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Key Points:
- Annual groundwater flow is an important and stable source to a mountain stream with its relative contribution increasing during drought
- Inflowing interflow is a major control on groundwater recharge in a snowmelt-dominated headwater basin
- Recharge is largest in the upper subalpine due to topographic focusing of interflow that is resilient to drought

Supporting Information:
- Supporting Information S1

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The Importance of Interflow to Groundwater Recharge in a Snowmelt-Dominated Headwater Basin

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Abstract Understanding the sensitivity of groundwater generation to climate in a mountain system is complicated by the tight coupling of snow dynamics to vegetation and topography. To address these feedbacks, we combine light detection and ranging (LiDAR)-derived snow observations with an integrated hydrologic model to quantify spatially and temporally distributed water fluxes across varying climate conditions in a Colorado River headwater basin. Results indicate that annual groundwater flow is an important and stable source of stream water. However, interflow decreases during drought as a function increased plant water use and the relative fraction of groundwater to streams increases. Seasonal snowmelt and vegetation water use regulate small recharge rates in the lower portions of the basin, but snowmelt transported via interflow from high mountain ridges toward convergent topographic zones defines preferential recharge in the upper subalpine. Recharge in this zone appears decoupled from annual climate variability and resilient to drought.

Plain Language Summary Accumulated snow in mountain basins is a critical water source, but little is known about how groundwater is influenced by changing snowpack. We combine airborne snow observations with a physically based hydrologic model to better understand how snowmelt is partitioned across the landscape and routed to streams. Results indicate that annual groundwater is an important and stable source of water to a mountain stream with the relative fraction of groundwater increasing during drought as a function of increased plant water use and decreased soil water flow (interflow). We find that the dominant mechanism generating groundwater is topography. Specifically, snowmelt is focused via interflow from steep, mountain ridges into the upper subalpine where slopes flatten and sparse conifer forests begin to grow. This mechanism of recharge appears resilient to drought and may buffer recharge under climate change. Lower in the basin, snowmelt occurs before peak vegetation water use to allow for some groundwater generation. Interflow and monsoon rains then subsidize plant water use once snowmelt ceases but do not generate substantive recharge. Understanding the key mechanisms of groundwater recharge in headwater basins allows us to better predict a mountain stream's response to change for improved water and environmental management.

1. Introduction

Mountain snowpack is a critical reservoir for downstream water users around the world (Viviroli & Weingartner, 2008) and is especially vulnerable to climate change (Clow, 2010; Lukas et al., 2014). Stream water contains surface runoff (SR), shallow, ephemeral subsurface flow through soil/regolith (interflow) and groundwater. Interflow is a function of permeability contrasts and is generally ephemeral through either perched conditions or a seasonally fluctuating water table. SR and interflow reach streams at timescales of days or weeks, while lithology and geologic structure can produce a wide range of groundwater flow paths and travel times to streams (Heidbüchel et al., 2012). A growing body of research identifies the potential importance of bedrock contributions to mountain streamflow (Gabrielli et al., 2012; Hale & McDonnell, 2016). Watersheds more dependent on groundwater could be buffered against climate extremes to enhance resilience for downstream water and environmental management (Taylor et al., 2012). Uncertainty in groundwater recharge and its influence of deeper groundwater in mountain systems limits our ability to predict their hydrologic future (Meixner et al., 2016), with broad economic and environmental implications (James et al., 2014).

Estimating recharge and groundwater discharge to streams is complicated by feedbacks between climate, vegetation, and topography, and by lack of data to characterize subsurface properties (Meixner et al., 2016), flow paths, and circulation depths (Frisbee et al., 2016). Estimating hydrologic partitioning is further hindered by the difficulty in quantifying snow distribution and snowmelt across the watershed (Deems et al., 2006; Harpold et al., 2012). Precipitation (P) and temperature lapse rates in mountain systems exert control on aridity or the ratio of potential evapotranspiration (PET) to precipitation such that higher elevations have more snow accumulation and lower atmospheric demand and are regions of potentially higher recharge in comparison to lower elevations where available water is lost back to the atmosphere through evapotranspiration (ET). Simple elevational lapse rates for precipitation often miss nuances related to storm patterns or redistribution of snow by wind and avalanche and do not capture the codependent relationships between vegetation structure with water and energy budget considerations that modify snow dynamics (Bales et al., 2006). Specifically, snow accumulation is shown to be higher in open versus undercanopy conditions because of decreased canopy interception (Broxton et al., 2015), but open areas are exposed to snow redistribution processes (Elder et al., 1991) as well as faster ablation due to increased net shortwave solar radiation (Molotch et al., 2009; Welch et al., 2016).

