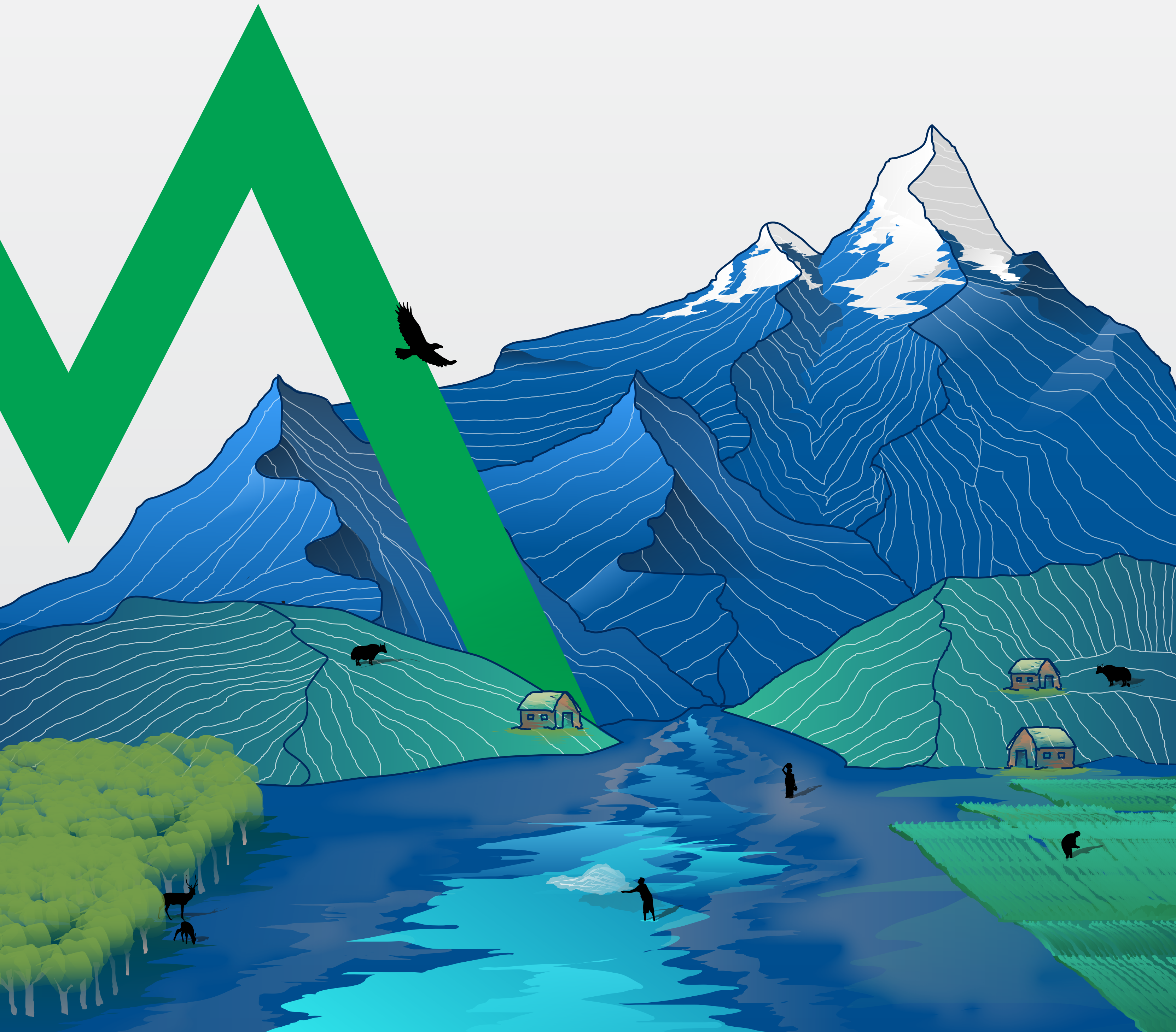
ICIMOD

Water, ice, society, and ecosystems in the Hindu Kush Himalaya

An outlook



Published by

International Centre for Integrated Mountain Development
GPO Box 3226, Kathmandu, Nepal

ISBN 978-92-9115-759-4 (print)
978-92-9115-758-7 (electronic)

DOI https://doi.org/10.53055/ICIMOD.1028

Production team

EDITORS
Rachana Chettri, Nagraj Adve, Carmen Wickramagamage, Kundan Shrestha

DESIGNER
Mohd Abdul Fahad and **Sudip Kumar Maharjan**

Citation

ICIMOD. (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, & J. F. Steiner [Eds.]). ICIMOD. https://doi.org/10.53055/ICIMOD.1028

Water, ice, society, and ecosystems in the Hindu Kush Himalaya

An outlook

ICIMOD

Editors

Philippus Wester, Sunita Chaudhary, Nakul Chettri, Miriam Jackson, Amina Maharjan, Santosh Nepal, and Jakob F. Steiner

Contents

Acronyms and abbreviations

ALT	Active layer thickness
AR6	Sixth assessment report
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AMSR-E	Advanced Microwave Scanning Radiometer-Earth Observing System
AWSs	Automatic weather stations
CBD	Convention on Biological Diversity
CC	Climate change
CHBS	Cryosphere, hydrosphere, biosphere, and society
CIDs	Climatic impact drivers
CMIP6	Coupled Model Intercomparison Project Phase 6
CrIDs	Cryospheric impact drivers
DEM	Digital elevation model
EbA	Ecosystem-based adaptation
Eco-DRR	Ecosystem-based disaster risk reduction
ECMWF	European Centre for Medium-Range Weather Forecasts
EDW	Elevation-dependent warming
ELA	Equilibrium line altitude
ERA5	ECMWF Reanalysis v5
GAMDAM	Glacial Area Mapping for Discharge from the Asian Mountains
GHCNd	Global Historical Climatology Network daily
GlaThiDa	Glacier Thickness Database
GLOFs	Glacial lake outburst foods
GRACE	Gravity Recovery and Climate Experiment
GRACE-FO	GRACE Follow-On
GSOD	Global Surface Summary of the Day
GWL	Global warming level
HI-WISE	Water, ice, society, and ecosystems in the Hindu Kush Himalaya

HKH	Hindu Kush Himalaya
HMA	High Mountain Asia
IBIS	Indus Basin Irrigation System
ICESat	Ice, Cloud, and Land Elevation Satellite
ICIMOD	International Centre for Integrated Mountain Development
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IWMI	International Water Management Institute
LLOFs	Landslide-dammed lake outburst floods
MAPs	Medicinal and aromatic plants
MoCTCA	Ministry of Culture, Tourism & Civil Aviation (Nepal)
MT	Megatons
nCIDs	Non-climatic impact drivers
NTFPs	Non-timber forest products
RCPs	Representative Concentration Pathways
RGI	Randolph Glacier Inventory
SAR	Synthetic aperture radar
SD	Snow depth
SDGs	Sustainable Development Goals
SMD	Sustainable mountain development
SSPs	Shared socio-economic pathways
SWE	Snow water equivalent
TCB	Tourism Council of Bhutan
TFDD	Transboundary Freshwater Dispute Database
TWCs	Transboundary water conflicts
UAV	Unmanned aerial vehicle
WGI	Working Group I

Acknowledgements

This *Water, ice, society, and ecosystems in the Hindu Kush Himalaya (HI-WISE)* assessment report provides a partial update to the first *HKH assessment report*, focusing on the interlinkages between cryosphere, water, ecosystems, and societies in the Hindu Kush Himalaya (HKH). The vision, encouragement, and support of the former Director General of the International Centre for Integrated Mountain Development (ICIMOD), David Molden, and the former Deputy Director General, Eklabya Sharma, to produce this report is deeply appreciated, as is the continued support and guidance of the current Director General, Pema Gyamtsho, and Deputy Director General, Izabella Koziell.

