Opinion

# The changing water cycle: the need for an integrated assessment of the resilience to changes in water supply in High-Mountain Asia

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Water sourced from Asian mountains is vital to the survival of an estimated 1.4 billion people, but current and anticipated changes in snow, ice cover, and precipitation patterns may threaten these supplies and, in turn, the food security of tens of millions of people. Despite the severity of this developing environmental hazard, the relative importance of each component of the water cycle still needs more detailed study so that those communities who will experience the greatest extremes in supply can be identified. Specifically, data showing how the contribution of meltwater varies with increasing distance downstream are lacking for many mountain catchments, although the use of stable isotope tracers provides some hope in this regard. Imprinted on regional-scale hydroclimatological controls of water availability are local-scale cultural beliefs and practices that have evolved over centuries, which determine who is able to access water supplies, for how long, and for what purpose. Building the resilience of human populations and the environment to future changes in water supply therefore depends on effective interdisciplinary team working to develop an understanding of the complex interactions between physical, socioeconomic, cultural, and historical factors, and that can only be properly realized if local communities are considered as an integral part of the research team. Developing simple and practical methods for water management, storage, and societal adaptation that are appropriate to the socioeconomic and political conditions of mountain-dwelling communities will only be sustainable if they are built on this integrated knowledge base. 

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## INTRODUCTION

The glaciers and snowfields of high-mountain Asia (and specifically the Himalaya for the purposes of this piece) provide a crucial source for the many rivers that flow across the Asian subcontinent, but they are diminishing rapidly in the face of sustained climate change.[1] Downstream, more than 1.4 billion people living in the foothills and lowlands are dependent on stream and river flows for food, energy, sanitation, industry, and tourism. Studies of future discharge with climate change have been largely uniform in predicting reduced flows[2,3] although recent work has suggested that in the short-term preparing for floods may be the most pressing policy priority for some catchments.[4] In mountain areas, demand tends to exceed supply during dry months (Figure 1), and this shortfall will likely increase with time,[5] potentially leading to large-scale crop failure and drought. Conversely, during the rainy season, extreme precipitation events threaten communities and infrastructure and such events are likely to be exacerbated under future scenarios. However, empirical data are scarce because of the challenging nature of the terrain and, in places, political instability, both of which can restrict access to certain parts of the range, and modeled data can vary significantly even when making short-term (20–30 years) projections.[2]

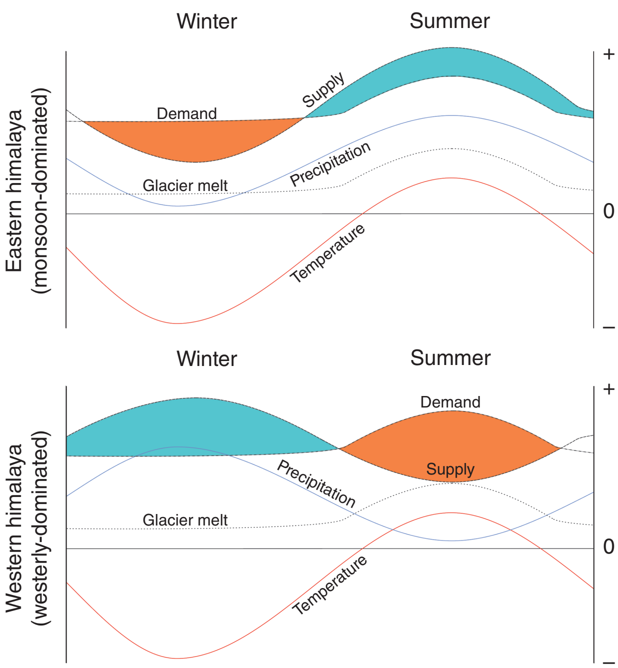


**FIGURE 1** | Schematic approximation of the timing of precipitation, temperature, and glacier melt maxima at opposite ends of the Himalayan range, and their relationship with natural water supply and community demand.

Forecasts of future runoff therefore tend to carry large uncertainty,[6] and identifying the communities most likely to experience severe changes in water supply is thus difficult.