Slope is an assumed first-order control on hydrologic partitioning with steep topography traditionally viewed as promoting fast-response flow to streams and less groundwater (Tetzlaff et al., 2009). However, recent studies have indicated that low-order streams are important to groundwater drainage and solute export as a function of spatially distributed snow accumulation (Carroll et al., 2018; Rumsey et al., 2015) and possible rock stress and fracturing (Jasechko et al., 2016). Ecological function is highly dependent on aridity gradients and can limit groundwater sourcing to streams with shallow lateral subsurface water subsidizing downgradient transpiration (Maxwell & Condon, 2016) and deeper rooted vegetation along lower portions of hillslopes drawing upon groundwater stores to meet ET demand (Maxwell et al., 2018). Aspect also serves as a fundamental control on hydrologic partitioning with snow persisting longer on northern aspects and promoting faster and deeper infiltration through the soil zone than observed on south facing slopes (Hinckley et al., 2013).

To understand the controls on spatiotemporal variability in groundwater recharge and routing to streams as a function of climate variability, we combine high-resolution snow observations with a fully coupled surface process and groundwater flow model over a multidecadal timescale. The integrated hydrologic modeling framework captures seasonal surface and groundwater interactions related to ET (including canopy interception, sublimation, groundwater ET, soil evaporation, and plant transpiration), interflow, recharge, change in groundwater storage, and groundwater-surface water exchanges derived from differential gradients (Huntington & Niswonger, 2012), and deep groundwater flow influenced by lithology and geologic structure. We pose the following questions for mountain hydrology:

1. How does snow accumulation influence groundwater contributions to streamflow?
2. What controls spatially distributed groundwater recharge?

2. Site Description and Modeling Strategy

East River, CO (ER, 85 km^2; Figure 1) is a seasonally snow-covered headwater basin of the Upper Colorado River. Climate is defined as continental subarctic. Stream discharge is dominated by snowmelt process with peak flows occurring in June and receding through the summer and fall. Monsoonal storm events occur in the late summer and can cause small, transient increases in streamflow. Baseflow, or groundwater dominated flow, occurs in the fall and winter months. A full description of the ER and observational networks is given by Carroll et al. (2018). Snow accumulation and ablation is simulated over the entire ER to take advantage of meteorological station data for model calibration and validation, but we focus on the 24 km^2 Copper Creek (CC) to explicitly look at groundwater-surface water interactions. Average estimated precipitation for 1987-2018 in CC is 1,390$\pm$27 mm/year of which 78$\pm$7% is snow. Elevation spans 2,880 to 4,128 m. Cenozoic igneous intrusions define the highest peaks and have upturned Paleozoic and Mesozoic sedimentary strata into steeply dipping hydro-stratigraphic units along the lower portion of CC. Talus, rock glaciers, and alluvial fans dominate surficial deposits within CC's glacially sculpted valleys (Gaskill et al., 1991). CC land cover is predominantly barren alpine conditions (50%) and conifer forests (36%) with smaller representations of meadows, shrubs, and aspen.

