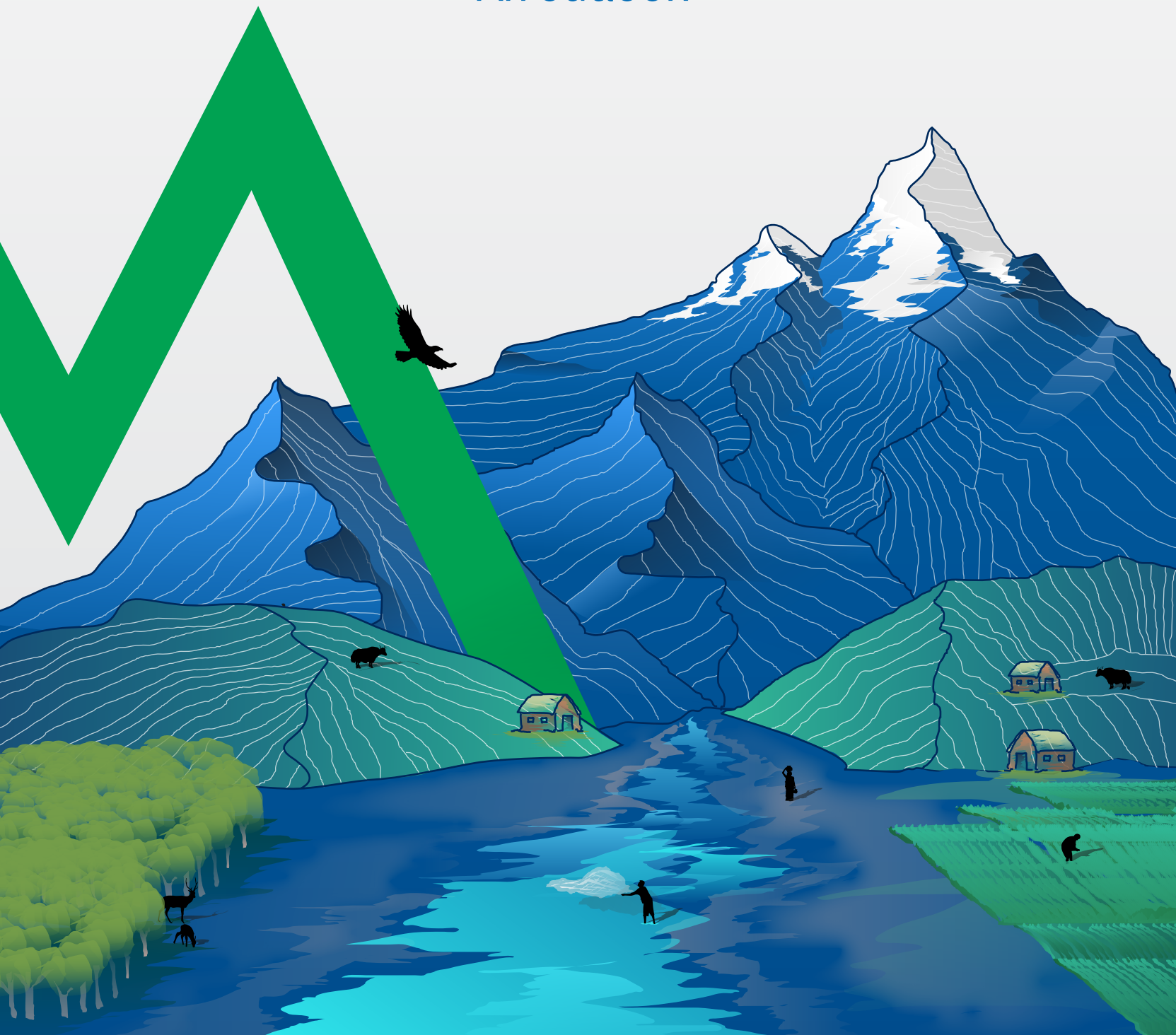


Water, ice, society, and ecosystems in the Hindu Kush Himalaya

An outlook



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ICIMOD

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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 floods
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

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Executive summary

Introduction

The Hindu Kush Himalayan (HKH) region, covering more than 4.2 million km², 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, Yangtze (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 confidence* – 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 km² in permafrost area in the western Himalaya between 2002–2004 and 2018–2020; and a loss of about 965 km² 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 $+4^{\circ}\text{C}$, 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 km² 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 km² to 6,932 km² 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 km² (13% area) in 2011–2040 to 1.07×106 km² 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 $24\% \pm 5\%$ (mean \pm standard error) increase in sediment load, and each 1°C increase in air temperature resulting in a $32\% \pm 10\%$ 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 existing 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.

CHAPTER 1

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Water, ice, society, and ecosystems in the Hindu Kush Himalaya: An introduction

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1.1. Introduction

The Hindu Kush Himalayan (HKH) region, covering more than 4.2 million km², 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. Hence, it is also known as the “Third Pole”. 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, Yangtze (Jinsha), and Yellow (Huang He) – that flow through 16 countries and provide freshwater services to 240 million people living in the HKH region and 1.65 billion downstream (Sharma et al., 2019).

Based on an assessment of the literature, this report shows that the HKH cryosphere 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. Projected changes are deeply concerning, showing a loss of at least one-third of the region’s glacier volume by 2100 if global warming is restricted to 1.5°C and much higher losses of up to two-thirds of glacier volume by 2100 under current emission rates and committed climate policy (Bolch et al., 2019). 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. For societies living at high elevations in the HKH, cryospheric change will also increase the risk of intangible cultural losses, such as loss of identity, rituals and traditions, place attachment, and cultural values (Adler et al., 2022). These losses are very difficult to quantify, but are arguably the most existential, comparable to the loss and extinction of species and ecosystems.

While the impact of climate change on glaciers, snow, and water resources is clear and supported by robust science focusing on high mountain areas (Hock et al., 2019; Adler et al., 2022), 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 changes affect the magnitudes 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 (Wester et al., 2019). 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 of the rapidly changing cryosphere in the HKH and its impacts on water, biodiversity, and societies, based on the latest science. The report explores the impact of climate change on cryospheric change, water resources, disasters, and subsequent impacts on people and ecosystems in the region. It focuses specifically on high-elevation ecosystems and the people living there, roughly defined as areas 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.

1.2. Assessment scope

This assessment covers the high mountain areas of the Hindu Kush, Karakoram, Himalaya, and Tibetan Plateau, contained in the eight countries of the HKH region (see Figure 1.1). The Tibetan Plateau lies at the region's centre. To the east lie the Qilian and Hengduan Shan and to the north the Kunlun Shan. The Himalayan arc, which lies along the southern flank, stretches from Namche Barwa (7,756 metres)

in the east to Nanga Parbat (8,125 metres) in the west, bounded by the Karakoram and the Hindu Kush mountains in the northwest. As well as being the source of 10 major (transboundary) rivers, the HKH region includes two additional river basins, namely the Interior Tibetan Plateau endorheic basin and the Helmand River, which originates in Afghanistan. The HKH boundary (see Figure 1.1) was developed by ICIMOD based on the K1 delineation of mountain areas (Kapos et al., 2000). All districts or similar

lowest-level administrative units in the eight HKH countries that encompass land lying at elevations of 300 metres or above have been included in the HKH region in their entirety. The region, therefore, also includes areas lying below elevations of 300 metres. It covers mountains, hills, and plains and is characterised by immense topographic and climatic heterogeneity. While the primary focus of this assessment is on areas above 2,000 metres, it also pays attention to downstream linkages where relevant.

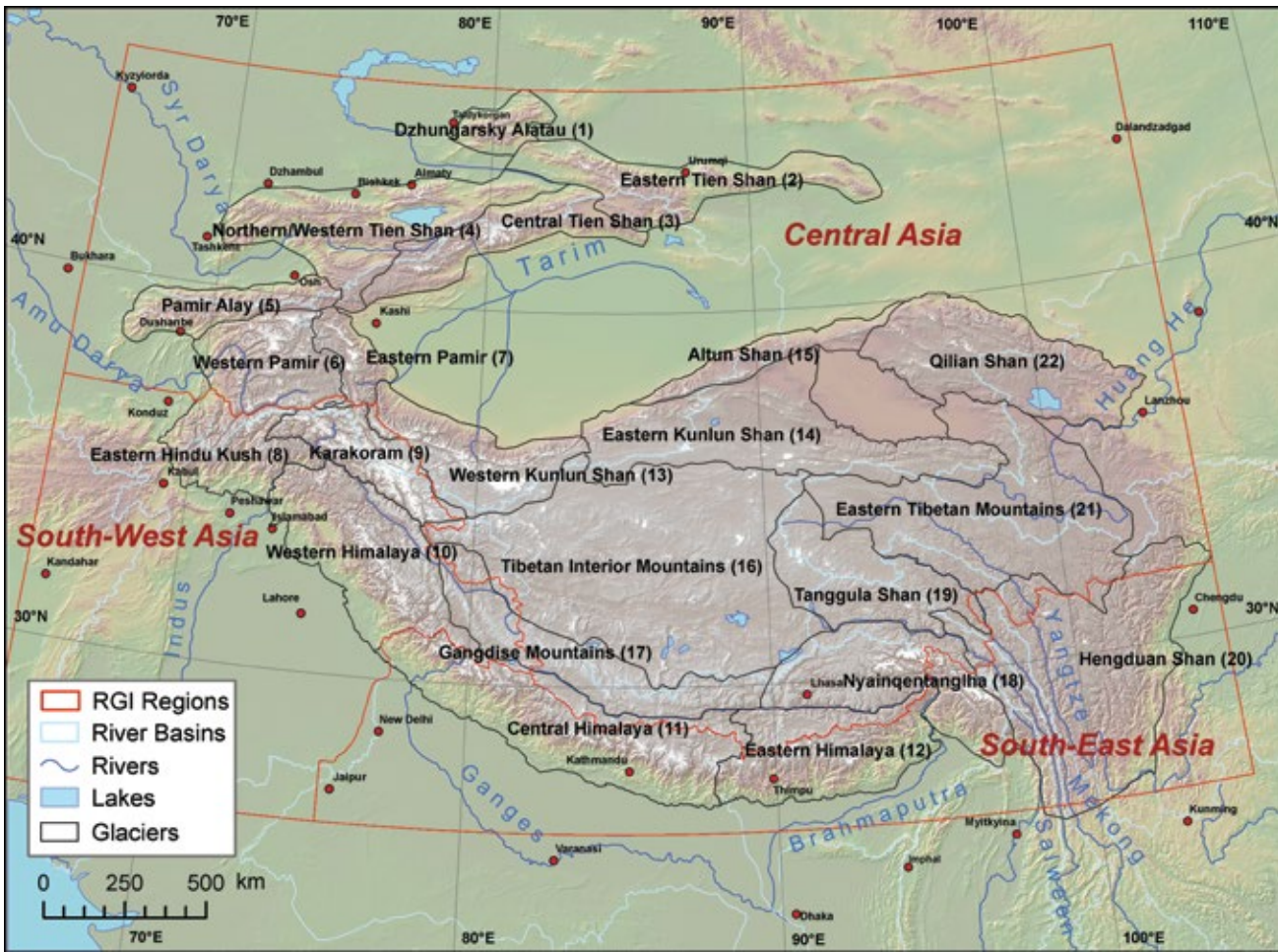
The HKH region is part of the High Mountain Asia (HMA) region, which also includes the Pamirs and the Tien Shan mountains to the west and north of the Tibetan Plateau (see Figure 1.2). The HMA region is generally understood to cover areas above 2,000 meters in elevation, and cryospheric modelling frequently focuses on the full HMA region, based on the 22 subregions shown in Figure 1.2. This delineation was used in the Cryosphere chapter of the *HKH assessment* report (Bolch et al., 2019) and is also used in this assessment with a focus on the HKH subregions (8–22).

FIGURE 1.1 THE HINDU KUSH HIMALAYAN REGION



FIGURE 1.2

HIGH MOUNTAIN ASIA SHOWING CRYOSPHERIC SUB-REGIONS (1-22), AND THE RANDOLPH GLACIER INVENTORY (RGI) REGIONS



Source: Bolch et al. (2019)

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. The IPCC approach was used to indicate the level of confidence in key findings (Ara Begum et al., 2022). The chapter overviews use three confidence levels – *medium*, *high*, and *very high confidence*. 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. 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.

1.3. Linkages between a changing cryosphere and water, society, and ecosystems

1.3.1. Key concepts

CRYOSPHERE AND HYDROSPHERE

The term cryosphere refers to the part of the Earth's surface covered by water in its solid form – including glaciers and ice caps, snow, frozen ground (including permafrost), and lake and river ice as well as cryospheric elements that are not present in the HKH, such as ice sheets and sea ice. Hence, the cryosphere has a significant overlap with the hydrosphere. As water can change its aggregate state at various temporal scales, the separation between the two domains is not always distinct. A lake can freeze over and thaw within a single day, snow changes from a liquid in the atmosphere to solid on the ground and back to liquid within days to months, while the same process for glaciers can take a hundred to a thousand years.

Lakes that form as ice retreats or dams a river, or as meltwater fills a depression are generally also investigated under the cryosphere, although they are not necessarily frozen. So are landforms created as ice advances or retreats, or as permafrost thaws. Snow can appear in many forms while still in the atmosphere and on the ground. Snow that lands on the accumulation area of glaciers transitions into ice that is then transported through a glacier body into the ablation area, where it will eventually turn into meltwater – over months, years, or even centuries. When water stored in the ground freezes, it is referred to as frozen ground or permafrost. The most common definition for permafrost is ground that remains below 0°C on average for at least two consecutive years. As water freezes and thaws within the soil over different time scales, it forms a direct link to the part of the hydrosphere referred to as the vadose zone, which encompasses soil moisture and associated processes of recharge and drainage of soils. As such, the cryosphere is a component of the hydrosphere, which includes all forms of water in its liquid and vapour forms.

HAZARDS AND RISKS

Mountain hazards and the ensuing risks to societies appear to be increasing due to climatic and cryospheric changes. Floods, flash floods, debris flows, glacial lake outburst floods (GLOFs), landslides, and avalanches are the most common mountain hazards, affecting the highest number of people in mountain regions globally (Adler et al., 2022). This report uses the updated IPCC definition of risk, which is “the potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems. In the context of climate change impacts, risks result from dynamic interactions between climate-related hazards with the exposure and vulnerability of the affected human or ecological system.” (Ara Begum et al., 2022: 132).

Compound hazards, the cumulative interactions between multiple hazards and/or hazard drivers, are increasingly occurring in high mountain environments. These range from rainfall during the peak melting season to unstable slopes from seismic shocks and increasing soil moisture. At the same time, and often as a result of compound drivers, hazards are becoming more cascading in nature (the domino effect), whereby a sequence of secondary events results in an impact significantly larger than the sum of individual or initial impacts. The term “multi-hazard” further helps to acknowledge the increasing occurrence of concurrent hazards that may interact (and hence become a compound event) or occur in parallel, resulting in a bigger impact than the sum of individual hazard impacts.

BIOSPHERE, BIODIVERSITY, AND ECOSYSTEMS

The biosphere refers to that part of the Earth where living things exist, or where life is sustained. It encompasses all the ecosystems on Earth, extending from the deep root systems of trees to the deepest parts of the oceans, from rainforests up to the highest peaks. This is where the diversity of life, i.e. “biodiversity”, exists.

Biodiversity, as defined in Article 2 of the Convention on Biological Diversity (CBD), is “the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which

they are part; this includes diversity within species, between species, and of ecosystems.” (CBD, 1992). Similarly, CBD defines “ecosystem” as a dynamic complex of plant, animal, and micro-organism communities and their non-material environment interacting as a functional unit (CBD, 2006).

This assessment focuses on biodiversity in high-elevation areas encompassing all ecosystems spatially connected to and directly benefitting from components of the cryosphere. In the HKH region, mountain biodiversity is a complex mosaic of ecosystems hosting and supporting diverse communities of plants, animals, and microorganisms and their intricate interactions with mountain-specific environments (Hudson et al., 2016; Pandit et al., 2014; Allan et al. 2019). The major ecosystems are high-elevation grasslands, forests, shrublands, agricultural land, barren land, rocky outcrops, human settlements, and water bodies (Xu et al., 2019). Above 3,000 metres, the dominant vegetation zones are the cool temperate zone, which supports coniferous forests; the sub-alpine zone, which supports riverine, temperate hardwood and dry forests; and the alpine zone, which supports alpine meadows and cold scrubs, while the western part of the HKH region is mostly covered with arid and semi-arid vegetation (Chettri et al., 2010; Xu et al., 2019). These create a unique mountain biosphere, which supports rich biodiversity at the genetic, species, and ecosystem levels, often with high endemism (Mittermeier et al., 2011).

SOCIETIES AND MOUNTAIN SPECIFICITIES

A society is defined as “a population marked by relative separation from surrounding populations and a distinctive culture” (Keesing, 1981, p. 518). In this report, HKH societies refers to the population in the HKH basins (in both mountain and downstream areas) and their activities as a whole, while mountain societies refers only to the population in the mountain areas and their activities. Similarly, a community is defined as “a place-oriented process of interrelated actions through which members of a local population express a shared sense of identity, while engaging in the common concerns of life” (Theodori, 2005, p. 662). Livelihood comprises the capabilities, assets (including both material and social resources), and activities required for a means

of living. A livelihood is said to be sustainable when it can withstand stress, recover from shocks, and maintain or enhance its capabilities and assets both now and in the future without depleting the natural resource base (Chambers & Conway, 1991).

While the above definitions are generic, of particular importance for mountain societies and livelihoods is the concept of mountain specificities, or specific characteristics of mountain areas, which was developed to capture the unique challenges that people in the mountains face (Jodha, 1992). The four main mountain characteristics that have been identified are limited accessibility, fragility, marginality, and diversity (Jodha, 1992). These are classified as either constraining features, such as accessibility, marginality, and fragility; or enabling features such as diversity, niche, and human adaptive capacity. The term accessibility not only captures the elements of distance and mobility, but also the lower availability of risk management options. Marginality refers to the relative endowments of mountain societies in terms of low resource productivity, reinforced by a lack of social and political capital. Fragility can best be understood as the susceptibility of a social or ecological system to stresses or shocks. Diversity, niche, and adaptive capacity capture different coping abilities and strategies that emerge from natural resources management, livelihood endowments, and cultural practices.

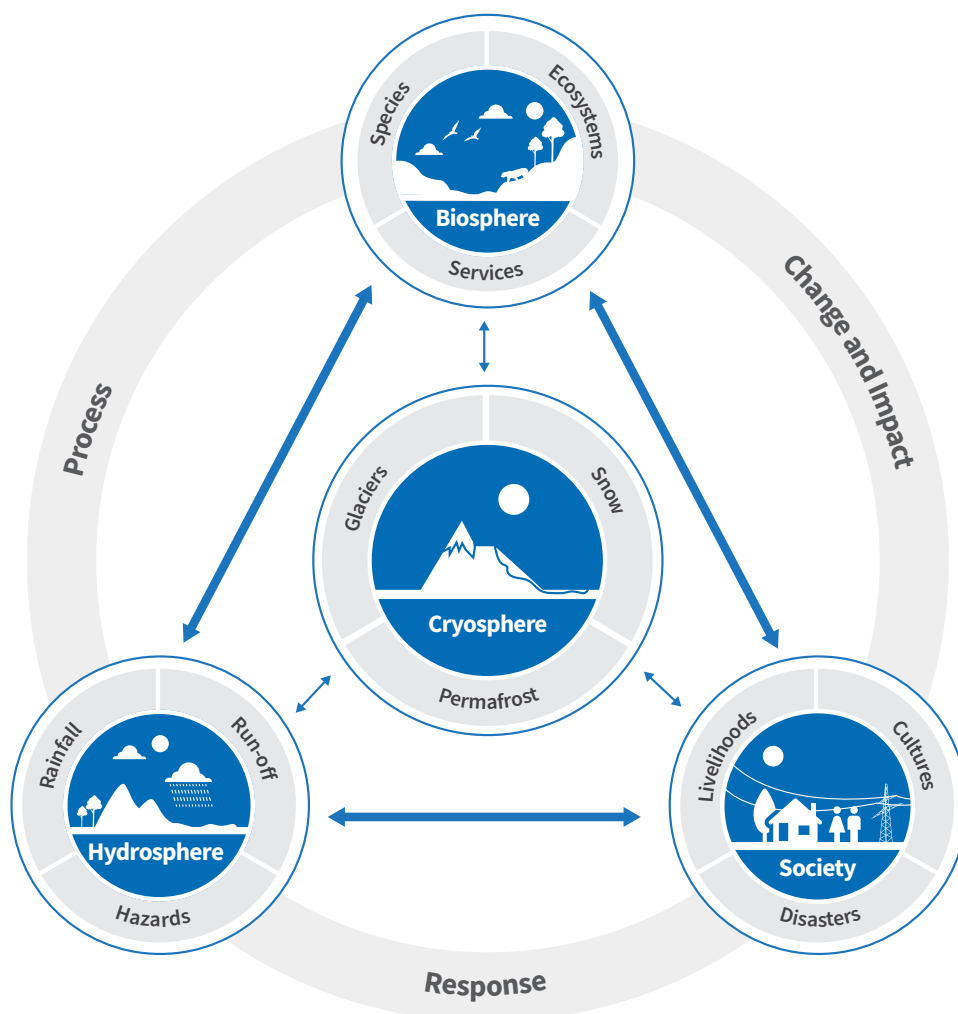
1.3.2. Linkages between the cryosphere, hydrosphere, biosphere, and society: A framework

Drawing from the earth system science understanding of the “Earth” as an integrated, symbiotic, and self-regulating complex system, this report aims to understand the complex interactions and feedbacks between different spheres – cryosphere, hydrosphere, biosphere, and society (CHBS). Rather than investigate the individual domains as closed entities, the CHBS framework views the four domains and their linkages through a more holistic lens. It provides a deeper, more integrated understanding of the dynamic interactions and processes within and between the spheres of the Earth system. This is particularly important as the cryosphere interacts with all the spheres: through

the provision of water (in solid and liquid forms) to the hydrosphere, by sustaining biodiversity through ecosystem services, and through linkages between the cryosphere and society – economies, livelihoods, cultures, and institutions. Cryospheric change and its impacts cannot be understood in isolation without consideration of the other CHBS domains as direct and indirect drivers of change, such as climate change and globalisation, which intersect across the four domains. Without holistic systems thinking, it is not possible to understand the interconnections and feedbacks between the different domains. Nor is it possible to effectively address associated issues and challenges or plan actions to strengthen people’s adaptive capacities and meet their sustainable development aspirations.

Figure 1.3 presents a framework showcasing the linkages between cryosphere, hydrosphere, biosphere, and society. Linkages focus on processes within and between the spheres, observed changes and impacts, and responses to these changes. Insights into the interconnections and interactions between cryosphere, water, ecosystems, and society help unravel the linkages. These interconnections are particularly important to consider in the context of climate and non-climate changes, as changes in one domain can have ripple effects throughout the CHBS spheres and can exacerbate feedback that may lead to further changes.

FIGURE 1.3 LINKAGES BETWEEN THE CRYOSPHERE, HYDROSPHERE, BIOSPHERE, AND SOCIETY



Beyond the biosphere that directly inhabits the cryosphere, links between the two spheres through water are obvious. As ice and snow melt or permafrost thaws, water flows into adjacent habitats and is used by its plant and animal species. As the water flows further downstream, plants and animals located along its course continue to use it. Glaciers and glacier beds are also host to unique and diverse communities of microorganisms. Because of specific micro-climatic conditions at high elevations, the cryosphere also supports high endemism in both plants and animals, and specific ecosystems such as peatlands.

As ice and snow retreat and frozen ground thaws, new spaces for vegetation growth appear. Increased net primary productivity is further supported by an increase in air temperatures at high elevations, which may also lead to species richness. However, the changing cryosphere can also be a threat to the biosphere. Mass wasting events due to receding ice, unstable slopes from thawing permafrost, and increased snowmelt can have detrimental effects on existing or developing ecosystems. Habitats may degrade or contract rapidly, and many species, especially native and endemic species, may disappear due to an increase in invasive species. Thus, this may contribute to a reduced quality, quantity, and diversity of ecosystem services, including a lower diversity of pollinators and their services.

More severe extreme events such as GLOFs, avalanches, or debris flows may coincide or combine and impact ecosystems significantly. Permafrost thaw can negatively impact plant and animal species diversity and populations, accelerating shifts in community structures, compositions, and processes. Future lack of snowmelt in areas where a negative trend is already apparent would sever a crucial water supply source. Additionally, algal growth on ice and dust deposition from surrounding dry areas can decrease surface albedo, accelerating melt. The presence or lack of shrubs and trees also both affect snowpack development.

Changes in the cryosphere can affect livelihoods and society either directly or through changes in ecosystems. Almost all livelihood sources in high mountain communities are linked to cryospheric services through water and ecosystems. Any changes

in the cryosphere will have direct implications for mountain livelihoods dependent on those services. For instance, agriculture is directly impacted by the availability of irrigation water and livestock by the availability of fodder. Both irrigation water and fodder availability are dependent on snow and meltwater. Similarly, cryosphere-related hazards can cause loss of life and livelihoods in mountain societies. The cultural, spiritual, and religious belief systems of mountain people are directly associated with cryospheric components such as snow cover, glaciers, and glacial lakes. The intangible losses in cultural heritage and belief systems – as mountains change colour or form permanently – is more difficult to assess and quantify. There are, however, direct effects as well, such as avalanches or high intensity snowfall affecting settlements and heritage sites.

Any change in the biosphere can directly affect livelihoods – either due to a change in sustenance; changes in the phenology of plants, including medicinal and aromatic plants; conflicts with wildlife; or changes in the landscapes people live in. The changing biosphere affects the water cycle by changes in evapotranspiration and may make soils less stable with higher risks of occurrence of hazards such as landslides and debris flow.

To understand how these linkages develop and how they can be affected by changes in the future, there is a need to understand what drives these changes. In principle, drivers of change can be differentiated as having either a climate change (CC) or a non-climate change (non-CC) related origin. This is not to be confused with the differentiation between anthropogenic and non-anthropogenic drivers. The rapid recession of glacier ice is driven by a rise in temperatures, a CC impact driver. Seismic shocks or the construction of a road, on the other hand, are clearly non-CC related drivers, the former non-anthropogenic and the latter anthropogenic. The attribution of what causes a certain effect is, however, more complex. For example, landslides have significantly increased in the central Himalaya in recent years. The 2015 Gorkha earthquake has been identified as an initial trigger for more unstable slopes (non-CC driver). However, the increased occurrence of landslides afterwards can possibly also be attributed to more intense rainfall (CC driver). Similarly, erosion in high mountain environments

can often be attributed to a changing permafrost landscape (CC driver), which is exacerbated where road construction has been intense (non-CC driver).

How societies experience and respond to both CC and non-CC drivers of change varies depending on their pre-existing socioeconomic vulnerabilities and adaptive capacities. In the HKH region, mountain specificities are a major bottleneck when it comes

to eradicating multi-dimensional poverty, which, in turn, limits the capacities of societies to respond adequately to changes. Besides the monitored and lived experiences of cryospheric changes, it is crucial to recognise the rapidly changing socioeconomic realities of mountain societies to better comprehend their adaptation capacities and needs.

1.4. Report outline

The four content chapters of this report weave a narrative of increasing connectedness focusing on the linkages between cryospheric change, water, ecosystems, and society. Chapter 2 starts with an overview of the changing climate in the HKH and the observed and projected impacts on the HKH cryosphere. Based on major recent advances in science, glacier mass changes between the 1970s and 2019 in the HKH have now been quantified with increased accuracy. The rate of glacier mass loss has increased significantly with an average of -0.17 m w.e. (metres water equivalent) per year for the period 2000–2009 to -0.28 m w.e. per year for 2010–2019 across the region. Importantly, the Karakoram range, known for balanced regional mass balances, showed slight wastage of -0.09 ± 0.04 m w.e. per year in 2010–2019, suggesting the ‘Karakoram Anomaly’ no longer holds. Projections for the future remain bleak, with the HKH glaciers losing 30–50% of their volume by 2100 if global warming remains below 2°C . For higher global warming levels, the loss of glacier volume will range from 55–80% by 2100.

With a few exceptions, snow cover has declined in most of the HKH region since the early 21st century. There has been a significant decrease in seasonal snow cover during the summer and winter months as well as a decline from mid-spring through mid-fall, indicating a seasonal shift. Snow cover days have generally declined at an average rate of five snow cover days per decade with most of the changes at lower elevation. At the same time, heavy snowfall events have increased in recent years with frequent snowstorms observed over the Tibetan Plateau and the Himalaya. These events are predicted to

continue to become more frequent and intense in the future. Overall, snow cover is likely to experience an accelerated loss under different global warming levels in the HKH. The contribution of snowmelt to streamflow is expected to decrease in the future and the onset of snow melting is expected to occur earlier.

Chapter 3 focuses on the consequences of cryospheric change on water resources and hazards in the HKH. Both snowmelt and glacier melt contribute substantially to river flows in the HKH, although their relative contribution decreases from West to East, from as high as 79% in the Amu Darya to a mere 5% in the Irrawaddy rivers. The contribution of melt run-off is high in the western HKH due to the westerlies, with winter snowfall playing an important role. In contrast, the Indian summer monsoon plays an important role in the eastern Himalaya, which is reflected in the 50–79% rainfall run-off contribution to rivers such as the Ganges, Brahmaputra, Irrawaddy, and Yellow. While glacier melt receives most of the attention, it is notable that snowmelt accounts for most of the cryospheric contribution to streamflow in all HKH river basins (between 5.1% in the Irrawaddy to 77.5% in the Helmand, while glacier melt ranges from 0% in the Irrawaddy to a high of only 5.1% in the Indus). With the projected decrease in snow fall and snowmelt in the coming century and the increase in glacier melt, ‘peak water’ will be reached around mid-century in most HKH river basins, while water availability overall is expected to decrease by the end of the century. However, the variability from basin to basin is large, and due to the large uncertainty in projections of future precipitation, confidence in estimates of future run-off remains low.

With a changing climate and increased exposure of livelihoods and infrastructure, the mountain hazard landscape has become more hazardous. A number of different slow- (e.g. sedimentation and erosion) and fast-onset hazards (e.g. flash floods) are occurring in the same watersheds and, in many cases, concurrently and often also in a cascading manner. While there is no clear evidence yet of an increasing trend of such hazards, it is clear that many events have been made possible due to a change in climate resulting in more meltwater, larger and more potentially dangerous lakes, unstable slopes from thawing permafrost, and increasing sediment loads in rivers. Future frequency and intensity estimates exist for only a limited number of hazards, particularly for events associated with increasing heavy precipitation, indicating an increasing trend although the evidence base is limited.

Chapter 4 focuses on high-elevation biodiversity and its linkages with the cryosphere, an important source of water for maintaining ecosystem health, enriching biological diversity, and providing ecosystem services. Biodiversity in the HKH is highly sensitive to climate change, which is leading to visible range shift of species to higher elevations, ecosystem degradation and changes, and invasion by alien species. Future projections of the impacts of climate change and cryospheric change on biodiversity show an increase in ecosystem vulnerability and a reduction in the flow of ecosystem services, with cascading effects of cryosphere loss on species composition, degradation of ecosystems, and an increasing imbalance in ecosystem functions, all resulting in more acute vulnerability to society.

Chapter 5 pulls together all these strands to analyse the linkages between cryospheric change and society, with a focus on high elevation areas. Both climatic and non-climatic drivers of change are strongly impacting the lives and livelihoods of mountain people as well as their capacity to respond or adapt to these changes. While the lives of mountain people have generally improved with increased accessibility and economic development, their marginal and vulnerable status has hardly changed, having probably worsened due to cryospheric change. As mountain societies strongly depend on agriculture, livestock, and the collection

and trading of medicinal and aromatic plants, they are particularly vulnerable to the adverse impacts of cryospheric change. More broadly, future cryospheric change will add more pressure on societies, particularly those living in transboundary glaciated river basins, where reliance on high mountain freshwater is high.

Meanwhile, both soft and hard limits to adaptation make mountain societies highly vulnerable to the changing cryosphere. To date, adaptation measures to address the impacts of cryospheric change have been mostly reactive, autonomous, and incremental in nature, and primarily limited to the household and community levels. Noticeably, there are large gaps between the adaptation needs of communities and their access to or the provision of necessary adaptation support and funds, which needs to be urgently addressed considering the increasing impacts of cryospheric change. Overall, adaptation constraints and limits and insufficient understanding of the interactions between cryospheric and non-climatic drivers and their impacts on mountain societies are hindering achievement of the Sustainable Development Goals.

References

- Adler, C., Wester, P., Bhatt, I., Huggel, C., Insarov, G.E., Morecroft, M.D., Muccione, V., & Prakash, A. (2022). Cross-Chapter Paper 5: Mountains. In 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.), *IPCC climate change 2022: Impacts, adaptation and vulnerability*. Contribution of Working Group II to the sixth assessment report of the Intergovernmental Panel on Climate Change (pp. 2273–2318). Cambridge University Press. https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_CCP5.pdf
- Allan JR, Watson JEM, Di Marco M, O'Bryan CJ, Possingham HP, Atkinson SC, et al. (2019) Hotspots of human impact on threatened terrestrial vertebrates. *PLoS Biol* 17(3): e3000158. <https://doi.org/10.1371/journal.pbio.3000158>
- Ara Begum, R., Lempert, R., Ali, E., Benjaminsen, T.A., Bernauer, T., Cramer, W., Cui, X., Mach, K., Nagy, G., Stenseth, N.C., Sukumar, R., & Wester, P. (2022). Point of departure and key concepts. In 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.), *IPCC climate change 2022: Impacts, adaptation and vulnerability*. Contribution of Working Group II to the sixth assessment report of the Intergovernmental Panel on Climate Change (pp. 121-196). Cambridge University Press. https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_Chapter01.pdf
- Bolch, T., Shea, J. M., Liu, S., Azam, F. M., Gao, Y., Gruber, S., Immerzeel, W. W., Kulkarni, A., Li, H., Tahir, A. A., Zhang, G., & Zhang, Y. (2019). Status and change of the cryosphere in the extended Hindu Kush Himalaya region. In P. Wester, A. Mishra, A. Mukherji, & A. B. Shrestha (Eds.), *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability and people* (pp. 209–255). Springer Nature Switzerland AG. https://doi.org/10.1007/978-3-319-92288-1_7
- CBD (1992). *Convention on Biological Diversity*, Secretariat of the Convention on Biological Diversity, Montreal, <https://www.cbd.int/doc/legal/cbd-en.pdf>
- CBD (2006). *Global Biodiversity Outlook 2*, Secretariat of the Convention on Biological Diversity, Montreal, 81 +vii pages. <https://www.cbd.int/doc/gbo/gbo2/cbd-gbo2-en.pdf>
- Chambers, R., & Conway, G. (1991). Sustainable rural livelihoods: Practical concepts for the 21st century. <http://www.smallstock.info/reference/IDS/dp296.pdf>
- Chettri, N., Sharma, E., Shakya, B., Thapa, R., Bajracharya, B., Uddin, K., et al., (2010). Biodiversity in the Eastern Himalayas: Status, trends and vulnerability to climate change. Climate change impact and vulnerability in the Eastern Himalayas, Technical report.2, pp.23. Kathmandu: ICIMOD.

- Hock, R., Rasul, G., Adler, C., Cáceres, B., Gruber, S., Hirabayashi, Y., Jackson, M., Kääh, A., Kang, S., Kutuzov, S., Milner, A., Molau, U., Morin, S., Orlove, B., & Steltzer, H. (2019). High mountain areas. In 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, & N. M. Weyer (Eds.), *IPCC special report on the ocean and cryosphere in a changing climate* (pp. 131–202). Cambridge University Press. <https://doi.org/10.1017/9781009157964>
- Hudson, A.M., Olsen, J.W., Quade, J., Lei, G., Huth, T.E., and Zhang, H. (2016). A regional record of expanded Holocene wetlands and prehistoric human occupation from paleo wetland deposits of the western Yarlung Tsangpo valley, southern Tibetan Plateau. *Quaternary Research*. <https://doi.org/10.1016/j.yqres.2016.04.001>
- 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., ... Baillie, J. E. M. (2020). Importance and vulnerability of the world's water towers. *Nature*, 577(7790), 364–369. <https://doi.org/10.1038/s41586-019-1822-y>
- Jodha, N.S. (1992). Mountain perspective and sustainability: A framework for development strategies. In N.S. Jodha, M. Banskota, & T. Partap (Eds.), *Sustainable mountain agriculture. Vol. 1, Perspectives and issues*, (pp. 41-82). New Delhi: Oxford and IBH Publishers.
- Keesing, R.M. (1981). *Cultural anthropology: A contemporary perspective*. Holt, Rinehart and Winston.
- Kapos V., Rhind J., Edwards M., Price M.F. & Ravilious C. (2000). Developing a map of the world's mountain forests. Forests in sustainable mountain development: a state of knowledge report for 2000 Task Force on Forests in Sustainable Mountain Development (pp. 4–19). <https://doi.org/10.1079/9780851994468.0004>
- Mittermeier, R. A., Turner, W. R., Larsen, F. W., Brooks, T. M., & Gascon, C. (2011). *Global biodiversity conservation: the critical role of hotspots*. In F.E. Zachos & J.C Habel (Eds.), *Biodiversity hotspots: distribution and protection of conservation priority areas*, Pp. 3-22. Springer Heidelberg Dordrecht London New York.
- Pandit, M.K., Manish, K., and Koh, L.P. (2014). Dancing on the roof of the world: ecological transformation of the Himalayan landscape. *BioScience*, vol.64 (11), pp.980-992. <https://doi.org/10.1093/BIOSCI%2FBIU152>
- Robertson, R. (1977). The meaning and concept of «society». In *Sociological Review Monograph* (Vol. 25, pp. 119-131). Sage Publications.
- Sharma, E., Molden, D., Rahman, A., Khatiwada, Y.R., Zhang, L., Singh, S.P., Yao, T., & Wester, P. (2019). Introduction to the Hindu Kush Himalaya assessment. In P. Wester, A. Mishra, A. Mukherji, & A.B. Shrestha (Eds.), *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability and people*. (pp. 1-16) Springer Nature Switzerland AG. https://doi.org/10.1007/978-3-319-92288-1_1
- Theodori, G. L. (2005). Community and Community Development in Resource-Based Areas: Operational Definitions Rooted in an Interactional Perspective. *Society & Natural Resources*, 18(7), 661–669. <https://doi.org/10.1080/08941920590959640>
- Wester, P., Mishra, A., Mukherji, A., & Shrestha, A. B. (Eds.), (2019). *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability and people*. Springer Nature Switzerland AG. <https://doi.org/10.1007/978-3-319-92288-1>

CHAPTER 2

RECOMMENDED CITATION

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Consequences of climate change for the cryosphere in the Hindu Kush Himalaya

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Chapter overview

KEY FINDINGS

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 mass loss increased by 65% through the study period with 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*).

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 under different global warming levels in the HKH (*medium confidence*).

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 km² in permafrost area in the western Himalaya between 2002–2004 and 2018–2020; and a loss of about 965 km² 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.

POLICY MESSAGES

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.

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 and agriculture accordingly.

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.

CHAPTER SUMMARY

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 Nyainqentanglha 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 km² 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 km² to 6,932 km² in the Uttarakhand Himalaya between 1970–2000 and 2001–2017. On the Tibetan Plateau, the area of permafrost degradation could range from 0.22×10^6 km² (13% area) in 2011–2040 to 1.07×10^6 km² 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.

KEY KNOWLEDGE GAPS

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 get a better understanding of how glaciers will react to future climate change and their subsequent effect on basin hydrology.

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.

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 landslides caused by permafrost degradation.

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.

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2.1. Introduction

The most important components of the cryosphere in the Hindu Kush Himalaya (HKH) are glaciers, snow, and permafrost. Glaciers and snow are highly visible features of the mountains in the HKH. In situ measurements of glaciers and snow are limited in extent and, where they exist, are generally sparse and lack continuity. However, recent advances in spatial and temporal resolution in satellite imagery have meant that our knowledge of snow and glacier extent and changes they have undergone has increased rapidly in just the last few years. More coordinated efforts by the glaciological community, such as in glacier projections under different climate scenarios, have meant that this field has also expanded rapidly.

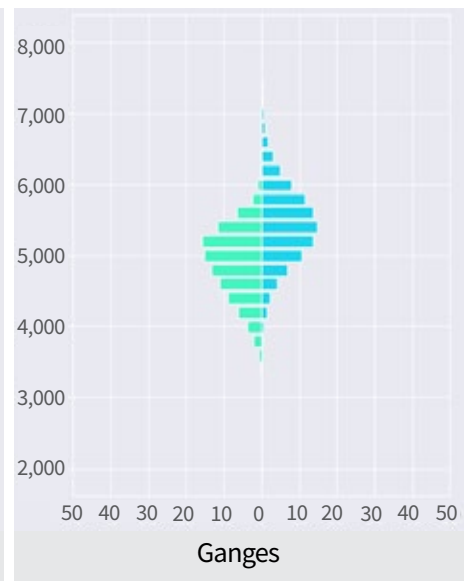
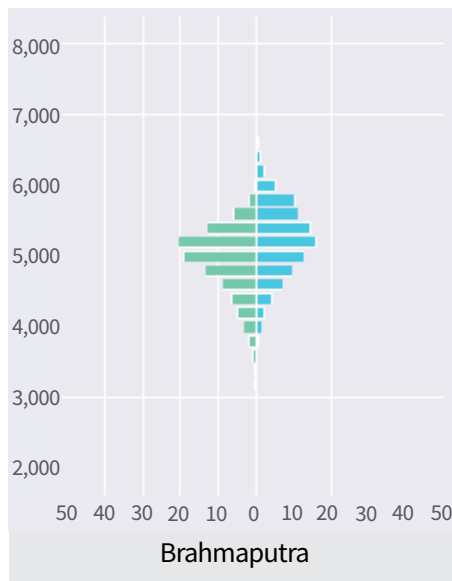
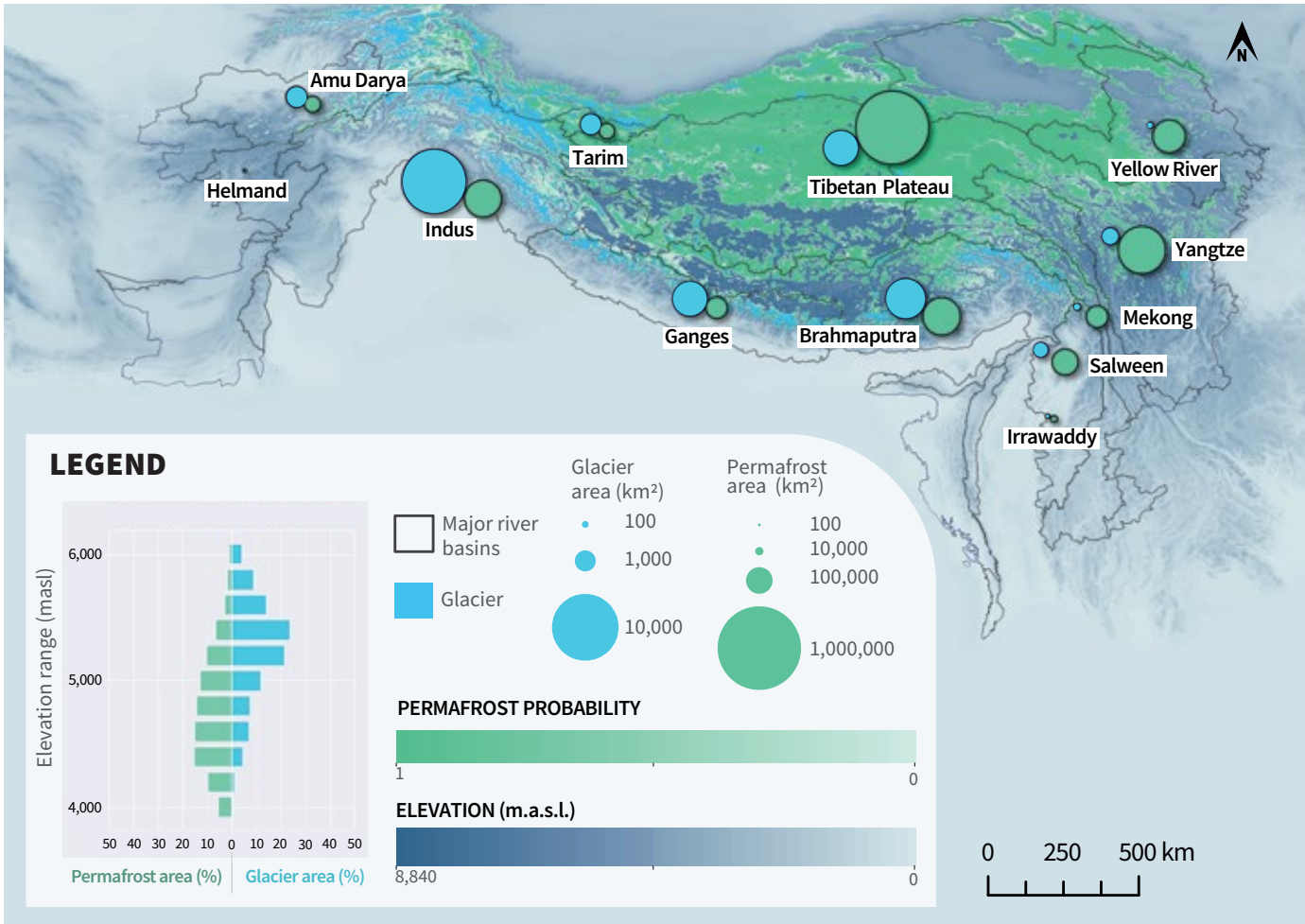
Permafrost is defined as ground that remains at or below 0 degrees Celsius (°C) for at least two consecutive years. By its nature, it is not visible in the same way that glaciers and snow cover are, but it covers a considerable area of the HKH (Figure 2.1). Hence, it is not possible to measure its extent from satellite imagery, although ground features related to

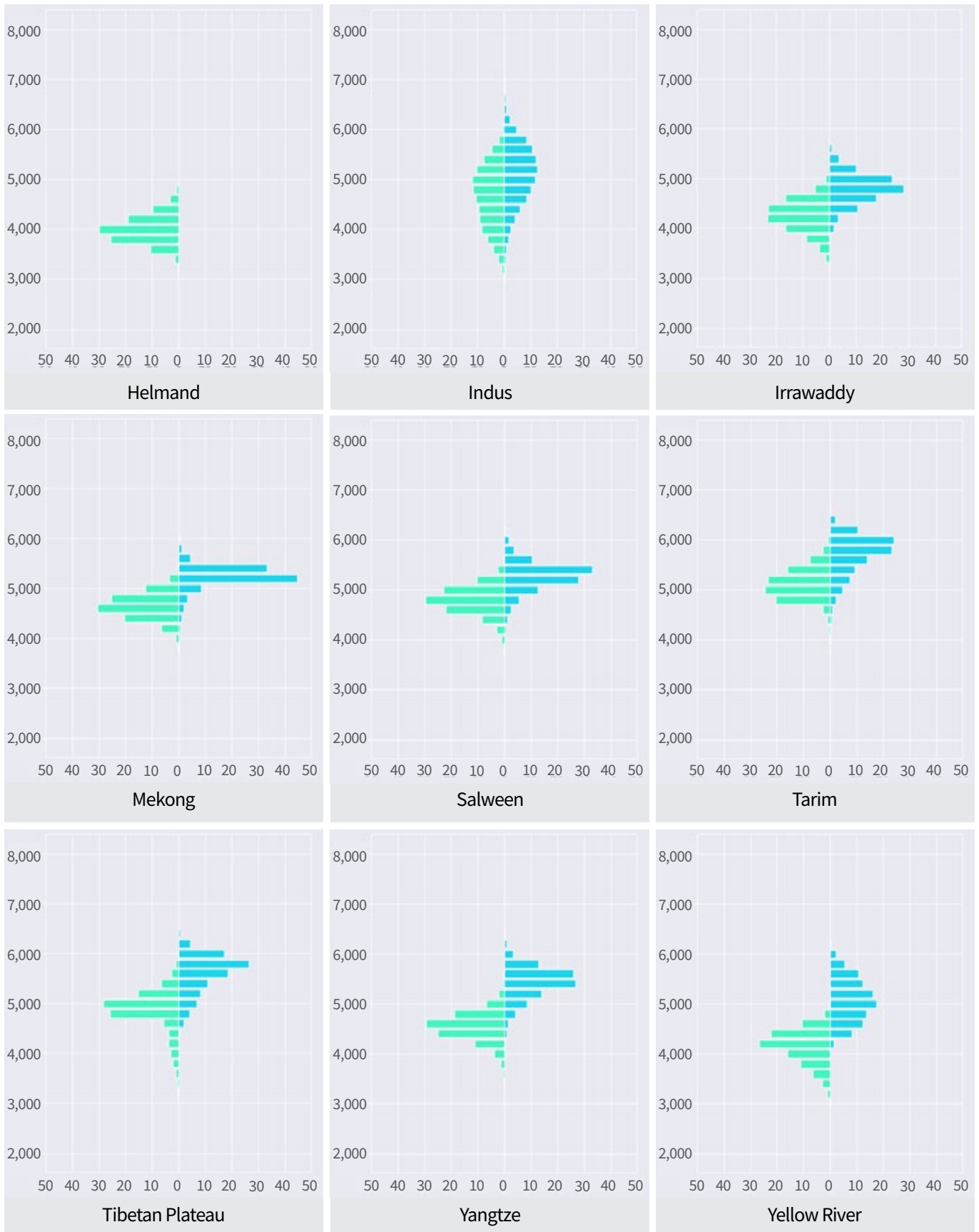
permafrost can be detected and used to train models to generate probability maps for the existence of permafrost. There have been several of these studies in recent years, but there are still very few ground-based measurements.

This chapter examines the effects that climate change will have on different components of the cryosphere in the HKH in the near future and the drivers of those changes. Advances in scientific understanding since the publication of *The Hindu Kush Himalaya assessment* report (Wester et al., 2019) are included as well as new knowledge on the status of the cryosphere since its publication. The chapter concludes by summarising the main current knowledge gaps concerning glaciers, glacial lakes, snow, and permafrost, and makes recommendations to address these gaps. The impacts of changes in the cryosphere on downstream hydrology and water resources, and natural hazards related to a changing cryosphere are covered in Chapter 3 of this report. The consequent impacts on ecosystems and livelihoods are covered in chapters 4 and 5 respectively.

FIGURE 2.1

DISTRIBUTION OF PERMAFROST (IN GREEN) AND GLACIERS (IN BLUE) AND SUMMARY STATISTICS FOR GLACIERS AND PERMAFROST IN THE MAJOR RIVER BASINS OF THE HKH





Notes: Boundaries of the portions of the river basins falling in the HKH outlined in dark grey. Blue circles represent glacier area (Randolph Glacier Inventory 6.0) and green circles represent permafrost area (Obu et al., 2019) in each river basin. Bar plots for each river basin indicate permafrost and glacier area in 200-metre elevation bins as a percentage of total permafrost and glacier area in the river basin falling in the boundary of the HKH, respectively.

2.2. The climate of the HKH region

2.2.1. The observed climate in the HKH

Tropical/subtropical climatic conditions dominate in the foothills of the HKH, transitioning to an alpine climate at higher elevations with permanently snow- and ice-covered peaks. The HKH region's meteorology is a unique example of the direct interplay of high-altitude mountains with complicated terrains, locally originating atmospheric weather patterns, and large-scale migratory weather systems. Because orography, the topographic relief of mountains, has an impact on large-scale air flows, mountain systems produce weather patterns that are highly changeable and relatively less predictable. Dynamic alterations brought on by orographic barriers and surface boundary forcings, such as changes in local temperature or humidity, created in difficult terrains further complicate this effect. In general, mountains have frictional effects on surface winds, block the passage of wind and weather systems, and cause vertical ascents and gliding flows across valleys. Mountains have the capacity to significantly alter the properties of weather systems through their interactions with them at various temporal and spatial scales (Pant et al. 2018).

The mountain ranges of the HKH are situated in a region of subtropical high pressure where seasonal pressure and the movement of wind systems from north to south typically affect seasonal weather. The amount of annual rainfall increases from west to east along the southern front of the range (Sabin et al., 2020). Most monsoon precipitation falls in the Lower Siwalik and Pir Panjal mountains of the Himalaya, whereas the high Himalaya, trans-Himalaya, and Karakoram ranges receive less precipitation (Bookhagen & Burbank, 2006). Over the western Himalaya, Hindu Kush, and Karakoram regions, these winter circulations and disturbances bring chilly winds and precipitation in the form of snow, largely connected with the troughs and low-pressure systems buried in these circulations known as western disturbances, which are mid-latitude weather systems that originate in the Mediterranean region (Madhura et al., 2015). There are different climatic sub-zones due to the large elevational range within the HKH, ranging

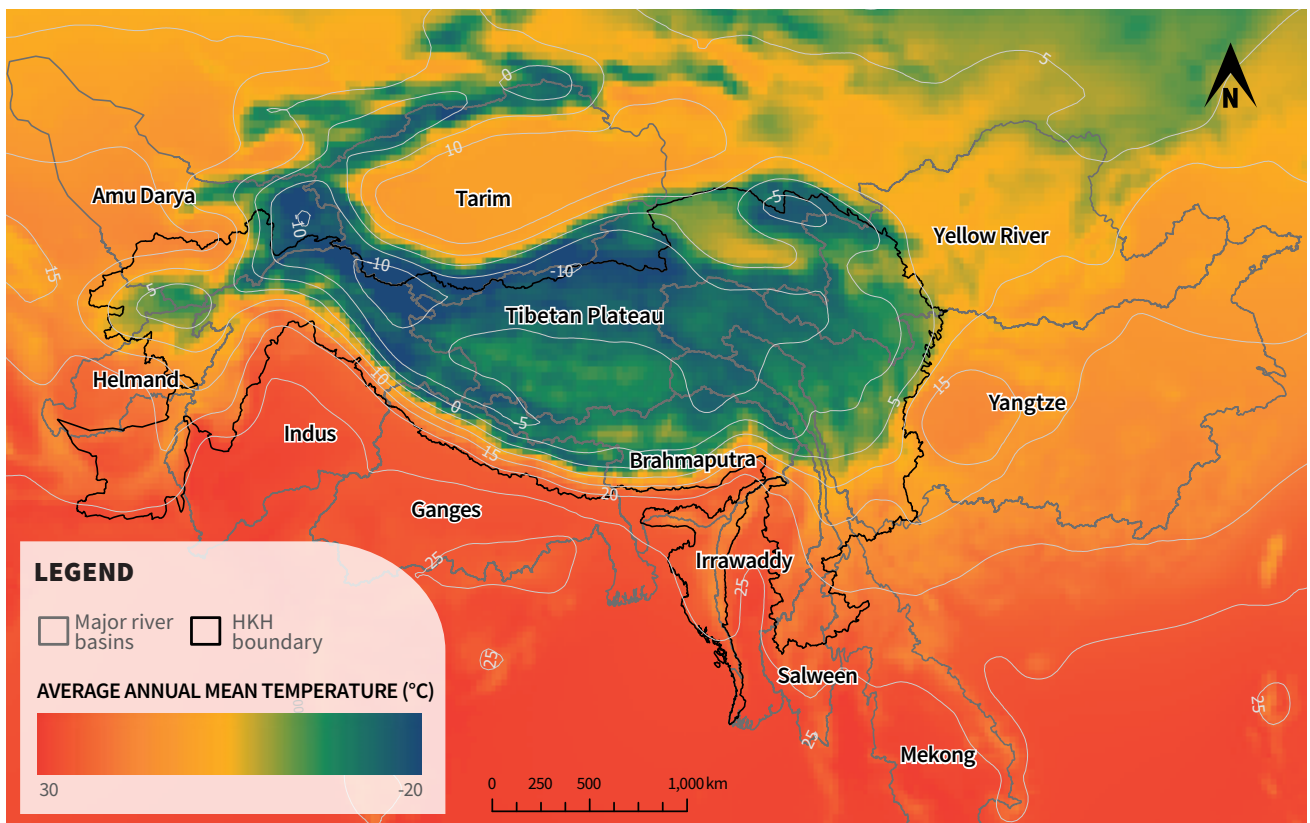
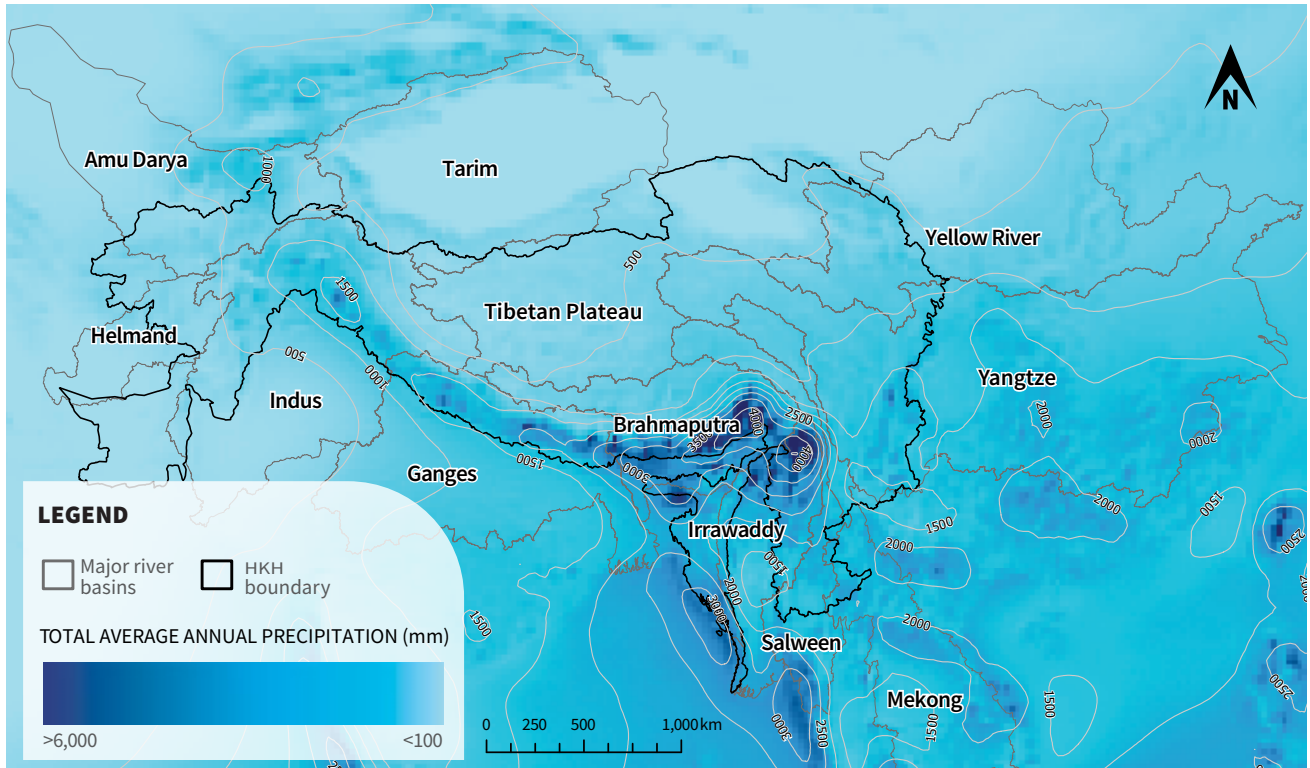
from the tropical zone below 1,000 metres above sea level (m a.s.l.) to the trans-Himalayan zone above 5,000 m a.s.l. The annual cycle of temperature and precipitation differs substantially in these different zones. Seasonal variations in the mean climate of the HKH are closely tied to the seasonal cycle of the regional atmospheric processes (Sabin et al., 2020). The observed weather and mean climate conditions over the HKH are summarised in Chapter 3 (see subsection 3.2) of *The Hindu Kush Himalaya assessment* report (Krishnan et al., 2019).