Building resilience to changes in water supply means providing communities and systems with the ability to anticipate and withstand short-lived extremes (i.e., flood and drought) as well as being able to adapt to long-term shifts in flow patterns. Adaptation is a key part of this process,[7,8] although it is widely recognized that adaptation can undermine resilience as well as enhance it.[9] Given the emphasis on people, successfully building resilience must then depend not only on environmental knowledge, but also on understanding local-scale politics and social arrangements.[10,11] Socioeconomic factors such as gender, caste, age, health, access to decision makers and education, and the ability to earn largely determine the susceptibility of individuals and communities to harm.[12] These parameters are built upon a foundation of political and social hierarchy developed over hundreds to thousands of years. The people of high-mountain Asia have a long history of coping in the face of socioeconomic and hydroclimatic adversity so indigenous knowledge of coping strategies is also a very valuable, and often under-utilized, resource.[13] Establishing the reasons behind the success or failure of previous actions is a good first step toward developing future interventions, and there may be design elements of traditional coping strategies that can be employed in new approaches to water management. Here, we outline how natural and social scientists as well as historians might work together to tackle the issues of changing water resources in South Asia, and the challenges that still need to be addressed for future water management.

## THE RECENT FUNDING CONTEXT—A PARADIGM SHIFT?

A longstanding obstacle to development in the mountain areas of Asia is the disconnect that exists between mountain-dwelling communities who possess the indigenous knowledge and groups with relevant academic expertise (e.g., engineers, scientists, health experts, sociologists, and historians).[14,15] Even within the academic community, barriers often exist between members of different research disciplines. In recent years funding bodies have sought to address this disconnect by directly targeting Official Development Assistance (ODA) countries in funding calls and explicitly requiring research teams to evidence both interdisciplinary working and community involvement at the application stage. Most major research councils (e.g., US National Science Foundation, Swiss National Science Foundation) already have dedicated funding streams for interdisciplinary research, but few have previously had the opportunity to specifically target ODA countries. This refocusing of research priorities marks an exciting new era.

A recent example of how the funding context has changed can be found in the UK, where in November 2015 the government launched a new strategy for its overseas aid titled 'Tackling global challenges in the national interest.'[16] The strategy had its origins in the Government's 2015 manifesto commitments, which included spending 0.7% of Gross National Income as ODA and continuing efforts to eradicate extreme poverty. The 0.7% commitment was made in the context of calls to reduce overseas aid led by a populist sector of the media (e.g., Ref [17]), and followed by a large proportion of the public,[18] hence the inclusion of 'national interest' in the report's title. Transparency, value for money, scrutiny, and improving partnerships between the UK and other countries were key components of the strategy. So too were the important elements of keeping aid untied and a poverty criterion to ensure that funds would be spent in the best interests of poor and marginalized communities suffering from conflict, discrimination and the negative impacts of climate change.[19]

A large part of this funding has been dedicated for bringing previously unconnected academic groups together to tackle 'global challenges' and funding calls have demanded an interdisciplinary approach. It marks a step change in research funding by specifically targeting ODA countries and has initiated a broad range of cross-disciplinary and cross-continental conversations that might previously not have taken place. Undoubtedly, complex problems that involve a range of physical, human, cultural, and political interactions, such as adapting to changes in water supply in South Asia, stand to benefit most from this unified approach.

