Technical Report

Mountain glaciers melting

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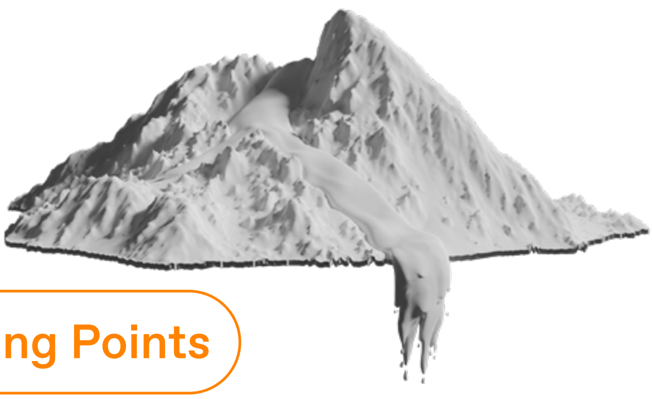

Risk Tipping Points

Interconnected Disaster Risks

2023

Technical Report

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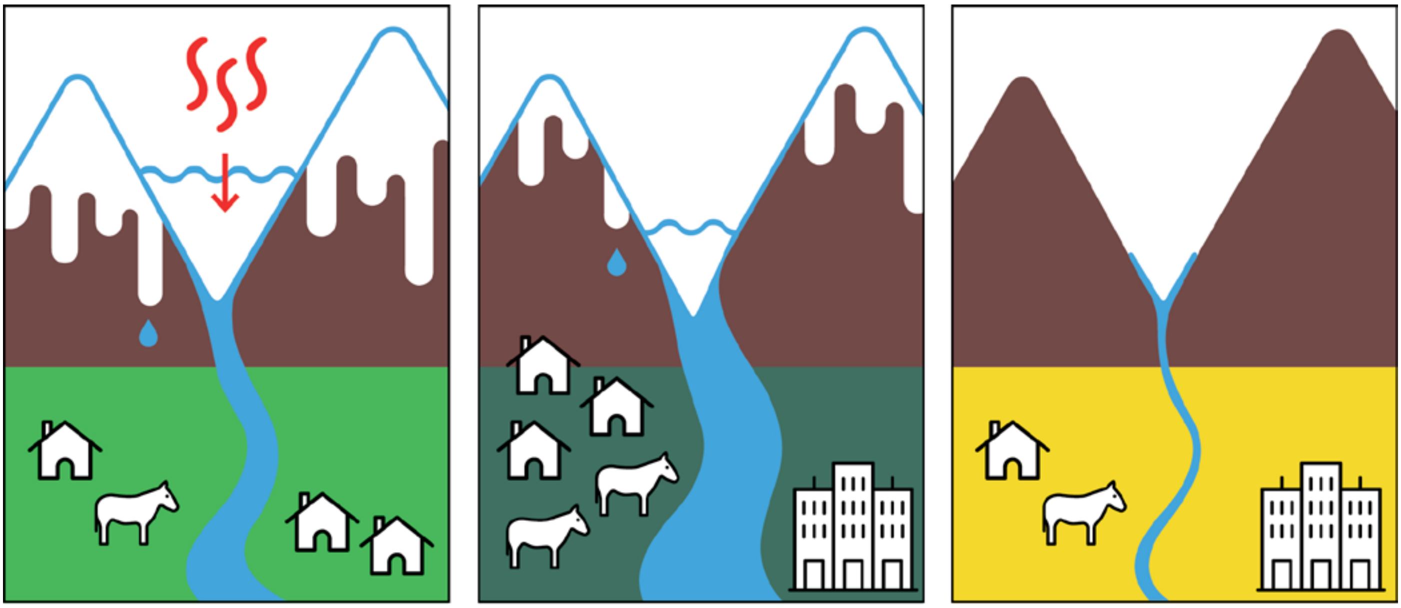
Abbreviations

GLOF	Glacial lake outburst flood
HMA	High Mountain Asia
HKKH	Hindu Kush-Karakoram-Himalayan mountain system
UNEP	United Nations Environment Programme
US EPA	United States Environmental Protection Agency
WGMS	World Glacier Monitoring Service

