THESIS

SKI AREA EFFECTS ON HEADWATER STREAMFLOW

Submitted by

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ABSTRACT

SKI AREA EFFECTS ON HEADWATER STREAMFLOW

Colorado headwater streams produce water supply for the West. The effects of singular land use changes on headwater watersheds have been studied at length, but much less is known about the combined interactions of multiple land use changes on headwater streamflow generation. We examined how the interactions of three land use changes associated with ski area developments (tree clearing, trail and road building, and artificial snow application) affected streamflow at a ski area in northern Colorado. Our study area included three watersheds with stratified levels of development, within a United States Forest Service ski area permit boundary. Three main creeks and their tributaries were equipped with twelve pressure transducers scheduled for data collection at continuous 15 minute intervals over two water years beginning in late summer 2019. Burgess Creek (5.91 km^2), which had the greatest degree of development and creek accessibility, was equipped with 9 data loggers; Priest Creek (2.35 km^2) had two monitoring sites, and Beaver Creek (2.28 km^2) had one. We initially performed an ANOVA comparison of our ski area stream data to two reference watersheds, Hot Spring Creek (14.87 km^2) and Spring Creek (2.65 km^2) and detected no significant differences in streamflow generation or timing. We then examined how streamflow generation and timing related to the degree of development and watershed characteristics using both univariate correlation analysis and multivariate models. Mean basin elevation was the most significant driver of the timing of flow delivery;

development also plays an obvious role in both streamflow generation and timing. Total seasonal and annual streamflow generation increase significantly with development, and the timing of streamflow is earlier in the season in developed watersheds. Overall, this study shows that development affects how and when streamflow is generated from forested headwater stream systems, but our conclusions apply to just one ski area in northern Colorado. Long-term stream monitoring across watersheds with multiple disturbances, like those seen on ski resorts, should be a priority to understand how water delivery is affected by development.

ACKNOWLEDGEMENTS

I want to first and with great emphasis, thank Stephanie Kampf, for our many head scratching, idea fomenting conversations about this work and beyond. She has guided me through my growth as a scientist and commiserated with me through my growth as a mother. I am truly lucky to have her curious and determined mind in my corner. My appreciation goes to the USDA Forest Service, Liz Schnackenberg, Tyler Carleton, and Sally Cariveau for funding, field access, and logistical assistance. Thanks to my committee, Steven Fassnacht and Ryan Morrison, for spending time on this work and all your thoughtful suggestions. I am also grateful to the Colorado Water Center for additional funding for this work.

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I would like to send my love and unmatchable gratitude to my family for standing with me, picking up the slack, building a home for me while I read (and read…) and showing up at every turn in a way that cannot be beat. Thank you to my parents and my sister, who offered anything they could to make this work easier. To my honey love husband who always tried to understand what I was doing and to my precocious child, who usually did, I love you both beyond measure. I also acknowledge all the ancestral lands of the Ute Indian Nuche, where I conducted this research.

Finally, I would like to send my deepest thanks to the mama moose who let me return home to my family, shaken yet unscathed, after I rudely interrupted hers. I would, however, like my earring back if you saw fit.

DEDICATION

I would like to dedicate this work to my daughter, who became a kid as her mama became a scientist.

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INTRODUCTION

Forested headwater streams are important sources of water supply. Made up of first and second order streams, headwater streams represent approximately two thirds of total stream channel length (Leopold, et al., 1964; Freeman et al. 2007; Kampf et al, 2021). Headwater streams are vulnerable to anthropogenic pressures, which can have compounding effects on downstream systems (de Jong, 2015). Ski areas are often located in steep forested headwater catchments, but few studies address how ski area development affects headwater streams (de Jong, 2009). Of available studies, the primary emphasis is on how ski areas affect stream channel geomorphology and solute or sediment transport (Wemple, 2007; David, 2009). The effects of the land use changes associated with ski areas on the delivery of surface water have not been quantified. Ski areas and their operations permanently alter terrain with tree clearing, trail and road building and snow making; these are all changes that could potentially affect streamflow. In this study, we examine whether these three developments have altered the magnitude and timing of streamflow delivery from headwater streams in a ski area in northern Colorado, USA.

Alterations to the hydrologic cycle and streamflow generation as a function of tree removal have been documented in many studies (Hibbert, 1967; Troendle, 1987; Stottlemyer and Troendle, 2001; Brown et al., 2005). In mesic headwater streams, loss of tree canopy can increase water availability by reducing both transpiration from removed trees and the potential for sublimation and evaporation of precipitation intercepted by tree canopy (Troendle and King, 1985). Reductions in evapotranspiration could make more water available for streamflow generation. However, a recent meta-analysis, shows that water yield does not always increase due to tree clearing (Goeking and Tarboten, 2020). This may be because early studies on the hydrologic effects of tree removal focused on stand replacing disturbance, but not all tree removal is stand replacing or permanent. Regrowing trees may consume the same or even greater water than the trees that were harvested (Kuczera, 1987; Moore et al., 2004; Delzon and Loustau, 2005). Snow accumulation does not always increase after tree clearing due to greater exposure of the snowpack to solar radiation and wind (Burles and Boon, 2011). Ski areas permanently remove trees for ski runs and reduce tree density for glade terrain, but they do not remove trees from entire headwater catchments.

Roads and trails within forested headwater stream systems constitute a small total area of impacted land per catchment area but a large impact on infiltration and streamflow generation (Wemple and Jones, 2003; Luce and Wemple, 2001). Roads modify flow pathways by reducing infiltration, intercepting subsurface flow along cut slopes, and creating more infiltration excess overland flow (Megahan, 1972; Luce and Cundy, 1994; Ziegler and Giambelluca, 1997; Wemple 2001; Kampf et al., 2021). Roads within forested headwater stream systems cut across catchments and can function as drainage divides, segmenting catchments into smaller sub catchments (Wemple and Jones, 2003). Excess overland flow intercepted from the subsurface can be routed quickly along roads and away from the natural drainage channel (Luce, 2002). United States Forest Service watershed condition classification includes road density as an indicator of watershed health (Potyondy and Geier, 2010). This document defines a density greater than 1.5 km km^{-2} as an indicator of poor or impaired condition

(Figure A1). Operational requirements of ski areas increase road density, and summer operations of ski areas typically include bike and hiking trails, which have similar impacts to roads. The increased density of roads and trails in ski areas may influence streamflow generation and timing.

Ski areas are in snowfall-dominated catchments, which are predicted to receive less precipitation as snow in future climate models (Klos et al., 2014). Ski areas rely on consistent snowpacks to keep operating, and many have transitioned to using more artificial snow to supplement natural snowpack (Bark et al., 2010). An artificial snowpack has different properties than a natural snowpack (Miklos et al., 2020). Application of artificial snow creates a denser, more homogenous, and deeper snowpack, which in turn melts out more slowly (Mikos et al., 2020; Keller et al., 2004). The homogeneity of artificial snowpack provides less pore space for air to insulate the ground surface compared to a natural snowpack. Greater snow water equivalent (SWE) found in artificial snowpack as compared to natural snowpack can delay snow ablation and the snow-free date (Rixon et al., 2004). Ground surfaces that are not well insulated may be colder, have longer frozen periods and experience more freeze/thaw swings that can limit snowmelt infiltration. Less infiltration coupled with greater artificial snowpack depth and SWE could lead to more water moving across the ground surface, draining quickly from the ski runs into mountain headwater streams.

While the effects of land use changes found on ski areas have been examined individually, we lack information on the aggregated impacts of tree removal, roads and trails, and snow-making on headwater streams in ski areas. The primary objective of this study is to examine how the timing and magnitude of streamflow vary between watersheds that are undeveloped forest compared to those with varying degrees of ski area development. This study was conducted in and near a ski area in northern Colorado.

2 SITE DESCRIPTION

2.1 Study watersheds

The study area consists of the three main study watersheds within the USFS permitted boundary of Steamboat Ski Resort, located in Routt County in northwestern Colorado, (Figure 1). The study watersheds are Burgess Creek, Priest Creek and Beaver Creek; a small portion of Fish Creek is within the ski area's permit boundary but was excluded from this study because it lacked any ski area development at the time of analysis. Burgess Creek flows ungauged into the Yampa River above USGS station 09239500; Beaver Creek and Priest Creek drain the resort into Walton Creek (ungauged) before joining the Yampa River also above the same station. Water used for artificial snow making is sourced from the Yampa River. Burgess Creek has greater stream length and more tributaries within the catchment boundary, and Priest Creek has the greatest change in channel elevation of the study watersheds (Table 1). Because of extensive grading in Beaver Creek watershed, all streams have been culverted, and they are only visible beyond the downstream boundary of the ski resort.

Table 1. Study watersheds within ski resort boundary. Stream length includes main channel and tributary lengths. Channel change in elevation is calculated by StreamStats as the "change in elevation divided by length between points 10 and 85 percent of distance along the longest flow path to the basin divide", (USGS, 2016)

Study Watershed	Stream length (km)	Tributaries (n)	Channel Change in Elevation (m km^{-2})
Burgess Creek	15	5	164
Priest Creek	3	2	237
Beaver Creek	4	2	113

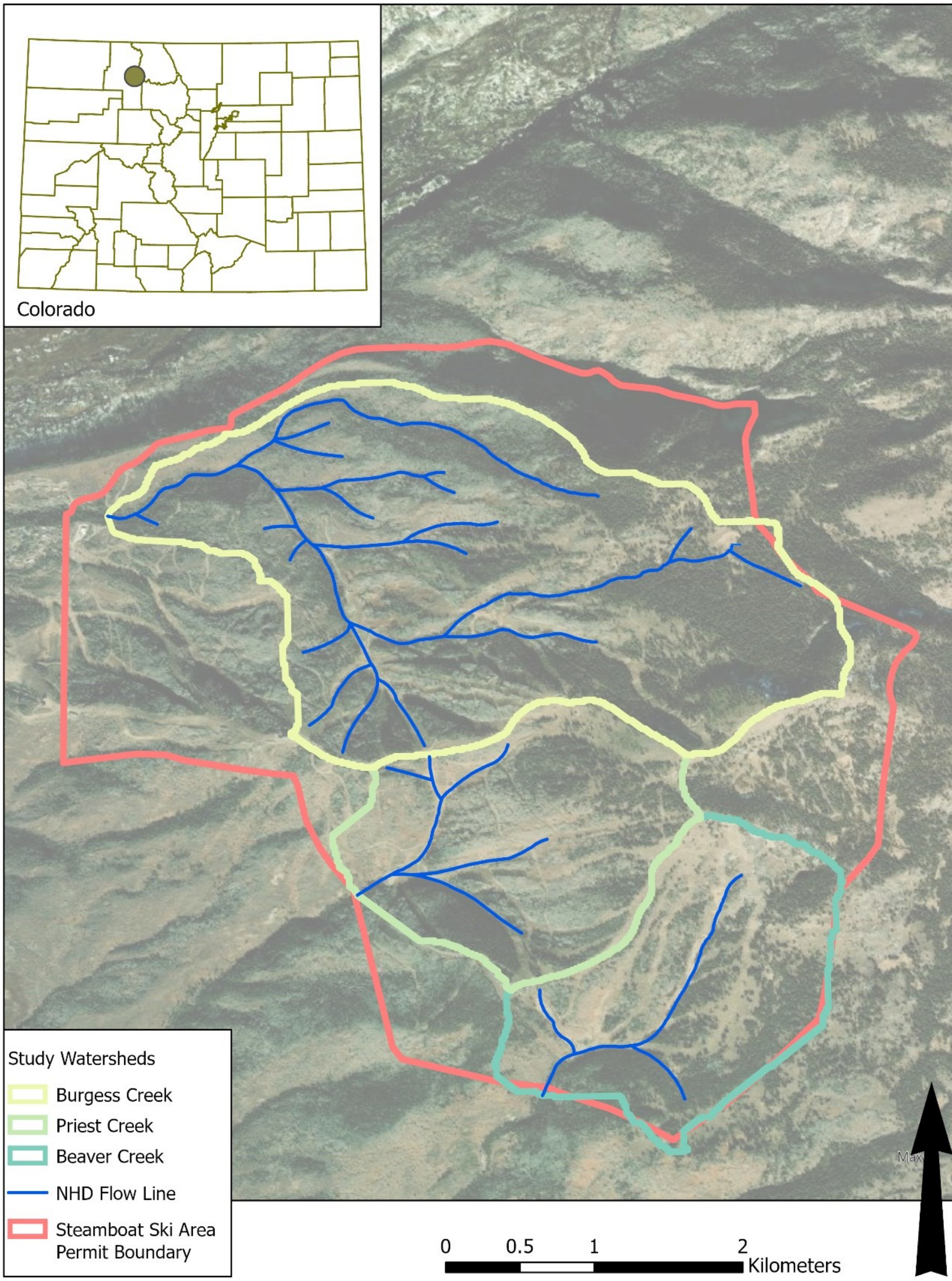

Figure 1. Study watersheds shown within the boundary area of Steamboat Ski Resort in the state of Colorado. Study watershed boundaries are delineated from StreamStats; ski area permitted boundary is provided from USFS, and stream channels are mapped from high resolution (V2) National Hydrography Dataset.

The climate station located in Steamboat Springs (Station ID 057936, 2085 m, WRCC) reported average annual precipitation of 602 mm and an average annual snowfall of 4231 mm (period of record 1893-2016). The ski area is in the transitional-persistent snow zones, with annual average snow persistence ranging from 62-89%. Snow persistence is defined as the percent of time with snow cover from January 1 – July 3 (Richer et al. 2013; Moore et al. 2015). The average annual monthly maximum temperature ranges from 1.9 – 28.1 °C and the annual monthly minimum temperature ranges from -16.4 to 6.4 °C (period of record 1981-2010, WRCC, 2021). The hydrographs of all study creeks have a strong seasonal snowmelt pattern, with large flow increases during spring snow ablation, peak flow in late May into early June, and a gradual recession after snow is all gone, punctuated by flashy peaks due to summer monsoon storms.

The study watersheds cover a combined 8.6 square kilometers of resort area and are predominately west facing. All study watersheds are within the forested montane zone, below tree line, with a maximum elevation of 3220 meters and a minimum elevation of 2250 meters (Figure 2a). Surface geology throughout the study area is primarily granite (Figure 2b). The northwest portion of Burgess Creek sits above a layer of felsic gneiss, and all three study watersheds contain some portion of biotite gneiss. Beaver Creek watershed is mostly underlain with glacial drift. Soils of the study area are mapped as Boatsteam-Storm family; very bouldery-Pineguest family complex, 30 to 55 percent slopes (35% of study area); Tolby family cobbly sandy loam, 30 to 60 percent slopes, extremely bouldery (29.3% of study area); and Leighcan-Lake Janee family-Bigtimber family complex, 1 to 30 percent slopes, very stony (24.3% of study area).

Hydrologic soil groups derived from study area soil reports are mapped as mostly group A, with units of B-D at higher elevations (Figure 2c.)

