UN WATER

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The United Nations World Water Development Report 2025

Mountains and glaciers
Water towers

unesco World Water Assessment Programme

Food and Agriculture Organization of the United Nations

ESCAP, UNECE, UNECLAC, UNESCWA

unesco Intergovernmental Hydrological Programme

UN-HABITAT FOR A BETTER URBAN FUTURE

UNIDO

WORLD METEOROLOGICAL ORGANIZATION

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SHORT SUMMARY

Billions of people depend on the fresh water that flows from increasingly fragile mountain environments

The water resources we receive from mountains are literally melting away before our eyes.

Mountains and alpine glaciers – often referred to as the world's 'water towers' – are becoming increasingly vulnerable to climate change and unsustainable human activities, threatening the water resources upon which billions of people and countless ecosystems depend.

The *United Nations World Water Development Report 2025* – ***Mountains and glaciers: Water towers*** calls attention to the essential services and benefits mountain waters and alpine glaciers provide to societies, economies and the environment. With a focus on the technical and policy responses required to improve water management in mountains, the report covers critical issues such as water supply and sanitation, climate change mitigation and adaptation, food and energy security, industry, disaster risk reduction and ecosystem protection.

Up to 60% of the world's fresh water originates in mountains

Addressing the global water crisis begins at the top.

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"Since wars begin in the minds of men and women it is in the minds of men and women that the defences of peace must be constructed"

UN WATER

The United Nations World Water Development Report 2025

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Water towers

Contents

Contents

Boxes, figures and tables

Boxes

Figures

Tables

Foreword

by **Audrey Azoulay**, *Director-General of UNESCO*

Regardless of where we live, we all depend in some way on mountains and glaciers – the water towers of our planet.

Mountains cover 33 million km^2 of the Earth's surface and are vital for sustaining life. They are home to over 1.1 billion people, or 15% of the world's population. Moreover, a further 2 billion people downstream depend on these natural reservoirs for freshwater resources from melting glaciers.

These glaciers – and the more than 3 billion people and countless ecosystems, such as forests, wetlands, soils and rivers, that rely on them – are at great risk. The World Water Development Report 2025 provides a comprehensive overview of the current state of glaciers and the cryosphere, highlighting the immense economic, environmental and societal threats that we are facing.

The report reveals that the Andes, which supply 50% of the water flowing into the Amazon River, have lost between 30% and 50% of their glaciers since the 1980s. It is projected that the Mount Kenya, Rwenzori and Kilimanjaro glaciers will have disappeared entirely by 2040 if no action is taken, while the 'Third Pole' – also known as the Hindu Kush–Karakoram–Himalayan system – could lose 50% of its glacier volume, which currently spans 100,000 km^2, by the year 2100.

Critically, this report highlights that many of the issues surrounding climate adaptation and water management are transnational, meaning that the most effective solutions require a multilateral approach.

UNESCO, as a United Nations specialized agency in water sciences and cooperation, plays a critical role in finding these solutions, through knowledge production and sharing, water education, and as a platform for international dialogue.

If not properly managed, our mountain and glacier-fed water systems risk becoming a frequent source of conflict, especially as these critical resources face growing challenges. However, we believe that strengthened transboundary water governance, supported by international cooperation, can serve as a powerful catalyst for fostering peace between neighbouring countries. In this spirit, the Transboundary Water Cooperation Coalition was launched at UNESCO Headquarters in 2022 to provide a platform for cooperation between countries that rely on shared water resources such as aquifers, lakes and river basins.

Our World Water Assessment Programme, which has coordinated the production of this report, is at the forefront of synthesizing and disseminating knowledge on sustainable water management on a global scale. This work helps us understand what is at stake – and what action we can take.

It is essential that the international community joins hands and mobilizes to protect glaciers and the cryosphere. To raise awareness and promote action, the United Nations General Assembly has declared 2025 as the International Year of Glaciers' Preservation. This is also the first year of the Decade of Action for Cryospheric Sciences, for which UNESCO has been appointed as the lead agency.

This report, published on behalf of the entire UN-Water family, would not have been possible without the support of all our partners. In particular, UNESCO thanks the Italian Government, which has supported the publication of the report for almost two decades.

We are at a crucial juncture for the protection of our world's water systems. I hope that this report will serve as a catalyst – locally, nationally and internationally – for rapid and collective action.

Audrey Azoulay

Foreword

by **Alvaro Lario**, *Chair of UN-Water* and
President of the International Fund for Agricultural Development

For billions of people, mountain meltwater is essential for drinking water and sanitation, food and energy security, and the integrity of the environment.

But today, as the world warms, glaciers are melting faster than ever, making the water cycle more unpredictable and extreme.

And because of glacial retreat, floods, droughts, landslides and sea-level rise are intensifying, with devastating consequences for people and nature.

The United Nations World Water Development Report 2025 – Mountains and glaciers: Water towers offers solutions to help us simultaneously mitigate and adapt to rapid changes in our frozen water resources.

This report provides a clear overview of the current state of play and recommends what needs to change.

By detailing the connections between mountain fresh water, essential services and the natural world, this publication highlights the critical importance of conserving the cryosphere to the achievement of the Sustainable Development Goals. The urgent need to drastically reduce carbon emissions is emphatically repeated.

Saving our glaciers is a survival strategy – one we must pursue together. To help coordinate the United Nations system, 2025 has been declared the International Year of Glaciers' Preservation and marks the start of the Decade of Action for Cryospheric Sciences, 2025–2034.

I would like to offer my sincere thanks to the various UN-Water Members and Partners and individuals who contributed their expertise to this important and timely report, and to recognize the invaluable coordination work of UNESCO and its World Water Assessment Programme in its production.

Alvaro Lario

Preface

by **Michela Miletto**, *UNESCO WWAP Coordinator*
and **Richard Connor**, *Editor-in-Chief*

"Please tell me what can I do. There must be something I can do."

Ernest Hemingway, The Snows of Kilimanjaro and Other Stories

Like the images of polar bears sitting on shrinking slabs of frozen sea ice, dramatic photos documenting the rapid retreat of alpine glaciers have become emblematic of humanity's impact on our planet and its environment.

The General Assembly of the United Nations proclaimed 2025 as the International Year of Glaciers' Preservation to raise awareness on the vital role glaciers, snow and ice play in the climate system and water cycle, as well as the far-reaching impacts of rapid glacial melt. However, the alpine cryosphere is not the only component of mountain systems subject to climate change and unsustainable human activities, affecting the *'water towers'* of the global water cycle. Mountains worldwide, including those in the tropics and small islands, are undergoing unprecedented changes. And we all ultimately live downstream.

As the 12th in a series of annual thematic reports, the 2025 edition of the *United Nations World Water Development Report* (UN WWDR) seeks to explore the importance of mountain waters for sustainable development, and the policy and management responses that need to be taken to ensure their perenniality and maximize the many opportunities they offer in a rapidly changing world of rising water demand and growing water scarcity.

As always, the report provides in-depth analyses of the subject through various social, economic and environmental perspectives, ranging from food and energy security to water supply, sanitation and disaster risk reduction. The analysis demonstrates how interventions in mountain regions affect people and ecosystems downstream, highlighting the need to protect and sustainably manage our fragile and vulnerable water tower systems. This is not only a local or regional challenge, but also a global one.

The UN WWDR 2025 presents the latest state-of-the-art scientific knowledge regarding the role mountains and glaciers play in addressing the global water crisis. Again this year, we have endeavoured to produce a balanced, fact-based and neutral account of the current state of knowledge, covering the most recent developments.

Although primarily targeted at policymakers and decision-makers, water resources managers, academics and the broader development community, we hope this report will also be well received by non-water specialists, including those who are engaged in the alleviation of poverty and humanitarian crises, in the pursuit of the human rights to water supply and sanitation, and in the advancement of the 2030 Agenda for Sustainable Development.

This latest edition of the UN WWDR is the result of a concerted effort among the chapter lead agencies listed in the Acknowledgements. The report also greatly benefited from the inputs and contributions of several other UN-Water Members and Partners, as well as from numerous universities, research institutions, scientific associations and non-governmental organizations, who all provided a wide range of relevant materials.

On behalf of the UNESCO World Water Assessment Programme (UNESCO WWAP) Secretariat, we would like to extend our deepest appreciation to the aforementioned agencies, the Members and Partners of UN-Water, and the writers and other contributors for collectively producing this unique and authoritative report. We are profoundly grateful to the Italian Government for funding the UNESCO WWAP and the production of the UN WWDR since 2008, and to the Regione Umbria for generously hosting the UNESCO WWAP Secretariat in Perugia, Italy. Their contributions have been instrumental to the production of the UN WWDR.

Our special thanks go to Ms Audrey Azoulay, Director-General of UNESCO, for her ongoing support to UNESCO WWAP and the production of the UN WWDR, and to Alvaro Lario, President of the International Fund for Agricultural Development and Chair of UN-Water.

Finally, we extend our most sincere gratitude to all our colleagues at the UNESCO WWAP Secretariat, whose names are listed in the Acknowledgements. The report could not have been completed without their professionalism and dedication.

Michela Miletto

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Chapter lead agencies

Food and Agriculture Organization of the United Nations (FAO), UNESCO (Intergovernmental Hydrological Programme – IHP, UNESCO Office in Nairobi and UNESCO WWAP), United Nations Human Settlements Programme (UN-Habitat), United Nations Industrial Development Organization (UNIDO), United Nations Regional Commissions (Economic Commission for Europe – UNECE, Economic Commission for Latin America and the Caribbean – UNECLAC, Economic and Social Commission for Asia and the Pacific – ESCAP, Economic and Social Commission for Western Asia – UNESCWA) and World Meteorological Organization (WMO).

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Executive summary

In alignment with the designation of 2025 as the International Year of Glaciers' Preservation and the 2022 resolution of the General Assembly of the United Nations on sustainable mountain development, this report draws worldwide attention to the importance of mountain waters, including alpine glaciers, in the sustainable development of mountain regions and the downstream societies that depend upon them, in the context of the rapidly changing mountain cryosphere.

Status of the world's water resources

According to the most recent global estimates (from 2021), the agriculture sector dominates freshwater withdrawals (72%), followed by industry (15%) and domestic (or municipal) use (13%). Sector-specific freshwater withdrawals vary considerably as a function of a country's level of economic development. Higher-income countries use more water for industry, whereas lower-income countries use 90% (or more) of their water for agricultural irrigation.

Over the period 2000–2021, global freshwater withdrawals increased by 14%, corresponding to an average growth rate of 0.7% per year. Most of this increase occurred in cities, countries and regions undergoing rapid economic development. Population growth does not appear to play a highly significant role in increasing demand for water. In fact, countries where per capita water use is the lowest, including several countries in Sub-Saharan Africa, are often those with the fastest growing populations.

Twenty-five countries – home to one-quarter of the world's population – face 'extremely high' water stress every year. Approximately 4 billion people, or half the world's population, experience severe water scarcity for at least part of the year.

Climate change is increasing seasonal variability in, and uncertainty about, water availability in most regions. Pollution, land and ecosystem degradation, and natural hazards can further compromise the availability of water resources.

Progress towards Sustainable Development Goal 6

Sustainable Development Goal (SDG) 6 seeks to ensure the availability and sustainable management of water and sanitation for all.

Progress towards all SDG 6 targets is off track – some severely.

For example, an estimated 2.2 billion people (27% of the global population) were without access to safely managed drinking water in 2022, with four out of five people living in rural areas lacking even basic drinking water services.

The situation concerning sanitation is worse, with 3.5 billion people worldwide lacking access to safely managed sanitation in 2022. Only half of the population had access to these services in Latin America and the Caribbean, and Central and Southern Asia. Coverage in Sub-Saharan Africa was a mere 24%.

Data gaps and deficiencies in monitoring continue to impede accurate assessment of the other SDG 6 targets, including on the management of water resources, water quality, water-related ecosystems and the enabling environment.

Mountain regions

As the 'water towers' of the world, mountains are an essential source of fresh water. They are vital for meeting basic human needs such as water supply and sanitation. These waters are also vital in ensuring food and energy security to billions of people living in and around mountain regions and in areas downstream.

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As the 'water towers' of the world, mountains are an essential source of fresh water

The main economic activities in mountain regions are agriculture, pastoralism, forestry, tourism, mining, cross-border trade and energy production. Mountain regions provide high-value products such as medicinal plants, timber and other forest products, unique mountain livestock and speciality agriculture products. They are global hotspots of agrobiodiversity, with a large fraction of the world's gene pools for agriculture and medicinal plants preserved in mountains.

Mountains feature a diverse range of ecological zones, each resulting from a specific combination of factors such as elevation, geomorphology, isolation and microclimatic conditions (e.g. insolation). Consequently, they often have higher endemic biodiversity than lowlands, including important genetic varieties of agricultural crops and animals. They also have an equally diverse range of human cultures.

Glaciers and the mountain cryosphere

The mountain cryosphere is one of the most-sensitive components of the Earth system to global climate change. Mountains generally supply more surface runoff per unit area than lowlands, due to higher precipitation and lower evaporation. Alpine glaciers also store and release water, albeit over much longer time-frames. In many high mountain regions, the formation of seasonal snow cover provides most of the freshwater storage.

Most of the world's glaciers, including those in mountains, are melting at an increasing rate. However, snow-melt accounts for a greater volume of streamflow in most river basins with a cryosphere component, and is often substantially higher than glacier melt.

Global warming is accelerating glacier melt, decreasing snow cover, increasing permafrost thaw, and prompting more extreme rainfall events and natural hazards. Water flows from mountains will become more erratic, uncertain and variable. Changes in the timing and volume of peak and low flow periods, increased erosion and sediment loads will affect water resources downstream, in terms of quantity, timing and quality.

Dust, combustion-related soot deposits including black carbon, and microbial and algal growth on snow and glacier surfaces are becoming more common due to increased frequency and/or intensity of dust storms, air pollution and wildfires. They can accelerate melt rates by decreasing surface albedo until the next snowfall.

The consequences of climate change, including higher temperatures, glacial recession, permafrost thaw and changing precipitation patterns, can affect flood and landslide risks. The processes associated with these risks, such as debris flows and floods, avalanches, rock- and icefalls, landslide dam outburst floods and glacial lake outburst floods (GLOFs), can pose significant threats to communities, wildlife and infrastructure.

Food and agriculture

Agriculture and pastoralism are essential sources of livelihoods for people in rural mountain areas. One in two rural mountain dwellers in developing countries are vulnerable to food insecurity. Remoteness and inaccessibility, as well as land degradation (which leads to poor quality soils) and large variations in seasonal water supply, combine to create significant challenges for mountain agriculture.

Mountain communities preserve many of the rarest crop varieties and medicinal plants. They have developed valuable traditional knowledge and techniques in crop cultivation, livestock production and water harvesting that help to sustain entire ecosystems.

Global warming is accelerating glacier melt, decreasing snow cover and prompting more extreme rainfall events and natural hazards

Indigenous Peoples in mountains have unique and valuable local knowledge, traditions and cultural practices that contribute to sustainable food systems, land management and biodiversity preservation. Terrace farming can be adapted to local slope conditions. Its numerous benefits include reducing surface water runoff, promoting water conservation, reducing soil erosion, stabilizing slopes, enhancing habitat and biodiversity production, and sustaining cultural heritage.

Responses to climate-driven impacts in mountains vary significantly in terms of goals and priorities, speed of implementation, governance and modes of decision-making, and the extent of financial and other resources to implement them. Adaptation responses commonly include changing farming practices, infrastructure development including for water storage, application of Indigenous knowledge, community-based capacity-building and ecosystem-based adaptation (EbA).

Human settlements and disaster risk reduction

Roughly 1.1 billion people live in mountain regions, two-thirds of whom live in towns and cities. The remoteness of mountain communities, difficult terrain and heightened exposure to natural hazards often lead to higher costs for transport, infrastructure, goods and services. These also pose particular challenges for the financing, development and maintenance of water supply and sanitation systems, drainage networks and other essential water infrastructure.

Rapid and unplanned urbanization in mountain regions is also placing pressure on fragile mountain ecosystems, affecting water availability, quality and security. Decentralized water and sanitation systems can be particularly effective in mountain regions, reducing the risk of infrastructure damage in rugged terrain subject to frequent landslides.

Natural hazards such as landslides, earthquakes, floods, GLOFs and avalanches can damage the water supply and sanitation infrastructure, and disrupt access to water, sanitation and hygiene services. Such hazards increase the vulnerability of already vulnerable and often marginalized mountain communities, and destabilize some of their wealth-generating sectors, including agriculture, tourism and biodiversity.

Examples of adaptation actions in mountain regions include: feasibility studies for building emergency storage and bypasses and controlled releases from glacial lakes; river basin management and planning for basin optimization; monitoring temporal changes in glaciers; and establishing GLOF risk reduction and early warning systems in glaciated river basins.

Industry and energy

Water-dependent industries have developed in mountain areas where water and other resources are found in relative abundance. In addition to industrial and energy production, water is also required to process minerals, produce timber and develop tourism in mountain areas.

Hydropower generation is one of the main industries in mountain areas. The presence of a slope and the shape of mountain valleys make it possible to generate hydropower without building large dams and reservoirs. However, the construction and presence of dams and reservoirs, transmission lines and substations can have a significant negative impact on fragile mountain ecosystems.

The remoteness of mountain communities, difficult terrain and heightened exposure to natural hazards often lead to higher costs for transport, infrastructure, goods and services

Beyond water availability, a significant challenge for industry and energy is the elevation at which it is possible to operate. As such conditions can generate huge investment and running costs, industrial activities are typically limited to those with high returns on investment.

Industrial and energy development can affect water quality. Remote mountain areas can be difficult to regulate, resulting in uncontrolled water withdrawals and discharges, including pollutants.

Responses are available and are being developed to make industry and energy production in mountain areas more sustainable. The circular economy promotes water-use reduction, recycling of used water and reuse of water resources. Environmentally sound technologies encompass practices such as the use of less-polluting technologies, better resource management and efficient waste recycling. The greening of grey infrastructure or its replacement with green infrastructure can be particularly effective in mountain areas.

Environment

Mountain and highland ecosystems provide essential ecosystem services to people living in mountains, and to billions in connected lowland areas. Water regulation (including water storage and flood regulation) is one of the most important services.

Other key ecosystem services include reducing the risk of erosion and landslides, cooling local temperatures, carbon sequestration, providing food and fibres, and maintaining pools of genetic resources for locally adapted crops and livestock.

Forests cover an estimated 40% of mountain areas, performing a protective function against natural hazards by stabilizing steep slopes, regulating flows to groundwater, reducing surface runoff and soil erosion, and mitigating the potential for landslides and floods. Unsustainable tree cultivation can lead to increased soil erosion and reduced soil water infiltration.

Mountain soils develop under harsh climatic conditions. They differ significantly from lowland soils, as they are shallower and more vulnerable to erosion. Such soils are easily and often degraded by various human activities, especially removal of vegetation that exposes the bare soil. The recovery of degraded soils and thus ecosystems at high elevations is slow.

At the ecosystem level, most of the options for addressing the impacts of changes in the cryosphere and high mountains involve conserving or restoring ecosystem functionality to maintain or enhance ecosystem services at local to regional scales through nature-based solutions (NbS) or EbA. These approaches are now commonly seen as an adaptation component in the nationally determined contributions of many mountain countries around the world.

Regional perspectives

Sub-Saharan Africa

Of continental Africa's land area, 20% is classified as mountains with an elevation over 1,000 metres above sea level (masl), with 5% rising above 1,500 masl. East Africa is the most mountainous region in Africa. The mountain regions are characterized by high levels of biodiversity; they provide ecosystem services, including water resources, to millions of people. In tropical and subtropical Sub-Saharan Africa, mountains have favourable environmental conditions and resources compared with the generally drier surrounding lowlands.

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In addition to industrial and energy production, water is also required to process minerals, produce timber and develop tourism in mountain areas

Agricultural production and food security within mountain regions and downstream lowlands are critically dependent on mountain waters. The degradation of mountain ecosystems reduces their ability to store and supply water downstream. This is particularly the case with deforestation of critically important montane forests.

Considering farming is the principal livelihood in the mountains of Sub-Saharan Africa, improving agricultural practices to reduce land degradation (soil conservation) is of critical importance. Promoting EbA (e.g. reforestation and conservation of montane forests reducing soil erosion) can enhance water retention and aquifer recharge and diminish the risk of natural hazards.

There are high population growth rates and density in the mountains of the region, with widespread poverty and a lack of alternative and resilient livelihoods. In many areas, the mountains are more densely populated than the lowlands.

Europe and Central Asia

Mountain ranges are the source of water for many rivers in Europe and Central Asia. Alpine snow and glacial melt ensure a slow release of water to downstream areas. However, climate change is leading to earlier seasonal snow-melt and smaller glaciers, thereby threatening the availability of water in the summer season. This has serious consequences for populations in downstream basins.

Water from the Alps is vitally important to large parts of Europe. Hydropower generation is the main reason for water abstraction, while other uses include industrial purposes, agricultural irrigation and snow-making.

The Carpathian Mountains are home to approximately 30% of European flora. Their semi-natural habitats such as mountain pastures and hay meadows are of great ecological and cultural importance.

Across the mountains of Central Asia, upstream countries experience energy shortages in winter and would like to expand their hydropower production, while downstream countries are largely dependent on water from the mountains for their agricultural production in the summer. These conflicting seasonal demands lead to political tensions among the riparian countries.

The improvement and exchange of knowledge and information, the strengthening of regional cooperation, the strengthening of in-country capacities on the cryosphere and mountain water management, and the raising of awareness and involvement of key stakeholders in developing and implementing action plans are needed.

Latin America and the Caribbean

Mountains occupy about one-third of the territory in Latin America and the Caribbean. They produce more water flow per land area than any other continent. Glaciers across the region are experiencing a significant overall reduction in volume, with several having disappeared entirely.

Water originating in the mountains is essential for producing high-value agricultural crops like coffee and cocoa. Mountain waters also generate most of the region's hydroelectric power, providing energy for cities and smaller communities downstream, as well as remote villages in mountain areas.

Alpine glaciers are disappearing at an alarming rate

The mountain areas in Latin America and the Caribbean are being increasingly affected by climate change and human activities. Water-related social conflicts have occurred in high-elevation areas of Andean countries, many of which can be attributed partially to mining activities, which can negatively affect the availability of water for downstream users.

In response, several countries have enacted policies and laws to protect these critical ecosystems. However, some systems have already surpassed critical thresholds, making it crucial to promote adaptive measures such as NbS (e.g. reforestation), cropping techniques and expanding water collection infrastructure. To implement these measures effectively, well-targeted funding, robust monitoring, capacity-building and inclusive governance frameworks are needed, fostering dialogue and inclusion of local communities to apply the best available practices adapted to local contexts in the mountain regions.

Asia and the Pacific

The Asia–Pacific region contains some of the world's highest mountains and most extensive glacier systems. This so-called Third Pole stores more ice and snow than any other region outside the Antarctic and Arctic. It is the origin of more than ten river systems that are vital for sustaining nearly 2 billion individuals in the river basins of Central, Northeast, South and Southeast Asia. The Third Pole is also one of the most biologically diverse and ecologically fragile areas in the world, and is home to a variety of cultures.

Alpine glaciers in the region are disappearing at an alarming rate, often faster than the global average. Over the long term, reduced water flows and increased droughts are expected to jeopardize food, water, energy and livelihood security in the Hindu Kush Himalaya region.

Energy use, environmental degradation and human activity are contributing to risks in other ways, with black carbon, heavy metals and persistent organic pollutants showing an increasing presence in the Third Pole.

Collaboration on engaging the diverse stakeholders and sectors affected by the trends is essential. Glacial melt and water-related crises must be addressed by strengthened adaptation measures, integrated water resources management (IWRM) and synergistic solutions for climate, nature and pollution, supported by transboundary collaboration, regional dialogue, advocacy and awareness-raising.

There is a need for expansion of the observational infrastructure in high mountain areas

Arab region

The mountain areas of the Arab region are often overlooked, despite the important role they play in providing water resources and other ecosystem services. They are home to thriving communities and centres of economic activity for tourism, agriculture and industry, which are often reliant on the ever-dwindling availability of freshwater resources, resulting in a reduced amount of renewable water per capita.

Meltwater can serve a crucial role for the agricultural sector, particularly in sustaining crops during the summer when precipitation is limited. Some aquifer-fed springs within the Arab region are primarily recharged from snow-melt. In Mount Lebanon and the Atlas Mountains, seasonal snowfall and overall precipitation are expected to decrease, affecting snow cover duration and depth and availability of freshwater resources. These projected reductions in snow cover signal an overall decrease in water supply, specifically during the dry season when it is most needed for irrigation. Water, sanitation and hygiene services may also be affected by reduced overall water resources in the long term.

Managed aquifer recharge is one adaptation measure that could be employed. Water harvesting could be used in the winter to mitigate the decrease in water availability in the summer resulting from climate change impacts on mountain areas in the Arab region, including the loss of snowpack.

Knowledge- and capacity-building

The high variability in mountain climate, topography, geology and vegetation – all of which influence the movement of water through the landscape – creates an exceptional need for representative hydrometeorological networks and robust information systems.

The sparseness of cryosphere monitoring in mountain regions exacerbates uncertainties in hydroglaciological predictions, enhancing the risk of water resources mismanagement. To understand cryospheric changes and improve the sustainability of mitigation and adaptation approaches, there is a need for expansion of the observational infrastructure in high mountain areas, and also for data to be open access.

Engagement and meaningful collaboration with Indigenous Peoples and local communities, with their prior informed consent, and the willingness to learn from stewardship of water systems evolved over generations will improve the collective ability to respond to changing mountain cryospheric and downstream hydrological conditions.

Institutional capacity can encompass the time and resources necessary to bring diverse people and perspectives together. Collaborative governance models often imply trade-offs that, while advantageous to society in the long term, may be undesirable to current beneficiaries from the status quo.

Participation in citizen science projects can provide valuable avenues for public engagement with the local environment, improve scientific literacy and encourage research careers. Collaboration between research organizations and community groups, where researchers develop the methods, education and training, is a common approach to ensure this requirement is met. In this process, locals should provide input on project scope to ensure the knowledge outcomes meet their community needs.

Governance and finance

The role of water governance in mountains has not received as much attention as in lower-lying lands, on which there has been a large amount of work, such as through IWRM.

International policy frameworks offer promising support to water governance and adaptation to climate-related changes in the mountains. Treaties and conventions are relevant enablers to promote cooperation and implementation at the mountain region scale.

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In some cases, national policies for water, agriculture, industry and energy are developed to favour low-lying regions of river basins

Most large rivers originate in mountain areas and often cross international borders. Transboundary water governance, based on a 'basin-level view' that considers mountain waters, can provide benefits to riparian countries. Regional cooperation among countries, including river basin governance initiatives, is an important mechanism for advancing climate adaptation in mountains. However, conflict between national interests within transboundary water agreements and the ineffectiveness of institutions to navigate coordination within the local context has hindered effective cooperation.

The management of mountain waters takes place primarily within country borders, through national legislation, policy and strategies. In some cases, national policies for water, agriculture, industry and energy are developed to favour low-lying regions of river basins, for instance, to serve more populous areas. National policies may often not fully reflect water sectoral issues within the mountains; rather, they tend to focus on mountains as sources for downstream users.

Development in mountains is generally more costly and difficult than in lowlands due to the rugged terrain and poor accessibility, restrictions on economies of scale, long distance from seaports and economic centres, and poorly developed industrial and service sectors. Costs related to transport, infrastructure, goods and services increase with elevation and isolation. These need to be considered in policy and financing, with calls for mountain-specific policies and programmes in national and global development plans.

Climate adaptation finance and private sector inclusion and contribution are key enablers for achieving the adaptation potential in mountains. While substantial funding is potentially available for investment in sustainable development in mountain regions, access to major support programmes has been relatively limited. This indicates a significant response option is underutilized. More specifically, innovative and affordable international, regional, national and local funds should be mobilized to support water, agriculture and energy planning and infrastructure investments.

Coda

Mountains provide life-sustaining fresh water to billions of people and countless ecosystems. As the world's water towers, their critical role in sustainable development cannot be ignored.

Actions must be taken to better understand and protect these fragile environments, increasingly threatened by climate change and unsustainable human activities.

Because nothing that happens in mountains stays in mountains.

In one way or another, ***we all live downstream***.

Prologue

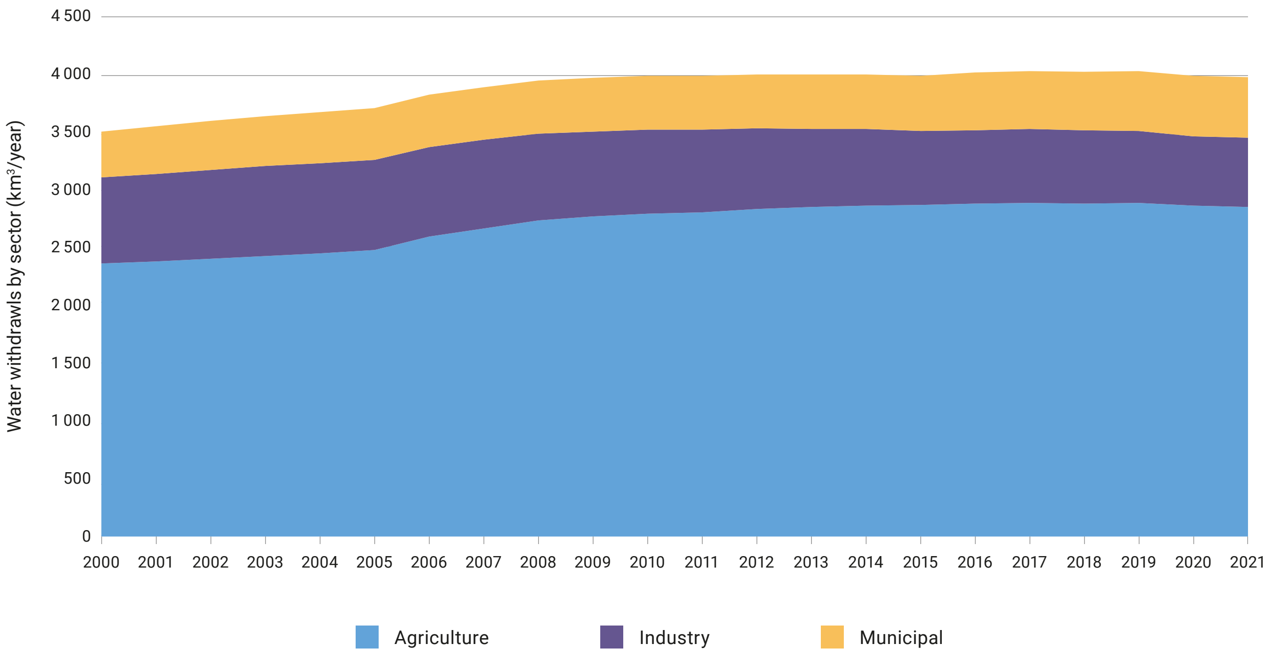
UNESCO WWAP
Richard Connor, Chorong Ahn and Beobkyung Kim

Trends in water demand and availability

According to the most recent global estimates from 2021 (FAO, n.d.), the agriculture sector dominates total water withdrawals (72%), followed by industry (15%) and domestic (or municipal) use (13%) (Figure P.1).

Over the period 2000–2021, total water withdrawals grew by 14% globally (from 3,500 km^3 in 2000 to just under 4,000 km^3 in 2021), giving an average increase of 0.7% a year. However, this growth has not been uniform across sectors. The greatest increase has occurred in agriculture (which includes self-supplied water withdrawn for irrigation, livestock and aquaculture), followed by the municipal use sector (which comprises water withdrawn primarily for direct use by the population). Freshwater withdrawals by industry (self-supplied) appear to have dropped by nearly 20% over the same period (Table P.1).

Figure P.1 Global total water withdrawals by major water-use sector, 2000–2021 (km^3/year)



Source: Authors, based on data from AQUASTAT (FAO, n.d.).

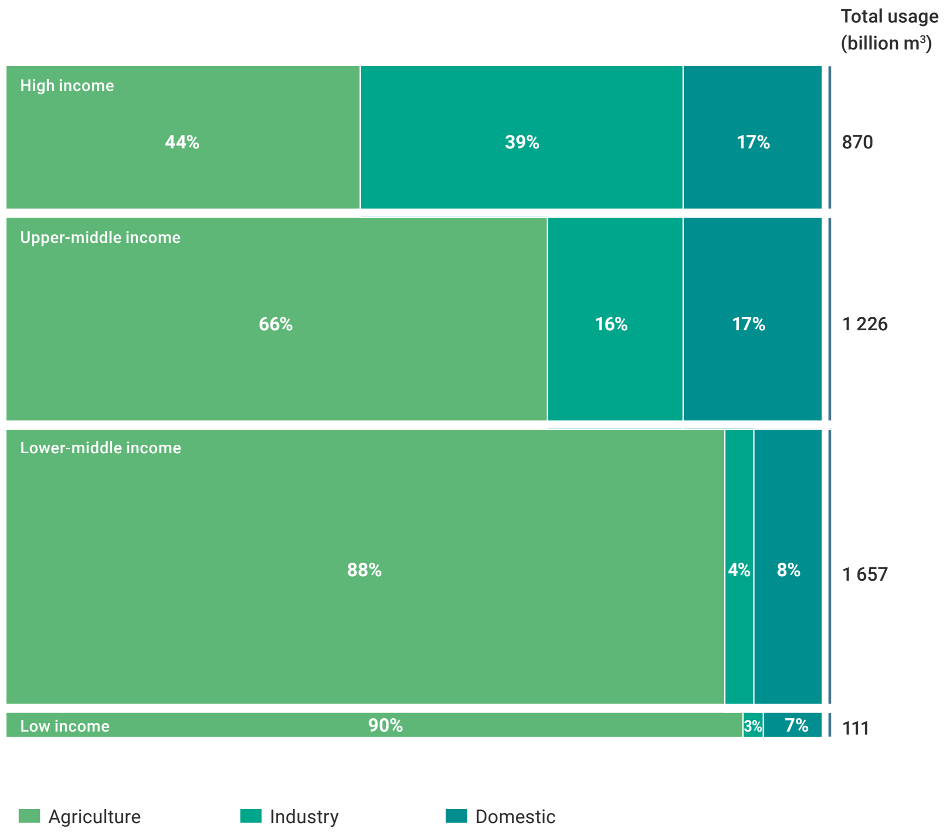
Table P.1 Global freshwater withdrawals by sector, 2000 and 2021

Year	Agricultural		Industrial		Municipal	
	Volume (km^3)	Percentage of total (%)	Volume (km^3)	Percentage of total (%)	Volume (km^3)	Percentage of total (%)
2000	2 365	67	746	21	396	11
2021	2 855	72	601	15	528	13

Source: Authors, based on data from AQUASTAT (FAO, n.d.).

Sector-specific freshwater withdrawals vary considerably as a function of countries' levels of economic development. Higher-income countries use more water for industry, whereas lower-income countries use 90% (or more) of their water for agricultural irrigation (Figure P.2).

Figure P.2
Water withdrawal by sector (% of total freshwater withdrawal) by income group, 2020



Note: The 'domestic' sector data in this figure are the same as those of the 'municipal' sector in Figure P.1 and Table P.1.

Source: Kashiwase and Fujs (2023, based on data from AQUASTAT). Licence CC BY 3.0 IGO.

However, the level to which the decrease in industry withdrawals mentioned above is related to improved water-use efficiency by industries in high- and upper-middle-income countries remains unclear, and this may be a topic worth pursuing.

Most of the increasing water demand occurs in cities, countries and regions undergoing rapid economic development

Future trends in water demand are notoriously difficult to estimate (United Nations, 2023). In general, increases are due mainly to socio-economic development and related changes in consumption patterns, including diet. Most of the increasing water demand occurs in cities, countries and regions undergoing rapid economic development, notably in emerging economies. However, population growth does not appear to play a highly significant role. In fact, countries where per capita water use is the lowest, including several countries in Sub-Saharan Africa, are often those with the fastest growing populations (United Nations, 2024a).

Although definitions vary, water availability (or scarcity) can be seen as a purely volumetric measurement, while water stress corresponds to availability as a function of demand (i.e. the ability, or lack thereof, to meet human and ecological demand for water).

Twenty-five countries – home to one-quarter of the world's population – face 'extremely high' water stress every year (Kuzma et al., 2023). Water availability generally varies in terms of location and timing, such that annual averages of water availability can mask severe water shortages (i.e. stress) that can occur during specific months or seasons throughout the year. The Intergovernmental Panel on Climate Change estimates that approximately 4 billion people, or half the entire world's population, experience severe water scarcity for at least part of the year (IPCC, 2023).

Climate change is increasing seasonal variability in, and uncertainty about, water availability in most regions (UNESCO/UN-Water, 2020; IPCC, 2023). Pollution, land and ecosystem degradation, and natural hazards can further compromise the availability of water resources and the sectors that depend upon them.

Progress towards Sustainable Development Goal 6

Sustainable Development Goal (SDG) 6 seeks to ensure the availability and sustainable management of water and sanitation for all. It focuses on drinking water, sanitation and hygiene, sustainable management of water resources, water quality, integrated water resources management (IWRM), water-related ecosystems and the enabling environment.

Progress towards all SDG 6 targets is off track – some severely (Figure P.3). Data gaps and deficiencies in monitoring continue to impede accurate assessment and effective implementation of necessary interventions.[1]

Figure P.3
Progress status of Sustainable Development Goal 6 targets, 2024

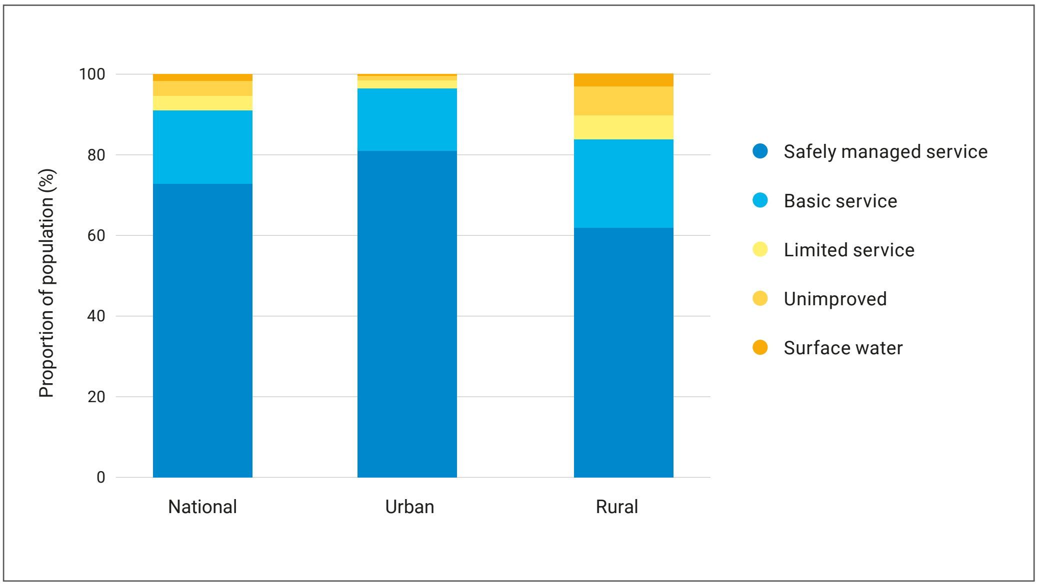
Source: United Nations (n.d.a).

[1] For detailed and up-to-date metrics, supplemental information and links to background reports on progress towards all SDG 6 targets and indicators, see www.sdg6data.org.

Target 6.1: Safe drinking water

An estimated 2.2 billion people (27% of the global population) were without access to safely managed drinking water in 2022 (Figure P4). Four out of five people lacking at least basic drinking water services lived in rural areas. The coverage gap between urban and rural was greatest in Sub-Saharan Africa and Latin America and the Caribbean (UNICEF/WHO, 2023).

Figure P.4 Proportion of population using safely managed drinking water services, 2022

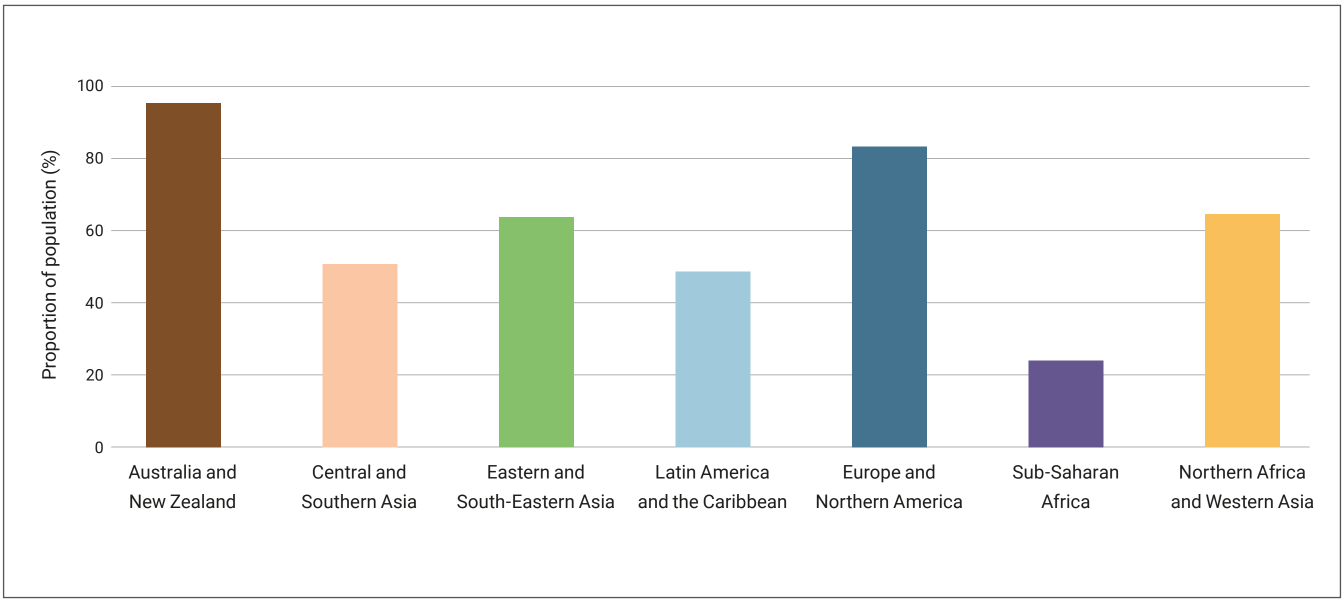


Source: United Nations (n.d.b, based on data from UNICEF/WHO (2023)).

Target 6.2: Access to sanitation and hygiene

As of 2022, 3.5 billion people worldwide lacked access to safely managed sanitation (UNICEF/WHO, 2023). The situation was particularly dire in Sub-Saharan Africa, where a mere 24% of the population used safely managed sanitation services. Lack of access also persists in other regions, such as Latin America and the Caribbean, and Central and Southern Asia, where only roughly 50% of the population had access to these services (Figure P.5).

Figure P.5 Proportion of population using safely managed sanitation services (Sustainable Development Goal Indicator 6.2.1a) in different regions, 2022



Source: United Nations (n.d.c, based on data from UNICEF/WHO (2023)).

Target 6.3: Water quality

SDG Indicator 6.3.1 tracks the proportion of total – industrial and household (domestic) – wastewater flows safely treated in compliance with national or local standards. The household component includes sewage and faecal sludge, treated on or off site, with linkages to Indicator 6.2.1a on sanitation. Unfortunately, *"There is an alarming lack of countries' reported wastewater statistics worldwide"*, and *"data are insufficient to establish global statistics on the proportion of total wastewater treated and safely treated"* (UN-Habitat/WHO, 2024, p. xiii).

In 2023, data on 91,000 water bodies from 120 countries revealed that 56% had good water quality (United Nations, 2024b). *"However, data collection and reporting on basic water quality parameters is beyond the capacity of many low- and lower middle-income countries. In 2023, over 2 million water quality measurements were used to report on this indicator [6.3.2], but the countries that represent the lowest-income half of the world contributed less than 3 per cent of this total (60,000)"* (UNEP, 2024a, pp. ix–x).

Target 6.4: Water-use efficiency and water stress level

"*Increasing water-use efficiency, for example by repairing leaking water distribution systems, using less thirsty crops and investing in new technology, results in more sustainable food and industrial production systems. Water savings are also often associated with energy savings, as less water needs to be extracted, treated, transported and heated"* (United Nations, n.d.d). This target's indicator (6.4.1) monitors the change in water-use efficiency over time, estimated as the ratio of dollar value added to the volume of water used.

Efficiency varies widely, influenced by a country's economic structure and the sectoral distribution of water. For example, *"In 2021, estimates ranged from below \$3/m³ in agriculture-dependent economies to over \$50/m³ in highly industrialized, service-based ones. Despite the average increase globally, around 58 per cent of countries still exhibit low water use efficiency (less than \$20/m³)"* (United Nations, 2024b, p. 21).

The monitoring of water stress levels provides an estimation of pressure by all sectors on the country's renewable freshwater resources. SDG Indicator 6.4.2 reached 18.6% in 2021, an increase of 2.7% since 2015 (FAO/UN-Water, 2024).

Target 6.5: Transboundary water cooperation

Out of 153 countries sharing transboundary rivers, lakes and aquifers, only 43 have 90% or more of their transboundary waters covered by operational arrangements. Only 26 countries have all their transboundary waters covered by operational arrangements (UNECE/UNESCO/UN-Water, 2024).

SDG Indicator 6.5.1 tracks the implementation of IWRM. *"Global progress in implementing integrated water resources management remains slow, however, edging up from a score of 49 per cent in 2017 to only 57 per cent in 2023. […] Significant efforts to accelerate implementation are needed, particularly in Central and Southern Asia, Latin America and the Caribbean, Oceania and sub-Saharan Africa"* (United Nations, 2024b, p. 21).

Target 6.6: Water-related ecosystems

This target encompasses the broad and ambitious goal of protecting and restoring water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes. Notably, the target is not quantified at the global level. As such, the target exists without information on the level of ambition expressed as a number or area of water-related ecosystems needing protection and/or restoration. However, *"The SDG 6.6.1 data trends show water-related ecosystems are continuing to face significant levels of degradation. This is primarily driven by pollution, dams, land conversion, over-abstraction, and climate change"* (UNEP, 2024b, p. 2).

Target 6.a: International cooperation on water and sanitation

Official development assistance (ODA) disbursements to the water sector steadily decreased from 2018 to 2020, then rose by 11% to US$9.1 billion in 2021 (United Nations, n.d.e). "*However, water sector ODA disbursements as a percentage of total ODA across all sectors decreased to 3.2% in 2022, a historical low, and continuing a downwards trend which has accelerated since the start of the COVID-19 pandemic in 2020*" (WHO, 2024, p. 40).

Target 6.b: Participatory water and sanitation management

Over 90% of countries reported having procedures for participation defined in law or policy for rural drinking water and water resources management over the 2021–2022 reporting cycle. However, "*less than one third of countries reported high or very high participation of communities in planning and management processes*" (WHO, 2022, p. 48).

References

FAO (Food and Agriculture Organization of the United Nations). n.d. AQUASTAT Dissemination System. FAO website. https://data.apps.fao.org/aquastat/?lang=en. (Accessed on 2 December 2024.)

FAO/UN-Water (Food and Agriculture Organization of the United Nations/UN-Water). 2024. *Progress on the Level of Water Stress – Mid-Term Status of SDG Indicator 6.4.2 and Acceleration Needs, with Special Focus on Food Security*. Rome, FAO. doi.org/10.4060/cd2179en.

IPCC (Intergovernmental Panel on Climate Change). 2023. Summary for policymakers. H. Lee and J. Romero (eds), *Climate Change 2023: Synthesis Report*. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, IPCC, pp. 1–34. www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf.

Kashiwase, H. and Fujs, T. 2023. Strains on freshwater resources. A. F. Pirlea, U. Serajuddin, A. Thudt, D. Wadhwa and M. Welch (eds), *Atlas of Sustainable Development Goals 2023*. Washington DC, World Bank. doi.org/10.60616/93he-j512.

Kuzma, S., Saccoccia, L. and Chertock, M. 2023. 25 Countries, Housing One-quarter of the Population, Face Extremely High Water Stress. World Resources Institute website. www.wri.org/insights/highest-water-stressed-countries.

UNECE/UNESCO/UN-Water (United Nations Economic Commission for Europe/United Nations Educational, Scientific and Cultural Organization/UN-Water). 2024. *Progress on Transboundary Water Cooperation: Mid-Term Status of SDG Indicator 6.5.2, with a Special Focus on Climate Change*. Geneva/Paris, United Nations/UNESCO. https://unesdoc.unesco.org/ark:/48223/pf0000391407?posInSet=1&queryId=1951bc54-df3b-44b4-9005-be568735fb16.

UNEP (United Nations Environment Programme). 2024a. *Progress on Ambient Water Quality: Mid-Term Status of SDG Indicator 6.3.2 and Acceleration Needs, with a Special Focus on Health*. Nairobi, UNEP. www.unwater.org/publications/progress-ambient-water-quality-2024-update.

—. 2024b. *Progress on Water-Related Ecosystems: Mid-Term Status of SDG Indicator 6.6.1 and Acceleration Needs with a Special Focus on Biodiversity*. Nairobi, UNEP. www.unwater.org/publications/progress-water-related-ecosystems-2024-update.

UNESCO/UN-Water (United Nations Educational, Scientific and Cultural Organization/UN-Water). 2020. *The United Nations World Water Development Report 2020: Water and Climate Change*. Paris, UNESCO. https://unesdoc.unesco.org/ark:/48223/pf0000372985.

UN-Habitat/WHO (United Nations Human Settlements Programme/World Health Organization). 2024. *Progress on the Proportion of Domestic and Industrial Wastewater Flows Safely Treated – Mid-Term Status of SDG Indicator 6.3.1 and Acceleration Needs, with a Special Focus on Climate Change, Wastewater Reuse and Health*. Nairobi/Geneva, UN-Habitat/WHO. www.unwater.org/publications/progress-wastewater-treatment-2024-update.

UNICEF/WHO (United Nations Children's Fund/World Health Organization). 2023. *Progress on Household Drinking Water, Sanitation and Hygiene 2000–2022: Special Focus on Gender*. New York, UNICEF/WHO. www.who.int/publications/m/item/progress-on-household-drinking-water--sanitation-and-hygiene-2000-2022---special-focus-on-gender.

United Nations. 2023. *The United Nations World Water Development Report 2023: Partnerships and Cooperation for Water*. Paris, United Nations Educational, Scientific and Cultural Organization (UNESCO). https://unesdoc.unesco.org/ark:/48223/pf0000384655.

—. 2024a. *The United Nations World Water Development Report 2024: Water for Prosperity and Peace*. Paris, United Nations Educational, Scientific and Cultural Organization (UNESCO). https://unesdoc.unesco.org/ark:/48223/pf0000388948?posInSet=2&queryId=7d456b10-1bbb-4395-86fa-063bc64acb8c.

—. 2024b. *The Sustainable Development Goals Report 2024*. New York, United Nations. https://unstats.un.org/sdgs/report/2024/.

—. n.d.a. SDG Progress by Target. United Nations website. https://unstats.un.org/sdgs/report/2024/sdg-progress-by-target/. (Accessed on 2 December 2024.)

—. n.d.b. Progress on Drinking Water (SDG Target 6.1). United Nations website. www.sdg6data.org/en/indicator/6.1.1. (Accessed on 2 December 2024.)

—. n.d.c. Progress on Sanitation (SDG Target 6.2). United Nations website. www.sdg6data.org/en/indicator/6.2.1a. (Accessed on 4 December 2024.)

—. n.d.d. Progress on Water-Use Efficiency (SDG Target 6.4). United Nations website. www.sdg6data.org/en/indicator/6.4.1. (Accessed on 4 December 2024.)

—. n.d.e. Progress on International Water Cooperation (SDG Target 6.a). United Nations website. www.sdg6data.org/en/indicator/6.a.1. (Accessed on 2 December 2024.)

WHO (World Health Organization). 2022. *Strong Systems and Sound Investments: Evidence on and Key Insights into Accelerating Progress on Sanitation, Drinking-Water and Hygiene. UN-Water Global Analysis and Assessment of Sanitation and Drinking-Water (GLAAS) 2022 Report*. Geneva, WHO. https://iris.who.int/handle/10665/365297.

—. 2024. *World Health Statistics 2024: Monitoring Health for the SDGs, Sustainable Development Goals*. Geneva, WHO. https://iris.who.int/handle/10665/376869.

Chapter 1

Introduction

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Mountains, often referred to as the world's 'water towers', play a unique and critical role in the global water cycle. They affect atmospheric circulation, which drives weather and precipitation patterns. They can store water in the form of ice and snow during cold seasons, releasing it during warmer seasons as a major source of fresh water for users downstream.

These mountain waters are vital for meeting basic human needs such as water supply and sanitation. They are essential for ensuring food and energy security (from irrigated agriculture to hydropower and thermal power cooling) to billions of people living in and around mountain regions and areas downstream. They also support economic growth through various water-reliant industries.

Alpine glaciers[2] also store and release water, albeit over long time-frames. While continental glaciers, notably those in Antarctica and Greenland, store vast amounts of fresh water in the form of ice, mountain glaciers have a far more direct impact on the availability of freshwater resources to meet human needs in the immediate and near future.

Water flows from mountains will become more variable, erratic and uncertain

Healthy mountain ecosystems promote flow regulation, aquifer recharge and sediment retention, among other environmental services. They often comprise robust plant, animal and microbial species, yet the ecosystems are fragile and vulnerable to rapid shifts in land cover and climate. Through erosion and sedimentation processes, mountain regions also provide essential nutrients (e.g. minerals) that support terrestrial, estuarine and coastal ecosystems, and fertilize soils downstream. Nevertheless, mountain regions are largely absent from the Sustainable Development Goals (SDGs), with the exception of SDG Targets 6.6, 15.1 and 15.4.

Climate change is accelerating glacier melt, decreasing snow cover, increasing permafrost thaw, and causing more extreme rainfall events and natural hazards. Water flows from mountains will become more variable, erratic and uncertain. Changes in the timing and volume of peak and low flow periods and increased erosion and sediment loads will affect water resources downstream, in terms of quantity, timing and quality (Alder et al., 2022). Many climate change adaptation strategies in mountains are fundamentally related to water. However, although mountain regions are warming more rapidly than lowlands, the current pace, depth and scope of (largely incremental) adaptation measures in mountain regions are insufficient to address future risks to global water security.

Pollution and water quality deterioration upstream invariably affect users downstream. Although little is known about trends in water quality in mountain regions, there is growing evidence for increases in sediment yields in high mountain areas driven by land-use changes (e.g. deforestation), climate change and cryospheric degradation (Li et al., 2021).

The already high dependence of lowland populations on mountain water resources will increase further by mid-century, mainly driven by socio-economic development. This highlights the urgency of improving mountain water governance through integrated river basin management, finance, and knowledge- and capacity-building, in order to meet the world's ever-growing demand for water.

Previous editions of *The United Nations World Water Development Report* have given only limited attention to the cryosphere[3] – including glaciers, snow cover dynamics and permafrost – or to alpine systems, both of which are closely related. In alignment with the designation of 2025 as the International Year of Glaciers' Preservation (General Assembly of the United Nations, 2022a) and the 2022 resolution on sustainable mountain development

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[2] Alpine glaciers are glaciers confined by surrounding mountain terrain; also called mountain glaciers.

[3] The part of the Earth's surface covered by water in its solid form – including glaciers, ice caps, snow, permanently frozen ground (permafrost), lake and river ice, ice sheets and sea ice. The cryosphere forms an important component of the hydrosphere and the global water cycle.

(General Assembly of the United Nations, 2022b), this report aims to draw worldwide attention to the importance of mountain waters, including alpine glaciers, in sustainable development of the mountain regions and the downstream societies that depend upon them, with a focus on the impacts of the rapidly changing mountain cryosphere.

As such, this report examines:

- The dynamics of mountains and alpine glaciers, and their role in the global water cycle as water towers, from a resources management perspective, with implications on water supply, storage and quality.

- The services and benefits mountain waters provide in supporting societies, economies and the environment, highlighting the challenges to users (e.g. human settlements, agriculture and industry) and opportunities (potential benefits) in terms of water supply and sanitation, climate change mitigation and adaptation, food and energy security, and ecosystem protection, restoration and maintenance.

The report also seeks to cultivate a view from a basin perspective, encompassing integrated water resources management, source to sea, transboundary cooperation and other similar interlinking concepts. However, it primarily concentrates on upstream challenges and related interventions, with a particular emphasis on glaciers, the cryosphere and alpine systems, including the latest key global metrics and state-of-the-art knowledge.

1.1 Mountain areas of the world

Several delineations of the world's mountain regions have been developed since the late 1990s, based on digital elevation models (Thornton et al., 2022), culminating with the one from the United Nations Environment Programme World Conservation Monitoring Centre in 2000 (Box 1.1; Kapos et al., 2000). This now serves as the basis for reporting under the 2030 Agenda for Sustainable Development.

Box 1.1 Delineating mountain regions

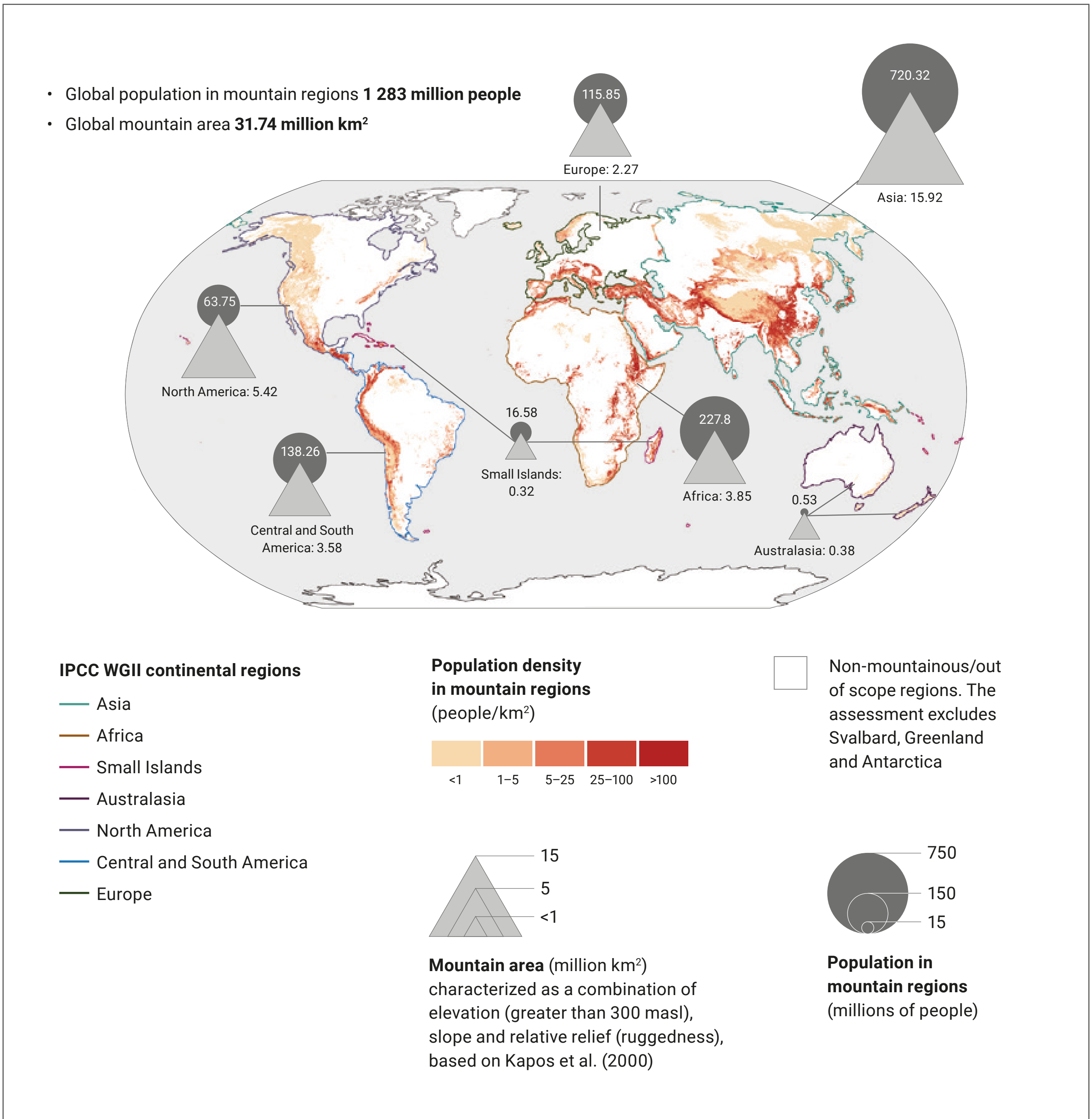
To delineate mountain regions, a combination of terrain characteristics is used: elevation, steepness of slope and relative relief (ruggedness), also termed 'local elevational range' (the difference between minimum and maximum elevation in a grid cell).

The United Nations Environment Programme World Conservation Monitoring Centre mountain delineation uses elevation ranges, with all land lying higher than 2,500 metres above sea level (masl) considered mountainous irrespective of ruggedness. Land lying between 300 masl and 2,500 masl is considered mountainous if slope or ruggedness values exceed predefined thresholds: between 300 m and 1,000 m elevation, a local elevation range of more than 300 m in a grid cell of 7 km radius; between 1,000 m and 1,500 m elevation, more than 5° slope or more than 300 m local elevation range (7 km radius); and between 1,500 m and 2,500 m elevation, more than 2° slope. These thresholds have been proven to be appropriate to exclude mid-elevation plateaux and include lower-elevation areas generally considered mountainous such as the Scottish Highlands (United Kingdom of Great Britain and Northern Ireland), the Massif Central (France) and the low mountains of the Caribbean islands, as well as hills and hilly forelands above 300 masl (Kapos et al., 2000).

Based on the World Conservation Monitoring Centre delineation, mountain regions cover around 33 million km² – or 24% of the global land surface, excluding Antarctica (Romeo et al., 2020). In 2015, some 1.1 billion people (around 15% of the world's population) resided in mountain regions (Figure 1.1) – nearly doubling from just over 575 million in 1975 (Thornton et al., 2022). For comparison, around 900 million people lived in deltas and low-lying coastal regions, including islands, in 2020 (Glavovic et al., 2022).

In 2017, most of the global mountain population (around 91%) lived in developing countries. Around 90% of the total mountain population lived at elevations between 1,500 metres above sea level (masl) and 2,500 masl, with only around 75 million people living higher than 2,500 masl (Tremblay and Ainslie, 2021).

Figure 1.1 Delineation of mountain regions and population densities, 2015



Note: IPCC WGII: Intergovernmental Panel on Climate Change Working Group II; masl: metres above sea level.

Source: Adler et al. (2022, fig. CCP5.1(a), p. 2278).

1.2 Mountain water usage and dependency

As the water towers of the world, mountains are an essential source of fresh water for (irrigated) agriculture, power generation, industry, and large and growing populations – in the mountains and also downstream. Generally, due to higher precipitation and lower evaporation, mountains supply more surface runoff per unit area than lowlands, providing 55–60% of global annual freshwater flows. However, specific values range from 40% to over 90% in different parts of the world (Viviroli et al., 2020). Figure 1.2 illustrates the dependencies of various lowland areas and populations on mountain water.

Key rivers that have been heavily influenced by water sources from mountains (>90% of the mean annual flow) include the Amu Darya, Colorado, Nile, Orange and Rio Negro. Rivers that have depended on mountain waters for more than 70% of their flow include the Euphrates, Indus, São Francisco, Senegal and Tigris (Viviroli et al., 2020).

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Mountains supply 55–60% of global annual freshwater flows

Major cities that have been critically dependent on mountain waters include Addis Ababa, Barcelona, Bogotá, Jakarta, Kathmandu, La Paz, Lima, Los Angeles, Melbourne, Mexico City, New Delhi, New York, Quito, Rio de Janeiro and Tokyo (Kohler et al., 2015).

The main economic activities in mountain regions are agriculture, pastoralism, forestry, tourism, mining, cross-border trade and energy production (see Chapter 5). Mountains provide high-value products such as medicinal plants, timber and other forest products, unique mountain livestock (e.g. alpacas, goats, lamas, vicuñas and yaks) and speciality agriculture products. They are global hotspots of agrobiodiversity, with a large fraction of the world's gene pools for agriculture and medicinal plants preserved in mountains (see Chapter 6).

Globally, up to two-thirds of irrigated agriculture may depend on mountain waters (see Chapter 3), while the number of people in lowlands that strongly depend on water from mountains increased worldwide from around 0.6 billion in the 1960s to some 1.8 billion in the 2000s. An additional 1 billion people in the lowlands benefit from supportive mountain runoff contributions (Viviroli et al., 2020).

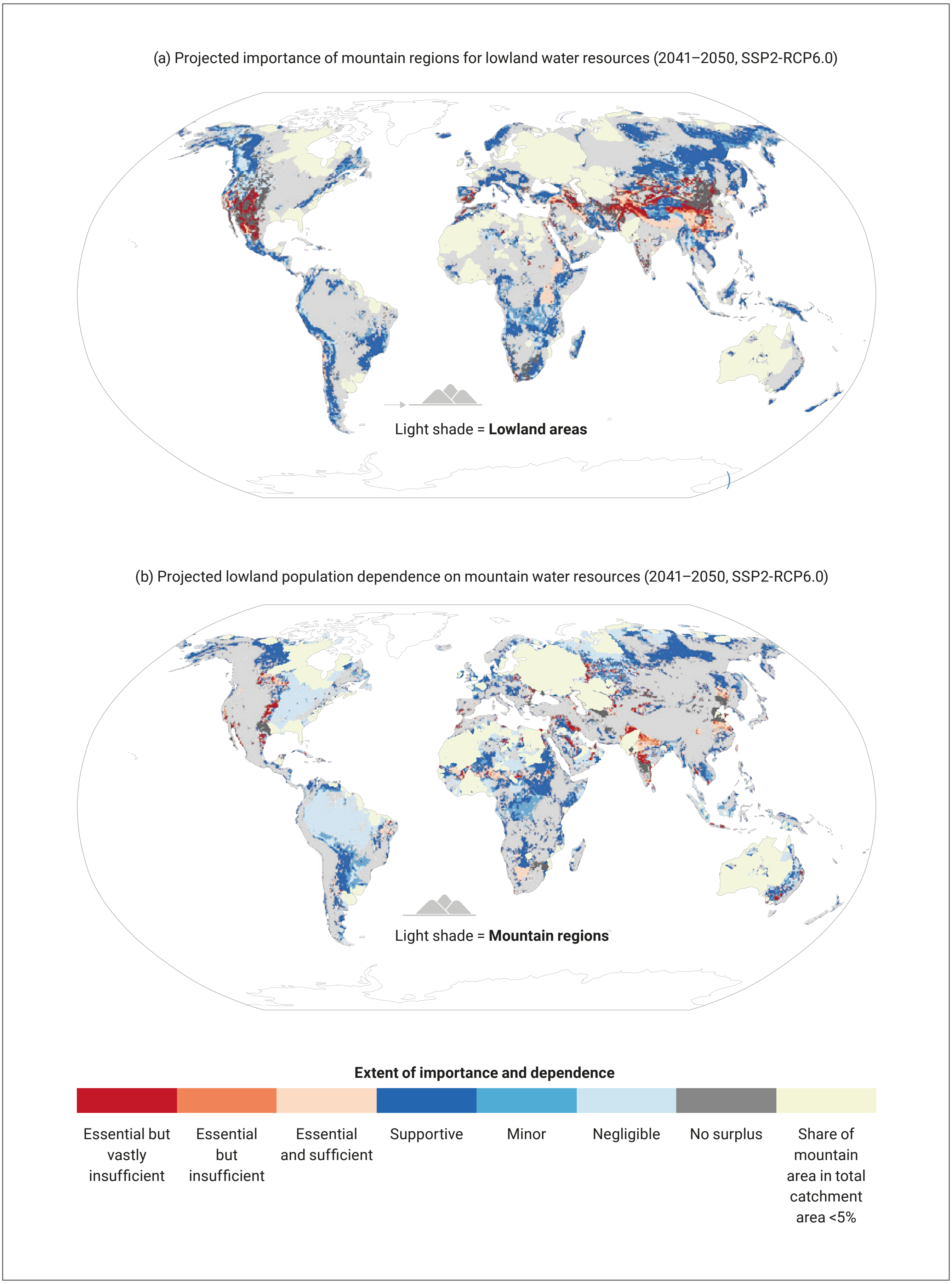
1.3 Mountain people and communities

The majority (78%) of urban land cover globally is outside the mountains (i.e. in the lowlands). Nevertheless, urbanization is also an important aspect in mountain regions, with a substantial share (66%) of the global mountain population living in towns and cities. In 2015, 34% of the global mountain population lived in cities with more than 50,000 inhabitants (compared with 50% in lowlands), including capitals such as Kathmandu, La Paz, Mexico City and Quito, 31% in towns and semi-dense areas (28% in lowlands), and 35% in rural areas, defined as settlements with fewer than 300 people per square kilometre (25% in lowlands) (Ehrlich et al., 2021).

Rapid urbanization in mountain regions poses particular challenges for the development of water supply and sanitation systems (see Chapter 4). The remoteness of mountain communities, the difficult terrain and heightened exposure to natural hazards often lead to higher costs for transport, infrastructure, goods and services. These also pose particular challenges for the financing, development and maintenance of water supply and sanitation systems, drainage networks and other essential water infrastructure. Data on the proportion of people with access to safely managed drinking water and sanitation services in mountain regions are often sparse or incomplete.

Although most people living in rural areas are engaged in farming or pastoral livelihoods, food and nutrition security in mountain regions is lower than in the lowlands, with 35–40% of the mountain population being food insecure and half of them suffering from chronic hunger (Romeo et al., 2020). Remoteness, inaccessibility, distance from roads and food markets, shorter growing seasons, large variability of water availability, and fragmented and small plots can contribute to shortfalls in local food production.

Figure 1.2 Projected importance of mountain regions and population dependence, 2041–2050 (SSP2-RCP6.0)

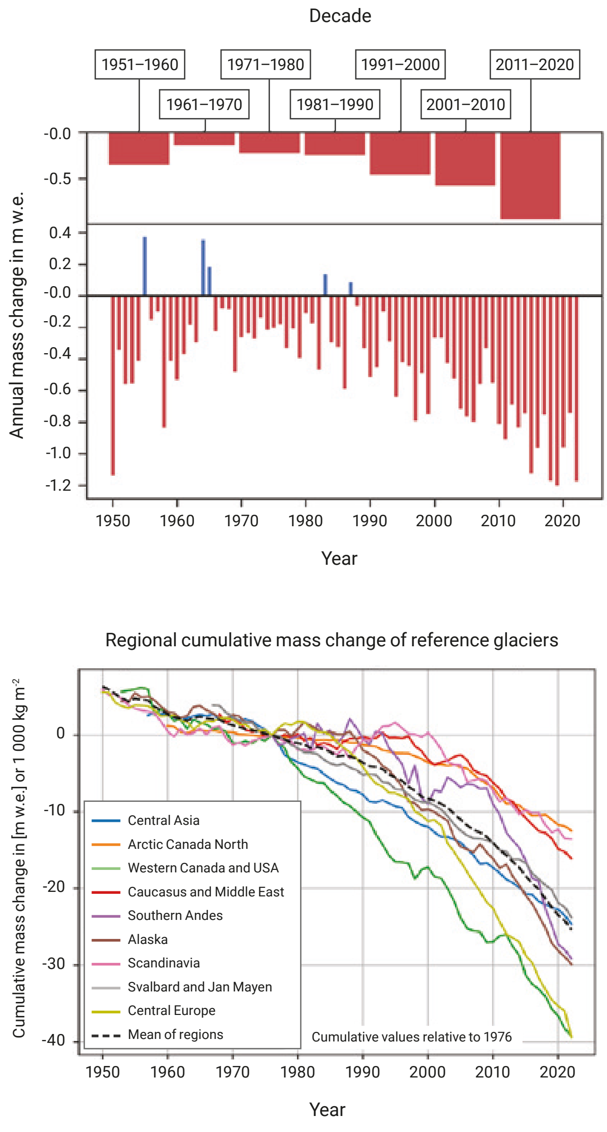


Source: Adler et al. (2022, fig. CCP5.2(a, b), p. 2282).

1.4 Mountain cryosphere, including glaciers

The mountain cryosphere is one of the components of the Earth system that is most sensitive to global climate change (see Chapter 2). It is undergoing rapid and largely irreversible changes because of pronounced warming. In several places, higher elevations appear to be warming faster than lower ones, and the impacts are becoming increasingly evident (Pepin et al., 2022). Most of the world's glaciers, including those in mountains, are melting at an accelerated rate worldwide (Figure 1.3). Combined with accelerating permafrost thaw, declining snow cover and more erratic snowfall patterns (Hock et al., 2019; Adler et al., 2022), this will have significant and irreversible impacts on local, regional and global hydrology, including water availability.

Figure 1.3
Glacier mass changes from around the world, 1950–2020



Note: Top: Annual and decadal mass changes of reference glaciers with more than 30 years of ongoing glaciological measurements. Bottom: Cumulative mass change compared to in 1976 for regional and global means based on data from reference glaciers. Annual mass change values are given on the y-axis in units of metres water equivalent (m w.e.) that correspond to tonnes per square metre (1,000 kg/m^2) and are calculated as arithmetic averages of regional means.