Graphical abstract



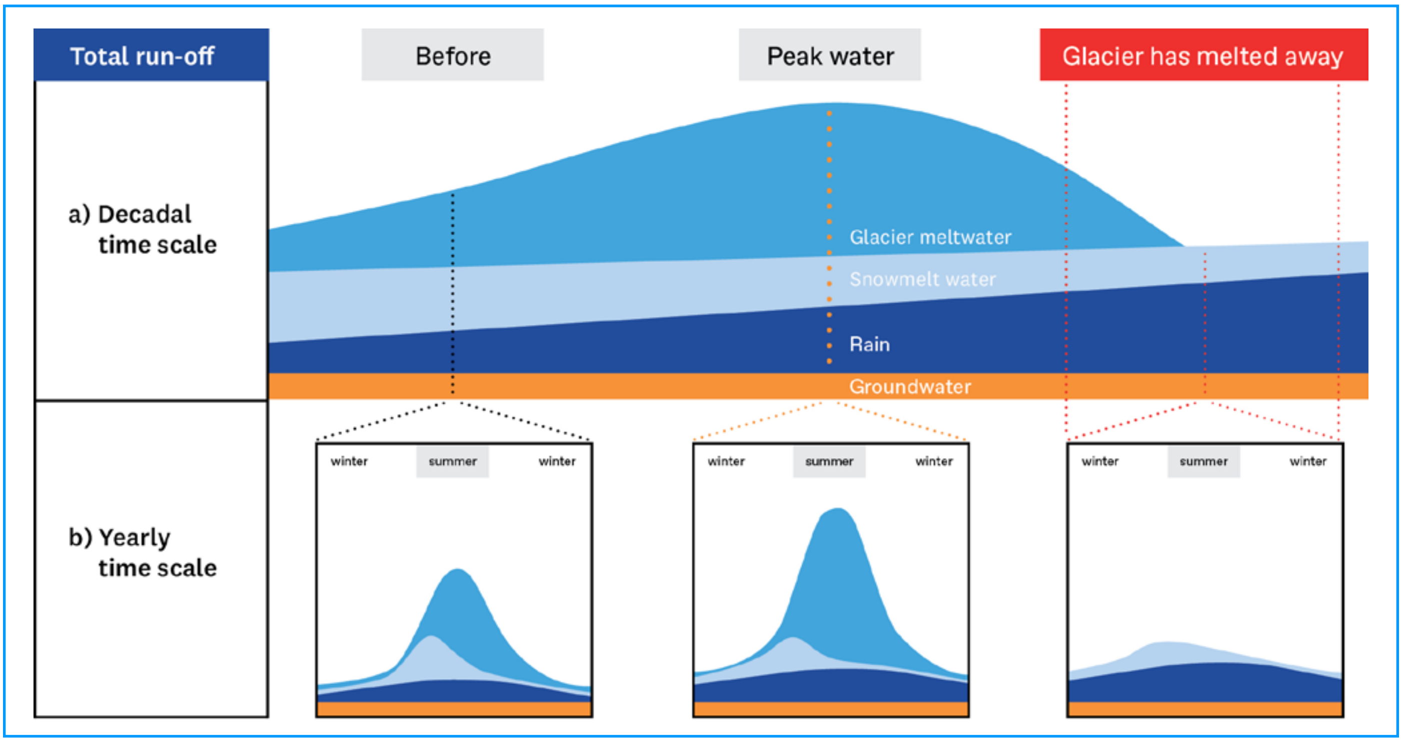
1. Increasing risk = Increasing global temperatures melt glaciers faster than they can grow back

2. Tipping point = Glacier meltwater maximum known as "peak water"

3. Tipped = Glacier meltwater will steadily decrease, reducing freshwater availability

1. Introduction

Mountain regions are known for their aesthetic landscapes, biodiverse habitats, and cultural significance. In particular, many mountains are known as the "water towers of the world" for their capacity to store fresh water in glaciers. In fact, glacier and snow meltwater supply water for drinking, irrigation, hydropower and ecosystems to entire regions. River basins with glaciers on their headwaters benefit from water stored as ice, representing a regulating water source for downstream river flow, particularly during the summer and in times of drought. However, human-induced global warming has caused glaciers to retreat (Marzeion and others, 2014), meaning the ice mass that has formed over many years is melting faster than what snowfall can replace. Currently, glaciers are melting at double the speed they have in the past two decades (Hugonnet and others, 2021). Between 2000–2019, glaciers lost 267 gigatons of ice per year (Hugonnet and others, 2021), and we are projected to lose around 50 per cent of glaciers (excluding Greenland and Antarctica) by 2100, even if global warming can be limited to 1.5°C (Rounce and others, 2023).



Schematic overview of total run-off changes from a river basin with large glacier cover as the glacier shrinks, and the relative components of run-off from different water sources: glacier (sky blue), snow excluding the glacier (light blue), rain (dark blue) and groundwater (orange). The exact partitioning between the different sources of water will vary between river basins. Because this is a simplified figure, permafrost is not included. Panel a) shows the changes in run-off over decades. Panel b) shows the changes in run-off over a year. Adapted from Hock and others (2019).

