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Abstract

The mountain cryosphere and groundwater play pivotal roles in shaping the hydrological cycle, yet their connectivity remains incompletely understood. Current knowledge on meltwater recharge and consequent groundwater discharge processes is more developed for snow- than glacier-groundwater connectivity. Estimates of meltwater recharge vary considerably, which is likely not only a function of inherent catchment characteristics but also of the different spatio-temporal scales involved and the uncertainties in the methods used. This hinders a comprehensive understanding of the mountain water cycle. As glaciers retreat and snowpack diminishes, the relative importance of groundwater for mountain catchment storage is expected to increase. However, shifting and declining recharge from the cryosphere may decrease absolute groundwater-related stores and fluxes, with as-yet unknown effects on catchment-scale hydrological processes. We therefore stress the need to better quantify mountain cryosphere-groundwater connectivity to predict climate change impacts on mountain water supply, supporting sustainable water resource management of dependent social-ecological systems.

1 Main

Earth's two largest freshwater reservoirs, outside the Greenland and Antarctic ice sheets, are mountain glaciers [1] and groundwater [2, 3]. Both reservoirs have crucial hydrological roles, providing water to billions of people around the world and buffering variable precipitation inputs to the terrestrial hydrological cycle [4–6]. Despite their vital importance for the world's water supply, the magnitudes and spatio-temporal patterns of connectivity between mountain glaciers and groundwater are generally not well understood [7]. This lack of understanding also extends to the wider mountain cryosphere, including snow and permafrost, and hampers assessments of water availability and hydrological risks across the upstream-downstream continuum in the world's mountain water towers. Addressing this knowledge gap is needed to support adaptive water management in times of unprecedented loss of cryospheric water storage and increasing downstream water demand [8, 9].

Glaciers and snow are a distinctive feature of the world's mountain water towers [4, 10], covering respectively 2% and 40% of the global mountain area (30e^6 km^2) [11, 12]. Together they are essential water resources and they provide an important buffering role against hydro-meteorological variability, albeit on different timescales, releasing meltwater during drier or warmer periods of the year when water demand is highest. Due to the orographic enhancement of precipitation, as well as colder temperatures at high elevations that promote snow and ice accumulation and reduced evapotranspiration, mountains provide up to ten times as much water per unit area as adjacent lowland regions [13]. Permafrost, another part of the mountain cryosphere, is widespread, covering around 50% of the global mountain area [14]. Although ice-rich permafrost can be important for local water supplies [15], the overall contribution of permafrost to water resources is minor when compared to snow and ice [16]. Its relevance is therefore mostly given by the influence on subsurface flowpaths, rather than by its significance in terms of water storage (Box 1).

Groundwater is present virtually everywhere below the Earth's surface, where it is concentrated in aquifers, defined here as saturated geological formations that are capable of storing and transmitting water. In mountain regions, aquifer configurations, storage volumes and hydraulic properties are highly variable due to differences in climate, surface topography and subsurface permeability and porosity [17]. The world's population strongly depends on groundwater for its water supply, including drinking water and irrigation (Box 2 and Box 3), either directly using springs and groundwater abstraction wells, or indirectly through the contribution of groundwater to surface water as river baseflow [18], which is also essential for ecosystems. Groundwater is a consistent and reliable source of water locally and regionally as it attenuates meteorological variations through its slow processes of recharge, subsurface storage and discharge. However, climate change is affecting recharge patterns, while over-abstraction is leading to groundwater depletion in many regions across the world [19]. These processes are both threatening present and future groundwater availability and, consequently, our water supplies.

Many cryo-hydrological processes pertaining to mountains (e.g., snowmelt and icemelt) are highly dependent on temperature, such that global warming strongly impacts mountain regions [20, 21]. Furthermore, ongoing climate change can be amplified at higher elevations [22, 23], exacerbating impacts on cryo-hydrological processes. In recent decades, a worldwide acceleration of glacier mass loss has been observed [9, 24], while seasonal snow cover duration and snow depths are also generally decreasing [22, 25, 26]. Likewise, mountain permafrost extent is in decline, but with largely unknown consequences for mountain water availability [27] (see Box 3). Together, these ongoing changes cause alterations in the timing and volume of meltwater supply, threatening mountain water supply and reducing the cryosphere's capacity to sustain streamflow during warmer and drier periods of the year, and in particular during droughts [28–30].

The lack of knowledge on the connectivity between the mountain cryosphere and groundwater relates to two aspects. First, the importance of groundwater in (high) mountain areas has only recently attracted considerable attention in the scientific community [31–36]. Due to steep terrain and shallow soils, groundwater storage in high mountainous regions was long assumed to be minimal and short-lived [37, 38], and meltwater recharge processes negligible. However, several recent studies showed considerable groundwater storage [33, 36, 39–42] in mountain areas in different types of mountain aquifers, possibly also connected to distant lowland aquifers [43, 44]. Second, mountain cryosphere and hydrology research has heavily focused on the visible changes such as glacier retreat, glacier volume loss [9], snow cover changes [25] and the consequent direct impacts on streamflow [45–48], without paying much attention to groundwater.

Our current understanding of cryosphere-groundwater interactions in mountains is limited by two main knowledge gaps: the limited understanding of 1) the fractions of glacier and snow meltwater that contribute to groundwater recharge, and 2) the spatial and temporal scales across which these interactions affect downstream water supply and ecosystems. While the connection of the cryosphere and mountain groundwater is key for understanding mountain water supply, most previous synthesis papers addressed these two systems separately [37, 49, 50], or focused on one specific cryospheric element [7]. The magnitude of the glacier- and snow meltwater connectivity with groundwater across scales thus critically requires further attention. We first introduce existing approaches that are used to understand and characterize largely invisible mountain groundwater processes. We follow by synthesizing and discussing current literature on glacier-, snowmelt recharge and the spatio-temporal scales of cryosphere groundwater connectivity (Sections 3-5) and conclude by identifying the specific knowledge gaps that need to be addressed (Section 6).

