate of water from a losing stream.

Estimates of hydraulic conductivity and vertical fluxes, show evidence of an anisotropic aquifer with a larger component of groundwater-surface water exchanges in the horizontal direction compared to the vertical direction (Table IV). Hydraulic conductivity estimates in heat flux calculations are commonly off by a factor of ten (Hester et al., 2009). However, BTC treatment and control values of vertical and horizontal exchange flows are reasonable when considering the component of total surface water gains or losses. Streambed sediments interact with the underlying heterogenous aquifer material and applying a homogeneous K value in the vertical and horizontal direction may lead to under or overestimates of exchange flows with the stream (Abimbola, 2020). This homogeneous K value assigned to the stream and aquifer may not account for the limiting transmissivity in the aquifer compared to the streambed sediments (Song et al., 2018, Mojarrad et al., 2019).

5.4. Recommendations

Understanding the spatial variability of hydraulic conductivity (K) in streambed sediments and different aquifer depths in these high-alpine environments should continue to be prioritized. We recommend increasing the number of slug tests as a method to estimate K, and to sieve a distribution of streambed sediments and aquifer material including distinct clay laminae and sand layers. Groundwater-surface water interactions are sensitive to these aquifer properties and are important to quantify in space to make restoration decisions (Niswonger et al., 2008).

Pre-restoration groundwater and surface-water measurements should be taken at the expected interval of post-restoration monitoring. The interval varies, but for a snowmelt driven system generally includes May to October with increased monitoring during runoff conditions and monthly monitoring during baseflow conditions.

The impact of single BDAs on groundwater flow direction is difficult to capture without have a dense piezometer network pre-restoration. It is advantageous to pick specific locations for BDA structures or to install near nests of piezometers to understand groundwater flow directions both pre and post restoration. Piezometers should be installed to a depth below the surface which withstands both wet and drier seasons groundwater variations. At the Blacktail and Basin Creek sites, groundwater will fluctuate greater than 0.5 m from wet to dry periods in the year. Groundwater levels fluctuate at these study sites up to 0.75 m in drier years, especially at distances further from the stream. If possible, piezometers should be installed during the dry season, when groundwater levels are near minimum to make it more likely that piezometers will not go dry.

Control and treatment streams should be surveyed pre-and-post restoration to understand changes in wetted perimeter, incision, sediment aggradation and sediment sizes. With pre and post-restoration survey data and groundwater elevations across an entire stream reach, the impact of BDAs, roads, and natural woody debris jams surface water balances and groundwater flow can be achieved.

6. Conclusions

Installing BDAs in historic beaver meadows in the BTC watershed has resulted in increased groundwater storage and alteration of stream flow regimes. During high stream flows, stream losses in the treatment reach due to the steep gradients caused by the BDAs cause the aquifer to fill up and transition to a neutral to gaining reach throughout the year. The control reach shows little overall return flow throughout the summer. During low-flow periods, both control and treatment reaches show stream losses, indicating that the groundwater mounds created by increased groundwater recharge in the treatment reaches during high flows, partly dissipate before base flow conditions. However, the treatment reach may be losing less overall during late-season flows compared to pre-restoration conditions from increases in groundwater elevations and varying hydraulic gradients which show both groundwater recharge and groundwater discharge across the reach. In drier years the BDA treatment reaches show a greater overall storage of water and a groundwater discharge. During wetter years the treatment reaches continue to have high exchanges between the stream and aquifer, compared to the control site. Installing BDAs in historic beaver meadows can be effective as a climate adaptation strategy but treatment design and site selection need to be guided by the restoration goals. Monitoring data are needed from a wide variety of BDA treatment designs in different hydrogeologic settings. These data can support process-based modeling approaches to allow for an improved mechanistic understanding of the dynamic effects of BDA installations on the reach and watershed scale.

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7. Appendix A: Blacktail and Basin Creek Monitoring Equipment Latitude, Longitudes and Elevations

A.1. Blacktail Creek Control Reach Monitoring Equipment

Blacktail Creek Control Equipment	Latitude (Decimal Degrees)	Longitude (Decimal Degrees)	Elevation (meters)	Elevation (feet)
A01	45.84258593	-112.4739099	1977.58	6488.12
A02	45.84257404	-112.4740063	1977.55	6488.03
A03	45.84254753	-112.4741457	1977.23	6486.97
A04	45.84250448	-112.4743638	1977.74	6488.64
A05	45.84247284	-112.4745685	1977.05	6486.40
A06	45.84243948	-112.4748004	1977.97	6489.42
A07	45.84241964	-112.4739994	1977.72	6488.58
A08	45.84238998	-112.4741441	1977.91	6489.20
A09	45.84236741	-112.4742324	1976.86	6485.77
A10	45.84235343	-112.4743756	1977.78	6488.78
A11	45.84221105	-112.4739303	1978.57	6491.36
A12	45.84217826	-112.474056	1978.50	6491.15
T01	45.84147035	-112.4736114	1980.35	6497.22
T02	45.84143494	-112.473789	1980.99	6499.31
T03	45.84141125	-112.473932	1979.73	6495.18
T04	45.84137785	-112.4740798	1980.93	6499.10
T05	45.84130062	-112.4735899	1982.09	6502.92
T06	45.84124581	-112.4737562	1982.01	6502.64
T07	45.84122554	-112.4738482	1982.15	6503.11
T08	45.84121772	-112.4735883	1981.71	6501.69
T09	45.84119253	-112.4736888	1982.25	6503.45
Upstream Control Staff Gage	45.84117509	-112.4734199	1982.43	6504.04
Downstream Control Staff Gage	45.8425911	-112.4740745	1977.58	6488.12
Midstream Control Staff Gage	45.84178407	-112.4738564	1979.60	6494.75

A.2. Blacktail Creek Treatment Reach Monitoring Equipment

Blacktail Creek Treatment Equipment	Latitude (Decimal Degrees)	Longitude (Decimal Degrees)	Elevation (meters)	Elevation (feet)
S01	45.84700401	-112.4772053	1970.96	6466.40
S02	45.84704699	-112.4770111	1970.42	6464.62
S03	45.84705361	-112.4769085	1969.70	6462.26
S04	45.84714455	-112.4766378	1969.56	6461.81
S0425	45.84721063	-112.4766864	1968.91	6459.68
S045	45.84719414	-112.4766729	1968.82	6459.38
S05	45.84717199	-112.4764161	1969.55	6461.78
S06	45.84726763	-112.4761267	1968.80	6459.31
S065	45.84733749	-112.4762078	1968.70	6458.99
S07	45.84730181	-112.4760397	1969.14	6460.44
S08	45.84718448	-112.4758311	1970.52	6464.95
S09	45.8470904	-112.4756482	1970.76	6465.76
S10	45.84658685	-112.4767094	1970.81	6465.91
S11	45.84658717	-112.4766841	1970.31	6464.26
S12	45.84659214	-112.4766409	1970.24	6464.03
Treatment Upstream Staff Gage	45.84660597	-112.476562	1969.81	6462.64
Treatment MidStream Staff Gage	45.84709352	-112.4765453	1969.05	6460.15
Treatment Downstream (Stream) Staff Gage	45.84733966	-112.4763557	1968.71	6459.04
Treatment Downstream Flow	45.84736695	-112.4763779	1968.24	6457.47
Treatment Downstream (Pond) Staff Gage	45.84722668	-112.4762452	1969.03	6460.08
Tributary Flow Location	45.84689789	-112.4753064	1971.92	6469.55
Stemp1	45.8466114	-112.4765341	1969.67	6462.17
Stemp2	45.84736225	-112.4763012	1968.76	6459.20
Stemp3	45.84708231	-112.4764841	1969.17	6460.53
Stemp4	45.84712586	-112.476623	1969.42	6461.35
Tributary Flow to BTC	45.84714705	-112.476397	1968.55	6458.50
BDA Structure Main Channel	45.84694788	-112.4766659	1968.89	6459.60
DownstreamBelowTreatment Staff Gage	45.84976789	-112.4781685	1961.94	6436.81