We are deeply grateful and wish to acknowledge the network that made this HI-WISE assessment report possible. The commitment, rigour and expertise shown by the Chapter Lead Authors and Authors, all freely contributing their time, is highly appreciated. As is customary in assessment reports, both the Chapter Lead Authors and the Authors are listed in alphabetical order and all authors agree to the full content of the chapter they contributed to. We deeply appreciate the time, rigour, and professionalism of the external expert reviewers, which has contributed significantly to both the content and credibility of this report. While not being exhaustive, we wish to acknowledge the following individuals, institutions, and governments for making this HI-WISE assessment report possible:

Chapter Lead Authors: Sunita Chaudhary, Nakul Chettri, Miriam Jackson, Amina Maharjan, Santosh Nepal, Jakob Steiner, and Philippus Wester.

Chapter Authors: Biraj Adhikari, Simon Allen, Mohd. Farooq Azam, Prashant Baral, Rasmus Benestad, Sanjeev Bhuchar, Hester Biemans, Fanny Brun, Rachana Chettri, Zhu Dan, Madhav Dhakal, Narayan Prasad Gaire, Sonu Khanal, Dongfeng Li, Arthur Lutz, Graham McDowell, Sher Muhammad, Avash Pandey, Binaya Pasakhala, Saurav Pradhananga, Randall Ritzema, Finu Shrestha, Milan Shrestha, Jakob Steiner, Markus Stoffel, Rupert Stuart-Smith, Amrit Thapa, Lang Wang, and Xiaoming Wang.

External Reviewers: Anamika Barua, Tobias Bolch, Ram Prasad Chaudhary, Purnamita Dasgupta, Walter Immerzeel, Sarala Khaling, David Molden, Marcus Nuesser, Christopher Scott, Christian Siderius, Pasang Sherpa, Roopam Shukla, Mark Snethlage, Daniel Viviroli, Patrick Wagnon, Sonam Wangchuk, and Yan Zhaoli.

Language Editors: Rachana Chettri, Nagraj Adve, Carmen Wickramagamage, and Kundan Shrestha

Design: Mohd Abdul Fahad and Sudip Kumar Maharjan

Secretariat: Bhawana Syangden and Rekha Khatri Thapa

For Chapter 4, we would like to thank Babar Khan and Samuel Thomas for reviewing and providing inputs, and Yi Shaoliang for reviewing the references. For Chapter 5, we would like to thank Anu Kumari Lama for reviewing and providing inputs on the Tourism section. We are also grateful to Shiwei Liu for preparing Figures 5.1 and 5.6 and Tao Wang for Figure 5.5.

Funding support for the assessment process leading to the production of this report was provided by the governments of Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, Norway, Pakistan, Sweden, Switzerland, and the United Kingdom, through core funding to ICIMOD. In particular, the earmarked core support of Switzerland to the Hindu Kush Himalaya Monitoring and Assessment Programme (HIMAP) from 2018 to 2022, under which this report was produced, is highly appreciated.

Authors and reviewers participating in the HI-WISE assessment are affiliated with numerous institutions inside and outside the HKH region. Their institutions have contributed to the assessment through the in-kind support of their staff. We wish to acknowledge the contributions of the following institutions, without implying an endorsement of the outcomes of the assessment by these institutions: Arizona State University, USA; Ashoka Trust for Research in Ecology and the Environment, Regional Office Eastern Himalaya, India; Chengdu Institute of Biology, Chinese Academy of Sciences, China; Daugherty Water for Food Global Institute at the University of Nebraska, USA; Free University Amsterdam, the Netherlands; FutureWater, the Netherlands; Indian Institute of Technology Guwahati, India; Indian Institute of Technology Indore, India; Institute of Economic Growth, India; International Water Management Institute, Nepal; National University of Singapore, Singapore; Norwegian Meteorological Institute, Norway; Peking University, China; Pennsylvania State University, USA; Potsdam Institute for Climate Impact Research, Germany; The Chinese University of Hong Kong, Hong Kong Special Administrative Region of China; The State Key Lab of Cryospheric Science, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Science, Lanzhou, China; Tribhuvan University, Nepal; Uncharted Waters, Australia; University of Alaska Fairbanks, USA; University of British Columbia, Canada; University of Calgary, Canada; University of Bern, Switzerland; University of Graz, Austria; University of Geneva, Switzerland; University of Grenoble Alpes, France; University of Heidelberg, Germany; University of Oxford, United Kingdom; University of St Andrews, Scotland; University of Zurich, Switzerland; Utrecht University, the Netherlands; Wageningen University and Research, the Netherlands.

Executive summary

Introduction

The Hindu Kush Himalayan (HKH) region, covering more than 4.2 million km^2, encompasses the highest mountain ranges in the world and contains the largest volume of ice on Earth outside of the polar regions, as well as large expanses of snow. Spanning some 3,500 km in length from Afghanistan in the west to Myanmar in the east, and covering parts or all of Pakistan, India, China, Nepal, Bhutan, and Bangladesh, the HKH is home to unique cultures, highly diverse landscapes, and all of the world's peaks above 7,000 meters. The region hosts all or parts of four global biodiversity hotspots supporting diverse flora and fauna – the Himalaya, the Indo-Burma, the Mountains of Central Asia, and the Mountains of Southwest China. The glacier- and snow-covered mountains of the HKH are an important source of water for 12 river basins, including 10 major (transboundary) rivers – the Amu Darya, Brahmaputra (Yarlung Tsangpo), Ganges, Indus, Irrawaddy, Mekong (Lancang), Salween (Nu), Tarim, Yangtse (Jinsha), and Yellow (Huang He) – that flow through 16 countries in Asia and provide freshwater services to 240 million people living in the HKH region and 1.65 billion downstream.

The HKH cryosphere (glaciers, snow, permafrost) is undergoing unprecedented and largely irreversible changes over human timescales, primarily driven by climate change. The impacts are becoming increasingly clear, with increased warming at higher elevations, the accelerated melting of glaciers, increasing permafrost thaw, declining snow cover, and more erratic snowfall patterns. The "water towers" of the HKH, critical for downstream regions, are some of the most vulnerable to these changes in the world.

Mountain communities are already living with the impacts of the accelerated melting of glaciers, changing snowfall patterns, growing variability in water availability, and increasing incidences of cryosphere-related hazards. These changes have a direct impact on their lives and livelihoods. Cryospheric change also poses threats to downstream infrastructure, human settlements, livelihoods, and broader economies. In the coming decades, floods and landslides are projected to increase and the timing, availability, and seasonal distribution of mountain water resources for large lowland populations will become more uncertain, especially affecting irrigated agriculture. These knock-on effects threaten not only the security of water, food, energy, ecosystems, and their services, but also the livelihood security of millions of people in Asia, and hence will have far-reaching consequences.