2 Current approaches to investigate mountain cryosphere-groundwater connectivity

To address the question of connectivity between the mountain cryosphere and groundwater, several properties of the mountain water system need to be quantified, including recharge magnitudes, groundwater volume, subsurface hydraulic properties and groundwater contributions to streamflow. In general, the high spatio-temporal variability, limited data, and the inability of directly measuring recharge and groundwater volumes, render this part of the mountain water cycle difficult to quantify. A combination of approaches, including multiple research disciplines, is therefore required. To frame the results on the connectivity across scales presented in the next sections, we summarize common measurement and modelling techniques and emphasize their uncertainties and current challenges. For further insights on mountain hydrogeology, readers are referred to recent reviews [7, 37, 50].

The most direct groundwater measurements come from groundwater monitoring wells at various depths. Such wells can be sampled or can be instrumented for continuous measurements of hydraulic heads. However, in mountain regions, the network of wells is extremely sparse due to logistical constraints [37]. Streamflow measurements, which are more abundant, are therefore used to infer transit time distributions or information on the catchment-scale groundwater contribution to streamflow. The latter are analysed by either separating the streamflow signal in a faster (sub)surface and a slow baseflow component, or by analysing the streamflow recession behaviour which provides information on the rate of catchment storage release to streamflow [51–54]. Many simplifying assumptions and knowledge of the local hydrogeological properties are needed to quantitatively attribute these streamflow signals to groundwater processes [55].

Hydrogeophysical methods such as electrical resistivity tomography, terrestrial gravimetry, environmental seismology or time-domain electromagnetic surveys can provide insights into subsurface structures, such as the lithology and the spatial distribution of groundwater occurrence [56–60]. Drawbacks are the rather limited area coverage (meters to a few kilometers) of such measurements and the challenge to relate them to hydraulic aquifer properties. At regional scales, remote sensing methods, such as used by the GRACE and GRACE-FO satellite missions, can provide information on monthly storage changes across large mountain ranges. The interpretation of these signals, however, is not straightforward as it is difficult to disentangle the contributions from glaciers, snow and groundwater storage [61–63].

To identify groundwater origins, flow paths and residence times, hydrological tracers are commonly used. These combined characteristics indicate how quickly groundwater is replenished and how it contributes to streamflow, springs or pumped wells. Residence time, transit time and groundwater age all characterize how quickly water moves through the subsurface, albeit with slightly different definitions. These timing characteristics are a function of (and help to constrain) recharge and discharge rates, aquifer storage volume and hydraulic properties. The underlying principle of environmental tracers is that water parcels from different hydrological compartments (surface water, groundwater, lakes, snow, glaciers) carry distinct tracer signatures due to the different water origins, flowpaths and processes that they have undergone. Alternatively, artificial tracers, such as dyes, may be introduced and subsequently tracked through the system. However, compared to environmental tracers, their applicability is strongly spatially and temporally limited. Stable water isotopes, major ions and water temperature are most often used as environmental tracers for cryospheric water source partitioning [64–69]. However, due to strongly overlapping hydrochemical and isotopic compositions of snow and glacial melt [69], distinguishing their contributions to streamflow and groundwater is challenging. In addition, for snowmelt, it is challenging to obtain a representative sample of its isotopic composition due to 1) the spatio-temporal variability of isotopes in precipitation itself and 2) the altering of the snowpack's isotopic composition via sublimation and internal gas and water exchange (isotopic fractionation) [69]. These challenges require caution when up-scaling measurements to larger scales [70]. For example, depending on whether snowfall, snowpack, or stream water during peak snowmelt season was used to define the snowmelt end-member signal, the snowmelt-sourced fractions of total recharge varied by more than 30% in a small mountainous boreal headwater catchment [71]. Emerging tracer techniques such as the analysis of dissolved gases [71–73] and environmental DNA sequencing (eDNA) [35, 42, 74, 75] have begun to address some of these challenges. However, due to the difficult access and complex spatial heterogeneity, tracer data from high-elevation mountain environments, where snow and glaciers are present, remain extremely limited.

In addition to measurements, conceptual and numerical models are used to understand and predict subsurface hydrological processes and their relation to surface water, extending the spatio-temporal scales of the analyses. In the simplest and most commonly applied configuration, groundwater storage changes can be derived via a residual water balance analysis [36]. The robustness of this approach, however, strongly depends on the accuracy with which the other water balance components can be estimated. Measuring hydrological fluxes such as precipitation, evaporation and snow/glacier melt, with high accuracy and spatial resolution is a challenge in mountain regions due to strong horizontal and vertical gradients. Moreover, the total groundwater storage cannot be identified through this approach [40, 71]. In so-called conceptual hydrological models, the role of groundwater storage is often strongly simplified by including a reservoir that represents the effect that delayed groundwater flow has on streamflow generation processes, without explicit consideration of groundwater-surface water interactions or the spatial distribution of groundwater processes [76]. Groundwater models that focus on the simulation of saturated groundwater flowpaths, heads and groundwater tables in mountain regions exist, and are applied at various scales [77–79]. However, they require detailed data on subsurface hydraulic properties, which are generally lacking in mountainous terrain. Moreover, such groundwater or coupled groundwater-recharge models often do not consider meltwater-related recharge processes. Fully integrated cryosphere-surface-subsurface hydrological models are most suited to quantify mountain cryosphere-groundwater connectivity, but currently often include only two out of the three key domains in detail. In mountain settings, the full potential of these models is still limited by insufficiently resolved, inaccurate, or missing meterological, cryospheric, and hydrogeological data [31, 80]. Additionally, implementing such models at high spatial resolution over large domains is computationally expensive.