A.3. Basin01 Control and Treatment Monitoring Equipment

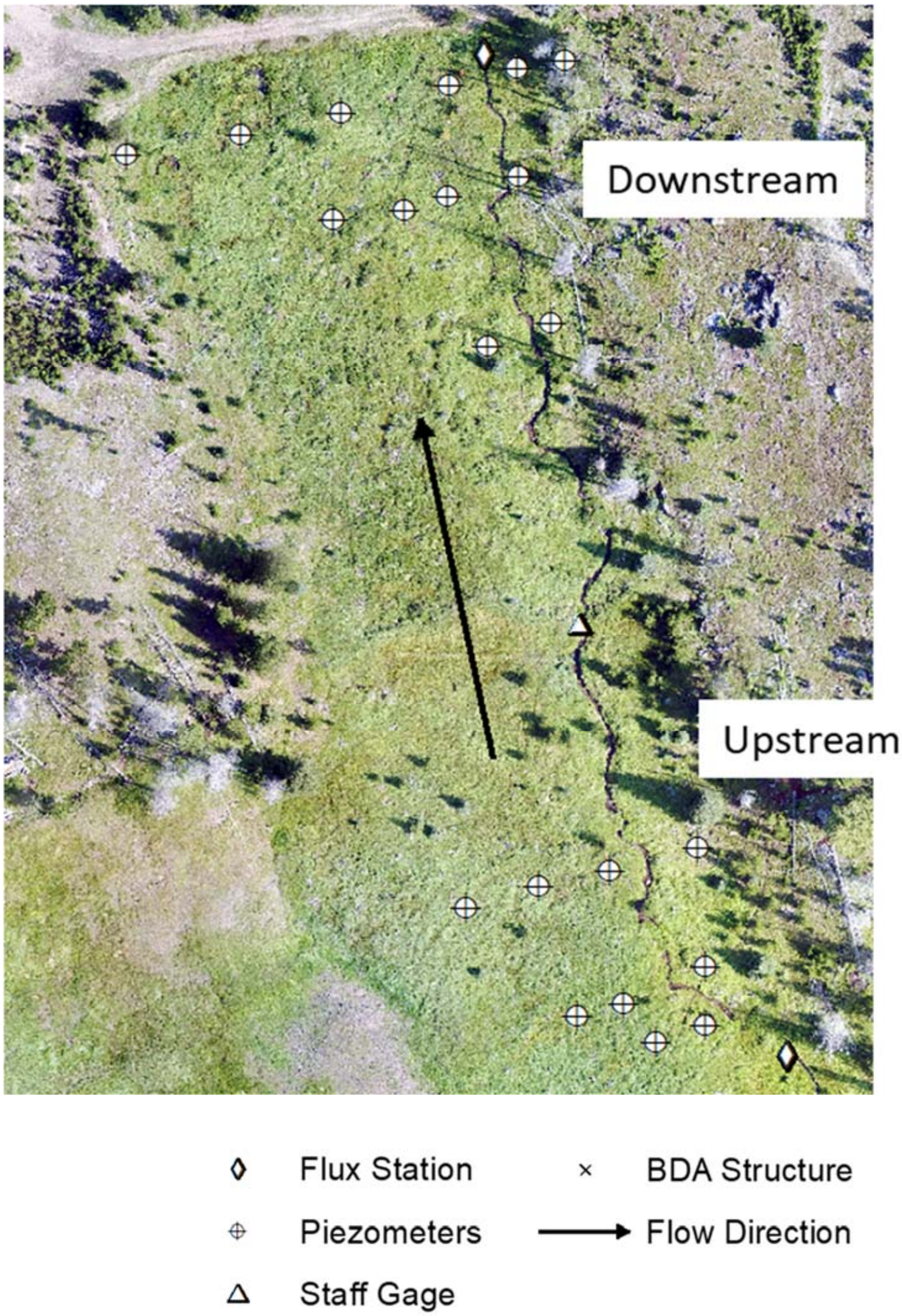
Basin Creek 01 Equipment	Latitude (Decimal Degrees)	Longitude (Decimal Degrees)	Elevation (feet)	Elevation (meters)
Basin01-Control01	45.84771598	-112.5266911	6013.46	1832.90
Basin01-Control02	45.84777524	-112.526869	6012.94	1832.74
Basin01-Control03	45.84784367	-112.5270483	6013.24	1832.84
Basin01-Control04	45.84789178	-112.5271812	6013.21	1832.83
Basin01-Control05	45.847931	-112.5272936	6013.04	1832.77
Basin01-Control06	45.84800895	-112.527486	6014.25	1833.14
Basin01-Control07	45.84792009	-112.5265652	6016.56	1833.85
Basin01-Control08	45.84797004	-112.5266567	6016.88	1833.95
Basin01-Control09	45.84800476	-112.5267488	6017.9	1834.26
Basin01-Control10	45.8480647	-112.5264316	6017.85	1834.24
Basin01-Control11	45.84810273	-112.5265771	6017.46	1834.12
Basin01-Control12	45.84814648	-112.5266766	6017.12	1834.02
Basin01-Treatment01	45.84591895	-112.5281231	5991.25	1826.13
Basin01-Treatment02	45.84590416	-112.5280485	5990.27	1825.83
Basin01-Treatment03	45.84588885	-112.5279598	5990.02	1825.76
Basin01-Treatment04	45.8458715	-112.5278788	5989.77	1825.68
Basin01-Treatment05	45.84584836	-112.5278154	5989.84	1825.70
Basin01-Treatment06	45.84604151	-112.5280842	5989.23	1825.52
Basin01-Treatment07	45.84603324	-112.5280152	5989.16	1825.50
Basin01-Treatment08	45.84601773	-112.5279087	5989.17	1825.50
Basin01-Treatment09	45.84600221	-112.5278518	5988.3	1825.23
Basin01-Treatment10	45.84613069	-112.528048	5987.03	1824.85
Basin01-Treatment11	45.84611283	-112.5279715	5986.54	1824.70
Basin01-Treatment12	45.84610423	-112.5279091	5986.7	1824.75

A.4. Basin02 Control and Treatment Monitoring Locations

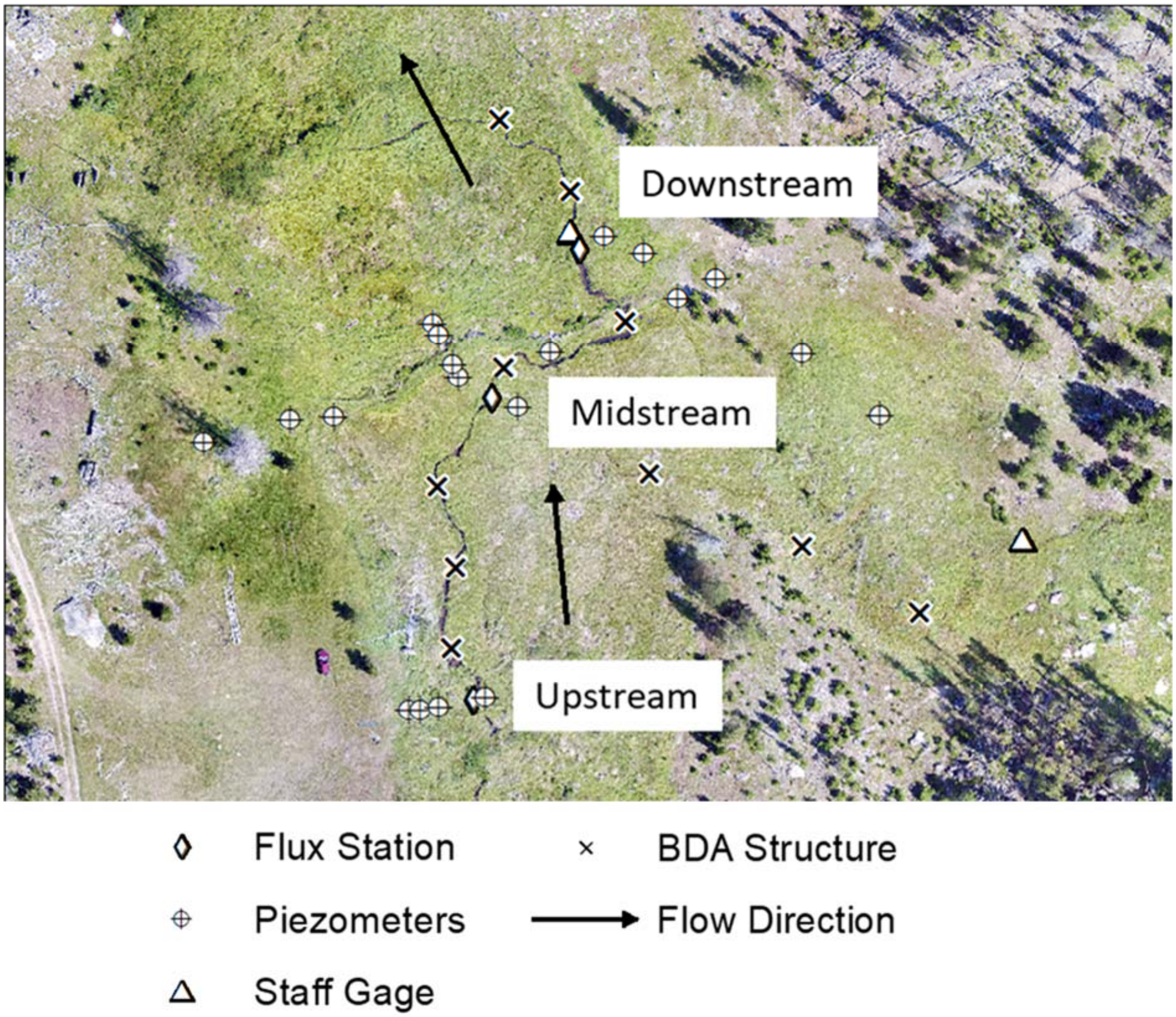
Basin Creek 02 Equipment	Latitude (Decimal Degrees)	Longitude (Decimal Degrees)	Elevation (feet)	Elevation (meters)
Basin02-Control01	45.842031	-112.5231708	6039.77	1840.92
Basin02-Control02	45.84195508	-112.5231241	6038.94	1840.67
Basin02-Control03	45.84188024	-112.5230715	6039.15	1840.73
Basin02-Control04	45.84179961	-112.5230247	6038.79	1840.62
Basin02-Control05	45.8417124	-112.5229725	6038.35	1840.49
Basin02-Control06	45.84198561	-112.523301	6038.27	1840.46
Basin02-Control07	45.84194453	-112.5232518	6038.49	1840.53
Basin02-Control08	45.8418805	-112.5232214	6038.16	1840.43
Basin02-Control09	45.84178245	-112.5231403	6038.18	1840.44
Basin02-Control10	45.84193079	-112.5234142	6038.09	1840.41
Basin02-Control11	45.84188175	-112.5233916	6037.56	1840.25
Basin02-Control12	45.84183745	-112.523359	6036.97	1840.07
Basin02-Treatment01	45.84145471	-112.524673	6024.61	1836.30
Basin02-Treatment02	45.8414248	-112.5246087	6023.76	1836.04
Basin02-Treatment03	45.84139717	-112.5245392	6023.68	1836.02
Basin02-Treatment04	45.84134784	-112.5247258	6024.13	1836.15
Basin02-Treatment05	45.84130905	-112.5246616	6022.5	1835.66
Basin02-Treatment06	45.84127514	-112.524574	6022.8	1835.75
Basin02-Treatment07	45.84121808	-112.5244808	6023.13	1835.85
Basin02-Treatment08	45.84119543	-112.524827	6022.28	1835.59
Basin02-Treatment09	45.84114874	-112.5247275	6021.33	1835.30
Basin02-Treatment10	45.84109663	-112.5246359	6021.34	1835.30
Basin02-Treatment11	45.84103383	-112.5244922	6021.19	1835.26
Basin02-Treatment12	45.84095813	-112.5243541	6021.63	1835.39

8. Appendix B: Blacktail Creek Monitoring Locations

B.1: Blacktail Creek Upstream Control Reach



B.2: Blacktail Creek Downstream Treatment Reach (Restored Oct. ’16):