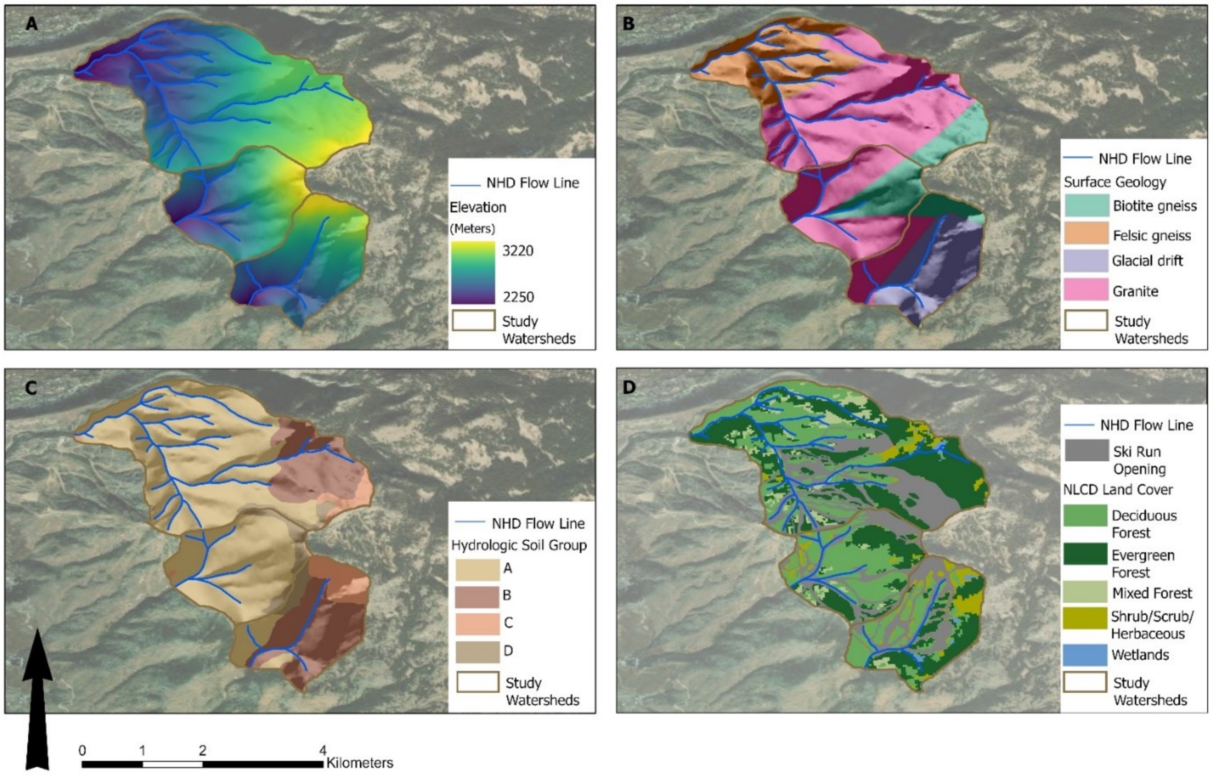

Figure 2. Physical watershed characteristics of study watersheds: a) 10-meter DEM elevation, b) USDA-USGS Mineral Resources geology c) SSURGO hydrologic soil groups and d) NCLD land cover dataset.

The land is managed and administered by the USFS by a ski area permit designation, and 33% of the existing land cover has been cleared for ski run openings within the study watershed boundaries (Figure 2d). Remaining vegetation is evergreen, deciduous and mixed forest with prominent patches of shrubland. Higher elevations and mesic slopes are dominated by lodgepole pine (*Pinus contorta*) and subalpine fir (*Abies lasiocarpa*); the primary deciduous species is quaking aspen (*Populus tremuloides*). Shrubs are Gambel oak (*Quercus gambelii*), sagebrush (*Artemisia tridentata*) and serviceberry (*Amelanchier alnifolia*) on the drier areas; riparian areas species are

Drummond's willow (*Salix drummondiana*) and Rocky Mountain willow (*Salix monticola*), thimbleberry (*Rubus parviflorus*), and raspberry (*Rubus idaeus*) (CSFS, 2010 and USFS 2018).

2.2 Reference watersheds

Flow metrics from the study watersheds are compared to two reference watersheds, a tributary to Spring Creek and Hot Spring Creek, both located off resort (Figure 3). Spring Creek tributary covers an area of 2.65 km^2 and changes 119 meters per km for a range in elevation from 2450 m – 2880m (Figure 4a). The geology of Spring Creek is mapped as biotite gneiss with some glacial drift in the southern portion of the watershed (Figure 4b). Soil in the tributary of Spring Creek is mapped as Boatsteam-Storm family, very bouldery; Pineguest family complex, 30 to 55 percent slopes (46.8% of watershed) and is represented mostly by hydrologic soil group A (Figure 4c). Vegetative cover of the tributary to Spring Creek is consistent with that found in the study watersheds (Figure 4d).

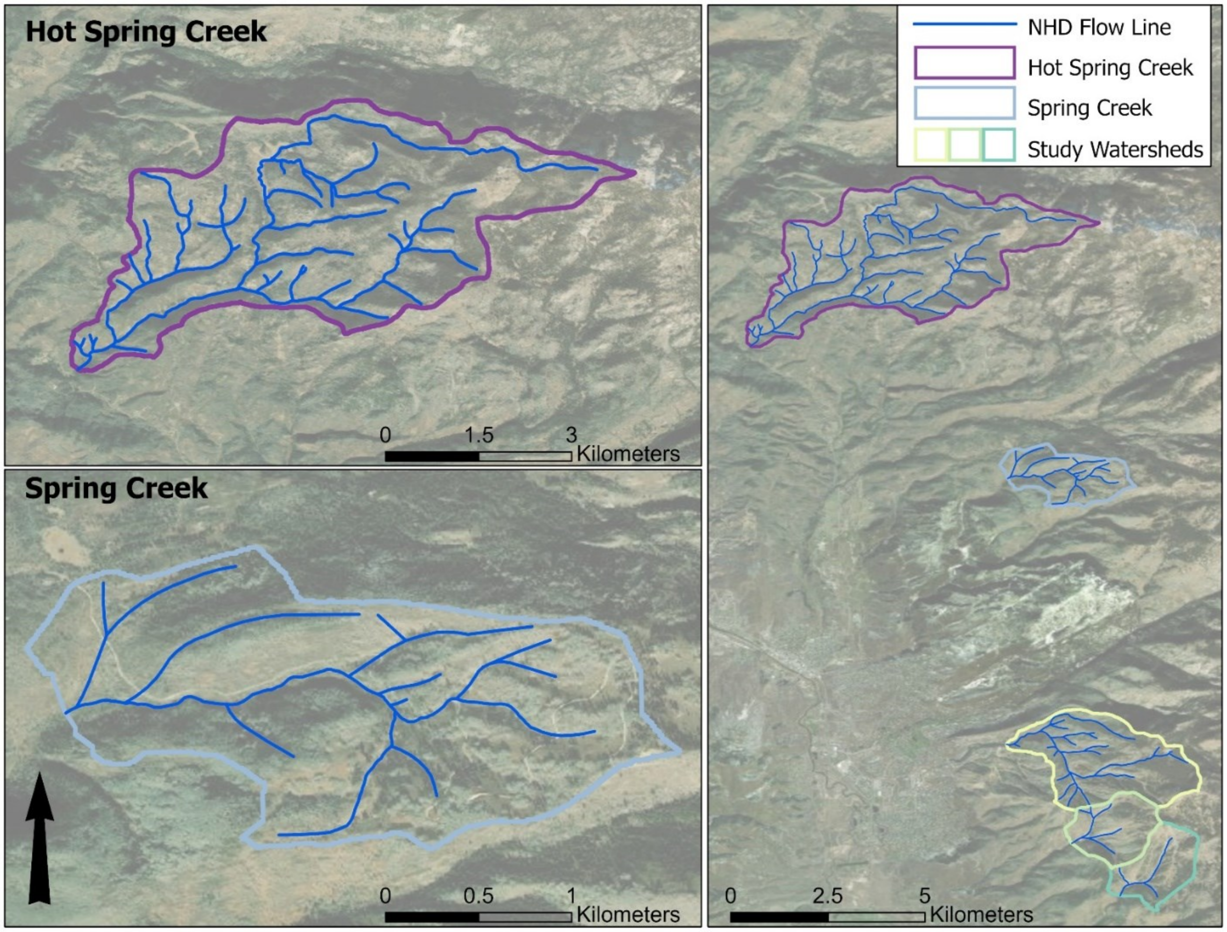

Figure 3. Reference watersheds without ski area development located 5-10 km north of the Steamboat Ski Area.

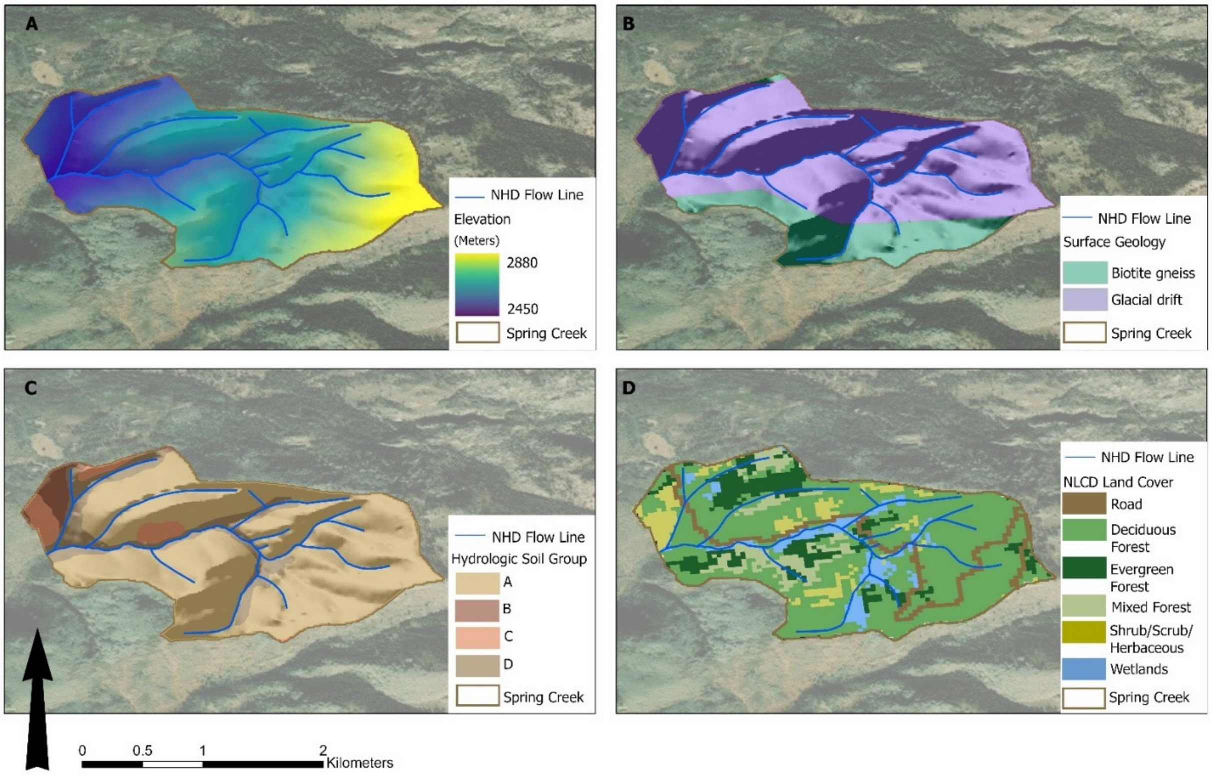

Figure 4. Physical watershed characteristics of Spring Creek tributary: a) 10 meter DEM elevation, b) USDA-USGS Mineral Resources geology c) SSURGO hydrologic soil groups and d) NCLD land cover dataset.

Hot Spring Creek sits further north and covers 14.78 km^2. The stream drops 65 meters per kilometer for an elevation range of 2300m to 3250m (Figure 5a). The geology of Hot Spring Creek is mapped as mostly granite with some glacial drift in the northern portion of the watershed (Figure 5b). The most prominent soil unit in Hot Spring Creek is Redyon, extremely stony-Rubble land complex, 30 to 60 percent slopes (37.2% of watershed). The watershed is mapped as mostly hydrologic soil group B (Figure 5c). Vegetative types match those found in the study watersheds as well as in the tributary to Spring Creek (Figure 5d).

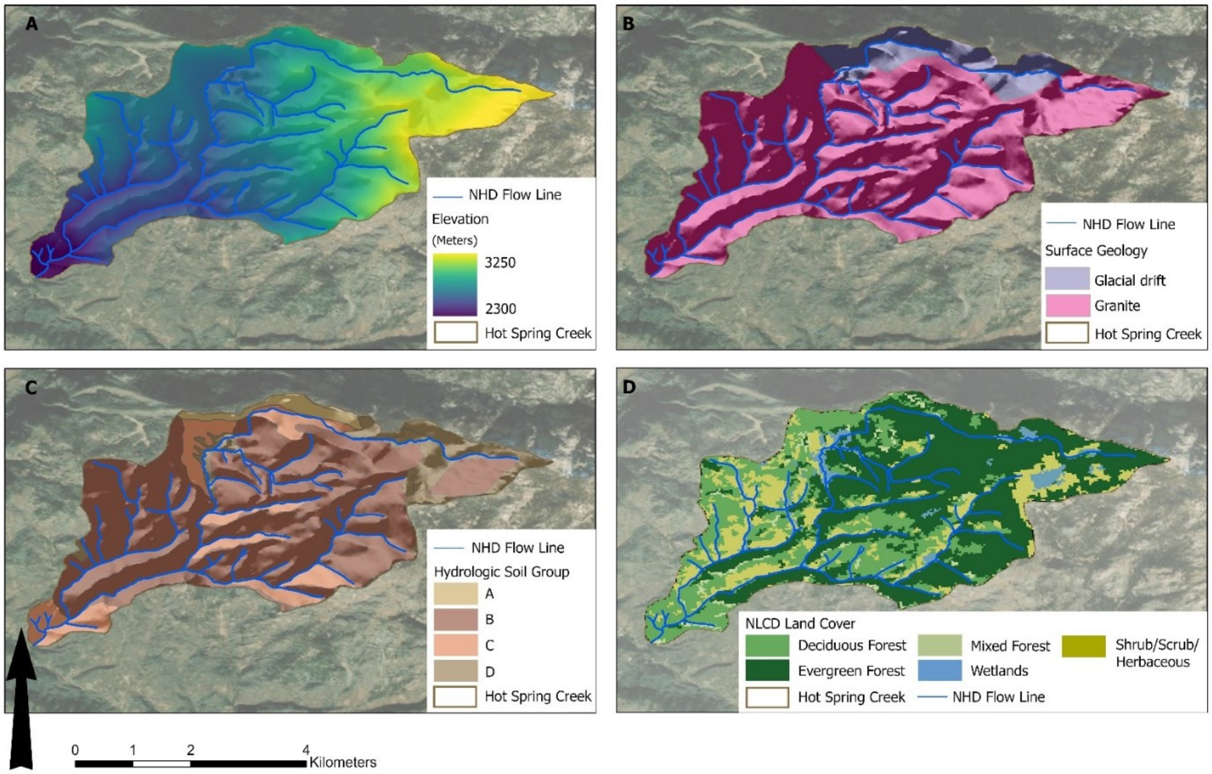

Figure 5. Physical watershed characteristics of Hot Spring Creek tributary: a) 10 meter DEM elevation, b) USDA-USGS Mineral Resources geology c) SSURGO hydrologic soil groups and d) NCLD land cover dataset.