Source: WMO (2023, fig. 14, p. 18, based on data from WGMS (2021)).

Snow-melt accounts for most cryospheric contributions to streamflow in most river basins with a cryosphere component, and is often substantially higher than glacier melt. Snow cover has decreased in nearly all mountain regions, especially in spring and summer, with an expected further decrease in coming decades. The magnitude and timing of snow-melt have already changed considerably, with trends in snow water equivalent being predominately negative across the world in the past few decades (Hock et al., 2019).

Most of the world's glaciers, including those in mountains, are melting at an accelerated rate worldwide

Mountain hazards, such as flash floods, debris flows, glacial lake outburst floods, landslides and avalanches, and the ensuing risks to societies, are expected to increase due to climate change, causing severe damage and disruption to people, communities and infrastructure (Adler et al., 2022).

References

Adler, C., Wester, P., Bhatt, I., Huggel, C., Insarov, G., Morecroft, M., Muccione, V. and Prakash, A. 2022. Mountains. H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem and B. Rama (eds), *Climate Change 2022: Impacts, Adaptation and Vulnerability.* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK/New York, Cambridge University Press, pp. 2273–2318. doi.org/10.1017/9781009325844.022.

Ehrlich, D., Melchiorri, M. and Capitani, C. 2021. Population trends and urbanisation in mountain ranges of the world. *Land*, Vol. 10, No. 3, Article 255. doi.org/10.3390/land10030255.

General Assembly of the United Nations. 2022a. International Year of Glaciers' Preservation, 2025. Resolution adopted by the General Assembly on 14 December 2022. Seventy-seventh session, A/RES/77/158. https://documents.un.org/doc/undoc/gen/n22/755/97/pdf/n2275597.pdf.

—. 2022b. Sustainable Mountain Development. Resolution adopted by the General Assembly on 14 December 2022. Seventy-seventh session, A/RES/77/172. https://documents.un.org/doc/undoc/gen/n22/756/81/pdf/n2275681.pdf.

Glavovic, B. C., Dawson, R., Chow, W., Garschagen, M., Haasnoot, M., Singh, C. and Thomas, A. 2022. Cities and settlements by the sea. H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem and B. Rama (eds), *Climate Change 2022: Impacts, Adaptation and Vulnerability.* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK/New York, Cambridge University Press, pp. 2163–2194. doi.org/10.1017/9781009325844.019.

Hock, R., Rasul, G., Adler, C., Cáceres, B., Gruber, S., Hirabayashi, Y., Jackson, M., Kääb, A., Kang, S., Kutuzov, S., Milner, A., Molau, U., Morin, S., Orlove, B. and Steltzer, H. 2019. High mountain areas. H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds), *Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK/New York, Cambridge University Press, pp. 131–202. doi.org/10.1017/9781009157964.004.

Kapos, V., Rhind, J., Edwards, M., Price, M. and Ravilious, C. 2000. Developing a map of the world's mountain forests. M. Price and N. Butt (eds), *Forests in Sustainable Mountain Development: A State of Knowledge Report for 2000.* International Union of Forest Research Organizations (IUFRO) Research Series 5. Wallingford, UK, CABI Publishing, pp. 4–19. doi.org/10.1079/9780851994468.0004.

Kohler, T., Balsiger, J., Rudaz, G., Debarbieux, B., Pratt, D. J. and Maselli, D. (eds). 2015. *Green Economy and Institutions for Sustainable Mountain Development: From Rio 1992 to Rio 2012 and Beyond.* Bern, Centre for Development and Environment (CDE)/Swiss Agency for Development and Cooperation (SDC)/University of Geneva/Geographica Bernensia. https://boris.unibe.ch/17634/1/Final_Version_Green_Economy_2015%282%29.pdf.

Li, D., Lu, X., Overeem, I., Walling, D. E., Syvitski, J., Kettner, A. J., Bookhagen, B., Zhou, Y. and Zhang, T. 2021. Exceptional increases in fluvial sediment fluxes in a warmer and wetter High Mountain Asia. *Science*, Vol. 374, No. 6567, pp. 599–603. doi.org/10.1126/science.abi9649.

Pepin, N. C., Arnone, E., Gobiet, A., Haslinger, K., Kotlarski, S., Notarnicola, C., Palazzi, E., Seibert, P., Serafin, S., Schöner, W., Terzago, S., Thornton, J. M., Vuille, M. and Adler, C. 2022. Climate changes and their elevational patterns in the mountains of the world. *Reviews of Geophysics*, Vol. 60, Article e2020RG000730. doi.org/10.1029/2020RG000730.

Romeo, R., Grita, F., Parisi, G. and Russo, L. 2020. *Vulnerability of Mountain Peoples to Food Insecurity: Updated Data and Analysis of Drivers*. Rome, Food and Agriculture Organization of the United Nations (FAO)/United Nations Convention to Combat Desertification (UNCCD). doi.org/10.4060/cb2409en.

Thornton, J. M., Snethlage, M. A., Sayre, R., Urbach, D. R., Viviroli, D., Ehrlich, D., Muccione, V., Wester, P., Insarov, G. and Adler, C. 2022. Human populations in the world's mountains: Spatio-temporal patterns and potential controls. *PLoS ONE,* Vol. 17, No. 7, Article e0271466. doi.org/10.1371/journal.pone.0271466.

Tremblay, J. C. and Ainslie, P. N. 2021. Global and country-level estimates of human population at high altitude. *Proceedings of the National Academy of Sciences of the United States of America (PNAS)*, Vol. 118, No. 18, Article e2102463118. doi.org/10.1073/pnas.2102463118.

Viviroli, D., Kummu, M., Meybeck, M., Kallio, M. and Wada, Y. 2020. Increasing dependence of lowland populations on mountain water resources. *Nature Sustainability*, Vol. 3, pp. 917–928. doi.org/10.1038/s41893-020-0559-9.

WGMS (World Glacier Monitoring Service). 2021. *Global Glacier Change Bulletin No. 4 (2018–2019).* Zurich, Switzerland, WGMS. https://wgms.ch/downloads/WGMS_GGCB_04.pdf.

WMO (World Meteorological Organization). 2023. *The Global Climate 2011-2020: A Decade of Accelerating Climate Change*. WMO-No. 1338. Geneva, WMO. https://library.wmo.int/records/item/68585-the-global-climate-2011-2020.

Chapter 2

Changes in the cryosphere and impacts on water

UNESCO IHP*

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Mountain regions span a wide range of elevations. In this chapter, 'high mountains' are defined as mountains where snow and ice play an important role in global freshwater provisioning (Viviroli et al., 2020; IPCC, 2023) and the local or regional hydrological cycle. Although the two are related, hydroclimate – as opposed to elevation – is a more relevant categorical basis for understanding impending changes in the mountain cryosphere and the consequences for water. Often called 'water towers', high mountains receive greater amounts of precipitation than lower-lying areas and are responsible for generating large amounts of runoff and streamflow (Immerzeel et al., 2020; Viviroli et al., 2020). Much of this precipitation occurs as snowfall, which is stored as seasonal snowpacks and glacial ice during cold periods and then released as meltwater during warmer periods.

High mountains receive greater amounts of precipitation than lower-lying areas and are responsible for generating large amounts of runoff and streamflow

It is often stated that about 2 billion people depend on mountains – and therefore on contributions from the melting cryosphere – for their freshwater supply. This is a number derived from the estimate that 2 billion people live in drainage basins that originate in mountains (Immerzeel et al., 2020; Viviroli et al., 2020). Nevertheless, the relative importance and contributions of melting snow, ice and frozen ground to downstream water resources availability and quality are often poorly understood and mischaracterized (Gascoin, 2024). Generalizations such as "*Himalayan glaciers alone provide water to 1.4 billion people*" (Milner et al., 2017, p. 9771) or "*Glaciers are crucial sources of life on Earth as they provide vital water resources to half of humanity for domestic use, agriculture and hydropower*" (UNESCO/IUCN, 2022, p. 3) can leave the inaccurate impression that, without glaciers, billions of people will be without water (Gascoin, 2024).

Glaciers play an important role in freshwater provisioning, but they do so with far more nuance and regional variation than the above claims suggest. It must be recognized that multiple other hydroclimatic processes are also involved in freshwater systems. In fact, in most high mountain areas, the seasonal snowpack, rather than glaciers, is the primary source of runoff (Barnett et al., 2005). Climate change is radically affecting all components of the mountain cryosphere. Therefore, the complexities of such impacts need to be explicitly examined and addressed.

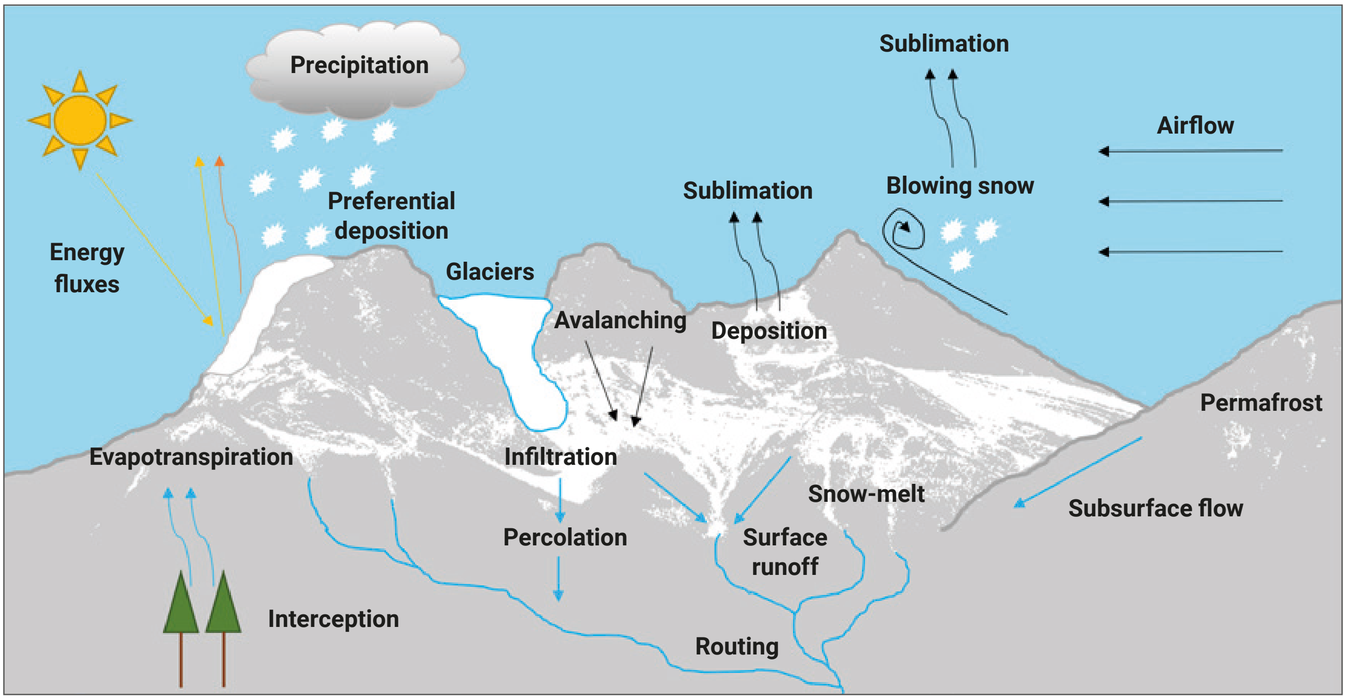
This chapter describes why high mountains are hydrologically significant and how the mountain cryosphere is changing. Global warming is amplified at most high elevations, and is reducing snow accumulation and snow cover duration, accelerating glacier mass loss and retreat, causing permafrost (permanently frozen ground) thaw, and advancing the timing and sometimes the rate of snow and ice melt, with high spatial and temporal variability (Pepin et al., 2022; IPCC, 2023). The previously predictable timing of warm season melt is being replaced by more variable rainfall-dominated runoff regimes, with complex downstream effects. The potential impacts of these changes on freshwater systems and the occurrence of extreme events (including droughts, floods, landslides and more) are discussed below, along with implications for downstream ecosystems and communities.

2.1 Dynamics of the mountain cryosphere

2.1.1 High mountain hydrological processes

Mountains form the headwaters of many rivers around the world, and so play a major role in the global hydrological cycle (Figure 2.1). Cyclical warm season melting of mountain snowpacks and glaciers releases fresh water, which can flow directly into streams and rivers or percolate into the ground, replenishing soil moisture and groundwater.

Figure 2.1 High mountain hydrological and cryospheric processes governing water supply



Source: Adapted from Bertoncini (2024, fig. 1.1, p. 5).

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In most high mountain areas, the seasonal snowpack, rather than glaciers, is the primary source of runoff

In many high mountain regions, the formation of seasonal snow cover provides most of the freshwater storage. This is referred to as 'snow water equivalent' (SWE) – the amount of water that a given volume of snowpack would yield if melted (Barnett et al., 2005). As shown in Figure 2.1, mountain snowpacks can be redistributed by wind through blowing snow (Pomeroy and Li, 2000), by gravity through snow avalanches (Bernhardt and Schultz, 2010) and by forests through interception (Hedstrom and Pomeroy, 1998). Mountain topography induces preferential deposition of snowfall on downwind slopes (Lehning et al., 2008). Blowing and intercepted snow are subject to high sublimation[4] losses that can reduce mountain SWE by up to half (Essery and Pomeroy, 2004; Pomeroy et al., 2022). Melt occurs preferentially on sunward-facing slopes, is faster during warm rainfalls, and is slower under forest canopies. Therefore, slope orientation and forest cover strongly control the peak and duration of snow-melt streamflow hydrographs (Marks et al., 1998; Ellis et al., 2013). Partitioning of meltwater between infiltration and runoff depends on melt rate, soil texture, saturation and the presence of seasonally or permanently frozen ground. Frozen ground reduces soil permeability; its occurrence diminishes with warming climate and increasing snow-free season duration.

Snow redistribution processes cause snow-melt volumes to have a strong sensitivity to changing vegetation. Expanding tundra shrubs can reduce snow redistribution and sublimation, thereby increasing SWE. Conversely, afforestation increases sublimation losses, thus reducing SWE. Snow-melt is especially sensitive to climate change, as it can increase or decrease mountain precipitation and increase air temperature and humidity, thereby decreasing the fraction of precipitation falling as snowfall, advancing the timing of snow-melt, causing changes in rain-on-snow (ROS) melt events, and accelerating or decelerating snow-melt rates. Melt rates generally decline with increasing vegetation.

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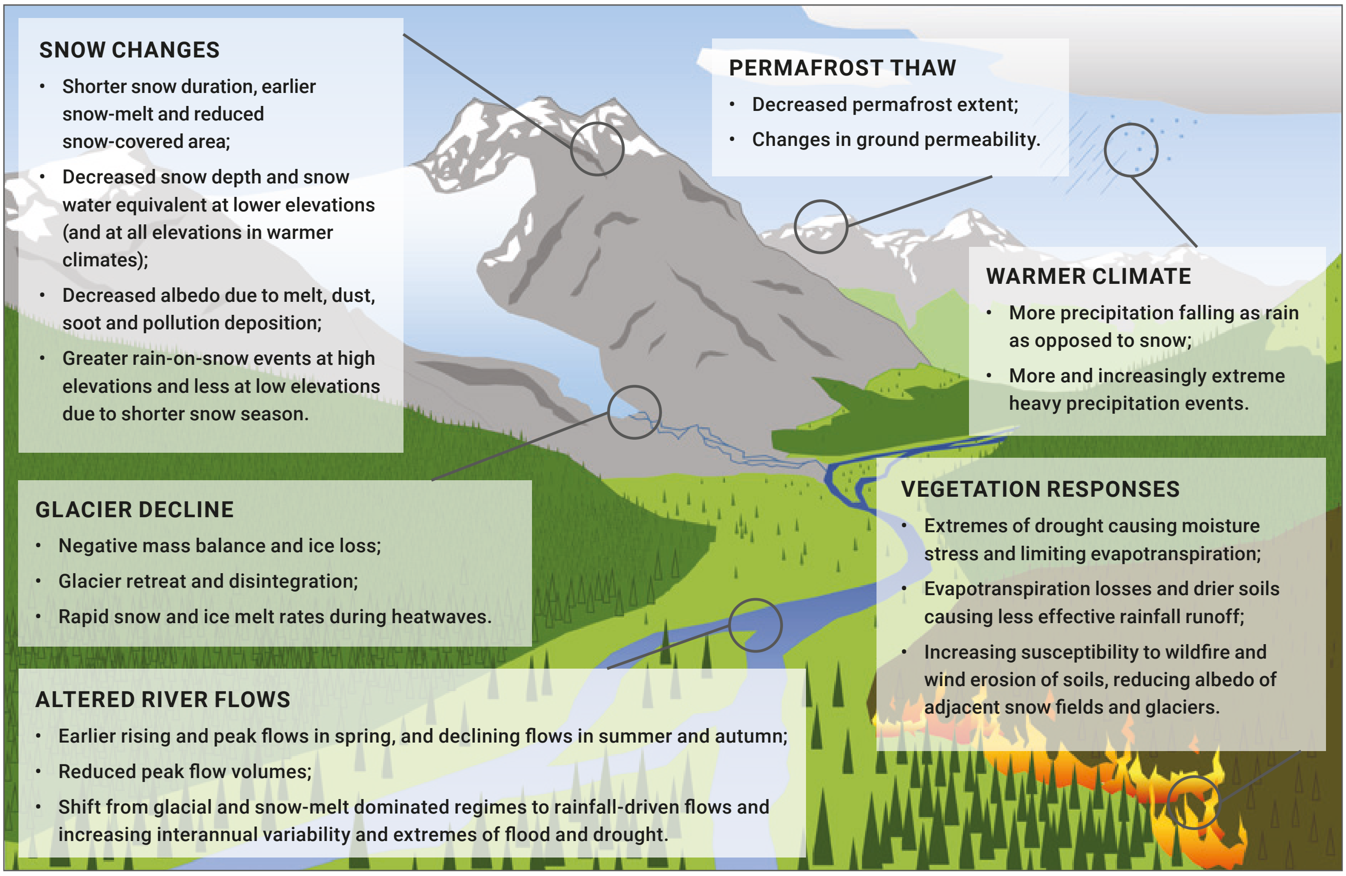
[4] Direct conversion of water from its solid form (snow or ice) to its gaseous form (water vapour), without first melting into liquid water (USGS, 2019).

Climatic conditions permitting, not all snow will melt. If left for many years, perennial snowpacks can develop into glacial ice (DeBeer et al., 2020). The seasonal accumulation of snow and gradual compression into firn[5] and then ice will increase the mass of a glacier, whereas warm season ablation[6] will decrease it. The glacier mass balance is the net difference between snow accumulation and snow and ice ablation. Ablation via melt and sublimation is strongly affected by snow cover duration, net radiation and temperature. These are affected by air temperature, cloud cover, ice surface albedo, winter snowfall and snow redistribution, and so are sensitive to climate change.

Dust, combustion-related soot deposits including black carbon, and microbial and algal growth on snow and glacier surfaces are becoming more common due to increased frequency and/or intensity of dust storms, air pollution and wildfires (Box 2.1). They can accelerate melt rates by decreasing surface albedo until the next snowfall (Aubry-Wake et al., 2022). However, if a rocky debris cover is sufficiently thick, an ice mass can be insulated from external warming and persist long after the rest of a glacier recedes (Miles et al., 2020).

Glacierized mountain environments have complex hydrology. The presence of glaciers increases snow accumulation and cold drainage winds, reduces stream temperatures and delays streamflow generation. Subglacial pathways guide meltwater through various terrains, including rock beds and moraines, and recharge groundwater, although these processes are often poorly understood (Müller et al., 2022). Figure 2.2 summarizes some of the expected shifts in high mountain environments due to atmospheric warming.

Figure 2.2 Key cryospheric and hydrological changes in high mountain regions under 21st century global warming



Source: Authors.

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5 An intermediate stage in the transformation of snow into glacial ice (USGS, 2013).

6 The loss of snow and ice from a glacier (e.g. through melt, evaporation, sublimation or calving) (USGS, 2013).

Box 2.1 Impact of black carbon, dust and other particulate matter deposition on snow and ice melt

With a warming climate, mountain regions globally are receiving emissions from an increasing number of wildfires and dust storms. Together with human activities, these are leading to growing deposition of black carbon and other particulate matter on glacier surfaces and perennial snowpacks. Such matter can be transported over vast distances, even from continent to continent. The impurities darken snow and ice surfaces, thus causing greater absorption of solar radiation. In addition, they may support microbial growth that can further darken the surface and hold impurities in place for long periods. This can significantly influence the surface energy balance, thereby increasing melt rates, especially during periods and at locations of high incoming solar radiation. This is increasingly being recognized as an important and influential factor (Zhang et al., 2021; Bertoncini et al., 2022).

There are complexities and interacting processes that make the impacts of particulate deposition less straightforward than simply enhancing melt rates. The deposition tends to be local to regional in scale, with considerable spatial variability. The effects may be short lived as subsequent snowfall covers the previous surface and refreshes the albedo, or as melt or rainfall events wash ice surfaces. However, in some locations, this can set up a positive feedback, where melting concentrates impurities and further darkens the surface and enhances the melt. Wildfire smoke can also reduce incoming solar radiation to the point of even causing surface cooling, counteracting the effect of a reduction in albedo (Aubry-Wake et al., 2022).

The deposition of black carbon and other particulates onto snow and ice surfaces can have a large impact on the surface energy balance and melt. How this is changing, how long lived the effects are, what feedback and process interactions are occurring, and how variable this is across the world are not well understood. It is therefore important to elucidate for predicting future water resources in mountain regions.

Soot-free Athabasca Glacier, Canada, October 1993

Photo: John Pomeroy.

Soot from wildfires and algae darken the Athabasca Glacier, August 2019

Photo: John Pomeroy.

2.1.2 Trends in the mountain cryosphere

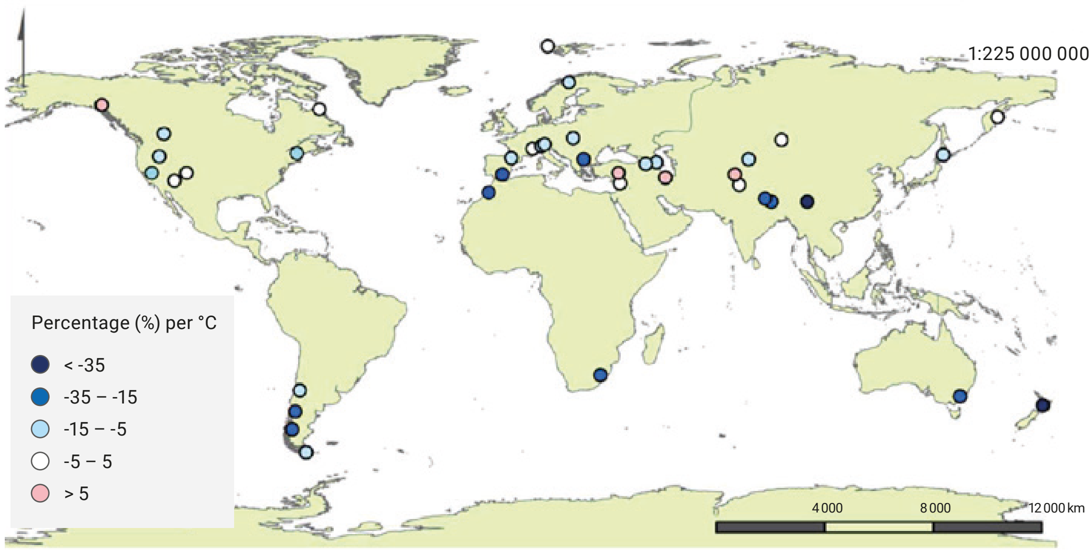
Evidence of atmospheric warming since the early 20th century is present in all mountain ranges. The effects are amplified at higher elevations in certain regions (Mountain Research Initiative EDW Working Group, 2015; Hock et al., 2019a; Pepin et al., 2022). The elevation at which rainfall transitions to snowfall is shifting upwards due to warming. Lower elevations and warmer climates are therefore undergoing greater decreases in snow cover depth and duration, whereas colder, higher elevations may experience increased peak SWE where precipitation increases and sublimation losses decrease with climate change (López-Moreno et al., 2020).

Evidence of atmospheric warming since the early 20th century is present in all mountain ranges

Trends across mountain basins include a greater fraction of precipitation falling as rain rather than snow, reduced snow redistribution and snow-covered area, and earlier snow-melt (Figure 2.2). This results in decoupling of the streamflow generation regime from the snow-melt regime, where the effect of 'snow damming' on the spring freshet[7] is rapidly reduced, leaving streamflows to respond rapidly to winter rainfall and associated melt events (López-Moreno et al., 2020).

Snow accumulation and peak SWE decrease more quickly with warming than melt rates increase (Pomeroy et al., 2022). The decrease of SWE with warming is greater on sunward-facing slopes, unforested areas and lower elevations, and the increase of melt rates with warming is greater at lower elevations and in warmer climates. ROS events are projected to decline with warming in most high mountain basins, with greater declines at lower elevations and in warmer climates, whereas increases in ROS are projected at high elevations and in colder climates (Figure 2.3; López-Moreno et al., 2021). As climate warming progresses, diminished snowpacks and earlier snow-melt, including more midwinter melt events, will reduce freshet volume and advance peak flows by weeks or months (López-Moreno et al., 2020).

Figure 2.3 Percentage change per 1°C of warming in the frequency of rain-on-snow (ROS) melt events in high mountains around the world, 1982–2014



Note: Pink dots correspond to mountains with the greatest increase in ROS event frequency with warming, and black dots the greatest decline.

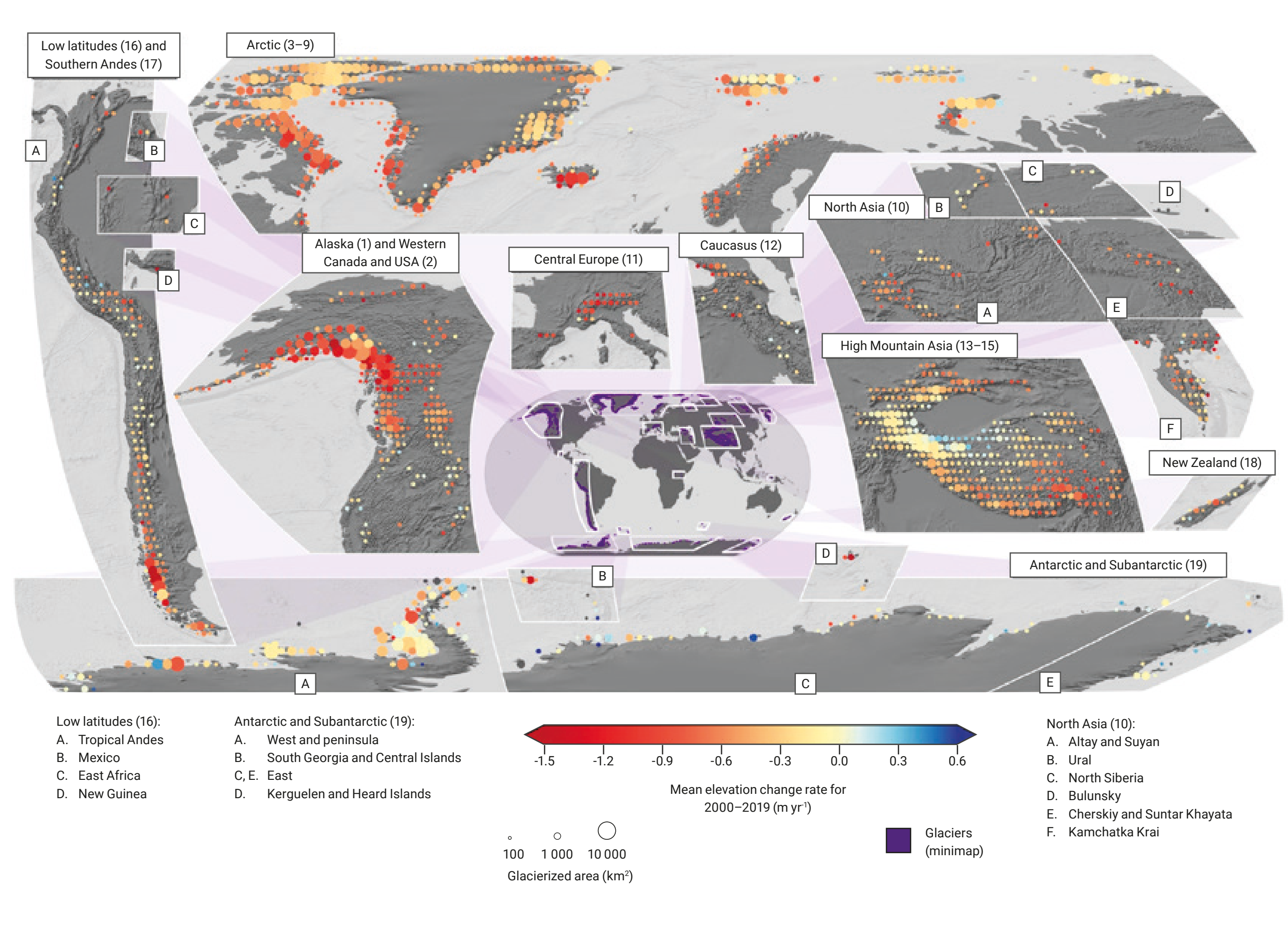
Source: López-Moreno et al. (2021, fig. 6, p. 7). Licence CC BY 4.0.

Mountain regions where snowpacks no longer persist through the warm season will inevitably see their glaciers disappear, as perennial snowpacks are necessary to sustain glacier mass. The retreat and loss of glaciers have been ongoing since the 20th century in most parts of the world (DeBeer et al., 2020; IPCC, 2023), and have accelerated in recent decades (Zemp et al., 2019). Most mountain glaciers around the world are thinning rapidly (Figure 2.4; Hugonnet et al., 2021) and are out of balance with the current climate. This means they will continue to shrink regardless of reductions in greenhouse gas emissions (Cook et al., 2023). Further atmospheric warming will exacerbate the imbalance globally; with

[7] A peak in streamflow arising from spring snow-melt.

global warming of between 1.5°C and 4°C, mountain glaciers worldwide are projected to lose 26% to 41% of their total mass by 2100, relative to 2015. A great number of individual glaciers will disappear entirely, leaving many currently glaciated mountain headwaters unglaciated (Rounce et al., 2023).

Figure 2.4 Global glacier surface elevation changes, 2000–2019



Note: Declining glacier surface elevation and ice loss are seen in mountain regions worldwide, with only a few limited areas where increases have been observed.

Source: Hugonnet et al. (2021, fig. 2, p. 727). This figure is reproduced with permission from SNCSC; the Attribution-ShareAlike 3.0 IGO (CC BY-SA 3.0 IGO) licence does not apply to this figure.

2.2 Impacts of changing mountain snow and ice conditions

2.2.1 Freshwater responses

The relative contributions of different cryosphere components (e.g. snow, glacial ice and permafrost) to freshwater supply vary regionally, topographically, interannually and seasonally. The impacts of cryospheric changes will depend upon how downstream systems – human and natural – respond to emerging surface water and groundwater supply, including the quantity, timing, duration and reliability of streamflow discharge. The loss of synchronization between the timing of mountain runoff and downstream demand is a great concern for water users. Regions where water use has historically coincided with warm season snow and glacier melt are the most vulnerable to change. Local variations must be considered when designing policy responses for mitigation and adaptation.

The contributions of glacier melt to available water supply vary in importance. For example, in the Tropical Andes, Buytaert et al. (2017) found that glacier melt contributed only 2.2% of annual available water in Quito, Ecuador, in a normal year. Whereas further south in La Paz, Plurinational State of Bolivia, they found glacier melt contributed 15% of the annual water supply, and in Huaraz, Peru, melt contributed 19%. Meanwhile, in the Bow River basin in Canada (home to 2 million people), snow-melt, rather than glacier melt, is of far greater importance to annual streamflow volume – snow-melt accounts for 60–80% of available flow (Fang and Pomeroy, 2023). As a major contributor to freshwater supply, mountain snow regimes – and specifically how mountain snow regimes are changing – should be a priority research area.

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Glacier melt drought buffering can be crucial for sustaining agricultural production

Although the significance of glaciers to freshwater supply is often overstated (Box 2.2), they do offer other important water security benefits. Drought buffering (referring to increases in glacial melt during hot, dry periods that can compensate for an otherwise lack of fresh water) can enhance downstream resilience to periods of water stress. Glaciers melt fastest during the warmest, driest periods, and so, especially once the mountain snowpack has been depleted, their rapid melt can play a critical role in maintaining streamflow until the end of the dry period (Hopkinson and Young, 1998).

In regions where the dry season coincides with the growing season, glacier melt drought buffering can be crucial for sustaining agricultural production. Buytaert et al. (2017) found that in the Tropical Andes, the monthly maximum area of irrigated land sourcing at least 25% of water from glacier melt doubled during drought years. For high mountain communities dependent on water derived from glacial inputs for food production or other crucial purposes, glacial recession may force changes to historical practices (see Box 3.4) or may render communities more dependent on increasingly uncertain surface water and groundwater resources. As mountain glaciers recede and disappear, high mountain regions will lose their valuable buffering capacity, and downstream regions may suffer decreased resilience to dry or drought conditions (Fang and Pomeroy, 2023).

Box 2.2 Caution against applying the 'peak water' concept in water resources policy

The concept of peak water is commonly used to discuss the impacts of glacial recession. It suggests that as glacier melt rates increase and glacier areas decrease with warming, there will be an initial increase in glacial discharge volumes to a 'peak' owing to melt rate increase, followed by a decline due to shrinking glacier coverage (Huss and Hock, 2018; Hock et al., 2019b).

This is an idealized concept that should be applied for glacier discharge only, and which may not be reflected in overall mountain headwater streamflows. Most streams in glacierized basins are not glacier fed only, and so other hydrological changes must be considered when making streamflow predictions (e.g. precipitation regime shifts, snowpack change, vegetation change and groundwater interactions).

For instance, mountain precipitation is predicted to increase in many parts of the world. Streamflow responses are unlikely to all follow a glacial melt peak and then decline trend, as most streamflow volumes are also influenced by snow-melt and rainfall runoff. Glaciers around the world are retreating; many of their seasonal contributions to discharge have expanded and will decline. For water resources management purposes, the idealized peak water trend weakens as the size of the basin increases where the basin outflow is further downstream from the glaciers.

It must also be emphasized that while high mountains are indeed 'water towers', the reliance of downstream communities on glaciers for their water resources is often mischaracterized (Viviroli et al., 2020). Claims overstating the importance of glaciers to global water resources are often made (e.g. that the "*Himalayan glaciers alone provide water to 1.4 billion people*" (Milner et al., 2017, p. 9771)), and leave the public with the inaccurate impression that, without glaciers, half of humanity will be without water (Gascoin, 2024).

The mountain cryosphere (including glaciers) plays an important role in freshwater provisioning; however, the relative significance of glaciers, snow and ice to freshwater resources is highly variable across time and space. Water resources managers and policymakers should be wary of this 'glacier sensationalism' and recognize if and how their local contexts differ from globally themed messages.

The relative contribution of glaciers to freshwater supply decreases with distance downstream from the glaciers. The examples in Figure 2.5 (Kaser et al., 2010) show that the downstream impact of glacier hydrology on river discharge declines substantially with distance from glaciers, and that contributions are insubstantial at the river outlet. Communities living closest to glacier termini will therefore be most vulnerable to the impacts of glacier recession, although the drought-resilience benefits remain relevant, even for distant downstream communities otherwise not overwhelmingly dependent on glaciers for their water resources. And although not well understood, mountain groundwater and the impacts of thawing permafrost on baseflow are expected to grow increasingly important as receding glaciers disappear (Arenson et al., 2022; van Tiel et al., 2024).

2.2.2 Ecological responses

Climate-induced changes in the mountain cryosphere are altering hydrological and water quality regimes. Snow and ice are habitats for many species, and are biologically active ecosystems (Jones et al., 2001). They play a key role in the biogeochemical cycling of carbon, nitrogen and other elements (Sharp and Tranter, 2017). In high mountain environments, anticipated ecological responses to a snowier and rainier climate include increasing availability of liquid water near the surface throughout the year, tree and shrub colonization of higher elevations, enhanced nutrient and contaminant mobility, growth of algae and other microorganisms, and greater organic carbon production (Rasouli et al., 2019; Verrall and Pickering, 2020).

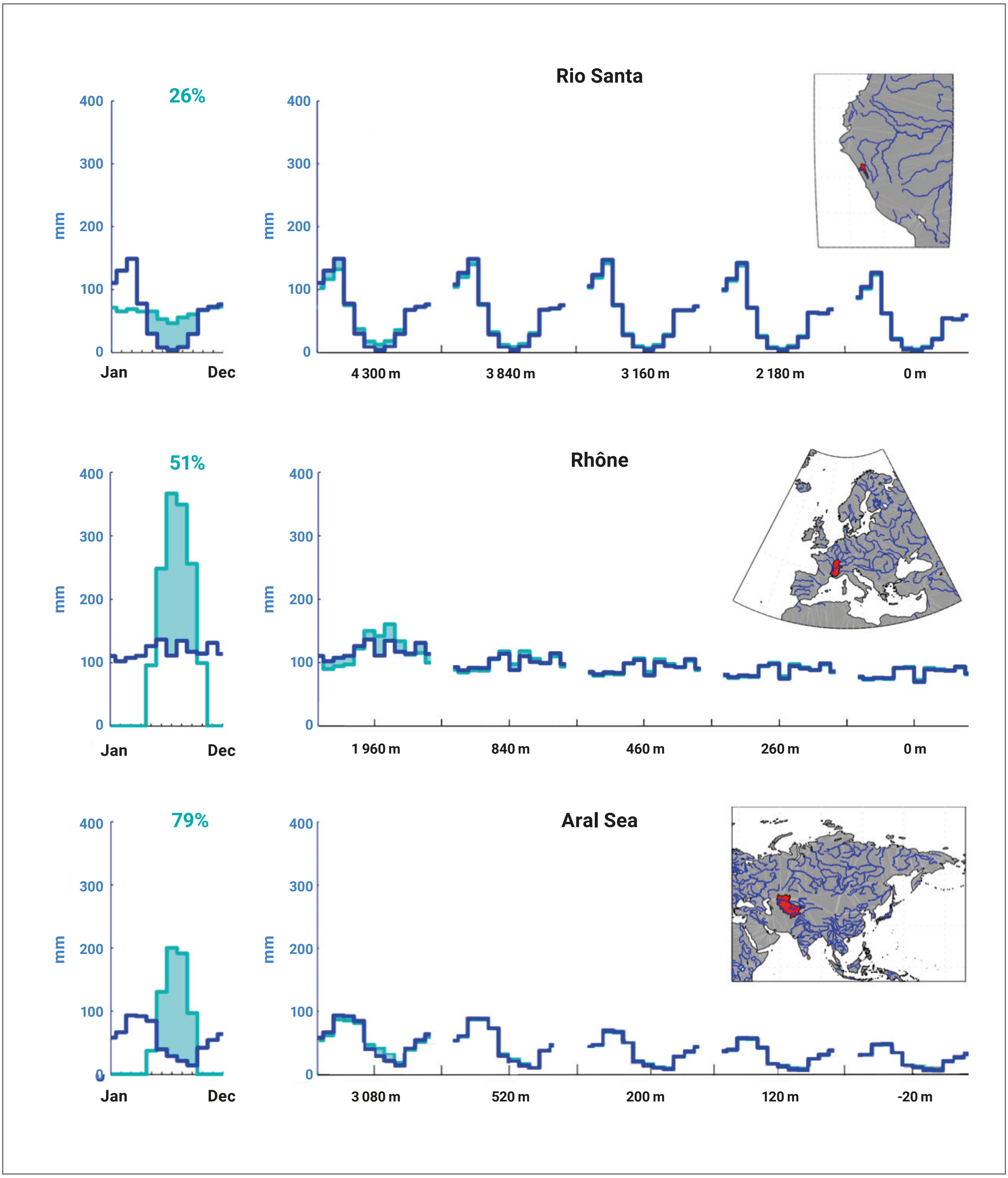
Deglaciation is projected to have major implications for aquatic food webs

Feedback effects between wildfires, dust storms and glacier algal growth have been observed with nutrients in the carbon deposits, creating fertile algal habitats that can accelerate melt by decreasing glacier and snow albedo (Williamson et al., 2019; Aubry-Wake et al., 2022). Water quality in mountain regions is also of concern. Some studies have suggested that permafrost degradation in mountain regions underlain by sulphide-bearing bedrock may facilitate the previously inhibited oxidation of sulphide minerals, thereby increasing heavy metal concentrations in groundwater stores (Ilyashuk et al., 2018) (see Chapter 6).

Hydroecological impacts extend downstream into riverine, lake and nearshore marine environments. Impacts include changes in sediment and thermal regimes, shifts in biogeochemical and contaminant fluxes, changes in habitat availability and quality, and modifications in species biodiversity patterns (Milner et al., 2017; Somers and McKenzie, 2020). Vanderwall et al. (2024) found that glacier-influenced lakes possess biogeochemical characteristics distinct from those of snow-fed mountain lakes. Deglaciation is projected to have major implications for aquatic food webs, with impacts in glacially fed lakes and streams being the most significant.

Glaciers play an important thermoregulating role in freshwater and nearshore marine habitats, with glacier meltwater and groundwater emanating from ice-bearing rock glaciers helping to maintain consistent, cool temperatures crucial for some fish species (Harrington et al., 2017; Somers and McKenzie, 2020). Alterations in mountain glacial runoff and temperature regimes have been found to have positive and negative effects on the sustainability of anadromous fish species, such as salmon (O'Neel et al., 2015). A significant proportion of the variation in nearshore pelagic algal abundance and distribution and abundance of zooplankton, fish and seabirds in Alaskan coastal ecosystems has been linked to changes in glacial freshwater input, particularly temperature and turbidity (Arimitsu et al., 2016). In high mountain arid regions, glaciers can also sometimes be the main source of fresh water supporting wetlands (Azócar and Brenning, 2010; Schaffer et al., 2019).

Figure 2.5 Glacier melt and precipitation contributions to river discharge in example major basins with mountain headwaters



Note: Left: Mass budget of glacierized areas (snow + ice), with monthly accumulation (dark blue), monthly ablation (turquoise) and volume of glacier snow and ice melt runoff (turquoise shading). Percentages indicate the annual precipitation on the glacier that runs off as seasonally delayed meltwater. Right: Effect of seasonally delayed snow and ice runoff on river discharge as a function of elevation (x-axis), starting at the glacier terminus and ending at the river's outlet, with annual precipitation (dark blue) and glacier snow and ice melt (turquoise).

Source: Adapted from Kaser et al. (2010, fig. 1, p. 20224). The Attribution-ShareAlike 3.0 IGO (CC BY-SA 3.0 IGO) licence does not apply to this figure.

2.2.3 Hazards

The consequences of climate change, including higher temperatures, glacial recession, permafrost thaw and changing precipitation patterns, can affect flood and landslide risks (Carrivick and Tweed, 2016; Chiarle et al., 2021). The processes associated with these risks, such as debris flows and floods, avalanches, rock- and icefalls, landslide dam outburst floods and glacial lake outburst floods (GLOFs)[8], are collectively referred to as 'geohazards'. They can pose significant threats to communities, wildlife and infrastructure in mountain regions (Chiarle et al., 2021). Although these events may occur in isolation, cascading effects (whereby one process triggers another) are possible, as are feedback effects between them (Box 2.3; Chiarle et al., 2021).

Geohazard events are being observed in mountain regions globally. For example, along the Teesta River in India, a GLOF in 2023 caused a rapid water surge reaching a height of 5–6 m. At least 30 fatalities were reported, and a hydroelectric dam was destroyed (ESCAP, 2023). In the Andes of central Chile, deglaciation likely played a role in the Parraguirre Creek landslide, which evolved into a debris flow event that travelled 57 km, killing 37 people and generating severe infrastructure damage in 1987 (Sepúlveda et al., 2023).

Box 2.3 Snow drought–wildfire–debris flow feedback

Feedback effects between snow and ice melt and downstream hydrological impacts and wildfire occurrences can exacerbate geohazard events. Severe wildfire seasons usually start with snow droughts consisting of early melt of a low snow water equivalent snowpack owing to warm, dry winters and exceptional spring heat (Westerling et al., 2006). Burned mountain forests can reduce interception capacities for rainfall and snowfall, soil moisture storage capacity due to burning of organic soils, and infiltration capacity, which increases the risk of snow-melt runoff and rain-on-snow floods.

The potential for debris flows and landslides can also increase, as ash and burned soils can increase the depth of loose, movable terrain. Along with dead or decaying vegetation, these factors may result in large volumes of debris entrainment during flood or slide events (Jakob et al., 2022; Vahedifard et al., 2024).

Climate change can increase the vulnerability of a slope to geohazard events. Through extreme precipitation events and heatwaves, it can trigger the onset of such events.

The consequences of geohazards include threats to human health and safety, wildlife habitat, infrastructure vitality and tourism industries. Landslides and avalanches can block and damage transport infrastructure and cause devastation to human settlements and activities (Carey et al., 2012; 2021). Flooding, especially ROS events and GLOFs, in mountain environments is equally concerning. Depending on the size, intensity and origin of the flood, debris entrainment and torrential currents can cause similar damage (Haeberli et al., 2017; Clague and O'Connor, 2021). These geohazards may also affect mountain tourism, mountaineering activities and emergency response capabilities, as such events can damage accessibility infrastructure, destroy sought-after sites, routes and scenery (Hanly and McDowell, 2024), and generate visitor hesitation (Wedgwood, 2014).

Geohazards result in real costs to people, livelihoods, infrastructure and economies. GLOFs alone have resulted in more than 12,000 deaths in the past 200 years, and have caused severe damage to farmland, homes, bridges, roads, hydropower plants and cultural assets,

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[8] Sudden and catastrophic floods caused by the failure of natural dams, typically formed by glacial moraines or ice, which contain glacial lakes. These events occur when water pressure builds up behind the dam, leading to its collapse, which can happen due to erosion, seismic activity or the sudden influx of meltwater.

often prompting further internal displacement (Shrestha et al., 2010; Carrivick and Tweed, 2016). The total area and number of glacial lakes have increased significantly since the 1990s as glaciers have receded. More of these lakes will develop over the next decades, creating new hotspots of potentially dangerous GLOF hazards and risks (Adler et al., 2022). As with many geohazards, damage is often higher in low- and middle-income countries (Box 2.4) than in high-income countries (Carrivick and Tweed, 2016).

Although not constrained to cryospheric geohazards, Stäubli et al. (2018) calculated that the absolute economic losses in mountain regions across 713 events between 1985 and 2014 exceeded US$56 billion, affected over 258 million people and resulted in over 39,000 deaths. Increases in population and urbanization in mountain regions may also increase the exposure of people and property to geohazard events and associated loss and damage (Thornton et al., 2022).

Box 2.4 Glacial lake outburst flood (GLOF) management in Peru

Communities in the Cordillera Blanca of Peru have long been managing GLOFs. Rockfalls, landslides and glaciers calving into water bodies have triggered events with devastating impacts. These have resulted in substantial engineering mitigation efforts to mitigate GLOF occurrences, including lowering of lake levels and reinforcing moraine dams to prevent erosion and failure.

There are now drainage pipes and tunnels, artificial dams and early warning systems across multiple lakes throughout the Andes (Mergili et al., 2020). These include drainage pipes leading away from Lake Palcacocha, which, in 1941, was the source of a GLOF that killed an estimated 1,600 people (Emmer, 2017; Carey et al., 2021).

The consequences of cryosphere changes are amplified for vulnerable populations (ICIMOD, 2022). For Indigenous Peoples and local communities (IPLCs) in mountain regions, the human impacts of cryosphere changes are profound and include the reduced ability to source food, pasture degradation, loss of culturally significant snow covers and deterioration of essential water sources (Figure 2.6) (Caretta et al., 2022). Women within such communities are especially vulnerable, as they often bear disproportionate responsibilities for food and water (ICIMOD, 2022).

2.3 Water management challenges

Water systems influenced by the mountain cryosphere extend far beyond mountain valleys. Snow and ice changes may affect downstream communities that do not necessarily identify with the mountains. Increased awareness of the cryosphere and its role in the global water cycle is thus important, especially among water managers and other decision-makers. Management and infrastructure planning are often based on historical data assuming stationarity. However, a changing climate has shown the fallacy of this assumption, especially for snow and ice-fed systems (Milly et al., 2008). This increases the need for modelling future risk to support long-term planning.

However, modelling requires inputs from global climate models, which have high uncertainty in high mountain areas (see Chapter 8). Filling monitoring and information gaps must be a priority, including capturing the real health, social and economic costs and identifying potentially disproportionate impacts across populations. Vulnerable and marginalized groups including women, people who are poor and IPLCs in high mountain areas will be disproportionately affected by the impacts of climate change (Caretta et al., 2022).

Figure 2.6 Impact of climate, water and cryosphere changes on Indigenous Peoples and local communities in cold regions

Source: Caretta et al. (2022, fig. 4.6, p. 572).

Snow and ice changes may affect downstream communities that do not necessarily identify with the mountains

As water towers, mountains play a vital role in freshwater storage and runoff generation. Shifts in the timing of seasonal snow-melt and from relatively reliable snow-melt freshets to more variable and less predictable rainfall-runoff regimes, coupled with losing the buffering capacity of glaciers, may decrease community resilience in times of stress (Somers et al., 2019; Carroll et al., 2024). Downstream lowlands often contribute little to mountain-sourced river streamflow. Therefore, even communities residing thousands of kilometres away can depend on high mountains for their water resources (including groundwater) and derive important resilience benefits from the mountain cryosphere (Whitfield et al., 2020).

Awareness of, and preparedness for, declines in the ecosystem services that the cryosphere provides must be integrated into regional, national and global policymaking. Mitigation and adaptation efforts include: urban and agricultural water use with alternative storage systems to make up for lost cryosphere water storage; preserving timing of flows through surface and subsurface storage; improving irrigation technology and efficiency; and enhancing water-use efficiencies. However, while efficiency is important, strategies to reduce absolute water demand will be critical. Such interventions must be locally borne and will require a multifaceted approach including strategies for reducing poverty and achieving gender equality and recognition of different cultural values and uses associated with water.

2.4 Conclusions

The impacts of mountain cryospheric decline on water resources are complex and vary across headwater basins and downstream regions. A decline in seasonal SWE and snow duration will cause a forward shift in melt timing, and declining freshet hydrograph peak with lower late season baseflows and greater dependency on rainfall runoff and groundwater discharge. This will affect water supplies and increase summer drought for vast downstream regions. Acceleration in timing and increasing magnitude of glacier melt with atmospheric warming can appear to mitigate diminished water supply from snow-melt, especially in the hottest, driest periods, in the short term. However, the increased timing and magnitude are transient, limited in volume and will diminish greatly later this century.

The timing and duration of meltwaters are crucial for ecosystem integrity, groundwater recharge and food security. Natural hazards, including landslides, floods and debris flows, and slow-onset disasters such as those associated with drought are influenced by the state of the cryosphere. The impacts on water availability and hazard levels are influenced by many factors; simple, one-size-fits-all analyses are not possible. This creates challenges for sustainable and equitable management of water quality and quantity for human health and well-being, terrestrial and aquatic ecosystem integrity, and strong economies and communities.

References

Adler, C., Wester, P., Bhatt, I., Huggel, C., Insarov, G., Morecroft, M., Muccione, V. and Prakash, A. 2022. Mountains. H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem and B. Rama (eds), *Climate Change 2022: Impacts, Adaptation and Vulnerability.* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK/New York, Cambridge University Press, pp. 2273–2318. doi.org/10.1017/9781009325844.022.

Arenson, L. U., Harrington, J. S., Koenig, C. E. and Wainstein, P. A. 2022. Mountain permafrost hydrology – A practical review following studies from the Andes. *Geosciences*, Vol. 12, No. 2, p. 48. doi.org/10.3390/geosciences12020048.

Arimitsu, M. L., Piatt, J. F. and Mueter, F. 2016. Influence of glacier runoff on ecosystem structure in Gulf of Alaska fjords. *Marine Ecology Progress Series*, Vol. 560, pp. 19–40. doi.org/10.3354/meps11888.

Aubry-Wake, C., Bertoncini, A. and Pomeroy, J. W. 2022. Fire and ice: The impact of wildfire-affected albedo and irradiance on glacier melt. *Earth's Future*, Vol. 10, No. 4, Article e2022EF002685. doi.org/10.1029/2022EF002685.

Azócar, G. F. and Brenning, A. 2010. Hydrological and geomorphological significance of rock glaciers in the dry Andes, Chile (27°–33°S). *Permafrost and Periglacial Processes*, Vol. 21, No. 1, pp. 42–53. doi.org/10.1002/ppp.669.

Barnett, T. P., Adam, J. C. and Lettenmaier, D. P. 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, Vol. 438, No. 7066, pp. 303–309. doi.org/10.1038/nature04141.

Bernhardt, M. and Schulz, K. 2010. SnowSlide: A simple routine for calculating gravitational snow transport. *Geophysical Research Letters*, Vol. 37, No. 11. doi.org/10.1029/2010GL043086.

Bertoncini, A. 2024. *Using Enhanced Observations to Improve Streamflow Prediction in Cold Mountain River Basins*. PhD thesis, University of Saskatchewan. https://hdl.handle.net/10388/15563.

Bertoncini, A., Aubry-Wake, C. and Pomeroy, J. W. 2022. Large-area high spatial resolution albedo retrievals from remote sensing for use in assessing the impact of wildfire soot deposition on high mountain snow and ice melt. *Remote Sensing of Environment*, Vol. 278, Article 113101. doi.org/10.1016/j.rse.2022.113101.

Buytaert, W., Moulds, S., Acosta, L., De Bièvre, B., Olmos, C., Villacis, M., Tovar, C. and Verbist, K. M. 2017. Glacial melt content of water use in the Tropical Andes. *Environmental Research Letters*, Vol. 12, No. 11, Article 114014. doi.org/10.1088/1748-9326/aa926c.

Caretta, M. A., Mukherji, A., Arfanuzzaman, M., Betts, R. A., Gelfan, A., Hirabayashi, Y., Lissner, T. K., Liu, J., Lopez Gunn, E., Morgan, R., Mwanga, S. and Supratid, S. 2022. Water. H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem and B. Rama (eds), *Climate Change 2022: Impacts, Adaptation and Vulnerability.* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK/New York, Cambridge University Press, pp. 551–712. doi.org/10.1017/9781009325844.006.

Carey, M., Huggel, C., Bury, J., Portocarrero, C. and Haeberli, W. 2012. An integrated socio-environmental framework for glacier hazard management and climate change adaptation: Lessons from Lake 513, Cordillera Blanca, Peru. *Climatic Change*, Vol. 112, pp. 733–767. doi.org/10.1007/s10584-011-0249-8.

Carey, M., McDowell, G., Huggel, C., Marshall, B., Moulton, H., Portocarrero, C., Provant, Z., Reynolds, J. M. and Vicuña, L. 2021. Chapter 8 – A socio-cryospheric systems approach to glacier hazards, glacier runoff variability, and climate change. W. Haeberli and C. Whiteman (eds), *Snow and Ice-Related Hazards, Risks, and Disasters (Second Edition)*. Amsterdam/Oxford, UK/Cambridge, USA, Elsevier, pp. 215–257. doi.org/10.1016/B978-0-12-817129-5.00018-4.

Carrivick, J. L. and Tweed, F. S. 2016. A global assessment of the societal impacts of glacier outburst floods. *Global and Planetary Change*, Vol. 144, pp. 1–16. doi.org/10.1016/j.gloplacha.2016.07.001.

Carroll, R. W., Niswonger, R. G., Ulrich, C., Varadharajan, C., Siirila-Woodburn, E. R. and Williams, K. H. 2024. Declining groundwater storage expected to amplify mountain streamflow reductions in a warmer world. *Nature Water*, Vol. 2, No. 5, pp. 419–433. doi.org/10.1038/s44221-024-00239-0.

Chiarle, M., Geertsema, M., Mortara, G. and Clague, J. J. 2021. Relations between climate change and mass movement: Perspectives from the Canadian Cordillera and the European Alps. *Global and Planetary Change*, Vol. 202, Article 103499. doi.org/10.1016/j.gloplacha.2021.103499.

Clague, J. J. and O'Connor, J. E. 2021. Chapter 14 – Glacier-related outburst floods. W. Haeberli and C. Whiteman (eds), *Snow and Ice-Related Hazards, Risks, and Disasters (Second Edition)*. Amsterdam/Oxford, UK/Cambridge, USA, Elsevier, pp. 467–499. doi.org/10.1016/B978-0-12-817129-5.00019-6.

Cook, S. J., Jouvet, G., Millan, R., Rabatel, A., Zekollari, H. and Dussaillant, I. 2023. Committed ice loss in the European Alps until 2050 using a deep-learning-aided 3D ice-flow model with data assimilation. *Geophysical Research Letters*, Vol. 50, No. 23, Article e2023GL105029. doi.org/10.1029/2023GL105029.

Cunsolo, A., Borish, D., Harper, S. L., Snook, J., Shiwak, I. and Wood, M. 2020. "You can never replace the caribou": Inuit experiences of ecological grief from caribou declines. *American Imago*, Vol. 77, No. 1, pp. 31–59. doi.org/10.1353/aim.2020.0002.

DeBeer, C. M., Sharp, M. and Schuster-Wallace, C. 2020. Glaciers and ice sheets. M. I. Goldstein and D. A. DellaSala (eds), *Encyclopedia of the World's Biomes*. Amsterdam/Oxford, UK/Cambridge, USA, Elsevier, pp. 182–194. doi.org/10.1016/B978-0-12-409548-9.12441-8.

Ellis, C. R., Pomeroy, J. W. and Link, T. E. 2013. Modeling increases in snowmelt yield and desynchronization resulting from forest gap-thinning treatments in a northern mountain headwater basin. *Water Resources Research*, Vol. 49, No. 2, pp. 936–949. doi.org/10.1002/wrcr.20089.

Emmer, A. 2017. Geomorphologically effective floods from moraine-dammed lakes in the Cordillera Blanca, Peru. *Quaternary Science Reviews*, Vol. 177, pp. 220–234. doi.org/10.1016/j.quascirev.2017.10.028.

ESCAP (Economic and Social Commission for Asia and the Pacific). 2023. Climate Catastrophe in the Sikkim Himalayas: Twin Tack Resilience Strategy. ESCAP website, blogs, 23 October 2023. www.unescap.org/blog/climate-catastrophe-sikkim-himalayas-twin-track-resilience-strategy.

Essery, R. and Pomeroy, J. 2004. Implications of spatial distributions of snow mass and melt rate for snow-cover depletion: Theoretical considerations. *Annals of Glaciology*, Vol. 38, pp. 261–265. doi.org/10.3189/172756404781815275.

Fang, X. and Pomeroy, J. W. 2023. Simulation of the impact of future changes in climate on the hydrology of Bow River headwater basins in the Canadian Rockies. *Journal of Hydrology*, Vol. 620, Article 129566. doi.org/10.1016/j.jhydrol.2023.129566.

Forbes, B. C., Turunen, M. T., Soppela, P., Rasmus, S., Vuojala-Magga, T. and Kitti, H. 2019. Changes in mountain birch forests and reindeer management: Comparing different knowledge systems in Sápmi, northern Fennoscandia. *Polar Record*, Vol. 55, No. 6, pp. 507–521. doi.org/10.1017/S0032247419000834.

Ford, J. D., Clark, D., Pearce, T., Berrang-Ford, L., Copland, L., Dawson, J., New, M. and Harper, S. L. 2019. Changing access to ice, land and water in Arctic communities. *Nature Climate Change*, Vol. 9, No. 4, pp. 335–339. doi.org/10.1038/s41558-019-0435-7.

Gascoin, S. 2024. A call for an accurate presentation of glaciers as water resources. *Wiley Interdisciplinary Reviews: Water*, Vol. 11, No. 2, Article e1705. doi.org/10.1002/wat2.1705.

Gentle, P. and Thwaites, R. 2016. Transhumant pastoralism in the context of socioeconomic and climate change in the mountains of Nepal. *Mountain Research and Development*, Vol. 36, No. 2, pp. 173–182. doi.org/10.1659/MRD-JOURNAL-D-15-00011.1.

Haeberli, W., Schaub, Y. and Huggel, C. 2017. Increasing risks related to landslides from degrading permafrost into new lakes in de-glaciating mountain ranges. *Geomorphology*, Vol. 293, pp. 405–417. doi.org/10.1016/j.geomorph.2016.02.009.

Hanly, K. and McDowell, G. 2024. The evolution of 'riskscapes': 100 years of climate change and mountaineering activity in the Lake Louise area of the Canadian Rockies. *Climatic Change*, Vol. 177, Article 49. doi.org/10.1007/s10584-024-03698-2.

Harrington, J. S., Hayashi, M. and Kurylyk, B. L. 2017. Influence of a rock glacier spring on the stream energy budget and cold-water refuge in an alpine stream. *Hydrological Processes*, Vol. 31, No. 26, pp. 4719–4733. doi.org/10.1002/hyp.11391.

Hedstrom, N. R. and Pomeroy, J. W. 1998. Measurements and modelling of snow interception in the boreal forest. *Hydrological Processes*, Vol. 12, No. 10–11, pp. 1611–1625. doi.org/10.1002/(SICI)1099-1085(199808/09)12:10/11<1611::AID-HYP684>3.0.CO;2-4.

Hock, R., Rasul, G., Adler, C., Cáceres, B., Gruber, S., Hirabayashi, Y., Jackson, M., Kääb, A., Kang, S., Kutuzov, S., Milner, A., Molau, U., Morin, S., Orlove, B. and Steltzer, H. 2019a. High mountain areas. H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds), *The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK/New York, Cambridge University Press, pp. 131–202. doi.org/10.1017/9781009157964.004.

Hock, R., Bliss, A., Marzeion, B. E. N., Giesen, R. H., Hirabayashi, Y., Huss, M., Radić, V. and Slangen, A. B. 2019b. GlacierMIP – A model intercomparison of global-scale glacier mass-balance models and projections. *Journal of Glaciology*, Vol. 65, No. 251, pp. 453–467. doi.org/10.1017/jog.2019.22.

Hopkinson, C. and Young, G. J. 1998. The effect of glacier wastage on the flow of the Bow River at Banff, Alberta, 1951–1993. *Hydrological Processes*, Vol. 12, No. 10–11, pp. 1745–1762. doi.org/10.1002/(SICI)1099-1085(199808/09)12:10/11%3C1745::AID-HYP692%3E3.0.CO;2-S.

Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L., Farinotti., D., Huss, M., Dussaillant, I., Brun, F. and Kääb, A. 2021. Accelerated global glacier mass loss in the early twenty-first century. *Nature*, Vol. 592, pp. 726–731. doi.org/10.1038/s41586-021-03436-z.

Huss, M. and Hock, R. 2018. Global-scale hydrological response to future glacier mass loss. *Nature Climate Change*, Vol. 8, No. 2, pp. 135–140. doi.org/10.1038/s41558-017-0049-x.

ICIMOD (International Centre for Integrated Mountain Development). 2022. *State of Gender Equality and Climate Change in South Asia and the Hindu Kush Himalaya*. Kathmandu, ICIMOD. https://lib.icimod.org/record/35996.

Ilyashuk, B. P., Ilyashuk, E. A., Psenner, R., Tessadri, R. and Koinig, K. A. 2018. Rock glaciers in crystalline catchments: Hidden permafrost-related threats to alpine headwater lakes. *Global Change Biology*, Vol. 24, No. 4, pp. 1548–1562. doi.org/10.1111/gcb.13985.

Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., Hyde, Brumby, S., Davies, B. J., Elmore, A. C., Emmer, A., Feng, M., Fernández, A., Haritashya, U., Kargel, J. S., Koppes, M., Kraaijenbrink, P. D. A., Kulkarni, A. V., Mayewski, P. A., Nepal, S., Pacheco, P., Painter, T. H., Pellicciotti, F., Rajaram, H., Rupper, S., Sinisalo, A., Shrestha, A. B., Viviroli, D., Wada, W., Xiao, C., Yao, T. and Baillie, J. E. M. 2020. Importance and vulnerability of the world's water towers. *Nature*, Vol. 577, pp. 364–369. doi.org/10.1038/s41586-019-1822-y.

Ingty, T. 2017. High mountain communities and climate change: Adaptation, traditional ecological knowledge, and institutions. *Climatic Change*, Vol. 145, No. 1, pp. 41–55. doi.org/10.1007/s10584-017-2080-3.

IPCC (Intergovernmental Panel on Climate Change). 2023. *Climate Change 2023: Synthesis Report*. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds)]. Geneva, IPCC, pp. 1–34. doi.org/10.59327/IPCC/AR6-9789291691647.001.

Jakob, M., Davidson, S., Bullard, G., Busslinger, M., Collier-Pandya, B., Grover, P. and Lau, C. A. 2022. Debris-flood hazard assessments in steep streams. *Water Resources Research*, Vol. 58, No. 4, Article e2021WR030907. doi.org/10.1029/2021WR030907.

Jones, H. G., Pomeroy, J. W., Walker, D. A. and Hoham, R. W. (eds). 2001. *Snow Ecology: An Interdisciplinary Examination of Snow-Covered Ecosystems*. Cambridge, UK, Cambridge University Press.

Kaser, G., Großhauser, M. and Marzeion, B. 2010. Contribution potential of glaciers to water availability in different climate regimes. *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 107, No. 47, pp. 20223–20227. doi.org/10.1073/pnas.1008162107.

Khalafzai, M.-A. K., McGee, T. K. and Parlee, B. 2019. Flooding in the James Bay region of Northern Ontario, Canada: Learning from traditional knowledge of Kashechewan First Nation. *International Journal of Disaster Risk Reduction*, Vol. 36, Article 101100. doi.org/10.1016/j.ijdrr.2019.101100.

Konchar, K. M., Staver, B., Salick, J., Chapagain, A., Joshi, L., Karki, S., Lo, S., Paudel, A., Subedi, P. and Ghimire, S. K. 2015. Adapting in the shadow of Annapurna: A climate tipping point. *Journal of Ethnobiology*, Vol. 35, No. 3, pp. 449–471. doi.org/10.2993/0278-0771-35.3.449.

Lehning, M., Löwe, H., Ryser, M. and Raderschall, N. 2008. Inhomogeneous precipitation distribution and snow transport in steep terrain. *Water Resources Research*, Vol. 44, No. 7. doi.org/10.1029/2007WR006545.

López-Moreno, J. I., Pomeroy, J. W., Alonso-González, E., Morán-Tejeda, E. and Revuelto, J. 2020. Decoupling of warming mountain snowpacks from hydrological regimes. *Environmental Research Letters*, Vol. 15, No. 11, Article 114006. doi.org/10.1088/1748-9326/abb55f.

López-Moreno, J. I., Pomeroy, J. W., Morán-Tejeda, E., Revuelto, J., Navarro-Serrano, F. M., Vidaller, I. and Alonso-González, E. 2021. Changes in the frequency of global high mountain rain-on-snow events due to climate warming. *Environmental Research Letters*, Vol. 16, No. 9, Article 094021. doi.org/10.1088/1748-9326/ac0dde.

Marks, D., Kimball, J., Tingey, D. and Link, T. 1998. The sensitivity of snowmelt processes to climate conditions and forest cover during rain-on-snow: A case study of the 1996 Pacific Northwest flood. *Hydrological Processes*, Vol. 12, No. 10–11, pp. 1569–1587. doi.org/10.1002/(SICI)1099-1085(199808/09)12:10/11<1569::AID-HYP682>3.0.CO;2-L.

Mergili, M., Pudasaini, S. P., Emmer, A., Fischer, J. T., Cochachin, A. and Frey, H. 2020. Reconstruction of the 1941 GLOF process chain at Lake Palcacocha (Cordillera Blanca, Peru). *Hydrology and Earth System Sciences*, Vol. 24, No. 1, pp. 93–114. doi.org/10.5194/hess-24-93-2020.

Miles, K. E., Hubbard, B., Irvine-Fynn, T. D., Miles, E. S., Quincey, D. J. and Rowan, A. V. 2020. Hydrology of debris-covered glaciers in High Mountain Asia. *Earth-Science Reviews*, Vol. 207, Article 103212. doi.org/10.1016/j.earscirev.2020.103212.

Milly, P. C., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P. and Stouffer, R. J. 2008. Stationarity is dead: Whither water management? *Science*, Vol. 319, No. 5863, pp. 573–574. doi.org/10.1126/science.1151915.

Milner, A. M., Khamis, K., Battin, T. J., Brittain, J. E., Barrand, N. E., Füreder, L., Cauvy-Fraunié, S., Már Gíslason, G., Jacobsen, D., Hannah, D. M., Hodson, A. J., Hood, E., Lencioni, V., Ólafsson, J. S., Robinson, C. T., Tranter, M. and Brown, L. E. 2017. Glacier shrinkage driving global changes in downstream systems. *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 114, No. 37, pp. 9770–9778. doi.org/10.1073/pnas.1619807114.

Mountain Research Initiative EDW Working Group. 2015. Elevation-dependent warming in mountain regions of the world. *Nature Climate Change*, Vol. 5, pp. 424–430. doi.org/10.1038/nclimate2563.

Müller, T., Lane, S. N. and Schaefli, B. 2022. Towards a hydrogeomorphological understanding of proglacial catchments: An assessment of groundwater storage and release in an Alpine catchment. *Hydrology and Earth System Sciences*, Vol. 26, No. 23, pp. 6029–6054. doi.org/10.5194/hess-26-6029-2022.

Norton-Smith, K., Lynn, K., Chief, K., Cozzetto, K., Donatuto, J., Hiza Redsteer, M., Kruger, L. E., Maldonado, J., Viles, C. and Whyte, K. P. 2016. *Climate Change and Indigenous Peoples: A Synthesis of Current Impacts and Experiences*. General Technical Report PNW-GTR-944. Portland, USA, United States Department of Agriculture, Forest Service, Pacific Northwest Research Station. doi.org/10.2737/PNW-GTR-944.

Nyima, Y. and Hopping, K. A. 2019. Tibetan lake expansion from a pastoral perspective: Local observations and coping strategies for a changing environment. *Society and Natural Resources*, Vol. 32, No. 9, pp. 965–982. doi.org/10.1080/08941920.2019.1590667.

O'Neel, S., Hood, E., Bidlack, A. L., Fleming, S. W., Arimitsu, M. L., Arendt, A., Burgess, E., Sergeant, C. J., Beaudreau, A. H., Timm, K., Hayward, G. D., Reynolds, J. H. and Pyare, S. 2015. Icefield-to-ocean linkages across the northern Pacific coastal temperate rainforest ecosystem. *BioScience*, Vol. 65, No. 5, pp. 499–512. doi.org/10.1093/biosci/biv027.

Pepin, N. C., Arnone, E., Gobiet, A., Haslinger, K., Kotlarski, S., Notarnicola, C., Palazzi, E., Seibert, P., Serafin, S., Schöner, W., Terzago, S., Thornton, J. M., Vuille, M. and Adler, C. 2022. Climate changes and their elevational patterns in the mountains of the world. *Reviews of Geophysics*, Vol. 60, No. 1, Article e2020RG000730. doi.org/10.1029/2020RG000730.

Pomeroy, J. W. and Li, L. 2000. Prairie and arctic areal snow cover mass balance using a blowing snow model. *Journal of Geophysical Research: Atmospheres*, Vol. 105, No. D21, pp. 26619–26634. doi.org/10.1029/2000JD900149.

Pomeroy, J. W., Brown, T., Fang, X., Shook, K. R., Pradhananga, D., Armstrong, R., Harder, P., Marsh, C., Costa, D., Krogh, S. A., Aubry-Wake, C., Annand, H., Lawford, P., He, Z., Kompanizare, M. and Lopéz Moreno, J. L. 2022. The cold regions hydrological modelling platform for hydrological diagnosis and prediction based on process understanding. *Journal of Hydrology*, Vol. 615, Article 128711. doi.org/10.1016/j.jhydrol.2022.128711.

Postigo, J. C. 2020. The role of social institutions in Indigenous Andean pastoralists' adaptation to climate-related water hazards. *Climate and Development*, Vol. 13, No. 9, pp. 780–791. doi.org/10.1080/17565529.2020.1850409.

Rasmus, S., Turunen, M., Luomaranta, A., Kivinen, S., Jylhä, K. and Räihä, J. 2020. Climate change and reindeer management in Finland: Co-analysis of practitioner knowledge and meteorological data for better adaptation. *Science of the Total Environment*, Vol. 710, Article 136229. doi.org/10.1016/j.scitotenv.2019.136229.

Rasouli, K., Pomeroy, J. W. and Whitfield, P. H. 2019. Are the effects of vegetation and soil changes as important as climate change impacts on hydrological processes? *Hydrology and Earth System Sciences*, Vol. 23, No. 12, pp. 4933–4954. doi.org/10.5194/hess-23-4933-2019.