2. Risk tipping point

Glaciers form over centuries as snow accumulates and gets compressed into a thick, dense mass. Their size changes with the seasons, usually melting in spring and summer and growing in winter. However, increasing global temperatures melt glaciers faster than they can grow back, causing them to shrink or retreat. Over time as glaciers retreat, much of the stored mass is released downstream as meltwater, feeding into rivers and watersheds. Over decades, the meltwater volume initially increases until a maximum is reached, known as "peak water." After this tipping point, glacier meltwater run-off steadily declines and will eventually stop altogether as the glacier disappears. These changing water availability patterns could have extreme consequences for humans, other species and ecosystems. Whether it is due to reduced freshwater availability or from sudden floods, around 1.9 billion people worldwide may be negatively affected by glacier melt (Immerzeel and others, 2020).

Importantly, as of 2017, around 45 per cent of all mountain glacier basins worldwide have already passed the tipping point of peak water (Huss and Hock, 2018). The tropical Andes is a particularly affected region, as more than 80 per cent of glaciers have passed peak water as of 2019 (McDowell and others, 2022). In other regions, such as Central Europe and western Canada, peak water has either already passed or is expected to occur within the next 10 years (Huss and Hock, 2018). In basins fed by the glaciers of High Mountain Asia (HMA), run-off is expected to rise in the next few decades as peak water is not expected until after the middle of the century (Huss and Hock, 2018).

3. How did we get here?

3.1 Drivers

3.1.1 Atmospheric/ocean warming

Glacier mass balance, or the difference between accumulation and loss of mass, fluctuates in response to atmospheric conditions like radiation, humidity, cloudiness, temperature and precipitation (Thompson and others, 2021); the latter two being the most influential factors (Solomina and others, 2016). Increasing atmospheric and ocean warming is likely to change precipitation patterns, bring less snowfall to glaciers (US EPA, 2016) and limit their winter growth potential.

With increasing global temperatures, glacier ice and snow melt faster (Solomina and others, 2016). In the Andes, annual warming has increased approximately 0.10°C per decade since 1939, and this trend seems likely to be enhanced by elevation (Vuille and others, 2008). In the Hindu Kush Himalaya (HKH) region, the mean minimum surface air temperature during 1901–2014 increased by approximately 0.20°C per decade, with the Tibetan Plateau and southern Pakistan experiencing the largest regional comparative change (Ren and others, 2017).

3.1.2 Lack of information

International cooperation for the systematic observation of glaciers started in 1894. These efforts were united later in 1986 under the World Glacier Monitoring Service (WGMS) to monitor glacier changes (WGMS, 2022). The WGMS collects data from different sources, including in-situ and satellite-based observations, which form the basis for hydrological modelling. However, glacial and hydrological processes are complex, and uncertainties remain on how meltwater moves through the hydrological system and contributes to water availability downstream (Buytaert and others, 2017).

Most glacio-hydrological models have been conducted in the HMA, followed by Europe and North America, whereas fewer studies have been conducted in South America, New Zealand and the Caucasus (van Tiel and others, 2020). The lack of reliable in-situ observation measures continues to make glacio-hydrological studies difficult (Lins, 2008; Gao and others, 2018; van Tiel and others, 2020). In the HMA region, high quality field measurements are difficult to conduct due to harsh environmental conditions (Gao and others, 2018). The glacierized mountains in the tropical Andes are also characterized as data-scarce regions (Muñoz and others, 2021). Other issues, such as social tensions, complex hydrological processes and low institutional capacity, challenge the development of more reliable glacio-hydrological studies for the tropical Andes (Muñoz and others, 2021).

On the other hand, glacio-hydrological modelling is not enough to understand the full extent of glacier-related risks. The risk of water scarcity, of glacial lake outburst floods (GLOFs) and of all other glacier-related risks are complex and multi-causal processes. To understand the full extent of the risks we face, beyond physical processes, the integration of social science and other transdisciplinary fields in research is required (Carey and others, 2017; McDowell and others, 2022). Overall, insufficient monitoring or inadequate models to estimate the extent of the risk may lead to inadequate or insufficient strategies to face the consequences of mountain glaciers melting.

3.1.3 Insufficient future planning

Climate-related changes, in particular hydrological processes, are already manifesting in ice-covered mountain systems and are prompting adaptation action (McDowell and others, 2019; McDowell and others, 2022). In nations with ice-covered mountain ranges, some adaptation actions have already occurred. However, the majority of responses address already-experienced climatic changes and often do not include a structured adaptation plan (McDowell and others, 2019). The short-term, autonomous and conservative nature of many adaptation actions suggests the need for increased engagement with scientific information to ensure alignment with climate change trajectories in mountain systems; further attention to the causes and consequences of differential vulnerability and promotion of transformative adaptation is also required (McDowell and others, 2019).

