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# Robust Adaptation Research in High Mountains: Integrating the Scientific, Social, and Ecological Dimensions of Glacio-Hydrological Change

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**Abstract:** Climate-related changes in glacierized watersheds are widely documented, stimulating adaptive responses among the 370 million people living in glacier-influenced watersheds as well as aquatic and riparian ecosystems. The situation denotes important interdependencies between science, society, and ecosystems, yet integrative approaches to the study of adaptation to such changes remain scarce in both the mountain- and non-mountain-focused adaptation scholarship. Using the example of glacio-hydrological change, it is argued here that this analytical limitation impedes the identification, development, and implementation of "successful" adaptations. In response, the paper introduces three guiding principles for robust adaptation research in glaciated mountain regions. Principle 1: Adaptation research should integrate detailed analyses of watershed-specific glaciological and hydro-meteorological conditions; glacio-hydrological changes are context-specific and therefore cannot be assumed to follow idealized trajectories of "peak water". Principle 2: Adaptation research should consider the complex interplay between glacio-hydrological changes and socio-economic, cultural, and political conditions; responses to environmental changes are non-deterministic and therefore not deducible from hydrological changes alone. Principle 3: Adaptation research should be attentive to interdependencies, feedbacks, and tradeoffs between human and ecological responses to glacio-hydrological change; research that does not evaluate these socio-ecological dynamics may lead to maladaptive adaptation plans. These principles call attention to the linked scientific, social, and ecological dimensions of adaptation, and offer a point of departure for future climate change adaptation research in high mountains.

**Keywords:** adaptation; climate change; mountains

## 1. Introduction

Mountains are the source of all major river systems, are important centers of bio-cultural diversity, and are conspicuous bellwethers of climate change [1,2]. Climate-related changes in mountain glaciers are already affecting water availability in many regions [3], with Intergovernmental Panel on Climate Change (IPCC) AR5 projections indicating further reductions in global glacier volumes of up to 85% by 2100 [4]. A small but growing body of research demonstrates how highland residents experience and respond to hydrological changes, and outlines how factors such as geographical isolation, dependence on resource-based livelihoods, and political underrepresentation increase susceptibility to the harmful effects of climate change [5,6]. Likewise, recent ecological research has shown how the structure and function of mountain ecosystems is being altered by ice loss as well as how such changes threaten biodiversity and mountain-sourced ecosystem services [7–9]. Insights from these diverse strands of research suggest important interdependencies between science, society, and ecosystems, yet integrative approaches to the study of adaptation remain scarce in both mountainous and non-mountainous regions. Here we argue that this lack of integration impedes the identification, development, and implementation of "successful" adaptations.

Using the example of glacio-hydrological change, this paper outlines key principles for robust mountain-focused adaptation research, providing a template for future studies in glaciated mountain regions and beyond. We are concerned primarily with adaptations in human systems and the role of integrative research in understanding and informing responses to climate change. This paper builds upon calls for more integrative climate change adaptation research in mountain environments, e.g., [6,10–16], and delineates a set of three guiding principles for robust adaptation research in glaciated mountain regions.

## 2. Scientific, Social, and Ecological Context

Mountain glaciers moderate the inter-annual variability of streamflow by storing water in wet periods and augmenting flow during dry periods, e.g., [17]. This "temporal redistribution effect" can account for a substantial proportion of seasonal flow in many regions [18]. However, climate-related changes in mountain glaciers are altering this important hydrological service, with implications for human well-being and ecosystem structure and function [2,19]. The IPCC AR5 reports with very high confidence that "almost all glaciers worldwide have continued to shrink as revealed by the time series of measured changes in glacier length, area, volume, and mass" [4]. In addition, most general circulation model (GCM) projections indicate that the average global surface temperature change is likely to increase 1.5 °C by 2100, with warming of 4 °C within the realm of possibility [4]. Reductions in glacier area drive a non-linear response in glacial meltwater generation known as peak water. Peak water suggests that enhanced energy fluxes from the atmosphere to glacier surfaces will increase meltwater generation until a discharge peak is reached; increased melt will then cause discharge to decrease as glacier area declines, ending at a discharge level less than pre-climate forcing values, e.g., [20]. Peak water will have important implications for human populations and ecosystems that depend on glacially sourced water [5,21]. Importantly, however, future precipitation characteristics will have a strong bearing on actual discharge dynamics, and will either weaken (more precipitation) or strengthen (less precipitation) the peak water profile at regional scales [17,18,22]. Likewise, regionally specific factors such as glacier regime (e.g., whether accumulation occurs in the summer or winter) can have a strong effect on the relative importance of peak water dynamics for overall water availability [18]. Thus, while high mountain hydrology is rapidly changing across the planet, the particular glacio-hydrological dynamics experienced by people and ecosystems will reflect the interaction of regionally specific climatic, glaciological, and hydrological conditions.

