The Role of Groundwater Flow in a Montane, Semi-Arid, Headwater Catchment

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Abstract

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upper Gordon Gulch and from hillslopes, and via short, shallow flowpaths in lower Gordon Gulch. Modelled groundwater accounts for approximately 16 to 34% of baseflow in the stream. Using Gordon Gulch as a case study, this model and data analysis contribute to a larger effort to understand and constrain the mechanisms driving groundwater recharge and groundwater-stream exchanges in semi-arid, headwater catchments.

Keywords: Surface water-groundwater interactions, groundwater modelling, MODFLOW, groundwater recharge, stream leakage, flowpaths, gaining stream

1. INTRODUCTION

Groundwater discharge to headwater streams is recognized as a critical component of the hydrologic system (Feth et al., 1966; Huntley, 1979; Hibbs and Darling, 1995; Maurer et al., 1997; Anderholm, 2000; Flint et al., 2001; Sanford et al., 2004; Aishlin and McNamara, 2011). While snowmelt provides most of the annual streamflow in mountain catchments, groundwater buffers streamflow in the absence of precipitation by discharging stored precipitation in the form of baseflow (Baraer et al., 2009; Gordon et al., 2015; Fujimoto et al., 2016; Carroll et al., 2018; Harrington et al., 2018; Saberi et al., 2019; Somers and McKenzie, 2020). In the Colorado Front Range of the Southern Rocky Mountains in North America, groundwater-derived baseflow can account for more than 75% of streamflow during dry conditions (Clow et al., 2003) and more than 60% during the early snowmelt season (Liu et al., 2004). This store and release process offers a mechanism for providing a reliable source to maintain streamflow, even during warmer and drier months, which often coincide with the highest environmental and anthropogenic demands (Harrison et al., 2021; Wilson and Guan, 2004; Markovich et al. 2019).

The growing recognition of the importance of groundwater in the mountain water budget has highlighted the need to quantify groundwater in specific settings such as semi-arid, subalpine, and/or forested catchments. However, few studies explicitly examine how groundwater interacts with the stream in mountain environments and even fewer model these interactions. For the studies that have coupled groundwater-surface water models, the focus has been on a mountain-to-coast watershed scale (Foster and Allen, 2015), bedrock outflow (Voeckler et al., 2014), and responses to climate-driven recharge rates (Engdahl and Maxwell, 2015; Anderson et al., 2019).

The limited number of studies on groundwater processes in mountain aquifers reflects some of the challenges in studying these systems, e.g., complex topography and geology, a lack of instrumentation, difficulties monitoring deep aquifer layers, and heterogeneity of flow and transport systems. All of these factors complicate the ability to create a regional flow model (Manning and Solomon, 2005). To reconcile these challenges, the scientific community must develop approaches to study subsurface responses that rely on shallower measurements that can constrain deeper flow and transport (Tokunaga et al., 2019).

The nearly continuous, nine-year record of monitoring in Gordon Gulch provided an opportunity to study the interaction of groundwater and streamflow. Our approach is to use a model of groundwater flow in Gordon Gulch and data from the watershed and surrounding areas to gain insights into the spatial and temporal patterns of groundwater recharge, and of groundwater contributions to streamflow.

2. STUDY AREA

Gordon Gulch is a small (2.6 km^2), semi-arid, montane, headwater catchment in the Colorado Front Range (**Figure 1**). The catchment is located approximately 30 km west of Boulder, Colorado (40.02°N, 105.48°W), within the Boulder Creek watershed at an elevation of 2,500 to 2,700 meters above sea level. The catchment averages 580 mm of precipitation annually with a mean annual air temperature of 6.5°C (**Table 1**). The catchment is divided into two sub-catchments, informally called upper and lower Gordon Gulch. The stream in Gordon Gulch is both ephemeral (upper reaches of upper Gordon Gulch) and perennial (lower Gordon Gulch).

Gordon Gulch is part of Boulder Creek Critical Zone Observatory (BcCZO) (Anderson et al., 2013), one of ten U.S National Science Foundation (NSF) Critical Zone Observatories that existed from 2007-2020 across the United States and Puerto Rico and examined climate, geology, vegetation, and watershed dynamics (White et al., 2015). Gordon Gulch was instrumented with six groundwater monitoring wells (three with automated pressure transducers), two meteorological (MET) stations, two stream gauges, lysimeters, time-lapse cameras, and snow depth poles (**Figure 1**). Additional data collection in the catchment included weekly and monthly water sampling (e.g., Burns et al., 2016; Mills et al., 2017), soil sampling (Dethier et al., 2012; Eilers et al., 2012; Gabor et al., 2014; Foster et al., 2015; Anderson et al., 2021a), airborne LiDAR (e.g., Harpold et al., 2014), and geophysical surveys (Befus et al., 2011; Leopold et al., 2013). These combined resources provide a wealth of data on Gordon Gulch and are utilized in the development of a groundwater flow model as part of this study.

Table 1. Climate summary for Gordon Gulch based on field measurements at meteorological stations within the catchment and nearby.

Parameter	**Value**	**Climate Station**	**P**
Mean annual air temperature	6.5°C	NF MET and SF MET[a]	2
Mean air temperature, warmest month (July)	17.5°C		
Mean air temperature, coldest month (February)	-3°C		
Temperature range over period of record	-23.7°C to 24.7°C		
Mean annual precipitation	580 mm	NADP CO94 station [b] NF MET and SF MET [a]	
Annual fraction of precipitation as snow[c]	59% - 70%	NADP CO94 station	2
Mean annual wind speed	1.8 m/s	NF MET and SF MET[a]	2

1. NF MET and SF MET are meteorological stations sited on north-facing and south-facing hillslopes in lower Gordon Gulch.
2. National Atmospheric Deposition Program (NADP) National Trends Network site CO94 is located 2 km southwest of Gordon Gulch at an elevation of 2,524 m.
3. Estimates for annual precipitation as snow made by Cowie, 2010 and Anderson and Rock, 2020 using data from the NADP CO94 station.