Rounce, D. R., Hock, R., Maussion, F., Hugonnet, R., Kochtitzky, W., Huss, M., Berthier, E., Compagno, L., Copland, L., Farinotti, D., Menounos, B. and McNabb, R. W. 2023. Global glacier change in the 21st century: Every increase in temperature matters. *Science*, Vol. 379, No. 6627, pp. 78–83. doi.org/10.1126/science.abo1324.

Schaffer, N., MacDonell, S., Réveillet, M., Yáñez, E. and Valois, R. 2019. Rock glaciers as a water resource in a changing climate in the semiarid Chilean Andes. *Regional Environmental Change*, Vol. 19, pp. 1263–1279. doi.org/10.1007/s10113-018-01459-3.

Sepúlveda, S. A., Tobar, C., Rosales, V., Ochoa-Cornejo, F. and Lara, M. 2023. Megalandslides and deglaciation: Modelling of two case studies in the Central Andes. *Natural Hazards*, Vol. 118, No. 2, pp. 1561–1572. doi.org/10.1007/s11069-023-06067-x.

Sharp, M. and Tranter, M. 2017. Glacier biogeochemistry. *Geochemical Perspectives*, Vol. 6, No. 2, pp. 173–174. doi.org/10.7185/geochempersp.6.2.

Shrestha, A. B., Eriksson, M., Mool, P., Ghimire, P., Mishra, B. and Khanal, N. R. 2010. Glacial lake outburst flood risk assessment of Sun Koshi basin, Nepal. *Geomatics, Natural Hazards and Risk*, Vol. 1, No. 2, pp. 157–169. doi.org/10.1080/19475701003668968.

Somers, L. D. and McKenzie, J. M. 2020. A review of groundwater in high mountain environments. *Wiley Interdisciplinary Reviews: Water*, Vol. 7, No. 6, Article e1475. doi.org/10.1002/wat2.1475.

Somers, L. D., McKenzie, J. M., Mark, B. G., Lagos, P., Ng, G. H. C., Wickert, A. D., Yarleque, C., Baraër, M. and Silva, Y. 2019. Groundwater buffers decreasing glacier melt in an Andean watershed – but not forever. *Geophysical Research Letters*, Vol. 46, No. 22, pp. 13016–13026. doi.org/10.1029/2019GL084730.

Stäubli, A., Nussbaumer, S. U., Allen, S. K., Huggel, C., Arguello, M., Costa, F., Hergarten, C., Martínez, R., Soto, J., Vargas, R., Zambrano, E. and Zimmermann, M. 2018. Analysis of weather-and climate-related disasters in mountain regions using different disaster databases. S. Mal, R. Singh and C. Huggel (eds), *Climate Change, Extreme Events and Disaster Risk Reduction: Towards Sustainable Development Goals*. Cham, Switzerland, Springer, pp. 17–41. doi.org/10.1007/978-3-319-56469-2_2.

Thornton, J. M., Snethlage, M. A., Sayre, R., Urbach, D. R., Viviroli, D., Ehrlich, D., Muccione, V., Wester, P., Insarov, G. and Adler, C. 2022. Human populations in the world's mountains: Spatio-temporal patterns and potential controls. *PLoS ONE*, Vol. 17, No. 7, Article e0271466. doi.org/10.1371/journal.pone.0271466.

UNESCO/IUCN (United Nations Educational, Scientific and Cultural Organization/International Union for the Conservation of Nature). 2022. *World Heritage Glaciers: Sentinels of Climate Change*. Paris/Gland, Switzerland, UNESCO/IUCN. doi.org/10.3929/ethz-b-000578916.

USGS (United States Geological Survey). 2013. Glossary of Glacier Terminology. USGS website. https://pubs.usgs.gov/of/2004/1216/f/f.html#:~:text=An%20intermediate%20stage%20in%20the,takes%20less%20than%20a%20year. (Accessed on 22 July 2024.)

—. 2019. Sublimation and the Water Cycle. USGS website. www.usgs.gov/special-topics/water-science-school/science/sublimation-and-water-cycle#:~:text=Sublimation%20is%20the%20conversion%20between,with%20no%20intermediate%20liquid%20stage. (Accessed on 22 July 2024.)

Vahedifard, F., Abdollahi, M., Leshchinsky, B. A., Stark, T. D., Sadegh, M. and AghaKouchak, A. 2024. Interdependencies between wildfire-induced alterations in soil properties, near-surface processes, and geohazards. *Earth and Space Science*, Vol. 11, No. 2, Article e2023EA003498. doi.org/10.1029/2023EA003498.

Vanderwall, J. W., Muhlfeld, C. C., Tappenbeck, T. H., Giersch, J., Ren, Z. and Elser, J. J. 2024. Mountain glaciers influence biogeochemical and ecological characteristics of high-elevation lakes across the northern Rocky Mountains, USA. *Limnology and Oceanography*, Vol. 69, No. 1, pp. 37–52. doi.org/10.1002/lno.12434.

Van Tiel, M., Aubry-Wake, C., Somers, L., Andermann, C., Avanzi, F., Baraer, M., Chiogna, G., Daigre, C., Das, S., Drenkhan, F., Farinotti, D., Fyffe, C. L., de Graaf, I., Hanus, S., Immerzeel, W., Koch, F., McKenzie, J. M., Müller, T., Popp, A. L., Saidaliyeva, Z., Schaefli, B., Schilling, O. S., Teagai, K., Thornton, J. M. and Yapiyev, V. 2024. Cryosphere–groundwater connectivity is a missing link in the mountain water cycle. *Nature Water*, Vol. 2, No. 7, pp. 624–637. doi.org/10.1038/s44221-024-00277-8.

Verrall, B. and Pickering, C. M. 2020. Alpine vegetation in the context of climate change: A global review of past research and future directions. *Science of the Total Environment*, Vol. 748, Article 141344. doi.org/10.1016/j.scitotenv.2020.141344.

Viviroli, D., Kummu, M., Meybeck, M., Kallio, M. and Wada, Y. 2020. Increasing dependence of lowland populations on mountain water resources. *Nature Sustainability*, Vol. 3, No. 11, pp. 917–928. doi.org/10.1038/s41893-020-0559-9.

Wedgwood, R. 2014. *Gone like a Ghost: The Ghost Glacier Failure and Subsequent Outburst Flood, Mt. Edith Cavell, Jasper National Park*. Sixth Canadian GeoHazards Conference – GeoHazards (Vol. 6). https://cgs.ca/docs/geohazards/kingston2014/Geo2014/pdfs/geoHaz6Paper201.pdf.

Westerling, A. L., Hidalgo, H. G., Cayan, D. R. and Swetnam, T. W. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. *Science*, Vol. 313, No. 5789, pp. 940–943. doi.org/10.1126/science.1128834.

Whitfield, P. H., Kraaijenbrink, P. D., Shook, K. R. and Pomeroy, J. W. 2020. The spatial extent of hydrological and landscape changes across the mountains and prairies of the Saskatchewan and Mackenzie basins. *Hydrology and Earth System Sciences Discussions*, pp. 1–68. doi.org/10.5194/hess-2019-671.

Williamson, C. J., Cameron, K. A., Cook, J. M., Zarsky, J. D., Stibal, M. and Edwards, A. 2019. Glacier algae: A dark past and a darker future. *Frontiers in Microbiology*, Vol. 10, Article 436973. doi.org/10.3389/fmicb.2019.00524.

Yager, K., Valdivia, C., Slayback, D., Jiménez, E., Meneses, R. I., Palabral, A., Bracho, M., Romero, D., Hubbard, A., Pacheco, P., Calle, A., Alberto, H., Yana, O., Ulloa, D., Zeballos, G. and Romero, A. 2019. Socio-ecological dimensions of Andean pastoral landscape change: Bridging traditional ecological knowledge and satellite image analysis in Sajama National Park, Bolivia. *Regional Environmental Change*, Vol. 19, No. 5, pp. 1353–1369. doi.org/10.1007/s10113-019-01466-y.

Zemp, M., Huss, M., Thibert, E., Eckert, N., McNabb, R., Huber, J., Barandun, M., Machguth, H., Nussbaumer, S. U., Gärtner-Roer, I., Thomson, L., Paul, F., Maussion, F., Kutuzov, S. and Cogley, J. G. 2019. Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. *Nature*, Vol. 568, No. 7752, pp. 382–386. doi.org/10.1038/s41586-019-1071-0.

Zhang, Y., Gao, T., Kang, S., Shangguan, D. and Luo, X. 2021. Albedo reduction as an important driver for glacier melting in Tibetan Plateau and its surrounding areas. *Earth-Science Reviews,* Vol. 220, Article 103735. doi.org/10.1016/j.earscirev.2021.103735.

Chapter 3

Food and agriculture

FAO
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This chapter is structured around three main topics: the state of mountain food security and agriculture, challenges due to climate change and other drivers affecting water availability for agriculture and food security, and potential response options.

3.1 Food security and agriculture

3.1.1 Food security in mountains

Agriculture and pastoralism are essential sources of livelihoods[9] for people in mountain areas[10] (FAO, 2019), where an estimated 1.1 billion live. In developing countries, an estimated 648 million people in mountain areas live in rural areas, where most of the population is engaged in agricultural and pastoral livelihoods. More than half (346 million) were estimated to be vulnerable to food insecurity in 2017. In other words, one in two rural mountain dwellers in developing countries lived in areas where the daily availability of calories and protein was estimated to be below the minimum threshold needed for a healthy life (Romeo et al., 2020) In the Hindu Kush Himalaya (HKH) region, more than 30% of the mountain population suffers from food insecurity, with women and children being most at risk (Wester et al., 2019).

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Agriculture and pastoralism are essential sources of livelihoods for people in mountain areas

Factors contributing to food insecurity in the mountains include climatic variability, extreme weather events, disasters caused by natural hazards, physical geography and socio-economics (Box 3.1). Food security can be further constrained by remoteness and inaccessibility (e.g. distance from roads and food markets), growing seasons, conflicts, land degradation (which leads to poor quality soils), large variations in water supply for agriculture and low levels of mechanization (Romeo et al., 2020).

Within river basins fed by cryosphere melt, agricultural productivity downstream in lowlands is threatened by the upstream cryosphere melt. Increasing levels of snow and ice melt are leading to greater seasonal variability (timing and volume) of runoff and river flow (Viviroli et al., 2020). This has been documented, for instance, in the Indo-Gangetic plains of South Asia, where it poses challenges for farmers within the Indus River basin who rely on cryosphere melt for dry season irrigation (Biemans et al., 2019).

3.1.2 Mountain agriculture

Mountain agriculture is broadly defined as agricultural activities on land surfaces at high elevations and on mountain slopes, including water harvesting and conservation practices. Agricultural production systems in mountains include the production of rainfed and irrigation crops, pastoral and agropastoral farming, forestry and agroforestry, freshwater fish capture and aquaculture (FAO, 2022). Small and fragmented plots of land – predominately cultivated by smallholder farmers[11] – characterize mountain agriculture. It has been estimated that 45% of the world's mountain areas are not, or are only marginally, suitable for growing crops, pastoralism or carrying out forestry activities (Romeo et al., 2020). As elevation increases, soils become shallower and less fertile, with lower temperatures that limit biological activity. Soils are often subjected to nutrient leaching through water and wind erosion in exposed areas. As a result, mountain soils are often less productive and more vulnerable than lowland soils (FAO, 2015a).

[9] Along with non-agricultural income sources such as remittances, small businesses, medicinal plants, wage labour and tourism (FAO, 2019).

[10] The Food and Agriculture Organization of the United Nations uses the United Nations Environment Programme World Conservation Monitoring Centre definition of mountains (Romeo et al., 2020, p. 8).

[11] Small-scale farmers, pastoralists, forest keepers and fishers who manage areas varying from less than 1 ha to 10 ha. Smallholders are characterized by family-focused motives such as favouring the stability of the farm household system, using mainly family labour for production and using part of the produce for family consumption.

Box 3.1 Food security and the Sustainable Development Goals (SDGs)

"*Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life"* (FAO, 1996, item 1). Food security has four dimensions: availability, accessibility, utilization and stability (FAO, 2014).

Food availability refers to the physical availability of adequate levels of food in a particular area.

Food accessibility refers to the physical and economic access to food.

Food utilization refers to food quality, safety and absorption, supported by an adequate health status.

Food stability is ensured when food availability, accessibility and utilization remain secure throughout the year and over a long period (World Bank Group, n.d.).

Food security is therefore critical for achieving numerous SDGs, including SDG 1 (no poverty), SDG 2 (zero hunger), SDG 3 (good health and well-being), SDG 6 (clean water and sanitation), SDG 12 (responsible consumption and production) and SDG 13 (climate action), and also SDG Indicator 15.4.2 (mountain green cover index).

Mountains have distinct features that affect agriculture development, including steep, sloping sides and sharp or rounded ridges and peaks. Cultivation areas are often small, and there is limited use of mechanization. Numerous mountain farmers have abandoned traditional agricultural systems, and increasingly rely on cash crops for their livelihoods (FAO, 2019). Climatic conditions due to elevation vary significantly, with large daily and seasonal temperature fluctuations. Crop growth is slower due to the lower temperatures at high elevations, with farmers typically harvesting one crop per year (FAO, 2015b).

Mountain communities preserve many of the rarest crop varieties and medicinal plants. They have developed valuable traditional knowledge and techniques in crop cultivation, livestock production and water harvesting that help to sustain entire ecosystems (Romeo et al., 2020).

Mountain communities preserve many of the rarest crop varieties and medicinal plants

Irrigated and rainfed agricultural production systems

Irrigated agriculture is typically practised in arid and semi-arid mountain areas, with annual rainfall less than 350 mm. The sources of water for irrigation include deep artesian wells, river water, locally stored water and harvested rainwater in catchments. Farmers using irrigation systems tend to diversify production to ensure food security, including growing high-value crops, vegetables, fruit trees and ornamentals. Field crops such as rice, wheat and maize are also cultivated (FAO, 2022).

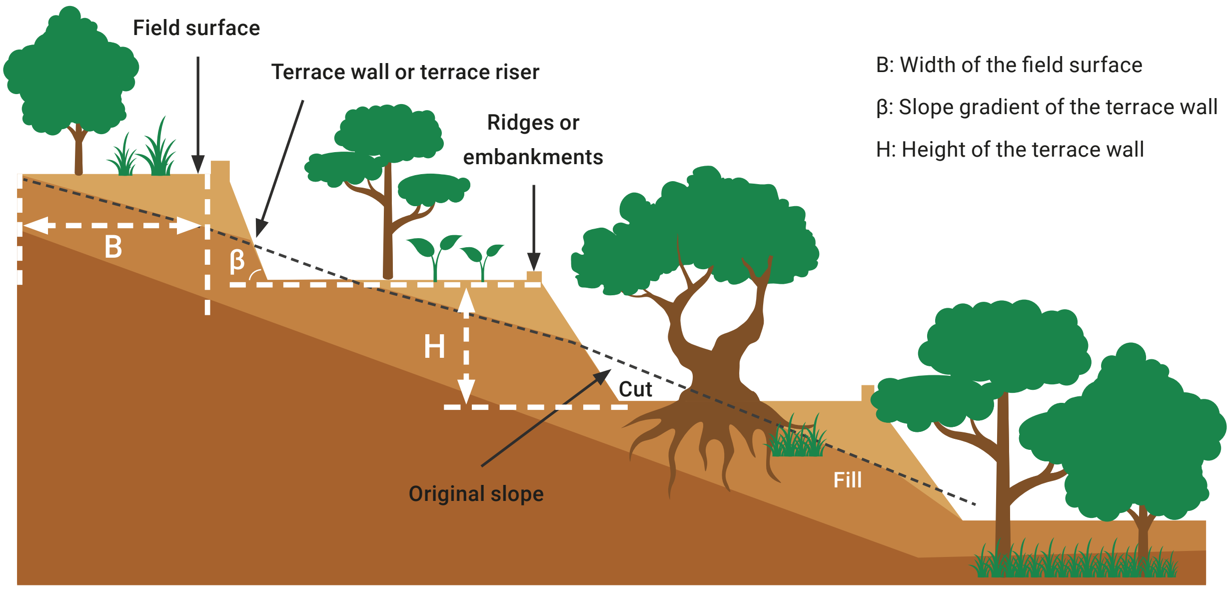
Rainfed mountain agriculture is practised when there is more than 400 mm of rainfall during the wet season. It is often used as a conservation agriculture approach, with minimum soil disturbance or zero tillage, stubble retention and crop rotation. Rainfed crops include: cereals such as barley, maize, rice and wheat; legumes such as chickpeas, peas and lentils; and horticultural crops such as fruit trees, grapes, vegetables and medicinal plants (FAO, 2019; 2022).

Mountain terrace agriculture

Terrace farming is widely practised on the slopes of mountains throughout the world (Chapagain and Raizada, 2017; FAO, 2022). It is an important source of food production and livelihood income generation for smallholder farmers. It has been practised for thousands of years, dating back to the 5th century BCE in China and Yemen (FAO, 2019).

Terrace farming is innovatively adapted to local slope conditions. Cut and fills of land/soil are constructed along the slope gradient (Figure 3.1). Arable land is expanded by constructing filling areas. The width of a terrace depends on the slope gradient: the steeper the slope, the narrower the terrace and the higher the terrace wall. Ridges or embankments play an important role in the interception of water runoff (Deng et al., 2021).

Figure 3.1 Sectional diagram of a slope terrace



Source: Based on Deng et al. (2021, fig. 1, p. 345).

Appropriately designed, constructed and maintained terrace farming offers numerous benefits (FAO, 2019). These include reducing surface water runoff and promoting water conservation, reducing soil erosion, stabilizing slopes, enhancing habitat and biodiversity production, and sustaining cultural heritage (Box 3.2) (Deng et al., 2021).

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Terrace farming is widely practised on the slopes of mountains throughout the world

Terrace farming supports the cultivation of numerous crops. These include field and horticultural crops, fodder and other crops that require specific management practices (e.g. irrigation), as well as agroforestry systems and aquaculture. Most terrace farms are under rainfed conditions. As a result, many terraces are not as productive as farms that have appropriate mechanization and irrigation (Chapagain and Raizada, 2017).

One challenge to cultivation is the risk of terraces collapsing – the higher the terrace wall, the greater the risk of failure. Other challenges that constrain production include: narrow and limited land for cultivation; significant labour input requirements; difficulties in the use of mechanization beyond traditional tools; and poor access to agricultural inputs, markets and services (Deng et al., 2021). Most terrace farms are managed traditionally using simple tools, limited animal draught power and relatively abundant household labour. Nevertheless, a small proportion of terrace farms have shifted from ancient to modern techniques (FAO, 2019).

Box 3.2 The Honghe Hani rice terraces system

The Honghe Hani rice terraces system, covering an area of around 70,000 ha, is located in Yunnan Province, China, on the southern slopes of Honghe Ailao Mountain. A complex system of channels has been constructed to divert water from the forested mountain tops to rice terraces. It provides multiple goods and services for local livelihoods, contributing to food and fuel requirements, while promoting ecological conservation and preserving local cultural practices (FAO, 2019). The system sustains traditional food crops and agricultural diversity, with 195 varieties of rice grown in the area, including 48 varieties of local rice. However, cultivation practices for high yield and uniform variety cropping, in addition to increasing tourism, are threatening the equilibrium of the Honghe Hani rice terraces system (Yang et al., 2017).

Honghe Hani rice terraces system in Yunnan Province, China

Photo: © FAO/Min Qingwen.*

The Honghe Hani rice terraces system was designated a Globally Important Agricultural Heritage Systems (GIAHS) site in 2010, as a ‘forest–village–terrace–water–culture’ system. GIAHS are defined as remarkable land-use systems and landscapes rich in globally significant biological diversity, evolving from the co-adaptation of a community with its environment (FAO, 2019). The initiative aims to establish a basis for international recognition, dynamic conservation and sustainable management of such systems. Agricultural functions of GIAHS include livelihoods, landscape conservation, agrobiodiversity conservation, traditional knowledge and ecosystem services.

The GIAHS initiative was launched in 2002 and became an official programme of the Food and Agriculture Organization of the United Nations in 2015. As of 2024, 89 sites in 28 countries received this global recognition (FAO, 2024). GIAHS are living examples of sustainable agricultural practices, contributing to the food and livelihood security of small-scale rural communities, while conserving cultures, traditional knowledge and building resilience (FAO, 2019). A high percentage of GIAHS sites are located in the mountains, where traditional tools and methods practised over centuries are used.

Pastoral and agropastoral livestock production systems

Pastoral livestock are fed on rainfed vegetation such as grasses, legumes, shrubs and other natural vegetation that provides forage. This practice remains common across many mountain and high-elevation areas, such as in the Tibetan steppe higher than 4,000 m above sea level (Sheehy et al., 2006). Excessive grazing may cause degradation of rangelands, soil erosion and loss of biodiversity. Agropastoral systems integrate the production of different types of livestock, natural pastures and various field crops such as barley, forage, shrubs and trees (FAO, 2022).

Forestry and agroforestry production systems

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Unsustainable tree cultivation can lead to increased soil erosion and reduced soil water infiltration

Forestry and agroforestry systems are important sources of livelihoods in mountains, providing essential environmental goods and services such as timber, fuelwood, carbon storage and other products that improve the lives of people living in mountains (see Chapter 6). Forests cover an estimated 40% of mountain areas, performing a protective function against natural hazards by stabilizing steep slopes, regulating flows to groundwater, reducing surface runoff and soil erosion, and mitigating the potential for landslides and floods. Unsustainable tree cultivation can lead to increased soil erosion and reduced soil water infiltration (Romeo et al., 2021; FAO, 2022).

Aquaculture and freshwater fish capture

Within landlocked mountain areas with no access to marine fishery resources, fish from lakes, rivers and reservoirs are an important source of animal protein, often on a seasonal basis (Petr and Swar, 2002; Alpiev et al., 2013). Fisheries in the mountains are relatively small scale (FAO, 2003), and so integrated agriculture–aquaculture systems can be particularly important in such areas. For example, fish farming in mountain rice terraces optimizes land productivity, profitability and sustainability. Fish improve soil fertility through increasing the availability of oxygen and by depositing nitrogen and phosphorus. They help to regulate the presence of rice pests, as fish control aquatic weeds and algae acting as hosts for pests that compete with rice for nutrients. In return, rice cultivation provides fish with planktonic, periphytic and benthic food. The water temperature is also maintained by the shading effect of rice, enabling fish to thrive during hot summer months (Chapagain and Raizada, 2017).

3.1.3 Downstream reliance on mountain waters for (irrigated) agriculture

At the global scale, water from the mountains makes a significant contribution to supplying irrigation in the lowlands. The contribution has been estimated to vary with different river basins and regions (Viviroli et al., 2020). For instance, some areas of the Indus basin particularly depend on mountain waters including cryosphere melt to supply lowland irrigation in the dry season (Biemans et al., 2019). The contribution of mountain water to supplying irrigation is of relative more importance in basins with limited alternative blue water resources (Viviroli et al., 2020).

3.2 Challenges

In high mountain areas such as in Afghanistan, India and Pakistan, snow and glacial meltwater is used for irrigation and helps retain soil moisture on pastures and grasslands (Rasul and Molden, 2019).

3.2.1 Climate-induced cryosphere melt impacts

Changes in the rate of glacier- and snow-melt affect the timing and volume of water runoff, and hence its availability for irrigated agriculture. This is of critical importance for agricultural production within the mountains and also in downstream lowlands (Milner et al., 2017; Hock et al., 2019). The high levels of poverty and food insecurity in some mountain communities contribute to their vulnerability to the impacts of such cryosphere changes on agriculture (Adler et al., 2022). This has been observed, for instance, in the HKH region (McDowell et al., 2019; Rasul and Molden, 2019).

At the intra-annual timescale within glacial-fed basins and rivers, a shift in timing towards an earlier spring snow-melt peak has been observed. This poses challenges to farmers to accurately predict the timing of water intake for irrigation systems and to manage spring crop planting schedules. Glacial melt and runoff are greatest in the summer and during the daytime, when air temperatures and solar radiation are highest. Within certain catchments dependent on glacial mass balance and local hydrological conditions, greater summer melt and runoff can benefit farmers through increased water availability for irrigation in the dry season. However, there are associated risks of local flooding due to additional summer meltwater (Hock et al., 2019).

Over time as glacier mass reduces, annual runoff initially increases within glacier-fed basins and rivers. After some years or decades, a certain point is reached – referred to as peak water (see Box 2.2) – after which runoff from glacial meltwater declines as glacial mass decreases, which can lead to decreased water availability for irrigation and agriculture. There is strong evidence that peak water has already passed in the glacier-fed rivers of the Tropical Andes, western Canada and the Swiss Alps (Hock et al., 2019). The limit and timing of glacier meltwater increase has not been explored in the extended HKH region (Wester et al., 2019).

Cryosphere melt impacts on agriculture within mountain areas

Irrigated and rainfed agriculture

Reductions in snow cover can also affect agriculture through direct effects on soil moisture

There is some evidence that reduction in streamflow due to glacier melt or reduced snow cover has led to reduced water availability for irrigation of crops, leading to a decline in agricultural yields in several mountain localities (Hock et al., 2019). This includes the Peruvian Andes – which have experienced reduced seasonal runoff due to glacier retreat negatively affecting crops (Bury et al., 2011) – and the Karakoram Mountains in Pakistan – with reduced seasonal water availability for irrigated crops due to glacial retreat and reduced snow cover (Nüsser and Schmidt, 2017; Nüsser et al., 2019). Conversely, an increase in water availability for irrigation leading to increased agricultural yields has been observed in the southern Andes, due to increased meltwater as a result of glacier retreat (Young et al., 2010).

Reductions in snow cover can also affect agriculture through direct effects on soil moisture. Rural communities depend on adequate levels of soil moisture at planting time, often derived from irrigation dependent on glacier- and snow-melt (Hock et al., 2019). This reduction has been reported in Nepal, where less snow cover has led to the drying of soils and lower yields of potatoes and fodder (Smadja et al., 2015).

Pastoralism

Changes in temperature and water regimes can affect mountain pastoralism (Hock et al., 2019). *"The changes in snow and glaciers adversely affect herders at their summer residences and winter camps in the Himalaya (Namgay et al., 2014) and in Scandinavian mountains (Mallory and Boyce, 2018). Reduced winter snowfall has led to poorer pasture quality [for livestock grazing] in Nepal (Gentle and Maraseni, 2012) and India (Ingty, 2017). […] Herders in Nepal reported of water scarcity in traditional water sources along migration routes (Gentle and Thwaites, 2016). Increased glacier melt water has caused lakes on the Tibetan Plateau to increase in size, covering pasture areas and leading pastoralists to alter their patterns of seasonal movement (Nyima and Hopping, 2019). However, rising temperatures, with associated effects on snow cover, have some positive impacts. Seasonal migration […] start[s] earlier in Northern Pakistan, and residence in summer pasture lasts longer (Joshi et al., 2013), as it does in Afghanistan (Shaoliang et al., 2012)"* (Hock et al., 2019, p. 172).

Cryosphere melt impacts on agriculture in downstream river basins

Glacial meltwater contributes an important source of water in the dry season for summer irrigation in the downstream lowlands. It can reduce the variability of river runoff from year to year, at distances of hundreds of kilometres away in some cases (Hock et al., 2019).

Lowland agricultural areas that receive irrigation water from rivers fed by glacier- and snow-melt are projected to face negative impacts in some regions, owing to reduced melt and runoff as glacial mass and snow cover decline over time (Hock et al., 2019; Viviroli et al., 2020). For example, river systems originating in the HKH region, such as the Indus River, depend significantly on glacier and snow meltwater for dry season pre-monsoon irrigation, and are particularly vulnerable to reduced melt as glacial mass and snow cover decreases over time (Biemans et al., 2019; Nie et al., 2021; Lutz et al., 2022; Molden et al., 2022) (Box 3.3). Furthermore, changes in the onset of spring melt and peak snow water melt are predicted to alter the timing of irrigation water delivery downstream in the HKH region and Central Asia (Hock et al., 2019), such as from the snow cover and glaciers of the Tien Shan mountains in Central Asia (Xenarios et al., 2018).

3.2.2 Other climate-induced impacts

Climate-related disasters have led to outmigration, with indirect negative impacts on labour to support agricultural practices

Irrigated agriculture and rainfed agriculture are affected through the increasing variability of seasonal and annual rainfall, making it difficult for farmers to accurate predict planting schedules and crop water management. Rising air temperatures lead to greater crop evapotranspiration, thus increasing water demand for crop production to maintain optimal yield. Rainfall and snow variability – in some cases leading to drought – have affected pasture and rangeland vegetation growth, negatively impacting livestock and the livelihoods of pastoralists (Hock et al., 2019). For instance, herders in Afghanistan, Nepal and Pakistan have perceived that erratic snowfall patterns and a decrease in rainfall resulted in vegetation of lower quality and quantity (Gentle and Thwaites, 2016).

Disasters caused by natural hazards – such as those due to erratic and heavy precipitation events, floods, droughts and landslides – have negatively affected the stable supply and transport of agricultural products within remote mountain areas, thus increasing food insecurity. Climate-related disasters have led to outmigration, with indirect negative impacts on labour to support agricultural practices, as witnessed for instance in Ghana, Thailand, United Republic of Tanzania and the HKH region. From 2003 to 2013 in developing countries, the agricultural sector has been affected by 25% of climate-related hazards, which were responsible for 80% of the damage and loss to livestock and crop production in mountain areas (Romeo et al., 2020).

Box 3.3 Indo-Gangetic basin reliance on cryosphere meltwater for irrigation

Within the Indus River basin during the pre-monsoon season, up to 60% of the total irrigation withdrawals originate from mountain glacier- and snow-melt, contributing to an additional 11% of total crop production. In some irrigated areas in the downstream Indus basin, over 50% of the rice and cotton yields can be attributed to glacier- and snow-melt. Although dependence in the floodplains of the Ganges is comparatively lower, meltwater is still essential during the dry season, in particular for crops such as rice and sugar cane. Based on data from 1981 to 2010, it has been estimated that 129 million farmers in the Indus and Ganges basins depend substantially on glacier- and snow-melt for their livelihoods. Such melt provides enough water to grow food crops to sustain the diet of an estimated 38 million people.

Source: Biemans et al. (2019).

3.2.3 Additional challenges

Access to food markets

For smallholder farmers, achieving and sustaining food security is related to their ability to sell produce, and to access and use market facilities (Romeo et al., 2020). Travel time to markets can increase the vulnerability of rural people, by reducing their access to alternative sources of food and their capacity to cope with food shortages. Transport challenges to food markets include road conditions, terrain, navigable rivers, watercourses and natural barriers.

Access to infrastructure and services

Food security at the household level is determined by factors such as education, health, gender, assets and expenses, as well as by regional-level conditions such as infrastructure, markets and enabling institutions. Mountain communities living in marginal areas often have limited capacity to develop adaptive measures for facing crises and emergencies, owing to relatively low income levels and access to external support and resources (Romeo et al., 2020).

Land degradation and deforestation

Land degradation in mountains detrimentally affects agricultural productivity, endangering the sustainability of crop production and animal husbandry, and threatening water security (UNCCD, 1994). In many developing countries, the impact of unsustainable agriculture practices on land degradation is high. In cases driven by agricultural expansion, deforestation negatively affects the regulation of water flows to groundwater and rivers, thus increasing soil erosion and contributing to increased likelihood of landslides and floods (FAO/UNEP, 2023).

Hazards

The frequency and intensity of hazards and disasters in mountains have increased in recent decades. Floods, debris flows, landslides and avalanches are the most often occurring hazards affecting the highest number of people in mountain regions. Such hazards have an overall detrimental impact on smallholder agricultural activities and food security (Adler et al., 2022). The migration and availability of agricultural labour is also affected by the incidence of hazards (Hock et al., 2019).

3.3 Responses

Responses to climate-driven impacts in mountains vary significantly in terms of goals and priorities, speed of implementation, governance and modes of decision-making, and the extent of financial and other resources to implement them (Adler et al., 2022). Adaptation responses commonly include changing farming practices, infrastructure development including water storage, application of Indigenous knowledge, community-based capacity-building and ecosystem-based adaptation (EbA) (McDowell et al., 2021).

Observed adaptation responses are largely incremental and mainly focus on early warning systems and the diversification of livelihood strategies in smallholder agriculture and pastoralism. However, there is limited evidence of the feasibility and long-term effectiveness of these measures in addressing climate-related impacts and related loss and damage (Hock et al., 2019; Adler et al., 2022).

3.3.1 Climate adaptation techniques in the mountains

Irrigated agriculture

Enhancing (liquid) water storage infrastructure is an effective strategy to mitigate water shortages, particularly in the dry season. The type and scale of storage vary depending on the hydrological site specifics and available materials. Common water storage infrastructure in mountains includes ponds, tanks, check-dams and reservoirs. These storage systems offer viable water sources to supplement irrigation systems in mountain regions (Viviroli et al., 2011; Hock et al., 2019; Adler et al., 2022).

Adaptation approaches for irrigation systems include: the adoption of new irrigation technologies and infrastructure, or the upgrade of existing infrastructure; the adoption of water conservation measures; system water rationing; efficiency improvements; and changing cropping patterns, all of which can be promoted through mountain-specific water user associations (Box 3.4) (Nüsser et al., 2019; Rasul et al., 2019; Rosa, 2022). These approaches represent robust, low-regrets adaptation measures (McDowell et al., 2019; Adler et al., 2022).

Indigenous Peoples in mountains have valuable knowledge that contributes to sustainable food systems, land management and biodiversity preservation

Rainfed agriculture

Mountain farmers practising rainfed agriculture have learned to adapt to varying rainfall and water availability through a variety of ways. These include adopting climate-smart agricultural practices, crop diversification, use of drought-resistant crops, soil conservation, water harvesting, building conservation ponds, developing drought early warning systems and applying Indigenous knowledge (Adhikari, 2018; Adler at al., 2022).

Pastoralism

Pastoral adaptation options include seasonal migration of livestock herds to more fertile pastures, as well as utilizing livestock insurance schemes, if they exist (Fassio et al., 2014; Gentle and Thwaites, 2016; Tiwari et al., 2020).

Freshwater fish capture

Managers can use lake-priority levels and ecosystem-specific strategies to decide about where and when to apply fisheries management action. These include using traditional stocking, preventing aquatic habitat loss, controlling invasive species and modifying harvesting practices (FAO, 2003; Tingley et al., 2019).

Watershed management

Watershed management approaches that include agricultural water requirements encompassing components of soils, biodiversity, forestry and ecosystems will strengthen overall resilience to climate change impacts, including cryosphere melt (Adler et al., 2022; FAO, 2023). Reforestation offers a sustainable land-use practice that promotes water retention in the soils and catchments, thus increasing water availability for agriculture. Mountain soils are particularly vulnerable and sensitive to degradation processes such as water erosion and loss of chemical and physical quality (FAO, 2015b).

Hazards

Most adaptation responses to natural hazards in mountain regions are reactive to specific climate stimuli or involve post-disaster recovery (McDowell et al., 2019). Hard structural measures such as constructing dykes, dams, reservoirs and embankments have been widely employed to contain hazards, along with the use of early warning systems, zonation and land management (Adler et al., 2022). EbA is widely recommended to mitigate risks from landslides (e.g. afforestation, reforestation and improved forest management), floods (e.g. river restoration and renaturation) and droughts (e.g. adapting watersheds) (FAO, 2023). Experience from Nepal highlights that introducing agroforestry to mountain agriculture promotes effective disaster risk reduction (Schick et al., 2018).

Box 3.4 Innovative adaptation to glacier melt affecting water availability for irrigated agriculture

In Ladakh, northern India, the storage of ice has a long history of providing water during the agricultural season (Hasnain, 2012). To cope with seasonal water scarcity at critical times for irrigation, villagers in the region have developed four types of ice reservoirs: basins, cascades, diversions and a form known locally as ice stupas. These ice reservoirs capture water in the autumn and winter, allowing it to freeze and holding it until spring, when it melts and flows down to fields (Clouse et al., 2017; Nüsser et al., 2019). They retain a previously unused portion of the annual flow and facilitate its use to supplement the flow in the following spring.

Increased irrigation frequency, yield, soil moisture and groundwater recharge are among the benefits observed. However, questions remain regarding this as a long-term adaptation strategy, as its operation depends on winter runoff and freeze–thaw cycles, both of which are sensitive to interannual variability. It also raises questions about the financial costs and labour requirements, which vary across the four types of ice reservoirs.

Ice stupas in Ladakh, India

Photo: © Naveen Macro/Shutterstock.*

Source: Adapted from Hock et al. (2019, box 2.3, p. 156).

3.3.2 Knowledge and capacity

Hydrological monitoring networks are extremely sparse within mountain regions, particularly in developing countries. Non-existent or limited hydrological data collection and monitoring severely limit anticipatory hazard planning and accurate hydrological assessments for water

Box 3.5 The Global Mountain Participatory Guarantee System (PGS) Network

[The Global Mountain PGS] Network represents [a] valid example of knowledge-sharing processes among mountain peoples, including Indigenous communities. Created in 2019 by 13 organizations of smallholder mountain producers from the Plurinational State of Bolivia, India, Kyrgyzstan, Mongolia, Nepal, Panama, Peru and the Philippines, the Global Mountain PGS Network is the first international network of Participatory Guarantee Systems. [...] The network links small-scale mountain farmers around the globe, promotes horizontal knowledge-sharing among partners and innovative south–south cooperation. Thanks to this network, mountain farmers' experiences can be shared, communicated and scaled up, maintaining the context-specific approach typical of PGS initiatives.

Source: Extracted from FAO (2021, p. 90).

management and agricultural production (Wilby, 2019; GEO Mountains, 2022). Hydrological assessments are urgently required in many mountains ranges globally. This includes the HKH region, where mountain waters support the agricultural livelihoods and water and energy requirements of over 2 billion people (Immerzeel et al., 2010; Wester et al., 2019). There is also the potential for citizen science to increase hydrological monitoring in mountains.
For instance by involving local populations in research and data gathering (Njue et al., 2019), thus representing an opportunity for data collection and public participation in water-related projects (Hegarty et al., 2021).

Indigenous Peoples in mountains have unique and valuable local knowledge, traditions and cultural practices that contribute to sustainable food systems, land management and biodiversity preservation (FAO, 2021). For instance, in the Andes, Indigenous knowledge has promoted access to local and regional seed supply networks and the adoption of new crop varieties (Skarbø and Van der Molen, 2014) (Box 3.5).

3.3.3 Governance

The Mountain Partnership is the only global governance structure for mountain regions. This voluntary alliance, established by the United Nations in 2002, brings together governments, intergovernmental organizations, non-governmental organizations and local communities. Through collaboration, knowledge-sharing and advocacy, the Mountain Partnership tackles challenges faced by mountain environments and communities, including food security and nutrition.

This collaborative approach to mountain governance empowers various stakeholders to work together for a common goal – a thriving future for mountain people and places. The Food and Agricultural Organization of the United Nations hosts the Secretariat, and is the lead agency for mountains within the United Nations system, as agriculture and food production are important drivers in mountain areas. The Framework for the Five Years of Action for the Development of Mountain regions (2023–2027) groups and guides activities on sustainable mountain development. The Mountain Partnership leads a commitment to action submitted at the United Nations 2023 Conference on the Midterm Comprehensive Review of Implementation of the Objectives of the International Decade for Action, "Water for Sustainable Development", 2018–2028, titled 'Advancing sustainable mountain development and protecting the "water towers" of the world'.

Regionally, several mountain organizations address specific challenges and opportunities in their respective areas (see Chapter 9). The Alpine Convention and the Carpathian Convention focus on sustainable development and conservation in the European mountain ranges of the Alps and Carpathians, respectively (Permanent Secretariat of the Alpine Convention, 2017). Meanwhile, the International Centre for Integrated Mountain Development in the HKH region promotes cooperation and knowledge-sharing across borders. The Consortium for the Sustainable Development of the Andean Ecoregion network works on sustainable development in the Andes Mountain range, focusing on community-driven initiatives and knowledge exchange between Andean nations.

3.4 Conclusions

Mountain agriculture faces numerous obstacles in achieving food security through sustainable and enhanced production. Climate change affecting rainfall variability, along with global warming leading to glacier- and snow-melt, will increasingly affect mountain water availability across different timescales, thus posing challenges to farmers in the mountains and to irrigated agriculture downstream. In addition to the remoteness and inaccessibility of mountains, climate change impacts are exacerbating the food security dimensions of availability, accessibility, utilization and stability.

It is necessary to ensure sufficient water downflow from the mountains to serve lowland irrigation

To create an enabling environment for implementation of adaptation interventions, important considerations include: capacity-building and strengthening knowledge management, including an increase in hydrological monitoring and data generation; developing agricultural plans and policies that fully take on board mountain communities context-specific requirements; enhancing local governance institutions including farmer organizations; supporting mountain farming systems that preserve agricultural diversity; and providing back-up with sufficient funds for implementation.

The need for effective governance to sustain highland and lowland food security is more important than ever. It is necessary to ensure sufficient water downflow from the mountains to serve lowland irrigation, and equally to preserve and enhance unique and diverse agricultural mountainscapes.

References

Adhikari, S. 2018. Drought impact and adaptation strategies in the mid-hill farming system of western Nepal. *Environments*, Vol. 5, No. 9, Article 101. doi.org/10.3390/environments5090101.

Adler, C., Wester, P., Bhatt, I., Huggel, C., Insarov, G., Morecroft, M., Muccione, V. and Prakash, A. 2022. Mountains. H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem and B. Rama (eds), *Climate Change 2022: Impacts, Adaptation and Vulnerability.* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK/New York, Cambridge University Press, pp. 2273–2318. doi.org/10.1017/9781009325844.022.

Alpiev, M., Sarieva, M., Siriwardena, S. N., Valbo-Jørgensen, J. and Woynárovich, A. 2013. *Fish Species Introductions in the Kyrgyz Republic.* FAO Fisheries and Aquaculture Technical Paper No. 584. Rome, Food and Agriculture Organization of the United Nations (FAO). www.fao.org/4/i3268e/i3268e.pdf.

Biemans, H., Siderius, C., Lutz, A. F., Nepal, S., Ahmad, B., Hassan, T., Von Bloh, W., Wijngaard, R. R., Wester, P., Shrestha, A. B. and Immerzeel, W. W. 2019. Importance of snow and glacier meltwater for agriculture on the Indo-Gangetic Plain. *Nature Sustainability*, Vol. 2, pp. 594–601. doi.org/10.1038/s41893-019-0305-3.

Bury, J. T., Mark, B. G., McKenzie, J. M., French, A., Baraer, M., Huh, K. I., Zapata Luyo, M. A. and Gómez López, R. J. 2011. Glacier recession and human vulnerability in the Yanamarey watershed of the Cordillera Blanca, Peru. *Climatic Change*, Vol. 105, pp. 179–206. doi.org/10.1007/s10584-010-9870-1.

Chapagain, T. and Raizada, M. N. 2017. Agronomic challenges and opportunities for smallholder terrace agriculture in developing countries. *Frontiers in Plant Science*, Vol. 8, Article 331. doi.org/10.3389/fpls.2017.00331.

Clouse, C., Anderson, N. and Shippling, T. 2017. Ladakh's artificial glaciers: Climate-adaptive design for water scarcity. *Climate and Development*, Vol. 9, No. 5, pp. 428–438. doi.org/10.1080/17565529.2016.1167664.

Deng, C., Zhang, G., Liu, Y., Nie, X., Li, Z., Liu, J. and Zhu, D. 2021. Advantages and disadvantages of terracing: A comprehensive review. *International Soil and Water Conservation Research*, Vol. 9, No. 3, pp. 344–359. doi.org/10.1016/j.iswcr.2021.03.002.

FAO (Food and Agriculture Organization of the United Nations). 1996. *Rome Declaration on World Food Security.* World Food Summit, Rome, 13–17 November 1996. Rome, FAO. www.fao.org/4/w3613e/w3613e00.htm.

—. 2003. *Mountain Fisheries in Developing Countries*. Rome, FAO. www.fao.org/3/y4633e/y4633e.pdf.

—. 2014. *Developing Sustainable Food Value Chains: Guiding Principles*. Rome, FAO. https://openknowledge.fao.org/server/api/core/bitstreams/e47d2ad8-5910-435e-a6b4-92dda2367dc7/content.

—. 2015a. *Understanding Mountain Soils: A Contribution from Mountain Areas to the International Year of Soils 2015*. Rome, FAO. https://openknowledge.fao.org/server/api/core/bitstreams/8d557f4f-9458-4140-8f6b-42c9309ed060/content.

—. 2015b. *Mapping the Vulnerability of Mountain Peoples to Food Insecurity*. Rome, FAO. https://openknowledge.fao.org/server/api/core/bitstreams/fc51a31f-4d11-45da-a9f3-5d44277ab231/content.

—. 2019. *Mountain Agriculture: Opportunities for Harnessing Zero Hunger in Asia*. Bangkok, FAO. www.fao.org/3/ca5561en/ca5561en.pdf.

—. 2021. *The White/Wiphala Paper on Indigenous Peoples' Food Systems*. Rome, FAO. doi.org/10.4060/cb4932en.

—. 2022. *The State of the World's Land and Water Resources for Food and Agriculture 2021: Systems at Breaking Point*. Main Report. Rome, FAO. doi.org/10.4060/cb9910en.

—. 2023. *Building Resilience into Watersheds: A Sourcebook*. Rome, FAO. doi.org/10.4060/cc3258en.

—. 2024. Globally Important Agricultural Heritage Systems (GIAHS). Agricultural Heritage Around the World. FAO website. www.fao.org/giahs/around-the-world/en. (Accessed on 6 November 2024.)

FAO/UNEP (Food and Agriculture Organization of the United Nations/United Nations Environment Programme). 2023. *Restoring Mountain Ecosystems: Challenges, Case Studies and Recommendations for Implementing the UN Decade Principles for Mountain Ecosystem Restoration*. Rome/Nairobi, FAO/UNEP. doi.org/10.4060/cc9044en.

Fassio, G., Battaglini, L. M., Porcellana, V. and Viazzo, P. P. 2014. The role of the family in mountain pastoralism: Change and continuity. *Mountain Research and Development*, Vol. 34, No. 4, pp. 336–343. doi.org/10.1659/MRD-JOURNAL-D-14-00019.1.

Gentle, P. and Maraseni, T. N. 2012. Climate change, poverty and livelihoods: Adaptation practices by rural mountain communities in Nepal. *Environmental Science and Policy*, Vol. 21, pp. 24–34. doi.org/10.1016/j.envsci.2012.03.007.

Gentle, P. and Thwaites, R. 2016. Transhumant pastoralism in the context of socioeconomic and climate change in the mountains of Nepal. *Mountain Research Development*, Vol. 36, No. 2, 173–182. doi.org/10.1659/MRD-JOURNAL-D-15-00011.1.

GEO Mountains. 2022. *Mountain Observations: Monitoring, Data, and Information for Science, Policy, and Society*. Policy Brief. GEO Mountains. https://geomountains.org/images/GEO_Mountains_Policy_Brief_IYSMD_2022.pdf.

Hasnain, M. 2012. *Artificial Glaciers in Ladakh: A Socio-Economic Analysis*. GERES India. www.geres.eu/wp-content/uploads/2019/10/Artifial-glaciers-Socio-economic-analysis.pdf.

Hegarty, S., Hayes, A., Regan, F., Bishop, I. and Clinton, R. 2021. Using citizen science to understand river water quality while filling data gaps to meet United Nations Sustainable Development Goal 6 objectives. *Science of the Total Environment*, Vol. 783, Article 146953. doi.org/10.1016/j.scitotenv.2021.146953.

Hock, R., Rasul, G., Adler, C., Cáceres, B., Gruber, S., Hirabayashi, Y., Jackson, M., Kääb, A., Kang, S., Kutuzov, S., Milner, A., Molau, U., Morin, S., Orlove, B. and Steltzer, H. 2019. High mountain areas. H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. S. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds), *The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK/New York, Cambridge University Press, pp. 131–202. doi.org/10.1017/9781009157964.004.

Immerzeel, W. W., Van Beek, L. P. H. and Bierkens, M. F. P. 2010. Climate change will affect the Asian water towers. *Science*, Vol. 328, No. 5984, pp. 1382–1385. doi.org/10.1126/science.1183188.

Ingty, T. 2017. High mountain communities and climate change: Adaptation, traditional ecological knowledge, and institutions. *Climatic Change*, Vol. 145, No. 1–2, pp. 41–55. doi.org/10.1007/s10584-017-2080-3.

Joshi, S., Jasra, W. A., Ismail, M., Shrestha, R. M., Yi, S. L. and Wu, N. 2013. Herders' perceptions of and responses to climate change in northern Pakistan. *Environmental Management*, Vol. 52, No. 3, pp. 639–648. doi.org/10.1007/s00267-013-0062-4.

Lutz, A. F., Immerzeel, W. W., Siderius, C., Wijngaard, R. R., Nepal, S., Shrestha, A. B., Wester, P. and Biemans, H. 2022. South Asian agriculture increasingly dependent on meltwater and groundwater. *Nature Climate Change*, Vol. 12, pp. 566–573. doi.org/10.1038/s41558-022-01355-z.

Mallory, C. D. and Boyce, M. S. 2018. Observed and predicted effects of climate change on Arctic caribou and reindeer. *Environmental Reviews*, Vol. 26, No. 1, pp. 13–25. doi.org/10.1139/er-2017-0032.

McDowell, G., Huggel, C., Frey, H., Wang, F. M., Cramer, K. and Ricciardi, V. 2019. Adaptation action and research in glaciated mountain systems: Are they enough to meet the challenge of climate change? *Global Environmental Change*, Vol. 54, pp. 19–30. doi.org/10.1016/j.gloenvcha.2018.10.012.

McDowell, G., Stevens, M., Lesnikowski, A., Huggel, C., Harden, A., Di Bella, J., Morecroft, M., Kumar, P., Joe, E. T., Bhatt, I. D. and the Global Adaptation Mapping Initiative. 2021. Closing the adaptation gap in mountains. *Mountain Research and Development*, Vol. 41, No. 3, pp. A1–A10. doi.org/10.1659/MRD-JOURNAL-D-21-00033.1.

Milner, A. M., Khamis, K., Battin, T. J., Brittain, J. E., Barrand, N. E., Füreder, L., Cauvy-Fraunié, S., Gíslason, G. M., Jacobsen, D., Hannah, D. M., Hodson, A. J., Hood, E., Lencioni, V., Ólafsson, J. S., Robinson, C. T., Tranter, M. and Brown, L. E. 2017. Glacier shrinkage driving global changes in downstream systems. *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 114, No. 37, pp. 9770–9778. doi.org/10.1073/pnas.1619807114.

Molden, D. J., Shrestha, A. B., Immerzeel, W. W., Maharjan, A., Rasul, G., Wester, P., Wagle, N., Pradhananga, S. and Nepal, S. 2022. The great glacier and snow-dependent rivers of Asia and climate change: Heading for troubled waters. A. K. Biswas and C. Tortajada (eds), *Water Security Under Climate Change*. Water Resources Development and Management. Singapore, Springer, pp. 223–250. doi.org/10.1007/978-981-16-5493-0_12.

Namgay, K., Millar, J. E., Black, R. S. and Samdup, T. 2014. Changes in transhumant agro-pastoralism in Bhutan: A disappearing livelihood? *Human Ecology*, Vol. 42, pp. 779–792. doi.org/10.1007/s10745-014-9684-2.

Nie, Y., Pritchard, H. D., Liu, Q., Hennig, T., Wang, W., Wang, X., Liu, S., Nepal, S., Samyn, D., Hewitt, K. and Chen, X. 2021. Glacial change and hydrological implications in the Himalaya and Karakoram. *Nature Reviews Earth & Environment*, Vol. 2, pp. 91–106. doi.org/10.1038/s43017-020-00124-w.

Njue, N., Stenfert Kroese, J., Gräf, J., Jacobs, S. R., Weeser, B., Breuer, L. and Rufino, M. C. 2019. Citizen science in hydrological monitoring and ecosystem services management: State of the art and future prospects. *Science of the Total Environment*, Vol. 693, Article 133531. doi.org/10.1016/j.scitotenv.2019.07.337.

Nüsser, M. and Schmidt, S. 2017. Nanga Parbat revisited: Evolution and dynamics of sociohydrological interactions in the Northwestern Himalaya. *Annals of the American Association of Geographers*, Vol. 107, No. 2, pp. 403–415. doi.org/10.1080/24694452.2016.1235495.

Nüsser, M., Dame, J., Kraus, B., Baghel, R. and Schmidt, S. 2019. Socio-hydrology of "artificial glaciers" in Ladakh, India: Assessing adaptive strategies in a changing cryosphere. *Regional Environmental Changes*, Vol. 19, pp. 1327–1337. doi.org/10.1007/s10113-018-1372-0.

Nyima, Y. and Hopping, K. A. 2019. Tibetan lake expansion from a pastoral perspective: Local observations and coping strategies for a changing environment. *Society and Natural Resources*, Vol. 32, No. 9, pp. 965–982. doi.org/10.1080/08941920.2019.1590667.

Permanent Secretariat of the Alpine Convention. 2017. *Alpine Convention Mountain Agriculture Platform: Mountain Agriculture*. Alpine Signals No. 8. Permanent Secretariat of the Alpine Convention. www.alpconv.org/fileadmin/user_upload/downloads/downloads_en/2_organisation_en/organisation_presidency_en/mountain_agriculture_A4_EN.pdf.

Petr, T. and Swar, S. B. (eds). 2002. *Cold Water Fisheries in the Trans-Himalayan Countries.* FAO Fisheries Technical Paper No. 431. Rome, Food and Agriculture Organization of the United Nations (FAO). https://openknowledge.fao.org/items/11b2bd1d-b9ef-49f1-9543-d59fd3c7c064.

Rasul, G. and Molden, D. 2019. The global social and economic consequences of mountain cryospheric change. *Frontiers in Environmental Science*, Vol. 7, Article 91. doi.org/10.3389/fenvs.2019.00091.

Rasul, G., Pasakhala, B., Mishra, A. and Pant, S. 2019. Adaptation to mountain cryosphere change: Issues and challenges. *Climate and Development*, Vol. 12, No. 4, pp. 297–309. doi.org/10.1080/17565529.2019.1617099.

Romeo, R., Grita, F., Parisi, F. and Russo, L. 2020. *Vulnerability of Mountain Peoples to Food Insecurity: Updated Data and Analysis of Drivers*. Rome, Food and Agriculture Organization of the United Nations (FAO)/United Nations Convention to Combat Desertification (UNCCD). doi.org/10.4060/cb2409en.

Romeo, R., Manuelli, S. R., Geringer, M. and Barchiesi, V. (eds). 2021. *Mountain Farming Systems – Seeds for the Future: Sustainable Agricultural Practices for Resilient Mountain Livelihoods*. Rome, Food and Agriculture Organization of the United Nations (FAO). doi.org/10.4060/cb5349en.

Rosa, L. 2022. Adapting agriculture to climate change via sustainable irrigation: Biophysical potentials and feedbacks. *Environmental Research Letters*, Vol. 17, No. 6, Article 063008. doi.org/10.1088/1748-9326/ac7408.

Schick, A., Wieners, E., Schwab, N. and Schickhoff, U. 2018. Sustainable disaster risk reduction in mountain agriculture: Agroforestry experiences in Kaule, mid-hills of Nepal. S. Mal, R. Singh, C. Huggel (eds), *Climate Change, Extreme Events and Disaster Risk Reduction: Towards Sustainable Development Goals*. Cham, Switzerland, Springer, pp. 249–264. doi.org/10.1007/978-3-319-56469-2_17.

Shaoliang, Y., Ismail, M. and Zhaoli, Y. 2012. Pastoral communities' perspectives on climate change and their adaptation strategies in the Hindukush-Karakoram-Himalaya. H. Kreutzmann (ed.), *Pastoral Practices in High Asia: Agency of 'Development' Effected by Modernisation, Resettlement and Transformation*. Advances in Asian Human-Environmental Research. Dordrecht, Netherlands (Kingdom of the), Springer. doi.org/10.1007/978-94-007-3846-1_17.

Sheehy, D. P., Miller, D. and Johnson, D. A. 2006. Transformation of traditional pastoral livestock systems on the Tibetan steppe. *Sécheresse*, Vol. 17, No. 1–2, pp. 142–151.

Skarbø, K. and Van der Molen, K. 2014. Irrigation access and vulnerability to climate-induced hydrological change in the Ecuadorian Andes. *Culture, Agriculture, Food and Environment*, Vol. 36, No. 1, pp. 28–44. doi.org/10.1111/cuag.12027.

Smadja, J., Aubriot, O., Puschiasis, O., Duplan, T., Grimaldi, G., Hugonnet, M. and Buchheit, P. 2015. Climate change and water resources in the Himalayas: Field study in four geographic units of the Koshi basin, Nepal. *Journal of Alpine Research*, Vol. 103, No. 2. doi.org/10.4000/rga.2910.

Tingley III, R. W., Paukert, C., Sass, G. G., Jacobson, P. C., Hansen, G. J. A., Lynch, A. J. and Shannon, P. D. 2019. Adapting to climate change: Guidance for the management of inland glacial lake fisheries. *Lake and Reservoir Management*, Vol. 35, No. 4, pp. 435–452. doi.org/10.1080/10402381.2019.1678535.

Tiwari, K. R., Sitaula, B. K., Bajracharya, R. M., Raut, N., Bhusal, P. and Sengel, M. 2020. Vulnerability of pastoralism: A case study from the high mountains of Nepal. *Sustainability*, Vol. 12, No. 7, Article 2737. doi.org/10.3390/su12072737.

UNCCD (United Nations Convention to Combat Desertification). 1994. *United Nations Convention to Combat Desertification in Those Countries Experiencing Serious Drought and/or Desertification, Particularly in Africa*. Paris, UNCCD. https://catalogue.unccd.int/936_UNCCD_Convention_ENG.pdf.

Viviroli, D., Archer, D. R., Buytaert, W., Fowler, H. J., Greenwood, G. B., Hamlet, A. F., Huang, Y., Koboltschnig, G., Litaor, M. I., López-Moreno, J. I., Lorentz, S., Schädler, B., Schreier, H., Schwaiger, K., Vuille, M. and Woods, R. 2011. Climate change and mountain water resources: Overview and recommendations for research, management and policy. *Hydrology and Earth System Sciences*, Vol. 15, No. 2, pp. 471–504. doi.org/10.5194/hess-15-471-2011.

Viviroli, D., Kummu, M., Meybeck, M., Kallio, M. and Wada, Y. 2020. Increasing dependence of lowland populations on mountain water resources. *Nature Sustainability*, Vol. 3, pp. 917–928. doi.org/10.1038/s41893-020-0559-9.

Wester, P., Mishra, A., Mukherji, A. and Shrestha, A. B. (eds). 2019. *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People*. Cham, Switzerland, Springer. lib.icimod.org/record/34383.

Wilby, R. L. 2019. A global hydrology research agenda fit for the 2030s. *Hydrology Research*, Vol. 50, No. 6, pp. 1464–1480. doi.org/10.2166/nh.2019.100.

World Bank Group. n.d. What is Food Security? World Bank Group website. www.worldbank.org/en/topic/agriculture/brief/food-security-update/what-is-food-security. (Accessed on 2 October 2024.)

Xenarios, S., Shenhav, R., Abdullaev, I. and Mastellari, A. 2018. Current and future challenges of water security in Central Asia. *Global Water Security: Lessons Learnt and Long-Term Implications*. Water Resources Development and Management. Singapore, Springer, pp. 117–142. doi.org/10.1007/978-981-10-7913-9_5.

Yang, L., Liu, M., Lun, F., Yuan, Z., Zhang, Y. and Min, Q. 2017. An analysis on crops choice and its driving factors in agricultural heritage systems: A case of Honghe Hani rice terraces system. *Sustainability*, Vol. 9, No. 7, Article 1162. doi.org/10.3390/su9071162.

Young, G., Zavala, H., Wandel, J., Smit, B., Salas, S., Jiménez, E., Fiebig, M., Espinoza, R., Díaz, H. and Cepeda, J. 2010. Vulnerability and adaptation in a dryland community of the Elqui Valley, Chile. *Climatic Change*, Vol. 98, pp. 245–276. doi.org/10.1007/s10584-009-9665-4.

Chapter 4

Human settlements and disaster risk reduction

UN-Habitat
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Mountain regions are important water towers, sustaining human settlements home to 14% of the world's population (Ehrlich et al., 2021). Such regions face a unique set of challenges that affect the provision of water, sanitation and hygiene (WASH) services (De Jong, 2015; Clerici et al., 2019; Zogaris et al., 2021). They are often exposed to natural hazards such as floods, landslides induced by extreme rainfall, debris flows, ice and snow avalanches, earthquakes and droughts.

This chapter focuses on the challenges and responses to WASH service provision and disaster risk reduction (DRR) in mountain regions. It highlights the impacts of rapid and unplanned urbanization, natural hazards and climate change on water availability, quality and security in such areas.

4.1 Challenges

4.1.1 Urbanization

Rapid and unplanned urbanization in mountain regions is placing pressure on fragile mountain ecosystems, affecting water availability, quality and security. Despite the challenges associated with difficult terrain and fragile ecosystems, the population in mountain regions has been steadily growing. Between 1975 and 2015, approximately 35% of mountain subregions experienced at least a twofold increase in population (Thornton et al., 2022). The proportion of urban residents within these mountain areas ranged from 6% to 39% over the same period (Ehrlich et al., 2021; Thornton et al., 2022).

Rapid and unplanned urbanization in mountain regions is placing pressure on fragile mountain ecosystems

Understanding urban expansion modes specific to mountain cities is therefore essential for sustainable planning, including for water resources (Jia et al., 2020). About 1.1 billion people live in mountain regions. Although the urbanization rate varies considerably across mountain ranges, approximately 34% of the population in mountains lives in cities, 31% in towns and semi-dense areas, and 35% in rural areas. Although the urbanization rate in mountains (66%) is lower than in lowlands (78%), the most populated and urbanized mountain ranges such as the Himalayas, Andes, Rockies and Alps are also those where urbanization rates are highest (Ehrlich et al., 2021).

Urbanization in mountain regions has major impacts on surface water and groundwater flow (Somers and McKenzie, 2020), and also on water quality (De Jong, 2015). It significantly alters the hydrological cycle, affecting the volume and quality of surface water. Steep slopes, altered natural water drainage patterns and paved surfaces decrease groundwater recharge and increase runoff, resulting in flash floods and soil erosion. Water quality may decline due to pollutants from increased tourism, untreated wastewater and industries. Legacy pollutants such as persistent organic pollutants, particularly polychlorinated biphenyls and dichlorodiphenyltrichloroethane, polycyclic aromatic hydrocarbons and heavy metals may be released into water sources due to ice- and snow-melt associated with climate change (Hodson, 2014).

For example, the Himalayan region in South Asia is densely populated and has experienced rapid urban growth in recent decades. Undoubtedly, urbanization in the region has created jobs and improved infrastructure, but it has also caused significant environmental and socio-economic issues. Disrupted hydrological regimes have reduced groundwater recharge and water availability, exacerbating water insecurity amid the impacts of climate change. Deforestation, biodiversity loss and the likelihood of natural hazards such as floods and landslides occurring have been increasing (Tiwari et al., 2018). Urban expansion has degraded fragile ecosystems, including forests, wildlife habitats and water sources. Addressing these challenges requires nature-based solutions (NbS) and mountain-specific urban planning to ensure sustainable development and resilience.

Box 4.1 Impacts of the 2021 Nepal flood disaster

On 15 June 2021, Melamchi Bazar in Nepal experienced a devastating flash flood from the Melamchi and Indrawati Rivers, resulting in 5 deaths, 20 missing persons and extensive damage. The Melamchi Drinking Water Project was also affected. This event was part of a series of floods that, over 3–4 days, led to 337 houses being damaged and 525 families being displaced. Critical infrastructure – such as 13 suspension bridges, 7 motorable bridges and numerous roads – was destroyed, severely affecting human settlements, agriculture and river-based livelihoods across a large area.

The floods also carried large debris from upstream, depositing it as far as 54 km away in Dolalghat. Additionally, a landslide on 18 June 2021 blocked the Tama Koshi River, forming a lake that threatened downstream areas. The National Disaster Risk Reduction and Management Authority reported the initial casualties and damage, and highlighted the urgent need for effective disaster risk management.

Source: Maharjan et al. (2021).

4.1.2 Natural hazards

Natural hazards such as landslides, earthquakes, floods, glacial lake outburst floods (GLOFs) and avalanches often occur in mountain regions (see Section 2.2.3). These can damage the water supply and sanitation infrastructure, and disrupt access to WASH services. For example, from 850 to 2022, 3,151 GLOF events were recorded across the world's major glaciated regions (Lützow et al., 2023). The damage to critical infrastructures such as roads, bridges, dams, water intake and flood protection structures, hydropower plants and power lines, and communication networks has been significant. Such hazards increase the vulnerability of already vulnerable and often marginalized mountain communities, and destabilize some of their wealth-generating sectors, including agriculture, tourism and biodiversity (Alfthan et al., 2018; Hock et al., 2019).

For instance, the April 2015 Nepal earthquake damaged water and sanitation facilities in surrounding areas: "*Out of a total 11,288 water supply systems in the 14 most affected districts, 1,570 sustained major damages, 3,663 were partially damaged and approximately 220,000 toilets were partially or totally destroyed*" (UN-Habitat, 2016, p. 4). As another example, Box 4.1 highlights the impacts of the 2021 Nepal flood disaster.

4.1.3 Climate change

Mountain habitats are highly sensitive to climate change. Increasing frequency, severity and intensity of extreme weather events can result in poor living conditions with compromised access to (often fragile) water and sanitation services. Rising temperatures and changing precipitation patterns due to climate change may affect water availability in mountain regions through increased exposure to hazards such as droughts and floods (Adler et al., 2022).

An increase in the intensity, frequency and duration of extreme precipitation can lead to a sudden rise in peak river flow, triggering flash floods in river valleys. In Nepal, a one-unit increase in the maximum 1 day precipitation led to a 33% rise in flood-related fatalities, and a one-unit rise in the number of heavy rain days and consecutive wet days increased landslide-related fatalities by 45% and 34%, respectively (Chapagain et al., 2024). Conversely, a precipitation deficit, especially due to decreases in scattered and consecutive low-intensity rainy days, reduces water percolation into the subsurface in steep areas. This adversely affects groundwater recharge and subsequently diminishes baseflow contributions to streams, natural springs and aquifer storage (Chapagain et al., 2021; Seneviratne et al., 2021).

Increased water stress has resulted in migration and displacement in highlands (Joshi and Dongol, 2018; Almulhim et al., 2024). During dry and hot seasons, water scarcity has resulted in poor hygienic practices and increased the risk of disease prevalence (Dhimal et al., 2015; Bhandari et al., 2020). Furthermore, pollution from poor sanitation, depletion of water sources, forest fires, mining and unsustainable agriculture can affect water availability and quality.

Regions that rely on mountain snowpack as a temporary water reservoir may also experience severe hydrological droughts as global temperatures increase (Seneviratne et al., 2021).

4.1.4 Mountain terrain

Mountain terrain – characterized by steep slopes, often difficult weather conditions, remote locations and poor road networks – poses significant challenges for the construction and maintenance of water and sanitation infrastructure. The topography of mountain regions favours the natural occurrence or construction of water reservoirs at high elevations and gravity-flow water systems, which can operate without costly energy requirements. However, constructing and maintaining water reservoirs, water treatment plants and distribution pipelines can be tedious and expensive. For communities not served by piped water, steep slopes and rocky terrain also limit the availability of surface water sources, making fetching water time-consuming and physically demanding, especially for women and girls, who are culturally the primary purveyors of water at the household level (Shrestha et al., 2019).

4.1.5 Mental health and psychosocial well-being

Mountain terrain poses significant challenges for the construction and maintenance of water and sanitation infrastructure

Extreme weather events in mountain regions can significantly affect health, not only in terms of physical injuries (Sumann et al., 2020) but also mental health and psychosocial well-being (Poudyal et al., 2021). For instance, communities in the Hindu Kush Himalaya region have been suffering with the impacts of climate change, particularly in recent years. Local populations in Ghizer district, in the Gilgit-Baltisan region of northern Pakistan, have experienced flash floods and landslides that destroyed the local infrastructure, agricultural lands and housing (Abbas and Khan, 2020).

Many mountain communities that rely on agriculture, tourism or forestry industries are vulnerable to the impacts of extreme weather events. Loss of livelihood due to crop failure and damage to infrastructure and tourism could potentially lead to economic instability. Inevitably, these events have a huge toll on the mental health of the local communities. Such experiences can cause stress, anxiety and post-traumatic stress disorder among those affected (WHO, 2022).

Populations may be hesitant to openly discuss mental health issues due to a fear of the social stigma associated with such conditions (Ebrahim, 2022). Furthermore, extreme weather conditions can isolate communities by disrupting routes and communication networks, leading to limited or no access to health and mental health services (Dewi et al., 2023). This challenge is exacerbated by the existing difficulties in accessing these services due to geographical remoteness or a shortage of trained professionals.

4.2 Responses

Improving access to WASH services and DRR in mountain regions requires prioritizing water in urban planning, and integrating WASH and DRR into nationally determined contributions (NDCs) and national adaptation plans (NAPs). Investment in climate-resilient infrastructure and community-based adaptation strategies, including local knowledge, is essential. Additionally, fostering cross-border collaboration will enhance resilience and help to mitigate the impacts of extreme weather events.

4.2.1 Urban and land-use planning

Urbanization in mountain regions can be planned better by putting WASH at the centre of urban and land-use planning. Effective urban land-use policies need to be developed and implemented for the protection and conservation of the urban environment and ecosystem services and for making urban systems climate resilient (Tiwari et al., 2018).

Sustainable land management practices, including reforestation and controlled grazing, have helped reduce soil erosion and improve water retention, for example, in the Alps. Soil management and reforestation efforts reflect the intent to stabilize slopes and increase the infiltration of melting snow and rainwater, boosting groundwater recharge and reducing the risk of flash floods (Repe et al., 2020).

4.2.2 Disaster risk reduction management

In mountain regions, DRR necessitates a blend of climate change adaptation and mitigation, strategic urban and land-use planning, use of engineering solutions, and development of early warning systems (EWS).

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Investment in climate-resilient infrastructure and community-based adaptation strategies is essential

Through the Nepal Karnali Water Activity, donors like the United States Agency for International Development have utilized hydrological models such as the Soil & Water Assessment Tool and Water Accounting+ to assess water resources use and availability in the Karnali River basin. These assessments inform local DRR management plans, guiding mitigation and adaptation strategies like pond construction, spring conservation and afforestation, and identifying flood- and drought-resistant crops.

Integrating climate change efforts and informed urban planning decisions is crucial to minimizing vulnerabilities, including for WASH provision. Collaborative research and policymaking is essential to address the unique challenges of mountain regions and protect their vital ecosystem services. Initiatives like the Global Mountain Safeguard Research and the Mountain Partnership aim to foster sustainable and resilient mountain communities, ensuring social and economic well-being while conserving mountain ecosystems (FAO, 2022; UNU-EHS, 2023).

4.2.3 Financing adaptation and climate-resilient infrastructure

A review of countries' NDCs[12] and NAPs[13] submitted to the United Nations Framework Convention on Climate Change prior to June 2024 suggests WASH and disaster management are priority sectors in mountainous developing countries (MDCs). Examples of adaptation actions in mountain regions include: feasibility studies for building emergency storage and bypasses and controlled releases from glacial lakes; river basin management and planning for basin optimization; monitoring temporal changes in glaciers; and establishing GLOF risk reduction systems and EWS in glaciated river basins.

The estimated adaptation finance needs specifically for MDCs amounts to US$187 billion per year (in 2021 prices), equivalent to 1.3% of their gross domestic product, for this decade. Adaptation finance needs in the health and sanitation, water supply and DRR sectors together account for almost 20% of the MDC total adaptation finance needs. However, the available international public adaptation finance flow in these countries in 2022 was only US$13.8 billion, thus indicating a large adaptation finance gap (see Chapter 9), including in the water supply, DRR, and health and sanitation sectors in mountain regions. Even though there are huge adaptation finance gaps, these sectors collectively account for nearly 30% of the current adaptation finance flow in MDCs (UNEP, 2024).

Climate-resilient infrastructure, such as reinforced embankments and flood diversion channels, can protect mountain communities and downstream users from the impacts of extreme weather events and changing hydrological patterns. The report *Climate Change 2022: Impacts, Adaptation and Vulnerability* (IPCC, 2022) highlights that infrastructure projects can be designed to withstand increased runoff from melting snow and ice, ensuring continued water provision for urban and agricultural use.

The case of the Rocky Mountains illustrates the importance of understanding seasonal water flux (summer, autumn and winter flows) in designing effective water service interventions (Rood, 2008; IPCC, 2022).

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[12] https://unfccc.int/NDCREG.

[13] https://napcentral.org/submitted-NAPs.

The short-term cost of delivering climate-resilient infrastructure is generally higher than that of conventional technologies. The additional cost can be prohibitive, thereby halting the development of appropriate technologies. Financial markets alone cannot be expected to absorb this additional cost, which therefore needs to be provided for by the state – until a critical mass is achieved and the technology cost can be driven down. Service providers may need support to develop technological solutions while maintaining their financial viability.

