A review of groundwater in high mountain environments

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Abstract
Mountain water resources are of particular importance for downstream populations but are threatened by decreasing water storage in snowpack and glaciers. Groundwater contribution to mountain streamflow, once assumed to be relatively small, is now understood to represent an important water source to streams. This review presents an overview of research on groundwater in high mountain environments (As classified by Meybeck et al. (2001) as very high, high, and mid-altitude mountains). Coarse geomorphic units, like talus, alluvium, and moraines, are important stores and conduits for high mountain groundwater. Bedrock aquifers contribute to catchment streamflow through shallow, weathered bedrock but also to higher order streams and central valley aquifers through deep fracture flow and mountain-block recharge. Tracer and water balance studies have shown that groundwater contributes substantially to streamflow in many high mountain catchments, particularly during low-flow periods. The percentage of streamflow attributable to groundwater varies greatly through time and between watersheds depending on the geology, topography, climate, and spatial scale. Recharge to high mountain aquifers is spatially variable and comes from a combination of infiltration from rain, snowmelt, and glacier melt, as well as concentrated recharge beneath losing streams, or through fractures and swallow holes. Recent advances suggest that high mountain groundwater may provide some resilience—at least temporarily—to climate-driven glacier and snowpack recession. A paucity of field data and the heterogeneity of alpine landscapes remain important challenges, but new data sources, tracers, and modeling methods continue to expand our understanding of high mountain groundwater flow.

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Mountains, which cover 24% of earth's land mass (Kapos, Rhind, Edwards, Price, & Ravilious, 2000), are a disproportionately important component of global water supply because they receive more precipitation than lowland areas, experience less evapotranspiration at high elevations, and contain large stores of water as snow and ice. Runoff from precipitation, meltwater from mountain snow pack and glaciers, and groundwater discharge (or exfiltration) provide a valuable water resource to surrounding areas which often include arid or semi-arid landscapes. Viviroli, Dürr, Messerli, Meybeck, and Weingartner (2007) estimate that more than half of mountain areas play either an essential or supporting role in downstream water supply. Furthermore, demand on mountain water resources is growing; Viviroli, Kumm, Meybeck, Wada, & Pierre (2020) estimate that 1.4 billion people will depend critically on mountain runoff by 2050.

In this review, we focus on areas that Meybeck, Green, & Vörösmarty (2001) classify (based on topographic roughness and maximum altitude) as “high and very high mountains” (e.g., much of the Andes, Himalayas, Karakoram, and Southern Rocky Mountains) and “mid-altitude mountains” (e.g., much of the Northern Rocky Mountains, European Alps, and Cascades; parts of the Sierra Nevada and Alaska Range) with a few examples from “high and very high plateaus” (e.g., mountainous portions of the Tibetan Plateau). Combined, these regions represent 15% of the earth's land area and are estimated to contribute 17% of global runoff (Meybeck et al., 2001). These areas exhibit alpine and subalpine characteristics such as steep slopes, exposed bedrock, talus fields, moraines, alpine grasslands, shrublands, and sub-alpine forest. For simplicity, we refer to these mid-altitude, high, and very high mountain regions as “high mountains” in the text. Some examples from “low mountain” environments are used where they make a relevant and transferable contribution to knowledge of higher mountain systems. These low mountain examples are explicitly identified as such.

Mountain regions are being subjected to larger temperature increases than lowland areas under anthropogenic climate warming. Average global temperature has increased by 1°C above pre-industrial levels and is expected to reach 1.5°C between 2030 and 2052 (Intergovernmental Panel on Climate Change [IPCC], 2018), with faster warming expected at higher elevations and depending on the season (IPCC, 2019; Vuille et al., 2018). This phenomenon, known as elevation-dependent warming, is of particular importance for the Andes and Himalayas where glaciers are located at very high elevations (Pepin et al., 2015). Changes in temperature dramatically alter mountain hydrological regimes by reducing water storage in snow and glaciers, increasing evapotranspiration and permafrost degradation (Barnett, Adam, & Lettenmaier, 2005; Immerzeel, van Beek, & Bierkens, 2010). Continuing and projected cryosphere decline will have negative impacts on downstream agriculture, hydropower, and water quality (IPCC, 2019). However, groundwater (subsurface water in the saturated zone) in high mountain environments may provide resiliency from the hydrological impacts of climate change in high mountain regions (Somers et al., 2019; Tague, Grant, Farrell, Choate, & Jefferson, 2008).

In mountain hydrologic research, the primary focus has often been cryosphere landscape features, such as glaciers and snowpack. While critically important, this research overlooks water that is “hidden” below the land surface. Our understanding of mountain groundwater processes has historically been limited by the scarcity and cost of well data, complexity and heterogeneity of mountain aquifers (including bedrock structural features), and variability of alpine climates (Manning & Solomon, 2005). Though some early studies hypothesized the importance of groundwater in the mountain hydrological system (Flerchinger, Cooley, & Deng, 1994; Forster & Smith, 1988b; Snow, 1972), groundwater was commonly considered a minor contributor to mountain streamflow because the steep slopes and shallow soil development were hypothesized to be small and short-lived storage reservoirs for groundwater (McGlynn, McDonnel, & Brammer, 2002; Weiler, McDonnell, Tromp-van Meerveld, & Uchida, 2005). However, recent work has demonstrated the substantial capacity for groundwater storage and discharge in mountain watersheds and its importance in buffering streamflow during dry periods (Liu, Williams, & Caine, 2004; Soulsby, Malcolm, Hellvell, Ferrier, & Jenkins, 2000 [low mountains]; Uhlenbrook, Frey, Leibundgut, & Maloszewski, 2002).

Groundwater processes in mountain regions differ from lower relief areas in three main ways: (a) water table position and hydraulic gradients are much higher which influence the dominant local flow paths and discharge rates (Forster & Smith, 1988a), (b) the near surface hydrogeologic stratigraphy is very complex due to the high energy depositional environment and glacial deposition processes (Cairns, 2014), and (c) the high relief of the surface topography drives deeper groundwater circulation, recharging regional and even continental scale flow systems and potentially allowing the geothermal temperature gradient to affect flow (Forster & Smith, 1988a).

We review primarily peer-reviewed research on groundwater processes in high mountain environments. Though our review is not exhaustive, we seek to provide a comprehensive overview of research on the subject. As summarized...
in Figure 1, we review studies from 1972 to present and note an increase in mountain groundwater research beginning in 2014. The Rocky Mountains are the most studied mountain range while the Himalayas received relatively little attention for groundwater research. We first outline the different types of high mountain aquifers and flow pathways that have been described in the literature and integrate them into a conceptual model of high mountain groundwater flow. Second, we describe research that has quantified the contribution of groundwater to streamflow in high mountain regions—mostly tracer studies and water balance studies. Third, we examine the suggested recharge sources and mechanisms for high mountain groundwater, and fourth, we look at numerical modeling approaches and their findings for high mountain environments as well as climate change impacts.

2 | MOUNTAIN AQUIFERS AND FLOW PATHWAYS

Sedimentologically, mountains are high-energy environments that experience a disproportionately large amount of weathering, erosion, and mass wasting. Furthermore, the vast majority of mountain ranges once hosted glaciers (or still do), leading to glacial depositional features such as till deposits, moraines, outwash plains, and so forth. Many of these deposits are highly heterogeneous and can act as storage reservoirs and/or conduits for groundwater. A single mountain watershed can include talus slopes, moraine and alluvial deposits, lacustrine clays, weathered and unweathered bedrock, geologic faulting, karst formations, permafrost, and rock glaciers (Barsch & Caine, 2007). Furthermore, these glacially derived features can control the presence and location of other alpine geomorphic features such as wetlands.

A considerable amount of research has focused on identifying subsurface features that store and transport groundwater in high mountains. In the literature, the importance assigned to different aquifers or pathways is somewhat dependent on the spatial scale of the study where headwater scale studies generally emphasize small scale coarse deposits and large-scale studies may attribute more flow to bedrock pathways.

2.1 | Coarse deposits

Coarse geomorphic units play an important role in storing and channeling groundwater flow in high mountains (Clow et al., 2003; Gordon et al., 2015; Hood & Hayashi, 2015; Käser & Hunkeler, 2016; Liu et al., 2004; Pierson, 1982; Somers et al., 2016; Szmigielski et al., 2018). Coarse deposits in high mountain regions include talus slopes, debris fans, alluvium, and some moraines. The relatively high permeability of these materials allows them to channel preferential flow
from steep alpine ridges, glacier forefields, and through valley bottom sediments, and their high porosity allows for potentially significant groundwater storage (Figure 2).