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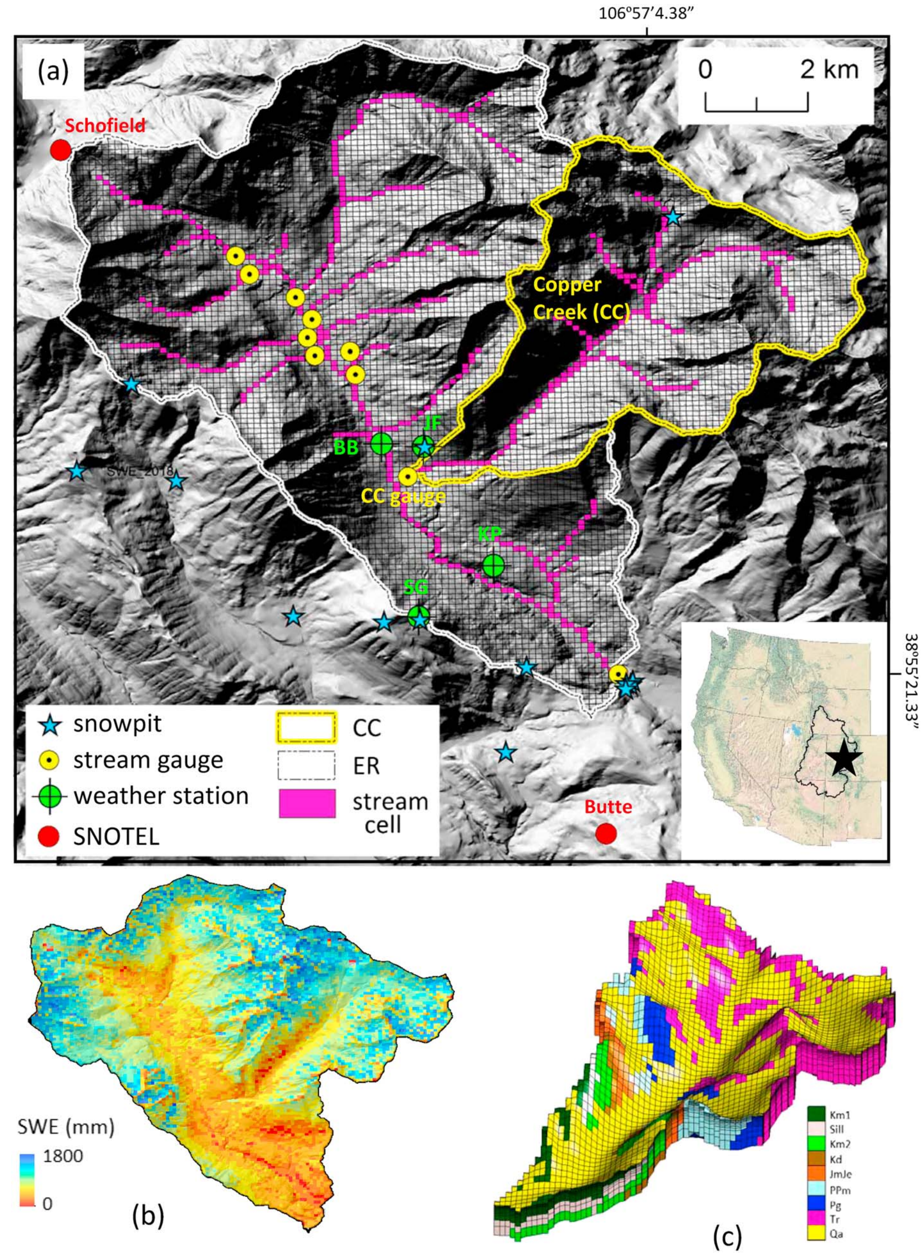

Figure 1. (a) East River (ER) infrastructure and model grid for simulating energy and snow processes with inset showing location in context of the western United States. (b) Airborne Snow Observatory snow water equivalent (SWE) on 4 April 2016, and (c) Copper Creek (CC) geologic model (Table S2).

Two SNOTEL stations (Figure 1; Schofield and Butte) reside in proximity of the ER domain and capture a wide range in snow accumulation and snowmelt scenarios (Figure S1 in the supporting information). Daily observations of solar radiation and additional snow depth time series were obtained from four weather stations (Figure 1; SG, KP, JF, and BB). Spatial distribution and persistence of snow depth at 3 m resolution was obtained from light detection and ranging (LiDAR)-based Airborne Snow Observatory (ASO; Painter et al., 2016) flown 4 April 2016 (Figure 1b), 30 March 2018, and 24 May 2018. Density modeling, validated by snowpit data, was used to develop 50 m maps of snow water equivalent (SWE). Observed stream discharge follows Carroll et al. (2018) for years 2016-2018. Daily discharge observations for years 2005-2009 were obtained from Peckarsky et al. (2014). Correlation of daily flows with the U.S. Geological Survey (USGS) stream gauge (ID: 09112500) located 30-km downstream from the CC outlet (r^2=0.79) backfilled missing discharge.

Hydrologic water budget estimates rely on the USGS Groundwater and Surface water Flow model (GSFLOW; Markstrom et al., 2008). GSFLOW dynamically couples the USGS Precipitation-Runoff Modeling System (Markstrom et al., 2015) and the Newton formulation of the USGS 3-D Modular Groundwater Flow model (Harbaugh, 2005; Niswonger et al., 2011). The finite difference grid resolution is 100 m with elevations resampled from the USGS National Elevation Dataset. LANDFIRE (2015) was used to derive parameters of dominant cover type, summer and winter cover density, canopy interception characteristics for snow and rain, and transmission coefficients for shortwave solar radiation (Figure S2).