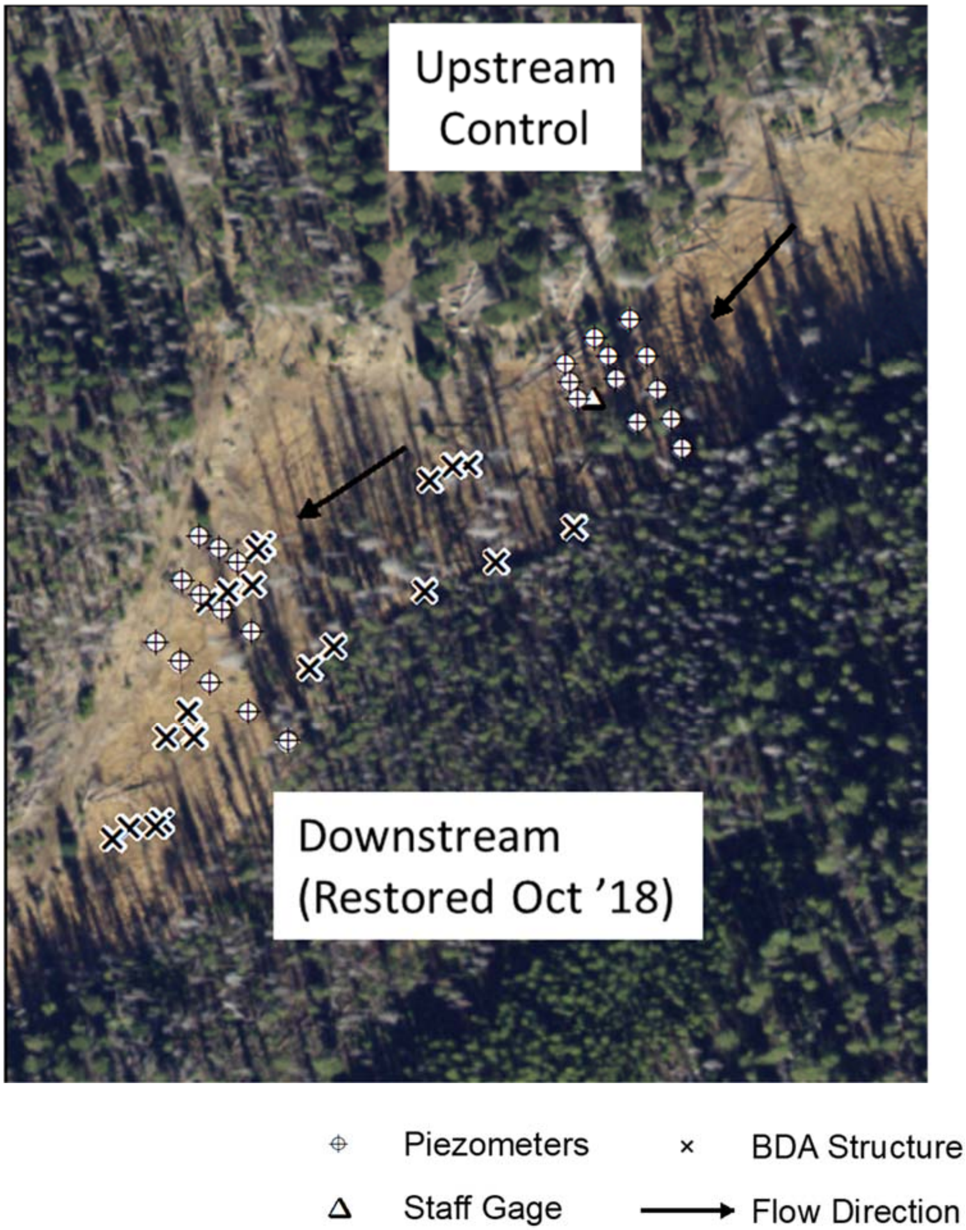


B.3: Blacktail Creek Transition Reach (Between Upstream Control and Downstream Treatment Reaches)