4.2.4 Promoting participatory, community-based strategies and actions

Communities in mountain regions have depended on Indigenous knowledge to build resilience to water- and sanitation-related challenges. Progress in civil engineering has aided the application of such knowledge, with the opportunity to construct modular systems such as reservoirs and tanks for water storage. Installing rainwater harvesting infrastructures in locations struggling for drinking water can also benefit mountain communities.

The use of community-based adaptation strategies – particularly involving the recognition of Indigenous Peoples' voices – can empower local communities to participate in water management decisions and incorporate local and traditional knowledge in designing and implementing solutions tailored to their specific needs.

4.2.5 Integrated water resources management

Communities in mountain regions have depended on Indigenous knowledge to build resilience to water- and sanitation-related challenges

Adapting the integrated water resources management (IWRM) blueprint to the local context in mountain regions can potentially help to address some water-related challenges such as the impacts of changes in snow cover and glacier retreat on water availability (see Box 2.2). For example, enhancing the water storage capacity by constructing new reservoirs and restoring traditional water storage systems like ponds and tanks can help buffer against seasonal water variability and mitigate the impacts of flash floods. It is also important to consider technological innovations such as efficient glacier monitoring and EWS (see Chapter 8) that can provide critical information on glacier melt and GLOFs (Taylor et al., 2023).

In some Andean nations, IWRM systems have been established to monitor glacier retreat and formation of glacial lakes, thus providing communities with early warnings, reducing the risk of sudden floods, and protecting lives and WASH infrastructure. National GLOF hazard and risk assessments in the Plurinational State of Bolivia and Peru are functioning to ensure water security – including provisioning services challenges – can be addressed in tandem with climate change impacts (Emmer et al., 2022).

4.2.6 Developing decentralized water and sanitation systems

Decentralized water and sanitation systems can be particularly effective in mountain regions (e.g. Box 4.2), reducing the risk of infrastructure damage during hazards in rugged terrain subject to frequent landslides. For instance, in the mountain regions of the Lao People's Democratic Republic and Nepal, community-led initiatives have successfully established resilient and sustainable water and sanitation solutions, demonstrating the effectiveness of decentralized approaches in challenging environments (IUCN, n.d.).

Box 4.2 A community-based gravity-fed piped water supply and sanitation system

In Xieng Ngeun, Luang Prabang, Lao People's Democratic Republic, 85% of households had no access to basic sanitation facilities, and the infrastructure was inoperative due to neglect. Villagers often had to walk long distances to collect water, which was frequently contaminated, leading to widespread health issues like diarrhoea.

To address the challenges, which were typical of most mountain areas (e.g. steep slopes, remoteness and a sparse population density), the United Nations Human Settlements Programme implemented a community-based water, sanitation and hygiene (WASH) pilot project targeting 1,221 households across six villages. A key component of the initiative was developing a gravity-fed piped water system, which leveraged the local topography to deliver water efficiently without the need for energy-intensive pumping systems. This approach, and revolving funds for community-managed sanitation improvements, successfully provided connections for over 90% of households in the target villages to the water supply network, up from 0%. Community involvement was emphasized, with residents trained to protect and maintain the water supply infrastructure.

The project also addressed several enduring challenges. For example, the absence of a formal drainage system was a significant issue for residents in low-lying areas prone to flooding. Moreover, the low population density previously complicated efforts to achieve economies of scale in WASH service provision, making it difficult to justify the cost of constructing and maintaining infrastructure extended to sparsely populated areas in such a rugged terrain.

With over 80% of households now connected to the water supply network and over 90% having access to basic sanitation, the Xieng Ngeun pilot project demonstrates the potential of community-based approaches in overcoming the unique challenges of water service provision in mountain regions.

Source: UN-Habitat (n.d.).

4.3 Conclusions

The multifaceted challenges facing human settlements in mountain regions, particularly with regard to water resources management, WASH, DRR and health issues, are subject to the increasing frequency and intensity of extreme weather events, such as GLOFs, landslides and flash floods. While there is a need to examine the extent to which WASH services are disrupted, community-level involvement has been an enabling factor in reducing public health risks in vulnerable mountain communities.

Responses to improve access to WASH and DRR include: prioritizing water in urban and land-use planning; prioritizing WASH and DRR in NDCs and NAPs; investing in climate-resilient infrastructure; and promoting community-based adaptation strategies that recognize and incorporate local and Indigenous knowledge. Adapting the IWRM blueprint to the local context can potentially address challenges such as the impacts of glacier retreat on water availability. Cross-border collaboration and strengthening DRR measures can help to mitigate the impacts of extreme events.

Coordinated policy actions to address these challenges point to IWRM as a framework that prioritizes balancing social, economic and environmental needs, incorporating traditional knowledge and modern technologies. The use of decentralized water and sanitation systems can enhance resilience and reduce infrastructure damage during disasters. Such systems empower local communities through capacity-building and participatory approaches, and ensure WASH strategies are culturally appropriate and locally relevant, which is crucial for effective climate adaptation and health support services in high-elevation landscapes.

This chapter also calls for investments in water- and climate-resilient infrastructure, such as reinforced embankments and flood diversion channels, and the application of NbS. Climate action and water security strategies for vulnerable communities living in high-elevation landscapes need to integrate health support services, including support systems for mental health.

References

Abbas, S. and Khan, A. 2020. Socioeconomic impacts of natural disasters: Implication for flood risk measurement in Damas Valley, District Ghizer, Gilgit-Baltistan, Pakistan. *Pakistan Geographical Review*, Vol. 75. No. 1, pp. 71–83. www.researchgate.net/publication/343098654.

Adler, C., Wester, P., Bhatt, I., Huggel, C., Insarov, G. E., Morecroft, M. D., Muccione, V. and Prakash, A. 2022. Mountains. H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem and B. Rama (eds), *Climate Change 2022: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK/New York, Cambridge University Press, pp. 2273–2318. doi.org/10.1017/9781009325844.022.

Alfthan, B., Gjerdi, H. L., Puikkonen, L., Andresen, M., Semernya, L., Schoolmeester, T. and Jurek, M. 2018. *Mountain Adaptation Outlook Series: Synthesis Report.* Nairobi/Vienna/Arendal, Norway, United Nations Environment Programme (UNEP)/GRID-Arendal. https://gridarendal-website-live.s3.amazonaws.com/production/documents/:s_document/412/original/SynthesisReport_screen.pdf?1544437610.

Almulhim, A. I., Alverio, G. N., Sharifi, A., Shaw, R., Huq, S., Mahmud, M. J., Ahmad, S. and Abubakar, I. R. 2024. Climate-induced migration in the Global South: An in depth analysis. *npj Climate Action*, Vol. 3, Article 47. doi.org/10.1038/s44168-024-00133-1.

Bhandari, D., Bi, P., Sherchand, J. B., Dhimal, M. and Hanson-Easey, S. 2020. Assessing the effect of climate factors on childhood diarrhoea burden in Kathmandu, Nepal. *International Journal of Hygiene and Environmental Health*, Vol. 223, No. 1, pp. 199–206. doi.org/10.1016/j.ijheh.2019.09.002.

Chapagain, D., Dhaubanjar, S. and Bharati, L. 2021. Unpacking future climate extremes and their sectoral implications in western Nepal. *Climatic Change*, Vol. 168, Article 8. doi.org/10.1007/s10584-021-03216-8.

Chapagain, D., Bharati, L., Mechler, R., Samir, K. C., Pflug, G. and Borgemeister, C. 2024. Understanding the role of climate change in disaster mortality: Empirical evidence from Nepal. *Climate Risk Management*, Vol. 46, Article 100669. doi.org/10.1016/j.crm.2024.100669.

Clerici, N., Cote-Navarro, F., Escobedo, F. J., Rubiano, K. and Villegas, J. C. 2019. Spatio-temporal and cumulative effects of land use-land cover and climate change on two ecosystem services in the Colombian Andes. *Science of the Total Environment*, Vol. 685, pp. 1181–1192. doi.org/10.1016/j.scitotenv.2019.06.275.

De Jong, C. 2015. Challenges for mountain hydrology in the third millennium. *Frontiers in Environmental Science*, Vol. 3. doi.org/10.3389/fenvs.2015.00038.

Dewi, S. P., Kasim, R., Sutarsa, I. N., Hunter, A. and Dykgraaf, S. H. 2023. Effects of climate-related risks and extreme events on health outcomes and health utilization of primary care in rural and remote areas: A scoping review. *Family Practice*, Vol. 40, No. 3, pp. 486–497. doi.org/10.1093/fampra/cmac151.

Dhimal, M., Ahrens, B. and Kuch, U. 2015. Climate change and spatiotemporal distributions of vector-borne diseases in Nepal: A systematic synthesis of literature. *PLoS ONE*, Vol. 10, Article e0129869. doi.org/10.1371/journal.pone.0129869.

Ebrahim, Z. 2022. Climate Disasters Trigger Mental Health Crisis in Pakistan's Mountains. Dialogue Earth website. https://dialogue.earth/en/climate/climate-disasters-trigger-mental-health-crisis-in-pakistans-mountains/.

Ehrlich, D., Melchiorri, M. and Capitani, C. 2021. Population trends and urbanisation in mountain ranges of the world. *Land*, Vol. 10, No. 3, Article 255. doi.org/10.3390/land10030255.

Emmer, A., Wood, J. L., Cook, S. J., Harrison, S., Wilson, R., Díaz-Moreno, A., Reynolds, J. M., Torres, J. C., Yarleque, C., Mergili, M., Jara, H. W., Bennett, G., Caballero, A., Glasser, N. F., Melgarejo, E., Riveros, C., Shannon, S., Turpo, E., Tinoco, T., Torres, L., Garay, D., Villafane, H., Garrido, H., Martínez, C., Apaza, N., Araujo, J. and Poma, C. 2022. 160 glacial lake outburst floods (GLOFs) across the Tropical Andes since the Little Ice Age. *Global and Planetary Change*, Vol. 208, Article 103722. doi.org/10.1016/j.gloplacha.2021.103722.

FAO (Food and Agriculture Organization of the United Nations). 2022. The Mountain Partnership Vision and Mission. Mountain Partnership website. www.fao.org/mountain-partnership/about/vision-and-mission/en#:~:text=By%202030%2C%20the%20Mountain%20Partnership,livelihood%20and%20well%2Dbeing%20of.

Hock, R., Rasul, G., Adler, C., Cáceres, B., Gruber, S., Hirabayashi, Y., Jackson, M., Kääb, A., Kang, S., Kutuzov, S., Milner, A., Molau, U., Morin, S., Orlove, B. and Steltzer, H. 2019. High mountain areas. H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds), *The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK/New York, Cambridge University Press, pp. 131–202. doi.org/10.1017/9781009157964.004.

Hodson, A. J. 2014. Understanding the dynamics of black carbon and associated contaminants in glacial systems. *Wiley Interdisciplinary Reviews* (*WIREs*)*: Water*, Vol. 1, No. 2, pp. 141–149. doi.org/10.1002/wat2.1016.

IPCC (Intergovernmental Panel on Climate Change). 2022. *Climate Change 2022: Impacts, Adaptation and Vulnerability.* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem and B. Rama (eds)]. Cambridge, UK/New York, Cambridge University Press. doi.org/10.1017/9781009325844.

IUCN (International Union for Conservation of Nature). n.d. Nepal. IUCN website. https://iucn.org/our-work/region/asia/countries/Nepal.

Jia, L., Ma, Q., Du, C., Hu, G. and Shang, C. 2020. Rapid urbanization in a mountainous landscape: Patterns, drivers, and planning implications. *Landscape Ecology*, Vol. 35, pp. 2449–2469. doi.org/10.1007/s10980-020-01056-y.

Joshi, N. and Dongol, R. 2018. Severity of climate induced drought and its impact on migration: A study of Ramechhap District, Nepal. *Tropical Agricultural Research*, Vol. 29, No. 2, pp. 194–211.

Lützow, N., Veh, G. and Korup, O. 2023. A global database of historic glacier lake outburst floods. *Earth System Science Data*, Vol. 15, No. 7, pp. 2983–3000. doi.org/10.5194/essd-15-2983-2023.

Maharjan, S. B., Steiner, J. F., Shrestha, A. B., Maharjan, A., Nepal, S., Shrestha, M. S., Bajracharya, B., Rasul, G., Shrestha, M., Jackson, M. and Gupta, N. 2021. *The Melamchi Flood Disaster. Cascading Hazard and the Need for Multihazard Risk Management*. Kathmandu, International Centre for Integrated Mountain Development (ICIMOD). https://lib.icimod.org/record/35284.

Poudyal, N. C., Joshi, O., Hodges, D. G., Bhandari, H. and Bhattarai, P. 2021. Climate change, risk perception, and protection motivation among high-altitude residents of the Mt. Everest region in Nepal. *Ambio*, Vol. 50, pp. 505–518. doi.org/10.1007/s13280-020-01369-x.

Repe, A. N., Poljanec, A. and Vrščaj, B. (eds). 2020. *Soil Management Practices in the Alps: A Selection of Good Practices for the Sustainable Soil Management in the Alps.* Ljubljana, EU Interreg Alpine Space. www.alpine-space.eu/wp-content/uploads/2022/06/46-1-links4soils-Soil%20Management%20Practices%20in%20the%20Alps%20-%20a%20collection-output.pdf.

Rood, S. B., Pan, J., Gill, K. M., Franks, C. G., Samuelson, G. M. and Shepherd, A. 2008. Declining summer flows of Rocky Mountain rivers: Changing seasonal hydrology and probable impacts on floodplain forests. *Journal of Hydrology*, Vol. 349, No. 3–4, pp. 397–410. doi.org/10.1016/j.jhydrol.2007.11.012.

Seneviratne, S. I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Di Luca, A., Ghosh, S., Iskandar, I., Kossin, J., Lewis, S., Otto, F., Pinto, I., Satoh, M., Vicente-Serrano, S. M., Wehner, M. and Zhou, B. 2021. Weather and climate extreme events in a changing climate. V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, Y. Chen, L. Goldfarb, M. I. Gomis, J. B. R. Matthews, S. Berger, M. Huang, O. Yelekçi, R. Yu, B. Zhou, E. Lonnoy, T. K. Maycock, T. Waterfield, K. Leitzell and N. Caud (eds), *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK/New York, Cambridge University Press, pp. 1513–1766. doi.org/10.1017/9781009157896.013.

Shrestha, S., Chapagain, P. S. and Ghimire, M. 2019. Gender perspective on water use and management in the context of climate change: A case study of Melamchi watershed area, Nepal. *Sage Open*, Vol. 9, No. 1. doi.org/10.1177/2158244018823078.

Somers, L. D. and McKenzie, J. M. 2020. A review of groundwater in high mountain environments. *Wiley Interdisciplinary Reviews (WIREs): Water*, Vol. 7, No. 6, Article e1475. doi.org/10.1002/wat2.1475.

Sumann, G., Moens, D., Brink, B., Brodmann Maeder, M., Greene, M., Jacob, M., Koirala, P., Zafren, K., Ayala, M., Musi, M., Oshiro, K., Sheets, A., Strapazzon, G., Macias, D. and Paal, P. 2020. Multiple trauma management in mountain environments: A scoping review. *Scandinavian Journal of Trauma, Resuscitation and Emergency Medicine*, Vol. 28, Article 117. doi.org/10.1186/s13049-020-00790-1.

Taylor, C., Robinson, T. R., Dunning, S., Carr, J. R. and Westoby, M. 2023. Glacial lake outburst floods threaten millions globally. *Nature Communications*, Vol. 14, Article 487. doi.org/10.1038/s41467-023-36033-x.

Thornton, J. M., Snethlage, M. A., Sayre, R., Urbach, D. R., Viviroli, D., Ehrlich, D., Muccione, V., Wester, P., Insarov, G. and Adler, C. 2022. Human populations in the world's mountains: Spatio-temporal patterns and potential controls. *PLoS ONE*, Vol. 17, No. 7, Article e0271466. doi.org/10.1371/journal.pone.0271466.

Tiwari, P. C., Tiwari, A. and Joshi, B. 2018. Urban growth in Himalaya: Understanding the process and options for sustainable development. *Journal of Urban and Regional Studies on Contemporary India*, Vol. 4, No. 2, pp. 15–27. https://core.ac.uk/download/pdf/222961854.pdf.

UNEP (United Nations Environment Programme). 2024. *Adaptation Gap Report 2024. Come Hell and High Water: As Fires and Floods Hit the Poor Hardest, it is Time for the World to Step Up Adaptation Actions*. Nairobi, UNEP. doi.org/10.59117/20.500.11822/46497.

UN-Habitat (United Nations Human Settlements Programme). 2016. *Nepal Earthquake 2015: Reviving Sanitation Campaign*. Global Sanitation Fund Lessons. Kathmandu, UN-Habitat. https://unhabitat.org/sites/default/files/documents/2019-05/gsf-021-eq-final.pdf.

—. n.d. Community-Based Water and Sanitation (WASH) Project in Xieng Ngeun Town, Luang Prabang Province, Lao PDR. The Mekong Region Water and Sanitation Initiative (MEK-WATSAN). UN-Habitat website. https://unhabitat.la/projects/community-based-wash-project-xieng-ngeun/.

UNU-EHS (United Nations University Institute for Environment and Human Security). 2023. 5 Insights Towards Systemic Risk Reduction in Mountains. UNU-EHS website, 9 October 2023. https://unu.edu/ehs/series/5-insights-towards-systemic-risk-reduction-mountains.

WHO (World Health Organization). 2022. *Mental Health and Climate Change: Policy Brief*. WHO. https://iris.who.int/handle/10665/354104.

Zogaris, S., Jayasinghe, A. D., Sanjaya, K., Vlami, V., Vavalidis, T., Grapci-Kotori, L. and Vanhove, M. P. M. 2021. Water management impacts on mountain rivers: Insights from tropical, subtropical and Mediterranean-climate basins. E. Dimitriou and C. Papadaki (eds), *Environmental Water Requirements in Mountainous Areas*. Elsevier, pp. 155–200. doi.org/10.1016/B978-0-12-819342-6.00004-X.

Chapter 5

Industry and energy

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It is a paradox that industry and energy are both perpetrators and victims of climate change in mountain areas and the cryosphere. Records from the middle of the 19th century point to glaciers retreating abruptly as the result of radiative forcing produced *"by increasing deposition of industrial black carbon to snow"* (see Box 2.1), particularly in western Europe (Sigl et al., 2018, p. 50; Beard et al., 2022a; 2022b). Global warming is exacerbating this retreat.

This chapter demonstrates how water use by the industry and energy sectors in mountain areas can be adapted to a rapidly changing cryosphere (IPCC, 2019), because of glacial melt and decrease in snow cover, and the changes this implies for water on the surface and underground.

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Water-dependent industries have developed in mountain areas where water and other resources are found in relative abundance

Just as industry and energy are important for water and glaciers in mountain areas, water is also important for industry and energy. Water-dependent industries have developed in mountain areas where water and other resources are found in relative abundance (Perlik, 2019; Modica, 2022). This has contributed to industrialization of mountain areas (Collantes, 2009). As a result, mountain areas in Europe have relatively more people employed in the industrial sector than in lowland areas (Nordregio, 2004). In Latin America, it has been estimated that 85% of hydropower generated in Andean countries is produced in mountain areas (Mountain Partnership, 2014). The provision of mineral drinking water is an important industry, as the resource is often extracted from mountain areas.

In addition to industrial and energy production – particularly in hydropower plants, and also in coal- and wood-fired power plants – water is also required to process minerals, produce timber and develop tourism in mountain areas (Talandier and Donsimoni, 2022). For instance: water is needed to make the artificial snow used in the ski industry when natural snow is not sufficient; water is the basis for rafting and sailing; and water is essential to recreational fisheries and the hospitality business (FAO/UN Tourism, 2023). The quantity and quality of water and aquatic biodiversity are affected by industry and energy production, as well as by climate change, for example, through glacier and permafrost melting and changes in the upper limits of tree and other vegetation lines (Zou et al., 2023).

There is a lack of evidence about trends in water-intensive industrial and energy development in mountain areas. As the economies of developing nations evolve, the shift away from agriculture and resource-extracting industries as the main economic drivers (Connor and Chaves Pacheco, 2024) has also reached mountain areas, with the services sector – including tourism, commerce, education and health care – often representing the largest employer.

Owing to the global expansion of water-dependent industries, it is likely that industrial use of water is also growing in mountains. For instance, at the global level, material resource extraction could increase by almost 60% above the 2020 level by 2060 (UNEP, 2024). In addition, importation of virtual water – meaning the flow of water hidden in the exchange of products and materials – is a significant factor of production for mountain industry.

The water going back to mountains in terms of traded goods and services should not be underestimated. Mountain areas can be constrained environments that require importing more virtual water than is being exported (Cabello et al., 2015; Malo-Larrea et al., 2022; Church, 2024).

5.1 Challenges

A significant challenge for industry and energy is the elevation at which it is possible to operate. This is related to slope, and also to temperature because frozen water is unsuitable for consumption and other uses. Nevertheless, there are industrial practices in glacier areas, as well as polar regions, such as mining, power transmission, telecom infrastructure and some tourism industry (Smith López et al., 2024). As such conditions can generate huge investment and running costs, industrial activities are typically limited to those with high returns on investment.

Global warming is making investment riskier owing to uncertainties and higher and cascading risks of natural hazards – such as glacial lake outbursts, avalanches, mudflows and floods – as well as technological ones – such as the failure of tailing dams and other infrastructure (Tuihedur Rahman et al., 2024).

At some point, temperatures increase and ice starts melting, mainly depending on elevation, latitude and season. The changing cryosphere is quickly moving the limits of how high it is possible to operate, as an increasing number of mountains do not have glaciers and snow. Rain and groundwater, including karst aquifers, are important for industry and energy. Changes in precipitation and soil permeability in mountain areas also represent a major technical challenge.

Managing a resource often perceived as locally abundant is challenging. People may take it for granted, particularly in areas that are fed by glaciers (but which are expected to melt faster with global warming). This may lead to overuse and drought – downstream and also in the mountain areas themselves (Orr et al., 2024). Climate change and changes in precipitation patterns often exacerbate drought.

The biggest challenge is the disconnect between local water availability and supply and water use to meet industrial and energy demand, which depends on local, national and global economies and markets. There may be demand for water-intensive products at times of water scarcity, which can lead to conflicts of use locally in mountain areas and between upstream and downstream communities (Füreder et al., 2018).

5.2 Impact of industrial pollution on water quality

Industrial and energy development can affect water quality (Figure 5.1). In addition, because of progressive population and economic decline, remote mountain areas can be difficult to regulate, resulting in uncontrolled water withdrawals and discharges, including pollutants (Machate et al., 2023). Industrial development and brownfield sites alter the water regime of sites and water-related ecosystems, and can result in the infiltration of pollutants into surface water and groundwater (Modica, 2022).

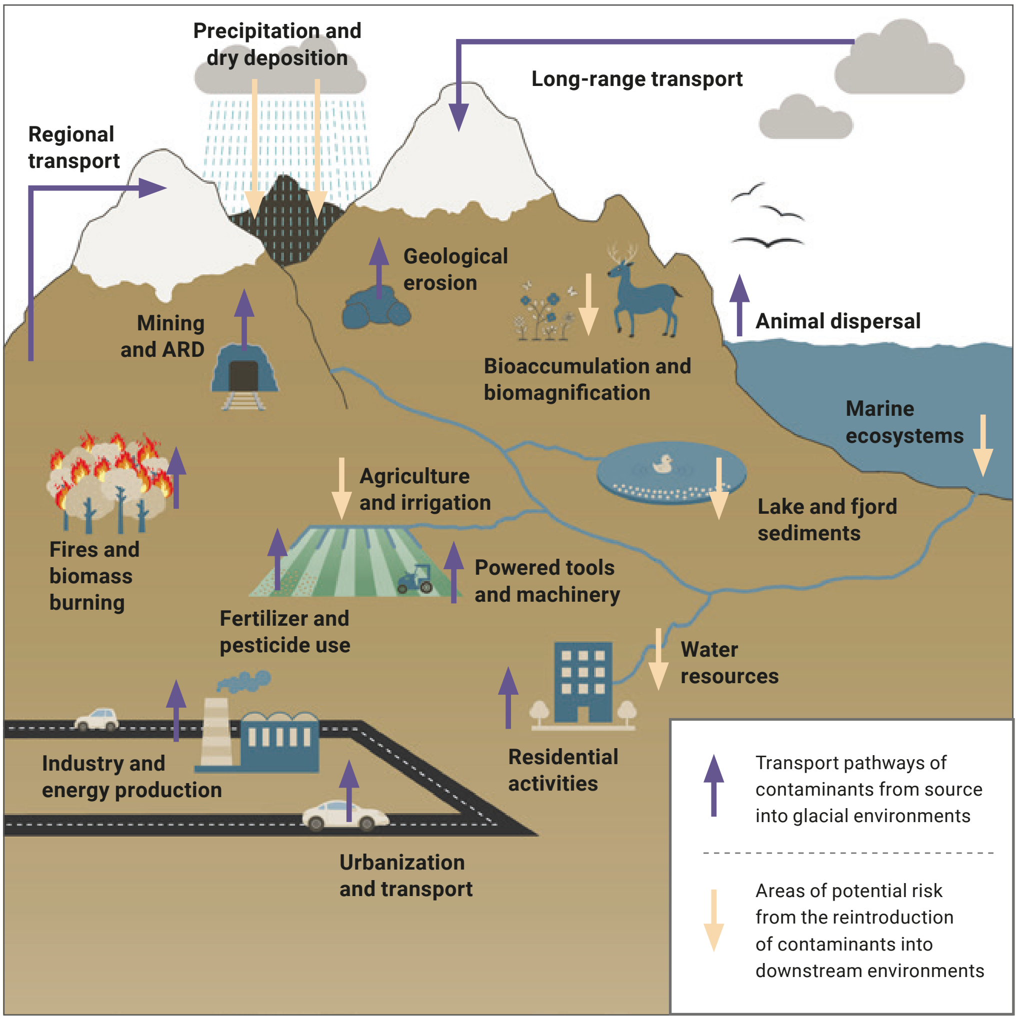
Mountain communities can be vulnerable to industrial water pollution

Industrial wastewater management can represent a major challenge in mountain areas, where slope can make it difficult to develop systems for on-site storage, treatment and reuse of water and waste. Insufficiently regulated activities such as mining and fish farming can result in significant leakage of pollutants, including heavy metals and persistent organic pollutants such as pesticides and antibiotics (Wright et al., 2011; UNIDO, 2017). The management of mining tailings, including from closed mines, is of critical importance, also considering the risk of natural hazards in mountain areas (Zoï Environment Network, 2013; UNECE, 2014).

Mountain communities can be vulnerable to industrial water pollution. Insufficiently regulated industrial and energy development can have negative repercussions for upstream and downstream areas. Downstream areas are dependent on and vulnerable to upstream developments, even if lowland areas are typically wealthier than mountain areas and therefore can count on more resources for their resilience (Perlik, 2015). In addition, negative transboundary impacts and industrial accidents involving water can exacerbate relations between upstream and downstream communities (UNECE, 2016).

Women, children, older people and persons with disabilities are often over-represented in mountain communities because of labour migration to wealthier areas (Mishra, 2002). This means that in mountain areas, industrial pollution particularly affects these groups.

Figure 5.1
Transport pathways and processes of deposition for contaminants within glaciated environments



Note: ARD: acid rock drainage.

Source: Based on Beard et al. (2022a, fig. 2, p. 635).

5.3 Examples of industrial and energy water use

One example of industrial and energy use of water in mountain areas is the large-scale extraction of lithium, used to produce batteries and derived from evaporation-based lithium brine mining methods, in the area spanning the southwest of the Plurinational State of Bolivia and northern Argentina and Chile. This area accounts for 56% of the world's total identified lithium resources. The activity exerts significant stress on surface water and groundwater, as well as on wetlands and other water-related ecosystems. This stress is consequently exerted also on the communities that depend on those waters. Around 2,000 m^3 of water is required to produce 1 tonne of lithium; this is in an area with an arid climate and low rainfall (UNECLAC, 2023).

Small-scale and artisanal mining can also have huge impacts upstream and downstream. For instance, the use of mercury in gold mining is dangerous for water quality and availability and public health (UNEP, 2012). Community and environmental movements play a key role in raising awareness and helping address these issues – the Pascua-Lama gold mine is a specific example (Box 5.1).

Box 5.1 Protecting glaciers from the impacts of mining: Pascua-Lama, Chile

Pascua-Lama is an open pit gold mining site located in the Andes, 3,800–5,200 m above sea level and straddling the border between Argentina and Chile. It illustrates the complex interplay of corporate, government and Indigenous interests, perspectives and perceptions through the lens of glaciers and water supply (Kronenberg, 2009; Amos-Landgraf, 2021).

The three glaciers involved are on the Chilean side and are small. Initially, a mining company received approval after an environment impact assessment to move the glaciers and put the ice on a nearby glacier. This plan met with opposition from local communities, internationally and the Chilean Government, based on potential threats to agriculture, the environment and health.

In 2006, the Chilean environmental authorities ruled that the mining company should not touch glaciers, but should protect and monitor them. The value of water availability through glacial runoff to downstream communities strongly influenced the decision. Smaller glaciers are more susceptible to global warming, and their value is likely to be more site specific (Kronenberg, 2009). As melting glaciers have come to symbolize global warming, political and societal issues may also have been factors.

In 2013, the mining project was put on hold after a petition from the Diaguita Indigenous community near the mine, citing overextraction of water from glaciers and the Estrecho River. In 2020, the First Environmental Court of Chile ordered the mine to be closed and fined the mining company. Among charges facing the company were contaminating the glacier-fed Estrecho River – an important regional water source for domestic and irrigation water – and not adequately evaluating the impact of the mine on the Andean glaciers. It was also stated that exploration boreholes had compromised groundwater filtration, causing pollution in local rivers.

The Pascua-Lama situation reflects changing preferences towards the preservation and value of glaciers, and resulted in legal protection of the glaciers involved. The project has encouraged a broad discussion of mining and its potential effects on glaciers.

The rapid development of hydropower-related cryptomining in mountain areas is a threat to the industry and energy sectors

Furthermore, the rapid development of hydropower-related cryptomining in mountain areas is a threat to the industry and energy sectors. Cryptomining is a key process in the issuance of cryptocurrency that uses specialized computing resources requiring vast amounts of cheap energy. Coal is the main source of energy used, with a 45% share, and hydropower the main source of renewable energy, with 16% (Chamanara and Madani, 2023). Both are often produced in mountain areas, with significant impacts on the quantity and quality of water resources (Table 5.1), as well as on power networks. For instance, in Central Asia, several cryptomines are operating in the mountains of Kazakhstan and Kyrgyzstan, where inexpensive electricity is available. This has increased the pressure on the power system to the point that, in January 2022, the whole Unified Energy System of Central Asia temporarily collapsed, resulting in a large-scale blackout that affected millions of people in the southern part of Kazakhstan, Kyrgyzstan and Uzbekistan.

Table 5.1 Annual water footprint of bitcoin mining across the world, 2020–2021

Country	Water footprint (million m³)	Water footprint (m³/person)
China	780.05	0.55
United States of America	205.73	0.62
Canada	150.01	3.85
Kazakhstan	104.18	5.31
Russian Federation	94.11	0.65
Malaysia	64.57	1.90
Germany	51.94	0.62
Norway	39.91	7.31
Iran (Islamic Republic of)	19.25	0.22
Thailand	17.98	0.25
Other countries	119.84	0.02

Sources: Elaboration by the author, based on data from Chamanara and Madani (2023, fig. 7, p. 17) and UNSD (n.d.).

The production of artificial snow uses a significant amount of water. For instance, in the Alps alone, it has used an estimated 280 million m^3 of water (Unbehaun and Pröbstl, 2006) and 2,100 GW of electricity (Hamberger and Doering, 2015). In 2009, the Alpine Convention reported that in two Swiss ski resort towns "*snowmaking accounts for 22% and 36% of the annual water abstraction*" and that "*artificial snowmaking can lead to conflicts with other water demands (e.g. drinking water supply)*" (Permanent Secretariat of the Alpine Convention, 2009, p. 65). To secure the necessary water supply for artificial snow production when water is scarce in winter, storage ponds have been built to store water when it is abundant in the summer and autumn.

Forestry and timber production are important for mountain areas, even if elevation and other factors make mountain forests on average less productive and profitable than lowland ones. Timber production and processing have therefore often shifted to lowlands (Price et al., 2011). Yet, mountain forests play a key role in water management (Schyns and Vanham, 2019). Depending on the types of trees, mountain forests can retain significant amounts of water and humidity in upper catchments, stabilize the soil and reduce erosion, thus helping to reduce the risk of water-related hazards. As such, they can be considered nature-based solutions. This is not so much the case of tree plantations for timber production, whose absorption capacity is typically lower than that of natural forests. Forestry impacts on water quality include "*sediment delivery, nutrient losses, carbon transport, metal and base cation releases*", as well as "*changes to acidity and temperature*" (Shah et al., 2022, p. 1).

5.4 Hydropower in mountain areas

Hydropower generation has been one of the main industries in mountain areas (WWAP, 2014). Its development started at the end of the 19th century in Europe and North America, where it slowed until the 1970s, because of increased resistance from environmental movements and shortage of suitable sites. In the rest of the world, hydropower development picked up after the Second World War and continues to be significant. Hydropower plants can be large (>100 MW), medium (15–100 MW) and small (<15 MW) in capacity.

Hydropower generation has been one of the main industries in mountain areas

A typical example of a large hydropower development in mountain areas is the Nurek dam, reservoir and hydropower plant in Central Asia. Located along the Vakhsh River in Tajikistan, it is part of a cascade that includes the Rogun hydropower plant, currently under construction (Rahimzoda, 2024). Nurek was part of an integrated development programme conceived in the 1960s, when the area was part of the former Soviet Union. It was meant to generate electricity for industrial development and to expand mountain farming through pumped irrigation, while regulating water for downstream irrigation and flood control for Tajikistan and downstream countries (Kalinovsky, 2021).

After generating most electricity produced in the country for four decades, Nurek is being modernized to optimize its functionality. However, the reservoir is progressively shrinking owing to siltation, and is thus losing its capacity to regulate water and generate power. The completion of other projects along the Vakhsh cascade, particularly Rogun, will help address this issue. The required financing is huge compared with the size of the country's economy, and so are the social and environmental impacts, which were assessed in cooperation with neighbouring countries (World Bank, 2014).

There are also many examples of medium and small hydropower plants in mountain areas, including run-of-the-river plants. The presence of a slope makes it possible to generate hydropower without building large dams and reservoirs. The design and siting of small hydropower plants usually lower the impact of hydropower generation on water resources, biodiversity and landscape. However, at high elevations, small hydropower plants are often not operational in cold weather due to freezing and a lack of precipitation (Katsoulakos and Kaliampakos, 2014).

Unregulated and badly planned development of small hydropower plants can have negative impacts on water resources. For instance, in Georgia, some rivers have dried up because of too many small hydropower plants (Japoshvili et al., 2021). In 2018, the Alpine Convention – a regional environmental agreement – published specific guidelines for the use of small hydropower plants (Platform Water Management in the Alps, 2018).

Hydropower plants in mountain areas can therefore be too large for the context but also too small to be effective. Their design is thus extremely important. Several important documents, taking into consideration the specificities of mountain areas, including cascade effects, are required to guide their development. For instance, a river basin management plan, a strategic environmental assessment, a national energy policy, a climate change risk assessment, an environmental and social impact assessment (not always for smaller projects), an environmental and social management plan, and operational rules may be necessary.

Glacier melt and precipitation runoff can flow down steep slopes over relatively short distances, making it suitable for generating power. The shape of mountain valleys is amenable for constructing dams. Building materials for coffer-dams[14] and other relevant structures can also be found locally in mountain areas. When machine rooms are built inside mountains, turbines and other hydropower plant components are protected from flooding, mudflows and other hazards.

Reservoirs in mountain areas can store large amounts of water to generate hydropower when it is needed and thus reduce seasonal dependency. Hydropower is becoming increasingly important with the development of renewable sources of energy, such as solar and wind, whose output is variable and needs to be balanced quickly to operate power networks. As such, hydropower reservoirs act as storage for water resources as well as for renewable energy (Permanent Secretariat of the Alpine Convention, 2017). Reservoirs can generate new ecosystems that may become biodiversity hotspots. For example, Vlasina Lake in Serbia is now protected under the Ramsar Convention on Wetlands.

[14] Temporary watertight enclosures to exclude water.

Mountain areas globally tend to have lower population density and less economic revenue than adjacent lowlands (Thornton et al., 2022). For this reason, the development of hydropower can have lower social and economic impacts upstream than in lowlands. Mountain communities and their leaders also tend to have limited human and financial resources to resist such developments. However, mountain areas are not disconnected from other regions. Mountain dwellers, urban elites and other stakeholders, even from the other side of the world, can join forces to propose alternatives for the development of areas otherwise destined for hydropower and large infrastructure projects (Perlik, 2019).

Environmental protection is a major driver of resistance to hydropower development, as mountain ecosystems are fragile

Environmental protection is a major driver of resistance to hydropower development, as mountain ecosystems are fragile. The construction and presence of dams and reservoirs, transmission lines and substations can have a significant impact. For example, dams create barriers to aquatic biodiversity, lengthy reservoirs create barriers to migration of large mammals, and construction works unsettle river beds, destroy wetlands, change habitats, hydrogeology and local climate, and disturb aquatic life (WWAP, 2014).

Fish passes and other techniques used to mitigate or compensate for damage are only partially effective (FAO/DVWK, 2002; Venus et al., 2020). River-bed designs, such as the ones piloted in the Loisach and Iller Rivers in Germany, can also help reduce some environmental impacts. However, they still depend on the availability of water (UNIDO/ICSHP, 2022). Sediments typically present in mountain waters also damage components and fill reservoirs, thus reducing the lifespan of hydropower plants. Sediment flushing and other techniques help to manage this problem. Hydropower plants can also be built in cascade along the same river to contain impact. The water–energy–food–environment nexus approach can be useful to address these issues (Wymann von Dach and Fleiner, 2019).

Mountain reservoirs have a role in adaptation to climate change, by storing water for use in times of drought and by storing high river flow, thus reducing the likelihood of flooding downstream (French Presidency of the Alpine Convention, 2020; Adler et al., 2022). They can be key infrastructure for disaster risk reduction, but can also be affected by earthquakes, landslides, mudslides, floods and structural deterioration. A well-known example is the Chamoli disaster of 2021 in northern India (Shugar et al., 2021), when a rock and glacier ice avalanche caused a mud and debris flood that destroyed two hydropower plants under construction downstream and worth over US$223 million. In 1963, 1,917 deaths were attributed to a similar event on the Vajont creek in northern Italy, when the dam overflowed, flooding a whole valley (Merlin, 2001). The mismanagement of mountain reservoirs can contribute to incidents, including transboundary ones.

Climate change is affecting hydropower generation owing to factors such as melting glaciers, changing patterns of precipitation and increasing evaporation. There are no data on how much existing and planned hydropower generation depends on glacier melt at the global level. It is therefore difficult to assess how the changing cryosphere is affecting hydropower and whether this is positively or negatively compensated for by other factors, such as increased precipitation and evaporation. There is also no evidence that global warming will increase the amount of water available for hydropower. It appears that increases in glacial melt are counterbalanced by increased evaporation (Cooley, 2023). Satellites reveal widespread decline in global lake water storage, including artificial reservoirs (Yao et al., 2023). Therefore, peak melt (see Box 2.2) may have already been reached globally, especially for hydropower plants with large reservoirs in lower elevations and latitudes, where evaporation is higher.

5.5 Responses for inclusive and sustainable industrial development

Responses are available and are being developed to make industry and energy production in mountain areas more sustainable. They can be clustered into three groups: the promotion of a circular water economy, the development of environmentally sound technologies (as well as the increase of environment, social and governance investment) and water stewardship.

The circular economy promotes water-use reduction, recycling of used water and reuse of water resources (WBCSD, 2017; Delgado et al., 2021). For instance, in Arequipa, Peru, a mining company in a mountain area addressed its need for water and the city's wastewater issues through a public–private partnership with the municipal water utility. The mining company funded and built a wastewater treatment plant, processing 95% of the city's sewage, using some for mining operations and releasing clean water into the local river. This solution enabled the mine's expansion, saved the city over US$335 million and revitalized the river, benefiting local farmers and residents (World Bank, 2019).

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The greening of grey infrastructure or its replacement with green infrastructure can be the best available technique for mountain areas

Pumped storage hydropower (PSH) utilizes excess off-peak electricity to pump water back into a reservoir, thus storing water and potential energy. PSH accounts for 95% of the world's electricity storage capacity, mostly in mountain areas (IRENA, 2023). The stored water is released to generate electricity during periods of high demand. Although consuming more energy than it generates and holding water upstream that can be lost to evaporation, the ability of PSH to provide water and energy storage and load balancing is valuable for power grid stability. For example, the Fengning power station in China is the world's largest pumped storage hydroelectric facility, with a 3,600 MW capacity. Construction began in 2013 and was completed in 2021 at a cost of US$1.87 billion. The station operates with two reservoirs: the lower can hold 66.15 million m^3 of water and the upper 48.83 million m^3. The Fengning power station is designed to provide 6,612 GWh of power generation capacity from storage a year (IRENA, 2020; Morales Pedraza, 2024).

Environmentally sound technologies (ESTs) encompass practices such as the use of less-polluting technologies, better resource management and efficient waste recycling. ESTs can form integrated systems that combine technical knowledge, operational procedures and organizational structures aimed at fostering sustainability. These technologies serve as greener alternatives to conventional methods, including efforts to reduce water and energy consumption in the production of artificial snow (Grünewald and Wolfsperger, 2019). Companies are improving valve technology to increase water-use efficiency and use oil-free compressors to ensure no oil ends up in the environment. Also, data can be harnessed to produce the right quantity and quality of snow, thus reducing the wasteful use of resources. A co-benefit is providing training opportunities and creating awareness about water and energy efficiency (TechnoAlpin, 2023).

When existing industry and power infrastructure does not meet modern standards of ESTs, the greening of grey infrastructure or its replacement with green infrastructure (WWAP/UN-Water, 2018), including rewilding, can be the best available technique for mountain areas.

Water stewardship, environment, social and governance investment, research and development, and regulatory oversight are key ingredients in cases where circular economy, EST and other effective responses are found (Kohler et al., 2012). There are few specific approaches for water use by industry and energy production in mountain areas (Scott et al., 2023). Attempts to develop specific bans on hydropower development and other types of infrastructure in mountain areas have failed to make it into binding legal instruments and strong policy tools, such as in the case of the 2005 Energy Protocol to the Alpine Convention, which provides only generic guidance (Austria/European Community/France/Germany/Italy/Liechtenstein/Monaco/Slovenia/Switzerland, 2005; ARE, 2014). Given the specificities of water use by the industry and energy sectors in mountain areas, particularly in a context of melting glaciers, it is hoped this example will inspire more specific approaches in the future (Katsoulakos and Kaliampakos, 2014).

References

Adler, C., Wester, P., Bhatt, I., Huggel, C., Insarov, G. E., Morecroft, M. D., Muccione, V. and Prakash, A. 2022. Mountains. H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem and B. Rama (eds), *Climate Change 2022: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK/New York, Cambridge University Press, pp. 2273–2318. doi.org/10.1017/9781009325844.022.

Amos-Landgraf, I. 2021. Chile's Pascua-Lama Mine Legally Shut Down, but Mining Exploration Continues. *State of the Planet*. New York, Columbia Climate School. https://news.climate.columbia.edu/2021/01/15/pascua-lama-mine-shut-down/.

ARE (Federal Office for Spatial Development, Switzerland). 2014. *Activity Report of the Energy Platform for the Years 2013–2014*. Bern, ARE.

Austria/European Community/France/Germany/Italy/Liechtenstein/Monaco/Slovenia/Switzerland. 2005. Protocol on the implementation of the Alpine Convention of 1991 in the field of energy (Energy Protocol). *Official Journal of the European Union*, L 337/36 EN of 22/12/2005. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L:2005:337:FULL.

Beard, D. B., Clason, C. C., Rangecroft, S., Poniecka, E., Ward, K. J. and Blake, W. H. 2022a. Anthropogenic contaminants in glacial environments I: Inputs and accumulation. *Progress in Physical Geography: Earth and Environment*, Vol. 46, No. 4, pp. 630–648. doi.org/10.1177/03091333221107376.

––. 2022b. Anthropogenic contaminants in glacial environments II: Release and downstream consequences. *Progress in Physical Geography: Earth and Environment*, Vol. 46, No. 5, pp. 790–808. doi.org/10.1177/03091333221127342.

Cabello, V., Willaarts, B. A., Aguilar, M. and Del Moral Ituarte, L. 2015. River basins as social-ecological systems: Linking levels of societal and ecosystem water metabolism in a semiarid watershed. *Ecology and Society*, Vol. 20, No. 3, p. 20. doi.org/10.5751/ES-07778-200320.

Chamanara, S. and Madani, K. 2023. *The Hidden Environmental Cost of Cryptocurrency: How Bitcoin Mining Impacts Climate, Water and Land*. Hamilton, Canada, United Nations University Institute for Water, Environment and Health (UNU-INWEH). doi.org/10.53328/INR23ASC02.

Church, J. M. 2024. *Policy Brief "Central Asia's Trade in Virtual Water: SPECA Policy Brief on Sustainable Trade and Water Management"*. 2024 Economic Forum, Dushanbe, 26 November 2024. United Nations Special Programme for the Economies of Central Asia (UNSPECA). https://unece.org/speca/documents/2024/11/working-documents/policy-brief-central-asias-trade-virtual-water-speca-0.

Collantes, F. 2009. Rural Europe reshaped: The economic transformation of upland regions, 1850–2000. *The Economic History Review*, Vol. 62, No. 2, pp. 306–323. doi.org/10.1111/j.1468-0289.2008.00439.x.

Connor, R. and Chaves Pacheco, S. M. 2024. *Global Employment Trends and the Water Dependency of Jobs*. Paris, United Nations Educational, Scientific and Cultural Organization (UNESCO). https://unesdoc.unesco.org/ark:/48223/pf0000388410.

Cooley, S. W. 2023. Global loss of lake water storage. *Science*, Vol. 380, No. 6646, p. 693. doi.org/10.1126/science.adi0992.

Delgado, A., Rodríguez, D. J., Amadei, C. A. and Makino, M. 2021. *Water in Circular Economy and Resilience (WICER)*. Washington DC, International Bank for Reconstruction and Development/The World Bank. https://openknowledge.worldbank.org/bitstream/handle/10986/36254/163924.pdf.

FAO/DVWK (Food and Agriculture Organization of the United Nations/Deutscher Verband für Wasserwirtschaft und Kulturbau). 2002. *Fish Passes: Design, Dimensions and Monitoring*. Rome, FAO/DVWK. www.fao.org/3/y4454e/y4454e.pdf.

FAO/UN Tourism (Food and Agriculture Organization of the United Nations/World Tourism Organization). 2023. *Understanding and Quantifying Mountain Tourism*. Rome/Madrid, FAO/UN Tourism. doi.org/10.18111/9789284424023.

French Presidency of the Alpine Convention. 2020. *Water Resources and Alpine Rivers: Adaptation to the Challenges of Climate Change. Report of the Conference Organized in the Framework of the French Presidency of the Alpine Convention*. Impérial Palace, Annecy, France, 18–19 February 2020. Innsbruck, Austria/Bolzano, Italy, Permanent Secretariat of the Alpine Convention. www.alpconv.org/fileadmin/user_upload/Fotos/Banner/Topics/watermanagement/Report_water_conference_Annecy_EN.pdf.

Füreder, L., Weingartner, R., Heinrich, K., Braun, V., Köck, G., Lanz, K. and Scheurer, T. (eds). 2018. *Alpine Water – Common Good or Source of Conflicts?* Proceedings of the ForumAlpinum 2018 and 7th Water Conference. Breitenwang, Austria, 4–6 June 2018. Austrian Academy of Sciences Press. doi.org/10.1553/forumalpinum2018.

Grünewald, T. and Wolfsperger, F. 2019. Water losses during technical snow production: Results from field experiments. *Frontiers in Earth Science*, Vol. 7, No. 78. doi.org/10.3389/feart.2019.00078.

Hamberger, S. and Doering, A. 2015. *Der gekaufte Winter: eine Bilanz der künstlichen Beschneiung in den Alpen* [The purchased winter: A review of artificial snow production in the Alps]. Munich, Germany, Gesellschaft für ökologische Forschung (GöF)/Bund Naturschutz in Bayern (BN). www.vzsb.de/media/docs/Der_gekaufte_Winter_-_8.12.2015.pdf. (In German.)

IPCC (Intergovernmental Panel on Climate Change). 2019. *The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK/New York, Cambridge University Press. doi.org/10.1017/9781009157964.

IRENA (International Renewable Energy Agency). 2020. *Innovation Landscape Brief: Innovative Operation of Pumped Hydropower Storage*. Abu Dhabi, IRENA. www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jul/IRENA_Innovative_PHS_operation_2020.pdf.

––. 2023. *The Changing Role of Hydropower: Challenges and Opportunities*. Abu Dhabi, IRENA. www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/Feb/IRENA_Changing_role_of_hydropower_2023.pdf.

Japoshvili, B., Couto, T. B. A., Mumladze, L., Epitashvili, G., McClain, M. E., Jenkins, C. N. and Anderson, E. P. 2021. Hydropower development in the Republic of Georgia and implications for freshwater biodiversity conservation. *Biological Conservation*, Vol. 263, No. 109359. doi.org/10.1016/j.biocon.2021.109359.

Kalinovsky, A. M. 2021. *Laboratory of Socialist Development: Cold War Politics and Decolonization in Soviet Tajikistan*. Ithaca, USA, Cornell University Press.

Katsoulakos, N. M. and Kaliampakos, D. C. 2014. What is the impact of altitude on energy demand? A step towards developing specialized energy policy for mountainous areas. *Energy Policy*, Vol. 71, pp. 130–138. doi.org/10.1016/j.enpol.2014.04.003.

Kohler, T., Pratt, J., Debarbieux, B., Balsiger, J., Rudaz, G. and Maselli, D. (eds). 2012. *Sustainable Mountain Development, Green Economy and Institutions: From Rio 1992 to Rio 2012 and Beyond*. Swiss Agency for Development and Cooperation (SDC)/Centre for Development and Environment (CDE). www.fao.org/3/cc9690en/cc9690en.pdf.

Kronenberg, J. 2009. *Global Warming, Glaciers and Gold Mining*. Proceedings of the 8th International Conference of the European Society for Ecological Economics. Ljubljana, 29 June–2 July 2009. https://center-hre.org/wp-content/uploads/2013/03/Kronenberg-Global-warming-Glaciers-and-Gold-Mining.pdf.

Machate, O., Schmeller, D. S., Schulze, T. and Brack, W. 2023. Review: Mountain lakes as freshwater resources at risk from chemical pollution.

Environmental Sciences Europe, Vol. 35, No. 3. doi.org/10.1186/s12302-022-00710-3.

Malo-Larrea, A., Santillán, V. and Torracchi-Carrasco, E. 2022. Looking inside the blackbox: Cuenca's water metabolism. *PLoS ONE*, Vol. 17, No. 9, Article e0273629. doi.org/10.1371/journal.pone.0273629.

Merlin, T. 2001. *Sulla pelle viva: come si costruisce una catastrofe, il caso del Vajont* [On living skin: How a catastrophe is constructed, the case of Vajont]. Sommacampagna, Italy, Cierre edizioni. https://edizioni.cierrenet.it/wp-content/uploads/2021/12/Sulla-pelle-viva_2021_anteprima.pdf. (In Italian.)

Mishra, H. R. 2002. Mountains of the developing world: Pockets of poverty or pinnacles for prosperity. *Unasylva*, Vol. 53, No. 1. www.fao.org/3/Y3549E/y3549e06.htm.

Modica, M. 2022. *Alpine Industrial Landscapes: Towards a New Approach for Brownfield Redevelopment in Mountain Regions*. Wiesbaden, Germany, Springer. doi.org/10.1007/978-3-658-37681-9.

Morales Pedraza, J. 2024. Toward a green economy in China: Current status and perspective in electricity generation. *Academia Green Energy*, Vol. 1, No. 1, pp. 1–28. doi.org/10.20935/AcadEnergy6236.

Mountain Partnership. 2014. *Why Mountains Matter for Energy: A Call for Action on the Sustainable Development Goals (SDGs)*. Rome, Food and Agriculture Organization of the United Nations (FAO). https://openknowledge.fao.org/handle/20.500.14283/cd1802en.

Nordregio (Nordic Centre for Spatial Development). 2004. *Mountain Areas in Europe: Analysis of Mountain Areas in EU Member States, Acceding and other European Countries*. Study for the European Commission, DG REGIO. Stockholm, Nordregio. https://archive.nordregio.se/en/Publications/Publications-2004/Mountain-areas-in-Europe/index.html.

Orr, B. J., Dosdogru, F. and Sánchez Santiváñez, M. 2024. Chapter 3: Land degradation and drought in mountains. S. Schneiderbauer, P. Fontanella Pisa, J. F. Shroder and J. Szarzynski (eds), *Safeguarding Mountain Social-Ecological Systems*. Amsterdam, Elsevier, pp. 17–22. doi.org/10.1016/B978-0-12-822095-5.00003-6.

Perlik, M. 2015. Mountains as global suppliers: New forms of disparities between mountain areas and metropolitan hubs. *Journal of Alpine Research*, Vol. 103, No. 3. doi.org/10.4000/rga.3142.

—. 2019. *The Spatial and Economic Transformation of Mountain Regions: Landscapes as Commodities*. London, UK, Routledge. doi.org/10.4324/9781315768366.

Permanent Secretariat of the Alpine Convention. 2009. *Water and Water Management Issues: Report on the State of the Alps.* Alpine Convention: Alpine Signals - Special Edition 2. Innsbruck, Austria/Bolzano, Italy, Permanent Secretariat of the Alpine Convention. www.alpconv.org/fileadmin/user_upload/Publications/RSA/RSA2_long_EN.pdf.

—. 2017. *Towards Renewable Alps: A Progress Report for the Period 2015–2016*. Innsbruck, Austria/Bolzano, Italy, Permanent Secretariat of the Alpine Convention. www.alpconv.org/fileadmin/user_upload/Publications/Towards_Renewable_Alps_2017.pdf.

Platform Water Management in the Alps. 2018. *Common Guidelines for the Use of Small Hydropower in the Alpine Region*. Innsbruck, Austria/Bolzano, Italy, Permanent Secretariat of the Alpine Convention. www.alpconv.org/fileadmin/user_upload/Organisation/AC/XI/ACXI_annex_24_2_EN.pdf.

Price, M. F., Gratzer, G., Alemayehu Duguma, L., Kohler, T., Maselli, D. and Romeo, R. (eds). 2011. *Mountain Forests in a Changing World: Realizing Values, Addressing Challenges*. Rome, Food and Agriculture Organization of the United Nations (FAO)/Mountain Partnership Secretariat/Swiss Agency for Development and Cooperation (SDC). www.fao.org/3/i2481e/i2481e.pdf.

Rahimzoda, S. 2024. Water–energy equation in Central and South Asia: A perspective from Tajikistan. Z. Adeel and B. Boër (eds), *The Water, Energy, and Food Security Nexus in Asia and the Pacific – Central and South Asia*. Cham, Switzerland, Springer. doi.org/10.1007/978-3-031-29035-0_4.

Schyns, J. F. and Vanham, D. 2019. The water footprint of wood for energy consumed in the European Union. *Water*, Vol. 11, No. 2, p. 206. doi.org/10.3390/w11020206.

Scott, C. A., Khaling, S., Shrestha, P. P., Sebastián Riera, F., Choden, K. and Singh, K. 2023. Renewable electricity production in mountain regions: Toward a people-centered energy transition agenda. *Mountain Research and Development*, Vol. 43, No. 1, pp. A1–A8. doi.org/10.1659/MRD-JOURNAL-D-21-00062.

Shah, N. W., Baillie, B. R., Bishop, K., Ferraz, S., Högbom, L. and Nettles, J. 2022. The effects of forest management on water quality. *Forest Ecology and Management*, Vol. 522, No. 120397. doi.org/10.1016/j.foreco.2022.120397.

Shugar, D. H., Jacquemart, M., Shean, D., Bhushan, S., Upadhyay, K., Sattar, A., Schwanghart, W., McBride, S., Van Wyk de Vries, M., Mergili, M., Emmer, A., Deschamps-Berger, C., McDonnell, M., Bhambri, R., Allen, S., Berthier, E., Carrivick, J. L., Clague, J. J., Dokukin, M., Dunning, S. A., Frey, H., Gascoin, S., Haritashya, U. K., Huggel, C., Kääb, A., Kargel, J. S., Kavanaugh, J. L., Lacroix, P., Petley, D., Rupper, S., Azam, M. F., Cook, S. J., Dimri, A. P., Eriksson, M., Farinotti, D., Fiddes, J., Gnyawali, K. R., Harrison, S., Jha, M., Koppes, M., Kumar, A., Leinss, S., Majeed, U., Mal, S., Muhuri, A., Noetzli, J., Paul, F., Rashid, I., Sain, K., Steiner, J., Ugalde, F., Watson, C. S. and Westoby, M. J. 2021. A massive rock and ice avalanche caused the 2021 disaster at Chamoli, Indian Himalaya. *Science*, Vol. 373, No. 6552, pp. 300–306. doi.org/10.1126/science.abh4455.

Sigl, M., Abram, N. J., Gabrieli, J., Jenk, T. M., Osmont, D. and Schwikowski, M. 2018. 19th century glacier retreat in the Alps preceded the emergence of industrial black carbon deposition on high-alpine glaciers. *The Cryosphere*, Vol. 12, No. 10, pp. 3311–3331. doi.org/10.5194/tc-12-3311-2018.

Smith López, C., Bogdan, A. M., Belcher, K. and Natcher, D. 2024. Advancing a WEF nexus security index for Alaska: An informed starting point for policy making. *Polar Geography*, Vol. 47, No. 2, pp. 71–89. doi.org/10.1080/1088937X.2024.2311785.

Talandier, M. and Donsimoni, M. 2022. Industrial metabolism and territorial development of the Maurienne Valley (France). *Regional Environmental Change*, Vol. 22, No. 1, p. 9. doi.org/10.1007/s10113-021-01845-4.

TechnoAlpin. 2023. *2023 Sustainability Report*. Bolzano, Italy, TechnoAlpin. www.technoalpin.com/fileadmin/user_upload/Nachhaltigkeit/Sustainability_Report_ENG.pdf.

Thornton, J. M., Snethlage, M. A., Sayre, R., Urbach, D. R., Viviroli, D., Ehrlich, D., Muccione, V., Wester, P., Insarov, G. and Adler, C. 2022. Human populations in the world's mountains: Spatio-temporal patterns and potential controls. *PLoS ONE*, Vol. 17, No. 7, Article e0271466. doi.org/10.1371/journal.pone.0271466.

Tuihedur Rahman, H. M., Ingram, S. and Natcher, D. 2024. The cascading disaster risk of water, energy and food systems. *Environmental Hazards*, Vol. 23, No. 5, pp. 423–442. doi.org/10.1080/17477891.2024.2323105.

Unbehaun, W. and Pröbstl, U. 2006. Cloudy prospects in winter sport: How competitive are the Austrian winter sport destinations under conditions of climate change? *Sustainable Solutions for the Information Society.* Eleventh International Conference on Urban Planning and Spatial Development for the Information Society. Vienna, pp. 381–387. https://programm.corp.at/cdrom2006/archiv/papers2006/CORP2006_UNBEHAUN.pdf.

UNECE (United Nations Economic Commission for Europe). 2014. *Safety Guidelines and Good Practices for Tailings Management Facilities*. Geneva, UNECE. https://unece.org/DAM/env/documents/2014/TEIA/Publications/1326665_ECE_TMF_Publication.pdf.

——. 2016. *Checklist for Contingency Planning for Accidents Affecting Transboundary Waters – with Introductory Guidance*. Geneva, UNECE. https://unece.org/DAM/env/documents/2016/TEIA/ece.cp.teia.34.e_Checklist_for_contingency.pdf.

UNECLAC (United Nations Economic Commission for Latin America and the Caribbean). 2023. *Lithium Extraction and Industrialization: Opportunities and Challenges for Latin America and the Caribbean*. Santiago, UNECLAC. https://repositorio.cepal.org/server/api/core/bitstreams/8d505030-7686-44e1-9f60-77ceb0610826/content.

UNEP (United Nations Environment Programme). 2012. *A Practical Guide: Reducing Mercury Use in Artisanal and Small-Scale Gold Mining*. Nairobi, UNEP. https://wedocs.unep.org/bitstream/handle/20.500.11822/11524/reducing_mercury_artisanal_gold_mining.pdf.

——. 2024. *Global Resources Outlook 2024: Bend the Trend – Pathways to a Liveable Planet as Resource Use Spikes. Global Resources Outlook 2024*. Nairobi, International Resource Panel, UNEP. https://wedocs.unep.org/20.500.11822/44901.

UNIDO (United Nations Industrial Development Organization). 2017. *Green Chemistry and Beyond Manufacturing Without POPs*. Vienna, UNIDO. www.unido.org/sites/default/files/2017-07/UNIDO_leaflet_08_ManufacturingWithoutPOPs_170124_final_0.pdf.

UNIDO/ICSHP (United Nations Industrial Development Organization/International Centre on Small Hydro Power). 2022. *World Small Hydropower Development Report 2022*. Vienna/Hangzhou, China, UNIDO/ICSHP. www.unido.org/WSHPDR2022.

UNSD (United Nations Statistics Division). n.d. UN Data: A World of Information. UNSD website. https://data.un.org/.

Venus, T. E., Smialek, N., Pander, J., Harby, A. and Geist, J. 2020. Evaluating cost trade-offs between hydropower and fish passage mitigation. *Sustainability*, Vol. 12, No. 20, p. 8520. doi.org/10.3390/su12208520.

WBCSD (World Business Council for Sustainable Development). 2017. *Business Guide to Circular Water Management: Spotlight on Reduce, Reuse and Recycle*. Geneva, WBCSD. https://docs.wbcsd.org/2017/06/WBCSD_Business_Guide_Circular_Water_Management.pdf.

World Bank. 2014. *Rogun Hydropower Project: Final Report of the Environmental and Social Panel of Experts*. Washington DC, World Bank. www.worldbank.org/en/country/tajikistan/brief/final-reports-related-to-the-proposed-rogun-hpp.

——. 2019. *Wastewater: From Waste to Resource – The Case of Arequipa, Peru*. Washington DC, World Bank. https://openknowledge.worldbank.org/server/api/core/bitstreams/120995b1-dbbb-5e48-b6b8-afbabe6f312f/content.

Wright, I. A., Wright, S., Graham, K. and Burgin, S. 2011. Environmental protection and management: A water pollution case study within the Greater Blue Mountains World Heritage area, Australia. *Land Use Policy*, Vol. 28, No. 1, pp. 353–360. doi.org/10.1016/j.landusepol.2010.07.002.

WWAP (United Nations World Water Assessment Programme). 2014. *The United Nations World Water Development Report 2014: Water and Energy*. Paris, United Nations Educational, Scientific and Cultural Organization (UNESCO). https://unesdoc.unesco.org/ark:/48223/pf0000225741.

WWAP/UN-Water (United Nations World Water Assessment Programme/UN-Water). 2018. *The United Nations World Water Development Report 2018: Nature-Based Solutions for Water*. Paris, United Nations Educational, Scientific and Cultural Organization (UNESCO). https://unesdoc.unesco.org/ark:/48223/pf0000261424.

Wymann von Dach, S. and Fleiner, R. 2019. *Shaping the Water–Energy–Food Nexus for Resilient Mountain Livelihoods*. Issue Brief on Sustainable Mountain Development. Bern, Centre for Development and Environment (CDE). doi.org/10.7892/boris.131606.

Yao, F., Livneh, B., Rajagopalan, B., Wang, J., Crétaux, J. F., Wada, Y. and Berge-Nguyen, M. 2023. Satellites reveal widespread decline in global lake water storage. *Science*, Vol. 380, No. 6646, pp. 743–749. doi.org/10.1126/science.abo2812.

Zoï Environment Network. 2013. *A Short Introduction to Environmental Remediation for Mining Legacies: Case Studies from ENVSEC Work in South East Europe.* Geneva, United Nations Environment Programme (UNEP)/Environment and Security Initiative (ENVSEC). https://zoinet.org/wp-content/uploads/2017/10/Mining-SEE-Ebook-.pdf.

Zou, L., Tian, F., Liang, T., Eklundh, L., Tong, X., Tagesson, T., Dou, Y., He, T., Liang, S. and Fensholt, R. 2023. Assessing the upper elevational limits of vegetation growth in global high-mountains. *Remote Sensing of Environment*, Vol. 286, No. 113423. doi.org/10.1016/j.rse.2022.113423.

Chapter 6

Environment

UNESCO WWAP
David Coates and Richard Connor

With contributions from: Elisabeth Bernhardt and Ansgar Fallendorf (UNEP)
and Birguy Lamizana Diallo (UNCCD)

Mountains feature a diverse range of ecological zones, each resulting from a specific combination of factors such as differences in elevation, geomorphology, isolation and microclimatic conditions (e.g. insolation). Consequently, they often have higher endemic biodiversity than lowlands, including important genetic varieties of agricultural crops and animals (FAO, 2019). They also have an equally diverse range of human cultures (UNEP/GRID-Arendal, 2022). Mountain systems are generally characterized by lower temperatures and higher precipitation than other landscapes (FAO, 2022), and host 25 of the world's 34 biodiversity hotspots (FAO/UNEP, 2023).

In mountain ecosystems, forests cover approximately 40% of the global mountain area. At higher elevations, forests give way to grasslands and alpine tundra, including permafrost and glaciers. Mountain soils develop under harsh climatic conditions. They differ significantly from lowland soils, as they are shallower and more vulnerable to erosion (Repe et al., 2020). Such soils are easily and often degraded by various human activities, especially removal of vegetation that exposes the bare soil. The recovery of degraded soils and thus ecosystems at high elevations is slow.

The Hindu Kush Himalaya (HKH) mountain range is the largest and highest alpine ecosystem in the world, with an average elevation of 4,000 m above sea level. Covering an area of more than 5 million km^2, it is the largest storehouse of snow and ice outside the Arctic and Antarctic, with about 100,000 km^2 of glaciers providing fresh water to more than 12,000 lakes and more than 10 river systems (UNEP, 2022a). Sixty per cent of the HKH region features seasonal cryosphere – snow, glaciers, permafrost and glacial lakes (ICIMOD, 2023). Other examples of unique ecosystems include the paramo ecosystem of the South American Andes (Box 6.1), the Carpathian Mountain range, the vast Antarctic, and the transition from lush rainforest to alpine meadows and snow-covered peaks on Mount Kilimanjaro in Africa.

Box 6.1 The paramos – a unique mountain ecosystem in South America

The paramos are distributed along the Neotropical Andean mountain range in Colombia, Ecuador, northern Peru and the Bolivarian Republic of Venezuela. They make up one of the most biodiverse high-elevation ecosystems, and are critical for the survival of millions of people – providing the main source of clean water for inhabitants of capital cities such as Bogotá and Quito.

Vegetation plays a major role in regulating the amount and quality of water supplied by these Andean 'water sponges'. In addition to aiding infiltration of water to the ground, plant cover also reduces evaporation compared with bare ground. Plants can also capture water from fog.

The paramos have also provided a source of medicinal plants, grazing and agricultural land for Indigenous Peoples. However, the landscapes are changing, and their functionality is being reduced.

Siecha lagoons, Chingaza paramo, Colombia

Photo: © Matthieu Cattin/Shutterstock.*

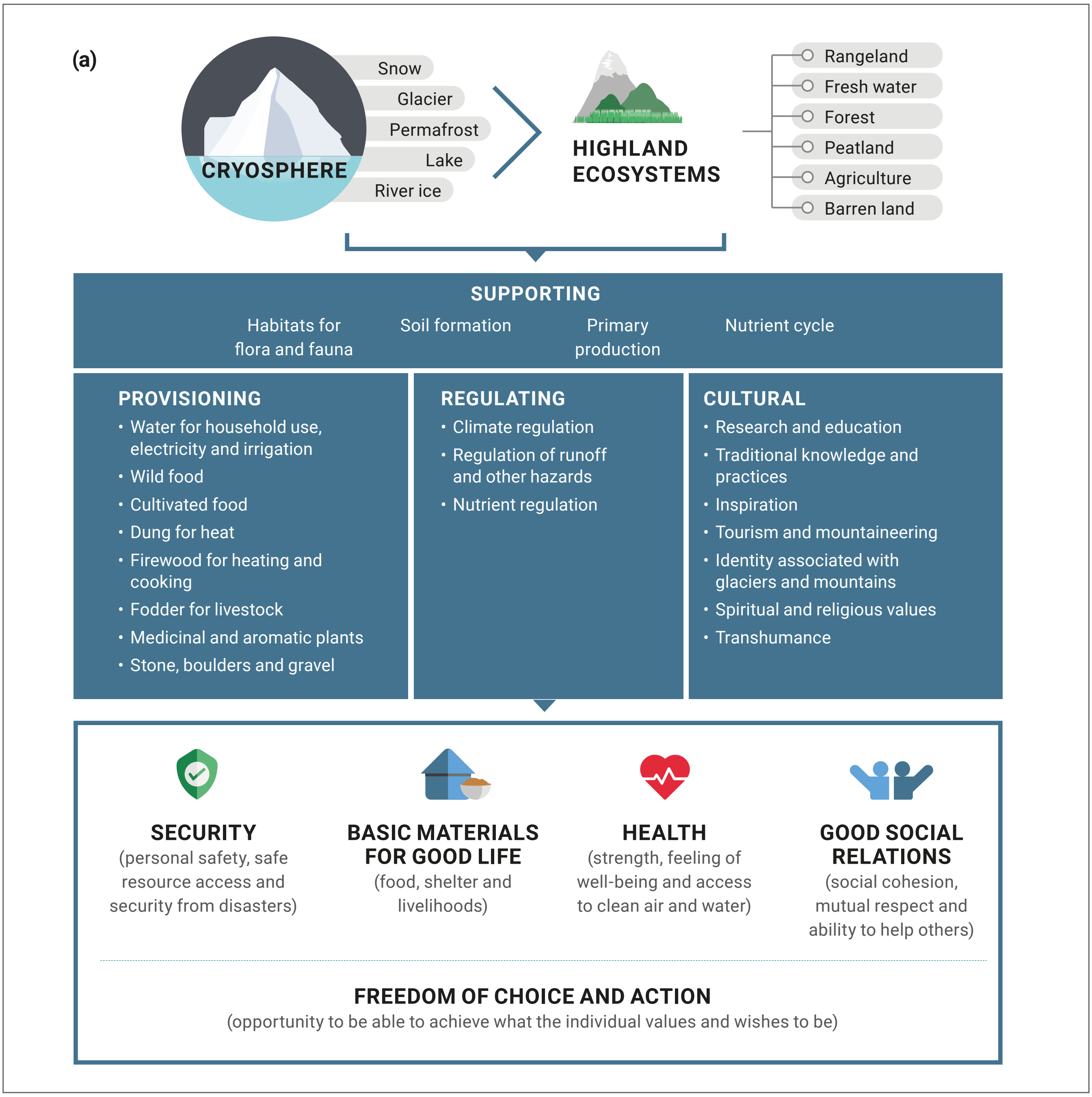
Source: Baruffol (2020).