Climate for water years 1987-2018 was simulated using minimum and maximum daily temperature lapse rates defined by the two SNOTEL stations. Daily Schofield precipitation was spatially distributed using the 2016 ASO SWE map adjusted for simulated losses associated with sublimation, canopy interception, and early melt prior to the flight. Solar radiation was calibrated to match weather station observations (Figure S3). Model verification of SWE accumulation and ablation relied on the 2018 ASO maps (Figure S4) and weather station snow depth (Figure S5). Maximum soil water storage is conceptualized as a field capacity threshold above which water is partitioned to either lateral interflow through the soil zone or allowed to percolate downward via gravity drainage into the unsaturated zone. The spatial distribution of soil storage is the product of rooting depth (Table S1 in the supporting information) and available water content as a function of soil type (Natural Resources Conservation Service, 1991). The CC geologic model contains nine hydro-stratigraphic units with 12 layers ranging in thickness from 8 to 120 m for a total thickness of 400 m. Hydraulic conductivity is assumed to decay with depth with surface values (Table S2) defined by matching average observed baseflow at the stream gauge. Calibration of CC daily hydrograph (Figure S6) was obtained by adjusting the partitioning of soil water in excess of field capacity between interflow and deeper drainage, the conductance rate of interflow, and the Jensen-Haise air temperature coefficient for PET (Jensen et al., 1969). Particle tracking (Pollock, 2016) used the steady state groundwater solution with spatially distributed recharge for the wettest, driest, and median water year. Particles were released to the water table surface in each model cell with stream cells excluded. The cumulative distribution function was calculated by extracting the deepest layer obtained by each particle weighted by its recharge rate.

3. Results

CC basin-scale annual water budget terms are plotted in Figure 2 as a function of aridity. Results indicate that CC is not water limited (PET/P<1.0) for all years simulated with results tracking slightly below the Budyko curve (Budyko, 1974) but above the lower limit established by Wang and Tang (2014). Lower ET efficiency compared to Budyko is indicative of snowmelt seasonality (Carey et al., 2010), a large fraction of snow to total precipitation (Berghuijs et al., 2014), input intensity (Wang & Tang, 2014), steep slopes reducing soil water residency time (Voepel et al., 2011), and loses to groundwater (Jones et al., 2012). On average, ET consumes 36% of annual precipitation. ET is dominated by soil ET (1.15 mm/day, 67% ET), followed by sublimation (0.22 mm/day; 13% ET), groundwater ET (0.19 mm/day, 11% ET), and canopy interception (0.15 mm/day, 9% ET). Streamflow source (Figure 2b) is divided into interflow (+SR; average 42% precipitation) and net groundwater flux (average 22% precipitation). Interflow experiences a nonlinear decline with increased aridity. In contrast, groundwater flux is relatively stable as a product of changing groundwater storage (Figure 2c). Water table elevations increase when aridity is lower than average, while water table elevations decline in response to groundwater released to streams during dry years. Approximately 50% of groundwater flow moves through the shallow alluvium, while 25% of groundwater reaches depths >100 m (Figure 2d). The bulk of deeply recharged water occurs in the more permeable and steeply dipping sedimentary strata in the lower portions of CC. Deeper flow paths also originate from ridges across the upper domain. Circulation depths are shifted shallower during wet years and deeper during dry years.

Maps of spatially distributed recharge and predictive variables (Figure S7) shows recharge predominates in the upper elevations where total snowmelt is high, water availability is large, and interflow is transported from steep ridges down gradient. During drought, snowmelt diminishes across the basin but inflowing interflow (IFI) remains robust in the upper elevations to maintain both ET/PET and recharge. Lower elevations experience reductions in IFI, water availability, and recharge. Figure 3 illustrates that recharge rates are highest within elevations demarking the transition from alpine to subalpine where