## RELATIVE CONTRIBUTIONS TO DISCHARGE

At the natural science end of the interdisciplinary spectrum lies researchers interested in how glacier and snowfield recession will alter the proportional contribution of ice melt, snow melt, precipitation, and groundwater to proglacial mountain river systems.[20,21] This is important not only for people living downstream who rely on the water for, e.g., irrigation and sanitation, but also for the specialized ecosystems that have established themselves in these often very cold and sediment-rich environments.[22] Broadly speaking, glacier contributions to flow are small in monsoon areas, but far more important where mountains feed into dry regions such as the Indus and the Tien Shan.[23] In the monsoon-dominated Eastern Himalaya even those river systems that are in close proximity to glaciers and snowfields may receive as little as 2% of their annual runoff from melt at the sub-basin scale, although in other areas it may be as high as 30%.[24] Further, many communities exploit nonglacially fed streams as their main water source rather than the fast-flowing and silt-laden main rivers,[12] so the impact of ice and snow recession may actually be small for some. Small hydroelectric schemes exist on a village or catchment level, but most water use is for domestic and agricultural purposes. Further west, the Indus receives around 40% of its annual discharge from glaciers,[2] and snowmelt contributions in some Himalayan basins can account for up to 75% of runoff[25] so the picture is rather different. Here, runoff is important for major hydroelectric and irrigation schemes as well as for more traditional domestic use[26] (Figure 2).

On a local scale, the strongest control on discharge is undoubtedly orography,[27] which largely determines precipitation distribution. In the transfer of that precipitation to the river, storage of water in groundwater reservoirs, soil and vegetation can all modulate the river discharge cycle, although patterns of reservoir recharge and purging appear to be spatially uniform, at least in Nepal.[28] During both winter (December–February) and summer (July–August) it is known that the timing and magnitude of river discharge is well-correlated with the degree of catchment glacierization,[28,29] but how the different sources (ice and snow-melt, precipitation, groundwater) interact at lower elevations remains poorly understood.[30] Perhaps most importantly, the relative contributions of these sources through time, i.e., seasonally, are entirely unquantified in many parts of Asia, making the forecasting of flows a challenging task.

The use of stable isotope tracers provides some hope in this regard. Studies focused on catchments both in the Himalaya[31–34] and other areas[35–37] have demonstrated that distinct chemical signatures can be identified that quantify the spatial and temporal variation in the contribution of glacier, snow, rainfall, and groundwater to stream flow, although a precise understanding of glaciohydrological response

  

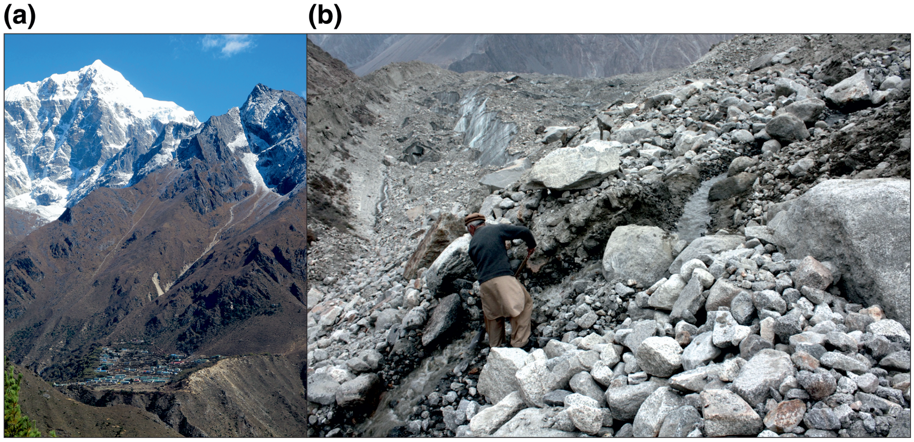


**FIGURE 2** | (a) Many Asian mountain-dwelling communities are located above the main river and rely on their water supply from springs and snow-melt. (b) In some parts of the range, villagers may tap directly into glacial meltwater (here, on the Ghulkin Glacier, Hunza, Pakistan) to maintain the local water supply.

through both space and time remains elusive. Naturally occurring oxygen ($^{18}O$) and hydrogen ($^{2}H$) isotopes can be used to determine the percentage contribution of each source water at high spatial and temporal resolutions (e.g., Ref [38]), and have been shown to be particularly effective at distinguishing glacial meltwater from precipitation and snowmelt.[39] Stable isotope analysis is relatively inexpensive (around US$ 75 per sample for laboratory processing), requires little to no field equipment other than the sampling bottles, and a single sampling event can provide suitable spatial differentiation in determining a range of water sources.[39] Where field data collection is a possibility, this approach therefore offers a quantitative analysis of how important rain, snow, and ice fractions are to river flow at a given point, and with increasing distance from the catchment headwaters. Combining such quantitative data with social and economic information about villages and villagers living in these downstream areas provides a simple metric for identifying those people who will be most impacted by changes in water supply, and therefore prioritizing where resilience-building efforts should focus (Box 1).