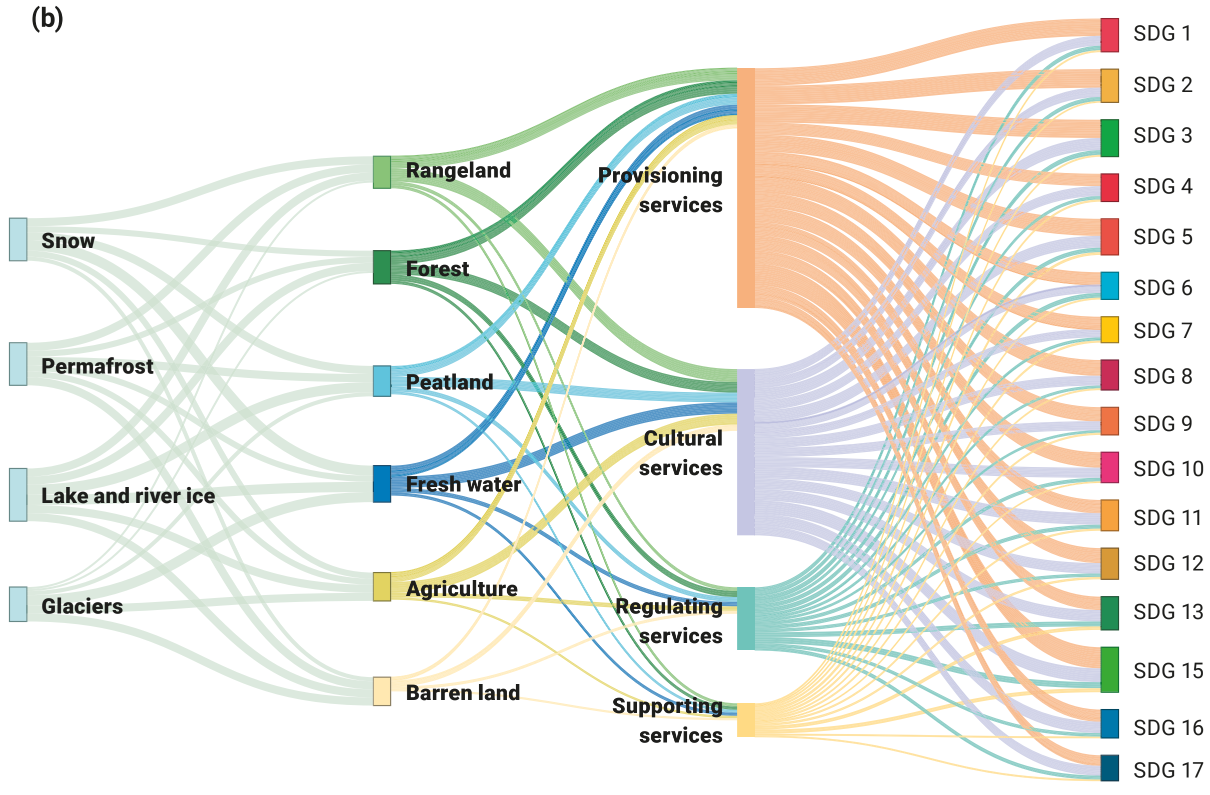
6.1 Ecosystem services of the mountain cryosphere

Mountain cryospheres and highland ecosystems provide essential ecosystem services to people living in mountains, and to billions in connected lowland areas (Figure 6.1a). These services contribute to the Sustainable Development Goals (Figure 6.1b). Water regulation (including water storage and flood regulation) is one of the most important services – for example, an estimated two-thirds of irrigated agriculture globally depends on runoff contributions from mountains (Adler et al., 2022; see Chapter 3). Other key ecosystem services include reducing the risk of erosion and landslides, cooling local temperatures, carbon sequestration, providing food and fibres, and maintaining pools of genetic resources for locally adapted crops and livestock (FAO/UNEP, 2023).

Mountain soils with permafrost contain approximately 66 Pg of soil organic carbon, which is 4.5% of the global pool (FAO, 2022). High-elevation peatlands are particularly important global carbon stores (UNEP, 2022b). Larger mountain ranges, such as the Andes, Greater Caucasus and HKH, are also significant in terms of climate regulation.

Figure 6.1 Ecosystem services provided by the mountain cryosphere and highland ecosystems (a), and links between these and the Sustainable Development Goals (SDGs) (b)





SDG 1: No poverty
SDG 2: Zero hunger
SDG 3: Good health and well-being
SDG 4: Quality education
SDG 5: Gender equality
SDG 6: Clean water and sanitation
SDG 7: Affordable and clean energy
SDG 8: Decent work and economic growth
SDG 9: Industry, innovation and infrastructure
SDG 10: Reduced inequalities
SDG 11: Sustainable cities and communities
SDG 12: Responsible consumption and production
SDG 13: Climate action
SDG 15: Life on land
SDG 16: Peace justice and strong institutions
SDG 17: Partnerships for the goals

Source: Chaudhary et al. (2023, figs 4.2 and 4.3, pp. 132–134).

Agriculture, including livestock, timber and other forest resources are often a mainstay of local livelihoods. High-elevation fisheries based on adapted fish species can be an important, and often overlooked, source of local livelihoods and food and nutrition security (FAO, 2003). Climate change has been altering glacial lake fisheries (Tingley et al., 2019).

6.2 Trends in cryosphere and mountain ecosystem services

Regions worldwide are facing profound impacts from climate change and uncontrolled human activities, such as deforestation, intensive agriculture, pollution and construction of infrastructure. In mountain areas, these can cause irreversible losses of biodiversity and ecosystems services (FAO/UNEP, 2023). As of 2020, 57% of the global mountain area was under intense pressure, with ecosystem degradation concentrated at lower mountain elevations, where most human activities occur (Elsen et al., 2020). For example, increased urbanization and mining have degraded several mountain ecosystems (Jiang et al., 2021). Extensive removal of vegetation and soil is required for the installation of skiing facilities, thereby affecting native vegetation and the structural properties of soils (Pintaldi et al., 2017). Poorly designed or managed waterworks, such as river channelization, can result in river bank erosion and sediment liberation, which affect water quality and the ecology of aquatic ecosystems (Mikuś et al., 2021).

There is a trend of increasing frequency and intensity of natural hazards in glacial and high mountain areas (see Chapter 2.). But not all hazards in mountain areas are due to climate change. Ecosystem degradation is implicated as a cause of or factor initiating or increasing the impact of many hazards. For example, severe deforestation and poor urban planning exacerbated a landslide in Freetown, Sierra Leone, in 2017, that killed over 1,000 people (Kargel et al., 2021).

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Agriculture, including livestock, timber and other forest resources are often a mainstay of local livelihoods

Hydrological changes will determine how most mountain ecosystems change, more so than the direct impacts of changes in temperature. Such hydrological changes are predicted to include short- to medium-term increases of seasonal runoff as the mountain cryosphere warms. And in the longer term, these changes include reduced runoff as the volume of water that mountains store decreases, but with changes in overall annual water supply depending on accompanying changes to precipitation (Adler et al., 2022). For example, in the Bolivian Cordillera Real, where wetland cover increased over the period 1984–2011 due to increases in extreme precipitation events and glacier melting, this trend is likely to be reversed with predicted future decreases in total precipitation and glacier runoff (Dangles et al., 2017). In the Greater Kinggan Mountains in northeastern China, about 30% of the wetland area has been projected to disappear by 2050, with this value doubling by 2100 under an alternative climate change scenario (Wang et al., 2022). In the Neotropical Andes, the size of the paramo ecosystem (Box 6.1) has been predicted to decrease in area by 30% by 2050 without factoring in destruction because of land-use change (Alfthan et al., 2018).

There are significant feedback loops with climate change. As high-elevation and high-latitude soils experience warmer air temperatures, and as permafrost is exposed as glaciers retreat, the increased thickening of the thawed and active layer results in significant carbon emissions. Unless rapidly covered with new vegetation growth, bare soils are subject to increased erosion and landslides (FAO, 2022). Under two climate change projection scenarios, the near-surface permafrost area will decrease by up to 66% and up to 99% by 2100. This is projected to release up to 240 Gt of carbon as carbon dioxide and methane to the atmosphere with the potential to significantly accelerate climate change (Meredith et al., 2019).

As mountains warm and the cryosphere retreats, species and ecological communities tend to shift to higher elevations, resulting in an overall greening of higher mountain elevations. The trend can have positive and negative impacts. *"Warming increases the net primary productivity as well as carbon uptake of tundra and alpine vegetation and elevates respiration, which may result in a significant change to the terrestrial carbon cycle and soil carbon storage"* (UNEP, 2022a, p. 17). The increase in vegetation coverage also strengthens the water-holding capacity of soil as the active layer thickens with permafrost warming and vegetation cover aids infiltration. However, desertification is expanding in some river source regions (ICIMOD, 2023). *"Upslope advances of non-native species are also becoming more common in mountain ecosystems, causing the suppression [and in extreme cases extinction] of native species and impacting the provision of ecosystem services"* (FAO/UNEP, 2023, p. 6).

While an increase in temperature at high elevations can contribute to the expansion of agricultural and plantation areas, it can be challenging to distinguish between the impacts of climate change and the direct influences of humans on these ecosystems. For example, some forests in the HKH region have undergone several phases of clearing, preservation and restoration (ICIMOD, 2023). The sharp decline in the cropland in some areas of the HKH region has been attributed to grassland protection projects and urbanization in the past two decades (Luan and Li, 2021).

During the snow-melt season in the spring and summer months, red snowfields – known as 'glacier blood' or 'watermelon snow' – have been found ubiquitously across the world, and are caused by blooms of red algae. These areas decrease surface albedo and enhance solar energy absorption, ultimately accelerating ice- and snow-melt (Lutz et al., 2015). Snow algae can be the main albedo reducers on wet snowpacks, and glacier ice algae can become the dominant albedo reducer (Halbach et al., 2022). In North America for example, individual glaciers had up to 65% of their surface area affected by bloom in one melt season, estimated to cause as much as 3 cm of snow meltwater equivalent averaged across the glacier surface (Engstrom and Quarmby, 2023). It is assumed this will affect runoff water quality, although detailed studies are lacking.

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Hydrological changes will determine how most mountain ecosystems change, more so than the direct impacts of changes in temperature

Observations and modelling indicate the influence of long-range transport of atmospheric pollution. For instance, ice cores and lake sediments have shown a dramatic increase in black carbon (see Box 2.1) and heavy metals like mercury since the 1950s in the HKH region, which reflects the increased emissions of air pollutants in South Asia (UNEP, 2022a). Once deposited on snow and ice surfaces, black carbon lowers the albedo of snow and ice surfaces (making them less reflective and more light absorbent), thus accelerating melting and increasing the rate of glacier retreat (Kang et al., 2020). This will accelerate the release of deposited persistent organic pollutants and heavy metals from the cryosphere.

In general, water quality data are particularly scarce for mountain water bodies (Machate et al., 2023), despite pollution being widespread in mountain areas, chiefly from agricultural, urban, mining and industrial activities (Elsen et al., 2020). Reliable data exist only for persistent organic pollutants, with increasing evidence that even remote mountain lakes are exposed to a wide range of organic pollutants with widespread chronic toxic risks to high-elevation aquatic biodiversity (UNEP, 2022a). For instance, in the Caucasus Mountains, the Georgian rivers of the Caspian Sea basin drainage area have been found to be polluted with heavy metals, oil and pesticides caused by drainage from large agricultural and mining enterprises. Pollution by heavy metals is reported for the Baksan River that originates in the Mount Elbrus region of the Russian Federation. And increased concentration of pesticides has been identified in groundwaters that provide a source of mineral waters in the North Caucasus (UNEP, 2024).

Trends in biodiversity in high mountains show a mixed picture. Biodiversity at the global level is being challenged with an extinction rate of about 20%. However, the rate in the HKH region is about 9% for vertebrates and 5% for plants (UNEP, 2022a). The region has undergone several successful conservation efforts, with an increase in populations of some species (e.g. Przewalski's gazelle and the Tibetan wild ass) and an expansion of protected areas (Fu et al., 2021). In recent decades, there has been growing concern in relation to the prevalent drivers of change such as climate change, the lack of transboundary conservation approaches, major infrastructure projects and the arrival and spread of alien invasive species (ICIMOD, 2023).

6.3 Responses

At the ecosystem level, most of the options for addressing the impacts of changes in the cryosphere and high mountains involve conserving or restoring ecosystem functionality to maintain or enhance ecosystem services at local to regional scales through nature-based solutions (NbS) or ecosystem-based adaptation (EbA). NbS for water was the topic of the 2018 edition of *The United Nations World Water Development Report* (WWAP/UN-Water, 2018). Ecosystem restoration is becoming increasingly applied in mountain areas (FAO/UNEP, 2023).

Box 6.2 Land degradation neutrality (LDN) approaches in mountains

A resilience framework for LDN applied at the national level helps achieve Sustainable Development Goal Target 15.3 – a land degradation neutral world by 2030. Applicable to all land, including mountains, the framework uses a holistic, inclusive and landscape-based approach governed by social and environmental safeguards to protect people and nature. It encourages the pursuit of long-term, integrated and nature-positive strategies that focus simultaneously on improving land productivity and rehabilitating, conserving and sustainably managing land and water resources, leading to healthier ecosystems and improved livelihoods for local communities.

Central to achieving LDN is the use of integrated land-use planning and integrated landscape management to manage the inevitable trade-offs between competing demands on land and to optimize the spatial mix of interventions.

The positive impacts that have been demonstrated in montane ecosystems range from reducing soil loss and improving production and income locally and more reliable streamflow downstream in times of drought and flood control after heavy precipitation. As of November 2024, 131 countries that were signatories to the United Nations Convention to Combat Desertification had set LDN targets to prevent the future loss of land-based natural capital by scaling up sound land management and restoration practices. The resilience framework for LDN is also an appropriate and nature-positive way forwards for other nations that are committed to the preservation of their pristine mountain regions.

Sources: Critchley et al. (2021) and Orr et al. (2017; 2024).

These approaches are commonly seen as an adaptation component in the nationally determined contributions of many mountain countries around the world. In a meta-review of 928 NbS projects assessed globally, 37% were designed to address flooding and 28% drought (UNEP, 2021a). A global review of 93 NbS in mountains, such as those deploying climate-smart agriculture, protection of existing forests, afforestation and agroforestry, confirmed the potential of NbS to promote sustainable trajectories (Palomo et al., 2021).

Where important ecosystem components are still in relatively good condition, the priority response is their conservation. Multiple benefits for vulnerable people can be provided by: restoring grasslands using native species to increase slope resilience, grazing opportunities and forage available during dry periods; water conservation and management using 'grey–green' approaches, including restoring riparian zones to reduce flooding and help maintain water quality; and using diversified agroecological farming practices to help improve food security and livelihoods (Swiderska et al., 2018).

Much work has been done on the protective functions of mountain forests. Teich et al. (2022) noted that effects differ greatly among countries, and also the need for standardized definitions and improved understanding and assessment of the protective functions. Food security, increasing resilience and climate change mitigation are widely cited as being delivered through agroforestry (Gidey et al., 2020). EbA has been effective in mountain regions at reducing risks from floods and landslides, improving water quality and supporting biodiversity conservation (Lavorel et al., 2019). However, recurrent disturbances can increase recovery times and reduce the effectiveness of NbS and EbA (Scheidl et al., 2020).

For cryosphere and mountain areas, a key response is to conserve or improve the health and stability of soils – and the ecosystem services they support – in the face of threats from human-induced degradation or global warming. Achieving land degradation neutrality is an overarching globally agreed goal that is particularly relevant to mountain areas in view of their vulnerability (Box 6.2). NbS actions often involve conserving, restoring or expanding grasslands at higher elevations or forests below the tree-line, which usually deliver multiple benefits, locally and regionally (Box 6.3).

Regional approaches often focus on land or soil management. For example, the Soil Conservation Protocol of the Alpine Convention emphasizes soil conservation and restoration, particularly regarding restoring skiing areas (Repe et al., 2020). However, using non-native tree species that typically absorb large amounts of water can also have negative impacts on water supplies (Xiao et al., 2020). For instance, afforestation in the mountain region of Chongqing and the Yunnan–Guizhou Plateau, southwest China, resulted in the uptake of an estimated 10% of the annual water supply, triggering water shortage events in 2015. Although changes in land use, including afforestation and reforestation, have had small inhibitory effects on water yield in some lowland sites in northeast China, they also had large positive impacts on stopping soil erosion (Wang et al., 2022). The management practices involved must also be considered. For example, forest management can significantly affect sediment delivery, nutrient losses, carbon transport, metal and base cation releases, and changes to acidity and temperature (Shah et al., 2022).

Box 6.3 Acción Andina: Forest landscape restoration in the high Andes

The mountains in the high Andes host rich forest ecosystems that support diverse wildlife and hundreds of millions of people across South America. They supply fresh water that feeds into the headwaters of the Amazon and directly to nearby villages and cities. Centuries of deforestation have reduced high Andean native forests to just 3–10% of their original extent, while climate change has accelerated glacial melt. Those who are most vulnerable – the people of the high Andes and their unique Indigenous culture – are disproportionately affected.

Global Forest Generation and Asociación Ecosistemas Andinos launched Acción Andina in 2018. The initiative aimed to protect and restore 1 million ha of critical native Polylepis high Andean forest ecosystems over the next two decades across the seven Andean countries (Argentina, Plurinational State of Bolivia, Chile, Colombia, Ecuador, Peru and Bolivarian Republic of Venezuela). Traditional knowledge and modern technology are integrated to restore forests, secure water, and protect landscapes and ecosystems, biodiversity and culture.

More than 6.5 million native trees have been planted across 3,359 ha of high Andean forests, with an additional 11,253 ha of native forests in new or renewed protected areas. Enhanced climate resilience and water security have also improved habitats for native species such as the Andean condor and the spectacled bear.

Source: FAO/UNEP (2023).

There is increasing recognition of the role that local communities and their knowledge play in identifying needs and implementing solutions. For example, in the paramos in central Ecuador, community-led efforts have proved to be far more effective than a government-led protected areas approach for improving water supplies to lower basin populations (Torres et al., 2023).

There is increasing recognition of the role that local communities and their knowledge play in identifying needs and implementing solutions

NbS, including EbA, are often combined with small-scale physical interventions in green–grey applications in mountain areas. For example, the physical sculpting of terraces on hill slopes (see Section 3.1.2) to reduce erosion and landslides is commonly combined with tree planting to improve overall benefits (Box 6.4). Local communities are often highly motivated. In some cases, additional incentives (financial or other) are important to increase community involvement until restoration results become visible and the financial sustainability of local livelihoods, through the creation of additional sources of income, increases the effectiveness of NbS measures (FAO/UNEP, 2023).

Major challenges remain. The following have been identified by the International Centre for Integrated Mountain Development in the HKH region (ICIMOD, 2023):

- the large variations in ecosystems and cultures, and local communities depending heavily on natural resources, require area-specific solutions with NbS that consider customized interventions grounded in an ecosystems-based understanding
- stronger science on mountain ecosystems is needed to increase understanding of the complex interlinkages among climate change, the cryosphere, ecosystems and society; conservation of shared heritage requires regional cooperation
- limited funding and policy gaps
- limited exchange and development of best practices
- insufficient monitoring and data

Box 6.4 Building mountain resilience: Torrent Catchment restoration in the Pamir Mountains of Afghanistan

In the mountainous and vulnerable area of Torrent Catchment in the Pamir Mountains of Afghanistan, a blend of small-scale physical interventions and agroforestry or forest restoration has been used to protect local communities from landslides, avalanches and other hazards. This has also increased water security and improved livelihoods in the area. Local communities led and implemented the interventions. Local tree species planted included fruit and nut trees that are tended by, and benefit the livelihoods of, local women (UNEP, 2021b).

Terraces constructed to stabilize slopes and limit soil erosion

Photo: © UNEP; source: UNEP (2021b, p. 18).

Check-dams, soil bunds and tree plantations to help stabilize slopes

Photo: © UNEP; source: UNEP (2021b, p. 22).

A wood-lot from tree stem cuttings to protect sloping lands

Photo: © UNEP; source: UNEP (2021b, p. 35).

Specific knowledge gaps requiring critical attention include: limited understanding of connectedness at the species, genetic and ecosystem levels and the impacts of climate change on this; interactions among permafrost, rangelands, wetlands and peatlands; and climate-driven hazards and their cascading impacts on species extinction and range retraction (ICIMOD, 2023).

Reliable long-term planning strategies for industrial and contaminated sites that consider the impacts of climate change are needed to avoid future environmental hazards from these sources (Langer et al., 2023). The need to better acknowledge the importance of high-elevation fisheries and incorporate into policies, management and investment has been recognized for decades (FAO, 2003).

Response options are context and site specific, often share enabling factors such as community support and co-benefits, often are not implemented within the context of climate change or ecosystem restoration, and are weakly linked to the implementation of national or regional policies (UNEP/GRID-Arendal, 2022).

The following key factors have been identified as important for mountain ecosystem restoration: local people and their involvement and empowerment; gender-responsive and socially inclusive approaches; exploring viability and mobilizing stakeholders; understanding the ecosystem and livelihoods context; analysing climate risks and vulnerability; understanding the role of ecosystem services in adaptation; developing an NbS or EbA strategy and designing actions accordingly; monitoring and evaluation for learning; and mainstreaming NbS and EbA and promoting synergies (Swiderska et al., 2018).

"*The strong support of governments, civil society and the private sector is essential to ensure and scale up adequate nature-positive investments, connect policy agendas and actions for mountains, boost regional coordination, and implement the Five Years of Action for the Development of Mountain Regions' global framework for action*" (FAO/UNEP, 2023, p. 47).

References

Adler, C., Wester, P., Bhatt, I., Huggel, C., Insarov, G. E., Morecroft, M. D., Muccione, V. and Prakash, A. 2022. Mountains. H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem and B. Rama (eds), *Climate Change 2022: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK/New York, Cambridge University Press, pp. 2273–2318. doi.org/10.1017/9781009325844.022.

Alfthan, B., Gjerdi, H. L., Puikkonen, L., Andresen, M., Semernya, L., Schoolmeester, T. and Jurek, M. 2018. *Mountain Adaptation Outlook Series: Synthesis Report*. Nairobi/Vienna/Arendal, Norway, United Nations Environment Programme (UNEP)/GRID-Arendal. https://gridarendal-website-live.s3.amazonaws.com/production/documents/:s_document/412/original/SynthesisReport_screen.pdf?1544437610.

Baruffol, M. 2020. Andean 'Water Sponges': The Role of Plants in Water Supply. Royal Botanic Gardens Kew website. www.kew.org/read-and-watch/paramos-andean-water-sponges.

Chaudhary, S., Chettri, N., Adhikari, B., Dan, Z., Gaire, N. P., Shrestha, F. and Wang, L. 2023. Effects of a changing cryosphere on biodiversity and ecosystem services, and response options in the Hindu Kush Himalaya. P. Wester, S. Chaudhary, N. Chettri, M. Jackson, A. Maharjan, S. Nepal and J. F. Steiner (eds), *Water, Ice, Society, and Ecosystems in the Hindu Kush Himalaya: An Outlook*. Kathmandu, International Centre for Integrated Mountain Development (ICIMOD), pp. 123–163. doi.org/10.53055/ICIMOD.1032.

Critchley, W., Harari, N. and Mekdaschi-Studer, R. 2021. *Restoring Life to the Land: The Role of Sustainable Land Management in Ecosystem Restoration*. United Nations Convention to Combat Desertification (UNCCD)/World Overview of Conservation Approaches and Technologies (WOCAT). www.unccd.int/sites/default/files/documents/2021-10/211018_RestoringLifetotheLand_Report%20%282%29.pdf.

Dangles, O., Rabatel, A., Kraemer, M., Zeballos, G., Soruco, A., Jacobsen, D. and Anthelme, F. 2017. Ecosystem sentinels for climate change? Evidence of wetland cover changes over the last 30 years in the Tropical Andes. *PLoS ONE*, Vol. 12, No. 5, Article e0175814. doi.org/10.1371/journal.pone.0175814.

Elsen, P. R., Monahan, W. B. and Merenlender, A. M. 2020. Topography and human pressure in mountain ranges alter expected species responses to climate change. *Nature Communications*, Vol. 11, Article 1974. doi.org/10.1038/s41467-020-15881-x.

Engstrom, C. B. and Quarmby, L. M. 2023. Satellite mapping of red snow on North American glaciers. *Science Advances*, Vol. 9, No. 47. doi.org/10.1126/sciadv.adi3268.

FAO (Food and Agriculture Organization of the United Nations). 2003. *Mountain Fisheries in Developing Countries*. Rome, FAO. www.fao.org/3/y4633e/y4633e.pdf.

—. 2019. *Mountain Agriculture: Opportunities for Harnessing Zero Hunger in Asia*. Bangkok, FAO. www.fao.org/3/ca5561en/CA5561en.pdf.

—. 2022. *The State of the World's Land and Water Resources for Food and Agriculture 2021: Systems at Breaking Point*. Main Report. Rome, FAO. doi.org/10.4060/cb9910en.

FAO/UNEP (Food and Agriculture Organization of the United Nations/United Nations Environment Programme). 2023. *Restoring Mountain Ecosystems: Challenges, Case Studies and Recommendations for Implementing the UN Decade Principles for Mountain Ecosystem Restoration*. Rome/Nairobi, FAO/UNEP. doi.org/10.4060/cc9044en.

Fu, B., Ouyang, Z., Shi, P., Fan, J., Wang, X., Zheng, H., Zhao, W. and Wu, F. 2021. Current condition and protection strategies of Qinghai-Tibet Plateau ecological security barrier. *Bulletin of Chinese Academy of Sciences (Chinese version)*, Vol. 36, No. 11, pp. 1298–1306. https://bulletinofcas.researchcommons.org/journal/vol36/iss11/5/.

Gidey, T., Oliveira, T. S., Crous-Duran, J. and Palma, J. H. N. 2020. Using the yield-SAFE model to assess the impacts of climate change on yield of coffee (*Coffea arabica* L.) under agroforestry and monoculture systems. *Agroforestry Systems*, Vol. 94, No. 1, pp. 57–70. doi.org/10.1007/s10457-019-00369-5.

Halbach, L., Chevrollier, L.-A., Doting, E. L., Cook, J. M., Jensen, M. B., Benning, L. G., Bradley, J. A., Hansen, M., Lund-Hansen, L. C., Markager, S., Sorrell, B. K., Tranter, M., Trivedi, C. B., Winkel, M. and Anesio, A. M. 2022. Pigment signatures of algal communities and their implications for glacier surface darkening. *Scientific Reports*, Vol. 12, Article 17643. doi.org/10.1038/s41598-022-22271-4.

ICIMOD (International Centre for Integrated Mountain Development). 2023. *Water, Ice, Society, and Ecosystems in the Hindu Kush Himalaya: An Outlook* [P. Wester, S. Chaudhary, N. Chettri, M. Jackson, A. Maharjan, S. Nepal and J. F. Steiner (eds)]. Kathmandu, ICIMOD. doi.org/10.53055/ICIMOD.1028.

Jiang, C., Yang, Z., Wen, M., Huang, L., Liu, H., Wang, J., Chen, W. and Zhuang, C. 2021. Identifying the spatial disparities and determinants of ecosystem service balance and their implications on land use optimization. *Science of the Total Environment*, Vol. 793, Article 148472. doi.org/10.1016/j.scitotenv.2021.148472.

Kang, S., Zhang, Y., Qian, Y. and Wang, H. 2020. A review of black carbon in snow and ice and its impact on the cryosphere. *Earth-Science Reviews*, Vol. 210, Article 103346. doi.org/10.1016/j.earscirev.2020.103346.

Kargel, J. S., Upadhyay, K., Maxwell, A., Ramos, A. G. M., Harrison, S., Shugar, D. H. and Haritashya, U. K. 2021. Part I: Climate Change, Land Use Change, and Mountain Disasters. Georgetown Journal of International Affairs website. https://gjia.georgetown.edu/2021/08/23/part-i-climate-change-land-use-change-and-mountain-disasters/.

Langer, M., Schneider von Deimling, T., Westermann, S., Rolph, R., Rutte, R., Antonova, S., Rachold, V., Schultz, M., Oehme, A. and Grosse, G. 2023. Thawing permafrost poses environmental threat to thousands of sites with legacy industrial contamination. *Nature Communications*, Vol. 14, Article 1721. doi.org/10.1038/s41467-023-37276-4.

Lavorel, S., Colloff, M. J., Locatelli, B., Gorddard, R., Prober, S. M., Gabillet, M., Devaux, C., Laforgue, D. and Peyrache-Gadeau, V. 2019. Mustering the power of ecosystems for adaptation to climate change. *Environmental Science & Policy*, Vol. 92, pp. 87–97. doi.org/10.1016/j.envsci.2018.11.010.

Luan, W. and Li, X. 2021. Rapid urbanization and its driving mechanism in the Pan-Third Pole region. *Science of the Total Environment*, Vol. 750, Article 141270. doi.org/10.1016/j.scitotenv.2020.141270.

Lutz, S., Anesio, A. M., Field, K. and Benning, L. G. 2015. Integrated 'omics', targeted metabolite and single-cell analyses of Arctic snow algae functionality and adaptability. *Frontiers in Microbiology*, Vol. 6, Article 1323. doi.org/10.3389/fmicb.2015.01323.

Machate, O., Schmeller, D. S., Schulze, T. and Brack, W. 2023. Review: Mountain lakes as freshwater resources at risk from chemical pollution. *Environmental Sciences Europe*, Vol. 35, Article 3. doi.org/10.1186/s12302-022-00710-3.

Meredith, M., Sommerkorn, M., Cassotta, S., Derksen, C., Ekaykin, A., Hollowed, A., Kofinas, G., Mackintosh, A., Melbourne-Thomas, J., Muelbert, M. M. C., Ottersen, G., Pritchard, H. and Schuur, E. A. G. 2019. Polar regions. H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds), *The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK/New York, Cambridge University Press, pp. 203–320. doi.org/10.1017/9781009157964.005.

Mikuś, P., Wyżga, B., Bylak, A., Kukuła, K., Liro, M., Oglęcki, P. and Radecki-Pawlik, A. 2021. Impact of the restoration of an incised mountain stream on habitats, aquatic fauna and ecological stream quality. *Ecological Engineering*, Vol. 170, Article 106365. doi.org/10.1016/j.ecoleng.2021.106365.

Orr, B. J., Cowie, A. L., Castillo Sánchez, V. M., Chasek, P., Crossman, N. D., Erlewein, A., Louwagie, G., Maron, M., Metternicht, G. I., Minelli, S., Tengberg, A. E., Walter, S. and Welton, S. 2017. *Scientific Conceptual Framework for Land Degradation Neutrality. A Report of the Science-Policy Interface*. Bonn, Germany, United Nations Convention to Combat Desertification (UNCCD). www.unccd.int/resources/reports/scientific-conceptual-framework-land-degradation-neutrality-report-science-policy.

Orr, B. J., Dosdogru, F. and Sánchez Santiváñez, M. 2024. Land degradation and drought in mountains. S. Schneiderbauer, P. Fontanella Pisa, J. F. Shroder and J. Szarzynski (eds), *Safeguarding Mountain Social-Ecological Systems*. Elsevier, pp. 17–22. doi.org/10.1016/B978-0-12-822095-5.00003-6.

Palomo, I., Locatelli, B., Otero, I., Colloff, M., Crouzat, E., Cuni-Sánchez, A., Gómez-Baggethun, E., González-García, A., Grêt-Regamey, A., Jiménez-Aceituno, A., Martín-López, B., Pascual, U., Zafra-Calvo, N., Bruley, E., Fischborn, M., Metz, R. and Lavorel, S. 2021. Assessing nature-based solutions for transformative change. *One Earth*, Vol. 4, No. 5, pp. 730–741. doi.org/10.1016/j.oneear.2021.04.013.

Pintaldi, E., Hudek, C., Stanchi, S., Spiegelberger, T., Rivella, E. and Freppaz, M. 2017. Sustainable soil management in ski areas: Threats and challenges. *Sustainability*, Vol. 9, No. 11, Article 2150. doi.org/10.3390/su9112150.

Repe, A. N., Poljanec, A. and Vrščaj, B. (eds). 2020. *Soil Management Practices in the Alps: A Selection of Good Practices for the Sustainable Soil Management in the Alps*. Ljubljana, EU Interreg Alpine Space. www.alpine-space.eu/wp-content/uploads/2022/06/46-1-links4soils-Soil%20Management%20Practices%20in%20the%20Alps%20-%20a%20collection-output.pdf.

Scheidl, C., Heiser, M., Kamper, S., Thaler, T., Klebinder, K., Nagl, F., Lechner, V., Markart, G., Rammer, W. and Seidl, R. 2020. The influence of climate change and canopy disturbances on landslide susceptibility in headwater catchments. *Science of the Total Environment*, Vol. 742, Article 140588. doi.org/10.1016/j.scitotenv.2020.140588.

Shah, N. W., Baillie, B. R., Bishop, K., Ferraz, S., Högbom, L. and Nettles, J. 2022. The effects of forest management on water quality. *Forest Ecology and Management*, Vol. 522, Article 120397. doi.org/10.1016/j.foreco.2022.120397.

Swiderska, K., King-Okumu, C. and Monirul Islam, M. 2018. *Ecosystem-Based Adaptation: A Handbook for EbA in Mountain, Dryland and Coastal Ecosystems*. London, International Institute for Environment and Development (IIED). www.iied.org/17460iied.

Teich, M., Accastello, C., Perzl, F. and Berger, F. 2022. Protective forests for ecosystem-based disaster risk reduction (Eco-DRR) in the alpine space. M. Teich, C. Accastello, F. Perzl and K. Kleemayr (eds), *Protective Forests as Ecosystem-based Solution for Disaster Risk Reduction (Eco-DRR)*. IntechOpen. doi.org/10.5772/intechopen.99505.

Tingley III, R. W., Paukert, C., Sass, G. G., Jacobson, P. C., Hansen, G. J. A., Lynch, A. J. and Shannon, P. D. 2019. Adapting to climate change: Guidance for the management of inland glacial lake fisheries. *Lake and Reservoir Management*, Vol. 35, No. 4, pp. 435–452. doi.org/10.1080/10402381.2019.1678535.

Torres, M. C., Naranjo, E., Fierro, V. and Carchipulla-Morales, D. 2023. Social technology for the protection of the *Páramo* in the Central Andes of Ecuador. *Mountain Research and Development*, Vol. 43, No. 4, pp. D1–D11. doi.org/10.1659/mrd.2022.00022.

UNEP (United Nations Environment Programme). 2021a. *Adaptation Gap Report 2020*. Nairobi, UNEP. www.unep.org/resources/adaptation-gap-report-2020.

—. 2021b. *Mountain Resilience: Torrent Catchment Restoration in the Pamir Mountains of Afghanistan*. UNEP. https://wedocs.unep.org/handle/20.500.11822/39982.

—. 2022a. *A Scientific Assessment of the Third Pole Environment*. Nairobi, UNEP. www.unep.org/resources/report/scientific-assessment-third-pole-environment.

—. 2022b. *Global Peatlands Assessment – The State of the World's Peatlands: Evidence for Action toward the Conservation, Restoration, and Sustainable Management of Peatlands*. Main report. Global Peatlands Initiative. Nairobi, UNEP. www.unep.org/resources/global-peatlands-assessment-2022.

—. 2024. *Caucasus Environment Outlook*. Second edition. Arendal, Norway/Tbilisi/Vienna, UNEP. www.unep.org/resources/report/caucasus-environment-outlook-second-edition.

UNEP/GRID-Arendal (United Nations Environment Programme/GRID-Arendal). 2022. *Mountains ADAPT: Solutions from the South Caucasus*. Nairobi, UNEP. https://wedocs.unep.org/xmlui/handle/20.500.11822/39788#:~:text=This%20booklet%20showcases%20adaptation.

Wang, H., Wang, W. J., Liu, Z., Wang, L., Zhang, W., Zou, Y. and Jiang, M. 2022. Combined effects of multi-land use decisions and climate change on water-related ecosystem services in Northeast China. *Journal of Environmental Management*, Vol. 315, Article 115131. doi.org/10.1016/j.jenvman.2022.115131.

WWAP/UN-Water (United Nations World Water Assessment Programme/UN-Water). 2018. *The United Nations World Water Development Report 2018: Nature-Based Solutions for Water*. Paris, United Nations Educational, Scientific and Cultural Organization (UNESCO). https://unesdoc.unesco.org/ark:/48223/pf0000261424.

Xiao, Y., Xiao, Q. and Sun, X. 2020. Ecological risks arising from the impact of large-scale afforestation on the regional water supply balance in Southwest China. *Scientific Reports*, Vol. 10, Article 4150. doi.org/10.1038/s41598-020-61108-w.

Chapter 7

Regional perspectives

7.1 Sub-Saharan Africa

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7.1 Sub-Saharan Africa

Africa accounts for 11% of the global mountain area, covering an area of around 1.5 million km^2 (Alweny et al., 2014). Of continental Africa's land area, 20% is classified as mountains with an elevation over 1,000 metres above sea level (masl), with 5% rising over 1,500 masl (FAO, 2015). East Africa is the most mountainous region in Africa. The mountains are characterized by high levels of biodiversity; they provide ecosystem services, including water resources, to millions of people (Capitani et al., 2019; Trisos et al., 2022). In tropical and subtropical Sub-Saharan Africa, mountains have favourable environmental conditions and resources compared with the generally drier surrounding lowlands. Mountains are important areas of agricultural production to support food security (Romeo et al., 2020).

This section on Sub-Saharan Africa comprises four parts. The first introduces the water towers in the region, including the hydrological significance to mountain communities and downstream users. The next discusses the challenges to the sustainability of water towers to store and supply water, including human impacts and climate change. An overview of management approaches and responses is then provided, highlighting the importance of mountain forest ecosystems to the sustainability of water towers. These are followed by conclusions for the region.

The mountains of Sub-Saharan Africa are a critical source of water for mountain communities and downstream users

7.1.1 Sub-Saharan Africa's water towers

The mountains of Sub-Saharan Africa (Figure 7.1) are a critical source of water for mountain communities and downstream users. Within a continent dominated by arid and semi-arid land areas, the mountains act as water towers – generating, storing and supplying water for agriculture, domestic and industrial requirements, including hydropower (Viviroli et al., 2007; 2020; UNEP, 2010; Nsengiyumva, 2019). The mountains are critical for water, food and energy security across the region.

Orographic rainfall provides Africa's mountains with high levels of water. This results in surface runoff, infiltration, groundwater flow and storage, or water stored seasonally or over many years as snow and ice (WMO, 2024a). Water is stored as glaciers within the mountains of East Africa, within the Democratic Republic of the Congo, Kenya, Uganda and the United Republic of Tanzania. Prior to 2019, these glaciers covered an estimated area of 4.4 km^2 (Veettil and Kamp, 2019), providing seasonal runoff to downstream catchments. Within Southern Africa, seasonal snowfall occurs on the summits of the Drakensburg Mountains bordering Lesotho and South Africa (Taylor et al., 2016). Through surface runoff, infiltration and groundwater flow, water is delivered from the mountains to the downstream lowlands.

African water towers are a critically important source for the transboundary rivers and basins of the Congo, Niger, Nile, Orange, Senegal, Tana and Zambezi Rivers. Within East Africa, the Ethiopian Highlands supply water to the Blue Nile, which makes a significant contribution to the annual flow of the River Nile (Awange, 2022). In West Africa, the Fouta Djallon Plateau is an important source for the Gambia, Niger and Senegal Rivers (Descroix et al., 2020). The Jos Plateau supplies numerous rivers including the Benue, Gongola, Niger and other rivers that discharge into Lake Chad. In Southern Africa, the Lesotho Highlands including the Drakensberg Mountains are a critical source of water (UNEP, 2012). The Angolan plateau is the primary source of the Okavango Delta (Lourenco and Woodborne, 2023). The water towers of Africa are also important for water resources in the lowlands, serving a variety of users. For instance, agricultural production and food security within mountain regions and downstream lowlands are critically dependent on mountain waters and the ecosystems that provide these services (Box 7.1).

Figure 7.1
Water towers in Africa

Note: In this index map, colour coding is related to topographic height, with brown and yellow at the lower elevations, rising through green, to white at the highest elevations. Blue areas on the map represent water within the mapped tiles, each of which includes shorelines or islands.

Source: JPL (2004).

7.1.2 Challenges

The capacity of Sub-Saharan Africa's water towers to accumulate, store and supply water to downstream users and mountain communities faces numerous challenges, particularly from intensification of human activities and the impacts of climate change.

There are high population growth rates and density in the mountains of the region, with widespread poverty and a lack of alternative and resilient livelihoods. As of 2017, Africa's mountains were home to an estimated 252 million people – 18% of the continent's population[15] – representing 23% of the global mountain population. Africa remains the second most populous mountain continent after Asia. In many areas, the mountains are more densely populated than the lowlands.

In 2017, an estimated 132 million rural mountain people were vulnerable to food insecurity in Africa, equating to two of out of every three rural people. This represents the highest proportion of all continental mountain regions globally (Romeo et al., 2020).

[15] Of the 18 million people living above 2,500 m in Africa in 2017, 17 million were in the highlands of Eastern Africa (Romeo et al., 2020).

Box 7.1 The importance of Madagascar's water towers for agriculture

While agriculture only accounts for roughly 20% of Madagascar's gross domestic product (World Bank, n.d.), approximately 80% of the population is engaged in agriculture (World Bank, 2023) for income and/or subsistence purposes. Approximately 2.5 million farms, of which smallholders represent the large majority, are dependent on continuous irrigation of rice and other crops (IFAD, n.d.).

In the eastern and northern parts of the island, several mountain peaks exceed 2,000 metres above sea level (masl) (Chaperon et al., 1993). The forested upper reaches of these mountains absorb seasonal rainfall and slowly release it into the watershed, supporting lowland agriculturists and urban settlements.

Located in the Tsaratanana reserve, Mount Maromokotro (2,876 masl) is the source of several major rivers. The Sambirano River irrigates areas to the west for cacao, rice and fruit production, including some of the more important agricultural exports of this island nation. The Sofia River forms a large watershed and is critical for agriculturists. The isolated Massif of Montagne d'Ambre, a protected area in the far north, is the main source of potable water for close to 200,000 people living in Antsiranana (Goodman et al., 2021) and for agriculture in the surrounding area.

Protected forested zones provide local buffers against the destructive impacts of cyclones and other natural hazards. Nevertheless, from 2001 to 2023, Madagascar's tree cover decreased by 29% (Global Forest Watch, n.d.). Changes in climate and land use (exacerbated by demographic growth) threaten the future of the country's forest resources and their biodiversity, which require further protection and conservation initiatives.

The degradation of mountain ecosystems reduces their ability to store and supply water downstream. This is particularly the case with deforestation of critically important montane forests. Land (soil) degradation through inappropriate land use and agricultural practices, including the impact of livestock overgrazing, is also detrimental (Ariza et al., 2013; Romeo et al., 2020). Large-scale and unsustainable mining has accelerated land degradation and ecosystem loss. Of the rural mountain people vulnerable to food insecurity in Africa in 2017, 86 million lived in areas characterized by land degradation detrimentally affecting agriculture-based livelihoods (Romeo et al., 2020). The absence of comprehensive hydrometeorological monitoring and data significantly hinders the understanding and urgency to restore forested areas to their primary state.

Climate change impacts exacerbate the challenge of managing Sub-Saharan Africa's seasonal rainfall variability (Trisos et al., 2022; WMO, 2022). Projections for the continent, including mountain regions, indicate increasing rainfall variability at the annual and intra-annual timescales, temperature rises and glacial melt. Extreme hydrological variability is projected to progressively amplify under all climate change scenarios (Trisos et al., 2022). By 2050, up to 921 million people in Sub-Saharan Africa could be exposed to water stress related to climate change (Dickerson et al., 2021). Floods, droughts and other natural hazards are expected to increase, within mountains in the region and also downstream of them. Furthermore, landslide frequency shows increasing trends in the mountain regions of Africa (Adler et al., 2022). Evidence suggests that disasters due to droughts, pests and changes in rainfall patterns have negative impacts on smallholder farmers' agricultural livelihoods (Shikuku et al., 2017).

Glacial melt has been observed in the mountains of East Africa (Trisos et al., 2022), with an estimated 80% loss in mass between 1990 and 2015 (EAC/UNEP/GRID-Arendal, 2016). For example, the total glacial area on Mount Kenya decreased by 44% during 2004–2016 (Prinz et al., 2016), that on Mount Kilimanjaro decreased from 4.8 km^2 in 1984 to 1.7 km^2 in 2011 (Cullen et al., 2013) and that in the Rwenzori Mountains decreased from ~2 km^2 in 1987 to

~1 km^2 in 2003 (Taylor et al., 2016). Declining glacial area is linked to rising air temperatures, and in the case of Mount Kenya and Mount Kilimanjaro, it is linked to declining rainfall and atmospheric moisture (Veettil and Kamp, 2019). Glaciers are projected to disappear before 2030 on Mount Kenya and the Rwenzori Mountains, and by 2040 on Mount Kilimanjaro (Trisos et al., 2022).

The impact of glacier disappearance on water resources in East Africa has been predicted to be minimal (Taylor et al., 2009; Adhikari et al., 2015; Veettil and Kamp, 2019) at the regional (macro) scale, as water from glaciers contributes relatively little to total river flows. For instance, in the Rwenzori Mountains between the Democratic Republic of the Congo and Uganda, glaciers have contributed less than 2% to the total discharge of the principal rivers during the dry and wet seasons (Taylor et al., 2009). However, localized seasonal impacts on water resources have been observed. For instance, around Mount Kilimanjaro, many canals in the foothills have dried up and the water levels of streams have been decreasing, leading to local conflicts over access to water (Gagné et al., 2014).

The timing and levels of rainfall delivered to mountains are of critical importance to the sustainability of Sub-Saharan African water towers

The timing and levels of rainfall delivered to mountains are of critical importance to the sustainability of Sub-Saharan African water towers. Rainfall is stored in and supplied from the mountains, as surface water runoff, river and groundwater flow to lowlands downstream. Within a regional context, rainfall is of more volumetric significance than glacial melt to downstream river flow in East Africa. Of the few studies that have examined rainfall projections specifically for mountain areas, East Africa is projected to receive 5–20% additional annual rainfall over the 21st century, albeit at medium confidence (Adler et al., 2022). Otherwise, across the rest of the continent, rainfall projections under climate change scenarios predict increasing annual and intra-annual variability, differing with each subregion (Trisos et al., 2022).

One study has examined how climate change (through rainfall variability) and land use generate water runoff in nine water towers of East Africa. Results indicated that water runoff is more sensitive to climate change (rainfall) than land-use change. However, for the surrounding downstream lowlands areas, the effects of land-use change had greater impacts on water runoff than climate change. East African water towers have seen a strong shift towards wetter conditions, especially in the period 2011–2019, whereas the potential evapotranspiration has gradually increased. Considering that most of the water towers were identified as being non-resilient to these changes, future water runoff is likely to also experience more extreme variations (Wamucii et al., 2021).

7.1.3 Responses

Many responses have been advocated to promote sustainable water management in the mountains, in response to climate change and also the intensification of human activities (Adler et al., 2022; Trisos et al., 2022).

Considering farming is the principal livelihood in the mountains of Sub-Saharan Africa, improving agricultural practices to reduce land degradation (soil conservation) is of critical importance (Romeo et al., 2020). Promoting ecosystem-based adaptation (EbA) (e.g. reforestation and conservation of montane forests reducing soil erosion) can enhance water retention and aquifer recharge and diminish the risk of hazards (Alweny et al., 2014; Nsengiyumva, 2019).

Considering the high proportion of transboundary rivers in Africa supplied by water towers, promoting transboundary cooperation of surface water and groundwater between riparians is an effective strategy to promote equitable benefit-sharing across the continent (United Nations, 2024).

Importance of forest ecosystems to Sub-Saharan Africa water towers

Interest in water towers (globally) has focused on glaciated mountains where temperature is a key factor in determining water runoff from glaciated mountain chains (Immerzeel et al., 2020). Forested mountains and other vegetation such as grass provide similar services (Viviroli and Weingartner, 2004). Mountain forests can capture, store, purify and release water to lowland areas (UNEP, 2014).

The water towers of East Africa have extensive montane forest ecosystems. These include the Albertine Rift, Ethiopian Highlands and Kenyan Highlands (Wamucii et al., 2021). The forests are characterized by high elevation and high humidity, and accumulate, store and supply water for lowland areas (UNEP, 2010). The montane forests mitigate floods and droughts, prevent soil erosion, maintain water quality, increase groundwater infiltration and influence the microclimate in and surrounding the forests (Mwangi et al., 2020).

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Climate change is projected to amplify the historically high seasonal rainfall variability across Sub-Saharan Africa

The water towers of Kenya are characterized by montane forests in the upper catchments of the Aberdare Range, Cherangani Hills, Mau Forest Complex, Mount Elgon and Mount Kenya. They are invaluable natural resources that support the country's water supply, energy production, agrarian-based economy, and biodiversity preservation and conservation (Kiplagat et al., 2011; Nyingi et al., 2013; Kanui et al., 2016; Ontumbi and Sanga, 2018; Schmitz, 2020; Takase et al., 2021).

The forested mountains are the sources of many of Kenya's rivers, providing an estimated 75% of the country's water resources utilized for irrigation, industrial requirements and hydropower (generating 60% of Kenya's electricity). However, the forests are being degraded by unplanned human settlements, overgrazing, deforestation and the conversion of forest land to agriculture. For example, the Mau Forest, which is one of Kenya's largest water catchment areas, lost an estimated quarter of its forest cover between 2000 and 2020. Such deforestation threatens the biodiversity within these forests and also disrupts the ecosystem services they provide. The Cherangani Hills and Mount Elgon are also experiencing similar degradation, further compounding the issue (Mwangi et al., 2020).

Efforts to conserve and restore these critical water towers include sustainable forest management practices, reforestation projects and policies that address the underlying causes of deforestation, such as poverty and land tenure issues. Enhancing participation, knowledge transfer and capacity-building of stakeholders, and targeting specific value chains (e.g. maize, tea and livestock) to promote livelihood resilience is also advocated (Mwangi et al., 2020). Engaging local communities (including women, youth and Indigenous Peoples) in conservation efforts and promoting alternative livelihoods can also help reduce the pressure on these forests (Kennedy et al., 2023).

7.1.4 Conclusions

This section has illustrated the importance of Sub-Saharan African water towers for mountain communities and downstream users. The conservation and rehabilitation of forests, soils and other related ecosystems services are critically important for the sustainability of the region's water towers. Climate change is projected to amplify the historically high seasonal rainfall variability across Sub-Saharan Africa. Therefore, mutually beneficial adaptation (including low-risk, low-regrets and autonomous measures) becomes all the more important to adapt to seasonality and to temper human environmental impacts on the mountains, thereby safeguarding the supply from water towers.

7.2 Europe and Central Asia

Mountain ranges are the source of water for many rivers in the region. Alpine snow and glacial melt ensure a slow release of water to downstream areas. However, climate change is leading to earlier seasonal snow-melt and reduced glaciers, thereby threatening the availability of water in the summer season. This has serious consequences for populations in downstream basins.

For example, the Colorado River in North America, which serves about 40 million people, gets most of its water from snowfall in the Rocky Mountains. Already stressed by overextraction, the river basin has been in drought since 2000. The situation may be exacerbated by warmer temperatures, which are causing more precipitation to fall as rain, which runs off more quickly than mountain snow (Robbins, 2019).

Mountains are socially and ecologically important areas. They are subject to many anthropogenic influences that also affect the hydrology of the area and, consequently, the availability of water downstream. Action is therefore needed to prevent further degradation of mountains, to preserve their social and ecological value as well as their function as water towers. As mountain ranges cover multiple countries, cooperation between the countries is needed to ensure proper management. The following describes these issues for some example mountain ranges within the United Nations Economic Commission for Europe region.[16]

7.2.1 The Alps

The Alps span eight countries: Austria, France, Germany, Italy, Liechtenstein, Monaco, Slovenia and Switzerland, and feed four major rivers: Danube, Po, Rhine and Rhône (Figure 7.2). Water from the Alps is vitally important to large parts of Europe (Permanent Secretariat of the Alpine Convention, 2009a).

Water from the Alps is vitally important to large parts of Europe

Alpine ecosystems and biodiversity are important for healthy water resources. Changes in land use are leading to smaller and more fragmented habitats, while climate change is putting pressure on natural landscapes, resulting in habitat degradation and species loss, thereby putting pressure on the water resources (Permanent Secretariat of the Alpine Convention, 2009a). The effects of climate change on the cryosphere and hydrosphere in the Alps are expected to lead to a decrease in annual river discharge where the runoff from the ice-covered part decreases by 45% and the total runoff decreases by 35% by 2100 relative to 2006. This will have significant downstream impacts on water quantity and quality, affecting hydropower, agriculture, forestry, tourism and aquatic ecosystems (Laurent et al., 2020).

Hydropower generation is the main reason for water abstraction in the Alps. Other uses include industrial purposes, agricultural irrigation and snow-making. These activities entail morphological alterations and, as a result, 16 out of 50 water bodies will possibly not achieve good ecological status in 2027 (Permanent Secretariat of the Alpine Convention, 2009b).

Integrated risk management and early detection of potential hazards related to climate change, such as avalanches, floods, mudflows and landslides, should be supported and promoted. Artificial snow-making can be an important adaptation strategy to enhance winter tourism and reduce glacier melt, but it can lead to user conflicts between the operators of snow-making systems and households and other water users. Artificial snow-making should be avoided, especially in ecologically sensitive and endangered habitats. Locally, insulating blankets have been used to reduce glacier melt (Box 7.2) (Permanent Secretariat of the Alpine Convention, 2009a; Jorio and Reusser, 2019).

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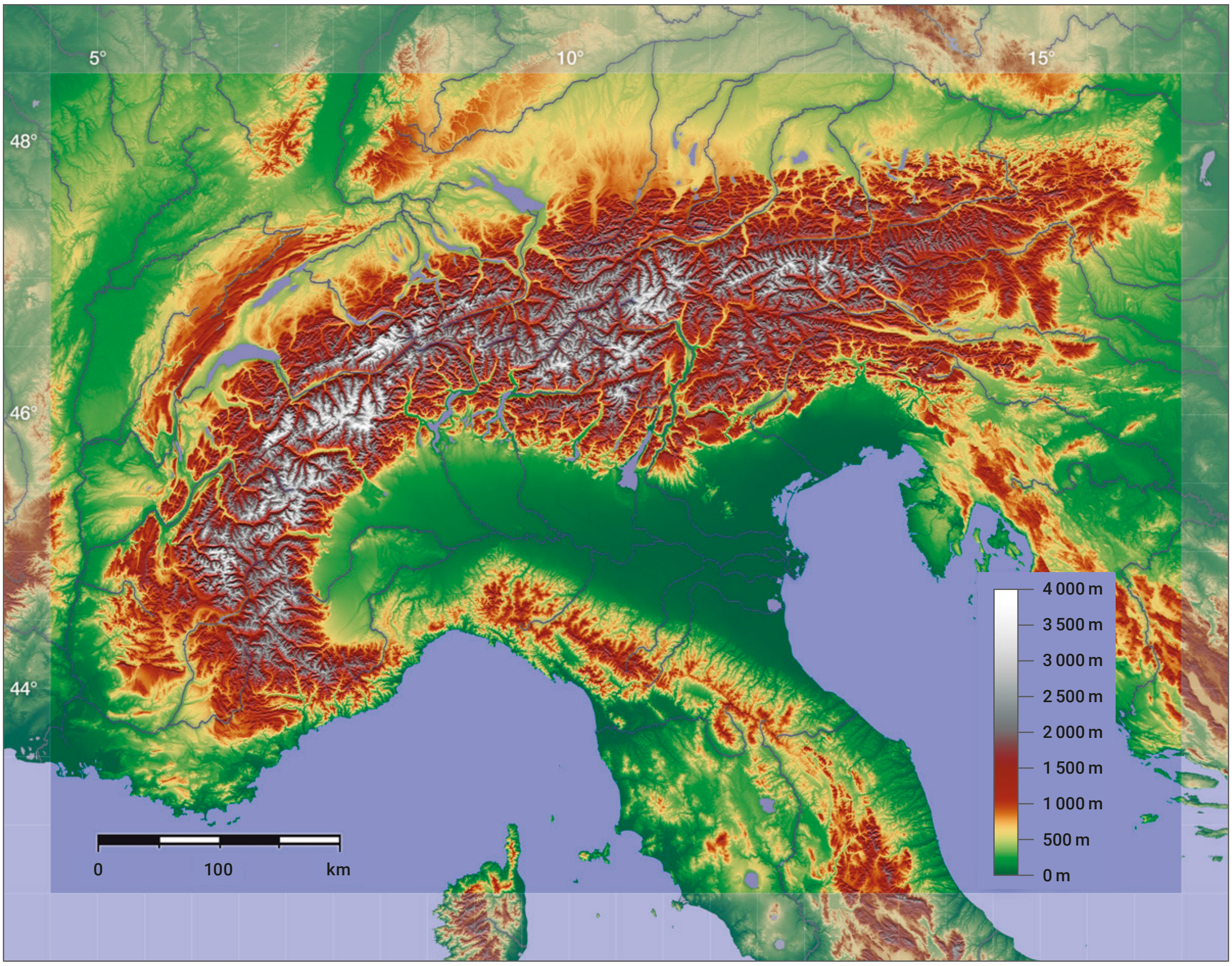
[16] The United Nations Economic Commission for Europe includes 56 Member States in Europe, North America and Asia (https://unece.org/member-states).

Figure 7.2 Topographical map of the Alps



Source: Ghosh (2021).

The Alpine Convention between the eight countries of the Alps was adopted in 1991, with the aim of sustainable development and protection of the entire mountain range. Reports on the state of the Alps are published periodically, to actively contribute to the discussion on the ecological, economic and social development of the Alps. For the seventh report, the Natural Hazards Platform of the Alpine Convention prepared a status quo analysis and recommendations for the improvement of risk governance to examine changes in the way society deals with natural hazards. Natural hazards such as rockfalls, glacier tongue destabilization, glacial lake outburst floods (GLOFs) and rock-ice avalanches associated with glacier and permafrost retreat (see Section 2.2.3) are expected to increase in frequency (Permanent Secretariat of the Alpine Convention, 2019). The Alpine Convention has also developed the Climate Action Plan 2.0 to achieve climate-neutral and climate-resilient Alps by 2050 as an important way to protect the mountain environment and reduce glacier melt (Permanent Secretariat of the Alpine Convention, 2022).

The International Commission for the Protection of the Rhine, through the International Commission for the Hydrology of the Rhine basin, is monitoring the glaciers that feed the Rhine River. In its work to update its climate change adaptation strategy, the International Commission for the Protection of the Rhine notes that the proportion of snow and glacier meltwater that stabilizes the flow of the Rhine during low water is expected to decrease as a result of climate change, and that there is therefore a need to restore natural water systems such as forests, wetlands and floodplains on the Rhine and in its catchment area (CHR, 2022; ICPR, 2022).

Box 7.2 Protecting glaciers with insulating blankets

For over ten years, the Rhône glacier in Valais, Switzerland, has been covered in white sheets designed to protect it from the Sun's rays. The goal is to preserve the ice grotto, one of the Alps' great tourist attractions. This approach is useful on a small scale where the aim is to slow melting at a local level for economic reasons. It is not designed to save a whole glacier. The costs would soon exceed the economic benefits. It is estimated it would take between €10 million and €100 million a year to cover the entire glacier (Jorio and Reusser, 2019).

Protective canvases on the Rhône glacier

Photo: © Zoltan Major/Shutterstock.*

The Carpathian Mountains are home to approximately 30% of European flora

7.2.2 The Carpathians

The Carpathian Mountain region is shared by Czechia, Hungary, Poland, Romania, Serbia, Slovakia and Ukraine. The Carpathian Mountains are home to approximately 30% of European flora and to Europe's largest populations of brown bear, wolf, lynx, European bison and rare bird species. The semi-natural habitats such as mountain pastures and hay meadows are of great ecological and cultural importance. The Carpathian Mountain region provides important ecosystem goods and services such as food, fresh water, forest products and tourism. The region drains into three major river basins: the Danube and the Dniester, which flow to the Black Sea, and the Vistula, which flows to the Baltic Sea (UNEP, 2023a; Climate-ADAPT, 2024).

Land abandonment, habitat conversion and fragmentation, deforestation, and unsustainable forestry and agriculture practices lead to increased runoff and erosion, and threaten biodiversity in the mountains. Agriculture is the main source of surface water and groundwater pollution (Climate-ADAPT, 2024). Climate change is leading to higher temperatures and an increase in the frequency and intensity of summer heatwaves. Precipitation patterns are predicted to change, with less rainfall in summer leading to reduced river flows and increased water scarcity, and more intense, short-duration rainfall with an increased risk of flooding, erosion and landslides affecting livelihoods and settlements. Snow seasons will become shorter, threatening local winter tourism, but extending the growing season for agriculture. Earlier snow-melt will reduce river flows, summer drinking water supplies and groundwater recharge, and will increase the risk of wildfires (Alberton et al., 2017).

The Russian Federation's full-scale invasion of Ukraine has dramatically affected the Carpathian region. It is putting significant pressure on natural resources, through pollution from the destruction of infrastructure (e.g. discharge of petroleum products into the Dniester and Vistula basins due to military attacks on oil depots and electricity stations (Shumilova et al., 2023; Dniester Basin Management Authority, 2024; Western Bug and Sian River Basin Management Authority, unpublished)). Forests are also affected by increased fuelwood consumption due to disruptions in the supply of liquid fuels and electricity, which increases flood risk. The war also poses major challenges to the management of protected areas, through, for example, a considerable reduction in funding for conservation and a reduction in personnel due to military mobilization (Ministry of Climate and Environment of Poland, 2022; UNEP, 2022a).

Increasing the integration between land-use and water management is required to the ensure the sustainability of natural resources. This includes protecting ecosystems, paying more attention to water retention in soils and water storage, rainwater harvesting, preventing surface erosion especially on agricultural land, preventing forest degradation and adapting the management of existing water infrastructure. Prevention of and preparedness for floods and landslides is also needed, including the development of flood maps and integrated hazard zone maps. The Carpathian countries have included many of these measures in their national environmental strategies (Alberton et al., 2017).

The Central Asian mountains are a major source of fresh water for hydropower, irrigation, drinking water and industrial production

The Framework Convention on the Protection and Sustainable Development of the Carpathians (Carpathian Convention) – a multinational environmental agreement between the seven Carpathian countries that entered into force in 2003 – aims to protect the natural and cultural heritage of the Carpathian region while promoting sustainable development. Local stakeholders and community representatives can participate in the Convention meetings as observers. They are also engaged through the so-called Carpathian Day, which is organized in conjunction with the Conference of the Parties to the Carpathian Convention. For instance, the Convention has led to the establishment of a transboundary Ramsar site in the Đerdap gorge (Iron Gate) National Park and improved protection of mountain forests. Climate adaptation is also being mainstreamed into other policy areas such as land-use management, agriculture and tourism (UNEP, 2023a; Climate-ADAPT, 2024).

The Carpathian Convention also works closely with the International Commission for the Protection of the Danube River (ICPDR, 2014). For example, the Danube Climate Adaptation Study (Ludwig-Maximilians-Universität of Munich, 2018) includes the impacts of climate change in the Carpathians, and the Danube Flood Risk Management Plan (ICPDR, 2021) includes flood risk management measures in the Carpathians that are then translated into practices for implementation by countries on the national level.

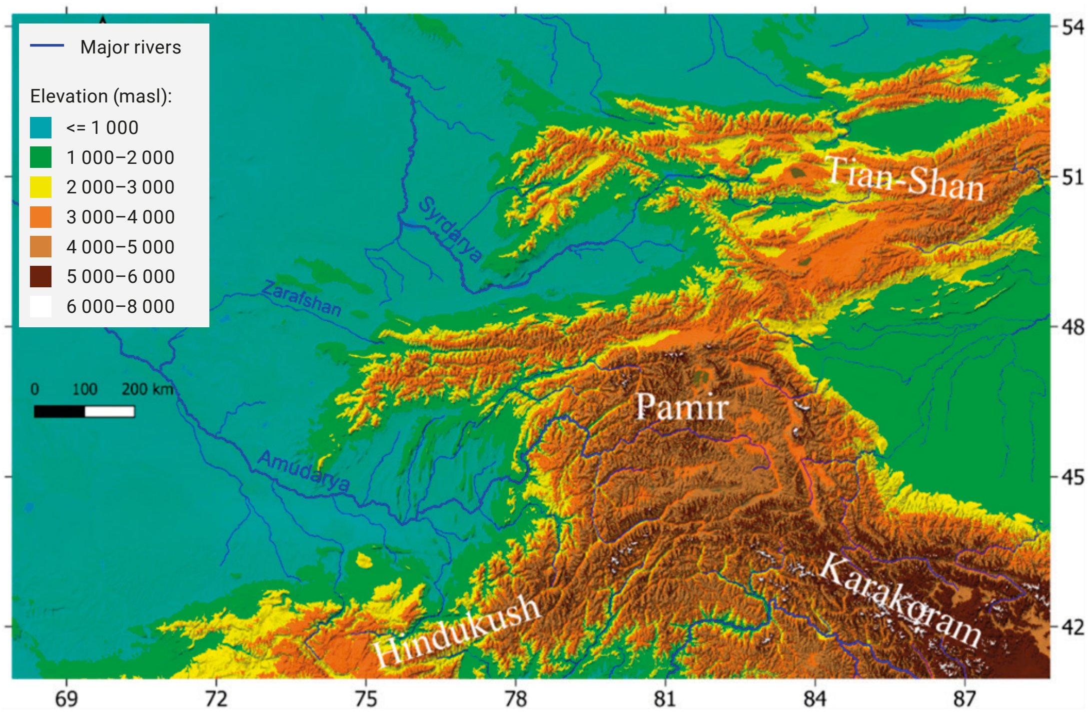
The Carpathian dimension is also well reflected in the activities of the Commission on Sustainable Use and Protection of the Dniester River Basin (Dniester Commission). For instance, its Working Group on Ecosystems and Biodiversity dedicates particular attention to the Carpathian region through taking measures for conserving and increasing forest resources and small rivers to improve water storage (Dniester Commission, 2024a). And its Working Group on Emergencies has identified a few priority areas in the Carpathians and performed flood risk modelling and mapping followed by development of the flood risk management plans according to the European Union Floods Directive (2007/60/EC) on the assessment and management of flood risks (Dniester Commission, 2024b).

7.2.3 Central Asia

The mountains of Central Asia include the Pamir and Tian Shan ranges, which cover parts of Afghanistan, China, Kazakhstan, Kyrgyzstan, Tajikistan and Uzbekistan (Figure 7.3), and the Karakoram range spanning China, India and Pakistan. These mountains contain glaciers; they are fragile ecosystems and are valuable for the social and cultural identity of their inhabitants. The Tian Shan range is known as the water tower of Central Asia. The Central Asian mountains are a major source of fresh water for hydropower, irrigation, drinking water and industrial production. The Aral Sea basin, which covers much of the area, is home to over 60 million people. Agriculture accounts for up to 90% of total water abstraction in that basin (Alford et al., 2015).

Kyrgyzstan and Tajikistan rely heavily on hydropower: nearly 90% of their electricity comes from hydroelectric production. These upstream countries experience energy shortages in winter and would like to expand their hydropower production (Zandi, 2023). Downstream countries, such as Kazakhstan, Turkmenistan and Uzbekistan, are largely dependent on water from the mountains for their agricultural production in the summer. For example, 80% of the flow of the Amu Darya and 74% of the flow of the Syr Darya water resources, which together provide 90% of Central Asia's river water, are formed in the mountains of Kyrgyzstan and Tajikistan (Russell, 2018). These conflicting seasonal demands lead to political tensions between the riparian countries (Pohl et al., 2017; CAWater-info, n.d.). Progress in cooperation was made possible by an agreement between Kyrgyzstan and Uzbekistan in 2021, in which the countries agreed on the supply of water in exchange for electricity (Climate Diplomacy, 2022).

Figure 7.3 Tian Shan and Pamir mountain ranges in Central Asia



Note: masl: metres above sea level.

Source: Umirbekov et al. (2022, fig. 1, p. 4).

Mountain ecosystems play a central role in regulating water flow and supply. For instance, vegetated areas like forests retain water and slowly release the water as surface water and groundwater. Clearing of forests can cause serious soil erosion, while the water regulation function of the forest is lost and flood risk may increase (Stecher et al., 2023). Ecosystems in the Central Asian mountains are affected by pollution, habitat fragmentation and degradation, and climate change. The supranational and multidimensional challenges to habitat conservation make it difficult for individual countries to effectively regulate and implement policies (Van der Graaf and Siarova, 2021; Zoï Environment Network, 2022).

To preserve the fragile ecosystems of the mountain areas of the Central Asian region, the Interstate Commission on Sustainable Development of the Central Asian Countries was established in 1994. The Commission aims to expand regional cooperation on the conservation and sustainable use of the mountain areas of Central Asia, in particular by strengthening the institutional framework for such cooperation in mountain ecosystems (Mosello et al., 2023).

Climate change in Central Asia is causing average temperatures to rise, leading to a general melting of glaciers in the region. Average annual precipitation is increasing, but the inter-annual variability of precipitation and related runoff is also increasing, which can lead to floods in winter and hydrological droughts in summer. Increasing variability has put pressure on the operation of hydropower plants, drinking water supplies and agricultural production (UNDP/ENVSEC, 2011; Sorg et al., 2012). Inadequate knowledge and data on natural resources, poor institutional cooperation, fragmented responsibilities and lack of resources delay effective action (GIZ, 2023).

Mountain countries recognize that many of the problems can only be tackled effectively by working together with their neighbours

Technical solutions, such as covering the ice with insulating blankets (Box 7.2), as tested in the Alps, or producing artificial snow to protect the glacier and buffer the runoff, have been proposed to preserve glaciers (Travers, 2023). However, these solutions are generally considered too costly to apply on a large scale, although they may provide temporary local relief (Ruggeri, 2023). In the meantime, the improvement and exchange of knowledge and information, the strengthening of regional cooperation, the strengthening of in-country capacities on the cryosphere and mountain water management, and the raising of awareness and involvement of key stakeholders in developing and implementing action plans are needed (GIZ, 2021; UNESCO, 2022).

The Central Asian Regional Glaciological Centre was established in 2017 to research the impacts of climate change on glaciers, snow and water resources, and to strengthen the coordination of research activities and information exchange in the mountainous region of Central Asia (UNESCO, n.d.). The Commission of the Republic of Kazakhstan and the Kyrgyz Republic on the Use of Water Management Facilities of Intergovernmental Status on Chu and Talas River discusses glaciers within its Working Group on Adaptation to Climate Change and Long-term Programs of Action. Also, the International Fund for Saving the Aral Sea considers glaciers as part of the water resources of the Aral Sea basin (EC IFAS, 2024).

7.2.4 Conclusions

The mountain ranges in this region are home to important ecosystems. They have cultural significance and are important sources of water for surrounding areas. However, they are threatened by demographic trends, energy and agricultural demands, tourism and climate change, which affect mountain water resources and water availability. Strategies and plans to mitigate these problems are being developed at national levels, but there is still a need for a more integrated approach such as linking land-use management with water management and creating incentives for the protection of mountain ecosystems. Mountain countries recognize that many of the problems can only be tackled effectively by working together with their neighbours.

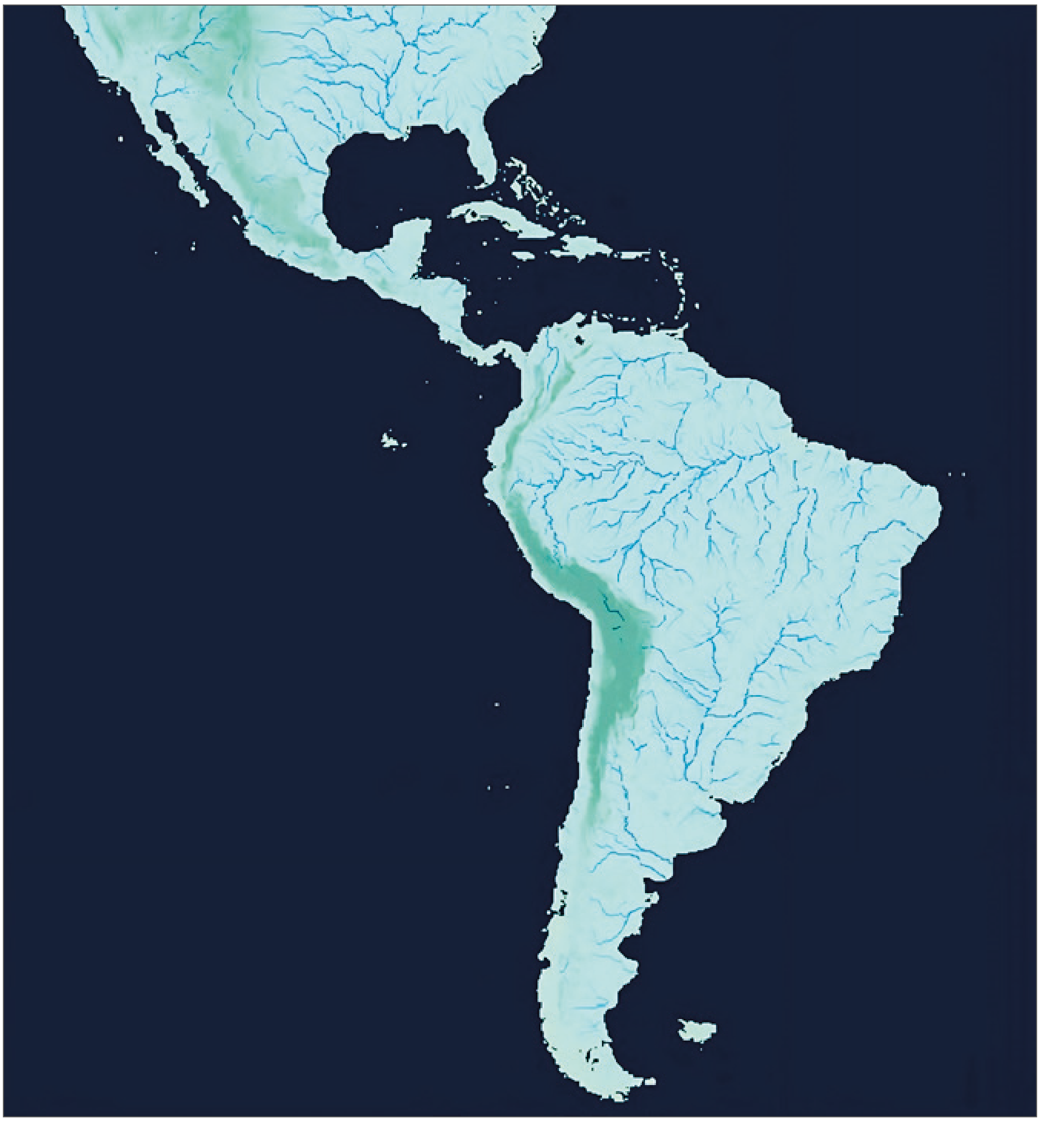
The Carpathian and Alpine Conventions and the Intergovernmental Commission on Central Asia reflect this need for cooperation. In addition, transboundary basin organizations such as the Dniester and Chu-Talas Commissions, the International Commission for the Protection of the Danube River, the International Commission for the Protection of the Rhine and the International Fund for Saving the Aral Sea pay considerable attention to mountains and glaciers in the overall river basin management process, as well as in specific thematic areas of cooperation such as adaptation, conservation, flood management and monitoring. Discussions in these transboundary organizations, where knowledge and experience are also exchanged, help to stimulate activities at the national level.