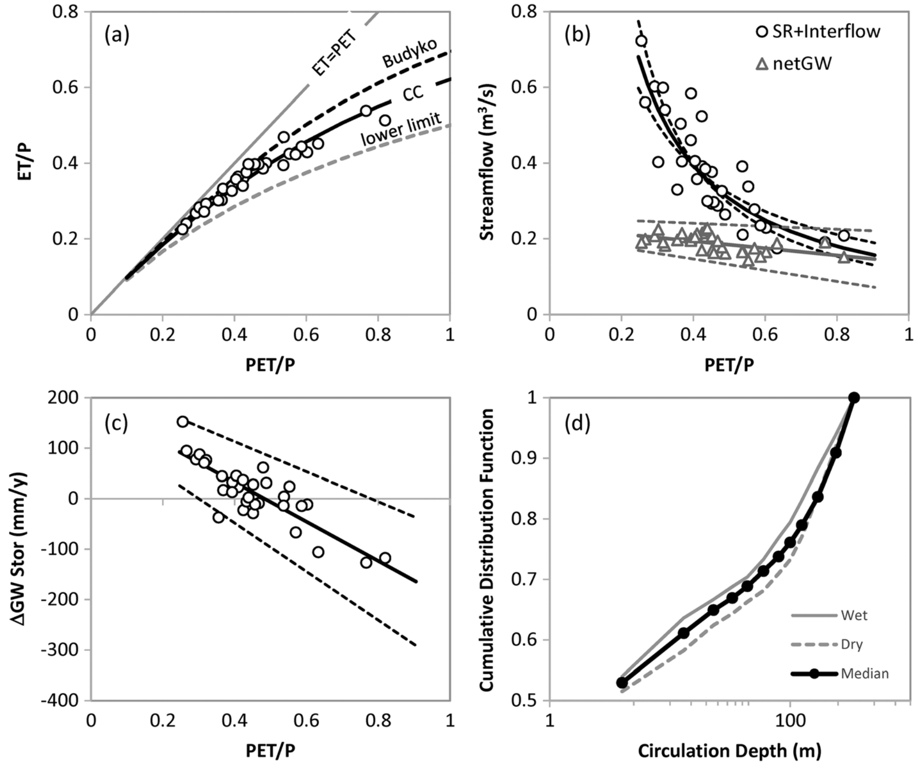

Figure 2. Copper Creek annual estimates water years 1987-2018: (a) fraction of precipitation (P) lost to evapotranspiration (ET) versus aridity with the Budyko Curve and the lower limit (Wang & Tang, 2014) provided, (b) stream water source, (c) net change in groundwater storage, and (d) recharge weighted groundwater depths for different climates. Markers indicate modeled layer midpoint. The 95% prediction intervals provided as dashed lines in (b) and (c).

low-density conifer forests exist. Maximum recharge rates occur at the initiation of conifer development where steep, alpine slopes flatten. During wet years, recharge increases uniformly over median conditions. Dry years see recharge stabilized at higher elevations until the point of maximum recharge. At lower elevations, the decline in recharge is coincident with increasing area of dense conifer forests, increased aridity, and declining water availability. Figure S8 indicates that in the alpine the fraction of precipitation is larger than the combined losses to ET and recharge and is a net exporter of interflow. Lower in the landscape, the sum of ET and recharge are in excess of precipitation and thus reliant on lateral flow. This lateral flow primarily subsidizes recharge in the upper subalpine and ET at lower elevations. Seasonality of fluxes (Figure S9) indicates snowmelt-driven recharge near ridges and in the montane and confirms that IFI is an important subsidy for large recharge rates in the upper subalpine and ET at lower elevations. Monsoon events are important to late season ET across ecotones but do not promote recharge below treeline.

Adjusted coefficients of determination for a median water year indicate that spatially distributed recharge is poorly described by indirect relationships to winter canopy density (r^2=0.07), PET/P (r^2=0.15), and ET/P (r^2=0.03) and the direct relationship to maximum snowmelt rate (r^2=0.15). Instead, stronger relationships are found with ET/PET (r^2=0.38), total snowmelt (r^2=0.32), and IFI (r^2=0.63). Predictability is improved by combining total snowmelt with IFI (r^2=0.78), and further improved by incorporating ET/PET (r^2=0.81). The influence of total snowmelt on recharge diminishes during dry years (r^2=0.24). Instead, recharge becomes more dependent on IFI (r^2=0.77) and ET/PET (r^2=0.61). Combining all three terms explains the majority of recharge variability during a dry year (r^2= 0.92). Regressions are provided in Figures S10 and S11. It is recognized that ET/PET is not independent of total melt (Table S3) though the Akaike Information Criteria using the sum squared residual indicates that additional information using all three terms sufficiently improves predictive quality of the regression (Table S4).