3 Glacier-groundwater connectivity

Glacier meltwater is often assumed to directly contribute to surface water, with minimal losses to groundwater on its way downstream [45, 47, 48, 81, 82]. However, a portion of glacier meltwater is now known to infiltrate and recharge mountain aquifers. The importance of this contribution and the spatio-temporal scales on which it operates remain highly uncertain [7]. This lack of knowledge raises the questions of how the glacier-groundwater connectivity affects the timing of glacier meltwater input to streamflow, and how the ongoing long-term decline of glacier meltwater will continue to affect mountain groundwater storage and discharge processes.

A few studies have measured glacier melt recharge processes (Figures 1a & 1c). Results suggest two different catchment zones where glacier-melt recharge occurs: 1) direct recharge at the glacier-bed (sub-glacial) from basal melt or surface melt that reaches the bed, and 2) indirect recharge from glacier-fed rivers or lakes in the glacier forefield or further downstream, through infiltration of surface water to groundwater through the stream or lakebed [53, 83, 84].

Sub-glacial recharge studies based on observations are limited and their results are likely highly dependent on the material and lithology at the glacier bed [85]. For example, a sedimentary aquifer (20-50 m thick) below an Icelandic glacier was being recharged by glacier meltwater and groundwater was discharged to the main sub-glacial channel, suggesting a limited sub-surface flowpath spatial extent [86]. Specific examples also exist for glacierized karstic areas, where several studies showed, depending on the flow conditions and drainage pathways, sub-glacial recharge to the underlying bedrock [87, 88]. In Switzerland, groundwater samples taken from a tunnel in fractured granite below glacierized areas showed considerable glacier meltwater recharge through a major fault structure, contributing to deep groundwater flows [89].

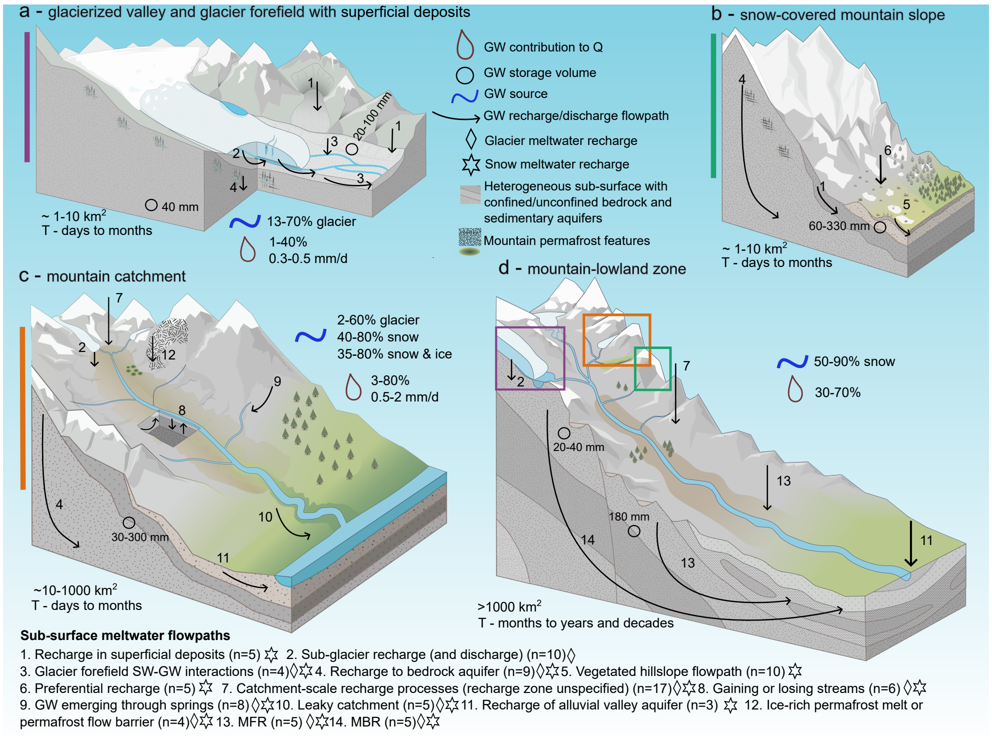

Fig. 1 Locations of meltwater recharge to groundwater and consequent meltwater flowpaths through the subsurface at different spatial scales. Available estimates of meltwater source contributions to groundwater, and the importance of groundwater for streamflow are indicated next to the respective panels (and further detailed in Table 1 of SI). An explanation of each flow path, including the number of related studies (SI), is given by the corresponding number and text at the bottom. Many of these flowpaths are not well quantified in the literature. Flowpaths were included at the corresponding spatial scales (panels) for which studies were found. Abbreviations stand for: GW = groundwater, SW = surface water, Q = streamflow, T = time scale, MFR = Mountain Front Recharge, MBR = Mountain Block Recharge and n = number of studies discussing this flowpath.

For indirect glacier meltwater recharge, more observational studies exist, mostly at small spatial scales [53, 90, 91]. In an Icelandic glacier forefield, 25-50% of groundwater recharge was estimated to be sourced from glacier meltwater [90]. In a Swiss glacier forefield, limited active storage was observed due to recharge and discharge fluxes being approximately balanced [53]. However, catchment scale analyses of streamflow for the same area revealed that there must be another catchment groundwater storage component (40 mm) or water flux that is able to maintain winter baseflow. This storage was hypothesized to be related to either groundwater storage in a bedrock aquifer or to winter glacier basal melt contributions. Similarly, in the Yukon, Canada, both groundwater contributions and basal melt were suggested as sources of winter baseflow [92]. These studies exemplify a common challenge whereby catchment storage can be observed but not conclusively attributed to a single source (e.g., basal melt or groundwater).