In this chapter, trends in precipitation and temperature have been presented from reanalysis data provided by ECMWF (European Centre for Medium-Range Weather Forecasts) using the ERA5 (ECMWF Reanalysis v5) version (Muñoz Sabater, 2021), which is the latest comprehensive ECMWF reanalysis climate data. ERA5 provides hourly estimates of the global atmosphere, land surface, and ocean waves from 1950, is updated daily with a latency of 5 days (Hersbach et al., 2020), and has a horizontal resolution of 31 kilometres (km). Seasonal distinctions may vary between and across basins, depending on the climatic variables considered for a given season. However, for the sake of consistency in making the comparison, we have chosen the following definitions for the four seasons across the basins: pre-monsoon (March–May), monsoon (June–September), post-monsoon (October–November), and winter (December–February).

The mean precipitation ranges from <100 millimetres (mm) to over 6,000 mm per year within the HKH (Figure 2.2, top). The precipitation hotspots lie in the Brahmaputra (~2,200 mm per year) and Irrawaddy river basins (~2,400 mm per year) whereas the lowest precipitation is observed on the Tibetan Plateau (~380 mm per year), Helmand (~380 mm per year), and Tarim (~210 mm per year) basins (Table 2.1). The western basins generally receive more precipitation during the winter months (mainly as snow), whereas more than 70% of the annual precipitation in the central and eastern basins of the Himalaya falls during the summer monsoon season. Most of the monsoon precipitation falls as rain. However, snowfall

FIGURE 2.2

TOTAL AVERAGE ANNUAL PRECIPITATION (TOP) AND AVERAGE ANNUAL MEAN TEMPERATURE (BOTTOM) FOR THE 12 MAJOR RIVER BASINS OF THE HKH FOR THE PERIOD 1951–2020



Data source: ERA5 (Muñoz Sabater, 2021)

is prevalent in the high-elevation areas of the basins. The annual and seasonal precipitation for 12 major river basins of the HKH are presented in Table 2.1.

The average annual mean temperature within the HKH ranges from -20°C to 30°C . The plains experience higher temperatures than the middle and high mountain regions throughout the year. The lowest basin average annual mean temperature is about -4°C , on the Tibetan Plateau, while the highest basin average (22°C) is observed in the Irrawaddy River Basin. The seasonal mean temperature is the lowest during the winter season and highest during the monsoon season in all the river basins. The mean temperature during the pre-monsoon and post-monsoon seasons is above zero for all the basins except the Tibetan Plateau. The seasonal mean

temperature decreases drastically after the monsoon, by at least 6°C , barring in the Irrawaddy and Mekong basins. In these two basins, the mean temperature stays relatively similar during the pre-monsoon, monsoon, and post-monsoon seasons. The average annual and seasonal mean temperatures for 12 major river basins of the HKH are presented in Table 2.1.

However, there are some studies which suggest that ERA5 data have a cold bias over the mountains (A. Khadka et al., 2022; Orsolini et al., 2019). This results in a considerable overestimation of snow depth, by a factor of up to 10, over the Tibetan Plateau (Orsolini et al., 2019) as well as of precipitation in the Himalaya above 4,000 m, by a factor of up to 3 (A. Khadka et al., 2022).

River basin	Precipitation (mm)					Temperature ($^{\circ}\text{C}$)				
	Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual	Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
Amu Darya	121.2	164.1	56.6	50.2	392	-3.8	9.5	20.4	5.0	9.1
Helmand	118.8	88.6	11.1	14.7	233	3.4	16.6	26.6	13.2	14.9
Indus	114.8	141.2	314.8	37.9	609	4.4	16.1	23.3	12.8	15.0
Tarim	16.4	52.4	127.5	15.8	212	-9.4	7.5	17.2	0.7	5.4
Ganges	72	116.6	1,050.6	68.7	1,308	13.3	24.2	25.8	19.5	21.2
Tibetan Plateau	18.4	62.7	282.8	19.5	383	-15.0	-4.3	6.0	-7.8	-4.1
Brahmaputra	152.8	513.6	1,383.2	170.9	2,221	-1.9	6.2	13.5	4.9	6.4
Irrawaddy	84.5	386.4	1,698.6	273.8	2,443	17.5	24.5	24.8	21.6	22.4
Salween	62.1	274.5	1,190.9	179.8	1,707	8.0	15.3	18.5	12.6	14.1
Mekong	61.6	343.8	1,090.0	214.9	1,710	17.5	22.7	23.5	20.1	21.2
Yangtze	127.5	365.9	739.7	142.4	1,376	0.8	11.4	20.4	9.4	11.4
Yellow River	26.6	109.8	408.3	59.7	604	-6.8	7.8	17.7	3.2	6.7

Data source: ERA5 (Muñoz Sabater, 2021)

Note: Under 'Tibetan Plateau', endorheic basins of the plateau are summarised.

2.2.2. Trends in temperature and precipitation

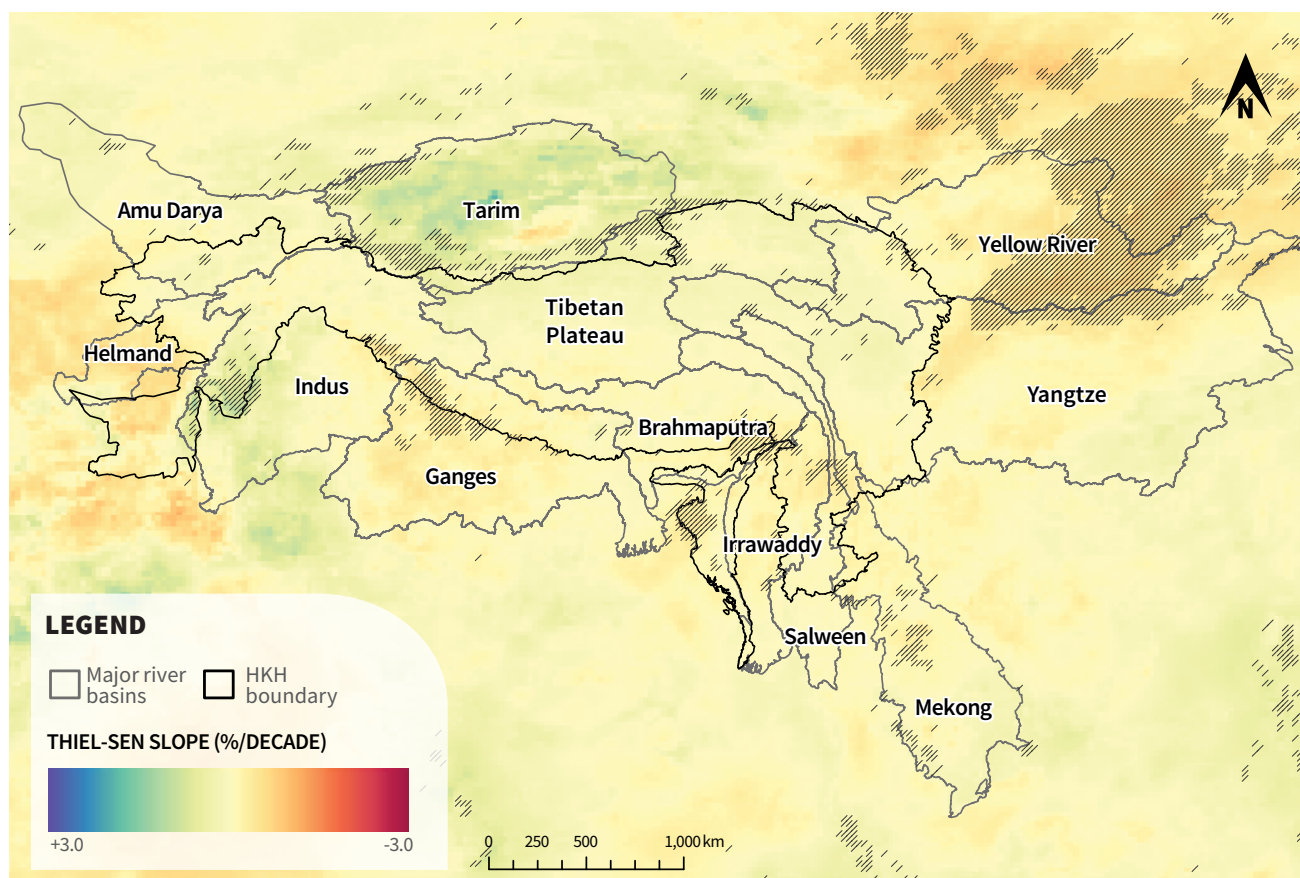
The decadal trends in precipitation and mean temperature have been calculated using the ERA5 reanalysis dataset for the 12 major river basins of the HKH for the period 1951–2020. It is important to note that reanalyses such as ERA5 may have limited accuracy due to inhomogeneities connected to changing inputs from observations over time, such as data from new and improved instruments on satellites becoming available. Nevertheless, the accuracy of ERA5 may be assessed to some extent through comparison with local, in situ observations. The significance and magnitude of the trends are determined using the non-parametric Mann–Kendall test and Thiel-Sen slope, respectively. The trend in precipitation ranges between -3% and $+3\%$ per decade in the 12 river basins (Figure 2.3, top).

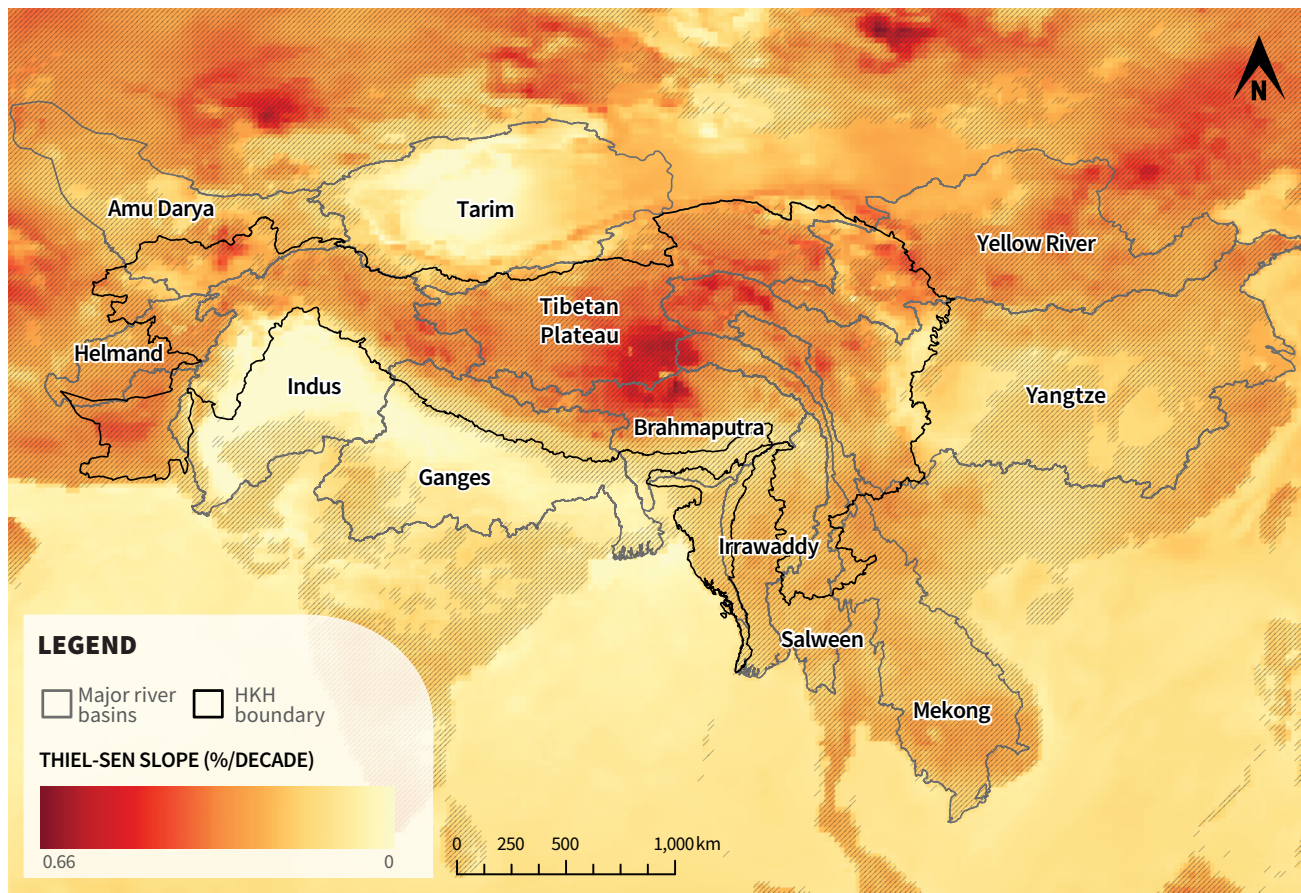
However, the trend is mostly non-significant in all areas except for the high-elevation areas of the Tarim Basin, some parts of the Ganges River Basin, and parts of the Yellow, Brahmaputra, and Irrawaddy river basins, where a significant decrease is noted. Similar results have also been observed over the HKH by Ren et al. (2017) using the China Meteorological Administration’s CMA Global Precipitation dataset V1.0 (CGP1.0). Kraaijenbrink et al. (2021) also found a similar range ($\pm 4\%$ per year) for the trend in annual precipitation using the ERA5 dataset over the HKH region for the period 1979–2019. The *Hindu Kush Himalaya assessment* report also concluded that, with the present data, precipitation did not show clear trends in the past six decades (Krishnan et al., 2019).

Conversely, the mean temperature is increasing significantly in all regions of the HKH with an average observed increase of $+0.28^\circ\text{C}$ per decade for the period

FIGURE 2.3

DECADAL TRENDS IN TOTAL ANNUAL PRECIPITATION (TOP) AND AVERAGE ANNUAL MEAN TEMPERATURE (BOTTOM) FOR THE 12 MAJOR RIVER BASINS OF THE HKH FOR THE PERIOD 1951–2020





Note: The diagonal lines indicate the regions where the trend is significant at a 0.01 level.
Data source: ERA5 (Muñoz Sabater, 2021)

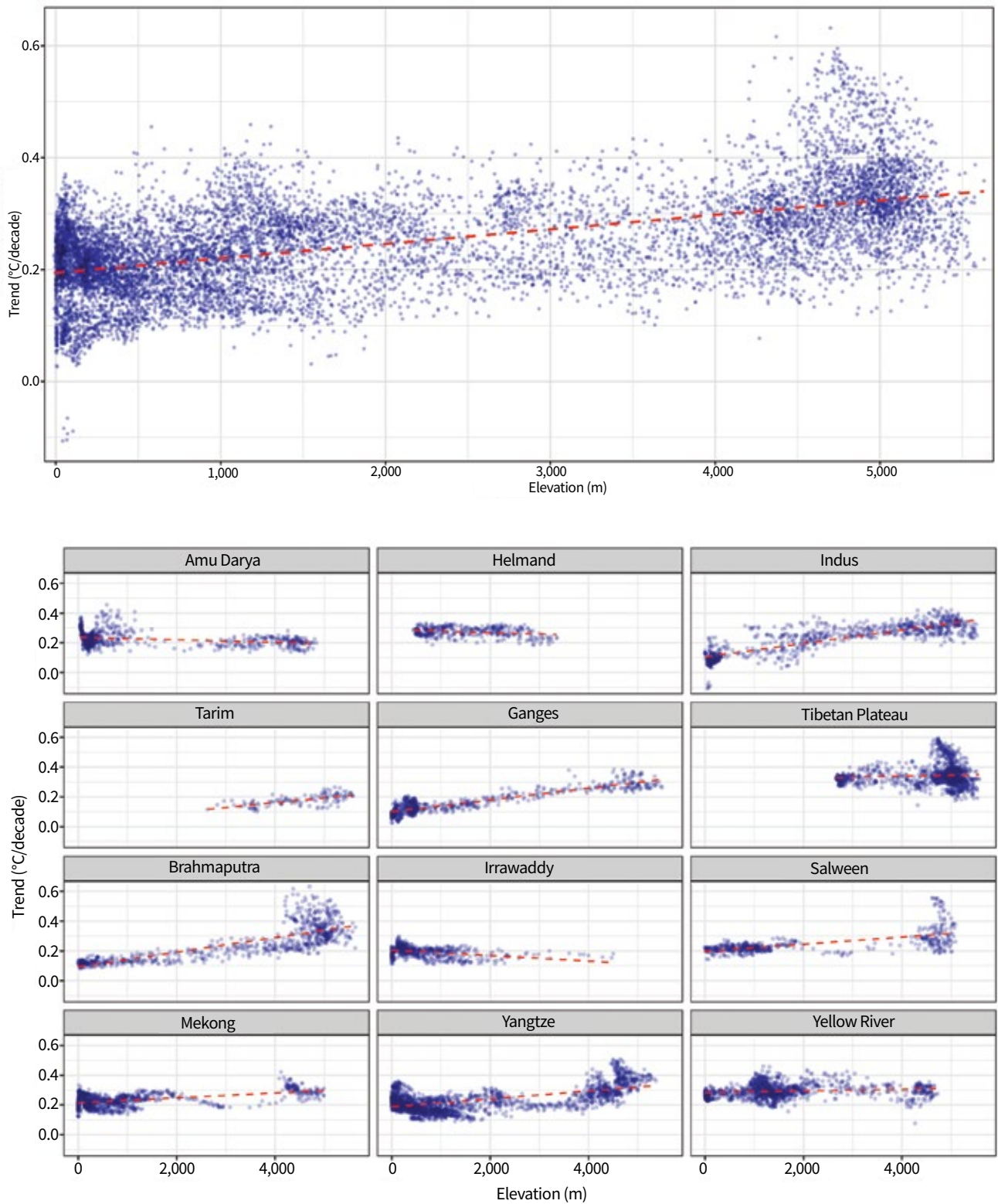
1951–2020. The range in the observed trends for the 12 river basins varies from +0.15°C per decade to +0.34°C per decade for the same period. The observed trend was up to +0.66°C per decade in parts of the Tibetan Plateau, Brahmaputra, Amu Darya, and the headwaters of the Mekong and Yangtze basins (Figure 2.2, bottom). This agrees with the analyses of observed changes and reanalysis products for the few areas of the HKH where data are available (Chhetri et al., 2020; Ren et al., 2017; Q.-L. You et al., 2017). Kraaijenbrink et al. (2021) also found similar trends (0°C–0.6°C per decade) in the mean temperature using the ERA5 dataset over the HKH region for the period 1979–2019. The mean temperature trend is non-significant in some regions of the Indus, Ganges, and Tarim basins. The strongest trends are observed for the Tibetan Plateau, Amu Darya, and Brahmaputra basins, and the headwaters of the Mekong and Yangtze basins. The results also show temperatures to be decreasing over northern India, but those trends are influenced by air pollution (aerosols) and land-use change (for example, irrigation) (Jia, et al., 2019).

2.2.3. Elevation-dependent warming

The ERA5 dataset for the period 1951–2020, including the trends in average temperatures at higher elevations, shows that the rate of warming is amplified with elevation (Figure 2.4). Here, grids where the values are significant at a 0.01 level (considered highly significant) have been used for the analysis. Areas of higher elevation (>4,000 m) show a greater decadal warming trend (~0.34°C per decade) than areas of lower elevation (<2,000 m) (~0.20°C per decade) for the whole of the HKH (Figure 2.4, top). Figure 2.4 (bottom) shows the decadal trends for the 12 major river basins of the HKH. The *Hindu Kush Himalaya assessment* report also documented the elevation dependence of the climate warming signal. A greater increase in winter mean temperature was seen, up to 0.6°C in high-elevation areas (>2,000 m) of the Tibetan Plateau, in comparison to low-elevation areas (<2,000 m) (Krishnan et al., 2019). Elevation-dependent warming (EDW) is observed in 9 out of 12 major river basins in the HKH with the strongest amplification

FIGURE 2.4

SCATTER PLOTS OF SIGNIFICANT DECADAL TEMPERATURE TRENDS WITH ELEVATION FOR THE PERIOD 1951–2020 FOR THE HKH (TOP) AND ITS 12 MAJOR RIVER BASINS (BOTTOM)



with elevation in the Brahmaputra Basin. Similar EDW is observed for the Ganges, Yangtze, and Indus basins. The Mekong, Tibetan Plateau, Salween, Yellow River, and Tarim basins also show EDW but to a lesser extent. However, in the Amu Darya, Irrawaddy, and Helmand basins, the warming trends are higher in low-elevation areas than at higher altitudes.

2.2.4. The complexity of extreme events

Extreme events can have severe consequences for nature and society, according to the contribution of Working Group I (WGI) to the *Sixth assessment report (AR6)* of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2021). The term 'extreme events' generally refers to a wide class of phenomena that historically have taken place only infrequently but with 'great force'. In the context of climate, an extreme weather event is defined in the AR6's WGII glossary (IPCC, 2022b) as 'an event that is rare at a particular place and time of year. Definitions of "rare" vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations. The characteristics of what is called extreme weather may vary from place to place in an absolute sense.'

Many phenomena that are considered extreme weather events are difficult to study due to a lack of reliable observations. For the climate in the HKH region, relevant extreme events include heatwaves, extreme precipitation, extreme snowfall, and typhoons, hence extreme precipitation and temperature events. However, they may also include 'compound events' in which several factors coincide and can lead to cascading risks. An example of such a compound event is high temperature that causes rapid snowmelt simultaneously with high rainfall. A recent example of a compound event combining a heatwave and high precipitation is the 2022 summer floods in Pakistan that had devastating consequences downstream.

The risk of heavy rainfall that may lead to flooding and mudslides (Fowler et al., 2021) is influenced both by the mean rainfall intensity (wet-day mean precipitation) as well as how often it rains (wet-day frequency). A recent analysis suggests that the probability of receiving more than 50 mm of rainfall

in a day has increased over Europe and the USA, where daily rain gauge data are readily available, and the increased risk is mainly attributable to higher mean rainfall intensities (Benestad et al., 2019). In the HKH region too, extreme precipitation is expected as the result of either more intense precipitation events, more days with precipitation, or a combination of both higher intensity rainfall and more rainy days.

An analysis of global rainfall patterns suggests that they have undergone dynamic changes over the period 1950–2020, leading to more concentrated and intense events, and that these changes seem to match the evolution in global mean temperature (Benestad et al., 2022; Bove et al., 2022; Fowler et al., 2021). This suggests that the rainfall amounts increase and become more extreme as (i) higher temperatures near the surface favour higher rates of evaporation and a faster turnaround of the global hydrological cycle, and (ii) because the rainfall is becoming more unevenly distributed and concentrated in localised wet spots.

According to Hock et al. (2019), even a low emissions climate projection suggests future increases in annual precipitation in the HKH of 5%–20% over the twenty-first century. Changes in the frequency and intensity of extreme precipitation events vary according to season and region. For example, the frequency and intensity of extreme rainfall events are projected to increase throughout the twenty-first century across the Himalayan–Tibetan Plateau mountains, particularly during the summer monsoon (Panday et al., 2015; Sanjay et al., 2017). This suggests a transition toward more episodic and intense monsoonal precipitation, especially in the easternmost part of the Himalayan range (Palazzi et al., 2013). At higher elevations, where local warming is insufficient to affect rain–snow partitioning, increases in total winter precipitation can lead to more snowfall; the *IPCC special report on the ocean and cryosphere in a changing climate* (Hock et al., 2019) has attributed 'medium confidence' to this finding.

Changing rainfall patterns and more frequent extreme events call for adaptation to a changed future climate in order for societies to cope (IPCC, 2022a). Climate change adaptation requires local or regional climate information. However, global climate models used for providing future outlooks (projections) are designed only to reproduce large-scale aspects of the Earth's climate system. Most extreme events occur at more

regional or local spatial scales. Having said that, the local climate is nevertheless dependent on the large-scale atmospheric circulation in addition to local geographical conditions. Information about these dependencies can be added to information we can draw from the global climate models themselves. The introduction of additional information concerning scale dependencies in climate research is called 'downscaling' (Benestad, 2016), but neither the global model nor downscaling (especially one single downscaling method) provides perfect information. Thus, it is important to use more than one strategy for downscaling (both dynamic and empirical–statistical) and to evaluate all steps of the process, from the global climate models to the downscaling methods. It is also important to take into account the presence of pronounced, natural regional climate variations that are chaotic, unpredictable, yet well-captured by global climate models (Deser et al., 2012), and to downscale a large selection of independent global climate model simulations in order to get robust results.

IPCC (2022a) also states, with medium confidence, that there have been increases in climate- and weather-related disasters in mountain regions over the last three decades, and that the frequency of such disasters has shown an increasing trend in the HKH. It is expected that changes in ice and snowmelt, seasonal increases in extreme rainfall, and the thawing of permafrost, all of which are projected for

the future with high confidence, will favour chain reactions and cascading processes that can have devastating effects downstream, well beyond the site of the original event (Beniston et al., 2018; Cui & Jia, 2015; Shugar et al., 2021; Terzi et al., 2019; Vaidya et al., 2019). Such effects involve both extreme events and their consequences for the cryosphere, as extreme temperatures affect conditions for thawing and freezing. Cascading hazards are discussed in Chapter 3, subsection 3.2.2.

The incidence of disasters is expected to worsen in the future due to some hazards becoming more pervasive, and also because the exposure of people and infrastructure is expected to increase with future environmental and socio-economic changes, both of which will deepen the disaster risks. For instance, in the Technical Summary of AR6's WGI report, Arias et al. (2021) observe, with medium confidence, that extreme precipitation is expected to increase in major mountain regions, with consequences such as increased floods and landslides. Rain-on-snow events intensify floods and result in widespread consequences for societies, and their recurrence is expected to increase (Hock et al., 2019). There is also high confidence that glacier retreat, slope instabilities, and heavy precipitation will affect the occurrence of landslides and floods, although there is considerable uncertainty in the direction of change regarding landslides (IPCC, 2021).

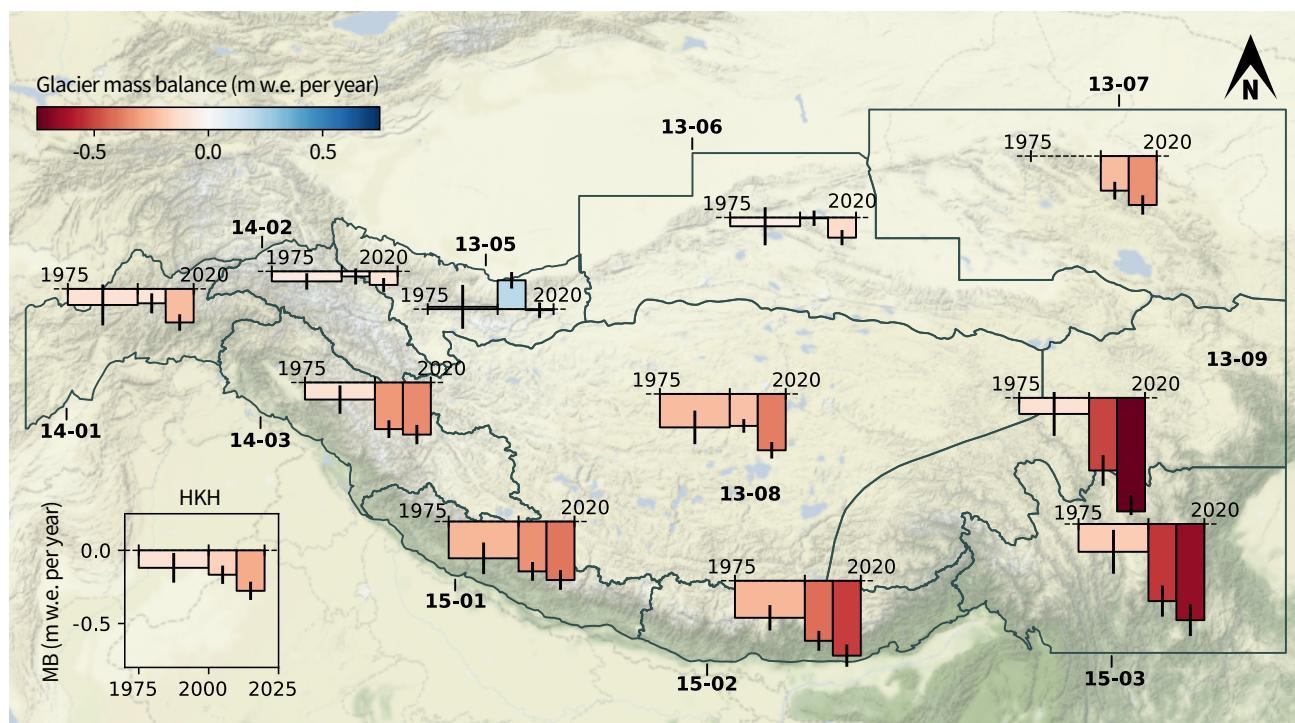
2.3. Glaciers

Glaciers are recognised as identifiers of climate change (Hock et al., 2019), with changes in mass clearly indicative of their response to changes in temperature especially, as well as to snowfall and other meteorological variables. Their contribution to streamflow varies in the extended HKH, from being relatively high in its western parts (Indus, Amu Darya) to a more limited contribution in the eastern parts (Ganges, Brahmaputra) (Lutz et al., 2014). Glaciers play an important role during droughts in maintaining streamflow (Pritchard, 2019). Since the publication of the *HKH assessment report* (Bolch et al., 2019), major advances in the monitoring and understanding of

glaciers in the HKH have been achieved. For example, mass changes between the 1970s and 2020 of large glacier-covered areas of the HKH have been quantified with unprecedented accuracy (King et al., 2019; Maurer et al., 2019; Zhou et al., 2018). Additionally, the sensitivity of glacier mass balance to meteorological variables has been assessed in different regions of the HKH (Sakai & Fujita, 2017; R. Wang et al., 2019). Nevertheless, knowledge gaps remain, and this report enables them to be refined and identifies which scientific questions ought to be prioritised in future (section 2.7).

FIGURE 2.5

GEODETIC MASS BALANCE OF GLACIERS IN EACH REGION OF THE HKH AND FOR THE WHOLE REGION (INSET) FOR 1975–1999, 2000–2009, AND 2010–2019



Notes and sources: The size of the bars and their colour depend on changes in the average mass balance, expressed in metres water equivalent per year (m w.e. per year). The vertical black lines show the uncertainty. The bold numbers beside each basin give the glacier region in the Randolph Glacier Inventory. For 1975–1999, we rely on a compilation of data from the literature; for the other periods, we rely solely on Hugonnet et al. (2021). Note that the spatial coverage for 1975–1999 is generally much lower than for the following two periods, during which the spatial coverage is always higher than 92% of the total glacier-covered regional area (see Table 2.2 for the spatial coverage for each region). The source data used to compile the region-wide mean mass balances for 1975–1999 are listed in Appendix 1.

TABLE 2.2

REGION-WIDE GLACIER MASS BALANCES FROM DIFFERENT REGIONS IN THE HKH OVER THE PERIODS 1975–1999, 2000–2009, AND 2010–2019

Region	Glacier area (km ²)	1975–1999 (m w.e. per year)	2000–2009 (m w.e. per year)	2010–2019 (m w.e. per year)
13-05 (West Kunlun)	8,141	0.02 ± 0.14 (2,356)	0.20 ± 0.05	-0.01 ± 0.04
13-06 (East Kunlun)	3,254	-0.06 ± 0.12 (642)	-0.01 ± 0.04	-0.14 ± 0.04
13-07 (Qilian Shan)	1,640	N. A. (0)	-0.24 ± 0.05	-0.33 ± 0.06
13-08 (Inner Tibet)	7,923	-0.23 ± 0.10 (1,947)	-0.22 ± 0.04	-0.39 ± 0.05
13-09 (South-east Tibet and Nyainqentanglha)	3,876	-0.11 ± 0.14 (1,055)	-0.50 ± 0.09	-0.78 ± 0.10
14-01 (Hindu Kush)	2,941	-0.11 ± 0.13 (841)	-0.10 ± 0.06	-0.23 ± 0.05
14-02 (Karakoram)	22,881	-0.07 ± 0.05 (10,694)	-0.03 ± 0.05	-0.09 ± 0.04
14-03 (Spiti Lahaul – West Himalaya)	7,776	-0.12 ± 0.09 (2,155)	-0.32 ± 0.05	-0.36 ± 0.06
15-01 (Central Himalaya)	5,450	-0.25 ± 0.10 (4,812)	-0.34 ± 0.05	-0.40 ± 0.06
15-02 (Eastern Himalaya)	4,904	-0.25 ± 0.08 (5,129)	-0.41 ± 0.06	-0.51 ± 0.07
15-03 (West Nyainqentanglha)	4,386	-0.19 ± 0.14 (615)	-0.53 ± 0.10	-0.66 ± 0.10
HKH	73,173	-0.12 ± 0.18 (30,246)	-0.17 ± 0.05	-0.28 ± 0.05

Notes: Region numbers follow the Randolph Glacier Inventory (RGI) numbering. For 1975–1999, the area covered by the different studies is indicated in brackets (in km²). Note that the spatial coverage for 1975–1999 is generally much lower than for the following periods, during which the spatial coverage is always higher than 92% of the total glacier-covered area. Some areas have been counted twice for the 1975–1999 period, leading to a total surveyed area larger than the glacier-covered area in the region 15-02. The term m w.e. per year refers to metres water equivalent per year.

Source data: See Appendix 1.

2.3.1. Observed glacier area, surface velocity, thickness, and debris cover in the HKH

Local and global observations of glacier mass balance and other glacier variables have been steadily increasing since the publication of *The Hindu Kush Himalaya assessment* (Bolch et al., 2019), benefiting both from long-term institutional support for field-based measurements, and from global-scale observations.

Glaciers occupy an area of approximately 73,173 ± 7,000 square kilometres (km²) in the HKH (Sakai, 2019) (Figure 2.1). The revised GAMDAM (Glacial Area Mapping for Discharge from the Asian Mountains) glacier inventory, GAMDAM V2 (Sakai, 2019), is now the consensus inventory from which almost all outlines of RGI 7.0 (Randolph Glacier Inventory Version 7) originate. Regionally homogeneous inventories, such as GAMDAM V2, are used extensively for geodetic and modelling studies at regional to global scales. However, local, and often more detailed, inventories contribute to supplementing and improving the regional

inventories and are thus highly valuable (Mölg et al., 2018; Racoviteanu et al., 2015), especially if multi-temporal and time stamped. Most of the available glacier outlines are accessible through the Glacier Land Ice Measurements from Space database (GLIMS & NSIDC, 2005, updated in 2018), which increases their visibility and availability.

Data regarding glacier surface velocities have become more readily available in recent years. First, NASA's ITS_LIVE (Inter-Mission Time Series of Land Ice Velocity and Elevation) project (Gardner et al., 2022) provides glacier surface velocity data as annual fields for all the glaciers of High Mountain Asia (HMA) at a 120-metre (m) resolution. The velocity fields are derived from the correlation of pairs of Landsat images and span the period 1985–2020. Similarly, Dehecq et al. (2019) derived annual surface velocities for the period 2000–2017 by applying feature tracking to over 900,000 pairs of Landsat-7 images, at a 240-m resolution, for 94% of all glaciers of HMA. However, the annual velocity fields have large voids in the glacier accumulation areas prior to 2013, due to the lack of contrast in textureless areas (Dehecq et al., 2019). Second, Millan et al. (2022) produced a high-

resolution (50-m) map of glacier velocity for the period 2017–2018, based on multi-sensor displacement measurements. The increased resolution is especially helpful for measuring the velocity of small glaciers; however, the velocity is available only for a given time stamp, which does not allow for the exploration of temporal changes in velocity (Dehecq et al., 2019). Using repeat-pass synthetic aperture radar (SAR) data acquired by the Sentinel-1 satellite constellation, Freidl et al. (2021) derived glacier surface velocity fields at a global scale, including all glaciers in the HKH, at up to a 6-day temporal resolution and at a 200-m spatial resolution, independent of weather conditions, daylight, and season.

Ice thickness is a critical parameter to model the future evolution of a glacier. Ice thickness is generally measured using radar sounding (Welty et al., 2020), which is a demanding and costly method. Consequently, very few measurements are publicly available for the region, through the GlaThiDa database (Glacier Thickness Database) for the HKH, only twelve glaciers have had their ice thickness measured and this number rises to 88 for the whole HMA, due to more numerous measurements in central Asia (Welty et al., 2020). Field measurements are complemented by model output estimates, which are based on glacier geometry, the regional field measurements, and incidentally ice surface velocity (Farinotti et al., 2019; Millan et al., 2022). Due to the scarcity of field measurements in HMA, the discrepancy between the two most up-to-date studies is the largest in this region, with the estimate from Millan et al. (2022) being 44% larger than the estimate from Farinotti et al. (2019). Uncertainties are large in both studies, and it is not possible to assess which study provides the best estimates of thickness for glaciers in the HKH, as there are no additional in situ measurements available to validate the two datasets. Both studies are based on an inverse modelling of surface velocities and are probably more accurate than estimates from the GlabTop (Glacier bed Topography) model (Frey et al., 2014). Airborne radar systems are a promising tool to map ice thickness over larger areas of HMA (Pritchard et al., 2020).

Many glaciers in the HKH have debris-covered tongues, whose debris thickness ranges from a few centimetres to more than one metre (Herreid & Pellicciotti, 2020). Depending on the RGI region and inventory considered, debris occupies 6%–19% of

the glacier area in HMA, with the highest coverage in the central Himalaya (Herreid & Pellicciotti, 2020; Scherler et al., 2018). Debris thickness and its properties are important factors in glacier surface mass balance, as thin debris tends to enhance ice melt whereas thick debris reduces ice melt (Nicholson & Benn, 2006). At a global scale, debris is found to reduce sub-debris ice melt by 37%. However, in some regions, similar rates of elevation change on debris-covered and clean-ice glacier tongues have also been observed, partially due to differences in glacier dynamics (Rounce et al., 2021). Field mapping of debris thickness is based primarily on manual excavation, which is extremely time-consuming and demanding. Alternatively, radar sounding allows the measurement of debris thickness, but is still a demanding task. As a consequence, available measurements of debris thickness in the HKH are very scarce (Giese et al., 2021; McCarthy et al., 2017; Nicholson & Mertes, 2017). The extent of debris cover can be mapped from optical and thermal imagery, with some inherent challenges (McCarthy et al., 2022; Rounce & McKinney, 2014).

2.3.2. Observed changes in glacier mass

While changes in glacier length and area show a delayed signal, glacier mass balance responds directly to climate and weather; thus, an assessment of glacier mass balance is essential to understanding climate change (Oerlemans, 2001; Zemp et al., 2019). The mass balance of glaciers has been measured using different methods, including conventional field methods (Østrem & Stanley, 1969), remote sensing methods (Bamber & Rivera, 2007; Brun et al., 2017; Shean et al., 2020), integration of remote sensing and field observations (Muhammad et al., 2019), and a variety of modelling approaches (Azam et al., 2018; Bolch et al., 2019; Shea et al., 2015).

OBSERVED GLACIER CHANGES FROM FIELD MEASUREMENTS

Long-term, continuous, and high-quality series of annual and seasonal mass balance measurements are needed to understand the variability in glacier mass balance under a changing climate (Zemp et al., 2019). Glacier mass balances have been measured using the conventional glaciological method (Østrem &

Stanley, 1969). The huge manual efforts on the ground needed, the high elevations, and harsh weather conditions in the HKH make it difficult to conduct long-term glaciological measurements; hence, the existing in situ studies are mostly of easily accessible, small-sized, and less debris-covered glaciers (Azam et al., 2018; Vishwakarma et al., 2022). Glacier mass balance observations have been conducted on 28 glaciers in the Himalayan Range (Table 2.3), 9 glaciers in the Pamir Range, and 11 glaciers on the Tibetan Plateau (Miles et al., 2021, supplementary Table 1; Yao et al., 2022). Unfortunately, no glacier has been observed for mass balance in the Karakoram. Some of the observations in the HKH are for a year only while some series are intermittent. Chhota Shigri Glacier provides the longest continuous mass balance series – since 2002 – and has had a mean mass wastage of -0.46 ± 0.40 metres water equivalent per year (m w.e. per year) (Mandal et al., 2020). The Mera, West

Changri Nup, Chorabari, Pokalde, Rikha Samba, Trakarding–Trambau, and Yala glaciers comprise the other continuous/ongoing observation series in the Himalaya (Table 2.3). Some of the observed glaciers, for example, Hamtah and Satopanth glaciers, are highly debris-covered and with steep headwalls, where accumulation often occurs through sporadic avalanches and regular accumulation measurements cannot be carried out (Azam et al., 2018). Due to the presence of inaccessible areas and debris cover, and avalanche feeding, the observed mass balance series are often biased, and hence need to be corrected using geodetic mass balance measurements over the same period (Zemp et al., 2015). The mass balance series for Chhota Shigri, Mera, and West Changri Nup glaciers have been systematically checked and corrected (Azam et al., 2016; Sherpa et al., 2017; Wagnon et al., 2020).

TABLE 2.3 FIELD GLACIOLOGICAL MASS BALANCE OBSERVATIONS IN THE HIMALAYA

Glacier name and location	Area (km ²)	Debris cover area (%)	Period studied	Mass balance (m w.e. per year)	Reference
Eastern Himalaya					
1. Changmexhangpu, Sikkim, India	5.6	50	1979–1986	-0.26	GSI (2001)
2. Gangju La, Pho Chhu, Bhutan	0.3	Clean	2003–2004; 2012–2014	-1.38 ± 0.18	Tshering & Fujita (2016)
Central Himalaya					
3. AX010, Shorang Himal, Nepal	0.6	Clean	1978–1979; 1995–1999	-0.69 ± 0.08	Fujita et al. (2001)
4. Chorabari, Garhwal Himalaya, India	6.7	53	2003–2010; 2015–2016	-0.72	Dobhal et al. (2013); Dobhal et al. (2021)
5. Dokriani, Garhwal Himalaya, India	7.0	6	1992–1995; 1997–2000;	-0.32	Dobhal et al. (2008)
6. Dunagiri, Garhwal Himalaya, India	2.6	~80	1984–1990	-1.04	GSI (1991)
7. Kangwure, Xixiabangma, China	1.9	Clean	1991–1993; 2008–2010	-0.57	S. Liu et al. (1996); Yao et al. (2012)
8. Mera, Dudh Koshi Basin, Nepal*	5.1	Clean	2007–2019	-0.41 ± 0.20	Wagnon et al. (2020)
9. Naimona'nyi, Naimona'nyi region, China	7.8	Clean	2005–2010	-0.56	Yao et al. (2012)
10. Pokalde, Dudh Koshi Basin, Nepal	0.1	Clean	2009–2015	-0.69 ± 0.28	Wagnon et al. (2013); Sherpa et al. (2017)
11. Rikha Samba, Hidden Valley, Nepal	4.6	Clean	2011–2017	-0.39 ± 0.32	Stumm et al. (2021)

12. Satopanth, Alaknanda Basin, India	19.0	58	2014–2015	–2	Laha et al. (2017)
13. Tipra Bank, Garhwal Himalaya, India	7.0	15	1981–1988	–0.14	Gautam and Mukherjee (1992)
14. Trakarding–Trambau Rolwaling Region, Nepal	31.7	14	2016–2018	–0.74	Sunako et al. (2019)
15. West Changri Nup, Dudh Koshi Basin, Nepal*	0.9	Clean	2010–2015	–1.24 ± 0.27	Wagnon et al. (2013); Sherpa et al. (2017)
16. Yala, Langtang Valley, Nepal	1.6	Clean	2011–2012	–0.80 ± 0.28	Stumm et al. (2021)

Western Himalaya					
17. Chhota Shigri, Lahaul–Spiti Valley, India*	15.5	3.4	2002–2014	–0.46 ± 0.40	Azam et al. (2016); Mandal et al. (2020)
18. Hamtah, Lahaul–Spiti Valley, India	3.2	~70	2000–2009; 2010–2012	–1.43	GSI (2011); Mishra et al. (2014)
19. Gara, Baspa Basin, India	5.2	17	1974–1983	–0.27	Raina (1977); Sangewar and Siddiqui (2007)
20. Gor Garang, Baspa Basin, India	2.0	~60	1976–1985	–0.38	Sangewar and Siddiqui (2007)
21. Kolahoi, Jhelum Basin, India	11.9	Clean	1983–1984	–0.27	Kaul (1986)
22. Naradu, Baspa Basin, India	4.6	~60	2000–2003; 2011–2015	–0.72	Koul and Ganjoo (2010)
23. Neh Nar, Jhelum Basin, India	1.3	Clean	1975–1984	–0.43	GSI (2001)
24. Patsio, Lahaul–Spiti Valley, India	2.25	10	2010–2017	–0.34	Angchuk et al. (2021)
25. Rulung, Zaskar Range, India	1.1	Clean	1979–1981	–0.11	Srivastava (2001); Sangewar and Siddiqui (2007)
26. Shaune Garang, Baspa Basin, India	4.9	24	1981–1991	–0.42	GSI (1992); Sangewar and Siddiqui (2007)
27. Shishram, Jhelum Basin, India	9.9	Clean	1983–1984	–0.29	Kaul (1986)
28. Stok, Ladakh, India	0.74	5	2014–2019	–0.39	Soheb et al. (2020)

Notes: Mass balance uncertainty is included when given in the original source. The asterisk refers to glaciers for which the glaciological and the geodetic mass balances have been compared.

OBSERVED GLACIER CHANGES FROM GEODETIC MEASUREMENTS

Despite a wide range of spaceborne sensors, such as GRACE (Gravity Recovery and Climate Experiment), GRACE-FO (GRACE Follow-On), ICESat (Ice, Cloud, and Land Elevation Satellite), and ICESat-2, measuring changes in mass or elevational changes (X. Wang et al., 2020), most of the recent knowledge about glacier

mass change at the scale of the HKH originates via geodetic measurements from satellite optical photogrammetry. Geodetic measurements consist of measuring changes in glacier volume from observed changes in elevation (Bolch et al., 2011). Elevation data originate from digital elevation models (DEMs), derived either from SAR or optical methods. In the HKH, the most successful methods relied on spy imagery from the 1960s and 1970s (from the satellites

Corona KH-4 and Hexagon KH-9) (for example, Bhattacharya et al., 2021; Bolch et al., 2011; Maurer et al., 2019), and on ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), Worldview, and Pléiades images for the period 2000–present (for example, Bhattacharya et al., 2021; Hugonnet et al., 2021; Shean et al., 2020).

Despite progress made in the automation of processing Kh-9 Hexagon images from the 1970s and 1980s (Dehecq et al., 2020; Maurer et al., 2016), there are still many uncovered areas, in particular on the Tibetan Plateau. The most comprehensive studies focused on the central Himalaya (King et al., 2019; Maurer et al., 2019), the Karakoram (Bolch et al., 2017; Zhou et al., 2017), the eastern Himalaya (Maurer et al., 2016), and the Tibetan Plateau and its surroundings (Zhou et al., 2018). In this assessment, we do not aim to be exhaustive, but consider selected studies with a large spatial coverage. These studies found moderate losses in glacier mass, with an average HKH-wide mass balance of -0.12 ± 0.18 m w.e. per year for the period 1975–2000. Over the same period, the most negative mass balance values are observed in the central and eastern Himalayan regions, of -0.25 m w.e. per year, while some regions are close to balance (Figure 2.5; Table 2.2).

For the period 2000–2019, the most comprehensive results were obtained from time series of the ASTER, Worldview, and Pléiades DEMs, which provided almost complete coverage of all glaciers in the HKH (Brun et al., 2017; Hugonnet et al., 2021; Shean et al., 2020). The three studies are based on different methodologies, that consist of extracting trends of elevation time series. They cover different periods, 2000–2016, 2000–2018, and 2000–2019 for Brun et al. (2017), Shean et al. (2020), and Hugonnet et al. (2021), respectively. Even though the periods covered differ slightly, the results for region-wide mass balances are in good agreement between the three studies. We present the most up-to-date results from Hugonnet et al. (2021) only, which has the advantage of splitting the results into sub-periods of 5/10 years. The rate of mass losses in the HKH accelerated through the study period. The mass balance is -0.17 m w.e. per year for the period 2000–2009 and -0.28 m w.e. per year for 2010–2019. The most negative mass balances are observed in the eastern HKH with the South-east Tibet and Nyainqentanglha regions reaching -0.78 ± 0.10 m w.e. per year for the period 2010–2019, while

the West Kunlun region shows a near-balanced mass budget of -0.01 ± 0.04 m w.e. per year over the same period (Figure 2.5). The Karakoram region, known for its balanced regional mass budget, showed slight wastage of -0.09 ± 0.04 m w.e. per year for 2010–2019. Bhattacharya et al. (2021) also suggested a phase of mass loss of the Karakoram glaciers, especially post-2013. These recent negative mass balance estimates suggest that the ‘Karakoram anomaly’ is probably over.

2.3.3. Projected changes in glacier mass

At the time of publication of the *Hindu Kush Himalaya assessment* report, only a few model runs were available to quantify the future evolution of glaciers in the HKH (Bolch et al., 2019). Coordinated efforts by the glacier community’s Glacier Model Intercomparison Project (known as glacierMIP) to model future glacier changes have led to a significant increase in the number of available projections under different shared socio-economic pathways (SSPs), with nine models now contributing to simulations (Edwards et al., 2021; Marzeion et al., 2020), versus only six models being included in the *Hindu Kush Himalaya assessment* report (Bolch et al., 2019)

PROJECTED CHANGES AT GLOBAL WARMING LEVELS UNDER THE PARIS AGREEMENT

At a global warming level (GWL) between 1.5°C and 2°C mentioned in the Paris Agreement, the glaciers of the HKH are expected to lose 30%–50 % of their volume by 2100 relative to 2015 (Edwards et al., 2021; Kraaijenbrink et al., 2017; Marzeion et al., 2020; Rounce et al., 2020). The corresponding, remaining glacier-covered areas range from 50% to 70%. At this GWL, the losses in glacier mass will be continuous through the twenty-first century. The specific mass balance rate (that is, the annual amount of mass loss and gain) will remain negative, even though it will become less negative by the end of the century, as glaciers retreat to higher elevations.

The regional differences between projected mass losses depend on the present-day mass balance, projected changes in air temperature and precipitation, and various glacier attributes, such as ice thickness (Shea et al., 2015), hypsometry (Miles et al., 2021), debris cover (Kraaijenbrink et al., 2017),

and whether they are lake- or land-terminating glaciers (King et al., 2019), etc. It is difficult to untangle each contribution, but the largest losses in mass and area will happen in areas with the lowest glacier cover. Regions with limited ice coverage (such as the northeastern Tibetan Plateau) will lose up to 70% of their glacier-covered area by 2100 (Kraaijenbrink et al., 2017).

PROJECTED CHANGES AT OTHER GLOBAL WARMING LEVELS

For higher GWLs of +3°C or +4°C, the remaining glacier volume by 2100 will range from 25% to 45% and from 20% to 30%, respectively, relative to 2015 (Edwards et al., 2021; Marzeion et al., 2020). For these GWLs, the specific mass balance rates are more and more negative throughout the twenty-first century, meaning that, on average, the annual mass losses each year are more than the losses of the year before. For a GWL of +4°C, only the heavily glacierised regions of West Kunlun and the Karakoram have a remaining glacier area of about 50% of their area in 2020. All other regions have a glacierised area that is less than 30% of their area in 2020 (Kraaijenbrink et al., 2017).

2.3.4. Towards a better understanding of glacier response to climate change

DRIVERS OF REGIONAL GLACIER MASS CHANGES

There is a growing body of literature that discusses the drivers of the observed glacier mass changes, in particular the contrasting pattern of recent glacier mass balance at the scale of the HKH. Depending on the climatology, glaciers are defined as maritime glaciers if they receive a large amount of precipitation, or as continental glaciers if they are in drier and colder environments. Maritime glaciers are more sensitive to climate change than their continental counterparts. In the HKH, the maritime glaciers of the eastern Himalaya and Nyainqentanglha regions are losing the most mass, while the continental glaciers of West Kunlun are stable (Sakai & Fujita, 2017; R. Wang et al., 2019).

However, the differential sensitivity hypothesis fails to fully explain the gains in glacier mass in the Karakoram and West Kunlun regions, which is referred to as the ‘Karakoram anomaly’ (Farinotti

et al., 2020; Gardelle et al., 2012). The precise physical drivers of the anomaly can be established with only moderate confidence, but some notable drivers are the summer cooling (Forsythe et al., 2017), increased winter snowfall (Norris et al., 2019), higher sensitivity to snowfall (Kumar et al., 2019), and increased irrigation which results in more evapotranspiration, and hence greater snowfall, which has reduced the net energy balance (de Kok et al., 2020). Two main explanations, probably both true and complementary, have been proposed to explain the Karakoram anomaly. A change in the large-scale atmospheric circulation may have contributed to intensified westerlies over this region, leading to more precipitation (Forsythe et al., 2017). And at a regional scale, an intensification of irrigation in the Tarim Basin over the last few decades has enhanced the local/regional convection and thus precipitation over the mountains. However, the persistence of the anomaly in the coming years is uncertain, and the most recent geodetic mass balance measurements hint at the apparent end of the anomaly due to strong increases in summer temperatures (Bhattacharya et al., 2021; Hugonnet et al., 2021).

DEBRIS COVER

As debris cover is an important control of glacier surface mass balance, there is a need to assess whether accounting for debris would modify glacier projections. Several major advances have been made recently in the understanding of the influence of debris and surface features (such as ice cliffs and supraglacial ponds) on the surface mass balance and dynamics of glaciers in the HKH. Maps of debris cover and debris thickness are now available for every glacier in the HKH (Herreid & Pellicciotti, 2020; Rounce et al., 2021; Scherler et al., 2018). A comprehensive mapping of surface features is not yet available, due to the challenges in mapping these small-scale features. The increasing availability of high-resolution multispectral images is a promising development (Kneib et al., 2021). Approaches combining modelling, field measurements, and remote sensing techniques have demonstrated the quantitative importance of ice cliffs and supraglacial ponds, which enhance melt by a factor of between 3 and 13 for ice cliffs (Buri et al., 2021) and between 9 and 17 for supraglacial ponds (Miles et al., 2018) relative to the melting of ice beneath debris.