While the impact of climate change on glaciers, snow, and water resources is clear and supported by robust science, the observed and projected impacts of cryospheric change on mountain societies and ecosystems have received less attention. Although the evidence base is growing, key questions arise, including:

- How will the hydrology of water systems at higher elevations change and how will this impact downstream water availability?
- How will cryospheric change affect the magnitude of and trends in underlying hazards and disasters at higher elevations and downstream?
- What are the implications of cryospheric change for ecosystems, species, livelihoods, and societies at high elevations?
- What kinds of actions and policies are needed for societies to respond in the short and long run?

The *HKH assessment* report, published in 2019, included chapters focusing specifically on climate change, cryosphere, water, and biodiversity. However, the ecological and social aspects of cryospheric change and the linkages with water resources, society, and ecosystems were not systematically assessed. In addition, the report only assessed literature published up to late 2017. With the rapid advances in cryospheric sciences and emerging evidence on the linkages between cryospheric change, water, ecosystems, and society, there is a need for an updated assessment specifically focusing on cryosphere–hydrosphere–biosphere–society linkages in the HKH. This *Water, ice, society, and ecosystems in the HKH* (HI-WISE) assessment report aims to meet this need by informing the people of the HKH, decision makers, practitioners, and the global community on the rapidly changing cryosphere in the HKH and its impacts on water, biodiversity, and societies, based on the latest science.

The assessment approach consisted of carefully reviewing the relevant chapters of the *HKH assessment* report, rigorous review of both peer-reviewed and grey literature, and analyses of updated climatic and cryospheric datasets. To indicate the level of confidence in key findings, three confidence levels – *medium, high,* and *very high confidenc*e – are used. These are italicised and in parentheses, and the attribution is based on an evaluation of the robustness of evidence and the degree of agreement for each statement. The report explores the impact of climate change on the cryosphere, water resources, disasters, and subsequent impacts on societies and ecosystems in the region. It focuses specifically on high-elevation ecosystems and the people living there, roughly defined as areas situated above 2,000 metres, while also giving attention to downstream linkages and the wider implications of climatic, cryospheric, ecological, and socioeconomic changes in the HKH.

Key findings

CRYOSPHERE

1. **Major advances in HKH glacier monitoring and analysis made in recent years show a significant acceleration of glacier mass loss by 65% in the HKH (*high confidence*) and reversal from mass gain/steady state to mass loss in the Karakoram (*medium confidence*).** Glacier mass changes between the 1970s and 2019 in most areas of the HKH have now been quantified with increased accuracy. The rate of glacier mass loss increased by 65%, from an average of –0.17 metres water equivalent (m w.e.) per year for the period 2000–2009 to –0.28 m w.e. per year for 2010–2019 (*high confidence*). The most negative mass balances are observed in the eastern part of the HKH. The Karakoram region, previously known for stable regional mass balances, showed slight wastage of –0.09 ± 0.04 m w.e. per year during 2010–2019, indicating the end of the Karakoram Anomaly (*medium confidence*).

2. **Snow cover extent has shown a clearly negative trend in the HKH region since the early twenty-first century with a few exceptions including the Karakoram (*high confidence*).** There has been a significant decrease in the seasonal snow cover during the summer and winter months, as well as a decline from mid-spring through mid-fall, indicating a seasonal shift (*high confidence*). Snow cover days generally declined at an average rate of five snow cover days per decade with most of the changes at lower elevation (*high confidence*). Snow cover is likely to experience an accelerated loss in the future under different global warming levels in the HKH (*medium confidence*).

3. **Still very little is known about permafrost, but what is known points to a decrease in permafrost occurrence (*medium confidence*).** There are few field observations of permafrost in the HKH, but existing measurements show changes in permafrost, and remote sensing confirms a decrease in permafrost cover in studied regions (*medium confidence*). Modelled results calculate a loss of about 8,340 km^2 in permafrost area in the western Himalaya between 2002–2004 and 2018–2020; and a loss of about 965 km^2 in the Uttarakhand Himalaya between 1970–2000 and 2001–2017. On the Tibetan Plateau, the area of permafrost degradation will increase, with most (about two-thirds) of the permafrost being degraded by 2071–2099 under high emissions scenarios.

WATER

1. **With accelerated glacier melt, 'peak water' will be reached around mid-century in most HKH river basins, and overall water availability is expected to decrease by the end of the century (*medium confidence*).** At higher elevations, an increase is expected (more melt or more rainfall). However, the variability from basin to basin is large, and due to the large uncertainty in future precipitation projections, our *confidence* in estimates of future discharge remains *low*. More confident projections of precipitation, snow water equivalent, as well as both evaporative and subsurface fluxes will be crucial to improving our ability to accurately determine future water availability in the HKH.
2. **With a changing climate and heightened awareness of the increased exposure of livelihoods and infrastructure to hazards, the mountain hazard landscape has become increasingly multi-dimensional (*high confidence*).** A number of different slow- (e.g. sedimentation and erosion) and fast-onset hazards (e.g. floods and glacial lake outburst floods [GLOFs]) are occurring in the same watersheds, frequently at the same time, and often also in a cascading manner, complicating our ability to implement early warning and adaptation measures. Future frequency and intensity estimates exist only for a limited number of hazards, with *medium confidence* in a *likely* increasing trend. Confidence in trends varies across hazards but is especially evident for slow-onset hazards related to glacier retreat as well as events associated with increasing heavy precipitation.
3. **Water sources in the high mountains are important not only for livelihoods and other demands in the immediate vicinity but also for the distant downstream areas that are heavily reliant on meltwater originating from mountains for agricultural, domestic, and industrial uses (*high confidence*).** Glacier and snowmelt provide a buffer for downstream irrigation demand in the spring season (*high confidence*), and it is *very likely* that the dependency on them will increase in future (*medium confidence*).

ECOSYSTEMS

1. **The cryosphere of the HKH is an important source of water for maintaining ecosystem health, supporting biological diversity, and providing ecosystem services (*very high confidence*).** This biodiversity-rich region – 40% of which is under protected area coverage – is characterised by interconnected and diverse ecosystems. Sixty percent of the region features seasonal cryosphere (snow, glacier, permafrost, and glacial lakes) – a major source of water and other ecosystem services (*very high confidence*).

2. **Multiple drivers of change, including climate change, are impacting the fragile HKH ecosystem and cryosphere, bringing cascading impacts on surrounding ecosystems and human wellbeing (*high confidence*).** As a fragile ecosystem, the HKH is extremely sensitive to climate change. Widespread shrinking of the cryosphere – attributable to climate change – is resulting in glacier mass loss, snow cover reduction, shrinkage of permafrost area, changes in hydrology, and increased natural hazards and disasters (*high confidence*). Cascading impacts have been reported in most ecosystems, affecting most inhabitant species (*high confidence*). A visible range shift of species to higher elevations, ecosystem degradation and changes, decrease in habitat suitability, species decline and extinction, and invasion by alien species have been reported, with significant negative impacts on the flow of ecosystem services, both increasing the vulnerabilities of biodiversity and people and affecting their wellbeing (*high confidence*).

3. **Future scenarios paint an alarming picture at the ecosystem and species levels – increased ecosystem vulnerability and lowered ecosystem services flows will result in disruptions to social–ecological resilience (*high confidence*).** There is increasing documentation of the cascading effects of cryosphere loss on ecosystems, including ecosystem degradation and changes in species structure and composition. Predicted scenarios show more extreme events taking place, with increasing imbalances in ecosystem functions resulting in more acute societal vulnerability (*high confidence*).