Proglacial moraines, composed of mostly cobbles and boulders, have been identified as important landforms for groundwater storage in the Canadian Rocky Mountains (Hood & Hayashi, 2015). Langston, Hayashi, & Roy (2013) estimated groundwater flow through a proglacial talus and moraine complex in the Canadian Rockies using salt tracing and energy balance approaches, and found that groundwater flow dominates the water balance of a tarn lake. This technique provided one of very few field-scale measurements of hydraulic conductivity of these materials, $10^{-3}$ m/s. Furthermore, groundwater flow through proglacial moraine/talus features can follow multiple, possibly disconnected flow paths and may exhibit distinct geochemical and hydrological characteristics (Roy & Hayashi, 2009) and collectively dampen and delay the transmission of snowmelt (Kurylyk & Hayashi, 2017). Hayashi (2019) expands on this research and shows that these talus aquifers have a fast recession of discharge (i.e., groundwater exfiltration) after recharge (e.g., from snowmelt or rainfall), followed by a longer slow recession. Furthermore, Hayashi notes that the hydrogeologic setting of the talus deposits (e.g., internal deposition structure, adjacency to wetlands, etc.) further controls groundwater discharge.

Elsewhere, in the Colorado Rocky Mountains, talus fields were found to contribute more than 40% of the total stream discharge during the summer (Liu et al., 2004). Glas et al. (2018) and Chavez (2013) propose conceptual models of groundwater recharge in proglacial valleys of the Peru's Cordillera Blanca where recharge is channeled through talus deposits, which line the valley walls, into an aquifer system beneath the valley floor. There, coarse talus aquifers are interbedded and confined by fine glaciolacustrine clays to create confined and sometimes artesian aquifers.

Coarse alluvial deposits can also channel groundwater flow through high mountain systems. Hydraulic conductivity and gradients were measured in 13 monitoring wells in a 10 km² alpine headwater catchment in British Columbia, Canada, to investigate the groundwater transport of industrial contaminants. Most groundwater flow through the catchment was channeled through unconfined coarse basal alluvial deposits above shale bedrock and groundwater flow accounted for approximately 15% of watershed outflow (Szmigielski et al., 2018). Käser & Hunkeler (2016) monitored a watershed in the Swiss Alps to assess the role of alluvial aquifers in basin discharge. The alluvial deposits were composed of sandy gravel and cobbles with variable silt content. Though the alluvial aquifer had limited spatial extent (3% of basin area), it played an important role in storing groundwater in the catchment and sustaining streamflow, by

**FIGURE 2** Schematic of groundwater flow through coarse high mountain geomorphic units including a debris fan, talus slope, and moraine complex. From Gordon et al. (2015)
providing a third of total stream discharge, during a drought. Furthermore, significant groundwater flow out of the watershed was found to occur through the alluvial aquifer below the stream channel.

2.2 Bedrock

Groundwater flow through bedrock represents an important flow path in the high mountain hydrological system. Several studies in the related discipline of hillslope hydrology illustrate the importance of flow through bedrock in steep slopes (Box 1). Early hillslope hydrological studies suggested that subsurface flow was concentrated in the soil layer above bedrock in steep hillslopes (Mosley, 1979; Tani, 1997). Since then, several hillslope studies have debunked this assumption. Tromp-van Meerveld, Peters, & McDonnell (2007) used a sprinkler plot study to physically simulate the infiltration of precipitation into bedrock in the Panola Mountain Watershed, GA (low mountain environment). They initially anticipated that subsurface water would flow toward the stream through the unconsolidated layer (coarse sandy loam, high permeability) above the bedrock (granodiorite, relatively low permeability), which was assumed impermeable in previous studies. Instead, they found that 91% of the water applied to a 66 m² study patch infiltrated into the bedrock layer. Another hillslope sprinkler plot study in the western Cascade Range in Oregon attempted to quantify the amount of “deep seepage” in a 172 m² hillslope plot underlain by thin soil above andesite and coarse breccia. The authors define deep seepage as infiltrated water that does not resurface in a collection trench below the hillslope plot but instead is detected in the stream at the catchment outlet. They found that 27% of the applied water went to deep seepage (Graham, Van Verseveld, Barnard, & McDonnell, 2010).

In high mountain watersheds, several studies have also suggested that substantial groundwater flow occurs through bedrock (Flerchinger & Cooley, 2000; Frisbee et al., 2011; Frisbee, Tolley, & Wilson, 2017; Fujimoto et al., 2016; Hilberg, 2016; Shaw et al., 2014; Voeckler, Allen, & Alila, 2014). Some studies focus on groundwater flow through
fractured and weathered shallow bedrock, occasionally assuming that deeper bedrock remains impermeable. Other research examines flow through deeper competent bedrock, which may still be fractured to a lesser extent. Frisbee et al. (2011) tested these competing conceptual models of high mountain streamflow generation using stream chemistry and numerical modeling. Their results suggested that streamflow was generated through both hillslope response and fully three-dimensional flow through bedrock (Figure 3b) and was not merely an aggregate of near-surface hillslope responses (Figure 3a; also see Voeckler et al. (2014) for a low-mountain examination of shallow versus deep bedrock flow). The distinction between shallow and deep bedrock is relative and defined on a case-by-case basis. Related research on MBR usually includes groundwater flow through deep bedrock aquifers to discharge in higher order streams in adjacent valleys, and is summarized in later in this review.

2.3 | Shallow, weathered bedrock

Given that bedrock permeability decreases exponentially with depth (Ren, Gragg, Zhang, Carr, & Yao, 2018), some studies rely on the assumption that groundwater flow through bedrock is concentrated near the bedrock surface where bedrock may be more heavily fractured (Flerchinger, Deng, & Cooley, 1993). For example, a recent study of borehole data in a fractured granite aquifer in the Laramie Range of the Rocky Mountains in Wyoming, indicated that the hydraulically significant zone, where hydraulic conductivity was above $10^{-10}$ m/s, was above 40–53 m below ground surface (Ren et al., 2018). Additionally, Andermann et al. (2012) used hydrograph data to calculate groundwater transit times which correspond to fractured basement rock. Unfortunately, it is rare for hydrological studies in mountain regions to have access to substantial data on hydrogeological properties of bedrock, due to the cost of collecting such data and difficulty in accessing remote and rugged locations.

2.4 | Deep bedrock

The depth of a local groundwater flow system is understood to increase with topographic relief (Toth, 1963). Therefore, mountain regions should theoretically experience enhanced groundwater circulation depths compared to low relief areas. Accordingly, several studies note the contribution of both shallow and deeper bedrock aquifers to streamflow in mountains. A recent hydrochemical study of Mount Daisen Volcano (a high mountain in a low-mid altitude mountain range), Japan, detected both shallow and deep bedrock groundwater contributions to streamflow in two small (4.0 and 6.6 km²) headwater catchments. Deep bedrock groundwater through ash, pumice, and pyroclastic deposits, reportedly dominated streamflow and contributed more streamflow per unit catchment area, further downstream (Fujimoto et al., 2016).

The temperature and geochemistry of high mountain groundwater and springs also provide evidence of circulation of meteoric water through deeper, intact bedrock in mountains (Gleeson, Manning, Popp, Zane, & Clark, 2018; Liu et al., 2008; Manning & Caine, 2007). Frisbee et al., (2017) estimated groundwater circulation depths in two watersheds of the Colorado and New Mexico Rocky Mountains. They used the geochemical signature of discharging groundwater to deduce the water temperature at depth (also known as geothermometry). They then convert the temperature to depth based on a previously estimated geothermal gradient. They found circulation depths range from 0.6 to 2.5 km
below ground surface, well below what might be considered shallow weathered bedrock. Furthermore, the cause of fracturing (i.e., volcanic versus tectonic) impacts the connectivity of fractures and therefore the permeability and circulation depth. They further suggest that model domains assigned in groundwater modeling efforts for mountain environments are often too shallow and cut off deeper flow paths. Despite the dramatic heterogeneity that can exist in mountain bedrock, a study in the Colorado Rocky Mountains yielded spatially consistent groundwater ages of 8–11 years in the fractured crystalline rock along an alpine stream. Their findings support the applicability of relatively simple numerical modeling of mountain groundwater systems where permeability mainly varies with depth (Manning & Caine, 2007).