All these process-based studies feed model parameterisations. Englacial debris transport is now modelled explicitly for individual glaciers (Scherler & Egholm, 2020; Wirbel et al., 2018), or can be parameterised for all the glaciers of the HKH (Compagno et al., 2022; Rowan et al., 2015). Distributed melt model parameterisation has also improved, and such models can now be applied at glacier to regional scales (Kraaijenbrink et al., 2017; Steiner et al., 2021). There are only two studies accounting explicitly for the effect of debris on future glacier evolution in the HKH (Compagno et al., 2022; Kraaijenbrink et al., 2017). Both found that including debris has only a small effect on the regional-scale evolution of glacier volume and area, as long-term, the thinning of debris-covered and debris-free glaciers under a changing climate is similar (Banerjee, 2017). However, for individual glaciers, the models show that the inclusion of debris has a strong influence on the dynamics and timing of glacier retreat.

HIGH-ELEVATION PROCESSES

Other elements of the surface mass and energy balance of glaciers have been investigated in selected places. These studies investigate surface mass balance processes in different regions (Fugger et al., 2022; Mandal et al., 2022). Some of the major uncertainties in surface mass balance are related to the role of turbulent fluxes, and in particular, sublimation (Steiner et al., 2018; Stigter et al., 2018). Wind erosion

(Litt et al., 2019) and refreezing (Saloranta et al., 2019; Stigter et al., 2021; Veldhuijsen et al., 2021) are likely major contributors to the surface mass and energy balance of glaciers and snow, especially at high elevations. However, the lack of automatic weather stations (AWSs) and mass balance measurements limits the applicability of these models to other climate settings. Recent campaigns aimed at installing and maintaining these AWSs might be fruitful, even though they are limited to specific and limited locations (A. Khadka et al., 2022; Matthews, Perry, Koch et al., 2020).

OTHER FACTORS RESPONSIBLE FOR GLACIER MASS CHANGES

Some specific features may also influence the response of glaciers to climate change. Lake-terminating glaciers are known to systematically lose more mass on average than neighbouring land-terminating glaciers (Brun et al., 2019, King et al., 2019; Pronk et al., 2021; Tsutaki et al., 2019). Moreover, the mass budgets of surge type glaciers and non-surge type glaciers are similar overall, showing that such instabilities in flows do not affect the glacier-wide mass balance of glaciers (Gardelle et al., 2013). Nevertheless, when glaciers are in a surging state, mass balance is impacted, negatively or positively, depending on the surge stage (Guillet et al., 2022, King et al., 2021; Sevestre & Benn, 2015).

2.4. Glacial lakes

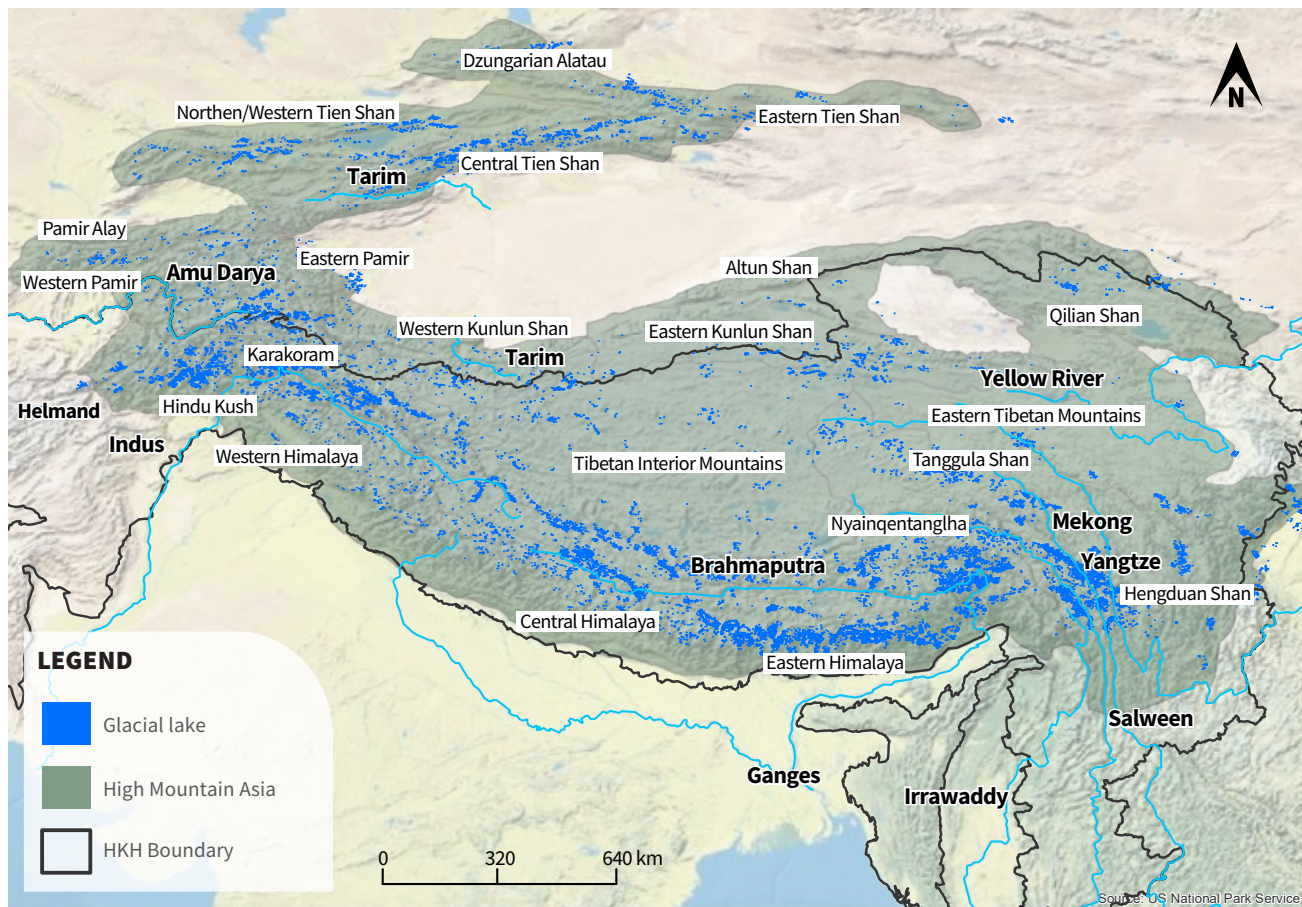
Glacial lakes form from glacial depressions, eroding the soil and sediment around them as they move. Glacial lakes form on the surface of glaciers (generally, debris-covered glaciers) as supraglacial lakes (Miles et al., 2017), behind moraines as proglacial lakes (Carrivick & Tweed, 2013), and beneath glaciers as subglacial lakes or englacial lakes (Livingstone et al., 2022). Some lakes formed during previous glacial recessions since the Little Ice Age from the early 14th to the mid-19th century but are now completely disconnected from the glacial source (Cook & Quincey, 2015). Glacier recession in response to climate change has resulted in an increase in, and expansion of glacial lakes globally (Shugar et al., 2020), in HMA (Cook & Quincey, 2015; Zheng et al., 2021), and in the HKH (Ahmed et al., 2021; W. Li et al., 2022).

Between 1990 and 2018, the number of known glacial lakes globally had increased to 14,394 (a 53% increase), with a total area of $8.95 \times 10^3 \text{ km}^2$ (a 51% increase) and an estimated volume of 156.5 km^3 (a 48% increase) (Shugar et al., 2020). W. Li et al. (2022) identified 9,673 glacial lakes in the HKH in 2020, with an increase in their number by 5,974 and in their area by 409 km^2 in the 30 years since 1990. Across HMA as a whole, 30,121 glacial lakes were mapped in 2018 with an area of $2080.12 \pm 2.28 \text{ km}^2$ (X. Wang et al., 2020) (see Figure 2.6).

Numerous studies have been conducted to map glacial lakes and changes in them over time in HMA and the HKH (Chen et al., 2021; W. Li et al., 2022; Maharjan et al., 2018; X. Wang et al., 2020; Zheng

FIGURE 2.6

DISTRIBUTION OF GLACIAL LAKES IN THE HKH AND THE REST OF HIGH MOUNTAIN ASIA IN 2018.



Source: Glacial lakes data X. Wang et al. (2020), HMA boundary Bolch et al. (2019)

et al., 2021). However, there are still discrepancies in their number and area (see Table 2.4) due to differences in the methodology applied, extent of lake inventory, the threshold size chosen, and delineation techniques used. Recently, an advanced technology based on SAR data and machine learning approaches has been used to identify and map glacial lakes in the HKH and HMA regions (Ortiz et al., 2022; Wangchuk & Bolch, 2020). Unmanned aerial vehicle (UAV) surveys, DEM differencing, time series of SAR data, and Google Earth Engine have been used to monitor and evaluate glacier flow velocity, moraine dam stability, ice-core moraine degradation, and slope stability of the headwalls surrounding glacial lakes (Nuth & Kaab, 2011; Wangchuk et al., 2022). This advanced technology and computing resources enable the development of an integrated approach for monitoring the susceptibility of glacial lakes to glacial lake outburst floods (GLOFs).

Numerous studies have suggested that the total area and number of glacial lakes have increased significantly since the 1990s (Nie et al., 2017; Shugar et al., 2020; G. Zhang et al., 2015; Zheng et al., 2021). The expansion of proglacial lakes as glaciers recede (Zheng et al., 2021), as well as the break-up of glacial snouts (Thompson et al., 2012) drive the increase in

the total area covered by glacial lakes. However, it is not the same for glacial lakes that are separated from glaciers. The development of distant glacial lakes is primarily influenced by regional precipitation, temperature, evapotranspiration, and human factors (C. Guo, 2017). Increased precipitation is most likely the primary driver of lake growth on the Tibetan Plateau (Brun et al., 2020). Based on approaches to modelling the development of future glacial lakes in HMA, a total of 25,285 overdeepenings with a total volume of $99.1 \pm 29.5 \text{ km}^3$ covering $2,683 \pm 812 \text{ km}^2$ was computed (Furian et al., 2021). The number and area of proglacial lakes are anticipated to increase substantially in the future, and lakes become increasingly vulnerable to mass movement (Furian et al., 2021).

Ice-adjacent lakes – as compared to disconnected lakes – can drain rapidly, resulting in the release of a significant volume of water, causing a GLOF that can damage downstream settlements and infrastructure. Many proglacial as well as ice-dammed lakes are expected to develop over the next decade due to continued glacier retreat (Furian et al., 2021; Zheng et al., 2021) with the emergence of new GLOF hotspots (Linsbauer et al., 2016; Zheng et al., 2021). A global database of recorded GLOFs (Lützow and

TABLE 2.4

NUMBER AND AREA OF GLACIAL LAKES IN SPECIFIED REGIONS FOR INDIVIDUAL YEARS, AND CHANGES IN NUMBER AND AREAS OF GLACIAL LAKES FOR DEFINED PERIODS.

Region	Year/Period	Number	Area (km ²)	Methodology	Reference
Central Himalaya	2010	1,314	197.22	Semi-automatic	Nie et al. (2013)
Eastern, central, and western Himalaya	2015	4,950	455.3	Semi-automatic	Nie et al. (2017)
HKH	2005	25,614	1,444	Semi-automatic	Maharjan et al. (2018)
HKH	1990–2020	5,974	408.93	Automatic	W. Li et al. (2022)
HMA	2010	5,701	682.4	Manual	G. Zhang et al. (2015)
HMA	2015	26,633	1,968.8	Semi-automatic	Zheng et al. (2021)
HMA	2016	21,249	1,577.38	Automatic	M. Zhang et al. (2021)
HMA	2017	15,348	1,395.24	Semi-automatic	Chen et al., (2021)
HMA	2018	30,121	2,080.12	Semi-automatic	X. Wang et al. (2020)
HMA	1990–2015	1,481	125.8	Semi-automatic	Zheng et al. (2021)
HMA	1990–2018	2,916	273.65	Semi-automatic	X. Wang et al. (2020)
HMA	2009–2017	3,342	220.64	Semi-automatic	Chen et al. (2021)

Note: The number and area for a period (such as 1990 – 2020) refers to an increase in these parameters over that time.

Veh, 2022) reports a total of 350 events for the HKH with 325 events occurring in the last 150 years. The majority of GLOFs in the region have occurred from ice- or moraine-dammed glacial lakes (Carrivick & Tweed, 2013; M. Liu et al., 2020, Nie et al., 2017). Most GLOFs in the Karakoram are from ice-dammed glacial lakes (Emmer et al., 2022, Y. Gao et al., 2021), whereas the majority in the rest of the HKH are from moraine-dammed lakes.

The risk of GLOFs occurring in HMA is predicted to triple by the end of the century, with a significant number of potential transboundary GLOFs, primarily in the eastern Himalaya (Zheng et al., 2021). However,

a recent study stated that it is still unclear whether the increase in the number of GLOFs reported globally is associated with warming temperatures or the growing research interest in them and the access to abundant data, even though some previous GLOFs now identified were unreported or unknown earlier (Veh et al., 2022). Despite this ambiguity, a comprehensive study with detailed ground investigations should be conducted to identify potentially dangerous glacial lakes (PDGLs) and prioritise their hazard levels to prevent or reduce the risk, damage, and loss that GLOFs have repeatedly caused to downstream communities.

2.5. Snow

Snow is an essential component of the mountain ecosystem and plays a key role in glacier nourishment and water availability, but also triggers mass movements and floods. Several regions of HMA are more dependent on snowmelt than glacier melt (Kraaijenbrink et al., 2021). Snow monitoring is critical in the HKH, particularly in the spring season, as it is important for daily use by downstream communities (T. Smith et al., 2017) for agriculture, energy, drinking water supply, and industry. Despite the significance of snow (Figure 2.7), its in situ monitoring is scarce in the HKH (Bolch et al., 2019). In particular, the major proportion of the snowpack remains at high elevations and is poorly measured (Smith & Bookhagen, 2018). In contrast, remote-sensing data provide large spatio-temporal coverage and are widely used for snow monitoring on regional and global scales (Desinayak et al., 2022; Hall et al., 2010; Notarnicola, 2022).

2.5.1. Observed and projected changes in snow cover and snow line elevations

Snow cover in the northern hemisphere shows a decreasing trend since the mid-twentieth century – probably due to greenhouse gas emissions and other human influences – with an earlier onset of snowmelt contributing to seasonal changes in streamflows (IPCC, 2022a). The trends in snow cover have been clearly negative in most of the HKH since the early twenty-first century (Ackroyd et al., 2021; Bormann et al., 2018; Desinayak et al., 2022), but there are a few exceptions, including the Karakoram, where the changes have been non-significant (Bilal et al., 2019; Thapa & Muhammad, 2020). There has been a significant decrease in seasonal snow cover during the summer and winter months, as well as a decline from mid-spring through mid-fall, indicating a shift in seasonality (Naegeli et al., 2022). Snow cover days generally declined in all mountain regions globally at an average rate of 5 snow cover days per decade since the mid-twentieth century with most of the changes at lower elevations, attributed to the conversion of solid precipitation to liquid precipitation due to warmer air temperatures in most places, causing an increase in melt throughout (Hock et al., 2019). Most of the river

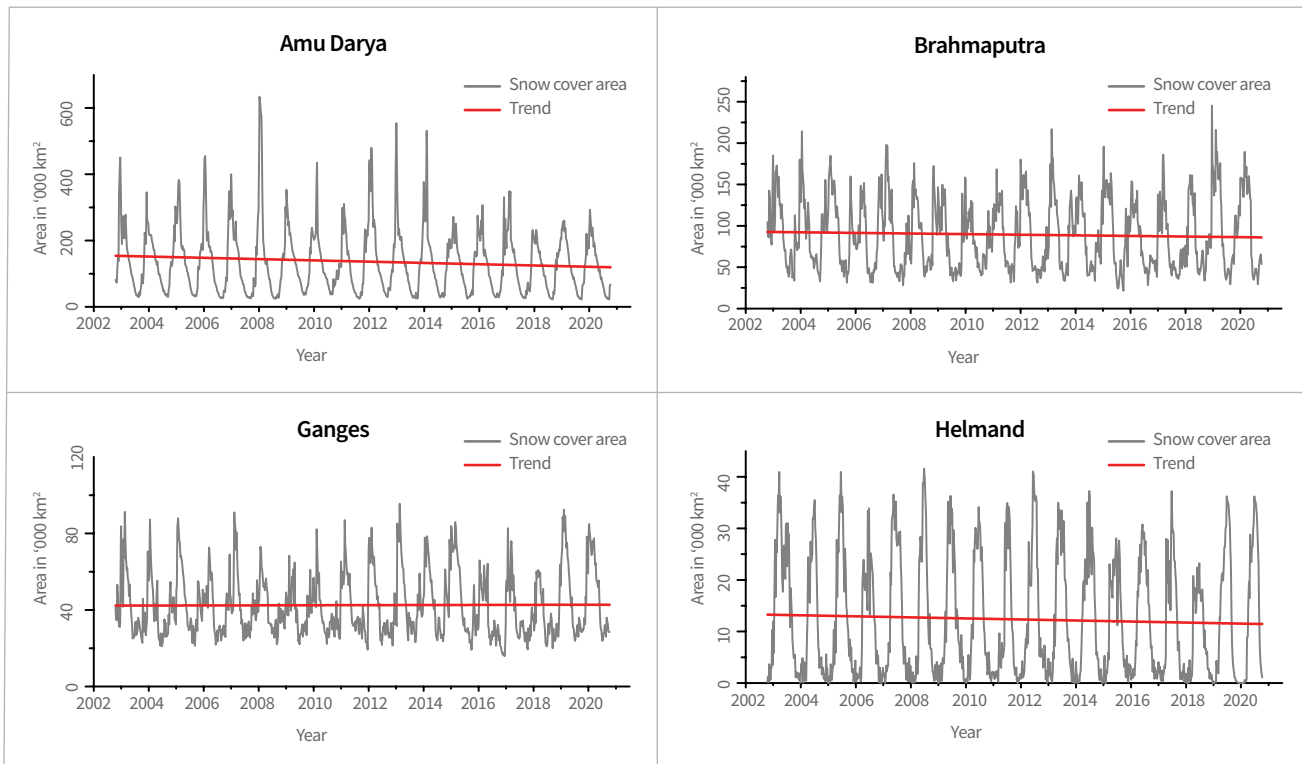
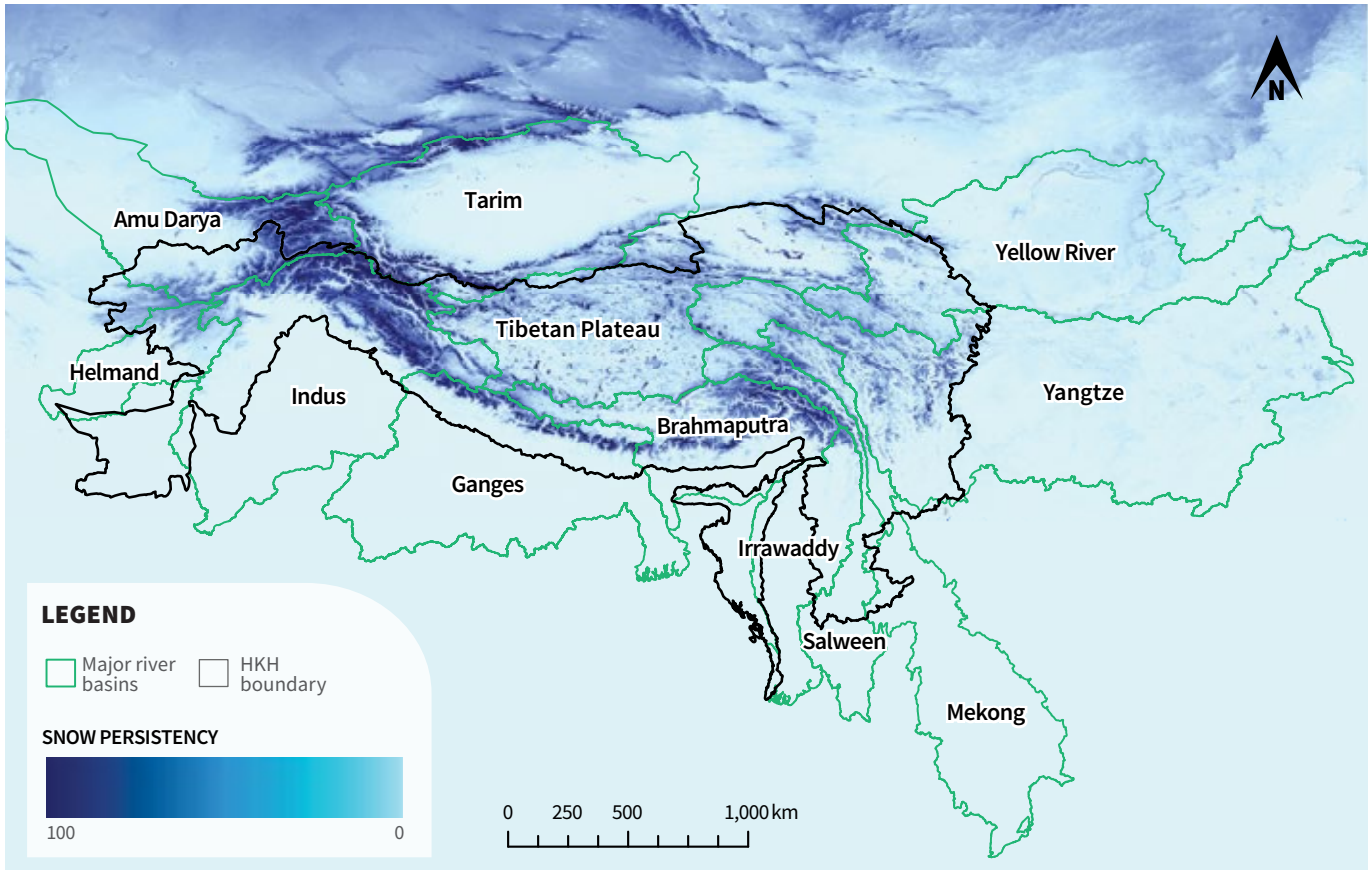
basins show a decreasing snow cover trend between 2003 to 2020 with a heterogeneous pattern on the Tibetan Plateau and the eastern Himalaya (Figure 2.7). The seasonal snow cover also shows significant fluctuations in the Mekong, Salween, Tarim, Tibetan Plateau, Yangtze, and Yellow river basins.

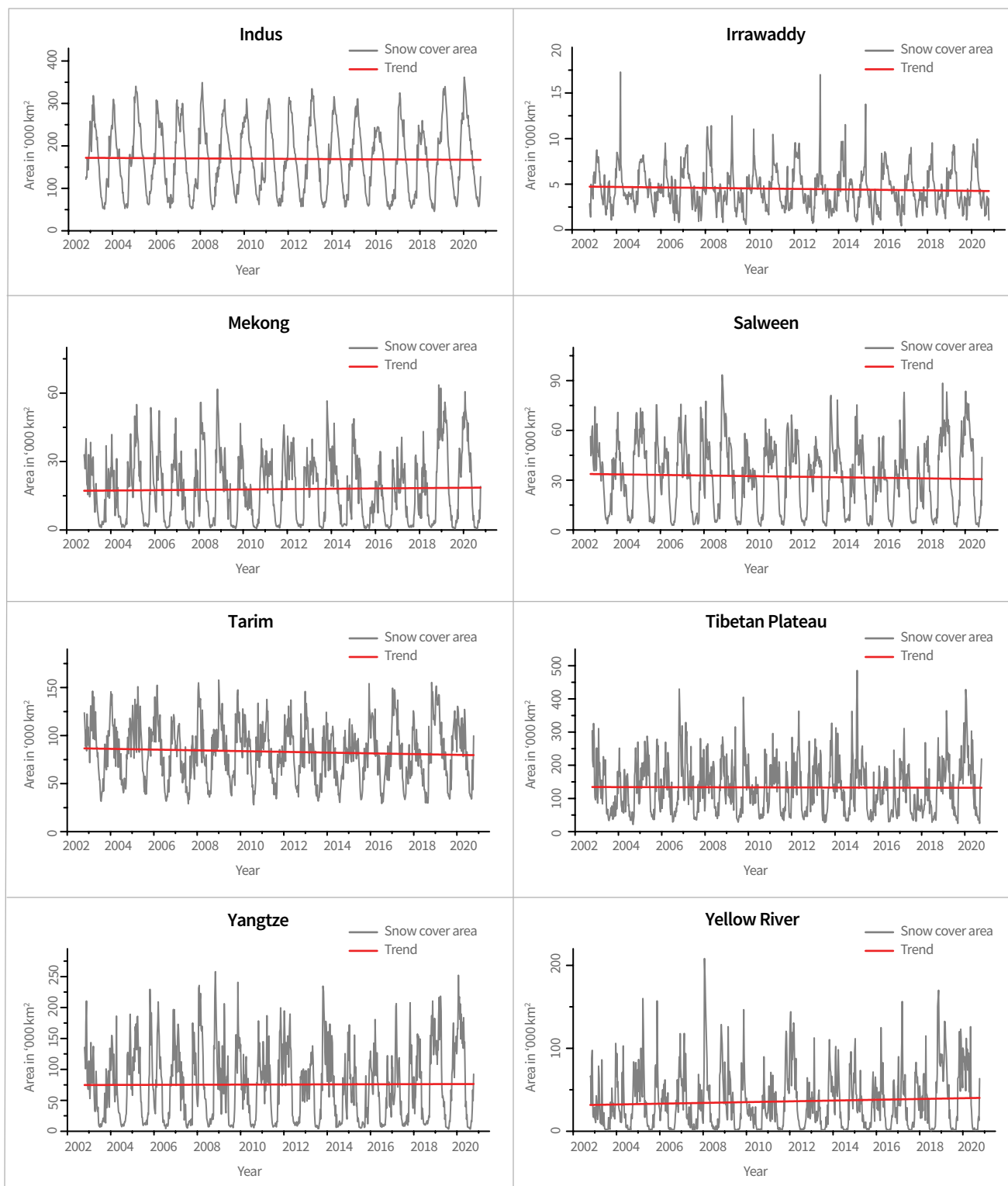
Snow line elevation at the end of the melting season showed a large spatial variability in HMA, with a statistically significant upward shift in 26.3% of its area and a statistically significant downward trend in 0.74% of its area between 2001 and 2016 (Tang et al., 2020). Tien Shan, Inner Tibet, South and East Tibet, eastern Himalaya, and Hengduan Shan experienced a significant shift upward, while there was no clear or significant trend in the Karakoram (Thapa & Muhammad, 2020), Pamir, Hindu Kush, West Kunlun, and the western Himalaya (Tang et al., 2020). The annual maximum snowline altitude, derived from Landsat, fluctuated between 4,917 m and 5,336 m in the Hunza catchment in the Karakoram Region between 2002 and 2016, whereas it fluctuated between 5,395 m and 5,565 m in Trishuli River sub-basin, central Himalaya (Racoviteanu et al., 2019). The regional snowline altitude in HMA generally decreases with an increase in latitude (Tang et al., 2020).

Few projections of future snowpack in the region are available. Snow cover is likely to experience an accelerated loss over the HKH region, including the Tibetan Plateau, under different global warming levels (Kraaijenbrink et al., 2021; Lalande et al., 2021). Nepal et al. (2021) predicted decreasing snow cover across all elevation bands in the Panjshir catchment, Afghanistan under CMIP5 (Coupled Model Intercomparison Project Phase 5) climate scenarios. Snowfall over HMA is projected to decrease by 18.9% and 32.8% under representative concentration pathway RCP4.5 and RCP8.5 climate scenarios, respectively, by the end of the century (Y. Li et al., 2020). Another study suggests that under RCP8.5, snowfall in the Indus Basin will decrease by 30%–50%, in the Ganges by 50%–60%, and in the Brahmaputra by 50%–70% in the last three decades of this century compared to the average snowfall between 1971 and 2000 (Viste & Sorteberg, 2015). With a temperature rise of 2°C, a widespread decrease in snow cover is projected for the northern hemisphere (Thackeray et

FIGURE 2.7

MEAN ANNUAL SNOW PERSISTENCY AND TREND IN SNOW-COVER AREA IN MAJOR RIVER BASINS OF THE HKH DURING 2003–2020 USING CLOUD-FREE MODIS DATA.





Source: Derived from Muhammad and Thapa (2020)

al., 2016) as early as the mid-21st century, which will adversely affect agriculture, energy production, and other sectors. The projected changes in precipitation patterns and the rise in temperatures (Krishnan et al., 2019) will reduce snow cover in the future (Nepal et al., 2021) and cause a shift in the snow line toward higher elevations (Mir et al., 2017).

Much of the current research uses optical remote sensing satellites such as MODIS, Landsat, and Sentinel-2. While the data from these sources can provide a long-term comparison of historical changes in snow cover, cloud cover and polar darkness can affect the results. The use of SAR data from space offers an alternative approach to monitoring snow

cover since it is independent of cloud cover and illumination conditions (Tsai et al., 2019). The existing estimates are also inconsistent in space and time due to variable methodologies and data sources. Furthermore, projections in precipitation are subject to high uncertainty. Future snow projections are likely to have biases when based on projected precipitation. Therefore, the assessment of future changes in snowpack is still subject to a great deal of uncertainty due to a lack of sufficient knowledge regarding underlying physical mechanisms (Q. You et al., 2020).

2.5.2. Measurements and changes in snow depth and snow water equivalent

Despite its significance, snow is one of the most poorly observed components of the cryosphere globally. Assessing snow depth (SD) and snow water equivalent (SWE) remains difficult over the HKH region because of heterogeneous snowpacks and the complex terrain. However, some effort has been made to establish field-based snow stations in the region (Kirkham et al., 2019; Matthews, Perry, Lane et al., 2020; Stigter et al., 2021). These measurements reveal spatio-temporal heterogeneity of the snowpack even in small catchments (Stigter et al., 2017). Emerging evidence suggests an important role for sublimation in the cryosphere of the HKH (for example, Azam et al. [2021]). Stigter et al. (2018) observed 1 mm of snow sublimation per day in the Langtang catchment, Nepal, during the post-monsoon season, which signifies a considerable loss of annual snowfall back to the atmosphere (~21%). Mandal et al. (2022) used a 11-year meteorological record from an AWS on a side moraine (at 4,863 m a.s.l.) of Chhota Shigri Glacier and computed the sublimation amounts to be 16%–42% of total winter precipitation. Research conducted in the Langtang catchment revealed that a significant fraction of snowmelt (>20%) is refrozen within the snowpack (Saloranta et al., 2019; Stigter et al., 2021; Veldhuijsen et al., 2022).

Wind transport and erosion are other key processes that influence the redistribution of snow and glacier mass balance in mountainous terrain. Wind plays a critical role in the sublimation of snow. Meteorological conditions such as low atmospheric pressure, high wind speed, and dry air favour sublimation in high-

elevation areas (Stigter et al., 2018). These studies so far only cover the central (Saloranta et al., 2019; Stigter et al., 2018) and western Himalaya (Mandal et al., 2022) and hence we have limited knowledge about how these processes affect larger basins and regional hydrology. So far, the influence of wind on the redistribution of snow has not been quantified in the Himalaya.

The maximum annual amount of water stored as snow over large regions in HMA decreased significantly during 1979–2019 (Kraaijenbrink et al., 2021). The average of the peak total SWE volume over HMA during 2000–2018, derived from high resolution HMA Snow Reanalysis (HMASR) data, is found to be around 163 km³. The lowest volume is observed in the water year 2001 and the highest in 2005 (Y. Liu et al., 2021). Coarser (25 km × 25 km) passive microwave data from 1987 to 2009 demonstrate the declining trend of SWE in HMA with the most negative trends from mid-elevation zones of most catchments (Smith & Bookhagen, 2018). High-resolution passive microwave data (3.125 km × 3.125 km) from 1987 to 2015 showed a similar decreasing trend but areas with a positive glacier mass balance record, such as the Pamir, Karakoram, Hindu Kush, and Kunlun mountains, experienced an increased volume of snow, particularly during the winter season (Smith & Bookhagen, 2020).

Consensus estimates of future snow depth/mass in the lower elevations of the Himalaya, European Alps, western North America, and subtropical Andes suggest they are projected to decline by 25% by 2050 regardless of GHG emission scenarios, and up to 50% under RCP4.5 and 80% under RCP8.5 by the end of this century (2081–2100) (Hock et al., 2019).

Despite these estimates, information on the spatio-temporal variability of SWE remains highly uncertain in HMA due to its complex terrain and limited field observations (Y. Liu et al., 2021). Most of the regional SD and SWE analysis is based on reanalysis data such as ERA5 and microwave remote sensing products such as AMSR-E (Advanced Microwave Scanning Radiometer-Earth Observing System), which do not provide sufficient information about SWE due to their coarser spatial resolution. High-resolution datasets generated by combining reanalysis data with optical remote sensing products such as HMASR provide a better picture of the spatio-temporal distribution of SWE in HMA but still have limitations in monsoon-dominated regions such as central and eastern

Himalaya due to persistent cloud cover (Y. Liu et al., 2021). Long-term snow mass information is derived from coarse (25-km) resolution images (Larue et al., 2017), excluding mountain areas with high SWE values or requiring bias correction under deep snow conditions (>150 mm SWE) (Pulliainen et al., 2020). The NASA-ISRO SAR (NISAR) mission is likely to reduce many of these uncertainties since it provides images detailed enough to see local changes, and yet has wide enough coverage to identify regional trends (NISAR, 2018).

2.5.3. Observed and projected changes in the snow season and extreme snow events

Snow remains on the ground for longer in the western than the eastern basins of the HKH. The average snow cover duration in five major river basins (Syr Darya, Amu Darya, Indus, Ganges, and Brahmaputra) from 2002 to 2017 was found to be 102 days. The general trends in snow cover duration across HMA indicate a decline in recent years at the rate of 0.844 days per year (Ackroyd et al., 2021). About 78% of mountainous regions globally demonstrate negative trends in snow cover duration, associated with a delayed onset of snowfall and earlier melt in 58% of the area (Notarnicola, 2020). By considering snow cover duration analysis at smaller spatial scales across HMA, the existing broad-scale assessment that uses coarser data could be refined.

Heavy snowfall has increased in recent years. Frequent snowstorms are observed over the Tibetan Plateau and the Himalaya (Fujita et al., 2017; Y. Liu et al., 2021). Anomalous snowfall has the potential to amplify avalanche hazards (Fujita et al., 2017). Such events are predicted to become more frequent and intense in future (Dong et al., 2020).

The contribution of snowmelt to streamflow is expected to diminish in future regardless of the climate scenario; however, the impacts of these changes depend largely on the magnitude of climate change (Kraaijenbrink et al., 2021). The onset of snowmelt is anticipated to occur earlier in the future (Khanal et al., 2021) but its influence

on the seasonality of river run-off in larger rivers may be dampened by increased rainfall. High-elevation catchments in the HKH region, however, are likely to be affected by the reduced snow cover duration and earlier snowmelt, as snow is their major source of water.

2.5.4. Relationship between elevation-dependent warming and snow

The distribution of snow strongly depends on latitude and elevation. The variable altitudinal distribution and melting of snow make it complex to directly compare the relationship between snow and temperature. While snow depth data are in principle suitable for understanding the relationship of snow and EDW, an altitudinal understanding of changes in snow depth is still lacking due to spatio-temporal assessment being limited (Smith & Bookhagen, 2018). The trends in elevation-dependent snow cover and snow depth remain unclear, with no consensus estimates (Q. You et al., 2020). Snow depth remains extremely sensitive to warming and has been observed to have decreased significantly at higher elevations compared to lower elevations on the Tibetan Plateau between 1980 and 2014 (Shen et al., 2021). The length of the snow-cover season is declining at all elevations, with the greatest rate of decline at 4,000–6,000 m a.s.l. in the Himalaya and the Tibetan Plateau (Desinayak et al., 2022).

The high snow cover persistence at higher elevations reduces the effects of the positive feedbacks responsible for EDW at low to middle elevations. Analysing the relationship between snow depth and EDW becomes more complex for extremely high elevations above 5,000 m due to the lack of data, or uncertainty in the models and gridded data in accurately capturing EDW (Y. Gao et al., 2018). Mountainous regions worldwide indicate a decrease in snow-covered area at high elevations and thus the data support a positive relationship between EDW and snow (Notarnicola, 2020), whereas no decline has been observed at similar elevations in the HKH (Desinayak et al., 2022). The relationship between EDW and snow is still not well established in the HKH and requires further investigation.

2.6. Permafrost

Research on mountain permafrost is currently more critical than ever due to climate change leading to a thawing permafrost, with unprecedented consequences (Oliva & Fritz, 2018). A comprehensive review of high mountain permafrost in the HKH region showed that the distribution of permafrost surpasses that of glaciers in almost all of the HKH (Gruber et al., 2017) (Figure 2.1). Estimates of permafrost area for the HKH vary, from 2.25×10^6 km² (Obu et al., 2019) and 2.09×10^6 km² (Gruber, 2012) to 1.19×10^6 km² (Ran et al., 2022). Despite varying estimates from multiple simulations, the wide-ranging presence of permafrost in the HKH is evident. A few existing field-based measurements suggest the existence of considerable areas of permafrost in the cold-arid Himalaya (Wani et al., 2020). As limited field-based evidence exists, rock glaciers are often considered as visual indicators of, and ground-truth data for the occurrence of permafrost in the HKH (Haq & Baral, 2019; Hassan et al., 2021; Khan et al., 2021; Pandey, 2019). This could, however, lead to overestimations of the extent of permafrost because rock glaciers generally represent more suitable premises for the existence of permafrost compared to adjoining ground (Cao et al., 2021).

The possible widespread impacts of a thawing permafrost due to climate change in this region are poorly understood. A broader understanding is necessary to recommend the appropriate adaptation actions to combat the scale and intensity of these impacts.

2.6.1. Observed changes in permafrost

There has recently been an increase in the number of permafrost-related investigations in the HKH. The number of scientific papers published after 2015 exceeds the total sum of research articles published before it. Studies before 2000 do not mention climate change and its impacts. Most of the studies published after 2000 focus on the geomorphological aspects of climate change and permafrost while only a few articles after 2015 discuss the hydrological consequences of a changing permafrost for the region.

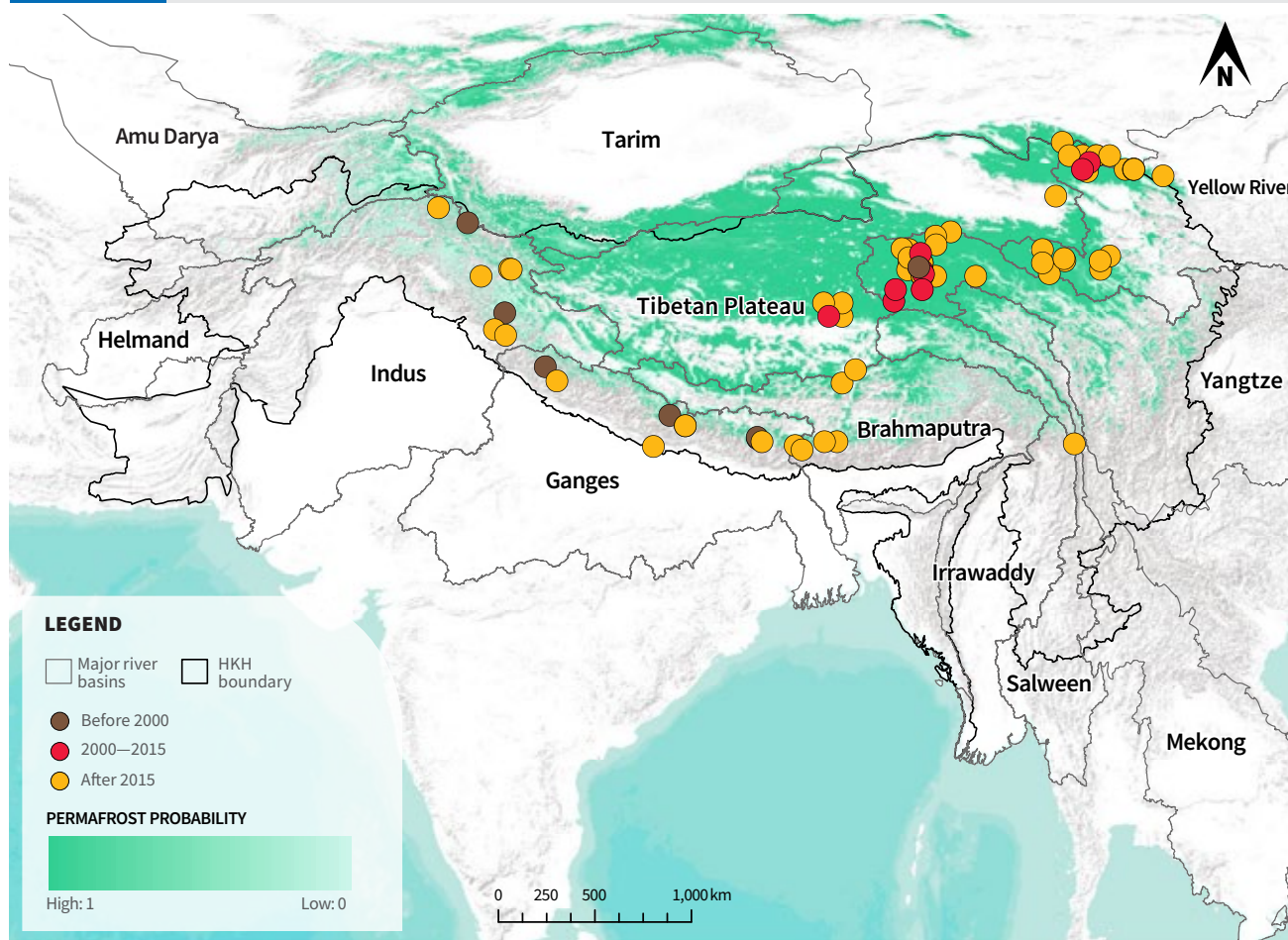
The average global permafrost temperature has increased by $0.29 \pm 0.12^\circ\text{C}$ between 2007 and 2016; the average mountain permafrost temperature increased by $0.19 \pm 0.05^\circ\text{C}$ over the same period (Biskaborn et al., 2019). Prolonged warming has led to permafrost degradation: continuous permafrost zones at lower elevations are turning wet whereas discontinuous permafrost zones at higher elevations are turning dry (H. Jin et al., 2022). Ground-based measurements from a cold and arid Himalayan region conclude that net radiation exerts the strongest influence on the ground thermal regime (Wani et al., 2021). Field observations suggest changes in Himalayan permafrost (Kalvoda & Emmer, 2021). Remote sensing estimates confirm a decrease in permafrost cover in the Indian Himalayan region. A loss of about 8,340 km² in permafrost area was calculated from modelled results for the western Himalaya between 2002–2004 and 2018–2020 (Khan et al., 2021). Another study indicated that the probable areal extent of permafrost decreased from 7,897 km² to 6,932 km² in the Uttarakhand Himalaya between 1970–2000 and 2001–2017 (Baral et al., 2020).

2.6.2. Consequences of changes in permafrost

The number of documents reporting loss and damage resulting from changes in the cryosphere due to climate change are relatively high for the HKH compared to other mountain ranges in the world (Huggel et al., 2019). Hazard assessments in the HKH generally depend on remote sensing for observing permafrost landscape dynamics (Scapozza et al., 2019). Disappearing subterranean ice, transitional permafrost landscapes, and mass wasting associated with a thawing permafrost are increasing threats to high-mountain communities and infrastructure (Haeberli et al., 2017; Huss et al., 2017). More frequent slope failure events in the high mountains can probably be linked to climate change causing subsequent changes in permafrost environments in the HKH. For instance, permafrost bedrock, exposed to thermal perturbation due to continuously amplified warming, could have triggered the Chamoli disaster in the Indian Himalaya in 2021 (Shugar et al., 2021).

FIGURE 2.8

OVERVIEW OF PERMAFROST AREA AND RESEARCH IN THE HKH



Notes: Articles representing permafrost research in the region were selected based on a systematic review. Dots indicate where investigations have been carried out, with different colours corresponding to the years of the study. Specific coordinates for latitude and longitude mentioned in the articles were plotted as dots. For studies where coordinates were mentioned as a range, mean values were taken.

Source: Obu et al. (2019) for permafrost area

In the HKH, permafrost hazards are reported mostly for the Karakoram, followed by the Himalaya (Ding et al., 2021). For example, changes in permafrost account for about 30% of road damage in the Qinghai-Tibetan Plateau. Mass wasting events, associated with permafrost degradation, will increase in future. It is anticipated that damage to infrastructure associated with permafrost degradation could cost several billion US dollars by 2100 globally (Hjort et al., 2022); such impacts on infrastructure are already visible in the HKH.

Seasonal ground deformation along the engineering corridor on the Qinghai-Tibetan Plateau fluctuated between -20 and +10 mm per year during 2015-2018 compared to -5 mm and +5 mm per year during 1997-1999 (Z. Zhang et al., 2019); recently developing

thaw slumps in permafrost areas can be linked to these increasing ranges in deformation. Seasonal slope deformations in permafrost sites at low elevations in the Bhutan Himalaya ranged from 5 mm to 17 mm in 2007-2011 (Dini et al., 2019), with maximum deformation occurring during the summer. The same study suggests that on gentle slopes and in high-elevation areas, the mean freeze-thaw related displacement was 10 mm, and the maximum deformation reached up to 28 mm; these deformations could be linked to changes in the groundwater table.

In the HKH, a thawing permafrost is responsible for changes in hydrology, increased sediment flux, and subsequent changes in the carbon cycle (H. Gao et al., 2021; D. Li et al., 2021). On the Tibetan Plateau,

changes in permafrost govern the hydrological equilibrium of thermokarst lakes, with significant spatial as well as temporal differences in hydrological regimes of thermokarst lake systems anticipated under continued warming and thawing of permafrost (Y. Yang et al., 2021).

Changes in permafrost impact the plant community through variations in soil moisture content, the groundwater table, biogeochemical cycles, and microbial species, eventually causing shifts in the composition and distribution of vegetation (X. Jin et al., 2021). On the Tibetan Plateau, climate change has led to an increase in above-ground net primary production (ANPP) in wet permafrost areas and a decrease in ANPP in dry non-permafrost areas (Yang et al., 2018). Climate change will almost equally affect the production and release of greenhouse gases from the active layer as well as greater depths of permafrost on the Tibetan Plateau (Mu et al., 2018).

This indicates that water availability – in a warming climate and changing permafrost conditions – will be crucial for biodiversity and ecosystem functioning on the Tibetan Plateau. Further, projections regarding the distribution of native plant species through to 2050 (J. You et al., 2018) indicated that the species could shift to higher elevations in search of appropriate habitats. However, many plant species could also adapt to different habitat conditions under changing permafrost conditions.

The management of freshwater stored in rock glaciers in permafrost regions of the HKH could be important under future climate change contexts as rock glacier meltwater streams could significantly contribute to downstream regions (Jones et al., 2019). For example, the Himalayan region of Nepal has more than 6,000 rock glaciers, covering an area of about 1,371 km² potentially storing 16.72–25.08 billion m³ of water (Jones et al., 2018). However, little is known about the consequences of thawing rock glaciers on downstream water quality in the HKH (Colombo et al., 2018).

In addition to overuse, continuously rising temperatures and a thawing permafrost are considered responsible for the gradual decline in the growth of the Himalayan caterpillar fungus, a valuable biological resource (Hopping et al., 2018).

2.6.3. Projections for permafrost

Although regional variations exist, there has been a consistent rise in the average temperature of high mountain permafrost worldwide since the 1980s (S. Smith et al., 2022); for several permafrost regions, the highest annual temperatures were observed in 2018–2019. Projections indicate that this warming and thawing will persist, but their degree and duration may differ for different regions. When projections of permafrost degradation for multiple RCPs (RCP2.6, RCP4.5, and RCP8.5) are compared, results indicate the largest areal degradation in 2010–2140, 2040–2070, and 2070–2100 for RCP8.5 (S. Zhao et al., 2022). Permafrost areas highly likely to degrade are distributed in East Asia and West Asia.

A recent study suggests that alpine permafrost (permafrost at high mountain elevations or on mountain plateaux) is more vulnerable to rising temperatures than circumpolar permafrost (Cheng et al., 2022). If the global average temperature was 2°C–3°C higher than the present, nearly 60% of alpine permafrost would be subjected to thawing. About 37.3% of the 0.80–1.28 × 10⁶ km² area of the Qinghai–Tibetan Plateau underlain by permafrost is endangered (Ni et al., 2021). Projections under RCP8.5 predict a reduction of approximately 42% in permafrost area by 2061–2080.

A recent permafrost map of the Tibetan Plateau shows that permafrost distribution could range between 105.47 × 10⁴ and 129.59 × 10⁴ km², with transitional and unstable permafrost areas covering about 42.29 × 10⁴ and 23.80 × 10⁴ km², respectively (Ran et al., 2021). Projections of permafrost distribution on the Tibetan Plateau through the end of the twenty-first century indicate the lowest degradation in 2011–2040 and the highest degradation in 2071–2099 for RCP2.6, RCP4.5, RCP6.0, and RCP8.5 (Lu et al., 2017). The increase in area undergoing permafrost degradation ranges from 12.95% in 2011–2040 for RCP6.0 to 64.31% in 2071–2099 for RCP8.5. Projections of permafrost active layer thickness (ALT) through the end of the twenty-first century (Zhao & Wu, 2019) indicate a significant increase in ALT in the northwestern region of the Tibetan Plateau. Changes in the ALT range from 5 centimetres (cm) to 30 cm in 2011–2040 for RCP2.6, RCP4.5, RCP6.0, and RCP8.5. The active layer thickness is projected to further increase in 2041–2070 and exceed 30 cm in 2071–2099 for warming levels of 3.1°C or higher above the 1981–2010 baseline.

2.7. Major knowledge gaps

The chapter on the cryosphere in *The Hindu Kush Himalaya assessment* report (Bolch et al., 2019) made several recommendations to close knowledge gaps about the cryosphere in the HKH. These are briefly summarised below (noted in *italics*), highlighting where gaps have been closed and where they remain open. Each section then moves to a single paragraph on gaps that have since been identified, and related recommendations.

2.7.1. Glaciers

Glaciers are the component of the cryosphere that receives the most attention in the region, and several of the recommendations have been followed. *Mass changes* have been successfully documented *before 2000* for the region, relying on declassified satellite imagery (Maurer et al., 2019). Similarly, a number of models have been employed to *estimate sub-debris melt* in the region (Rounce et al., 2015; Steiner et al., 2021), also addressing ice melt from features such as cliffs (Buri et al., 2021) and ponds (Miles et al., 2018). Scherler and Egholm (2020) also showed the potential of ice flow models including debris transport. Model intercomparisons have so far not been attempted for any of these approaches, likely also due to the small number of different approaches taken.

A crucial gap remaining is the *paucity of measurements of ice and debris thickness and their melt response throughout a glacier*. Ice thickness data have been collated at a global scale but such estimates for glaciers in the HKH diverge considerably (Farinotti et al., 2019; Millan et al., 2022), with implications for future projections of loss of mass and dynamic behaviour. However, field validation is still lacking. Debris thickness has also been identified as the crucial variable in estimating sub-debris melt and has been computed on a global scale (Rounce et al., 2021). However, measurements from the HKH are scarce (McCarthy et al., 2017; Rounce & McKinney, 2014), with few observations outside the central Himalayan region (Muhammad et al., 2020). The rapid development of satellite technology has made new progress possible, including the observation of seasonal melt from space by relying on repeated radar data from different configurations (Jakob et al., 2021; Scher et al., 2021). The efficient use

of radar data requires more investigation into the relationship between penetration depth of the wave and surface melt on glacier surfaces (G. Li et al., 2021). To understand the dynamic behaviour of ice, investigations into ice temperatures and percolation are crucial but remain rare (Gilbert et al., 2020). Such measurements will be crucial for our understanding of the recently highlighted importance of glacier detachments (Kääb et al., 2021) and break-offs of hanging glaciers (Shugar et al., 2021).

RECOMMENDATIONS

- Field measurements of ice thickness, debris thickness, ice temperatures, and glacier velocity should be continued to further expand field validation of regional and global datasets.
- Better integration of observations of essential glacier processes (such as ice dynamics, glacier calving, debris, and surface features) and models is needed to improve future projections.
- Glaciers should not be studied in isolation but as part of the high-elevation water cycle and more effort should be devoted to integrating advanced glacier models with hydrological models.
- Attribution of glacier change to anthropogenic forcing should be investigated in the region, to make clear where and how climate change manifests itself.

2.7.2. Glacial lakes

Glacial lake risk assessments, including projected changes in lake extent and volume, have been conducted on a regional scale (Furian et al., 2022; Zheng et al., 2021) as well as for more localised cases (N. Khadka et al., 2021; Muhammad et al., 2021; Sattar, Goswami et al., 2021; Sattar, Haritashya et al., 2021). Projections generally refer to an increase in lake volume; however, future sediment fluxes are ignored, and could also lead to aggradation (Furian et al., 2022; Steffen et al., 2022). A standardised approach for hazard and risk assessments is still lacking. Uncertainties in permafrost estimates also hamper hazard projections. While new lake inventories have been compiled and increasingly easy access to satellite imagery makes this possible repeatedly (Chen et al., 2021; X. Wang et al., 2020), estimates of

total lake area and number vary considerably due to different approaches taken and image resolutions used. Manually delineated inventories (X. Wang et al., 2020) capture considerably smaller lakes but are more labour-intensive and subject to operator bias.

Lake level changes have been observed over the past few decades due to glacial melt (Song et al., 2016; Zheng et al., 2021) as an important component of the cryosphere in the southeastern Tibetan Plateau. Secondary effects on ecosystems around, and downstream of these lakes have, however, not been investigated so far.

RECOMMENDATIONS

- UAV surveys of glacial lake dams have been performed but some results are not yet easily available. Studies should investigate dam stability and ice content through in situ (for example, ground-penetrating radar/GPR) surveys.
- Multi-sensor as well as machine-learning approaches should be used to explore the ability to capture all lakes, including small ones and those with varying areas. This would help reconcile previous estimates that diverge widely.
- Lake formation due to glacier calving and the associated positive feedback mechanisms are poorly understood. Observation-based studies linked with modelling are recommended to unravel these mechanisms.
- Field surveys should investigate the secondary effects of changes in lake area on the surrounding geomorphology, ecosystems, and hydrology.

2.7.3. Snow

Estimates of *changes in regional snow line elevations* using optical imagery have received some attention (Girona-Mata et al., 2019; Racoviteanu et al., 2019; Tang et al., 2020). Conversely, studies on the *rain-snow transition* remain rare (Y. Li et al., 2020). However, there have been studies on the *influence of pollution transport on the snow energy balance*. While these would previously often focus on the Tibetan Plateau, work has also been forthcoming on the southern slopes of the HKH (Santra et al., 2019; Skiles et al., 2018). The *monitoring of snow water equivalent using microwave data* has also seen some initial work but is generally still hampered by the coarse resolution of the products and the lack

of ground validation (Smith & Bookhagen, 2018). Similarly, the lack of validation from field sites hampers understanding of the *spatial variability of snowpack changes*. Lievens et al. (2019) showed the potential of Sentinel-1 data for snow depth retrieval from space, which was also validated for sites in the HKH. However, seasonal snow depth changes remain poorly covered in field-based models for a lack of knowledge about specific properties like albedo (Stigter et al., 2021), which makes accuracy in time and space a challenge.

Continuous snow monitoring has been successful in a few locations, showing the potential of multiple sensors on the ground (Bair et al., 2019; Kirkham et al., 2019). However, process understanding of snowpack development remains poor. Initial work has been conducted on sublimation (Gascoin, 2021; S. Guo et al., 2021; S. Guo et al., 2022; Mandal et al., 2022; Stigter et al., 2018) and refreezing (Stigter et al., 2021; Veldhuijsen et al., 2021) but local changes in albedo and wind-driven erosion (Mott et al., 2018) have gained no further attention and should be prioritised. These processes are not only crucial for simulating snowpack evolution and melt but also for a better understanding of avalanche hazards (Reuter et al., 2022; Vionnet et al., 2018). Additionally, the increasing patchiness of snow cover needs further attention, as it has influences on the local surface boundary layer above (Mott et al., 2017), as well as permafrost and the resulting storage capacity of soil below (T. Zhang, 2005).

RECOMMENDATIONS

- More studies need to be conducted on field processes, including wind-blown snow, interception, and the effect of light-absorbing particles on snow.
- Investments in benchmark snow observatories where SWE, snow depth, snowfall, turbulence, and the energy balance are monitored are required to understand key snow processes such as sublimation, refreezing, and the energy balance of the snowpack.
- Studies investigating the effects of a changing snowpack and snow cover on ecosystems should be conducted in different climatic environments.
- High-intensity snowfall events as well as rain-on-snow events in a hazard context need further attention.