SOCIETIES

1. **Improvements in the lives of mountain people have generally followed increased accessibility and economic development. Despite this, their marginal and vulnerable status has hardly changed (*medium confidence*).** In fact, marginality and vulnerability have probably worsened as the climate changes and the cryosphere changes with it (*medium confidence*). Mountain societies dependent on agriculture, livestock, and medicinal and aromatic plants are facing the serious adverse effects of cryospheric change (*high confidence*). Cryospheric change will continue to have significant implications for societies, particularly those that rely on high mountain freshwater (*high confidence*).

2. **Intensifying cryospheric change, population growth, and infrastructure development in mountainous areas have exposed communities to increased cryosphere-related hazards (*medium confidence*).** The risks posed by cryosphere-related hazards are becoming more unpredictable, and future cryosphere-related disasters will be costlier and deadlier (*medium confidence*). Risk perception among mountain societies – whether communities over- or underestimate potential cryosphere-related hazards and disaster risks – is a significant determinant of how cryospheric change and the associated adverse consequences will be identified and prioritised (*medium confidence*).

3. **The adaptation approaches undertaken by mountain societies so far have been largely autonomous and incremental in nature, mostly limited to the household and community levels (*high confidence*).** There are large gaps between the adaptation needs of communities and their access to or the provision of the necessary adaptation support (*high confidence*). There are soft as well as hard limits to adaptation, which constrain responses and make mountain livelihoods highly vulnerable to a changing cryosphere (*high confidence*).

Policy messages

CRYOSPHERE

1. **The evidence of the impact of a changing climate on glaciers is clear.** Policy makers need to evaluate the effects these changes are having and will have in the future as glaciers continue to shrink. It will be crucial to identify the expected changes as well as associated opportunities and risks that glacier changes will have on ecosystems and livelihoods in order to develop appropriate adaptation strategies.

2. **There is strong evidence that snowmelt plays the most important role for river run-off in the HKH among all cryosphere components but that its absolute volume will decrease in future and peak flow will shift, with large variability between basins.** Snowfall is projected to become less frequent but more intense and increasing temperatures will affect the volume of the snowpack negatively. Governments should be aware of the expected changes and align their planning for infrastructure, agriculture, and livelihoods accordingly.

3. **Permafrost is the cryosphere component for which there is the least knowledge.** Potential consequences of changing permafrost include elevated risks for livelihoods and infrastructure. Hence, governments should emphasise ground monitoring, especially where there are substantial infrastructure or communities that could be affected. Communication of the potential consequences should be included in strategies related to the cryosphere.

WATER

1. **It is important to know the relevant contributions of different water resources to river flows and prepare for seasonal shifts in water availability.** The relative importance of different components of the cryosphere and other sources of water differs between the basins in the HKH. Decision makers should identify the dominant water sources and processes in their region to prioritise relevant investigations and adaptation measures. This will become even more relevant for anticipating whether river flows are expected to increase or decrease in the future and how seasonal shifts will evolve. This has crucial consequences for the downstream use of water resources as well as the occurrence of water-related hazards.

2. **Much more effort is needed to prepare adaptation strategies for multi-hazards and cascading event chains.** Adaptation strategies to respond to risks from mountain hazards need to take into account the increased likelihood of multi-hazards and cascading events due to climate change. This requires monitoring solutions able to capture different types of processes. To evaluate the impact of complex hazard chains, simulations should consider running a multitude of (concurrent) scenarios involving all types of possible hazards. With a complex interplay of risks, it is imperative that all possible impacts are evaluated to avoid maladaptation, which can result from adapting to some, but not all, hazards, increasing overall vulnerability to climate change.

3. **It is crucial to prepare for an increased dependence on meltwater.** With the increased likelihood of extreme hydrological events (floods, droughts), being able to forecast water availability several months ahead should be a priority. Model estimates of water supply can be made more robust with better knowledge of downstream demand on upstream supply from meltwaters and advance projections of available water and its routing through rivers and subsurface storage.

ECOSYSTEMS

1. **HKH ecosystems are complex and have specificities.** Integrated approaches and regional interventions that minimise vulnerability – for ecosystems and human wellbeing – are required to address extreme events. The HKH region is characterised by large variations in ecosystems and cultures, and its local communities depend heavily on natural resources. Blanket approaches to minimising vulnerability will prove ineffective here. Nature-based solutions that consider customised interventions and are grounded in an ecosystems-based understanding could make for a possible, effective approach.

2. **Stronger science on mountain ecosystems is needed to increase understanding of their complexities.** Though climate science is gaining attention and investments in research are increasing, improving understanding of the complex interlinkages between climate change, cryosphere, ecosystems, and society needs urgent attention. Only then will designing and implementing interventions to increase resilience and develop adaptation capacity be possible.

3. **The HKH region is a global asset.** Conservation of its shared heritage requires regional cooperation. Considered the "Water Tower of Asia", the HKH contributes water and ecosystem services to a quarter of humanity. This shared heritage and its fragile ecosystems are facing regional challenges. Therefore, actions to address them also need to be regional in scale. South–South cooperation and implementation of the HKH Call to Action to sustain mountain environments and improve livelihoods could be promising ways forward.

SOCIETIES

1. **It is urgent to address adaptation needs through synergised sectoral policies.** Effective adaptation is key to maintaining sustainable mountain development, which increases the capacity of mountain societies to adapt – with enhanced speed, scope, and depth. To facilitate sustainable development in the mountains, policies across multiple sectors need to address the myriad pressures faced by mountain societies, taking into consideration their needs and aspirations, including the need to adapt to a changing cryosphere. Sectoral policies need to examine the nature, extent, and implications of the soft and hard limits to adaptation and guide the development of synergised adaptation actions. This is particularly important in the context of socioeconomic and political marginalisation and warming beyond 1.5°C. There is also the need to plan anticipatory responses to potentially irreversible changes in the cryosphere of the HKH.

2. **Implementing inclusive adaptation policies and practices is critical for sustainable mountain development in the HKH.** The tenets of social and environmental justice and sustainable development must be incorporated into adaptation policies and practices if vulnerable and marginalised communities are to respond effectively to changes in the cryosphere. Policies need to ensure the protection of the non-economic assets of mountain societies – cultural heritage and spiritual and religious beliefs, for instance, which are critical for societal well-being, but are threatened by cryospheric change.

3. **Strengthening regional and global cooperation and collaboration is urgently needed to address the impacts of cryospheric change.** There is an urgent need to cultivate cooperation in the generation, exchange, and sharing of knowledge among global, regional, national, and local actors in the common interest and for co-benefits. Collaborative efforts to understand the transboundary implications of cryospheric change can not only help fill existing knowledge gaps but also strengthen cooperation on data and information sharing, cross-learning, and scaling of adaptation options from one location to another. Regional and global cooperation are needed for technical and financial assistance to facilitate adaptation and mitigation, and to advocate for matters of common interest to mountain societies.