As many mountain ranges occur in tectonically active regions, other studies use mountain groundwater from hot springs as observation points of deep crustal groundwater processes (Diamond, Wanner, & Waber, 2018; Newell, Jessup, Hilton, Shaw, & Hughes, 2015; Van Hinsberg et al., 2017) though these are beyond the scope of this review. There is an ongoing need to quantify the fraction of groundwater discharge to mountain streams that follows very deep (>500 m approximately) flow paths and the impact of neglecting these deep flow paths in modeling.

### 2.5 Karst aquifers

Karst aquifers, when present, can store and transmit large volumes of water in high mountain regions. Karst formations occur in limestone rocks through which tunnel-like flow paths have developed through dissolution (White, 2002). Due to the abundance of limestones and dolomites in the European Alps, much of the published research on karst formations in high mountains is from this region (Chen et al., 2018; Corniello, Ducci, Ruggieri, & Iorio, 2018; Gremaud, Goldscheider, Savoy, Favre, & Masson, 2009; Gremaud & Goldscheider, 2010; Lauber & Goldscheider, 2014; Turk et al., 2015; Vigna & Banzato, 2015).

Karst aquifers in high mountain regions often have relatively short transit times. Infiltration can be diffuse or concentrated through sinking streams, swallow holes or fractures. Groundwater discharge to the surface often occurs through springs (Gremaud & Goldscheider, 2010; Vigna & Banzato, 2015). A tracer study of high alpine karst systems in the Limestone Wetterstein Mountains of the German Alps estimated transit times for three components of groundwater discharge: 3–13 days, 2.9–4.9 months, and >1 year for fast, intermediate, and slow flow components, respectively (Lauber & Goldscheider, 2014). Gremaud et al. (2009) used 19 tracer tests to infer the internal structure of the Tsanfleuron–Sanetsch karst aquifer system in the Swiss Alps. Tracer transit times were short (5–57 hr) and did not correlate to the distance from the injection point to the spring, indicating the heterogeneity of the system. Groundwater flow occurred in distinct flow paths, largely following the limestone and marl stratification, and fold structures served to direct many of the observed flow paths which converged to discharge at Glarey Spring. Cross-layer flow was also observed through fractures and faults. Elsewhere, short transit times have also been observed in Karst systems in the western Himalayas of India (Shah, Jeelani, & Jacob, 2017). Conduit flow often dominates river baseflow in karst mountains but matrix flow becomes appreciable during dryer periods as observed in the Rocky Mountains of Utah (Neilson et al., 2018).

### 2.6 Permafrost and rock glaciers

Groundwater in high mountain environments can also exist in the solid phase as ice-rich permafrost and rock glaciers. These features occur at high elevations and/or latitudes where mean annual air temperature is sufficiently low. Permafrost is perennially frozen ground which remains at or below 0°C for two or more consecutive years. The spatial coverage of permafrost (isolated to continuous) in mountains varies mainly with elevation and aspect but other factors like vegetation and snow coverage also impact groundwater temperature and therefore permafrost occurrence (Gruber et al., 2017). Permafrost that has substantial pore water is called ice-rich permafrost (Ge, McKenzie, Voss, & Wu, 2011) and can represent an important store of groundwater (Clow et al., 2003). Rock glaciers, on the other hand, are deposits of rock debris cemented by interstitial ice that originated from former glaciers or from the re-freezing of glacier melt (Harrington et al., 2018). Rock glaciers can be important source water for baseflow in alpine environments (Williams, Knauf, Caine, Liu, & Verplanck, 2006) and influence stream water quality (Williams, Knauf, Cory, Caine, & Liu, 2007).

Permafrost acts as a barrier to groundwater flow (Mckenzie et al., 2020). In high mountain areas where topographic gradients are high, permafrost limits deeper groundwater flow paths that would otherwise occur (Ge et al., 2011; Rogger et al., 2017). Evans et al. (2015) used field observations and groundwater modeling to investigate the role of permafrost in a headwater mountain watershed of the Qinghai-Tibet Plateau. In total, 50–80% of the 25 km² mountain watershed
is underlain by permafrost at higher elevations. They estimated, using thermal modeling, that the supra-permafrost (or active) layer ranged from 0.6 to 3.3 m deep above 3,400 m elevation. The results of their groundwater modeling indicated that 95% of volumetric flow was channeled through the supra-permafrost layer. For comparison, lower in the catchment where no permafrost exists, 89% of volumetric flow occurred within 108 m of ground surface through surficial deposits. Thus, permafrost creates a shallow, perched flow system. Current baseflow in the watershed contributes 43% of streamflow from June to November. As the climate warms, permafrost will continue to degrade, increasing the hydraulic conductivity of the subsurface and increasing baseflow.

Rock glaciers can act as an important store of subsurface water on multiple time scales in alpine environments. Perennial ice melt can contribute non-negligible amounts of water to rivers, particularly in periods of deglaciation and in semi-arid and arid environments (Jones, Harrison, Anderson, & Betts, 2018; Jones, Harrison, Anderson, & Whalley, 2019; Williams et al., 2006). Globally, it is estimated that rock glaciers store approximately 83 Gt of water, around 1/456 as much water as glaciers hold globally (Jones et al., 2018).

Rock glaciers can act as barriers to groundwater flow when they contain substantial ice, or conduits for groundwater flow when they contain little ice. Harrington et al. (2018) studied an inactive rock glacier in the Canadian Rockies. Geophysical surveys showed that the rock glacier contained little ground ice and that perennial melt was small. The coarse debris of the rock glacier then acted much like an unconfined aquifer that contributed 50% of summer streamflow in a headwater catchment. In the same study area, Harrington, Hayashi, & Kurylyk (2017) found that springs discharging from the rock glacier cooled the average stream temperature by 3°C and the maximum daily stream temperature by 5°C degrees. In July and August, groundwater provides an important downstream thermal refuge for at-risk cold-water fish species.

Rock glaciers have also been shown to influence the geochemistry of groundwater and the surface waters they feed by enhancing mechanical weathering of rock and providing meltwater for continued dissolution and solute transport during dry periods. However, it has also been suggested that rock glaciers and permafrost can reduce weathering in colder areas by limiting rock exposure to liquid water (Ilyashuk, Ilyashuk, Psenner, Tessadri, & Koinig, 2018). Thies, Nickus, Tolotti, Tessadri, & Krainer (2013) found higher concentrations of dissolved ions and heavy metals in alpine streams fed in-part by active rock glaciers compared to adjacent streams with no input from rock glaciers in the Tyrolean Alps. At a nearby field site, Ilyashuk et al. (2018) found elevated dissolved ions, heavy metals, and rates of macroinvertebrate deformities, all as a result of enhanced acid rock drainage, in two alpine lakes fed by rock glaciers compared to a nearby lake which had no rock glaciers in its catchment. Rock glaciers can also be important nutrient sources in high mountain environments. For example, Williams et al. (2007) observed much higher nitrate concentrations in rock glacier discharge compared to other surface water in the Rocky Mountains of Colorado and Wyoming, and suggest that microbial activity within the rock glaciers themselves is responsible for the high concentrations.

### 2.7 Wetlands

Wetlands are geomorphic features with the water table at or near the land surface for extended periods of time, leading to unique hydrophilic soils, plants, and hydrologic functionality. For wetlands to form, poorly draining substrates (e.g., glaciolacustrine clays) and a wet climate (i.e., precipitation well in excess of evapotranspiration) are required (Tarnocai et al., 1997). Given the extensive till deposits and higher precipitation rates in mountain regions, wetlands often form and can act as carbon sinks and biodiversity hot-spots (Buytaert, Cuesta-Camacho, & Tobón, 2011). Mountain wetlands are described by many different terms geographically and across hydrology, ecology, and geomorphology literature including páramo, jalca, pampa, bofedal, bog, fen, peatland, and mire (Buytaert & Beven, 2011; Maldonado Fonkén, 2015; Tarnocai et al., 1997; Tomaselli et al., 2018).

Several studies have examined the hydrologic function of wetlands and meadows in high mountain catchments (Chignell, Laituri, Young, & Evangelista, 2019; Chimner et al., 2019; Cooper et al., 2010, 2019; Lowry, Loheide, Moore, & Lundquist, 2011; Millar, Cooper, & Ronayne, 2018; Mosquera, Lazo, Célleri, Wilcox, & Crespo, 2015; Mosquera et al., 2016; Polk et al., 2017; Streich & Westbrook, 2019). Due to their excess of water and decreasing permeability with drying, wetlands can self-regulate to keep the water table near the land surface (Rezanezhad et al., 2016). The relatively high porosity of alpine wetland soils provides an important groundwater store, slowing the movement of water from high to low elevations (Mosquera et al., 2015) and attenuating high flows (Buytaert & Beven, 2011). In the wider hydrogeological context, alpine wetlands often have a dual-hydrologic function: they receive shallow runoff and precipitation, but due to perennial saturation, also may serve as groundwater recharge areas (Winter, 1999). Groundwater dynamics of alpine wetlands can also be affected by beaver (Castor canadensis and Castor fiber) activity in some mountain ranges in western North America, Eurasia, and Argentina (Morrison, Westbrook, & Bedard-Haughn, 2014; Pietrek & Fasola, 2014). Beaver dams have the net effect of
raising the water table, which increases groundwater recharge (Karran, Westbrook, & Bedard-Haughn, 2018) and enhances hyporheic flows (Lautz, Siegel, & Bauer, 2006). Some studies have suggested that alpine wetlands may be particularly sensitive to climate change and glacier recession (Polk et al., 2017).