3 METHODS

3.1 Design

Monitoring locations within both the ski area and reference watersheds were selected in a collaboration with USFS personnel in the summer of 2019. The goal was to measure nested watersheds across a range of drainage areas and levels of ski area development. Site selection was also based on access from ski area roads and measurability of streams. To measure stream stage and discharge we needed confined, single channel reaches with relatively smooth flow to give stable pressure readings. Because of heavy resort use during both summer and winter seasons, sites also needed to be discrete to avoid recreational user interactions.

The set of selected sites includes 12 monitoring sites representing main channel and tributary locations within the ski area (Figure 6) and reference watersheds (Figure 7). The most heavily instrumented watershed is Burgess Creek, which has four pressure transducers nested on Burgess Creek main channel and four tributaries equipped with pressure transducers. One Burgess Creek tributary has two pressure transducers nested within the catchment. Priest Creek watershed has one pressure transducer on the main channel and another on a tributary. Beaver Creek study watershed has one main channel site equipped with a pressure transducer.

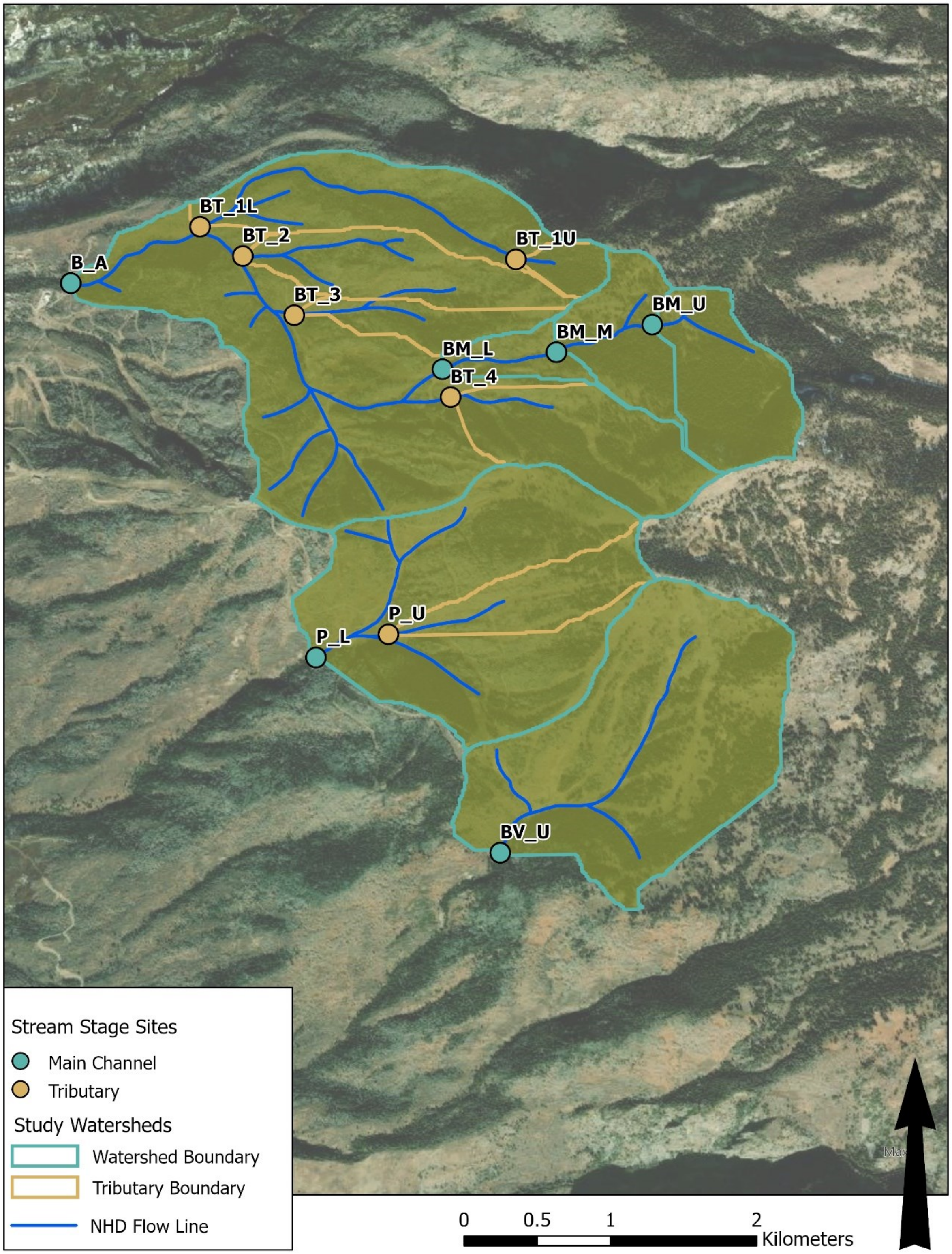

Figure 6. Stream monitoring sites within the ski area, where teal represents study watershed boundaries and orange indicates tributary boundaries. The location of pressure transducers, along with site identification is indicated. For complete site names see Table 2.

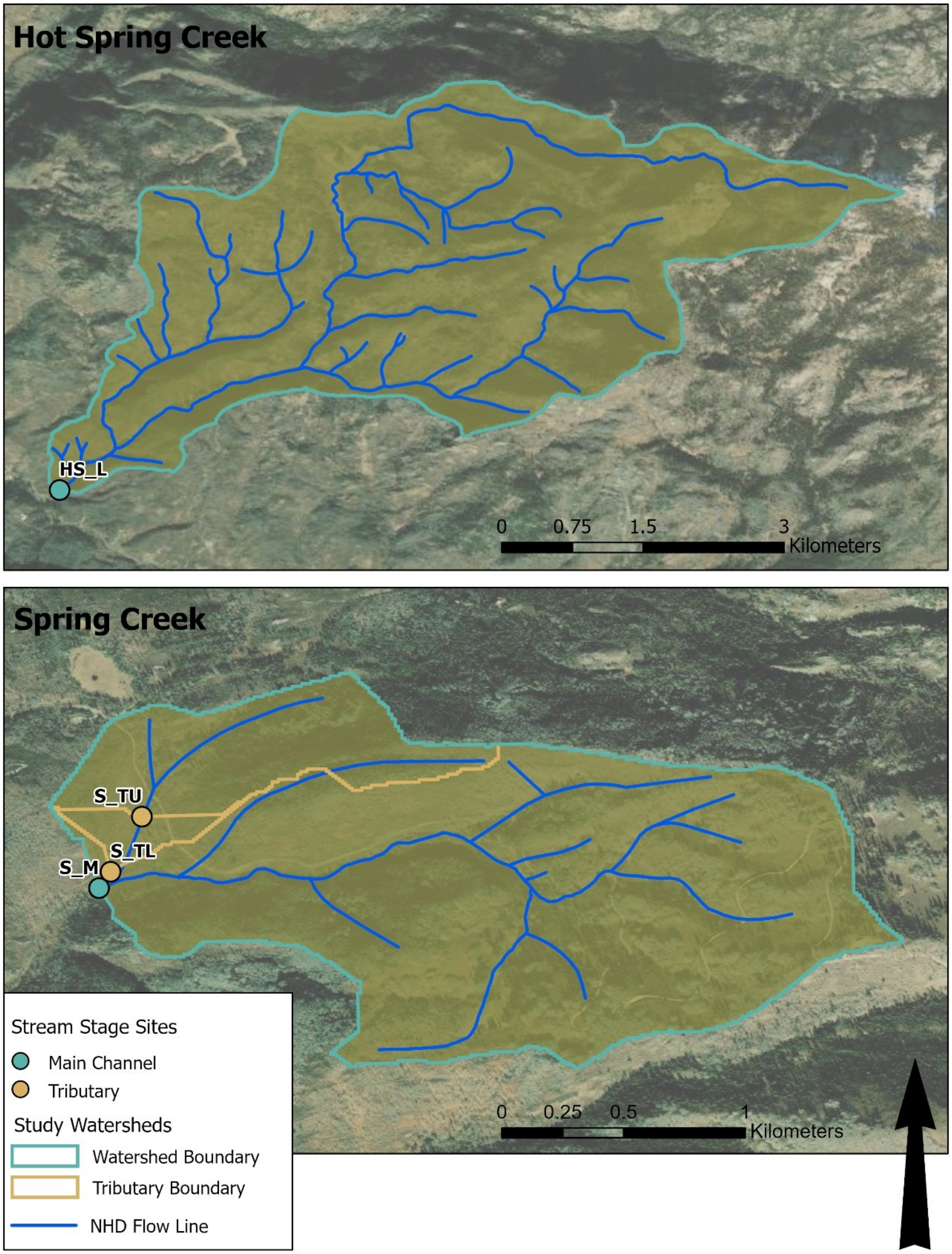

Figure 7. Reference watersheds identified by site identification and by tributary or main channel. For complete site names see Table 2.

The contributing area to each monitoring location was determined using USGS StreamStats (USGS, 2016). Watershed boundaries were loaded into Esri ArcGIS (version 10.7.4), and the Summarize Elevation tool was used with a 10-meter digital elevation model (DEM) to collect watershed characteristics (Table 2). Watershed characteristics identified were contributing drainage area (km^2), mean basin elevation (m), mean slope (%) and mean aspect (degrees). Study and reference watersheds drain 0.27 km^2-14.87 km^2, have a mean elevation of 2550- 3050 meters, have gradual slope (mean 12-18%) and generally face SW – NW (202-318 degrees).

Table 2. Stream flow monitoring sites and their drainage area characteristics. Note: both main channel and tributary study sites (Trib) were selected and are identified in their names. Nested catchments are named by position in catchment from lower elevations to upper elevations.

Name	Site	Area (km^2)	Mean Basin Elevation (m)	Mean Slope (%)	Channel Change in Elevation (m km^{-2})	Mean aspect (degrees)
Burgess Creek All	B_all	5.91	2748	18	164	299
Burgess Creek Lower	BM_L	1.28	2993	13	146	309
Burgess Creek Mid	BM_M	1.09	3016	12	122	318
Burgess Creek Upper	BM_U	0.63	3049	14	167	325
Burgess Creek Trib 1 L	BT_1L	0.96	2649	19	247	278
Burgess Creek Trib 1 U	BT_1U	0.12	2949	13	286	287
Burgess Creek Trib 2	BT_2	0.59	2654	21	329	272
Burgess Creek Trib 3	BT_3	0.27	2715	21	370	285
Burgess Creek Trib 4	BT_4	0.72	2992	17	278	308
Beaver Creek Main	BV	2.28	2920	12	113	202
Hot Spring Creek Main	HS_L	14.87	2761	16	64	249
Priest Main	P_L	2.35	2848	21	237	255
Priest Main Upper	P_U	0.43	2951	22	390	239
Spring Creek	S_M	2.65	2644	27	119	292
Spring Creek Trib L	S_TL	0.50	2553	14	124	290
Spring Creek Trib U	S_TU	0.43	2560	14	137	302

Sites were also stratified by the degree of ski area development within the drainage areas (Figure 8). Geospatial data for ski run locations, snow pipe locations, and trails were provided by the USFS in 2019, and no additional development occurred during the study period. Development types considered were the area (km^2) of ski run openings and the length of bike and hike trails and roads (trails, km) within each drainage. Ski run and trail development types were also normalized by contributing basin area, where ski run opening is presented as a ratio of ski run to total watershed area in percent, and trails are presented as a density ($km\ km^{-2}$). Snow-making was represented as a binary yes/no variable based on the presence/absence of snow-making equipment in the watershed. Burgess Creek has the greatest degree and mix of development types, and reference site Spring Creek has trail development, but no ski runs within the watershed (Table 3). Thus, the only fully undeveloped watershed is Hot Spring Creek.

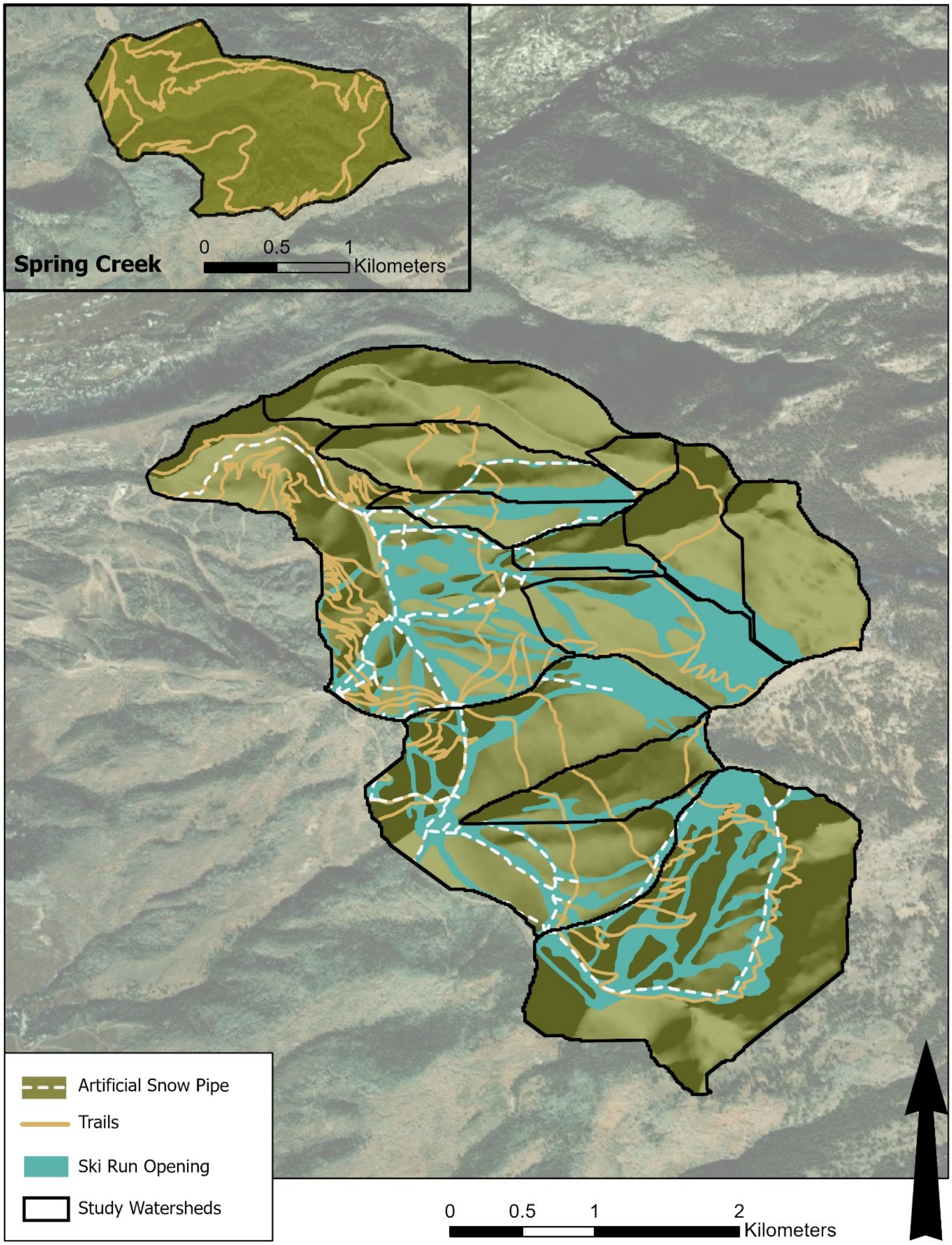

Figure 8. Development extent on ski area and (inset) Spring Creek catchment.