Summary of Chapter 2: Cryosphere

The mean temperature is significantly increasing in all the regions of the HKH (*high confidence*) with an average observed trend of +0.28°C per decade (range +0.15°C per decade to +0.34°C per decade for individual basins) for the period 1951–2020. The highest trends are observed for the Tibetan Plateau, Amu Darya, and Brahmaputra basins and headwaters of the Mekong and Yangtze basins (up to +0.66°C per decade in parts of these river basins). The trend in precipitation is mostly insignificant except in the high elevated areas of the Tarim Basin and some parts of the Ganges Basin and shows a significant decrease in parts of the Yellow, Brahmaputra, and Irrawaddy basins (*medium confidence*). It ranges between −3% to +3% per decade in the 12 river basins of the HKH.

Increased warming rates at higher elevations are observed in nine of the 12 basins with the strongest amplification with elevation in the Brahmaputra Basin (*medium confidence*). A similar effect is observed in the Ganges, Yangtze, and Indus basins. However, the Amu Darya, Irrawaddy, and Upper Helmand basins show a warming trend that is higher in low-elevation areas than in high-elevation ones.

In recent years, there have been major advances in glacier monitoring, and in quantifying with higher precision the magnitude and extent of changes in glacier area and volume. The release of previously classified high-resolution satellite imagery and the ever-improving spatio-temporal resolutions of contemporary satellite imagery mean that glacier mass changes (from the 1970s to 2019) of glaciers in the HKH have now been quantified with an unprecedented accuracy (*high confidence*). The measurement of meteorological variables in different regions has increased. As the number of glacier mass balance (and energy balance) series of more than a few years, as well as the length of these series, increases, there are growing opportunities to better understand the sensitivity of glacier surface mass balance to climate. Satellite-derived glacier surface velocities are now more readily available, with annual surface velocities available for 1985–2020 for almost all of the glaciers in the HKH (with voids in many of the glacier accumulation areas).

Glacier mass balance has become increasingly negative, with rates increasing from –0.17 m w.e. per year from 2000–2009 to –0.28 m w.e. per year from 2010–2019, suggesting an acceleration in mass loss. The most negative mass balances are observed in the eastern part of the HKH within the Southeast Tibet and Nyainqêntanglha regions showing –0.78 ± 0.10 m w.e. per year for 2010–2019, while the West Kunlun region shows a near-balanced mass budget of –0.01 ± 0.04 m w.e. per year. The Karakoram region, known previously for balanced regional mass balances, showed a slight wastage of –0.09 ± 0.04 m w.e. per year for 2010–2019. These results indicate moderate mass loss of the Karakoram glaciers, especially post-2013 and suggest that the Karakoram Anomaly – anomalous behaviour of glaciers in the Karakoram, showing stability or even growth – has probably come to an end.

The number of available future glacier projections under different climate projections has increased in recent years. For a global warming level between 1.5°C to 2°C, the HKH glaciers are expected to lose 30%–50% of their volume by 2100 (*very high confidence*). The corresponding remaining glacier-covered areas range from 50% to 70%. The mass losses will be continuous through the twenty-first century. The specific mass balance rate will remain negative, even though it will become less negative by the end of the century as glaciers retreat to higher elevations. For higher global warming levels, the remaining glacier volume will range from 20% to 45%, with the specific mass balance rates more and more negative throughout the twenty-first century. For a global warming level of +4°C, the heavily glacier-covered regions of West Kunlun and Karakoram will have their remaining glacier area reduced to about 50% of their 2020 area; in all other regions, glacier-covered area will be reduced to less than 30% of the 2020 area.

Globally, glacial lakes have increased and expanded as a result of glacier recession. The total area and number of glacial lakes have increased significantly since the 1990s (*very high confidence*). More proglacial lakes will develop over the next decades due to continued glacier retreat *(high confidence)*. Lake expansion is expected to create new hotspots of potentially dangerous glacial lakes, with implications for glacial lake outburst flood (GLOF) hazards and risk (*high confidence*). GLOF risk is expected to increase in the future, also increasing the potential for transboundary events with cross-border impacts, e.g. a glacial lake may lie within the borders of one country, but the main impact of a GLOF event may be across the border in another country.

Snow cover has shown a decreasing trend since the middle of the twentieth century, probably due to an earlier onset of snowmelt (*very high confidence*). Snow cover trends have been clearly negative in most of the HKH since the early twenty-first century with only a few exceptions. There has been a significant decrease in seasonal snow cover during the summer and winter months. Snow cover days have generally declined at an average rate of five snow cover days per decade with most of the changes at lower elevations. Snowline elevation at the end of the melting season over the HKH shows a statistically significant upward shift in over a quarter of the area and a statistically significant downward trend in less than 1% of the area. Although there are few projections of future snowpack in the region, snow cover is likely to have an accelerated loss under different global warming levels over the HKH, including the Tibetan Plateau (*medium confidence*). The snow cover extent will reduce by between 1% and 26% for an average temperature rise between 1.1°C and 4°C. Heavy snowfall has increased in recent years with frequent snowstorms observed over the Tibetan Plateau and the Himalaya (*high confidence*). These events are predicted to continue to become more frequent and intense in the future. The contribution of snowmelt to streamflow is expected to decrease under all climate scenarios. The onset of snow melting is expected to occur earlier in the future but its influence on the seasonality of river run-off in larger rivers may be dampened by increased rainfall.

Field observations show changes in Himalayan permafrost, and remote sensing estimates confirm decrease in permafrost cover in the Indian Himalayan region. Modelled results show a loss of about 8,340 km^2 in permafrost area for the western Himalaya between 2002–2004 and 2018–2020 and that the probable areal extent of permafrost decreased from 7,897 km^2 to 6,932 km^2 in the Uttarakhand Himalaya between 1970–2000 and 2001–2017. On the Tibetan Plateau, the area of permafrost degradation could range from 0.22×106 km^2 (13% area) in 2011–2040 to 1.07×106 km^2 in 2071–2099 (64.3% area). Changes in permafrost account for about 30% of road damage in the Qinghai–Tibet Plateau. Many mass wasting events are associated with permafrost degradation and are projected to increase in future (*medium confidence*). Change in the active layer thickness ranges from 5–30 cm in 2011–2040 for different warming levels. The active layer thickness is projected to further increase in 2041–2070 and exceed 30 cm in 2071–2099 for warming of 3.1°C or higher above the 1981–2010 baseline.

Summary of Chapter 3: Water

In the HKH, snowmelt and glacier melt contribute substantially to river and groundwater flows, although the magnitude of their contribution varies with scale and per river basin. The cryosphere regulates river run-off by generally releasing water from April to October – primarily as snowmelt during April–June and glacier melt during June–October, which also replenishes aquifers. The relative contribution of melt from the cryosphere to river run-off increases from east to west, from as high as 79% in the Amu Darya to merely 5% in the Irrawaddy in the eastern Himalaya (*high confidence*). The contribution of melt run-off is relatively high in the western HKH due to the westerlies, because of which winter snowfall plays an important role. In contrast, the summer monsoon plays an important role in the eastern HKH, which is reflected in the 50%–79% rainfall run-off contribution to river basins – including the Ganges, Brahmaputra, Irrawaddy, and Yellow – in that region. Snowmelt accounts for the large majority of cryospheric contributions to streamflow in all basins (*high confidence*), with an expected further decrease in the coming century (*medium confidence*). The magnitude and timing of snowmelt have already changed considerably, with trends in snow water equivalent predominately negative across the whole region between 1979 and 2019.