2.1 Topography

Gordon Gulch is in an area of rolling, relatively low relief terrain found between the steep topography of the crest of the Front Range and the mountain front at the western edge of the High Plains (Anderson et al., 2006). The catchment is outside and below the extent of the Pleistocene glaciers but above the incised bedrock canyon (Anderson et al., 2021a). Gordon Gulch is oriented approximately east to west, creating distinct north- and south-facing slopes. Slope aspect exerts control on weathering depths (Anderson et al., 2013; Anderson et al., 2014), snowpack depth and persistence (Langston et al., 2015), shallow subsurface hydrology (Hinckley et al., 2014), vegetation (Peet, 1981), and evapotranspiration rates (Barnard et al., 2017). On the north-facing slopes, vegetation is dense and populated by lodgepole pine (*Pinus contorta*); south-facing slopes are less vegetated and populated by shrubs, grasses and a scattering of ponderosa pine trees (*Pinus ponderosa*) (Adams et al., 2014). In the northern hemisphere, south-facing slopes intercept a greater amount of solar, shortwave radiation than the north-facing slopes (Fan et al., 2019), resulting in thinner snowpacks with multiple cycles of snow accumulation and melt (Anderson et al., 2021a; Rush et al., 2021). Conversely, the north-facing slopes retain a snowpack from the late fall through spring and experience more pervasive frost due to the colder temperatures (Rush et al., 2021). In addition to greater thickness of weathered rock and saprolite on north-facing slopes (Befus et al., 2011), the saprolite is more porous and granulated than on south-facing slopes, where it is more intact and fractured (Bandler, 2016).

Although slope aspect is not expressly addressed in this study, it is acknowledged that this may be a critical mechanism driving differences in groundwater recharge in the catchment (e.g., Hinckley et al., 2014;

2017; Langston et al., 2015; Rush et al., 2021). Differences in the annual precipitation, snow depth and duration, and evapotranspiration rates across the north- and south-facing slopes are apparent in field data and discussed in detail in Supporting Information.

2.2 Geology

The bedrock underlying Gordon Gulch is Precambrian biotite gneiss, with minor granodiorite intrusions (Gable, 1996). Four hydrogeologic units are recognized in Gordon Gulch: soil, saprolite, weathered bedrock, and fresh bedrock (Anderson et al., 2021a) (**Figure 2**)**.** Weathered bedrock is fractured and moderately chemically altered bedrock. Saprolite is mechanically weak weathered rock that retains its original bedrock fabric and represents a transitional phase between bedrock and soil (Anderson et al., 2007). Gordon Gulch soils are comprised of sand and silty sands (Dethier et al., 2012; Hinckley et al., 2014).

Depth of the weathering front (representing the base of weathered bedrock) averages 12 m in Gordon Gulch based on seismic refraction surveys (Befus et al., 2011), but varies considerably. Unweathered bedrock may be at the surface (˜10% of the catchment is comprised of bedrock outcrops, Anderson et al., 2021a), or up to 30 m deep (Dethier and Lazarus, 2006). The weathering front tends to be deeper on the north-facing slopes (10-15 m) than the south-facing slopes (5-10 m), resulting in different thicknesses of saprolite and weathered bedrock across the two aspects (Befus et al., 2011) (**Figure 2**). Soil has a uniform depth of 0.4±0.2 m on both aspects, not including outcrops (Anderson et al., 2021a).

Groundwater is unconfined in the soil, saprolite, and weathered bedrock and within fractured bedrock (Henning, 2016). Hydraulic conductivity varies greatly across these hydrogeologic units and exerts control over groundwater flow. The differences in the hydraulic conductivity and layer thickness are believed to result in different rates of recharge, hydraulic gradients, and water table elevations across the north-and south-facing slopes (Bandler, 2016; Henning, 2016).

3. DATA AND METHODS

All data sources and models used are described in detail in this section. We use data collected in Gordon Gulch from 2012-2020 (**Figure 3**). Data were processed and analysed by water year (October 1 through September 30) to identify seasonal, annual, and interannual trends, from which we compute an average water year that we use to calibrate and drive the groundwater flow model (**Figure 4**).

We first describe the catchment-scale water budget and the data used to estimate the budget on an annual scale. We then describe additional data used to drive and constrain the groundwater model. Finally, we describe the groundwater flow model.

3.1 Catchment-Scale Water Budget

The catchment-scale water budget includes all storage and fluxes in Gordon Gulch both above and below the water table. The catchment-scale water budget for a headwater catchment is:

$P - \mathrm{ET}_c - \ Q_C = \ S_c$ (1)

where the subscript c denotes that the term is catchment-scale and includes surface and subsurface processes. P is total precipitation, $\mathrm{ET_c}$ is the total evapotranspiration (sum of evaporative losses from surface and soil vadose zone waters and plant transpiration), $\mathrm{Q_c}$ is total streamflow out of the catchment, and $\Delta \mathrm{S_c}$ is the change in water storage in groundwater and the vadose zone (**Figure 2**).

3.1.1 Precipitation

Precipitation measurements were recorded at three meteorological stations. Two meteorological stations are located on opposing aspect hillslopes within Gordon Gulch, the north-facing (NF MET) and south-facing (SF MET) stations (**Figure 1**); these recorded daily precipitation in unheated tipping buckets at 10-minute intervals from 2012 to 2020 (Anderson and Ragar, 2021a; Anderson and Ragar, 2021b). The NF MET station is purposely located under the tree canopy, while the SF MET station is in the open. The third meteorological station, National Atmospheric Deposition Program (NADP) National Trends Network site CO94, is a heated tipping bucket located approximately 2 km southwest of Gordon Gulch at an elevation of 2,524 m. CO94 has collected daily precipitation measurements since 1986, and the precipitation phase (rain, snow, mixed, or unknown) is identified. None of the stations had a complete precipitation record. Therefore, a ranked, gap-fill procedure was performed to create a complete daily precipitation record for water years 2012 – 2020, with CO94 data ranked highest and NF MET station data ranked lowest (see Supporting Information). No station accounted for undercatch or vegetation interception; we assumed these processes to be minimal and did not adjust the data to account for them.

