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EDITED BY
João de Deus Vidal Jr.,
Leipzig University, Germany

REVIEWED BY
Madhab Rijal,
Mid-West University, Nepal
Ruizhe Liu,
Tianjin University, China

*CORRESPONDENCE
Jonas Geschke
jonas.geschke@unibe.ch

†These authors have contributed equally to this work

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From glacier retreat to sustainable development: how a climate-resilient water management can contribute to transformative change in mountains

Jonas Geschke[1*†], Katharina Michael[2†] and Tallulah Gundelach[3†]

[1]Institute of Plant Sciences, University of Bern, Bern, Switzerland, [2]Division Biosciences, Section Integrative Ecophysiology, Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI), Bremerhaven, Germany, [3]Secretariat of the German Advisory Council on Global Change Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen (WBGU), Berlin, Germany

Mountains are particularly affected by climate change, and its impacts on mountains and associated glaciers are increasingly well understood. The changes in downstream water flow regimes have far-reaching impacts on nature and people. Yet, climate change adaptation in mountains is lagging behind. Using the requirements of a climate-resilient water management, we explore ice reservoirs and dams as local climate change adaptation measures, addressing glacier retreat through compensating for the loss of ice storage. Based on this, we identify specific demands to promote sustainable development in mountain regions affected by glacier retreat. While glacier retreat can only be counteracted by limiting global warming, context-specific and effective adaptation to changing mountain environments should address socio-economic challenges as well as safeguarding ecosystem services equally.

KEYWORDS

climate change adaptation, water storage, ice reservoirs, dams, watershed management, global governance, indigenous and local knowledge, monitoring

1 Introduction

Approximately 10% of the global land area is covered by permanent ice (i.e., the ice sheets of Greenland and Antarctica as well as glaciers; Vaughan et al., 2013). Glaciers alone account for only 0.5% of the global land area (Vaughan et al., 2013) and cover a correspondingly small proportion of the world's mountains (Figure 1). Yet, glaciers are of immense importance for both nature and people. Mountains and associated glaciers are key water providers to subjacent lowlands, crucial for livelihoods, industry and ecosystems (Viviroli et al., 2020). Almost half of the world's mountains provide supportive or essential water resources for downstream areas (Viviroli et al., 2020). Therefore, the globally accelerating melting and loss of glaciers (hereafter