2.7.4. Permafrost

The number of permafrost monitoring sites has increased in the HKH, and efforts towards transnational cooperation have increased. Future work should build on these catchment-scale studies and ensure the exchange of data and experience.

As a number of recent hazard events have been associated with a thawing permafrost, systematic documentation of observed changes that may have, or could result in hazards should be carried out in the HKH (Byers et al., 2020; Coe, 2020). Studies that link a changing permafrost to ecosystems, livelihoods, and infrastructure development are lacking in the HKH. Field measurements have been limited to surface and borehole temperature measurements on the Tibetan Plateau (Sun et al., 2020; L. Zhao et al., 2021). Outside of the Tibetan Plateau, surface temperature measurements have been carried out at a few locations whereas borehole measurements have not been attempted.

RECOMMENDATIONS

- Permafrost should be elevated in national discourses on the cryosphere both among the public as well as at multiple government levels to create awareness about its associated challenges.
- In close collaboration with global networks of permafrost researchers, a regional platform should be established that enables collaboration and the exchange of knowledge.

- Dedicated observation sites should be established in the HKH region with a plan for sustainable monitoring.
- Research into the relation between changes in snow and permafrost should be prioritised, as well as how changes in permafrost affect ecosystems, infrastructure, and livelihoods.

2.7.5. Conclusions

Important progress has been made in research on all components of the cryosphere in the HKH in recent years. Monitoring, process understanding, and remote sensing capacities have increased, resulting in an improved understanding of changes in ice, snow, and permafrost as well as associated water resources. Future focus in research should be on making a link between crucial fields within the cryosphere (for example, the effect of a changing snowpack on permafrost) and beyond (for example, the effects of changing glacier melt on livelihoods in the HKH or of changing glacial lakes on ecosystems). While field monitoring should still be promoted and expanded, care should be taken to enable the long-term sustainability of well-instrumented catchments. The rapidly developing remote sensing capabilities need to be closely monitored to make data readily available for research purposes as well as policy support. There is increasing attention to hazards associated with the cryosphere. An assessment of vulnerable livelihoods, infrastructure, and ecosystems should be attempted to enable focused studies on relevant cryospheric processes.

References

- Ackroyd, C., Skiles, S. M., Rittger, K., & Meyer, J. (2021). Trends in snow cover duration across river basins in High Mountain Asia from daily gap-filled MODIS fractional snow covered area. *Frontiers in Earth Science*, 9, Article 713145. <https://doi.org/10.3389/feart.2021.713145>
- Ahmed, R., Wani, G. F., Ahmad, S. T., Sahana, M., Singh, H., & Ahmed, P. (2021). A review of glacial lake expansion and associated glacial lake outburst floods in the Himalayan region. *Earth Systems and Environment*, 5, 695–708. <https://doi.org/10.1007/s41748-021-00230-9>
- Angchuk, T., Ramanathan, A., Bahuguna, I. M., Mandal, A., Soheb, M., Singh, V. B., Mishra, S., & Vatsal, S. (2021). Annual and seasonal glaciological mass balance of Patsio Glacier, western Himalaya (India) from 2010 to 2017. *Journal of Glaciology*, 67(266), 1137–1146. <https://doi.org/10.1017/jog.2021.60>
- Arias, P. A., Bellouin, N., Coppola, E., Jones, R. G., Krinner, G., Marotzke, J., Naik, V., Palmer, M. D., Plattner, G.-K., Rogelj, J., Rojas, M., Sillmann, J., Storelvmo, T., Thorne, P. W., Trevis, B., AchutRao, K., Adhikary, B., Allan, R. P., Armour, K., ... Zickfeld, K. (2021). Technical summary. In V. Masson-Delmotte, P. Zhai, S. L. Pirani, S. L. Connors, C. Pean, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Mathews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu & B. Zhou (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* (pp. 33–144). Cambridge University Press. <https://doi.org/10.1017/9781009157896.002>
- Azam, M. F., Kargel, J. S., Shea, J. M., Nepal, S., Haritashya, U. K., Srivastava, S., Maussion, F., Qazi, N., Chevallier, P., Dimri, A. P., Kulkarni, A. V., Cogley, J. G., & Bahuguna, I. (2021). Glaciohydrology of the Himalaya-Karakoram. *Science*, 373(6557), Article eabf3668. <https://doi.org/10.1126/science.abf3668>
- Azam, M. F., Ramnathan, A. L., Wagnon, P., Vincent, C., Linda, A., Berthier, E., Sharma, P., Mandal, A., Angchuk, T., Singh, V. B., & Pottakkal, J. G. (2016). Meteorological conditions, seasonal and annual mass balances of Chhota Shigri Glacier, western Himalaya, India. *Annals of Glaciology*, 57(71), 328–338. <https://doi.org/10.3189/2016AoG71A570>
- Azam, M. F., Wagnon, P., Berthier, E., Vincent, C., Fujita, K., & Kargel, J. S. (2018). Review of the status and mass changes of Himalayan-Karakoram glaciers. *Journal of Glaciology*, 64(243), 1–14. <https://doi.org/10.1017/jog.2017.86>
- Bair, E. H., Rittger, K., Skiles, S. M., & Dozier, J. (2019). An examination of snow albedo estimates from MODIS and their impact on snow water equivalent reconstruction. *Water Resources Research*, 55(9), 7826–7842. <https://doi.org/10.1029/2019WR024810>
- Bamber, J. L., & Rivera, A. (2007). A review of remote sensing methods for glacier mass balance determination. *Global and Planetary Change*, 59(1–4), 138–148. <http://dx.doi.org/10.1016/j.gloplacha.2006.11.031>
- Banerjee, A.: Brief communication: Thinning of debris-covered and debris-free glaciers in a warming climate, *The Cryosphere*, 11, 133–138, <https://doi.org/10.5194/tc-11-133-2017>
- Baral, P., Haq, M. A., & Yaragal, S. (2020). Assessment of rock glaciers and permafrost distribution in Uttarakhand, India. *Permafrost and Periglacial Processes*, 31(1), 31–56. <https://doi.org/10.1002/ppp.2008>
- Benestad, R. (2016). Downscaling climate information. *Oxford Research Encyclopedia of Climate Science*. Retrieved January 2, 2023, from <https://doi.org/10.1093/acrefore/9780190228620.013.27>
- Benestad, R. E., Lussana, C., Lutz, J., Dobler, A., Landgren, O. A., Haugen, J. E., Mezghani, A., Casati, B., & Parding, K. M. (2022). Global hydro-climatological indicators and changes in the global hydrological cycle and rainfall patterns, *PLOS Climate*, PCLM-D-21-00079R1. <https://doi.org/10.1371/journal.pclm.0000029>
- Benestad, R. E., Parding, K. M., Erlandsen, H. B., & Mezghani, A. (2019). A simple equation to study changes in rainfall statistics. *Environment Research Letters*, 14(8), Article 084017. <https://doi.org/10.1088/1748-9326/ab2bb2>
- Beniston, M., Farinotti, D., Stoffel, M., Andreassen, L. M., Coppola, E., Eckert, N., Fantini, A., Giacomoni, F., Hauck, C., Huss, M., Huwald, H., Lehning, M., López-Moreno, J.-I., Magnusson, J., Marty, C., Morán-Tejeda, E., Morin, S., Naaïm, M., Provenzale, A., ... Vincent, C. (2018). The European mountain cryosphere: A review of its current state, trends, and future challenges. *The Cryosphere*, 12, 759–794. <https://doi.org/10.5194/tc-12-759-2018>
- Bhattacharya, A., Bolch, T., Mukherjee, K., King, O., Menounos, B., Kapitsa, V., Neckel, N., Yang, W., & Yao, T. (2021). High Mountain Asian glacier response to climate revealed by multi-temporal satellite observations since the 1960s. *Nature Communications*, 12, Article 4133. <https://doi.org/10.1038/s41467-021-24180-y>
- Bilal, H., Chamhuri, S., Mokhtar, M. B., & Kanniah, K. D. (2019). Recent snow cover variation in the Upper Indus Basin of Gilgit Baltistan, Hindukush Karakoram Himalaya. *Journal of Mountain Science*, 16(2), 296–308. <https://doi.org/10.1007/s11629-018-5201-3>

- Biskaborn, B. K., Smith, S. L., Noetzi, J., Matthes, H., Vieira, G., Streletskiy, D. A., Schoeneich, P., Romanovsky, V. E., Lewkowicz, A. G., Abramov, A., Allard, M., Boike, J., Cable, W. L., Christiansen, H. H., Delaloye, R., Diekmann, B., Drozdov, D., Etzelmüller, B., Grosse, G., ... Lantuit, H. (2019). Permafrost is warming at a global scale. *Nature Communications*, *10*(1), 1–11. <https://doi.org/10.1038/s41467-018-08240-4>
- Bolch, T., Pieczonka, T., & Benn, D. I. (2011). Multi-decadal mass loss of glaciers in the Everest area (Nepal Himalaya) derived from stereo imagery. *The Cryosphere*, *5*, 349–358. <https://doi.org/10.5194/tc-5-349-2011>
- Bolch, T., Pieczonka, T., Mukherjee, K., & Shea, J. (2017). Brief communication: Glaciers in the Hunza catchment (Karakoram) have been nearly in balance since the 1970s. *The Cryosphere*, *11*(1), 531–539. <https://doi.org/10.5194/tc-11-531-2017>
- Bolch, T., Shea, J. M., Liu, S., Azam, F. M., Gao, Y., Gruber, S., Immerzeel, W. W., Kulkarni, A., Li, H., Tahir, A. A., Zhang, G., & Zhang, Y. (2019). Status and change of the cryosphere in the extended Hindu Kush Himalaya region. In P. Wester, A. Mishra, A. Mukherji, & A. B. Shrestha (Eds.), *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability and people* (pp. 209–255). Springer Nature Switzerland AG. Retrieved December 5, 2019, from https://doi.org/10.1007/978-3-319-92288-1_7
- Bookhagen, B., & Burbank, D. W. (2006). Topography, relief, and TRMM-derived rainfall variations along the Himalaya. *Geophysical Research Letters*, *33*(8). <https://doi.org/10.1029/2006GL026037>
- Bormann, K. J., Brown, R. D., Derksen, C., & Painter, T. H. (2018). Estimating snow-cover trends from space. *Nature Climate Change*, *8*(11), 924–928. <https://doi.org/10.1038/s41558-018-0318-3>
- Bove, C. B., Mudge, L., & Bruno, J. F. (2022). A century of warming on Caribbean reefs. *PLOS Climate*, *1*(3), Article e0000002. <https://doi.org/10.1371/journal.pclm.0000002>
- Brombierstäudl, D., Schmidt, S., & Nüsser, M. (2021). Distribution and relevance of aufeis (icing) in the Upper Indus Basin. *Science of the Total Environment*, *780*, Article 146604. <https://doi.org/10.1016/j.scitotenv.2021.146604>
- Brun, F., Berthier, E., Wagnon, P., Käab, A., & Treichler, D. (2017). A spatially resolved estimate of High Mountain Asia glacier mass balances from 2000 to 2016. *Nature Geoscience*, *10*, 668–673. <https://doi.org/10.1038/ngeo2999>
- Brun, F., Treichler, D., Shean, D. & Immerzeel, W. W. (2020). Limited contribution of glacier mass loss to the recent increase in Tibetan Plateau lake volume. *Frontiers in Earth Science*, *8*, Article 582060. <https://doi.org/10.3389/feart.2020.582060>
- Brun, F., Wagnon, P., Berthier, E., Jomelli, V., Maharjan, S. B., Shrestha, F., & Kraaijenbrink, P. D. A. (2019). Heterogeneous influence of glacier morphology on the mass balance variability in High Mountain Asia. *JGR Earth Surface*, *124*(6), 1331–1345. <https://doi.org/10.1029/2018JF004838>
- Buri, P., Miles, E. S., Steiner, J. S., Ragettli, S., & Pellicciotti, F. (2021). Supraglacial ice cliffs can substantially increase the mass loss of debris-covered glaciers. *Geophysical Research Letters*, *48*(6), Article e2020GL092150. <https://doi.org/10.1029/2020GL092150>
- Byers, A. C., Chand, M. B., Lala, J., Shrestha, M., Byers, E. A., & Watanabe, T. (2020). Reconstructing the history of glacial lake outburst floods (GLOF) in the Kanchenjunga Conservation Area, East Nepal: An interdisciplinary approach. *Sustainability*, *12*(13), Article 5407. <https://doi.org/10.3390/su12135407>
- Cao, B., Li, X., Feng, M., & Zheng, D. (2021). Quantifying overestimated permafrost extent driven by rock glacier inventory. *Geophysical Research Letters*, *48*(8), Article e2021GL092476. <https://doi.org/10.1029/2021GL092476>
- Carrivick, J. L., & Tweed, F. S. (2013). Proglacial lakes: Character, behaviour and geological importance. *Quaternary Science Reviews*, *78*, 34–52. <https://doi.org/10.1016/j.quascirev.2013.07.028>
- Chen, F., Zhang, M., Guo, H., Allan, S., Kargel, J. S., Haritashya, U. K., & Watson, C. S. (2021). Annual 30 m dataset for glacial lakes in High Mountain Asia from 2008 to 2017. *Earth System Science Data*, *13*(2), 741–766. <https://doi.org/10.5194/essd-13-741-2021>
- Cheng, F., Garzzone, C., Li, X., Salzmann, U., Schwarz, F., Haywood, A. M., Tindall, J., Nie, J., Li, L., Wang, L., Abbott, B. W., Elliott, B., Liu, W., Upadhyay, D., Arnold, A., & Tripathi, A. (2022). Alpine permafrost could account for a quarter of thawed carbon based on Plio-Pleistocene paleoclimate analogue. *Nature Communications*, *13*, Article 1329. <https://doi.org/10.1038/s41467-022-29011-2>
- Chettri, N., Shrestha, A. B., & Sharma, E. (2020). Climate change trends and ecosystem resilience in the Hindu Kush Himalayas. In A. P. Dimri, B. Bookhagen, M. Stoffel, & T. Yasunari (Eds.), *Himalayan Weather and Climate and their Impact on the Environment* (pp. 525–552). Springer International Publishing. https://doi.org/10.1007/978-3-030-29684-1_25
- Coe, J. A. (2020). Bellwether sites for evaluating changes in landslide frequency and magnitude in cryospheric mountainous terrain: A call for systematic, long-term observations to decipher the impact of climate change. *Landslides*, *17*(11), 2483–2501. <https://doi.org/10.1007/s10346-020-01462-y>

- Colombo, N., Salerno, F., Gruber, S., Freppaz, M., Williams, M., Fratianni, S., & Giardino, M. (2018). Review: Impacts of permafrost degradation on inorganic chemistry of surface fresh water. *Global and Planetary Change*, *162*, 69–83. <https://doi.org/10.1016/j.gloplacha.2017.11.017>
- Compagno, L., Huss, M., Miles, E. S., McCarthy, M. J., Zekollari, H., Dehecq, A., Pellicciotti, F., & Farinotti, D. (2022). Modelling supraglacial debris-cover evolution from the single-glacier to the regional scale: An application to High Mountain Asia. *The Cryosphere*, *16*, 1697–1718. <https://doi.org/10.5194/tc-16-1697-2022>
- Cook, S. J., & Quincey, D. J. (2015). Estimating the volume of alpine glacial lakes. *Earth Surface Dynamics*, *3*, 559–575. <https://doi.org/10.5194/esurf-3-559-2015>
- Cui, P., & Jia, J. (2015). Mountain hazards in the Tibetan Plateau: Research status and prospects. *National Science Review*, *2*(4), 397–402. <https://doi.org/10.1093/nsr/nwv061>
- Dehecq, A., Gardner, A. S., Alexandrov, O., McMichael, S., Hugonnet, R., Shean, D., & Marty, M. (2020). Automated processing of declassified KH-9 Hexagon satellite images for global elevation change analysis since the 1970s. *Frontiers in Earth Science*, *8*. <https://doi.org/10.3389/feart.2020.566802>
- Dehecq, A., Gourmelen, N., Gardner, A. S., Brun, F., Goldberg, D., Nienow, P. W., Berthier, E., Vincent, C., Wagnon, P., & Trouvé, E. (2019). Twenty-first century glacier slowdown driven by mass loss in High Mountain Asia. *Nature Geoscience*, *12*, 22–27. <https://doi.org/10.1038/s41561-018-0271-9>
- de Kok, R. J., Kraaijenbrink, P. D. A., Tuinenburg, O. A., Bonekamp, P. N. J., & Immerzeel, W. W. (2020). Towards understanding the pattern of glacier mass balances in High Mountain Asia using regional climatic modelling. *The Cryosphere*, *14*(9), 3215–3234. <https://doi.org/10.5194/tc-14-3215-2020>
- Deser, C., Knutti, R., Solomon, S., & Phillips, A. S. (2012). Communication of the role of natural variability in future North American climate. *Nature Climate Change*, *2*(11), 775–779. <https://doi.org/10.1038/nclimate1562>
- Desinayak, N., Prasad, A. K., El-Askary, H., Kafatos, M., & Asrar, G. R. (2022). Snow cover variability and trend over the Hindu Kush Himalayan region using MODIS and SRTM data. *Annales Geophysicae*, *40*(1), 67–82. <https://doi.org/10.5194/angeo-40-67-2022>
- Ding, Y., Mu, C., Wu, T., Hu, G., Zou, D., Wang, D., Li, W., & Wu, X. (2021). Increasing cryospheric hazards in a warming climate. *Earth-Science Reviews*, *213*. <https://doi.org/10.1016/j.earscirev.2020.103500>
- Dini, B., Daout, S., Manconi, A., & Loew, S. (2019). Classification of slope processes based on multitemporal DInSAR analyses in the Himalaya of NW Bhutan. *Remote Sensing of Environment*, *233*, Article 11408. <https://doi.org/10.1016/j.rse.2019.111408>
- Dobhal, D. P., Gergan, J. T. & Thayyen, R. J. (2008). Mass balance studies of the Dokriani Glacier from 1992 to 2000, Garhwal Himalaya. *Indian Bulletin of Glaciological Research*, *25*, 9–17.
- Dobhal, D. P., Mehta, M., & Srivastava, D. (2013). Influence of debris cover on terminus retreat and mass changes of Chorabari Glacier, Garhwal region, central Himalaya, India. *Journal of Glaciology*, *59*(217), 961–971. <https://doi.org/10.3189/2013JoG12J180>
- Dobhal, D. P., Pratap, B., Bhambri, R., & Mehta, M. (2021). Mass balance and morphological changes of Dokriani Glacier (1992–2013), Garhwal Himalaya, India. *Quaternary Science Advances*, *4*, Article 100033. <https://doi.org/10.1016/j.qsa.2021.100033>
- Dong, H., Li, Q., Zhu, X., Zhang, X., Zhang, Z., Shi, J., & He, Y. (2020). Analysis of the variability and future evolution of snowfall trends in the Huaihe River Basin under climate change. *Frontiers in Earth Science*, *8*, Article 594704. <https://doi.org/10.3389/feart.2020.594704>
- Edwards, T. L., Nowicki, S., Marzeion, B., Hock, R., Goelzer, H., Seroussi, H., Jourdain, N. C., Slater, D. A., Turner, F. E., Smith, C. J., McKenna, C. M., Simon, E., Abe-Ouchi, A., Gregory, J. M., Larour, E., Lipscomb, W. H., Payne, A. J., Shepherd, A., Agosta, C., ... Zwinger, T. (2021). Projected land ice contributions to twenty-first-century sea level rise. *Nature*, *593*(7857), 74–82. <https://doi.org/10.1038/s41586-021-03302-y>
- Emmer, A., Allen, S. K., Carey, M., Frey, H., Huggel, C., Korup, O., Mergili, M., Sattar, A., Veh, G., Chen, T. Y., Cook, S. J., Correas-Gonzalez, M., Das, S., Diaz Moreno, A., Drenkhan, F., Fischer, M., Immerzeel, W. W., Izagirre, E., Joshi, R. C., ... Yde, J. C. (2022). Progress and challenges in glacial lake outburst flood research (2017–2021): A research community perspective. *Natural Hazards and Earth System Sciences*, *22*(9), 3041–3061. <https://doi.org/10.5194/nhess-22-3041-2022>
- Farinotti, D., Huss, M., Furst, J. J., Landmann, J., Machguth, H., Maussion, F., & Pandit, A. (2019). A consensus estimate for the ice thickness distribution of all glaciers on Earth. *Nature Geoscience*, *12*(3), 168–173. <https://doi.org/10.1038/s41561-019-0300-3>
- Farinotti, D., Immerzeel, W. W., de Kok, R. J., Quincey, D. J., & Dehecq, A. (2020). Manifestations and mechanisms of the Karakoram glacier anomaly. *Nature Geoscience*, *13*, 8–16. <https://doi.org/10.1038/s41561-019-0513-5>
- Forsythe, N., Fowler, H. J., Li, X.-F., Blenkinsop, S., & Pritchard, D. (2017). Karakoram temperature and glacial melt driven by regional atmospheric circulation variability. *Nature Climate Change*, *7*, 664–670. <https://doi.org/10.1038/nclimate3361>

- Fowler, H. J., Lenderink, G., Prein, A. F., Westra, S., Allan, R. P., Ban, N., Barbero, R., Berg, P., Blenkinsop, S., Do, H. X., Guerrero, S., Haertler, J. O., Kendon, E. J., Lewis, E., Schaer, C., Sharma, A., Villarini, G., Wasko, C., & Zhang, X. (2021). Anthropogenic intensification of short-duration rainfall extremes. *Nature Reviews Earth and Environment*, 2, 107–122. <https://doi.org/10.1038/s43017-020-00128-6>
- Frey, H., Machguth, H., Huss, M., Huggel, C., Bajracharya, S., Bolch, T., Kulkarni, A., Linsbauer, A., Salzmann, N., & Stoffel, M. (2014). Estimating the volume of glaciers in the Himalayan-Karakoram region using different methods. *The Cryosphere*, 8, 2313–2333. <https://doi.org/10.5194/tc-8-2313-2014>
- Friedl, P., Seehaus, T., & Braun, M. (2021). Global time series and temporal mosaics of glacier surface velocities derived from Sentinel-1 data. *Earth System Science Data*, 13(10), 4653–4675. <https://doi.org/10.5194/essd-13-4653-2021>
- Fugger, S., Fyffe, C. L., Fatichi, S., Miles, E., McCarthy, M., Shaw, T. E., Ding, B., Yang, W., Wagnon, P., Immerzeel, W., Liu, Q., & Pellicciotti, F. (2022). Understanding monsoon controls on the energy and mass balance of glaciers in the central and eastern Himalaya. *The Cryosphere*, 16, 1631–1652. <https://doi.org/10.5194/tc-16-1631-2022>
- Fujita, K., Inoue, H., Izumi, T., Yamaguchi, S., Sadakane, A., Sunako, S., Nishimura, K., Immerzeel, W. W., Shea, J. M., Kayastha, R. B., Sawagaki, T., Breashears, D. F., Yagi, H., & Sakai, A. (2017). Anomalous winter-snow-amplified earthquake-induced disaster of the 2015 Langtang avalanche in Nepal. *Natural Hazards and Earth System Sciences*, 17(5), 749–764. <https://doi.org/10.5194/nhess-17-749-2017>
- Fujita, K., Kadota, T., Rana, B., Kayastha, R. B., & Ageta, Y. (2001). Shrinkage of glacier AX010 in Shorong Region, Nepal in 1990s. *Bulletin of Geological Research*, 18, 51–54.
- Furian, W., Loibl, D., & Schneider, C. (2021). Future glacial lakes in High Mountain Asia: An inventory and assessment of hazard potential from surrounding slopes. *Journal of Glaciology*, 67(264), 653–670. <https://doi.org/10.1017/jog.2021.18>
- Furian, W., Maussion, F., & Schneider, C. (2022). Projected 21st-century glacial lake evolution in High Mountain Asia. *Frontiers in Earth Science*, 10(March), 1–21. <https://doi.org/10.3389/feart.2022.821798>
- Gao, H., Wang, J., Yang, Y., Pan, X., Ding, Y., & Duan, Z. (2021). Permafrost hydrology of the Qinghai-Tibet Plateau: A review of processes and modeling. *Frontiers in Earth Science*, 8. <https://doi.org/10.3389/feart.2020.576838>
- Gao, Y., Chen, F., Lettenmaier, D. P., Xu, J., Xiao, L., & Li, X. (2018). Does elevation-dependent warming hold true above 5000 m elevation? Lessons from the Tibetan Plateau. *Npj Climate and Atmospheric Science*, 1(1), Article 19. <https://doi.org/10.1038/s41612-018-0030-z>
- Gao, Y., Liu, S., Qi, M., Xie, F., Wu, K., & Zhu, Y. (2021). Glacier-related hazards along the international Karakoram highway: Status and future perspectives. *Frontiers in Earth Science*, 9, Article 611501. <https://doi.org/10.3389/feart.2021.611501>
- Gardelle, J., Berthier, E., & Arnaud, Y. (2012). Slight mass gain of Karakoram glaciers in the early twenty-first century. *Nature Geoscience*, 5(5), 322–325. <https://doi.org/10.1038/ngeo1450>
- Gardelle, J., Berthier, E., Arnaud, Y., & Kääh, A. (2013). Region-wide glacier mass balances over the Pamir-Karakoram-Himalaya during 1999–2011. *The Cryosphere*, 7(4), 1263–1286. <https://doi.org/10.5194/tc-7-1263-2013>
- Gardner, A. S., Fahnestock, M. A., & Scambos, T. A. (2022). MEaSUREs ITS_LIVE regional glacier and ice sheet surface velocities, Version 1 [Data Set]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. <https://doi.org/10.5067/6II6VW8LLWJ7>
- Gascoin, S. (2021). Snowmelt and snow sublimation in the Indus Basin. *Water*, 13(19), Article 2621. <https://doi.org/10.3390/w13192621>
- Gautam, C. K., & Mukherjee, B. P. (1992). Synthesis of glaciological studies on Tipra Bank Glacier Bhyundar Ganga Basin, district Chamoli. Uttar Pradesh (FS 1980–1988) Geological Survey of India, Northern Region, Lucknow.
- Geological Survey of India. (1991). *Annual general report, Part 8. Volume 124*. Ministry of Mines, Government of India.
- Geological Survey of India. (1992). *Annual general report. Part 8. Volume 125*. Ministry of Mines, Government of India.
- Geological Survey of India. (2001). *Glaciology of Indian Himalaya*. Special Publication no 63. Ministry of Mines, Government of India.
- Geological Survey of India. (2011). *Annual general report, Part 8. Volume 144*. Ministry of Mines, Government of India.
- Giese, A., Arcone, S., Hawley, R., Lewis, G., & Wagnon, P. (2021). Detecting supraglacial debris thickness with GPR under suboptimal conditions. *Journal of Glaciology*, 67, 1108–1120. <https://doi.org/10.1017/jog.2021.59>
- Gilbert, A., Sinisalo, A., Gurung, T. R., Fujita, K., Maharjan, S. B., Sherpa, T. C., & Fukuda, T. (2020). The influence of water percolation through crevasses on the thermal regime of a Himalayan mountain glacier. *The Cryosphere*, 14, 1273–1288. <https://doi.org/10.5194/tc-14-1273-2020>
- Girona-Mata, M., Miles, E. S., Ragettli, S., & Pellicciotti, F. (2019). High-resolution snowline delineation from Landsat imagery to infer snow cover controls in a Himalayan catchment. *Water Resources Research*, 55(8), 6754–6772. <https://doi.org/10.1029/2019WR024935>

- GLIMS & NSIDC (2005/2018). Global land ice measurements from space glacier database. International GLIMS community and the National Snow and Ice Data Center. Boulder, USA. <https://doi.org/10.7265/N5V98602>
- Gruber, S. (2012). Derivation and analysis of a high-resolution estimate of global permafrost zonation. *The Cryosphere*, 6, 221–233. <https://doi.org/10.5194/tc-6-221-2012>
- Gruber, S., Fleiner, R., Guegan, E., Panday, P., Schmid, M. O., Stumm, D., Wester, P., Zhang, Y., & Zhao, L. (2017). Review article: Inferring permafrost and permafrost thaw in the mountains of the Hindu Kush Himalaya region. *The Cryosphere*, 11(1), 81–99. <https://doi.org/10.5194/tc-11-81-2017>
- Guillet, G., King, O., Lv, M., Ghuffar, S., Benn, D., Quincey, D., & Bolch, T. (2022). A regionally resolved inventory of High Mountain Asia surge-type glaciers, derived from a multi-factor remote sensing approach. *The Cryosphere*, 16(2), 603–623. <https://doi.org/10.5194/tc-16-603-2022>
- Guo, C. K. (2017). *The change of glacial lakes and its influence in Everest region* [Unpublished master's thesis]. Hunan University of Science and Technology, China.
- Guo, S., Chen, R., Han, C., Liu, J., Wang, X., & Liu, G. (2021). Five-year analysis of evaporesublimation characteristics and its role on surface energy balance SEB on a midlatitude continental glacier. *Earth and Space Science*, 8(12), Article e2021EA001901. <https://doi.org/10.1029/2021EA001901>
- Guo, S., Chen, R., & Li, H. (2022). Surface sublimation/evaporation and condensation/deposition and their links to westerlies during 2020 on the August-One Glacier, the semi-arid Qilian Mountains of Northeast Tibetan Plateau. *Journal of Geophysical Research: Atmospheres*, 127(11), Article e2022JD036494. <https://doi.org/10.1029/2022JD036494>
- Haerberli, W., Schaub, Y., & Huggel, C. (2017). Increasing risks related to landslides from degrading permafrost into new lakes in de-glaciating mountain ranges. *Geomorphology*, 293(B), 405–417. <https://doi.org/10.1016/j.geomorph.2016.02.009>
- Hall, D. K., Riggs, G. A., Foster, J. L., and Kumar, S. V.: Development and evaluation of a cloud-gap-filled MODIS daily snow-cover product, *Remote Sens. Environ.*, 114, 496–503, <https://doi.org/10.1016/j.rse.2009.10.007>, 2010
- Haq, M. A., & Baral, P. (2019). Study of permafrost distribution in Sikkim Himalayas using Sentinel-2 satellite images and logistic regression modelling. *Geomorphology*, 333, 123–136. <https://doi.org/10.1016/j.geomorph.2019.02.024>
- Hassan, J., Chen, X., Muhammad, S., & Bazai, N. A. (2021). Rock glacier inventory, permafrost probability distribution modeling and associated hazards in the Hunza River Basin, Western Karakoram, Pakistan. *Science of the Total Environment*, 782, Article 146833. <https://doi.org/10.1016/j.scitotenv.2021.146833>
- Herreid, S., & Pellicciotti, F. (2020). The state of rock debris covering Earth's glaciers. *Nature Geoscience*, 13, 621–627. <https://doi.org/10.1038/s41561-020-0615-0>
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., ...Thépaut, J.-N. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146, 1999–2049. <https://doi.org/10.1002/qj.3803>
- Hjort, J., Streletskiy, D., Doré, G., Wu, Q., Bjella, K., & Luoto, M. (2022). Impacts of permafrost degradation on infrastructure. *Nature Reviews Earth and Environment*, 3(1), 24–38. <https://doi.org/10.1038/s43017-021-00247-8>
- Hock, R., Rasul, G., Adler, C., Cáceres, B., Gruber, S., Hirabayashi, Y., Jackson, M., Kääh, A., Kang, S., Kutuzov, S., Milner, A., Molau, U., Morin, S., Orlove, B., & Steltzer, H. (2019). High mountain areas. In 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, & N. M. Weyer (Eds.), *IPCC special report on the ocean and cryosphere in a changing climate* (1st ed., pp. 131–202). Cambridge University Press. <https://doi.org/10.1017/9781009157964>
- Hopping, K. A., Chignell, S. M., & Lambin, E. F. (2018). The demise of caterpillar fungus in the Himalayan region due to climate change and overharvesting. *Proceedings of the National Academy of Sciences*, 115(45), 11489–11494. <https://doi.org/10.1073/pnas.1811591115>
- Huggel, C., Muccione, V., Carey, M., James, R., Jurt, C., & Mechler, R. (2019). *Loss and damage in the mountain cryosphere. Regional Environmental Change*, 19, 1387–1399. <https://doi.org/10.1007/s10113-018-1385-8>
- Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L., Farinotti, D., Huss, M., Dussailant, I., Brun, F., & Kääh, A. (2021). Accelerated global glacier mass loss in the early twenty-first century. *Nature*, 592(7856), 726–731. <https://doi.org/10.1038/s41586-021-03436-z>
- Huss, M., Bookhagen, B., Huggel, C., Jacobsen, D., Bradley, R. S., Clague, J. J., Vuille, M., Buytaert, W., Cayan, D. R., Greenwood, G., Mark, B. G., Milner, A. M., Weingartner, R., & Winder, M. (2017). Toward mountains without permanent snow and ice. *Earth's Future*, 5(5), 418–435. <https://doi.org/10.1002/2016EF000514>
- IPCC. (2021). *Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the Intergovernmental Panel on Climate Change* (V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou [Eds.]). Cambridge University Press. In press. doi:10.1017/9781009157896

- IPCC. (2022a). *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. Lösschke, V. Möller, A. Okem, & B. Rama [Eds.]). Cambridge University Press. doi:10.1017/9781009325844
- IPCC. (2022b). Annex II: Glossary (V. Möller, R. van Diemen, J. B. R. Matthews, C. Méndez, S. Semenov, J. S. Fuglestedt, & A. Reisinger [Eds.]). In H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Lösschke, 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* (pp. 2897–2930). Cambridge University Press. doi:10.1017/9781009325844.029
- Jakob, L., Gourmelen, N., Ewart, M., & Plummer, S. (2021). Spatially and temporally resolved ice loss in High Mountain Asia and the Gulf of Alaska observed by CryoSat-2 swath altimetry between 2010 and 2019. *The Cryosphere*, 15(4), 1845–1862. <https://doi.org/10.5194/tc-15-1845-2021>
- Jia, G., Shevliakova, E., Artaxo, P., De Noblet-Ducoudré, N., Houghton, R., House, J., Kitajima, K., Lennard, C., Popp, A., Sirin, A., Sukumar, R., & Verchot, L. (2019). Land–climate interactions. In P. R. Shukla, J. Skea, E. Calvo Buendía, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, & J. Malley (Eds.), *Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. <https://doi.org/10.1017/9781009157988.004>
- Jin, H., Huang, Y., Bense, V. F., Ma, Q., Marchenko, S. S., Shepelev, V. V., Hu, Y., Liang, S., Spektor, V. V., Jin, X., Li, X., & Li, X. (2022). Permafrost degradation and its hydrogeological impacts. *Water*, 14(3). <https://doi.org/10.3390/w14030372>
- Jin, X. Y., Jin, H. J., Iwahana, G., Marchenko, S. S., Luo, D. L., Li, X. Y., & Liang, S. H. (2021). Impacts of climate-induced permafrost degradation on vegetation: A review. *Advances in Climate Change Research*, 12(1), 29–47. <https://doi.org/10.1016/j.accre.2020.07.002>
- Jones, D. B., Harrison, S., Anderson, K., Selley, H. L., Wood, J. L., & Betts, R. A. (2018). The distribution and hydrological significance of rock glaciers in the Nepalese Himalaya. *Global and Planetary Change*, 160, 123–142. <https://doi.org/10.1016/j.gloplacha.2017.11.005>
- Jones, D. B., Harrison, S., Anderson, K., & Whalley, W. B. (2019). Rock glaciers and mountain hydrology: A review. *Earth-Science Reviews*, 193, 163–190. <https://doi.org/10.1016/j.earscirev.2019.04.001>
- Kääb, A., Jacquemart, M., Gilbert, A., Leinss, S., Girod, L., Huggel, C., Falaschi, D., Ugalde, F., Petrakov, D., Chernomorets, S., Dokukin, M., Paul, F., Gascoin, S., Berthier, E., & Kargel, J. (2021). Sudden large-volume detachments of low-angle mountain glaciers: More frequent than thought. *The Cryosphere*, 15, 1751–1785. <https://doi.org/10.5194/tc-2020-243>
- Kalvoda, J., & Emmer, A. (2021). Mass wasting and erosion in different morphoclimatic zones of the Makalu Barun region, Nepal Himalaya. *Geografiska Annaler, Series A: Physical Geography*, 103(4), 368–396. <https://doi.org/10.1080/04353676.2021.2000816>
- Kaul, M. K. (1986). Mass balance of Liddar glaciers. *Transactions of the Institute of Indian Geographers*, 8, 95–112.
- Khadka, A., Wagnon, P., Brun, F., Shrestha, D., Lejeune, Y., & Arnaud, Y. (2022). Evaluation of ERA5-Land and HARv2 reanalysis data at high elevation in the Upper Dudh Koshi Basin (Everest region, Nepal). *Journal of Applied Meteorology and Climatology*, 61, 931–954. <https://doi.org/10.1175/JAMC-D-21-0091.1>
- Khadka, N., Chen, X., Nie, Y., Thakuri, S., Zheng, G., & Zhang, G. (2021). Evaluation of glacial lake outburst flood susceptibility using multi-criteria assessment framework in Mahalangur Himalaya. *Frontiers in Earth Science*, 8. <https://www.frontiersin.org/article/10.3389/feart.2020.601288>
- Khan, M. A. R., Singh, S., Pandey, P., Bhardwaj, A., Ali, S. N., Chaturvedi, V., & Ray, P. K. C. (2021). Modelling permafrost distribution in western Himalaya using remote sensing and field observations. *Remote Sensing*, 13(21). <https://doi.org/10.3390/rs13214403>
- Khanal, S., Lutz, A. F., Kraaijenbrink, P. D. A., van den Hurk, B., Yao, T., & Immerzeel, W. W. (2021). Variable 21st century climate change response for rivers in High Mountain Asia at seasonal to decadal time scales. *Water Resources Research*, 57(5), Article e2020WR029266. <https://doi.org/10.1029/2020WR029266>
- King, O., Bhattacharya, A., Bhambri, R., & Bolch, T. (2019). Glacial lakes exacerbate Himalayan glacier mass loss. *Science Reports*, 9, Article 18145. <https://doi.org/10.1038/s41598-019-53733-x>
- King, O., Bhattacharya, A., & Bolch, T. (2021). The presence and influence of glacier surging around the Geladandong ice caps, North East Tibetan Plateau. *Advances in Climate Change Research*, 12(3), 299–312. <https://doi.org/10.1016/j.accre.2021.05.001>

- Kirkham, J. D., Koch, I., Saloranta, T. M., Litt, M., Stigter, E. E., Moen, K., Thapa, A., Melvold, K., & Immerzeel, W. W. (2019). Near real-time measurement of snow water equivalent in the Nepal Himalayas. *Frontiers in Earth Science*, 7. <https://doi.org/10.3389/feart.2019.00177>
- Kneib, M., Miles, E. S., Jola, S., Buri, P., Herreid, S., Bhattacharya, A., Watson, C. S., Bolch, T., Quincey, D., & Pellicciotti, F. (2021). Mapping ice cliffs on debris-covered glaciers using multispectral satellite images. *Remote Sensing of Environment*, 253, Article 112201. <https://doi.org/10.1016/j.rse.2020.112201>
- Koul, M. N., & Ganjoo, R. K. (2010). Impact of inter- and intra-annual variation in weather parameters on mass balance and equilibrium line altitude of Naradu Glacier (Himachal Pradesh), NW Himalaya, India. *Climatic Change*, 99, 119–139. <https://doi.org/10.1007/s10584-009-9660-9>
- Kraaijenbrink, P. D. A., Bierkens, M. F. P., Lutz, A. F., & Immerzeel, W. W. (2017). Impact of a global temperature rise of 1.5 degrees celsius on Asia's glaciers. *Nature*, 549(7671), 257–260. <https://doi.org/10.1038/nature23878>
- Kraaijenbrink, P. D. A., Stigter, E. E., Yao, T., & Immerzeel, W. W. (2021). Climate change decisive for Asia's snow meltwater supply. *Nature Climate Change*, 11(7), 591–597. <https://doi.org/10.1038/s41558-021-01074-x>
- Krishnan, R., Shrestha, A. B., Ren, G., Rajbhandari, R., Saeed, S., Sanjay, J., Syed, A., Vellore, R., Xu, Y., You, Q., & Ren, Y. (2019). Unravelling climate change in the Hindu Kush Himalaya: Rapid warming in the mountains and increasing extremes. In P. Wester, A. Mishra, A. Mukherji, & A. B. Shrestha A. (Eds.), *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability and people* (pp. 57–97). Springer Nature Switzerland AG. <https://doi.org/10.1007/978-3-319-92288-1>
- Kumar, P., Saharwardi, M. S., Banerjee, A., Azam, Md. F., Dubey, A. K., & Murtugudde, R. (2019). Snowfall variability dictates glacier mass balance variability in Himalaya-Karakoram. *Science Reports*, 9, Article 18192. <https://doi.org/10.1038/s41598-019-54553-9>
- Laha, S., Kumari, R., Singh, S., Mishra, A., Sharma, T., Banerjee, A., . . . Shankar, R. (2017). Evaluating the contribution of avalanching to the mass balance of Himalayan glaciers. *Annals of Glaciology*, 58(75pt2), 110–118. <https://doi.org/10.1017/aog.2017.27>
- Lalande, M., Ménégot, M., Krinner, G., Naegeli, K., & Wunderle, S. (2021). Climate change in the High Mountain Asia in CMIP6. *Earth System Dynamics*, 12(4), 1061–1098. <https://doi.org/10.5194/esd-12-1061-2021>
- Larue, F., Royer, A., De Seve, D., Langlois, A., Roy, A., & Brucker, L. (2017). Validation of GlobSnow-2 snow water equivalent over Eastern Canada. *Remote Sensing of Environment*, 194, 264–277. <http://dx.doi.org/10.1016/j.rse.2017.03.027>
- Li, D., Lu, X., Overeem, I., Walling, D. E., Syvitski, J., Kettner, A. J., Bookhagen, B., Zhou, Y., & Zhang, T. (2021). Exceptional increases in fluvial sediment fluxes in a warmer and wetter High Mountain Asia. *Science*, 374(6567), 599–603. <https://doi.org/10.1126/science.abi9649>
- Li, G., Li, Y., Lin, H., Ye, Q., & Jiang, L. (2021). Two periods of geodetic glacier mass balance at Eastern Nyainqentanglha derived from multi-platform bistatic SAR interferometry. *International Journal of Applied Earth Observation and Geoinformation*, 104, Article 102541. <https://doi.org/10.1016/j.jag.2021.102541>
- Li, W., Wang, W., Gao, X., Wang, X., & Wang, R. (2022). Inventory and spatiotemporal patterns of glacial lakes in the HKH-TMHA region from 1990 to 2020. *Remote Sensing*, 14(6), Article 1351. <https://doi.org/10.3390/rs14061351>
- Li, Y., Chen, Y., Wang, F., He, Y., & Li, Z. (2020). Evaluation and projection of snowfall changes in High Mountain Asia based on NASA's NEX-GDDP high-resolution daily downscaled dataset. *Environmental Research Letters*, 15(10), Article 104040. <https://doi.org/10.1088/1748-9326/aba926>
- Lievens, H., Demuzere, M., Marshall, H.-P., Reichle, R. H., Brucker, L., Brangers, I., de Rosnay, P., Dumont, M., Giroto, M., Immerzeel, W. W., Jonas, T., Kim, E. J., Koch, I., Marty, C., Saloranta, T., Schober, J., & de Lannoy, G. J. M. (2019). Snow depth variability in the Northern Hemisphere mountains observed from space. *Nature Communications*, 10(1), 1–12. <https://doi.org/10.1038/s41467-019-12566-y>
- Linsbauer, A., Frey, H., Haeberli, W., Machguth, H., Azam, M. F., & Allen, S. (2015). Modelling glacier-bed overdeepenings and possible future lakes for the glaciers in the Himalaya-Karakoram region. *Annals of Glaciology*, 57(71), 119–130. <https://doi.org/10.3189/2016AoG71A627>
- Litt, M., Shea, J., Wagnon, P., Steiner, J., Koch, I., Stigter, E., & Immerzeel, W. (2019). Glacier ablation and temperature indexed melt models in the Nepalese Himalaya. *Science Reports*, 9, Article 5264. <https://doi.org/10.1038/s41598-019-41657-5>
- Liu, M., Chen, N., Zhang, Y., & Deng, M. (2020). Glacial lake inventory and lake outburst flood/debris flow hazard assessment after the Gorkha earthquake in the Bhoté Koshi Basin. *Water*, 12(2), Article 464. <https://doi.org/10.3390/w12020464>
- Liu, S., Xie, Z., Song, G., Ma, L., Ageta, Y. (1996). Mass balance of Kangwure (flat-top) Glacier on the north side of Mt. Xixiabangma, China. *Bulletin of Glacier Research* 14, 37–43.

- Liu, Y., Fang, Y., & Margulis, S. A. (2021). Spatiotemporal distribution of seasonal snow water equivalent in High Mountain Asia from an 18-year Landsat–MODIS era snow reanalysis dataset. *The Cryosphere*, *15*(11), 5261–5280. <https://doi.org/10.5194/tc-15-5261-2021>
- Livingstone, S. J., Li, Y., Rutishauser, A., Sanderson, R. J., Winter, K., Mikucki, J. A., Bjornsson, H., Bowling, J. S., Chu, W., Dow, C. F., Fricker, H. A., McMillan, M., Ng, F. S. L., Ross, N., Siegert, M. J., Seigfried, M., & Sole, A. J. (2022). Subglacial lakes and their changing role in a warming climate. *Nature Reviews Earth and Environment*, *3*, 106–124. <https://doi.org/10.1038/s43017-021-00246-9>
- Lu, Q., Zhao, D., & Wu, S. (2017). Simulated responses of permafrost distribution to climate change on the Qinghai-Tibet Plateau. *Scientific Reports*, *7*, Article 3845. <https://doi.org/10.1038/s41598-017-04140-7>
- Lutz, A. F., Immerzeel, W. W., Shrestha, A. B., & Bierkens, M. F. P. (2014). Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. *Nature Climate Change*, *4*(7), 587–592. <https://doi.org/10.1038/nclimate2237>
- Lützow, Natalie, & Veh, Georg. (2022). Glacier Lake Outburst Flood Database V3.0 (3.0) [Data set]. Zenodo. <https://doi.org/10.5281/zenodo.7330345>
- Madhura, R. K., Krishnan, R., Revadekar, J. V., Mujumdar, M., & Goswami, B. N. (2015). Changes in western disturbances over the Western Himalayas in a warming environment. *Climate Dynamics*, *44*(3), 1157–1168. <https://doi.org/10.1007/s00382-014-2166-9>
- Maharjan, S. B., Mool, P. K., Lizong, W., Xiao, G., Shrestha, F., Shrestha, R. B., Khanal, N. R., Bajracharya, S. R., Joshi, S., Shai, S., & Baral, P. (2018). *The status of glacial lakes in the Hindu Kush Himalaya*. ICIMOD Research Report 2018/1. ICIMOD. <https://doi.org/10.53055/ICIMOD.742>
- Mandal, A., Angchuk, T., Azam, M. F., Ramanathan, A., Wagnon, P., Soheb, M., & Singh, C. (2022). 11-year record of wintertime snow surface energy balance and sublimation at 4863 m a.s.l. on Chhota Shigri Glacier moraine (western Himalaya, India). *The Cryosphere*, *16*, 3775–3799. <https://doi.org/10.5194/tc-16-3775-2022>
- Mandal, A., Ramanathan, A., Azam, M. F., Angchuk, T., Soheb, M., Kumar, M., Pottakkal, J. G., Vatsal, S., Mishra, S., & Singh, V. B. (2020). Understanding the interrelationships among mass balance, meteorology, discharge and surface velocity on Chhota Shigri Glacier over 2002–2019 using in situ measurements. *Journal of Glaciology*, *66*(259). <https://doi.org/10.1017/jog.2020.42>
- Marzeion, B., Hock, R., Anderson, B., Bliss, A., Champollion, N., Fujita, K., Huss, M., Immerzeel, W. W., Kraaijenbrink, P., Malles, J.-H., Maussion, F., Radic, V., Rounce, D. R., Sakai, A., Shannon, S., van de Wal, R., & Zekollari, H. (2020). Partitioning the uncertainty of ensemble projections of global glacier mass change. *Earth's Future*, *8*, Article e2019EF001470. <https://doi.org/10.1029/2019EF001470>
- Matthews, T., Perry, L. B., Koch, I., Aryal, D., Khadka, A., Shrestha, D., Abernathy, K., Elmore, A. C., Seimon, A., Tait, A., Elvin, S., Tuladhar, S., Baidya, S. K., Potocki, M., Birkel, S. D., Kang, S., Sherpa, T. C., Gajurel, A., & Mayewski, P. A. (2020). Going to extremes: Installing the world's highest weather stations on Mount Everest. *Bulletin of the American Meteorological Society*, *101*, E1870–E1890. <https://doi.org/10.1175/BAMS-D-19-0198.1>
- Matthews, T., Perry, L. B., Lane, T. P., Elmore, A. C., Khadka, A., Aryal, D., Shrestha, D., Tuladhar, S., Baidya, S. K., Gajurel, A., Potocki, M., & Mayewski, P. A. (2020). Into thick(er) air? Oxygen availability at humans' physiological frontier on Mount Everest. *Science*, *23*(12), Article 101718. <https://doi.org/10.1016/j.isci.2020.101718>
- Maurer, J. M., Rupper, S. B., & Schaefer, J. M. (2016). Quantifying ice loss in the eastern Himalayas since 1974 using declassified spy satellite imagery. *The Cryosphere*, *10*(5), 2203–2215. <https://doi.org/10.5194/tc-10-2203-2016>
- Maurer, J. M., Schaefer, J. M., Rupper, S., & Corley, A. (2019). Acceleration of ice loss across the Himalayas over the past 40 years. *Science Advances*, *5*(6), Article eaav7266. <https://doi.org/10.1126/sciadv.aav7266>
- McCarthy, M., Miles, E., Kneib, M., Buri, P., Fugger, S., & Pellicciotti, F. (2022). Supraglacial debris thickness and supply rate in High-Mountain Asia. *Communications Earth and Environment*, *3*, 269. <https://doi.org/10.1038/s43247-022-00588-2>
- McCarthy, M., Pritchard, H. D., Willis, I., and King, E. (2017). Ground-penetrating radar measurements of debris thickness on Lirung Glacier, Nepal. *Journal of Glaciology*, *63*(239), 543–555. <https://doi.org/10.1017/jog.2017.18>
- Miles, E., McCarthy, M., Dehecq, A., Kneib, S., Fugger, S., & Pellicciotti, F. (2021). Health and sustainability of glaciers in High Mountain Asia. *Nature Communications*, *12*, Article 2868. <https://doi.org/10.1038/s41467-021-23073-4>
- Miles, E., Willis, I., Arnold, N., Steiner, J., & Pellicciotti, F. (2017). Spatial, seasonal and interannual variability of supraglacial ponds in the Langtang Valley of Nepal, 1999–2013. *Journal of Glaciology*, *63*(237), 88–105. <https://doi.org/10.1017/jog.2016.120>
- Miles, E. S., Willis, I., Buri, P., Steiner, J. F., Arnold, N. S., & Pellicciotti, F. (2018). Surface pond energy absorption across four Himalayan glaciers accounts for 1/8 of total catchment ice loss. *Geophysical Research Letters*, *45*(19), 10464–10473. <https://doi.org/10.1029/2018GL079678>

- Millan, R., Mouginit, J., Rabatel, A., & Morlighem, M. (2022). Ice velocity and thickness of the world's glaciers. *Nature Geoscience*, 15(2), 124–129. <https://doi.org/10.1038/s41561-021-00885-z>
- Mir, R. A., Jain, S. K., Jain, S. K., Thayyen, R. J., & Saraf, A. K. (2017). Assessment of recent glacier changes and its controlling factors from 1976 to 2011 in Baspa Basin, Western Himalaya. *Arctic, Antarctic, and Alpine Research*, 49(4), 621–647. <https://doi.org/10.1657/AAAR0015-070>
- Mishra, R., Kumar, A., & Singh, D. (2014). Long term monitoring of mass balance of Hamtah Glacier, Lahaul and Spiti district, Himachal Pradesh. *Geological Survey of India*, 147(8), 230–231.
- Mott, R., Schlogl, S., Dirks, L., & Lehning, M. (2017). Impact of extreme land surface heterogeneity on micrometeorology over spring snow cover. *Journal of Hydrometeorology*, 18(10), 2705–2722. <https://doi.org/10.1175/JHM-D-17-0074.1>
- Mott, R., Vionnet, V., & Grünewald, T. (2018). The seasonal snow cover dynamics: Review on wind-driven coupling processes. *Frontiers in Earth Science*, 6. <https://doi.org/10.3389/feart.2018.00197>
- Mu, C., Li, L., Wu, X., Zhang, F., Jia, L., Zhao, Q., & Zhang, T. (2018). Greenhouse gas released from the deep permafrost in the northern Qinghai-Tibetan Plateau. *Scientific Reports*, 8, Article 4205. <https://doi.org/10.1038/s41598-018-22530-3>
- Muhammad, S., Li, J., Steiner, J. F., Shrestha, F., Shah, G. M., Berthier, E., Guo, L., Wu, L., & Tian, L. (2021). A holistic view of Shisper Glacier surge and outburst floods: From physical processes to downstream impacts. *Geomatics, Natural Hazards and Risk*, 12(1), 2755–2775. <https://doi.org/10.1080/19475705.2021.1975833>
- Muhammad, S. and Thapa, A.: An improved Terra–Aqua MODIS snow cover and Randolph Glacier Inventory 6.0 combined product (MOYDGL06*) for high-mountain Asia between 2002 and 2018, *Earth Syst. Sci. Data*, 12, 345–356, <https://doi.org/10.5194/essd-12-345-2020>, 2020.
- Muhammad, S., Tian, L., Ali, S., Latif, Y., Wazir, M. A., Goheer, M. A., Saifullah, M., Hussain, I., & Shiyin, L. (2020). Thin debris layers do not enhance melting of the Karakoram glaciers. *Science of The Total Environment*, 746, Article 141119. <https://doi.org/10.1016/j.scitotenv.2020.141119>
- Muhammad, S., Tian, L., & Nüsser, M. (2019). No significant mass loss in the glaciers of Astore Basin (North-Western Himalaya), between 1999 and 2016, *Journal of Glaciology*, 65(250), 270–278. <https://doi.org/10.1017/jog.2019.5>
- Muñoz Sabater, J. (2021). ERA5-Land hourly data from 1950 to 1980. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). 10.24381/cds.e2161bac (accessed November 12, 2022).
- Mölg, N., Bolch, T., Rastner, P., Strozzi, T., & Paul, F. (2018) A consistent glacier inventory for the Karakoram and Pamir regions derived from Landsat data: Distribution of debris cover and mapping challenges. *Earth System Science Data Discussions*, 1–44. <https://doi.org/10.5194/essd-2018-35>
- Naegeli, K., Franke, J., Neuhaus, C., Rietze, N., Stengel, M., Wu, X., & Wunderle, S. (2022). Revealing four decades of snow cover dynamics in the Hindu Kush Himalaya. *Scientific Reports*, 12(1), Article 13443. <https://doi.org/10.1038/s41598-022-17575-4>
- Nepal, S., Khatiwada, K. R., Pradhananga, S., Kralisch, S., Samyn, D., Bromand, M. T., Jamal, N., Dildar, M., Durrani, F., Rassouly, F., Azizi, F., Salehi, W., Malikzooi, R., Krause, P., Koirala, S., & Chevallier, P. (2021). Future snow projections in a small basin of the Western Himalaya. *Science of the Total Environment*, 795, Article 148587. <https://doi.org/10.1016/j.scitotenv.2021.148587>
- Ni, J., Wu, T., Zhu, X., Hu, G., Zou, D., Wu, X., Li, R., Xie, C., Qiao, Y., Pang, Q., Hao, J., & Yang, C. (2021). Simulation of the present and future projection of permafrost on the Qinghai-Tibet Plateau with statistical and machine learning models. *Journal of Geophysical Research: Atmospheres*, 126(2), Article e2020JD033402. <https://doi.org/10.1029/2020JD033402>
- Nicholson, L. & Benn, D. I. (2006). Calculating ice melt beneath a debris layer using meteorological data. *Journal of Glaciology*, 52(178), 463–470. <https://doi.org/10.3189/172756506781828584>
- Nicholson, L. & Mertes, J. (2017). Thickness estimation of supraglacial debris above ice cliff exposures using a high-resolution digital surface model derived from terrestrial photography. *Journal of Glaciology*, 63(242), 989–998. <https://doi.org/10.1017/jog.2017.68>
- Nie, Y., Liu, Q., & Liu, S. (2013). Glacial lake expansion in the central Himalayas by Landsat images, 1990–2010. *PLoS ONE*, 8(12), Article e83973. <https://doi.org/10.1371/journal.pone.0083973>
- Nie, Y., Sheng, Y., Liu, Q., Liu, L., Liu, S., Zhang, Y., & Song, C. (2017). A regional-scale assessment of Himalayan glacial lake changes using satellite observations from 1990 to 2015. *Remote Sensing of Environment*, 189, 1–13. <https://doi.org/10.1016/j.rse.2016.11.008>
- NISAR. (2018). *NASA-ISRO SAR (NISAR) mission science users' handbook*. NASA Jet Propulsion Laboratory.
- Norris, J., Carvalho, L. M. V., Jones, C., & Cannon, F. (2019). Deciphering the contrasting climatic trends between the central Himalaya and Karakoram with 36 years of WRF simulations. *Climate Dynamics*, 52, 159–180. <https://doi.org/10.1007/s00382-018-4133-3>