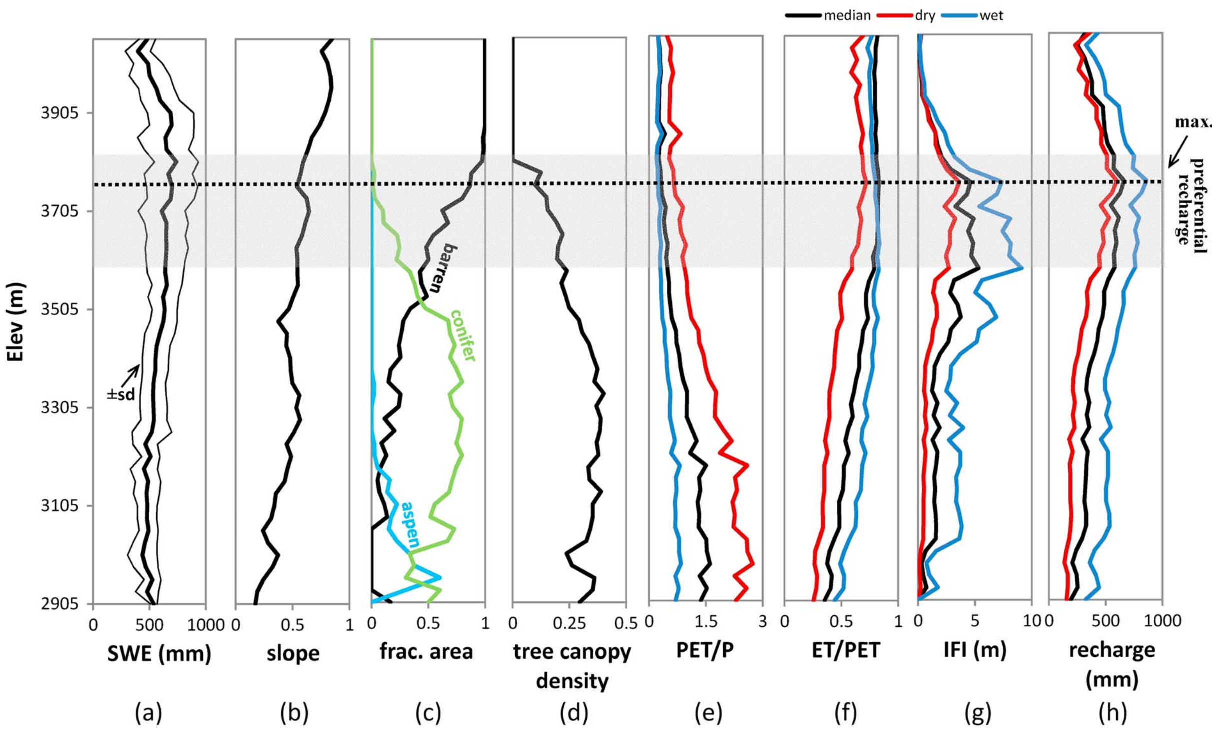

Figure 3. Copper Creek elevation gradients defining mean (a) snow water equivalent (SWE), (b) slope (c) fraction of basin area for major land cover types, (d) tree canopy density, (e) aridity, (f) water availability, (g) inflowing interflow, and (h) recharge. Wet, median, and dry water years indicated.

4. Discussion

Carroll et al. (2018) quantified seasonal stream source across 11-nested subbasins in the ER using the multivariable statistical method of end-member mixing analysis. Research suggested that steep subbasins dominated by upper subalpine conditions of low-density conifer forest promote a greater fraction of groundwater (fGW) in streamflow. We build upon this empirical approach using a physically based modeling strategy for spatial and temporal assessment of water fluxes across simulated climate gradients. ASO accounts for snow redistribution by observing where snow resides as opposed to where it initially fell. This effectively moves snow off mountain ridges and into cirque valleys and upper subalpine regions of the basin. Model validation shows that we properly account for the snow accumulation and persistence in these regions found critical to predicting water resources (Hammond et al., 2018; Mote et al., 2018). Simulated snow losses via interception and sublimation average 0.34 mm/day and fall within the range observed using eddy covariance (0.32-0.36 mm/day) in a similar Colorado basin north of the ER (Sexstone et al., 2016). We estimate total average annual ET losses in CC at 623±50 mm/year. This is higher than basin-wide ER estimates by Tran et al. (2019) at 550 mm/year for elevations 2,950 to 3,200 m and 300 mm/year at higher elevations. However, our inclusion of snow redistribution as well as lateral flow and groundwater to subsidize ET is not accounted for by Tran et al. (2019) and may explain differences in results. With reasonable water budget components, we can move toward answering questions pertaining to groundwater.

4.1. How does snow accumulation influence groundwater contributions to streamflow?

We find that average annual fraction of groundwater contributions to CC streamflow are substantial at 35±7%. This independently validates Carroll et al. (2018) assessment using end-member mixing analysis that found CC 33±8% groundwater during an average water year. Work also aligns with regional analyses in basins above 3,000 m in the Upper Colorado River containing 40-45% groundwater (Miller et al., 2016). We evaluate groundwater over time as a function of climate and find groundwater flow to streams remains stable across the multidecadal simulation despite variability in snowpack conditions. While there is stability in simulated groundwater flux, the relative contribution of groundwater to streams varies considerably (fGW=21-52%) as a function of aridity and the tight coupling between basin-scale ET and interflow. During low snowpack years, ET/P increases at the expense of lateral flow through the soil zone. Reduced water availability modulates some of these losses to produce nonlinear reductions in interflow and increases in fGW. We did not address phenology. Future work will need to assess how reduced snowpack or earlier snowmelt imposes on seasonal forest productivity (e.g., Knowles et al., 2018), and explore how transient phenology may cascade hydrologically to impose on (or modulate) recharge and streamflow.