2.8 | Conceptual model of groundwater flow in high mountains

High mountain watersheds each contain some combination of the hydrogeological features outlined above. The individual flow regimes depend on which features are present as well as the rock type, topography, and climate. Subsurface heterogeneities can also cause inter-basin flow where groundwater is exported or imported across the boundary of the topographically defined watershed (Fan, 2019). Figure 4 summarizes the groundwater aquifers and flow paths described in the previous sections. At headwater scales, flow paths through coarse deposits like talus and moraines are particularly important to the catchment water balance. At larger scales, alluvial and valley bottom aquifers become increasingly important as well as deeper groundwater flow paths.

3 | QUANTIFYING GROUNDWATER CONTRIBUTION TO HIGH MOUNTAIN RIVERS

Tracer methods (natural and artificial) and water balance studies provide useful techniques to quantify different water sources in hydrological systems. Tracer methods are particularly useful in high mountain regions because they do not necessarily require long-term monitoring, and data can be collected in remote areas and rugged landscapes through periodic synoptic water sampling (as opposed to continuous data collection). Water balance studies, while generally more data intensive, can serve as a measurement of groundwater storage, flow, and discharge/exfiltration. Table 1 summarizes results of studies which have quantified groundwater contribution to high mountain streamflow using a variety of methods.

**FIGURE 4** Conceptual model of high mountain hydrogeological processes including groundwater flow through subsurface features, such as talus slopes, moraines, valley bottom sediments, and bedrock, and the influence of permafrost and geological structures. Modified from Somers et al. (2019)
| Reference                          | Groundwater contribution to streamflow (%) | Time of year | Mountain range | Catchment area (km²) | Notes                                                                 |
|-----------------------------------|-------------------------------------------|--------------|----------------|----------------------|----------------------------------------------------------------------|
| Andermann et al., 2012            | 66                                        | Annually     | Himalayas      | 137,000              | For three large Himalayan basins                                      |
| Baraer, Mckenzie, Mark, Bury, & Knox, 2009 | 70                                        | Dry season   | Andes          | 64                   |                                                                       |
| Baraer et al., 2015               | 24–80                                      | Dry season   | Andes          | 27–88                | Four watersheds range from 24 to 80% groundwater contribution         |
| Burns et al., 2001                | 50                                        | February     | Panola Mountain | 0.1                  | Contribution of “riparian groundwater” during a storm in a montane  |
|                                   |                                           |              | United States  |                      | forest (sub-alpine environment)                                       |
| Carroll et al., 2018              | 29–43                                      | Annually     | Rocky Mountains| 85                   | Nested catchment study also provides groundwater contributions for 10 |
|                                   | 18                                        | Baseflow     |                |                      | sub-basins                                                           |
|                                   |                                           | Snowmelt falling |              |                      |                                                                     |
|                                   |                                           | limb          |                |                      |                                                                     |
| Chen, Hartmann, Wagener, & Goldscheider, 2018 | 87                                        | Annually     | Alps           | 35                   | Karst springs are the main groundwater contributor                   |
| Clow et al., 2003                 | >75                                       | During storms and winter baseflow | Rocky Mountains | 6.9                  |                                                                       |
| Cowie et al., 2017                | 19                                        | Annually     | Rocky Mountains| 2.25                 | For an alpine (19%) and a sub-alpine (31%) catchment                 |
|                                   | 31                                        |              |                | 5.36                 |                                                                      |
| Engel et al., 2016                | 37–49                                      | Annually     | Alps           | 11.2                 |                                                                     |
|                                   | 42–62                                      |              |                | 18.6                 |                                                                     |
| Evans, Ge, & Liang, 2015          | 43                                        | June–November| Tibetan plateau| 25                   |                                                                       |
| Frisbee, Phillips, Campbell, Liu, & Sanchez, 2011 | 14–44                                      |              | Rocky Mountains| 1.600                |                                                                       |
|                                   | 18–78                                      |              |                |                      |                                                                     |
| Fujimoto et al., 2016             | 30–37<sup>b</sup>                          | Baseflow     | Mount Daisen volcano, Japan | 3.0                 |<sup>b</sup> Contribution of “deep” groundwater to two nested |
|                                   | 83<sup>b</sup>                             | conditions   |                | 6.3                  | catchments                                                          |
| Gordon et al., 2015               | 50                                        | Dry season   | Andes          | 0.5                  |                                                                       |
| Harrington, Mozil, Hayashi, & Bentley, 2018 | 50<sup>b</sup>                             | Summer baseflow | Rocky Mountains | 2.5                  |<sup>b</sup> Only groundwater discharge from rock glacier (<20% of |
|                                   | Up to 100<sup>b</sup>                     | Winter       |                |                      | watershed area)                                                      |
| Huth, Leydecker, Sickman, & Bales, 2004 | 10–20<sup>b</sup>                         | Rising limb of | Sierra Nevada  | 19                   |<sup>b</sup> Old water (stored in catchment prior to current year’s |
|                                   |                                            | snowmelt hydrograph |                |                      | snowfall) contribution                                               |
| Käser & Hunkeler, 2016            | 15<sup>b</sup>                             | Anually      | Alps           | 52                   |<sup>b</sup> Only alluvial groundwater contribution to streamflow in |
|                                   | 85<sup>b</sup>                             | Last week of drought |                | 52                   | two nested catchments                                                |
|                                   | 35<sup>b</sup>                             | Last week of drought |                | 194                  |                                                                       |
| Kosugi et al., 2006               | 65–71                                      | Annually     | Japan          | 0.00024              |                                                                       |
A challenge in high mountain research is that these regions are often data poor due to the difficulty in making physical field measurements for groundwater studies (e.g., installing piezometers) in remote sites with difficult access. The use of geochemical tracers helps to overcome this challenge. Geochemical tracers include dissolved ions and isotopes of water and solutes, and are frequently used to detect groundwater discharge in high mountain watersheds (Baraer et al., 2009, 2015; Burns et al., 2001; Carey, Boucher, & Duarte, 2013; Carroll et al., 2018; Cowie et al., 2017; Engel et al., 2016; Frisbee et al., 2011; Huth et al., 2004; Liu et al., 2004; Liu, Conklin, & Shaw, 2017; Mark & McKenzie, 2007; McKenzie, Mark, Thompson, Schotterer, & Lin, 2010; Neilson et al., 2018; Saberi et al., 2019; Shaw et al., 2014).

Groundwater, having been in contact with geologic materials for extended periods of time, usually has a higher concentration of dissolved ions than precipitation, surface runoff, glacier melt, or snowmelt. Groundwater that has followed a longer flow path and/or has a longer residence time may also have a higher concentration of solutes. This leads to a trend of increasing solute concentrations lower in a watershed which has been observed in the field (Frisbee et al., 2011) but that can be limited by mineral solubilities in different geological or climatic settings. Additionally, the ratio between the different ionic concentrations can be related to the geologic material through which the groundwater flows (Clow & Sueker, 2000; Hem, 1985). This difference in hydrochemical signature is used along with conservative