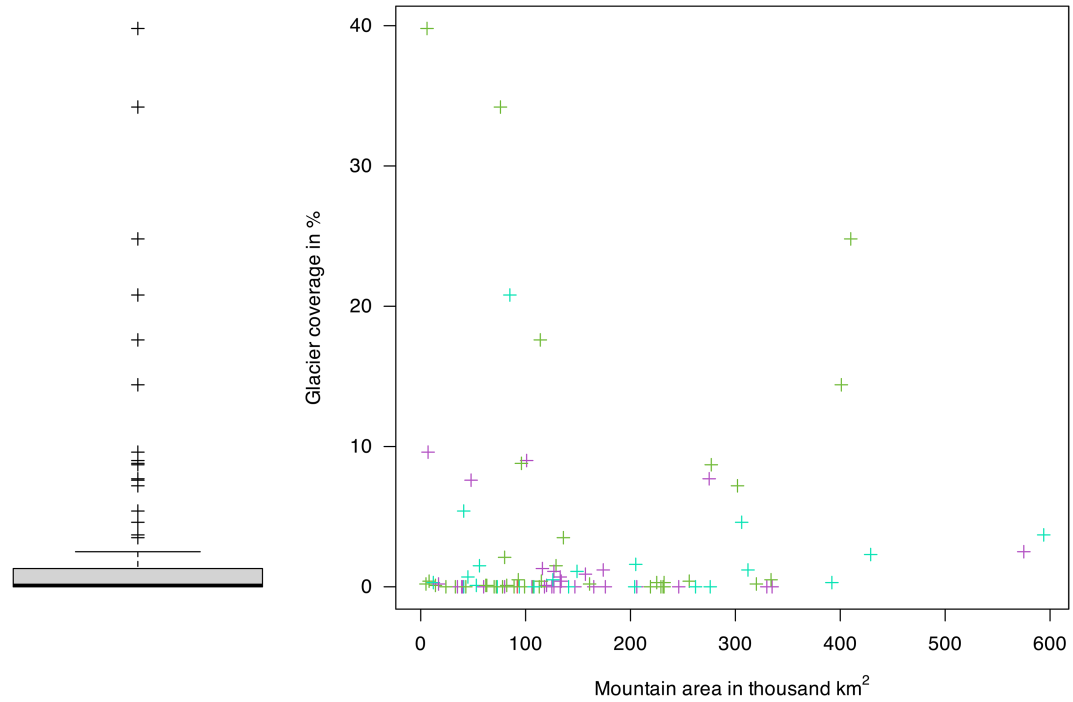

FIGURE 1
The proportion of glacier coverage of the world's mountains, given as distribution range (left) and in relation to the mountain area extent (right), split into 94 mountain regions located in the Americas (green, 40), Europe and Central Asia (purple, 30) Asia and the Pacific (turquoise, 22), and Africa (orange, 2). The six most extreme outliers, with a glacier coverage of around 14% and higher, are the Kalaallit Nunaat (Greenland), the mountains of South-Central Alaska (US), the Karakoram mountain range (Afghanistan, China, India, Pakistan), the Arctic Cordillera (Canada, Greenland), the Saint Elias Mountains (Canada, US), and the mountains of the South Atlantic Islands (Bouvet Island, the Falkland Islands, South Georgia and the South Sandwich Islands, Saint Helena). Data: Snethlage et al. (2022a; 2022b) and RGI Consortium (2023). For the calculation, the two datasets were rasterized and dissolved using R, for 291 by Snethlage et al. (2022a) preselected mountain regions, of which 197 do not have glaciers. We acknowledge the range of challenges associated with mapping glaciers (also see Windnagel et al., 2022). The values are therefore subject to caveats and intended as illustrative only. Further, and in accordance with scientific literature, glaciers melt quicker than most mapping initiatives work. Therefore, the percentage of glacier coverage likely already is smaller nowadays than illustrated here.

glacier retreat) should be of particular concern, as its effects can be felt not only in direct vicinity to the glaciers but across associated mountain regions and beyond (Hock et al., 2019; Hugonnet et al., 2021). Glacier retreat is threatening the functioning of ecosystems and socio-economic systems across scales, including the global common goal of sustainable development. Glacier retreat affects, for example, agriculture and food security (SDG 2), health (SDG 3), water quality and supply (SDG 6), the production of hydropower (SDG 7), the development of sustainable tourism (SDG 8) (Wang, 2024), and ecosystem functioning (SDG 15) (Losapio et al., 2025).

Besides glacier area changes, changing snowfall and precipitation dynamics are common cryospheric and hydrological changes (Aggarwal et al., 2022). The resulting pressure on water availability and supply will be exacerbated by weak water governance and potential socio-economic conflicts, which will further challenge water management and threaten water security (Drenkhan et al., 2023). Accordingly, the impacts of changing water resources on livelihoods and the economic sector were identified as one of four (future) key risks across sectors and regions in mountain areas (Adler et al., 2022). However, management approaches addressing the effects of climate change in mountains are still insufficient, causing an adaptation and realization gap across mountain regions (Hock et al., 2019; McDowell et al., 2021).

Glacier retreat can only be halted by anthropogenic climate change mitigation. Hence, transformative action is needed for dealing with glacier retreat and its consequences, globally and regionally. Glacier retreat is observed globally but its impacts manifest differently among regions and across scales, therefore require context-specific policy responses. However, the impacts of glacier retreat are complex and evolving. In fact, they happen simultaneously, both upstream and downstream, different in character but all interconnected, questioning the adequacy of current and planned adaptation responses to future risks in mountain regions (Adler et al., 2022).