While streamflow is sensitive to the choice of bedrock permeability, the sensitivity of circulation depth to bedrock parameterization (e.g., depth decay, anisotropy, and storage) was not explored. Given a lack of constraint on subsurface routing and the inherent nonuniqueness of calibration in groundwater modeling, results presented are considered a single-case scenario. Results suggest that the resilience of groundwater flux in mountain streams is dictated by changes in groundwater storage. The responsiveness of groundwater storage to snow accumulation occurs because the majority of groundwater is estimated to move through either the permeable alluvium or near-surface fractured bedrock; both are well connected to surface water input from snowmelt. The remaining groundwater component, however, is predicted to move through deeper fractured bedrock and steeply dipping sedimentary strata. Drier scenarios lower water table depths and extend circulation downward. An overall shift toward higher aridity in these headwater basins has the potential to decouple changes in groundwater storage to annual climate variability, increase lag, and shift compensatory effects of groundwater to streams toward longer timescales. Changes in near-surface and deep groundwater dynamics will also modify the variation of solute concentrations across headwater subcomponents. For example, water quality is likely to degrade (e.g., increasing sulfate and metals) with deeper water tables (Manning et al., 2013), geochemical evolution along longer flow paths (Bondu et al., 2016) and stream waters becoming more dependent on solute-rich ground water.

4.2. What controls spatially distributed groundwater recharge?

Previous work has shown that deeper snow melts later and faster (Musselman et al., 2017) and contributes more groundwater to streams (Barnhart et al., 2016). We connect these ideas mechanistically with the concept of interflow as it relates to landscape position (Figure 4). In situ snowmelt produces recharge in the higher alpine regions where ET is low in comparison to precipitation, but shallow soil storage, low permeability bedrock, and steep topography redistribute snowmelt downgradient as interflow. This shallow, ephemeral flow then supports large recharge rates in topographic convergence zones coincident with low-density conifer forests of modest ET demand and within ephemeral stream channels located higher in the basin (Anderson & Burt, 1978). Work corroborates the Landscape Continuum Model (Seastedt et al., 2004) that highlights topographic controls in high-elevation systems to transport water and nutrients downslope with the treeline receiving the greatest amplification of resources. Knowles et al. (2015) found that ET just above treeline was stabilized by the addition of snow redeposited from wind such that losses to the atmosphere in this zone were relatively decoupled from annual precipitation variability. Similar but from the perspective of groundwater recharge, we find that topographic focusing creates a persistent source and sink of snowmelt from the alpine to the upper subalpine. The resilience of the IFI-supported recharge during dry periods suggests that recharge to the bedrock aquifer in CC is largely permeability-limited rather than precipitation-limited and decoupled from interannual climate variability. Insensitivity of high-elevation mountain recharge to climate warming is contrary to what has generally been emphasized in prior studies —reduced snowpack may lead to significantly reduced recharge (Meixner et al., 2016). However, Meixner et al. (2016) suggests that permeability-limiting factors, such as low vadose storage capacity, could buffer reductions. Our work supports the permeability-limited concept with a mechanism of transporting snowmelt via interflow into the upper subalpine for deeper drainage. Future work will expand the modeled domain to test if this phenomenon is wide-spread in high snowfall watersheds, with possible upscaling through a Budyko-framework.

Lower in the landscape, seasonal dynamics and timing of snowmelt are important to hydrologic partitioning. Snowmelt is low in response to lower snow accumulation but occurs prior to peak consumptive demand to generate small amounts of recharge that taper quickly once the growing season commences. Interflow then supplements ET demand in the dense conifer forests and the montane environment with little/no generation of recharge once summer begins. The importance of interflow to support down-gradient consumption in the