| Reference                     | Groundwater contribution to streamflow (%)a | Time of year | Mountain range | Catchment area (km²) | Notes                                                                 |
|-------------------------------|-------------------------------------------|--------------|----------------|----------------------|----------------------------------------------------------------------|
| Liu et al., 2004              | 54                                        | Snowmelt     | Rocky Mountains | 0.08                 | Baseflow (28%) + talus water (36%)                                   |
| Liu, Bales, Conklin, & Conrad, 2008 | 20b                                       | December–July | Rocky Mountains | 13.4                 | Two arid catchments, groundwater contribution here is thermal meteoric water. The balance of streamflow was from lateral subsurface flow. |
| Maurya et al., 2011           | 10–20                                     | Annually     | Himalayas      | 19,600               |                                                                      |
| Saberi et al., 2019           | 34–77                                     | Dry season   | Andes          | 7.5                  | Proglacial watershed                                                  |
| Shaw, Conklin, Nimz, & Liu, 2014 | ~0–10b                                    | Snowmelt     | Sierra Nevada  | No area given        | Estimated from Figure 5                                              |
|                               | ~60–80b                                   | Baseflow     |                |                      |                                                                      |
| Somers et al., 2019           | 37                                        | Annually     | Andes          | 170                  | Proglacial watershed                                                  |
| Wang, Li, & Jiang, 2017       | 38                                        | During "summer flood" | Tianshan Mountains | 308                  |                                                                      |
| Williams, Wilson, Tshering, Thapa, & Kayastha, 2016 | 60–77b                                   | July (monsoon) | Himalayas | No area given (Study area is along a 30 km stretch of headwater river) | Summing shallow and deep groundwater contributions |
|                               | 13–42b                                    | September (post-monsoon) |          |                      |                                                                      |
| A. M. Wilson, Williams, Kayastha, & Racoviteanu, 2016 | 0–24b                                     | May (pre-monsoon) | Himalayas | 350                  | Values for “reacted meltwater” not necessarily synonymous with groundwater. |
|                               | 15–21b                                    | October/November (post-monsoon) |          |                      |                                                                      |

aWhere multiple groundwater contribution percentages are listed, the study either looks at different times of year or at more than one catchment as indicated.
bSee corresponding note.
mixing analysis to quantify the contributions of different source waters. Two commonly used methods of mixing analysis include end-member mixing analysis (Burns et al., 2001; Hooper, Christophersen, & Peters, 1990) and the similar hydrochemical basin characterization method (Baraer et al., 2015; Saberi et al., 2019).

Similarly, stable isotopes of water (δ¹⁸O and δ²H) can be used in combination with mixing analysis to quantify contributions to streamflow if there is a significant difference in isotopic values between groundwater and stream water. The use of stable isotopes of water as tracers presents some additional challenges as the isotopic composition of precipitation is highly variable, as a function of altitude, season, and moisture sources (Lachniet & Patterson, 2002) and may require extensive seasonal baseline data for proper interpretation (Carey et al., 2013; Mark & Mckenzie, 2007).

Several seminal field studies in the United States and Scotland (low mountains) used geochemical tracers to establish that groundwater is a substantial contributor to mountain streamflow despite the pervasive conception that near-surface flow alone dominates mountain hydrological systems (Burns et al., 2001; Clow et al., 2003; Liu et al., 2004; Soulsby et al., 2000 (low mountains)). For example, Liu et al. (2004) used isotopic and geochemical tracers to estimate groundwater contribution to streamflow in two small (0.08 and 2.25 km²) watersheds of the Colorado Front Range. They found that sub-surface flow (defined as the sum of soil water, baseflow, and talus water) contributed more than two thirds of streamflow in both catchments. More specifically, 54% of streamflow originated from baseflow in the smaller catchment and 28% of streamflow originated from baseflow, plus 36% from talus deposits, in the larger catchment.

Subsequent work with geochemical tracers has geographically expanded our understanding of groundwater discharge to different mountain hydrological regimes in the Rockies (Carroll et al., 2018; Cowie et al., 2017; Frisbee et al., 2011; Liu et al., 2008), Andes (Baraer et al., 2009, 2015; Saberi et al., 2019), Alps (Engel et al., 2016; Schmieder, Garvelmann, Marke, & Strasser, 2018), Himalayas (Jeeani, Bhat, & Shivanna, 2010; Maurya et al., 2011; Williams et al., 2016; A. M. Wilson et al., 2016), Tianshan Mountains (Wang et al., 2017), and Canadian North (Carey et al., 2013). For example, in Wolf Creek, Yukon, Canada (a low- to mid-altitude mountain watershed with alpine characteristics), (Carey et al., 2013) showed that water stored in near-surface soils within the catchment dominated the snowmelt hydrograph based on a multi-year combination of isotope and major ion data. Through tracer studies, even glacierized environments were shown to have substantial groundwater inflow to rivers. Baraer et al. (2015) found that groundwater contributes 24–80% of dry season stream discharge in four proglacial valleys of the Cordillera Blanca in the northern Peruvian Andes, while Wang et al. (2017) found that groundwater contributed 38% of streamflow in a glacierized watershed of the Tianshan Mountains in China. More recent work has increased the spatial and temporal resolution of results, examined fine-scale groundwater flow paths and made use of new tracers such as chloride isotopes (Shaw et al., 2014), sulfur isotopes (Urióstegui, Bibby, Esser, & Clark, 2017), and dissolved noble gasses (Gleeson et al., 2018).

### 3.2 Heat, dye, and chloride tracers

In addition to natural geochemical tracers, heat, dye, and chloride (and other ions less commonly) can also be used to trace sources of streamflow and groundwater flow through high mountain aquifers. Langston et al. (2013) used heat tracing along with chloride tracing to estimate the hydraulic conductivity of an alpine moraine in the Canadian Rocky Mountains. Gordon et al. (2015) combined geochemical sampling with Rhodamine dye tracing to quantify groundwater contribution to streamflow in proglacial valleys of the Peruvian Andes. Somers et al. (2016) used a combination of rhodamine dye tracing and heat tracing to calculate that 29% of stream flow came from groundwater over a 4 km reach in the Peruvian Andes. Tracers have also been used to characterize flow paths through mountain geomorphic features (Gremaud et al., 2009; Roy & Hayashi, 2009).

### 3.3 Water balance studies

Various types of water balance studies have been employed in high mountain environments to quantify groundwater storage, recharge, and discharge (Andermann et al., 2012; Clark et al., 2014; Cochand, Christie, Ormstein, & Hunkeler, 2019; Flerchinger & Cooley, 2000; Hood, Roy, & Hayashi, 2006; Hood & Hayashi, 2015; McClymont, Hayashi, Bentley, Muir, & Ernst, 2010; Paznekas & Hayashi, 2016). Water balance studies capitalize on the difference in timing between water inputs (precipitation-evapotranspiration, snowmelt, glacier melt) and outputs (stream discharge) from a catchment to provide an indication of transient catchment water storage and discharge. One limitation of water balance studies is that the calculation of groundwater storage is subject to errors from the measurement of all other hydrologic fluxes (Winter, 1981).
Andermann et al. (2012) examined 30 years of river discharge records from three large Himalayan basins and show hysteresis in the relationship between precipitation and streamflow throughout the year. This hysteresis indicates substantial transient water storage which can be explained by groundwater storage. They use hydrological modeling to estimate that the volume of water flowing through the groundwater system represents two thirds of annual streamflow and is approximately six times greater than the glacier and snowmelt contribution.

Similarly, Hood and Hayashi (2015) used detailed measurement and modeling of hydrological fluxes, including precipitation, snowmelt, and streamflow, in a proglacial headwater catchment in the Canadian Rocky Mountains to characterize the timing of groundwater recharge, discharge, and storage capacity. They show that peak groundwater storage is 60–100 mm averaged over the watershed area. This groundwater storage is much less than the peak snowpack storage (500–640 mm snow water equivalent) but is important when compared to the average fall and winter baseflow which is typically less than 0.5 mm/d.

Cochand et al. (2019) employed a similar water balance approach to Hood and Hayashi (2015) but found a larger change in groundwater storage during the snowmelt period of 300 mm or 45% of the pre-melt snow water equivalent in the Valais Alps of Switzerland. Accordingly, Cochand et al.'s minimum stream baseflow was higher than Hood and Hayashi’s at 0.9 mm/d indicative of more groundwater storage.

3.4 What controls groundwater contribution to high mountain streamflow?

The above tracer and water balance studies estimate a wide range of groundwater contributions to high mountain streams, summarized in Table 1. The extent to which groundwater contributes to streamflow in mountain environments is controlled by several different factors. Forster and Smith (1988b) suggested that surface topography, geology, climate, and regional heat flux all affect groundwater flow and water table position in mountains. It should also be noted that mountain groundwater contribution to streamflow is spatially and temporally variable within a given watershed (Neilson et al., 2018; Payn, Gooseff, McGlynn, Bencala, & Wondzell, 2009) and can be correlated to antecedent moisture content in the previous year (Baraer et al., 2009; Burns et al., 2001). Furthermore, the lag time between recharge and discharge is dependent on the scale of groundwater flow paths.

