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Looking beyond glaciers to understand mountain water security

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Preface

Changes in the mountain cryosphere impact on water security of downstream societies and resilience of water-dependent ecosystems and their services. However, assessing mountain water security still requires better understanding of the complex interaction between glacial meltwater and coupled human-natural systems. In this context, we call for a refocusing from glacio-hydrological monitoring and modelling to a more integrated social-ecological perspective of the wider catchment hydrology. This shift requires locally-relevant knowledge production strategies, and integrating of such knowledge into a collaborative science-policy-community framework. This approach, combined with hydrological risk assessment, can support the development of robust, locally tailored and transformational adaptation strategies.

Main body text

In many mountain regions of the world, the cryosphere is an important component of water provision for downstream societies, as it contributes to dry-season flows and sustains diverse ecosystems[1,2]. However, glaciers and snowpack are expected to continue declining[3,4]. Many of the world's glacierized catchments have already passed peak water, a point at which diminishing glacier and snowpack lead to steadily reducing seasonal runoff[5]. The implications for downstream water security which is shaped by complex social-ecological processes, are manifold. These include a wide range of hydrological risks such as reduced and less reliable water availability, changes in water quality, and other altered ecosystem services[1,5,6]. Nonetheless, the exact impacts on many social-ecological systems are not clear yet.

This is in part due to the limited spatiotemporal understanding of glacier mass and snowpack changes and how these affect downstream social-ecological systems. Well-developed monitoring of relevant natural and human systems represents a basis for assessing mountain water security. However, a recent assessment of global glacier monitoring strategies[7] highlights that the majority of countries showed a "poorly developed" monitoring network or no network at all. Only six countries – all situated in high-income countries of North America and Europe – were considered to have a “well developed” glacier monitoring strategy. In these regions, meteorological parameters are also typically better-monitored. New remote sensing techniques have the potential to provide more extensive glacier and snowpack monitoring. Recent applications include weekly snow depth retrievals for the northern hemisphere[8] and globally-resolved glacier ice thickness variations at the scale of 10 s of meters[4]. However, large-scale geodetic approaches such as ice thickness estimations are generally constrained to decadal timescales with little information on seasonal mass changes which are highly relevant to water security. Furthermore, they are often affected by considerable instrument noise, and remain poorly constrained due to the lack of validation points in remote mountain regions. The paucity of observational data has also direct consequences for future projections to constrain model parameters through cross-validation and to improve process understanding. For example, glacier mass fluctuations are still not adequately represented in computational models (e.g. through the appropriate parameterization of energy balance and ice flow equations), leading to substantial uncertainty in future projections[9].

However, these knowledge gaps extend, and may even be more severe, beyond the cryosphere. Downstream water availability is determined by wider catchment hydrology (i.e. the totality of cryospheric and non-cryospheric surface and subsurface water stores)[10,11]. For example, data on non-cryospheric precipitation in mountain areas are crucial to assess water availability, and remain a major challenge in terms of availability, continuity and quality[12]. This is especially problematic in complex mountain topography, which gives rise to strong local atmospheric gradients such as orographic effects, and renders coarse-resolution climate models unprecise predictors of future precipitation changes[13,14]. In addition to scaling issues, uncertainties on large-scale atmospheric circulation patterns remain prevalent. Prominent examples are the South Asian monsoon[15], or zonal wind patterns controlling moisture transport from the Amazon to the Andes[16] that all exert a major control on precipitation regimes at regional scale. As a result, even the sign of future precipitation change remains often unclear and debated. Nevertheless, the most recent Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) confirms the general trend that climatic extremes intensify with wet (dry) regions getting wetter (drier) with more pronounced heavy precipitation events in some mountain regions[17]. Uncertainties around the frequency and magnitude of future droughts and their implication for water management remain high. Similar data gaps are present for other hydrological processes such as soil moisture, vegetation dynamics, and groundwater.