The 915 million people living in mountains represent a rich tapestry of cultural, ethnic, and linguistic groups [23,24]. Mountain livelihoods include cash- and resource-based endeavors, but in the developing countries where most mountain people live and in more remote ranges in developed nations, resource-based livelihoods are most common [24]. Such livelihoods can be broadly classified as agricultural, animal husbandry, mixed agriculture, and agroforestry [25]. Hunting and fishing have received less attention in the literature, but are also essential resource-based livelihoods in some areas [24]. For many mountain communities, remoteness, dependence on resource-based livelihoods, and exclusion from state services means that they are highly reliant on local ecosystem services, including freshwater from mountain glaciers [8]. In view of this dependence, it is worrying that ~370 million people live in watersheds where glaciers provide at least 10% of annual discharge and that ~119 million people live in watersheds where glacial meltwater comprises at least 50% of total discharge for at least one month per year [26–28].

Mountains are significant centers of biodiversity, with several ranges containing world-leading levels of species richness and endemism [29]. However, despite their diversity, mountain ecosystems are exceptionally sensitive to environmental change [30]. For example, numerous mountain flora and fauna are adapted to the unique thermal, sediment, and nutrient dynamics of snow- and ice-influenced rivers [31], suggesting that changes in glacio-hydrological dynamics will significantly impact aquatic ecosystems [32,33]. Impacts on downstream marine ecosystems are also expected [34]. It is concerning that the ecological roles of species reliant on cold water are largely unknown, and the possible consequences of their loss for higher trophic levels such as fish, amphibians, birds, and mammals (including humans) are highly uncertain [35]. Given strong interdependencies between highland communities and mountain environments [8], glacio-hydrological changes are likely to drive socio-ecological system level impacts.

## 3. Existing Mountain-Focused Adaptation Research

Adaptation research provides insights about how people and institutions respond to changes in the environment, including who adapts, how they adapt, and what effect their adaptations have on reducing harm or accessing new opportunities [36]. Adaptations can take various forms, such as efforts to prevent loss, spread or share loss, diversify livelihoods, or migration to reduce exposure to climatic stimuli [37]. Adaptation research also elucidates how and why the ability to devise and implement adaptations varies according to socio-economic and political factors (e.g., access to information, poverty, marginalization), and therefore plays a key role in targeting efforts to increase adaptive capacity and reduce vulnerability [38,39]. There is also an emerging focus on the unintended consequences of adaptation, including how human adaptations impact ecosystems and the supply of ecosystem services that ultimately underpin human well-being [40,41]. For more, McDowell, et al. [42] provide a mountain-focused summary of core themes in the climate change adaptation scholarship.