Paznekas & Hayashi (2016) analyzed streamflow records of 18 mountain watersheds in the Rocky and Columbia mountain ranges in Canada. Since snowmelt, precipitation, and glacier melt are negligible during the winter, they examined winter baseflow to determine what controls groundwater flow. Precipitation in the previous year was uncorrelated to winter baseflow, leading the authors to conclude that the groundwater storage was completely filled each year and that winter baseflow depended on stationary variables like bedrock and topography. They found that bedrock geology exerted a strong control on winter baseflow where watersheds underlain by younger sedimentary rocks had higher winter baseflow than those underlain by older metamorphic rock (also see Liljedahl, Gädeke, O’Neel, Gatesman, & Douglas (2017) and Tsinnajinnie (2018)). Similarly, water balance studies by Cochand et al. (2019) and Hood & Hayashi (2015) show that quartzite bedrock in the Opabin watershed of the Canadian Rockies accommodates much less annual groundwater storage than the evaporites present in a catchment of the Swiss Alps.

Other researchers have indicated that the watershed size influences the relative and absolute contribution of groundwater to streamflow in high mountains. Several authors have noted that groundwater inputs were higher downstream, closer to the outflow of their study catchments (Cowie et al., 2017; Frisbee et al., 2011; Fujimoto et al., 2016; Soulsby et al., 2000), and that as watershed scale increases, new larger scale groundwater flow paths are incorporated into the hydrological system. This can be considered an extension of seminal hydrogeological theory by Toth (1963) outlining nested groundwater flow systems. Baraer et al. (2015) also points out that relative groundwater contribution to streamflow is related to glacierized area in the Cordillera Blanca and therefore relative groundwater contribution increases with basin area as the relative glacier coverage diminishes. While increased groundwater contribution with distance downstream is detectable in individual watersheds, the phenomenon is not clearly generalizable across watersheds in the current literature given large differences in precipitation regimes, basin characteristics, extent of glaciers and snowpack.

4 RECHARGE SOURCES AND PATHWAYS

Accurate quantification of groundwater recharge allows for better management of groundwater resources. Groundwater in high mountain areas is recharged by precipitation in the form of rain and/or snowmelt, and glacier melt. The
amount of groundwater recharge is spatially variable and is affected by sharp gradients in climate, vegetation, geology, and topography (Goulden et al., 2012; Smerdon, Allen, Grasby, & Berg, 2009; Smith, Moore, Weiler, & Jost, 2014; Urióstegui et al., 2017). The groundwater recharge that originates in mountains can be important for distal groundwater systems in adjacent lowlands, potentially several hundred kilometers away. This large-scale phenomenon is called mountain system recharge (MSR) (Ajami, Troch, Maddock, Meixner, & Eastoe, 2011; Ajami, Meixner, Dominguez, Hogan, & Maddock, 2012; Markovich, Manning, Condon, & McIntosh, 2019; Wahi, Hogan, Ekwurzel, Baillie, & Eastoe, 2008).

4.1 | Recharge from rain and snowmelt

Precipitation is the primary driver of groundwater recharge. In high mountains, recharge from precipitation can occur as diffuse recharge from rain or snowmelt, or as seepage from ephemeral or perennial streams (Smerdon et al., 2009). The low temperatures and associated vegetative community in mountains also lower the amount of evapotranspiration, which substantially enhances the potential for recharge with increasing elevation (Goulden et al., 2012; Goulden & Bales, 2014).

At lower elevations and/or latitudes, rain may dominate year-round. However, given the high elevation of many high mountain regions, seasonal snowmelt often plays an important role in recharging the groundwater system (Earman, Campbell, Phillips, & Newman, 2006; Flerchinger, Cooley, & Ralston, 1992; Lowry, Deems, Loheide, & Lundquist, 2010). In the spring, the snowpack melts and some of the meltwater follows shallow or preferential flow paths and produces high river flows during freshet. At the same time, the annual pulse of meltwater percolates toward the saturated zone (Hammond, Harpold, Weiss, & Kampf, 2019). In the Sierra Nevada of California, analysis of short-lived cosmogenic sulfur isotopes revealed that less than 15% of freshet streamflow originated from the previous winter's snow pack and that a significant fraction of the annual snowmelt was recharging the groundwater system (Urióstegui et al., 2017). Snowmelt is a more efficient contributor to streamflow (through shallow runoff) than rainfall because the concentrated period of infiltration allows less time for evapotranspiration compared to intermittent precipitation and snowmelt generally occurs in the spring when potential evapotranspiration is lower. Deeper groundwater recharge seems to be less sensitive to snow and rain fraction (Hammond et al., 2019; Liu et al., 2008) though groundwater recharge from losing mountain streams is certainly affected.

Groundwater recharge from precipitation in high mountains can be spatially variable for several reasons. More precipitation occurs at higher elevations due to the orographic effect. Lower temperatures and more snow coverage often decrease evapotranspiration at higher altitudes (Gurtz, Baltensweiler, & Lang, 1999). Locally, slope and aspect can affect the amount of precipitation received, snow accumulation, alter snowmelt patterns and evapotranspiration (Flerchinger & Cooley, 2000; Gurtz et al., 1999; Luce, Tarboton, & Cooley, 1998). Additionally, less or different vegetation may be present at higher elevations, decreasing transpiration and thereby increasing recharge with elevation (Goulden et al., 2012; Gurtz et al., 1999). Valley bottoms and depressions can be sites of groundwater discharge which prevents recharge from occurring. Smerdon et al. (2009) found that groundwater recharge varied from 0–20 mm/year at low elevations and from 20–50 mm/year at higher elevations in a semi-arid low- to mid-altitude mountain watershed in the Okanagan Basin of British Columbia, Canada. Hydraulic conductivity of subsurface materials can also control groundwater response to precipitation (Smith et al., 2014) and geomorphic features of high mountain basins can redistribute groundwater recharge. For example, alluvial fan aquifers can channel flow into valley bottom aquifers (Glas et al., 2018; Smerdon et al., 2009; Winter et al., 1999).

4.2 | Recharge from glaciers

Relatively little is known about interactions between mountain glaciers and the groundwater system in high mountain regions (Gordon et al., 2015; Gremaud & Goldscheider, 2010; Levy, Robinson, Krause, Waller, & Weatherill, 2015; Liljedahl et al., 2017; Ó Dochartaigh et al., 2019; Saberi et al., 2019; Somers et al., 2019; Vuille et al., 2018). Meanwhile, the importance of these linkages is increasing as mountain glaciers retreat globally under climate change. Only a handful of studies estimate the extent to which groundwater in proglacial watersheds is recharged by glacier melt, either directly below the glacier, at the glacier margin, or through glacial lakes and streams (Gremaud & Goldscheider, 2010; Levy et al., 2015; Liljedahl et al., 2017; Ó Dochartaigh et al., 2019; Saberi et al., 2019; Somers et al., 2019).
Most glacier melt occurs on the glacier surface under meteorological forcing, and a small amount occurs beneath the glacier as a result of friction from glacier flow, heat transfer from water flow, and geothermal heat flux. Supraglacial meltwater drains over the surface of the glacier and toward the base through fractures, crevasses, and moulins (Ravier & Buoncristiani, 2017). In Karst systems, glacier melt recharges groundwater through a combination of swallow holes and fractures. These features can occur beneath the glacier, intersecting small meltwater streams near the glacier toe or intersecting proglacial rivers (Gremaud & Goldscheider, 2010). In these rapid karst conduits, strong diurnal and seasonal patterns are observed in streamflow corresponding to glacier melt (Gremaud et al., 2009). Some studies consider glaciers themselves as a barrier to groundwater recharge near mountain tops, channeling melt closer to the glacier margin where recharge occurs through percolation or seepage from proglacial streams (Forster & Smith, 1988b). At longer time scales, glacial loading/unloading can alter the hydraulic conductivity of subsurface materials by compressing pores and fractures (lowering K) or by creating new fractures (increasing K) (Ravier & Buoncristiani, 2017).

Two coupled groundwater and surface water studies in the Andes estimate glacier melt contribution to groundwater. Saberi et al. (2019) use field data and numerical modeling of a proglacial headwater catchment on Volcán Chimborazo in Ecuador to estimate that 18% of groundwater discharge is sourced from glaciers which cover 34% of the watershed area. Somers et al. (2019) examine a proglacial watershed in the tropical Andes of Peru and estimate that glaciers contribute approximately 2% of groundwater discharge to the Shullcas River which has approximately 2% basin glacier coverage. Using contrasting methods, Liljedahl et al. (2017) examined two glacierized watersheds in the Alaska Range. They found that glacier melt contributed 15 to 28% of annual streamflow in a watershed with 3% areal glacier coverage. Furthermore, differential stream gauging revealed that 46% of annual streamflow was lost to the underlying aquifer in headwater streams. These three studies demonstrate a wide spectrum of glacier-groundwater connections and more research is required to determine what governs this relationship.