Insufficient future planning indicates a fundamental issue of risk perception, or people's judgement about the characteristics and severity of a risk. In the ice-covered peaks of the Cordillera Blanca in the north of Peru, the risk of water scarcity is recognized by some technical experts but not by others, and the matter is generally not

Mount Illimani, the guardian of La Paz, Bolivia. Its peaks are barely illuminated by the last rays of daylight, while the city is already lit up © Rodrigo Gonzalez / Unsplash prioritized by national institutions (Motschmann and others, 2020). Water scarcity, being a problem of water availability, is driven by water use and demand, but most glacio-hydrological models do not consider current and future water withdrawals (Motschmann and others, 2020). Additionally, water use and demand is regulated by government and management decisions, a sensitive process which tends to be contested. Despite the challenges, the principle of equity should guide present and forward-looking decisions, so that access to water is ensured for people and other species from the top of mountains all the way to the coast.

3.2 Root causes

3.2.1 Human-induced greenhouse gas emissions

Human-induced greenhouse gas emissions trap solar radiation and warm the atmosphere, increasing global temperature and driving mountain glaciers melting. The prevalent and ongoing global ice loss that has been documented in the past 100–150 years is a direct result of anthropogenic greenhouse gas emissions (Solomina and others, 2016). Glaciers have been retreating since the second half of the nineteenth century in response to human-induced global warming (Marzeion and others, 2014) but are currently melting at double the speed they have for the past two decades (Hugonnet and others, 2021). By the end of the century, around 50 per cent of glaciers (excluding Greenland and Antarctica) will be lost even when limiting global warming to 1.5°C (Rounce and others, 2023).

Limiting global mean temperature requires immediate, rapid and large-scale reductions in greenhouse gas emissions. However, current pledges are not enough to reach the 1.5°C target, and the Earth's temperature could rise 2.7°C by the end of the century (UNEP, 2021). This temperature increase could result in the near-complete deglaciation of entire regions including Central Europe, western Canada, the United States, and New Zealand (Rounce and others, 2023).

3.2.2 Insufficient risk management

A lack of awareness or preparation relating to risk management and response hamper societies' abilities to avoid or reduce the impacts of hazards in glacial mountain systems. For instance, melting glaciers can lead to different hazards such as water insecurity, sea level rise (Rounce and others, 2023), mountain slope instability, which contributes to both the sedimentation of rivers and near-shore marine ecosystems (Milner and others, 2017), and to the risk of GLOFs. GLOFs are sudden-onset events, caused by the failure of a natural dam containing a glacial lake that wreaks widespread destruction as water, rocks and mud flow downstream through agricultural land and cities. Compared to GLOFs, reduced water availability is often considered less urgent for some people. For example, national authorities in Peru are more concerned about GLOFs than about reduced water availability, while local populations are comparatively more concerned about water scarcity than authorities (Motschmann and others, 2020). It is often the case that slow-onset hazards are ignored as their effects are less visible (van der Geest and van den Berg, 2021), but people directly dealing with the slow but impending risk perceive it differently.

3.3 Influences

Reaching a risk tipping point with mountain glaciers melting can also have cascading effects in other systems and may influence them to reach risk tipping points themselves. Mountain glaciers provide reliable meltwater that supports ecosystems and the hydrological cycle. As mountain glaciers melt and we approach a risk tipping point, we will lose critical water availability that allows ecological and human systems to function.

For instance, mountain glaciers melting will change aquatic and terrestrial ecosystems in ways that threaten various species, especially those that have adapted to cold glacial conditions, and further increase the risk of **Accelerating extinctions**. Invertebrates are particularly at risk and are likely to become extinct in places where glaciers disappear completely (Wilkes and others, 2023). For example, the stonefly *Rhabdiopteryx* and three species of non-biting midges in the Alps face the risk of extinction as glaciers retreat. These stoneflies and midges in the Alps are important sources of food for fish, birds and mammals (Fell and others, 2017; Wilkes and others, 2023).

Reduced glacier meltwater also increases the risk of **Groundwater depletion** in two ways. On one hand, glacier melt is often a reliable source of water for aquifer recharge (He and others, 2023). In a proglacial aquifer in Iceland, it was found that more than half of its recharge comes from glacier meltwater (Ó Dochartaigh and others, 2019). In the Tibetan Plateau river basin of the Lhasa glacier, meltwater contributes to 10 per cent of the total groundwater recharge of the aquifer and up to 34.8 per cent for the aquifer section under the Yangbajing sub-basin (Chen and others, 2021). On the other hand, some basins experience reduced streamflow as a result of reduced glacier melt, which is likely to drive farmers to consume more groundwater for irrigation (Biemans and others, 2019).