- Notarnicola, C. (2020). Hotspots of snow cover changes in global mountain regions over 2000–2018. *Remote Sensing of Environment*, 243, Article 111781. <https://doi.org/10.1016/j.rse.2020.111781>
- Notarnicola, C. (2022). Overall negative trends for snow cover extent and duration in global mountain regions over 1982–2020. *Scientific Reports*, 12(1), Article 13731. <https://doi.org/10.1038/s41598-022-16743-w>
- Nuth, C., & Kääb, A. (2011). Co-registration and bias corrections of satellite elevation data sets for quantifying glacier thickness change. *The Cryosphere*, 5, 271–290. <https://doi.org/10.5194/tc-5-271-2011>
- Obu, J., Westermann, S., Bartsch, A., Berdnikov, N., Christiansen, H. H., Dashtseren, A., Delaloye, R., Elberling, B., Etzelmuller, B., Kholodov, A., Khomutov, A., Kaab, A., Leibman, M. O., Lewkovic, A. G., Panda, S. K., Romanovsky, V., Way, R. G., Westergaard-Nielsen, A., Wu, T., ... Zou, D. (2019). Northern Hemisphere permafrost map based on TOP modelling for 2000–2016 at 1 km² scale. *Earth-Science Reviews*, 193, 299–316. <https://doi.org/10.1016/j.earscirev.2019.04.023>
- Oerlemans, J. (2001). *Glaciers and climate change* (1st ed.). Routledge.
- Oliva, M., & Fritz, M. (2018). Permafrost degradation on a warmer Earth: Challenges and perspectives. *Current Opinion in Environmental Science & Health*, 5, 14–18. <https://doi.org/10.1016/j.coesh.2018.03.007>
- Orsolini, Y., Wegmann, M., Dutra, E., Liu, B., Balsamo, G., Yang, K., de Rosnay, P., Zhu, C., Wang, W., Senan, R., & Arduini, G. (2019). Evaluation of snow depth and snow cover over the Tibetan Plateau in global reanalyses using in situ and satellite remote sensing observations. *The Cryosphere*, 13(8), 2221–2239. <https://doi.org/10.5194/tc-13-2221-2019>
- Ortiz, A., Tian, W., Sherpa, T. C., Shrestha, F., Matin, M., Dodhia, R., Ferres, J. M. L., & Sankaran, K. (2022). Mapping glacial lakes using historically guided segmentation models. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 15, 9226–9240. <https://doi.org/10.1109/JSTARS.2022.3215722>
- Østrem, G., & Stanley, A. (1969). *Glacier mass balance measurements: A manual for field and office work*. Canadian Department of Energy, Mines and Resources and The Norwegian Water Resources and Electricity Board.
- Palazzi, E., von Hardenberg, J., & Provenzale, A. (2013). Precipitation in the Hindu-Kush Karakoram Himalaya: Observations and future scenarios. *Journal of Geophysical Research Atmospheres*, 118(1), 85–100. <https://doi.org/10.1029/2012JD018697>
- Panday, P. K., Thibeault, J., Frey, K. E. (2015). Changing temperature and precipitation extremes in the Hindu Kush-Himalayan region: An analysis of CMIP3 and CMIP5 simulations and projections. *International Journal of Climatology*, 35(10), 3058–3077. <https://doi.org/10.1002/joc.4192>
- Pandey, P. (2019). Inventory of rock glaciers in Himachal Himalaya, India using high-resolution Google Earth imagery. *Geomorphology*, 340, 103–115. <https://doi.org/10.1016/j.geomorph.2019.05.001>
- Pant, G. B., Pradeep Kumar, P., Revadekar, J. V., & Singh, N. (2018). *Climate change in the Himalayas*. Springer. <https://doi.org/10.1007/978-3-319-61654-4>
- Pritchard, H. D. (2019). Asia's shrinking glaciers protect large populations from drought stress. *Nature*, 569(7758), 649–654. <https://doi.org/10.1038/s41586-019-1240-1>
- Pritchard, H. D., King, E. C., Goodger, D. J., McCarthy, M., Mayer, C., & Kayastha, R. (2020). Towards Bedmap Himalayas: Development of an airborne ice-sounding radar for glacier thickness surveys in High-Mountain Asia. *Annals of Glaciology*, 61(81), 35–45. <https://doi.org/10.1017/aog.2020.29>
- Pronk, J. B., Bolch, T., King, O., Wouters, B., & Benn, D. I. (2021). Contrasting surface velocities between lake- and land-terminating glaciers in the Himalayan region. *The Cryosphere*, 15(12), 5577–5599. <https://doi.org/10.5194/tc-15-5577-2021>
- Pulliaainen, J., Luojus, K., Derksen, C., Mudryk, L., Lemmetyinen, J., Salminen, M., Ikonen, J., Takala, M., Cohen, J., Smolander, T., & Norberg, J. (2020). Patterns and trends of Northern Hemisphere snow mass from 1980 to 2018. *Nature*, 581(7808), 294–298. <https://doi.org/10.1038/s41586-020-2258-0>
- Racoviteanu, A. E., Arnaud, Y., Williams, M. W., & Manley, W. F. (2015). Spatial patterns in glacier characteristics and area changes from 1962 to 2006 in the Kanchenjunga–Sikkim area, eastern Himalaya. *The Cryosphere*, 9(2), 505–523. <https://doi.org/10.5194/tc-9-505-2015>
- Racoviteanu, A. E., Rittger, K., & Armstrong, R. (2019). An automated approach for estimating snowline altitudes in the Karakoram and eastern Himalaya from remote sensing. *Frontiers in Earth Science*, 7. <https://www.frontiersin.org/articles/10.3389/feart.2019.00220>
- Ragetti, S., Bolch, T., & Pellicciotti, F. (2016). Heterogeneous glacier thinning patterns over the last 40 years in Langtang Himal, Nepal. *The Cryosphere*, 10(5), 2075–2097. <https://doi.org/10.5194/tc-10-2075-2016>
- Raina, V. K., Kaul, M. K., & Singh, S. (1977). Mass-balance studies of Gara glacier. *Journal of Glaciology*, 18(80), 415–423. <https://doi.org/10.3189/S0022143000021092>

- Ran, Y., Li, X., Cheng, G., Che, J., Aalto, J., Karjalainen, O., Hjort, J., Luoto, M., Jin, H., Obu, J., Hori, M., Yu, Q., & Chang, X. (2022). New high-resolution estimates of the permafrost thermal state and hydrothermal conditions over the northern Hemisphere. *Earth System Science Data*, *14*, 885–884. <https://doi.org/10.5194/essd-14-865-2022>
- Ran, Y., Li, X., Cheng, G., Nan, Z., Che, J., Sheng, Y., Wu, Q., Jin, H., Luo, D., Tang, Z., & Wu, X. (2021). Mapping the permafrost stability on the Tibetan Plateau for 2005–2015. *Science China Earth Sciences*, *64*, 62–79. <https://doi.org/10.1007/s11430-020-9685-3>
- Ren, Y.-Y., Ren, G.-Y., Sun, X.-B., Shrestha, A. B., You, Q.-L., Zhan, Y.-J., Rajbhandari, R., Zhang, P.-F., & Wen, K.-M. (2017). Observed changes in surface air temperature and precipitation in the Hindu Kush Himalayan region over the last 100-plus years. *Advances in Climate Change Research*, *8*(3), 148–156. <https://doi.org/10.1016/j.accre.2017.08.001>
- Reuter, B., Viallon-Galinier, L., Horton, S., van Herwijnen, A., Mayer, S., Hagenmuller, P., & Morin, S. (2022). Characterizing snow instability with avalanche problem types derived from snow cover simulations. *Cold Regions Science and Technology*, *194*, Article 103462. <https://doi.org/10.1016/j.coldregions.2021.103462>
- Rounce, D. R., Hock, R., McNabb, R. W., Millan, R., Sommer, C., Braun, M. H., Malz, P., Maussion, F., Mougnot, J., Seehaus, T. C., & Shean, D. E. (2021). Distributed global debris thickness estimates reveal debris significantly impacts glacier mass balance. *Geophysical Research Letters*, *48*(8), Article e2020GL091311. <https://doi.org/10.1029/2020GL091311>
- Rounce, D. R., Hock, R., & Shean, D. E. (2020). Glacier mass change in High Mountain Asia through 2100 using the open-source python glacier evolution model (PyGEM). *Frontiers in Earth Science*, *7*, Article 331. <https://doi.org/10.3389/feart.2019.00331>
- Rounce, D. R., & McKinney, D. C. (2014). Debris-thickness of glaciers in the Everest area (Nepal Himalaya) derived from satellite imagery using a nonlinear energy balance model. *The Cryosphere*, *8*, 1317–1329. <https://doi.org/10.5194/tc-8-1317-2014>
- Rounce, D. R., Quincey, D. J., & McKinney, D. C. (2015). Debris-covered glacier energy balance model for Imja–Lhotse Shar Glacier in the Everest region of Nepal. *The Cryosphere*, *9*(6), 2295–2310. <https://doi.org/10.5194/tc-9-2295-2015>
- Rowan, A. V., Egholm, D. L., Quincey, D. J., & Glasser, N. F. (2015). Modelling the feedbacks between mass balance, ice flow and debris transport to predict the response to climate change of debris-covered glaciers in the Himalaya. *Earth and Planetary Science Letters*, *430*, 427–438. <https://doi.org/10.1016/j.epsl.2015.09.004>
- Sabin, T. P., Krishnan, R., Vellore, R., Priya, P., Borgaonkar, H. P., Singh, B. B., & Sagar, A. (2020). Climate change over the Himalayas. In R. Krishnan, J. Sanjay, C. Gnanaseelan, M. Mujumdar, A. Kulkarni, & S. Chakraborty (Eds.), *Assessment of climate change over the Indian region: A report of the Ministry of Earth Sciences (MoES), Government of India*. Springer Open. https://doi.org/10.1007/978-981-15-4327-2_11
- Sakai, A. (2019). Brief communication: Updated GAMDAM glacier inventory over high-mountain Asia. *The Cryosphere*, *13*(7), 2043–2049. <https://doi.org/10.5194/tc-13-2043-2019>
- Sakai, A. & Fujita, K. (2017). Contrasting glacier responses to recent climate change in high-mountain Asia. *Science Reports*, *7*, Article 13717. <https://doi.org/10.1038/s41598-017-14256-5>
- Saloranta, T., Thapa, A., Kirkham, J. D., Koch, I., Melvold, K., Stigter, E., Litt, M., & Møen, K. (2019). A model setup for mapping snow conditions in High-Mountain Himalaya. *Frontiers in Earth Science*, *7*. <https://doi.org/10.3389/feart.2019.00129>
- Sangewar, C. V., & Siddiqui, M. A. (2007). *Thematic compilation of mass balance data on glaciers of Satluj Catchment in Himachal Himalaya (Field Season: 2006-07)*. Geological Survey of India, Northern Region.
- Sanjay, J., Krishnan, R., Shrestha, A. B., Rajbhandari, R., & Ren, G.-Y. (2017). Downscaled climate change projections for the Hindu Kush Himalayan region using CORDEX South Asia regional climate models. *Advances in Climate Change Research*, *8*(3), 185–198. <https://doi.org/10.1016/j.accre.2017.08.003>
- Santra, S., Verma, S., Fujita, K., Chakraborty, I., Boucher, O., Takemura, T., Burkhart, J. F., Matt, F., & Sharma, M. (2019). Simulations of black carbon (BC) aerosol impact over Hindu Kush Himalayan sites: Validation, sources, and implications on glacier runoff. *Atmospheric Chemistry and Physics*, *19*(4), 2441–2460. <https://doi.org/10.5194/acp-19-2441-2019>
- Sattar, A., Goswami, A., Kulkarni, A. V., Emmer, A., Haritashya, U. K., Allen, S., Frey, H., & Huggel, C. (2021). Future glacial lake outburst flood (GLOF) hazard of the South Lhonak Lake, Sikkim Himalaya. *Geomorphology*, *388*, Article 107783. <https://doi.org/10.1016/j.geomorph.2021.107783>
- Sattar, A., Haritashya, U. K., Kargel, J. S., Leonard, G. J., Shugar, D. H., & Chase, D. V. (2021). Modeling lake outburst and downstream hazard assessment of the Lower Barun Glacial Lake, Nepal Himalaya. *Journal of Hydrology*, *598*, Article 126208. <https://doi.org/10.1016/j.jhydrol.2021.126208>
- Scapozza, C., Ambrosi, C., Cannata, M., & Strozzi, T. (2019). Glacial lake outburst flood hazard assessment by satellite Earth observation in the Himalayas (Chomolhari area, Bhutan). *Geographica Helvetica*, *74*, 125–139. <https://doi.org/10.5194/gh-74-125-2019>

- Scher, C., Steiner, N. C., & McDonald, K. C. (2021). Mapping seasonal glacier melt across the Hindu Kush Himalaya with time series synthetic aperture radar (SAR). *The Cryosphere*, 15(9), 4465–4482. <https://doi.org/10.5194/tc-15-4465-2021>
- Scherler, D., Wulf, H., & Gorelick, N. (2018). Global assessment of supraglacial debris-cover extents. *Geophysical Research Letters*, 45(21), 11798–11805. <https://doi.org/10.1029/2018GL080158>
- Scherler, D., & Egholm, D. L. (2020). Production and transport of supraglacial debris: Insights from cosmogenic ¹⁰Be and numerical modeling, Chhota Shigri Glacier, Indian Himalaya. *Journal of Geophysical Research: Earth Surface*, 125(10). <https://doi.org/10.1029/2020JF005586>
- Sevestre, H. & Benn, D. I. (2015). Climatic and geometric controls on the global distribution of surge-type glaciers: Implications for a unifying model of surging. *Journal of Glaciology*, 61(228), 646–662. <https://doi.org/10.3189/2015JoG14J136>
- Shea, J. M., Immerzeel, W. W., Wagnon, P., Vincent, C., & Bajracharya, S. (2015). Modelling glacier change in the Everest region, Nepal Himalaya. *The Cryosphere*, 9(3), 1105–1128. <https://doi.org/10.5194/tc-9-1105-2015>
- Shean, D. E., Bhushan, S., Montesano, P., Rounce, D. R., Arendt, A., & Osmanoglu, B. (2020). A systematic, regional assessment of High Mountain Asia glacier mass balance. *Frontiers in Earth Sciences*, 7, 363. <https://doi.org/10.3389/feart.2019.00363>
- Shen, L., Zhang, Y., Ullah, S., Pepin, N., & Ma, Q. (2021). Changes in snow depth under elevation-dependent warming over the Tibetan Plateau. *Atmospheric Science Letters*, 22(9), Article e1041. <https://doi.org/10.1002/asl.1041>
- Sherpa, S. F., Wagnon, P., Brun, F., Berthier, E., Vincent, C., Lejeune, Y., Arnaud, Y., Kayastha, R. B., & Sinisalo, A. (2017). Contrasted surface mass balances of debris-free glaciers observed between the southern and the inner parts of the Everest region (2007–15). *Journal of Glaciology*, 63(240), 637–651. <https://doi.org/10.1017/jog.2017.30>
- Shugar, D. H., Burr, A., Haritashya, U. K., Kargel, J. S., Watson, C. S., Kennedy, M. C., Bevington, A. R., Betts, R. A., Harrison, S., & Strattman, K. (2020). Rapid worldwide growth of glacial lakes since 1990. *Nature Climate Change*, 10(10), 939–945. <https://doi.org/10.1038/s41558-020-0855-4>
- Shugar, D. H., Jacquemart, M., Shean, D., Bhushan, S., Upadhyay, K., Sattar, A., Schwanghart, W., McBride, S., de Vries, M. V. W., Mergili, M., Emmer, A., Deschamps-Berger, C., McDonnell, M., Bhambri, R., Allen, S., Berthier, E., Carrivick, J. L., Clague, J. J., Dokukin, M., ... Westoby, M. J. (2021). A massive rock and ice avalanche caused the 2021 disaster at Chamoli, Indian Himalaya. *Science*. <https://doi.org/10.1126/science.abh4455>
- Skiles, S. M., Flanner, M., Cook, J. M., Dumont, M., & Painter, T. H. (2018). Radiative forcing by light-absorbing particles in snow. *Nature Climate Change*, 8(11), 964–971. <https://doi.org/10.1038/s41558-018-0296-5>
- Smith, S. L., O'Neill, H. B., Isaksen, K., Noetzli, J., & Romanovsky, V. E. (2022). The changing thermal state of permafrost. *Nature Reviews Earth & Environment*, 3(1), 10–23. <https://doi.org/10.1038/s43017-021-00240-1>
- Smith, T., & Bookhagen, B. (2018). Changes in seasonal snow water equivalent distribution in High Mountain Asia (1987 to 2009). *Science Advances*, 4(1), Article e1701550. <https://doi.org/10.1126/sciadv.1701550>
- Smith, T., & Bookhagen, B. (2020). Assessing multi-temporal snow-volume trends in high mountain Asia from 1987 to 2016 using high-resolution passive microwave data. *Frontiers in Earth Science*, 8, Article 559175. <https://doi.org/10.3389/feart.2020.559175>
- Smith, T., Bookhagen, B., & Rheinwalt, A. (2017). Spatiotemporal patterns of High Mountain Asia's snowmelt season identified with an automated snowmelt detection algorithm, 1987–2016. *The Cryosphere*, 11(5), 2329–2343. <https://doi.org/10.5194/tc-11-2329-2017>
- Soheb, M., Ramanathan, A., Angchuk, T., Mandal, A., Kumar, N., & Lotus, S. (2020). Mass-balance observation, reconstruction and sensitivity of Stok glacier, Ladakh region, India, between 1978 and 2019. *Journal of Glaciology*, 66(258), 627–642. <https://doi.org/10.1017/jog.2020.34>
- Song, C., Sheng, Y., Ke, L., Nie, Y., & Wang, J. (2016). Glacial lake evolution in the southeastern Tibetan Plateau and the cause of rapid expansion of proglacial lakes linked to glacial-hydrogeomorphic processes. *Journal of Hydrology*, 540, 504–514. <https://doi.org/10.1016/j.jhydrol.2016.06.054>
- Srivastava, D. (Ed.). (2001). *Glaciology of Indian Himalaya: A bilingual contribution in 150 years of Geological Survey of India*. Special Publication No. 63. Vedam Books.
- Steffen, T., Huss, M., Estermann, R., Hodel, E., & Farinotti, D. (2022). Volume, evolution, and sedimentation of future glacier lakes in Switzerland over the 21st century. *Earth Surface Dynamics*, 10(4), 723–741. <https://doi.org/10.5194/esurf-10-723-2022>
- Steiner, J. F., Kraaijenbrink, P. D. A., & Immerzeel, W. W. (2021). Distributed melt on a debris-covered glacier: Field observations and melt modeling on the Lirung Glacier in the Himalaya. *Frontiers in Earth Science* [preprint]. <https://doi.org/10.3389/feart.2021.678375>

- Steiner, J. F., Litt, M., Stigter, E. E., Shea, J., Bierkens, M. F. P., & Immerzeel, W. W. (2018). The importance of turbulent fluxes in the surface energy balance of a debris-covered glacier in the Himalayas. *Frontiers in Earth Science*, 6. <https://doi.org/10.3389/feart.2018.00144>
- Stigter, E. E., Litt, M., Steiner, J. F., Bonekamp, P. N. J., Shea, J. M., Bierkens, M. F. P., & Immerzeel, W. W. (2018). The importance of snow sublimation on a Himalayan glacier. *Frontiers in Earth Science*, 6. <https://doi.org/10.3389/feart.2018.00108>
- Stigter, E. E., Steiner, J. F., Koch, I., Saloranta, T. M., Kirkham, J. D., & Immerzeel, W. W. (2021). Energy and mass balance dynamics of the seasonal snowpack at two high-altitude sites in the Himalaya. *Cold Regions Science and Technology*, 183, Article 103233. <https://doi.org/10.1016/j.coldregions.2021.103233>
- Stigter, E. E., Wanders, N., Saloranta, T. M., Shea, J. M., Bierkens, M. F. P., & Immerzeel, W. W. (2017). Assimilation of snow cover and snow depth into a snow model to estimate snow water equivalent and snowmelt runoff in a Himalayan catchment. *The Cryosphere*, 11(4), 1647–1664. <https://doi.org/10.5194/tc-11-1647-2017>
- Stumm D., Joshi S.P., Gurung T.R. and Silwal G. (2021). Mass balances of Yala and Rikha Samba glaciers, Nepal, from 2000 to 2017. *Earth System Science Data* 13(8), 3791–3818. <https://doi.org/10.5194/essd-13-3791-2021>
- Sun, Z., Zhao, L., Hu, G., Qiao, Y., Du, E., Zou, D., & Xie, C. (2020). Modeling permafrost changes on the Qinghai–Tibetan plateau from 1966 to 2100: A case study from two boreholes along the Qinghai–Tibet engineering corridor. *Permafrost and Periglacial Processes*, 31(1), 156–171. <https://doi.org/10.1002/ppp.2022>
- Sunako, S., Fujita, K., Sakai, A., & Kayastha, R. (2019). Mass balance of Trambau Glacier, Rolwaling region, Nepal Himalaya: In-situ observations, long-term reconstruction and mass-balance sensitivity. *Journal of Glaciology*, 65(252), 605–616. <https://doi.org/10.1017/jog.2019.37>
- Tang, Z., Wang, X., Deng, G., Wang, X., & Jiang, Z. (2020). Spatiotemporal variation of snowline altitude at the end of melting season across High Mountain Asia, using MODIS snow cover product. *Advances in Space Research*, 66(11), 2629–2645. <https://doi.org/10.1016/j.asr.2020.09.035>
- Terzi, S., Torresan, S., Schneiderbauer, S., Critto, A., Zebisch, M., & Marcomini, A. (2019). Multi-risk assessment in mountain regions: A review of modelling approaches for climate change adaptation. *Journal of Environmental Management*, 232, 759–771. <https://doi.org/10.1016/j.jenvman.2018.11.100>
- Thackeray, C. W., Fletcher, C. G., Mudryk, L. R., & Derksen, C. (2016). Quantifying the uncertainty in historical and future simulations of northern hemisphere spring snow cover. *Journal of Climate*, 29(23), 8647–8663. <https://doi.org/10.1175/JCLI-D-16-0341.1>
- Thapa, A., & Muhammad, S. (2020). Contemporary snow changes in the Karakoram region attributed to improved MODIS data between 2003 and 2018. *Water*, 12(10), Article 2681. <https://doi.org/10.3390/w12102681>
- Thompson, S. S., Benn, D. I., Dennis, K., & Luckman, A. (2012). A rapidly growing moraine-dammed glacial lake on Ngozumpa Glacier, Nepal. *Geomorphology*, 145–146, 1–11. <https://doi.org/10.1016/j.geomorph.2011.08.015>
- Tsai, Y.-L. S., Dietz, A., Oppelt, N., & Kuenzer, C. (2019). Remote sensing of snow cover using spaceborne SAR: A review. *Remote Sensing*, 11(12), Article 1456. <https://doi.org/10.3390/rs11121456>
- Tshering, P., & Fujita, K. (2016). First in situ record of decadal glacier mass balance (2003–2014) from the Bhutan Himalaya. *Annals of Glaciology*, 57(71), 289–294. <https://doi.org/10.3189/2016AoG71A036>
- Tsutaki, S., Fujita, K., Nuimura, T., Sakai, A., Sugiyama, S., Komori, J., & Tshering, P. (2019). Contrasting thinning patterns between lake- and land-terminating glaciers in the Bhutanese Himalaya. *The Cryosphere*, 13, 2733–2750. <https://doi.org/10.5194/tc-13-2733-2019>
- Vaidya, R. A., Shrestha, M. S., Nasab, N., Gurung, D. R., Kozo, N., Pradhan, N. S., Wasson, R. J., Shrestha, A. B., Gurung, C. G., & Bajracharya, A. (2019). Disaster risk reduction and building resilience in the Hindu Kush Himalaya. In P. Wester, A. Mishra, A. Mukherji, & A. B. Shrestha (Eds.), *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability and people* (pp. 389–419). Springer Nature Switzerland AG. https://doi.org/10.1007/978-3-319-92288-1_11
- Veh, G., Lützow, N., Kharlamova, V., Petrakov, D., Hugonnet, R., & Korup, O. (2022). Trends, breaks, and biases in the frequency of reported glacier lake outburst floods. *Earth's Future*, 10, Article e2021EF002426. <https://doi.org/10.1029/2021EF002426>
- Veldhuijsen, S. B. M., de Kok, R., Stigter, E. E., & Steiner, J. F. (2021). Spatial and temporal patterns of snowmelt refreezing in a Himalayan catchment. *Journal of Glaciology*, 68(268), 1–21. <https://doi.org/10.1017/jog.2021.101>
- Vionnet, V., Guyomarc'h, G., Lafaysse, M., Naaimbouvet, F., Giraud, G., & Deliot, Y. (2018). Operational implementation and evaluation of a blowing snow scheme for avalanche hazard forecasting. *Cold Regions Science and Technology*, 147, 1–10. <https://doi.org/10.1016/j.coldregions.2017.12.006>

- Vishwakarma, B. D., Ramsankaran, R., Azam, M. F., Bolch, T., Mandal, A., Srivastava, S., Kumar, P., Sahu, R., Navinkumar, P. J., Tanniru, S. R., Javed, A., Soheb, M., Dimri, A. P., Yadav, M., Devaraju, B., Chinnasamy, P., Reddy, M. J., Murugesan, G. P., Arora, M., ... Bamber, J. (2022). Challenges in understanding the variability of the cryosphere in the Himalaya and its impact on regional water resources. *Frontiers in Water*, 4, Article 909246. <https://doi.org/10.3389/frwa.2022.909246>
- Viste, E., & Sorteberg, A. (2015). Snowfall in the Himalayas: An uncertain future from a little-known past. *The Cryosphere*, 9(3), 1147–1167. <https://doi.org/10.5194/tc-9-1147-2015>
- Wagon, P., Brun, F., Khadka, A., Berthier, E., Shrestha, D., Vincent, C., Arnaud, Y., Six, D., Dehecq, A., Menegoz, M., & Jomelli, V. (2020). Reanalysing the 2007–19 glaciological mass-balance series of Mera Glacier, Nepal, Central Himalaya, using geodetic mass balance. *Journal of Glaciology*, 67(261), 117–125. <https://doi.org/10.1017/jog.2020.88>
- Wagon, P., Vincent, C., Arnaud, Y., Berthier, E., Vuillermoz, E., Gruber, S., Menegoz, M., Gilbert, A., Dumont, M., Shea, J. M., Stumm, D., & Pokhrel, B. K. (2013). Seasonal and annual mass balances of Mera and Pokalde glaciers (Nepal Himalaya) since 2007. *The Cryosphere*, 7, 1769–1786. <https://doi.org/10.5194/tc-7-1769-2013>
- Wang, R., Liu, S., Shangguan, D., Radić, V., & Zhang, Y. (2019). Spatial heterogeneity in glacier mass-balance sensitivity across High Mountain Asia. *Water*, 11(4), Article 776. <https://doi.org/10.3390/w11040776>
- Wang, X., Guo, X., Yang, C., Liu, Q., Wei, J., Zhang, Y., Liu, S., Zhang, Y., Jiang, Z., & Tang, Z. (2020). Glacial lake inventory of high-mountain Asia in 1990 and 2018 derived from Landsat images. *Earth System Science Data*, 12(3), 2169–2182. <https://doi.org/10.5194/essd-12-2169-2020>
- Wangchuk, S., & Bolch, T. (2020). Mapping of glacial lakes using Sentinel-1 and Sentinel-2 data and a random forest classifier: Strengths and challenges. *Science of Remote Sensing*, 2, Article 100008. <https://doi.org/10.1016/j.srs.2020.100008>
- Wangchuk, S., Bolch, T., & Robson, B. A. (2022). Monitoring glacial lake outburst flood susceptibility using Sentinel-1 SAR data, Google Earth Engine, and persistent scatterer interferometry. *Remote Sensing of Environment*, 271, Article 112910. <https://doi.org/10.1016/j.rse.2022.112910>
- Wani, J. M., Thayyen, R. J., Gruber, S., Ojha, C. S. P., & Stumm, D. (2020). Single-year thermal regime and inferred permafrost occurrence in the upper Ganglax catchment of the cold-arid Himalaya, Ladakh, India. *Science of The Total Environment*, 703, Article 134631. <https://doi.org/10.1016/j.scitotenv.2019.134631>
- Welty, E., Zemp, M., Navarro, F., Huss, M., Fürst, J. J., Gärtner-Roer, I., Landmann, J., Machguth, H., Naegeli, K., Andreassen, L. M., Farinotti, D., Li, H., & GliThaDa contributors (2020). Worldwide version-controlled database of glacier thickness observations. *Earth System Science Data*, 12(4), 3039–3055. <https://doi.org/10.5194/essd-12-3039-2020>
- Wester, P., Mishra, A., Mukherji, A., & Shrestha, A. B. (Eds.). (2019). *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability and people*. Springer Nature Switzerland AG. <https://doi.org/10.1007/978-3-319-92288-1>
- Wirbel, A., Jarosch, A. H., & Nicholson, L. (2018). Modelling debris transport within glaciers by advection in a full-Stokes ice flow model. *The Cryosphere*, 12(1), 189–204. <https://doi.org/10.5194/tc-12-189-2018>
- Yang, Y., Hopping, K. A., Wang, G., Chen, J., Peng, A., & Klein, J. A. (2018). Permafrost and drought regulate vulnerability of Tibetan Plateau grasslands to warming. *Ecosphere*, 9(5), Article e02233. <https://doi.org/10.1002/ecs2.2233>
- Yang, Y., Wu, Q., Liu, F., & Jin, H. (2021). Spatial-temporal trends of hydrological transitions in thermokarst lakes on Northeast Qinghai-Tibet Plateau based on stable isotopes. *Journal of Hydrology*, 597, Article 126314. <https://doi.org/10.1016/j.jhydrol.2021.126314>
- Yao, T., Bolch, T., Chen, D., Gao, J., Immerzeel, W., Piao, S., Su, F., Thompson, L., Wada, Y., Wang, L., Wang, T., Wu, G., Xu, B., Yang, W., Zhang, G., & Zhao, P. (2022). The imbalance of the Asian water tower. *Nature Reviews Earth & Environment*, 3, 618–632. <https://doi.org/10.1038/s43017-022-00299-4>
- Yao, T., Thompson, L., Yang, W., Yu, W., Gao, Y., Guo, X., Yang, X., Duan, K., Zhao, H., Xu, B., Pu, J., Lu, A., Xiang, Y., Kattel, D. B., & Joswiak, D. (2012). Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. *Nature Climate Change*, 2, 663–667. <https://doi.org/10.1038/nclimate1580>
- You, J., Qin, X., Ranjitkar, S., Loughheed, S. C., Wang, M., Zhou, W., Ouyang, D., Zhou, Y., Xu, J., Zhang, W., Wang, Y., Yang, J., & Song, Z. (2018). Response to climate change of montane herbaceous plants in the genus *Rhodiola* predicted by ecological niche modelling. *Scientific Reports*, 8, Article 5879. <https://doi.org/10.1038/s41598-018-24360-9>
- You, Q., Wu, F., Wang, H., Jiang, Z., Pepin, N., & Kang, S. (2020). Projected changes in snow water equivalent over the Tibetan Plateau under global warming of 1.5° and 2°C. *Journal of Climate*, 33(12), 5141–5154. <https://doi.org/10.1175/JCLI-D-19-0719.1>

- You, Q.-L., Ren, G.-Y., Zhang, Y.-Q., Ren, Y.-Y., Sun, X.-B., Zhan, Y.-J., Shrestha, A. B., & Krishnan, R. (2017). An overview of studies of observed climate change in the Hindu Kush Himalayan (HKH) region. *Advances in Climate Change Research*, 8(3), 141–147. <https://doi.org/https://doi.org/10.1016/j.accr.2017.04.001>
- Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S. U., Hoelzle, M., Paul, F., Haeberli, W., Denzinger, F., Ahlstrøm, A. P., Anderson, B., Bajracharya, S., Baroni, C., Braun, L. N., Cáceres, B. E., Casassa, G., Cobos, G., Dávila, L. R., Delgado Granados, H., Demuth, M. N., ... Vincent, C. (2015). Historically unprecedented global glacier decline in the early 21st century. *Journal of Glaciology*, 61(228), 745–762. <https://doi.org/10.3189/2015JoG15J017>
- 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., & Cogley, J. G. (2019). Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. *Nature*, 568, 382–386. <https://doi.org/10.1038/s41586-019-1071-0>
- Zhang, G., Yao, T., Xie, H., Wang, W., & Yang, W. (2015). An inventory of glacial lakes in the Third Pole region and their changes in response to global warming. *Global and Planetary Change*, 131, 148–157. <https://doi.org/10.1016/j.gloplacha.2015.05.013>
- Zhang, M., Chen, F., Zhao, H., Wang, J., & Wang, N. (2021). Recent changes of glacial lakes in the High Mountain Asia and its potential controlling factors analysis. *Remote Sensing*, 13(18), Article 3757. <https://doi.org/10.3390/rs13183757>
- Zhang, T. (2005). Influence of the seasonal snow cover on the ground thermal regime: An overview. *Reviews of Geophysics*, 43(4). <https://doi.org/10.1029/2004RG000157>
- Zhang, Z., Wang, M., Wu, Z., & Liu, X. (2019). Permafrost deformation monitoring along the Qinghai-Tibet Plateau engineering corridor using InSAR observations with multi-sensor SAR datasets from 1997–2018. *Sensors*, 19(23), Article 5306. <https://doi.org/10.3390/s19235306>
- Zhao, D., & Wu, S. (2019). Projected changes in permafrost active layer thickness over the Qinghai-Tibet Plateau under climate change. *Water Resources Research*, 55(9), 7860–7875. <https://doi.org/10.1029/2019WR024969>
- Zhao, L., Zou, D., Hu, G., Wu, T., Du, E., Liu, G., Xiao, Y., Li, R., Pang, Q., Qiao, Y., Wu, X., Sun, Z., Xing, Z., Sheng, Y., Zhao, Y., Shi, J., Xie, C., Wang, L., Wang, C., & Cheng, G. (2021). A synthesis dataset of permafrost thermal state for the Qinghai-Tibet (Xizang) Plateau, China. *Earth System Science Data*, 13(8), 4207–4218. <https://doi.org/10.5194/essd-13-4207-2021>
- Zhao, S., Cheng, W., Yuan, Y., Fan, Z., Zhang, J., & Zhou, C. (2022). Global permafrost simulation and prediction from 2010 to 2100 under different climate scenarios. *Environmental Modelling and Software*, 149. Article 105307. <https://doi.org/10.1016/j.envsoft.2022.105307>
- Zheng, G., Allen, S. K., Bao, A., Ballesteros-Canovas, J. A., Huss, M., Zhang, G., Li, J., Yuan, Y., Jiang, L., Yu, T., Chen, W., & Stoffel, M. (2021). Increasing risk of glacial lake outburst floods from future Third Pole deglaciation. *Nature Climate Change*, 11(5), 411–417. <https://doi.org/10.1038/s41558-021-01028-3>
- Zhou, Y., Li, Z., & Li, J. (2017). Slight glacier mass loss in the Karakoram region during the 1970s to 2000 revealed by KH-9 images and SRTM DEM. *Journal of Glaciology*, 63(238), 331–342. <https://doi.org/10.1017/jog.2016.142>
- Zhou, Y., Li, Z., Li, J., Zhao, R., & Ding, X. (2018). Glacier mass balance in the Qinghai-Tibet Plateau and its surroundings from the mid-1970s to 2000 based on Hexagon KH-9 and SRTM DEMs. *Remote Sensing of Environment*, 210, 96–112. <https://doi.org/10.1016/j.rse.2018.03.020>

Appendix

Source data used to compile region-wide mean glacier mass balances for 1975–1999

Region ID	Study	Area covered (km ²)	Starting year	Ending year	Specific mass balance (m w.e. per year)	Specific mass balance uncertainty (m w.e. per year)
14-01	Zhou et al. (2018)	841	1975	2000	-0.11	0.13
15-01	Bhattacharya et al. (2021)	490	1974	2004	-0.3	0.1
15-01	King et al. (2019)	1,095	1974	2000	-0.21	0.08
15-01	King et al. (2019)	540	1974	2000	-0.26	0.08
15-01	King et al. (2019)	744	1974	2000	-0.24	0.11
15-01	King et al. (2019)	840	1974	2000	-0.27	0.1
15-01	Zhou et al. (2018)	578	1975	2000	-0.28	0.11
15-01	Zhou et al. (2018)	228	1975	2000	-0.23	0.18
15-01	Ragetli et al. (2016)	100	1974	2006	-0.24	0.08
15-01	Maurer et al. (2019)	197	1975	2000	-0.25	0.07
14-02	Bolch et al. (2017)	2,868	1974	1999	-0.01	0.09
14-02	Zhou et al. (2017)	7,826	1973	2000	-0.09	0.03
15-02	King et al. (2019)	746	1974	2000	-0.29	0.1
15-02	King et al. (2019)	869	1974	2000	-0.2	0.08
15-02	Zhou et al. (2018)	689	1975	2000	-0.3	0.12
15-02	Maurer et al. (2016)	365	1974	2006	-0.17	0.05
15-02	Maurer et al. (2019)	2,460	1975	2000	-0.26	0.06
14-03	Zhou et al. (2018)	776	1975	2000	-0.04	0.1
14-03	Maurer et al. (2019)	1,379	1975	2000	-0.16	0.08
15-03	Zhou et al. (2018)	615	1975	2000	-0.19	0.14
13-05	Zhou et al. (2018)	1,147	1975	2000	-0.02	0.14
13-05	Zhou et al. (2018)	1,209	1975	2000	0.05	0.14
13-06	Zhou et al. (2018)	642	1975	2000	-0.06	0.12
13-08	Bhattacharya et al. (2021)	344	1975	2000	-0.22	0.07
13-08	Bhattacharya et al. (2021)	168	1976	2001	-0.24	0.13
13-08	Zhou et al. (2018)	317	1975	2000	-0.25	0.15
13-08	Zhou et al. (2018)	720	1975	2000	-0.22	0.12
13-08	Maurer et al. (2019)	398	1975	2000	-0.23	0.06
13-09	Zhou et al. (2018)	1,055	1975	2000	-0.11	0.14
14-01	Zhou et al. (2018)	841	1975	2000	-0.11	0.13
15-01	Bhattacharya et al. (2021)	490	1974	2004	-0.3	0.1
15-01	King et al. (2019)	1,095	1974	2000	-0.21	0.08
15-01	King et al. (2019)	540	1974	2000	-0.26	0.08
15-01	King et al. (2019)	744	1974	2000	-0.24	0.11

CHAPTER 3

RECOMMENDED CITATION

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Consequences of cryospheric change for water resources and hazards in the Hindu Kush Himalaya

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Chapter overview

KEY FINDINGS

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.

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.

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*).

POLICY MESSAGES

It is important to know the relevant contributions of different water sources 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 near 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.

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.

It is crucial to prepare for an increased dependence on meltwater. With 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.

CHAPTER SUMMARY

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 $32\% \pm 10\%$ 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.

KEY KNOWLEDGE GAPS

Despite the progress made over the past decades in the study of the water resources of the HKH, significant knowledge gaps remain. These gaps can be categorised as process and monitoring gaps that require distinct strategies to address them as well as gaps attributable to a lack of comprehensive documentation and inclusion of local and Indigenous knowledge. The process and monitoring gaps pertain specifically to understanding and quantifying the key cryospheric components of glaciers, snow, and permafrost and their contribution to high mountain hydrology in the HKH, both under historic climatic conditions and, crucially, under projected climatic change. Knowledge gaps must also be closed 'below' the high mountain areas by considering how cryospheric change will exacerbate cascading hazard risks and affect water demands and water use systems in downstream areas.

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.

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3.1. Introduction

The Hindu Kush Himalaya (HKH) region is part of what is often referred to as the Third Pole due to its vast expanse of ice and snow, and is known as one of the important water towers of the world (Immerzeel et al., 2020; Viviroli et al., 2007). To understand the region, it is crucial to have an overview of its water resources, associated hazards, and the resulting upstream–downstream linkages. This chapter investigates the physical manifestations of these crucial aspects of the water cycle. While it will point out where linkages to downstream impacts and demands exist, it does not go in further depth into ecological impacts (covered in Chapter 4), or societal and economic aspects (covered in Chapter 5).

Ranging from tropical climates in the south-east, with among the highest annual rainfall rates on the planet, to perennially frozen high-altitude areas, the region is subject to complex (Bookhagen & Burbank, 2006; Palazzi et al., 2013) and often still relatively understudied atmospheric dynamics (Viste & Sorteberg, 2015). The complexity of the terrain makes it challenging to resolve any climate variable in space. Additionally, the change in time is crucial as high elevations such as the HKH have experienced a faster rise in temperatures than other areas of the globe (Pepin et al., 2015). The regional climate is naturally the crucial input to understand the region's water resources and the cryosphere.

The HKH is the source of some of the largest rivers on the planet, but water resources also manifest themselves elsewhere. Lakes and soils also hold water and some of it returns to the atmosphere as evaporation before it can turn into discharge.

Together with the cryosphere (covered in Chapter 2), water resources can also drive various forms of hazards. With the exceptional elevational gradients across the HKH, these hazards can result in disasters of great magnitude. There has been considerable scientific debate on whether these hazards have changed in frequency and intensity in the past and if they will do so in the future. With changing vulnerabilities and increasing levels of exposure, it becomes even more difficult to project how this will alter the consequent risks for society.

In this chapter, we investigate our state of knowledge about the quality and quantity of climatic drivers, water resources, and their implications for present and future hydrological regimes, as well as water-related hazards and note the most significant impacts recorded. However, we do not further investigate interactions with the demand side or cascading risks that propagate beyond the domain of the physical sciences. The chapter concludes with a discussion of key gaps in knowledge, and suggests some relevant strategies to address the same.

3.2. Changes in water resources

Climate-related changes are impacting hydrological regimes across the HKH. The IPCC's recent, *Sixth assessment report* (AR6) also suggested that the Asian region is likely to face a scenario of too much and too little water under climate change, which will affect the socio-economic development of the region. In this section, we discuss the effects of a changing cryosphere on water resources, and water-related hazards in the HKH under a changing climate. We also look at the role of the cryosphere in mountain hydrology and how meltwater and water availability will change in the future.

3.2.1. Role of the cryosphere in mountain river hydrology

Cryospheric melt plays an important role in mountain hydrology (Azam et al., 2018; Biemans et al., 2019; Bolch et al., 2019). In the HKH, snowmelt and glacier melt contribute substantially to river flows although the magnitude of their contribution varies with scale (Khanal et al., 2021). Dynamic water storage in components of the cryosphere (comprising glaciers, snow, permafrost and seasonally frozen ground, and river and lake ice), either in a solid or liquid state, regulates run-off by releasing water generally from April to October – primarily snowmelt during April–June, and glacier melt during June–October (Azam et al., 2021). Lutz et al. (2014) suggested that the contribution of glacier melt and snowmelt is higher in the western Himalaya (for example, ~62% in the Upper Indus) and lower in the eastern Himalaya (for example, ~19% in the Upper Ganges), whereas the melt run-off contribution to the Upper Brahmaputra (25%), Upper Salween (36%), and Upper Mekong (33%) lies in between. Among these five river basins, the highest glacier run-off contribution is in the Upper Indus (41%) and the highest snowmelt run-off contribution is in the Upper Mekong (32%).

Khanal et al. (2021) estimated the melt run-off contribution of 15 river basins of High Mountain Asia (HMA). HMA is defined as the region within 57°–113°E and 22°–47°N, encompassing the Tibetan

Plateau and the adjacent mountain ranges – Tien Shan, Pamir, Hindu Kush, and Karakoram in the west, the Himalaya in the south and south-east, and Qilian Shan in the east. The glacier melt, snowmelt, rainfall run-off, and base flow contributions for the 12 major river basins within the HKH region are presented in Table 3.1. The locations of the basins are shown in Figure 3.1 (page 82).

Table 3.1 shows that the contribution of melt run-off can vary widely, from as high as 79% in the Amu Darya, with sources in the far west of the HKH, to merely 5% in the Irrawaddy in the eastern Himalaya. The contribution of melt run-off is relatively high in the western HKH region due to westerlies, because of which winter snowfall plays an important role (Khanal et al., 2021; Lutz et al., 2014). In contrast, the Indian summer monsoon plays an important role in the eastern Himalaya, which is reflected in the 50%–79% rainfall run-off contribution to river basins in that region, such as the Ganges, Brahmaputra, Irrawaddy, and Yellow river basins.

It is also notable that snowmelt contributes a larger fraction of run-off than glacier melt, but its share in different basins varies widely (Table 3.1). This finding is confirmed by a further in-depth study on the role of snowmelt in the region. This study also shows that the magnitude and timing of snowmelt have already changed considerably but trends in snow water equivalent (SWE) have been predominately negative across the whole region between 1979 and 2019 (Kraaijenbrink et al., 2021).

Figure 3.1 shows the contributions of both rainfall run-off and melt run-off to HMA's rivers. It indicates that rainfall run-off is higher in the eastern river basins such as the Ganges, Brahmaputra, Irrawaddy, and Mekong whereas the contribution of melt run-off is higher in the western river basins such as the Amu Darya.

Other studies conducted at micro to macro scales also indicate similar patterns of higher melt run-off in the western HKH region than in the eastern. In the Hunza River Basin, with a catchment area of 13,700 square kilometres (km²), glacier melt run-off ranges from 33% to 47% and snowmelt from 45% to 50% across the years (Shrestha et al., 2015). In the glaciated catchments of the central Himalaya such as the Upper Dudh Koshi Basin (146 km²) in the Everest

TABLE 3.1

CONTRIBUTION OF GLACIER MELT, SNOWMELT, AND RAINFALL RUN-OFF TO THE TOTAL DISCHARGE OF 12 MAJOR RIVER BASINS OF THE HKH FROM 1985 TO 2014

Basin	Area ('000 km ²)	Glacier area (%)	Precipitation (mm per year)	Run-off (mm per year)	Glacier melt run-off (%)	Snowmelt run-off (%)	Rainfall run-off (%)	Base flow (%)
Amu Darya	268	4.36	676	407	4.4	74.4	5.4	15.8
Helmand	74	0	360	195	0	77.5	5.2	17.4
Indus	473	6.28	832	577	5.1	39.7	43.9	11.4
Tarim	1,081	3.10	335	47	3.2	23.9	47.3	25.6
Ganges	202	4.37	1,763	1,293	3.1	10.3	64.7	22.0
Tibetan Plateau	415	0.83	451	117	2.3	15.3	32.8	49.6
Brahmaputra	400	2.73	2,018	1,575	1.8	13.2	62.1	22.8
Irrawaddy	49	0.15	3,638	3,223	0	5.1	78.2	16.7
Salween	119	1.45	1,091	627	1.4	14.7	55.7	28.3
Mekong	111	0.26	1,066	528	0.3	7.4	55.1	37.2
Yangtze	687	0.39	1,127	849	0.2	5.5	71.0	23.3
Yellow River	273	0.05	751	468	0.1	9.6	63.9	26.5

Note: Under 'Tibetan Plateau', endorheic basins of the plateau are summarised.

Source: Khanal et al. (2021)

region, snowmelt contributes 41% and glacier melt 46% of the total streamflow (Mimeau et al., 2019). For the same basin downstream, with a catchment area of 3,712 km², the snowmelt contribution decreases to about 29% (Nepal et al., 2014). Similarly, in the small catchment of Langtang (360 km²), the contribution of snowmelt varies between 20% and 30% while glacier melt varies between 13% and 62% (Immerzeel et al., 2013; Racoviteanu et al., 2013; Ragetli et al., 2015). However, for the larger basins, the contribution drops to 9%–14% (snowmelt) and 7%–11% (glacier melt) for Trishuli, downstream of Langtang (4,603 km²), Marsyangdi (4,062 km²), and Tamor (3,990 km²) (Kayastha et al., 2020). Studies at various scales indicate differences in the contribution of melt run-off mainly because of different methods used (for example, models relying on fully distributed versus semi-distributed resolution of physical processes in space or relying on simple temperature-dependent melt models versus a full energy balance) and the varying degrees to which processes are replicated in the models. These include the definition of glacier melt and snowmelt among studies (for example, processes with as yet little evidence,

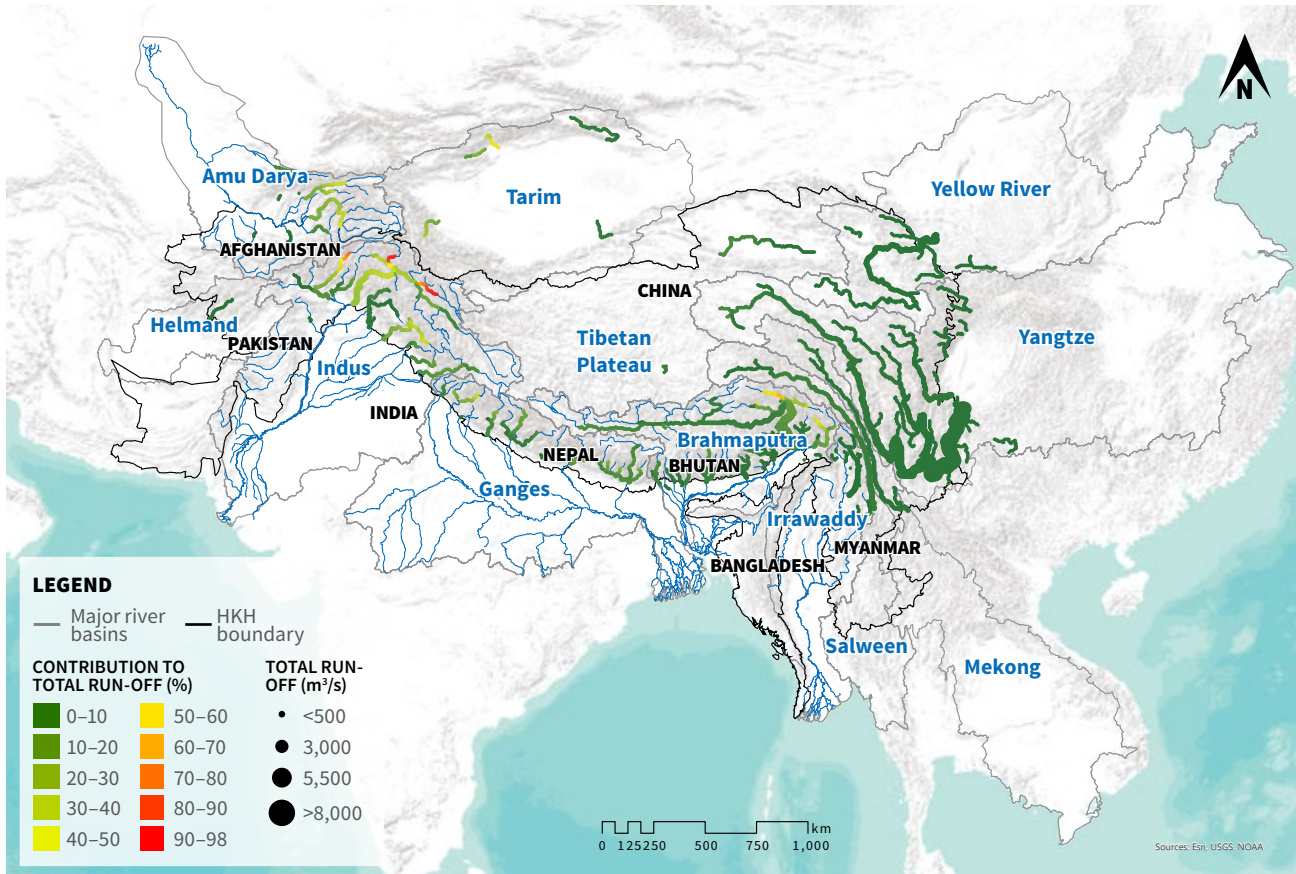
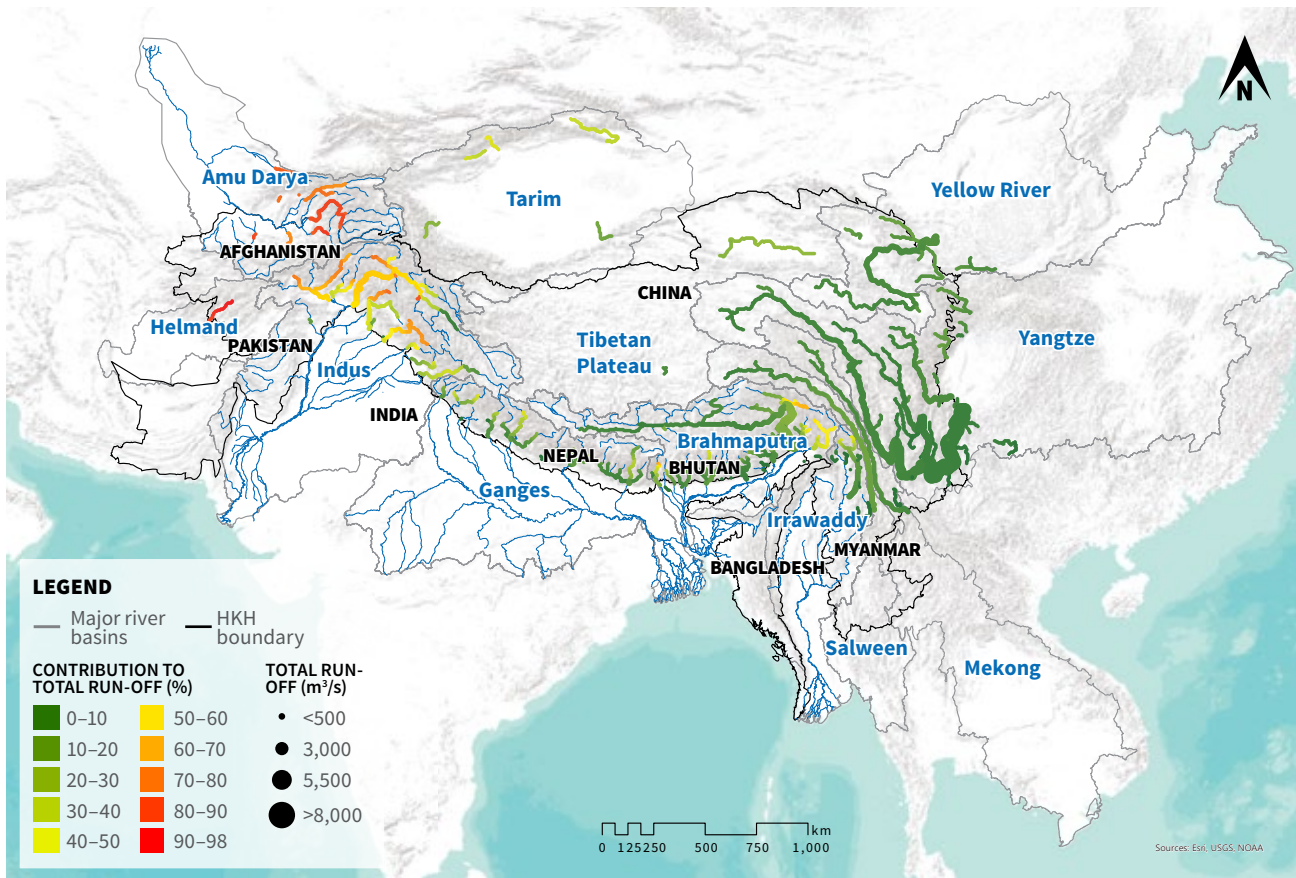
such as sublimation or subsurface flows, are often either ignored or resolved in a simplistic manner), input data, interpolation techniques, spatial representation, and time periods (Azam et al., 2021; Tiel et al., 2020).