Beyond water availability, water security is also inextricably linked to human vulnerabilities and needs, and sustainable development[18]. Information on these components is severely limited such as socioeconomic factors including water demand and adaptive capacity. Population growth and expansion of irrigated agriculture and hydropower capacity will increase future pressure on water resource allocation and access[19], particularly in lower-middle income regions including the Tropical Andes[20], Central Asia[21,22] and the Himalayas[23]. These pressures are likely to be exacerbated by weak water governance leading to increasing water stress and potential conflicts and thus challenging future water management and threatening long-term water security[2,6]. Ensuring mountain water security therefore requires a holistic understanding of the complex links between cryospheric changes, climate change and coupled human and natural downstream systems[24]. It is pivotal to integrate people and the wider catchment context into transdisciplinary research, which then supports the development of effective and locally tailored adaptation strategies. These strategies need to go beyond incremental measures only recognizing increasing severity of climate change impacts and potential limits of current adaptation processes[25]. Moreover, to achieve transformational adaptation for future water security, an integrated social-environmental perspective is needed that includes human vulnerabilities, risks and diverse knowledge co-production processes.

Here, we analyse the complex interconnections between the cryosphere, the wider catchment hydrology and coupled human and natural downstream systems to identify current gaps in process understanding and the most significant bottlenecks in developing suitable adaptation strategies for mountain water security.

Tracing meltwater in a catchment context

Past research has highlighted the role of glacier shrinkage in overall reductions of surface water supply[5,26]. However, the significance of glacier shrinkage in the context of water security is much more complex and depends on how meltwater propagates through the terrestrial water cycle including the relative contribution of non-glacial water sources[1,27]. This requires understanding the principal water stores and their fluxes (e.g. storage capacity, residence time and hydrological connectivity; Figure 1) combined with reliable estimates of human water demand. Wider catchment hydrology including surface and subsurface water stores can play a crucial role for seasonal and interannual storage and release of water[28,29] and thus buffer glacier shrinkage[10,11]. This buffer function has barely been explored in assessments of water shortage risks under glacier shrinkage, and is imperative to be considered for climate change adaptation.

Surface and subsurface water stores, such as mountain wetlands, can provide a major contribution to streamflow[30]. Furthermore, wetlands can improve water quality by retaining pollutants such as heavy metals from acid rock drainage in recently deglaciating areas[31]. However, these sensitive systems are often under threat of anthropogenic activities such as land-use change, livestock grazing and peat extraction. Glacier-fed wetlands might be particularly sensitive to reduced glacial streamflow which may cause their fragmentation and reduction[32]. While first research for the Tropical Andes attributes decreasing wetland area and water storage following a delayed peak water signal to glacier shrinkage[33], other evidence suggests non-glacial surface stores as pivotal to controlling wetland extent[28]. The specific hydroclimatic connections and geomorphic setting may therefore determine the magnitude of glacier shrinkage affecting wetlands and other water stores[34]. Extensive wetland monitoring networks would provide the basis for understanding their hydrological response to climate change and glacier shrinkage. Such an effort requires quantifying wetland storage dynamics and their connectivity to other surface and subsurface water stores including glaciers and deeper groundwater systems[29].

The characteristically long residence time and large storage capacity of groundwater stores (Figure 1) make them a strategically important water source that may buffer the loss of meltwater inputs from retreating glaciers[34]. The foreland geology of glacierized valleys is often characterized by the presence of significant surficial (alluvial and glaciofluvial) aquifers that can contribute up to 70% of downstream river flow outside of the dominant melt season[11,29,35]. Overburden materials such as talus piles and moraines can facilitate meltwater infiltration to deeper confined groundwater aquifers that may discharge into surface water stores further downstream[29]. In some cases these overburden materials can form significant groundwater stores in their own right, temporarily storing high mountain runoff with residence times long enough to contribute to river flow throughout the year[34]. Groundwater chemistry[36] and numerical modelling[37] analyses also indicate that deeper groundwater circulation through the mountain bedrock can contribute to downstream runoff along flow pathways that can extend kilometres deep. Recent evidence indicates that the long term sustainability of proglacial aquifers is complex and could be directly influenced by glacier retreat[10]. However, the significance of proglacial groundwater systems to downstream water provision is still poorly understood[34].