Other risk tipping point cases discussed in our research can raise the risk of mountain glaciers melting. See the **Space debris** and **Unbearable heat** technical reports for more details.

A mountain glacier in the Himalayan region.
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4. Where are we headed? Current and future impacts

4.1 Ecosystem damage and biodiversity loss

As was mentioned in section 3.3, mountain glaciers melting leads to shrinking habitats for many species adapted to cold glacial conditions. Glaciers are naturally isolated habitats since they are separated by mountain ranges and long distances between each other. Even for species with the ability to migrate, moving from one glacial environment to another would be nearly impossible. As glaciers shrink, mountain species may find themselves on the "escalator of extinction," where they must either continually move up the mountain to stay in their preferred glacial conditions or risk being outcompeted by other species moving into their range (Losapio and others, 2021). Currently, less than half of glacial areas worldwide are located within protected areas, adding to the risk of biodiversity loss in glacial zones and emerging ecosystems once glaciers retreat (Bosson and others, 2023). Establishing more protected areas on ice-covered land and its surroundings promotes the ecological evolution of glaciers and the reduction of human-induced perturbations on deglaciated areas, though not eliminating them completely.

4.2 Water insecurity

Glacier meltwater contributes to urban and rural water supply and is critically important during dry and drought periods. In the city conglomerate of La Paz and El Alto in Bolivia, glacier meltwater contributes to 14.8 per cent of water supply during a normal year and as much as 85.7 per cent in drought years (Buytaert and others, 2017; Hock and others, 2019). People in La Paz and El Alto have already experienced water scarcity during the 2016 drought (one of the worst in 25 years), when some people had access to water for only three hours every three days; others were unable to access water at all (Cullen, 2018). Glacial meltwater also contributes to domestic water supply for 725,000 people in rural areas in the Andean mountains of Ecuador, Peru and Bolivia (Buytaert and others, 2017). Water stress is, however, not solely a response to environmental or climatic conditions but is also driven by societal factors, such as politics and power relations (Carey and others, 2017; Adler and others, 2019).

4.3 Food insecurity

Glacier meltwater is crucial for irrigated agriculture, especially during dry periods. As we approach a risk tipping point of mountain glaciers melting, this meltwater contribution will eventually diminish, leading to decreased food production with likely consequences on people's income and food intake. In the Indus and Ganges basins, 129 million farmers substantially depend on snow and glacier melt, using it to provide food crops to sustain a balanced diet for 38 million people (Biemans and others, 2019). The effects of glacier and snow melt reductions are often amplified by climate changes and social aspects related to water and crop management, and may directly or indirectly lead to food insecurity, especially for people who are already highly vulnerable (Carey and others, 2017; Nie and others, 2021; Madrigal-Martínez and others, 2022).

4.4 Livelihood loss

Glacier-fed rivers contribute to livestock production, irrigated agriculture, domestic water use, hydropower and tourism. As such, a reduction in meltwater volumes has the potential to generate significant impacts on people's livelihoods (Carey and others, 2017). It was calculated that the largest relative reduction in streamflow is for basins in Central Asia (Aral Sea, Indus, Tarim, Balkhash) and South America (Santa, Colorado, Rapel) (Huss and Hock, 2018) with a discharge reduction of up to 30 per cent (Huss and Hock, 2018).

A vicuna roams at the foothill of the Chimborazo volcano, Ecuador's central Andes, in February 2019. © Pablo Cozzaglio / AFP

The waters from glacier-fed rivers are crucial for farmers. This is the case for farmers who use water from the Indus and Ganges (Biemans and others, 2019) and those in the tropical Andes as well. At least 25 per cent of water used for irrigation by small-scale farmers in the highlands of the tropical Andes comes from glacier melt (Buytaert and others, 2017). For instance, rural villagers of Peru living at the foot of the Quelccaya glacier also faced water scarcity and livelihood loss during the 2021 drought, experiencing drinking water shortages and losing up to one-third of their alpaca herds, which represent their main source of income (Ponce and others, 2023). Mountain regions, such as Bolivia's altiplano, are often particularly vulnerable to adverse effects on livelihoods due to the high dependence on agriculture and already existing patterns of poverty.

At the same time, glaciers are natural wonders that attract tourists to high mountain communities around the world and bring economic revenue. Studies indicate that in different parts of the world, accessing glaciers has become more difficult and dangerous due to slope instability (Salim, 2023). The sector has already adapted to the changing conditions of slopes and unreliable snowfall, but the risk to people's livelihoods remains (Steiger and others, 2019; Salim, 2023).