4.3 Mountain system, mountain-front, and MBR

Since mountains receive more precipitation than nearby lowlands and are often subjected to less evapotranspiration at higher elevations where vegetation is sparse (Goulden & Bales, 2014), they can play an important role in replenishing central valley (or basin) aquifers, particularly in arid or semi-arid regions (Ajami et al., 2011; Manning & Solomon, 2003, 2005; Meixner et al., 2016; Wahi et al., 2008). Groundwater recharge that originates in mountains (the mountain block), or in the transition between mountains and the basin valley floor (the mountain front), and feeds a basin aquifer, is known collectively as MSR (Wahi et al., 2008). MSR can be subdivided into MBR and mountain-front recharge (MFR). MBR is sub-surface flow from the mountains to the basin aquifer. MFR is sub-surface flow from the mountain front zone toward the basin aquifer and mostly occurs where mountain streams and rivers reach the mountain front and subsequently infiltrate through the streambed (Figure 5; Bresciani et al., 2018; Wahi et al., 2008; J. L. Wilson & Guan, 2013). Either MBR or MFR can dominate MSR to basin aquifers depending on the setting, and noble gasses have been used as a tracer to differentiate between the two (Manning & Solomon, 2003).

Broadly speaking, groundwater recharge that occurs in high mountains may follow two different paths: (a) it may follow a relatively shallow flow path and discharge into mountain streams or (b) it may flow through deeper bedrock toward the central valley aquifer of the basin as MBR. Welch and Allen (2014) used numerical groundwater models to investigate the partitioning of groundwater recharge between discharge to a mountain stream within a defined watershed (baseflow) and MBR. They found that 12–15% of total recharge became MBR which was eventually discharged to a higher order river in the basin, while 85–88% of recharge contributed to low-order mountain streams within the defined watershed. Though not the focus of this review, an in-depth review of MBR is presented by Markovich et al. (2019).

5 Numerical modeling of groundwater in high mountains

A variety of numerical modeling approaches (e.g., conceptual water balance, linear reservoir, finite volume, finite difference, finite element) have been used to investigate high mountain groundwater dynamics with varying amounts of constraining field data. Conceptual water balance and linear reservoir models use simplified parameterizations of groundwater recharge, storage, and discharge, and may or may not be spatially distributed. They are frequently employed in surface-focused hydrological models to represent groundwater processes. Distributed two- and three-dimensional groundwater flow models discretize the subsurface into grid cells or elements and apply Darcy’s Law to simulate groundwater flow.
Early numerical modeling of groundwater in high mountain massifs was performed by Forster and Smith (1988a, 1988b) and emerged before much of the field-based work summarized in this review. They developed a steady-state, two-dimensional, finite element, free-surface approach for modeling groundwater flow and heat transfer in mountain regions with the goal of quantifying the factors that control groundwater flow in mountains. Sensitivity analysis found that the simulated groundwater flow and water table position were most sensitive to: (a) the topographic slope profile (convex versus concave profile), (b) bulk permeability, (c) available infiltration, (d) presence of alpine glaciers, and (e) basal heat flow, among 17 parameters investigated. Since then, conceptual hydrological models have been used to highlight how subsurface flow slows the transmission of precipitation to rivers (Andermann et al., 2012; Jódar et al., 2017; Pohl, Knoche, Gloaguen, Andermann, & Krause, 2015; Tague & Grant, 2009) and two- and three-dimensional modeling based on Darcy’s Law has been applied.
in a variety of high mountain settings. Of these, some studies have focused on groundwater flow through bedrock (Gleeson & Manning, 2008; Ofterdinger, Renard, & Loew, 2014; Welch & Allen, 2014) or valley sediments (Ciruzzi & Lowry, 2017), while others have coupled groundwater and surface water modeling (Engdahl & Maxwell, 2015; Foster & Allen, 2015; Voeckler et al., 2014), incorporated interactions with glaciers (Saberi et al., 2019; Somers et al., 2019), and/or permafrost and frozen soil (Evans et al., 2015; Evans, Ge, Voss, & Molotch, 2018; Ge et al., 2011). Numerical modeling studies of central valley aquifers often simplify hydrological processes above the mountain front and use MSR as a boundary condition to model basin aquifers (Manning & Solomon, 2005).

Furthermore, simulations often indicate that the water table is located far below ground surface below mountain ridges, up to several hundred meters (Forster & Smith, 1988b; Ofterdinger et al., 2014; Somers et al., 2019). While data to constrain this are scarce, upland wells in the Okanagan region of British Columbia, Canada (low to mid-altitude mountains) were found to have water table depth in excess of 91 m (Smerdon et al., 2009).

Reconciling small-scale observations of hydrological and hydrogeological processes with watershed scale models of mountain catchments remains challenging. Longer and deeper groundwater flow paths come into play with increasing watershed area. As previously noted, Frisbee et al. (2011) tested two types of modeling approaches for a large (1,600 km²) mountain watershed in the Colorado Rocky Mountains. They found that a fully three-dimensional hydrological model worked much better than a two-dimensional model made up of many hillslopes to recreate observed data. Furthermore, Frisbee et al. (2017) suggest that the modeled domain of many mountain groundwater models may be too shallow to accurately represent deep groundwater circulation.

### 5.1 High mountain groundwater under climate change

High mountain regions are being subjected to faster climate warming than lowlands (Pepin et al., 2015). Increasing air temperatures reduce winter snow pack, cause peak snowmelt flows to occur earlier in the spring, and drive glacier retreat and permafrost degradation in mountains. Glacier and snow loss threaten mountain water resources, particularly during the summer, autumn or dry season when mountain streamflow is low and water demand is high (Barnett et al., 2005). Meanwhile the number of people who depend on mountain water resources is expected to increase (Viviroli et al., 2020).

The buffering capacity of groundwater is expected to provide some resilience against climate change-driven hydrologic changes in high mountains by continuing to store water during wet periods and discharge water during dry periods. Studies on this topic often combine numerical models with climate projections and many have focused on the western United States (Engdahl & Maxwell, 2015; Evans et al., 2018; Huntington & Niswonger, 2012; Markovich, Maxwell, & Fogg, 2016; Tague et al., 2008; Tague & Grant, 2009) with a few others focusing on the Andes (Somers et al., 2019) and the Tibetan Plateau (Evans et al., 2015; Ge et al., 2011).

The geology underlying a high mountain watershed is an important control on the streamflow response to climate change—often as important as snow distribution and melt timing. Higher permeability bedrock is better able to maintain streamflow in response to earlier snowmelt but at the cost of depleting groundwater supplies during summer (Markovich et al., 2016; Tague et al., 2008; Tague & Grant, 2009). Low permeability basins do not lose as much groundwater storage but are more sensitive to the timing of snowmelt, where an earlier freshet results in an earlier peak in groundwater discharge. Huntington & Niswonger (2012) explain that this phenomenon can lead to decreasing summer streamflow, even when annual precipitation is increasing in low-storage granitic watersheds in the Sierra Nevada.

The presence of glaciers and permafrost further complicate high mountain groundwater response to climate change. Mountain glacier melt contribution to groundwater recharge is variable and poorly constrained (Levy et al., 2015; Liljedahl et al., 2017; Ó Dochartaigh et al., 2019; Saberi et al., 2019; Somers et al., 2019). Somers et al. (2019) integrate groundwater, surface water, and glacier melt modeling and apply downscaled climate projections to a proglacial watershed in the Peruvian Andes. They find that as the glaciers in the watershed disappear, groundwater contribution to streamflow remains large and relatively consistent in the short term. In the long term, however, evapotranspiration increases with temperature, decreasing groundwater recharge and exfiltration. The resulting dry-season streamflow is projected to decrease by 20–50% (representative concentration pathways [emissions scenarios] 4.5 and 8.5, respectively) by 2,100.

In mountain watersheds with extensive permafrost, degradation of permafrost is expected to increase hydraulic conductivity of the sub-surface, decrease peak flows, and increase baseflow (Evans et al., 2015; Ge et al., 2011; Rogger
et al., 2017). Modeling of a groundwater system in the Qinghai-Tibet Plateau suggests a three-fold increase in baseflow will result from a 2°C increase in mean annual air temperature (Evans et al., 2015). Furthermore, changes in seasonal soil freezing will impact both groundwater recharge and baseflow (Evans et al., 2018).