From 2012 to 2020, average annual precipitation in Gordon Gulch ranged from 415 mm to 836 mm, with a mean value of 580 mm. April, May, and July were the wettest months of the year, accounting for approximately 42% of the annual precipitation (**Figure 3a** and **Figure 4a**). July was the most variable month (outside of the exceptional September event in 2013; Gochis et al., 2015), with mean monthly precipitation ranging from 29 mm to 214 mm. The winter months (November through January) were the driest, contributing only 12% to total annual precipitation.

3.1.2 Streamflow

The unnamed stream in Gordon Gulch is perennial, albeit low in winter, in the lower part of the catchment, and ephemeral in upper Gordon Gulch. Flow is intermittent in some segments of the channel during summer (Martin et al., 2021). There are two stream gages in Gordon Gulch; one at the top of the steep reach between upper and lower Gordon Gulch and one at the downstream end of lower Gordon Gulch (**Figure 1**). Stage measurements were recorded at 10-minute intervals using pressure transducers (Anderson and Ragar, 2021c). Streamflow for the lower gauge is computed using a stage-discharge rating curve derived from the automatic stage and manual discharge measurements made by salt dilution. Because of challenges imposed by snow and ice and very low discharge in winter, streamflow data is unavailable from approximately November to April each year (dates vary). Streamflow from the lower gauge is used as part of this study because of its location at the catchment outlet, which represents streamflow out of Gordon Gulch.

Over water years 2012 – 2019, streamflow averaged 13 x 10^{-3} m^3/s. There are three distinct seasonal streamflow regimes in Gordon Gulch: a low-flow period from August through March (averaging 0.64 x $10^{-3} m^3/s$), a period of peak streamflow associated with spring snowmelt and rain in April through May (averaging 37 x 10^{-3} m^3/s), and a period of streamflow recession in the June and July (averaging 9.7 x 10^{-3} m^3/s) (**Figure 3c** and**Figure 4d**). Peak spring streamflow in most years analysed occurred between mid-April and late May and is attributed to sustained snowmelt and rain. The late-spring snowmelt results in a hydrograph with a steep rising limb and a drawn-out falling limb that lasts from summer through early fall. However, as water year 2012 illustrates, rapid increases in stream discharge can occur during the summer due to heavy rainfall events (**Figure 4d**). Over the study period, three summer rainstorms produced streamflow at rates that nearly met or surpassed the spring discharge peak; July 2012, September 2013, and July 2015. Cowie (2010) suggested that summer rain events may keep the unsaturated zone moisture high enough to push soil water out of the aquifer and into the stream channel.

3.1.3 Evapotranspiration

Evapotranspiration was not measured in Gordon Gulch, but if we assume in Equation 1 that on annual timescales $\Delta S_c = 0$, then ET_c can be estimated as the difference between total annual precipitation and streamflow:

$\mathrm{ET}_c = P - Q_C$ (2)

Using Equation 2 and measurements of precipitation and streamflow for WY 2012 through 2019, ET_c is estimated to average 500 mm/yr in Gordon Gulch.

3.2 Data used in the Groundwater Flow Model

3.2.1 Snowmelt

As snow melts, the water becomes available for evaporation, runoff, and/or infiltration. In Gordon Gulch, precipitation that falls as snow during the winter is stored in snowpacks, creating a lag between the timing of snowfall and when liquid water is available (Hale et al., 2022). We used changes in snow depth (ignoring compaction) and average snow density to compute snowmelt.

Snow depth was visually estimated by reviewing 10-minute time-lapse imagery, when available, from two cameras in Gordon Gulch for water years 2012 – 2019 (Anderson and Ragar, 2021d). These cameras are aimed at snow poles on the north- and south-facing slopes, so the depth of the snow can be visually estimated using the markers on the snow poles as a guide. These records are incomplete. No data was available for some locations in some years, and there were gaps in the time-series of images in other years.

Snow density in Gordon Gulch was calculated from measurements made in snow pits dug on 16 dates between 2008 and 2017 (Anderson and Rock, 2020). Snow melt, as snow water equivalent (SWE), was calculated by multiplying negative changes in daily snow depth by average snow density (see Supporting Information).

Average annual SWE was approximately 254 mm per water year and ranged from 170 to 320 mm. The majority of snowmelt occurred in April and 54% of total annual snowmelt occurred between February through April (**Figure 3b** and **Figure 4b, c**).

3.2.2 Groundwater Levels

Groundwater levels were monitored in three wells in upper Gordon Gulch. The wells are arrayed along a transect across the catchment (**Figures 1 and 2**) at positions on the north-facing slope (well 1), the valley bottom (well 2), and the south-facing slope (well 6). The wells were equipped with Solinst Levelogger Junior non-vented pressure transducers operating at ten-minute intervals (Anderson and Ragar, 2021e); atmospheric pressure corrections were made with a Solinst Barologger that was hung in a tree near the wells (Salberg, 2021). Well construction details for the monitoring wells are presented in **Table 2** .

Depth to water measurements were made at the three monitoring wells during water years 2012 – 2019 (see **Figure 3d** and**Figure 4e**). The topography of the water table mimicked land surface topography with deeper groundwater on the hillslopes (average depth to water of 5.7 m and 9.3 m at the south and north-facing slope wells, respectively) and shallower water table in the valley bottom (average depth to water of 0.7 m at the valley well) (**Table 2**). On the hillslopes, the water table stayed within the saprolite hydrogeologic layer throughout the year (**Figure 2**), while near the channel along the valley bottom the water table reached the ground surface at times. Peak water table elevations usually occurred in the spring, following snowmelt and/or spring rain, and decreased throughout the summer except during some large summer rainstorms. Throughout the water year, water table elevations fluctuated by approximately 1.8 m but ranged from 0.8 m (valley well in 2019) up to 4.5 m (south-facing well in 2013) (**Table 2**).