Accordingly, glacier retreat in the Hindu Kush-Karakoram-Himalayan mountain region has recently been identified as one example of a "regional water emergency with a planetary dimension" (WBGU, 2024). Such water emergencies are characterized by a complex interplay of water-related challenges, including the consequences of climate change for the water cycle, water availability and quality, as well as increasing human pressure on water resources (WBGU, 2024). They can have far-reaching, even transregional effects, affect large numbers of people or large natural areas, and therefore be of planetary relevance (WBGU, 2024; Drewes et al., 2025). To address regional water emergencies and meet the challenges imposed by the effects of climate change and other anthropogenic global change drivers, current water management approaches should be revised and adapted. A climate-resilient water management approach can play a key role in climate change adaptation, in the protection of ecosystems and in negotiating and overcoming conflicting objectives and uses of water (WBGU, 2024). A climate-resilient water management can therefore enable transformative change and sustainable development. According to the WBGU, seven principles of action (e.g., managing blue and green water across sectors or increasing adaptability in the face of continuous change) need to be considered (also see WBGU, 2024, ch. 5.2). More practically and based on these principles of action, the WBGU proposed four requirements for the development, selection and implementation of measures for ensuring a socially balanced climate-resilient water management (also see WBGU, 2024, ch. 6.1.2).

In this policy brief, we apply those management requirements (Figure 2) to two specific water storage measures, namely ice reservoirs and dams, taken in response to glacier retreat: By assessing their efficacy on different time scales, context-specific feasibility, potential multiple benefits and unintended consequences, we explore whether these specific measures contribute to a climate-resilient water management in mountain regions. The resulting observations are used to identify demands for realizing a socially balanced climate-resilient water management and sustainable development in the mountain context, from the local to the global level.

2 Exploring human-made local water storage measures in response to glacier retreat

Climate change mitigation is essential to protect glaciers and glacier-dependent communities. Conservation measures such as glacier blanketing (Clouse, 2022), for example, are important but can only contribute to slowing down glacier retreat. Protecting glacier environments from self-warming effects caused by exposed stones and soil, for example by refocusing conservation efforts on rock glaciers (Brighenti et al., 2021; Wagner et al., 2021), are also unlikely to stop glacier retreat.

Even without further global warming, the effects of glacier retreat on water availability are already and will be increasingly felt. Therefore, climate change adaptation is inevitable. We recognize that various relevant conservation and management measures exist and contribute to adaptation efforts. However, and that is our focus here, it is particularly critical that future water management targeting water security in mountains and beyond can compensate for the increasing reduction of the water storage of glaciers. While we acknowledge that natural water storage options play a role in current water management plans (e.g., glacial lakes), we focus on two specific human-made water storage measures: Small-scale and seasonal water management using ice reservoirs, and comparably large-scale and permanent artificial structures such as dams and associated water reservoirs.

2.1 Ice reservoirs

Ice reservoirs (also called artificial glaciers) are small-scale, local water harvesting structures located below glaciers. They manage stream flow, for example through cascades, diversions, basin structures or as so-called ice stupas (i.e., conical ice towers), to freeze water during winter for its use in spring (Nüsser et al., 2018, 2019; Nepal et al., 2023). In the Himalaya, for example, the construction of ice reservoirs has historically been used to reduce