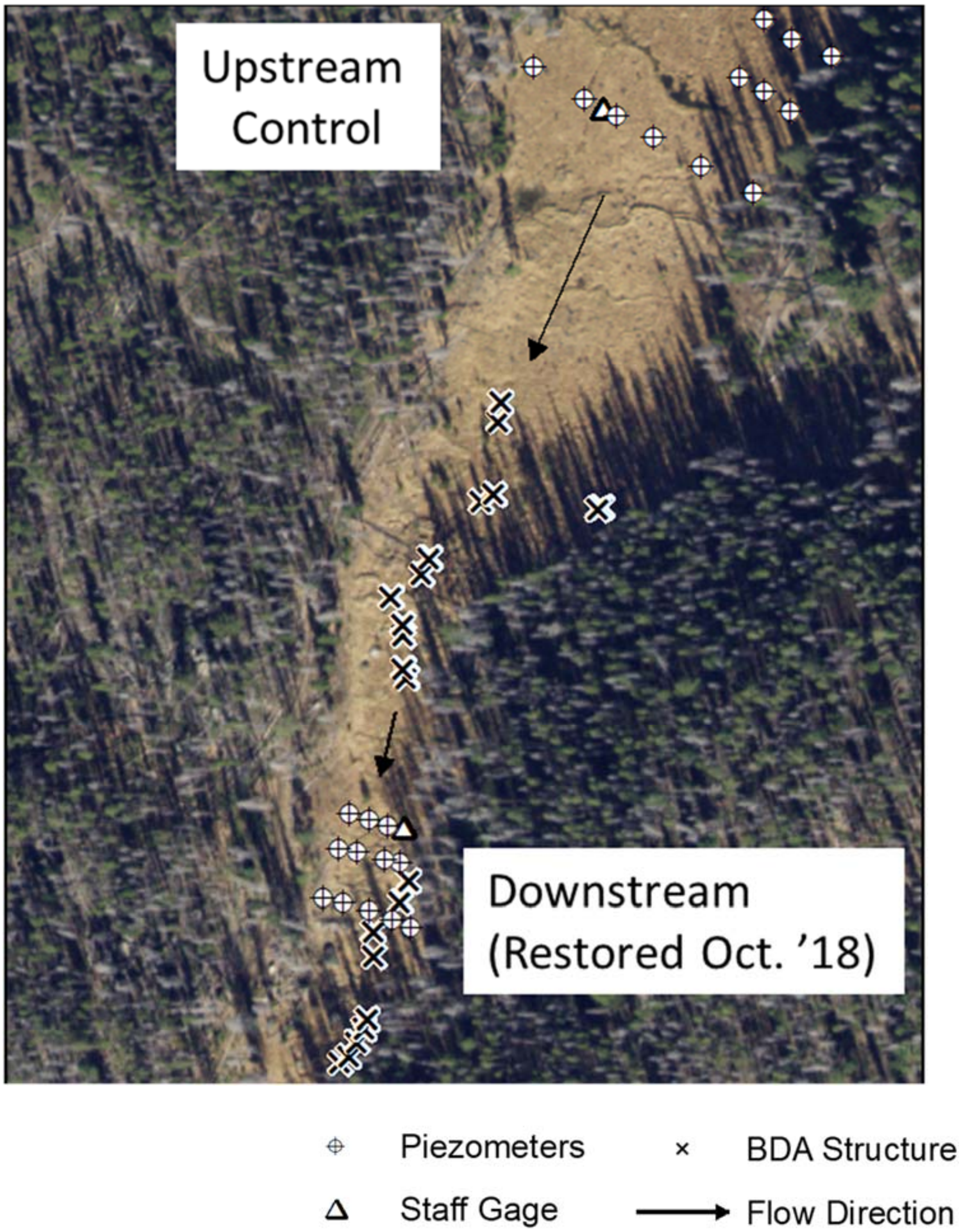
BTC Treatment Upstream

BTC Control Downstream

B.4: Basin01 Control and Treatment Equipment

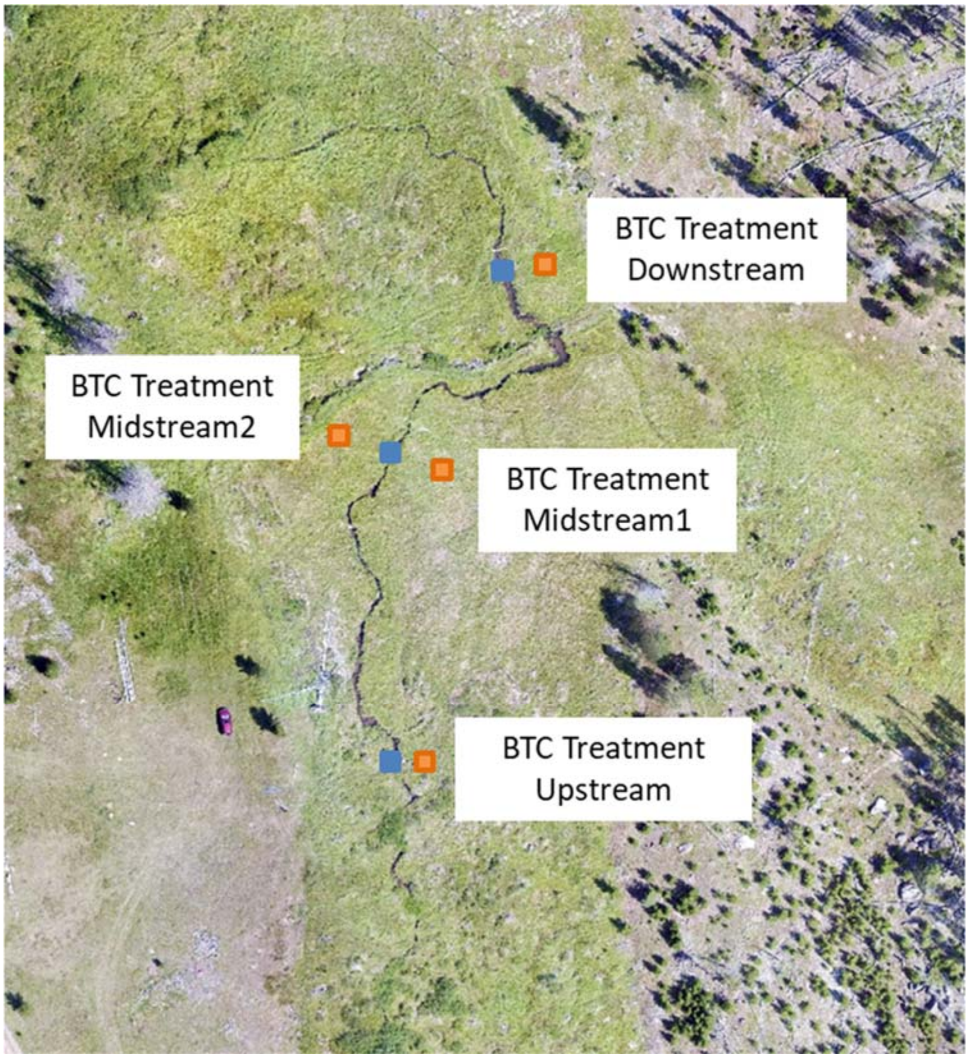


B.5: Basin02 Control and Treatment Equipment

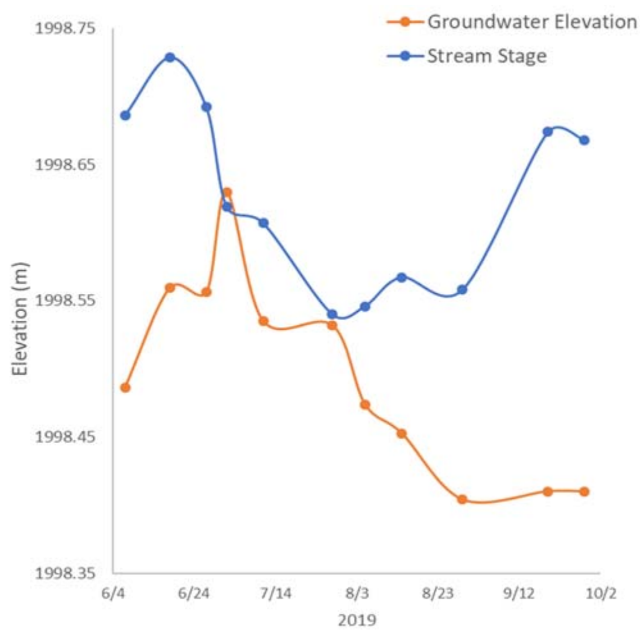


9. Appendix C: Blacktail Creek Treatment Stream Stage and Groundwater Elevations:

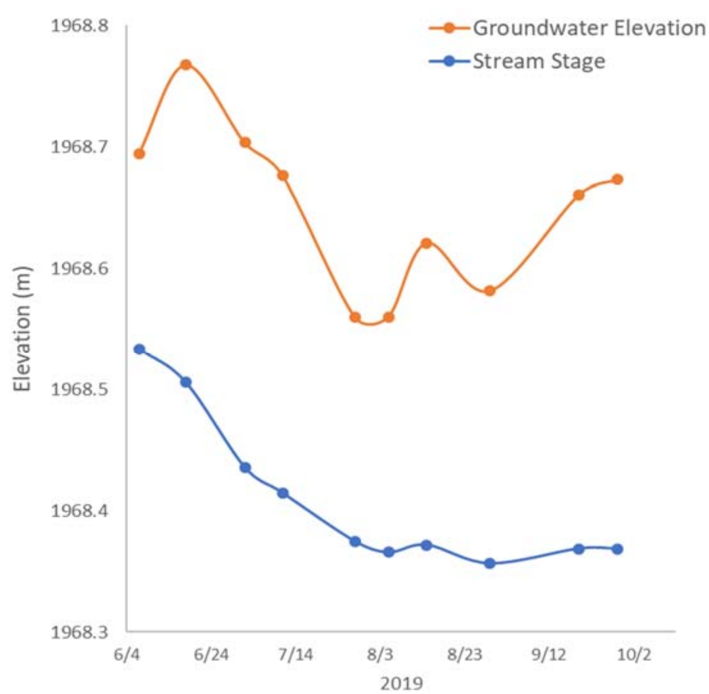
C.1: Blacktail Creek Treatment Monitoring Locations



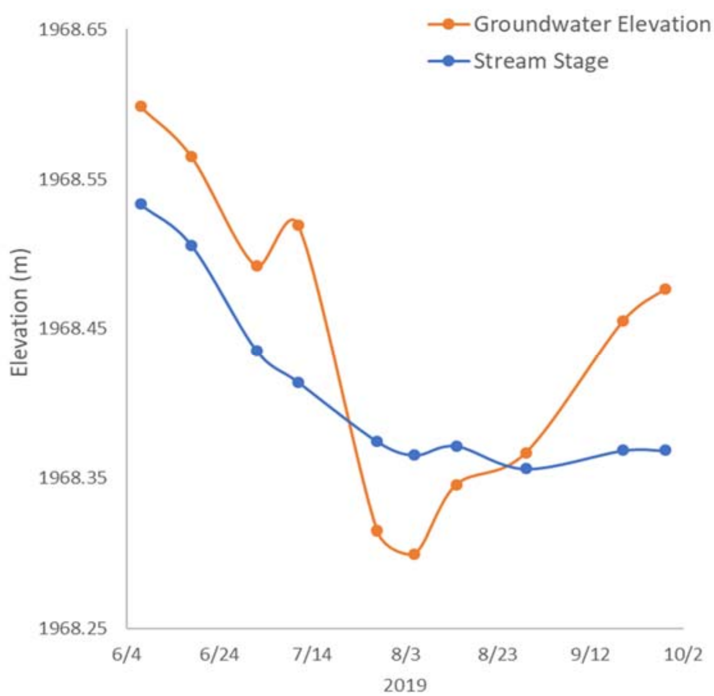
C.1.1: Blacktail Creek Treatment Upstream



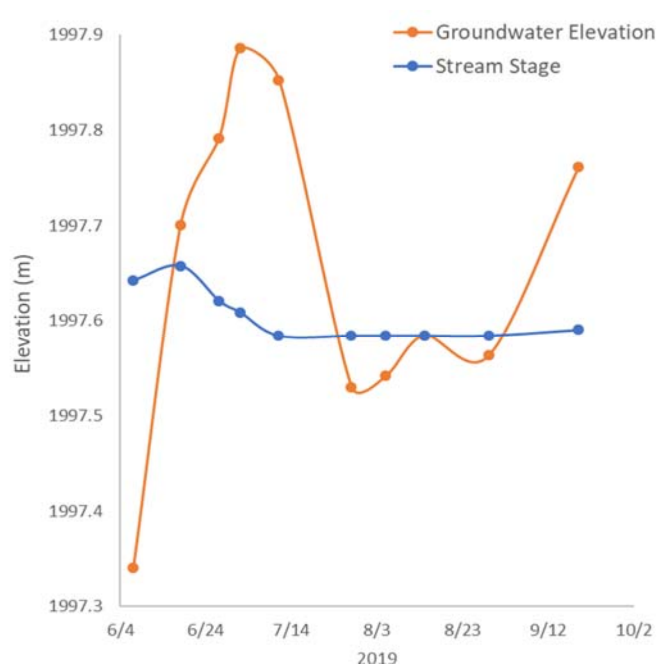
C.1.2: Blacktail Creek Treatment Midstream1



C.1.3: Blacktail Creek Treatment Midstream2

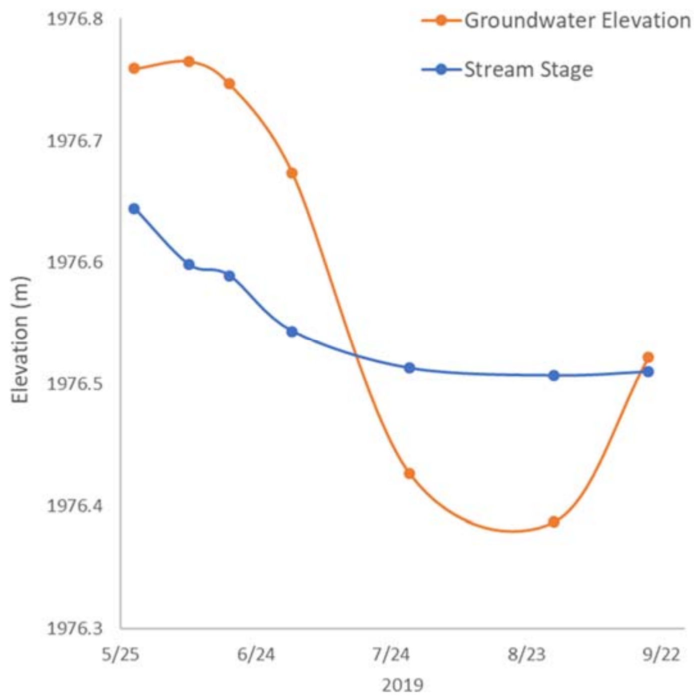


C.1.4: Blacktail Creek Treatment Downstream



C.2: Blacktail Creek Control Stream Stage & Groundwater Elevation

C.2.1: Blacktail Creek Control Downstream



10. Appendix D: Groundwater Elevations and Stream Stages

Groundwater values are top of casing to water surface (feet)
Red values denote dry wells (no water detected)
Staff gage readings are raw field value (feet)
Staff gage elevations are top of 3.33' staff gage