Table2. Well descriptions for the monitoring wells in Gordon Gulch.

Well ID	**Elevation of well top (m)**	**Well depth (m)**	**Screened interval (m)**	**Depth to water (m)** mean (min - max)	**Weathering description**[b,c,d]	**Position in catchment**
Well 1	2633	18.55	9.41 – 18.55	9.3 (8.0 – 9.9)	Tan/brown weathered rock to 12.2 m; grey weathered rock to 14.60 m; unweathered below	North-facing slope
Well 2	2623	4.45	1.41 – 4.45	0.7 (0 – 1.4)	Brown “loamy” material to 4.45 m	Riparian / catchment valley
Well 6	2643	17.34	8.20 – 17.34	5.7 (1.7 – 6.3)	Slow drilling; unweathered bedrock at 7.60 m	South-facing slope

1. Based on depth to water measurements from 2011 to 2019.
2. Anderson and Ragar, 2021f
3. Anderson and Ragar, 2021g
4. Anderson and Ragar, 2021h
5.

3.3 Groundwater Flow Model

A catchment-scale model was developed for Gordon Gulch using MODFLOW-NWT (Niswonger et al., 2011), which is a version of MODFLOW (Harbaugh, 2005) that is capable of handling unconfined aquifer conditions found in headwater catchments. In addition to using a three-dimensional, finite-difference numerical method to solve equations of groundwater flow (Harbaugh, 2005), MODFLOW-NWT applies a smoothed continuous function of groundwater heads to rewet unconfined cells that have run dry, ensuring that these cells remain active (Niswonger et al., 2011). MODFLOW-NWT calculates head at the center of each model cell and groundwater flow at the interface of adjoined cells.

The groundwater flow model represents flow in the saturated zone and does not treat the vadose zone. Inflows to the model domain include groundwater recharge from precipitation and SWE and leakage from the surface stream to the aquifer. Outflows include groundwater seepage to the stream and evapotranspiration from below the water table. We describe the model domain and considerations that guided our choices for model parameters in this section. In some cases, we calibrated parameters to obtain the best fit between simulated and observed values of key outputs. Initial conditions were derived from running the model in steady state, driven by mean annual values of precipitation and ET (**Table 2**). We used the average water year (**Figure 4**) constructed from daily observations over water years 2012-2020 to drive a transient model, and ran the model for ten model years.

3.3.1 Model Domain and Parameterization

The three-dimensional groundwater flow model domain was delineated laterally by the catchment boundaries of Gordon Gulch and extended vertically to a depth of 75 m (**Figure 5**). The surface topography was represented by a 20 m digital elevation model (DEM) derived from a 1 m digital surface model (DSM) from airborne LiDAR collected in August 2010 (Anderson et al., 2012). The four primary hydrogeologic units (soil, saprolite, weathered bedrock, and bedrock) were discretized into 13 model layers that range from 1 to 30 m in thickness, as summarized in **Table 3** . The model is approximately 3000 m by 1500 m, surrounding the entire 2.6 km^2 area of Gordon Gulch. The model is discretized to 25 m by 25 m cells. There are 77 rows, 108 columns, and 13 layers of cells.

Hydrogeologic unit thicknesses were estimated from geophysical surveys (Befus et al., 2011; Leopold et al., 2013; Bandler, 2016), soil pits (Eilers et al., 2012; Shea, 2013; Anderson et al., 2021a), and well logs (Dethier and Lazarus, 2006; Anderson and Ragar, 2021f,g,h), summarized in Salberg (2021). Each hydrogeologic unit is treated as a distinct but homogenous unit of uniform thickness in the model. Initial values of hydraulic conductivity were based on field measurements, including double-ring infiltrometer tests in soil (Buraas, 2009), slug tests in saprolite and weathered bedrock (Henning, 2016), lab measurements on field samples (Hinckley et al., 2014), and on literature values for comparable materials summarized in Salberg (2021). The model is unconfined to a depth of 11 m, representing the base of the weathered bedrock. The base of the groundwater flow model at a depth of 75 m represents low-permeability bedrock and is set as a no-flow boundary. The topographically-delineated catchment boundaries are inferred to act as groundwater divides and are also set as no-flow boundaries. Five constant head cells (four on the model boundary and one at an internal topographic high) were assigned to maintain topographic control on the head values at these locations.

MODFLOW's streamflow-routing (SFR) package was used to simulate exchanges with the Gordon Gulch stream. The SFR package calculates fluxes between groundwater and the stream based on head and the hydraulic gradient between them during each time step, using Darcy's law (Prudic et al., 2004). The stream was assigned a stage of 0.10 m, channel width of 0.25 m, stream gradient of 0.026, and streambed thickness of 0.75 m. Streambed conductance was initially set to 2 m/d and adjusted during the calibration process. A model gauge was assigned at the outlet of the lower reach (aligned with the lower stream gauge in the field) to report modelled baseflow moving out of the catchment.

MODFLOW recharge (RCH) and groundwater evapotranspiration (ET) packages were applied to simulate inputs and outputs to the aquifer system. Recharge is defined as the total water available to enter the subsurface, which includes rainfall and snowmelt as SWE. Recharge and ET rates were assigned across the entire model domain. Recharge rates in the model vary monthly and were based on mean daily rates calculated using precipitation and snowmelt data from water years 2012 to 2019. ET rates for Gordon Gulch and vicinity have been assessed from as low as 180 mm/yr (Langston et al., 2015) to over 1200 mm/yr (Knowles et al., 2015) (summarized in Salberg, 2021). For the model, ET rate was used as a fitting parameter during model calibration and ET was assigned an extinction depth of 5 m.

Model initial conditions for our transient models (in which annual seasonal cycles drove the simulations) were derived by running MODFLOW under steady state conditions. The recharge value for the steady state run were derived from the average of approximately 10^{-4} m/d for the months of July, August, and September, i.e., during recession conditions at the end of the water year. Head values derived from the steady-state run were then used as the initial head condition for transient runs.