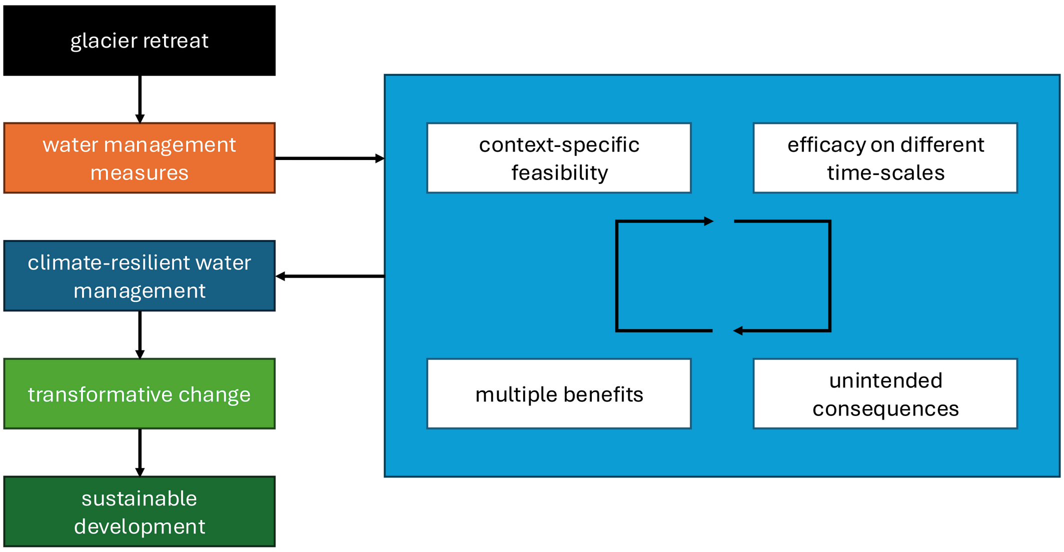

FIGURE 2
Conceptual flowchart from glacier retreat to sustainable development. While conventional conservation and management strategies may also contribute to sustainable development, assessing water management measures through a climate-resilient water management lens can facilitate transformative change towards sustainable development. This includes a consideration of the measures' efficacy on different time scales, context-specific feasibility, potential multiple benefits, and unintended consequences (WBGU, 2024).

seasonal water scarcity at the beginning of the growing season in April and May, benefitting agriculture and local households (Clouse, 2017; Nüsser et al., 2018, 2019). Structures like ice stupas are estimated to hold up to one million liters of water (Palmer, 2022). However, the amount of water stored in ice reservoirs varies and depends on local climate conditions (e.g., freeze-thaw cycles), topographic conditions (e.g., altitude, slope) and extreme events (e.g., flash floods, landslides) (Vince, 2009; Nüsser et al., 2018; Oerlemans et al., 2021). Therefore, the overall feasibility of ice reservoirs depends on these factors. For example, ice stupas are more feasible in regions with cold, arid climates with long winters and high elevations, where they can grow up to 30 meters tall, than in other alpine climates (e.g., the European Alps), where they only grow up to 10–12 meters tall (Palmer, 2022). In addition, ice reservoirs are only seasonal water storage options; their feasibility is strongly dependent on winter freezing to allow for water release in spring (Nüsser et al., 2019). Thus, climate change increases the uncertainty on future viable locations. Moreover, ice reservoir structures can be costly and require ongoing maintenance, adding barriers to their realization and long-term operation in regions with harsh working conditions and a lack of financial means (Norphel, 2009; Nüsser et al., 2019; Palmer, 2022). Often found in mountains, small-scale (farming) communities generally face financial and technical challenges in the implementation of climate change adaptation measures (Rasul et al., 2020; Aggarwal et al., 2022). They may especially run into economic burdens when applying high-cost adaptation measures. At the same time, the use of ice reservoirs can lead to multiple benefits: The need for maintenance can create jobs, increase the understanding of water management and foster sustainable resource use. Economic benefits can include higher yields, potential double harvests and additional income for local communities, for example from growing trees for timber or cash crops like potatoes (Norphel, 2009; Nüsser et al., 2018, 2019). Social benefits can include less water-related disputes at the community level and reduced migration to urban areas (Norphel, 2009). Moreover, ice reservoirs are important for recharging groundwater aquifers, increasing the discharge from natural springs, and for soil moisture and vegetation cover (Norphel, 2009). Unintended consequences of ice reservoirs primarily entail reduced water availability downstream, potentially leading to upstream-downstream conflicts (Palmer, 2022).