Climate change is projected to cause significant changes in the cryosphere and subsequently impact the hydrological cycle and overall water availability in the HKH. The actual changes will vary significantly – from sub-catchment to river basin scales and from daily to seasonal and decadal time scales in the climatically and hydrologically diverse HKH region. Snowmelt and glacier melt dominate run-off generated at higher elevations, whereas rainfall run-off and base flow processes dominate run-off generation at lower elevations. Some river basins are currently experiencing a decrease in run-off; others are seeing an increase in run-off, as contributions from snow and glacier melt increase in coming years (*medium confidence*). With accelerated glacier melt, 'peak water' will be reached around mid-century in most basins of the HKH, and water availability is expected to decrease overall by the end of the century (*medium confidence*).

Future river run-off is *likely* to see larger changes at higher than at lower elevations, but projections show large differences between river basins as well as across different climate projections. At higher elevations, total water availability will increase, either due to an increase in the melt contribution until 'peak water' is reached or due to an increase in rainfall in the future. However, this increased water availability levels off and decreases when lower elevations dominated by rainfall run-off are considered. Even though the total water availability at higher elevations will increase, changes in the timing and magnitude of peak water availability and seasonality impose a serious threat to the livelihoods of people living in these regions.

In river basins in the western part of the HKH (the Amu Darya, Helmand, and Indus) with a melt-dominated hydrological regime, the onset of melting may shift one to two months earlier in the year. In particular, flows may decline in the second half (July–September) of the present peak melt season. For river basins dominated by southern and south-eastern rainfall (the Ganges, Brahmaputra, Irrawaddy, Mekong, and Salween), no strong seasonal shifts are projected. With flows being heavily influenced by the monsoon, changes in flows will mainly be driven by changes in the magnitude and timing of monsoon precipitation. For rivers with a larger role for meltwater, a stronger seasonal shift to earlier months is expected.

In the mid-hills of the HKH, springs are the main source of water for domestic and productive uses (*high confidence*). At higher elevations, springs are recharged by snowmelt and glacier melt and their flows will be negatively affected by decreasing melt (*medium confidence*). The direct response of springs to precipitation, in particular to rainfall, is well established (*high confidence*), while meltwater may contribute significantly to groundwater recharge in high mountain areas – e.g. meltwater contributes up to 83% of annual groundwater recharge in the Upper Indus River Basin. The contribution of melt to springs will likely start decreasing by mid-century (*low confidence*) but evidence even at the level of process understanding is weak and there is a lack of understanding of the interrelationships between the cryosphere and springs.

Multiple water- and cryosphere-related disasters have been recorded in recent years. There is *low confidence* in an increasing trend of the underlying hazards, suggesting the increasing trend in the frequency of disasters in the HKH is primarily due to increased exposure. However, it is *very likely* that many events have been made more likely to occur or, in some cases, possible due to climate change resulting in more meltwater, larger and more potentially dangerous lakes, unstable slopes from thawing permafrost, and increasing sediment loads in rivers.

There is a considerable overlap between different types of high mountain hazards, in both their genesis and occurrence as cascading hazards with compound drivers, whereby a sequence of secondary events results in an impact that is significantly larger than the initial impact. The effect of road construction on the increasing number of landslides following slope instabilities after the 2015 earthquake in Nepal is clearly non-climatic. Similarly, as hydropower and road infrastructure are increasingly being constructed in the upstream areas of watersheds, the risk of exposure to mass flow events is increasing. Confirmed climatic drivers include increasing rainfall intensities and higher temperatures, resulting in higher amounts of glacier and snowmelt that drive short-term lake expansion and soil saturation. Thawing permafrost or frost cracking due to changing permafrost in headwalls has been found to be on the increase and it is possible that it has contributed to recent cascading events.

The retreat of mountain glaciers has increased the size and number of glacial lakes, but there is limited evidence of an increase in the numbers of GLOFs in recent decades in the HKH *(high confidence)*. However, a three-fold increase in GLOF risk across the HKH is projected by the end of the twenty-first century. There is notable regional variation, from east to west across the HKH, in projected glacial lake development, with glacial lakes in the eastern Himalaya already projected to be close to their maximum extent, and near a situation of 'peak GLOF risk' by 2050 under all climate scenarios. Meanwhile, lakes in the western Himalaya and Karakoram will continue to increase significantly into the late twenty-first century and beyond.

There is growing evidence for increases in sediment yields in high mountain areas driven by climate change and cryospheric degradation. On average, the suspended sediment load from HKH headwaters has increased by ~80% over the past six decades in response to accelerating glacier melt and permafrost thaw and increased precipitation. Fluvial sediment loads will *very likely* increase in the coming decades in a warmer and wetter HKH, with each 10% increase in precipitation projected to result in a 24% ± 5% (mean ± standard error) increase in sediment load, and each 1°C increase in air temperature resulting in a 32% ± 10% increase in sediment load.

Large avalanches of rock and/or ice are expected *(high confidence)* to increase in frequency and magnitude under a warmer climate, with implications for associated, far-reaching cascading processes. This is underpinned by detailed examinations of several recent cascading events in the HKH, which show an initial mass movement originating from a zone likely to have been destabilised by recent deglaciation and/or degrading permafrost, and often, unusually warm or wet conditions preceding the disaster. In view of future climate change, such triggering factors are expected to become increasingly prevalent and relevant over the coming decades.

Water resources from the high mountains, from melt or precipitation, are crucial for mountain agriculture, water supply, and the recharge of aquifers and springs *(high confidence)*. Large-scale model studies have also shown that they play a large role in providing water to distant downstream regions, especially for irrigation *(medium confidence)*. An estimated 129 million farmers in the Indus, Ganges, and Brahmaputra basins currently depend on water that originates from glacier melt and snowmelt to irrigate their crops. Especially during the warm and dry months before the monsoon rains start, the availability of meltwater flow is crucial to irrigate their crops. Meltwater from glaciers and snow plays an especially important role as a buffer during drought periods.

The dependence of irrigated agriculture on both meltwater and groundwater is projected to increase. Due to earlier melting, the amount of meltwater available for irrigation at the end of the spring season (May) will increase. However, later in the season, meltwater availability will decrease. Combined with a higher variability in rainfall run-off, it is likely that groundwater will be used to compensate for the lower surface water availability, potentially leading to further overdraft and depletion of aquifers.

Summary of Chapter 4: Ecosystems

Global and regional drivers of biodiversity loss — such as land use change and habitat loss, pollution, climate change, and invasive alien species — are prevalent and increasing in the HKH *(high confidence)*. For example, by 2100, the Indian Himalaya could see nearly a quarter of its endemic species wiped out *(medium confidence)*. Although countries in the region already place a premium on functional ecosystems and ecosystem services – over 40% of all land in the HKH lies within protected area systems *(very high confidence)*, ecosystems are in stress or are subject to risks – from a changing climate, varying government policies, and expanding markets (*high confidence*).

The HKH, also referred to as the "Third Pole", is an important repository of cryosphere outside the North and South poles (*very high confidence*). As the youngest mountain ecosystem, the HKH region is also significant in terms of the history of its formation, which has created geodiversity, multiple elevational gradients, and micro-climates (*very high confidence*). These variations enable diversity in vegetation zones that enrich biodiversity, including ecosystems diversity. The resulting ecosystem services provide direct services to 240 million people in the HKH region and support a further 1.65 billion people downstream (*very high confidence*). The region hosts significant ecoregions and global biodiversity hotspots, which form part of the 40% of area under formal protection. Such formal mechanisms reflect the commitment of the region's countries to conservation. They have helped ensure the protection of its fragile ecosystems and habitats, which host many charismatic species, and of the ecosystem services that contribute to the wellbeing of its people (*high confidence*).