Table3 . Hydraulic parameters and calibrated values for the hydrogeologic units and associated model layers used in the MODFLOW-NWT model.

Hydrogeologic unit	**Unit discretization (# of model layers)**	**Aquifer type**	**Range of K from literature (m/d)**	**Model calibrated value of K (m/d)**	**Total model unit thickness (m)**
Soil	1	Unconfined	0.02– 20.7	16	1

Hydrogeologic unit	Unit discretization (# of model layers)	Aquifer type	Range of K from literature (m/d)	Model calibrated value of K (m/d)	Total model unit thickness (m)
Saprolite	5		6 x10^{-3} – 3.5	1.7 x10^{-1} – 5.7 x10^{-1}	10
Weathered Bedrock	3	Confined	3.2 x10^{-2} – 17.3	1 x10^{-2}	5
Bedrock	4		9 x10^{-5} – 2	3.2 x10^{-5}	59
Streambed	-	-	-	7.6	0.75

3.3.2 Model Calibration

Estimating Baseflow for Model Calibration

Because MODFLOW computes flows into and out of the stream from the groundwater aquifer, we used stream baseflow to calibrate the model. Baseflow is the slowly varying component of streamflow that is generally ascribed to groundwater. Despite its importance, separating baseflow from streamflow is challenging, contributing to some ambiguity about the term. For instance, some define baseflow by water source, usually identified as deep groundwater (e.g., Hall, 1968; Weirman et al., 2019), while others define baseflow by hydrograph analysis as the slowly varying component of hydrographs (Hewlett and Hibbert, 1967; Foks et al., 2019). Another approach is to identify baseflow from stream chemistry (e.g., Hooper et al., 1990; Mills et al., 2017). While the details differ, baseflow is associated with the background flow in the channel, which most would attribute to discharge from groundwater.

We used the USGS Groundwater Toolbox (Barlow et al., 2017) to estimate the baseflow component of measured streamflow by applying the Eckhardt digital filter to measured stream discharge from lower Gordon Gulch for water years 2012 – 2019 (see Supporting Information). The Eckhardt method uses a two-parameter recursive digital filter to parse hydrographs into direct runoff and baseflow (Eckhardt, 2005). High-frequency variations in the hydrograph are assumed to be direct runoff derived from surface runoff and interflow within the vadose zone, while low-frequency variations are considered baseflow derived from stored groundwater (Eckhardt, 2005).

Transient Model Calibration

A ten-year transient simulation was run, driven by seasonal variations in climate parameters (precipitation and snowmelt) for the average water year (based on 2012-2019, **Figure 4**). In the transient model, time is divided into a periods of constant driving conditions (ET and recharge) called stress periods. We used total of 140 stress periods in the ten-year model run, each of 30 days duration, except for May, for which we used stress periods of 10 days to account for high and variable rates of recharge. Each stress period is discretized into three-day time steps. Driving conditions are held constant for each stress period until the subsequent stress period.

We used the average water year (**Figure 4**) daily groundwater levels recorded at well 1 (north-facing slope) (**Figure 6a**) and well 6 (south-facing slope) (**Figure 6b**) and mean estimated baseflow (**Figure 7a**) as calibration targets for modelled head and modelled baseflow in the transient model. During calibration, values of recharge, ET, and hydraulic conductivity of the hydrogeologic units were adjusted through trial-and-error until a good match was obtained between simulated seasonal patterns of baseflow (**Figure 7**) and groundwater table elevation (**Figure 6**).

Comparison to the Catchment Scale Water Budget

Transient model results from MODFLOW were compared to the catchment-scale water budget calculated using data collected in Gordon Gulch to confirm the model produced reasonable results (i.e., model results did not exceed values of precipitation, streamflow, or ET estimated for the catchment). For instance, the observed runoff ratio (defined as the ratio of streamflow to precipitation) for Gordon Gulch is 14% using mean annual values collected from 2012-2019. If the groundwater system is in steady state, the runoff ratio provides a first order estimate of groundwater recharge each year. In Gordon Gulch during the study period, the observed runoff ratio limits water available for groundwater recharge to 80 mm per year. This means groundwater recharge estimated by the model should not exceed 80 mm/yr to be considered a reasonable result.

4. RESULTS

4.1 Transient Groundwater Model Calibration

Values of recharge, ET, and hydraulic conductivity of the hydrogeologic units were adjusted in the transient groundwater model runs until we obtained acceptable fits to the average water year water table elevation records and estimated baseflow (**Figures 6** and **7**). Several aspects were considered in selecting acceptable calibration results. First, the calibrated hydraulic conductivity values (**Table 3**) were comparable to previously published values for similar rock types. Second, the topography of the water table in the final time step of the calibrated transient model (**Figure 8**) is, as expected, a subdued version of the ground surface topography. The calibrated model matches in a general way the patterns of water table elevation and baseflow for the average water year (**Figures 6**and **7**). The magnitude of peak baseflow is lower than the average water year target, but it and the timing of the spring peaks in head and in baseflow fall within the range of values for the ensemble of water years. Moreover, modelled water table elevation and baseflow closely match targeted values for the rest of the simulated water year.

R^2 values were calculated for modelled and observed values of head and baseflow as a first order assessment of the correlation between the modelled values and the field data. The R^2 value for baseflow was 0.92, indicating a strong correlation between the modelled and observed values (**Figure 7c**). The mean absolute error was 7 x 10^{-3} m^3/s. R^2 values for simulated and observed heads were lower than for baseflow: R^2 was 0.50 at the north-facing slope and was 0.10 at the south-facing slope well. Values of the mean absolute error further corroborate this difference. The mean absolute error for the north-facing slope well was 0.10 m and 0.28 m for the south-facing slope well (Figure 6c). The springtime groundwater level elevation is lagged at the south-facing well (Figure 6a, b), offering explanation (in addition to underestimated spring values) as to why the correlation between the observed and modelled data is weaker at the south-facing well than the north-facing well.