2.2 Dams and associated reservoirs

At larger scales, artificial structures such as dams and associated reservoirs are widely used for water storage. They buffer low water flows and can alleviate water scarcity (Birkmann et al., 2022). Farinotti et al. (2016) estimated that reservoirs constructed at deglacierized sites in the European Alps, for example for (temporary) water storage, seasonal redistribution of water and hydropower production, could compensate for up to 65% of the runoff currently provided by glaciers in summer by 2100. The potentially installable water storage capacity in the European Alps exceeds demand (Farinotti et al., 2016). The theoretical global storage volume of such reservoirs corresponds to about 48% of the runoff from all glaciers (Farinotti et al., 2019). This however remains theoretical, as the feasibility of constructing dams is highly context- and location-specific. For example, it depends on technical capacities and available economic resources as well as future global warming and resulting environmental changes (Farinotti et al., 2016, 2019; Bednar-Friedl et al., 2022). Farinotti et al. (2016, 2019) argue that the construction of dams may be more feasible at recently deglacierized sites, as the environmental costs may be comparatively lower there – but they also state that a wide-spread installation of artificial water storage structures is neither feasible nor desirable. In addition, reservoir sedimentation may reduce the efficacy and feasibility of using dams and associated reservoirs for water storage as it can lead to the loss of water storage capacity. For example, a study by Perera et al. (2022) estimated 26% of storage capacity loss by 2050 for 47,403 large dams assessed across 150 countries. Multiple benefits can arise when dams serve additional purposes beyond water storage, for example natural hazard management or as early warning systems (Adler et al., 2022). Moreover, hydropower production is a key additional benefit of dams, especially in regions with energy security concerns. Building dams at the roughly 185,000 currently deglacierized sites theoretically could create a hydropower potential of up to 35% of hydropower produced globally (Farinotti et al., 2019). However, large-scale artificial water storage structures like dams can have unintended environmental and social consequences. For example, dams lead to river fragmentation and interruption of streamflow, resulting in a loss of habitat connectivity (Grill et al., 2019; Thieme et al., 2024). Dams also alter sediment and, consequently, nutrient transport downstream, which can have adverse effects on associated ecosystems (e.g., Kondolf et al., 2014; He et al., 2024). Moreover, while dams and associated reservoirs may alleviate water stress for communities upstream, they can increase water shortages and vulnerability to droughts and floods downstream. This can further increase the potential for socio-economic conflicts between mountain and adjacent lowland regions (Kellner and Brunner, 2021; Caretta et al., 2022). Considering climate mitigation, recent studies found that hydropower reservoirs may be associated with increased greenhouse gas emissions (Song et al., 2018; Maavara et al., 2020).

2.3 Observations

This exploration provides insights into putative benefits as well as challenges related to human-made water storage reservoirs across scales. Of course, such analyses can be more extensive, but a scientific review is out of scope of this Policy Brief. Despite the limited focus on only two specific adaptation measures for water storage in response to glacier retreat, the associated socio-economic complexity, spatial diversity as well as the multiple underlying systemic interconnections lead to the following observations: i. indigenous and local knowledge, local adaptation measures, and recent scientific evidence are often insufficiently connected to one another. Therefore, measures applied at the local scale may not be resilient enough to future (climatic, environmental and socio-economic) changes; ii. measures are often local and incremental,

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and lack government and systemic support; iii. upscaling and mainstreaming of adaptation measures are often challenging; iv. potential upstream-downstream conflicts in water availability and use resulting from adaptation measures (e.g., those that divert streamflow) are often insufficiently considered and addressed across multiple government and/or other stakeholder levels; and v. unintended (environmental) consequences are often insufficiently considered ahead of time. Based on these and complementary observations in the existing literature (e.g., McDowell et al., 2019, 2021; Adler et al., 2022; Muccione et al., 2024), we formulate (policy) recommendations.