Other observational studies have investigated glacier-groundwater links at larger spatial scales (Figure 1c), without specifying the zone where glacier melt recharge occurred. For example, for a glacier-fed river in Alaska, approximately half of the upstream annual streamflow (and ca. 20% of the summer streamflow) was lost over a 55 km river section, resulting in an estimated 200 mm/a of recharge to the underlying aquifer consisting of unconsolidated alluvium deposits [34]. This estimate was found to be twice as large as the potential snowmelt recharge in the downstream lowland region. The study attributed half the long-term glacier net volume loss to groundwater recharge contribution, corresponding to roughly 25% of the total annual recharge. In the Northwest United States (US) glacier-influenced eDNA was found in spring waters at distances up to 10 km from glaciers in volcanic terrain and across topographic divides [35]. Studies from the Upper Indus Basin and Southwest China respectively indicate that 44-46% and 35% of groundwater originated from glacier melt [93–95]. Using satellite gravimetry over a 13-year period, (an unknown proportion of) glacier mass loss across the Canadian Rockies was assumed to be stored in downstream aquifers, due to a concomitant increase in basin water storage confirmed by increased baseflow in downstream rivers [61].

Recent studies have also attempted to model, rather than observe, glacier-groundwater connectivity. Due to limited evidence of where glacier melt recharge occurs (direct or indirect), models have used a range of assumptions. At the glacier-specific scale, sub-glacial drainage models simulate the flow of water below glaciers, sometimes explicitly including its interaction with the underlying sedimentary groundwater aquifer [96, 97]. However, because the primary aim of such models is to investigate glacier sliding rather than their hydrogeological role, these models are rarely integrated into catchment-scale models and usually do not account for flow through bedrock aquifers as [96]. In glacio-hydrological models, glacier meltwater may flow through several conceptual reservoirs to simulate the delayed contribution of meltwater to streamflow. However, it is often unclear if these reservoirs represent only the firn and englacial processes or also sub-glacial groundwater processes [98–100].

At larger catchment scales, this distinction of reservoirs becomes important as it determines the possible flowpaths, and the degree to which meltwater is delayed. At these larger scales, only a few models include glacier-groundwater connectivity [78, 83, 101], while in most cases only the snow-groundwater connectivity is considered [81, 102]. Coupled groundwater-hydrological models of Andean catchments found that between 14% [103] and 9% [78] of total glacier melt recharged groundwater in surficial and fractured bedrock aquifers. From the groundwater perspective, these and similar studies found 2% [78], 10% [104], 13-17% [83] and 60% [105] of groundwater recharge comes from glacier meltwater, for catchments with 2% (Peru), 2% (China), 60% (Iceland) and 46% (Tibetan Plateau, basal melt recharge only) glacier cover, respectively.

Also at regional scales, groundwater-flow models have been coupled to meltwater recharge, but despite the presence of glaciers, the role of glacier meltwater recharge is not always quantified explicitly [33]. In general, however, the majority of modelling studies, especially at larger scales, use more simple groundwater parametrizations, such as a lumped or distributed groundwater reservoirs without lateral groundwater flow due to the absence of detailed subsurface information. Such simplifications often force groundwater to discharge to streamflow at the outlet of the model domain [46, 78, 91, 106] and hamper assessment of spatial patterns of groundwater discharge. Without explicitly modelling groundwater heads, the partitioning of glacier melt to recharge has to be parameterized. For example, for regional scale modelling of streamflow in High Mountain Asia, such a partitioning parameter for glacier melt was determined by model calibration against streamflow far downstream, and varied between 10% to 40% in the main river basins [101, 107, 108]. At the global scale, glaciers (and mountains more generally) are practically ignored as a source of recharge. Due to the coarse resolution of global groundwater models, which smooths the topography, mountain water tables are located at great depth and recharge processes and groundwater flow are thus considered negligible [19].

Overall, information on glacier meltwater recharge to groundwater is extremely scattered, due to the complexity of the system, the different research fields and methods involved, and the many assumptions that have to be made in the absence of sufficient data. Moreover, estimates are highly variable due to study-specific settings regarding hydro-geologic conditions and the proximity to glaciers.

4 Snow-groundwater connectivity

In many mountain settings, snowmelt produces a major pulse of recharge to groundwater, which in turn helps to sustain streamflow in the dry or warm season [50, 109–114] (Figure 1b). Snowmelt-groundwater connectivity has generally received broader attention compared to glacier-groundwater connectivity, with multiple field-based studies suggesting that, across mid-latitude mountain ranges, between 40% and 80% of groundwater recharge originates from snowmelt [71, 93, 113, 115–118] (Figure 1c). While some of these observed differences in snowmelt contributions to groundwater recharge are attributable to the different periods and climates investigated, hydrogeological properties and measurement uncertainties (see Section 2) also result in considerable variability in estimated recharge rates [36, 40, 119–121].

This large contribution of snowmelt to groundwater (40-80%) is commonly explained by the concept of preferential recharge (Figure 1b). In comparison to liquid precipitation and per unit volume, a larger fraction of snowmelt could contribute to recharge [71]. For example, in the Western US, snowmelt was shown to contribute at least 40–70% of total groundwater recharge, despite only 25–50% of average annual precipitation occurring as snow [122]. Preferential snowmelt recharge is hypothesized to be a result of the short duration and large volume of snowmelt, coupled with low evaporation during the snowmelt period, promoting percolation to deeper layers and consistent groundwater recharge during the spring snowmelt period [110, 122, 123]. Additionally, a thicker seasonal snowpack insulates the subsurface, preventing the soil from freezing and promoting infiltration at the onset of snowmelt compared to a thin or intermittent snowpack, which moreover does not generate enough melt to reach soil field capacity and generate groundwater recharge [124]. However, it is often unclear if this process is explained by differences in summer and winter precipitation recharge efficiency, or by rainfall versus snowmelt recharge efficiency [125]. For example, high-intensity short-duration summer convective storms, summing up to a third of the annual precipitation, were shown to provide less than 10% of the recharge compared to cold season precipitation (occurring as an unspecified mix of snow and rain) [126]. This showcases a remaining research gap in snow-groundwater connectivity, namely, could winter rainfall recharge groundwater as efficiently as snowmelt in mountain regions? If preferential recharge from snowmelt indeed occurs, in a warming world with more precipitation occurring as rainfall rather than snowfall, recharge could decrease despite constant amounts of precipitation [123]. An additional concern relates to a shift in timing of recharge from spring snowmelt to winter rainfall and how this might affect the timing of groundwater discharge to streams in systems with seasonal storage capacity, particularly relevant to support streamflow during the summer months and low flows [109, 127, 128]