Table 3. Development characteristics of each watershed. Note: trails includes both hike and bike trails as well as roads.*

Site	Ski Run Opening (km^2)	Ski Run Opening (%)	Trails* (km)	Trails per catchment (km km^{-2})	Snow Pipe	Development Type
B_All	1.47	25	27.03	4.57	yes	Developed
BM_L	0.19	15	1.27	0.99	yes	Developed
BM_M	0.11	10	1.18	1.08	no	Developed
BM_U	0.05	08	0.23	0.37	no	Reference
BT_1L	0.00	01	0.88	0.92	no	Reference
BT_1U	0.00	02	0.27	2.22	yes	Reference
BT_2	0.10	18	1.89	3.23	yes	Developed
BT_3	0.11	40	0.62	2.29	yes	Developed
BT_4	0.41	56	2.85	3.96	no	Developed
BV	0.69	30	7.01	3.08	yes	Developed
HS_L	0.00	00	0.00	0.00	no	Reference
P_L	0.70	30	7.32	3.11	yes	Developed
P_U	0.08	18	1.30	3.01	no	Developed
S_M	0.00	00	16.10	6.07	no	Reference
S_TL	0.00	00	4.72	9.48	no	Reference
S_TU	0.00	00	3.67	8.46	no	Reference

3.2 Measurements

Steam stage sites were equipped with Onset HOBO 30-foot depth water level data loggers U20 and U20L (Part # U20L-01 and # U20-001-01). Two different types of water level data loggers were used based on existing instrumentation availability from USFS and available budget to purchase new equipment. Loggers were installed in stilling wells with stage plates for larger channels and a modified stilling well with in smaller channels (Figure 9). Modified stilling wells were designed to be stable and low profile within small stream channels; these were slotted at the base and measured no more than 0.5 meters in length. Each modified stilling well had a stream elevation measurement point indicated on the well casing for consistent readings. Water level data loggers were installed at the stream bed surface between August 2019 and June 2020 (Table A1). Pressure readings were recorded at a 15-minute interval time step, selected to be short enough to log flashy storm flows and long enough to maintain memory capacity over winter. Because accessibility was limited in winter and spring, logging timestep was consistent over the study timeframe to be sure to catch snowmelt signals.

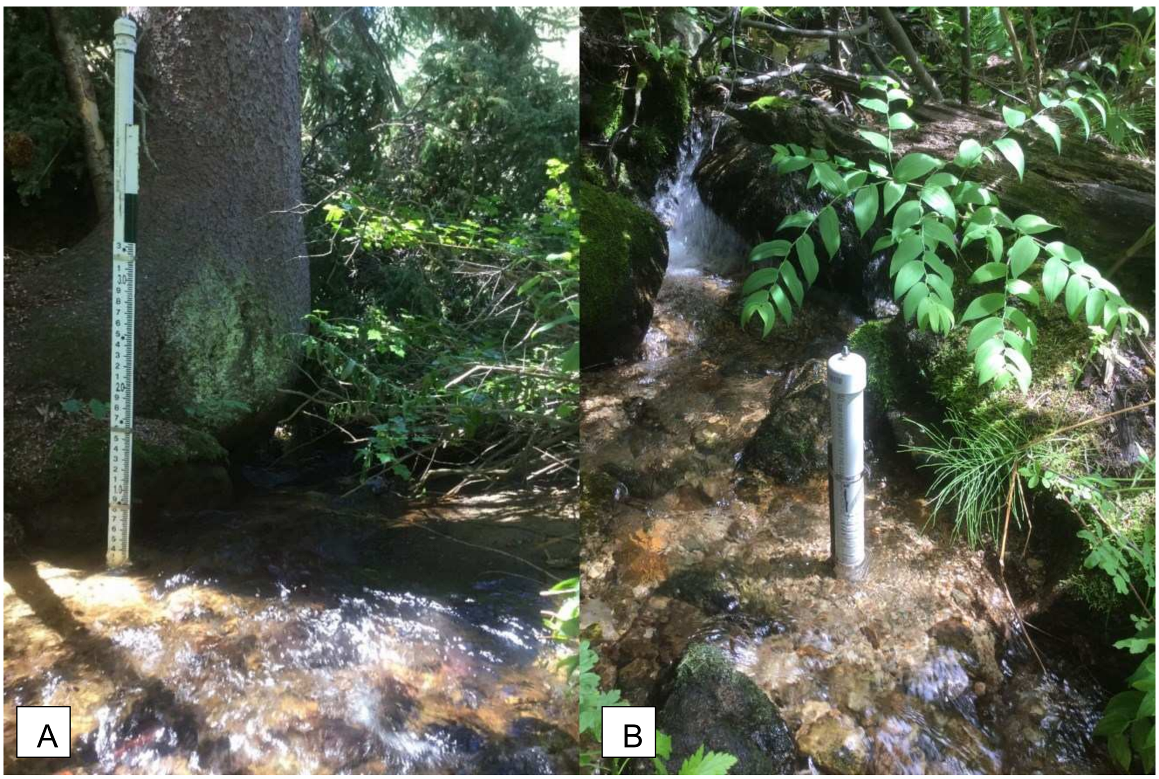

Figure 9. Stream stage installation types, a) stilling well with stage plate and b) modified mini stilling well.

We collected two full melt cycles in 11 of 16 sites, beginning mid-March of water year 2020 (WY20) though the following water year of 2021 (WY21). Five pressure transducers, BM_M, BT_2, P_L, P_U and HS_L, were installed when sites were accessible from snow in WY20, beginning in mid-May when snowmelt had already peaked. For these five, the complete dataset for WY21 is available.

Manual discharge measurements were taken during the rising limb, peak snowmelt discharge and falling limb at main channel, tributary and reference watersheds during Spring, 2021 (Figure A2a and A2b). Manual discharge volumes were measured using either a Pygmy current meter, salt dilution, or the bucket method. The Pygmy current meter method, as described by Carter and Davidian (1968), sums discharge across stream cross section transects and is used in larger flowing, straight channel streams with a uniform bed. Dilution gaging and bucket methods were used in first and second order streams, where the channel could not accommodate the current meter requirements. The salt dilution method follows Kilpatrick and Cobb (1984) with iodized table salt for the tracer slug injection. A Reed conductivity meter or a HOBO freshwater conductivity data logger (part number U24-001) were placed at least 10 meters below the point of injection to allow proper tracer mixing. Discharge is calculated from a time-concentration curve and equals the mass of the salt over the area under the curve. Dilution gaging was run twice per site per discharge reading. If stream reaches were too short or flows low enough to inhibit tracer mixing, streamflow was caught in a bucket, and the time to fill was recorded in the bucket method. The bucket discharge measurements were repeated at least five times until similar rates of flow were achieved.

Air pressure was recorded at the B_all site with HOBO U20 data logger at the same time step as in stream loggers. To clean the data, we subtracted air pressure from stream pressure sensor values, then offset the stage values to match manual stage measurements. Manual discharge measurements taken at each site and manual stage measurements were used to develop rating curves for each monitoring location. We used JMP statistical software to explore best curve fits (SAS JMP). For all sites, a bivariate fit with a square root transformed response provided the best fit, when extrapolation errors were considered (Equation 1).

$$\sqrt{Discharge} = intercept * slope(Stage) \qquad \text{Eq. 1}$$

Plots of fit equations for each site are presented in Figure A2a and Figure A2b, including coefficient of determination (r^2) and slope coefficient. We applied the rating curves to the site stage measurements then converted to daily discharge in mm by normalized by contributing area and summing across each day.

Streamflow data were supplemented with hydrologic input data available from gridded precipitation data (PRISM, 2004) and snow persistence (Hammond, 2020). Dry Lake SNOTEL (Station ID: 457) is within Spring Creek reference site catchment, and Rabbit Ears (Station ID: 709) and Tower (Station ID: 825) are within 8 km of the study site. Steamboat Ski Corporation slope maintenance director provided the volume of artificial snow administered across the entire study area (Peterson, email communication). This value was normalized across all catchments that have snow pipe within their boundaries for a total seasonal depth of water added by artificial snow application.

3.3 Data analysis

To examine the magnitude of streamflow at the study watersheds we computed seasonal sums for winter (December, January, and February - DJF), spring (March, April, May - MAM), summer (June, July and August - JJA) and fall (September, October and November - SON) as well as total water year streamflow. To examine the timing of streamflow, we computed cumulative discharge starting on April 1 through the end of each water year (September 30). We then identified the dates when 10, 25, 50, 75, and 90% of the cumulative April-September streamflow (Q10, Q25, Q50, Q75, Q90) had passed through the gaging location. The earlier quantiles (Q10, Q25) represent the rising limb of the snowmelt hydrograph, and the later quantiles (Q75, Q90) represent the recession limb. The center of mass quantile, Q50, represents near peak flow.

With the full dataset of flow metrics, we used ANOVA to test whether streamflow variables in ski area watersheds was significantly different from reference watersheds. To examine how watershed characteristics and ski area development relate to flow metrics, we evaluated univariate correlations between predictors and flow metrics. Predictor variables include basin characteristics (Table 2) and development variables (Table 3). The development variables were computed in two ways, as actual values (ski run area, trail length) and as area-normalized values (ski run % of watershed, trail density in km km^{-2}). To achieve normal distribution, five predictor variables were log transformed (area, average slope, ski run percent, ski run area and train length), and trail density was square root transformed. To avoid collinearity, we split the development dataset into two subsets (length/area and area-normalized), each paired with the full set of basin characteristics. Cross correlation analysis evaluated the similarity amongst predictor variables.

With each dataset, we then performed a multivariate regression analysis for each flow metric. For the multivariate analysis we added climate predictor variables from Dry

Lake SNOTEL to address differences within water years: Peak SWE (snow water equivalent), average temperature, and total precipitation. These were not included in univariate analysis because we do not have separate climate data for each watershed. We also added two categorical development variables: developed vs. reference and snow pipe (yes/no). The general equation for multivariate regression considers that multiple predictors may influence a certain outcome together and combine with a unitless coefficient to identify the strength of the influence. Equation 2 sets y equal to our flow metric response variables while β is the coefficient for each predictor, and x is the predictor variable (Hothorn et al. 2008).

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n \qquad \text{(Eq. 2)}$$

Full models, where all predictors are considered (for complete list, see Table 2), were evaluated by Akaike information criteria (AIC) full subset selection (Barton 2020; Sakamoto et al, 1986). AIC selection focuses on explaining the most amount of variation with the simplest model and greater number of degrees of freedom. With the AIC tool from the stats base R package, the full model is assigned an AIC value; then a predictor term is dropped, and a new AIC value is assigned. The model with the lowest AIC value then drops another predictor term until the overall lowest AIC value can be determined. We evaluated models for overfitting and determined the collective significance values, the relative contribution of predictors and the AIC value for each selected model.

4 RESULTS

4.1 Snow and streamflow

WY20 was a higher snow year than WY21 (Figure 10). Peak SWE values at Dry Lake (site 457) and Tower (site 709) SNOTEL were 40% greater in WY20 than WY21 and 70% greater at Tower SNOTEL (site 825). Peak SWE at Dry Lake was 627 mm in WY20 and 437 mm in WY21; Tower station's peak SWE values were 1250 mm and 909 mm for the two consecutive years. Rabbit Ears peak SWE values were 681 mm in WY20 and 411 mm in WY21. Snow remained on the ground seven (Rabbit Ears), eleven (Dry Lake) and sixteen (Tower) days later in the season in WY20 than in WY21. The average annual temperatures from each SNOTEL station were 5.3°C, 2.6°C and 0.8°C in WY20 for Dry Lake, Rabbit Ears and Tower, respectfully; Average temperatures were warmer by 0.6-1.0 degrees in WY21, registering 6.0°C, 3.6°C, and 1.4°C for the same series of stations as above.

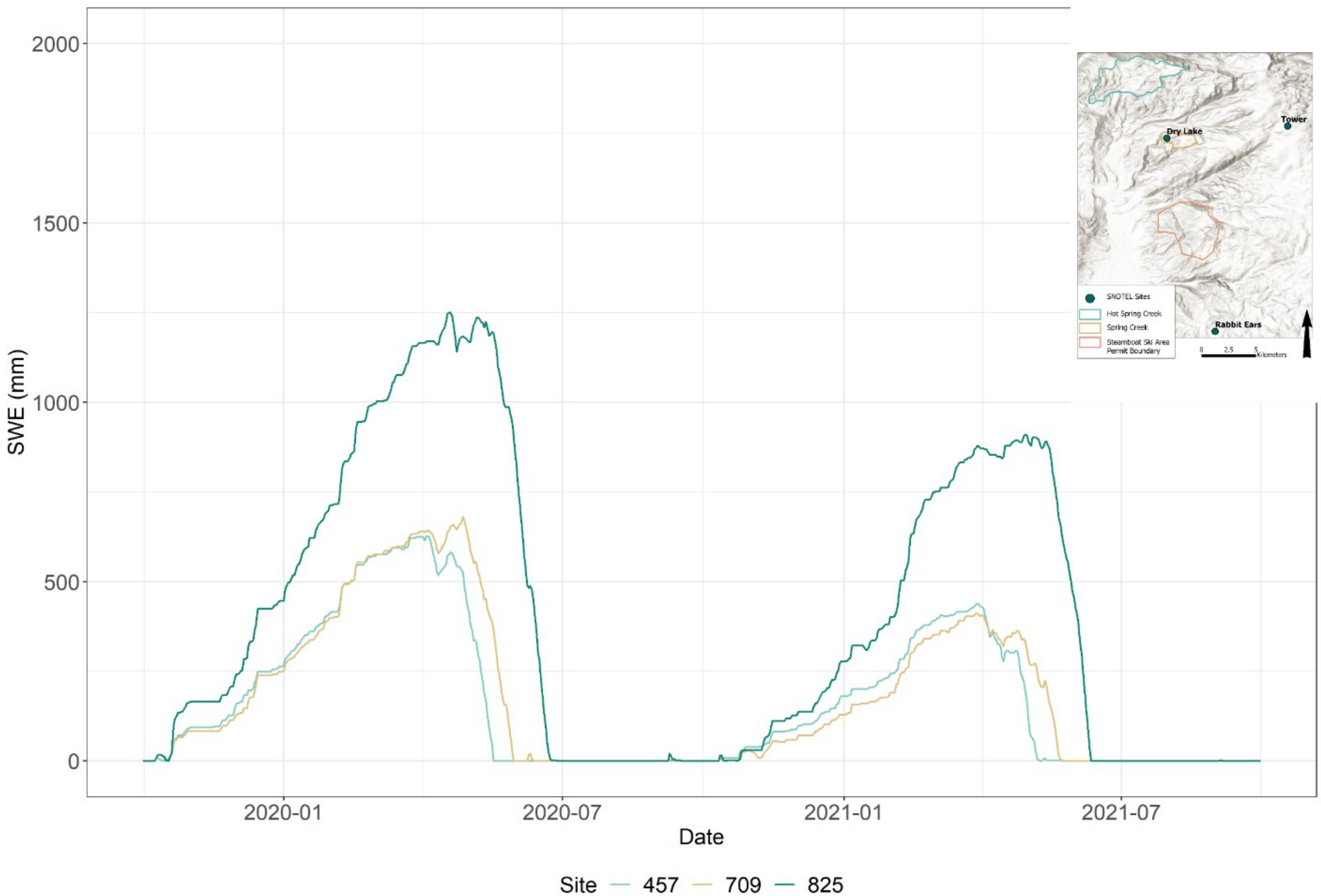

Figure 10. Niveograph reporting SWE from the three closest SNOTEL stations to the study area, Dry Lake (site 457), Rabbit Ears (site 709) and Tower (site 825). Dry Lake station is within the Spring Creek catchment boundary.