## BOX 1

### USE OF GEOCHEMICAL AND ISOTOPIC TRACERS IN DETERMINING STREAM FLOW SOURCES IN GLACIAL ENVIRONMENTS

Oxygen and hydrogen stable isotopes (d$^{18}$O and d$^{2}$H, respectively) have been shown to be effective in differentiating snowmelt, glacier melt, precipitation, and groundwater contributions to stream flow. Isotopes are atoms of the same element which have different numbers of neutrons, and hence differences in mass, often termed ‘heavy’ or ‘light.’ The unique isotopic composition or ‘signatures’ of different water sources (called end-members) caused by various biological, physical, and chemical reactions or processes result in changes to the ratio of heavy to light isotopes [expressed as delta (d) values, in parts per thousands (‰), relative to a standard of known composition[40]]. Knowledge of these variations can be used in conjunction with end member mixing analysis (EMMA) to identify and quantify the contribution of various water sources to stream flow.

More recently, geochemical compounds have been used to differentiate between ‘reacted’ and ‘unreacted’ source waters within glacierized catchments.[31] Reacted waters are those sources which flow at the bedrock interface, including moraines and glacial till which results in elevated solute levels in comparison to ‘unreacted’ waters which have much lower solute levels. In practice, these differences in chemical composition and concentration can be used to differentiate between groundwater and subglacial flow (‘reacted’ source waters) and snow and glacial melt (‘unreacted’ waters).[31] If the geology of a location is complex, geochemical tracers may also be used to determine the contribution of different tributary or groundwater spring sources.

  

## PEOPLE AND CULTURE

In the mountains of Asia, the ability to absorb a major environmental change, and therefore the resilience of an individual or community, is undeniably linked to poverty, since the availability of funds determines the ability of a group to invest in the most effective solutions.[41] The poorest communities are rural mountain-dwellers, marginalized both economically and politically,[42] and without access to education that would provide the skills for, and knowledge of, adaptation practices. Without surplus resources, the poor target their investment to respond to short-term shock events rather than as planned initiatives,[43] and in times of pressure, sell their assets and withdraw their young from social groups and educational provision to earn money as laborers.[41] They report only being able to partially recover from shocks due to limitations in health care, infrastructure, and livelihood opportunities, thus becoming unable to break free from the poverty trap. Some communities may migrate to escape environmental pressures, but even then it is only those people who are able to dispose sufficient financial and social capital rather than the poorest and least resilient.[44]

The motivation for a community to adopt a given adaptation measure is, to some degree, driven by people's perceptions of the hazard rather than by scientific evidence,[42] so an understanding of indigenous knowledge and belief is an important part of identifying adaptation solutions. In India and Nepal, reports suggest that community perceptions of climate and water supply are in line with scientific evidence; warmer mean annual temperatures, reduction in snow cover, an advance in the onset of the monsoon, and a reduction in water from groundwater springs.[45] There is a realization that traditional approaches to water use and conservancy may not be sufficient,[42,46] but there also remains a disconnect between the scientific and local communities, that represents a major barrier to research outputs becoming adopted in policy.[47] Going forward, there is a need for researchers to provide clearly communicated options for adaptation derived through collaboration with the stakeholders themselves, and detailing associated uncertainties and costs.[48]

The people of South Asia have been managing and conserving natural resources for many centuries and have lived through many previous environmental shocks. There therefore already exists a vast knowledge base on which new interventions can be constructed.[46] Community participation has long been heralded as the 'right way' to conduct scientific research, but perhaps more importantly the success or failure of a given strategy may depend on its adoption (or not) by the community.[14] Gaining an understanding of cultural beliefs and traditions is therefore a critical step toward gaining credibility with key stakeholders[49] and ensuring the development is sustainable. This trust may only be developed by communicating with mountain-dwellers themselves, but often a wealth of supporting information can be found in texts and pictures that portray historical scenes or accounts of tradition, or report the formation of local management and political structures (Box 2).