Besides a shift in the precipitation phase, a warming climate may also cause increased evapotranspiration rates due to higher atmospheric moisture demand, extended growing seasons, and vegetation expansion into deglaciated terrain and upward shifts in eco-zones. These hydroclimatic changes are all expected to affect the quantity and timing of snowmelt recharge [129–132]. So far, such a shift in groundwater recharge has not been generally observed in mountain regions. An exception is a study in a snow-dominated region, Fennoscandia, [133] where a significant decrease in groundwater levels was observed due to the northwards migration of the temperate climate zone. Such decreases in groundwater levels, likely related to changes in recharge, will in turn influence the volume and timing of snowmelt-sourced groundwater reaching streams [134, 135].

Many studies addressing the topic of snow-groundwater connectivity have either been conducted in arid climates or in regions with cool, wet winters and dry, warm summers. These studies have focused on environments with seasonal snowpack and in vegetated mountain ranges, below or near the tree line. In other environments, where the snowpack is intermittent, where snowfall and snowmelt occur simultaneously during the wet season, or when little precipitation occurs during the cold season, the mechanisms behind snow recharge, the potential for preferential snowmelt recharge, and predicted changes remain less explored [123]. Similarly, snow-recharge mechanisms remain understudied in rocky, coarse surficial deposits and hillslopes above the vegetation elevation limit [136–138] (Figure 1b).

Quantifying recharge from snowmelt is further complicated by the difficulty in obtaining accurate snow storage volume. While remote sensing products are increasingly able to capture small-scale patterns and spatial variability in snow depths [139, 140], the uncertainty associated with obtaining snow-water equivalent is still a challenge [141]. Similarly, while hydrological models can be used to estimate snow water equivalent, capturing the complex precipitation patterns and redistribution processes in mountain terrain remains difficult [142–145]. Moreover, it is still unclear at what scale snow processes need to be resolved to capture snowmelt recharge.

5 Reconciling cryosphere-groundwater connectivity across scales

In parallel to improving our physical understanding of cryosphere-groundwater connectivity, its relevance for mountain water availability must be assessed. This requires an additional understanding of mountain aquifers and their (dis)connections to other parts of the hydrological system across scales. These connections determine where, when and at what rate cryosphere-sourced groundwater re-emerges through springs, discharges to surface water bodies, or can be pumped from groundwater wells at lower elevations. At small scales (catchments <10 km^2), there is a growing understanding of how unconsolidated surficial deposits store and release meltwater, contributing to short-term catchment storage (Figure 1a). Recent studies in the Canadian Rockies [40, 146–149], the Alps [150], the Peruvian Andes [64, 151, 152]), and other regions [37, 153], have shown that moraine, talus, alluvium and also saprolite can store and transmit considerable amounts of groundwater. Groundwater in surficial deposits can be disconnected (a perched aquifer) or connected (an unconfined or confined aquifer) to the deeper fractured rock groundwater system and/or the stream network. Shallow flow paths through talus slopes and moraines generally have transit times on the order of days to months [53, 149]. Meanwhile, the presence of permafrost and/or frozen ground can impact infiltration capacity, flow paths, seasonal storage capacity and transit times in these coarse deposits (see Box 1). As glaciers continue to retreat, unconsolidated sediments are exposed which may alter the subsurface storage capacity and recharge processes in the pro-glacial zone, with unknown hydrological consequences.

As catchment size increases (10-100 km^2), the dominant aquifer properties, types and flowpaths can change. Local-scale measurements of hydraulic conductivity may not be representative at such scales, due to subsurface heterogeneity and inclusion of macropores, bedrock fractures, geologic structures, etc.[154]. Moving downstream, flowpaths through alluvial deposits and bedrock may become more important than through talus and moraine (Figure 1b and c). Alluvial aquifers in mountains can have residence times from months up to a few years [155, 156] while bedrock can have a large range of residence times from several months to many years. For example, a study in the Colorado Rocky Mountains found baseflow ages between 3 and 12 years for a relatively small (24 km^2), snow-dominated headwater catchment [157]. Several studies also noted larger relative contributions of older (e.g., decades to millennia), deeper groundwater, but not necessarily originating from the cryosphere, to streamflow as the spatial scale increases [32, 42, 158, 159]. At the same time, the proportion of streamflow sourced from direct glacier- and snowmelt decreases with increasing spatial scale, as opposed to the proportions of rainfall and groundwater, because the area fraction covered by glaciers and snow decreases [45, 64]. A similar relation is expected to be true for the proportion of mountain groundwater and baseflow that is sourced from glacier/snow melt. However there is limited evidence of how meltwater-sourced groundwater evolves from up- to downstream, as groundwater sources (rain, snow and ice) are often not distinguished [160–162]. Additionally, anthropogenic interventions (e.g., hydropower operations, groundwater pumping, etc.) become more prevalent moving downstream, and can significantly affect our ability to monitor and model groundwater recharge and streamflow generation [163].