The depth of artificial snow added to the ski area each operational season was computed by normalizing the total volume of water (in acre feet) by the area of catchments that had snow making equipment within the boundaries. The resulting depth of water was then added to natural snow for an input value. Calculated artificial snow values added to each catchment with snow making equipment are 67mm in WY20 operational season and 71mm the following year (Table 4). Artificial snow accounts for 6-8% of total input if assuming all water used for snow making accumulates on the ground. Estimation of mean water loss due to sublimation during artificial snow production is 21% (Grünewald & Wolfsperger, 2019), which would reduce the input further to 53-56 mm. Runoff ratios from total discharge over total input, calculated as natural precipitation plus artificial snow, range from 0.09 - 0.51 in WY20, excluding sites with incomplete records, and 0.06-0.58 in WY21.

Table 4. Precipitation and discharge by site and runoff ratio for each water year. Artificial snow as per Peterson, personal email communication. Note: for sites without a complete period of record, see methods, runoff ratio could not be calculated.

Site	Natural Precipitation (mm)	Artificial snow (mm)	Input (mm)	Q (mm)	**Runoff Ratio (Q/Input)**
WY20					
B_All	1005	53	1058	345	0.33
BM_L	1101	53	1154	280	0.24
BM_M	1101	0	1101	NA	NA
BM_U	1101	0	1101	94	0.09
BT_1L	1101	0	1101	270	0.25
BT_1U	1101	53	1154	276	0.24
BT_2	1101	53	1154	NA	NA
BT_3	1101	53	1154	330	0.29
BT_4	1101	0	1101	515	0.47
BV	986	53	1039	363	0.35
HS_L	932	0	932	NA	NA
P_L	1101	53	1154	NA	NA
P_U	1101	0	1101	NA	NA
S_M	936	0	936	476	0.51
S_TL	805	0	805	322	0.40
S_TU	805	0	805	105	0.13
WY21					
B_All	862	56	918	207	0.23
BM_L	949	56	1005	198	0.20
BM_M	949	0	949	284	0.30
BM_U	949	0	949	60	0.06
BT_1L	949	0	949	343	0.36
BT_1U	949	56	1005	430	0.43
BT_2	949	56	1005	129	0.13
BT_3	949	56	1005	295	0.29
BT_4	949	0	949	389	0.41
BV	838	56	894	402	0.45
HS_L	742	0	742	246	0.33
P_L	949	56	1005	386	0.38
P_U	949	0	949	129	0.14
S_M	720	0	720	419	0.58
S_TL	609	0	609	296	0.49
S_TU	609	0	609	149	0.24

Stream hydrographs grouped by location are shown in Figure 11. All sites on the main channel of Burgess Creek with complete 2020-2021 datasets had greater magnitude peak flow in WY20 than WY21 (Figure 11a). The site furthest downstream, B_all, had two prominent spring melt pulses in WY20. Flow peaked at B_all four days earlier than at the lower main channel site and three days earlier than the upper main channel site (Table 5). The falling limb into base flow was steep for the lowest and highest sites (B_all and BM_U) on the main channel and more gradual for the two mid-elevation sites (BM_L and BM_U). Peak flow on the main channel in WY21 was lower in magnitude and earlier by 13 days for the lowest site compared to WY20. However, the upper two sites peaked nearly the same time in both years. BM_U had a muted snow melt signal in WY21 compared to the previous year and reached baseflow earlier than the three lower sites.

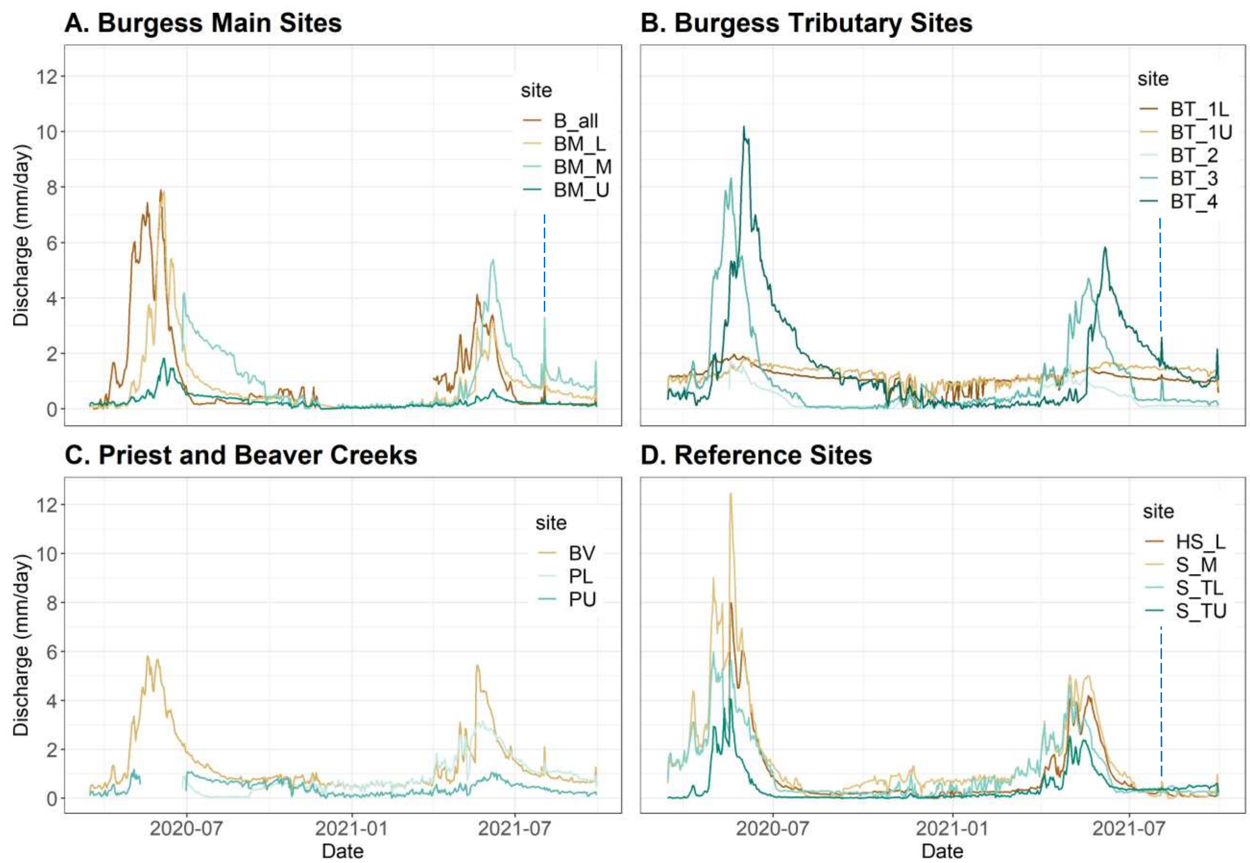

Figure 11. Study hydrographs for (a) Burgess Creek main channel (b) Burgess Tributaries, (c) Priest and Beaver Creek and (d) reference hydrographs, March 15, 2020 - September 30, 2021. See Figures 6 and 7 for locations and Table 2 for complete site names. Vertical dashed line shows the 8/2/2021 rain event.

Table 5. Peak discharge value and date for all sites. Note: for sites with incomplete WY20 data, peak discharge could not be calculated.

Site	WY20 Peak Q (mm day^{-1})	WY20 Peak Date	WY21 Peak Q (mm day^{-1})	WY21 Peak Date
B_All	7.90	6/1	4.12	5/19
BM_L	7.84	6/5	3.16	6/6
BM_M	NA	NA	5.38	6/6
BM_U	1.83	6/4	0.72	6/6
BT_1L	1.96	5/21	1.49	5/20
BT_1U	1.86	6/4	1.70	6/6
BT_2	NA	NA	1.63	4/30
BT_3	8.33	5/18	4.71	5/19
BT_4	10.18	5/31	5.83	6/5
BV	5.82	5/17	5.45	5/19
HS_L	NA	NA	4.20	5/19
P_L	NA	NA	3.16	5/25
P_U	NA	NA	1.05	6/4
S_M	12.48	5/18	5.02	4/30
S_TL	5.97	4/30	4.64	4/30
S_TU	4.07	5/17	2.55	4/30

Burgess Creek tributaries 3 and 4 (BT_3 and BT_4) had similar hydrographs to the main channel sites, with a greater magnitude peak flow in WY20 than in WY21 and a clear snowmelt pulse in the rising and falling limb (Figure 11b). Peak flow at BT_4 lagged BT_3 by 13 days in WY20 and by 17 days in WY21. BT_4 also had 22-23% more total water year flow than BT_3, partly because of the steeper falling limb of the hydrograph at BT_3. Tributaries 1 upper and 1 lower (BT_1U and BT_1L) and 2 (BT_2) did not show such prominent snowmelt pulses when compared to BT_3 and BT_4. These tributaries had gradual rising and falling limbs and muted peaks in WY20 and no obvious snowmelt pulse in WY21.

We analyzed two water years for Beaver Creek and WY21 only in Priest Creek (Figure 11c). In WY20, Beaver Creek had two nearly identical peaks, on 5/17 and then again on 5/28, and peak flow of similar magnitude in WY21. Priest Creek had a more muted hydrograph compared to Beaver Creek in WY21, and the lower Priest Creek site (P_L) peaked earlier than the upper site (P_U) by 10 days.

Reference sites on Hot Spring Creek and Spring Creek (HS_L, S_M, S_TL and S_TU) display hydrographs like Burgess main and Burgess tributaries 3 and 4, with more flow in WY20 than in WY21 (Figure 11d). We started collecting data on Hot Spring Creek on May 16, 2020, at which point the hydrograph may have already started on the falling limb. Spring Creek sites show a clear melting pattern across the watershed with melt pulses at each site at roughly the same time. This clear pattern of melt in Spring Creek continued in WY21, joined by Hot Spring Creek with a clear rising limb and three obvious melt pulses followed by a defined falling limb.

Across the study area, a clear rain response in the hydrographs is evident on August 2, 2021. The following results are associated with this specific rain event only. The rain event signal was observed on all main stem sites on Burgess Creek, though a lower magnitude was observed on the upper site (BM_U). The rain event signal was strong on the 3rd and 4th tributaries to Burgess Creek (BT_3 and BT_4), muted at the lower site on the first tributary (BT_1L) and barely registered on the upper site on the first tributary as well as at the 2nd tributary (BT_1U and BT_2). The upper site on Priest Creek (P_U) showed a faint rain event signal, while a strong signal was clear at the lower Priest Creek site and the Beaver Creek site (P_L and BV). Hot Spring Creek and the lowest site on Spring Creek (HS and S_M) also showed this rain event, while the smaller tributaries (S_TU and S_TL) showed little indication of an event on the hydrograph.

4.2 ANOVA comparison of reference and developed watersheds

We divided sites into two categories for ANOVA comparison of flow metrics. Developed sites are all sites on Steamboat Mountain except the top-most site on Burgess Creek main channel (BM_U) and both upper and lower sites on Burgess Creek tributary 1 (BT_1U and BT_1L). These three sites are included in the reference category because they have less than 10% ski area opening (Table 3).

We compared seasonal streamflow sums for Winter, Spring, Summer, and Fall, and total streamflow for the study period (Figure 12). ANOVA results indicate no significant differences in seasonal streamflow between developed and reference sites. However, the median discharge for developed sites was less than for reference sites in Winter and Spring. In Summer and Fall, median discharge was greater for developed sites compared to reference sites. Seasonal variability in developed sites was greatest in Spring and Summer.

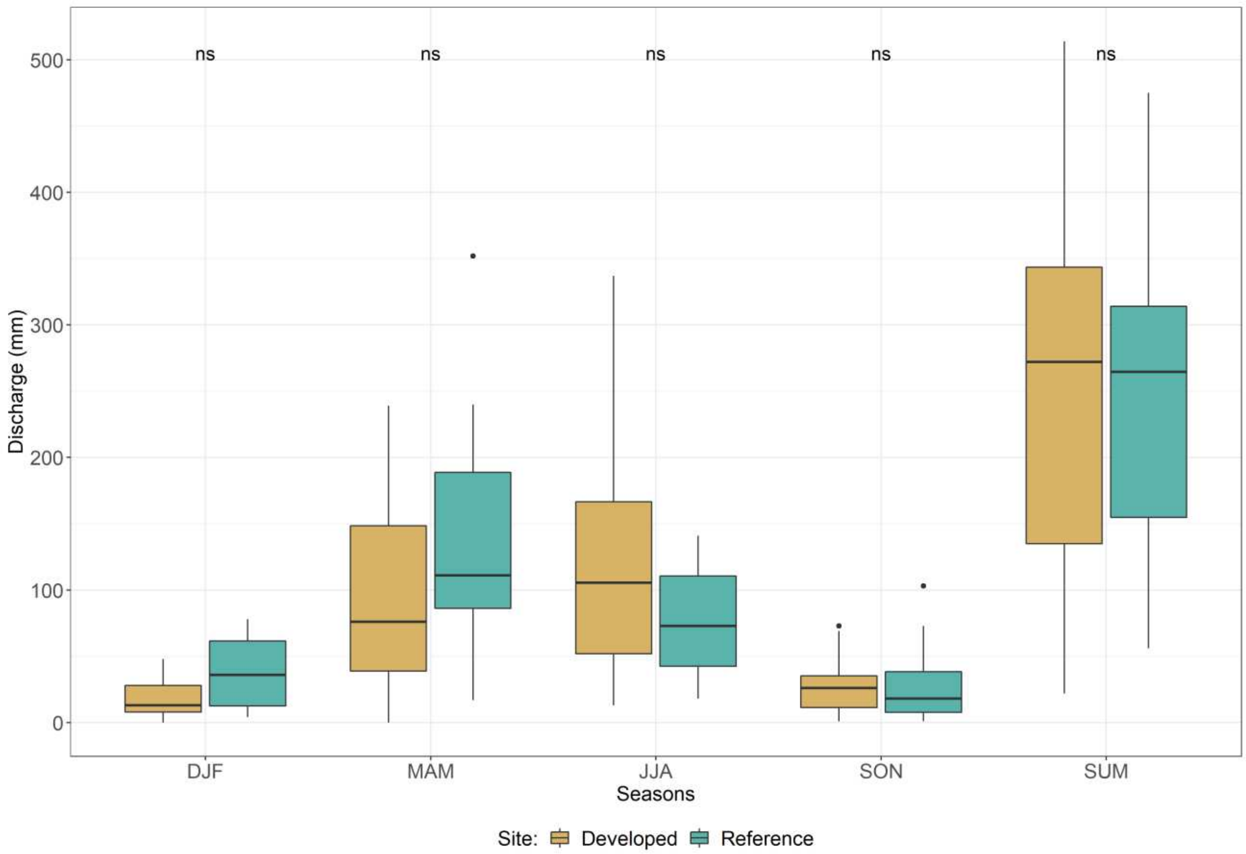

Figure 12. Boxplot comparison of seasonal total streamflow by watershed type (developed, reference) for winter (DJF), spring (MAM), summer (JJA) and fall (SON) and total water year (SUM). The label 'ns' indicates comparisons that are not significant. In this plot, whiskers are the minimum to the lower quartile and the upper quartile to the maximum, boxes represent the interquartile ranges, and the line within the box represents the median. Outliers are plotted as separate points.