7.3 Latin America and the Caribbean

Water towers in Latin America and the Caribbean occupy about one-third of the regional territory (FAO, 2000), and produce more water flow per land area than any other continent (Bretas et al., 2020). The mountains of the region include the Sierra Madre in Mexico, the Central American Cordillera, the Sierras and Highlands of the Caribbean, the Brazilian Highlands and the Andes (Figure 7.4) (FAO, 2000). The Andes Mountain range (the longest mountain chain in the world, extending over 7,000 km) is the largest supplier to the region's water flows (FAO, 2000), contributing to 50% of the flow of the Amazon River (Bretas et al., 2020).

As of 2017, approximately 25% (167 million people) of the population in Latin America and the Caribbean lived in mountains, of which 112 million resided in urban areas. Some 17 million people lived in mountain areas often vulnerable to intense climate variability and soil degradation (Romeo et al., 2020).

Figure 7.4
Main mountain ranges and rivers in Latin America and the Caribbean



Note: Darker greens represent elevations over 1,000 m above sea level.

Source: Authors.

Glaciers across the region are experiencing a significant overall reduction in volume (WMO, 2023). Several have disappeared entirely, including the Ventorrillo glacier in Mexico, the Chacaltaya glacier in the Plurinational State of Bolivia (WGMS, 2024) and the Humboldt glacier in the Bolivarian Republic of Venezuela (Reyes Haczek, 2022). According to the Intergovernmental Panel on Climate Change, global warming has caused glacier loss in the Andes, ranging from 30% to 50% of the area since the 1980s, marking one of the most significant declines globally (IPCC, 2022). At the southern end of the Andes, glacial mass loss has been estimated at around 22.9 Gt per year (Dussaillant et al., 2019).

Since the mid-19th century Colombia has lost 90% of its glacial area. This is a concerning trend exemplified by the rapid disappearance of the Sierra Nevada de Santa Marta glacier, which is one of the few glaciers located near the Caribbean Sea (<50 km away). It is a source for over 30 rivers, an irreplaceable site for biodiversity and sacred to the four Indigenous communities settled in the area, consisting of more than 30,000 people (IDEAM, 2021). As the volume of the glacier decreases, the flows that supply drinking water and food to populations are affected, forcing people to move and leave behind their environment, their beliefs and the legacy left by their ancestors. The situation has also been aggravated by social conflicts over land use, where armed groups are controlling land illegally, leaving the Indigenous communities no other choice than to flee (Cajar, 2024).

Climate change and human activities have accelerated deforestation in the Andes, which contain crucial ecosystems for capture of fresh water. For instance, high Andean native forests have reduced to just 3–10% of their original extent, putting Indigenous communities at risk of severe water insecurity (FAO/UNEP, 2023). Similar degradation processes are faced in other mountain areas of the region.

7.3.1 Challenges and interventions for water management

Food and agriculture

Water originating in the mountains is essential for producing high-value agricultural crops like coffee and cocoa in countries such as Brazil, Colombia, Ecuador, Guatemala, Mexico, Peru and the Bolivarian Republic of Venezuela.

Water originating in the mountains is essential for producing high-value agricultural crops like coffee and cocoa

In the Andean region, this water is also crucial for cultivating staple foods like potatoes, corn and quinoa (Wymann von Dach et al., 2014). Andean agriculture represents 3–13% of the national gross domestic product and 7–34% of the employed population in the region (UNECLAC, 2024). Food exports have been estimated to account for 18–54% of total exports (Olmos, 2017). Between 15% and 17% of total cropland within the Andean countries is located within the Andes Mountain range, with the larger proportion of mountain cropland concentrated in the north, in Colombia, Ecuador and Peru (Devenish and Gianella, 2012; Schoolmeester et al., 2018). Changing hydrological conditions in the Bolivian Andes have shrunk the area in which llamas can graze, forcing some farmers to turn to fish farming (UNEP, 2023b). An impact associated with the reduction of Andean glaciers, along with the increase in temperature, the reduction in cold hours and the decrease in water availability, is the effect on the production of winter crops, fruit trees, vineyards and some forest species in Chile and the central western region of Argentina (Magrin et al., 2014).

The community of Cebollullo in La Paz, Plurinational State of Bolivia, relies on water from the Illimani glacier for irrigation. However, climate change has accelerated glacier melt, thereby reducing water availability and disrupting agricultural practices. To address this, farmers have reintroduced an ancient irrigation system using zigzag furrows, which slows water flow and reduces soil erosion (IDB, 2020).

The Phinaya community in Peru depends on alpaca and vicuña fibre and meat. It faces challenges due to rising temperatures above 4,000 masl, leading to drying wetlands, water shortages and disease. A pilot project built dams in small periglacial lagoons, improving water availability for camelids and restoring wetlands and pastures. This has enhanced camelid farming and improved the quantity and quality of alpaca fibre (Canales Sierra, 2018). The melting of glaciers in Peru's Cordillera Blanca has caused seven of the nine basins to cross a critical threshold due to reduction in surface water flow and river discharge during the dry season, exceeding the limits of adaptation[17] (Samaniego et al., 2017).

[17] Thresholds where the goals of an individual or system can no longer be protected through adaptive actions because the adaptive capacity of organisms and communities has been exceeded (Klein et al., 2014). Transformative adaptation offers options and strategies that can be used to reorganize systems when they reach their limits, such as relocating production to cooler areas or diversifying into other crops (Samaniego et al., 2017).

In Guatemala's dry corridor, which crosses the Central American Cordillera, farmers struggle with climate variability, drought periods and increasingly frequent extreme weather events, which disrupt traditional planting schedules. To address these challenges, a programme has been implemented in the departments of Chiquimula, El Progreso and Zacapa, reaching 6,000 farming families across 60 communities. These areas are particularly affected by adverse climatic conditions, socio-economic challenges and limited access to resources. The Participatory Integrated Climate Services for Agriculture programme enhances access to reliable climate information, enabling communities to make informed decisions about their agriculture. More than 5,000 community leaders have been empowered through training workshops to apply this knowledge (Valdivia Araica et al., 2023).

Human settlements

Cities that depend on glacier meltwater for their supply of domestic water have experienced substantial reductions in availability from this source

Cities that depend on glacier meltwater for their supply of domestic water have experienced substantial reductions in availability from this source (IPCC, 2022). For instance, between 1970 and 2010, the area of the glaciers supplying water to Lima diminished by 43% due to rising temperatures causing ice to melt. Consequently, by 2010, the city's potential water availability had reduced to 125 m^3 per inhabitant per year, one of the lowest in the region[18] (González Molina and Vacher, 2014). If the trend of rising temperatures continues, then an acceleration of melting as well as increased runoff in sub-basins may occur (see Box 2.2). Later, when the glacier reservoir is reduced, the contributions of meltwater will be lower (González Molina and Vacher, 2014).

Similarly, Santiago, which relies partially on water from melting ice, has been facing a significant risk due to a megadrought. With a rainfall deficit of 20–40%, there has been a noticeable reduction in snow accumulation, as well as lower reservoir volumes and groundwater levels (Garreaud et al., 2019). This jeopardizes Santiago's water supply, especially during the summer, when up to 70% of the city's water comes from glaciers (Aguas Andinas, 2024).

In Bogotá, approximately 80% of the city's drinking water comes from the Chingaza paramo, while the Sumapaz paramo and the Guerrero complex of paramos contribute 5% and 15%, respectively (Canal Capital, 2023). Notably, the Chingaza system has experienced a significant reduction in its water levels, which have dropped by 85% due to the El Niño phenomenon, a prolonged dry season and high temperatures, causing water rationing in the city of 8 million inhabitants in April 2024 (Ownby, 2024).

To address similar problems in Ecuador, communities in the Central Highlands participated in an ecosystem service payment programme, receiving direct economic incentives (US$30 per hectare per year) supported by the central government through the Socio Páramo programme (Torres et al., 2023). Led by young community members, these communities implemented strategies based on social technology, promoting community participation and local knowledge to protect and restore the paramo. The strategies included designating protected areas for water recharge, reducing grazing and restoring native vegetation, combined with economic incentives and development opportunities. The results showed a slowdown in the rate of paramo loss to 3.3% from the second period (2000–2008) to the third period (2013–2021) based on satellite images. While government involvement has been significant, the effectiveness of paramo protection has been greatest in areas where decisions were made locally, highlighting the importance of community participation in the sustainable management of water resources and resilience to climate change (Torres et al., 2023).

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18 On average, in 2021, the total annual renewable water resources per capita in the Andean countries was 41,090 m^3 (FAO, n.d.).

In Intag, Ecuador, a water and forest conservation project has benefited 38 communities, reaching approximately 7,000 people. The initiative has created community-managed watershed reserves, acquired by a local non-governmental organization and sustainably managed by local groups. This approach has improved water quality, prevented floods and landslides, and promoted ecotourism while reducing emigration. By involving communities in managing these reserves, the project has enhanced their appreciation of conservation efforts and fostered local empowerment (UNDP, 2019; FAO/UNEP, 2023).

Industry and energy

In addition to mountains being a vital source of water, they also generate sustainable energy for cities and smaller communities downstream, as well as remote villages in mountain areas. In Latin America, 85% of hydroelectric power came from mountain sources in 2013 (Mountain Partnership, 2013).

Most countries in the Tropical Andes depend on meltwater from ice and snow to meet the demand for electricity production

Most countries in the Tropical Andes depend on meltwater from ice and snow to meet the demand for electricity production. For instance, around 92% of energy generation in Ecuador comes from hydroelectric power plants (Ministry of Energy and Mines of Ecuador, n.d.). One estimate concerning Canon del Pato (one of Peru's largest hydropower plants) projected that the complete disappearance of glaciers could result in a 15% reduction in the plant's electricity production (UNESCO/IUCN, 2022).

Reduction in precipitation levels also affects hydropower production. Argentina and Chile are expected to experience notable reductions in their hydropower generation between 2020 and 2100, in most scenarios (IEA, 2021). These are mainly due to lower levels of average precipitation (because of climate change) in the central Andes and Patagonia, and the associated reduction in the streamflow across major river basins.

Water-related social conflicts have occurred in high-elevation areas of Andean countries, many of which can be attributed partially to mining activities. Beyond water extraction, mining alters basins to some extent, both on the surface (e.g. removal of soil or vegetation cover, alteration or damming of rivers, removal of glaciers and modification of topography) and below it, which negatively affects the availability of water for downstream users (Altomonte and Sánchez, 2016). In Chile, in the mountain range between Copiapó and Rancagua, by 2010, mining projects had affected 4.5 km^2 of rock glaciers, resulting in an estimated loss of around 24,106 m^3 of fresh water (Bodin, 2019). For comparison, the Juncal Norte glacier (7.6 km^2), located close to Santiago, lost 1.5 km^2 of its area between 1955 and 2006 (Bown et al., 2008).

Environmental protection

Argentina has a specific, ratified law dedicated to glacier protection. Enacted in October 2010 as Law 26.639, titled the Minimum Budget Regime for the Preservation of Glaciers and the Periglacial Environment, its primary aim is to safeguard glaciers as strategic water reserves and biodiversity hotspots, recognizing their value as scientific repositories and tourist attractions. This legislation imposed strict prohibitions, including on the release of toxic pollutants, construction activities, mining, hydrocarbon exploration and industrial installations (Government of Argentina, 2010). Chile is developing initiatives aimed at enacting glacier protection legislation. A bill with approval from the Senate Environment Committee, with explicit provisions for permafrost protection, was presented in 2022 (Commission on Environment and National Assets, 2022).

Certain glaciers and snowy mountain areas receive indirect protection by virtue of their inclusion in designated spaces such as national parks or other protected areas. For instance, in Colombian territory, six glaciers have been safeguarded since 1959 under the status of National Natural Parks, in accordance with the mandates of the Political Constitution of 1991, which designated them as assets for public use, characterized by their inalienable, imprescriptible and unseizable nature – meaning they cannot be transferred, are not subject to expiration and cannot be seized or confiscated (García Pachón, 2018). Similarly, in Ecuador, high-elevation areas with perpetual snowfall are encompassed within various protected areas. A substantial portion of Chilean territory is integrated into the National System of Protected Wild Areas of the State, incorporating numerous glaciers into the designated areas (Ministry of National Assets of Chile, 2023).

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The mountain areas in Latin America and the Caribbean are being increasingly affected by climate change and human activities

Confronted with the changes in the water mass in mountain areas, numerous countries in the region are advancing research and monitoring initiatives to address this pressing issue (see Chapter 8). For instance, the Plurinational State of Bolivia has been actively monitoring glaciers in the basins of the cities of El Alto and La Paz since October 2023 (Ministry of Foreign Affairs of the Plurinational State of Bolivia, 2023). Chile boasts a network of glaciological stations comprising at least 80 monitoring points, facilitating comprehensive assessment of glacier dynamics (Ministry of Public Works of Chile, 2023).

7.3.2 Conclusions

The mountain areas in Latin America and the Caribbean are being increasingly affected by climate change and human activities. These disruptions affect the hydrological cycle, which threatens the livelihood of communities that rely on agriculture. Moreover, these disturbances have far-reaching consequences in lower-lying areas and urban centres that depend on the mountain water sources for drinking water and energy supply.

In response, several countries in the region have enacted policies and laws to protect these critical ecosystems. Some systems have already surpassed critical thresholds, making it crucial to promote adaptive measures such as: (a) implementing nature-based solutions (NbS), including reforestation, (b) adopting and embracing traditional practices, such as water harvesting and sowing techniques widely employed by Indigenous communities in the region, (c) pursuing transformative adaptation strategies to meet water demands for crops and secure livelihoods and (d) expanding water collection infrastructures.

To implement these measures effectively, well-targeted funding, robust monitoring, capacity-building and inclusive governance frameworks are needed, fostering dialogue and inclusion of local communities to apply the best available practices adapted to local contexts in the mountain regions.

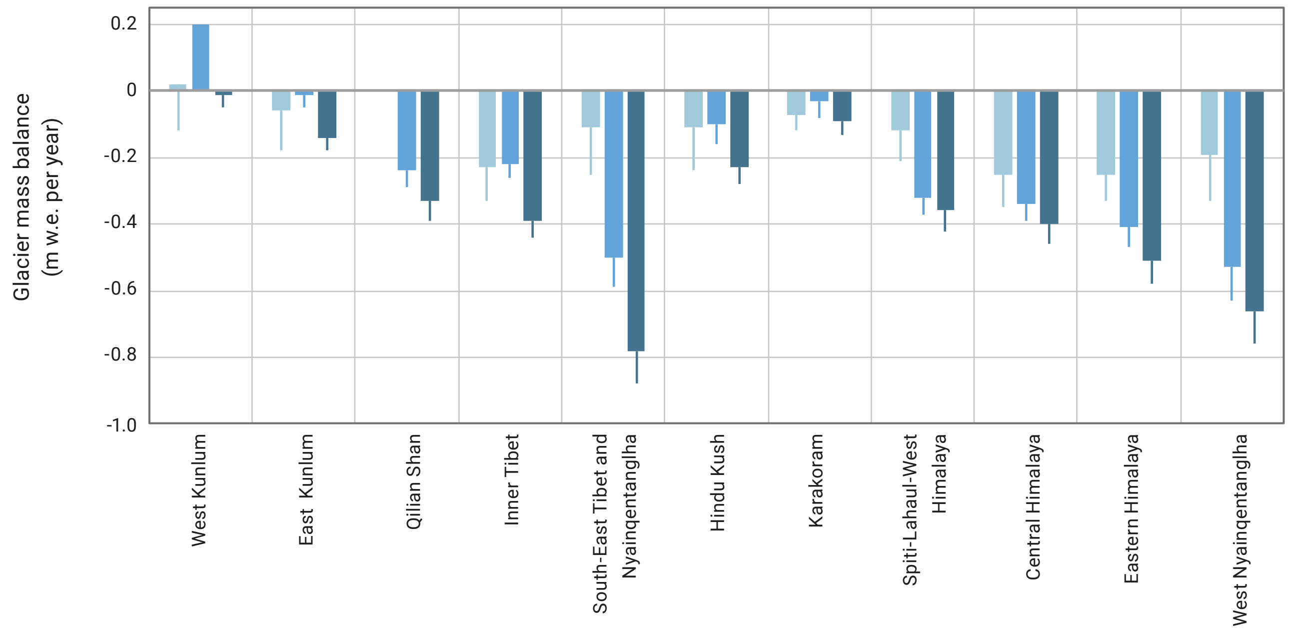
7.4 Asia and the Pacific

The Asia–Pacific region contains some of the world's highest mountains and most extensive glacier systems. The Tibetan Plateau and surrounding Pamir–Hindu Kush Himalaya (HKH) mountain ranges and the Hengduan, Tien Shan and Qilian mountains encompass 5 million km^2 of high mountains, with 100,000 km^2 of glaciers. This so-called Third Pole – also sometimes referred to as the water tower of Asia – stores more ice and snow than any other region outside the Antarctic and Arctic (UNEP, 2022b). The Third Pole is the origin of more than ten river systems that are vital for sustaining nearly 2 billion individuals in the river basins of Central, Northeast, South and Southeast Asia (ICIMOD, 2023). Although it is projected to warm faster than the global average (UNEP, 2022b), the Third Pole is one of the most biologically diverse and ecologically fragile areas in the world, and is home to a variety of cultures.

7.4.1 Trends and impacts

The mountains and glaciers in the Asia–Pacific region are among the most vulnerable to ongoing climatic, societal and environmental changes (Immerzeel et al., 2020). Glaciers in the HKH region are disappearing at an alarming rate: 65% faster in 2011–2020 than in the previous decade (ICIMOD, 2023). They are also melting faster than the global average (Mani, 2021), with the most significant losses concentrated in the eastern HKH region (Figure 7.5).

Figure 7.5 Region-wide glacier mass balances, expressed in metres water equivalent (m w.e.) per year from different areas in the Hindu Kush Himalaya region over the periods 1975–1999, 2000–2009 and 2010–2019



Note: A value of −1.0 m w.e. per year represents a mass loss of 1,000 kg/m^2 of ice cover or an annual glacier-wide ice thickness loss of about 1.1 m per year, as the density of ice is only 0.9 times the density of water.

Source: ESCAP/UNEP/ILO/UNFCCC RCC Asia-Pacific/UNIDO (2023, fig. 20, p. 74), based on data from Jackson et al. (2023).

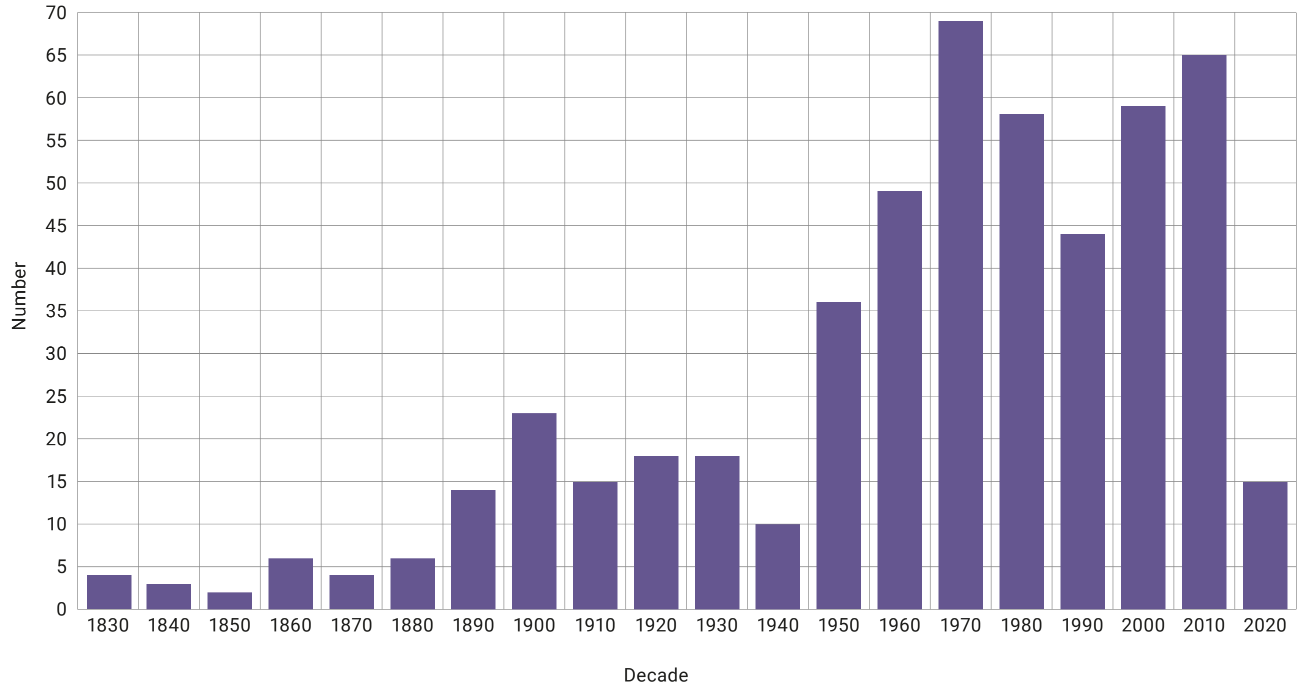
The Asia–Pacific region contains some of the world's highest mountains and most extensive glacier systems

It has been projected that under global warming scenarios of 1.5–2°C, glacier volume in the HKH region may reduce by 30–50% by 2100. If global warming exceeds 2°C, these glaciers may shrink down to 20–45% of their 2020 volume (ICIMOD, 2023).

These warming and melting trends will cause important changes. Increases in total runoff in the Third Pole region have been projected, with the largest impacts in the monsoon-dominated river basins. For rivers like the Indus where the contributions of glacier- and snow-melt are high, increasing streamflow is expected to peak (see Box 2.2), then diminish (Wester et al., 2019; UNEP 2022b).

While impacts vary by river basin, research reiterates the role of glacial melt as a contributor to GLOFs (see Section 2.2.3), flash floods and landslides (Adler et al., 2022) and elevated damage to human settlements, farm and pasture production, transport networks and hydropower energy systems. In the last 190 years, more than 7,000 fatalities (Shrestha, 2023) are estimated to have resulted from increasingly frequent GLOFs arising from the rapid formation and expansion of glacial lakes (Figure 7.6). The risk of GLOFs occurring in the HKH region has been predicted to triple by the end of the century, with a significant number of GLOFs affecting other downstream countries, primarily in the eastern Himalayas (Zheng et al., 2021). Many of the consequences will go beyond the limits of adaptation.

Figure 7.6 Number of recorded glacial lake outburst floods per decade in High Mountain Asia, 1830s–2020s



Source: Adapted from Shrestha (2023).

The deposition of black carbon has been found to enhance glacial melt

In the long term, reduced water flows and increased droughts are expected to jeopardize food, water, energy and livelihood security in the HKH region (Mani, 2021), as well as disrupt ecosystems and escalate risks of conflict and migration (Caretta et al., 2022). The most vulnerable and marginalized populations are often at the highest risk, including mountain farmers and Indigenous communities.

Energy use, environmental degradation and human activity are contributing to these risks in other ways, with black carbon (see Box 2.1), heavy metals and persistent organic pollutants showing an increasing presence in the Third Pole (UNEP, 2022b). The deposition of black carbon (from incomplete combustion of fossil fuels, and the combustion of biomass, including forest fires) has been found to enhance glacial melt to different extents depending on the location deposited, whether deposited in fresh snow, or on ice and other factors (Kang et al., 2020). One study estimated the glacier mass lost on the Tibetan Plateau over 40 years at approximately 450 km^3, 20–80 km^3 of which was attributed to the effects of black carbon and other light-absorbing deposits (Zhang et al., 2018). With the desiccation of the Aral Sea and its surrounding area, the Aralkum Desert is now considered among the most harmful dust sources worldwide. This desert, which has been disturbed by human action, is a source of pollutants like heavy metals and pesticides that travel long distances, accelerating glacial melt and contaminating freshwater systems (Zhang et al., 2020; Banks et al., 2022; Chen et al., 2022).

In addition to the Third Pole region, glacial melt and threats to mountain ecosystems are also a key concern in the Pacific. For example, retreat of glaciers has been observed in the Southern Alps in New Zealand, and by 2100, the country is projected to lose 88% of its ice volume as compared to 2011. Invasion of non-native species, climate change and human activities pose important challenges to mountain ecosystems in Pacific small island developing states, leading to changes in water yield, fire risk and biodiversity threats (Frazier and Brewington, 2020).

The trends and impacts noted above underscore the importance of collaboration on adaptation strategies and measures to mitigate the consequences, especially for vulnerable regions.

7.4.2 Regional and transboundary cooperation

Regional cooperation on glacier monitoring has played a vital role in detecting critical trends. Several important steps, as outlined below, have been taken to strengthen institutional arrangements for cooperation across shared river basins, with scientific cooperation and early warning systems (EWS) being the areas of focus. These provide models for mountain regions with shared river basins seeking to address the impacts of climate change and glacier melt, within and outside the Asia–Pacific region.

Regional cooperation on glacier monitoring has played a vital role in detecting critical trends

International scientific cooperation on the Third Pole to strengthen EWS and impact analysis

The establishment of the World Meteorological Organization's Third Pole Regional Climate Centre Network (TPRCC-Network) is a key development aimed at meeting the climate and cryosphere service requirements specific to the Third Pole region. The three nodes of the TPRCC-Network include a Northern Node (led by China), a Southern Node (led by India) and a Western Node (led by Pakistan), with China having the overall coordinating role (WMO, 2024b). The Economic and Social Commission for Asia and the Pacific along with the International Centre for Integrated Mountain Development, Third Pole Environment, Global Cryosphere Watch, Global Energy and Water Exchanges and Mountain Research Initiative are contributing partners of the TPRCC-Network. The demonstration phase was launched in June 2024 in Lijiang, China. The network is expected to support EWS and impact analysis. It issues periodic consensus statements integrating observational data, historical trends and forecasts that provide an overview of air temperature, precipitation, snow cover, extreme events and hazards observed during the preceding season and offer an outlook for the upcoming season.

Joint research and early warning through a Central Asian network of mountain observatories

The Central Asian Regional Glaciological Centre was established as a Category 2 centre under the auspices of the United Nations Educational, Scientific and Cultural Organization in Kazakhstan upon the country's ratification of an agreement in 2017. It provides a platform for transboundary scientific and technical cooperation on glacier monitoring in Central Asia (UNESCO, 2024; n.d.). In 2023, the centre signed a memorandum of understanding with representatives from Central Asian national and other hydrometeorological monitoring institutions to establish multilateral cooperation and a basis to advance glaciological research within the Central Asian network of mountain observatories. The network has been supported to deliver initial open datasets from past monitoring activities and will strengthen related monitoring capacities in the region (Mountain Research Initiative/GEO Mountains, 2023). Collaborative activities have so far included joint studies, field expeditions and installation of an EWS for moraine lake outbursts.

Transboundary cooperation in the HKH region

The International Centre for Integrated Mountain Development led the HKH Call to Action that was endorsed through a Ministerial Declaration in 2020. This call, which engaged multiple stakeholders through consultative workshops at the draft stage, strongly urged: cooperation at all levels in the HKH region, recognition of the uniqueness of the HKH mountain people, concerted climate action, accelerated actions on nine mountain priorities, enhanced ecosystem resilience and halting of biodiversity loss, regional data-sharing, and science and knowledge cooperation (ICIMOD, 2020). The Call to Action has enhanced partnerships for sustainable mountain development among countries in the HKH region and supported the mountain agenda in global forums (ICIMOD, n.d.). It has received new impetus through the second HKH Ministerial Mountain Summit in 2024.

Collaboration on engaging the diverse stakeholders and sectors that will be affected by the trends is essential

Access to near-live data and forecasts in the Mekong River basin

The Mekong River basin is vulnerable to the impacts of climate change and glacial melt. Since 2008, 49 automatic hydrometeorological stations, established under the Mekong Hydrological Cycle Observing System Project, across Cambodia, southern China, Lao People's Democratic Republic, Thailand and Viet Nam, have been collecting data, including water level and rainfall. These stations transmit almost real-time data at 15 minute intervals to the Mekong River Commission Secretariat and national agencies responsible for disaster risk reduction and water resources management. The daily status of water levels, weekly forecasts, long-term averages, flash flood alerts and drought forecasts are among data and information readily available on the Mekong River Commission Secretariat website (MRC, n.d.).

7.4.3 Pathways forwards

Collaboration on engaging the diverse stakeholders and sectors that will be affected by the trends is essential. Glacial melt and water-related crises must be addressed by strengthened adaptation measures, integrated water resources management (IWRM), and synergistic solutions for climate, nature and pollution, supported by transboundary collaboration, regional dialogue, advocacy and awareness-raising.

Addressing climate, nature and air pollution pressures on glaciers

Implementing economically and technically feasible measures like improving brick kiln efficiency and incentivizing households to switch to cleaner fuels such as liquefied petroleum gas and solar energy can make important contributions towards containing glacial melt by reducing emissions of black carbon (Mani, 2021). Measures to mitigate drying trends in the Aral Sea basin and reduce dust storms are important, including through NbS, which also require further attention in the context of adaptation planning. Tackling dust and black carbon emissions can reduce pressures on glaciers by conserving their albedo properties and improving environmental conditions.

Joint adaptation planning

While water-related crises are possibly the most important focus for climate adaptation in the high mountain areas of Asia and the Pacific, joint adaptation strategies developed across national and administrative boundaries are essential. Investments in resilient infrastructure, NbS, effective and credible EWS, strengthened and accessible impact analysis and risk assessment, including at the sectoral level, are needed to identify critical risks, areas for further research, and opportunities for outreach and engagement with the sectors affected. At the same time, environmental monitoring networks that track changing water quantity and quality are needed.

Amid a growing number of institutional initiatives, a framework for action can help to ensure coordination across development partners and to mobilize projects and investments that respond to local and transboundary threats. Long-term adaptation planning approaches such as the adaptation pathways method, and approaches such as EbA and livelihood and economic diversification, are also critical.

Several cooperation initiatives emphasize the empowerment and integration of local communities, including Indigenous Peoples, youth and vulnerable groups

Twin-track strategy for managing risk and building community resilience and empowerment

Managing glacial hazards like GLOFs requires a twin-track integrated approach.

Track 1: Strengthening EWS. To trigger early or anticipatory action, EWS must be people centred, impact based and risk informed. They should consider complex and cascading risks such as cloudbursts linked to GLOFs and tailored to the needs of critical lifeline sectors such as energy, water, transport, and information and communications technology through risk assessment and impact forecasting.

Track 2: Enhancing infrastructure resilience. Resilient infrastructure that can withstand and adapt to hazards should be developed, as well as infrastructure for resilience that can support broader social and economic resilience. This approach assumes high significance in multi-hazard risk hotspots and must be supported by comprehensive risk mapping and integrated assessment. The critical infrastructure sectors must be designed to handle interconnected risks, ensuring systemic resilience against local emergencies and disruptions.

Several cooperation initiatives emphasize the empowerment and integration of local communities, including Indigenous Peoples, youth and vulnerable groups, in EWS and broader adaptation processes. The Asia–Pacific region can benefit from scaling up examples of community-based flood early warning systems and similar innovations to strengthen transboundary cooperation in shared river basins (Box 7.3).

Operational arrangements for transboundary watercourses and IWRM

The severe implications of glacial melting on water resources management in downstream areas and sharing of transboundary watercourses in the Asia–Pacific region require high attention. Despite significant progress in regional monitoring, data-sharing and forecasting systems, basic measures to put in place IWRM in river basins, whether transboundary or internal, lag behind other global regions.

As of 2023, only two Asian countries sharing transboundary waters – Cambodia and Mongolia – had 90% or more of their waters covered by the kinds of operational arrangements that are increasingly important for managing the impacts of changing hydrological regimes, as compared to 23 in Europe and North America (United Nations, n.d.). This basic requirement of effective water resources management still requires investment and attention in the Asia–Pacific region, particularly where climate change and environmental pollution trends will continue to affect water availability and quality.

Box 7.3 A transboundary community-based flood early warning system (CBFEWS)

As of 2017, telemetry-based early warning systems in Sitamarhi District, India, and Mahottari District, Nepal – involving local communities, partner organizations and government agencies and supported by the International Centre for Integrated Mountain Development – had delivered timely flood information to over 19,000 households (nearly 100,000 individuals) (ICIMOD, 2017). Formal information channels usually take time to disseminate warnings to remote areas, which are often the most vulnerable. However, CBFEWS rely on more direct methods, such as mobile phone communication, that ensure timely information exchange.

For the Ratu River – a transboundary river between India and Nepal – a CBFEWS was implemented in communities along its banks. During a flood on 12 August 2017, the CBFEWS along the Ratu River helped to improve flood disaster preparedness in Shrikhandi village, Sitamarhi District, Bihar. The early warning instrument set up by the International Centre for Integrated Mountain Development and Yuganter (a local non-governmental organization) provided seven to eight hours of lead time, allowing local communities to take proactive measures, including relocating to safer places.

Sources: ICIMOD (2017) and Singh Shrestha and Sherchan (2018).

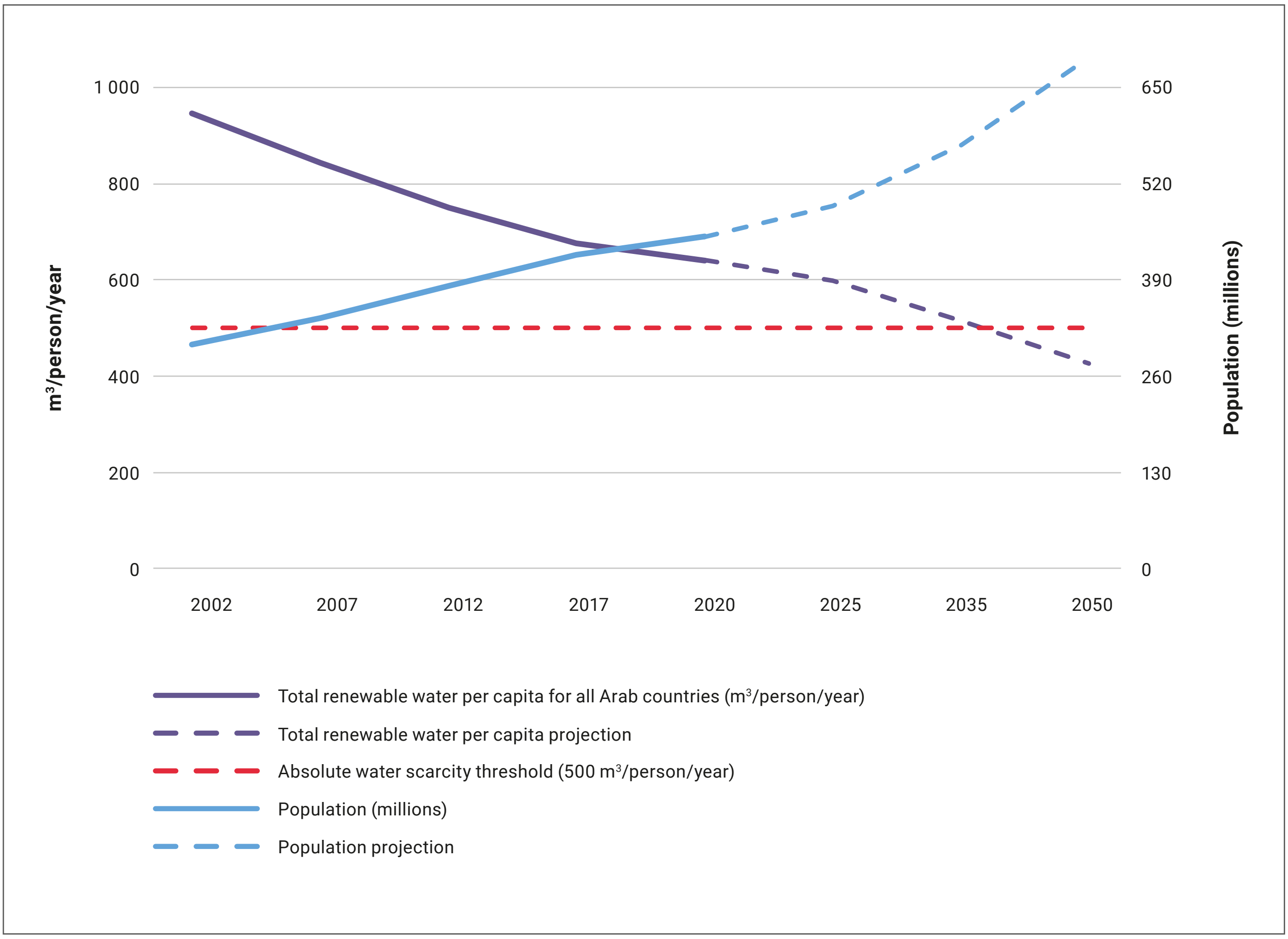
7.4.4 Conclusions

Human activities and climate change are posing a critical threat to the mountains and glaciers of the Asia–Pacific region, exacerbating the complex hydrological challenges that the region faces. Integrated solutions that increase the region's adaptive capacity and resilience, while reducing pressures on glaciers and water ecosystems, are vital. Transboundary adaptation efforts based on the principles of cooperation and stakeholder empowerment have demonstrated the benefits of regional collaboration. Building on this progress, strengthening of transboundary approaches that synergize water sector policies with broader climate and socio-environmental objectives is needed in the region.

7.5 Arab region

The mountain areas of the Arab region are often overlooked, despite the important role they play in providing water resources and other ecosystem services. They are also home to thriving communities and centres of economic activity for tourism, agriculture and industry, which are often reliant on the ever-dwindling availability of freshwater resources resulting in a reduced amount of renewable water per capita. With the projected population growth, the entire Arab region will be below the absolute water scarcity threshold by 2050 (Figure 7.7).

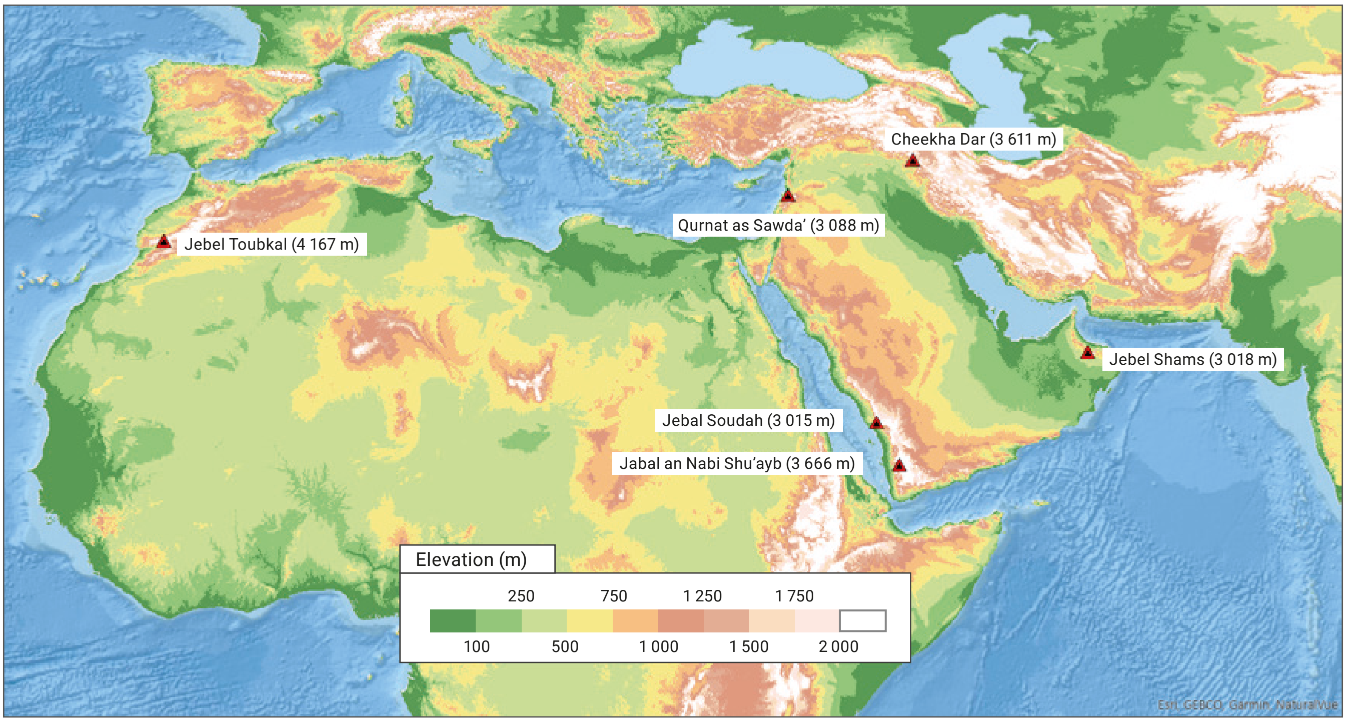
Figure 7.7 Past and projected future decrease in renewable water per capita with estimated population growth in the Arab region, 2002–2050



Source: Adapted from ESCWA (2022, fig. 9, p. 28).

Approximately one-third of the people who live in the Arab region resides over 600 masl.[19] Snowfall accumulates in several mountains over winter, including in Mount Lebanon, the High Atlas Mountains, the Zagros Mountains and the Asir Mountains (Figure 7.8). As temperatures rise during spring, the melting snowpack feeds into streams, reservoirs and aquifers located at lower elevations. Meltwater can serve a crucial role for the agricultural sector, particularly in sustaining crops during the summer when precipitation is limited. Two such mountain areas are the Mount Lebanon range that extends along nearly the full length of Lebanon's interior and the Atlas Mountain range in North Africa, which stretches through Algeria, Morocco and Tunisia, reaching its highest peak in Morocco.

Figure 7.8 Mountain peaks and ranges in the Arab region



Source: Authors.

7.5.1 Impacts of climate change on snow cover

Meltwater released from snowpack is a major water resource for lowland coastal regions and inland plains, which are population and economic centres, in the Arab region. Snow water equivalent (SWE) – the hydrological equivalent of the liquid water available in the snowpack – can provide key information to implement appropriate water management measures (see Section 2.1.1). A decrease in SWE results in a decrease in available water resources that depend on snow such as water available for groundwater recharge, spring flow and soil moisture.

Some aquifer-fed springs within the Arab region, such as the Assal spring in Lebanon, are primarily recharged from snow-melt (Doummar et al., 2018). It has been estimated that snow contributes 50–60% of the water volume in Lebanon's rivers and springs, which feeds into groundwater aquifers (Shaban, 2020). However, estimating SWE, based on approximated snow depth and density, is time-consuming (Fayad, 2019). While SWE data are rarely available in the Arab region, snow cover duration and depth can serve as good proxies for SWE (Sturm et al., 2010).

[19] Authors' calculations, based on geographic information system data.

As temperatures are projected to increase due to climate change (rising by up to 3.5°C and 4.5°C by 2100, based on the reference period 1986–2005, in Mount Lebanon and the Atlas Mountains, respectively; ESCWA et al., 2017), seasonal snowfall and overall precipitation are expected to decrease, affecting snow cover duration, depth and overall availability of freshwater resources. Historical estimates from remote sensing in Mount Lebanon reported that approximately two-thirds of precipitation was derived from snowfall, totalling 40–43 cm of SWE on average annually (Shaban et al., 2004). Later in situ measurements revealed snow cover duration was approximately 160 days and snow depth 50–80 cm at elevations higher than 2,700 masl, translating to 36–158 cm of SWE (Fayad et al., 2017). Similarly, snow cover duration at high elevations typically exceeds 90 days in the Atlas Mountains, resulting in 20 cm of SWE and exceeding 80 cm of SWE during wet years (Hanich et al., 2022).

Some aquifer-fed springs within the Arab region, such as the Assal spring in Lebanon, are primarily recharged from snow-melt

Regional climate modelling outputs from the EURO-CORDEX domain (Jacob et al., 2013) have been used to assess climate change impacts upon snow cover duration and snow depth in Mount Lebanon and the Atlas Mountains. The domain extended into North Africa and the eastern Mediterranean with a spatial resolution of 12.5 km. Models were selected based on their suitability to analyse snow cover duration and snow depth (Frei et al., 2018) and included two scenarios based on representative concentration pathways (RCP4.5 and RCP8.5).

In Mount Lebanon and the Atlas Mountains, snowpack projections show a general decreasing trend and will nearly cease by the end of this century. The projected reductions of snow cover duration range from 7% to 10% per decade in Mount Lebanon (Figure 7.9) and 6% to 10% in the Atlas Mountains (Figure 7.10). Similarly, snow depth is projected to decrease by up to 9% per decade in both locations (Figures 7.11 and 7.12).

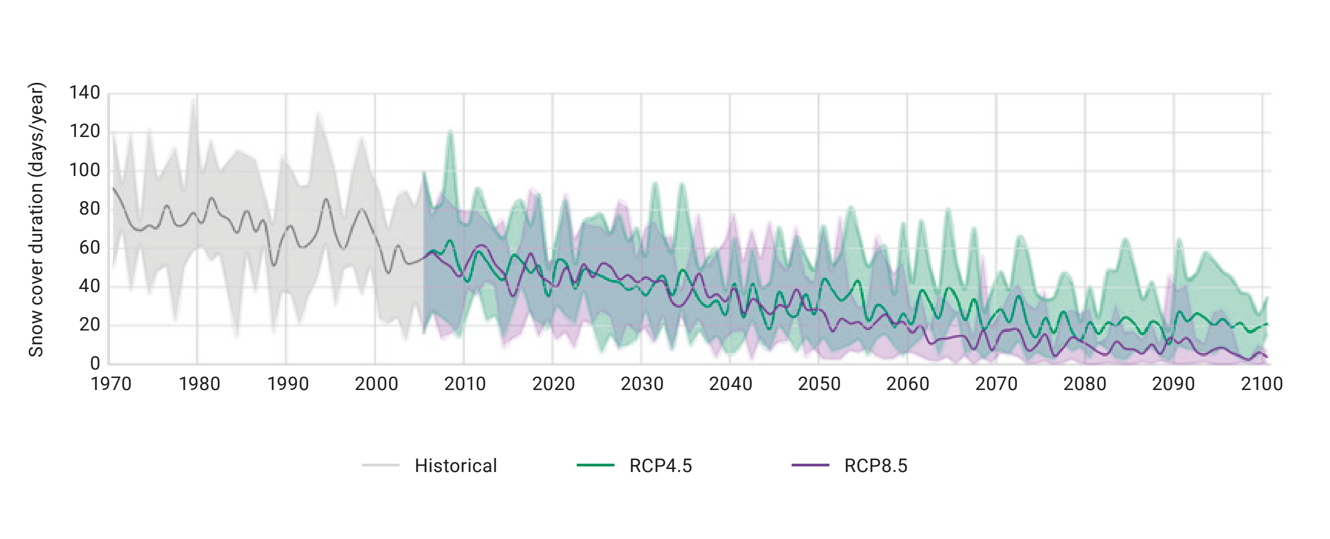
A study in Mount Lebanon concurs, projecting that the snow-line which reaches 1,500 masl will shift to 1,700 masl by 2050 and to 1,900 masl by 2090. In addition to the shift of snow level, snow will melt earlier in the spring, affecting aquifer recharge and springs flow, thereby reducing the irrigation water supply (MoE/UNDP/GEF, 2015). These projected reductions in snow cover signal an overall decrease in water supply, specifically during the dry season when it is most needed for irrigation. Water, sanitation and hygiene services may also be affected by reduced overall water resources in the long term.

7.5.2 Adaptation measures

The reduction in snow cover duration and snow depth will severely affect snow hydrology, SWE and overall water availability. This calls for sound adaptation measures. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change identified several enabling conditions that could be used to support climate change adaptation in the Arab region. These included capacity-building to increase knowledge of climate change impacts, empowering vulnerable groups (such as women and rural communities) as key stakeholders, and using forecasting and prediction platforms (IPCC, 2022).

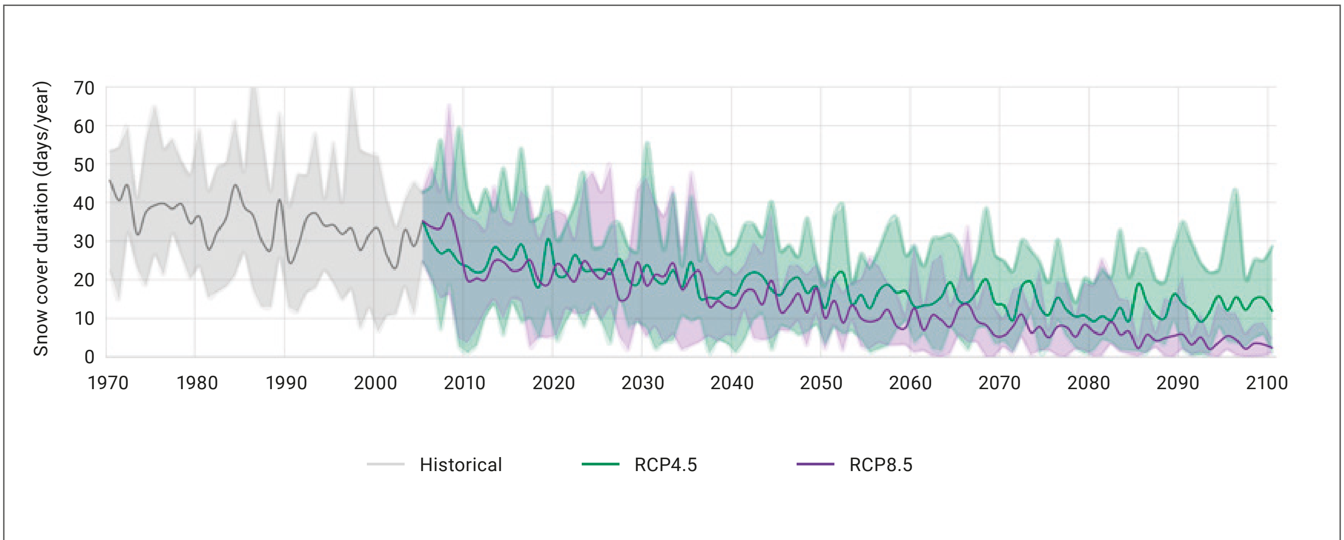
The services industry (including winter tourism) employs 63% of working women in Lebanon. Therefore, it is crucial to support women via capacity-building and funding for new economic activities that allow them to adapt to the predicted drop in snowfall and subsequent impact on winter tourism activities (ESCWA/UNFPA/NCLW, 2022). Women also account for 43% of the agriculture workforce in Lebanon, and thus will need programmes and funding to counter any impacts of reduced snow-melt on irrigation water resources and their income (UN Women, 2023).

Figure 7.9 Annual snow cover duration time series in Mount Lebanon (higher than 2,000 m above sea level), 1970–2100



Source: Authors, based on an ensemble of six selected EURO-CORDEX regional climate modelling outputs.

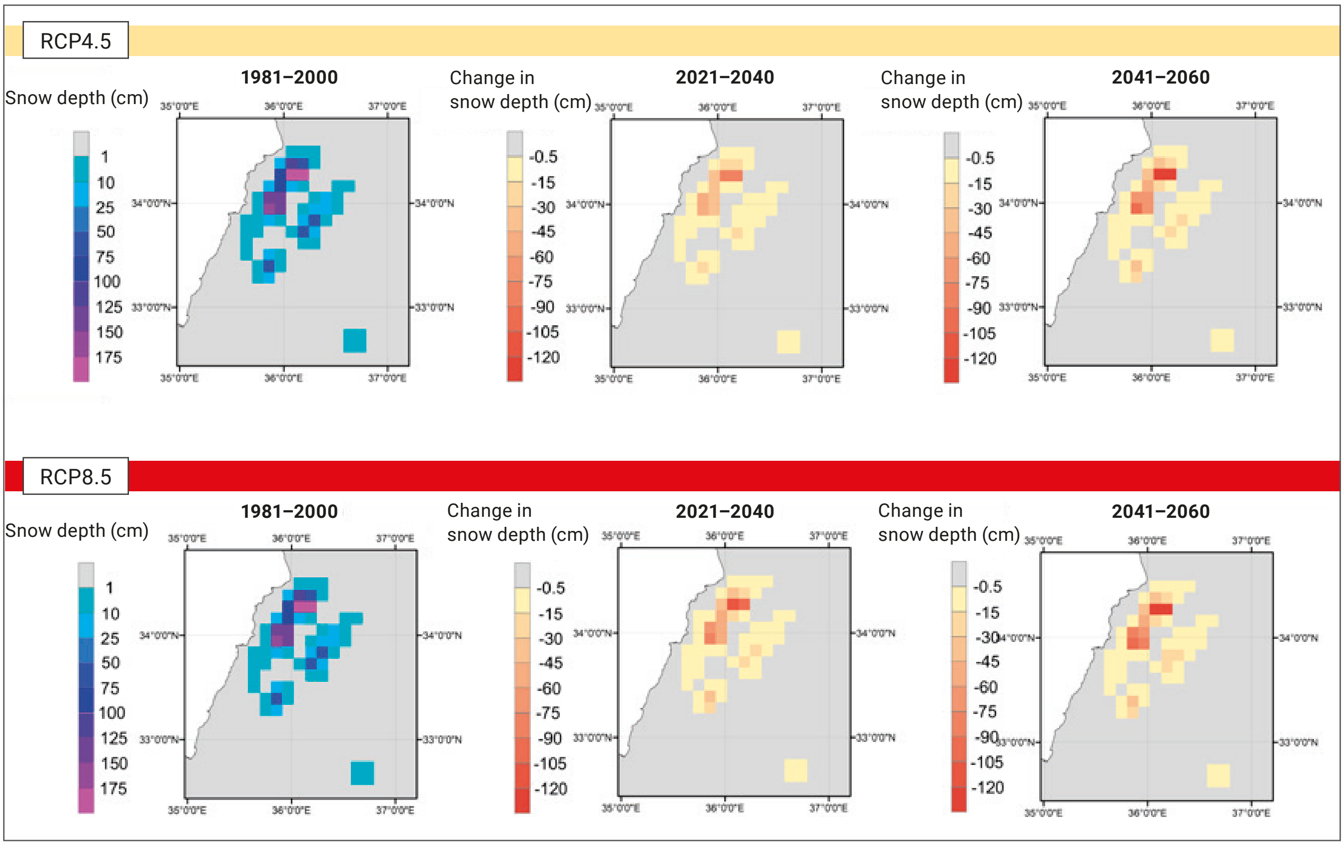
Figure 7.10 Annual snow cover duration time series in the Atlas Mountains (higher than 2,000 m above sea level), 1970–2100



Source: Authors, based on an ensemble of six selected EURO-CORDEX regional climate modelling outputs.

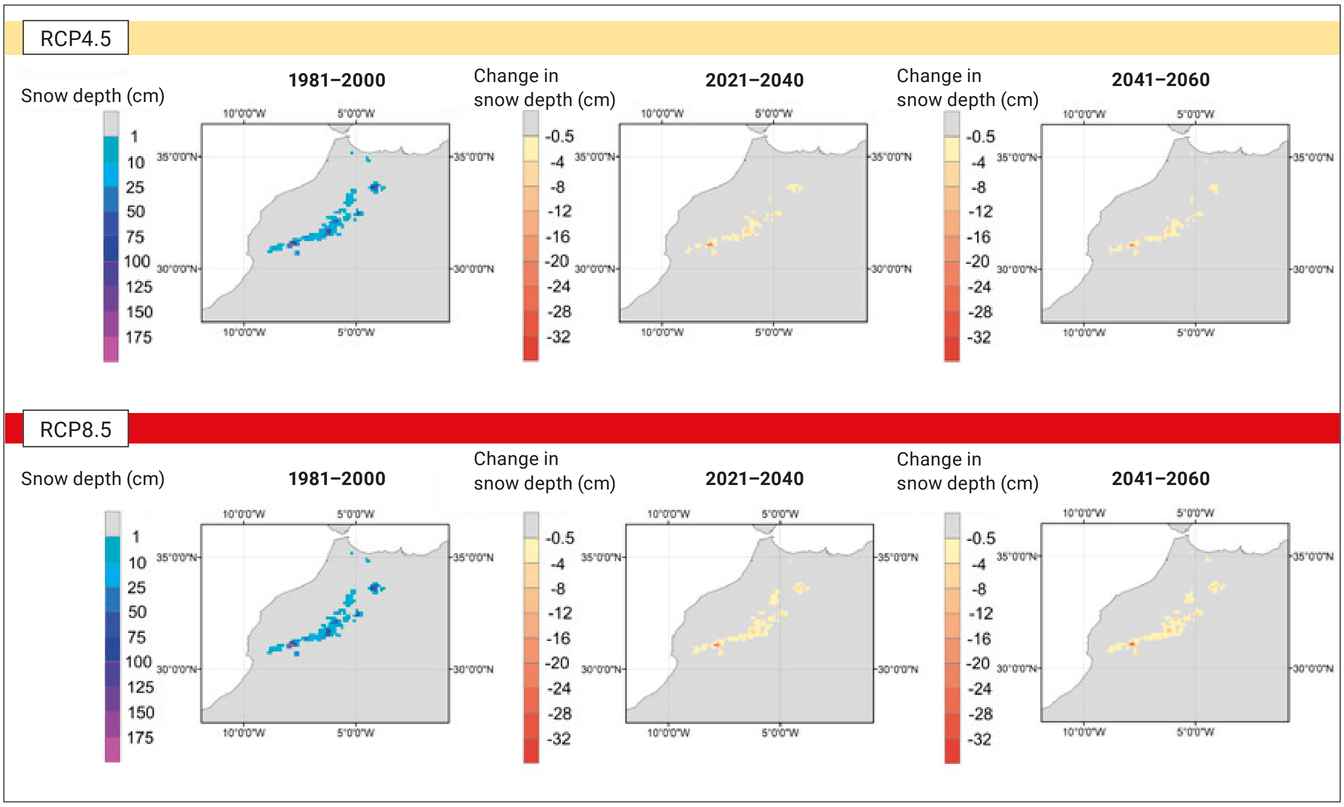
A climate-proof watershed management design and resilience package, informed by climate forecasting models from the Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region, was developed for the Nahr al Kalb basin in Lebanon, which includes part of Mount Lebanon. The basin includes the municipality of Kfardebian, recognized in 2024 as the capital of Arab winter tourism. Climate change will adversely affect such communities who are economically dependent on winter tourism. The impacts will include a reduction in household incomes for those dependent on winter tourism revenues resulting from a shortened ski season with fewer tourists.

Figure 7.11 Change in average seasonal snow depth (October–March) in Mount Lebanon over the periods 1981–2000, 2021–2040 and 2041–2060



Source: Authors, based on an ensemble of six selected EURO-CORDEX regional climate modelling outputs.

Figure 7.12 Change in average seasonal snow depth (October–March) in the Atlas Mountains over the periods 1981–2000, 2021–2040 and 2041–2060



Source: Authors, based on an ensemble of six selected EURO-CORDEX regional climate modelling outputs.

The design and resilience package suggested several interventions, including the diversification of livelihoods through sustainable tourism that expands beyond winter activities. This includes promoting year-round nature-based agritourism and ecotourism. Policymakers were advised to identify and map local attractions, provide support and capacity development to local businesses, develop necessary infrastructure (rehabilitated hiking trails) and provide appropriate communication materials to attract visitors. The basin also includes agricultural land, namely apple and other fruit trees. Hill lake construction (a reservoir) is recommended as an economically feasible option to increase water storage to help sustain irrigation in the extended dry season (ESCWA/ACSAD/Ministry of Energy and Water of Lebanon/FAO, 2022). This is an example of the work being done to support mountain populations and communities as they confront the irreversible impacts of climate change and the decline of important water resources. The same suggested activities may help to mitigate the negative environmental impacts of heavy winter tourism, which have led to increased pollution, deforestation and reductions in snow quality in areas of Lebanon like Tannourine (Delly, 2024).

The reduction in snow cover duration and snow depth will severely affect snow hydrology, SWE and overall water availability

Managed aquifer recharge is another watershed adaptation measure that could be employed in similar scenarios. Water harvesting could be used in the winter to mitigate the decrease in water availability in the summer resulting from climate change impacts on mountain areas in the Arab region, including the loss in snowpack.

In Morocco, rural development strategies must be better adapted to climate change so that territorial and livelihood resilience can be improved as climate change affects snow cover and water availability in its mountain communities. This requires improving the availability of data that capture the different visions and priorities of rural stakeholders with respect to rural development. The Green Morocco Plan, established in 2008, is leading to the emergence of a new policy for managing natural resources and promoting Indigenous knowledge with respect to ecosystem management. The plan encourages adaptation measures in the event of climate change. It aims to improve small-scale agriculture in marginal areas by subsidizing tree planting on sloping land and implementing water-efficient techniques such as drip irrigation as an adaptive response to climate change and the projected decrease in available water resources (Agence Pour Le Développement Agricole, n.d.). This development is dependent on the integrated management of environmental resources (water, forest, soil, etc.) at the scale of large watersheds to overcome the diverse water availability and demands across mountain and plain areas.

7.5.3 Conclusions

The impacts of climate change on seasonal snowfall and precipitation, and thus the overall availability of water in the Arab region, are already apparent and likely to become more extreme in the future. Snowpack plays a crucial role in storing water for release during the dry season. However, it is decreasing due to climate change. In mountain communities in the Arab region in general and specifically in Lebanon and Morocco, this will affect economic activities such as tourism and agriculture. Going forwards, cross-sectoral climate adaptation measures including NbS, more efficient irrigation and crop selection techniques, and smart economic diversification strategies are needed to address the challenges.

References

Adhikari, U., Nejadhashemi, A. P. and Herman, M. R. 2015. A review of climate change impacts on water resources in East Africa. *Transactions of the ASABE*, Vol. 58, No. 6, pp. 1493–1507. doi.org/10.13031/trans.58.10907.

Adler, C., Wester, P., Bhatt, I., Huggel, C., Insarov, G., Morecroft, M., Muccione, V. and Prakash, A. 2022. Mountains. H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem and B. Rama (eds), *Climate Change 2022: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK/New York, Cambridge University Press, pp. 2273–2318. doi.org/10.1017/9781009325844.022.

Agence Pour Le Développement Agricole. n.d. Approaches to Implementation of the Two Pillars of the Green Morocco Plan. Agence Pour Le Développement Agricole website. www.ada.gov.ma/en/approaches-implementation-two-pillars-green-morocco-plan.

Aguas Andinas. 2024. *Resumen de Información ESG* [Information Summary ESG]. www.aguasandinasinversionistas.cl/~/media/Files/A/Aguas-IR-v2/sustainability-reports/es/2023/ESG%20INFORMATION%20SUMMARY%202023%20sv%20-%20Espaol.pdf. (In Spanish.)

Alberton, M., Andresen, M., Citadino, F., Egerer, H., Fritsch, U., Götsch, H., Hoffmann, C., Klemm, J., Mitrofanenko, A., Musco, E., Noellenburg, N., Pettita, M., Renner, K. and Zebisch, M. 2017. *Outlook on Climate Change Adaptation in the Carpathian Mountains*. Mountain Adaptation Outlook Series. Nairobi/Vienna/Arendal, Norway/Bolzano, Italy, United Nations Environment Programme (UNEP)/GRID-Arendal/Eurac Research. www.grida.no/publications/381.

Alford, D., Kamp, U. and Pan, C. 2015. *The Role of Glaciers in the Hydrologic Regime of the Amu Darya and Syr Darya Basins*. Report No. ACS12128. Washington DC, World Bank. https://openknowledge.worldbank.org/server/api/core/bitstreams/94d8d53f-c8ff-53c7-899b-3d01f5eb8c85/content.

Altomonte, H. and Sánchez, R. J. 2016. *Hacia una Nueva Gobernanza de los Recursos Naturales en América Latina y el Caribe*. Libros de la CEPAL No. 139 [Towards a New Governance of Natural Resources in Latin America and the Caribbean. UNECLAC Books No. 139]. LC/G.2679-P. Santiago, United Nations Economic Commission for Latin America and the Caribbean (UNECLAC). www.cepal.org/es/publicaciones/40157-nueva-gobernanza-recursos-naturales-america-latina-caribe. (In Spanish.)

Alweny, S., Nsengiyumva, P. and Gatarabirwa, W. 2014. *Africa Sustainable Mountain Development Technical Report No. 1*. Kampala/Cambridge, UK, Albertine Rift Conservation Society (ARCOS). doi.org/10.13140/RG.2.2.11656.16640.

Ariza, C., Maselli, D. and Kohler, T. 2013. *Mountains: Our Life, Our Future. Progress and Perspectives on Sustainable Mountain Development from Rio 1992 to Rio 2012 and Beyond*. Bern, Swiss Agency for Development and Cooperation (SDC)/Centre for Development and Environment (CDE). https://boris.unibe.ch/47827/1/Mountain_Synthesis_Report.pdf.

Awange, J. 2022. GHA's water tower: Ethiopian highlands. *Food Insecurity & Hydro-Climate in Greater Horn of Africa: Potential for Agriculture Amidst Extremes*. Cham, Switzerland, Springer, pp. 107–142. doi.org/10.1007/978-3-030-91002-0_6.

Banks, J. R., Heinold, B. and Schepanski, K. 2022. Impacts of the desiccation of the Aral Sea on the Central Asian dust life-cycle. *Journal of Geophysical Research: Atmospheres*, Vol. 127, No. 21, Article e2022JD036618. doi.org/10.1029/2022JD036618.

Bodin, X. 2019. Impactos de la evolución de los glaciares rocosos en los Andes semí-áridos [Impacts of rock glacier evolution in semi-arid Andes]. M. Turrel, *Luis Lliboutry – El Hombre que Descifró los Glaciares* [Luis Lliboutry – The man who decoded the glaciers]. Santiago, Aguas Andinas, pp. 241–242. https://hal.science/hal-03083932. (In Spanish.)

Bown, F., Rivera, A. and Acuña, C. 2008. Recent glacier variations at the Aconcagua basin, Central Chilean Andes. *Annals of Glaciology*, Vol. 48, pp. 43–48. doi.org/10.3189/172756408784700572.

Bretas, F., Casanova, G., Crisman, T., Embid, A., Martin, L., Miralles, F. and Muñoz, R. 2020. *Agua para el Futuro: Estrategia de Seguridad Hídrica para América Latina y el Caribe* [Water for the Future: Water Security Strategy for Latin America and the Caribbean]. Inter-American Development Bank (IDB). doi.org/10.18235/0002816. (In Spanish.)

Cajar. 2024. Alerta urgente: Sobre desplazamiento forzado masivo del pueblo Wiwa de la Sierra Nevada de Santa Marta [Urgent Alert: On the Massive Forced Displacement of the Wiwa People of the Sierra Nevada de Santa Marta]. Cajar website, 27 February 2024. www.colectivodeabogados.org/organizaciones-de-derechos-humanos-denunciamos-desplazamiento-masivo-del-pueblo-indigena-wiwa-de-la-snsm-alerta-urgente/. (In Spanish.)

Canal Capital. 2023. ¿De dónde viene el agua que consumimos en Bogotá? [Where Does the Water We Consume in Bogotá Come From?]. Canal Capital website, 30 August 2023. www.canalcapital.gov.co/eureka/donde-viene-el-agua-de-bogota. (In Spanish).

Canales Sierra, L. 2018. *Construcción de Diques para la Cosecha de Agua en Lagunas Periglaciares* [Construction of Dams for Water Harvesting in Periglacial Lagoons]. Lima, CARE Perú. (In Spanish.)

Capitani, C., Garedew, W., Mitiku, A., Berecha, G., Hailu, B. T., Heiskanen, J., Hurskainen, P., Platts, P. J., Siljander, M., Pinard, F., Johansson, T. and Marchant, R. 2019. Views from two mountains: Exploring climate change impacts on traditional farming communities of Eastern Africa highlands through participatory scenarios. *Sustainability Science*, Vol. 14, pp. 91–203. doi.org/10.1007/s11625-018-0622-x.

Caretta, M. A., Mukherji, A., Arfanuzzaman, M., Betts, R. A., Gelfan, A., Hirabayashi, Y., Lissner, T. K., Liu, J., Lopez Gunn, E., Morgan, R., Mwanga, S. and Supratid, S. 2022. Water. H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds), *Climate Change 2022: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK/New York, Cambridge University Press, pp. 551–712. doi.org/10.1017/9781009325844.006.

CAWater-info (Portal of Knowledge for Water and Environmental Issues in Central Asia). n.d. Knowledge Base. Degradation of Glaciers. CAWater-info website. Interstate Commission for Water Coordination of Central Asia (ICWC). http://cawater-info.net/bk/7-3_e.htm. (Accessed on 27 November 2024.)

Chaperon, P., Danloux, J. and Ferry, L. 1993. *Fleuves et rivières de Madagascar – Ony sy renirano eto Madagasikara* [Rivers and Watercourses of Madagascar]. Collection Monographies hydrologiques, No. 10. Paris, ORSTOM. (In French.)

Chen, Z., Gao, X. and Lei, J. 2022. Dust emission and transport in the Aral Sea region. *Geoderma*, Vol. 428, Article 116177. doi.org/10.1016/j.geoderma.2022.116177.

CHR (International Commission for the Hydrology of the Rhine basin). 2022. When the Melt Water is Missing: More Often Low Water Expected in the Rhine in the Future. CHR website, 11 July 2022. www.chr-khr.org/en/news/when-melt-water-missing-more-often-low-water-expected-rhine-future.

Climate-ADAPT. 2024. Adaptation in Carpathian Mountains. Climate-ADAPT website. https://climate-adapt.eea.europa.eu/en/countries-regions/transnational-regions/carpathian-mountains/general. (Accessed on 12 November 2024.)

Climate Diplomacy. 2022. How Much Progress Has Been Made on Kyrgyz-Uzbek Water Cooperation? Climate Diplomacy website, 1 July 2022. https://climate-diplomacy.org/magazine/cooperation/how-much-progress-has-been-made-kyrgyz-uzbek-water-cooperation.

Commission on Environment and National Assets. 2022. Proyecto de Ley. Sobre Protección de Glaciares [Glacier Protection Bill]. Boletines No. 11,876-12 and 4,205-12, refundidos. National Congress of Chile. www.camara.cl/legislacion/ProyectosDeLey/tramitacion.aspx?prmID=12397&prmBOLETIN=11876-12. (In Spanish.)

Cullen, N. J., Sirguey, P., Mölg, T., Kaser, G., Winkler, M. and Fitzsimmons, S. J. 2013. A century of ice retreat on Kilimanjaro: The mapping reloaded. *The Cryosphere*, Vol. 7, No. 2, pp. 419–431. doi.org/10.5194/tc-7-419-2013.

Delly, F. Z. 2024. Balancing tourism and environmental conservation in Lebanon's changing climate. *Beirut Political Review*, 28 February 2024. https://beirutpoliticalreview.org/publications/f/the-environment-tourism-and-lebanons-changing-climate.

Descroix, L., Faty, B., Manga, S. P., Diedhiou, A. B., Lambert, L. A., Soumaré, S., Andrieu, J., Ogilvie, A., Fall, A., Mahé, G., Sombily Diallo, F. B., Diallo, A., Diallo, K., Albergel, J., Tanimoun, B. A., Amadou, I., Bader, J. C., Barry, A., Bodian, A., Boulvert, Y., Braquet, N., Couture, J. L., Dacosta, H., Dejacquelot, G., Diakité, M., Diallo, K., Gallese, E., Ferry, L., Konaté, L., Nka Nnomo, B., Olivry, J. C., Orange, D., Sakho, Y., Sambou, S. and Vandervaere, J. P. 2020. Are the Fouta Djallon highlands still the water tower of West Africa? *Water*, Vol. 12, No. 11, Article 2968. doi.org/10.3390/w12112968.

Devenish, C. and Gianella, C. (eds). 2012. *20 years of Sustainable Mountain Development in the Andes: From Rio 1992 to 2012 and Beyond*. Regional Report. Consorcio para el Desarollo Sostenible de la Ecorregión Andina (CONDESAN). https://openknowledge.fao.org/server/api/core/bitstreams/17b3c4fe-863e-4475-b12e-269d5578be58/content.

Dickerson, S., Cannon, M. and O'Neill, B. 2021. Climate change risks to human development in Sub-Saharan Africa: A review of the literature. *Climate and Development*, Vol. 14, No. 6, pp. 1–19. doi.org/10.1080/17565529.2021.1951644.

Dniester Basin Management Authority. 2024. З Міжнародним днем Дністра! [Happy International Dniester Day!]. Dniester Basin Management Authority website. https://vodaif.gov.ua/z-mizhnarodnym-dnem-dnistra-2/. (In Ukrainian.) (Accessed on 27 November 2024.)