D.1.1. Blacktail Creek Control Groundwater Elevations

BTC Control Piezometer	A01	A02	A03	A04	A05	A06
Top of Casing Elevation (ft)	6488.12	6488.03	6486.97	6488.64	6486.40	6489.42
Piezometer Total Length (ft)	3.63	4.21	3.86	4.19	2.44	3.30
6/16/2017	1.59	0.85	1.21	2.36	1.35	1.56
7/13/2017	2.29	1.4	2.26	3.53	2.27	2.65
8/16/2017	3.48	2.63	2.95	4.15	2.3	3.2
10/6/2017	2.91	1.28	1.55	2.71	1.86	2.41
5/30/2018	1.4	0.53	0.61	1.72	0.49	1.25
7/14/2018	1.72	0.99	0.51	1.63	0.45	1.86
8/7/2018	2.31	1.28	0.6	1.76	0.49	2.68
9/4/2018	2.85	1.73	0.74	1.87	0.58	2.92
9/29/2018	2.78	1.33	0.73	1.86	0.6	2.66
5/28/2019	1.49	0.95	1.21	1.68	0.59	1.28
6/9/2019	1.63	0.93	1.03	1.93	0.92	1.39
6/18/2019	1.82	0.99	1.47	1.94	0.82	1.66
7/2/2019	2.08	1.23	1.87	2.5	1.53	2.12
7/28/2019	2.78	2.04	2.35	3.33	1.82	3.03
8/29/2019	2.58	2.16	2.48		2.32	1.98
9/19/2019	3.37	1.72	1.86	3.12	2.2	3.12
BTC Control Piezometer	**A07**	**A08**	**A09**	**A10**	**A11**	**A12**
Top of Casing Elevation (ft)	6488.58	6489.20	6485.78	6488.78	6491.36	6491.15
Piezometer Total Length (ft)	2.34	2.00	1.64	2.50	2.00	3.70
6/16/2017	1.32	1.59	2.23	2.67	1.94	3.14
7/13/2017	1.88	2.76	3.09	2.75	2.31	4.04
8/16/2017	2.9	2.78	3.25	2.75	3.32	4.4
10/6/2017	1.54	1.82	2.34	2.79	3.2	3.56
5/30/2018	1.3	0.92	1.91	2.4	1.73	2.88
7/14/2018	1.15	0.72	1.85	2.71	1.26	3.42
8/7/2018	1.35	0.87	1.98	2.75	1.84	3.59
9/4/2018	1.52	1.12	2.16	2.76	2.27	3.67
9/29/2018	1.49	1.07	2.07	2.72	2.35	3.45
5/28/2019	1.21	1.47	1.82	2.38	1.6	2.7
6/9/2019	1.29	1.37	1.95	2.48	1.17	1.83

6/18/2019	1.39	1.33	2.09	2.55	0.52	2.95
7/2/2019	1.62	1.61	2.22	2.68	0.84	3.27
7/28/2019	2.29	2.51	2.82	2.75	2.3	3.87
8/29/2019	2.39	2.57	3.25	2.75	2.54	3.99
9/19/2019	2.07	2.07	2.06	2.72	2.39	3.75
BTC Control Piezometer	**T01**	**T02**	**T03**	**T04**	**T05**	**T06**
Top of Casing Elevation (ft)	6497.22	6499.31	6495.18	6499.10	6502.92	6502.64
Piezometer Total Length (ft)	3.22	4.03	3.64	2.96	3.14	3.17
6/16/2017	1.65	2.04	2.4	1.46	2.02	1.88
7/13/2017	2.61	3.17	3.32	2.42	2.82	2.83
8/16/2017	2.87	3.66	3.28	2.47	2.81	2.82
10/6/2017	1.98	2.26	2.68	1.59	2.3	2.1
5/30/2018	1.08	1.13	1.05	0.93	0.92	0.19
7/14/2018	1.99	2.78	3.27	2.19	2.41	2.78
8/7/2018	2.6	3.17	3.28	2.45	2.76	2.82
9/4/2018	2.88	3.23	3.29	2.48	2.76	2.82
9/29/2018	2.69	2.86	3.27	2.46	2.74	2.81
5/9/2019	1.71	1.77	1.2	1.42	2.12	1.51
5/16/2019	0.91	0.97	0.2	-0.08	0.99	0.21
5/28/2019	1.62	1.75	2.28	1.35	2.35	1.96
6/9/2019	1.69	1.89	2.4	1.4	2.27	1.83
6/18/2019	1.82	2.02	2.52	1.46	2.21	1.87
7/2/2019	2.18	2.38	2.83	1.7	2.38	2.22
7/28/2019	2.8	3.12	2.75	2.46	2.76	2.8
8/29/2019	3.6	2.62	3.47	2.93	2.38	2.99
9/19/2019	2.75	2.82	3.26	1.95	2.75	2.8

BTC Control Piezometer	**T07**	**T08**	**T09**
Top of Casing Elevation (ft)	6503.11	6501.69	6503.45
Piezometer Total Length (ft)	3.19	4.75	3.53
6/16/2017	1.85	2.44	2.72
7/13/2017	2.92	3.61	3.12
8/16/2017	2.91	3.88	3.25
10/6/2017	2.21	2.81	3.14
5/30/2018	0.12	1.12	0.47
7/14/2018	2.9	3.27	3.25
8/7/2018	2.92	3.23	3.61
9/4/2018	2.91	3.66	3.23
9/29/2018	2.92	3.22	3.44
5/9/2019	1.46	2.8	2.4
5/16/2019	0.16	1.3	0.5
5/28/2019	1.41	2.16	2.41

6/9/2019	1.59	2.45	2.73
6/18/2019	1.6	2.52	2.79
7/2/2019	2.2	2.9	3.21
7/28/2019	2.93	3.74	3.21
8/29/2019	2.92	3.64	3.55
9/19/2019	2.84	3.49	3.16

D.1.2. Blacktail Creek Control Stream Stage Readings

BTC Control Staff Gages	Upstream Control Staff Gage	Downstream Control Staff Gage	Midstream Control Staff Gage
Elevation (ft)	6504.04	6488.12	6494.75
6/16/2017	1.39	1.24	0.79
7/13/2017	1.15	0.94	0.62
8/16/2017	1.19	0.83	0.51
10/6/2017	1.18	0.97	0.62
5/30/2018	1.97	2	1.1
7/14/2018	1.49	1.67	0.78
8/7/2018	1.27	1.49	0.62
9/4/2018	1.07	1.34	0.51
9/29/2018	1.14	1.28	0.51
5/9/2019	1.43	1.65	0.71
5/16/2019	1.59	1.79	0.81
5/28/2019	1.82	1.92	0.99
6/9/2019	1.69	1.77	0.78
6/18/2019	1.48	1.74	0.73
7/2/2019	1.24	1.59	0.59
7/11/2019	1.19	1.65	0.55
7/28/2019	1.05	1.49	0.45
8/5/2019	1.08	1.5	0.5
8/29/2019	1.07	1.47	0.42
9/19/2019	0.98	1.48	0.48

D.2.1. Blacktail Creek Treatment Groundwater Elevation

BTC Treatment PZ	S01	S02	S03	S04	S05	S06
Top of Casing Elevation (ft)	6466.40	6464.62	6462.26	6461.81	6461.78	6459.31
Piezometer Total Length (ft)	3.58	4.17	2.96	5.4	5.5	3.43
7/28/2016	N	3.31	1.76	4.78	4.6	2.34
10/1/2016	N	2.7	1.47	3.93	4.32	2.09
5/9/2017	2.49	2.27	1.59	2.9	3.35	2.13
5/24/2017	1.76	1.67	1.42	2.75	3.1	1.61
6/16/2017	2.09	1.89	1.45	2.96	3.37	1.79
7/13/2017	3.13	2.88	1.64	3.53	3.65	2.14
8/16/2017	3.52	3.31	1.98	4.09	3.88	2.44
10/6/2017	2.65	2.09	1.73	3.14	3.67	2.01
5/30/2018	1.77	1.61	1.5	2.91	3.2	1.74
7/14/2018	2.19	2.15	1.82	3.5	3.62	2.15
8/7/2018	2.4	2.18	1.87	3.73	3.8	2.37
9/4/2018	2.45	2.15	1.8	3.84	3.9	2.35
9/29/2018	2.37	1.98	1.72	3.56	3.89	2.17
5/9/2019	1.81	1.56	1.64	2.82	2.87	2.39
5/25/2019	1.71	1.45	1.8	3.78	3.28	2.2
6/3/2019	2.03	1.7	1.9	3.14	3.58	2.03
6/18/2019	2.25	1.9	1.83	4.13	4.2	2.05
7/2/2019	2.52	2.18	2.12	3.81	3.85	2.21
7/28/2019	3.07	2.92	2.5	4.57	4.1	2.46
8/14/2019	2.98	2.55	1.94	4.32	4	2.34
8/29/2019	3.13	2.65	2.04	4.35	4.07	2.37
9/19/2019	2.87	2.28	1.98	3.88	4.04	2.2
9/28/2019	2.84	2.22	1.86	3.69	4	2.16
BTC Treatment PZ	**S07**	**S08**	**S09**	**S10**	**S11**	**S12**
Top of Casing Elevation (ft)	6460.44	6464.95	6465.76	6465.92	6464.26	6464.03
Piezometer Total Length (ft)	3.92	3.25	3.5	3.21	3.04	4.67
7/28/2016	3.44	N	2.86	2.19	1.16	3.97
10/1/2016	2.24	2.59	2.73	2.22	1.06	3.49
5/9/2017	1.72	1.84	1.21	1.75	1.23	3.14
5/24/2017	1.16	1.4	0.98	1.39	0.98	3
6/16/2017	1.21	1.42	1.01	1.49	0.99	3.12
7/13/2017	2.29	3.15	1.31	1.71	0.96	3.28
8/16/2017	3.29	3.14	2.54	3.64	1.34	2.12
10/6/2017	1.66	2.98	1.55	1.94	1.18	3.21
5/30/2018	2.58	2.21	0.93	1.28	0.78	2.74
7/14/2018	2.11	2.72	1.06	1.25	0.69	3.06

8/7/2018	2.7	2.99	1.73	1.28	0.66	3.07
9/4/2018	2.67	3.16	2.28	1.28	0.65	3.05
9/29/2018	2.25	3.03	2.12	1.21	0.59	3.08
5/9/2019	1.6	2.3	1.16	1.25	0.73	2.75
5/25/2019	1.48	2.25	1.14	1.29	0.62	3.04
6/3/2019	1.67	2.27	1.12	1.13	0.68	3.35
6/18/2019	2.03	2.35	1.14	1.27	0.68	3.53
7/2/2019	2.3	2.83	1.26	1.32	0.76	3.27
7/28/2019	2.74	3.23	1.73	1.66	0.88	3.62
8/14/2019	2.84	3.22	1.85	1.62	0.76	3.34
8/29/2019	2.85	3.22	1.95	1.67	0.74	3.33
9/19/2019	2.4	3.26	1.97	1.61	0.8	3.21
9/28/2019	2.35	3.07	1.86	1.54	0.75	3.16