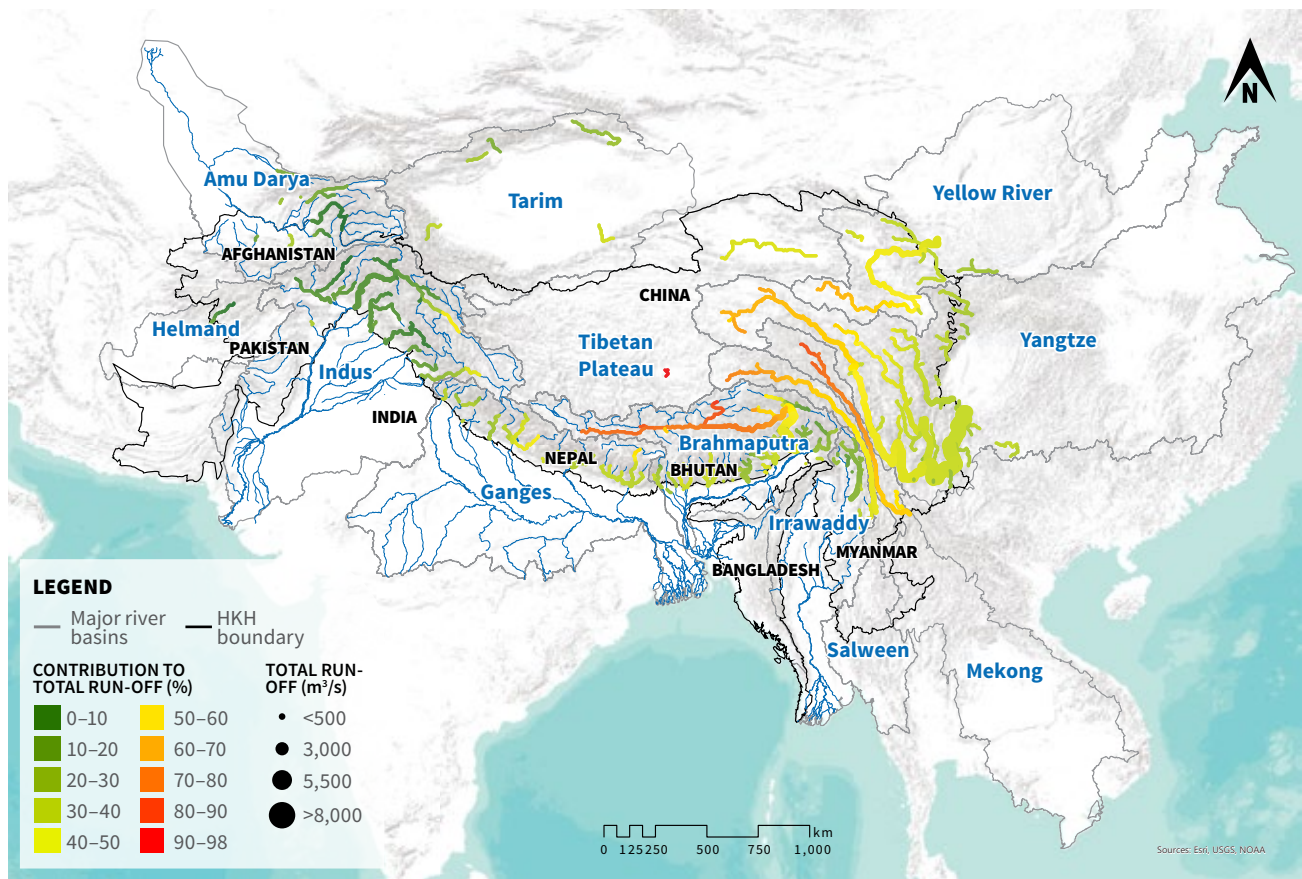
Meltwater is most important in high-elevation, proximal reaches of the HKH river basins. Meltwater volumes are greatest during the spring, summer, and early autumn, when snowmelt and ice melt typically are at their highest due to the higher temperatures in those seasons. In the monsoon-dominated basins, where monsoonal rain increases river flows, the share of meltwater declines in summer (Azam et al., 2021).

Modelling for a specific glacier catchment in the western Himalaya already suggests an increase in melt run-off, reflected in a negative mass balance for the second half of the twentieth century (Engelhardt et al., 2017). However, such studies that combine an analysis of the cryosphere and hydrology of a river basin remain limited. For the Karakoram, an analysis of river flow data in the Upper Indus

FIGURE 3.1

CONTRIBUTIONS OF SNOWMELT (FIRST), GLACIER MELT (SECOND), AND BASE FLOWS (THIRD) TO TOTAL RIVER DISCHARGE OF HKH RIVER BASINS, 1985–2014





Source: Khanal et al. (2021)

Basin suggests an increase in flows until the 1990s, with a decrease ever since. But this data does not directly mirror the mass loss or gain of glaciers in the region, suggesting other processes to be of relevance (Reggiani et al., 2017). Further north, in the Tien Shan, streamflows only started to increase in the 1990s but the variability in response between different sub-catchments within the Tien Shan remains large, also suggesting the importance of a better understanding of multiple processes (Shen et al., 2018).

3.2.2. Role of the cryosphere in springs hydrology

Glaciers are reducing significantly in area and are retreating – hence their lengths are reducing – at an alarming rate in the HKH (see Chapter 2). Many places are also experiencing erratic snowfall and a reduction in permafrost due to climate change (Bolch et al., 2019). However, the outcomes of these changes for the region’s water regime, especially its groundwater, are yet to become clear

(Prakash, 2020). Only a limited number of studies have been conducted in identifying groundwater, particularly spring recharge sources in the high mountain areas of the HKH region due to the limited hydrometeorological monitoring programmes. However, a few studies indicate that meltwater contributes significantly to groundwater recharge in the high mountain areas. Meltwater contributes up to 83% of annual groundwater recharge in the Upper Indus River Basin. Of this, the share of glacier melt is 44% and snowmelt 39% (Lone et al., 2021).

Springs are the main source of water for domestic and productive uses in the mid-hills (Scott et al., 2019). At higher elevations, springs have direct connections with glaciers and the decline in glaciers may affect water flows (Merrey et al., 2018). The projected further decline in glacial mass may not affect groundwater systems significantly until the middle of the century. However, after 2050, the changes in climatic conditions will likely affect spring systems, reducing their recharge and flows (Prakash, 2020). Accelerated thawing of permafrost can also impact artesian groundwater – whereby

groundwater recharge or discharge (as springs) can occur in localised taliks – as well as spring water chemistry via changed hydrological flow paths and the release of solutes from thawed materials (Gruber et al., 2017). However, there is still a lack of understanding of the interrelationships between the cryosphere and springs, and a regional science-based approach is necessary to fill this knowledge gap.

There are very few studies on springs in the high mountains. Panwar (2020) shows an inverse relation of spring discharge with precipitation and a positive correlation with the melting of snow/glaciers in the Kashmir Himalaya. With a rise in temperatures during March–July, an increase in spring discharge is witnessed. However, in the months that follow, there is a reduction in discharge which results from surpassed infiltration capacities and an increase in the run-off amount (August–November) and later, minimal melting due to low temperatures (December–February). Spring discharge during March (the wettest month, with ~200 mm of precipitation) is less than in June (only 80 mm of precipitation). During June–July, high temperatures support the melting of snow/ice, resulting in a considerable addition to groundwater recharge. Enhanced recharge associated with high temperatures and glacial melt in the summer months distinguishes the role of upstream snow-fed areas as a recharge zone. A study of karst springs from the Kashmir Valley in India showed that snowmelt dominantly contributes to spring flows (55%–96%), followed by glacier melt (5%–36%) and rain (4%–34%) (Jeelani et al., 2017).

Some studies have been carried out in the middle mountains of the HKH to establish the relationship between precipitation and spring discharge and recharge in small and distributed areas. In the Indian Himalaya, particularly in Sikkim and Uttarakhand, rainfall and spring discharge are well correlated (F. Zhang et al., 2019). A study conducted in western Nepal indicated that rainfall contributes significantly to springs (Matheswaran et al., 2019). Studies on the middle mountains of Sikkim, India indicated that springs are recharged by precipitation (Tambe, Dhakal et al., 2020; Tambe, Rawat et al., 2020), and that spring discharge generally showed an annual periodic rhythm, suggesting a strong direct response to rainfall (Tambe et al., 2012).

3.2.3. Evapotranspiration and sublimation

Evaporative fluxes – including evapotranspiration over land, evaporation over water bodies, and sublimation over ice and snow – have so far received limited attention in the HKH.

Studies of the Tibetan Plateau have investigated evapotranspiration on a regional scale using satellite data or reanalysis products (Shenbin et al., 2006; Song et al., 2017) as well as climate data of multiple weather stations (W. Wang et al., 2013), or as part of regional hydrological models (Khanal et al. [2021]; Figure 3.2). Trends vary across the region and even between studies, some suggesting an increase and others a decrease over past decades. The link to the cryosphere comes via the question of whether the evaporative fluxes are water- or energy-limited, and to what degree the changing active layer and resulting availability of soil moisture, impacted by a thawing permafrost, plays a role.

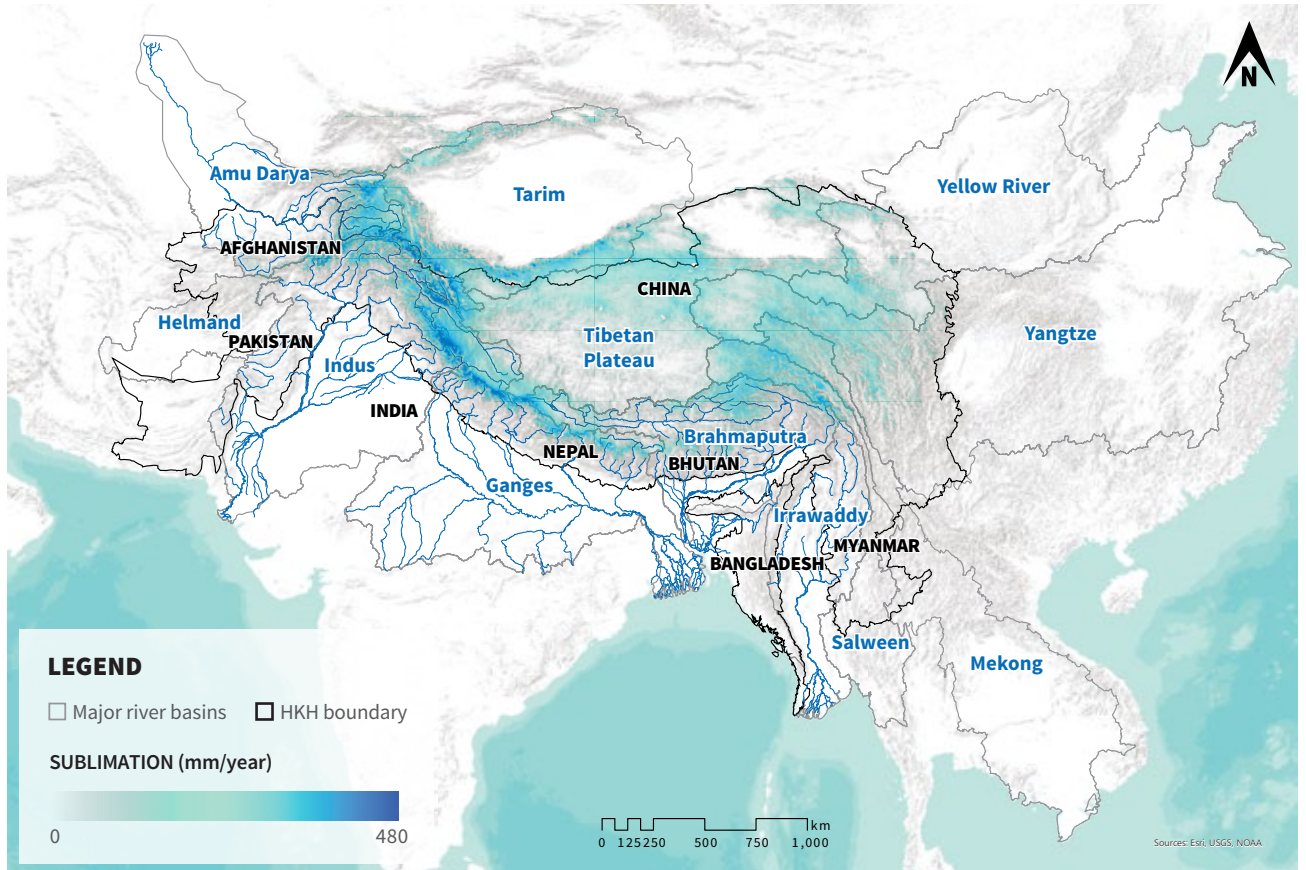
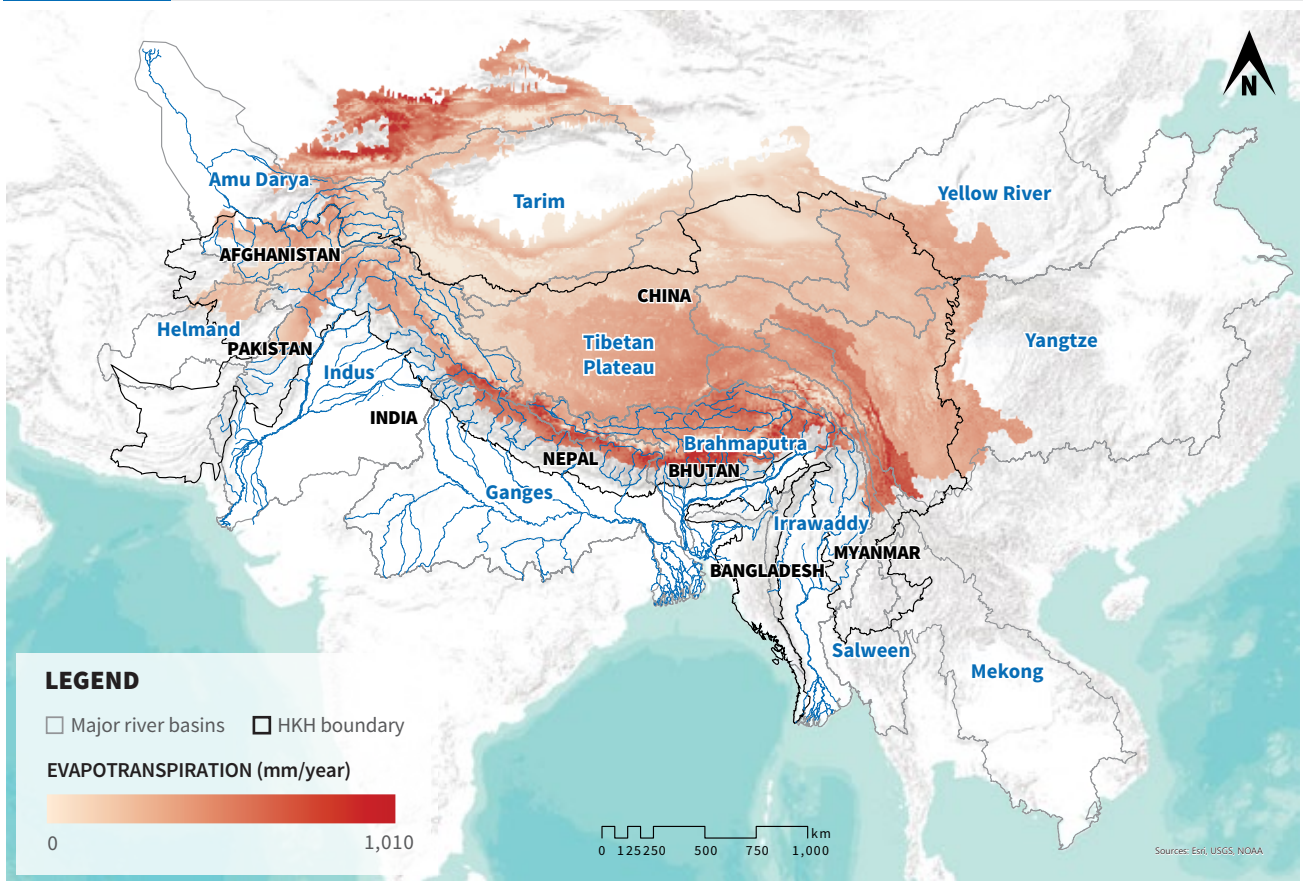
However, field studies to validate large-scale investigations or investigate processes in more detail remain rare. Limited investigations have measured evapotranspiration using the eddy covariance method (Chang et al., 2017) and lysimeters (L. Wang et al., 2020). These field studies suggest that solar radiation, and hence cloud cover, plays the most important role in determining evaporative fluxes, air temperature is a poor proxy, and the influence of wind speed varies between locations.

A study investigating evaporative fluxes from lakes on the Tibetan Plateau suggests that ~51.7 km³ per year of lake water evaporates to the atmosphere over all lakes (B. Wang et al., 2020), approximately twice the amount of glacier mass and 6 times the amount of permafrost mass lost each year.

Evaporative fluxes over snow and ice – sublimation – have previously been only addressed scantily. Regional estimates have been recently attempted, and field studies measuring sublimation on, or close to glacier surfaces agree well on sublimation rates in the order of 1 mm per day with strong seasonal variations (Guo et al., 2021, 2022; Mandal et al., 2022; Stigter et al., 2018). Over debris-covered ice, this process is more complex and comparable to evapotranspiration over ground (Steiner et al., 2018).

FIGURE 3.2

MEAN ANNUAL EVAPOTRANSPIRATION (TOP) AND SUBLIMATION (BOTTOM) IN HMA FOR 1985–2014



Data source: Khanal et al. (2021)

3.2.4. Future changes in melt run-off

The expected regional warming varies from 1.8°C to 2.2°C in different parts of the HKH if global warming were to be limited to 1.5°C above the pre-industrial level, as targeted by the Paris Agreement of 2015. The projected regional warming over the HKH is expected to result in wastage of about one- to two-thirds of its glacier mass by the end of the twenty-first century under various climate scenarios (Kraaijenbrink et al., 2017). With much larger variability in space, it is also expected to result in considerable further reduction of the snowpack across all basins of the HKH, with significant impacts on streamflows (Kraaijenbrink et al., 2021). Moreover, the suggested warming is greater at higher elevations, due to elevation-dependent warming (Pepin et al., 2015; Chapter 2, this volume), indicating that the regional warming trends are possibly an underestimate (Bolch et al., 2019). The projected changes in regional temperatures and precipitation over the twenty-first century (Kraaijenbrink et al., 2017; Krishnan et al., 2019) will affect the snow cover and mass balance of glaciers in the HKH; therefore, changes in the volume of, and seasonality in snowmelt and glacier melt are expected. Two effects that follow from this climatic change – which have a considerable impact on melt run-off – are reduction in glacier surface albedo due to less snow, resulting in the increased absorption of solar radiation and therefore increased melting, and an earlier onset of snowmelt and glacier melt and a delayed onset of snow cover, resulting in longer melt periods (Azam et al., 2021).

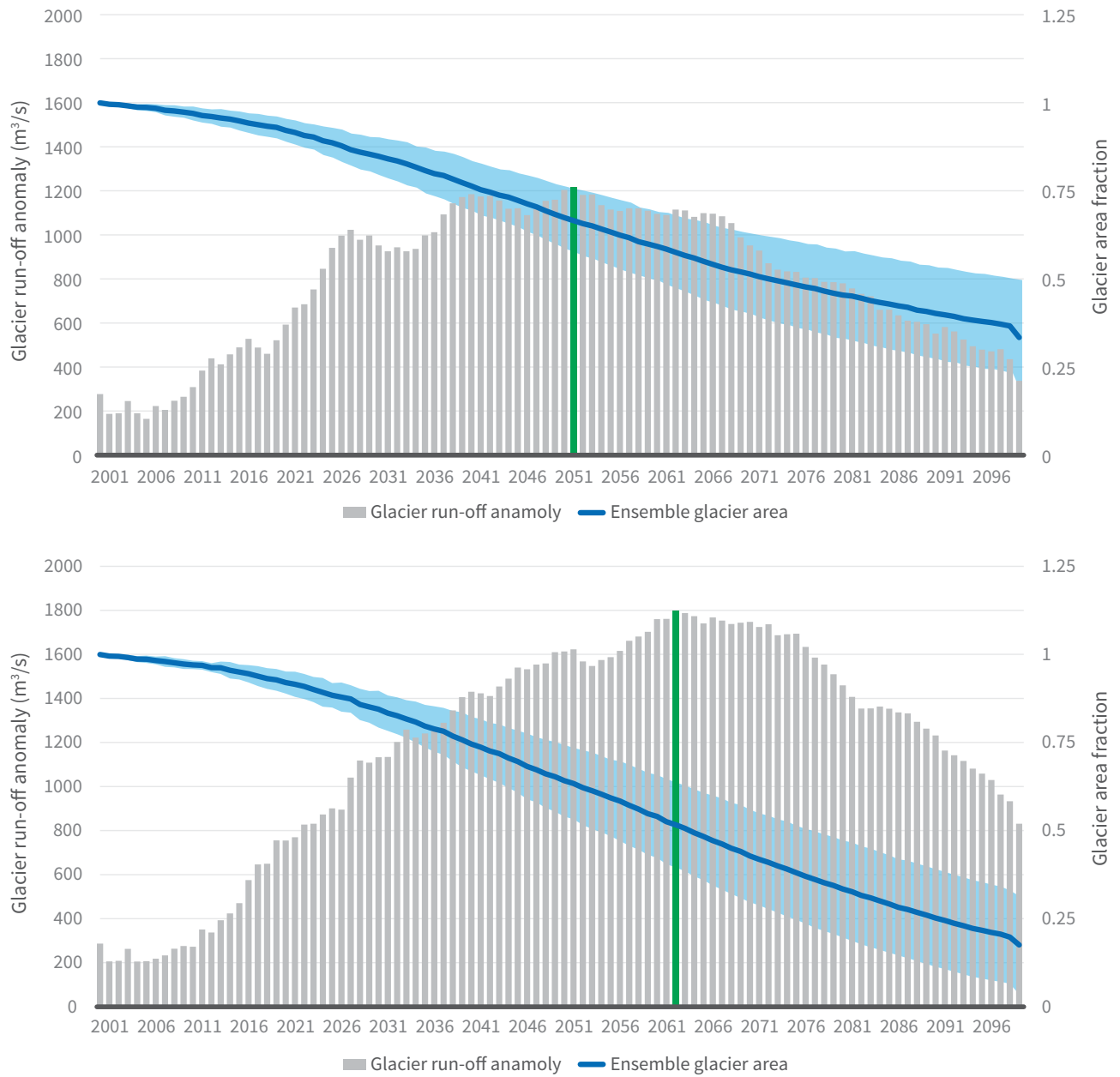
A recent global-scale study suggested a general rise in annual glacier run-off until the mid-21st century (Huss & Hock, 2018). A dedicated regional study, focused on two watersheds – Baltoro (in the Karakoram) and Langtang (in the central Himalaya) – in different climatic regimes, projected an increasing total run-off until the end of the twenty-first century (Immerzeel et al., 2013). However, in the Baltoro Watershed, the rise in total run-off is mainly due to increased glacier melt, while in the Langtang Watershed it is due to higher monsoonal precipitation. Increasing glacier melt throughout the

twenty-first century was also projected in the Shigar Watershed (in the Karakoram) due to an increase in both temperature and winter precipitation (Soncini et al., 2015). Conversely, in the Upper Indus Basin, decreased glacier melt in combination with increased snowmelt, leading to an overall reduction in river run-off, has also been suggested (Hasson, 2016). Studies focusing on the entire HKH region, suggested an increasing river run-off until 2050, mainly due to increased glacier melt in the Upper Indus Basin (Nie et al., 2021) and increased monsoonal precipitation in the Upper Ganges and Brahmaputra basins (Lutz et al., 2022). Nie et al. (2021) projected that the glacier area will decline with accelerated melt throughout the twenty-first century, leading to peak glacier melt run-off in the 2050s under the representative concentration pathway (RCP)4.5 and in the 2060s under RCP8.5 (Figure 3.3).

The peak melt contribution is highlighted in Figure 3.3 by the green vertical bars. A recent, detailed review suggested large uncertainties and some exceptions to these projected increases in river run-off in the HKH. However, despite these reported uncertainties and exceptions in future increases in river run-off, the trends in seasonal shifts of snowmelt and glacier melt are rather consistent (Azam et al., 2021). An early onset of snowmelt has been suggested despite the overall reduction in run-off in the Upper Indus Basin (Hasson, 2016). In the Shigar Watershed (in the Upper Indus Basin), snowmelt is projected to start in April rather than June by the late twenty-first century (2090–2099) under RCP8.5 (Soncini et al., 2015). The general increasing snowmelt and glacier melt run-off and shifts in their seasonality throughout the twenty-first century will undoubtedly have a complex and dynamic set of impacts on agriculture, hydropower, and fragile ecosystems in the HKH, demanding proactive responses by policy makers, local communities, and the international community working for sustainable development.

FIGURE 3.3

PROJECTED PEAK GLACIER MELT RUN-OFF (7-YEAR MOVING AVERAGE) AND GLACIER AREA FRACTION UNDER RCP4.5 (TOP) AND RCP8.5 (BOTTOM) FOR 2001–2100 IN THE INDUS RIVER BASIN



Note: The dark blue line shows the change in glacier area for 2001–2100. The shaded area represents a standard deviation of ± 1 . The green vertical bars represent the peak water contribution from glacier run-off.

Data source: Nie et al. (2021)

3.2.5. Projected changes in water availability and extremes

Climate change is expected to cause significant changes in the cryosphere and subsequently impact the hydrological cycle and overall water availability in the HKH (Huss & Hock, 2018; Kraaijenbrink et al., 2017; Krishnan et al., 2019). The responses of hydrological processes to climate change depends on spatiotemporal scales and varies significantly from sub-catchment to river basin scales and sub-daily to seasonal and decadal time scales (Khanal et al., 2021; H. Zheng et al., 2018). The responses differ in the climatically and hydrologically diverse HKH region, where 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. Responses also vary from east to west and south to north depending on the regional climate and hydrological regimes. Using Coupled Model Intercomparison Project Phase 6 (CMIP6) climate change projections, Khanal et al. (2021) found that an increasing fraction of rainfall, attributed to a warming climate, results in a faster translation of precipitation into run-off and in a higher magnitude of peak run-off by the end of the century (2071–2100) in the upstream areas of all 15 river basins in HMA. Data for 12 major river basins of the HKH is presented in Figure 3.4. The earlier onset of snowmelt and glacier melt run-off results in earlier peak flows by the end of the century for the Amu Darya and Indus river basins, which fall under the ‘glacio-nival’ hydrological regime category.

Depending on the selected combination of projected temperature and precipitation, that is, warm-wet, cold-wet, warm-dry, and cold-dry, future changes in total water availability differ (Khanal et al., 2021). The total water availability increases (decreases) for the end of the century for wet (dry) conditions. On average, under wet (dry) conditions, the total water availability increases (decreases) by 23%–26% (–23% to –27.2%) for the Ganges, 28%–30% (–16% to –17%) for the Indus, and 18%–21% (–22% to –25%) for the Brahmaputra River Basin. Similar contrasting results between the scenarios are reported by earlier regional studies based on CMIP5 projections for these basins, which illustrates the uncertainty regarding any assessment of climate change impacts in this region (Wijngaard et al., 2017; H. Zheng et al., 2018).

In the HKH, the changes in future total water availability are larger at higher elevations compared to lower elevations for the different hydrological regimes (Khanal et al., 2021). At higher elevations, the total water availability increases either due to an increase in the melt contribution until ‘peak water’ is reached or due to an increase in the liquid precipitation fraction in the future. Both conditions are mainly driven by increased temperatures or precipitation. However, this increased water availability levels off and decreases when lower regions dominated by rainfall run-off are considered. Also, the uncertainties are rather large, mainly stemming from uncertainties in future projections for precipitation (Azam et al., 2021).

Seasonal shifts are expected for the future with changing melt patterns and the onset and retreat of the monsoon. In the snow and glacier meltwater-dominated Upper Indus Basin, flows likely increase in the shoulder seasons, spring and autumn, whereas flows during the peak flow season slightly decline (Lutz et al., 2016). In river basins in the western part of the HKH with a melt-dominated hydrological regime (Amu Darya, Helmand, and the Indus), the onset of melting may shift 1 to 2 months earlier in the year (Huss & Hock, 2018). In particular, flows may decline in the second half (July–September) of the present peak melt season. These findings are in line with those for the Upper Indus Basin (Azmat et al., 2020; Lutz et al., 2016). For river basins dominated by southern and south-eastern rainfall (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. These findings are in line with projections for the Indus, Ganges, Brahmaputra, Salween, and Mekong basins (Lutz et al., 2022). A general conclusion is that for rivers with a larger role for meltwater, a stronger seasonal shift to earlier months is expected (Azmat et al., 2020; Khanal et al., 2021).

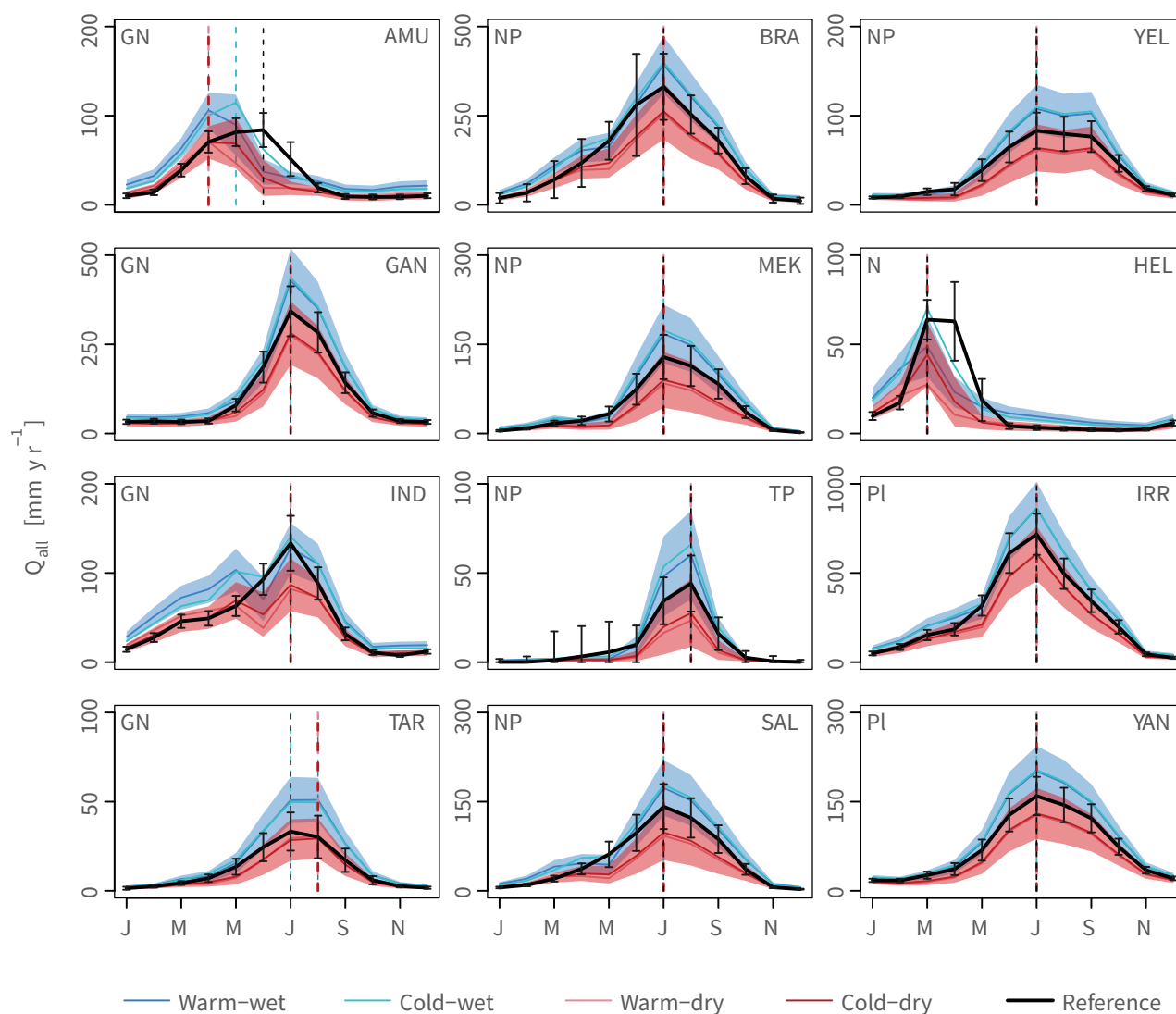
With climate change, not only are average flows expected to increase but also the frequency and magnitude of hydrological extremes (Adler et al., 2022). A reduced buffering capacity due to loss of glacier ice and snow storages contributes further to more erratic flows. High flow extremes are expected to increase strongly across the Upper Indus, Ganges,

and Brahmaputra river basins (Wijngaard et al., 2017). A study of the Brahmaputra Basin indicates an increase in both high- and low-flow extremes (Mohammed et al., 2017). Even though the total water availability at higher elevations increases,

the changes in the timing and magnitude of peak water availability and seasonality impose a serious threat for the livelihoods of people living in these regions (Biemans et al., 2019; Immerzeel et al., 2020; Khanal et al., 2021).

FIGURE 3.4

CHANGES IN THE MEAN ANNUAL CYCLES OF TOTAL RUN-OFF (Q_{all}) BY THE END OF THE CENTURY (2071–2100) IN THE 12 MAJOR RIVER BASINS OF THE HKH, FOR THE FOUR HYDROLOGICAL REGIMES



Notes: The coloured lines represent the mean of four groups of future scenarios, consisting of 12 dT/dP combinations each, warm-wet (6°C–8°C, 10%–40%), cold-wet (3°C–5°C, 10%–40%), warm-dry (6°C–8°C, –30%–0%), and cold-dry (3°C–5°C, –30%–0%). The colour shadings represent a standard deviation of ± 2 for a group of scenarios (only shown for warm-wet and cold-dry). The black solid lines represent the reference (1985–2014) mean annual cycle of total run-off. The vertical black error bars represent the total estimated variance calculated, using the first-order second-moment method for the reference climate for 1985–2014. The vertical dashed lines represent the peak flow months for each group of scenarios. The text on the top left and top right gives the hydrological regime (GN – glacio-nival, NP – nival-pluvial, N – nival, PI – pluvial) and basin name, respectively.

Data source: Khanal et al. (2021)

3.3. Water-related hazards in the HKH

The recent contribution to the IPCC's *Sixth assessment report* with a focus on mountains (Adler et al., 2022) found that, with respect to hazards, Asia has received the most attention in the scientific literature from all continents. It finds a predominantly negative impact, while attribution confidence remains low, and the contribution of climate change remains at a medium level in a three-tier grading system (see Figure CCP5.4 therein). While the frequency of disasters shows an increasing trend in the HKH, the same is due both to a changing climate as well as to increased exposure (the latter is discussed in more detail in Chapter 5 in this volume). In the following subsections, we discuss observed hazards in the HKH mountains related to the cryosphere and the hydrosphere since 2015. This is followed by a discussion of our ability to attribute these events to a changing climate, a look into possible changes in their frequency and nature, and the specific role of changing sediment loads from

mass movements. We close with an outlook into a future with uncertain trends and consequences.

3.3.1. Observed hazards in recent years

The HKH region has experienced a wide variety of hazards related to the cryosphere and hydrosphere in recent years. Few of these have so far been documented comprehensively. There exists considerable overlap between different types of hazards, in both their genesis and occurrence as cascading hazards. The types of hazards documented in the HKH are shown in Figure 3.5. While there is evidence for all, peer-reviewed academic literature remains unavailable as yet for some (for example, snow droughts, which refers to a lack of snowfall or snowpack in seasons where they would otherwise be expected to be present), is limited to single digits for others (for example, avalanches, hanging glaciers), but has seen more than 250 published papers for glacial lake outburst floods (GLOFs) alone since 2017 (Emmer et al., 2022).

FIGURE 3.5

A SCHEMATIC REPRESENTATION OF THE DOCUMENTED HAZARDS RELATED TO THE CRYOSPHERE AND HYDROSPHERE IN THE HKH

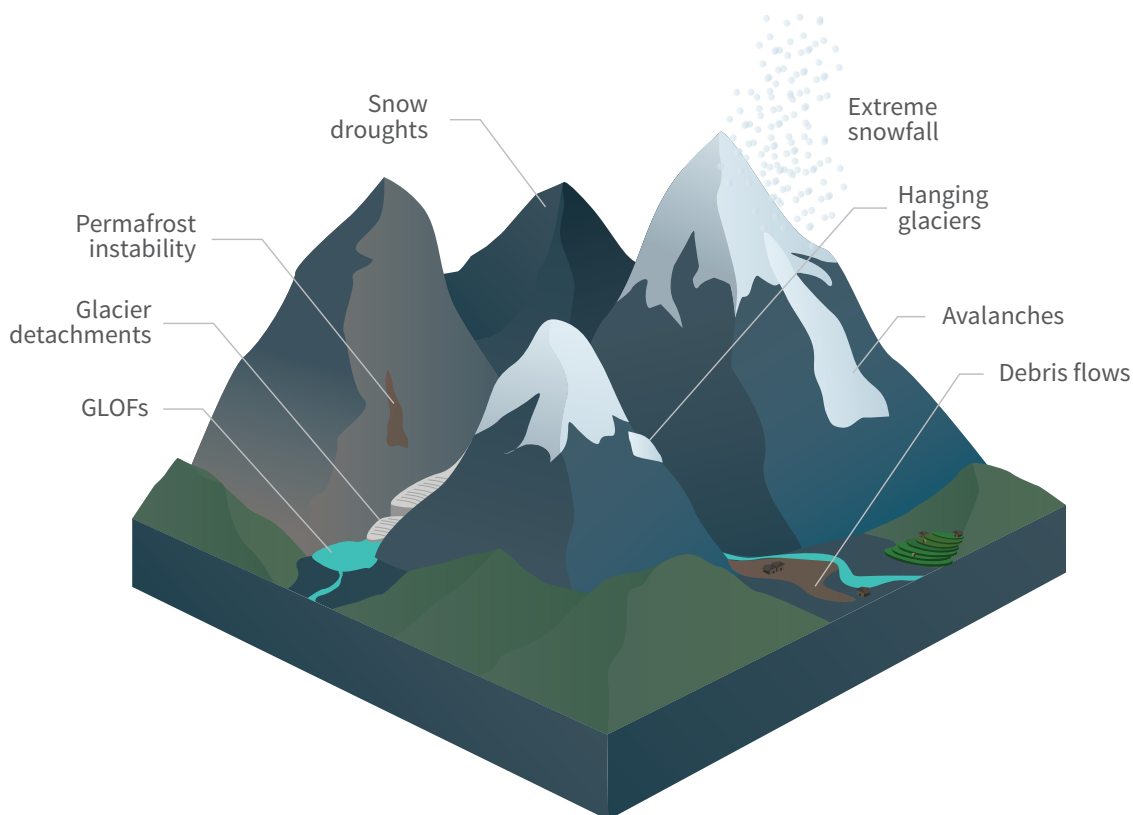
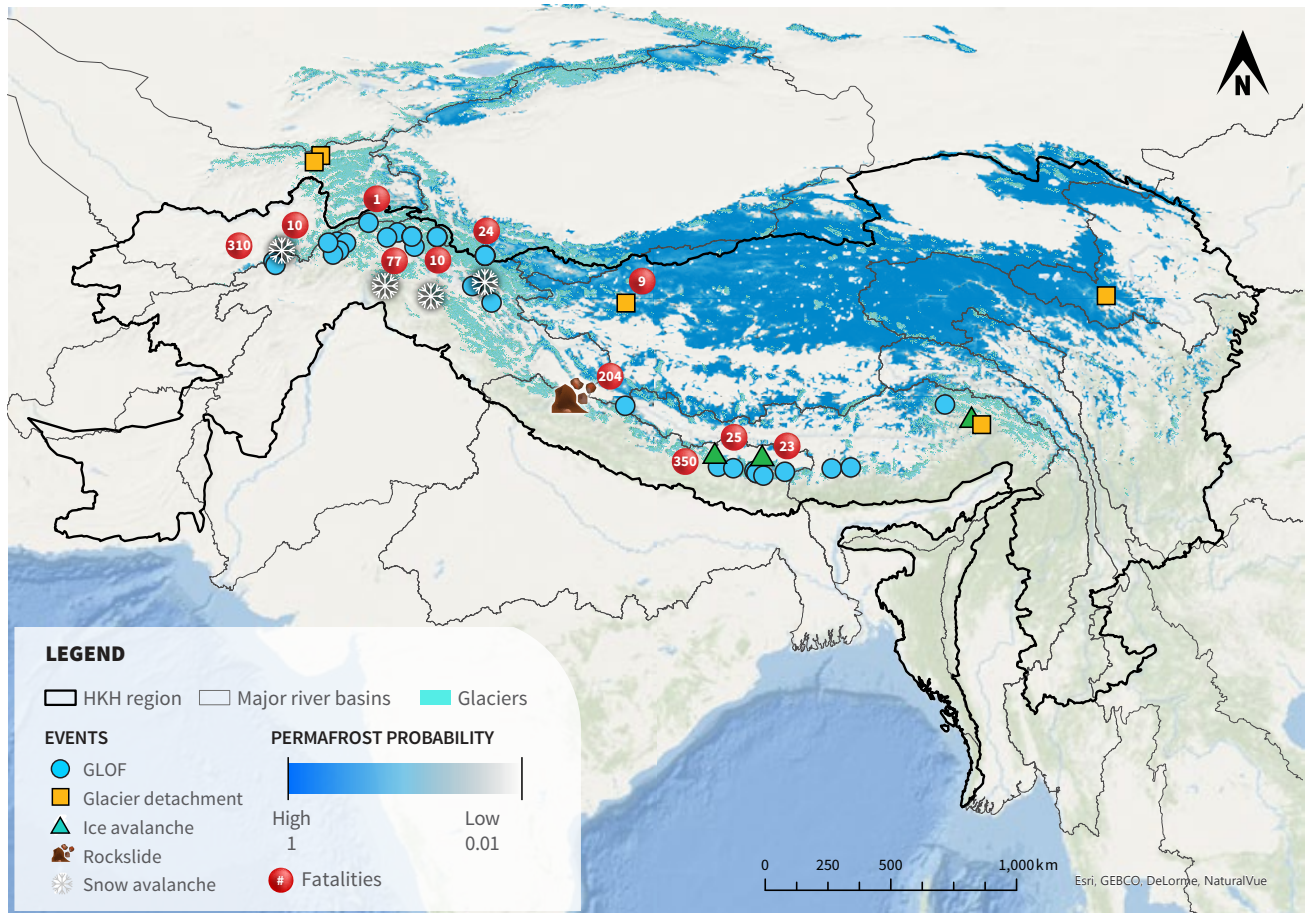


FIGURE 3.6

OVERVIEW OF ALL RECORDED CRYOSPHERE-RELATED EVENTS IN THE HKH SINCE 2015



Notes: Events are coloured and symbolised by type. Numbers indicated are fatalities for individual events. Permafrost probability is based on data from Obu (2021). The bold black outline marks the HKH outline, permafrost extent is shown in blue, glacier outlines are shown in cyan.

Of all the types of hazards, avalanches get initiated at the highest elevations. A study on the western Himalaya suggests that rising temperatures in the last century have contributed to an increase in the occurrence of snow avalanches (Ballesteros-Cánovas et al., 2018). Snow and ice avalanches with casualties or considerable infrastructural damage are generally limited to a few singular events, but total fatalities are larger than for any other hazard. An overview of cryosphere-related hazards in the HKH since 2015 is presented in Figure 3.6.

Large co-seismic events occurred during the 2015 Gorkha earthquake that caused numerous casualties in the Everest region (Bartelt et al., 2016). A multi-component avalanche destroyed a village completely and killed more than 250 people in the Langtang catchment (Fujita et al., 2017; Kargel et al., 2016). These two recent events in the central Himalaya were avalanches that included not only snow but

parts of hanging glaciers, debris, and underlying rock. In similarly steep terrain, events with a much larger proportion of bedrock have been documented in the Indian Himalaya, on Siachen Glacier in 2010 (Berthier & Brun, 2019) and in Chamoli in 2021 (Shugar et al., 2021), the latter killing more than 200 people and causing considerable infrastructural damage, including serious damage to two downstream hydropower plants under construction. A similar event occurred in 2017 on the Sedongpu Glacier in south-eastern Tibet (Chen et al., 2020; Käab et al., 2021) and the Lower Barun Lake in Nepal the same year (Byers et al., 2019). While there are individual changes potentially linked to a warming climate, such as unstable headwalls or overlying glacier tongues, in none of these events could climate change be identified as the definite reason for their occurrence. However, nearly all of them propagated downstream into cascading, multi-hazard events,

a frequent phenomenon in the HKH (Kirschbaum et al., 2019; Rusk et al., 2022). Here, these mass flow events pair with other processes that have been better documented and which are partly attributed to climate change.

Lake outburst floods can occur from temporary or permanent lakes that are either ice- or moraine-dammed in the case of glacial lakes (GLOFs) or dammed by landslide material (landslide-dammed lake outburst floods, LLOFs). While there has been clear evidence for an increase in the number of lakes in the region during recent decades (Nie et al., 2017), a study finds no clear evidence for an increase in the occurrence of GLOFs at least for moraine-dammed lakes (Veh et al., 2019), or at best a very heterogeneous response that still remains difficult to disentangle (Harrison et al., 2018; Veh et al., 2022). For GLOFs from ice-dammed lakes, the record remains too short and scant to reach definite conclusions; however, a few events have been well documented in recent years. Such GLOFs often happen as surging glaciers block valleys, a common phenomenon in the Karakoram. During recent years, repeat GLOFs due to such valley blockages have been reported for Kyagar, Khurdopin, and Shisper glaciers (Bhambri et al., 2020; Muhammad et al., 2021; Round et al., 2017).

GLOFs can also occur as sudden drainages of supraglacial lakes, an event documented in the Everest region in 2015, on the Lothse Glacier in 2016 (Rounce et al., 2017), and on Changri Shar Glacier in 2017 (Miles et al., 2018). Satellite imagery and news reports from the Pakistan Hindu Kush reveal similar events in 2019 and 2020 on Rogheli Glacier, causing substantial damage to a hydropower project, and in 2018 on Badswat Glacier, flooding a village. There were also repeat events in 2018 and 2021 in the Pishgor Valley in Panjshir, Afghanistan, with 10 fatalities.

Most of these GLOFs have caused debris flows downstream that subsequently increased risks to life, livelihoods, and property, as solid deposits generally make agricultural land unusable for years and can cause larger damage to infrastructure. Even without a water source, such mass movements have however been observed. The initial mass volumes of rock and ice in the case of Langtang in Nepal, Chamoli in India, and Sedongpu in China were relatively small compared to the final volume of material that was

mobilised along their runout paths. In all cases, massive debris flows caused heavy destruction or valley blockages downstream.

Debris flows have also occurred in lower regions, driven by heavy rainfall. This has been especially intense in the central Himalaya, where the combination of slope instability caused by the 2015 earthquake and subsequent monsoons has resulted in many dozens of debris flows (Dahlquist & West, 2019). While an intensification of short-duration rainfall extremes is expected in Asia in general (Fowler et al., 2021; Kim & Bae, 2020), there is no clear indication how this will impact its mountainous areas. An especially large event, following a high-precipitation event, occurred in June 2021 in the Melamchi catchment in Nepal, in which repeat debris flows caused heavy damage to infrastructure, displaced dozens of families, and led to multiple fatalities (Maharjan et al., 2021). Besides the instability of slopes caused by the earthquake, which has been shown to have effects for multiple years after the event itself (Kincey et al., 2021), a changing state of permafrost may also have contributed to some of these disasters. However, our knowledge about the state of the active layer remains limited in the region due to a lack of field evidence.

A phenomenon that has only been described in more detail in very recent years is glacier detachments. Contrary to break-offs of ice at high elevations that generally lead to powder avalanches, or glacier surges where ablation zones accelerate but only do so over many days or weeks and never detach from the actual glacier itself, a number of events have been documented in which parts of the ablation zone of a glacier have rapidly collapsed and caused an ice avalanche (Kääb et al., 2021; Leinss et al., 2021; Tian et al., 2017). Such events are limited to the northern fringes of the HKH and the Tibetan Plateau. Increasing amounts of meltwater at the base of these glacier tongues are a potential reason for some of these detachments and could be linked to rising temperatures (Kääb et al., 2018).

Insights on droughts in mountainous areas in the HKH remain limited. Investigations from the Kosi Basin suggest an increase in the frequency of soil moisture droughts in recent decades (Nepal, Pradhananga, et al., 2021). Conversely, snow cover is

projected to decrease in the future with potentially dire consequences in basins dependent on snowmelt as a resource (Kraaijenbrink et al., 2021; Nepal, Khatiwada, et al., 2021).

Similarly, poorly documented are heavy snowfall events or blizzards. For example, Cyclone Hudhud claimed multiple lives within a few days in 2014 and the huge amounts of accumulated snow possibly contributed subsequently to the large Langtang avalanche in 2015 triggered by the Gorkha earthquake (Fujita et al., 2017).

3.3.2. From compound events to cascading hazards

Compound drivers (Zscheischler et al., 2020) are increasingly documented associated with hazards occurring in high mountain environments. At the same time, and often as a result of compound drivers, hazards have often become cascading in nature, whereby a sequence of secondary events result in an impact that is significantly larger than the initial impact (Collins et al., 2019; Kirschbaum et al., 2019). In the context of hazards, cascading events are sometimes interchangeably referred to as multi-hazard (or consequently multi-risk). The term ‘multi-hazard’ further helps to acknowledge the increasing occurrence of concurrent hazards that may interact (and hence be a compound event) or occur in parallel, resulting in a bigger impact than any single hazard would (Tilloy et al., 2019). Adler et al. (2022) suggest that the state of our knowledge allows us to state with high confidence that the increasingly concurrent occurrence of drivers makes cascading impacts a common feature in mountain hazards.

During recent years, a number of compound and/or cascading events have been recorded in the HKH, along with its drivers and major processes (Table 3.2). For most events, the documentation of process chains as well as downstream impacts remains patchy. While casualties and infrastructural damages are recorded, information about long-term effects on the economy, ecosystems, and livelihoods is rare. Analyses of any feedback effects between impacts of mass flows and aspects like human migration (within the watersheds or outside of them) or infrastructure investment (especially road and hydropower construction) remain lacking (see also Chapter 5).

Events with high impacts on human settlements (for example, the Melamchi flood disaster or the Badswat GLOF; see Table 3.2) have caused significant displacement of local populations without the possibility of their returning for multiple years.

Compound drivers of cascading events and associated risks are both non-climatic as well as climatic. The effect of road construction on the increasing number of landslides following slope instabilities after the 2015 earthquake has already been shown (Kincey et al., 2021; McAdoo et al., 2018; Rosser et al., 2021). Similarly, as hydropower and road infrastructure is increasingly being constructed in the upstream areas of watersheds, the risk of exposure to mass flow events has been increasing (D. Li et al., 2022). Other drivers include the frequent occurrence of glacier surges that block river discharge that is released rapidly during the warmer seasons (specifically occurring in the Karakoram), as well as seismic shocks and their after-effects, visible today especially from the Wenchuan, Kashmir, and Gorkha earthquakes (Kincey et al., 2021; S. Zhang et al., 2014).

Confirmed climatic drivers include increasing rainfall intensities and higher temperatures, resulting in large (snow and ice) melt amounts that drive short-term lake expansion and soil saturation. Intense snowfall causing the failure of underlying ice or rock surfaces has been hypothesised to be a potential driver in a few isolated events. Thawing permafrost or the frost cracking due to changing permafrost in headwalls has been found to be on the increase elsewhere (Gruber & Haeberli, 2007) and it is possible that it has contributed to recent cascading events. However, permafrost mapping and studies remain scarce in the HKH, which precludes more certainty on this topic. A definite attribution to anthropogenic climate change however remains elusive and so far has not been attempted in the HKH. In subsection 3.3.3, we outline an approach for the example of GLOFs.

TABLE 3.2 OVERVIEW OF ALL RECORDED CRYOSPHERE-RELATED EVENTS IN THE HKH SINCE 2015						
Event	Date	Type	Processes	Drivers (confirmed, suspected)	Casualties	References
Langtang avalanche	2015	Cascading + compound	Hanging glacier avalanche	Seismic impact, <i>snowfall</i>	350	(Fujita et al., 2017)
Supraglacial GLOFs at Changri Shar and Lhotse	2015/2016/2017	Cascading	GLOF (supraglacial lake)	Glacier melt	–	(Miles et al., 2018; Rounce et al., 2017)
Landslides and debris flows in Nepal	2015–till date	Cascading + compound	Earthquake, landslides	Seismic impact, precipitation	NA	(Kincey et al., 2021; Sharma et al., 2022)
Sedongpu avalanche and glacier detachment	2017/2018	Cascading	Avalanche, glacier detachment, debris flow	<i>Surging glacier, snow accumulation</i>	–	(Kääb et al., 2021)
Langmale rockfall and GLOF	2017	Cascading	Rockfall, GLOF	Not clear	–	(Byers et al., 2019)
Ice-dammed GLOFs at Khurdopin, Shisper, and Kyagar glaciers	2017–2022 (annually)	Compound	GLOF (ice-dammed lake)	Surging glacier, glacier melt, <i>snowmelt</i>	–	
Darmander/Rogheli/Badswat GLOFs	2018/2019	Compound + cascading	GLOF, debris flows	Snow and glacier melt, <i>high intensity rainfall</i>	–	
Chamoli rockslide	02/2021	Compound + cascading	Ice and rockslide, debris flow	<i>Ice melt, permafrost thaw</i>	204	(Shugar et al., 2021)
Melamchi debris flow	06/2021	Compound + cascading	GLOF, LLOF, debris flow	Intense precipitation, <i>snowmelt, permafrost thaw</i>	25	(Maharjan et al., 2021)

Notes: Type, processes involved, and drivers (confirmed as well as *suspected*) are based on the references given. If no reference is given, it means the information is based on local sources. Casualties are given only for events where they can be ascertained and may be underestimations due to poor documentation of downstream impacts.

3.3.3. Attribution of high-mountain cryosphere change and cryosphere-related hazards

GLOFs from moraine- or ice-dammed lakes occur primarily through two mechanisms: (i) a dam breach leading to a rapid draining of the lake, or (ii) a moraine-overtopping wave induced by a landslide or avalanche. In either case, the flood hazard is a consequence of the characteristics of the moraine dam, the size of the lake, and the likelihood of a triggering event (T. Zhang et al., 2022). The recession of lake-terminating glaciers can expand existing proglacial lakes or form new lakes in the wake of their retreat (Linsbauer et al., 2015). Consequently, the anthropogenic contribution to glacier retreat is a key determinant of human influence on GLOF hazards and their occurrence.

Glacier retreat is an established consequence of anthropogenic climate change (Eyring et al., 2021; Hock et al., 2019; Roe et al., 2017; Zemp et al., 2015). Globally, virtually all glacier mass loss has been attributed to anthropogenic climate forcing (Roe et al., 2021).

The response of any individual glacier to changes in climate depends on its climatological and geographical setting. These factors include the glacier geometry, underlying topography, the presence of debris cover, or contact with a glacial lake (Shean et al., 2020). Local factors, including glacier response to shifting precipitation patterns, can dampen or amplify mass-balance responses to temperature-induced changes in equilibrium line altitude (ELA), explaining departures from the dominant picture of predominantly temperature-induced glacier retreat, such as the Karakoram Anomaly (Farinotti et al., 2020).

The IPCC's *Sixth assessment report (AR6)* did not identify formal climate change attribution studies for individual glaciers in the HKH, although glaciers in the region are included in attribution literature underlying the IPCC's assessment (e.g. Hirabayashi et al., 2016). Nevertheless, observations of glacier retreat since the mid-nineteenth century across much of the HKH region (Bolch et al., 2012), existing literature on the drivers and mechanisms of retreat in the region, and attribution of glacier retreat in other regions provide empirical and theoretical

bases that suggest that the observed changes in HKH glacier lengths can *very likely* be attributed primarily to human influence.

ATTRIBUTION OF CHANGES IN TEMPERATURE AND PRECIPITATION

The IPCC's *Sixth assessment report* assessed that anthropogenic warming is approximately equal to observed global warming between 1850–1900 and 2010–2019 (Eyring et al., 2021). Since the mid-twentieth century, anthropogenic influence has also been the main contributor to increases in surface temperature in high mountain regions (Hock et al., 2019). Regional assessments applying optimal fingerprinting methods found that the observed temperature change over India can be attributed primarily to greenhouse gas forcing, balanced by cooling due to other anthropogenic forcings, largely associated with aerosols and land-use change (Dileepkumar et al., 2018). Anthropogenic forcing is also the dominant driver of annual and seasonal temperature change in regions surrounding the HKH, including Central Asia (Peng et al., 2019) and western China (Y. Wang et al., 2018).