Dniester Commission. 2024a. Working Group on Ecosystems and Biodiversity. Dniester Commission website. https://dniester-commission.org/en/joint-management/dniester-commission/working-groups/working-group-on-ecosystems-and-biodiversity/.

—. 2024b. Working Group on Emergencies. Dniester Commission website. https://dniester-commission.org/en/joint-management/dniester-commission/working-groups/working-group-on-emergencies/.

Doummar, J., Kassem, A. H. and Gurdak, J. J. 2018. Impact of historic and future climate on spring recharge and discharge based on an integrated numerical modelling approach: Application on a snow-governed semi-arid karst catchment area. *Journal of Hydrology*, Vol. 565, pp. 636–649. doi.org/10.1016/j.jhydrol.2018.08.062.

Dussaillant, I., Berthier, E., Brun, F., Masiokas, M., Hugonnet, R., Favier, V., Rabatel, A., Pitte, P. and Ruiz, L. 2019. Two decades of glacier mass loss along the Andes. *Nature Geoscience*, Vol. 12, pp. 802–808. doi.org/10.1038/s41561-019-0432-5.

EAC/UNEP/GRID-Arendal (East African Community/United Nations Environment Programme/GRID-Arendal). 2016. *Sustainable Mountain Development in East Africa in a Changing Climate*. Mountain Adaptation Outlook Series. Arusha, United Republic of Tanzania/Nairobi/Arendal, Norway, EAC/UNEP/GRID-Arendal. www.grida.no/publications/119.

EC IFAS (Executive Committee of the International Fund for Saving the Aral Sea). 2024. Water Resources. EC IFAS website. https://ecifas.kz/en/drugie-resursy/vodnye-resursy-basseyna-aralskogo-morya.

ESCAP/UNEP/ILO/UNFCCC RCC Asia-Pacific/UNIDO (Economic and Social Commission for Asia and the Pacific/United Nations Environment Programme/International Labour Organization/Regional Collaboration Centre for Asia–Pacific of the United Nations Framework Convention on Climate Change/United Nations Industrial Development Organization). 2023. *2023 Review of Climate Ambition in Asia and the Pacific: Just Transition Towards Regional Net-Zero Climate Resilient Development*. United Nations. www.unescap.org/kp/2023/2023-review-climate-ambition-asia-and-pacific-just-transition-towards-regional-net-zero.

ESCWA (Economic and Social Commission for Western Asia). 2022. *Groundwater in the Arab Region – ESCWA Water Development Report 9*. Beirut, United Nations. www.unescwa.org/publications/water-development-report-9.

ESCWA (Economic and Social Commission for Western Asia) et al. 2017. *Arab Climate Change Assessment Report – Main Report*. Beirut, United Nations. www.unescwa.org/publications/riccar-arab-climate-change-assessment-report.

ESCWA/ACSAD/Ministry of Energy and Water of Lebanon/FAO (Economic and Social Commission for Western Asia/Arab Center for the Studies of Arid Zones and Dry Lands/Ministry of Energy and Water of Lebanon/Food and Agriculture Organization of the United Nations). 2022. *Climate-Proof Watershed Management Design and Resilience Package: Nahr el Kalb Basin*. Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region (RICCAR) Technical Report. Beirut, United Nations. www.unescwa.org/sites/default/files/pubs/pdf/climate-proof-watershed-management-design-resilience-nahr-el-kalb_0.pdf.

ESCWA/UNFPA/NCLW (Economic and Social Commission for Western Asia/United Nations Population Fund/National Commission for Lebanese Women). 2022. *Women's Economic Participation in Lebanon: A Mapping Analysis of Laws and Regulations*. Beirut, United Nations. www.unescwa.org/sites/default/files/pubs/pdf/women-economic-participation-lebanon-mapping-analysis-laws-english.pdf.

FAO (Food and Agriculture Organization of the United Nations). 2000. Twenty-sixth FAO Regional Conference for Latin America and the Caribbean, Mérida, Mexico, 10–14 April 2000. Sustainable Development in Mountain Areas. www.fao.org/4/x4442e/x4442e.htm.

—. 2015. *Mapping the Vulnerability of Mountain Peoples to Food Insecurity*. Rome, FAO. https://openknowledge.fao.org/handle/20.500.14283/i5175e.

—. n.d. AQUASTAT Dissemination System. FAO website. https://data.apps.fao.org/aquastat/?lang=en&share=f-97207b8a-f0f7-4b27-8a0b-64ba7477c4e4. (Accessed on 20 November 2024.)

FAO/UNEP (Food and Agriculture Organization of the United Nations/United Nations Environment Programme). 2023. *Restoring Mountain Ecosystems: Challenges, Case Studies and Recommendations for Implementing the UN Decade Principles for Mountain Ecosystem Restoration*. Rome/Nairobi, FAO/UNEP. doi.org/10.4060/cc9044en.

Fayad, A. 2019. *Evaluation of the Snow Water Resources in Mount Lebanon Using Observations and Modelling*. PhD thesis, hydrology, Université Paul Sabatier-Toulouse III, 2017. NNT: 2017TOU30364. tel-01755397v2. https://theses.hal.science/tel-01755397v2.

Fayad, A., Gascoin, S., Faour, G., Fanise, P., Drapeau, L., Somma, J., Fadel, A., Al Bidar, A. and Escadafal, R. 2017. Snow observations in Mount Lebanon (2011–2016). *Earth System Science Data*, Vol. 9, No. 2, pp. 573–587. doi.org/10.5194/essd-9-573-2017.

Frazier, A. G. and Brewington, L. 2020. Current changes in alpine ecosystems of Pacific Islands. *Encyclopedia of the World's Biomes*, pp. 607–619. Elsevier. doi.org/10.1016/B978-0-12-409548-9.11881-0.

Frei, P., Kotlarski, S., Liniger, M. A. and Schär, C. 2018. Future snowfall in the Alps: Projections based on the EURO-CORDEX regional climate models. *The Cryosphere*, Vol. 12, No. 1, pp. 1–24. doi.org/10.5194/tc-12-1-2018.

Gagné, K., Rasmussen, M. B. and Orlove, B. 2014. Glaciers and society: Attributions, perceptions, and valuations. *Wiley Interdisciplinary Reviews (WIREs): Climate Change*, Vol. 5, No. 6, pp. 793–808. doi.org/10.1002/wcc.315.

García Pachón, M. P. 2018. La Conservación de Glaciares y Humedales como Ecosistemas Proveedores de Agua Dulce a Través del SINAP [Conservation of Glaciers and Wetlands as Freshwater Supply Ecosystems through the National System of Protected Areas (SINAP)]. A. Embid Irujo and M. P. García Pachón (eds), *La Conservación de la Naturaleza: Su Régimen Jurídico en Colombia y España* [Nature Conservation: Its Legal Regime in Colombia and Spain]. Bogotá, Externado University of Colombia, pp. 85–115. doi.org/10.57998/bdigital.handle.001.2118. (In Spanish.)

Garreaud, R. D., Boisier, J. P., Rondanelli, R., Montecinos, A., Sepúlveda, H. H. and Veloso-Águila, D. 2019. The central Chile mega drought (2010–2018): A climate dynamics perspective. *International Journal of Climatology*, Vol. 40, No. 1, pp. 421–439. doi.org/10.1002/joc.6219.

Ghosh, D. 2021. Alps Mountain Range. WorldAtlas website, 18 March 2021. www.worldatlas.com/mountains/alps-mountain-range.html.

GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH). 2021. *Regional Action Plan for a Joint Political Dialogue on Climate, Environment and Security.* GIZ. https://greencentralasia.org/en/category/regional-action-plan/.

––. 2023. *Regional Climate Change Adaptation Strategy for Central Asia*. GIZ. https://greencentralasia.org/en/regional-climate-change-adaptation-strategy-in-central-asia/.

Global Forest Watch. n.d. Madagascar. Global Forest Watch website. www.globalforestwatch.org/dashboards/country/MDG/. (Accessed on 2 December 2024.)

González Molina, S. and Vacher, J.-J. (eds). 2014. *El Perú Frente al Cambio Climático: Resultados de Investigaciones Franco-peruanas* [Peru Facing Climate Change: Results of French and Peruvian Research]. Institut de Recherche pour le Devélopment (IRD). https://repositoriodigital.minam.gob.pe/handle/123456789/1029. (In Spanish.)

Goodman, S. M., Raherilalao, M. J. and Wohlhauser, S. (eds). 2021. *Les aires protégées terrestres de Madagascar: Leur histoire, description et biota* [Terrestrial protected areas of Madagascar: Their history, description and biota]. Antananarivo, Association Vahatra. (In French.)

Government of Argentina. 2010. *Ley 26.639: Régimen de Presupuestos Mínimos para la Preservación de los Glaciares y del Ambiente Periglacial* [Law 26.639: Minimum Budget Regime for the Preservation of Glaciers and the Periglacial Environment]. https://servicios.infoleg.gob.ar/infolegInternet/anexos/170000-174999/174117/norma.htm. (In Spanish.)

Hanich, L., Chehbouni, A., Gascoin, S., Boudhar, A., Jarlan, L., Tramblay, Y., Boulet, G., Marchane, A., Baba, M. W., Kinnard, C., Simonneaux, V., Fakir, Y., Bouchaou, L., Leblanc, M., Le Page, M., Bouamri, H., Er-Raki, S. and Khabba, S. 2022. Snow hydrology in the Moroccan Atlas Mountains. *Journal of Hydrology: Regional Studies*, Vol. 42, Article 101101. doi.org/10.1016/j.ejrh.2022.101101.

ICIMOD (International Centre for Integrated Mountain Development). 2017. Reaching the Most Vulnerable Across the Border: Community-Based Flood Early Warning Systems. ICIMOD website, 12 August 2017. www.icimod.org/article/reaching-the-most-vulnerable-across-the-border-community-based-flood-early-warning-systems/.

––. 2020. *The HKH Call to Action to Sustain Mountain Environments and Improve Livelihoods in the Hindu Kush Himalaya*. Summary. Kathmandu, ICIMOD. doi.org/10.53055/ICIMOD.1.

––. 2023. *Water, Ice, Society, and Ecosystems in the Hindu Kush Himalaya: An Outlook* [P. Wester, S. Chaudhary, N. Chettri, M. Jackson, A. Maharjan, S. Nepal and J. F. Steiner (eds)]. Kathmandu, ICIMOD. doi.org/10.53055/ICIMOD.1028.

––. n.d. The Hindu Kush Himalaya Ministerial Mountain Summit 2020. ICIMOD website. www.icimod.org/hkhmms/.

ICPDR (International Commission for the Protection of the Danube River). 2014. The ICPDR and its observers: Inspiring wider interaction with stakeholders. *Danube Watch,* pp. 25–27. www.icpdr.org/sites/default/files/nodes/documents/dw2014_1.pdf.

––. 2021. *Danube Flood Risk Management Plan: Update 2021.* Vienna, ICPDR. www.icpdr.org/sites/default/files/nodes/documents/dfrmp_update_2021_lores_0.pdf.

ICPR (International Commission for the Protection of the Rhine). 2022. ICPR to Start Updating Climate Change Adaptation Strategy in Autumn 2022: Third Extreme Low Water in 20 Years Underlines Urgency. ICPR website, 15 September 2022. www.iksr.org/en/press/press-releases/press-releases-individual-presentation/iksr-beginnt-ab-herbst-2022-mit-aktualisierung-der-strategie-zur-anpassung-an-den-klimawandel-drittes-extremes-niedrigwasser-in-20-jahren-unterstreicht-die-dringlichkeit?no_cache=1&sword_list%5B0%5D=glacier&cHash=18f033335f10a05898b0ef4a1ce973a2.

IDB (Inter-American Development Bank). 2020. *Impactful Innovations: Lessons from Family Agriculture on Adaptation to Climate Change in Latin America and the Caribbean*. 2015 Competition for Successful Cases. Washington DC, IDB. https://publications.iadb.org/es/publications/english/viewer/Impactful-Innovations-Lessons-from-Family-Agriculture-on-Adaptation-to-Climate-Change-in-Latin-America-and-the-Caribbean.pdf.

IDEAM (Institute of Hydrology, Meteorology and Environmental Studies). 2021. *Informe del Estado de los Glaciares Colombianos 2020* [Report on the State of Colombian Glaciers 2020]. Bogotá, IDEAM. www.siac.gov.co/glaciares. (In Spanish.)

IEA (International Energy Agency). 2021. *Climate Impacts on Latin American Hydropower*. Paris, IEA. www.iea.org/reports/climate-impacts-on-latin-american-hydropower.

IFAD (International Fund for Agricultural Development). n.d. Madagascar. IFAD website. www.ifad.org/en/w/countries/madagascar. (Accessed on 2 December 2024.)

Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., Hyde, S., Brumby, S., Davies, B. J., Elmore, A. C., Emmer, A., Feng, M., Fernández, A., Haritashya, U., Kargel, J. S., Koppes, M., Kraaijenbrink, P. D. A., Kulkarni, A. V., Mayewski, P. A., Nepal, S., Pacheco, P., Painter, T. H., Pellicciotti, F., Rajaram, H., Rupper, S., Sinisalo, A., Shrestha, A. B., Viviroli, D., Wada, Y., Xiao, C., Yao, T. and Baillie, J. E. M. 2020. Importance and vulnerability of the world's water towers. *Nature*, Vol. 577, No. 7790, pp. 364–369. doi.org/10.1038/s41586-019-1822-y.

IPCC (Intergovernmental Panel on Climate Change). 2022. *Climate Change 2022: Impacts, Adaptation and Vulnerability.* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem and B. Rama (eds)]. Cambridge, UK/New York, Cambridge University Press. doi.org/10.1017/9781009325844.

Jackson, M., Azam, M. F., Baral, P., Benestad, R., Brun, F., Muhammad, S., Pradhananga, S., Shrestha, F., Steiner, J. F. and Thapa, A. 2023. Consequences of climate change for the cryosphere in the Hindu Kush Himalaya. P. Wester, S. Chaudhary, N. Chettri, M. Jackson, A. Maharjan, S. Nepal and J. F. Steiner (eds), *Water, Ice, Society, and Ecosystems in the Hindu Kush Himalaya: An Outlook*. Kathmandu, International Centre for Integrated Mountain Development (ICIMOD), pp. 17–71. doi.org/10.53055/ICIMOD.1030.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Bøssing Christensen, O., Bouwer, L. M., Braun, A., Colette, A., Déqué, M., Georgievski, G., Georgopoulou, E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hempelmann, N., Jones, C., Keuler, K., Kovats, S., Kröner, N., Kotlarski, S., Kriegsmann, A., Martin, E., van Meijgaard, E., Moseley, C., Pfeifer, S., Preuschmann, S., Radermacher, C., Radtke, K., Rechid, D., Rounsevell, M., Samuelsson, P., Somot, S., Soussana, J., Teichmann, C., Valentini, R., Vautard, R., Weber, B. and Yiou, P. 2013. EURO-CORDEX: New high-resolution climate change projections for European impact research. *Regional Environmental Change*, Vol. 14, pp. 563–578. doi.org/10.1007/s10113-013-0499-2.

Jorio, L. and Reusser, K. 2019. Glaciers and the Changing Landscape in the Alps. Swissinfo.ch website, 26 August 2019. www.swissinfo.ch/eng/sci-tech/swiss-glaciers-series-3-000-4-500-metres_glaciers-and-the-changing-landscape-in-the-alps/45181238.

JPL (Jet Propulsion Laboratory). 2004. Photojournal. JPL website. National Aeronautics and Space Administration (NASA). https://photojournal.jpl.nasa.gov/catalog/pia04965.

Kang, S., Zhang, Y., Qian, Y. and Wang, H. 2020. A review of black carbon in snow and ice and its impact on the cryosphere. *Earth-Science Reviews*, Vol. 210, Article 103346. doi.org/10.1016/j.earscirev.2020.103346.

Kanui, I., Kibwage, T. and Murangiri, M. R. 2016. Water tower ecosystems services and diversification of livelihood activities to neighbouring communities; A case study of Chyulu Hills water tower in Kenya. *Journal of Geography, Environment and Earth Science International,* Vol. 6, No. 4, pp. 1–12. doi.org/10.9734/JGEESI/2016/26620.

Kennedy, C. M., Fariss, B., Oakleaf, J. R., Fa, J. E., Baruch-Mordo, S. and Kiesecker, J. 2023. Indigenous Peoples' lands are threatened by industrial development; Conversion risk assessment reveals need to support Indigenous stewardship. *One Earth*, Vol. 6, pp. 1032–1049. doi.org/10.1016/j.oneear.2023.07.006.

Kiplagat, J. K., Wang, R. Z. and Li, T. X. 2011. Renewable energy in Kenya: Resource potential and status of exploitation. *Renewable and Sustainable Energy Reviews*, Vol. 15, No. 6, pp. 2960–2973. doi.org/10.1016/j.rser.2011.03.023.

Klein, R. J. T., Midgley, G. F., Preston, B. L., Alam, M., Berkhout, F. G. H., Dow, K. and Shaw, M. R. 2014. Adaptation opportunities, constraints, and limits. C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds), *Climate Change 2014: Impacts, Adaptation and Vulnerability. Part A: Global and Sectoral Aspects*. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK/New York, Cambridge University Press, pp. 899–943. doi.org/10.1017/CBO9781107415379.021.

Laurent, L., Buoncristiani, J.-F., Pohl, B., Zekollari, H., Farinotti, D., Huss, M., Mugnier, J.-L. and Pergaud, J. 2020. The impact of climate change and glacier mass loss on the hydrology in the Mont-Blanc massif. *Scientific Reports*, Vol. 10, Article 10420. doi.org/10.1038/s41598-020-67379-7.

Lourenco, M. and Woodborne, S. 2023. Defining the Angolan Highlands Water Tower, a 40 plus-year precipitation budget of the headwater catchments of the Okavango Delta. *Environmental Monitoring and Assessment*, Vol. 195, No. 7, p. 859. doi.org/10.1007/s10661-023-11448-7.

Ludwig-Maximilians-Universität of Munich. 2018. *Revision and Update of the Danube Study.* Final Report prepared on behalf of the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety of Germany, Ludwig-Maximilians-Universität of Munich and the International Commission for the Protection of the Danube River (ICPDR). www.icpdr.org/sites/default/files/nodes/documents/danube_climate_adaptation_study_2018.pdf.

Magrin, G. O., Marengo, J. A., Boulanger, J.-P., Buckeridge, M. S., Castellanos, E., Poveda, G., Scarano, F. R. and Vicuña, S. 2014. Central and South America. V. R. Barros, C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects*. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK/New York, Cambridge University Press, pp. 1499–1566. www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-PartB_FINAL.pdf.

Mani, M. (ed.). 2021. *Glaciers of the Himalayas: Climate Change, Black Carbon, and Regional Resilience.* South Asia Development Forum. Washington DC, International Bank for Reconstruction and Development/The World Bank. https://openknowledge.worldbank.org/server/api/core/bitstreams/ff8b1264-d631-5d3d-814f-80f509c82aa9/content.

Ministry of Climate and Environment of Poland. 2022. Impact of War on Natural Environment of the Carpathians in Ukraine. Department of Nature Conservation. www.gov.pl/attachment/9ed63b69-87d8-4c52-a74a-1c88385f5508.

Ministry of Energy and Mines of Ecuador. n.d. Ecuador consolida la producción eléctrica a partir de fuentes renovables [Ecuador Consolidates Electricity Production from Renewable Sources]. Ministry of Energy and Mines of Ecuador website. www.recursosyenergia.gob.ec/ecuador-consolida-la-produccion-electrica-a-partir-de-fuentes-renovables/#:~:text=Bajo%20este%20precepto%2C%20es%20importante,%2C%20geotermia%2C%20entre%20otras. (In Spanish.)

Ministry of Foreign Affairs of the Plurinational State of Bolivia. 2023. Bolivia fortalece el sistema de monitoreo de glaciares andinos [Bolivia Strengthens the Monitoring System of Andean Glaciers]. Ministry of Foreign Affairs of the Plurinational State of Bolivia website, 31 October 2023. https://cancilleria.gob.bo/mre/2023/10/31/11918/. (In Spanish.)

Ministry of National Assets of Chile. 2023. Decreto 25 - Crea el "Parque Nacional Glaciares de Santiago", en la Comuna de San José de Maipo, Provincia de Cordillera, Región Metropolitana [Decree 25 - Creates the "Santiago Glaciers National Park" in the Commune of San José de Maipo, Cordillera Province, Metropolitan Area]. Ministry of National Assets of Chile. www.bcn.cl/leychile/navegar?idNorma=1195043. (In Spanish.)

Ministry of Public Works of Chile. 2023. *Dirección General de Aguas del MOP instala dos nuevas estaciones glaciológicas en la región de Magallanes y de la Antártica Chilena* [MOP Directorate-General for Water installs two new glaciological stations in the region of Magallanes and Chilean Antarctica]. https://dga.mop.gob.cl/noticias/Paginas/DetalledeNoticias.aspx?item=1010.

MoE/UNDP/GEF (Ministry of Environment, Republic of Lebanon/United Nations Development Programme/Global Environment Facility). 2015. *Economic Costs to Lebanon from Climate Change: A First Look*. Beirut, MoE/UNDP. http://www.studies.gov.lb/getattachment/Sectors/Environment/2016/ENV-16-11/env-16-11.pdf.

Mosello, B., Foong, A., Viehoff, A. and Rüttinger, L. 2023. *Regional Consultation on Climate Change and Security in Central Asia*. Berlin/Vienna, Adelphi Research/Organization for Security and Co-operation in Europe (OSCE). https://adelphi.de/system/files/document/Regional%20consultation%20on%20climate%20change%20and%20security%20in%20central%20asia.pdf.

Mountain Partnership. 2013. *Why Mountains Matter for Energy: A Call for Action on the Sustainable Development Goals (SDGs)*. Food and Agriculture Organization of the United Nations. www.fao.org/fileadmin/templates/mountain_partnership/doc/POLICY_BRIEFS/SDGs_and_mountains_energy_en.pdf.

Mountain Research Initiative/GEO Mountains. 2023. *MRI Mountain Observatories Working Group & GEO Mountains Workshop in Central Asia: Workshop Report*. Almaty, Kazakhstan, 18–20 April 2023. doi.org/10.48350/183023.

MRC (Mekong River Commission). n.d. Hydrometeorological Monitoring. MRC website. www.mrcmekong.org/our-work/functions/basin-monitoring/hydrometeorological-monitoring/.

Mwangi, K. K., Musili, A. M., Otieno, V. A., Endris, H. S., Sabiiti, G., Hassan, M. A., Tsehayu, A. T., Guleid, A., Atheru, Z., Guzha, A. C., De Meo, T., Smith, N., Lubanga Makanji, D., Kerkering, J., Doud, B. and Kanyanya, E. 2020. Vulnerability of Kenya's water towers to future climate change: An assessment to inform decision making in watershed management. *American Journal of Climate Change*, Vol. 9, No. 3, pp. 317–353. doi.org/10.4236/ajcc.2020.93020.

Nsengiyumva, P. 2019. African mountains in a changing climate: Trends, impacts, and adaptation solutions. *Mountain Research and Development*, Vol. 39, No. 2, pp. 1–8. doi.org/10.1659/MRD-JOURNAL-D-19-00062.1.

Nyingi, D. W., Gichuki, N. and Ogada, M. O. 2013. Freshwater ecology of Kenyan highlands and lowlands. P. Paron, D. O. Olago and C. T. Omuto (eds), *Developments in Earth Surface Processes*, Vol. 16, pp. 199–218. doi.org/10.1016/B978-0-444-59559-1.00016-5.

Olmos, X. 2017. *Sostenibilidad Ambiental en las Exportaciones Agroalimentarias: Un Panorama de América Latina* [Environmental Sustainability in Agri-Food Exports: An Overview of Latin America]. Project Document. Santiago, United Nations Economic Commission for Latin America and the Caribbean (UNECLAC). https://repositorio.cepal.org/server/api/core/bitstreams/a63d47d6-c0c5-4a0a-93bd-456f684d1739/content. (In Spanish.)

Ontumbi, G. M. and Sanga, J. K. 2018. Kenya's water towers; A scenario scrutiny of Njoro sub catchment, Eastern Mau towers. International *Journal of Scientific and Technological Research (IJSTER)*, Vol. 1, No. 1, pp. 6–15.

Ownby, J. 2024. La crisis hídrica de Bogotá: "Solo nos puede salvar el cielo" [Bogotá's Water Crisis: "Only Heaven Can Save Us"]. El País website, 18 April 2024. https://elpais.com/america-colombia/2024-04-18/la-crisis-hidrica-de-bogota-solo-nos-puede-salvar-el-cielo.html. (In Spanish.)

Permanent Secretariat of the Alpine Convention. 2009a. *Water and Water Management Issues: Report on the State of the Alps*. Alpine Convention: Alpine Signals - Special Edition 2. Summary. Innsbruck, Austria/Bolzano, Italy. Permanent Secretariat of the Alpine Convention. www.alpconv.org/fileadmin/user_upload/Publications/RSA/RSA2_summary_EN.pdf.

—. 2009b. *Water and Water Management Issues: Report on the State of the Alps*. Alpine Convention: Alpine Signals - Special Edition 2. Innsbruck, Austria/Bolzano, Italy. Permanent Secretariat of the Alpine Convention. www.alpconv.org/fileadmin/user_upload/Publications/RSA/RSA2_long_EN.pdf.

—. 2019. *Natural Hazard Risk Governance: Report on the State of the Alps*. Alpine Convention: Alpine Signals – Special Edition 7. Innsbruck, Austria/Bolzano, Italy. Permanent Secretariat of the Alpine Convention. www.alpconv.org/fileadmin/user_upload/Publications/RSA/RSA7_EN.pdf.

—. 2022. *Multi-annual Work Programme of the Alpine Conference 2023–2030*. Innsbruck, Austria/Bolzano, Italy. Permanent of the Alpine Convention. www.alpconv.org/fileadmin/user_upload/Organisation/AC/XVII/AC_MAP_2023-2030_en_web.pdf.

Pohl, B., Kramer, A., Hull, W., Blumstein, S., Abdullaev, I., Kazbekov, J., Reznikova, T., Strikeleva, E., Interwies, E. and Görlitz, S. 2017. *Rethinking Water in Central Asia: The Costs of Inaction and Benefits of Water Cooperation*. Adelphi/CAREC. https://carececo.org/Rethinking%20Water%20in%20Central%20Asia.pdf.

Prinz, R., Nicholson, L. I. Mölg, T., Gurgiser, W. and Kaser, G. 2016. Climatic controls and climate proxy potential of Lewis Glacier, Mt. Kenya. *The Cryosphere*, Vol. 10, No. 1, pp. 133–148. doi.org/10.5194/tc-10-133-2016.

Reyes Haczek, A. 2022. Venezuela ya se quedó sin glaciares. ¿Qué pasa en el resto de la región? [Venezuela has Already Lost its Glaciers. What Happens in the Rest of the Region?]. CNN website, 5 August 2022. https://cnnespanol.cnn.com/2022/08/05/glaciares-nivel-del-mar-america-latina-caribe-omm-orix/. (In Spanish.)

Robbins, J. 2019. The West's Great River Hits its Limits: Will the Colorado Run Dry? Yale Environment 360 website, 14 January 2019. https://e360.yale.edu/features/the-wests-great-river-hits-its-limits-will-the-colorado-run-dry.

Romeo, R., Grita, F., Parisi, F. and Russo, L. 2020. *Vulnerability of Mountain Peoples to Food Insecurity: Updated Data and Analysis of Drivers*. Rome, Food and Agriculture Organization of the United Nations (FAO)/United Nations Convention to Combat Desertification (UNCCD). doi.org/10.4060/cb2409en.

Ruggeri, A. 2023. Could Giant Blankets and Other Extreme Actions Save Glaciers? Scientific American website, 6 March 2023. www.scientificamerican.com/article/could-giant-blankets-and-other-extreme-actions-save-glaciers/.

Russell, M. 2018. *Water in Central Asia: An Increasingly Scarce Resource*. European Union. www.europarl.europa.eu/RegData/etudes/BRIE/2018/625181/EPRS_BRI(2018)625181_EN.pdf.

Samaniego, J., Galindo, L. M., Mostacedo Marasovic, S. J., Ferrer Carbonell, J., Alatorre, J. E. and Reyes, O. 2017. *Adaptación al Cambio Climático en el Sector Agropecuario en América Latina y el Caribe: Síntesis de Políticas Públicas sobre Cambio Climático* [Adaptation to Climate Change in the Agricultural Sector in Latin America and the Caribbean: Synthesis of Public Policies on Climate Change]. United Nations Economic Commission for Latin America and the Caribbean (UNECLAC). Santiago, United Nations. www.cepal.org/sites/default/files/news/files/sintesispp_cc_adaptacion_al_cambio_climatico_en_alac.pdf. (In Spanish.)

Schmitz, T. 2020. Investing in ecosystems for water security: The case of the Kenya water towers. R. C. Brears (ed.), *The Palgrave Handbook of Climate Resilient Societies*. Cham, Switzerland, Palgrave Macmillan. doi.org/10.1007/978-3-030-32811-5_23-1.

Schoolmeester, T., Johansen, K. S., Alfthan, B., Baker, E., Hesping, M. and Verbist, K. 2018. *The Andean Glacier and Water Atlas – The Impact of Glacier Retreat on Water Resources*. Paris/Arendal, Norway, United Nations Educational, Scientific and Cultural Organization (UNESCO)/GRID-Arendal. https://unesdoc.unesco.org/ark:/48223/pf0000265810.

Shaban, A. 2020. Snow cover. *Water Resources of Lebanon*. World Water Resources. Vol. 7. Cham, Switzerland, Springer. doi.org/10.1007/978-3-030-48717-1_5.

Shaban, A., Faour, G., Khawlie, M. and Abdallah, C. 2004. Remote sensing application to estimate the volume of water in the form of snow on Mount Lebanon. *Hydrological Sciences Journal*, Vol. 49, No. 4, pp. 643–653. doi.org/10.1623/hysj.49.4.643.54432.

Shikuku, K. M., Winowiecki, L., Twyman, J., Eitzinger, A., Perez, J. G., Mwongera, C. and Läderach, P. 2017. Smallholder farmers' attitudes and determinants of adaptation to climate risks in East Africa. *Climate Risk Management*, Vol. 16, pp. 234–245. doi.org/10.1016/j.crm.2017.03.001.

Shrestha, F. 2023. Glacial Lake Outburst Floods in High Mountain Asia Documented in Regional Effort. International Centre for Integrated Mountain Development website, 15 December 2023. www.icimod.org/media-advisory/glacial-lake-outburst-floods-in-high-mountain-asia-documented-in-regional-effort/.

Shumilova, O., Tockner, K., Sukhodolov, A., Khilchevskyi, V., De Meester, L., Stepanenko, S., Trokhymenko, G., Hernández-Agüero, J. A. and Gleick, P. 2023. Impact of the Russia–Ukraine armed conflict on water resources and water infrastructure. *Nature Sustainability,* Vol. 6, pp. 578–586. doi.org/10.1038/s41893-023-01068-x.

Singh Shrestha, M. and Sherchan, U. 2018. Communicating Flood Early Warning in the Ratu Watershed. International Centre for Integrated Mountain Development website, 30 July 2018. www.icimod.org/communicating-flood-early-warning-in-the-ratu-watershed/.

Sorg, A., Bolch, T., Stoffel, M., Solomina, O. and Beniston, M. 2012. Climate change impacts on glaciers and runoff in Tien Shan (Central Asia). *Nature Climate Change*, Vol. 2, pp. 725–731. doi.org/10.1038/nclimate1592.

Stecher, G., Hohensinner, S. and Herrnegger, M. 2023. Changes in the water retention of mountainous landscapes since the 1820s in the Austrian Alps. *Frontiers in Environmental Science*, Vol. 11. doi.org/10.3389/fenvs.2023.1219030.

Sturm, M., Taras, B., Liston, G. E., Derksen, C., Jonas, T. and Lea, J. 2010. Estimating snow water equivalent using snow depth data and climate classes. *Journal of Hydrometeorology*, Vol. 11, No. 6, pp. 1380–1394. doi.org/10.1175/2010JHM1202.1.

Takase, M., Kipkoech, R. and Essandoh, P. K. 2021. A comprehensive review of energy scenario and sustainable energy in Kenya. *Fuel Communications*, Vol. 7, Article 100015. doi.org/10.1016/j.jfueco.2021.100015.

Taylor, R. G., Mileham, L., Tindimugaya, C. and Mwebembezi, L. 2009. Recent glacial recession and its impact on alpine riverflow in the Rwenzori Mountains of Uganda. *Journal of African Earth Sciences*, Vol. 55, No. 3–4, pp. 205–213. doi.org/10.1016/j.jafrearsci.2009.04.008.

Taylor, S. J., Ferguson, J. W. H., Engelbrecht, F. A., Clark, V. R., Van Rensburg, S. and Barker, N. 2016. The Drakensberg Escarpment as the great supplier of water to South Africa. *Developments in Earth Surface Processes*, Vol. 21, pp. 1–46. doi.org/10.1016/B978-0-444-63787-1.00001-9.

Torres, M. C., Naranjo, E., Fierro, V. and Carchipulla-Morales, D. 2023. Social technology for the protection of the *Páramo* in the central Andes of Ecuador. *Mountain Research and Development*, Vol. 43, No. 4, pp. D1–D11. doi.org/10.1659/mrd.2022.00022.

Travers, J. 2023. Covering Glaciers with Blankets to Hide the Ice – and the Real Problem. Columbia Climate School website, 13 January 2023. https://news.climate.columbia.edu/2023/01/13/covering-glaciers-with-blankets-to-hide-the-ice-and-the-real-problem/.

Trisos, C. H., Adelekan, I. O., Totin, E., Ayanlade, A., Efitre, J., Gemeda, A., Kalaba, K., Lennard, C., Masao, C., Mgaya, Y., Ngaruiya, G., Olago, D., Simpson, N. P. and Zakieldeen, S. 2022. Africa. H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem and B. Rama (eds), *Climate Change 2022: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK/New York, Cambridge University Press, pp. 1285–1455. doi.org/10.1017/9781009325844.011.

Umirbekov, A., Peña-Guerrero, M. D. and Müller, D. 2022. Regionalization of climate teleconnections across Central Asian mountains improves the predictability of seasonal precipitation. *Environmental Research Letters*, Vol. 17, No. 5, Article 055002. doi.org/10.1088/1748-9326/ac6229.

UNDP (United Nations Development Programme). 2019. *DECOIN: Ecuador*. Equator Initiative Case Studies. New York, UNDP. www.equatorinitiative.org/wp-content/uploads/2019/12/DECOIN-Ecuador-1.pdf.

UNDP/ENVSEC (United Nations Development Programme/Environment and Security). 2011. *The Glaciers of Central Asia: A Disappearing Resource*. UNDP. http://cawater-info.net/pdf/glaciers_of_central_asia.pdf.

UNECLAC (United Nations Economic Commission for Latin America and the Caribbean). 2024. CEPALSTAT: Statistical Databases and Publications. UNECLAC website. https://statistics.cepal.org/portal/cepalstat/dashboard.html?theme=2&lang=en. (Accessed on 10 June 2024.)

UNEP (United Nations Environment Programme). 2010. *Africa Water Atlas*. Nairobi, Division of Early Warning and Assessment, UNEP. https://na.unep.net/atlas/viewAtlasBookWithID.php?atlasID=1112.

—. 2012. *Sustainable Mountain Development. RIO 2012 and Beyond. Why Mountains Matter for Africa*. UNEP. https://openknowledge.fao.org/server/api/core/bitstreams/1278fa8d-0853-4aef-a2af-c935cb643428/content.

—. 2014. *Africa Mountains Atlas*. Nairobi, UNEP. https://wedocs.unep.org/handle/20.500.11822/9301.

—. 2022a. *The Environmental Impact of the Conflict in Ukraine: A Preliminary Review.* EO/2466/NA. Nairobi, UNEP. https://wedocs.unep.org/20.500.11822/40746.

—. 2022b. *A Scientific Assessment of the Third Pole Environment*. Nairobi, UNEP. www.unep.org/resources/report/scientific-assessment-third-pole-environment.

—. 2023a. The Carpathian Convention Marks its 20th Anniversary with a New Biodiversity Framework and a Transboundary Protected Wetland. UNEP website, 12 October 2023. www.unep.org/news-and-stories/press-release/carpathian-convention-marks-its-20th-anniversary-new-biodiversity.

—. 2023b. Shrinking Glaciers Upend Lives Across South America. UNEP website, 15 March 2023. www.unep.org/news-and-stories/story/shrinking-glaciers-upend-lives-across-south-america.

UNESCO (United Nations Educational, Scientific and Cultural Organization). 2022. *Improving Knowledge of Central Asian Glaciers and their Resilience to Climate Change*. ATA-2022/PI/2. UNESCO. https://unesdoc.unesco.org/ark:/48223/pf0000382818.

—. 2024. *Category 2 Institutes and Centres: Reviews and Renewals – Part I: Central Asian Regional Glaciological Centre (Kazakhstan)*. Two hundred and nineteenth session of the Executive Board. Paris, UNESCO. https://unesdoc.unesco.org/ark:/48223/pf0000388450.

—. n.d. Central Asian Regional Glaciological Centre. Central Asian Regional Glaciological Centre website. https://cargc.org/en/.

UNESCO/IUCN (United Nations Educational, Scientific and Cultural Organization/International Union for the Conservation of Nature). 2022. *World Heritage Glaciers: Sentinels of Climate Change*. Paris/Gland, Switzerland, UNESCO/IUCN. https://unesdoc.unesco.org/ark:/48223/pf0000383551.

United Nations. 2024. *The United Nations World Water Development Report 2024: Water for Prosperity and Peace*. Paris, United Nations Educational, Scientific and Cultural Organization (UNESCO). https://unesdoc.unesco.org/ark:/48223/pf0000388948.

—. n.d. Progress on Transboundary Water Cooperation (SDG Target 6.5). SDG 6 Data website. https://sdg6data.org/en/indicator/6.5.2. (Accessed on 3 September 2024.)

UN Women. 2023. *Women in the Agro-Food Sector in Lebanon: A Review of the Legislative Framework*. Beirut, UN Women. https://arabstates.unwomen.org/sites/default/files/2023-12/psdp-legislativeframework.pdf.

Valdivia Araica, A., Navarro, C. and Hernández, M. 2023. Climate Services: A Strategy for Increasing Resilience in Guatemala's Dry Corridor. Alliance Biodiversity & CIAT website, 3 September 2023. https://alliancebioversityciat.org/stories/stories/climate-services-strategy-to-increase-resilience-corridor-dry-guatemala.

Van der Graaf, L. and Siarova, H. 2021. Multifaceted Threats to Biodiversity in Central Asia. Global Waste Cleaning Network website, 25 September 2021. https://gwcnweb.org/2021/09/25/multifaceted-threats-to-biodiversity-in-central-asia/.

Veettil, B. K. and Kamp, U. 2019. Global disappearance of tropical mountain glaciers: Observations, causes, and challenges. *Geosciences*, Vol. 9, No. 5, p. 196. doi.org/10.3390/geosciences9050196.

Viviroli, D. and Weingartner, R. 2004. The hydrological significance of mountains: From regional to global scale. *Hydrology and Earth System Sciences*, Vol. 8, No. 6, pp. 1017–1030. doi.org/10.5194/hess-8-1017-2004.

Viviroli, D., Dürr, H. H., Messerli, B., Meybeck, M. and Weingartner, R. 2007. Mountains of the world, water towers for humanity: Typology, mapping, and global significance. *Water Resources Research*, Vol. 43, No. 7. doi.org/10.1029/2006WR005653.

Viviroli, D., Kummu, M., Meybeck, M., Kallio, M. and Wada, Y. 2020. Increasing dependence of lowland populations on mountain water resources. *Nature Sustainability*, Vol. 3, pp. 917–928. doi.org/10.1038/s41893-020-0559-9.

Wamucii, C. N., van Oel, P. R., Ligtenberg, A., Gathenya, J. M. and Teuling, A. J. 2021. Land use and climate change effects on water yield from East African forested water towers. *Hydrology and Earth System Sciences*, Vol. 25, No. 11, pp. 5641–5665. doi.org/10.5194/hess-25-5641-2021.

Wester, P., Mishra, A., Mukherji, A. and Shrestha, A. B. (eds). 2019. *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People*. Cham, Switzerland, Springer. lib.icimod.org/record/34383.

Western Bug and Sian River Basin Management Authority in Ukraine. Unpublished. 'Information obtained from N. Kruta, Western Bug and Sian River Basin Management Authority, private communication, 14 May 2024.

WGMS (World Glacier Monitoring Service). 2024. *Fluctuations of Glaciers Database*. Zurich, Switzerland, WGMS. doi.org/10.5904/wgms-fog-2024-01.

WMO (World Meteorological Organization). 2022. *The State of the Climate in Africa 2021*. WMO-No. 1300. Geneva, WMO. https://library.wmo.int/idurl/4/58070.

——. 2023. *State of the Climate in Latin America and the Caribbean 2022*. WMO-No. 1322. Geneva, WMO. https://library.wmo.int/idurl/4/66252.

——. 2024a. *State of the Climate in Africa 2023*. WMO-No. 1360. Geneva, WMO. https://library.wmo.int/idurl/4/69000.

——. 2024b. *1st Third Pole Climate Forum Consensus Statement (TPCF-1)*. Third Pole Regional Climate Forum, Lijiang, China, 4–6 June 2024. https://reliefweb.int/report/afghanistan/1st-third-pole-climate-forum-consensus-statement-tpcf-1-summary-climate-december-2023-april-2024-and-climate-outlook-june-september-2024.

World Bank. 2023. Madagascar: Making an Impact on Land Reform and Agriculture. Results Briefs. World Bank website. www.worldbank.org/en/results/2023/11/19/madagascar-making-an-impact-on-land-reform-and-agriculture.

——. n.d. World Bank Group Data. Agriculture, forestry, and fishing, value added (% of GDP) – Madagascar. World Bank website. https://data.worldbank.org/indicator/NV.AGR.TOTL.ZS?end=2023&locations=MG&start=2023&view=bar. (Accessed on 29 November 2024.)

Wymann von Dach, S., Romeo, R., Vita, A., Wurzinger, M. and Kohler, T. (eds). 2014. *La Agricultura de Montaña es Agricultura Familiar: Una Contribución de las Zonas de Montaña al Año Internacional de la Agricultura Familiar 2014* [Mountain Agriculture is Family Farming: A Contribution of Mountain Areas to the International Year of Family Farming 2014]. Rome, Food and Agriculture Organization of the United Nations (FAO)/Centre for Development and Environment (CDE)/BOKU. www.fao.org/3/a-i3480s.pdf. (In Spanish.)

Zandi, M. 2023. Central Asia's Clean Energy Opportunity: Hydropower. Atlantic Council website, 2 June 2023. www.atlanticcouncil.org/blogs/energysource/central-asias-clean-energy-opportunity-hydropower/.

Zhang, Y., Kang, S., Sprenger, M., Cong, Z., Gao, T., Li, C., Tao, S., Li, X., Zhong, X., Xu, M., Meng, W., Neupane, B., Qin, X. and Sillanpää, M. 2018. Black carbon and mineral dust in snow cover on the Tibetan Plateau. *Cryosphere*, Vol. 12, pp. 413–431. doi.org/10.5194/tc-12-413-2018.

Zhang, Y., Gao, T., Kang, S., Sprenger, M., Tao, S., Du, W., Yang, J., Wang, F. and Meng, W. 2020. Effects of black carbon and mineral dust on glacial melting on the Muz Taw glacier, Central Asia. *Science of The Total Environment*, Vol. 740, Article 140056. doi.org/10.1016/j.scitotenv.2020.140056.

Zheng, L., Gaire, N. P. and Shi, P. 2021. High-altitude tree growth responses to climate change across the Hindu Kush Himalaya. *Journal of Plant Ecology*, Vol. 14, No. 5, pp. 829–842. doi.org/10.1093/jpe/rtab035.

Zoï Environment Network. 2022. *Mountains of Central Asia: Supporting Biodiversity Safeguards in the Era of an Infrastructure Boom in Kyrgyzstan, Kazakhstan, and Uzbekistan*. IMPACT Report. CEPF-Zoï Project, 2021–2022. https://zoinet.org/wp-content/uploads/2022/06/CEPF-impact-2022-en.pdf.

Chapter 8

Knowledge- and capacity-building

UNESCO IHP*
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[1] University of Saskatchewan, [2] ICIMOD, [3] University of Calgary, [4] Tribhuvan University, [5] University of Chile and [6] International Association of Hydrological Sciences

The hydrological fundamentals of high mountain regions need to be better understood to support decision-making. Priority policies are needed to: reduce gaps in the collection of hydrometeorological data in mountain regions; develop physically based, integrated atmosphere–cryosphere–hydrology–ecology–human models; expand training to allow for the integration of different knowledge types (e.g. biophysical data, socio-economic data, and Indigenous and local knowledge); and facilitate the participation of Indigenous Peoples and local communities (IPLCs) and women in knowledge-gathering processes.

8.1 High mountain data and knowledge gaps

8.1.1 Data and models for adaptation and risk management

The high variability in mountain climate, topography, geology and vegetation – all of which influence the movement of water through the landscape – creates an exceptional need for representative hydrometeorological networks and robust information systems. High variability also contributes to uncertainties in mountain hydrometeorology – conditions in valley bottoms can be vastly different from those on mountain tops, despite small horizontal distances between them.

Hydrometeorological observations and predictions in high mountain areas are uncertain due to sparse monitoring networks and low-resolution models. Natural mountain snow and ice regimes are driven by precipitation and thermodynamics, and are affected by sharp elevational gradients in both. As a result, coarsely downscaled climate and weather models provide poor hydrometeorological predictions at scales finer than a few kilometres. These models need the capability to resolve convection, orographic precipitation processes and precipitation phases, to improve their accuracy (Karki et al., 2017).

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The hydrological fundamentals of high mountain regions need to be better understood to support decision-making

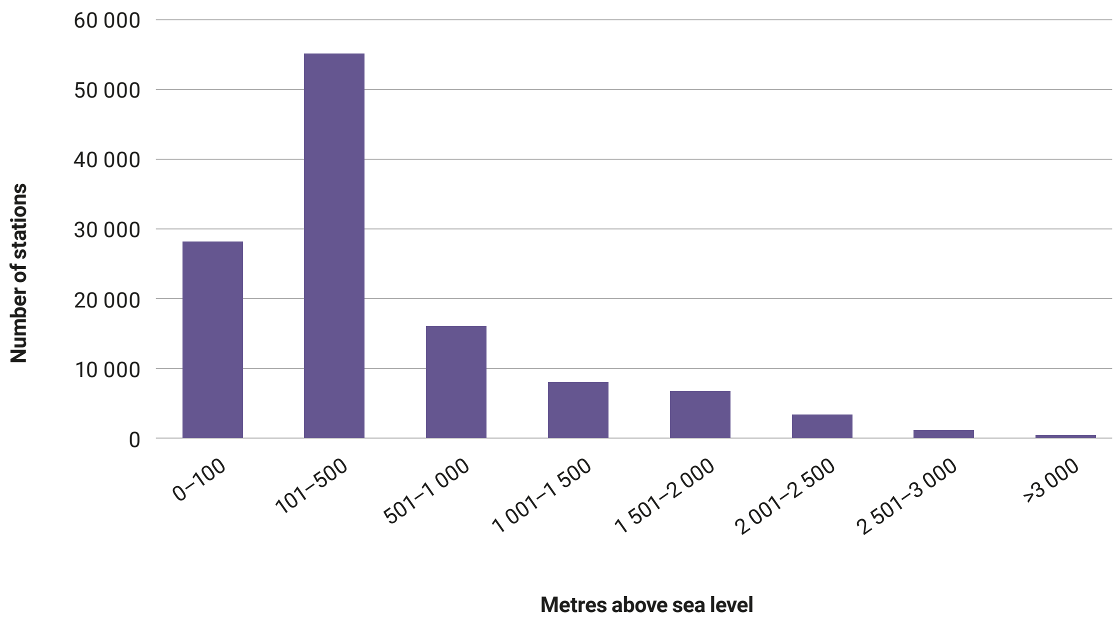
Hydroglaciological models need to operate at scales as fine as a few hundred metres and account for complex terrain windflow and slope aspect, to resolve snow redistribution and ice ablation patterns (Pradhananga and Pomeroy, 2022). Model predictions can benefit from bias correction and data assimilation, making in situ observations crucial for improving the understanding of climate–cryosphere interactions. However, obtaining these observations in mountain regions is difficult, as mountains are often high, rugged and remote, and feature considerable hazards and threats to human safety (IPCC, 2019).

The Hindu Kush Himalaya (HKH) region exemplifies this challenge: only 28 of over 50,000 glaciers have their mass balances actively measured (ICIMOD, 2023). Reference mass balance glaciers have been typically selected based on criteria such as accessibility, safety and simple geometry (Østrem, 2006), which may not fully represent the diversity of the glaciers across the broader regional context. Mountain snowpack, weather and streamflow observations are also biased towards more easily accessible low elevations.

The low-elevation bias (Figure 8.1) is incredibly problematic given the strong influence of elevation on hydrometeorological conditions, and has left the high mountains virtually unmonitored in many regions (Mountain Research Initiative EDW Working Group, 2015). Snow courses and snow pillows are predominately situated in forest clearings at mid-elevations. Even the few at high elevations are often located on relatively flat terrain, thus failing to capture the variability of snow redistribution and ablation dynamics in mountains (Bales et al., 2006).

The sparseness of cryosphere monitoring in mountain regions exacerbates uncertainties in hydroglaciological predictions, enhancing the risk of water resources mismanagement. The sparseness of historical data hinders the capacity to calculate risk and examine changes over time. Limited data also leads to acceptance of coarse model resolution, oversimplified modelling approaches and inadequate representation of hydrometeorological dynamics. Ideally, glacier hydrometeorological, hydrometric and mass balance measurement networks would be coordinated and expanded. In addition to financial, logistical and access barriers, there remains the practical limitation that as a glacier disintegrates, it becomes more difficult to consistently measure, thus making network expansions technically challenging.

Figure 8.1 Historical global distribution of hydrometeorological stations by elevation, 1750–2024



Note: Not all of these stations are currently active. High mountains (mountain regions where snow and ice play an important role in global freshwater provisioning and the local or regional hydrological cycle) vary in elevation, but most are at least 2,000 metres above sea level (masl) and some reach over 6,000 masl.

Source: Based on data from NCEI NOAA (n.d.).

As a glacier disintegrates, it becomes more difficult to consistently measure, thus making network expansions technically challenging

Remote sensing techniques such as airborne LiDAR and satellite altimetry can provide valuable information. However, they require in situ observations for validation and calibration. There is a great need for a satellite system capable of measuring mountain snow water equivalent (SWE) at high resolution; current satellites can estimate snow-covered area, but not SWE, in complex terrain.

Reducing such data gaps is essential for decreasing uncertainty and mitigating risks. Early warning systems and other mitigation interventions often rely heavily on field-deployed technology. Drought and flood prediction, optimal operation of dams and spillways, and deployment of debris nets, dry dams and dugouts to mitigate debris flows depend on robust understanding of the underlying physical systems.

To understand cryospheric changes and improve the sustainability of mitigation and adaptation approaches, there is a need for expansion of the observational infrastructure in high mountain areas, and also, importantly, for data to be open access. Expanding observations requires conducting regular and expanded glacier mass balance measurements and SWE survey transects, monitoring frozen ground thermal and soil moisture conditions, establishing more high-elevation weather stations for consistent variable monitoring including solid precipitation, temperature and snow depth, and establishing more high-elevation hydrometric, groundwater monitoring wells and lake-level stations.

There is also a need for training and deployment of mountain field technicians capable of conducting glacier, snow and hydrometric surveys, maintaining automated equipment and processing data into actionable outputs. As citizen science is explored as an option to increase data collection (Section 8.3.2), further requirements may include the need to develop validated, standardized methods tailored to public capacities and additional capacity to maintain oversight mechanisms for data-collection systems.

After data have been collected, using the information requires further human, technical and financial capacities in data management systems (Section 8.4). Having open and freely accessible data and integrated observation, prediction and service systems for mountain basins can be pivotal in supporting information usability (Adler et al., 2019), and is an area where national policy can contribute. Funding to sustain the above is necessary, although not an inherent barrier to collaborative research networks (as exemplified in Box 8.1).

Having open and freely accessible data for mountain basins can be pivotal in supporting information usability

International collaborations have been valuable in streamlining cryosphere research. For example, the International Association of Cryospheric Sciences, through the United Nations Educational, Scientific and Cultural Organization International Hydrological Programme, developed the *Glossary of Glacier Mass Balance and Related Terms* (Cogley et al., 2011) to help standardize mass balance data collection and the *International Classification for Seasonal Snow on the Ground* (Fierz et al., 2009). Standardized classification systems such as these are important for maintaining cohesion in international scientific practices and are essential for conducting global analyses.

Many public and private sector agencies engage in mountain cryosphere research and monitoring – nationally, regionally and internationally. Collaborative research networks can be a powerful and feasible tool for overcoming knowledge gaps and avoiding redundancies in research or resource deployment. Mountain ranges and basins are often transboundary, and are rarely considered as a single management unit. Individual institutions often do not have the capacity or mandate to operate the monitoring, modelling and assessment of mountain areas. This is why developing integrated observation, prediction and service systems throughout mountain basins is a valuable means of overcoming capacity and resource gaps.

Improved hydroglaciological models can bridge some data gaps. They are needed for enhanced prediction of cryospheric and hydrological changes in mountain regions. The accumulation and melt of seasonal snow and glaciers are influenced by processes that are spatially heterogeneous, sensitive to climate perturbations and rapidly changing (see Chapter 2), and yet not well represented in most models (Pomeroy et al., 2022).

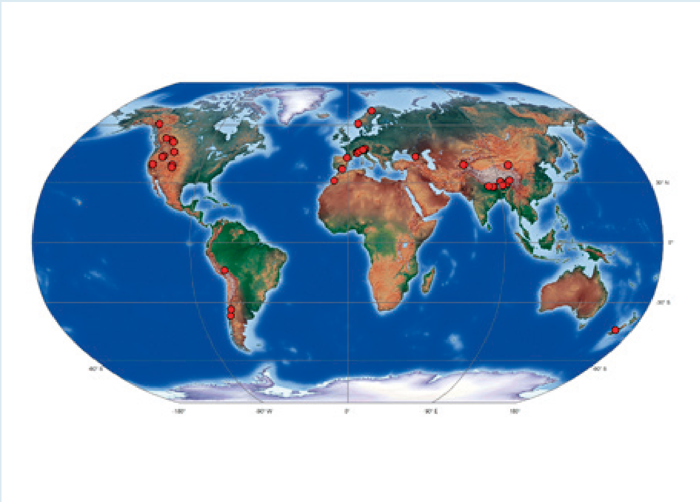
It is imperative that predictive models for mountains be grounded in the appropriate physics and not rely on data-driven, empirical or oversimplified approaches (e.g. temperature index melt models). This is due to the complex thermodynamics in the mountain cryosphere and the sparseness of available observations for calibration. As computational capacity increases along with understanding of eco- and social-hydrology, these hydroglaciological models must be coupled with ecological and social system models, as well as data assimilation. This will allow them to be able to predict not only the hydrological system but also the potential impacts on people, societies, economies and ecosystems, as well as to examine feedbacks and transient changes and to forewarn of trade-offs and unintended consequences of adaptation solutions.

Developing integrated mountain information systems is demanding. Figure 8.2 identifies the basic components of a hydrological information system, but hydrometeorological, ecological and socio-economic inputs are also needed to even determine initial objectives (WMO, 2020). The identification of needs can benefit tremendously from transdisciplinary cross-cutting networks – not only among scientists from different disciplines but also with representatives from various cultural, social, economic and political dimensions of society. To design fit-for-purpose interdisciplinary research that addresses real-time

Box 8.1 International Network for Alpine Research Catchment Hydrology (INARCH)

INARCH is a cross-cutting project of the Global Energy and Water Exchanges Hydroclimatology Panel of the World Climate Research Programme.[a] It strives to: (i) measure and understand high mountain atmospheric, hydrological, cryospheric, biological and human–water interaction processes, (ii) improve their prediction as coupled systems and (iii) diagnose their sensitivities to climate change and propose how they may be managed to promote water sustainability under global change (Pomeroy et al., 2015).

The network features 56 scientists and 38 well-instrumented research basins in 18 countries and 6 continents, operating since 2015 with no central funding. Instead, INARCH leverages other activities to achieve collective aims, with a philosophy and commitment to open data with major efforts to compile and publish these data (Pomeroy and Marks, 2024). Its success is due to the enthusiasm and hard work of individual researchers, maintaining active engagement through annual workshops in high mountain locations adjacent to research basins, and working collaboratively on initiatives such as INARCH's Common Observing Period Experiment (2022–2024). INARCH's science outcomes have underpinned the World Meteorological Organization's High Mountain Summit and the United Nations International Year of Glaciers' Preservation 2025.



Locations of INARCH research basins in mountain regions around the world

Source: Authors.

Example of an INARCH automated hydrometeorological station deployed to a high mountain basin: Qilian Mountains, China

Photo: John Pomeroy.

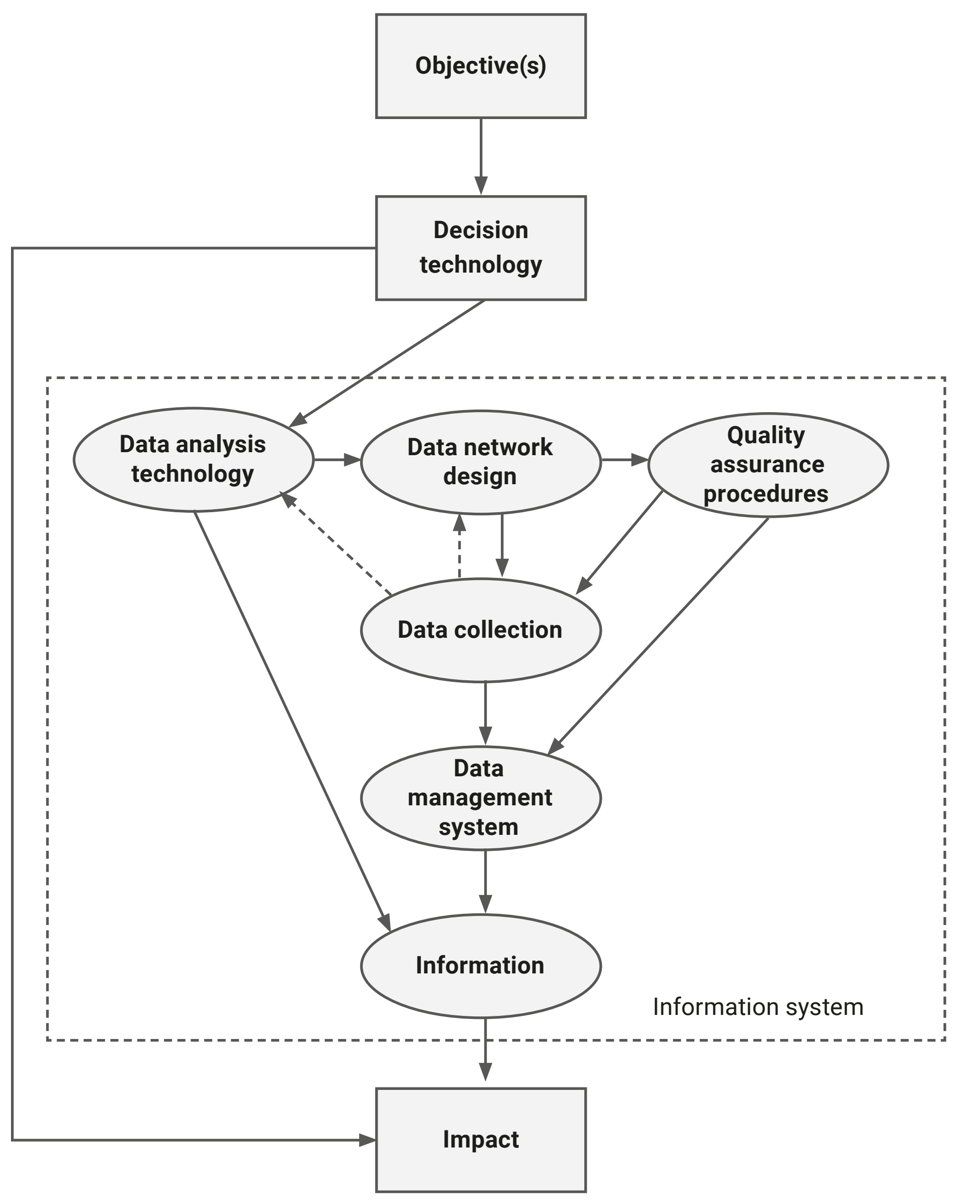
[a] For further information, please see https://inarch.usask.ca/.

Developing integrated mountain information systems is demanding

needs, a cross-sectoral mix of inputs is important, since they can help identify who the key actors are (e.g. affected communities, experts in the field and existing organizations with similar mandates), what policy and regulatory frameworks must be considered (e.g. transboundary water sharing agreements), overlapping research needs on the subject and opportunities for collaborative synergies.

Overburden of information is generally recognized as a problem in research and policymaking. It can be minimized significantly by bringing people together for a conversation to identify key directions, resources and scientific considerations. The benefits of interdisciplinary and cross-regional collaboration cannot be overstated. In the case of high mountain regions, such collaboration is necessary to capture the breadth of water systems components – atmospheric, hydrological, glaciological, ecological and human.

Figure 8.2
Components of a hydrological information system

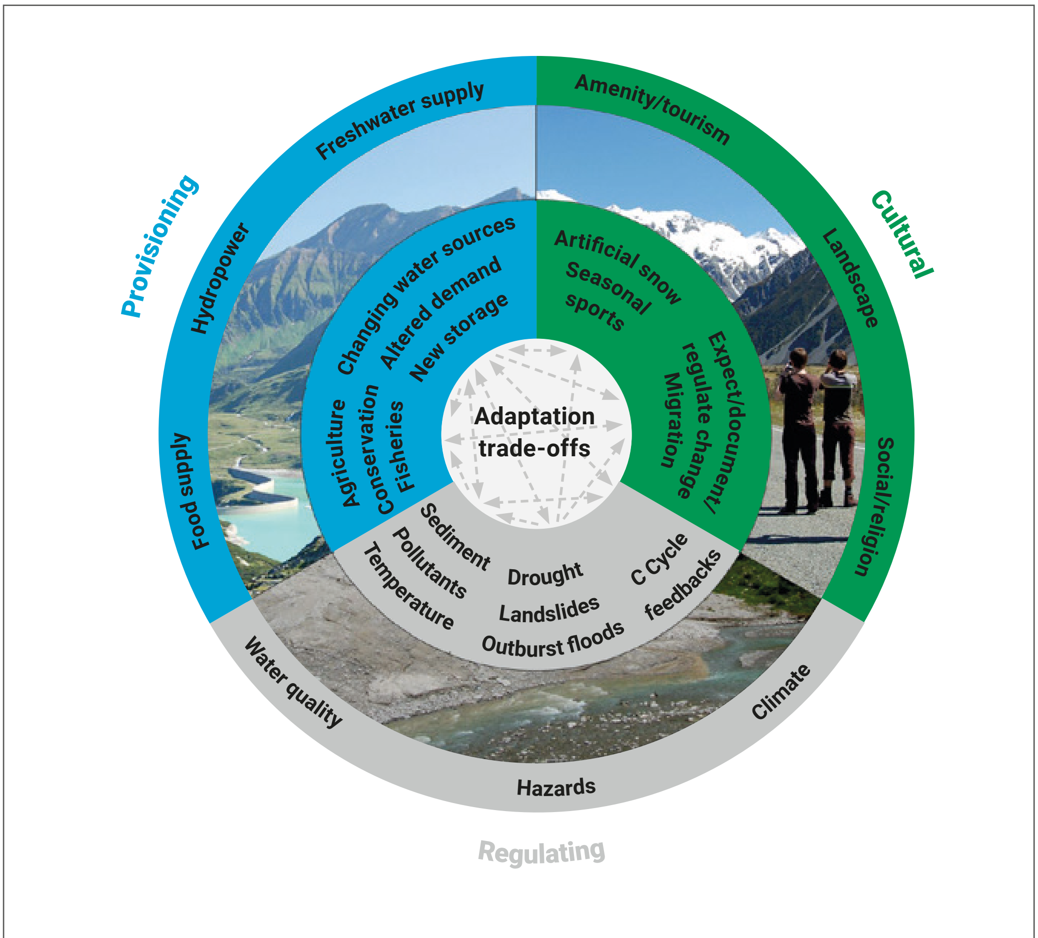


Source: WMO (2020, fig. I.2.2, p. I.2-4).

8.1.2 Ecological and environmental data gaps

The impacts of changing cryosphere conditions on ecological systems are not fully known (see Chapter 6). Environmental considerations are often framed through the lens of ecosystem services – the benefits that natural systems provide to humans for free that would otherwise need to be manufactured or created, such as adequate, potable water (Mengist et al., 2020). Ecosystem impacts deserve recognition in their own right – the value of an ecosystem is not inherently derived from the human use of it. When preparing for changing environmental conditions, efforts to explicitly recognize ways in which humans currently (and perhaps unknowingly) benefit from various mountain ecological processes is necessary for policy direction and to identify vulnerable populations. Milner et al. (2017) highlighted the importance of improving the capability to predict the timing, magnitude and duration of mountain cryosphere melt to inform necessary actions for a range of socio-economic ecosystem services, including provisioning, regulating and cultural services (Figure 8.3).

Figure 8.3
Conceptual framework integrating the effects of cryospheric shrinkage on provisioning, regulating and cultural aspects of ecosystem services



Source: Milner et al. (2017, fig. 3, p. 9775). The Attribution-ShareAlike 3.0 IGO (CC BY-SA 3.0 IGO) licence does not apply to this figure.

There are few long-term research projects on terrestrial, aquatic and marine ecosystem connections. Additional integrated studies addressing community linkages to alpine ecosystems and their adaptations to change are needed. Priority areas include understanding the impacts of cryosphere degradation on water quality, terrestrial and aquatic species distribution and productivity, local agricultural production, subsistence-related wildlife habitat and their respective relationships to water, food and health security. For example, concerns over the productivity of medicinal plants and the sustainability of herding-based livelihoods are pronounced in the HKH region, as the sensitivity of alpine environments and frequently limited options for adaptation in such extreme environments has forced migration in some circumstances (ICIMOD, 2023). Engagement with high mountain communities is vital in this regard to map ecosystem interdependencies and vulnerabilities.

As the full implications of cryosphere changes in mountain regions are unknown, the risk of crossing ecological and socio-economic sustainability thresholds is high (IPCC, 2019). Mitigation and adaptation solutions are needed, although they may not always be possible. Fundamental changes to human–environment relationships may be necessary. For example, the disappearance of snow- and glacier-fed streams has forced a Nepali community to relocate its entire village, as the water necessary to sustain crop production and livestock disappeared (Rauniyar, 2024). In this circumstance, mild adaptation and mitigation were not possible; the only true 'solution' was to fundamentally change the villagers' relationship with the surrounding environment. Fully integrated assessments of ecosystem impacts are needed to better understand such linkages and vulnerabilities, as well as the short- and long-term impacts on human health, social fabrics, cultures and livelihoods.

8.2 Contributions of Indigenous, gendered and local knowledge

Engagement and meaningful collaboration with IPLCs, with their prior informed consent and the willingness to learn from stewardship of water systems evolved over generations, will improve the collective ability to respond to changing mountain cryospheric and downstream hydrological conditions. Women have traditionally been marginalized in water management consultations, and IPLCs in mountain regions are among the most affected and yet disproportionately overlooked populations when it comes to political participation and resource allocation (Latchmore et al., 2018). While IPLCs account for 6% of the global population, they constitute 15% of the world's poorest populations, and are disproportionately affected by climate events and related water impacts (Tsosie, 2007; Amnesty International, n.d.; United Nations, n.d.).

Women have traditionally been marginalized in water management consultations

IPLCs have long-standing connections to land and water in mountain regions, which are deeply rooted in their cultural, spiritual and subsistence practices. These connections are characterized by a profound understanding of and respect for the natural environment, where traditional knowledge systems have been developed over generations to manage and sustain ecosystems. For instance, in the Andes, the Quechua and Aymara Peoples' agricultural terraces and water management systems are testament to their sophisticated adaptation to high-elevation environments. Similarly, in the Himalayas, IPLCs such as the Sherpa and Ladakhi maintain intricate relationships with their mountain homelands, where spiritual practices and daily livelihoods are tied intimately to the landscape.

This interconnectedness underscores the critical role that Indigenous stewardship – especially that of Indigenous women, who are often water protectors – plays in the preservation of mountain ecosystems and the sustainable use of their resources (Kelkar and Tshering, 2002; Cave and McKay, 2016). The cultural and spiritual significance of these regions often transcends practical uses, encompassing a holistic world-view that sees land and water as integral to identity and well-being.

IPLCs in mountain regions have intimate connections with the land that can, and should, be brought to bear on what is needed to achieve sustainable development. While all IPLCs are different, interconnectivity between water, land and humans is a cornerstone of many of their world-views, unlike those of Western science, which typically consider them through the lens of natural resources, biophysical assets or commodities, often in a segregated manner. The absence of a holistic world-view in Western science fundamentally opposes relationships between IPLCs and the natural environment. This is an area where Western ways of knowing can learn from IPLCs, especially given the need for more holistic approaches to achieve sustainable and equitable development.

Box 8.2 Co-developing a strategy for Indigenous Peoples and local community (IPLC) water research

Global Water Futures is a pan-Canadian research programme designed with IPLC water experts and knowledge keepers. Research project and proposal evaluation criteria were designed jointly by academic and Indigenous knowledge keepers – a process that ultimately identified priority themes for research projects according to IPLC values.

Key areas included: capacity-building in monitoring and data acquisition to facilitate citizen science; support for data-sharing and computer apps; improving understanding of environmental needs and flows; and recognition of the overlaps and differences between Western and IPLC approaches to science and knowledge (GWF, n.d.). Based on experiences presented at a workshop, a request for proposals was developed, and the Indigenous co-led proposals were peer reviewed by IPLC knowledge holders. The resulting projects addressed IPLC water concerns and were presented at the United Nations 2023 Conference on the Midterm Comprehensive Review of Implementation of the Objectives of the International Decade for Action, “Water for Sustainable Development”, 2018–2028.

Building on this process, Indigenous representatives from across the research network were brought together to share their perspectives on collaborative water research. Titled *Everyone Together*, the 2023 statement began by reaffirming: *“We have a responsibility to design research as stewards of our land, waters, and peoples”* (GWF, 2023, p. 2). The statement further identified an ethical space in which community wellness is a primary objective, research observes and abides by local protocols, knowledge is supported and funded equitably, and intellectual property remains in communities. This collaborative approach included and is applicable to mountain water environments.

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services assessed the diverse nature of world-views and value systems (IPBES, 2022). In addition, Chapter 6 of the 2024 edition of *The United Nations World Water Development Report* provided an example of the implications for water (United Nations, 2024). These approaches contrast with Western frameworks that have often rendered policy targets or objectives misaligned with the needs and values of the communities on the ground, such as by prioritizing one or two ‘representative indicators’ according to downstream economic, energy or urban needs (Latchmore et al., 2018). Co-developing research projects (Box 8.2) can reduce these gaps and ensure they are contextually relevant and IPLC led.

IPLCs in mountain regions can provide deep and well-informed long-term perspectives on the impacts of cryosphere changes and their consequences. The collective knowledge of IPLCs represents an overlooked and important resource, especially in under-researched and data-sparse regions.

In High Mountain Asia, scientific literature on snow and ice avalanches is limited. However, local awareness of cryosphere-related hazards is well known to affected communities and has been translated intergenerationally (Acharya et al., 2023). In Nepal, some Buddhist-sacred walls stand in locations that have historically been avalanche runout zones – a hazard that has been particularly dangerous for yak-herding populations in the area (Emerman et al., 2016; Acharya et al., 2023). The walls represent reminders not to cross or build structures in the paths, as these are where deities have expressed their wrath through natural hazards. These cultural forms of knowing have been passed through generations, but are not typically captured or recognized in Western science.

8.3 Enhancing capacity

8.3.1 Institutional needs and human capacity development

Political boundaries rarely coincide with river basin drainage divides. This makes mountain river basin management jurisdictionally complex and dependent on cooperation, communication and data-sharing across various political units, including transboundary settings (e.g. between municipal districts, subnational regions and countries). A given river basin may not cover the same spatial extent as underlying groundwater aquifers or overlying icefields, which adds another layer of governance complexity when it comes to ensuring water access.

The management of water resources may also be fragmented within political units, as various sectors and authorities interact with water in different manners. Water used for drinking water, sanitation and hygiene may fall under a public health jurisdiction, whereas water used for irrigation may fall under institutions responsible for agriculture, and water used for hydropower may fall under economic development, despite the possibility that these sectors all draw water from the same source.