**BOX 2**

### SPIRITUAL, CULTURAL, AND SOCIAL ASPECTS OF WATER

In many parts of South Asia water has significant spiritual and cultural meaning as well as being critical to sustaining life. Hot water springs in Nepal (tato pani) are well known for their healing powers although local villagers believe many have lost their powers because of the masses of people, frequently trekkers, who use and 'pollute' them. In Sikkim, and other parts of the Eastern Himalaya, traditional belief is that goddesses dwell at the sources of springs and they are therefore important places of worship,[46] and an important focal point for social arrangements. Water also plays an important role in the Hindu festival of Holi, which celebrates the victory of good over evil by recreating the sprinkling of colored water over Prahlada, a follower of Hindu god Vishnu, during Mahabharata times.

Socially, water is very much the domain of the woman. Its collection is a female duty, even when the source is far from the home, and its primary domestic uses, in cooking and washing, are dominantly female tasks. These duties persist even while the woman is in heavy labor, although often not during menstruation or if they have recently given birth, since they are considered unclean at these times.[50] Although much less prevalent than in recent decades, the caste system still exists in parts of Nepal and India, and higher caste groups may reject, or have to cleanse (by dipping gold), water that has come into contact with a lower caste person. Ritual contamination can only be remedied by bathing, isolated from those who are not contaminated—so water is also seen to be vitally important as a substance to confer purity.[50]

  

## HISTORY, POLITICS, AND WATER MANAGEMENT

High-mountain Asia features an extreme topography and climate, but the risk people experience from changing environments is a social as much as a 'natural' construct. The resilience of a community to environmental change develops over time as humans interact with each other, pass on knowledge, and better understand the landscapes and hydroscapes in which they have settled. Accounts of previous disasters, knowledge of traditional practices and establishing the history of legislative and management structures are fundamental to the design of appropriate adaptation strategies because they define the existing arrangements for water access.[51]

Knowledge of the environmental history of most Asian countries is patchy, but work in other regions suggests establishing historical perspectives is critical to understanding modern-day arrangements. Sustained socioeconomic inequalities, for example, explain why some groups have come to live on marginal land that is susceptible to flooding in the Indus Basin.[52] On the other hand, traditional building techniques in seismically active Kashmir have proved more resistant to earthquakes than many 20th century concrete construction techniques. These strategies can also be embedded in regional cultures. In the Philippines, for example, frequent exposure to earthquakes and typhoons encouraged the development of informal mutual-aid societies, perhaps as early as the mid-1600s[53]. The past, then, can yield valuable lessons for risk reduction in the present and future.

While ethnographies of societies that live with hazard are well-established in the social sciences,[54] archival history remains an underutilized resource for investigating how past societies have adapted to risky environments. For states with long histories, like Nepal, official archives represent a valuable repository of institutional memory (cf., Ref [55]). State archives and historical literature typically contain official reports, unofficial manuscript material, images and maps. These data can reveal interactions between social and environmental processes.[56] Tax-collection requires a detailed official knowledge of land tenure systems and population information, which can be used to reconstruct past settlement patterns.[57] In combination with physical and geomorpological research into landscape change, such records can demonstrate the effect that environmental instability had on settlements over time. Historical records, both written and pictorial, can also contain a wealth of qualitative data about regional variations in water-use practices and the types of agriculture and irrigation practices appropriate to different conditions.[58,59] These data can be used to constrain the potential need to adapt for communities living under a variety of analogous conditions today.

Archives also reveal the changing institutional context of water-management policies at national and local scales, as historians have shown in other parts of South Asia.[59,60] In Nepal, for example, state-built irrigation canals have historically characterized valleys and the southern lowlands,[61] whereas less formal but equally functional systems operate in the mountains, although even remote upland communities can rarely fully escape engagement with state structures.[62] Understanding state priorities in managing water and pursuing development policies is therefore critical to gauging the extent to which communities might be willing, and able, to adopt new resilience practices in the face of changing conditions.