Improving estimates of water demand

Many mountain water-fed regions are under pressure from growing water demand[2,21], yet most human water use occurs at considerable distance from the cryosphere. Therefore, assessing the spatiotemporal occurrence of water use is crucial to understand whether changes in the cryosphere and the wider catchment hydrology will have a major impact on water security[1,27]. In the last two decades, global hydrological models and datasets have been developed and applied to estimate global water demand and support integrated water resource management[38–40]. While such models and data can support the quantitative evaluation of changes in water demand, they still struggle with issues of coarse resolution, high uncertainties, and the scarcity of validation data[38]. In addition, it remains challenging to connect the outputs of large-scale hydrological models with specific local water management questions, which are often highly context-specific.

Higher-resolution regional gridded datasets of sectoral water demand in mountain regions have been derived directly from national datasets of water use and distribution[41]. These are likely to be more relevant to end users, but should also capture intra-annual variability of water demand at specific catchment points. This is only achievable through improved data collection strategies in combination with local knowledge of water use (e.g. withdrawals, consumption patterns) and must be considered in combination with a better understanding of surface and subsurface flow pathways and stores to inform catchment management and adaptation planning.

Reliable projections of future water demand at relevant temporal scales for climate change assessments (i.e. towards the mid-century or 2100) are hampered by high uncertainty about future development of regions. In many lower-middle income mountain regions, water demand projections beyond a few years become increasingly uncertain due to e.g. high political instabilities, institutional turnover, social conflicts and economic volatility[21,42]. These constraints cannot be overcome by improving model frameworks and data collection. A step forward represents a water balance model approach that integrates stakeholder-driven expert assessments with local knowledge to develop a wide range of scenario-based trajectories of water demand[43].

Integrating hydrological risk and water security

A growing number of people using glacier-fed water resources has been affected by water scarcity in the last decades[2,44]. During the 20th century, water shortage (i.e. low physical water availability per capita) and stress (i.e. low water availability relative to demand) have considerably increased, resulting in high overall water scarcity in locations such as the Bolivian-Peruvian Altiplano, Central-Western Himalayas or Southern Rockies[45]. However, water scarcity is not only shaped by physical water availability (relative to water demand) but also by poor quality[46], allocation and limited access to water determined by sociopolitical and economic constraints[47,48]. This situation can often be found in lower-middle income regions with large social and economic inequalities and institutional fragilities such as in the Himalayas[23], Central Asia[21] and Andes[48]. In these regions, highly vulnerable, poor and often-marginalized groups such as indigenous peoples, rural communities and women are disproportionately affected. A common framework to analyse these multi-dimensional challenges builds on water security integrating both an adequate quantity and acceptable quality of water available to users[49,50]. This encompasses concepts of appropriate water governance that ensures access to safe water, and explicitly includes thresholds beyond which social-ecological systems are increasingly vulnerable[51]. The assessment of hydrological risk as part of water security should be a key element of such frameworks[50]. This would allow a better evaluation of water-related shocks, threats or tipping points[18].

The focus on risks provides a useful perspective to deal with complex coupled human and natural systems under high uncertainty[52]. Risk is typically defined as dynamic interaction of climate-related hazards, and both human-natural exposure and vulnerabilities to the hazards[3,53]. Hazard is understood as the potential occurrence of a natural or human-induced physical event or trend for negative consequences (e.g. a drought). Vulnerabilities include a variety of concepts related to the propensity of human and natural systems to be adversely affected, as associated with sensitivities to harm, coping capacity (i.e. to withstand or absorb harm), and adaptive capacity (i.e. to anticipate, adjust and transform harm). Exposure refers to the presence of human and natural systems in places and settings to be adversely affected. However, the assessment of each component is often limited by siloed definitions (e.g. hazards from glacier shrinkage, drought or flood)[54], multiple, overlapping and contested concepts (e.g. risks and vulnerabilities)[55], and poorly defined metrics (for all components). Hydrological research in glacierized mountain regions has analysed a limited set of the distinct risk components and parameters relevant to water security[2,56] including combined sudden-onset (e.g. lake outburst floods) and slow-onset (e.g. drought) risk assessments[54,57]. A concerted effort of the most recent Sixth Assessment Report of the IPCC analyses risk consistently as 'potential for adverse consequences'[53] to social-ecological systems. This definition explicitly includes uncertainties and considers both impacts of and responses to climate change. The latter links directly to the fact that societal responses to climate change impacts can reduce or exacerbate risks which then closely relates to successful adaptation and maladaptation, respectively. This understanding highlights the dynamic, interwoven and complex nature of risks which is intrinsically connected to social-ecological processes.