4.5 Migration/displacement

The changes experienced by ice-covered mountains are also influencing human mobility. As mountain glaciers retreat and the atmosphere warms, mountain regions are experiencing altered patterns in water availability, mass movements, floods and other cryosphere-induced changes (Hock and others, 2019). For example, these changes cause decreased agricultural production which motivates workers to migrate, either permanently or temporarily, from agricultural areas to urban centres in search for alternative sources of income (Hock and others, 2019). Highland residents in the tropical Andes, for instance, are concerned over water availability as they observe glacier and precipitation changes, which are especially critical for agriculture (Raoul, 2015; Buytaert and others, 2017; Motschmann and others, 2020). In Nepal's mountains, severe declines in agricultural and pastoral production as a result of decreased snow cover and altered climatic patterns have motivated people to migrate to the city or to relocate to lower lands (Prasain, 2018; Rauniyar, 2023). For three villages in Nepal, this dire situation ultimately pushed farmers to leave their lands and relocate to lower lands (Prasain, 2018).

4.6 Loss of safety

Glacier meltwater is considered a reliable water source contributing to streamflow during dry months, particularly in arid regions. As glaciers melt and peak water passes, this modulating effect will steadily decline over time. In the tropical Andes during a normal year, the number of users that consistently rely on water sources with a high contribution of glacier melt is limited. However, this dependence rises significantly during drought conditions. For example, the number of domestic users increases from 391,000 during a normal year, to 3.92 million in a drought year (Buytaert and others, 2017). Slope instability and morphological changes are also associated with glacier retreat (Milner and others, 2017), which increases the risk of GLOFs, rockfall and landslides, putting people and infrastructure in danger. In the past ten centuries, glacier floods have resulted in 6,300 documented fatalities in Central Asia, 5,745 in the Andes and 393 in the Alps (Carrivick and Tweed, 2016). In river basins where the contribution of glacier meltwater is high and arid conditions prevail, like the Indus, Aral and Chu, water availability also reduces the risk of social instability, conflict and sudden migrations (Pritchard, 2019).

4.7 Cultural heritage loss

The loss and eventual disappearance of glaciers represent an intangible loss for all people with a strong connection to glacial environments. For some communities, mountain glaciers have sacred and symbolic meanings like in the Peruvian Andes, the Nepalese Himalaya and the Meili Snow Mountains of Yunnan, China (Allison, 2015). In the Peruvian Andes, indigenous communities such as the Quechua, have a deep spiritual and cultural connection to glaciers and mountains. In Quechua, ice-covered mountains are called Apus, representing spiritual beings and deities to which indigenous people devote dedicated practices and ceremonies (Motschmann and others, 2020). Offerings are made to appease the mountain spirit and ensure a good harvest, protection and the overall well-being of people, but as these landscapes change so do spiritual practices and beliefs (Motschmann and others, 2020; Carey and others, 2017). On the other side of the world, in the Italian Alps, glaciers are linked to peoples' sense of identity and are indisputably important for tourism (Jurt and others, 2015).

4.8 Infrastructure damage

GLOFs represent a major hazard with a strong destructive potential to damage infrastructure, property, land and take people's lives. The number and size of glacier lakes worldwide has grown rapidly and so has population size, settlements and infrastructure in downstream areas which increases exposure. Globally, 15 million people are exposed to impacts of GLOF risk, and more than half of these people are found in just four countries: India, Pakistan, Peru and China (Taylor and others, 2023). The HMA region has the highest potential to experience the impacts of GLOF, and it is also the region where people live closest to glacial lakes (Taylor and others, 2023). At a national scale, Bhutan and Nepal have been found to have the greatest economic losses associated with glacier floods (Carrivick and Tweed, 2016).

4.9 Loss of opportunity

Glaciers form on land as snow accumulates and gets compressed into layers of ice over many centuries. They are present on all continents and act as a natural archive, holding information on Earth's past climate and environmental changes (Del Bello, 2019). For instance, ice cores from a glacier in France revealed traces of heavy metal pollution long before the beginning of the industrial era, leading to the discovery that lead and silver mining and smelting were already practiced during the Roman Empire (Preunkert and others, 2019). Eventually, as glaciers disappear, so will our potential to learn and discover information about the past. We will have lost the valuable and unique opportunity to study the information stored in them and further understand long-term global changes.

5. The future we want to create

To assess solutions for avoiding risk tipping points, we must consider these key questions: Does the solution attempt to prevent negative system changes or focus on adapting to the changes? Does the solution work within the current system or drive a fundamental reimagining of the system? Answering these questions is critical for understanding how different actions advance risk reduction goals and yield varied outcomes, including potential consequences and trade-offs. To navigate this, we have developed the ADAT2 framework, which classifies solutions into four categories: Adapt-Delay, Adapt-Transform, Avoid-Delay, and Avoid-Transform — see the main report for details.