4.2 Groundwater Budget for Gordon Gulch

To assess the processes occurring at and below the water table, the groundwater budget was extracted from the catchment-scale water budget. This budget does not include fluxes and processes within the canopy, at the ground surface, or within the vadose zone that do not reach the water table. The groundwater budget can be numerically expressed as (modified from King, 2011; Scanlon et al., 2002):

$$R \; - \; \mathrm{ET}_{\mathrm{gw}} \; \pm \; Q_{\mathrm{gw}} \; = \; S_{\mathrm{gw}}(3)$$

where R is recharge (the portion of total precipitation that reaches the groundwater table) and is the inflow to the groundwater system, ET_{gw} is evapotranspiration of water from below the water table, Q_{gw} is the net exchange between groundwater and the stream, and S_{gw} is the change in groundwater storage in the saturated zone (**Figure 2**).Q_{gw} may be either a gain or loss to the groundwater system, depending on the relative magnitudes of groundwater discharge to the stream (Q_{out}) versus stream leakage to groundwater (Q_{in}).

The modelled groundwater budget for Gordon Gulch is presented in**Table 4** . The volume flux of simulated exchanges (m^3/yr) were area-normalized to Gordon Gulch to produce a net change represented in millimetres per year (mm/yr). Using model results, the annual groundwater budget includes 62 mm of groundwater recharge from precipitation and snowmelt, 56 mm of groundwater lost to ET, and 13 mm of groundwater lost to the stream. Groundwater exchanges with the stream represented a net loss of 13 mm from the aquifer, which is the sum of 6 mm of groundwater added to the water table from stream leakage (Q_{in}) and 19 mm of water removed from the water table into the stream (Q_{out}). There is a net annual increase in groundwater storage (S_{gw}) of 6 mm. Although constant head cells were included in the model to exert a topographic control on head, water from these cells were a minimal component of the model groundwater budget, representing only 0.1% and 0.04% of inflows and outflows, respectively.

Table 4 . Groundwater budget of Gordon Gulch based on the calibrated transient model. Fluxes in mm/yr are normalized to the catchment area. All fluxes in the budget are into or out of the groundwater system; for example, ET_{gw} is the evapotranspiration loss from groundwater. Constant head is a model term that represents flow from the modelled constant head cells to maintain head.

Groundwater Budget Component	**Input**	**Input**	**Input**	**Output**	**Output**	**Output**	**Input - Output**	**Input - Outpu**
	m^3/yr	**mm/yr**	**% of Total Modelled Inflows**	**m^3/yr**	**mm/yr**	**% of Total Modelled Outflows**	**m^3/yr**	**mm/y**
Recharge (R) (precipitation and SWE)	160,781	62	57%	-	-	0%	160,781	62
Evapotranspiration below the water table (ET_{gw})	-	-	0%	144,666	56	51%	-144,666	-56
Change in aquifer storage (ΔS_{gw})	105,487	41	37%	88,588	34	31%	16,899	6
Net groundwater-stream exchange ($\Delta Q = Q_{out} - Q_{in}$)							-33,072	-13

Groundwater Budget Component	Input	Input	Input	Output	Output	Output	Input - Output	Input - Outpu
Stream leakage to the aquifer (Q_{in})	*16,696*	*6*	*6%*	-		-	*16,696*	*6*
Groundwater discharge to the stream (Q_{out})	-	-	-	*49,768*	*19*	*18%*	*-49,768*	*-19*
Constant head	166	0.1	0.10%	101	0.0	0.04%	65	0
Total	283,130	109	100%	283,124	109	100%	6	0.0*

*Without rounding, inputs – outputs = 0.003 mm/yr

4.3 Groundwater – Stream Exchanges

Snapshots of the spatial distribution of groundwater-stream exchanges at four times over an average water year (**Figure 9**) shows that Gordon Gulch is overall a gaining stream. Gaining stream conditions dominate lower Gordon Gulch throughout the water year and throughout the channel in the spring**.** In January, the model shows no net exchange in the upper reaches of the channel. In May, gaining stream conditions extend up both upper tributaries, and net fluxes from groundwater to the stream increase to their highest values. In July, the extent of gaining reaches contracts downstream, a result in accord with field mapping of summer streamflow in Gordon Gulch (Martin et al., 2021). In September, the groundwater-stream exchanges, while dominantly gaining, are very low. Annually, despite the presence of stream segments with losing conditions, the rates of stream leakage to the aquifer were consistently lower than rates of groundwater discharge to stream, resulting in a net discharge of groundwater to the stream as baseflow (**Table 4**).

4.4 Groundwater Flowpaths and Velocity

To examine groundwater flowpaths, advective transport was simulated during the ten-year transient period using the forward particle tracking method in MODPATH. MODPATH is a MODFLOW post-processor that uses the distribution of head to calculate velocity and trace particle flowpaths (Pollock, 2012). Particles were placed in upstream locations and tracked over ten model years to reveal groundwater flowpaths in soil, saprolite, weathered bedrock, and bedrock.

Over most of the catchment, the water table is below the soil hydrogeologic layer, and instead lies within the saprolite hydrogeologic layer, even during times of peak water table levels (**Figure 2**). Particle tracking in MODFLOW, used to visualize flowpaths within the model, show interesting patterns in groundwater flowpaths within and between the hydrogeologic layers below the soil (**Figure 10**). Unsurprisingly, modelled groundwater flowpaths follow topographic gradients. The topography creates hydraulic gradients that drive groundwater down side slopes towards the catchment valley floor (**Figure 10b**) and down the valley floor toward the outlet (**Figure 10 a and c**). These gradients drive water into the saprolite and weathered bedrock in upper Gordon Gulch and on side slopes. Some deep recharge occurs into the bedrock also, but low hydraulic conductivity limits groundwater fluxes in this layer.