Technical expertise is the necessary foundation upon which agencies and services in the decision-making realm should aim to improve

Managing the diversity and complexity of water resources therefore requires inputs from a range of disciplines and actors. Improving the institutional capacity to address these challenges requires cross-cutting training programmes, including basic education across mountain-relevant physical and social sciences. Transdisciplinarity must also be complemented by integrative capacity – the ability to use different types and sources of data and opinions that are discipline specific and potentially contradictory, and still choose a path forwards. To make such decisions in the face of conflicting priorities and resource scarcity – as is increasingly the case with water – requires substantial technical and integrative skills. Technical expertise is the necessary foundation upon which agencies and services in the decision-making realm should aim to improve the 'soft skills' needed to navigate trade-off landscapes, including analytical, communication and problem-solving skills, the ability to understand others' perspectives and the ability to defend decisions.

Institutional capacity can encompass the time and resources necessary to bring diverse people and perspectives together. The time requirements of these processes should not be underestimated, nor should the willingness or ability to collaborate be assumed. Collaborative governance models often imply trade-offs that, whereas advantageous to society in the long term, may be undesirable to current beneficiaries from the status quo. Establishing a clear, coherent vision for the future can be vital in the face of diverging perspectives. Agreed-upon values can create an umbrella under which differing parties may agree (e.g. 'fresh water for all'). Although potentially laborious, meaningful engagement is a foundation of sustainable policy and project development. Inclusive dialogue can reduce the risk of unanticipated outcomes, empower marginalized groups and maintain decision-maker accountability.

8.3.2 Citizen science and community engagement

Engaging the public in scientific processes has been proposed as a means of reducing capacity gaps and encouraging awareness of and appreciation for the natural environment (UNESCO, 2021). Citizen science refers to knowledge gathered and created scientifically by members of the public (McDonough Mckenzie et al., 2017). Participation in citizen science projects can provide valuable avenues for public engagement with the local environment, improve scientific literacy and encourage research careers (Rigler et al., 2022). Citizen science can also be a powerful mechanism for empowering youth and women by providing work experience and leadership roles, as well as addressing community needs. In data-sparse regions such as mountains, citizen science is of increasing interest as a means of filling monitoring capacity gaps.

For citizen science projects to inform scientific processes, the methodology and measurements must be sound and verifiable for consistency, accuracy and validity (McDonough Mckenzie et al., 2017). Collaboration between research organizations and community groups, where researchers develop the methods, education and training, is a common approach to ensure this requirement is met (Rigler et al., 2022) (e.g. Box 8.3). In this process, locals should provide input on project scope to ensure the knowledge outcomes meet their community needs.

Box 8.3 Research Centre for Alpine Ecosystems (CREA)-Mont Blanc: A legacy of citizen science in the Alps

CREA in France has been running citizen science programmes since 2004. Over 5,000 community members have participated in research programming across eight citizen science projects, which have collectively amassed over 40,000 data points (e.g. plant phenological characteristics such as budding/flowering dates and leaf colour change). An online hub rates the projects based on skill level needed and includes instructions and procedures for participants to follow. Findings are uploaded through an online portal, managed by research professionals. For example, Phénoclim – CREA's flagship citizen science project – generates plant phenology data and has been used to study climate impacts on alpine ecosystems (Bison et al., 2019).

Citizen science can inform and support local decision-making

Citizen science projects come in many forms. Common data points crowdsourced in mountain regions include wildlife tracking (Rueda-Uribe et al., 2024), plant identification and phenology mapping (Bison et al., 2019) and streamflow observations (Etter et al., 2020; Scheller et al., 2024). Web-based approaches for public participation, namely user-friendly apps that allow participants to upload imagery and numbers into a monitored platform, are of growing interest in remote or poorly monitored regions (Rigler et al., 2022). However, the evaluation of data validity, as opposed to the use of data, remains the primary focus of citizen science literature (McDonough Mckenzie et al., 2017; Strobl et al., 2020).

Validity concerns are the main obstacle to citizen science as a means to fill gaps. For research and science applications, measurement standards such as those of the International Organization for Standardization must be met, and consistency must be verifiable. The publication of peer-reviewed datasets in citizen science projects would be beneficial. However, this implies that some oversight and involvement by research and monitoring institutions are necessary, thus subjecting citizen science to similar capacity and resource limitations as traditional institutional approaches.

The value of citizen science should not be limited to research and monitoring. It can be a valuable tool for outreach, education, and community engagement and literacy in scientific disciplines and mountain environments. It can also inform and support local decision-making (Etter et al., 2023).

8.4 Information-sharing and communication

There are several steps between the generation of data and information products and their usability at the policy level. Information for decision-making purposes often needs to be synthesized and communicated in terms of specific targets (e.g. statistical probabilities of extreme events, projected crop yields and economic returns, or species distribution and health over time), whereas communications targeting public audiences may instead focus on simple 'big picture' ideas that lack specific details. Agencies (e.g. government, funding and research agencies) should take care to distinguish between local versus global statistics, especially when it comes to the mountain cryosphere as the complexity of mountain water resources is often mischaracterized (see Box 2.2).

Generating relevant information from raw hydrometeorological data demands substantial institutional capacity. Data points such as temperature, precipitation, streamflow, glacier mass and soil moisture need to be manipulated and analysed multiple times before they can be applied. For example: physical measurements need to be uploaded into data repositories, then corrected and validated by research technicians; raw datasets need to be input into databases and visualized or modelled in order to be interpreted; the validity and usefulness of models must be rigorously tested; and the calculation of risk and meaning of data trends over time must be translated into an appropriate language for the target audience. Each of these transformation steps has certain capacity needs, ranging from technical capacity to interpret data, financial resources to maintain historical data inventories, communicative skills to translate information into policy needs and user-friendly language, and human resources to facilitate linkages across each step (Schuster-Wallace et al., 2015).

One line of data or one analytical angle will rarely be sufficient to inform policy decisions

One line of data or one analytical angle will rarely be sufficient to inform policy decisions. This implies the additional need for decision-making bodies to possess integrative capacity – the ability to consider the needs and inputs of multiple sectors simultaneously (Section 8.3.1). The roles of hydrological and hydrometeorological agencies are primarily in providing information on the status of the climate, extremes and water resources trends to aid in risk management (WMO, 2020). However, the diversity of water resources uses and demands means that traditional water management projects must also consider for example additional, non-hydrological data such as socio-economic, ecosystem dynamics, political structures governing water rights and transboundary arrangements, and accessibility divides across, gender, age, ethnicity and class (WMO, 2009; Rowe and Schuster-Wallace, 2023).

A variety of information types is therefore needed simultaneously for sound decision-making. The different types must be made available or communicated in a manner that allows cross- and inter-sectoral projects to react and adapt appropriately to the actions of others. This can challenge assessment agencies who need to consider a diversity of water users and data formats, requiring wider skillsets and training, technical expertise among staff, and the need for continual reviews of data-collection scopes and processes.

The cross-cutting nature of water resources and mountain ecosystems can challenge the responsibility for data management and the provision of operational services. Institutional capacity for data interpretation and decision-making may face responsibility barriers, in that without explicit mandates or policies to address high mountain regions and make cross-sectoral considerations, ecosystem, human and hydrometeorological considerations may be siloed. Adopting integrative management into policy frameworks and legislation may be necessary to ensure holistic approaches to the challenges, and also the institutionalizing of interbasin cooperation through transboundary agreements.

Information-sharing networks (e.g. Box 8.1), cross-sectoral collaborations and stakeholder engagement can be powerful tools to reduce integrative capacity gaps and create sustainable outcomes. Inclusive dialogue creates opportunities for other considerations to be raised. Local participation in decision-making processes can be imperative for the long-term viability of policies and projects. Distrust or bias, for example against foreign or colonial institutions, can hinder local project uptake (Box 8.4).

Box 8.4 Beyond technical capacity: The importance of trust in project success

Laguna 513 in the Cordillera Blanca of the Peruvian Andes is a lake formed in the 1960s following glacial recession. It has been the source of repeated glacial lake outburst floods (GLOFs; see Section 2.2.3) since then (Huggel et al., 2020). After a GLOF in 2010 damaged municipal infrastructure and agricultural land downslope of the lake, local and national authorities, with help from international experts and organizations, quickly developed a GLOF early warning system (EWS) to protect inhabitants from future events. However, five years after the EWS implementation, in 2016, a group of locals dismantled the monitoring instrumentation at Laguna 513. Extreme drought conditions had fostered rumours that the technical equipment was somehow contributing to the lack of rainfall, and the mix of distrust and desperation drove locals to act.

From a capacity-building standpoint, an important takeaway from the Laguna 513 event is that despite the operational triumph of the EWS, the social context became a determining factor in its overall success. The case of Laguna 513 is not isolated; cases of local interference with foreign-operated projects have been observed elsewhere in Peru, the Himalayas, the Andes and the Alps. As important as project development and technical capacity is, at the end of the day, acceptance and understanding by relevant communities is needed for solutions to have a lasting impact (Huggel et al., 2020).

These situations serve as a reminder that even technical approaches should be embedded within social, political and cultural contexts, and that the effectiveness of data-driven systems are subject to local buy-in. Without inclusive project design – including the communication and education of research intent and anticipated outcomes – sustainability cannot be achieved (Huggel et al., 2020). As summarized in the 2022 Dushanbe Declaration from the High-Level Panel on improving knowledge, education and communication, there needs to be continued investment in community engagement, innovative communication mechanisms, solution and data repositories, research for impact, and enhanced capacity and awareness across sectors and institutions (Second High-Level Conference on the International Decade for Action “Water for Sustainable Development” 2018–2028, 2022).

8.5 Conclusions

Addressing the impacts of changes in the mountain cryosphere depends strongly on observations, knowledge and capacity in mountain regions and also downstream. The sparseness of high-elevation hydrometeorological, cryospheric and ecological observations impairs the validation and representativeness of models in high mountain environments. This is a major impediment to developing solutions to the impacts of cryospheric changes.

Improving the capacity of monitoring services to generate basic hydrometeorological data and conduct localized analyses to improve model accuracy must be a priority. Abundant, reliable data are fundamental to sound decision-making. Information- and data-sharing networks at national and regional scales (e.g. Regional Climate Centres that facilitate long-term monitoring programmes and lead the production and dissemination of products and services), as well as citizen science, offer means of reducing data gaps (WMO, 2024).

Integration of observation, modelling and service strategies may help overcome impediments to development in mountain basins. Improvements in technical capacity must also be complemented with investments in human capacity. Transdisciplinary education and communication training within decision-making institutions relevant to mountain regions and downstream areas are particularly important in this respect. IPLCs should also be included in decision-making processes, and their different knowledge systems respected.

The need for, and interest in, addressing mountain cryosphere changes is urgent, but to do so, everyone needs to work together, across governance and societal boundaries.

References

Acharya, A., Steiner, J. F., Walizada, K. M., Ali, S., Zakir, Z. H., Caiserman, A. and Watanabe, T. 2023. Snow and ice avalanches in high mountain Asia–scientific, local and Indigenous knowledge. *Natural Hazards and Earth System Sciences*, Vol. 23, pp. 2569–2592. doi.org/10.5194/nhess-23-2569-2023.

Adler, C., Huggel, C., Orlove, B. and Nolin, A. 2019. Climate change in the mountain cryosphere: Impacts and responses. *Regional Environmental Change*, Vol. 19, pp. 1225–1228. doi.org/10.1007/s10113-019-01507-6.

Amnesty International. n.d. Indigenous Peoples' Rights. Amnesty International website. www.amnesty.org/en/what-we-do/indigenous-peoples/#:~:text=Overview,speak%20more%20than%204%2C000%20languages. (Accessed on 22 October 2024.)

Bales, R. C., Molotch, N. P., Painter, T. H., Dettinger, M. D., Rice, R. and Dozier, J. 2006. Mountain hydrology of the western United States. *Water Resources Research*, Vol. 42, No. 8. doi.org/10.1029/2005WR004387.

Bison, M., Yoccoz, N. G., Carlson, B. Z. and Delestrade, A. 2019. Comparison of budburst phenology trends and precision among participants in a citizen science program. *International Journal of Biometeorology*, Vol. 63, No. 1, pp. 61–72. doi.org/10.1007/s00484-018-1636-x.

Cave, K. and McKay, S. 2016. Water song: Indigenous women and water. *Solutions*, Vol. 7, No. 6, pp. 64–73.

Cogley, J. G., Hock, R., Rasmussen, L. A., Arendt, A. A., Bauder, A., Braithwaite, R. J., Jansson, P., Kaser, G., Möller, M., Nicholson, L. and Zemp, M. 2011. *Glossary of Glacier Mass Balance and Related Terms*. IHP-VII Technical Documents in Hydrology No. 86, IACS Contribution No. 2. Paris, United Nations Educational, Scientific and Cultural Organization Intergovernmental Hydrological Programme (UNESCO IHP). https://unesdoc.unesco.org/ark:/48223/pf0000192525.

Emerman, S. H., Adhikari, S., Panday, S., Bhattarai, T. N., Gautam, T., Fellows, S. A., Anderson, R. B., Adhikari, N., Karki, K. and Palmer, M. A. 2016. The integration of the direct and indirect methods in lichenometry for dating Buddhist sacred walls in Langtang Valley, Nepal Himalaya. *Arctic, Antarctic, and Alpine Research*, Vol. 48, No. 1, pp. 9–31. doi.org/10.1657/AAAR0015-026.

Etter, S., Strobl, B., van Meerveld, I. and Seibert, J. 2020. Quality and timing of crowd-based water level class observations. *Hydrological Processes*, Vol. 34, No. 22, pp. 4365–4378. doi.org/10.1002/hyp.13864.

Etter, S., Strobl, B., Seibert, J., van Meerveld, I., Niebert, K. and Stepenuck, K. 2023. Why do people participate in app-based environment-focused citizen science projects? *Frontiers in Environmental Sciences*, Vol. 11, Article1105682. doi.org/10.3389/fenvs.2023.1105682.

Fierz, C., Armstrong, R. L., Durand, Y., Etchevers, P., Greene, E., McClung, D. M., Nishimura, K., Satyawali, P. K. and Sokratov, S. A. 2009. *The International Classification for Seasonal Snow on the Ground*. IHP-VII Technical Documents in Hydrology No. 83, IACS Contribution No. 1. Paris, United Nations Educational, Scientific and Cultural Organization Intergovernmental Hydrological Programme (UNESCO IHP). https://unesdoc.unesco.org/ark:/48223/pf0000186462.

GWF (Global Water Futures). 2023. *Everyone Together. Global Water Futures Mistawasis Nêhiyawak Water Gathering Statement*. GWF, University of Saskatchewan. https://gwf.usask.ca/indigenization/water-gathering-statement.php.

—. n.d. Indigenous Research Co-Creation. Co-developing a Strategy for Indigenous Community Water Research. GWF website. University of Saskatchewan. https://gwf.usask.ca/km/co-creation.php#CoCreationWorkshop. (Accessed on 17 May 2024.)

Huggel, C., Cochachin, A., Drenkhan, F., Fluixá-Sanmartín, J., Frey, H., García Hernández, J., Jurt, C., Muñoz, R., Price, K. and Vicuña, L. 2020. Glacier Lake 513, Peru: Lessons for early warning service development. *WMO Bulletin*, Vol. 69, No. 1, pp. 45–52. https://library.wmo.int/records/item/57750-vol-69-1-2020?offset=8.

ICIMOD (International Centre for Integrated Mountain Development). 2023. *Water, Ice, Society, and Ecosystems in the Hindu Kush Himalaya: An Outlook* [P. Wester, S. Chaudhary, N. Chettri, M. Jackson, A. Maharjan, S. Nepal and J. F. Steiner (eds)]. Kathmandu, ICIMOD. doi.org/10.53055/ICIMOD.1028.

IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services). 2022. *Summary for Policymakers of the Methodological Assessment Report on the Diverse Values and Valuation of Nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Bonn, Germany, IPBES Secretariat. doi.org/10.5281/zenodo.6522392.

IPCC (Intergovernmental Panel on Climate Change). 2019. *The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK/New York, Cambridge University Press. doi.org/10.1017/9781009157964.

Karki, R., Hasson, S. U., Schickhoff, U., Scholten, T. and Böhner, J. 2017. Rising precipitation extremes across Nepal. *Climate*, Vol. 5, No. 1, p. 4. doi.org/10.3390/cli5010004.

Kelkar, G. and Tshering, P. 2002. *Women of the Mountains: Gender Roles, Relations, Responsibilities and Rights*. Conference Proceedings at International Centre for Integrated Mountain Development (ICIMOD), Paro, October, pp. 1–4. https://lib.icimod.org/record/21093.

Latchmore, T., Schuster-Wallace, C. J., Roronhiakewen Longboat, D., Dickson-Anderson, S. E. and Majury, A. 2018. Critical elements for local Indigenous water security in Canada: A narrative review. *Journal of Water and Health*, Vol. 16, No. 6, pp. 893–903. doi.org/10.2166/wh.2018.107.

McDonough MacKenzie, C. M., Murray, G., Primack, R. and Weihrauch, D. 2017. Lessons from citizen science: Assessing volunteer-collected plant phenology data with Mountain Watch. *Biological Conservation*, Vol. 208, pp. 121–126. doi.org/10.1016/j.biocon.2016.07.027.

Mengist, W., Soromessa, T. and Legese, G. 2020. Ecosystem services research in mountainous regions: A systematic literature review on current knowledge and research gaps. *Science of the Total Environment*, Vol. 702, Article 134581. doi.org/10.1016/j.scitotenv.2019.134581.

Milner, A. M., Khamis, K., Battin, T. J., Brittain, J. E., Barrand, N. E., Füreder, L., Cauvy-Fraunié, S., Már Gíslason, G., Jacobsen, D., Hannah, D. M., Hodson, A. J., Hood, E., Lencioni, V., Ólafsson, J. S., Robinson, C. T., Tranter, M. and Brown, L. E. 2017. Glacier shrinkage driving global changes in downstream systems. *Proceedings of the National Academy of Sciences of the United Sates of America*, Vol. 114, No. 37, pp. 9770–9778. doi.org/10.1073/pnas.1619807114.

Mountain Research Initiative EDW Working Group. 2015. Elevation-dependent warming in mountain regions of the world. *Nature Climate Change*, Vol. 5, pp. 424–430. doi.org/10.1038/nclimate2563.

NCEI NOAA (National Centers of Environmental Information, National Oceanic and Atmospheric Administration). n.d. Global Historical Climatology Network daily (GHCNd) [Dataset]. NCEI NOAA website. www.ncei.noaa.gov/products/land-based-station/global-historical-climatology-network-daily. (Accessed on 16 May 2024.)

Østrem, G. 2006. History of scientific studies at Peyto Glacier. M. N. Demuth, D. S. Munro and G. J. Young (eds), *Peyto Glacier – One Century of Science*. Saskatoon, Canada, National Water Research Institute Science, Environment Canada, pp. 1–23.

Pomeroy, J. and Marks, D. (eds). 2024. Hydrometeorological data from mountain and alpine research catchments. [Special Issue]. *Earth System Science Data*. https://essd.copernicus.org/articles/special_issue871.html.

Pomeroy, J. W., Bernhardt, M. and Marks, D. 2015. Research network to track alpine water. *Nature*, Vol. 521, pp. 32–32. doi.org/10.1038/521032c.

Pomeroy, J. W., Brown, T., Fang, X., Shook, K. R., Pradhananga, D., Armstrong, R., Harder, P., Marsh, C., Costa, D., Krogh, S. A., Aubry-Wake, C., Annand, H., Lawford, P., He, Z., Kompanizare, M., Lopez, J. I. and Moreno, J. L. 2022. The cold regions hydrological modelling platform for hydrological diagnosis and prediction based on process understanding. *Journal of Hydrology*, Vol. 615, Article 128711. doi.org/10.1016/j.jhydrol.2022.128711.

Pradhananga, D. and Pomeroy, J. W. 2022. Diagnosing changes in glacier hydrology from physical principles using a hydrological model with snow redistribution, sublimation, firnification and energy balance ablation algorithms. *Journal of Hydrology*, Vol. 608, Article 127545. doi.org/10.1016/j.jhydrol.2022.127545.

Rauniyar, T. 2024. The drought that forced a Himalayan village in Nepal to relocate. BBC News, 23 May 2024. www.bbc.com/future/article/20240522-the-drought-that-forced-a-himalayan-village-in-nepal-to-relocate.

Rigler, G., Dokou, Z., Khadim, F. K., Sinshaw, B. G., Eshete, D. G., Aseres, M., Amera, W., Zhou, W., Wang, X., Moges, M., Azage, M., Li, B., Holzer, E., Tilahun, S., Bagtzoglou, A. and Anagnostou, E. 2022. Citizen science and the Sustainable Development Goals: Building social and technical capacity through data collection in the upper Blue Nile Basin, Ethiopia. *Sustainability*, Vol. 14, No. 6, Article 3647. doi.org/10.3390/su14063647.

Rowe, A. M. and Schuster-Wallace, C. 2023. Implementing EDI across a large formal research network: Contributing to equitable and sustainable water solutions for a changing climate. *Geoforum*, Vol. 147, Article 103881. doi.org/10.1016/j.geoforum.2023.103881.

Rueda-Uribe, C., Herrera-Alsina, L., Lancaster, L. T., Capellini, I., Layton, K. K. and Travis, J. M. 2024. Citizen science data reveal altitudinal movement and seasonal ecosystem use by hummingbirds in the Andes Mountains. *Ecography*, Vol. 2024, No. 3, Article e06735. doi.org/10.1111/ecog.06735.

Scheller, M., van Meerveld, I., Sauquet, E., Vis, M. and Seibert, J. 2024. Are temporary stream observations useful for calibrating a lumped hydrological model? *Journal of Hydrology*, Vol. 632, Article 130686. doi.org/10.1016/j.jhydrol.2024.130686.

Schuster-Wallace, C. J., Sandford, R., Dickin, S. K., Vijay, M., Laycock, K. and Adeel, Z. 2015. *Water in the World We Want: Catalysing National Water-Related Sustainable Development*. Hamilton, Canada, United Nations University Institute for Water, Environment and Health (UNU-IWEH). https://reliefweb.int/report/world/water-world-we-want-catalysing-national-water-related-sustainable-development.

Second High-Level Conference on the International Decade for Action "Water for Sustainable Development" 2018–2028. 2022. *Final Declaration from Dushanbe 2022 to New York 2023*. Dushanbe, 6–9 June 2022. https://dushanbewaterprocess.org/wp-content/uploads/2022/06/2022-final-declaration-final-draft-0608-en-final-1.pdf.

Strobl, B., Etter, S., van Meerveld, I. and Seibert, J. 2020. Accuracy of crowdsourced streamflow and stream level class estimates. *Hydrological Sciences Journal*, *Special Issue: Hydrological Data: Opportunities and Barriers*, Vol. 65, No. 5. doi.org/10.1080/02626667.2019.1578966.

Tsosie, R. A. 2007. Indigenous People and environmental justice: The impact of climate change. *University of Colorado Law Review*, Vol. 78, p. 1625.

UNESCO (United Nations Educational, Scientific and Cultural Organization). 2021. *UNESCO Recommendation on Open Science.* Paris, UNESCO. doi.org/10.54677/MNMH8546.

United Nations. 2024. *The United Nations World Water Development Report 2024: Water for Prosperity and Peace*. Paris, United Nations Educational, Scientific and Cultural Organization (UNESCO). https://unesdoc.unesco.org/ark:/48223/pf0000388948.

—. n.d. International Day of the World's Indigenous Peoples. United Nations website. www.un.org/en/observances/indigenous-day/background. (Accessed on 19 June 2024.)

WMO (World Meteorological Organization). 2009. *Guide to Hydrological Practices*, Volume II. WMO-No. 168. Geneva, WMO. https://library.wmo.int/records/item/36066-guide-to-hydrological-practices-volume-ii?offset=7.

—. 2020. *Guide to Hydrological Practices*, Volume I. WMO-No. 168. Geneva, WMO. https://library.wmo.int/records/item/35804-guide-to-hydrological-practices-volume-i?offset=6.

—. 2024. Inaugural Session of the Third Pole Climate Forum (TPCF 1) and Meeting of Third Pole Regional Climate Centre Network (TPRCC-Network) Task Team. WMO website. https://community.wmo.int/en/en/activity-areas/climate/meetings/inaugural-session-third-pole-climate-forum-tpcf-1-and-meeting-third-pole-regional-climate-centre-network-tprcc-network-task-team.

Chapter 9

Governance and finance

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Water governance relates to the management of water, including policies, institutions and decision-making processes for water use and conservation.[20] Mountain water governance has developed in unique manners over time, and is context specific to each mountain range. The role of water governance in mountains has not received as much attention as in lower-lying lands, on which there has been a large amount of work, such as through integrated water resources management (Molden et al., 2013).

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The role of water governance in mountains has not received as much attention as in lower-lying lands

Mountain water governance requires attention in the context of the increasing competition for water, the changing dynamics of climate and related impacts, and other global challenges. The growing pressures on water resources from socio-economic development, combined with shifts in seasonal water availability from the warm to the cold season, increase the complexity of water governance. Further understanding and collaboration is required at a range of levels and scales – within the mountains and also downstream – to address complex governance challenges and socio-ecological systems. Within present discourse and practice, mountain water governance often equates to source protection and watershed management, and how it will affect and benefit downstream users in the lowlands.

This chapter first overviews mountain water governance through international agreements and policy frameworks. Next, it examines regional conventions for transboundary river basin cooperation, as many rivers originate in mountains and cross international borders. An overview is then presented on national-level policy and implementation, relating to development interests and how communities manage their waters. Finally, financial aspects of mountain water governance are explored.

9.1 Mountain water governance at the international level

International policy frameworks offer promising support to water governance and adaptation to climate-related changes in the mountains, while addressing sustainable development. Evidence suggests that treaties and conventions are relevant enablers to promote cooperation and implementation at the mountain region scale (Dinar et al., 2016). However, globally, there is limited evidence to systematically assess their effectiveness in addressing specific challenges posed by changes in the mountain cryosphere (Hock et al., 2019).

Several agreements characterize the historical development of international mountain frameworks. The importance of mountains was formally recognized internationally at the United Nations Conference on Environment and Development in 1992. Chapter 13 of the Agenda 21 Action Plan was dedicated to sustainable mountain development (UNCED, 1992). It stressed: the importance of mountain environments at global, regional and local levels; protecting natural resources including water; enhancing the livelihoods of communities and Indigenous Peoples; and promoting international cooperation on mountains. By endorsing Chapter 13 at the highest political level, including over 178 United Nations Member States, the international community for the first time formally signalled its common concern and plan of action (Romeo et al., 2022).

A decade later, the United Nations declared 2002 as the International Year of Mountains. The outcome document of the United Nations Conference on Sustainable Development, titled The Future We Want, recognized that *"Mountain ecosystems play a crucial role in providing water resources to a large portion of the world's population"* (General Assembly of the United Nations, 2012, p. 41).

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[20] The special report on *The Ocean and Cryosphere in a Changing Climate* refers to governance as an *"effort to establish, reaffirm or change formal and informal institutions at all scales to negotiate relationships, resolve social conflicts and realise mutual gains"* (IPCC, 2019, p. 687).

In 2008, the General Assembly of the United Nations adopted Resolution 62/196 on sustainable mountain development. It recognized that mountains provide indications of climate change, through the retreat of glaciers and changes in seasonal runoff that may affect sources of fresh water. Challenges to sustainable mountain development were identified, including growing water demand (notably downstream) and the consequences of erosion, deforestation, watershed degradation and disasters. The resolution emphasized the importance of mountains as headwaters and sources of water for often densely populated downstream areas (General Assembly of the United Nations, 2008).

International policy frameworks offer promising support to water governance and adaptation to climate-related changes in the mountains

More recently, the General Assembly of the United Nations declared 2022 as the International Year of Sustainable Mountain Development, proposed by the Government of Kyrgyzstan and sponsored by 94 countries.

Mountain waters have also received attention from other international frameworks, such as the Paris Agreement (UNFCCC, 2015) and the Sendai Framework for Disaster Risk Reduction 2015–2030 (General Assembly of the United Nations, 2015a). These frameworks highlighted the importance of monitoring and reporting on targets and indicators relevant for water governance.

The Convention on the Protection and Use of Transboundary Watercourses and International Lakes (Water Convention) provides a unique global legal and intergovernmental platform for transboundary cooperation in water management, and can be instrumental for mountain sustainable management and conservation. The Convention obliges and helps countries to develop and implement transboundary agreements and to set up joint bodies for transboundary cooperation covering also mountain regions. Moreover, the Convention ensures a source-to-sea approach where the basin from upstream to downstream is managed as a holistic system.

The United Nations Sustainable Development Goals (SDGs) (General Assembly of the United Nations, 2015b) may offer additional prospects to strengthen water governance under a changing cryosphere, given that monitoring and reporting on key water-related targets and indicators, and their interaction across other SDGs, include the provision of water as a condition for development. However, there has been limited evidence to assess their effectiveness on an evidentiary basis (Hock et al., 2019).

9.2 Regional mountain water governance

Most large rivers originate in mountain areas and often cross international borders. Transboundary water governance, based on a 'basin-level view' that considers mountain waters, can provide benefits to riparian countries. Regional cooperation among countries, including river basin governance initiatives, is an important mechanism for advancing climate adaptation in mountains (Molden et al., 2013; Mishra et al., 2019). Treaties or agreements can: enhance riparian cooperation through increased monitoring and data generation to address the chronic lack of data in mountain regions; help identify and resolve gaps in human and institutional technical capacity; establish joint management committees; promote information-sharing; and promote and foster dialogue and diplomacy between riparians (Adler et al., 2022).

Research on regional mountain governance initiatives has identified some components relevant to mountain waters (Box 9.1). While initial agreements between riparians are often insufficient or too general to induce sustained cooperation, such agreements create the groundwork for additional treaties that do elicit increased cooperation[21] (e.g. those

[21] Customary international law and general principles also govern the uses of transboundary waters, which can be beneficial for facilitating cooperation.

Conflict between national interests within transboundary water agreements, as well as the effectiveness of institutions to navigate coordination within local context, have hindered effective cooperation

that are more specific and targeted at a given problem in the basin). Climatic-induced increasing hydrological variability drives countries to exhibit cooperative behaviour, notably at the operational scale (e.g. water management from shared infrastructure between riparians). However, once hydrological variability increases beyond a certain threshold, cooperative behaviour can be negatively affected (Dinar et al., 2016). Conflict between national interests within transboundary water agreements, as well as the effectiveness of institutions to navigate coordination within local context, have hindered effective cooperation (Kliot et al., 2001; Hayat et al., 2022).

The following three regional agreements provide examples of transboundary water cooperation in the mountains.

The **Hindu Kush Himalaya** (HKH) mountain range extends over 3,500 km, and is shared by eight countries (Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal and Pakistan). The mountains are the source of ten major river basins. The region is home to 240 million people, and an estimated 1.65 billion people downstream depend on mountain waters for drinking water and sanitation, food (irrigation), energy (hydropower) and ecosystem services (habitats, environmental flows and rich cultural values). Glacier- and snow-melt are important components of streamflow, with their relative contributions increasing with elevation and proximity to glacier and snow reserves. Groundwater from springs in the mid-hills of the HKH region is also an important contributor to river baseflow (Wester et al., 2019).

In the HKH region, effective transboundary cooperation to improve water governance is lacking. The focus of intergovernmental initiatives has been on (national-level) political and economic interests, rather than social and environmental well-being at the regional scale. Water governance is characterized by hybrid formal–informal regimes with a prevalence of informal institutions at the local level and formal state institutions at national and regional levels. Synergy and support between state and informal water management institutions is often lacking. Gender inequalities are prevalent in institutions, translating into unequal access to water. At the regional level, data-sharing and improved cooperation on water sharing are often impeded by lack of trust. Data- and information-sharing are crucial steps for transboundary disaster risk reduction, such as for glacial lake outburst floods (see Section 2.2.3) and river floods. Mistrust between riparians limits benefit-sharing in water and its related services like irrigation, energy and navigation (Wester et al., 2019).

Box 9.1 Components of regional mountain governance initiatives

Key features of regional mountain governance initiatives include:

- Territoriality: spatial scope of the initiative, in terms of members' jurisdictions and the spatial ambit of the arrangements.
- Institutional formality: degree of justification, or informality, and means of enforcement.
- Sectoral integration: number of sectors and institutional mechanisms linking them.
- Vertical coordination: diversity and nature of involvement by governmental actors at different levels, as well as acceptance of and mechanisms for applying subsidiarity.
- Civil society participation: degree and nature of involvement of non-governmental organizations and the private sector.
- Science–policy interface: nature of institutional mechanisms for bilateral exchange between policymakers and scientists.
- Funding arrangements: assessment of funding sources and outlays, to the extent that information is available.
- Climate change related ecosystem-based adaptation, including for water.

Source: Extracted from Balsiger et al. (2020, pp. 5–6).

Critical components to enhance water governance and transboundary cooperation have been identified for the HKH region (see Section 7.4). These include: the need for formal frameworks as a foundation for regional cooperation; the importance of knowledge-sharing platforms to facilitate regional cooperation; and the need for an appropriate mechanism to manage conflicts and equitably distribute benefits (Wester et al., 2019).

While river basin (local) transboundary cooperation has a long history in the HKH region, mountain range-wide governance is a recent phenomenon (Box 9.2). The language of transboundary cooperation is somewhat plagued by political and territorial agendas and interests. It can be considered more favourable to pursue riparian cooperation framed as regional cooperation within mountain ranges.

Box 9.2 Hindu Kush Himalaya (HKH) High-Level Task Force

In a progressive move to strengthen mountain range-wide governance, the eight HKH countries created the HKH High-Level Task Force, to follow up on earlier recommendations by the HKH Call to Action (ICIMOD, 2020). The countries approved the High-Level Task Force during the first HKH Ministerial Mountain Summit in 2020. The meeting of ministers from across the eight countries signed an historically significant declaration agreeing to strengthen regional cooperation in the HKH region. Senior government officials now collaborate in the HKH High-Level Task Force, to monitor progress on the HKH Call to Action and to assess the potential for institutional mechanisms to strengthen regional cooperation.

The HKH Call to Action provides a road map for the future of the region, framed around six actions:

1. Cooperate at all levels across the HKH region for sustainable and mutual benefits.

2. Recognize and prioritize the uniqueness of the HKH mountain people.

3. Take concerted climate action at all levels to keep global warming to 1.5°C by 2100.

4. Take accelerated actions to achieve the Sustainable Development Goals and nine mountain priorities.

5. Enhance ecosystem resilience; halt biodiversity loss and land degradation.

6. Regional data- and information-sharing, and science and knowledge cooperation.

Transboundary water cooperation and governance is addressed in the Call to Action.

For example, Action 5 calls on the HKH countries to implement programmes on freshwater ecosystems, including the cryosphere and watersheds, to sustain water quality and flows in the rivers of the HKH region by adopting river basin management at the transboundary scale. The HKH countries need to integrate freshwater and aquatic ecosystems into national and subnational policies and strategies. This includes environmental and social impact assessments in development projects such as for hydropower, dams and roads. It also advocates incentivizing payments for ecosystem services for people who protect catchment areas of hydropower stations, and for drinking water supply and tourism.

And Action 6 calls for data generation and sharing on climate variables, including for water, energy and food security, biodiversity and mountain poverty. It proactively promotes riparian cooperation in open data-sharing for public goods and services.

Sources: Adapted from ICIMOD (2020) and Adaptation at Altitude (n.d.).

The **Alpine Convention** (see Section 7.2.1) is an international treaty to address transboundary cooperation in the Alps, signed in 1991, with a permanent secretariat and governing body (Romeo et al., 2022). The convention includes Austria, France, Germany, Italy, Liechtenstein, Monaco, Slovenia, Switzerland and the European Union. It is one of only two legally binding mountain treaties, along with the Carpathian Convention (Balsiger et al., 2020). It identifies 12 areas through eight legally binding protocols.[22] Yet there is no water protocol, with water management being a cross-cutting dimension (Balsiger, 2007; Lackner and Psenner, 2007). Water management is under the legal jurisdiction of national governments. The Alpine Convention Secretariat aids member countries by developing guidelines on topics such as climate change impacts on water resources in the Alps (Permanent Secretariat of the Alpine Convention, 2014). The convention has provided opportunities for accelerating adaptation measures through mainstreaming riparian policy responses, promoting partnership building and networking (Balsiger, 2007).

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The management of mountain waters takes place primarily within country borders, through national legislation, policy and strategies

The **Carpathian Convention** was established in 2003 to protect the second-largest mountain range in Europe (see Section 7.2.2). It includes Czechia, Hungary, Poland, Romania, Serbia, Slovakia and Ukraine (Secretariat of the Carpathian Convention, 2020). It is the only multilevel governance mechanism for the entire Carpathian area, providing a framework for cooperation and multisectoral policy coordination, a platform for joint strategies for sustainable development and a forum for dialogue among all stakeholders involved (Climate-ADAPT, n.d.). The United Nations Environment Programme hosts the Secretariat of the Carpathian Convention. The Carpathian Convention's working group includes a long-term vision to adapt to climate change. Article 6 of the convention focuses on sustainable and integrated river basin management. There is also a working group on adaptation that mentions the vulnerability of water and ecosystems to climate change and adaptation in its mandate.

9.3 National and local mountain water governance

The management of mountain waters takes place primarily within country borders, through national legislation, policy and strategies. Policy formulation and implementation take place within a country's political economic context. In some cases, national policies for water, agriculture, industry and energy are developed to favour low-lying regions of river basins, for instance, to serve more populous areas. National policies may often not fully reflect water sectoral issues within the mountains; rather, they tend to focus on mountains as sources for downstream users.

Recommendations by international frameworks and transboundary agreements provide guidance for national policy development and strategies. Several considerations and approaches are universally recommended to improve mountain water governance. These include: strengthening collaboration and increasing monitoring including data collection and sharing; engaging with diverse Indigenous knowledge and local knowledge; promoting gender equality; prioritizing inclusive development and climate adaptation approaches to reduce mountain poverty; and establishing conflict resolution platforms/mechanisms and benefit-sharing arrangements between riparians (Adler et al., 2022).

Evidence from the HKH region highlights that policy implementation in countries will improve only if national governments recognize the multisectoral and cross-scalar nature of water governance. Implementation depends on the engagement of various stakeholders, including Indigenous communities and women, and engaging with local knowledge. There is a need for facilitating upstream and downstream interactions for improving landscape-level governance. Strengthening community participation and decentralization, promoting multi-stakeholder development and addressing implementation challenges are recommended at

[22] Spatial planning and sustainable development, Mountain farming, Nature protection and landscape conservation, Mountain forests, Tourism, Energy, Soil conservation and Transport.

the national level. Governments need to create regulatory frameworks and local institutional arrangements to enable the expansion of successful initiatives to empower community action and inspire community–government partnerships (Wester et al., 2019).

Mountain regions could accrue substantial benefits if governance were to prioritize more inclusive development and adaptation approaches. These include respectful engagement with the diverse Indigenous knowledge and local knowledge systems in the mountains, and a sustained effort to tackle the root causes of vulnerability. This would require: improved coordination and monitoring activities; more inclusive decision-making mechanisms including for small-scale farmers, women, Indigenous systems and youth groups; and a substantial increase in funding for sustainable mountain development. These key governance enablers are an important response to the challenges facing mountain regions, especially in relation to mountain waters.

Glacier protection laws

Only a few countries have laws specifically dedicated to the protection or preservation of glaciers. Argentina's Glacier National Glacier Act (see Section 7.3.1), aimed at prohibiting mining in glacier and permafrost areas, was approved in 2010 and upheld by Argentina's Supreme Court in 2018 (Taillant, 2019). In 2024, Tajikistan passed a law outlining the legal, economic and organizational basis for the protection of glaciers as objects of the environment and strategic sources of water resources (Republic of Tajikistan, 2024). Other countries such as Chile (see Box 5.1) and Kyrgyzstan have proposed similar laws identifying glaciers as protected areas (Iribarren Anacona et al., 2018).

As glaciers are dynamic systems, such legal frameworks can be complex and difficult to adopt and enforce. They may include considerations with regard to water supply and quality, and preventive or emergency measures to address glacial hazards, while balancing different views and needs in order to avoid social, environmental and economic conflicts.

9.4 Valuation and finance

While some of the goods and services provided by mountain environments – such as timber, hydropower and minerals – may have a measurable economic value (e.g. extraction costs versus profits), environmental benefits and values are much more difficult to monetize – clean water, air and biodiversity are classic examples. Furthermore, mountain resources are themselves inherently complex and interrelated, so they constitute a joint product rather than a single one.

Examining losses and damages caused by natural hazards also provides some insight into the overall value of mountain regions (Box 9.3).

National governments are important sources of investment, usually through sectoral instruments such as agriculture and water policy

Financial resources availability

National governments are important sources of investment, usually through sectoral instruments such as agriculture and water policy. Different territorial cooperation programmes with some 'mountain component' can also provide funding. In developing countries, bilateral and multilateral donors may provide some additional funding (Balsiger et al., 2020).

Adaptation finance and private sector inclusion and contribution are key enablers for achieving the adaptation potential in mountains (Mishra et al., 2019; UNEP, 2023). While substantial funding is potentially available for investment in sustainable development in mountain regions, access to major support programmes has been relatively limited. This indicates a significant response option is underutilized (McDowell et al., 2020). More specifically, innovative and affordable international, regional, national and local funds should be mobilized to support water, agriculture and energy planning and infrastructure investments. Enhanced uptake of available support and funding could help to ease the burden for mountain communities and countries, for which the capacity and ability of actors to identify, access and mobilize resources need strengthening. Some enabling factors have been identified to encourage financial investment in the mountains (Box 9.4) (Wymann von Dach et al., 2016).

Box 9.3 Economic losses from natural hazards in mountains

Between 1985 and 2014, reported economic damage costs in mountain regions from flood and mass movements (including those not directly linked to the cryosphere) were highest in the Hindu Kush Himalaya region (US$45 billion), followed by the European Alps (US$7 billion) and the Andes (US$3 billion) (Stäubli et al., 2018). In Peru, the cost of glacier shrinkage for the energy sector has been estimated at US$740 million annually, with an overall reduction of 11–15% in electricity production (Vergara et al., 2007). Similarly, Switzerland, which uses hydropower to generate over half of the country's energy, was projected to lose about 21% of its annual inflow in the 2031–2050 period compared with 1991–2010, and a further reduction in hydropower potential due to cryosphere shrinkages was expected (Gaudard et al., 2013).

Records on monetary damage often include only the value of destroyed infrastructure, and do not assess agricultural land values (Muhammad et al., 2021), or long-term damage to the road, health or education infrastructures (Shrestha et al., 2023). Heightened risks of climate hazards combined with changing meltwater supplies have hardest hit Indigenous Peoples and local mountain communities who rely on glacier- and snow-melt to sustain their livelihoods. These communities often endure non-economic or intangible loss and damage, such as loss of cultural heritage and sacred landscapes, which also threatens their capacity to adapt (Adler et al., 2022).

Source: Adapted from UNEP (2023).

Box 9.4 Factors encouraging financial investment in mountains

- An enabling national environment. This includes a national policy for mountain regions, linked to overall national development policy, that can encourage and coordinate public investment.
- Security is a precondition for investment. This relates to political stability, as well as trusted leadership, rule of law, and secure access to resources such as land, credit, savings and insurance, for local, national and international investors.
- Investment should preferably be decentralized, with a focus on small and medium enterprises. Reasons are the dispersed settlement, dissected topography and low population density in many mountains compared with lowlands. Small- and medium-sized towns present opportunities for implementing these investment principles.
- Political and fiscal decentralization is important to take account of the great diversity, often over short distances, in environment, society and culture. It entails devolving power, competence and funding to subnational and local bodies.
- Transboundary collaboration creates opportunities for investment, as mountain regions often straddle national boundaries. These include investing in transit infrastructure, transboundary water management infrastructure and disaster risk reduction strategies. Transboundary river basin organizations and basin authorities could facilitate or host riparian states' joint investment planning, thereby streamlining efficient innovative blended finance mechanisms.
- Knowledge and research. Local and scientific knowledge and capacity development are important for tailoring investment to specific natural and cultural conditions. Monitoring the outcomes of investment is important for illustrating the benefits for mountain communities and ecosystems as well as for investors, and thus for attracting more investment in sustainable mountain development in the future.

Source: Adapted from Wymann von Dach et al. (2016, p. 67).

Development in mountains is generally more costly and difficult than in lowlands due to the rugged terrain and poor accessibility, restrictions on economies of scale, long distance from seaports and economic centres, and poorly developed industrial and service sectors. Costs related to transport, infrastructure, goods and services increase with elevation and isolation. This needs to be considered in policy and financing, with calls for mountain-specific policies and programmes in national and global development plans.

Development in mountains is generally more costly and difficult than in lowlands

While the importance of ecosystem services (see Chapter 6) provided by mountains is widely acknowledged, mountain people who contribute to sustaining these resources are seldom compensated. Policies and investments will be more sustainable if they promote the equitable sharing of benefits from the development of mountain waters with mountain people. Mountain waters provide ample scope for the development of investment and compensation mechanisms for safeguarding mountain ecosystems, as well as for improving mountain livelihoods. This could be, for instance, through participatory funding for watershed management and direct benefit-sharing (e.g. of hydropower income streams with people living in the vicinity of the power plants).

Upland–lowland production linkages and trade terms tend to be asymmetrical, favouring the lowlands, with extractive industries such as mining, hydropower generation and timber harvesting tending to be of little benefit to mountain people. Focusing on joint investment plans that cover multiple sectors – such as energy, agriculture, fisheries, drinking water, transport and ecosystem services – can provide interesting risk–return profiles. Integrated joint investment plans can also help reduce the likelihood of conflict by creating a common understanding of sectoral, political and generational interests based on current and future water availability, offering interesting risk reduction properties for investors (UNCDF, 2021).

References

Adaptation at Altitude. n.d. Hindu Kush Himalaya. Adaptation at Altitude website. https://mountains-connect.org/mountain-range-hindu-kush-himalaya/.

Adler, C., Wester, P., Bhatt, I., Huggel, C., Insarov, G. E., Morecroft, M. D., Muccione, V. and Prakash, A. 2022. Mountains. H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem and B. Rama (eds), *Climate Change 2022: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK/New York, Cambridge University Press, pp. 2273–2318. doi.org/10.1017/9781009325844.022.

Balsiger, J. 2007. *Regionalism Reconsidered: The Alpine Convention as a Model of Earth System Governance*. Paper presented at the 2007 Amsterdam Conference on the Human Dimensions of Global Environmental Change, 24–26 May 2007.

Balsiger, J., Dupuits, E. and Scolobig, A. 2020. *International Experience in Transboundary Mountain Governance: Insights for Andean Cooperation*. Geneva, Institute for Environmental Governance and Territorial Development, University of Geneva. https://archive-ouverte.unige.ch/unige:145756.

Climate-ADAPT. n.d. Carpathian Convention. Climate-ADAPT website. https://climate-adapt.eea.europa.eu/metadata/organisations/carpathian-convention.

Dinar, S., Katz, D., De Stefano, L. and Blankespoor, B. 2016. *Climate Change and Water Variability: Do Water Treaties Contribute to River Basin Resilience?* Policy Research Working Paper No. 7855. Washington DC, World Bank. https://documents.worldbank.org/en/publication/documents-reports/documentdetail/209901476193940390/climate-change-and-water-variability-do-water-treaties-contribute-to-river-basin-resilience.

Gaudard, L., Gilli, M. and Romerio, F. 2013. Climate change impacts on hydropower management. *Water Resources Management*, Vol. 27, pp. 5143–5156. doi.org/10.1007/s11269-013-0458-1.

General Assembly of the United Nations. 2008. Sustainable Mountain Development. Resolution adopted by the General Assembly on 19 December 2007. Sixty-second session, A/RES/62/196. https://documents.un.org/doc/undoc/gen/n07/475/53/pdf/n0747553.pdf.

—. 2012. The Future We Want. Resolution adopted by the General Assembly on 27 July 2012. Sixty-sixth session, A/RES/66/288. www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_66_288.pdf.

—. 2015a. Sendai Framework for Disaster Risk Reduction 2015–2030. Resolution adopted by the General Assembly on 3 June 2015. Sixty-ninth session, A/RES/69/283. www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_69_283.pdf.

—. 2015b. Transforming Our World: The 2030 Agenda for Sustainable Development. Resolution adopted by the General Assembly on 25 September 2015. Seventieth session, A/RES/70/1. www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_70_1_E.pdf.

Hayat, S., Gupta, J., Vegelin, C. and Jamali, H. 2022. A review of hydro-hegemony and transboundary water governance. *Water Policy*, Vol. 24, No. 11, pp. 1723–1740. doi.org/10.2166/wp.2022.256.

Hock, R., Rasul, G., Adler, C., Cáceres, B., Gruber, S., Hirabayashi, Y., Jackson, M., Kääb, A., Kang, S., Kutuzov, S., Milner, A., Molau, U., Morin, S., Orlove, B. and Steltzer, H. 2019. High mountain areas. H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds), *The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK/New York, Cambridge University Press, pp. 131–202. doi.org/10.1017/9781009157964.004.

ICIMOD (International Centre for Integrated Mountain Development). 2020. *The HKH Call to Action to Sustain Mountain Environments and Improve Livelihoods in the Hindu Kush Himalaya*. Kathmandu, ICIMOD. doi.org/10.53055/ICIMOD.1.

IPCC (Intergovernmental Panel on Climate Change). 2019. Annex I: Glossary [Weyer, N. M. (ed.)]. H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds), *The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK/New York, Cambridge University Press, pp. 677–702. doi.org/10.1017/9781009157964.015.

Iribarren Anacona, P., Kinney, J., Schaefer, M., Harrison, S., Wilson, R., Segovia, A., Mazzorana, B., Guerra, F., Farías, D., Reynolds, J. M. and Glasser, N. F. 2018. Glacier protection laws: Potential conflicts in managing glacial hazards and adapting to climate change. *Ambio*, Vol. 47, pp. 835–845. doi.org/10.1007/s13280-018-1043-x.

Kliot, N., Shmueli, D. and Shamir, U. 2001. Institutions for management of transboundary water resources: Their nature, characteristics and shortcomings. *Water Policy*, Vol. 3, No. 3, pp. 229–255. doi.org/10.1016/S1366-7017(01)00008-3.

Lackner, R. and Psenner, R. 2007. *The Water Balance of the Alps: What do we need to Protect the Water Resources of the Alps?* Proceedings of the Conference held at Innsbruck University, 28–29 September 2006. Innsbruck University Press. doi.org/10.26530/OAPEN_503830.

McDowell, G., Harris, L., Koppes, M., Price, M. F., Chan, K. M. A. and Lama, D. G. 2020. From needs to actions: Prospects for planned adaptations in high mountain communities. *Climatic Change*, Vol. 163, pp. 953–972. doi.org/10.1007/s10584-020-02920-1.

Mishra, A., Appadurai, A. N., Choudhury, D., Regmi, B. R., Kelkar, U., Alam, M., Chaudhary, P., Mu, S. S., Ahmed, A. U., Lotia, H., Fu, C., Namgyel, T. and Sharma, U. 2019. Adaptation to climate change in the Hindu Kush Himalaya: Stronger action urgently needed. P. Wester, A. Mishra and A. B. Shrestha (eds), *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People*. Cham, Switzerland, Springer, pp. 457–490. doi.org/10.1007/978-3-319-92288-1_13.

Molden, D., Hurni, H., Zimmermann, A. and Wymann von Dach, S. 2013. Focus issue: Water governance in mountains. *Mountain Research and Development*, Vol. 33, No. 3, pp. 193–94. doi.org/10.1659/mrd.3303.

Muhammad, S., Li, J., Steiner, J. F., Shrestha, F., Shah, G. M., Berthier, E., Guo, L., Wu, L.-X. and Tian, L. 2021. A holistic view of Shisper Glacier surge and outburst floods: From physical processes to downstream impacts. *Geomatics, Natural Hazards and Risk*, Vol. 12, No. 1, pp. 2755–2775. doi.org/10.1080/19475705.2021.1975833.

Permanent Secretariat of the Alpine Convention. 2014. Framework Convention: Guiding Principles for Sustainable Life in the Alps. Alpine Convention website. www.alpconv.org/en/home/convention/framework-convention/.

Republic of Tajikistan. 2024. *Закон Республики Таджикистан о защите ледников* [Law of the Republic of Tajikistan about Protection of Glaciers]. No. 2026. Dushanbe. https://faolex.fao.org/docs/pdf/taj224299.pdf. (In Russian.)

Romeo, R., Manuelli, S. and Abear, S. 2022. The International Year of Sustainable Mountain Development 2022: An opportunity to promote action for mountains. *Frontiers in Sustainable Food Systems*, Vol. 6, No. 933080. doi.org/10.3389/fsufs.2022.933080.

Secretariat of the Carpathian Convention. 2020. *Long-Term Vision 2030 Towards Combating Climate Change in the Carpathians*. Carpathian Convention Working Group on Climate Change. Sixth Meeting of the Conference of the Parties to the Framework Convention on the Protection and Sustainable Development of the Carpathians. http://www.carpathianconvention.org/tl_files/carpathiancon/Downloads/03%20Meetings%20and%20Events/COP/2020_COP6_Online/official%20documents/CC%20COP6%20DOC10_Long_Term_Vision_2030_FINAL%20DRAFT.pdf.

Shrestha, F., Steiner, J. F., Shrestha, R., Dhungel, Y., Joshi, S. P., Inglis, S., Ashraf, A., Wali, S., Walizada, K. M. and Zhang, T. 2023. A comprehensive and version-controlled database of glacial lake outburst floods in High Mountain Asia. *Earth System Science Data*, Vol. 15, No. 9, pp. 3941–3961. doi.org/10.5194/essd-15-3941-2023.

Stäubli, A., Nussbaumer, S. U., Allen, S. K., Huggel, C., Arguello, M., Costa, F., Hergarten, C., Martínez, R., Soto, J., Vargas, R., Zambrano, E. and Zimmermann, M. 2018. Analysis of weather- and climate-related disasters in mountain regions using different disaster databases. S. Mal, R. B. Singh and C. Huggel (eds), *Climate Change, Extreme Events and Disaster Risk Reduction: Towards Sustainable Development Goals*. Sustainable Development Goals Series. Cham, Switzerland, Springer, pp. 17–41. doi.org/10.1007/978-3-319-56469-2_2.

Taillant, J. D. 2019. Argentine Supreme Court Upholds Glacier Law. Center for Human Rights and Environment website. https://center-hre.org/argentine-supreme-court-upholds-glacier-law/.

UNCDF (United Nations Capital Development Fund). 2021. *Blue Peace Financing Initiative: Solving Local Water and Sanitation Challenges Through Cooperation and Sustainable Financing*. UNCDF. www.uncdf.org/article/7569/blue-peace-financing-initiative-solving-local-water-and-sanitation-challenges-through-cooperation-and-sustainable-financing.

UNCED (United Nations Conference on Environment and Development). 1992. Managing fragile ecosystems: Sustainable mountain development. *Agenda 21*. UNCED, Rio de Janeiro, Brazil. https://sustainabledevelopment.un.org/content/documents/Agenda21.pdf.

UNEP (United Nations Environment Programme). 2023. *Underfinanced. Underprepared. Inadequate Investment and Planning on Climate Adaptation Leaves World Exposed.* Adaptation Gap Report 2023. Nairobi, UNEP. doi.org/10.59117/20.500.11822/43796.

UNFCCC (United Nations Framework Convention on Climate Change). 2015. *Paris Agreement*. United Nations. https://unfccc.int/sites/default/files/english_paris_agreement.pdf.

Vergara, W., Deeb, A., Valencia, A., Bradley, R., Francou, B., Zarzar, A., Grünwaldt, A. and Haeussling, S. 2007. Economic impacts of rapid glacier retreat in the Andes. *EOS*, Vol. 88, No. 25, pp. 261–264. doi.org/10.1029/2007EO250001.

Wester, P., Mishra, A., Mukherji, A. and Shrestha, A. B. (eds). 2019. *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People*. Cham, Switzerland, Springer. lib.icimod.org/record/34383.

Wymann von Dach, S., Bachmann, F., Borsdorf, A., Kohler, T., Jurek, M. and Sharma, E. 2016. *Investing in Sustainable Mountain Development: Opportunities, Resources and Benefits*. Sustainable Mountain Development Series. Bern, Centre for Development and Environment (CDE)/University of Bern/Bern Open Publishing (BOP). http://www.carpathianconvention.org/tl_files/carpathiancon/Downloads/04%20Publications%20-%20Press%20-%20Gallery/Documents%20and%20Publications/CDE_2016_Investing%20in%20Sustainable%20Mountain%20Development.pdf.

Chapter 10

Conclusions

UNESCO WWAP
Richard Connor

Why mountains matter to everyone

Covering nearly one-quarter of the global land surface, mountains provide 55–60% of the world's annual freshwater flows. As the 'water towers' of the world, they are a vital source of fresh water for billions of people – in the mountains and downstream. They also supply other essential, and often unique, natural resources, goods and services used worldwide. Despite their fundamental importance, mountain regions generally receive much less attention than other parts of the world, and are largely absent from global policy agendas. Lying at the intersection of the water–climate–biodiversity crises, their critical role in sustainable development cannot be ignored.

The main economic activities in mountain regions are agriculture, pastoralism, forestry, tourism, mining, cross-border trade and energy production. Mountains provide high-value products such as medicinal plants, timber and other forest products, unique mountain livestock and speciality agriculture products. They are global hotspots of agrobiodiversity, with a large fraction of the world's gene pools for agriculture and medicinal plants preserved in mountains.

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Mountain regions generally receive much less attention than other parts of the world, and are largely absent from global policy agendas

As a result of climate change, mountain regions are warming rapidly, which affects their comportment in the water cycle in unprecedented and, in many cases, unpredictable ways. Although the accelerating rate at which alpine glaciers are melting has received considerable and well-deserved attention, the seasonal snowpack, rather than glaciers, is the primary source of runoff in most high mountain areas. However, the relative importance and contributions of melting snow, ice and frozen ground to downstream water resources availability and quality are often poorly understood and mischaracterized (see Chapter 2).

The consequences of climate change, including higher temperatures, glacial recession, permafrost thaw and changing precipitation patterns, can increase the risks of natural hazards such as landslides, floods and debris flows. The total area and number of glacial lakes have increased significantly since the 1990s as glaciers have receded. More of these lakes will develop over the next decades, creating new hotspots of potentially dangerous glacial lake outburst floods.

Unsustainable land-use practices, from deforestation to the rapid expansion of towns and cities, and pollution from human activities such as mining, threaten the hydrological balance of these fragile regions, their ecosystems, and the life and livelihoods they support from source to sea.

Over 1 billion people (around 15% of the world's population) reside in mountain regions, most (90%) of whom live in developing countries. About two-thirds of the global mountain population live in towns and cities. The difficult terrain, increased exposure to natural hazards and higher costs in mountain regions make it more challenging to develop and maintain water supply and drainage networks, water treatment plants and source protection in these rapidly urbanizing areas (see Chapter 4).

Up to one-half of rural mountain dwellers in developing countries suffer from food insecurity, with women and children being most at risk (see Chapter 3). Factors contributing to food insecurity include remoteness and inaccessibility (e.g. distance from roads and food markets), limited growing seasons, large variations in seasonal water supply for agriculture and low levels of mechanization.

Water-dependent industries have developed in mountain areas where water and other resources are found in relative abundance (see Chapter 5). In addition to energy production (e.g. for hydropower), water is also required to extract and process minerals, produce timber and develop tourism. Remote mountain areas can be difficult to regulate, resulting in uncontrolled water withdrawals and discharges, including industrial pollutants that can affect water quality for mountain and downstream communities.

Water-related ecosystem services provided by mountains include water storage and flood regulation, and protection against erosion and landslides. Mountains feature a diverse range of ecological zones and often have higher endemic biodiversity than lowlands, including important genetic varieties of agricultural crops and animals (see Chapter 6). Hydrological changes will determine how most mountain ecosystems change, more so than the direct impacts of changes in temperature.

Responses: Moving forwards

Water plays a fundamental role in **climate change adaptation** in mountains. Most documented adaptation efforts in mountain regions address water-related aspects (e.g. precipitation variability and extremes, including drought, flooding and water availability) through measures such as developing **early warning systems**. Water also plays a role in adaptation in other sectors, such as agriculture, disaster risk reduction, and tourism and recreation.

As some 30% of the world's forests are located in mountain regions, the potential for carbon storage and sequestration is substantial. However, with the exception of forest protection and reafforestation for carbon storage, opportunities for **climate change mitigation**, including through land use and land-use change, are often limited.

Evidence suggests treaties and conventions are relevant enablers to promote cooperation and implementation at the mountain region scale

Water conservation efforts in mountain regions, including restoration and protection of particularly vulnerable areas (e.g. wetlands), watershed management and judicious water use, are robust, low-regret adaptation measures. Efforts to 'grow ice' in the winter through snow-making and ice stupas to augment early meltwater flows in the spring have also been attempted, with some success at small/local scales.

Reducing water-related risks in mountain areas will require addressing the root causes of vulnerability, which include poverty, marginalization and inequitable gender dynamics. Acknowledging and respecting the many cultures and diverse **Indigenous and local knowledge** in the mountains, which form the backbone of community adaptive capacity, can create strong foundations for site-specific integrated adaptation and mitigation strategies. Inclusive governance structures and processes, including the design and implementation of policies and measures, can help realize that capacity.

The growing pressures on water resources from socio-economic development combined with shifts in seasonal water availability from the warm to the cold season will increase the complexity of **water governance**. Improvements in river basin management require more than additional human-built infrastructure.

International policy frameworks offer promising support to water governance and adaptation to climate-related changes in the mountains, while addressing sustainable development. Evidence suggests treaties and conventions are relevant enablers to promote cooperation and implementation at the mountain region scale.

The importance of mountains as headwaters and sources of water for often densely populated downstream areas was recognized by the General Assembly of the United Nations in 2008, with the adoption of Resolution 62/196 on sustainable mountain development. Water governance in mountains often equates with 'source protection' and watershed management, benefiting downstream users. It is therefore in everyone's interest to govern and manage (and finance) mountain regions sustainably.

As most large rivers originate in mountain areas and are frequently shared among several countries, **transboundary water governance** based on a 'basin-level view' that carefully considers mountain waters can provide large benefits to riparian countries. **Regional cooperation** among countries to foster transboundary landscape and river basin governance is an important mechanism for advancing sustainable development in mountains, particularly as many mountain ranges and mountain ecosystem services are transboundary in nature. Treaties or agreements can enhance cooperation through data- and information-sharing, help to fill gaps in human and institutional technical capacity, and promote and foster dialogue and diplomacy.

Costs related to transport, infrastructure, goods and services increase with elevation and isolation

The recommendations of international frameworks and transboundary agreements provide guidance for national policy development and strategies. However, the management of mountain waters takes place primarily within country borders, through **national legislation, policy and strategies**. Policy formulation and implementation take place within a country's political economic context. In some cases, national policies for water, agriculture, industry and energy are developed to favour the low-lying regions of river basins, for instance, to serve more populous areas. National policies may often not fully reflect water sectoral issues within the mountains; rather, they tend to focus on mountains as sources for downstream users.

Although substantial funding is potentially available for **investments** in sustainable development in mountain regions, access to major support programmes has been relatively limited, indicating a significant response option is underutilized. Enhanced uptake of available **support and funding** could help to ease the burden for mountain communities and countries, for which the capacity and ability of actors to identify, access and mobilize resources need strengthening.

In general, development in mountains is more costly and difficult than in lowlands due to the rugged terrain and poor accessibility, restrictions on economies of scale, long distance from seaports and economic centres, and poorly developed industrial and service sectors. Costs related to transport, infrastructure, goods and services increase with elevation and isolation. This needs to be considered in **policy and financing**, with calls for mountain-specific policies and programmes in national and global development plans.

Understanding mountain hydrology and the role of the cryosphere is important for sustainable development and anticipatory planning and action in light of the substantial changes under way. However, many mountain regions are poorly monitored with regard to even basic parameters such as temperature and precipitation. In addition, most monitoring stations are located in lower-elevation mountain valleys, providing scant coverage of higher-elevation mountain climate.

The lack of **data and long-term monitoring and research** on the mountain cryosphere, and more broadly mountain waters, hinders taking effective action, and is a key area for investment in **long-term knowledge- and capacity-building**.

In a world of growing water scarcity, improving knowledge of present and future mountain water resources is of fundamental importance. This calls for sustained investments in costly long-term high-elevation monitoring stations of glaciers and climate, as well as **integrative science across all disciplines**, to better understand mountain waters and societies. Full and open access to all water data would also be commendable.

Coda

Mountains provide life-sustaining fresh water to billions of people and countless ecosystems. As the world's water towers, their critical role in sustainable development cannot be ignored.

Actions must be taken to better understand and protect these fragile environments, increasingly threatened by climate change and unsustainable human activities.

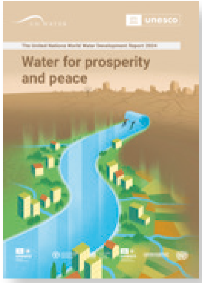
Because nothing that happens in mountains stays in mountains.

In one way or another, ***we all live downstream***.

Abbreviations and acronyms

CBFEWS	Community-based flood early warning system(s)
CREA	Research Centre for Alpine Ecosystems
DRR	Disaster risk reduction
EbA	Ecosystem-based adaptation
EST	Environmentally sound technology
EWS	Early warning system(s)
GIAHS	Globally Important Agricultural Heritage System(s)
GLOF	Glacial lake outburst flood
HKH	Hindu Kush Himalaya
INARCH	International Network for Alpine Research Catchment Hydrology
IPLC	Indigenous Peoples and local community
IWRM	Integrated water resources management
LDN	Land degradation neutrality
masl	Metres above sea level
MDC	Mountainous developing country
NAP	National adaptation plan
NbS	Nature-based solution(s)
NDC	Nationally determined contribution
ODA	Official development assistance
PGS	Participatory Guarantee System
PSH	Pumped storage hydropower
ROS	Rain on snow
SDG	Sustainable Development Goal
SWE	Snow water equivalent
TPRCC-Network	Third Pole Regional Climate Centre Network
WASH	Water, sanitation and hygiene

THE UNITED NATIONS WORLD WATER DEVELOPMENT REPORT



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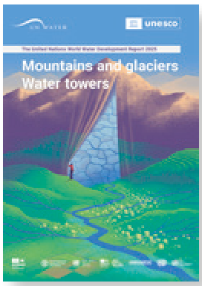

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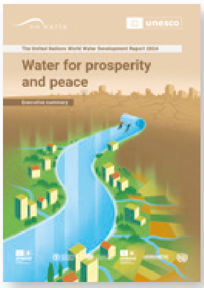

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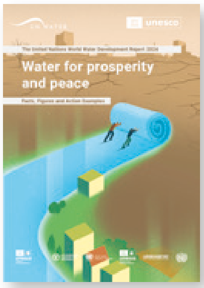

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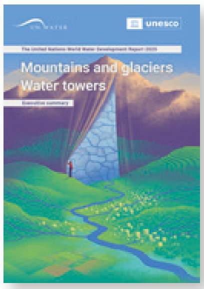

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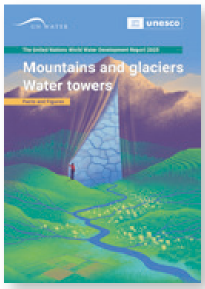

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World Water
Assessment Programme

UN-WATER REPORTS AND OTHER RELEVANT PUBLICATIONS

UN-Water coordinates the efforts of United Nations entities and international organizations working on water and sanitation issues. By doing so, UN-Water seeks to increase the effectiveness of the support provided to Member States in their efforts towards achieving international agreements on water and sanitation. UN-Water publications draw on the experience and expertise of UN-Water's Members and Partners.

The United Nations World Water Development Report (WWDR)

The WWDR is UN-Water's flagship report on water and sanitation issues, focusing on a different theme each year. The report is published by the United Nations Educational, Scientific and Cultural Organization (UNESCO) on behalf of UN-Water, and its production is coordinated by the UNESCO World Water Assessment Programme. The report gives insight on main trends concerning the state, use and management of fresh water and sanitation, based on work done by the Members and Partners of UN-Water. Launched in conjunction with World Water Day, the report provides decision-makers with knowledge and tools to formulate and implement sustainable water policies. It also offers best practices and in-depth analyses to stimulate ideas and actions for better stewardship in the water sector and beyond.

United Nations System-wide Strategy for Water and Sanitation

As follow-up to the United Nations 2023 Water Conference, General Assembly resolution A/RES/77/334 requested "the Secretary-General to present a United Nations system-wide water and sanitation strategy in consultation with Member States before the end of the seventy-eighth session of the General Assembly". The goal of the Strategy is to enhance United Nations system-wide coordination and delivery of water-related priorities resulting in more strategic, effective, coherent and efficient support to Member States in their efforts to accelerate progress on national plans and priorities, internationally agreed water-related goals and targets, and transformative solutions to current and future water-related challenges. The strategy was launched in July 2024 at the High Level Political Forum on Sustainable Development in New York.

UN-Water Global Analysis and Assessment of Sanitation and Drinking-Water (GLAAS)

The GLAAS report is produced by the World Health Organization (WHO) on behalf of UN-Water. It provides a global update on the policy frameworks, institutional arrangements, human resource base, and international and national finance streams in support of water and sanitation. It is a substantive input into the activities of Sanitation and Water for All as well as the progress reporting on Sustainable Development Goal (SDG) 6.

Progress reports of the WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation and Hygiene (JMP)

The JMP is affiliated with UN-Water and is responsible for global monitoring of progress towards SDG 6 targets for universal access to safe and affordable drinking water and adequate and equitable sanitation and hygiene services. Every two years, the JMP releases updated estimates and progress reports for water, sanitation and hygiene in households (as part of the progress reporting on SDG 6), schools and health care facilities.

UN-Water Country Acceleration Case Studies

To accelerate the achievement of SDG 6 targets as part of the SDG 6 Global Acceleration Framework, UN-Water releases SDG 6 Country Acceleration Case Studies to explore countries' pathways to achieving accelerated progress on SDG 6 at the national level. The case studies document replicable good practices for achieving the SDG 6 targets as well as look at how progress can be accelerated across SDG 6 targets in a country. Since 2022, nine studies have been released from Brazil, Cambodia, Costa Rica, Czechia, Ghana, Jordan, Pakistan, Senegal and Singapore. Three new ones are planned to be released in July 2025 from Bhutan, Rwanda and Saudi Arabia.

Policy and Analytical Briefs

UN-Water's Policy Briefs provide short and informative policy guidance on the most pressing freshwater-related issues that draw upon the combined expertise of the United Nations system. Analytical Briefs provide an analysis of emerging issues and may serve as basis for further research, discussion and future policy guidance.

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WORLD WATER DAY AND THE UNITED NATIONS WORLD WATER DEVELOPMENT REPORT

The United Nations designates specific days, weeks, years and decades as occasions to mark particular events or topics in order to promote, through awareness and action, the objectives of the Organization.

International observances are occasions to educate the general public on issues of concern, to mobilize political will and resources to address global problems, and to celebrate and reinforce achievements of humanity.

The majority of observances have been established by resolutions of the United Nations General Assembly. World Water Day (22 March) dates back to the 1992 United Nations Conference on Environment and Development where an international observance for water was recommended.

The United Nations General Assembly responded by designating 22 March 1993 as the first World Water Day. It has been held annually since then and is one of the most popular international days together with International Women's Day (8 March), the International Day of Peace (21 September) and Human Rights Day (10 December).

Every year, UN-Water — the UN's coordination mechanism on water and sanitation — sets a theme for World Water Day corresponding to a current or future water-related challenge. This theme also inspires the theme of the United Nations World Water Development Report that is presented on World Water Day. The publication is UN-Water's flagship report and provides decision-makers with tools to formulate and implement sustainable water policies. The report also gives insight on main trends including the state, use and management of fresh water and sanitation, based on work by the Members and Partners in UN-Water.

The report is published by UNESCO, on behalf of UN-Water, and its production is coordinated by the UNESCO World Water Assessment Programme.

Mountains – often referred to as the world's 'water towers' – are becoming increasingly vulnerable to climate change and unsustainable human activities, threatening the water resources upon which billions of people and countless ecosystems depend.

The United Nations World Water Development Report 2025 – ***Mountains and glaciers: Water towers*** calls attention to the essential services and benefits mountain waters and alpine glaciers provide to societies, economies and the environment. With a focus on the technical and policy responses required to improve water management in mountains, the report covers critical issues such as water supply and sanitation, climate change mitigation and adaptation, food and energy security, industry, disaster risk reduction and ecosystem protection.

In alignment with the designation of 2025 as the International Year of Glaciers' Preservation and the 2022 resolution of the General Assembly of the United Nations on sustainable mountain development, this report draws worldwide attention to the importance of mountain waters, including alpine glaciers, in the sustainable development of mountain regions and the downstream societies that depend upon them, in the context of the rapidly changing mountain cryosphere.

The **United Nations World Water Development Report** *is UN-Water's flagship report on water and sanitation issues, focusing on a different theme each year. The report is published by UNESCO, on behalf of UN-Water and its production is coordinated by the* **UNESCO World Water Assessment Programme***. The report gives insight on main trends concerning the state, use and management of fresh water and sanitation, based on work done by the Members and Partners of UN-Water. Launched in conjunction with World Water Day, the report provides decision-makers with knowledge and tools to formulate and implement sustainable water policies. It also offers best practices and in-depth analyses to stimulate ideas and actions for better stewardship in the water sector and beyond.*

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