5.1 Avoid

Avoid actions alter the system to prevent crossing risk tipping points. In the case of mountain glaciers melting, we can slow down our progression toward the risk tipping point by reducing greenhouse gas emissions. Mountain glaciers worldwide are retreating, a trajectory that is, for the most part, inescapable (Kääb and others, 2012). In fact, getting to an environment where mountain glaciers grow instead of shrink would necessitate a return to a planetary glaciation cycle, the next of which has been postponed thousands of years beyond its natural occurrence due to human-induced global warming (Ganopolski and others, 2016; Steffen and others, 2018)

If humanity manages to halt human-induced greenhouse gas emissions and limit global temperature rise to 1.5°C, 64 per cent of the present-day ice in the HMA glaciers will remain by the end of the century (Kraaijenbrink and others, 2017). However, at current greenhouse gas emission pathways, reaching the 1.5°C goal is extremely ambitious and possibly unlikely (UNEP, 2021; Stiell, 2023). In which case, HMA glaciers could lose between 49-64 per cent of their mass by the end of the century (Kraaijenbrink and others, 2017). Nonetheless, every reduction in greenhouse gas emission matters because every degree of temperature change affects the amount of glacier mass lost (Rounce and others, 2023). Attention should also be placed in black carbon air pollution, as it has been found to contribute to the darkening of snow and surfaces which further increases the melting of glaciers, snow cover and sea ice (Kang and others, 2020).

5.2 Adapt

Reaching a peak water risk tipping point may be inevitable for some mountain glaciers, but there are still opportunities to plan ahead and adapt to these changes. **Adapt** actions reduce exposure and vulnerability to post-tipping point impacts and prepare for sustainable living within the new system. The main adaptation needed is that past peak water, glacier meltwater becomes a less reliable source of water during dry periods. Luckily, adapting to decreased water availability can be done in different ways; for example, collecting and storing water — water harvesting — would delay the worst impacts during dry months. Water harvesting techniques in the Andes date back to pre-Inca times. Today, a combination of strategies that build on ancient knowledge are used to divert water, storing it in reservoirs used to promote soil humidity around the area and water infiltration upstream for downstream availability (Schoolmeester and others, 2018; Varillas, 2018; Hensley, 2019).

In HMA, the tradition of creating or growing glaciers has existed for at least 150 years, but ice towers (ice stupas) invented by engineer Sonam Wangchuk have gained a lot of attention since 2013 (Palmer, 2022). The ice towers are built inexpensively under below-zero temperatures by spraying water on to conical structures of wood and steel and are seen as an alternative to building traditional high-elevation water reservoirs (Palmer, 2022). Though an inexpensive alternative, the extremely low temperatures required are rarely found outside the Himalayan Ladakh Valley, and it requires a village to keep the pipes that transport the water from freezing (Palmer, 2022). Currently, at least 54 ice stupas have been built, which benefit 26 villages in the Ladakh Valley (Palmer, 2022). Another ice stupa was built in the Swiss Alps as part of a research project that studies how to improve this water storing

An ice stupa, which acts as an artificial glacier, stands in the middle of the cold desert of Ladakh, India.
© Naveen Macro / Shutterstock

alternative. Other forms of water harvesting can be as simple as installing a tank, an alternative that households in the Hindu Kush-Karakoram-Himalayan (HKKH) mountain system have already resorted to (Shrestha and others, 2015; Maharjan and others, 2023).

Adapting to reduced water availability can also be done by using water more efficiently. For example, urban water infrastructure efficiency can be improved by reducing leakages in the distribution system, while different measures can be implemented to make irrigation systems more efficient and improve agricultural practices (Cullen, 2018; Maharjan and others, 2023). There is also transformative power in ecosystem conservation, restoration (Schoolmeester and others, 2018) and other nature-based solutions, as soil and vegetation contribute to the water cycle with longer-term and multidimensional benefits. Overall, particularly because water's path from source to sink crosses human-made boundaries, stronger cooperation at different scales is essential to deal with the impacts of cryosphere change (Maharjan and others, 2023), and equitable access to water must be a matter of common interest.

5.3 From Delay to Transform

The consequences of mountain glaciers melting have already been observed, and our chances to revert our trajectory towards the significant reduction or even disappearance of some of these glaciers is unlikely. However, by addressing the root causes and drivers of risk, we can make societies more resilient to change and uncertainty. Since the root causes and drivers of the risk tipping point for mountain glaciers melting are so diverse, we need several actions working together simultaneously as a package of solutions to tackle the problem from all angles. These solutions must be done not only to **delay** the worst impacts from occurring, but also to **transform** the system that created these problems in the first place. We can incite more profound changes that shift our behaviours and values and transform our relationship with nature and our view of water as an inexhaustible resource.