At larger scales (e.g., catchments of 100-10000 km^2), mountain block recharge and mountain front recharge, together called Mountain System Recharge (MSR), can provide important water resources far (e.g., 10-100 km) downstream [44]. Mountain block recharge is used to describe situations in which groundwater recharged in mountains flows underground into adjacent lowland valley aquifers (Figure 1d). For mountain front recharge, instead, water from mountain streams infiltrates into the ground where the mountain zone transitions to lower elevated areas and alluvial plains, also recharging the lowland valley aquifer. Reconciling the small-scale meltwater recharge processes with such larger-scale understanding of MSR remains difficult [164]. This is partly because large-scale models generally cannot resolve small features like moraines and talus slopes and their ability to delay meltwater. Furthermore, the observational and modelling techniques used for small-scale hydrological studies are often distinctively different from those used for MSR studies. Estimates suggest that 5-50% of groundwater in central valley fill aquifers originates as MSR, with the higher proportions being observed in arid climates [43]. However, the portion of this recharge originating from glacier and snow melt is generally unknown and there are very few studies which assess how cryosphere change impacts MSR. In one such study, a numerical groundwater model is used to conclude that lowland aquifers located >80 km downstream of the Canadian Rocky Mountain range are unlikely to be impacted by glacier retreat since the simulated flow time exceeds tens of thousands of years [79]. However, this study does not account for mountain front recharge. The conclusions drawn also contrast with recent gravimetry research in this area previously discussed [61], illustrating the knowledge gap. Reconciling small- and large-scale mountain hydrogeology is complicated by the very different timescales involved. Indeed, glacier coverage may have been very different in the past, when mountain system recharge entered the subsurface.

Questions related to mountain water resources therefore span a range of spatio-temporal scales (Figure 2) and it is imperative that each question is addressed at the scale of interest using appropriate methods. For example, hydrochemistry, hydrometric and glacier surface monitoring are best suited to small spatial- and temporal-scale questions while global hydrogeologic datasets, satellite-derived snow water equivalent or gravimetry data and larger networks of groundwater observation wells are needed for larger-scale questions. However, smaller-scale studies may also benefit from the constantly increasing capabilities of remotely-sensed datasets [9, 12, 165–167].

Developing conceptual understanding and predictive models that apply coherently across scales is a major challenge given the complexity and scale-dependent characteristics of mountain environments. Efforts have been made to build or couple numerical models that simulate cryospheric processes (e.g., snow and ice), surface flows (streamflow, overland flow) and 3D, variably-saturated groundwater flow (e.g., [31, 78, 80, 168, 169]). These integrated models potentially enable the combination of observations that span various scales, thus allowing for synthesis and prediction. While such models cannot presently be applied at high resolution across mountain ranges due to data and computational limitations, they could be further developed in well-monitored catchments and their applicability may also increase as computational capacity increases. Their numerous, internally-consistent spatio-temporal outputs (including groundwater storage, groundwater levels, evapotranspiration, streamflow) could then be related to environmental covariates (e.g., geology, elevation, glacier cover, climate, etc.), and enable predictions of those quantities elsewhere, potentially by exploiting machine learning model architectures [170]. Many of these integrated models also simulate solute transport, opening the door for water chemistry field data to be used to evaluate model performance [171].

Effectively addressing questions of future mountain water supply requires the translation of our collective observational data, models and understanding, obtained through dedicated studies at rather small scales, across much more extensive mountain regions, including the connections between mountain and downstream aquifers.

6 Implications of the changing mountain cryosphere and its groundwater connectivity for water supply

Visible changes in the cryosphere and their relation to meltwater availability are increasingly being quantified, but the respective impacts on groundwater and subsequent streamflow generation remain largely unknown. Understanding the importance of subsurface flowpaths and the role of groundwater in mountain regions is critical to untangle both the fate of meltwater in the hydrological cycle and the sensitivity of groundwater to a changing meltwater supply due to climate change.

Recent research indicates a clear capacity for groundwater storage in mountain regions and underlines its importance for mountain water supply (Figure 1 and SI Table 1). Since meltwater from snow and glaciers largely contributes to the water supply of mountain regions, particularly at seasonal timescales, meltwater recharge processes cannot be neglected. Whilst snow recharge processes are often considered in our conceptual understanding of the mountain water cycle, the quantification of glacier melt contributions to recharge remains elusive. Although the volume of glacier melt may be smaller than the volume of snowmelt due a smaller coverage of glaciers compared to the seasonal snowpack, its distinct later-summer/mid dry-season contribution potentially increases the importance of glaciers as a source of recharge. On top of that, much of the meltwater-groundwater literature focuses on snow in lower mountain regions, leaving a knowledge gap for groundwater recharge at higher elevations. Estimates of the groundwater recharge that is sourced from glacier and snow melt vary widely (between 2-60% for glaciers and between 40-80% for snow), but indicate that both subsurface flowpaths of meltwater and the consequent delay in flow need to be part of our conceptual understanding of the mountain water cycle.

To unravel the role of mountain groundwater for water supply and its sensitivity to climate change, we need to expand our understanding of the relevance of high-elevation recharge processes and the subsequent subsurface flowpaths. A holistic approach is needed, integrating different research fields and methods (meteorology, glaciology, snow and catchment hydrology, hydrogeology, geology, ecohydrology, socio-hydrology and remote sensing) to assess the importance of mountain groundwater at catchment and larger scales. A multitude of processes need to be quantified and we stress three of them. First, the partitioning of glacier melt and snowmelt into groundwater recharge