Despite these efforts, the HKH region and its biodiversity are threatened by a range of drivers of change. The rise in temperature and changes in precipitation patterns are discernible and have cascading impacts on HKH ecosystems and society (*medium confidence*). Even if global warming is limited to 1.5°C, the HKH is likely to face serious impacts in terms of species loss, ecosystem structure, and productivity, resulting in lowered ecosystem services flows (*high confidence*). The HKH cryosphere and adjacent ecosystems – high-elevation rangelands, wetlands, and peatlands – are sources of ecosystem services to some of the world's most marginalised communities. The region's large and contiguous plant and animal habitats host fragile ecosystems that also support highland herding communities (*very high confidence*). About 67% of the HKH's ecoregions and 39% of the global biodiversity hotspots are still outside protected areas and exposed to different drivers of change (*very high confidence*).

Increasing vulnerability in high-elevation regions where the cryosphere is dominant is attributable to climate change, over-exploitation, air and water pollution, and invasion by alien species (*very high confidence*). Literature on the degradation of these vulnerable ecosystems record changes to a wide range of plant and animal community structures and productivity, including the productivity of medicinal plants. These have implications for the age-old cultures of herding communities dependent on highland ecosystems for their livelihoods and lowland communities whose water and energy (hydropower) needs are supported by the HKH cryosphere (*medium confidence*).

Climate change impacts have wide-ranging and cascading effects on the cryosphere and related ecosystems, biodiversity, and ecosystem services – including on nature-based trade and tourism, health, and culture. These changes, which also affect the subsistence livelihoods of HKH communities, are detrimental to the achievement of the Sustainable Development Goals (*high confidence*).

As the cryosphere changes, impacts on biodiversity at the ecosystem, genetic, and species levels mean an overwhelming majority of animal and plant species are negatively affected, sometimes to extinction (*high confidence*). There is increasing evidence of impacts on ecosystems and ecosystem services, changes in soil nutrient composition, changes in the phenology of plants, range shifts from lower to higher elevations, increase in invasive alien species, and changes in structural and population compositions in both plant and animal populations (*high confidence*). Observations on trade-offs have also been made: Some species in the eastern Himalaya are benefiting from warming temperatures and changes in precipitation levels, leading to higher growth and productivity. Furthermore, scenario analyses show these trends will increase in the future, with large implications on the wellbeing of people dependent on HKH resources (*medium confidence*).

While science on the cryosphere and related changes has strengthened considerably in recent years, understanding of the interactions between cryospheric components and consequent impacts on high-elevation ecosystems and biodiversity is limited (*very high confidence*). Adaptation options for mountain biodiversity remain poorly understood (*high confidence*). While these challenges are persistent and ever increasing, practices incorporating participatory approaches and community-led adaptation are also being reported (*high confidence*). Watershed, springshed, and landscape approaches are gradually being incorporated into adaptation, ecosystem restoration, and disaster risk reduction measures (*high confidence*). These approaches are heterogeneous and context-specific, varying greatly depending on the issues, conditions, and contexts at play.

Though cryosphere and biodiversity at the ecosystem, genetic, and species levels are highly interconnected, understanding of the links between cryosphere and biodiversity across the HKH is limited (*very high confidence*). In recent years, research into and knowledge on the impacts of climate change on the cryosphere have increased, but research into the impacts of cryospheric changes on ecosystems and species, including at the genetic level, is only slowly emerging. Documentation on ecosystems and species is sporadic, and largely available only for the higher taxa. Huge knowledge gaps – linkage gaps, impact gaps, and response gaps – persist (*very high confidence*). The HKH remains a data-deficit region, where long-term research that considers spatial and temporal scales remains lacking (*medium confidence*). There are few representative long-term research stations for environmental and biophysical studies. Additionally, there are major gaps in the social sciences and in holistic research that investigates the interconnectedness of cryosphere, biodiversity, and their different elements (*very high confidence*).

Policy interventions are currently limited to small pockets. These need to be scaled up if ecosystem-based adaptation is to be supported (*very high confidence*). As a contiguous ecosystem, the HKH faces cascading impacts that have regional implications. Therefore, regional cooperation among HKH countries needs to be prioritised, and investments in research capacity, data generation and sharing, and the implementation of multidisciplinary approaches are needed for coordinated responses that are ultimately more effective (*very high confidence*).

Summary of Chapter 5: Societies

The HKH region is experiencing non-climatic as well as cryospheric drivers of change (*high confidence*). Cryospheric change in the region has implications for the lives and livelihoods of more than 1.9 billion people. Understanding the intersections between cryospheric change and societies is essential to undertaking effective adaptation policies and practices to achieve the Sustainable Development Goals.

People in the HKH region are experiencing multiple climatic and non-climatic drivers of change. These drivers of change are interwoven and have significant impact on the lives and livelihoods of mountain people as well as their capacity to respond or adapt to these changes. Mountainous areas in the region have witnessed economic growth and infrastructural and technological development, which is expected to continue (*high confidence*). Access of local communities to governmental institutions and their services is improving (*high confidence*), but this is also resulting in a weakening of traditional institutions (*high confidence*), with implications for adaptive capacity.

The major livelihoods of mountain communities are agriculture, livestock, tourism, and the collection and trading of medicinal and aromatic plants. The contribution of cryospheric services to these mountain livelihoods is high (*high confidence*). Cryospheric change, particularly changes in snowfall pattern, have adversely affected the livelihoods of communities (*high confidence*). Major adverse impacts include crop loss and failure, fodder shortage, livestock deaths, decrease in the availability of medicinal and aromatic plants, and degradation of aesthetic experiences. In many areas, communities have abandoned agriculture and pastoralism in response to cryospheric change and other non-climatic drivers of change (*medium confidence*). These impacts have increased the socioeconomic vulnerability of mountain communities (*high confidence*), including food and nutrition insecurity. However, there are a few short-term positive impacts of cryospheric change on agriculture, pastoralism, and tourism – such as improved access to previously inaccessible sites for animal grazing and tourism. As the cryosphere changes along with the social, economic, and political dynamics in mountain societies, these cryosphere–livelihood linkages may gradually decrease (*low confidence*).

High mountain communities in the HKH region are heavily dependent on snow and glacial meltwater to meet their water needs (*high confidence*). This reliance is not limited to mountainous areas. Water supply systems in downstream regions, including in densely populated urban settlements, are dependent on meltwater for domestic and commercial purposes (*high confidence*). Along with growing demand, poor management, and insufficient infrastructure, cryospheric change is likely to further exacerbate water shortages in the region (*high confidence*). Water stress in transboundary river basins in the HKH region – particularly the Indus, Ganges, and Amu Darya – have led to both conflicts as well as cooperation for managing water resources among the countries sharing the river basins (*medium confidence*).

Components of the cryosphere also play a major role in the cultural, religious, and spiritual beliefs and practices of high mountain societies and influence their well-being (*medium confidence*). Human societies have ascribed spiritual relevance to the high mountains since ancient times; pilgrimages to the mountains have been made since the beginning of recorded human history. Tied to the spiritual reverence Indigenous communities hold for their natural environs is the understanding that there is a need to protect the local environment, including its cryospheric components (*low confidence*). Loss of the aesthetic properties of the mountains, glaciers, and snow cover could be perceived as a loss of honour and pride and be interpreted as consequences of diminished morality and ethics (*low confidence*). These effects could potentially decrease the attractiveness of high mountain sites for tourists, impacting local livelihoods (*low confidence*).