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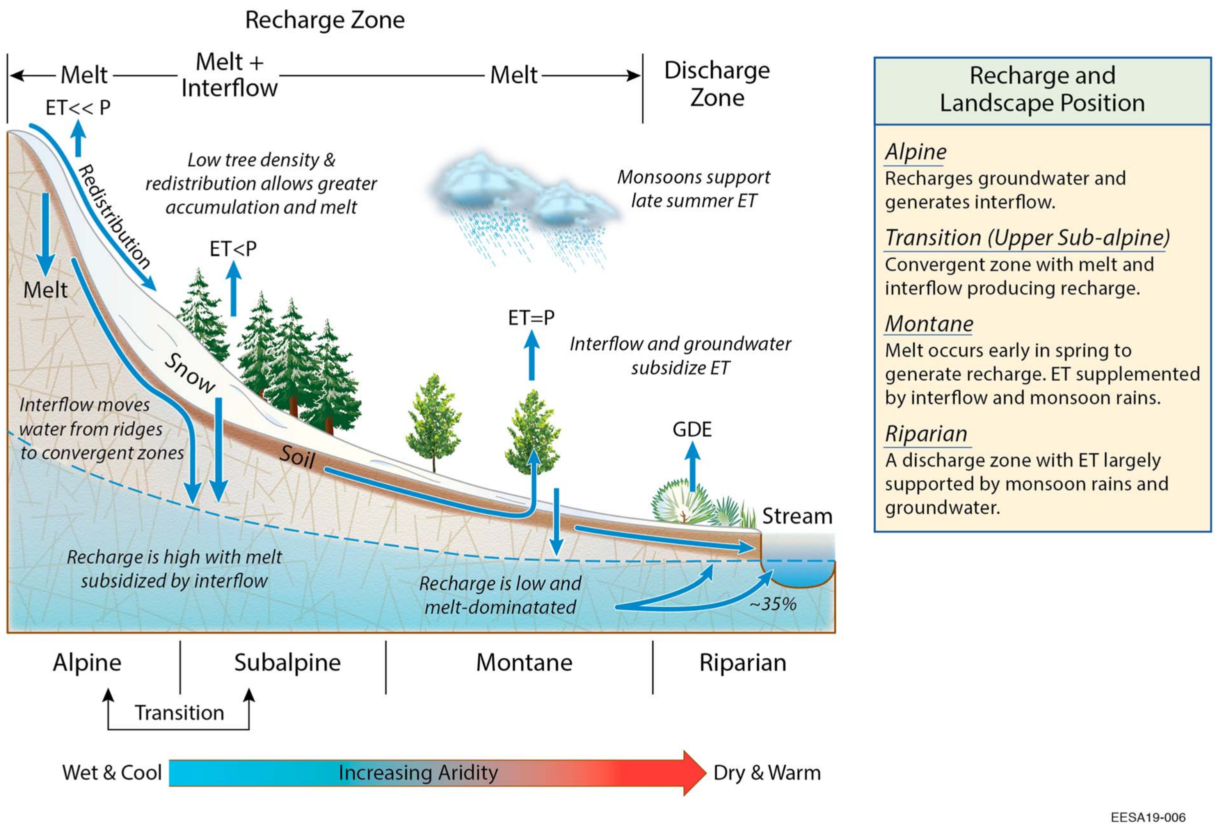

Figure 4. Conceptual model of water fluxes across landscape gradients in topography, aridity, and ecotones to highlight dominant mechanisms of recharge. GDE=groundwater dependent ecosystem.

lower portions of CC is supported by other studies in which increased above ground productivity (Swetnam et al., 2017), soil carbon stocks (Perdrial et al., 2018), and hydrologic vegetation gradients (Hwang et al., 2012) are observed in downslope, convergent topography. Monsoon rains also support late summer productivity (Berkelhammer et al., 2017), and it is theorized that a weak monsoon may result in high groundwater use by phreatophytes (Carroll et al., 2017) and a reduction in late summer stream flow. Our results support the hypothesis presented by others (Carroll et al., 2018; Cowie et al., 2017; Zhang et al., 2018) that the upper subalpine dominates groundwater recharge in mountain systems. However, we emphasize that while coupled vegetation and in situ snow dynamics are particularly important in the lower reaches of the basin, the dominant control on maximum recharge in the upper subalpine is topographically focused interflow transported from the alpine.

5. Conclusions

Complex terrain results in codependent relationships between climate, topography, geology, and vegetation that influence water storage and movement. Using a combination of detailed snow observations and an integrated hydrologic model, we find that groundwater is an important and stable source to a mountain stream across variable snowpack. Stability in groundwater flow to streams is maintained through changes in groundwater storage. However, the relative fraction of groundwater in streams is sensitive to reduced snowpack through increased consumptive demand and the reduction of interflow. While groundwater flow in the surface alluvium is predominant, a significant portion of hydrologically active groundwater reaches depths in excess of 100 m, with the relative fraction projected to increase in response to reduced snow accumulation. Seasonal snowmelt is important to recharge in the lower elevations of the modeled domain but recharge is low, ceases when the growing season commences and is sensitive to drought. Instead, snowmelt transported via interflow from the alpine ridges toward the upper subalpine forms a preferential recharge zone as a function of convergent topography, and this mechanism may buffer groundwater recharge in a drying climate.

Acknowledgments

Model characterization is provided in the supporting information. Model files archived at doi:10.21952/WTR/1508390. Work supported by the U.S. Department of Energy Office of Science under contract DE-AC02-05CH11231 as part of Lawrence Berkeley National Laboratory Watershed Function Science Focus Area and the USGS 104(g) grant/cooperative agreement G16AP00196.

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