BTC 1" Treatment Piezometer	**Stemp1**	**Stemp2**	**Stemp3**	**Stemp4**
Top of Casing Elevation (ft)	6462.17	6459.20	6460.53	6461.35
Piezometer Total Length (ft)	4.93	5.73	5.66	8.78
6/7/2019	1.42	2.86	1.56	2.69
6/18/2019	1.28	1.68	1.32	2.8
6/27/2019	1.4	1.38	1.46	
7/2/2019	1.64	1.07	1.53	3.04
7/11/2019	1.68	1.18	1.62	2.95
7/28/2019	1.9	2.24	2	3.62
8/5/2019	1.88	2.2	2	3.67
8/14/2019	1.81	2.06	1.8	3.52
8/29/2019	1.84	2.13	1.93	3.45
9/19/2019	1.46	1.48	1.67	3.16
9/28/2019	1.48	1.46	1.63	3.09

D.2.2. Blacktail Creek Treatment Stream Stage Data

BTC Treatment Staff Gages	Treatment Upstream Staff Gage	Treatment Downstream (Pond) Staff Gage	Treatment MidStream Staff Gage	Treatment Downstream (Stream) Staff Gage
Elevation (ft)	6462.64	6460.08	6460.15	6459.04
7/28/2016	0.1	0.4		
10/1/2016	0.16	0.48		
5/24/2017	1.2	1.8		
6/16/2017	0.88	1.59		
7/13/2017	0.62	1.04		
8/16/2017	0.54	1.21		
10/6/2017	0.69	1.3		
5/30/2018	1.27	1.68		
7/14/2018	1.02	1.48		
8/7/2018	0.78	1.31		
9/4/2018	0.66	1.19		
9/29/2018	0.66	1.26		
5/9/2019	0.79	1.37		
5/16/2019	1.03	1.46		
5/25/2019	1.02	1.48		
5/28/2019	1.26	1.57		
6/3/2019	0.95	1.43		
6/7/2019			1.62	1.62
6/18/2019	0.94	1.37	1.53	1.67
7/2/2019	0.75	1.25	1.3	1.55
7/11/2019	0.68	1.19	1.23	1.51
7/28/2019	0.52	1.04	1.1	1.43
8/5/2019	0.54	1.04	1.07	1.43
8/14/2019	0.54	1.06	1.09	1.43
8/19/2019			1	1.43
8/29/2019	0.51	1.06	1.04	1.43
9/19/2019	0.59	0.98	1.08	1.45
9/28/2019	0.57	0.99	1.08	1.46

D.3.1. Basin01 Control Groundwater Elevations

Basin01 Control Piezometer	**B01-C01**	**B01-C02**	**B01-C03**	**B01-C04**	**B01-C05**	**B01-C06**
Ground Elevation (ft)	6013.46	6012.94	6013.24	6013.21	6013.04	6014.25
Ground to Top Pipe (ft)	1	0.94	0.83	0.99	0.52	0.96
6/23/2017		2.97	2.47	2.51	2.13	2.35
7/14/2017	2.45	3.12	2.48	2.62	3.12	2.48
8/16/2017	2.6	3.15	2.46	2.55	1.92	2.58
10/6/2017	2.24	2.42	2.22	2.22	1.72	2.28
6/1/2018	1.87	2.13	1.94	2.05	1.4	2.51
7/16/2018	2.01	2.76	2.22	2.23	1.54	2.14
8/8/2018	2.06	2.76	2.27	2.3	1.64	2.23
9/6/2018	1.08	1.75	1.45	1.33	1.22	1.25
10/2/2018	1	1.41	1.21	1.19	1.07	1.11
6/4/2019	0.99	1.41	1.48	1.32	1.1	1.27
6/25/2019	0.99	1.5	1.68	1.22	1.05	1.28
8/19/2019	1.15	1.64	1.25	1.5	0.81	1.5
9/12/2019	1.03	1.29	1.08	1.01	0.6	1.21
10/18/2019	0.9	1.31	1.08	1.02	0.71	1.15
Basin01 Control Piezometer	**B01-C07**	**B01-C08**	**B01-C09**	**B01-C10**	**B01-C11**	**B01-C12**
Ground Elevation (ft)	6016.56	6016.88	6017.9	6017.85	6017.46	6017.12
Ground to Top Pipe (ft)	0.95	0.96	0.93	0.79	0.86	0.97
6/23/2017	2.2	2.23	2.34	2.02	1.96	1.57
7/14/2017	2.18	2.24	2.31	2.03	1.91	1.95
8/16/2017	2.15	2.48	2.85	2.15	2.29	2.27
10/6/2017	2.08	2.32	2.37	1.87	2.06	2.05
6/1/2018	2.02	2.15	2.25	2.04	1.89	1.91
7/16/2018	2.03	2.16	2.3	1.71	1.9	1.81
8/8/2018	2.02	2.28	2.35	1.74	1.94	1.9
9/6/2018	1.02	1.23	1.46	0.92	1.08	0.83
10/2/2018	1.02	1.28	1.49	0.96	1.1	0.88
6/4/2019	1.2	1.21	1.43	0.01	1.5	0.92
6/25/2019	1.09	1.25	1.46	0.23	1.04	0.85
8/19/2019	1.09	1.23	1.5	0	1.02	0.96
9/12/2019	1.06	1.21	1.39	0	1.02	0.8
10/18/2019	1.03	1.21	1.41	0	0.91	0.81

D.3.2. Basin01 Treatment Groundwater Elevations

Basin01 Treatment Piezometer	B01-T01	B01-T02	B01-T03	B01-T04	B01-T05	B01-T06
Ground Elevation (ft)	5991.25	5990.27	5990.02	5989.77	5989.84	5989.23
Ground to Top Pipe (ft)	0.97	1.05	1.01	1.03	0.96	0.99
6/23/2017	4.32	3.55	2.8	2.85	2.74	3.15
7/14/2017	4.34	4.03	3.17	2.9	2.94	3.16
8/16/2017	4.32	4.2	3.36	3.23	3.24	3.18
10/6/2017	4.05	3.05	2.41	2.86	2.88	2.85
6/1/2018	2.17	2.5	2.01	2.39	2.48	2.3
7/16/2018	3.61	2.95	2.3	2.82	2.4	2.97
8/8/2018	4.06	3.35	2.68	2.86	2.54	3.08
9/6/2018	3.38	2.55	1.83	1.9	1.81	2.07
10/2/2018	2.98	2.06	1.37	1.88	1.81	1.98
10/23/2018	2.99	2.13	1.28	1.42	1.49	2.05
6/4/2019	2.6	1.83	1.1	1.4	1.52	1.96
6/25/2019	2.94	2.09	1.15	1.42	1.61	2.03
8/19/2019	3.3	2.93	1.67	1.67	1.79	1.85
9/12/2019	3.22	2.9	1.27	1.57	1.76	1.26
10/18/2019	2.91	1.94	1.15	1.47	1.71	1.73
Basin01 Treatment Piezometer	**B01-T07**	**B01-T08**	**B01-T09**	**B01-T10**	**B01-T11**	**B01-T12**
Ground Elevation (ft)	5989.16	5989.17	5988.3	5987.03	5986.54	5986.7
Ground to Top Pipe (ft)	0.95	1.04	0.97	0.97	0.97	1
6/23/2017	3.2	3.19	2.66	2.16	2.57	2.82
7/14/2017	3.16	3.39	2.79	2.25	2.7	2.85
8/16/2017	3.16	3.6	2.91	2.47	2.77	2.63
10/6/2017	2.7	3.11	2.59	2.23	2.42	2.27
6/1/2018	2.25	2.74	2.16	2.02	2.19	2.66
7/16/2018	2.77	2.81	2.56	2	2.1	2.72
8/8/2018	3.17	2.8	2.66	2.05	2.16	1.91
9/6/2018	2.31	1.91	1.76	1.19	1.21	1.65
10/2/2018	1.74	1.98	1.52	1.08	1.2	1.73
10/23/2018	2.04	1.92	1.22	1.17	1.21	1.52
6/4/2019	1.69	1.79	1.07	1.13	1.15	1.61
6/25/2019	1.92	1.83	1.16	1.21	1.18	1.95
8/19/2019	2.25	1.85	1.6	1.11	1.09	1.58
9/12/2019	1.61	1.87	1.35	1.19	1.18	1.58
10/18/2019	1.61	1.89	1.3	1.12	1.21	1.58

D.4.1. Basin02 Control Groundwater Elevations

Basin02 Control Piezometer	**B02-C01**	**B02-C02**	**B02-C03**	**B02-C04**	**B02-C05**	**B02-C06**
Ground Elevation (ft)	6039.77	6038.94	6039.15	6038.79	6038.35	6038.27
Ground to Top Pipe (ft)	0.94	1.35	0.96	0.97	0.7	1
6/1/2018	2.44	1.55	2.18	1.82	2.14	1.95
7/16/2018	2.94	1.87	2.2	2.35	2.14	2.05
8/8/2016	2.95	2.15	2.45	2.36	2.16	2.2
9/6/2018	2.85	2.26	2.57	2.38	2.17	2.35
10/2/2018	2.96	2.9	2.62	2.39	2.18	2.41
6/4/2019	2.84	2.86	2.8	3.03	2.08	2.29
6/25/2019	3.03	2.02	2.55	2.36	2.08	2.3
8/19/2019	2.12	2.39	2.82	2.27	3.12	2.6
9/12/2019	3	2.23	2.73	2.45	2.12	2.49
10/18/2019	3.05	1.41	2.67	2.45	2.13	2.52
Basin02 Control Piezometer	**B02-C07**	**B02-C08**	**B02-C09**	**B02-C10**	**B02-C11**	**B02-C12**
Ground Elevation (ft)	6038.49	6038.16	6038.18	6038.09	6037.56	6036.97
Ground to Top Pipe (ft)	0.6	0.96	1.08	0.61	0.94	0.83
6/1/2018	0.6	1.82	1.76	2.05	1.33	1.31
7/16/2018	0.83	1.91	2.02	1.7	1.67	1.48
8/8/2016	1	2.04	2.12	1.8	1.83	1.6
9/6/2018	1.2	2.11	2.21	1.87	2	1.72
10/2/2018	1.24	2.04	2.27	1.92	1.87	1.78
6/4/2019	1.46	1.98	2.42	1.81	1.86	1.41
6/25/2019	1.47	2.06	2.44	1.86	1.82	1.54
8/19/2019	2.29	1.51	2.47	1.75	2.15	1.97
9/12/2019	1.57	2.07	2.55	2.06	1.86	1.73
10/18/2019	1.5	2.04	2.7	2.15	1.84	1.82