Cryosphere-related hazards in the region have caused significant losses and damages of property, infrastructure, and lives, including tangible and intangible cultural heritage (*high confidence*). These disasters have led to a loss of traditional knowledge, increased social and economic burdens, and caused psychological stress and displacement (*high confidence*). People's perceptions of cryosphere-related risks are shaped by socioeconomic, cultural, religious, and political factors, all of which determine their responses (*low confidence*). Cryosphere-related hazards are becoming more complex and devastating as they are increasingly interlinked with other environmental extremes (e.g., landslides, rockfall, seismic activity, and heavy rain), creating cascading hazards (*medium confidence*). The exposure of people and infrastructure to these hazards has increased due to a rise in population and an intensification of economic activities in the region (*medium confidence*). Cryosphere-related hazards are projected to increase in the HKH region in the future, adding investment burdens with long-term implications for national and regional economies (*medium confidence*).

Understanding of the implications of cryospheric change on livelihoods, water supply, and cultural heritage in upstream and downstream communities remains inadequate for robust adaptation action and effective sustainable development (*high confidence*).

Adaptation measures adopted by households and communities in response to cryospheric change can be broadly categorised as behavioural, technological, infrastructural, financial, regulatory, institutional, and informational. Behavioural and technological measures are the most reported across different sectors. These measures are mostly reactive, autonomous, and incremental in nature, and unable to fulfil the necessary speed, depth, and scope of adaptation (*high confidence*). With cryospheric change possibly taking on unprecedented trajectories, these measures may not be effective in the long term. There are concerns that communities may not be able to cope with an increased magnitude and complexity of extreme events as they try and navigate persistent socioeconomic challenges (*high confidence*).

Local communities are already abandoning their traditional livelihoods and settlements, pointing towards an evident adaptation deficit to cryospheric change (*medium confidence*). Constraints and limits to adaptation, along with insufficient understanding of the interactions between cryospheric and non-climatic drivers and the associated impacts on mountain societies, could potentially hinder the overall target of achieving the Sustainable Development Goals (*medium confidence*). To address this, there is an urgent need to integrate adaptation to cryospheric change with sustainable development, specifically in the high mountains (*high confidence*).

Key knowledge gaps

Each content chapter ends with an identification of key knowledge gaps. These were arrived at by revisiting the knowledge gaps identified in the *HKH assessment* report where relevant and evaluating progress made in addressing them. New knowledge gaps based on the assessment underlying this report were also identified.

CRYOSPHERE

1. There are very few direct measurements of ice and debris thickness on debris-covered glaciers. Estimates at a global scale show significant variations. More field measurements of these variables as well as ice temperature and annual/seasonal glacier surface mass balances are highly recommended to develop a better understanding of how glaciers will react to future climate change and their subsequent effect on basin hydrology.

2. There are few in situ measurements of snow depth and snow water equivalent resulting in a limited understanding of spatial variability of snowpack changes. In many parts of the HKH, snowmelt is much more important to run-off than glacier melt. These measurements and related measurements (such as high-altitude hydrometeorological measurements) urgently need to be increased and expanded.

3. There are very few in situ measurements of ground temperature and borehole measurements to obtain both the present ground temperature as well as historical changes. There is also a lack of knowledge of the existence of permafrost and its importance to both the water cycle and natural hazards. More measurements are needed, especially in regions where road construction projects are being planned or undertaken and where people live in the vicinity of permafrost and are hence more vulnerable to hazards caused by permafrost degradation.

4. There are very few studies in the HKH on the effects of changes in all elements of the cryosphere on ecosystems and livelihoods. This also includes the relationship between changes in the cryosphere and natural hazards related to these changes. A greater emphasis should be placed on holistic studies.

WATER

1. Parts of the water balance – notably, evaporative fluxes and subsurface processes – remain poorly measured, understood, or included in modelling efforts. More monitoring efforts need to be directed to these underexplored aspects to be able to investigate these processes. Research proposals addressing such understudied processes should receive heightened attention for funding, ideally in catchments that already have existing measurement networks. This also requires transboundary institutional and political mechanisms to provide sustainable, stable, and long-term support. More of such sentinel catchments should be strategically established in the HKH region, with a view to cover as much topographic and climatic variability as possible.

2. While hazards are well documented, it is, so far, not clear which processes of the hydrosphere or cryosphere are dominant in their genesis. Increased attention should be given to monitor aspects of the cryosphere that are likely relevant for future hazards – especially the development of permafrost and slope instability, snow cover and snowpack development and its links to avalanche formation, and precipitation and melt dynamics influencing the stability of periglacial terrain.

3. The availability and relevance of Indigenous and local knowledge in the HKH has already been documented in many cases. Efforts to integrate this knowledge into adaptation strategies have, however, been limited. More funds and human resources should be made available to document these knowledge systems and interact with stakeholders to discuss how they can be combined with modern technologies for sustainable development in mountain regions.

ECOSYSTEMS

1. The cryosphere and biodiversity are highly interconnected at the species, genetic, and ecosystems levels, but understanding of this connectedness and the impacts of climate change on the same is limited.

2. Though permafrost is an important component and contributor to alpine ecosystems – rangelands, wetlands, and peatlands, the interactions between these systems and their interfaces remain under-explored.

3. Climate-driven hazards and their cascading impacts on extinctions and range retractions, although already widespread, are poorly researched and reported. This is largely due to a failure to survey the distribution of species at a sufficiently fine resolution to enable detection of decline and attribute it to climate change.

SOCIETIES

1. The interactions between the cryospheric and non-climatic drivers of socio-ecological changes and their respective influence on the lives and livelihoods of mountain societies – including non-economic aspects such as spiritual practices and belief systems – remain insufficiently understood. Without better understanding of the cascading consequences of cryospheric change and associated adaptations, the extent of actual or potential maladaptation – responses that shift the burden of addressing cryospheric change to other places (downstream as well as transboundary), systems (ecosystems), or times (future) – will be difficult to anticipate and avoid. There is an urgent need to improve understanding of the complex nature of cryosphere-related hazards, including their transboundary consequences and implications for losses and damages.

2. Interdisciplinary studies examining the nexus of changes in the cryosphere, hydrosphere, biosphere, and society will help inform adaptation measures that attend to the myriad pressures faced by mountain societies. Greater involvement with local and Indigenous communities, including greater

respect for diverse knowledge systems, is essential to identifying adaptation options that attend to context-specific experiences of the interlinked processes of change.

3. Both the effectiveness and inclusiveness of exiting adaptation measures remain poorly understood. Evaluation of the effectiveness of adaptation should be informed by tenets of social and environmental justice and, more broadly, of sustainable development.

4. Given the significant shortfalls in existing adaptation efforts, there are concerns about what global warming beyond 1.5°C will mean for cryosphere-dependent socioeconomic systems in the HKH. There is an urgent need to initiate research that examines the nature, extent, and implications of the hard limits to adaptation associated with warming beyond 1.5°C. Such studies should be undertaken with the aim of informing anticipatory responses to projected reductions in the cryosphere of the HKH.