We elaborated a set of archetype systems with specific hydroclimatic (dry and wet) and socioeconomic (low and high vulnerabilities) conditions to conceptualize the interconnection between upstream and downstream risk potential (Figure 2). The underlying basin processes of risk to water security can – in a simplified conceptual form – be decomposed into the main hydrological components contributing to river flow (Figure 2a), the potential for water shortage (Figure 2b) and the key components of risk to water security (Figure 2c). These archetypes illustrate how the spatially distributed social-environmental basin processes are key to understand the complex interplay of water shortage hazards, socioeconomic processes shaping human vulnerabilities and location-specific exposure. For instance, an apparently high risk potential caused by meltwater reductions in headwaters can be modulated by low exposure, i.e. low density of population and assets in place to be adversely affected. In turn, large and highly exposed population centres in downstream areas are often situated at considerable distance from the cryosphere and exhibit reduced vulnerabilities given improved socioeconomic conditions. High risk potential of these urban systems may depend on other variables such as increasing water demand and exposure, and reduced water quality. Furthermore, the compound effects of socioeconomic and environmental conditions can considerably exacerbate or attenuate risk.

Toward transformational adaptation

Water security is paramount for achieving many of the 17 UN Sustainable Development Goals (SDGs) and climate-resilient development[51]. In the last decade, climate change adaptation research has shifted from engineering-dominated 'predict-and-provide' paradigms towards more transdisciplinary approaches[58]. Adaptation strategies should embrace flexible and low-regret solutions[59]. Such measures need to perform cost-effectively, based on risk assessments under a variety of possible future pathways robust against high uncertainties[60], which can typically be found in the data-scarce Himalayas or Andes.

While adaptation has often been understood as incremental, i.e. increasing the application and efficiency of well-known measures, the pace and magnitude of impacts from global change, however, requires more profound changes. Adaptive strategies therefore need to hold the potential to induce fundamental shifts in state and interaction of social-ecological systems at large scales or intensity addressing root causes of vulnerabilities, which is commonly understood as transformational adaptation[25,61]. We highlight selected incremental and transformational adaptation options to social-environmental impacts, which potentially enable effective long-term reduction of human vulnerabilities and hydrological risks (Figure 3). We argue that it is paramount to assess upstream-downstream relationships of water users under principles of water security, to understand how upstream water withdrawals affect downstream use (e.g. by deteriorating water quality) and how downstream water demand shapes upstream water management and availability (e.g. water storage and allocation). In (seasonally) dry mountain regions, such as the Tropical Andes of Peru and Bolivia[26], Central Asia[21] and the Western Himalayas[23], water supply systems have often been enhanced by constructing large reservoirs. But such interventions are often contested, as they potentially trigger local water conflicts[62] and increase water demand that coevolves with additional supply[63]. These negative effects can exacerbate human vulnerabilities and risks to water security[64] and need to be addressed with small and decentralized reservoir management in accordance with improved water governance and awareness explicitly involving local stakeholders (Figure 3).

Scientists and policy-makers are increasingly exploring nature-based solutions (NBS) as innovative and transformational adaptation strategies leveraging natural processes that support a diverse range of ecosystem services and important co-benefits[19,65]. NBS have been implemented across mountain regions, e.g. linked to headwater management through wetland restoration or bioremediation approaches to buffer deteriorating water quality (Figure 3), several of them including transformational approaches[65]. These interventions can provide a cost-effective solution to increase the buffer function of wider catchment hydrology to water loss from glacier shrinkage through enhanced water infiltration and storage. NBS can be part of robust, low-/no-regret strategies to deal with uncertain natural and human processes, as they are often considered flexible and robust under changing conditions because of the multiple benefits that they may provide[19]. They can be complementary to the limited benefits of grey infrastructure enhancing its performance, lifespan, and adaptability[66]. There is a large potential for financing NBS adaptation options considering that its total investment share of current water management infrastructure remains below 1%[19]. However, a stronger scientific focus on NBS and policy recommendation to deploy them at larger scale is hampered by limited scientific evidence on the specific benefits. Extension of measuring and analysing specific points in the basin are needed to confirm a successful implementation and long-term benefits of NBS.