We also compared streamflow timing for the developed sites versus reference sites using flow quantiles (Figure 13). We found no sigificant differences in quantiles comparisons between developed versus reference sites. In developed sites, the 10th, 25th and 50th quantiles were reached later in the season than at reference sites, whereas the 70th and 90th quantiles of flow were reached on average eariler than at reference sites. The 70th and 90th flow quantiles had the largest spead in interquartile range, with reference sites having more variability in when the flow quantile was reached.

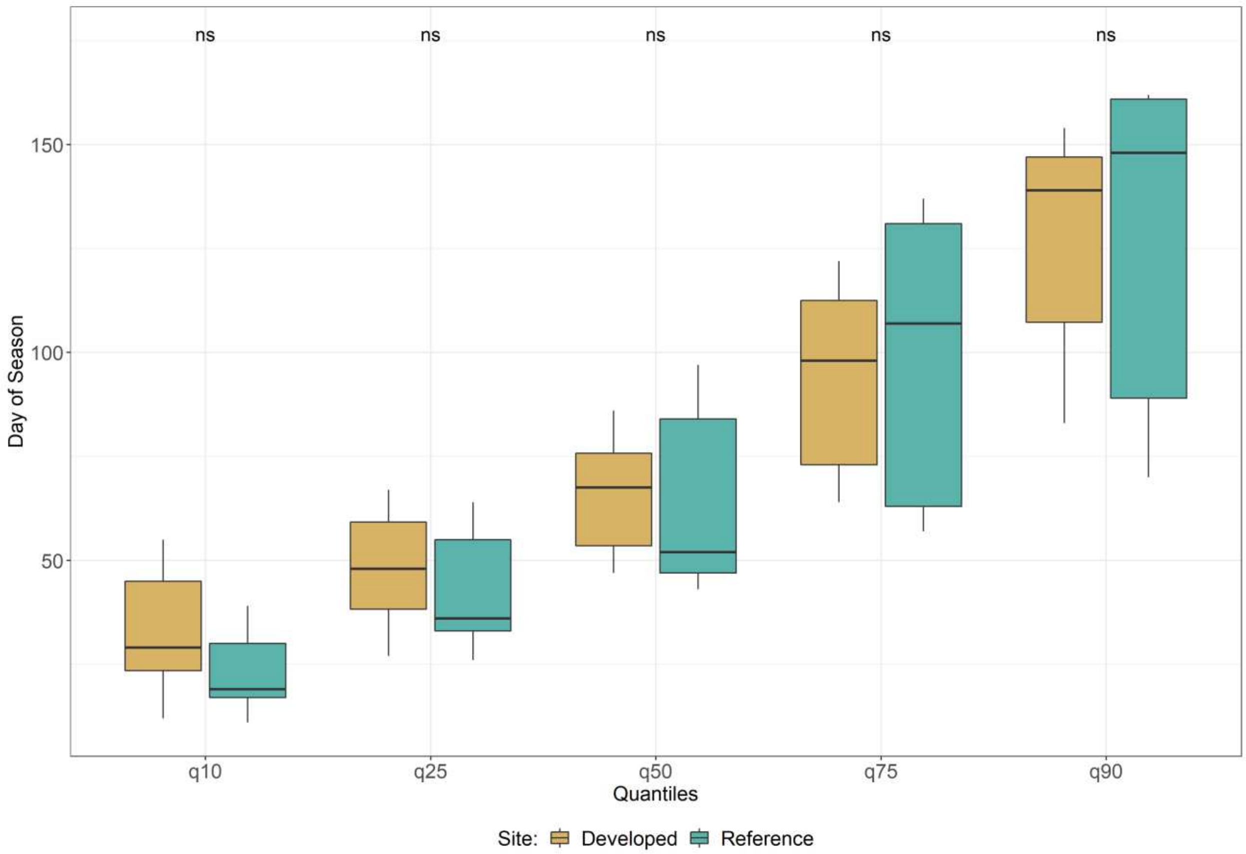

Figure 13. Boxplot comparison for the Day of Season (DOS) that each quantile of flow of reached by watershed type (developed, reference) for the 10th, 25th, 50th, 70th and 90th quantiles. The label 'ns' indicating comparisons that are not significant. In this plot, whiskers are the minimum to the lower quartile and the upper quartile to the maximum, boxes represent the interquartile ranges, and the line within the box represents the median. There are no outliers in flow quantiles.

4.3 Drivers of streamflow variability

Streamflow predictor variables were first evaluated for cross correlation, an indication of similarity in variables (Figure 14). Mean elevation is significantly correlated to average slope; change in elevation is also significantly correlated to slope and additionally to basin area. In addition to change in elevation, area is significantly correlated to length of trails and area of ski run opening. Trail density is significantly correlated to both area and area-normalized ski run opening. The highest correlation is between trail length and ski run area (r=0.94). Because these variables are highly correlated, we chose to use the area-normalized variables (trail density and ski run percent) for later multivariate modeling.

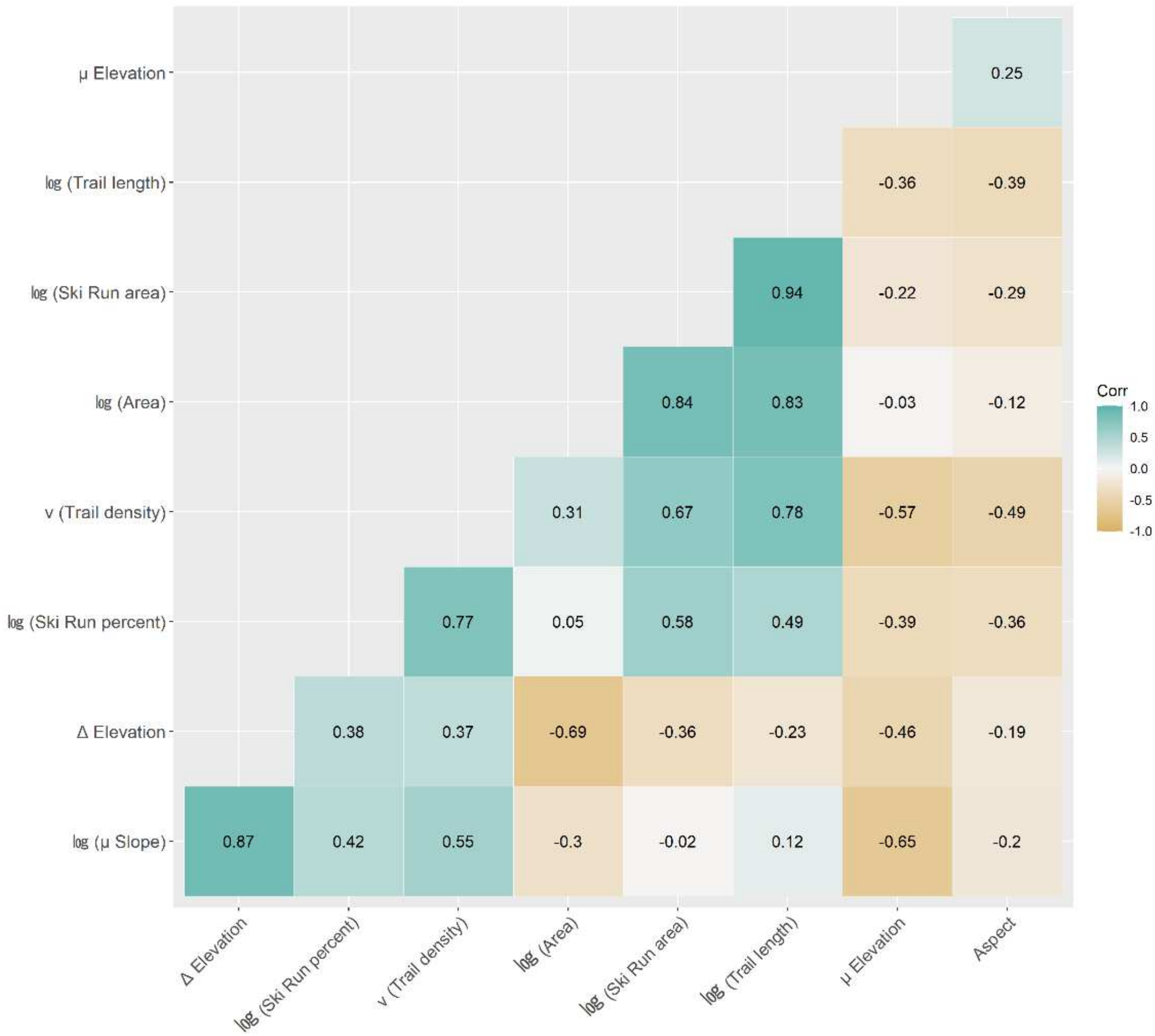

Figure 14. Cross-correlation matrix for predictor variables. Correlation is significant where Pearson correlation coefficients are greater than 0.63.

To examine what factors drive streamflow, we evaluated whether the predictor variables, basin characteristics and development types, correlate with seasonal streamflow and flow quantiles for developed study sites only (Figure 15). Of the terrain variables, aspect has a significant negative correlation to summer, fall, and winter seasonal streamflow in WY21, as well as total seasonal streamflow in WY21. Mean catchment elevation has a significant positive correlation to all quantiles, meaning higher elevations are associated with later snowmelt hydrographs. Mean catchment elevation is significantly negatively correlated with summer streamflow in both water years, indicating the higher elevation streams support lower summer baseflow. Average slope is significantly negatively correlated to 25th and 50th quantiles in WY20 and the 75th and 90th quantiles in both years. This indicates that steeper slopes have earlier snowmelt hydrographs in some cases. Average slope is significantly positively correlated to summer streamflow in WY20.

Of the development variables, a clear pattern emerges. Almost all quantiles, excluding 10th quantile of WY21, are negatively correlated to development variables, and all seasonal streamflow is positively correlated to development variables. This indicates that development has caused earlier snowmelt hydrographs and higher streamflow. When ski runs are represented as total areas, this variable is significantly positively correlated to summer streamflow in WY20 and to fall and total streamflow in both water years of the study period. When ski runs are represented as a percentage of each watershed, this variable is significantly positively correlated to all seasonal flow metrics except winter streamflow in WY21. Ski runs (both as area and percent) were not significantly correlated with flow quantiles, with the exception of a negative correlation between area and the 25th quantile in WY2020.

Trail length was significantly correlated to summer and total streamflow in WY20 and to fall and total streamflow in WY21. Trail density was significantly correlated to all seasonal streamflows except spring streamflow in WY20 and winter streamflow in WY21; for spring streamflow the Pearson's critical value for correlation significance is almost achieved. Most correlations between trail variables and quantiles were not significant, except for a negative correlation between trail length and the 25^{th} quantile in WY20 and negative correlations with trail density for the 25^{th} and 50^{th} quantiles of flow in WY20 and the 75^{th} quantile of flow in WY21.

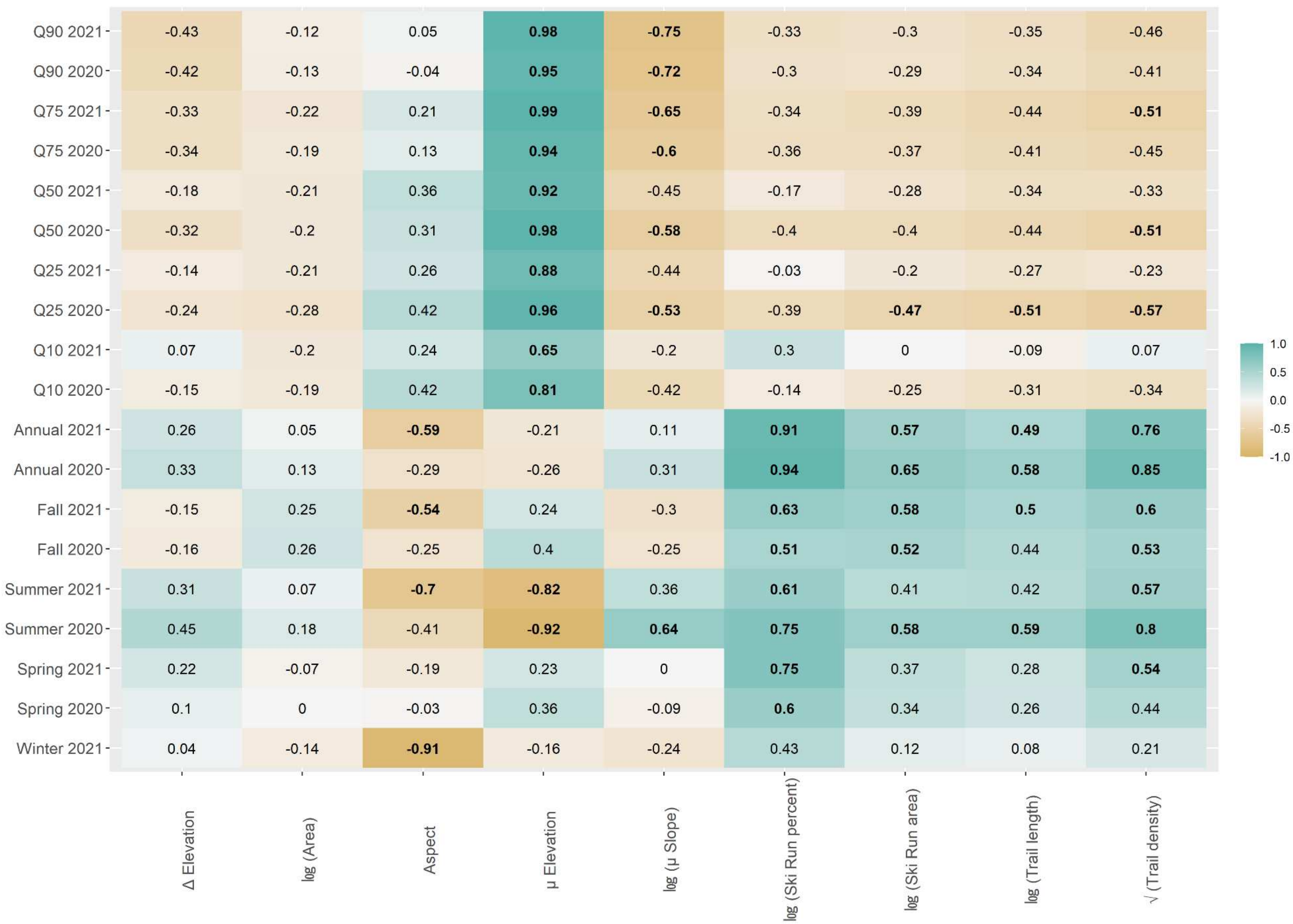

Figure 15. Correlation matrix between flow metrics (day of season for quantile of flow and seasonal sums of streamflow) versus terrain and development variables versus. Correlations exceeding Pearson's critical value for significance (0.468) are highlighted in bold text in the matrix.