Attribution of changes in precipitation extremes is more region-specific and evidence in the region is limited. Extreme precipitation events are increasing in frequency in north-western (Malik et al., 2016), western (Madhura et al., 2015), and central HKH (Talchabhadel et al., 2018), but such trends have not been observed in the eastern HKH (Doblas-Reyes et al., 2021).

Although actual attribution in the region is still lacking, it has been noted in AR6 that “most of the observed intensification of heavy precipitation over land regions is likely due to anthropogenic influence” (Seneviratne et al., 2021). Locally, studies have also already shown human influence on precipitation dynamics, for example, through aerosols (Adhikari & Mejia, 2021) or irrigation (Devanand et al., 2019).

ATTRIBUTION OF CHANGING GLOF HAZARDS IN THE HKH

The retreat of mountain glaciers has increased the size and number of glacial lakes (Shugar et al., 2020). In the HKH region, analyses of remote-sensing data showed that the number and area of

glacial lakes have increased during 1990–2010. Lakes close or adjacent to glacier termini – for which the relationship between glacier retreat and lake size is the most direct – have undergone the largest changes in area (G. Zhang et al., 2015). Between 1990 and 2015, 401 new glacial lakes formed across the western, central, and eastern Himalaya, and lake area increased by 14.1% across the region (Nie et al., 2017). These increases in glacial lake area have been attributed to glacier retreat (W. Wang et al., 2015) and have led to an increase in the number of glacial lakes identified as potentially dangerous (Bolch et al., 2019).

Recent research demonstrated a clear link between human-induced climate change and an observed GLOF event and ongoing risk of a GLOF from a glacial lake in Peru (Stuart-Smith et al., 2021). No such formal attribution studies have been conducted to date in the HKH region, although Zheng, Mergili, et al. (2021) provided a strong argument for linking a landslide from a destabilised lateral moraine and a related outburst of the rapidly expanding Jinwuco Lake in 2020 to anthropogenic warming and glacier retreat. Substantial increases in the number and size of glacial lakes are projected to occur and result in elevated GLOF risk across the HKH due to future climate change (Furian et al., 2021, 2022; Zheng, Allen, et al., 2021). The IPCC's AR6 stated that many newly-formed lakes in the HKH will develop at the foot of steep slopes, and that the risk of avalanches from steep, glaciated slopes and mass movement resulting from reduced slope stability as permafrost degrades is increasing across the region (Ranasinghe et al., 2021). Given the consistency in the relationship between observed and projected climate change, glacier retreat, and GLOF hazards, these findings provide a strong indication that existing changes in GLOF hazards can also be attributed to anthropogenic influences.

The increase in GLOF hazards through the formation and expansion of glacial lakes has not yet translated into an elevated rate of flood events. Despite increases in the number and size of glacial lakes, there is limited evidence of an increase in the numbers of GLOFs in recent decades worldwide (Harrison et al., 2018). This is in line with observations from the HKH, where the frequency of GLOFs from moraine-dammed lakes has not increased since the late 1980s (Veh et al., 2019). This is likely to be a consequence of the

sequential timescales over which (i) glacier retreat responds to climatic perturbations, and (ii) GLOFs occur following glacier retreat and lake formation or expansion. Mountain glacier lengths respond to changes in climate on multi-decadal timescales (Jóhannesson et al., 1989). As glaciers retreat, an additional period of time, which may extend to decades or centuries, will elapse before GLOF-triggering events occur.

The magnitude of the anthropogenic contribution to individual GLOF events will differ across both climatic as well as topographic settings. The size of this contribution will depend on whether climate change has led to the formation or expansion of a lake, the extent to which observed changes in glacier length exceed the range of fluctuations that can be explained by natural variability alone, and whether or not anthropogenic climate change has played a role in the GLOF trigger, for instance by undermining slope stability.

3.3.4. Observed and projected changes in erosion and sediment loads driven by cryospheric degradation and a changing hydrology

CURRENTLY OBSERVED CHANGES IN EROSION AND SEDIMENT LOADS, AND THEIR DRIVERS

Climate change and associated cryospheric degradation can severely alter erosion and sediment transport in high mountain areas that has a bearing on land degradation, soil productivity, hydropower systems, water quality, and aquatic ecosystems. Here, we synthesise the available evidence regarding increased erosion and sediment loads in the pristine headwaters in HMA from the scientific literature, presenting evidence for increases in sediment yields driven by climate change and cryospheric degradation. On average, the suspended sediment load from HMA headwaters has increased by ~80% over the past six decades in response to accelerating glacier melt and permafrost thaw, and increased precipitation (D. Li et al., 2021). In the western Himalaya, the increased sediment yields coincide with accelerating glacier recession. In the Chandra River of the Ganges Basin, a two-fold increase in suspended sediment load has been observed between

1978–1995 and 2017, accompanied by a 67% reduction in the mass of low-elevation glaciers (Singh et al., 2020). In the headwaters of the Yangtze River, the thawing of ice-rich permafrost and the associated expansion of active erodible landscapes have led to a net increase in suspended sediment load by 135% between 1985–1997 and 1998–2016 (D. Li et al., 2020, 2021). In the headwaters of the Brahmaputra River, the suspended sediment load has increased by ~70%, mainly due to increased precipitation and because of intensified glacier melt and thawing of permafrost (Shi et al., 2022). Furthermore, erosion and sediment load in years with GLOFs have been reported to be significantly higher than those without (Cook et al., 2018), although the long-term trends of changes in the magnitude and frequency of GLOFs in HMA remain largely uncertain (Veh et al., 2019; Zheng, Allen, et al., 2021). There exists a link between extreme precipitation (and the resulting increase in rainfall erosivity) and sediment yields. However, while this has been investigated in downstream areas of watersheds originating in the HKH (X. Xu et al., 2021; Z. Xu et al., 2021), it has so far not been investigated within the HKH itself.

Observations on bedload (for example, gravels and boulders) transport in HMA are extremely rare. However, knowledge on bedload is especially relevant to the operation of hydropower systems and aquatic habitats for fishes and macroinvertebrates. In a changing climate, the bedload flux in HMA's rivers could also have increased substantially over the past decades due to the increasing discharge and will likely continue to increase in the future (D. Li et al., 2021).

In addition to the multi-decadal increases in erosion and sediment loads in HMA, decreased sediment loads or stability in sediment loads have also been reported (D. Li et al., 2018; Swarnkar et al., 2021). Such distinctive trends are often due to the impacts of human activities (for example, large amounts of sediment inflow trapped in large reservoirs [D. Li et al., 2018]) and the large storage of sediment in the sediment cascade system (for example, substantial sediment deposition on floodplains and wide alluvial valleys [Sinha et al., 2019]).

FUTURE PERSPECTIVES ON DOWNSTREAM IMPACTS OF CHANGING EROSION AND SEDIMENT LOADS

Using a climate elasticity model (that evaluates the effects of changing temperature and precipitation), a recent study stated that fluvial sediment loads will *very likely* increase in the coming decades in a warmer and wetter HMA (D. Li et al., 2021). The modelling results show that, on average, a 10% increase in precipitation results in a $24\% \pm 5\%$ (mean \pm standard error) increase in sediment load, and that a 1°C increase in air temperature results in a $32\% \pm 10\%$ increase in sediment load. For a less extreme climate change scenario (that is, temperature increases by 1.5°C and precipitation increases by 10% by 2050, relative to the 1995–2015 averages), the total sediment load from HMA as a whole will increase from 1.94 ± 0.80 billion tonnes per year (Gt per year) at present to 3.32 ± 1.18 Gt per year. For an extreme climate change scenario, (that is, temperature increases by 3°C and precipitation increases by 30% by 2050, relative to the same baseline period, 1995–2015), the total sediment load from HMA will likely more than double. However, the predicted future fluvial sediment load from HMA represents projections reflecting the impact of climate change on sediment export from basin outlets located both within and towards the margins of HMA. As such, they are therefore not the direct reflection of the actual sediment output from HMA's rivers, because sediment storage in downstream, wide alluvial valleys, future reservoir construction, and land-use changes could also impact sediment loads substantially (Syvitski et al., 2022).

In a warmer future associated with more precipitation extremes, sediment yields in glacierised basins in HMA can be expected to initially increase, driven by increased glacial erosion and sediment supply, increased transport capacity (meltwater discharge), expanded subglacial drainage networks, and increased rainstorms and extreme floods (Herman et al., 2021). However, with continuing glacier recession, there will be an eventual decline in sediment yields due to the reduced glacial erosion and meltwater when glaciers shrink below a certain size and landscape stabilisation through negative feedbacks (for example, the formation of alluvial fans decreasing sediment connectivity and colonisation by vegetation in proglacial areas [Lane et al., 2017]). The duration of the current increasing phase of

sediment yields is likely scale-dependent, with the timing of ‘peak sediment yield’ close to the timing of ‘peak discharge’ of nearby glaciers and decades to centuries later in larger, downstream regions (D. Li et al., 2022).

Increased riverine sediment loads will not only threaten hydropower systems through causing reservoir sedimentation, conduction canal or tunnel sedimentation in run-of-the-river hydropower projects, and turbine abrasion, reducing reservoir lifespans and affecting reservoir services for water supply, hydropower generation, irrigation, and flood control (D. Li et al., 2022). The rising riverine sediment concentrations can also negatively impact water quality and aquatic ecosystems. Fine, suspended sediment particles constitute an important vector for the transport of phosphorus and most heavy metals, such as mercury, chromium, arsenic, and lead. Thus, climate change is likely to increase sediment-associated nutrient and contaminant fluxes in HMA’s rivers. Furthermore, suspended sediment is a key vector for organic carbon transport; the precise role of erosion and sediment delivery in mobilising organic carbon from glacial and permafrost landscapes and delivering it to fluvial systems could be substantial. Current fluvial sediment in HMA could carry a total of 20–60 million tonnes (Mt) of carbon per year, and this number could more than double by 2050 under extreme climate change scenarios (D. Li et al., 2021). More observations are needed to assess the positive feedback between climate warming, permafrost degradation, and the carbon cycle.

3.3.5. What to expect: Projected changes for mountain hazards

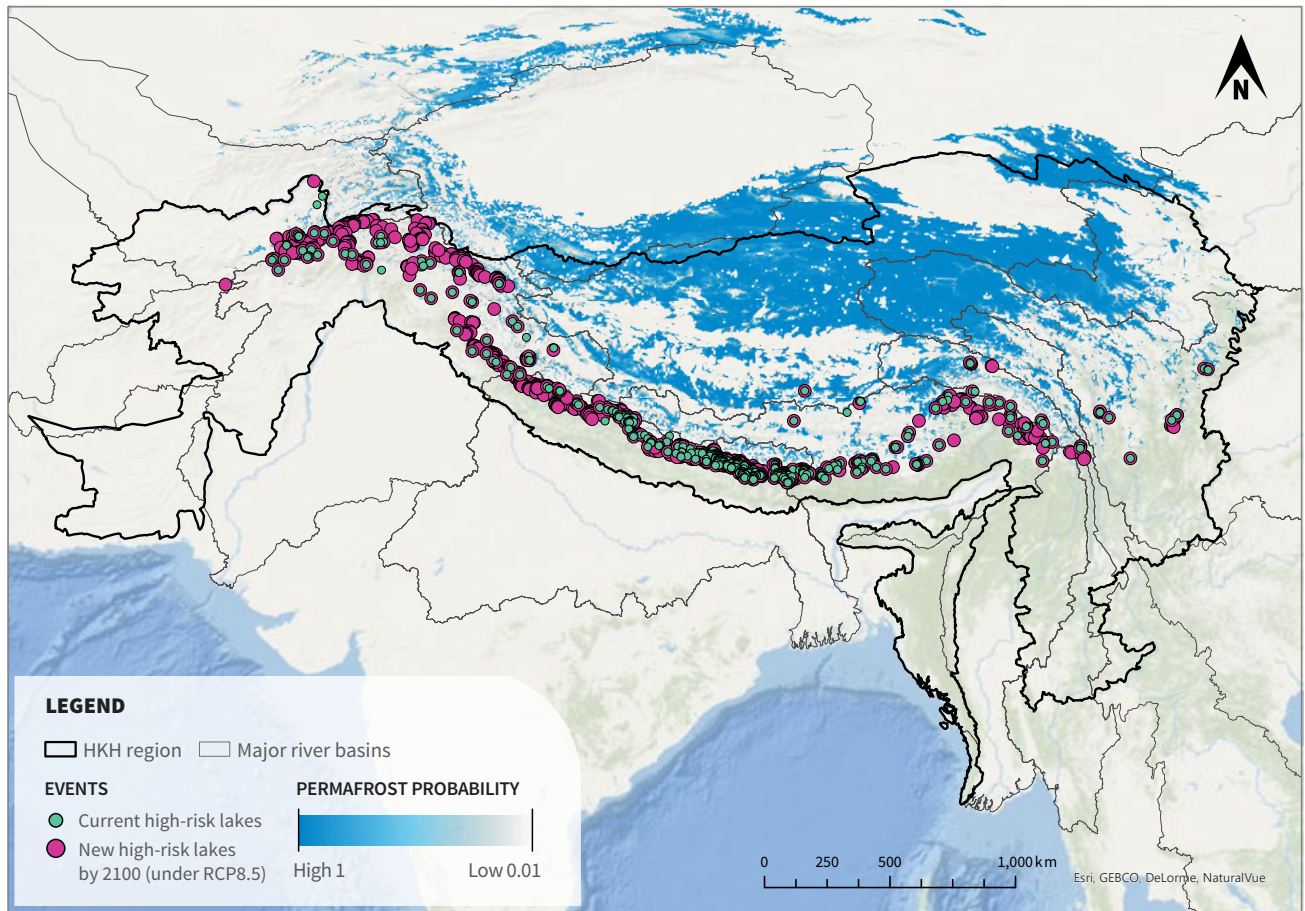
Few studies have systematically modelled and assessed projected changes in cryosphere-related hazards in the HKH. As a consequence, projections are typically based on inferences from what has been observed in the past, both in the HKH and more widely in other regions, and what can be expected based on a physical understanding of the underlying processes and their linkages. Therefore, even an absence of evidence regarding, or ambiguity in past trends does not necessarily allow us to discard a certain process from happening in the future.

As assessed by the IPCC, confidence is generally highest concerning projected changes in GLOFs, owing to the continued growth of existing lakes, and the formation of many new lakes anticipated over the coming century in most mountain regions (Hock et al., 2019). As a consequence, South Asia, the Tibetan Plateau, and Central Asia have been highlighted as regions where severe disruption to people and infrastructure can be expected from flooding, under global warming levels of 1.5°C–3°C above pre-industrial levels (Adler et al., 2022). This finding is underpinned by several regional and local studies that project significant future glacial lake expansion as depressions in glacier beds are exposed by retreating ice (Furian et al., 2021; Mal et al., 2021; Rashid & Majeed, 2018; Sattar et al., 2021; Zheng, Allen, et al., 2021).

Considering not only the future expansion of glacial lakes, but also the physical characteristics of lake catchments and dam areas as well as exposure of communities and infrastructure downstream, Zheng, Allen, et al. (2021) demonstrated a potential 3-fold increase in GLOF risk across HMA 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 RCP scenarios. Meanwhile, lakes in the western Himalaya and Karakoram will continue to increase significantly into the late twenty-first century and beyond. Not only does lake expansion increase the potential magnitude of future events, it also brings lakes closer towards steep and potentially destabilised mountain headwalls, increasing the likelihood of rock-ice avalanches triggering an outburst event (Haerberli et al., 2016; Sattar et al., 2021). Relative to current conditions, GLOF risk will increase most significantly in the central and western Himalayan regions, but the eastern Himalaya, including transboundary basins of Tibet and Nepal, remain the primary GLOF risk hotspot under all RCP scenarios (Figure 3.7; Zheng, Allen, et al., [2021]). Over longer timescales, and under larger warming scenarios, the Karakoram could emerge as a new major hotspot of GLOF hazards and risk (Furian et al., 2021; Zheng, Allen, et al., 2021), although there is large uncertainty in this prognosis given the current anomalous behaviour

FIGURE 3.7

CURRENT AND POTENTIAL HIGH-RISK LAKES IN THE HKH



Note: The black line marks the HKH outline, permafrost extent is shown in blue, and glacier outlines are shown in white.

Sources: Obu (2021); Zheng, Allen, et al. (2021)

of glaciers in this region. Not considered by existing studies is the longevity of current and future glacial lakes, which may be affected by catchment erosion and sedimentation. If results from the European Alps are taken as indicative for the HKH, as much as 50% of the projected future lakes may be transient features, disappearing again before the end of the century owing to their being refilled with sediments (Steffen et al., 2022).

Hock et al. (2019) concluded, with *medium confidence*, that snow avalanches are projected to decline in number and runout distance at lower elevations, while avalanches involving wet snow will occur more frequently. With very few studies focusing on the HKH, a more nuanced regional assessment cannot be provided. At least in the western Himalayan region, Ballesteros-Cánovas et al. (2018) suggest, based on an extrapolation of reconstructed trends,

that climate warming will continue to increase the hazard of avalanches, as warmer air temperatures in winter and early spring favour the more frequent occurrence of large, wet snow avalanches, which are able to reach populated valley bottoms. Devastating high elevation snow, or mixed snow-ice avalanches in Langtang, Nepal and Gayari, Pakistan (Fujita et al., 2017; Saif et al., 2022) highlight the particular threat of earthquakes occurring during periods of heavy snow loading. Extremely heavy precipitation events are expected to become more frequent in the future. At the highest elevations, this precipitation will continue to fall as snow, and large, earthquake-triggered snow avalanches are likely to be high-impact but low-frequency threats in the HKH.

Large avalanches of rock and/or ice are expected (with high confidence) to increase in frequency and magnitude under a warmer climate, with

implications for associated, far-reaching cascading processes (Hock et al., 2019). This is underpinned by detailed examinations of several recent cascading events in the HKH, including a rock avalanche-triggered GLOF in the Upper Barun, Nepal (Byers et al., 2019), catastrophic floods generated by rock-ice avalanches along the Seti River, Nepal and Chamoli, India (Kropáček et al., 2021; Shugar et al., 2021; Siddique et al., 2022), and repeated rock-ice avalanches blocking the Yarlung Tsangpo River in eastern Tibet (W. Li et al., 2022). While climate change cannot be directly attributed as the cause for any one of these or earlier events, a common finding has been the identification of 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 preconditioning and triggering factors are expected to become increasingly prevalent and relevant over the coming decades (Adler et al., 2022; Hock et al., 2019). At high elevations, cold permafrost is degrading slowly in response to atmospheric warming, leading to potential long-term and deep-seated destabilisation processes that could persist for centuries, even after atmospheric warming stabilises (Gruber et al., 2017; Shugar et al., 2021).

The drivers of large-scale detachments of low-gradient glacier tongues remain insufficiently understood. Nonetheless, the hypothesised requirement for partially or fully thawed glacier bed conditions and the presence of liquid water would point to a possible mechanism by which climate change could increase the frequency of such events in the future as well (Kääb et al., 2021; Leinss et al., 2021). A warmer climate increases the amount of meltwater, and may thus favour the development of instabilities, particularly in cold, dry environments, while thawing beneath and at the sides of glaciers could reduce shear stresses (Kääb et al., 2021).

Climate change and its influence on hazard processes is finally only one driver of future disaster risks in the HKH, and future changes in exposure and societal vulnerabilities could potentially lead to vastly different risk scenarios, especially where political, economic, and social conditions facilitate or impede effective disaster risk reduction (Zheng, Allen, et al., 2021). The current and planned expansion of hydropower infrastructure high into alpine valleys is of particular concern in relation to future GLOF risk (Mal et al., 2021; W. Wang et al., 2022), and risks associated with other avalanche-triggered cascading processes (Shugar et al., 2021).

3.4. Cumulative impacts on water use systems

The importance of the cryosphere for societies goes much beyond the provision of water and ecosystem services to people living in high mountain areas. Especially in river basins where the downstream plains receive little precipitation or highly variable precipitation, or both, but where human activity is high, the water resources originating from the mountains are crucial for a secure and stable downstream water supply. Over the past few years, research into the quantification of these upstream-downstream dependencies, and the impacts of climate-related cryospheric changes on downstream

water users has advanced significantly (Mukherji et al., 2019; Rasul & Molden, 2019).

Upstream and downstream linkages occur at different scales. The magnitude and nature of problems and related effects differ between the local micro catchment scale and the regional macro river basin scale. The activities and processes, both natural and anthropogenic, in upstream areas can influence downstream resources such as water availability and river morphology. For example, deforestation, erosion, water diversion, and infrastructure can alter the natural flow of a river and can affect water availability in downstream areas. Changes in wet and dry years have also already resulted in changes in agricultural area, crop

yields, and an increase in damages in downstream areas (Bastakoti et al., 2017). Understanding these linkages can help integrated land and water planning and management (Flügel et al., 2018).

Glaciers, snow, permafrost and seasonally frozen ground, river and lake ice, glacial lakes, wetlands, and springs are the key components of the cryosphere and high mountain hydrosphere in the HKH. They provide provisioning, regulating, supporting, and cultural services, as well as disservices (Mukherji et al., 2019). The services are important not only for mountain communities but also in the lowlands (Rasul & Molden, 2019), and the disservices in the form of ice or snow avalanches or GLOFs can have far-reaching, cascading impacts (see subsection 3.4.2). From a water resources perspective, cryospheric services are important for sustaining river flows, recharging groundwater, and water use systems such as irrigation, domestic water supply, and hydropower (Scott et al., 2019).

3.4.1. Impacts of cryospheric change on agricultural and livestock services

In many river basins around the world, mountains provide a disproportionately high share of run-off to river basins, either from snowmelt run-off from glaciated catchments or contributions from streams, and therefore are important contributors to rivers flowing through downstream plains. Due to the increasing water consumption in those downstream areas, the global dependence on mountain water has risen immensely between the 1960s and the present, and is projected to increase further towards the middle of the twenty-first century (Viviroli et al., 2020). Many large irrigation systems are located in areas that are highly dependent on mountain water, implying that food production in those areas face the same dependence. In a comparative analysis, the water towers in the HKH (Indus, Ganges–Brahmaputra, Amu Darya, and Tarim Interior) were identified as among the most important in the world, because of their relatively high water supply from glacier melt and snowmelt combined with large downstream water demands (Immerzeel et al., 2020). Moreover, these five river basins – especially the Indus Basin – are also ranked among the most vulnerable to further increasing

pressures on water resources resulting from a combination of growing population, climate change, governance, and hydro-political tensions.

In the Indus Basin, more than 60% of the total annual flow that enters the Arabian Sea originates from snowmelt and glacier melt, but the meltwater contribution to the flow varies through the year (Biemans et al., 2019). Due to larger volumes of monsoon precipitation in India and Bangladesh as compared to Pakistan, the meltwater contribution to the flows of the Ganges and Brahmaputra river basins is much less, at around 10% and 20% respectively.

Quantifying the impacts of cryospheric processes on downstream water resources requires a good understanding and accurate representation of the spatial and temporal water demand and supply patterns, especially in a region where water shortages are mainly related to a spatial and temporal mismatch between water availability and demand, rather than an absolute shortage. In recent years, the representation in hydrological models of seasonal irrigation demands of complex cropping systems has improved (Biemans et al., 2016; Mathison et al., 2021). Additionally, the representation of the lateral transport and distribution of mountain water through irrigation canals, which is essential to understand the importance of mountain water for downstream uses, has also improved. It has been estimated that 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 continuous availability of meltwater flow is crucial to irrigate the *kharif* (summer) crops, rice and cotton (Biemans et al., 2019). This buffering role of meltwater during dry periods has also been analysed and confirmed elsewhere (Pritchard, 2019), and is expected to continue during the rest of the twenty-first century (Ultee et al., 2022).

Glacier melt has already accelerated over past decades due to climate change (Hugonnet et al., 2021), and will further increase before eventually decreasing (Kraaijenbrink et al., 2017). Maybe most important in the shorter term for water users downstream is the projected seasonal shift in

meltwater flows to earlier in the spring (Lutz et al., 2016). Only a few studies have quantitatively assessed the complex interactions between seasonal dynamics in meltwater flows and agricultural water demand. Qin et al. (2020) performed a global analysis in which they focused on snowmelt use for irrigation under climate change. Because the HKH stores the world's largest volumes of ice and snow outside of the poles, and also has a very intensive agricultural system, unsurprisingly most of the global hotspots of snow-dependent agriculture are found to be the river basins originating in the HKH. A 4°C warming scenario for the Indus and Amu Darya river basins will result in a decrease of 10–15 percentage points in the share of irrigation demand that can be met by snowmelt, which will have to be met by other sources of water (Qin et al., 2020).

A recent study describing a similar analysis focusing on the Indus, Ganges, and Brahmaputra basins presented a slightly different picture, with a lower decrease in meltwater's contribution to irrigation (Lutz et al., 2022). The study combined both snowmelt and glacier melt – the latter releasing water slower than snow – and also incorporated the expected increase in irrigated area due to socio-economic developments. It concluded that the dependence of irrigated agriculture on both glacier melt and snowmelt and groundwater will gradually increase. Due to earlier melting, the amount of meltwater available for irrigation during the beginning of the *kharif* season will increase. However, later in the season, meltwater availability will decrease. Combined with a higher variability in rainfall run-off, groundwater will be used to compensate for the lower surface water availability, potentially leading to further overdraft and depletion of aquifers.

Farmers rely on snowmelt and glacier melt run-off for irrigating land (Biemans et al., 2019). As mentioned earlier, meltwater supplies up to 83% of annual groundwater recharge in the Upper Indus River Basin, emphasising the importance of the cryosphere in sustaining groundwater resources in the basin (Lone et al., 2021). Meltwater-derived recharge is split evenly between glacier meltwater (44% of annual recharge) and snowmelt (39%); in contrast, rainfall contributes only 17% of annual recharge. Snowmelt is also an important source of soil moisture, which is critical for crop growth and therefore the food security of mountain

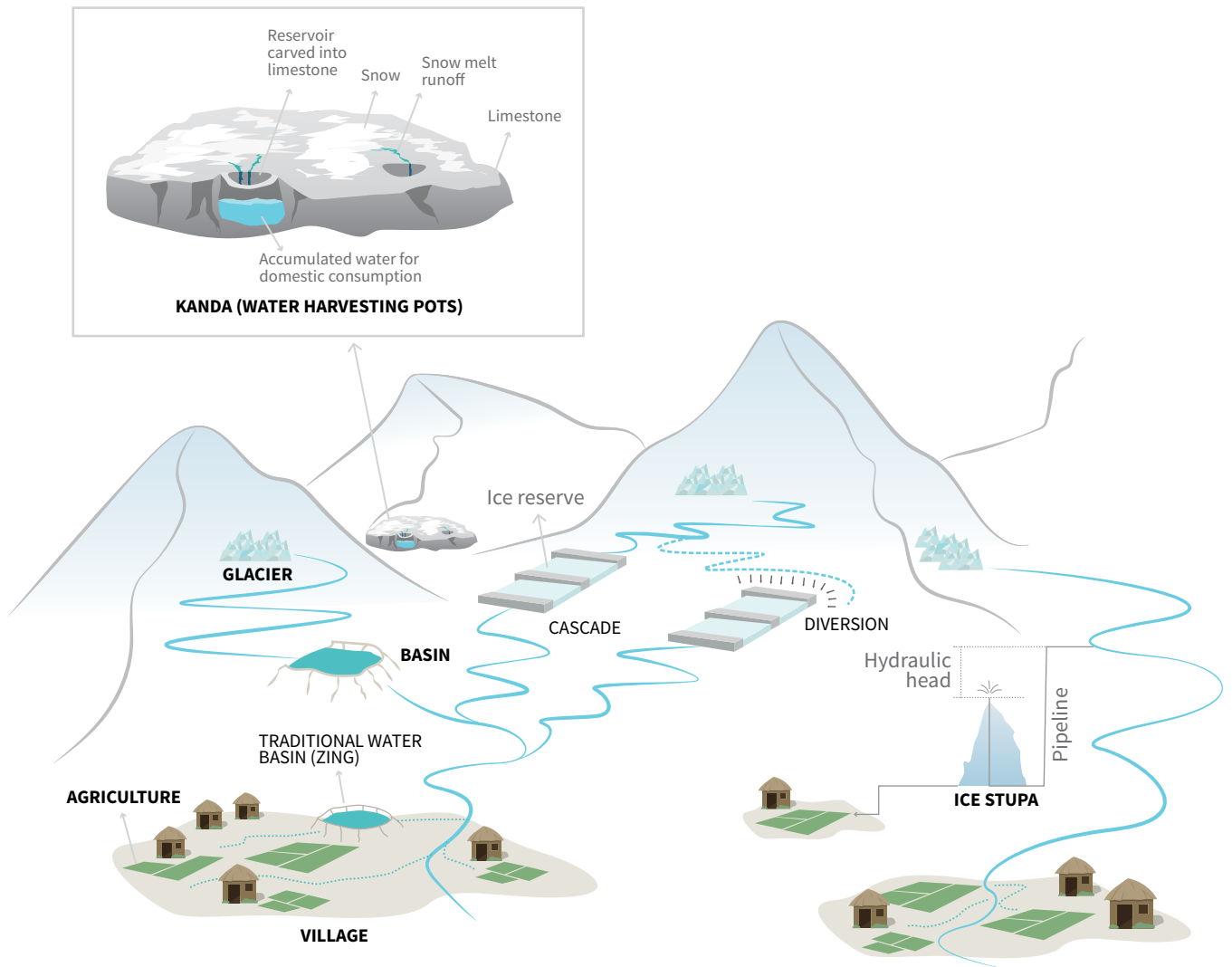
communities. River and spring water is also used for agriculture (Hill, 2017; Nüsser, Dame, Parveen et al., 2019).

In the Indus Basin, snowmelt and glacier melt account for up to 60% of total withdrawal for irrigation during the pre-monsoon season and contribute an additional 11% to total crop production. Although there is less reliance on meltwater in the Ganges floodplain, it is still required during the dry season for crops such as sugarcane. In the Brahmaputra Basin, the reliance on meltwater is negligible. Snowmelt and glacier melt supply enough water to cultivate sufficient food crops to provide 38 million people a nutritious diet (Biemans et al., 2019).

Irrigation systems differ based on biophysical, social, and governance factors such as the extent of irrigated area, water allocation and rules and regulations about distribution, topography, glacier size, water availability, and other factors (Wagle et al., 2021). In Ladakh, India, irrigation is entirely dependent on meltwater from glaciers and snowfields. Highland communities construct artificial glaciers to access water for irrigation and other needs during the dry months (Figure 3.8; Nüsser, Dame, Kraus, et al. [2019]). In Afghanistan, rural communities harvest snow and run-off in *kandas* (Figure 3.8), underground water tanks that are carved out in limestone catchments, particularly in the rangelands for herders and livestock, as well as in water-scarce villages for drinking. In the upper basins of the HKH, cryospheric disasters such as flash floods, landslides, riverbank erosion, GLOFs, sedimentation, and periodic avalanches, warming-induced melt, as well as turbulent/variable flows, low temperatures, depletion of springs, and water shortages are common threats to agricultural systems (Clouse et al., 2017; Hill, 2017; Nüsser, Dame, Kraus, et al., 2019; Scott et al., 2019). Climate change is accelerating the melting process, and intensifying water shortages, with adverse impacts on snow- and glacier-fed irrigation systems (Figure 3.8). Many irrigation systems in the Upper Indus Basin have become inoperable as a result of glacier retreat, and irrigation canals are routinely destroyed by GLOFs, floods, river bank erosion, and sedimentation, necessitating a great deal of labour and time to restore them (Dhakal et al., 2021). As a result, many arable fields are lying barren.

FIGURE 3.8

ICE AND SNOW RESERVOIR SYSTEMS IN THE HKH FOR WATER SECURITY DURING LEAN SEASONS



Source: Nüsser, Dame, Kraus, et al. (2019)

Poudel (2011) found that the hydrological consequences of declining snow and ice mass reduced access to water for irrigation, resulting in the abandonment of large swathes of agricultural fields in the villages of Upper Mustang and Upper Manang, Nepal. Over the course of eight decades, 39.5% of the total cultivated land in Upper Mustang has been abandoned. About 35% of the cultivated land in Ghiling hamlet in Upper Mustang has been abandoned owing to a dwindling supply of water for irrigation. Other manifestations of reduced water

availability, according to this study, were the drying up of springs and a decrease in soil moisture in fields. The farmers in Upper Mustang used to irrigate their fields twice a year and those in Upper Manang three times a year but now they need to water their fields about 4–6 times a year. The declining water availability in irrigation sources on the one hand and an increased requirement for irrigation on the other cause water scarcity and land abandonment. This has also led to increased conflicts over irrigation water in the villages. Also in Nepal, Langtang experiences

heavy snowfall, avalanches, and landslides because of changing snowfall and rainfall patterns, and temperature increases, resulting in fodder and water shortages for livestock and increased animal mortality (Tuladhar et al., 2021).

The majority of the towns in the HKH's high mountains and mid-hills rely on spring water for household and agricultural uses. There are only a few publications that discuss the interconnections between springs and changes in the cryosphere. Kulkarni et al. (2021) reported that as springs in the Baspa and Spiti basins in India have largely dried due to decreased snowfall, many farmers have started drawing water from high-elevation meltwater streams using pipes, and from the Baspa River for irrigation. Due to the depletion of springs, farmers in the Spiti Basin have created temporary water storage and diversion structures out of stones.

3.4.2. Cascading impacts and upstream–downstream linkages

Changes in the cryosphere and subsequent hydrological processes are having biophysical, socio-economic, and cultural impacts in the HKH.

Mountains face cascading hazards, the cascading sequence being a chain of events triggered by multiple hazards upstream to downstream under the influence of topography and gravity. In 2021, a major cascading event occurred in Melamchi Municipality, Nepal, owing to multiple factors and processes occurring at various locations along the Melamchi River (Maharjan et al., 2021). The study cited found rapid snowmelt due to unusual warming, along with heavy precipitation in the river's headwaters. This resulted in the erosion of glacial deposits and a large deposition of moraine in the valleys downstream. Incessant rain led to the sudden mobilisation of moraine material, triggering flash floods that lasted for 3–4 days. This multi-hazard event turned into a cascading disaster in which the cumulative impacts were much larger than the sum of the individual hazards. As many as 337 houses were damaged, 525 families displaced, 13 suspension bridges washed away, and over 1.75 km² of irrigated land damaged. Due to this disaster, the opening of the Melamchi water supply scheme to Kathmandu has been indefinitely delayed.

Similarly, the Chamoli disaster – triggered by a large rock-ice avalanche that caused a huge debris flow – in Uttarakhand, India, in 2021 had immediate effects on hydropower and other infrastructure, and led to a significant loss of life (Shugar et al., 2021). Meena et al. (2021) investigated the water quality along the course of the Ganges River and its tributaries after the event. They chose four locations to study the changes in the water quality associated with the Chamoli disaster and the inadvertent effects of greater sediment load in the river channels. They strategically chose locations near the disaster-affected dam in the upper reaches and sandbar areas on the floodplain in the lower reaches to study the abrupt changes associated with the large increase in the volume of water flows (due to flooding) and the greater turbidity and chlorophyll concentrations in the rivers. Changes were observed in water flows from the source (Tapovan) until the downstream location of Bijnor. The visual comparison between before and after the event showed a qualitative increase in the sediment concentrations in the rivers after the event. Eight days after the event, a main channel for water supply to Delhi recorded 80 times the permissible level of sediment in the water, indicative of the far-reaching consequences such disasters can have. They attributed these changes to the increase in the water level after the Chamoli disaster, associated with the large volume of debris in the river.

3.5. Key knowledge gaps and potential pathways forward

Despite advances in understanding regarding the effects of cryospheric change in the HKH on water resources, especially within the last decade, critical gaps remain. This section summarises some of those key gaps and suggests some potential pathways forward.

3.5.1. Knowledge gaps

Knowledge gaps regarding cryospheric change in the HKH can be broadly categorised into process gaps and monitoring gaps. Process gaps are when little is known about certain fundamental hydrological processes in the cryosphere, even though they may dramatically affect water resource availability downstream or have indirect impacts through related processes, such as hazard risks. The concept ‘process gap’ could also be extended to hydrological modelling efforts intended to describe cryospheric hydrology: though physical processes may be understood, research efforts may not have translated this understanding into studies, models, or analyses.

Monitoring gaps may exist in situations in which hydrological processes are understood, but physical constraints or insufficient resources for research have hindered primary data collection and subsequent hydrological characterisation of cryospheric components and their changes over time, or the calibration and validation of models. Furthermore, inadequate longevity of research support may produce lapses in the long-term data streams required to capture inter-annual variability and climatic trends.

These two types of knowledge gaps are not fully distinct: some process understanding is required to design effective monitoring approaches, and alternately, efforts to fill monitoring gaps may, in some situations, elucidate further process gaps. Nonetheless, the distinctions are maintained here as the approaches used to fill these gaps may differ considerably in content and duration. These process and monitoring gaps can be grouped into five domains, described below.

GAPS REGARDING THE CONTRIBUTION OF KEY CRYOSPHERIC COMPONENTS TO HIGH MOUNTAIN HYDROLOGY

Prior sections in this chapter have described the critical importance of the cryosphere in the HKH in supplying water across multiple water uses for billions of people downstream, as well as in driving upstream and downstream hazards. Yet, critical gaps remain in our understanding of the role of glaciers, snow, and permafrost in the hydrological cycle in high mountain areas of the HKH.

Reviews, primarily over the last decade, have identified a series of these knowledge gaps (Immerzeel et al., 2010; Turner & Annamalai, 2012; Wester et al., 2019). Critical process gaps include permafrost dynamics: there is little knowledge concerning the contribution of permafrost to the hydrology of the HKH river systems, and to mountain hydrology in general. Furthermore, monsoon dynamics have been poorly understood, and recent monsoon studies (Azmat et al., 2020) lack explicit linkages to cryospheric hydrology.

Monitoring gaps in high mountain areas of the HKH have been especially prevalent, due to the physical difficulties in collecting data in a harsh climate and inaccessible terrain. These gaps have been reflected in all the three major cryospheric components, though not to similar degrees. Glacier dynamics have been perhaps better understood (Nie et al., 2021; Srivastava & Azam, 2022) than snow or permafrost, but a scarcity of observations on glacier mass balance have persisted, and the limits of increases in glacier meltwater and its timing, that is, ‘peak water’, remain unknown in the HKH. The relative contributions of ice and snow to streamflows have not been well understood, exacerbated by a general lack of snow data in the region. Wester et al. (2019) have described lacking streamflow data, important not only for estimating water supplies for downstream regions but also as a response signal for cryospheric and sub-surface dynamics upstream, as a key gap. Some specific streamflow data gaps have included (i) inadequate times series (in quality and duration) of river discharge for discharge trend analysis, (ii) discharge rating curves for high mountain areas that are generally unavailable or undocumented (and therefore of questionable quality), resulting in (iii) overall difficulty in characterising streamflow trends.

The non-representative nature and poor quality of data originating from a scarcity in sites that monitor precipitation, discussed in further detail below, continue to hinder hydrological characterisation across the region.

Some recent advances have begun to fill some of these process and monitoring gaps (Khanal et al., 2021; Nie et al., 2021; Srivastava & Azam, 2022; Wani et al., 2020). However, perhaps with the exception of peak water analyses (Hock et al., 2019; Huss & Hock, 2018; Nie et al., 2021), little progress in substantially filling these gaps is evident.

Furthermore, some process gaps not emphasised by previous reviews need to be highlighted:

- Recent hydrological modelling analyses (for example, Huss & Hock, 2018) have been regional or global in scope and have not emphasised robust testing and validation. Such macro-scale analysis can overlook key differences and processes that become evident at more granular scales.
- There is a growing recognition of the importance of springs and mountain groundwater, but little is known about mountain subsurface water flows and storage, and linkages between the cryosphere and subsurface flows have only been minimally studied. Aside from the generic treatment of the subject by Somers and McKenzie (2020), only one recent study (Illien et al., 2021) has addressed subsurface flows at higher elevations in the HKH, and this study did not extend to the cryosphere.
- Evaporation and sublimation processes, particularly over snow, are poorly understood. Though analyses of evaporation and sublimation from the cryosphere did not receive much research attention previously, several recent studies have begun to fill this gap (Guo et al., 2021; Mandal et al., 2022; Stigter et al., 2018), though it is important to note that these studies directly examine sublimation only over ice surfaces.
- The linkages between cryospheric change and sediment transport in the HKH river systems are important to understand because of their

potential for significant downstream impacts, but they are not well understood.

- The effects of cryospheric changes in the HKH on downstream water quality have not been studied. These changes are important to understand not only for human health, but also for ecosystem health.
- More widely, linkages between cryospheric change and high-elevation ecosystem change, for example, shifts in tree lines, are not well understood. For instance, thus far, only one study has focused on evapotranspiration – a key hydrological process linked to ecosystems – in high-elevation vegetation (L. Wang et al., 2020).

GAPS IN PROJECTIONS OF HIGH-ELEVATION MOUNTAIN HYDROLOGY UNDER A CHANGING CLIMATE

Some recent studies (for example, Khanal et al., 2021; Lutz et al., 2014) have attempted to move beyond the analysis of historic mountain hydrology to hydrologic projections under climate change over the coming decades. However, these studies are only preliminary forays into a critically important research domain, and significant process gaps regarding future HKH hydrology still exist. For instance, no known studies have considered the hydrological dynamics of high-elevation land surfaces that have until now been permanently covered by ice, snow, and permafrost, but which will likely lose that cover within the next several decades. In addition to land surface considerations, predicted shifts of the snowline, snow-to-rain transitions, and rain-on-snow phenomena have not been studied in the HKH.

GAPS IN THE CONSIDERATION OF GEOGRAPHIC AND INTER-BASIN VARIABILITY

The geographic trend of increasing meltwater proportions in basin discharges from east to west across the HKH region is well known. However, this longitudinal trend masks strong elevational and climatic gradients and hydrological changes over relatively short distances in the high elevations, and high inter-basin variability of ice and snow (Wester et al., 2019).

Monitoring efforts have been too spatially and temporally scattered to properly capture this variability, particularly in the distribution of precipitation (a monitoring gap). Furthermore, inter-catchment comparisons, needed to discern similarities in hydrological processes and differences between catchments and across elevational and precipitation gradients, are lacking, as is distributed forcing of precipitation in modelling analysis (process gaps).

GAPS IN KNOWLEDGE REGARDING THE EFFECTS OF CRYOSPHERIC CHANGE ON INTER-RELATED AND CASCADING DISASTER RISKS

Water-related disasters are growing in frequency and severity in the HKH, as climate change signals become increasingly apparent. However, little is known about how cryospheric shifts will induce secondary changes in mountain and downstream hazards, cascading hazards, and compound risks. This is true not only for ‘acute’ hazards, but also for ‘slow’ hazards such as droughts. Changing melt patterns, precipitation extremes, shifts in snow–rain interactions, and changes in permafrost are anticipated to encourage slope destabilisation, landslides, and sediment mobilisation, but these processes are poorly understood and therefore represent key process gaps.

GAPS IN KNOWLEDGE REGARDING THE CUMULATIVE IMPACTS OF CRYOSPHERIC CHANGE ON WATER USE SYSTEMS

Lowland populations downstream of the HKH are increasingly dependent on water supplies from the cryosphere, especially those areas situated downstream of the western HKH. Shifting cryospheric water supplies will shape downstream water demands, water uses, livelihoods, and infrastructure, though the linkages between upstream supplies and downstream uses are not well understood in the region. The impacts on urban water uses are especially poorly addressed. Though not cryospheric process gaps per se, these linkages are essentially ‘feedback loops’ between upstream supplies and downstream demands, and represent broader human–environment process gaps.

3.5.2. Responses and suggested strategies

The discussion above has outlined both process gaps and monitoring gaps across five domains. Advancements over the last two decades have both identified and incrementally filled some of the process gaps, while others have remained unaddressed. Ongoing efforts to fill these process gaps should continue in parallel with efforts directed at filling monitoring gaps, which are arguably the most limiting. Enhanced monitoring and subsequent data streams, accompanied by rigorous data quality assurance measures and metadata, are needed to better characterise how the cryosphere in the HKH has changed over time, and to project how changes will unfold in the future. They are also needed to calibrate and validate hydrological modelling and spatiotemporal extrapolation, and to support efforts to predict changes in mountain risks and hazards. Comprehensive, efficient, and cost-effective strategies are needed to fill the remaining gaps. Some suggested strategies are offered below.

Strategy 1

Establish a network of sentinel high-elevation collaborative research watersheds. The selected research watersheds ideally would (i) contain non-negligible glacier, snow, and permafrost areas, (ii) be carefully selected to ensure distribution across the geographic extent of the high-elevation HKH and to capture climatic and elevational gradients, and (iii) be explicitly linked to downstream water demands, water uses, and known hazard risks.

In situ monitoring within these sites would

- Characterise and monitor upslope cryospheric components, including snow water equivalent.
- Measure streamflow at the outlet.
- Include meteorological monitoring.
- Test and deploy novel techniques such as hydrochemistry, isotope analysis, and cosmic ray neutron sensor technology.
- Include citizen science primary data collection as an additional data stream.

- Emphasise long-term monitoring, as decadal time-series are necessary.
- Be explicitly linked to downstream water demands and uses that are of critical interest.

The selection of research watersheds could build on, and add value to some existing monitoring sites (Figure 3.9). Monitoring sites – defined as locations where more than one variable is monitored at more than a single coordinate for at least one year and the data is either openly accessible or has been published in peer-reviewed literature – exist in three countries so far. In India, observations focus specifically on permafrost in Ladakh (Wani et al., 2021) and glaciers in the western Himalaya at Dokriani and Chhota Shigri (Srivastava & Azam, 2022). In Nepal, the Langtang catchment covers many aspects of the water balance (Steiner et al., 2021), while field sites on Trambau Glacier, the Khumbu Glacier, and in the Hidden Valley focus mainly on glaciological observations. In China, the Tanggula and the Tuotuo He research sites have provided the basis for many studies so far and the Mahan (Wu et al., 2022) and Hulu catchments (Han et al., 2018) have also been documented more recently.

Keeping downstream water demands, water uses, and known hazard risks in view when establishing the sentinel monitoring sites would enable subsequent study of the impacts of upstream cryospheric changes on populations and ecosystems downstream.

Strategy 2

Build on previous research efforts, and couple the monitoring network (Strategy 1) with remote sensing and hydrological modelling to enable the extrapolation of current, historical, and projected changes to the cryosphere across the HKH, and the impact of those changes on downstream water resources.

Some key elements of this strategy would be to (i) encourage application of studies that link hydrology to other domains, such as ecosystems and livelihoods, (ii) include mountain subsurface flows as well as surface water flows, (iii) enable cross-catchment comparisons, (iv) encourage

linkages between micro-, meso-, and macro-scale analyses, and (v) carefully consider the underlying assumptions in climate projections and use ensemble approaches when appropriate.

The estimation of impacts on downstream water supply and demand must account for shifts in population and infrastructure, and thus, projections of how these will change in the future must be formulated in parallel with projections of cryospheric and hydrospheric change. These projections may additionally inform the design of the monitoring network and provide context for biophysical analysis. Some key issues to address in these projections would include: Where are urban areas projected to grow? What areas of the HKH are projected to depopulate? How will agriculture and land use shift under a changing climate?

Strategy 3

Develop institutional and political mechanisms to ensure long-term and stable support for these activities, as well as data access.

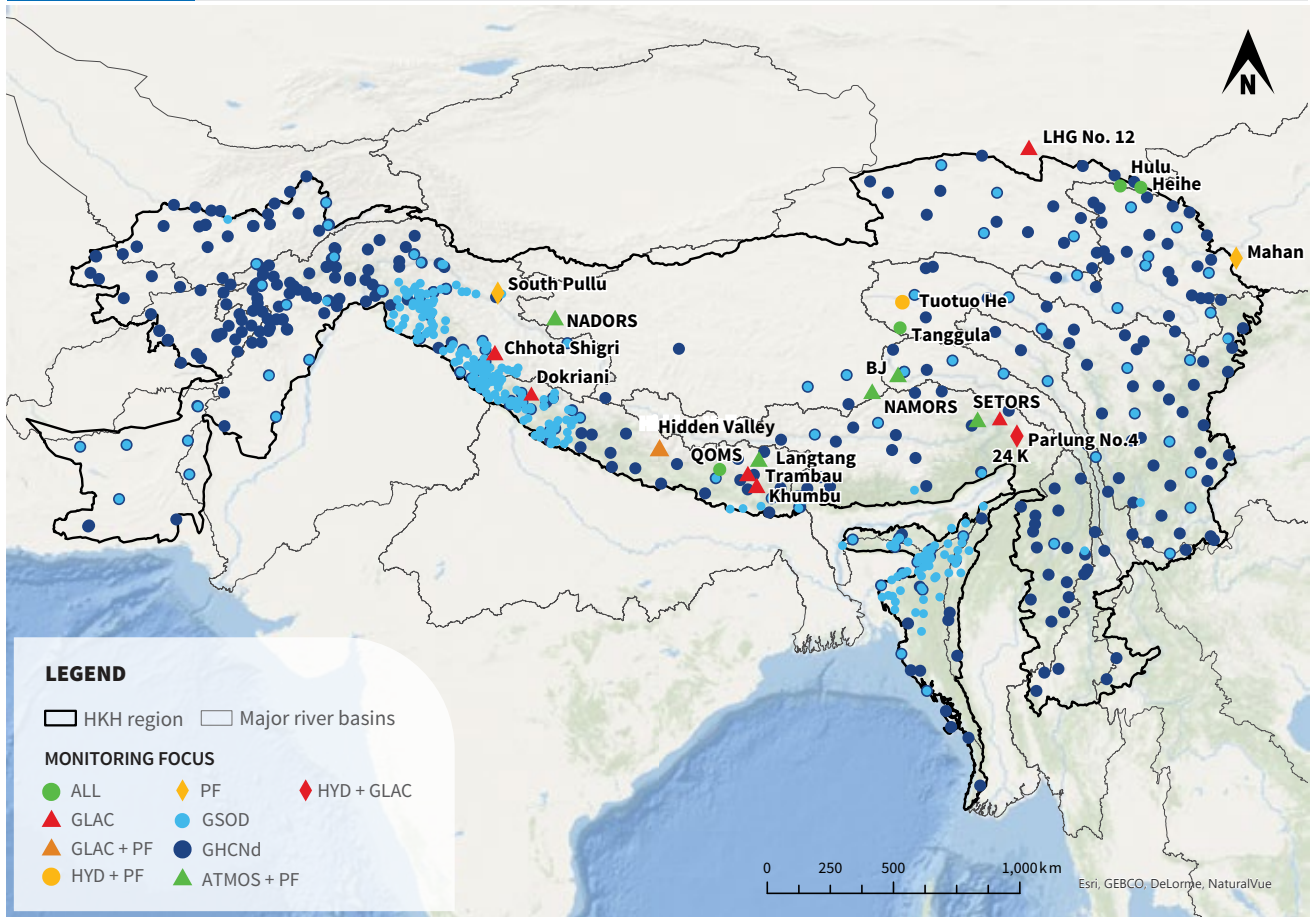
Cryosphere monitoring efforts are of little benefit if those efforts do not produce the long-term data streams required to identify trends and to calibrate and validate models. Effective efforts furthermore depend upon long-term research support, and upon stable institutional and political commitments that enable it. Without these commitments, cryosphere monitoring will continue to be subject to uncertain and short-term project financing, and therefore likely to be intermittent and disjointed. It is crucial, therefore, that institutional and political mechanisms are developed in parallel with ‘technical’ aspects to ensure their longevity. Those institutional mechanisms will need to be transboundary in nature, as they will assuredly need to cross political boundaries at the district, provincial, and likely national levels.

Strategy 4

Establish frameworks that allow for the inclusion of local and Indigenous knowledge in decision-making processes and adaptation strategies.

FIGURE 3.9

DEDICATED MONITORING SITES IN HIGH ELEVATION CONTEXTS, ABOVE 3,500 m, IN THE HKH



Notes: Monitoring sites that have been operational for at least 1 year and observe more than one variable are shown. ALL denotes set-ups that include climatic, glaciological, snowfall, and permafrost observations, HYD refers to sites that focus on hydrology (including sediments), GLAC to sites that focus on glaciers (for example, mass balance or on-glacier meteorology), and PF to sites focusing on soil/ground measurements. GHCNd (Global Historical Climatology Network daily) stations are government-run stations (Thornton et al., 2022). GSOD (Global Surface Summary of the Day; see <https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.ncdc:C00516>) is a data set curated by the USAF Climatology Center. The bold black marks the HKH outline, permafrost extent is shown in blue (Obu, 2021), and glacier outlines are shown in white.

The value of local and Indigenous knowledge in mountain areas has been emphasised in recent literature on mountains in general (Adler et al., 2022) and in the region in specific studies on hazards (Emmer et al., 2022), upstream–downstream linkages (Bastakoti et al., 2017), and livelihoods (Tuladhar et al., 2021). However, there is still a vast body of untapped knowledge, especially in relation to the cryosphere and its role in water supply as well as an immediate hazard, that remains unexplored. Future scientific studies should pay more attention to explore this in their respective fields as part of a review of existing knowledge on the topic. This would not only allow for a more comprehensive understanding of present challenges in mountain

areas but in turn also allow for a better dissemination of new emerging knowledge in the process of exchange between scientists and mountain communities in the HKH.

Although knowledge gaps will remain, it is vital to act now based on the knowledge we already have about the present state of the HKH and how key hydrological variables might change in the future. It is critical that strategies for the mitigation of, and adaptation to climate change are based on current understanding. New data and knowledge can then continue to inform decision-making processes as understanding deepens.