According to McDowell et al.'s [6] global assessment of adaptation in glaciated mountain regions, peer-reviewed publications documenting human adaptations are relatively rare in the mountain-focused literature ($n$ = 36). However, this number does not reflect studies published in non-peer-reviewed reports, peer-reviewed studies that have been published since the McDowell et al. 2014 review, or studies published in non-English language journals. Here, contributions such as UNEP's Mountain Adaptation Outlook series and High Mountains Adaptation Partnership (HiMAP) publications, recent studies such as that by Mills-Novoa et al. [15], and non-English language works such as Llosa, et al. [43], are increasing our understanding of adaptation in mountain regions. The existing literature suggests that changes to hydrological systems are the most common climate-related issue driving adaptations, that most adaptations are reactionary rather than anticipatory, that most adaptations are carried out at the community level, and that adaptations are frequently embedded within responses to concurrent non-climatic stressors [6]. Although autonomous adaptations (i.e., devised without external support) have been most widely documented to date (*ibid*.), evidence of planned adaptations (i.e., deliberate policy development) is becoming more common, particularly in program reports and policy documents, e.g., [44]. Adaptation research is clustered in sub-ranges within a select number of mountainous countries (e.g., Cordillera Blanca, Peru), is methodologically heterogeneous, and is based primarily on individual case studies [6]. Little is known about the outcomes of adaptation initiatives (*ibid*.). Moreover, research focusing on the socio-ecological interdependencies, feedbacks, and tradeoffs inherent in adaptation to climate change are critically lacking, paralleling the broader adaptation literature (*ibid*.). Although mountain-focused adaptation research remains limited compared to other glaciated regions such as the Arctic [45], there is now a sufficient level of understanding to begin synthesizing key insights and identifying guiding principles for more robust adaptation research in rapidly changing high mountain watersheds.

## 4. Principles for Robust Mountain-Focused Adaptation Research

Robust mountain-focused adaptation research is defined here as research that supports the identification, development, and implementation of "successful" adaptations. We distinguish the role of research in *identifying* successful adaptations from its role in *developing* and *implementing* adaptations. The former relates to the capacity to recognise success, including the success of autonomous adaptations, whereas the latter points relate to the role of research in the process of adaptation planning. Here, we emphasize that research only plays a supporting role in adaptation planning, and that the achievement of successful adaptations hinges on far more than just robust research, for instance, decision-making contexts and available resources. Finally, in lieu of a commonly accepted definition of successful adaptation [46], we draw on Adger, et al. [47] and Eriksen and Brown [48] to distill five criteria of successful adaptation (see Moser and Boykoff [49] for more on the challenges of defining and achieving "success"):

- Effective—Adaptation achieves its goals.
- Efficient—Benefits of adaptation outweigh the cost of implementation.
- Equitable—Distributional consequences of adaptation benefit the most vulnerable.
- Legitimate—Inclusive decision-making processes underpin adaptation.
- Sustainable—Attentive to social and ecological needs now and into the future.

When these criteria are not met, responses to glacio-hydrological change may be ineffectual or even maladaptive. We argue that there are three guiding principles that must be addressed for research to be capable of supporting the identification, development, and implementation of successful adaptations to glacio-hydrological change.

### *4.1. Principle 1—Attention to Watershed-Specific Conditions*

Adaptation research should be attentive to watershed-specific glacio-hydrological conditions; glacio-hydrological changes are context-specific and therefore cannot be assumed to follow idealized trajectories of "peak water". For example, in the Peruvian Andes, rapid warming, relatively small glaciers, and high ice turnover rates have led to short reaction times between climate forcing and mass balance/discharge changes [50]. Hydrological research suggests that glacial discharge in the Peruvian Andes has already passed peak water and that discharge values will continue to decline as glaciers shrink and disappear [50]. In the Indus River watershed, streamflow is dominated by glacier melt, contributing 41% of total annual discharge in the river, with runoff projected to increase until at least 2080 due to accelerating melt of large glaciers in the upper basin [51,52]. In this region, increasing discharge is consistent with the rising limb of the peak water curve. In the Central and Eastern Himalaya, the peak water signal is much weaker due to the relatively small proportion of glacially derived runoff during peak discharge (i.e., during the summer monsoon) [18]. Given such variability, the integration of regional scale glaciological and hydro-meteorological observations are essential in order to accurately characterize contemporary hydrological changes at the watershed scale, complementing local insights about socially relevant hydrological dynamics, as per [53]. As well, regional scale watershed research is needed to clarify the nature of hydrological changes experienced by aquatic and riparian ecosystems. Moreover, and critically, integrated regional climate, glaciological, and hydrological modeling is essential for understanding trajectories of change and informing evidence-based anticipatory adaptation planning. Here, addressing data gaps and integrating glacio-hydrological models into adaptation studies will be critical [54,55].