Increased exploitation of mountain aquifers through the construction of abstraction boreholes could also serve to alleviate water supply stress where significant groundwater stores exist and where viable abstraction yield can meet local demand sustainably (Figure 3). Potential yield hinges essentially on local hydrogeological factors including aquifer permeability, storage, and depth. Yield may also be limited by other factors such as economic constraints on the number and depth of boreholes or jurisdictional and transboundary questions. These complex issues highlight the need for an integrated upstream-downstream perspective including cross-border cooperation within an inclusive science-policy-community dialogue framework[67]. The long-term viability of groundwater exploitation will depend strongly on the degree to which abstraction is offset by surface recharge (e.g. rainfall and meltwater infiltration) and subsurface recharge from the mountain block[68]. Consideration of the sustainability of abstractions would be particularly important for regions that become reliant on groundwater as a major water source. For these regions, over-abstraction could lead to a gradual decline in water supply. Knock-on effects to ecosystem services that depend on groundwater inflows should also be considered as part of any groundwater exploitation strategies.

New arrangements for knowledge creation, and better use of existing evidence, can alleviate the data scarcity and limited knowledge that hamper the design and implementation of effective adaptation strategies[69]. One promising approach is the integration of local knowledge and indigenous knowledge with scientific knowledge into a common baseline (Figure 3), commonly referred to joint knowledge production[70,71]. The use of diverse sources of knowledge can enrich and complement modelling efforts, for instance as tools to scrutinize, calibrate, and potentially falsify models[72]. Joint knowledge production may also make citizen science approaches more integrative and inclusive. Methods from citizen science may strengthen local monitoring and management, and have shown to contribute to extensive data collection in the Tropical Andes of Ecuador and Peru[73]. To minimize undesired outcomes, such as the use of citizens as low-cost workforce[73] or imposing unilateral dominant scientific knowledge[71], collaborative and co-designed joint knowledge production processes should ideally occur since the early research planning with attention to local practices and governance[70]. A stronger exchange and collaboration of science with local water management practices can potentially increase the engagement of local communities and policy, and thus attenuate frequently occurring water conflicts in many lower-middle income mountain regions[42]. Such a collaborative science-policy-community framework and shared understanding can reduce knowledge asymmetries[67], empower local stakeholders and reduce their vulnerabilities, and enhance the effectiveness of adaptation measures considering incremental and transformational co-production processes[51,74]. However, the implementation of such a framework requires careful management considering trade-offs between the needs of different groups of water use (e.g. upstream-downstream, rural-urban) and sectors (e.g. hydropower and agriculture)[23].

Lastly, the potential barriers and 'limits to adaptation', i.e. the point at which adaptation actions fail to protect things that are assigned a value[75], need to be further addressed in mountain water security research. Adaptation limits primarily result from societal processes and represent thus socially constructed boundaries linked to e.g. cultural and behavioural habits, power structures, governance, institutional processes and risk management which vary over time[76]. Many of the socially constructed limits are considered as 'soft' limits that could be overcome if, for instance, a stronger focus is put on increased awareness, improved capacities, trust-building measures and polycentric governance in adaptation decisions[75,77]. On the contrary, biophysical limits (e.g. loss of meltwater from glaciers and snowpack, total available water supply) are often regarded as 'hard' limits that cannot be overcome. Therefore, it is critical to put efforts in shifting the soft limits where transformation adopts a central role. We argue that in order to achieve incremental and transformational adaptation for mountain water security, a targeted and evidence-based transdisciplinary collaboration between science, policy and local communities is required that points to the missing links in the terrestrial water cycle. Despite efforts to increase the evidence base to inform adaptation planning, it is clear that residual knowledge gaps and uncertainties will remain. To address such uncertainties, the use of multiple estimates and model ensembles for stochastic environmental simulation[78,79] should be adopted more widely, as is already commonplace in climate projections. Formal and informal methods for uncertainty analysis are increasingly common and should be promoted further, especially in a context of risk assessment[80]. For these strategies to be adopted, locally relevant jointly produced knowledge needs to be fed into fully coupled multi-models that include future risk scenarios of coupled human and natural systems.