Groundwater recharge in several mountain regions is projected to decrease as the climate changes. In the western United States, declining snowpack is projected to decrease recharge to mountain aquifers and MSR alike (Meixner et al., 2016). In addition to declining snowpack, increasing temperatures stimulate evapotranspiration and decrease groundwater recharge in high mountains. In a warming climate, vegetation type, coverage, and activity in high mountains will change as cold-limited vegetation encroaches on higher elevations, increasing ET, and decreasing recharge (Goulden et al., 2012). Goulden & Bales (2014) examined the relationship between precipitation, ET, and elevation in California’s Sierra Nevada. Using a space-for-time approach, they projected a 28% increase in ET across the entire King’s River basin and a corresponding 26% decrease in river flow by 2,100. Increasing groundwater age of spring water in the Sierra Nevada, from 1997 to 2003 provides field evidence of decreasing groundwater recharge (Manning et al., 2012).

Though this review has focused on water quantity, high mountain groundwater quality may also be affected by climate change in some regions. For example, ice—in the form of glaciers, permafrost or rock glaciers—can isolate to sulfide bearing rocks but also contributes to mechanical weathering of rock. As glaciers, rock glaciers and permafrost retreat upslope, previously frozen ground is exposed to more liquid water and higher temperatures facilitating oxidation of sulfides which causes acid rock drainage and leads to high concentrations of heavy metals (Ilyashuk et al., 2018).

6 | CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

Historically, high mountain research has focused on the visually stunning aspects of mountains including glaciology, geology, and ecology. Though not visible, groundwater is a critically important component of high mountain hydrological systems and has special importance for water resource management in the face of environmental change. As our review demonstrates, groundwater research in high mountain environments has received increasing attention in recent years. A variety of field and modeling studies have described the hydrogeologic functioning of mountain geomorphic features. Small-scale studies tend to highlight the importance of coarse deposits including talus and alluvium in storing and transmitting groundwater, while larger-scale studies often emphasize the role of valley-bottom and bedrock flow paths. Tracer and water balance studies have demonstrated that groundwater is an important contributor to streamflow in a variety of high mountain regions, particularly during low-flow periods. High Mountain groundwater recharge, driven by rain, snowmelt, and glacier melt, can be highly spatially variable and is an important source of recharge to distal basin aquifers. Numerical modeling has provided important insights into high mountain groundwater flow, though best-practices are not well established. In the face of a warming climate, groundwater will provide resilience to high mountain hydrological systems, though the nature of the response is controlled by complex interactions between geological conditions, changes to snow and glacier melt regimes, presence of permafrost and vegetation impacts on recharge.

Despite the strides made in recent years, there remain significant gaps in our understanding of high mountain groundwater systems. Specifically, the field is still limited by a scarcity of field data and relatedly, representing the high degree of heterogeneity in numerical modeling remains challenging and limits our ability to project the impacts of climate change.

6.1 | Future directions to combat data limitations

Groundwater observation wells are particularly scarce in high mountain environments. Those that exist are often located in valley bottoms where they are more easily accessible and hydraulic head is more stable. Furthermore, long-term hydraulic head measurements are scarce. This lack of data limits our ability to constrain groundwater levels in modeling studies leading to high uncertainty in conclusions. Forster & Smith (1988b) pointed out that overestimating the bedrock permeability by a factor of 5 led to underestimates in water table elevation by more than 1,000 m in their seminal modeling study. Addressing this uncertainty remains a critical challenge today and is particularly difficult in remote data-scarce regions like the Andes and Himalayas.
Increased investment in high mountain groundwater monitoring, particularly in uplands, is a good starting point to combat data limitations, though it is important to remember that no number of wells will produce a perfect model. Water sampling of existing wells, springs and surface waters is a relatively low-cost way to investigate groundwater processes in remote high mountains and new information continues to emerge from innovative applications of natural and artificial tracers (Frisbee et al., 2017; Gremaud et al., 2009). Furthermore, geophysical investigations can help to visualize complex subsurface structures and improve our understanding of groundwater storage and flow in high mountains (Glas et al., 2019; Harrington et al., 2018; Ó Dochartaigh et al., 2019).

In the face of limited funding for increased data collection, an open-access data sharing system on high mountain groundwater systems is needed, potentially as a part of an existing mountain-data sharing initiative such as GEO GNOME (Mountain Research Initiative, n.d.). There is also potential to harness under-utilized data in the gray literature. Mining activities are common in mountain regions globally, for which geotechnical and hydrogeologic data is collected and often reported for mine planning and environmental assessments. Tunneling projects (for road and rail transportation) can also provide similar data (Corniello et al., 2018). Though data may be proprietary, site-specific data-sharing agreements are often possible for academic research projects (Gleeson et al., 2011; Scibek, Gleeson, & McKenzie, 2016). A comprehensive accessible dataset of high mountain groundwater observations would allow for better comparison between sites and, with enough data, would allow for better statistical understanding of how such systems work.

6.2 Representing heterogeneity

High mountains are incredibly complex hydrogeological environments and many studies focus on individual geomorphic features. It remains difficult to reconcile small- and large-scale studies of groundwater processes in high mountain watersheds. Small-scale processes, such as flow through individual talus features or upwelling springs in valley bottoms, are difficult to incorporate in watershed-scale models that often have grid cells up to several hundred meters in diameter. Likewise, it is unclear when and how to quantify or simulate deep flow through the mountain block when modeling high mountain watersheds. Furthermore, many numerical models are not designed to simulate multi-scale

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**BOX 2 HIGH MOUNTAIN GROUNDWATER AND PEOPLE**

Mountain hydrology (including groundwater) is critical for society in multiple and complex ways. Mountains act as “water towers” for both local inhabitants and downstream users (Viviroli et al., 2020). Globally, the retreat of mountain glaciers and snowpack, including the resulting variability in discharge, has a variety of human impacts on municipal water supply, hydropower, food security, and culture (Carey et al., 2017). High mountain communities are already experiencing climate change impacts and are particularly vulnerable (Gurgiser et al., 2016; Heikkinen, 2017). Though groundwater provides some resilience to high mountain water resources, it is also vulnerable to long-term climate change (Somers et al., 2019).

Human activity impacts high mountain groundwater systems, both intentionally and inadvertently. For example, livestock grazing is a common practice in mountain regions globally. However, over grazing is thought to compress the near-surface soil and increase runoff (e.g., in the Ecuadorian páramo; Buytaert et al., 2006). Groundwater-based adaptation strategies have been proposed in mountain regions as ways to increase groundwater recharge. It is hypothesized that increased groundwater recharge during wet seasons will increase baseflow during dry periods (Ochoa-Tocachi et al., 2019; Somers et al., 2018).

While mountain hydrology and hydrogeology are important research areas, future changes in water-use are likely to exceed changes in water supply (de Jong, 2015). Long-term and thoughtful collaboration with local scientists, stakeholders, and social scientists, is critical to ensure that high mountain groundwater research is useful to society. Local user experiences can provide important avenues for knowledge development and future research directions. As Carey et al. (2014) show, the broad evaluation and quantification of mountain water resources is much more complicated than simply measuring flows but must also include accounting for social dimensions of water usage.
processes and some groundwater flow models will not converge (result in errors) if sharp boundaries between high- and low-permeability units exist, particularly in regions of very steep topographic gradients—all fundamental high mountain characteristics.

Going forward, new data collection techniques and modeling methods may help to fill remaining knowledge gaps. For example, remote sensing may be useful in collecting higher spatial resolution hydrological data in remote high mountain regions, such as soil moisture (Wigmore, Mark, McKenzie, Baraer, & Lautz, 2019) and spatially variable precipitation and snowmelt (Girona-Mata, Miles, Ragettli, & Pellicciotti, 2019). Furthermore, geochemical tracers can be used in combination with numerical modeling to constrain model parameters in data-poor regions (Doyle, Gleeson, Manning, & Mayer, 2015). There may also be potential to use geomorphometry of mountain landforms to infer hydrological storage and functioning (after Cairns, 2014; Carlier, Wirth, Cochand, Hunkeler, & Brunner, 2019; Gleeson & Manning, 2008). Given the research focus on remote sensing of mountain glaciers, there should be additional applicable proglacial geospatial datasets available. Improved data coverage and better methods to represent and model heterogeneous groundwater systems will help to guide mountain water resource management in the face of a changing climate (Box 2).

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Lauren D. Somers: Conceptualization (lead), Writing original draft (lead), Making figures (lead), Writing review and editing (equal). Jeffrey M. McKenzie: Conceptualization (supporting), Writing original draft (supporting), Writing review and editing (equal).

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