### *4.2. Principle 2—Attention to the Human Dimensions of Hydrological Change*

Adaptation research should consider the complex interplay between glacio-hydrological changes and socio-economic and political conditions. It is well established in the wider human dimensions of climate change literature that adaptive capacity (and therefore vulnerability) varies widely within and among communities due to the effects of power, marginalization, and difference [56,57]. In view of this, mountain-focused adaptation research must endeavor to understand the role of non-climatic circumstances in influencing how people experience and respond to glacio-hydrological change [58]. This requires fieldwork in climate-affected areas as well as the integration of local voices in problem identification, description, and resolution. Such "human dimensions" studies in the mountain-focused literature include those by Mark et al. [53], Macchi et al. [59], and McDowell et al. [58]. Adaptation studies that do not assess social conditions will be incapable of identifying vulnerability hotspots, determining whether autonomous adaptations are adequate, or providing appropriate information for adaptation planning. For example, theory suggests, e.g., [37,39,57,60], that regions experiencing significant hydrological changes may not be the areas most in need of assistance in developing adaptation initiatives. If residents in such regions have high levels of social and cultural capital, experience equitable socio-economic conditions, and are embedded within supportive social networks, their vulnerability to hydrological changes may be relatively low (e.g., some communities in the European Alps), e.g., [61]. Conversely, through evaluating the human dimensions of glacio-hydrological change, researchers can recognise regions where high vulnerability to even minor hydrological changes is likely a function of difficult non-climatic circumstances (for instance, several communities in the Eastern Himalaya), e.g., [58]. Understanding the socio-economic and political conditions that influence lived experiences of glacial-hydrological change is therefore a precondition of robust adaptation research.

### *4.3. Principle 3—Attention to Socio-Ecological Dynamics*

Adaptation research should be attentive to interdependencies, feedbacks, and tradeoffs between human and ecological responses to glacio-hydrological change. This principle is particularly relevant in the context of mountain systems, where there are strong and consequential connections between highland communities and ecosystems [7,62]. For example, highland agriculture in the Peruvian Andes—which is threatened by glacio-hydrological changes—is essential for both household sustenance and the persistence of biodiversity-sustaining heterogeneity in the landscape [8,10]. Theory suggests, e.g., [63–68], that, when research does not attend to socio-ecological dynamics, there is an increased possibility that study findings will lead to adaptation projects that generate unintended consequences. For example, while building a large dam downstream of a retreating glacier may reduce the impacts of glacio-hydrological change for mountain communities, its effect on environmental flows will adversely impact downstream ecosystems [69]. This is an example of a maladaptive response that shifts the burden of environmental change from humans to ecosystems [40,41]. Likewise, without due attention to how ecosystems are changing in response to climate forcing, it will be difficult to devise adaptations that accommodate the needs of non-human organisms. However, research that is attentive to interdependencies, feedbacks, and tradeoffs between human and ecological systems will be better able to recognize such problems and, consequently, to inform the development of adaptations that are both socially and ecologically tenable [67]. For example, such research can help to identify opportunities to leverage synergies between human well-being, ecosystem services, and biodiversity conservation. Thus, to avoid unintended consequences and maladaptation, and to capitalize on the benefits of coupled systems analysis, we strongly suggest that future mountain-focused adaptation research embrace a socio-ecological systems lens.

Combined, the principles described here contribute to understanding all criteria of successful adaptation and therefore provide a solid analytical basis for understanding and informing responses to glacio-hydrological change (Table 1).