D.4.2. Basin02 Treatment Groundwater Elevations

Basin02 Treatment Piezometer	B02-T01	B02-T02	B02-T03	B02-T04	B02-T05	B02-T06
Ground Elevation (ft)	6024.61	6023.76	6023.68	6024.13	6022.5	6022.8
Ground to Top Pipe (ft)	1.03	1.11	1.16	1.07	0.94	1.04
6/1/2018	2.9	2.12	1.69	2.37	1.07	1.36
7/16/2018	3.59	2.57	2.07	3.92	1.57	2.07
8/8/2016	3.73	2.62	2.11	3.02	1.71	2.09
9/6/2018	4.02	2.76	2.14	3.1	1.8	2.11
10/2/2018	3.73	2.63	2.12	3.12	1.73	2.13
6/4/2019	2.82	2.24	1.75	2.52	0.99	1.59
6/25/2019	2.98	2.14	1.8	2.59	1.01	1.7
8/19/2019	3.59	2.66	2.13	3.05	1.47	2.07
9/12/2019	3.51	2.53	2.02	3.92	1.25	1.91
10/18/2019	3.51	2.59	2.03	2.92	1.28	1.89
Basin02 Treatment Piezometer	**B02-T07**	**B02-T08**	**B02-T09**	**B02-T10**	**B02-T11**	**B02-T12**
Ground Elevation (ft)	6023.13	6022.28	6021.33	6021.34	6021.19	6021.63
Ground to Top Pipe (ft)	1.07	1.05	1.03	1.11	1.08	1.13
6/1/2018	1.79	2.39	1.13	1.37	1.28	2.18
7/16/2018	2.21	2.32	1.72	1.82	1.57	1.63
8/8/2016	2.21	2.58	1.95	1.99	1.72	1.93
9/6/2018	2.28	2.79	2.03	2.03	1.79	2.16
10/2/2018	2.26	2.89	1.93	1.98	1.69	2.13
6/4/2019	1.93	2.17	1.51	1.65	1.39	1.37
6/25/2019	2.08	2.23	1.63	1.7	1.32	1.6
8/19/2019	2.4	2.64	1.84	1.8	1.47	1.92
9/12/2019	2.5	2.67	1.66	1.75	1.4	1.99
10/18/2019	2.22	2.68	1.6	1.74	1.36	2.04

D.5.1. Basin01 and Basin02 Stream Stage Data

Basin Creek Staff Gages	Basin01 Control Staff Gage	Basin01 Treatment Staff Gage	Basin02 Control Staff Gage	Basin02 Treatment Staff Gage
Elevation (ft)	6015.52	5992.93	6039.83	6025.27
6/23/2017	0.66	0.5		
7/14/2017	0.58	0.4		
8/16/2017	0.82	0.2		
10/6/2017	0.99	0.4		
6/1/2018	1.29	1		
7/16/2018	0.82	0.64		
8/8/2018	0.75	0.55		
9/6/2018	0.65	0.43	0.73	0.53
10/2/2018	0.77	0.6	0.87	0.56
10/12/2018	0.8	0.63		
6/4/2019	0.94	0.63	0.73	1.22
6/25/2019	0.86	0.64	0.61	1.14
8/19/2019	1.1	0.8	0.48	0.96
9/12/2019	1.24	0.45	0.57	1.03
10/18/2019	1.03	0.58	0.59	1.11

11. Appendix E: Blacktail Creek Average Daily Stream flow

E.1. Blacktail Creek Control Stream flow

Blacktail Creek	2018 Average Daily Flows (ft^3s^{-1})		2018 Average Daily Flows (ft^3s^{-1})	
Date	Upstream Control	Downstream Control	Upstream Control	Downstream Control
9-May	13.72	10.70	3.24	2.57
10-May	14.90	11.90	3.08	2.44
11-May	15.78	12.44	3.52	2.99
12-May	14.99	10.37	3.99	3.66
13-May	14.92	10.86	4.13	3.78
14-May	14.61	10.31	4.07	3.89
15-May	13.41	9.83	4.19	4.06
16-May	13.22	9.89	4.75	4.76
17-May	13.81	10.53	6.80	8.19
18-May	15.93	13.18	6.32	5.19
19-May	14.63	12.01	5.36	3.84
20-May	13.06	10.36	5.05	3.58
21-May	13.20	9.57	5.18	3.74
22-May	18.46	12.16	5.28	3.90
23-May	19.32	14.02	5.08	3.92
24-May	16.42	11.47	5.25	4.14
25-May	14.31	10.92	6.08	5.29
26-May	14.04	9.65	6.62	5.77
27-May	13.18	8.36	6.34	5.40
28-May	13.96	10.38	7.66	6.85
29-May	12.82	8.29	6.33	5.22
30-May	13.13	11.32	6.32	5.11
31-May	17.87	19.35	7.13	6.25
Jun	19.86	18.08	6.81	5.69
1-Jun	14.49	11.85	6.30	4.95
2-Jun	13.26	10.72	5.88	4.47
3-Jun	12.60	9.18	5.45	3.96
4-Jun	12.09	8.54	5.21	3.73
5-Jun	11.52	7.74	5.13	3.62
6-Jun	11.45	7.41	5.85	4.17
7-Jun	10.82	6.39	6.09	4.55
8-Jun	9.90	5.72	5.56	4.19
9-Jun	11.79	8.18	5.20	3.75
10-Jun	10.29	5.89	4.81	3.33

11-Jun	9.42	5.10	4.59	3.20
12-Jun	8.58	4.54	6.93	7.02
13-Jun	8.07	4.05	4.79	4.70
14-Jun	8.02	4.37	3.72	3.48
15-Jun	16.25	19.45	3.58	3.33
16-Jun	11.50	10.08	3.98	3.72
17-Jun	17.30	22.42	3.76	3.51
18-Jun	14.86	16.98	3.28	3.07
19-Jun	12.78	13.33	3.71	3.33
20-Jun	13.54	15.94	4.30	3.71
21-Jun	13.10	14.96	3.83	3.36
22-Jun	12.66	13.48	3.55	3.05
23-Jun	11.30	11.69	3.40	2.88
24-Jun	10.14	9.81	3.18	2.73
25-Jun	9.12	8.55	3.17	2.64
26-Jun	8.47	7.66	3.78	3.28
27-Jun	8.39	9.39	3.03	3.06
28-Jun	11.23	11.35	2.43	2.62
29-Jun	9.42	7.84	2.30	2.46
30-Jun	8.17	6.76	2.23	2.27
Jul	7.51	6.18	2.25	2.11
1-Jul	7.11	5.84	2.58	2.29
2-Jul	6.60	5.61	2.42	2.12
3-Jul	6.28	4.98	2.25	1.95
4-Jul	6.03	4.49	2.15	1.66
5-Jul	6.08	4.18	2.12	1.52
6-Jul	5.83	3.95	2.84	2.17
7-Jul	5.67	3.70	3.30	2.80
8-Jul	5.37	3.28	2.31	1.89
9-Jul	5.13	3.27	2.12	1.74
10-Jul	4.94	2.92	2.03	1.64
11-Jul	4.72	2.76	2.03	1.66
12-Jul	4.49	3.51	2.00	1.62
13-Jul	4.31	4.08	2.01	1.59
14-Jul	4.15	3.98	2.73	2.18
15-Jul	4.65	4.67	3.45	3.08
16-Jul	4.09	3.81	2.28	2.01
17-Jul	3.64	3.49	1.98	1.74
18-Jul	3.39	3.24	1.88	1.62
19-Jul	3.13	3.10	1.77	1.57
20-Jul	2.97	3.01	1.76	1.59

21-Jul	2.71	2.84	1.66	1.54
22-Jul	2.54	2.74	1.59	1.53
23-Jul	2.40	2.60	1.50	1.50
24-Jul	2.26	2.46	1.46	1.49
25-Jul	2.07	2.32	1.49	1.48
26-Jul	1.95	2.21	1.48	1.46
27-Jul	1.83	2.08	1.49	1.57
28-Jul	1.60	1.93	1.64	1.71
29-Jul	1.51	1.87	1.63	1.70
30-Jul	1.43	1.76	1.52	1.59
31-Jul	1.33	1.64	1.60	1.54
Aug	1.23	1.51	1.65	1.59
1-Aug	1.08	1.51	1.46	1.45
2-Aug	1.17	1.64	1.31	1.41
3-Aug	1.03	1.47	1.17	1.41
4-Aug	0.89	1.25	1.19	1.38
5-Aug	0.96	1.10	1.23	1.40
6-Aug	0.93	1.00	1.80	1.88
7-Aug	0.91	1.02	2.00	1.95
8-Aug	0.93	1.00	1.68	1.63
9-Aug	0.94	0.94	1.57	1.53
10-Aug	0.92	0.92	1.47	1.47
11-Aug	0.92	0.89	1.42	1.44
12-Aug	0.90	0.86	1.50	1.53
13-Aug	0.92	0.79	1.54	1.58
14-Aug	0.95	0.86	1.49	1.51
15-Aug	1.07	0.96	1.46	1.48
16-Aug	1.01	0.90	1.42	1.46
17-Aug	1.13	1.12	1.35	1.46
18-Aug	1.44	1.25	1.25	1.37
19-Aug	1.25	1.05	1.73	1.72
20-Aug	1.04	0.87	2.03	1.92
21-Aug	0.97	0.79	1.65	1.62
22-Aug	0.89	0.76	1.45	1.26
23-Aug	0.99	1.01	1.39	1.21
24-Aug	1.80	1.69	1.37	1.26
25-Aug	1.32	1.04	1.33	1.21
26-Aug	1.13	0.88	1.34	0.97
27-Aug	1.03	0.78	1.30	0.76
28-Aug	1.01	0.74	1.24	0.78
29-Aug	0.99	0.67	1.20	0.78