Multivariate models were developed to predict each streamflow metric using area-normalized development predictors (Table 6). All models chosen by AIC selection to describe streamflow generation metrics were significant to p-value less than 0.01, except winter streamflow and annual streamflow. Null models were selected for winter and annual streamflow generation model sets. Mean basin elevation was the only predictor needed to sufficiently describe spring flow.

Summer total flow is influenced by change in elevation and slope. For development variables, snow pipe is a significant predictor of summer flow along with trail density. Fall total streamflow is influenced by elevation and includes aspect, all development variables except snow pipe, and total precipitation.

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*Table 6. Multivariate model results, by AIC selection. Levels of significance: ns>0.1, • >0.05, * > 0.01, ** > 0.001, *** > 0.0001. A null model is selected for winter flows and annual total streamflow.*

		Winter	Spring	Summer	Fall	Annual	Q10	Q25	Q50	Q75	Q90
Area Normalized	Area							•			
	Elevation		**		*		***	***	***	***	**
	Change in Elevation			*					ns		
	Slope			**			*				ns
	Aspect				•		**				ns
	Snow Pipe (Yes)			•			*	•	**	*	*
	Ski Run Opening Percent				**			*	***	***	***
	Trail Density			*	*			•	*	*	*
	Development (Reference)			ns	ns		***				
	Peak SWE per Water Year (WY)						*				
	Average Tempurature per WY									*	*
	Total Precipitation per WY				***						
	Model P-Value		**	**	***		***	***	***	***	***
	DF		30	26	25		20	21	21	21	19
	AIC		360	368	280		175	162	177	219	240

All flow quantile models chosen by AIC selection were significant to less than 0.01. Flow quantile models generally included more predictors than seasonal streamflow models. Mean basin elevation was selected as a significant predictor ($p<0.01$) for all quantile models area-normalized input data sets. Elevation, slope and aspect were terrain variables selected for Q10, which also included snow pipe, development status, and peak SWE in the area-normalized input set. The Q25 model using area-normalized input data include area, elevation, and all development variables as predictors.

Predictors of peak flow represented by Q50 are mean elevation, change in elevation, and all the development variables for area-normalized datasets. Like Q50, Q75 is predicted by the complete set of development variables and mean basin elevation, except Q75 excludes change in elevation. Average annual temperature is the climate predictor of Q75.

Late season flow timing represented by the Q90 flow metric has the same input variables as Q75 and also includes aspect and slope as nonsignificant predictors of late season flow.

5 DISCUSSION

5.1 Development effects on streamflow

Results of this study demonstrate that streamflow generation and timing are different in catchments with ski area development than in reference undeveloped catchments (Figures 12 and 13). Several lines of evidence support this conclusion. In univariate correlation analysis, the percentage of the basin cleared of trees for ski runs correlates with higher total flow and earlier flow timing (Figure 15). In multivariate analysis, development variables are also significant predictors of streamflow metrics (Table 6). Although development clearly does affect streamflow, we also see that headwater streamflow generation at this study site is complex and best explained by multiple predictors (Table 6). The high variability in flow between sites explains why ANOVA comparisons between developed and reference sites for both streamflow generation (seasonal sums) (Figure 12) and the timing of the flow (flow quantiles) (Figure 13) were not statistically significant.

Developed watersheds have additional artificial snow accumulation added to ski runs, and ski runs are areas with permanent tree removal (Figure 8). These watersheds also include numerous road and trails, which decrease infiltration of melted snow (Figure 8). Snow making likely increases streamflow due to the added water input. Snow pipe is a significant predictor in the multivariate models for summer flow and all flow quantiles except Q25 (Table 6). Added depths of water from artificial snow were 53mm in WY20 operational season and 56mm in WY21 operational season, or 5-7% of total input (Table 4). This is not a large increase in input, but it may be enough to produce greater streamflow. In this study, we assume uniform distribution of applied snow in basins with snow-making equipment because we only had information about the total water used for snow-making. A more refined dataset of artificial snow distribution could show which sub-watersheds received more or less artificial snow.

In all but winter of WY21, the percent of basin cleared for ski area opening is strongly correlated to seasonal streamflow generation (Figure 15). In addition to the added snow from snow making, ski runs may accumulate more snow due to lack of canopy interception (Boon, 2012; Barnhart et al., 2016). Reduced transpiration can also leave more water in the watersheds to supply higher streamflow. Because trees have been removed, more incoming shortwave radiation reaches the snow surface on ski runs. This may cause the earlier snowmelt hydrograph timing documented for developed sites (Figure 11 and Troendle, 1985). Accumulated snow on ski runs also experiences greater pack metamorphism from increased pressure from skier and machine compaction, which can reduce albedo and further increase net shortwave radiation (Weihs, et al., 2020). Snowpack metamorphism may also alter the timing of melt; increased density of the snowpack could delay melt timing. Since we did not observe later streamflow response, this change in snow density may not be a dominant influence on streamflow timing changes (Figure 15).

Once snowpack ablation begins, melt water may contact more impervious surfaces of roads and trails that more rapidly route melt water to streams. Trail variables are significant predictors of most flow quantiles in the multivariate models (Table 6). This may be because the more rapid flow routing in developed areas contributes to the earlier snowmelt hydrograph timing at developed watersheds (Figures 11 and 15). Trail density is also the variable with the highest correlation to Q25 and Q50 of WY20 and Q75 in WY21 (Figure 15) Univariate correlations indicate earlier streamflow timing with greater trail length and density, consistent with the idea that snowmelt water is routed more rapidly to streams in watersheds with more trails and roads. The 1.5 km km^{-2} trail density established as an indicator of watershed health (USFS, 2010, Figure A1) is not associated with a threshold change in streamflow (Figure 16), and most of the catchments in the study area have trail densities greater than this threshold.

Finally, development as a categorical variable has a significant effect on spring flow and the 10^{th} and 25^{th} quantiles in length models and the 10^{th} quantile in multivariate models (Table 6). Interestingly, the components of a developed watershed, artificial snow (snow pipe), ski run clearing and trail building are selected in many more models than the categorical development predictor (Table 6).

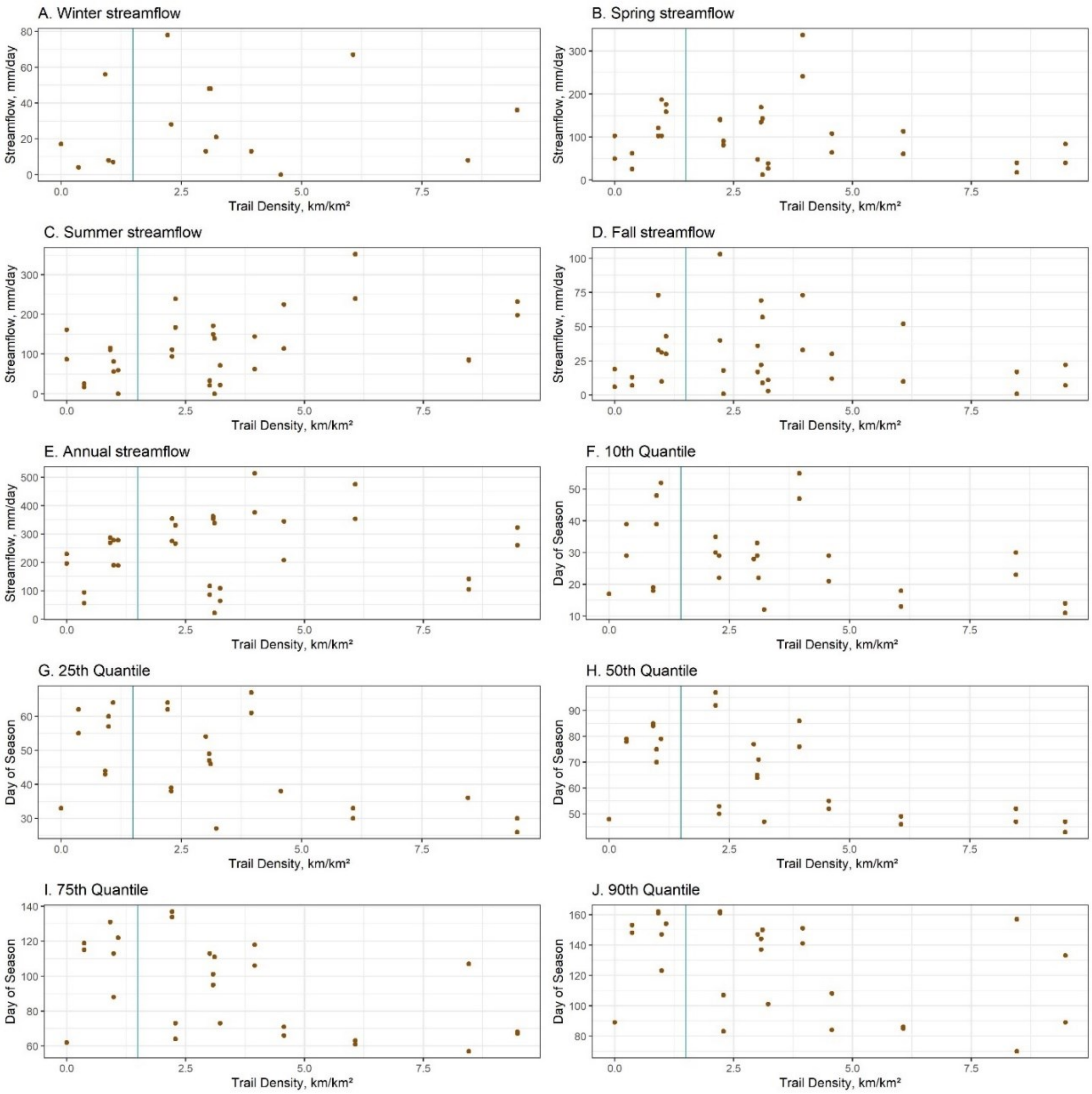

Figure 16. Streamflow metrics vs. trail densities for both water years. Vertical line is at 1.5 km km^{-2}, the density at which point a watershed is deemed in poor condition (USFS, 2010).

5.2 Other variables affecting streamflow

Although we did identify some dominant effects of ski area development, multiple other factors can cause variability in streamflow between study sites. Streamflow can be generated via surface flow paths, shallow subsurface flow paths, or deeper groundwater

(Dunne and Black, 1970, Freeze, 1975; Beven, 2006). The smallest drainage area headwater sites at Burgess Creek (BM_U) and its tributaries (BT_1U, BT_1L and BT_2) had low streamflow generation and very muted snowmelt hydrographs compared to streams with larger drainage areas (Figures 6 and 11). This indicates that less of the snowmelt water reached these channels. These catchments have limited tree removal within their boundaries (10% or less, see Table 2), and reduced water yield could be due to sublimation of snow intercepted in the forest canopy or of snow redistributed from the canopy by wind transport (Strasser et al., 2008). Snow sublimation can be a significant portion of the snow mass balance and has been found to contribute 28% to overall snow loss in mountain environments (Sextone, et al., 2019). Snow depth can be significantly different depending on the leeward or windward position of the forest edge effect; these differences can be greater than the difference between forested and open area (Currier & Lundquist, 2018).

Another reason for low flow in these headwater catchments could be that they are net groundwater recharge areas, supplying water to deeper subsurface flow paths (Frisbee, 2011). The headwater site locations for BM_U and BT_1U are close to the start of the channel network, where channelization is just beginning to occur (Figure 6). The more limited channel incision in headwater streams means that these sites are not likely connected to deeper subsurface flow paths, in contrast to more deeply incised channels further downstream (Becker, 2005; Gleeson, 2008). However, BT_1L and BT_2 tributary sites are lower in elevation where they could more likely connect to subsurface flow (Figure 2 and 6). Since observed streamflow production at these sites is muted, the channels of these small catchments are likely not intercepting deeper groundwater flow and are instead areas with high groundwater export to other basins (Figure 11 and Gleeson, 2008).

Streamflow generation increases further downstream along the main channel of Burgess Creek where channels are larger and more deeply incised (Figure 11 and Frisbee, 2011). At this position in the channel network, the more deeply incised channels likely access deeper subsurface flow paths. Tributaries 3 and 4 produce more streamflow than any site on the main channel of Burgess Creek (Figure 6 and Table 5). The percentage of contributing basin that is cleared of trees is greatest at these two sites, with 40% and 56% tree clearing for BT_3 and BT_4 respectively (Table 3), which could provide an explanation for the increased streamflow.

Of all predictor variables for streamflow, mean basin elevation is the terrain variable with the strongest correlation to streamflow timing (Figure 15). Hydrograph timing is later at higher elevations. This is not a surprise; the highest elevations melt the later because of the strong correlation between increased elevation and both decreased temperatures and increased precipitation (Dingman, 1981). Both of these factors lead to higher peak snow accumulation with increasing elevation. A hypsometric analysis of peak SWE for the three closest SNOTEL stations showed an increase of 83mm of SWE per 100 meters of elevation gain, averaged across 2020 and 2021 (Figure 10). The greater cold content of colder and deeper snowpacks at higher elevations means that more energy and time are required for the snowpack to warm to the melting point, causing later snowmelt runoff. Mean basin elevation also plays a striking role in summer seasonal streamflow, where the strong negative correlation means that higher elevation sites produce less summer flow, evidence that these sites may not be connected to deeper subsurface flow paths that would sustain higher summer baseflow (Figure 15).

Slope is negatively correlated to most WY20 flow quantiles, indicating that flow starts earlier on steeper slopes (Figure 15). Flow routing is likely quicker in the higher gradient and steeper catchments (Figure 2). Greater summer flows are strongly correlated to higher average basin slope meaning that steeper basins delivered more water in the summer months; the reason for this is uncertain and is perhaps related to interactions between slope and other variables that increase flow. The slope aspects in the study are all similar between watersheds, so an aspect effect is not expected. The negative correlation between aspect and streamflow can be likely be related to interactions between aspect and other variables.

Area is a significant predictor for summer and fall stream flow and for early flow quantiles, Q10 and Q25 (Table 6). This shows that area normalizing flow does not completely remove the area effect. Area - normalization helps make streamflow units comparable between watersheds of different sizes, but it does not remove the area effect entirely because of the multi-scale subsurface flow paths. The smaller headwater catchments have some of the lowest runoff ratios, indicating they are net recharge areas for groundwater, whereas the larger basins can gain more of this subsurface flow (Table 4). This is true for the upper site on Burgess Creek (BM_U) and the upper site on Spring Creek (S_TU) where the small runoff ratio of 0.09 (BM_U) and 0.13 (S_TU) is an indication that most of the precipitation is recharging groundwater rather than discharging at the site (Table 4).

The difference between water years as identified by climate variables is rarely a consistent significant predictor in multivariate models, meaning that differences in sites are more important than differences between the water year for predicting streamflow magnitude and timing. The range of variability in runoff ratio between sites is 0.42 and 0.52 for each individual water year (Table 7). The range of difference in runoff ratio between years at a given site is less, only 0.29, confirming that site variability dominates over a year effect for these two years of study.

Table 7. Range of variability for site runoff ratios (see Table 5) and year difference between runoff ratios. Note: sites with NA in WY20 are omitted here.