To ensure water access to humans and ecosystems now and in the future, we need to use water efficiently and avoid waste. We can decrease our overall water use, optimize our water use practices through reuse and recycle, as well as retaining, protecting and conserving water for the future (Morseletto and others, 2022). By viewing water as a precious element that serves different roles to humans, other species and physical processes, we can reshape how we manage it. While adapt solutions mentioned before include measures to reduce water waste, such as improved distribution and irrigation systems, we can further choose to implement a circular mentality to water use.

The sense of separation and dominance can also hinder humans from recognizing the interconnections mountain glaciers have with societies, ecosystems and physical processes. Indigenous and traditional knowledge can play a crucial role in this transformation. For example, ancestral water harvesting and agricultural practices practiced by the Incas in the Andes have proven to improve soil humidity with the profundity of *qochas* — Quechua word meaning "small lagoon" — while also promoting aquifer recharge and water availability further downstream (Varillas, 2018). Nature-based solutions like this contribute to solving societal challenges while promoting biodiversity and hydrological processes.

More broadly, the Andean ancestral worldview embraces the concept of being one with nature. For example, *buen vivir* or "living well" is a harmonious and holistic set of views that gives equal priority to the well-being of people and nature. The concept challenges the idea of development seen as infinite economic growth. The Bolivian and Ecuadorian constitutions are pioneers in adopting the concept of *buen vivir* into their constitutions and in recognizing the right to nature (Gregor Barié, 2014; Bonilla Maldonado, 2018).

Additionally, collaboration at all scales is required to deal with the challenges posed by mountain glaciers melting. Carbon dioxide released in the atmosphere keeps rising, and climate promises keep being broken (Guterres, 2022); ambitious and immediate actions are of the essence. It is projected that 50 per cent of glaciers will be lost by 2100 whether we manage to limit the rise of the global mean temperature to 1.5°C or not; nevertheless, every increase in global temperature matters (Rounce and others, 2023). Reducing human-induced greenhouse gas emissions is still urgent and needed in order to save as many glaciers as possible from complete disappearance. We need true and transformative cooperation to limit global warming but also to continue managing current and future water resources despite increased risk and uncertainty. For instance, cooperation in transboundary ice-covered river basins in the HKKH is essential (Shrestha and others, 2015; Nie and others, 2021; Maharjan and others, 2023) but so is managing the risk of GLOFs and water scarcity in Andean communities (Motschmann and others, 2020). As mountain glaciers melt, we need to recognize that glacial meltwater contributes to water availability from the top of mountains to the oceans. This perspective should be considered when making decisions on how to use water and ensure that there is enough water for humans and other species.

We have the foresight and responsibility to ourselves and future generations to address the risks associated with the melting of mountain glaciers. Though the risk of GLOFs and water shortages are perceived as having different degrees of urgency (Motschmann and others, 2020), we can create systems that are resilient and that can help to adapt to both phenomena. This process needs to start now to minimize the worst impacts.

Construction of a dam in a qocha during a farmer's contest. © Helvetas Swiss Intercooperation / PACC project

6. Conclusion

Mountain glaciers melting poses critical challenges for socioecological systems. Past the risk tipping point of peak water, there will be a steady decline in water availability that presents a situation we will have to adapt to. In some places, peak water has already been crossed, and in others, it is only a matter of time before reaching this risk tipping point. The consequences of this trend are multifaceted and have significant implications for both the environment and human societies.

Mountain glaciers play a crucial role in providing fresh meltwater, essential for various aspects of life such as the ecosystem's health, people's livelihoods, economies and cultural heritage. The root causes and drivers outlined are what pushes us towards this risk tipping point, and represent the key elements that must be addressed to improve our preparedness of mountain glaciers melting.

We need to act now, as the trajectory towards mountain glacier retreat is unavoidable. First, drastic and sustained reductions in human-induced greenhouse gas emissions is paramount to limit the worst impacts from occurring. Adaptation measures such as water harvesting, efficient water use and ecosystem conservation will help communities survive and thrive under conditions of declining water availability. Transformational change requires profound changes in our behaviours and values such that a global sense of responsibility and cooperation are developed. We also need to value and conserve water resources by shifting societal attitudes towards water: from a disposable resource to a precious and essential element of life that cannot be wasted or mismanaged. We know what is ahead of us, and we need to prepare for the future consequences of glacier loss.

7. References

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Cover Image Credit: A young Tibetan woman carries her baby at the Nojin Kangsang glacier, Tibet Autonomous Region of the People's Republic of China, February 2007.