30-Aug	0.98	0.66	1.13	0.78
31-Aug	0.99	0.61	1.09	0.79
Sep	1.04	0.66	1.05	0.80
1-Sep	1.07	0.61	1.00	0.82
2-Sep	1.06	0.59	1.47	1.36
3-Sep	1.03	0.59	1.48	1.44
4-Sep	1.02	0.57	1.31	1.30
5-Sep	1.00	0.58	1.88	1.98
6-Sep	0.96	0.57	1.44	1.55
7-Sep	1.00	0.59	2.04	2.25
8-Sep	1.08	0.64	1.40	1.50
9-Sep	1.14	0.69	1.17	1.17
10-Sep	1.12	0.69	1.06	1.09
11-Sep	1.12	0.94	0.98	1.01
12-Sep	1.87	0.94	0.92	0.98
13-Sep	1.31	0.72	0.96	1.10
14-Sep	1.23	0.66	0.95	1.13
15-Sep	1.22	0.72	1.00	1.23

E.2. Blacktail Creek Treatment Stream flow

Blacktail Creek	2018 Average Daily Flows (ft^3s^{-1})		2019 Average Daily Flows (ft^3s^{-1})	
Date:	Upstream Treatment	Downstream Treatment	Upstream Treatment	Downstream Treatment
9-May	7.67	13.31	3.17	5.29
10-May	8.38	14.22	2.96	4.97
11-May	8.64	15.26	3.48	5.40
12-May	8.33	13.63	4.17	5.91
13-May	7.90	13.58	4.41	5.97
14-May	7.71	12.89	4.52	5.98
15-May	7.06	12.51	4.66	6.12
16-May	7.15	12.53	5.54	6.96
17-May	7.37	13.07	8.36	9.44
18-May	8.04	14.98	6.78	8.77
19-May	7.55	13.85	4.90	6.92
20-May	7.23	12.72	4.51	6.47
21-May	6.97	12.40	4.75	6.55
22-May	9.58	14.57	5.17	6.82
23-May	11.76	15.61	5.21	6.90
24-May	10.21	12.48	5.37	6.88

25-May	9.93	11.51	6.52	8.07
26-May	9.75	11.39	6.69	8.58
27-May	9.29	10.28	6.51	8.12
28-May	9.61	10.75	7.67	9.37
29-May	9.52	10.01	5.96	7.92
30-May	9.67	9.97	5.74	7.71
31-May	12.33	15.69	6.71	8.47
Jun	9.63	11.76	6.30	8.33
1-Jun	15.57	21.44	5.62	7.47
2-Jun	11.93	14.16	5.16	6.91
3-Jun	10.26	12.27	4.66	6.22
4-Jun	9.68	11.41	4.34	5.84
5-Jun	9.28	10.73	4.28	5.68
6-Jun	8.92	10.02	5.02	6.16
7-Jun	8.78	10.01	5.73	6.80
8-Jun	8.54	9.23	5.31	6.35
9-Jun	8.04	8.34	4.80	5.82
10-Jun	8.98	10.03	4.32	5.27
11-Jun	8.99	8.33	4.13	4.98
12-Jun	8.81	7.72	7.55	7.93
13-Jun	7.53	6.91	6.24	6.85
14-Jun	6.98	6.61	4.59	5.11
15-Jun	6.96	6.40	4.31	4.87
16-Jun	12.22	16.76	4.76	5.19
17-Jun	9.61	11.00	4.75	5.14
18-Jun	12.92	18.39	4.14	4.39
19-Jun	11.88	16.14	4.49	4.63
20-Jun	10.63	14.30	5.15	5.30
21-Jun	10.72	14.91	4.82	5.03
22-Jun	10.49	14.93	4.44	4.68
23-Jun	10.27	14.50	4.42	4.56
24-Jun	9.46	12.89	4.24	4.43
25-Jun	8.78	11.65	4.23	4.37
26-Jun	8.36	10.84	5.04	4.96
27-Jun	8.10	10.05	5.12	5.28
28-Jun	7.93	9.86	4.41	4.50
29-Jun	9.48	12.59	4.23	4.23
30-Jun	8.81	10.51	4.21	4.12
Jul	5.17	5.35	3.65	3.58
1-Jul	7.51	8.93	3.38	3.28
2-Jul	7.15	8.22	3.26	3.23

3-Jul	7.41	7.91	3.01	3.05
4-Jul	7.50	7.63	2.79	2.87
5-Jul	6.64	7.19	2.68	2.75
6-Jul	6.31	6.73	3.13	3.13
7-Jul	6.13	6.13	4.14	4.31
8-Jul	6.04	5.90	2.79	3.08
9-Jul	5.84	5.75	2.52	2.82
10-Jul	5.70	5.47	2.35	2.64
11-Jul	5.65	5.28	2.35	2.59
12-Jul	5.56	5.14	2.38	2.63
13-Jul	5.36	4.96	2.27	2.49
14-Jul	5.31	4.90	2.68	2.84
15-Jul	5.34	5.03	4.05	4.24
16-Jul	5.23	5.04	2.65	2.77
17-Jul	5.38	5.52	2.28	2.32
18-Jul	5.09	5.27	2.12	2.15
19-Jul	4.85	4.85	2.03	2.01
20-Jul	4.60	4.72	2.02	2.00
21-Jul	4.43	4.55	1.96	1.92
22-Jul	4.42	4.48	1.85	1.82
23-Jul	4.18	4.32	1.42	1.67
24-Jul	4.02	4.27	1.40	1.57
25-Jul	3.87	4.21	1.38	1.53
26-Jul	3.69	4.14	1.35	1.49
27-Jul	3.59	4.04	1.28	1.38
28-Jul	3.56	3.89	1.38	1.48
29-Jul	3.45	3.87	1.56	1.66
30-Jul	3.28	3.75	1.34	1.44
31-Jul	3.10	3.61	1.33	1.43
Aug	2.21	2.31	1.54	1.64
1-Aug	2.90	3.57	1.28	1.38
2-Aug	2.77	3.42	1.16	1.26
3-Aug	2.74	3.25	1.12	1.22
4-Aug	2.68	3.14	1.12	1.22
5-Aug	2.64	3.18	1.10	1.20
6-Aug	2.61	3.24	1.23	1.33
7-Aug	2.43	2.80	2.41	2.51
8-Aug	2.41	2.41	1.77	1.87
9-Aug	2.28	2.24	1.67	1.77
10-Aug	2.22	2.19	1.51	1.61
11-Aug	2.22	2.17	1.47	1.57

12-Aug	2.19	2.15	1.43	1.53
13-Aug	2.22	2.10	1.60	1.70
14-Aug	2.18	2.10	1.44	1.54
15-Aug	2.25	1.99	1.42	1.52
16-Aug	2.06	1.92	1.33	1.42
17-Aug	1.92	1.95	1.39	1.40
18-Aug	1.97	2.07	1.35	1.35
19-Aug	1.93	2.03	1.74	1.59
20-Aug	2.03	1.97	2.04	2.25
21-Aug	2.30	2.38	1.66	1.92
22-Aug	2.20	2.24	1.44	1.63
23-Aug	1.90	1.99	1.39	1.59
24-Aug	1.87	1.83	1.37	1.53
25-Aug	1.88	1.73	1.31	1.49
26-Aug	1.78	1.78	1.24	1.38
27-Aug	2.31	2.49	1.25	1.35
28-Aug	2.14	2.15	1.22	1.24
29-Aug	2.02	1.88	1.19	1.06
30-Aug	1.79	1.70	1.17	1.01
31-Aug	1.73	1.63	1.18	0.96
Sep	1.67	1.38	1.19	0.96
1-Sep	1.81	1.51	1.16	0.89
2-Sep	1.75	1.49	1.61	0.99
3-Sep	1.66	1.43	1.98	2.14
4-Sep	1.71	1.43	1.72	1.54
5-Sep	1.70	1.42	2.53	2.44
6-Sep	1.56	1.42	1.93	1.94
7-Sep	1.49	1.42	2.83	2.70
8-Sep	1.46	1.36	2.07	2.19
9-Sep	1.54	1.27	1.82	1.84
10-Sep	1.55	1.27	1.67	1.64
11-Sep	1.65	1.25	1.60	1.02
12-Sep	1.56	1.29	1.54	0.87
13-Sep	1.75	1.18	1.59	0.84
14-Sep	1.96	1.22	1.64	0.96
15-Sep	1.56	1.14	1.76	0.91
16-Sep	1.83	1.84	1.76	1.02
17-Sep	1.79	1.44		
18-Sep	1.77	1.39		
19-Sep	1.59	1.35		

12. Appendix F: Specific Conductivity Values

F.1. Blacktail Creek Control and Treatment Surface Water SC

Blacktail Creek SC (µscm^{-1})	Control Upstream	Control Downstream	Control Midstream	Treatment Upstream	Treatment Midstream	Treatment Downstream	Treatment Tributary
6/20/2019	168	167	167	165	163	155	60
6/27/2019	174	173	173	173	173	163	62
7/2/2019	184	183	183	182	182	172	65
7/11/2019	198	197	197	193	194	184	71
7/28/2019	224	223	223	221	221	208	71
8/5/2019	229	229	229	230	230	216	75
8/23/2019				199	201	192	82
8/29/2019	237	237	237	238	238	223	74
9/19/2019	217	218	218	219	219	206	76

F.2. Blacktail Creek Treatment Groundwater SC

Blacktail Creek SC (µscm^{-1})	Stemp1	Stemp2	Stemp3	Stemp4
6/20/2019	188	307	286	253
6/27/2019	176	301	271	256
7/2/2019	192	295	195	258
7/11/2019	184	284	200	265
7/28/2019	213	249	217	287
8/5/2019	221	248	249	371
8/23/2019	216	252	266	434
8/29/2019	221	258	287	448
9/19/2019	207	286	350	484

SIGNATURE PAGE

This is to certify that the thesis prepared by Evan Graham Norman entitled "Hydrologic Response of Headwater Streams Restored with Beaver Dam Analogue Structures" has been examined and approved for acceptance by the Department of Geoscience, Montana Technological University, on this 16th day of April 2020.

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