Site	**WY20 Runoff Ratio (Q/Input)**	**WY21 Runoff Ratio (Q/Input)**	**Year difference**
B_all	0.33	0.23	0.10
BM_L	0.24	0.20	0.05
BM_U	0.09	0.06	0.02
BT_1L	0.25	0.36	-0.12
BT_1U	0.24	0.43	-0.19
BT_3	0.29	0.29	-0.01
BT_4	0.47	0.41	0.06
BV	0.35	0.45	-0.10
S_M	0.51	0.58	-0.07
S_TL	0.40	0.49	-0.09
S_TU	0.13	0.24	-0.11
Range across sites	**0.42**	**0.52**	**0.29**

5.3 Study limitations

My overall goal in this study was to analyze flow variations across multiple watersheds with stratified levels of development. Comparing developed catchments to undeveloped catchments rests on an assumption of spatial similarities between basins.

Patchy land ownership between private and public land and difficult stream access made this hard to find in our study sites. Hot Spring Creek is a much larger watershed than catchments situated on the resort and therefore may behave differently than watersheds of smaller sizes found on the resort. Due to access and time constraints, I also did not have as many sizes of undeveloped watersheds as in the developed dataset.

Site access also limited the duration of the field dataset. The onset of the corona virus pandemic led to limitations on federal field work during WY20, so no manual discharge readings were taking during WY20. A rating curve relates stream stage to manual discharge readings and a robust curve that captures flow variability will ideally have manual readings that span the full range of site discharges. During WY21, when field work opened up, increased snowmelt infiltration from dry pre-snow conditions and low peak snow accumulation led to early and low snowmelt runoff coupled a short hydrograph duration, in some instances to a little as 4 weeks. With so few opportunities for manual discharge readings across the full hydrograph, our rating curves are incomplete but as good as they could be given the circumstances. A rating curve that lacks good fit may propagate uncertainty through flow computations. This can be due to measurement errors or curve fit errors and can have impacts on the ability to extrapolate accurate flow. Most common extrapolation errors occur at the extremes, the high and low flows, where there may be no anchor for the curve. Hydrograph response in our study area was rapid and a complete picture of rising limb and peak flow may not have been adequately captured. A robust rating curve was possibly further impacted by number of sites initially selected. With all the benefits of hindsight, it is possible that this study was designed to be too large for one person to realistically manage. Greater attention could have been paid to fewer sites, but at the loss of statistical strength.

A more precise portrait of artificial and natural precipitation input across the study area could have been helpful in identifying differences in basin response. Snow poles and rain gauges had been installed at the study sites to help characterize input, but equipment failure, inability to download data and fix problems during WY20, and vandalism led to a limited dataset for input. We used PRISM data to compute average precipitation and temperature, but the coarse scale of PRISM ($4km^2$) is too large to predict individual basin variability. SNOTEL stations each represent a single spatial point on the landscape and were not located within the study watersheds. A future study of small catchment streamflow generation should include a more refined climate variable timestep series that reflects more nuance in its analysis. It is also possible that characterizing streamflow generation at the seasonal timestep may miss important indications of streamflow variability. Future analysis could focus on a monthly or bi-weekly timestep of accumulation to better capture the individual components of streamflow generation for comparison.

Finally, we must acknowledge that multivariate analyses are not definitive indicators of the importance of a variable because different predictor combinations can produce similar results and the opposite is equally valid. Our understanding of this system can be guided by these model results but cannot be determined from them.

6 CONCLUSIONS

This research evaluated variations in streamflow generation on a ski resort in Northern Colorado. By comparing catchments with ski area development to undeveloped catchments we found that development increased streamflow, likely because of added snow and possibly reduced transpiration. Development also shifted hydrograph timing earlier in the year, likely because more solar radiation exposure initiated earlier snowmelt, and water was routed more quickly to streams via roads and trails. Although results point to a significant effect of development on streamflow, many other factors create high streamflow variability between catchments. Elevation changes snow accumulation and melt timing; slope changes timing of flow routing, and catchment size with its position in basin influences whether the site is a net groundwater exporter or whether it intercepts deeper groundwater flow paths that supply sustained baseflow.

The interactions of land use changes in ski areas are common across developed ski areas in headwater forested catchments in Colorado and other mountain regions. Altering the production of streamflow can change the physical characteristics of a functioning watershed by altering temperature and channel geomorphology (Zhi, et al., 2020; Miller, et al., 2021), loss of habitat diversity (Poff et al., 1997), and impacting overall stream ecology (Palmer, et al., 1997; Paukert et al., 2011; Coble & Kolb, 2012). No evidence of stream degradation was visible, although we did not conduct measurements of stream channel morphology to verify this. Future research could examine both geomorphic and ecological responses to ski area development. Given the importance of functioning forested headwater streams for water supply, we see a critical need to examine the implications of development in these areas.

Our study examined just one ski area, but it can be an entry point into a broader understanding of how headwater watersheds are affected by multiple disturbances. This type of research requires long-term monitoring and study sites across a wide physiographic range of variables (Lindenmayer, et al., 2012). As population expands into mountain regions and climate perturbations alter water supply patterns, more data must be a priority to tackle shifts in streamflow generation.

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6. Road and Trail Condition Indicator	The density and distribution of roads and linear features within the watershed indicates the hydrologic regime is substantially intact and unaltered.	The density and distribution of roads and linear features within the watershed indicate there is a moderate probability that the hydrologic regime is substantially altered.	The density and distribution of roads and linear features within the watershed indicate there is a higher probability that the hydrologic regime (timing, magnitude, duration, and spatial distribution of runoff flows) is substantially altered.
Attributes	**GOOD (1) Functioning Properly**	**FAIR (2) Functioning at Risk**	**POOR (3) Impaired**
Open Road Density	Default road/trail density: < 1 mi/mi^2, OR a locally determined threshold for good conditions supported by Forest Plans or analysis and data.	Default road/trail density: 1 - 2.4 mi/mi^2, OR a locally determined threshold for fair conditions supported by Forest Plans or analysis and data.	Default road/trail density: >2.4 mi/mi^2, OR a locally determined threshold for poor conditions supported by Forest Plans or analysis and data.
Road and Trail Maintenance	BMPs for the maintenance of designed drainage features are applied to >75% of the roads, trails, and water crossings in the watershed.	BMPs for the maintenance of designed drainage features are applied to 50 to 75% of the roads, trails, and water crossings in the watershed.	BMPs for the maintenance of designed drainage features are applied to <50% of the roads, trails, and water crossings in the watershed.
Proximity to Water	No more than 10% of road/trail length is located within 300 feet of streams and water bodies or hydrologically connected to them.	10 - 25% of road/trail length is located within 300 feet of streams and water bodies or hydrologically connected to them. .	More than 25% of road/trail length is located within 300 feet of streams and water bodies or hydrologically connected to them. .
Mass Wasting	Very few roads are on unstable landforms or rock types subject to mass wasting with little evidence of active movement or evidence of road damage. There is no danger of large quantities of debris being delivered to the stream channel due to mass wasting.	Few roads are on unstable landforms or rock types subject to mass wasting with moderate evidence of active movement or road damage. There is some danger of large quantities of debris being delivered to the stream channel. It is not a primary concern in this watershed.	Most roads are on unstable landforms or rock types subject to mass wasting with extensive evidence of active movement or road damage. Mass wasting that could deliver large quantities of debris to the stream channel is a primary concern in this watershed.

Figure A1. Road and Trail Condition Rating Rule Set, from Potyondy and Geier (2010), page 43, condition is defined here as 2.4 mi mi^{-2} and converted to 1.5 km km^{-2}.for this study.

Table A1. Site installation for study and reference stage loggers, for complete names see Table 2 and locations see Figures 6 and 7.

Site	Serial Number	Location (X)	Location (Y)	Timestep (min)	Equipment type
B_All	2301851	348710.5	4481090	15	U20
BM_L	2301855	350632.2	4480466	15	U20
BM_M	2301850	351227.2	4480570	15	U20
BM_U	20098800	351729.8	4480749	15	U20
BT_1L	2301853	349389.3	4481461	15	U20
BT_1U	2301858	351029.2	4481208	15	U20
BT_2	20098801	349608.6	4481259	15	U20
BT_3	20098799	349867.7	4480849	15	U20
BT_4	2301778	350669.6	4480276	15	U20
BV	20688258	350866.9	4477170	15	U20L
HS_L	20669867	344063.8	4491586	15	U20L
P_L	2301774	349934.9	4478519	15	U20
P_U	20669871	350314.4	4478669	15	U20
S_M	20654312	348870.4	4487925	15	U20L
S_TL	20669869	348908.1	4487993	15	U20L
S_TU	20669870	349010.4	4488216	15	U20L

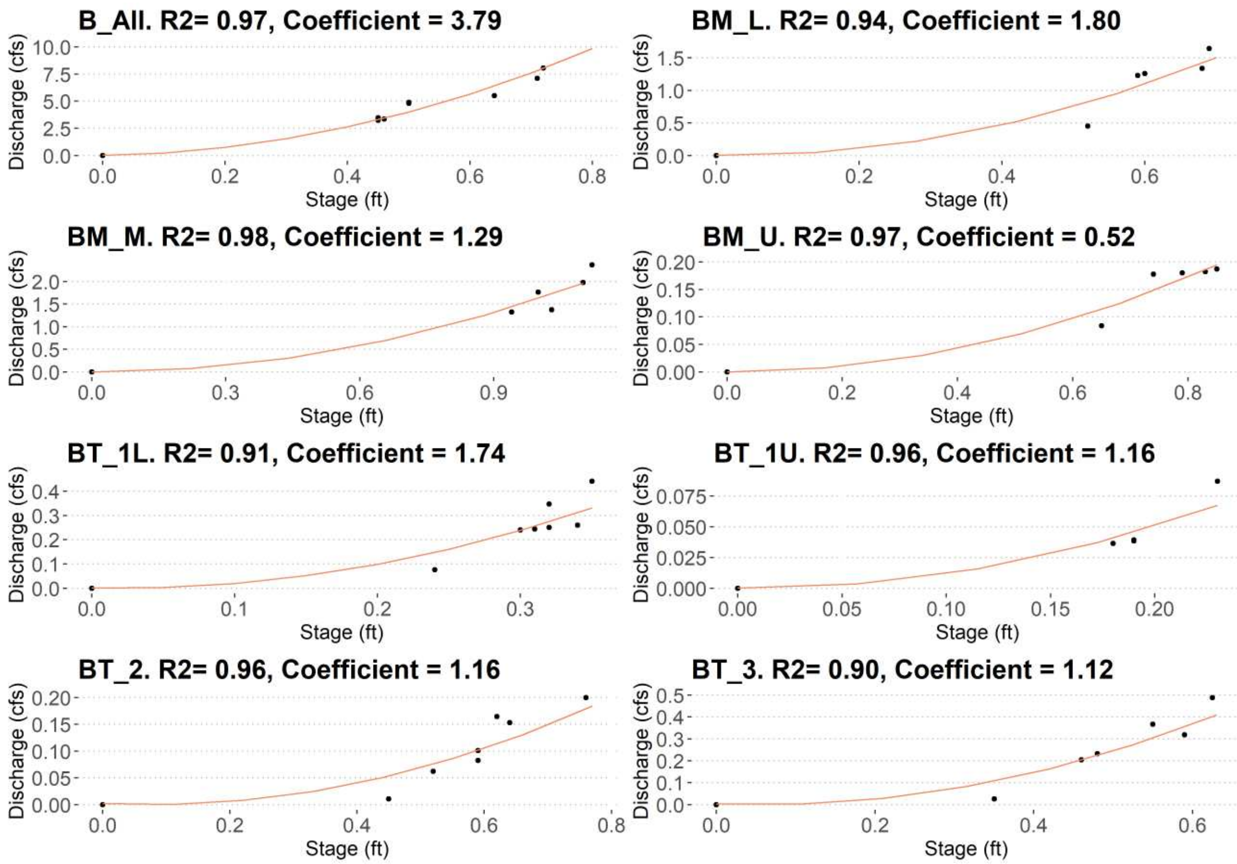

Figure A2a. Relationship between manual discharge measurements and stream stage readings. Coefficient of determination value and β values is also included.

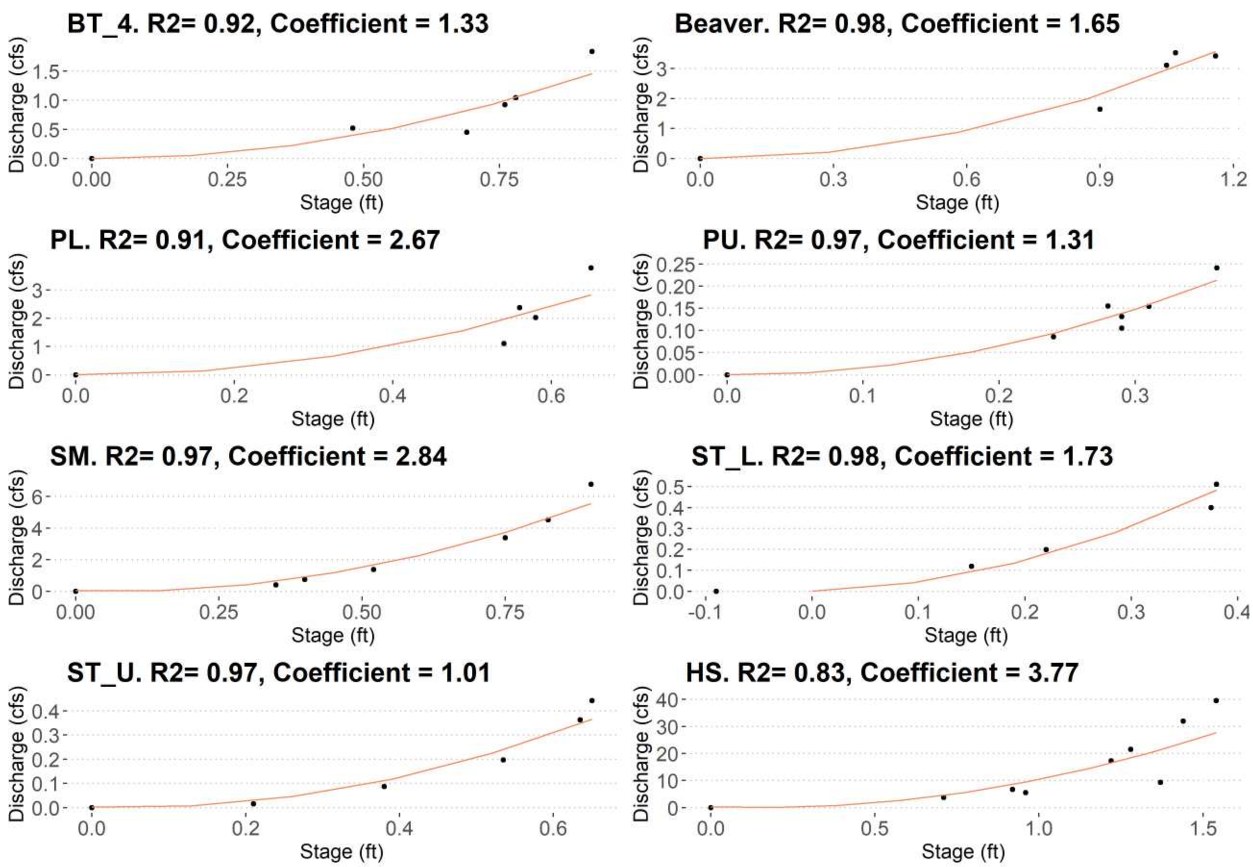

Figure A2b. Relationship between manual discharge measurements and stream stage readings. Coefficient of determination value and β values is also included.