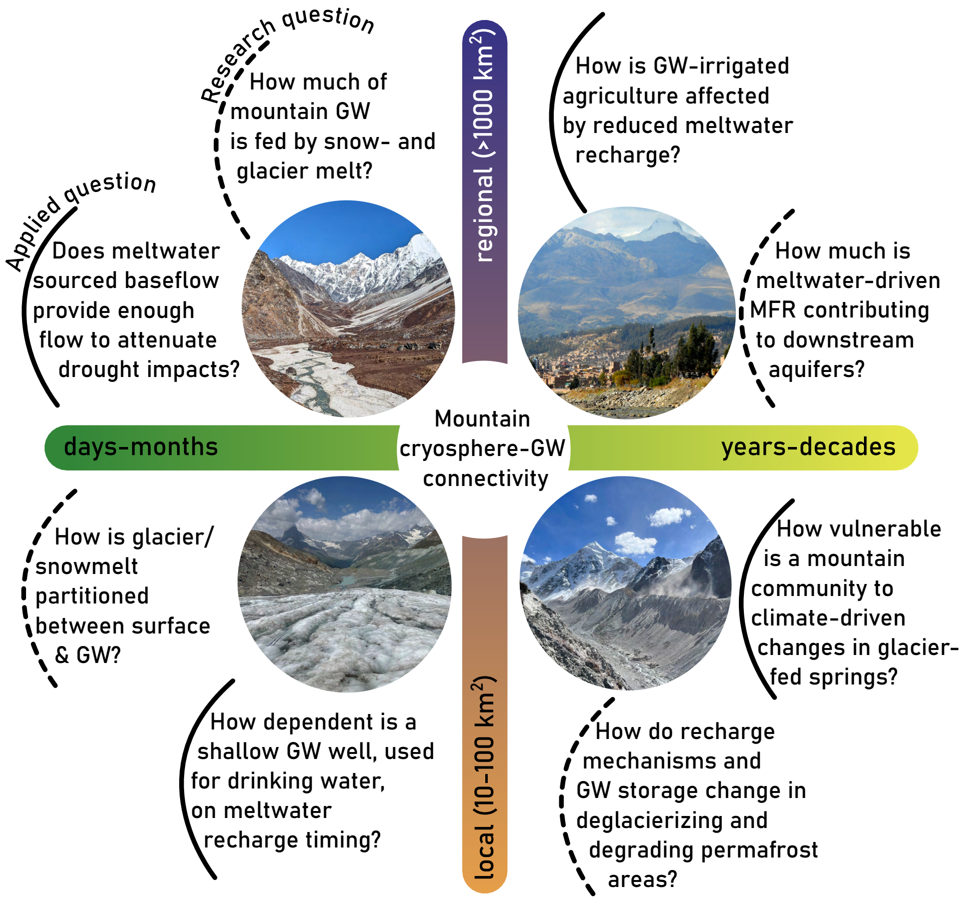

Fig. 2 Key research questions (dashed bows) and applied water-management questions (solid bows) related to spatial (vertical axis) and temporal (horizontal axis) scales of cryosphere-groundwater connectivity in mountain regions. Note that some research questions have implications over centennial time scales too, but this timescale is rarely addressed in water management, and therefore not mentioned explicitly. GW: groundwater; MFR: Mountain Front Recharge.

and runoff needs to be understood in relation to different climates, different geologies and terrain characteristics. This will aid to assess how much of the meltwater contributes directly to downstream streamflow and will enable a parametrization of meltwater recharge processes in hydrological models. A particular challenge here is the presence of multiple recharge zones, both directly at the glacier/snow subsurface interface and further downstream through surface-groundwater interactions. Second, the meltwater contributions to groundwater recharge need to be investigated in relation to non-cryosphere recharge sources to better understand the preferential recharge mechanisms of ice and snow. This, together with information on storage capacity and response times, could indicate how sensitive groundwater and springs are to changing meltwater sources and consequent altered timing of recharge. Most studies reviewed here have characterized this element of source contribution to groundwater in conceptual, or relative terms but more absolute quantitative results are required. Third, a quantification of mountain groundwater contributions to streamflow is needed to examine the relevance of the aforementioned processes in terms of water supply on average and particularly during dry periods. Besides the quantification of these processes, key knowledge gaps relate to the spatial and temporal scales at which these processes operate. This requires an understanding of how mountain aquifers are connected to the surface water network and a characterization of the subsurface in terms of hydraulic conductivity, permeability and aquifer extent, which together determine storage volumes and groundwater discharge processes.

Ways forward to quantify these processes include 1) developing new tracer methods that can identify meltwater flowpaths at various spatial scales and distinguish between snow and glacier melt contributions, 2) improving observations of mountain water balance terms at high spatial and temporal resolutions to constrain potential recharge estimates and determining groundwater storage changes, 3) designing model experiments and using existing streamflow data to determine residence times of mountain groundwater storages, 4) compiling a global dataset of mountain groundwater wells to understand mountain groundwater dynamics at large scales and examine its relations with melt processes, and 5) developing methods to scale and transfer findings to unobserved locations and regions, for example, by making use of hybrid modelling - combining machine learning and physical models.

Overall, we stress that ignoring mountain cryosphere-groundwater connectivity may have crucial implications for our current understanding of the mountain water cycle, and in particular for assessing future changes. From the cryosphere and streamflow perspective, meltwater contribution could be underestimated when only looking at quick responding streamflow dynamics [90, 103]. The meltwater-groundwater connectivity delays the meltwater supply, potentially extending the role of meltwater for downstream regions in space and time. Especially during droughts, it is crucial to understand where and when water is stored and released for an effective management of water resources. In light of climate change, with retreating glaciers and diminishing snowpack, the part of the streamflow affected by changing glacier- and snowmelt is incorrectly attributed when assuming that all estimated meltwater directly contributes to surface water. Moreover, the relative role of mountain groundwater in catchment storage will increase when ice and snow storages are disappearing. The hydrological consequences are as yet unknown. On the one hand, reduced meltwater recharge may lead to an overall decline in total recharge, shift in timing of recharge processes and altered groundwater-surface water interactions [172, 173], while on the other hand, glacier retreat, uncovering coarse deposits, and thawing permafrost may change the subsurface storage capacity [174]. A comprehensive understanding of these changes in future mountain water supply is critical for effectively managing water resources for increasingly groundwater-dependent social-ecological systems in our mountain water towers and downstream regions.