3 (Policy) recommendations

Current scientific evidence outlines that worldwide glacier retreat makes new approaches to water management in mountains necessary, requiring a challenging balancing act between concurrent local and global action (Figure 3). While adaptation measures towards more sustainable glacier meltwater storage (and its subsequent use) need to be designed according to their local context-specificity, they can only become effective when implemented across space and time (i.e., considering landscape-scale effects as well as short- and long-term adaptation needs). In the context of mountains, we therefore highlight the following recommendations, targeted at governance authorities as well as conservation management and practice at the local (e.g. water authorities), regional, supra-national (e.g., European Union) and global (e.g., United Nations) level:

3.1 Take a holistic approach to water management in mountains

Downstream water availability is determined by the wider watershed hydrology, comprising both cryospheric and non-cryospheric surface and subsurface water stores (Drenkhan et al., 2023). Therefore, water management in mountains should include glaciers and their direct surroundings, the mountain ecosystem where the glacier is located, and all downstream and lowland areas and systems (i.e., both human and nature) affected by glacier meltwater regime changes. This requires a more holistic approach, including considering the wider watershed area and social-environmental and socio-economic contexts:

- Water management in mountains should include a context-specific, cooperative glacier watershed management. Decision-making processes should be open-ended, meaning that all relevant interest groups and stakeholders from a glacier watershed area should be invited to participate. The needs of different upstream and downstream water users as well as natural systems should be assessed and integrated into these processes to avoid local conflicts. Only a common understanding of the specific challenges and needs that exist in a watershed area can lead to fair and inclusive conservation and management decisions.
- Besides glacier meltwater, a specific focus should be placed on managing the hidden: groundwater. Groundwater stores are invisible, fed by glaciers, and a key water source for nature and agriculture (Somers and McKenzie, 2020; Drenkhan et al., 2023). Groundwater recharge will be important to meet global food demands (Misra, 2014) but the global water cycle is under pressure from global warming and human activities (Kuang et al., 2024). A climate-resilient water management in mountains should therefore include considerations of groundwater management (also see Somers et al., 2019; Mukherjee et al., 2024), especially with respect to downstream water provision.
- Natural ecosystems significantly contribute to climate change adaptation. An effective area-based conservation

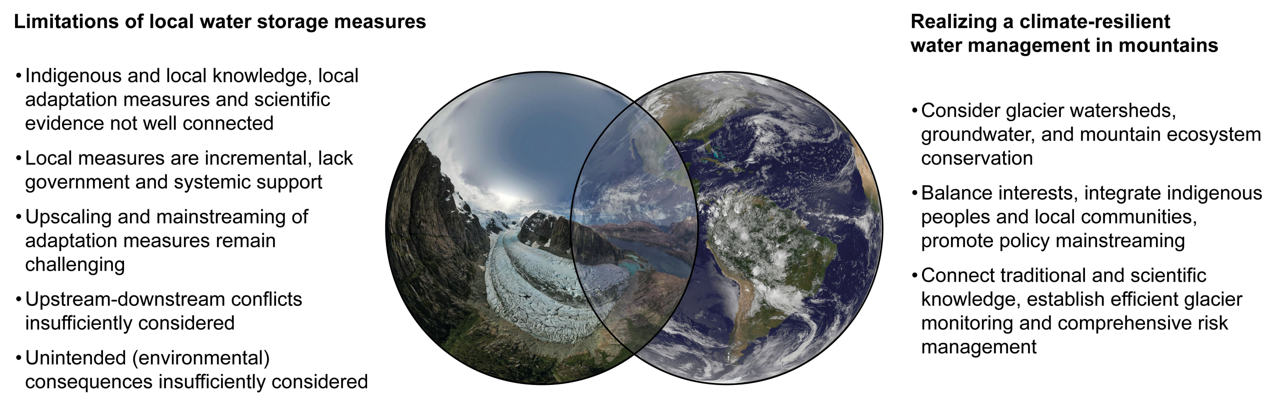

FIGURE 3
A climate-resilient water management with regard to glacier retreat faces a challenging balancing act between local and global action. At the local level, glacier retreat is addressed by different adaptation measures. For local water storage measures such as ice reservoirs and dams, we observe certain limitations to their implementation (left). On this basis, we identified specific demands for an effective sustainable development in mountain regions affected by glacier retreat (right). Also see the main text for details. Images: the Bernal Glacier, Patagonian Andes, instagram.com/eyeeseeicee, and planet Earth, weltkugel-globus.de/die-erde (both last accessed on 26.05.2025).