**Table 1.** Relationship of principles to criteria of successful adaptation.

| Principle | Main Relationship to Criteria of Success | Example | Illustrative Studies |
|---|---|---|---|
| Attention to watershed-specific conditions | Effectiveness<br>Efficiency<br>Sustainability | Assessment of watershed-specific glacio-hydrological dynamics enhances understanding of current climate stimuli and trajectories of hydrological change, supporting evidence-based adaptation planning. | Naz et al. [54]<br>Immerzeel et al. [70]<br>Viviroli et al. [71] |
| Attention to the human dimensions of hydrological change | Effectiveness<br>Efficiency<br>Equitability<br>Legitimacy | Inclusion of local perspectives in adaptation research supports the identification of vulnerability hotspots as well as appreciation for the diverse concerns, preferences, and aspirations of climate-affected communities. | Mark et al. [53]<br>McDowell et al. [58]<br>Macchi et al. [59] |
| Attention to socio-ecological dynamics | Effectiveness<br>Sustainability | Evaluation of socio-ecological system dynamics helps identify critical social and ecological interdependencies as well as adaptation options that attend to both human well-being and biodiversity conservation. | Presently undeveloped in the mountain-focused adaptation literature. Cognate work includes:<br>Bury et al. [10]<br>Carey et al. [16]<br>Xu et al. [62] |

## 5. Discussion

The guiding principles outlined above provide a necessary analytical framework for studies that are intent on supporting the identification, development, and implementation of successful adaptations to glacio-hydrological change in mountain regions. The principles are intentionally broad to allow for project-specific interpretations, the inclusion of multiple conceptual and theoretical traditions, and engagement with diverse methodologies. Nonetheless, we emphasize that the integration of all three principles is essential for robust mountain-focused adaptation research (i.e., to generate information that engages with all five criteria of successful adaptation). For example, scientific research on glacio-hydrological change is of limited utility for adaptation planning if it is not understood in the context of human and ecological water needs. Likewise, although socio-economic and political conditions have a strong influence on lived experiences of climate change, hydrological changes are a material reality affecting life in mountains, suggesting that scientific research on glacio-hydrological change should continue to inform adaptation plans. Moreover, human adaptations to glacio-hydrological change could become a major driver of environmental degradation if socio-ecological dynamics and unintended consequences are not considered and evaluated in research that supports adaptation planning.

We expect that such complexities are the norm and therefore contend that integrating insights from watershed science, the human dimensions of climate change, and socio-ecological systems research is essential for understanding and supporting adaptations that improve human well-being while also protecting fragile mountain ecosystems. At present, studies integrating Principles 1 (watershed science) and 2 (human dimensions) are evident in the mountain-focused adaptation literature, e.g., [72]. However, despite a growing consensus about the importance of integrated systems approaches in mountain research [73,74], substantive engagement with Principle 3 (socio-ecological systems) is conspicuously lacking. Consequently, despite an expanding corpus of good and informative mountain-focused adaptation research, studies meeting our definition of robust adaptation research are presently lacking. This situation is indicative of the substantial challenges of transdisciplinary research but also presents an exciting opportunity for productive collaborations and meaningful innovation.

Finally, although this paper is focused on adaptation, in some instances, socio-ecological conditions may require responses that are transformational in nature (see [65,75–77] for more). Studies embracing the principles described herein will be better able to recognize situations where adaptive responses fall short and to determine for whom/what and why.

## 6. Conclusions

This paper outlined three guiding principles for studies intent on supporting the identification, development, and implementation of successful adaptations to changes in mountain glaciers. In doing so, it responded to calls for more integrative climate change adaptation research in mountain environments, identifying why insights from regional scale glaciological and hydro-meteorological observations and modeling, the human dimensions of climate change, and socio-ecological systems literature will be essential for achieving a robust understanding of adaptation to glacio-hydrological change in mountain regions. However, our emphasis on the integration of science, society, and system dynamics has broader applicability, and can be used to frame research evaluating adaptation to other climate-related changes in and beyond mountain regions. We suspect that the principles outlined in this paper will resonate with adaptation researchers working in mountain environments, and look forward to seeing them integrated into future assessments of adaptation to glacio-hydrological change in mountain regions.

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