Along the channel in upper Gordon Gulch, flowpaths are dominantly oriented down-valley within saprolite and weathered rock layers, with minor emergent flow to the channel, and some flowpaths that verge downward into unweathered bedrock (**Figure 10a**). On side slopes, flow in saprolite and weathered rock is nearly parallel to the steep topographic gradient towards the stream, but with some divergence into deeper layers (**Figure 10b**). Along the valley bottom in lower Gordon Gulch, flowpaths are oriented down valley, but everywhere with a component of flow upwards (**Figure 10c**). This pattern of shallow groundwater emerging from the saprolite into the stream channel in this reach is consistent with the persistent gaining stream conditions in lower Gordon Gulch (**Figure 9**).

Groundwater flow velocity estimates indicate that the slowest flowing groundwater in the catchment occurs on the hillslopes through saprolite and weathered bedrock at approximately 0.6 to 0.8 meters per year, respectively. Particles released in bedrock beneath the weathered bedrock remained fairly stationary throughout the simulation, indicating slow to minimal groundwater flow in the bedrock. Along the valley bottom although head gradients are low, shallow, upward flowpaths moved groundwater from upper saprolite and soil into the stream.

5. DISCUSSION

5.1 Catchment-Scale Water Budget vs. Modelled Groundwater Budget

The groundwater budget based on transient model results from MODFLOW was compared to the catchment-scale water budget for Gordon Gulch to gain perspective on the groundwater processes relative to catchment-wide processes. The comparison shows that groundwater plays a significant role in the catchment. **Figure 11** presents a schematic diagram of the catchment-scale water budget compared to the groundwater budget.**Figure 12** shows the monthly fluctuations of the two water budgets (catchment-scale and groundwater) and the variation in the fraction of groundwater in the catchment-scale water budget.

Overall, model results produced a groundwater budget that was reasonable within the context of the catchment-scale water budget. MODFLOW-estimated recharge in Gordon Gulch was approximately 11% of total annual precipitation (including snowmelt and rain). Compared to studies of settings similar to Gordon Gulch, estimated recharge ranges from 14% (Huntley, 1979) to 52.5% (King, 2011) with a range of rates in-between (Earman et al., 2006; Kormos et al., 2015).

To obtain a rough estimate of the percent of recharge from precipitation in Gordon Gulch, the water table fluctuation method was applied to groundwater levels (see Supplemental Information). Based on results from the water table fluctuation method, recharge ranged from 19-38% of total annual precipitation. However, compared to the catchment-scale, modelled recharge is less than the calculated runoff ratio of 14%, indicating the total modelled recharge is consistent with catchment-scale groundwater recharge (up to 80 mm). Overall, modelled recharge is compatible with the supply estimated from the catchment-scale water budget.

5.1 Temporal Trends in Groundwater Recharge

The observational data of water table fluctuations in Gordon Gulch shows that groundwater recharge is concentrated in one or two recharge events per water year (**Figure 4c** and **Figure 12**). In most years, the greatest water table rise and recharge occurs in the spring, driven by precipitation and sustained snowmelt. On average, precipitation during April and May accounts for approximately 30% of total annual precipitation and the recharge during those months represented 50% of total annual recharge. This seasonal recharge event is visible in the rising groundwater levels measured in wells (**Figure 4c**) and simulated by the model (**Figure 6**). Following the springtime recharge event, groundwater elevations generally recede until the spring of the following water year.

In some years, measured well levels record a secondary recharge event in the summer, driven by heavy rainfall in convective storms associated with the North American monsoon (Mahoney et al., 2015). Recently, such events have been identified as significant in snow-dominated alpine settings (Carroll et al., 2020). Between 2012 and 2020, summer recharge events were observed in Gordon Gulch in 2012, 2013, and 2015 (**Figure 4**). Although the response of the groundwater table to summer recharge is usually not as pronounced as the response to the primary spring recharge event, these elevate the water table, which promotes a greater groundwater response to recharge the following spring. This secondary recharge event is not well represented in our simulations (**Figure 6**), which are driven by an average annual precipitation record in which the summer monsoon storms are only weakly represented. Because the timing, size and occurrence of intense summer rain is more variable than spring rain and snowmelt, the impact of these heavy summer storms is muted in the average annual precipitation record we used. Nonetheless, the broad peak in simulated groundwater levels from June-July (**Figure 6**) represents this secondary influence.

5.2 Groundwater-Stream Interactions

5.2.1 Groundwater and Stream Baseflow

Modelled groundwater discharge to the stream (baseflow) accounts for approximately 16% of the observed total annual streamflow in the average water year (**Figure 11**). The modelled result is lower than determinations of baseflow in Gordon Gulch based on other methods. Our analysis of observed stream hydrographs using the Eckhardt two-parameter method showed that baseflow accounts for approximately 34% of streamflow for water years 2012 - 2019. Cowie et al. (2017) used end-member mixing analysis for Gordon Gulch, and found that baseflow ranged from 23 – 33% of streamflow from 2010 to 2012, averaging 28% annually. One reason that the model results are lower than these other methods likely arises from MODFLOW underestimating baseflow in the spring. The 20 m grid cells in the model give a coarse rendering of the head gradients near the ˜1m wide channel. The impact of the low resolution of the MODFLOW grid near the channel is likely to be greatest when head gradients are high, as occurs in spring. Moreover, our average water year modelling approach obscures the impact of highly variable summer rain events on baseflow. Mills et al. (2017) detected a period of baseflow in Gordon Gulch from late July to early October in 2011 that bore geochemical signatures of deep flowpaths. In 2012, however, recharge from a series of July storms increased streamflow but yielded geochemistry associated with shallow flowpaths. These dynamics are muted by the modelling assumptions used here.