of mountain ecosystems, through both protected areas and other effective area-based conservation measures (also see Maxwell et al., 2020), therefore is key for sustainable development. Considering subnational and transboundary reporting on the conservation of mountains can play an important role in adaptation management (Ly et al., 2023). In particular, also to support downstream water security, groundwatershed areas should be given a special priority (Huggins et al., 2023).

3.2 Strengthen mountain visibility in policy and enhance (international) cooperation

As mountains and the impacts of glacier retreat cross borders, transboundary attention and action is needed. Fostering (international) cooperation will be key to a climate-resilient water management in mountains. Otherwise, conflicts between upstream- and downstream regions are likely and could destabilize socio-economic systems (Carey et al., 2017). Mountains and their biodiversity need context-specific conservation and management, indigenous peoples and local communities, and recognition in strategic policy frameworks:

- Balancing interests between water demands and uses is essential, for example between agriculture, rapid urbanization and water for human consumption, or hydropower production, whilst also honoring the water demands of nature (Orlove, 2009). Otherwise, unintended consequences may arise. For example, the creation of alternative water uses may lead to environmental trade-offs (Elsaid et al., 2020; Pratap et al., 2021). Similarly, social conflicts, for example between small farmers and large agribusinesses, can lead to socio-economic instabilities (Carey et al., 2017). Therefore, improved knowledge of the water use across sectors and the implementation of a socially balanced and climate-resilient water management are necessary.
- Integrating indigenous peoples and local communities and their knowledge into conservation and management can considerably advance sustainable development in mountains (Ingty, 2017). This particularly includes the aspects of climate-resilience, nature-based solutions, biodiversity and various knowledge systems. Given their crucial role in nature conservation, the formal participation of indigenous peoples and local communities in global policy processes should be further promoted (e.g., Nepal et al., 2023). The establishment of the Subsidiary Body on Article 8(j) under the Convention on Biological Diversity (CBD, 2024) sets an important benchmark.
- Political recognition of the critical importance of mountains and glaciers is limited. While the Sustainable Development Goals (SDGs) acknowledge the role of mountains for sustainable development (UNEP et al., 2020), the overall attention to mountains in global policy frameworks could be higher (Wehrli, 2014; Makino et al., 2019). An appropriate recognition could enable political and institutional spillover effects and increase the realization potential of climate change adaptation measures (Aggarwal et al., 2022). Policy mainstreaming, as for example provided via the Alpine Climate Board, can enhance adaptation in mountains (Adler et al., 2022). Moreover, the processes of the Rio Conventions should address mountains and glaciers more explicitly, including but not limited to designated agenda items at their Conferences of the Parties.

3.3 Focus more on prevention instead of reaction

The effectiveness of climate change adaptation measures relies on their adaptivity to new and evolving risks. Therefore, to counteract unintended consequences, a climate-resilient water management addressing glacier retreat should proactively take upcoming system changes into account. Climate change adaptation measures concerted across scales are likely to support valuable co-benefits. Valuing different knowledge systems as well as advancing and/or promoting monitoring and risk management practices that consider both the present and the future are key:

- Preserving the knowledge and cultural heritage of indigenous peoples and local communities is of utmost importance for climate change adaptation in mountains (Ingty, 2017). To this end, and to ensure future resilience to climate change, traditional knowledge and local adaptation measures should be connected with current scientific information (also see McDowell et al., 2021), and vice versa. Promoting knowledge co-production in mountain contexts could increase adaptation effectiveness, lower risks and close data gaps (Adler et al., 2022; Aggarwal et al., 2022; Drenkhan et al., 2023).
- A comprehensive understanding of the links between cryospheric changes, climate change and the interactions between human and natural systems downstream is crucial for ensuring water security in mountains (Drenkhan et al., 2023). To generate knowledge about the current glacier extent as well as to conduct robust water regime forecasting, glacier watershed management needs an efficient and multi-scale glacier monitoring system (Bocchiola et al., 2011; Windnagel et al., 2022). Existing initiatives, such as the World Glacier Monitoring Service (WGMS; https://wgms.ch), the Global Land Ice Measurements from Space initiative (GLIMS; https://www.glims.org) or the Randolph Glacier Inventory (RGI; http://www.glims.org/rgi_user_guide/welcome.html) are a good basis, but have potential to improve, for example, their data actuality and use of a (more) harmonized methodology (The GlaMBIE Team, 2025). While coordination and monitoring networks can

contribute to overcoming existing data and knowledge deficiencies and increase the efficiency of implementation (Adler et al., 2022), many countries do not have a well-developed glacier monitoring network (Drenkhan et al., 2023). For this, a climate-resilient water management in mountains requires additional research cooperation, technological innovation and adequate funding to organize a robust global glacier monitoring system.

- A comprehensive risk management that considers context-specificities and climate change impacts across space and time is key to future glacier watershed management. In response to the increasing anthropogenic impact on hazard occurrences, emerging future risks and the complex systemic nature of disaster risks, mountain regions should develop a comprehensive, cooperative and transboundary disaster risk management and foster an integrated and transdisciplinary understanding of disaster risk(s), built on knowledge co-production and community participation in mountain regions (e.g., Alcantara-Ayala et al., 2022a, 2022b).

4 Conclusions

Mountains and their biodiversity are intricately linked to sustainable development (Payne et al., 2020). Yet, a climate change adaptation gap remains, as the biophysical and socio-economic challenges across mountain regions are diverse and interacting with adjacent lowlands, thus precluding "one-size-fits-all responses" (Adler et al., 2022). Considering future water management in mountains, there is no way around glaciers. Glaciers may be small in area but are significant in relevance. In times of global warming, glaciers are among the first ecosystem features to be lost. Glacier retreat may be regional, but its impacts are global. To meet current and future needs of nature and people, water management in mountains needs to be refined.

To realize a climate-resilient water management, planned measures can be assessed for their climate resilience using the four requirements proposed by the WBGU (2024): their efficacy on different time scales, context-specific feasibility, potential multiple benefits and unintended consequences. Based on the exploration of two water storage examples, ice reservoirs and dams, we made observations on deficiencies in climate-resilient water management in mountains and developed recommendations to address these. Long-term climate change adaptation efficacy will depend on a holistic approach to water management, strengthening mountain visibility in policy and enhancing international cooperation, and focusing more on prevention than on reaction. This entails ensuring a fair distribution of available (water) resources and governance structures (informal or formal) with a mandate to coordinate their use under extreme climate variability; if necessary, also through accountability mechanisms. Complementary, a secured funding, investments in adaptation measures and appropriate (technological) training opportunities are important before glacier retreat outpaces adaptation efforts.

While there seems to be growing interest in the effects of and adaptation to glacier retreat, research still remains insufficient with regard to the character and magnitude of the consequences of present and future changes in water availability for nature and humans. The international community therefore must stand together to cope with the water emergency of glacier retreat. Announcing 2025 as the International Year of Glaciers' Preservation and March 21st as the periodic World Day for Glaciers is symbolic and may have a motivating effect, but the implementation of effective action remains to be further promoted.

Author contributions

JG: Conceptualization, Visualization, Writing – original draft, Writing – review & editing. KM: Conceptualization, Writing – original draft, Writing – review & editing. TG: Conceptualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declare that no Generative AI was used in the creation of this manuscript.

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