## CONCLUSION

The issue of changing water supplies in mountain regions of the world is likely to become an increasingly topical as the climate continues to warm and precipitation patterns become less predictable. Adaptation is currently hampered by clear knowledge gaps and particularly uncertainty,[63] however, specifically in how the constituent components of river flow vary

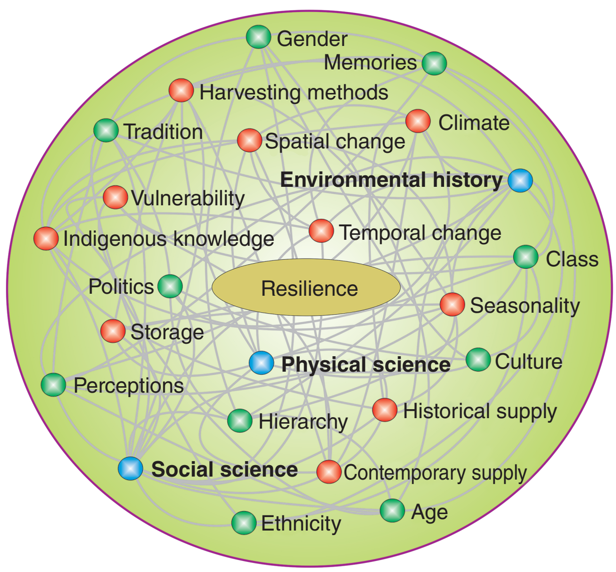


**FIGURE 3** | Social science, physical science, and environmental history (in blue) are well-positioned to tackle the issue of changing water supplies in mountain regions, sharing many common foci of study (in red) and being driven by many of the same controlling factors (in green).

  

as water travels from the mountains to the lowlands, and how this variability changes between catchments and regions. Some data exist on mountain communities and their cultures, practices and political and management structures, but some of the more remote and inaccessible areas of South Asia remain unstudied. Historical texts and pictures may provide valuable contextual information that even in isolation helps understanding of modern-day arrangements, but the location of these valuable datasets, and in some regions whether they exist at all, is often unknown.

The true value of each of these data sources can only be realized once they are properly integrated. Quantitative data on river and stream flows are only partially useful if information about who uses the water, from which sources, and for what purposes, does not exist. Social surveys with local people will only bear fruit if researchers have credibility with their subjects, something that only a deep understanding of the history and culture of a region can provide. Designed solutions will not be effective if any of these components are missing, since they need to be implemented in the most appropriate locations, adopted by the local communities, and based on local management and political structures that have developed over many centuries. Building resilience therefore requires people at its core. If future water management is to prove successful, indigenous knowledge and people should thus form the foundation for the interdisciplinary approach, identifying problems and designing solutions, rather than representing subjects for study or a useful source of data. Bidirectional capacity building then becomes an inherent product of the research, which holds much greater value for development acceleration in the long term than traditional North–South knowledge transfer. Equally, if knowledge, solutions and interventions are coproduced, they are more likely to be adopted by those people facing environmental changes and therefore increase their resilience to current and future disturbances.

The factors that determine the resilience of a person or population to environmental change are so intertwined that single disciplines are unable to tackle major development challenges in isolation (Figure 3). With an explicit requirement in recent major funding calls to demonstrate interdisciplinary working, it is likely that a unified approach will become more the rule than the exception in future studies tackling major global challenges. Success will most likely come to open-minded teams who accept that there will be some heated discussion in the process of realignment. The coincident focus on ODA countries means that some of the most marginalized communities may ultimately benefit from this approach, but as numerous studies have shown in recent years building projects from the bottom-up is likely to be more effective in terms of impact than anything that is designed by academics in isolation. Charities and nongovernmental organizations will therefore play an increasingly critical role in bridging the gap between academic and indigenous communities and policy interface.

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