Box 1: Mountain permafrost

Permafrost is defined as ground which has an annual average temperature below 0°C for at least two years. The impacts of permafrost degradation on water resources in mountainous regions are not well known [49, 175], as most permafrost research focuses on high latitudes [176], with very different vegetation, soil, geology, and topography. The limited research available on permafrost in mountainous regions has a strong focus on rock glaciers, which represent only a small component of mountain permafrost [27]. The three-dimensional nature of permafrost leads to large knowledge gaps and uncertainties regarding its age, distribution and volume [14]. In the Swiss Alps, one of the best-studied regions in terms of mountain cryosphere, mountain permafrost is widespread, with an estimated total volume equivalent to $\sim 1/4$ of the volume of all Swiss glaciers [175].

Thawing mountain permafrost has two important hydrological consequences: 1) ground ice melt, acting as a source of (ground)water, and 2) changes in flow paths and water storage as permafrost degrades. Only a few quantitative estimates of ground ice melt contributions to the water cycles exist, mostly concerning the melt of rock glaciers [15, 177]. While such meltwater amounts are small they can be relevant in dry regions and are expected to increase importance in the future [16]. The influence of permafrost on water flow paths is better understood. Permafrost presence can limit deeper groundwater flow and reduce subsurface storage [178]. From Arctic permafrost research, it is known that a warming climate can increase the hydraulic conductivity of permafrost through the formation of so-called taliks, i.e. unfrozen sections of ground within the permafrost. Such taliks can also lead to increased groundwater recharge and baseflow [178] and may be applicable to mountain perfmafrost groundwater hydrology too. Another effect is a decrease in flood peaks with disappearing alpine permafrost [179], due to increased storage [180]. Based upon a limited number the continued thaw of permafrost has likely relevant implications for groundwater hydrology, including changes in volume, residence times, contributions to streamflow, and water quality.

Box 2: Groundwater security, risks and adapatation strategies of mountain communities

For centuries, groundwater management has played a pivotal role in the subsistence of mountain communities [181]. Ancestral groundwater-based supply systems can be found across mountain regions including, for example, puqios (spring source with galleries) in the Western Andes of Peru and Chile, spring boxes (seepage and collection system) in the Himalaya, nymphaeum (groundwater well with canals) in the Alps, and qanats (groundwater well with galleries) across the Middle East and Asia [182]. Still, nowadays, many mountain communities rely on groundwater springs as their major water source [181]. Changes in the source of meltwater springs may decrease water security of mountain communities. Declining groundwater levels can take an additional dimension in traditional mountain communities, as it can imply a loss of cultural and spiritual values [182]. In parts of the Andes and the Himalaya, for instance, high-mountain landscape features – including glaciers and other components of the water cycle – are perceived as living beings within a divine and cosmological order. Disruption of this structure, such as glacier retreat and reduction of snow cover, can affect the spiritual connection between these communities and surrounding mountains [183, 184]. Adaptation efforts to counteract the increasing risk of falling groundwater levels comprise a variety of sustainable groundwater management strategies, including both water abstraction measures and interventions to increase groundwater recharge. For the latter, nature-based solutions, sometimes combined with ancestral water management techniques, play an increasingly important role. Examples in the tropical Andes and throughout the Himalayas include wetland irrigation [185], reactivation of old infiltration canals [186], construction of rustic micro-reservoirs [187], as well as other water sowing and harvesting techniques [182]. When addressing adaptation strategies to the changing mountain groundwater system, it is imperative to include a wider social-ecological perspective which considers human vulnerabilities and risks, and integrates shared local and/or traditional knowledge with scientific evidence [188].

Box 3: Mountain water quality

Meltwater contributions to groundwater recharge, storage and discharge are often considered through the lens of water quantity, as opposed to water quality, even if the latter is critically important for water security. Meltwater generally provides a clean supply of groundwater recharge, but the subsurface through which it travels can have varying influences. In cases where the subsurface acts as a filter, which is typically the case in alluvial sand and gravel aquifers, subsurface flowpaths can improve water quality. However, when meltwater travels through fractured bedrock containing naturally occurring contaminants, the subsurface may also enrich meltwater with solutes and unwanted constituents, such as nitrate and potentially toxic elements [189–191]. How, and where, this possibly contaminated meltwater is exported to streams and springs depends on the water table elevation and specific flow path [192], and may change with shifting recharge dynamics. Over the last two decades, there have been growing concerns about the impacts of legacy contaminants deposition on glaciers via the atmosphere [193, 194], but little is known about how these contaminants might percolate to the groundwater, potentially contaminating local and downstream aquifers. Glacier retreat also affects water physical-chemical characteristics such as temperature and turbidity, critical for endemic biotics, and the ability to dilute watershed pollutants during the low flow season [29]. How these water quality concerns propagate to the subsurface or are influenced by changing meltwater subsurface flowpaths is not well understood. In addition, permafrost thaw can degrade water quality by mobilizing toxic elements, persistent organic pollutants and nutrients including carbon and nitrogen, leading to their release into surface and groundwater [191, 195–198].

Author contributions

MVT, CAW and LS conceived and designed the study, developed the figures and wrote the manuscript. MVT and CAW prepared table 1 of SI. CA, CD, CF, FA, FK, GC, KT, MB, SH, TM, VY and ZS assisted in the writing of workshop outputs, which formed the basis of the current manuscript. AP, BS, DF, FD, JT, OS contributed to the writing and editing of the manuscript. All authors contributed to the discussion that led to the writing of this perspective paper, provided feedback on the draft and approved the final version of the manuscript.

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