The discrepancy may also be due to differences in the definitions of baseflow used by each method. The Eckhardt two-parameter method considers baseflow to be the low-frequency portion of streamflow that responds slowly to precipitation, while groundwater discharge simulated by MODFLOW is exclusively sourced from the saturated zone (Eckhardt, 2005; Harbaugh, 2005). Therefore, the modelled estimate of 16% may be underestimated because of unaccounted for unsaturated and vadose zone contributions to streamflow, which are known to contribute to baseflow in Gordon Gulch (Smull, 2015). Additionally, overestimating ET_{gw} likely underestimated Q_{gw} by removing excess groundwater that otherwise could have been discharged to the stream. Alternatively, the Eckhardt two-parameter method may overestimate baseflow due to the oversimplification of baseflow generation processes by digital filter methods (Xie et al., 2020). Together, these methods show that baseflow contributes from 16-34% of total annual discharge, and therefore we conclude that groundwater is overall a critical source of sustaining streamflow in Gordon Gulch. The groundwater flow model is useful for identifying the spatial and temporal variations in groundwater flow to the channel.

5.2.2 Seasonality of Groundwater-Stream Interactions

Net groundwater-stream exchanges are positive throughout the year, indicating the stream is under gaining conditions year-round (meaning groundwater discharge to the stream (Q_{out}) exceeds stream leakage to the aquifer (Q_{in})). However, seasonally, the fraction of groundwater baseflow to total streamflow varies significantly. Groundwater discharge to the stream peaks during periods of increased precipitation that elevate the water table and increase hydraulic head gradients from hillslopes to the channel. The most likely time for these conditions to occur is in the period between April and July (**Figure 12**). Monthly precipitation is highest in spring, when it is augmented by snowmelt, with a second peak in summer due to intense convective storms (Barry, 1973). The highest rates of groundwater discharge occur in May, at rates up to 0.17 x 10^{-3} m^3/s. The period of April through July accounts for 42% of total annual precipitation as well as 77% of total annual streamflow at the downstream gage, and experiences greater groundwater discharge to the stream (accounting for 61% of total annual groundwater discharge to the stream). The connection between increased streamflow and groundwater discharge corroborates Wilson's (2017) finding that the magnitude of groundwater-stream exchanges correlates with the magnitude of streamflow.

5.3 Groundwater Flowpaths

Groundwater in Gordon Gulch is primarily flowing through the weathered bedrock layers under the catchment, rather than in the thin soil layer. The wells in Gordon Gulch (**Figure 2**) show that groundwater on hillslopes is several meters below the surface (represented by well 1 on the north-facing slope and well 6 on the south-facing slope). Only in the riparian area near the channel is groundwater in the soil layer (well 2). Despite flowing through lower permeability saprolite and weathered rock to reach the channel from hillslopes, the steep topographic gradients help drive flow though these hydrogeologic layers (**Figure 10 a, b**). The simulation results show that most of the groundwater discharge to the stream occurs in lower Gordon Gulch (**Figure 9**), driven by shallow, upward gradients towards the stream along the valley floor (**Figure 10c**). The model flowpaths suggest that a small fraction of groundwater in upper Gordon Gulch and on steep hillslopes follows deeper flowpaths into weathered bedrock (**Figure 10 a, b**). These deeper flowpaths emerge further downstream in lower Gordon Gulch.

Several lines of evidence support the picture of deep flowpaths through weathered rock supporting stream baseflow. First, observed peak streamflow precedes peak water table elevations in wells by 1-4 days (**Figure 3**). Moreover, the springtime rise in head in the hillslope wells (north-facing slope well 1 and south-facing slope well 6) ranges from 1-3 m (**Figure 3**), while the stage in the stream rises by ~0.15 m in lower Gordon Gulch (Anderson and Ragar, 2021c). These data imply that the steepest head gradients in the groundwater system occur a few days after the discharge peak. Moreover, the small range in channel stage minimize the streambed leakage effect of elevated stream head (Huntington and Niswonger, 2012). The rising water table represents water storage in the weathered rock and saprolite under hillslopes, which subsequently supports stream baseflow. Another line of evidence comes from hydrochemistry of the stream. There is a persistent downstream increase in the concentrations of bedrock-derived solutes (e.g., Ca^{+2} and silica) from upper to lower Gordon Gulch (Anderson et al., 2021b), as would be expected for the pattern of increasing groundwater contributions to streamflow shown in**Figure 9** . The saprolite and weathered bedrock layers thus act as a storage and delivery system, adding groundwater to the aquifer system and delivering this groundwater to lower Gordon Gulch and, ultimately, the stream throughout the year.

6. CONCLUSIONS

MODFLOW was employed to study the spatial and temporal distribution of groundwater recharge and groundwater-surface water interactions in Gordon Gulch as an example of the hydrogeologic system in a semi-arid, montane environment. Field measurements of groundwater elevation and baseflow estimated from stream discharge measurements were used to calibrate the model. Model results and supporting field data characterize Gordon Gulch as an interconnected system highly dependent on and responsive to precipitation and snowmelt, and with connectivity between groundwater and the stream and from upper to lower Gordon Gulch. Groundwater recharge is concentrated in one or two events each water year. Commonly, the main recharge event is associated with high spring precipitation coupled with snowmelt, with peak recharge and runoff occurring in May. In some years, summer convective storms can produce similar increases in water table elevation and discharge. Groundwater flows within the saprolite and weathered rock layers under hillslopes, with a component that verges into deeper rock layers. Flowpaths are shallow and emergent along the channel in lower Gordon Gulch. MODFLOW simulations show that Gordon Gulch is a gaining stream, particularly in springtime and in the lower basin. This study highlights the importance of groundwater in a semi-arid, montane, headwater catchment. Our model offers a promising use as an assessment of the groundwater budget in similar environments. Future investigations on the spatial and temporal distribution of groundwater recharge and groundwater-surface water interactions are warranted considering the importance of water resources in montane, headwater environments.

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DATA AVAILABILITY

Data from the Boulder Creek Critical Zone Observatory is publicly accessible through https://czo-archive.criticalzone.org/boulder/data/ This work was supported by the NSF Critical Zone Observatory program funding that built and supported Boulder Creek CZO (NSF EAR-0724960 and EAR-1331828).

Supporting Information

A. Summary of Hydrogeologic Units in Gordon Gulch

B. Precipitation Data Analysis

C. Snow Depth and Melt Data

D. Groundwater Level Data

E. Baseflow Estimate Procedure

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