Rethinking mountain water security

A more variable water supply and growing water demand exert increasing pressure on water resources and their availability, threatening future water security and management in many mountain regions. We argue that the poor understanding of interactions between the atmosphere, cryosphere, glacial and non-glacial water stores, and people hamper climate change adaptation and long-term water security. Meaningful assessments of mountain water security require thus a holistic social-ecological perspective that interlinks the wider catchment hydrology considering surface and subsurface stores including deeper groundwater flows, and people with improved process understanding of human water demand. Water security assessments can then be leveraged by using a fully coupled hydrological risk framework. This approach needs to integrate multiple social-ecological vulnerabilities and the degree of exposure to water shortage under a variety of possible future scenarios of glacier shrinkage and socioeconomic development. Therefore, it is paramount to consider the spatiotemporal propagation of meltwater through the terrestrial water cycle for interrelated upstream and downstream systems. We call for improving data and diverse knowledge collection, and integrating those into a collaborative science-policy-community framework. This approach can support a wide set of incremental and transformational strategies that guide effective, robust and locally tailored adaptation pathways. These may include nature-based solutions to increase the buffer function of wider catchment hydrology to water loss from glacier shrinkage to enhance long-term water security.

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Figure captions

Fig. 1. Components and interactions of the hydrological cycle within a catchment context.

Overview of hydrological key components, pathways, and buffers in non-glacierized and glacierized catchments. Overland flow (white arrows) from surface stores (glaciers, snowpack, lakes, wetlands and rivers) interacts with pathways involving subsurface stores including proglacial aquifers (e.g. glacial moraines), wetlands, overburden materials (e.g. talus piles) and surficial and bedrock aquifers. For each key hydrological component, black circles show if storage is predominantly limited to the surface (SW), subsurface (SS) or both (SSW). Blue-filled circles indicate the buffer function of these stores for streamflow contribution at short-term (hours to a few days), seasonal (months) or interannual (several years) level. With downstream distance, mixing of cryospheric and non-cryospheric surface and subsurface stores increases and relative contribution of cryospheric streamflow decreases.

Fig. 2. Conceptual representation of the upstream-downstream gradient of risks and its contributing factors in a glacierized basin.

A diverse set of spatially distributed social-environmental processes determines risk to water security in a glacierized basin. (1) Decomposition of processes contributing to (a) river discharge (see Figure 1), (b) water shortage potential, and (c) hydrological risk. See section 'Integrating hydrological risk and water security' for a detailed definition and discussion of risk and its components. (2) Three archetypical systems with specific hydroclimatic (dry and wet) and socioeconomic (low and high vulnerabilities) conditions that illustrate how the spatial pattern of selected drivers of risk (water supply, water demand, human vulnerabilities) may affect water security and differ between catchments. (a) Archetype of a highly-vulnerable and dry catchment. Risks to water security may occur where low water availability, high demand, and high human vulnerabilities intersect. (b) Archetype of a highly-vulnerable and wet catchment. Water security risk is lower because of higher water availability but may still occur as a result of high human vulnerabilities. (c) Archetype of a low-vulnerability and wet catchment. Hydrological risks are considerably reduced due to low levels of human vulnerabilities at high water supply. Section (1) uses the trends of archetype (2a).

Fig. 3. Social-environmental drivers of risk and adaptation options to achieve mountain water security.

Drivers of risk (dashed red semicircles) to mountain water security and adaptation options (black semicircles) that potentially enable effective long-term reduction of human vulnerabilities and hydrological risks. Adaptation to increasingly severe and complex impacts on water security may require transformational approaches. These can include changing practices and regimes of management, and allocation of water infrastructure and resources, the implementation of nature-based solutions, the exploration of sustainable groundwater abstraction from mountain aquifers and joint knowledge production. The latter refers to the integration of local, indigenous and scientific knowledge into a common evidence base through a collaborative science-policy-community framework. This process potentially fosters shared understanding of the state of water security, addresses challenges of data scarcity and limited process understanding and enhances the effectiveness of adaptation in rapidly transforming glacier and mountain landscapes.