References

- Adhikari, P., & Meija, J. F. (2021). Influence of aerosols on clouds, precipitation and freezing level height over the foothills of the Himalayas during the Indian summer monsoon. *Climate Dynamics*, 57(1), 395–413. <https://doi.org/10.1007/s00382-021-05710-2>
- Adler, C., Wester, P., Bhatt, I., Huggel, C., Insarov, G. E., Morecroft, M. D., Muccione, V., & Prakash, A. (2022). Cross-Chapter Paper 5: Mountains. In H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegria, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama (Eds.), *Climate change 2022: Impacts, adaptation and vulnerability* (pp. 2273–2318). Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. <https://doi.org/10.1017/9781009325844.022>
- Azam, M. F., Kargel, J. S., Shea, J. M., Nepal, S., Haritashya, U. K., Srivastava, S., Maussion, F., Qazi, N., Chevallier, P., Dimri, A. P., Kulkarni, A. V., Cogley, J. G., & Bahuguna, I. M. (2021). Glaciohydrology of the Himalaya-Karakoram. *Science*, 373(6557). <https://doi.org/10.1126/science.abf3668>
- Azam, M. F., Wagnon, P., Berthier, E., Vincent, C., Fujita, K., & Kargel, J. S. (2018). Review of the status and mass changes of Himalayan-Karakoram glaciers. *Journal of Glaciology*, 64(243), 61–74. <https://doi.org/10.1017/jog.2017.86>
- Azmat, M., Wahab, A., Huggel, C., Qamar, M. U., Hussain, E., Ahmad, S., & Waheed, A. (2020). Climatic and hydrological projections to changing climate under CORDEX-South Asia experiments over the Karakoram-Hindukush-Himalayan water towers. *Science of The Total Environment*, 703, Article 135010. <https://doi.org/10.1016/j.scitotenv.2019.135010>
- Ballesteros-Cánovas, J. A., Trappmann, D., Madrigal-González, J., Eckert, N., & Stoffel, M. (2018). Climate warming enhances snow avalanche risk in the Western Himalayas. *Proceedings of the National Academy of Sciences*, 115(13), 3410–3415. <https://doi.org/10.1073/pnas.1716913115>
- Bartelt, P., Buser, O., Valero, C. V., & Bühler, Y. (2016). Configurational energy and the formation of mixed flowing/powder snow and ice avalanches. *Annals of Glaciology*, 57(71), 179–188. <https://doi.org/10.3189/2016AoG71A464>
- Bastakoti, R. C., Bharati, L., Bhattarai, U., & Wahid, S. M. (2017). Agriculture under changing climate conditions and adaptation options in the Koshi Basin. *Climate and Development*, 9(7), 634–648. <https://doi.org/10.1080/17565529.2016.1223594>
- Berthier, E., & Brun, F. (2019). Karakoram geodetic glacier mass balances between 2008 and 2016: Persistence of the anomaly and influence of a large rock avalanche on Siachen Glacier. *Journal of Glaciology*, 65(251), 494–507. <https://doi.org/10.1017/jog.2019.32>
- Bhambri, R., Watson, C. S., Hewitt, K., Haritashya, U. K., Kargel, J. S., Pratap Shahi, A., Chand, P., Kumar, A., Verma, A., & Govil, H. (2020). The hazardous 2017–2019 surge and river damming by Shipare Glacier,

- Karakoram. *Scientific Reports*, 10(1), 1–14. <https://doi.org/10.1038/s41598-020-61277-8>
- Biemans, H., Siderius, C., Lutz, A. F., Nepal, S., Ahmad, B., Hassan, T., von Bloh, W., Wijngaard, R. R., Wester, P., Shrestha, A. B., & Immerzeel, W. W. (2019). Importance of snow and glacier meltwater for agriculture on the Indo-Gangetic Plain. *Nature Sustainability*, 2(7), 594–601. <https://doi.org/10.1038/s41893-019-0305-3>
- Biemans, H., Siderius, C., Mishra, A., & Ahmad, B. (2016). Crop-specific seasonal estimates of irrigation-water demand in South Asia. *Hydrology and Earth System Sciences*, 20(5), 1971–1982. <https://doi.org/10.5194/hess-20-1971-2016>
- Bolch, T., Kulkarni, A., Kaab, A., Huggel, C., Paul, F., Cogley, J. G., Frey, H., Kargel, J. S., Fujita, K., Scheel, M., Bajracharya, S., & Stoffel, M. (2012). The state and fate of Himalayan glaciers. *Science*, 336(6079), 310–314. <https://doi.org/10.1126/science.1215828>
- Bolch, T., Shea, J. M., Liu, S., Azam, F. M., Gao, Y., Gruber, S., Immerzeel, W. W., Kulkarni, A., Li, H., Tahir, A. A., Zhang, G., & Zhang, Y. (2019). Status and change of the cryosphere in the extended Hindu Kush Himalaya region. In P. Wester, A. Mishra, A. Mukherji, & A. Bhakta Shrestha (Eds.), *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability and people* (pp. 209–255). Springer Nature Switzerland AG. https://doi.org/10.1007/978-3-319-92288-1_7
- Bookhagen, B., & Burbank, D. W. (2006). Topography, relief, and TRMM-derived rainfall variations along the Himalaya. *Geophysical Research Letters*, 33(8). <https://doi.org/10.1029/2006GL026037>
- Byers, A. C., Rounce, D. R., Shugar, D. H., Lala, J. M., Byers, E. A., & Regmi, D. (2019). A rockfall-induced glacial lake outburst flood, Upper Barun Valley, Nepal. *Landslides*, 16(3), 533–549. <https://doi.org/10.1007/s10346-018-1079-9>
- Chang, Y., Wang, J., Qin, D., Ding, Y., Zhao, Q., Liu, F., & Zhang, S. (2017). Methodological comparison of alpine meadow evapotranspiration on the Tibetan Plateau, China. *PLoS ONE*, 12(12). <https://doi.org/10.1371/journal.pone.0189059>
- Chen, C., Zhang, L., Xiao, T., & He, J. (2020). Barrier lake bursting and flood routing in the Yarlung Tsangpo Grand Canyon in October 2018. *Journal of Hydrology*, 583, Article 124603. <https://doi.org/10.1016/j.jhydrol.2020.124603>
- Clouse, C., Anderson, N., & Shippling, T. (2017). Ladakh's artificial glaciers: Climate-adaptive design for water scarcity. *Climate and Development*, 9(5), 428–438. <https://doi.org/10.1080/17565529.2016.1167664>
- Collins, M., Sutherland, M., Bouwer, L., Cheong, S.-M., Frölicher, T., Combes, H. J. D., Roxy, M. K., Losada, I., McInnes, K., Ratter, B., Rivera-Arriaga, E., Susanto, R. D., Swingedouw, D., & Tibig, L. (2019). Extremes, abrupt changes and managing risk. In 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, & N. M. Weyer (Eds.), *IPCC special report on the ocean and cryosphere in a changing climate* (1st ed., pp. 589–655). Cambridge University Press. <https://doi.org/10.1017/9781009157964>
- Cook, K. L., Andermann, C., Gimbert, F., Adhikari, B. R., & Hovius, N. (2018). Glacial lake outburst floods as drivers of fluvial erosion in the Himalaya. *Science*, 362(6410), 53–57. <https://doi.org/10.1126/science.aat4981>
- Dahlquist, M. P., & West, A. J. (2019). Initiation and runout of post-seismic debris flows: Insights from the 2015 Gorkha earthquake. *Geophysical Research Letters*, 46(16), 9658–9668. <https://doi.org/10.1029/2019GL083548>
- Devanand, A., Huang, M., Ashfaq, M., Barik, B., & Ghosh, S. (2019). Choice of irrigation water management practice affects Indian summer monsoon rainfall and its extremes. *Geophysical Research Letters*, 46(15), 9126–9135. <https://doi.org/10.1029/2019GL083875>
- Dhakal, M. P., Ali, A., Khan, M. Z., Wagle, N., Shah, G. M., Maqsood, M. M., & Ali, A. (2021). Agricultural water management challenges in the Hunza River Basin: Is a solar water pump an alternative option?*. *Irrigation and Drainage*, 70(4), 644–658. <https://doi.org/10.1002/ird.2563>
- Dileepkumar, R., AchutaRao, K. M., & Arulalan, T. (2018). Human influence on sub-regional surface air temperature change over India. *Scientific Reports*, 8(1), Article 8967. <https://doi.org/10.1038/s41598-018-27185-8>
- Doblas-Reyes, F. J., Sörensson, A. A., Almazroui, M., Dosio, A., Gutowski, W. J., Haarsma, R. J., Hamdi, R., Hewitson, B., Kwon, W.-T., Lamptey, B. L., Maraun, D., Stephenson, T. S., Takayabu, I., Terray, L., Turner, A., & Zuo, Z. (2021). Linking global to regional climate change. In V. Masson-Delmotte, P. M. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (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* (pp. 1363–1512). Cambridge University Press.

- Emmer, A., Allen, S. K., Carey, M., Frey, H., Huggel, C., Korup, O., Mergili, M., Sattar, A., Veh, G., Chen, T. Y., Cook, S. J., Correas-Gonzalez, M., Das, S., Diaz Moreno, A., Drenkhan, F., Fischer, M., Immerzeel, W. W., Izagirre, E., Joshi, R. C., ... Yde, J. C. (2022). Progress and challenges in glacial lake outburst flood research (2017–2021): A research community perspective. *Natural Hazards and Earth System Sciences*, 22(9), 3041–3061. <https://doi.org/10.5194/nhess-22-3041-2022>
- Engelhardt, M., Ramanathan, A., Eidhammer, T., Kumar, P., Landgren, O., Mandal, A., & Rasmussen, R. (2017). Modelling 60 years of glacier mass balance and runoff for Chhota Shigri Glacier, Western Himalaya, Northern India. *Journal of Glaciology*, 63(240), 618–628. <https://doi.org/10.1017/jog.2017.29>
- Eyring, V., Gillett, N. P., AchutaRao, K. M., Barimalala, R., Barreiro Parrillo, M., Bellouin, N., Cassou, C., Durack, P. J., Kosaka, Y., McGregor, S., Min, S., Morgenstern, O., & Sun, Y. (2021). Human influence on the climate system. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (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* (pp. 423–552). Cambridge University Press.
- Farinotti, D., Immerzeel, W. W., de Kok, R. J., Quincey, D. J., & Dehecq, A. (2020). Manifestations and mechanisms of the Karakoram glacier anomaly. *Nature Geoscience*, 13(1), 8–16. <https://doi.org/10.1038/s41561-019-0513-5>
- Flügel, W.-A., Nepal, S., & Shrestha, A. B. (2018). *Framework for upstream–downstream linkages of land and water management in the Hindu Kush Himalaya (HKH) region*. HI-AWARE Working Paper No. 15. ICIMOD. <https://lib.icimod.org/record/33880>
- Fowler, H. J., Lenderink, G., Prein, A. F., Westra, S., Allan, R. P., Ban, N., Barbero, R., Berg, P., Blenkinsop, S., Do, H. X., Guerreiro, S., Haerter, J. O., Kendon, E. J., Lewis, E., Schaer, C., Sharma, A., Villarini, G., Wasko, C., & Zhang, X. (2021). Anthropogenic intensification of short-duration rainfall extremes. *Nature Reviews Earth & Environment*, 2(2), 107–122. <https://doi.org/10.1038/s43017-020-00128-6>
- Fujita, K., Inoue, H., Izumi, T., Yamaguchi, S., Sadakane, A., Sunako, S., Nishimura, K., Immerzeel, W. W., Shea, J. M., Kayastha, R. B., Sawagaki, T., Breashears, D. F., Yagi, H., & Sakai, A. (2017). Anomalous winter-snow-amplified earthquake-induced disaster of the 2015 Langtang avalanche in Nepal. *Natural Hazards and Earth System Sciences*, 17(5), 749–764. <https://doi.org/10.5194/nhess-17-749-2017>
- Furian, W., Loibl, D., & Schneider, C. (2021). Future glacial lakes in High Mountain Asia: An inventory and assessment of hazard potential from surrounding slopes. *Journal of Glaciology*, 67(264), 653–670. <https://doi.org/10.1017/jog.2017.86>
- Furian, W., Maussion, F., & Schneider, C. (2022). Projected 21st-century glacial lake evolution in High Mountain Asia. *Frontiers in Earth Science*, 10(March), 1–21. <https://doi.org/10.3389/feart.2022.821798>
- Gruber, S., Fleiner, R., Guegan, E., Panday, P., Schmid, M.-O., Stumm, D., Wester, P., Zhang, Y., & Zhao, L. (2017). Review article: Inferring permafrost and permafrost thaw in the mountains of the Hindu Kush Himalaya region. *The Cryosphere*, 11(1), 81–99. <https://doi.org/10.5194/tc-11-81-2017>
- Gruber, S., & Haeberli, W. (2007). Permafrost in steep bedrock slopes and its temperature-related destabilization following climate change. *Journal of Geophysical Research: Earth Surface*, 112(F2). <https://doi.org/10.1029/2006JF000547>
- Guo, S., Chen, R., Han, C., Liu, J., Wang, X., & Liu, G. (2021). Five-year analysis of evapostublimation characteristics and its role on surface energy balance SEB on a midlatitude continental glacier. *Earth and Space Science*, 8(12), e2021EA001901. <https://doi.org/10.1029/2021EA001901>
- Guo, S., Chen, R., & Li, H. (2022). Surface sublimation/evaporation and condensation/deposition and their links to westerlies during 2020 on the August-One Glacier, the semi-arid Qilian Mountains of Northeast Tibetan Plateau. *Journal of Geophysical Research: Atmospheres*, 127(11), Article e2022JD036494. <https://doi.org/10.1029/2022JD036494>
- Haerberli, W., Schaub, Y., & Huggel, C. (2016). Increasing risks related to landslides from degrading permafrost into new lakes in de-glaciating mountain ranges (invited review paper). *Geomorphology*, 293(B), 405–417. <https://doi.org/10.1016/j.geomorph.2016.02.009>
- Han, C., Chen, R., Liu, Z., Yang, Y., Liu, J., Song, Y., Wang, L., Liu, G., Guo, S., & Wang, X. (2018). Cryospheric hydrometeorology observation in the Hulu Catchment (CHOICE), Qilian Mountains, China. *Vadose Zone Journal*, 17(1), Article 180058. <https://doi.org/10.2136/vzj2018.03.0058>

- Harrison, S., Kargel, J. S., Huggel, C., Reynolds, J., Shugar, D. H., Betts, R. A., Emmer, A., Glasser, N., Haritashya, U. K., Klimeš, J., Reinhardt, L., Schaub, Y., Wiltshire, A., Regmi, D., & Vilímek, V. (2018). Climate change and the global pattern of moraine-dammed glacial lake outburst floods. *Cryosphere*, *12*(4), 1195–1209. <https://doi.org/10.5194/tc-12-1195-2018>
- Herman, F., De Doncker, F., Delaney, I., Prasicek, G., & Koppes, M. (2021). The impact of glaciers on mountain erosion. *Nature Reviews Earth & Environment*, *2*(6). <https://doi.org/10.1038/s43017-021-00165-9>
- Hill, J. K. W. (2017). Supporting farmer-managed irrigation systems in the Shigar valley, Karakorum: Role of the government and Aga Khan Rural Support Programme. *Journal of Mountain Science*, *14*(10), 2064–2081. <https://doi.org/10.1007/s11629-017-4496-7>
- Hirabayashi, Y., Nakano, K., Zhang, Y., Watanabe, S., Tanoue, M., & Kanae, S. (2016). Contributions of natural and anthropogenic radiative forcing to mass loss of northern hemisphere mountain glaciers and quantifying their uncertainties. *Scientific Reports*, *6*(1), Article 29723. <https://doi.org/10.1038/srep29723>
- Hock, R., Rasul, G., Adler, C., Cáceres, B., Gruber, S., Hirabayashi, Y., Jackson, M., Kääh, A., Kang, S., Kutuzov, S., Milner, A., Molau, U., Morin, S., Orlove, B., & Steltzer, H. (2019). High mountain areas. In H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama, & N. Weyer (Eds.), *IPCC special report on the ocean and cryosphere in a changing climate* (pp. 131–202). Cambridge University Press.
- Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L., Farinotti, D., Huss, M., Dussaillant, I., Brun, F., & Kääh, A. (2021). Accelerated global glacier mass loss in the early twenty-first century. *Nature*, *592*(7856), 726–731. <https://doi.org/10.1038/s41586-021-03436-z>
- Huss, M., & Hock, R. (2018). Global-scale hydrological response to future glacier mass loss. *Nature Climate Change*, *8*(2), 135–140. <https://doi.org/10.1038/s41558-017-0049-x>
- Illien, L., Andermann, C., Sens-Schönfelder, C., Cook, K. L., Baidya, K. P., Adhikari, L. B., & Hovius, N. (2021). Subsurface moisture regulates Himalayan groundwater storage and discharge. *AGU Advances*, *2*(2), Article e2021AV000398. <https://doi.org/10.1029/2021AV000398>
- 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., ... Baillie, J. E. M. (2020). Importance and vulnerability of the world's water towers. *Nature*, *577*(7790), 364–369. <https://doi.org/10.1038/s41586-019-1822-y>
- Immerzeel, W. W., Pellicciotti, F., & Bierkens, M. F. P. (2013). Rising river flows throughout the twenty-first century in two Himalayan glacierized watersheds. *Nature Geoscience*, *6*(9), 742–745. <https://doi.org/10.1038/ngeo1896>
- Immerzeel, W. W., van Beek, L. P. H., & Bierkens, M. F. P. (2010). Climate change will affect the Asian water towers. *Science*, *328*(5984), 1382–1385. <https://doi.org/10.1126/science.1183188>
- Jeelani, G., Shah, R. A., Deshpande, R. D., Fryar, A. E., Perrin, J., & Mukherjee, A. (2017). Distinguishing and estimating recharge to karst springs in snow and glacier dominated mountainous basins of the western Himalaya, India. *Journal of Hydrology*, *550*, 239–252. <https://doi.org/10.1016/j.jhydrol.2017.05.001>
- Jóhannesson, T., Raymond, C., & Waddington, E. (1989). Time-scale for adjustment of glaciers to changes in mass balance. *Journal of Glaciology*, *35*(121), 355–369. <https://doi.org/10.3189/S002214300000928X>
- Kääh, A., Jacquemart, M., Gilbert, A., Leinss, S., Girod, L., Huggel, C., Falaschi, D., Ugalde, F., Petrakov, D., Chernomorets, S., Dokukin, M., Paul, F., Gascoïn, S., Berthier, E., & Kargel, J. (2021). Sudden large-volume detachments of low-angle mountain glaciers: More frequent than thought. *The Cryosphere*, *15*, 1751–1785. <https://doi.org/10.5194/tc-15-1751-2021>
- Kääh, A., Leinss, S., Gilbert, A., Bühler, Y., Gascoïn, S., Evans, S. G., Bartelt, P., Berthier, E., Brun, F., Chao, W.-A., Farinotti, D., Gimbert, F., Guo, W., Huggel, C., Kargel, J. S., Leonard, G. J., Tian, L., Treichler, D., & Yao, T. (2018). Massive collapse of two glaciers in western Tibet in 2016 after surge-like instability. *Nature Geoscience*, *11*(2), 114–120. <https://doi.org/10.1038/s41561-017-0039-7>
- Kargel, J. S., Leonard, G. J., Shugar, D. H., Haritashya, U. K., Bevington, A., Fielding, E. J., Fujita, K., Geertsema, M., Miles, E. S., Steiner, J., Anderson, E., Bajracharya, S., Bawden, G. W., Breashears, D. F., Byers, A., Collins, B., Dhital, M. R., Donnellan, A., Evans, T. L., ... Young, N. (2016). Geomorphic and geologic controls of geohazards induced by Nepal's 2015 Gorkha earthquake. *Science*, *351*(6269). <https://doi.org/10.1126/science.aac8353>

- Kayastha, R. B., Steiner, N., Kayastha, R., Mishra, S. K., & McDonald, K. (2020). Comparative study of hydrology and icemelt in three Nepal river basins using the Glacio-Hydrological Degree-Day Model (GDM) and observations from the Advanced Scatterometer (ASCAT). *Frontiers in Earth Science*, 7. <https://www.frontiersin.org/articles/10.3389/feart.2019.00354>
- Khanal, S., Lutz, A. F., Kraaijenbrink, P. D. A., van den Hurk, B., Yao, T., & Immerzeel, W. W. (2021). Variable 21st century climate change response for rivers in High Mountain Asia at seasonal to decadal time scales. *Water Resources Research*, 57(5), Article e2020WR029266. <https://doi.org/10.1029/2020WR029266>
- Kim, J.-B., & Bae, D.-H. (2020). Intensification characteristics of hydroclimatic extremes in the Asian monsoon region under 1.5 and 2.0°C of global warming. *Hydrology and Earth System Sciences*, 24(12), 5799–5820. <https://doi.org/10.5194/hess-24-5799-2020>
- Kincey, M. E., Rosser, N. J., Robinson, T. R., Densmore, A. L., Shrestha, R., Pujara, D. S., Oven, K. J., Williams, J. G., & Swirad, Z. M. (2021). Evolution of coseismic and post-seismic landsliding after the 2015 Mw 7.8 Gorkha earthquake, Nepal. *Journal of Geophysical Research: Earth Surface*, 126(3), Article e2020JF005803. <https://doi.org/10.1029/2020JF005803>
- Kirschbaum, D., Watson, C. S., Rounce, D. R., Shugar, D. H., Kargel, J. S., Haritashya, U. K., Amatya, P., Shean, D., Anderson, E. R., & Jo, M. (2019). The state of remote sensing capabilities of cascading hazards over High Mountain Asia. *Frontiers in Earth Science*, 7. <https://doi.org/10.3389/feart.2019.00197>
- Kraaijenbrink, P. D. A., Bierkens, M. F. P., Lutz, A. F., & Immerzeel, W. W. (2017). Impact of a global temperature rise of 1.5 degrees celsius on Asia's glaciers. *Nature*, 549(7671), 257–260. <https://doi.org/10.1038/nature23878>
- Kraaijenbrink, P. D. A., Stigter, E. E., Yao, T., & Immerzeel, W. W. (2021). Climate change decisive for Asia's snow meltwater supply. *Nature Climate Change*, 11(7), 591–597. <https://doi.org/10.1038/s41558-021-01074-x>
- Krishnan, R., Shrestha, A. B., Ren, G., Rajbhandari, R., Saeed, S., Sanjay, J., Syed, Md. A., Vellore, R., Xu, Y., You, Q., & Ren, Y. (2019). Unravelling climate change in the Hindu Kush Himalaya: Rapid warming in the mountains and increasing extremes. In P. Wester, A. Mishra, A. Mukherji, & A. B. Shrestha (Eds.), *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability and people* (pp. 57–97). Springer Nature Switzerland AG. https://doi.org/10.1007/978-3-319-92288-1_3
- Kropáček, J., Vilímek, V., & Mehrishi, P. (2021). A preliminary assessment of the Chamoli rock and ice avalanche in the Indian Himalayas by remote sensing. *Landslides*, 18(10), 3489–3497. <https://doi.org/10.1007/s10346-021-01742-1>
- Kulkarni, A. V., Shirsat, T. S., Kulkarni, A., Negi, H. S., Bahuguna, I. M., & Thamban, M. (2021). State of Himalayan cryosphere and implications for water security. *Water Security*, 14, Article 100101. <https://doi.org/10.1016/j.wasec.2021.100101>
- Lane, S. N., Bakker, M., Gabbud, C., Micheletti, N., & Saugy, J.-N. (2017). Sediment export, transient landscape response and catchment-scale connectivity following rapid climate warming and Alpine glacier recession. *Geomorphology*, 277, 210–227. <https://doi.org/10.1016/j.geomorph.2016.02.015>
- Leinss, S., Bernardini, E., Jacquemart, M., & Dokukin, M. (2021). Glacier detachments and rock-ice avalanches in the Petra Pervogo range, Tajikistan (1973–2019). *Natural Hazards and Earth System Sciences*, 21(5), 1409–1429. <https://doi.org/10.5194/nhess-21-1409-2021>
- Li, D., Li, Z., Zhou, Y., & Lu, X. (2020). Substantial increases in the water and sediment fluxes in the headwater region of the Tibetan Plateau in response to global warming. *Geophysical Research Letters*, 47(11), Article e2020GL087745. <https://doi.org/10.1029/2020GL087745>
- Li, D., Lu, X., Overeem, I., Walling, D. E., Syvitski, J., Kettner, A. J., Bookhagen, B., Zhou, Y., & Zhang, T. (2021). Exceptional increases in fluvial sediment fluxes in a warmer and wetter High Mountain Asia. *Science*, 374(6567), 599–603. <https://doi.org/10.1126/science.abi9649>
- Li, D., Lu, X., Walling, D. E., Zhang, T., Steiner, J. F., Wasson, R. J., Harrison, S., Nepal, S., Nie, Y., Immerzeel, W. W., Shugar, D. H., Koppes, M., Lane, S., Zeng, Z., Sun, X., Yegorov, A., & Bolch, T. (2022). High Mountain Asia hydropower systems threatened by climate-driven landscape instability. *Nature Geoscience*, 15(7), 520–530. <https://doi.org/10.1038/s41561-022-00953-y>
- Li, D., Lu, X. X., Yang, X., Chen, L., & Lin, L. (2018). Sediment load responses to climate variation and cascade reservoirs in the Yangtze River: A case study of the Jinsha River. *Geomorphology*, 322, 41–52. <https://doi.org/10.1016/j.geomorph.2018.08.038>
- Li, W., Zhao, B., Xu, Q., Scaringi, G., Lu, H., & Huang, R. (2022). More frequent glacier-rock avalanches in Sedongpu gully are blocking the Yarlung Zangbo River in eastern Tibet. *Landslides*, 19(3), 589–601. <https://doi.org/10.1007/s10346-021-01798-z>

- Linsbauer, A., Frey, H., Haeberli, W., Machguth, H., Azam, M. F., & Allen, S. (2015). Modelling glacier-bed overdeepenings and possible future lakes for the glaciers in the Himalaya–Karakoram region. *Annals of Glaciology*, 57(71), 119–130. <https://doi.org/10.3189/2016AoG71A627>
- Lone, S. A., Jeelani, G., Deshpande, R. D., Mukherjee, A., Jasechko, S., & Lone, A. (2021). Meltwaters dominate groundwater recharge in cold arid desert of Upper Indus River Basin (UIRB), western Himalayas. *Science of The Total Environment*, 786, Article 147514. <https://doi.org/10.1016/j.scitotenv.2021.147514>
- Lutz, A. F., Immerzeel, W. W., Kraaijenbrink, P. D. A., Shrestha, A. B., & Bierkens, M. F. P. (2016). Climate change impacts on the Upper Indus hydrology: Sources, shifts and extremes. *PLOS ONE*, 11(11), Article e0165630. <https://doi.org/10.1371/journal.pone.0165630>
- Lutz, A. F., Immerzeel, W. W., Shrestha, A. B., & Bierkens, M. F. P. (2014). Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. *Nature Climate Change*, 4(7), 587–592. <https://doi.org/10.1038/nclimate2237>
- Lutz, A. F., Immerzeel, W. W., Siderius, C., Wijngaard, R. R., Nepal, S., Shrestha, A. B., Wester, P., & Biemans, H. (2022). South Asian agriculture increasingly dependent on meltwater and groundwater. *Nature Climate Change*, 12(6), 566–573. <https://doi.org/10.1038/s41558-022-01355-z>
- Madhura, R. K., Krishnan, R., Revadekar, J. V., Mujumdar, M., & Goswami, B. N. (2015). Changes in western disturbances over the Western Himalayas in a warming environment. *Climate Dynamics*, 44(3), 1157–1168. <https://doi.org/10.1007/s00382-014-2166-9>
- Maharjan, S. B., Steiner, J. F., Shrestha, A. B., Maharjan, A., Nepal, S., Shrestha, M., Bajracharya, B., Rasul, G., Shrestha, M., Jackson, M., & Gupta, N. (2021). *The Melamchi flood disaster: Cascading hazard and the need for multihazard risk management*. ICIMOD. <https://www.icimod.org/article/the-melamchi-flood-disaster/>
- Mal, S., Allen, S. K., Frey, H., Huggel, C., & Dimri, A. P. (2021). Sectorwise assessment of glacial lake outburst flood danger in the Indian Himalayan Region. *Mountain Research and Development*, 41(1), R1–R12. <https://doi.org/10.1659/MRD-JOURNAL-D-20-00043.1>
- Malik, N., Bookhagen, B., & Mucha, P. J. (2016). Spatiotemporal patterns and trends of Indian monsoonal rainfall extremes. *Geophysical Research Letters*, 43(4), 1710–1717. <https://doi.org/10.1002/2016GL067841>
- Mandal, A., Angchuk, T., Azam, M. F., Ramanathan, A., Wagnon, P., Soheb, M., & Singh, C. (2022). An 11-year record of wintertime snow surface energy balance and sublimation at 4,863 m a.s.l. on Chhota Shigri Glacier moraine (western Himalaya, India). *The Cryosphere*, 16, 3775–3799. <https://doi.org/10.5194/tc-2021-386>
- Matheswaran, K., Khadka, A., Dhaubanjari, S., Bharati, L., Kumar, S., & Shrestha, S. (2019). Delineation of spring recharge zones using environmental isotopes to support climate-resilient interventions in two mountainous catchments in far-western Nepal. *Hydrogeology Journal*, 27(6), 2181–2197. <https://doi.org/10.1007/s10040-019-01973-6>
- Mathison, C., Challinor, A. J., Deva, C., Falloon, P., Garrigues, S., Moulin, S., Williams, K., & Wiltshire, A. (2021). Implementation of sequential cropping into JULESv5.2 land-surface model. *Geoscientific Model Development*, 14(1), 437–471. <https://doi.org/10.5194/gmd-14-437-2021>
- McAdoo, B. G., Quak, M., Gnyawali, K. R., Adhikari, B. R., Devkota, S., Rajbhandari, P. L., & Sudmeier-Rieux, K. (2018). Roads and landslides in Nepal: How development affects environmental risk. *Natural Hazards and Earth System Sciences*, 18(12), 3203–3210. <https://doi.org/10.5194/nhess-18-3203-2018>
- Meena, S. R., Bhuyan, K., Chauhan, A., & Singh, R. P. (2021). Changes in the flood plains and water quality along the Himalayan rivers after the Chamoli disaster of 7 February 2021. *International Journal of Remote Sensing*, 42(18), 6984–7001. <https://doi.org/10.1080/01431161.2021.1944696>
- Merrey, D. J., Hussain, A., Tamang, D. D., Thapa, B., & Prakash, A. (2018). Evolving high altitude livelihoods and climate change: A study from Rasuwa District, Nepal. *Food Security*, 10(4), 1055–1071. <https://doi.org/10.1007/s12571-018-0827-y>
- Miles, E. S., Watson, C. S., Brun, F., Berthier, E., Esteves, M., Quincey, D. J., Miles, K. E., Hubbard, B., & Wagnon, P. (2018). Glacial and geomorphic effects of a supraglacial lake drainage and outburst event, Everest region, Nepal Himalaya. *The Cryosphere*, 12(12), 3891–3905. <https://doi.org/10.5194/tc-12-3891-2018>
- Mimeau, L., Esteves, M., Zin, I., Jacobi, H.-W., Brun, F., Wagnon, P., Koirala, D., & Arnaud, Y. (2019). Quantification of different flow components in a high-altitude glacierized catchment (Dudh Koshi, Himalaya): Some cryospheric-related issues. *Hydrology and Earth System Sciences*, 23(9), 3969–3996. <https://doi.org/10.5194/hess-23-3969-2019>

- Mohammed, K., Islam, A. S., Islam, G. T., Alfieri, L., Bala, S. K., & Khan, Md. J. U. (2017). Extreme flows and water availability of the Brahmaputra River under 1.5 and 2°C global warming scenarios. *Climatic Change*, 145(1), 159–175. <https://doi.org/10.1007/s10584-017-2073-2>
- Muhammad, S., Li, J., Steiner, J. F., Shrestha, F., Shah, G. M., Berthier, E., Guo, L., Wu, L., & Tian, L. (2021). A holistic view of Shisper Glacier surge and outburst floods: From physical processes to downstream impacts. *Geomatics, Natural Hazards and Risk*, 12(1), 2755–2775. <https://doi.org/10.1080/19475705.2021.1975833>
- Mukherji, A., Sinisalo, A., Nüsser, M., Garrard, R., & Eriksson, M. (2019). Contributions of the cryosphere to mountain communities in the Hindu Kush Himalaya: A review. *Regional Environmental Change*, 19(5), 1311–1326. <https://doi.org/10.1007/s10113-019-01484-w>
- Nepal, S., Khatiwada, K. R., Pradhananga, S., Kralisch, S., Samyn, D., Bromand, M. T., Jamal, N., Dildar, M., Durrani, F., Rassouly, F., Azizi, F., Salehi, W., Malikzooi, R., Krause, P., Koirala, S., & Chevallier, P. (2021). Future snow projections in a small basin of the Western Himalaya. *Science of The Total Environment*, 795, Article 148587. <https://doi.org/10.1016/j.scitotenv.2021.148587>
- Nepal, S., Krause, P., Flügel, W.-A., Fink, M., & Fischer, C. (2014). Understanding the hydrological system dynamics of a glaciated alpine catchment in the Himalayan region using the J2000 hydrological model. *Hydrological Processes*, 28(3), 1329–1344. <https://doi.org/10.1002/hyp.9627>
- Nepal, S., Pradhananga, S., Shrestha, N. K., Kralisch, S., Shrestha, J. P., & Fink, M. (2021). Space-time variability in soil moisture droughts in the Himalayan region. *Hydrology and Earth System Sciences*, 25(4), 1761–1783. <https://doi.org/10.5194/hess-25-1761-2021>
- Nie, Y., Pritchard, H. D., Liu, Q., Hennig, T., Wang, W., Wang, X., Liu, S., Nepal, S., Samyn, D., Hewitt, K., & Chen, X. (2021). Glacial change and hydrological implications in the Himalaya and Karakoram. *Nature Reviews Earth & Environment*, 2(2), 91–106. <https://doi.org/10.1038/s43017-020-00124-w>
- Nie, Y., Sheng, Y., Liu, Q., Liu, L., Liu, S., Zhang, Y., & Song, C. (2017). A regional-scale assessment of Himalayan glacial lake changes using satellite observations from 1990 to 2015. *Remote Sensing of Environment*, 189, 1–13. <https://doi.org/10.1016/j.rse.2016.11.008>
- Nüsser, M., Dame, J., Kraus, B., Baghel, R., & Schmidt, S. (2019). Socio-hydrology of “artificial glaciers” in Ladakh, India: Assessing adaptive strategies in a changing cryosphere. *Regional Environmental Change*, 19(5), 1327–1337. <https://doi.org/10.1007/s10113-018-1372-0>
- Nüsser, M., Dame, J., Parveen, S., Kraus, B., Baghel, R., & Schmidt, S. (2019). Cryosphere-fed irrigation networks in the Northwestern Himalaya: Precarious livelihoods and adaptation strategies under the impact of climate change. *Mountain Research and Development*, 39(2), R1–R11. <https://doi.org/10.1659/MRD-JOURNAL-D-18-00072.1>
- Obu, J. (2021). How much of the Earth’s surface is underlain by permafrost? *Journal of Geophysical Research: Earth Surface*, 126(5), Article e2021JF006123. <https://doi.org/10.1029/2021JF006123>
- Palazzi, E., von Hardenberg, J., & Provenzale, A. (2013). Precipitation in the Hindu-Kush Karakoram Himalaya: Observations and future scenarios. *Journal of Geophysical Research Atmospheres*, 118(1), 85–100. <https://doi.org/10.1029/2012JD018697>
- Panwar, S. (2020). Vulnerability of Himalayan springs to climate change and anthropogenic impact: A review. *Journal of Mountain Science*, 17(1), 117–132. <https://doi.org/10.1007/s11629-018-5308-4>
- Parveen, S., Winiger, M., Schmidt, S., & Nüsser, M. (2015). Irrigation in Upper Hunza: Evolution of socio-hydrological interactions in the Karakoram, Northern Pakistan. *Erdkunde*, 69(1), 69–85. <https://www.jstor.org/stable/24365265>
- Peng, D., Zhou, T., Zhang, L., & Zou, L. (2019). Detecting human influence on the temperature changes in Central Asia. *Climate Dynamics*, 53(7–8), 4553–4568. <https://doi.org/10.1007/s00382-019-04804-2>
- Pepin, N., Bradley, R. S., Diaz, H. F., Baraer, M., Caceres, E. B., Forsythe, N., Fowler, H., Greenwood, G., Hashmi, M. Z., Liu, X. D., Miller, J. R., Ning, L., Ohmura, A., Palazzi, E., Rangwala, I., Schöner, W., Severskiy, I., Shahgedanova, M., Wang, M. B., ... Yang, D. Q. (2015). Elevation-dependent warming in mountain regions of the world. *Nature Climate Change*, 5(5), 424–430. <https://doi.org/10.1038/nclimate2563>
- Poudel, D. P. (2011). How Himalayan dwellers rely on common-pool resources (CPRs) for livelihood? Mustang, trans-Himalayan Nepal. *Global Journal of Human-Social Science*, 11(3), 1–7.

- Prakash, A. (2020). *Retreating glaciers and water flows in the Himalayas: Implications for governance*. Policy Brief No. 400. Observer Research Foundation. https://www.orfonline.org/wp-content/uploads/2020/09/ORF_IssueBrief_400_HimalayanGlaciers.pdf
- Pritchard, H. D. (2019). Asia's shrinking glaciers protect large populations from drought stress. *Nature*, 569(7758), 649–654. <https://doi.org/10.1038/s41586-019-1240-1>
- Qin, Y., Abatzoglou, J. T., Siebert, S., Huning, L. S., AghaKouchak, A., Mankin, J. S., Hong, C., Tong, D., Davis, S. J., & Mueller, N. D. (2020). Agricultural risks from changing snowmelt. *Nature Climate Change*, 10(5), 459–465. <https://doi.org/10.1038/s41558-020-0746-8>
- Racoviteanu, A. E., Armstrong, R., & Williams, M. W. (2013). Evaluation of an ice ablation model to estimate the contribution of melting glacier ice to annual discharge in the Nepal Himalaya. *Water Resources Research*, 49(9), 5117–5133. <https://doi.org/10.1002/wrcr.20370>
- Ragetti, S., Pellicciotti, F., Immerzeel, W. W., Miles, E. S., Petersen, L., Heynen, M., Shea, J. M., Stumm, D., Joshi, S., & Shrestha, A. (2015). Unraveling the hydrology of a Himalayan catchment through integration of high resolution in situ data and remote sensing with an advanced simulation model. *Advances in Water Resources*, 78, 94–111. <https://doi.org/10.1016/j.advwatres.2015.01.013>
- Ranasinghe, R., Ruane, A. C., Vautard, R., Arnell, N., Coppola, E., Cruz, F. A., Dessai, S., Islam, A. S., Rahimi, M., Ruiz Carrascal, D., Sillmann, J., Sylla, M. B., Tebaldi, C., Wang, W., & Zaaboul, R. (2021). Climate change information for regional impact and for risk assessment. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (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* (pp. 1767–1926). Cambridge University Press.
- Rashid, I., & Majeed, U. (2018). Recent recession and potential future lake formation on Drang Drung Glacier, Zaskar Himalaya, as assessed with earth observation data and glacier modelling. *Environmental Earth Sciences*, 77(12), 429. <https://doi.org/10.1007/s12665-018-7601-5>
- Rasul, G., & Molden, D. (2019). The global social and economic consequences of mountain cryospheric change. *Frontiers in Environmental Science*, 7. <https://www.frontiersin.org/articles/10.3389/fenvs.2019.00091>
- Reggiani, P., Mukhopadhyay, B., Rientjes, T. H. M., & Khan, A. (2017). A joint analysis of river runoff and meteorological forcing in the Karakoram, Upper Indus Basin. *Hydrological Processes*, 31(2), 409–430. <https://doi.org/10.1002/hyp.11038>
- Roe, G. H., Baker, M. B., & Herla, F. (2017). Centennial glacier retreat as categorical evidence of regional climate change. *Nature Geoscience*, 10(2), 95–99. <https://doi.org/10.1038/ngeo2863>
- Roe, G. H., Christian, J. E., & Marzeion, B. (2021). On the attribution of industrial-era glacier mass loss to anthropogenic climate change. *The Cryosphere*, 15(4), 1889–1905. <https://doi.org/10.5194/tc-15-1889-2021>
- Rosser, N., Kinsey, M., Oven, K., Densmore, A., Robinson, T., Pujara, D. S., Shrestha, R., Smutny, J., Gurung, K., Lama, S., & Dhital, M. R. (2021). Changing significance of landslide hazard and risk after the 2015 Mw 7.8 Gorkha, Nepal earthquake. *Progress in Disaster Science*, 10, Article 100159. <https://doi.org/10.1016/j.pdisas.2021.100159>
- Rounce, D. R., Byers, A. C., Byers, E. A., & McKinney, D. C. (2017). Brief communication: Observations of a glacier outburst flood from Lhotse Glacier, Everest area, Nepal. *The Cryosphere*, 11(1), 443–449. <https://doi.org/10.5194/tc-11-443-2017>
- Round, V., Leinss, S., Huss, M., Haemmig, C., & Hajnsek, I. (2017). Surge dynamics and lake outbursts of Kyagar Glacier, Karakoram. *The Cryosphere*, 11(2), 723–739. <https://doi.org/10.5194/tc-11-723-2017>
- Rusk, J., Maharjan, A., Tiwari, P., Chen, T.-H. K., Shneiderman, S., Turin, M., & Seto, K. C. (2022). Multi-hazard susceptibility and exposure assessment of the Hindu Kush Himalaya. *Science of The Total Environment*, 804, Article 150039. <https://doi.org/10.1016/j.scitotenv.2021.150039>
- Saif, B., Tahir, M., Sultan, A., Iqbal, M. T., Iqbal, T., Shah, M. A., & Gurmani, S. (2022). Triggering mechanisms of Gayari avalanche, Pakistan. *Natural Hazards*, 112(3), 2361–2383. <https://doi.org/10.1007/s11069-022-05269-z>
- Sattar, A., Goswami, A., Kulkarni, A. V., Emmer, A., Haritashya, U. K., Allen, S., Frey, H., & Huggel, C. (2021). Future glacial lake outburst flood (GLOF) hazard of the South Lhonak Lake, Sikkim Himalaya. *Geomorphology*, 388, Article 107783. <https://doi.org/10.1016/j.geomorph.2021.107783>

- Scott, C. A., Zhang, F., Mukherji, A., Immerzeel, W., Mustafa, D., & Bharati, L. (2019). Water in the Hindu Kush Himalaya. In P. Wester, A. Mishra, A. Mukherji, & A. B. Shrestha (Eds.), *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability and people* (pp. 257–299). Springer Nature Switzerland AG. https://doi.org/10.1007/978-3-319-92288-1_8
- Seneviratne, S. I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Di Luca, A., Ghosh, S., Iskandar, I., Kossin, J., Lewis, S., Otto, F. E. L., Pinto, I., Satoh, M., Vicente-Serrano, S. M., Wehner, M., & Zhou, B. (2021). Weather and climate extreme events in a changing climate. In V. Masson-Delmotte, P. M. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (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* (pp. 1513–1766). Cambridge University Press.
- Sharma, S., Talchabhadel, R., Nepal, S., Ghimire, G. R., Rakhali, B., Panthi, J., Adhikari, B. R., Pradhanang, S. M., Maskey, S., & Kumar, S. (2022). Increasing risk of cascading hazards in the central Himalayas. *Natural Hazards*. <https://doi.org/10.1007/s11069-022-05462-0>
- Shean, D. E., Bhushan, S., Montesano, P., Rounce, D. R., Arendt, A., & Osmanoglu, B. (2020). A systematic, regional assessment of High Mountain Asia glacier mass balance. *Frontiers in Earth Science*, 7, 363. <https://doi.org/10.3389/feart.2019.00363>
- Shen, Y.-J., Shen, Y., Fink, M., Kralisch, S., Chen, Y., & Brenning, A. (2018). Trends and variability in streamflow and snowmelt runoff timing in the southern Tianshan Mountains. *Journal of Hydrology*, 557, 173–181. <https://doi.org/10.1016/j.jhydrol.2017.12.035>
- Shenbin, C., Yunfeng, L., & Thomas, A. (2006). Climatic change on the Tibetan Plateau: Potential evapotranspiration trends from 1961–2000. *Climatic Change*, 76(3), 291–319. <https://doi.org/10.1007/s10584-006-9080-z>
- Shi, X., Zhang, F., Lu, X., Zhang, Y., Zheng, Y., Wang, G., Wang, L., Jagirani, M. D., Wang, T., & Piao, S. (2022). The response of the suspended sediment load of the headwaters of the Brahmaputra River to climate change: Quantitative attribution to the effects of hydrological, cryospheric and vegetation controls. *Global and Planetary Change*, 210, Article 103753. <https://doi.org/10.1016/j.gloplacha.2022.103753>
- Shrestha, M., Koike, T., Hirabayashi, Y., Xue, Y., Wang, L., Rasul, G., & Ahmad, B. (2015). Integrated simulation of snow and glacier melt in water and energy balance-based, distributed hydrological modeling framework at Hunza River Basin of Pakistan Karakoram region. *Journal of Geophysical Research: Atmospheres*, 120(10), 4889–4919. <https://doi.org/10.1002/2014JD022666>
- Shugar, D. H., Burr, A., Haritashya, U. K., Kargel, J. S., Watson, C. S., Kennedy, M. C., Bevington, A. R., Betts, R. A., Harrison, S., & Strattman, K. (2020). Rapid worldwide growth of glacial lakes since 1990. *Nature Climate Change*, 10(10), 939–945. <https://doi.org/10.1038/s41558-020-0855-4>
- Shugar, D. H., Jacquemart, M., Shean, D., Bhushan, S., Upadhyay, K., Sattar, A., Schwanghart, W., McBride, S., de Vries, M. V. W., Mergili, M., Emmer, A., Deschamps-Berger, C., McDonnell, M., Bhambri, R., Allen, S., Berthier, E., Carrivick, J. L., Clague, J. J., Dokukin, M., ... Westoby, M. J. (2021). A massive rock and ice avalanche caused the 2021 disaster at Chamoli, Indian Himalaya. *Science*. <https://doi.org/10.1126/science.abh4455>
- Siddique, T., Haris, P. M., & Pradhan, S. P. (2022). Unraveling the geological and meteorological interplay during the 2021 Chamoli disaster, India. *Natural Hazards Research*, 2(2), 75–83. <https://doi.org/10.1016/j.nhres.2022.04.003>
- Singh, A. T., Sharma, P., Sharma, C., Laluraj, C. M., Patel, L., Pratap, B., Oulkar, S., & Thamban, M. (2020). Water discharge and suspended sediment dynamics in the Chandra River, Western Himalaya. *Journal of Earth System Science*, 129(1), 206. <https://doi.org/10.1007/s12040-020-01455-4>
- Sinha, R., Gupta, A., Mishra, K., Tripathi, S., Nepal, S., Wahid, S. M., & Swarnkar, S. (2019). Basin-scale hydrology and sediment dynamics of the Kosi river in the Himalayan foreland. *Journal of Hydrology*, 570, 156–166. <https://doi.org/10.1016/j.jhydrol.2018.12.051>
- Somers, L. D., & McKenzie, J. M. (2020). A review of groundwater in high mountain environments. *WIREs Water*, 7(6), Article e1475. <https://doi.org/10.1002/wat2.1475>
- Soncini, A., Bocchiola, D., Confortola, G., Bianchi, A., Rosso, R., Mayer, C., Lambrecht, A., Palazzi, E., Smiraglia, C., & Diolaiuti, G. (2015). Future hydrological regimes in the Upper Indus Basin: A case study from a high-altitude glacierized catchment. *Journal of Hydrometeorology*, 16(1), 306–326. <https://doi.org/10.1175/JHM-D-14-0043.1>
- Song, L., Zhuang, Q., Yin, Y., Zhu, X., & Wu, S. (2017). Spatio-temporal dynamics of evapotranspiration on the Tibetan Plateau from 2000 to 2010. *Environmental Research Letters*, 12(1), 014011. <https://doi.org/10.1088/1748-9326/aa527d>

- Srivastava, S., & Azam, Md. F. (2022). Functioning of glacierized catchments in monsoon and alpine regimes of Himalaya. *Journal of Hydrology*, 609(71), Article 127671. <https://doi.org/10.1016/j.jhydrol.2022.127671>
- Steffen, T., Huss, M., Estermann, R., Hodel, E., & Farinotti, D. (2022). Volume, evolution, and sedimentation of future glacier lakes in Switzerland over the 21st century. *Earth Surface Dynamics*, 10(4), 723–741. <https://doi.org/10.5194/esurf-10-723-2022>
- Steiner, J. F., Gurung, T. R., Joshi, S. P., Koch, I., Saloranta, T., Shea, J., Shrestha, A. B., Stigter, E., & Immerzeel, W. W. (2021). Multi-year observations of the high mountain water cycle in the Langtang catchment, Central Himalaya. *Hydrological Processes*, 35(5), Article e14189. <https://doi.org/10.1002/hyp.14189>
- Steiner, J. F., Litt, M., Stigter, E. E., Shea, J., Bierkens, M. F. P., & Immerzeel, W. W. (2018). The importance of turbulent fluxes in the surface energy balance of a debris-covered glacier in the Himalayas. *Frontiers in Earth Science*, 6. <https://doi.org/10.3389/feart.2018.00144>
- Stigter, E. E., Litt, M., Steiner, J. F., Bonekamp, P. N. J., Shea, J. M., Bierkens, M. F. P., & Immerzeel, W. W. (2018). The importance of snow sublimation on a Himalayan glacier. *Frontiers in Earth Science*, 6. <https://doi.org/10.3389/feart.2018.00108>
- Stuart-Smith, R. F., Roe, G. H., Li, S., & Allen, M. R. (2021). Increased outburst flood hazard from Lake Palcacocha due to human-induced glacier retreat. *Nature Geoscience*, 14(2), 85–90. <https://doi.org/10.1038/s41561-021-00686-4>
- Swarnkar, S., Tripathi, S., & Sinha, R. (2021). Understanding hydrogeomorphic and climatic controls on soil erosion and sediment dynamics in large Himalayan basins. *Science of The Total Environment*, 795, Article 148972. <https://doi.org/10.1016/j.scitotenv.2021.148972>
- Syvitski, J., Ángel, J. R., Saito, Y., Overeem, I., Vörösmarty, C. J., Wang, H., & Olago, D. (2022). Earth's sediment cycle during the Anthropocene. *Nature Reviews Earth & Environment*, 3(3), 179–196. <https://doi.org/10.1038/s43017-021-00253-w>
- Talchabhadel, R., Karki, R., Thapa, B. R., Maharjan, M., & Parajuli, B. (2018). Spatio-temporal variability of extreme precipitation in Nepal. *International Journal of Climatology*, 38(11), 4296–4313. <https://doi.org/10.1002/joc.5669>
- Tambe, S., Dhakal, S., Dhakal, D., Sharma, G., Sherpa, P. N., Kulkarni, H., Bhutia, N. T., Dhakal, D., Pradhan, S., Sinha, U. K., Tiwari, A., Kharel, G., Phukan, I., & Arrawatia, M. L. (2020). Scaling up spring revival in the Himalaya: Graduating from spring-centric to aquifer-centric nature-based solutions. In S. Dhyani, A. K. Gupta, & M. Karki (Eds.), *Nature-based solutions for resilient ecosystems and societies* (pp. 29–50). Springer. https://doi.org/10.1007/978-981-15-4712-6_2
- Tambe, S., Kharel, G., Arrawatia, M. L., Kulkarni, H., Mahamuni, K., & Ganeriwala, A. K. (2012). Reviving dying springs: Climate change adaptation experiments from the Sikkim Himalaya. *Mountain Research and Development*, 32(1), 62–72. <https://doi.org/10.1659/MRD-JOURNAL-D-11-00079.1>
- Tambe, S., Rawat, G. S., Bhutia, N. T., Sherpa, P. N., Dhakal, S., Pradhan, S., Kulkarni, H., & Arrawatia, M. L. (2020). Building sustainability in the Eastern Himalaya: Linking evidence to action. *Environment, Development and Sustainability*, 22(6), 5887–5903. <https://doi.org/10.1007/s10668-019-00456-8>
- Thornton, J. M., Pepin, N., Shahgedanova, M., & Adler, C. (2022). Coverage of in situ climatological observations in the world's mountains. *Frontiers in Climate*, 4. <https://www.frontiersin.org/articles/10.3389/fclim.2022.814181>
- Tian, L., Yao, T., Gao, Y., Thompson, L., Mosley-Thompson, E., Muhammad, S., Zong, J., Wang, C., Jin, S., & Li, Z. (2017). Two glaciers collapse in western Tibet. *Journal of Glaciology*, 63(237), 194–197. <https://doi.org/10.1017/jog.2016.122>
- Tiel, M. van, Stahl, K., Freudiger, D., & Seibert, J. (2020). Glacio-hydrological model calibration and evaluation. *WIREs Water*, 7(6), Article e1483. <https://doi.org/10.1002/wat2.1483>
- Tilloy, A., Malamud, B. D., Winter, H., & Joly-Laugel, A. (2019). A review of quantification methodologies for multi-hazard interrelationships. *Earth-Science Reviews*, 196, Article 102881. <https://doi.org/10.1016/j.earscirev.2019.102881>
- Tuladhar, S., Pasakhala, B., Maharjan, A., & Mishra, A. (2021). Unravelling the linkages of cryosphere and mountain livelihood systems: A case study of Langtang, Nepal. *Advances in Climate Change Research*, 12(1), 119–131. <https://doi.org/10.1016/j.accr.2020.12.004>
- Turner, A. G., & Annamalai, H. (2012). Climate change and the South Asian summer monsoon. *Nature Climate Change*, 2(8), 587–595. <https://doi.org/10.1038/nclimate1495>

- ul Hasson, S. (2016). Future water availability from Hindukush-Karakoram-Himalaya Upper Indus Basin under conflicting climate change scenarios. *Climate*, 4(3), 40. <https://doi.org/10.3390/cli4030040>
- Ultee, L., Coats, S., & Mackay, J. (2022). Glacial runoff buffers droughts through the 21st century. *Earth System Dynamics*, 13(2), 935–959. <https://doi.org/10.5194/esd-13-935-2022>
- Veh, G., Korup, O., von Specht, S., Roessner, S., & Walz, A. (2019). Unchanged frequency of moraine-dammed glacial lake outburst floods in the Himalaya. *Nature Climate Change*, 9(5), 379–383. <https://doi.org/10.1038/s41558-019-0437-5>
- Veh, G., Lützw, N., Kharlamova, V., Petrakov, D., Hugonnet, R., & Korup, O. (2022). Trends, breaks, and biases in the frequency of reported glacier lake outburst floods. *Earth's Future*, 10(3), Article e2021EF002426. <https://doi.org/10.1029/2021EF002426>
- Viste, E., & Sorteberg, A. (2015). Snowfall in the Himalayas: An uncertain future from a little-known past. *The Cryosphere*, 9(3), 1147–1167. <https://doi.org/10.5194/tc-9-1147-2015>
- Viviroli, D., Dürr, H. H., Messerli, B., Meybeck, M., & Weingartner, R. (2007). Mountains of the world, water towers for humanity: Typology, mapping, and global significance. *Water Resources Research*, 43(7). <https://doi.org/10.1029/2006WR005653>
- Viviroli, D., Kumm, M., Meybeck, M., Kallio, M., & Wada, Y. (2020). Increasing dependence of lowland populations on mountain water resources. *Nature Sustainability*, 3(11), 917–928. <https://doi.org/10.1038/s41893-020-0559-9>
- Wagle, N., Dhakal, M. P., & Shrestha, A. B. (2021). Adaptation strategies to address challenges of traditional agricultural water management in the Upper Indus Basin. *Mountain Research and Development*, 41(3), R24–R31. <https://doi.org/10.1659/MRD-JOURNAL-D-20-00059.1>
- Wang, B., Ma, Y., Su, Z., Wang, Y., & Ma, W. (2020). Quantifying the evaporation amounts of 75 high-elevation large dimictic lakes on the Tibetan Plateau. *Science Advances*, 6(26), Article eaay8558. <https://doi.org/10.1126/sciadv.aay8558>
- Wang, L., He, X., Steiner, J. F., Dongwei, Z., Wu, J., Wang, S., & Ding, Y. (2020). Models and measurements of seven years of evapotranspiration on a high elevation site on the Central Tibetan Plateau. *Journal of Mountain Science*. <https://doi.org/10.1007/s11629-020-6051-1>
- Wang, W., Xiang, Y., Gao, Y., Lu, A., & Yao, T. (2015). Rapid expansion of glacial lakes caused by climate and glacier retreat in the Central Himalayas. *Hydrological Processes*, 29(6), 859–874. <https://doi.org/10.1002/hyp.10199>
- Wang, W., Xing, W., Shao, Q., Yu, Z., Peng, S., Yang, T., Yong, B., Taylor, J., & Singh, V. P. (2013). Changes in reference evapotranspiration across the Tibetan Plateau: Observations and future projections based on statistical downscaling. *Journal of Geophysical Research: Atmospheres*, 118(10), 4049–4068. <https://doi.org/10.1002/jgrd.50393>
- Wang, W., Zhang, T., Yao, T., & An, B. (2022). Monitoring and early warning system of Cirenmaco glacial lake in the central Himalayas. *International Journal of Disaster Risk Reduction*, 73, Article 102914. <https://doi.org/10.1016/j.ijdrr.2022.102914>
- Wang, Y., Sun, Y., Hu, T., Qin, D., & Song, L. (2018). Attribution of temperature changes in Western China. *International Journal of Climatology*, 38(2), 742–750. <https://doi.org/10.1002/joc.5206>
- Wani, J. M., Thayyen, R. J., Gruber, S., Ojha, C. S. P., & Stumm, D. (2020). Single-year thermal regime and inferred permafrost occurrence in the upper Ganglass catchment of the cold-arid Himalaya, Ladakh, India. *Science of The Total Environment*, 703, Article 134631. <https://doi.org/10.1016/j.scitotenv.2019.134631>
- Wani, J. M., Thayyen, R. J., Ojha, C. S. P., & Gruber, S. (2021). The surface energy balance in a cold and arid permafrost environment, Ladakh, Himalayas, India. *The Cryosphere*, 15(5), 2273–2293. <https://doi.org/10.5194/tc-15-2273-2021>
- Wester, P., Mishra, A., Mukherji, A., & Shrestha, A. B. (Eds.). (2019). *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability and people*. Springer Nature Switzerland AG. <https://doi.org/10.1007/978-3-319-92288-1>
- Wijngaard, R. R., Lutz, A. F., Nepal, S., Khanal, S., Pradhananga, S., Shrestha, A. B., & Immerzeel, W. W. (2017). Future changes in hydro-climatic extremes in the Upper Indus, Ganges, and Brahmaputra River basins. *PLOS ONE*, 12(12), Article e0190224. <https://doi.org/10.1371/journal.pone.0190224>
- Wu, T., Xie, C., Zhu, X., Chen, J., Wang, W., Li, R., Wen, A., Wang, D., Lou, P., Shang, C., La, Y., Wei, X., Ma, X., Qiao, Y., Wu, X., Pang, Q., & Hu, G. (2022). Permafrost, active layer, and meteorological data (2010–2020) at the Mahan Mountain relict permafrost site

- of northeastern Qinghai–Tibet Plateau. *Earth System Science Data*, 14(3), 1257–1269. <https://doi.org/10.5194/essd-14-1257-2022>
- Xu, X., Lyu, D., Lei, X., Huang, T., Li, Y., Yi, H., Guo, J., He, L., He, J., Yang, X., Guo, M., Liu, B., & Zhang, X. (2021). Variability of extreme precipitation and rainfall erosivity and their attenuated effects on sediment delivery from 1957 to 2018 on the Chinese Loess Plateau. *Journal of Soils and Sediments*, 21(12), 3933–3947. <https://doi.org/10.1007/s11368-021-03054-2>
- Xu, Z., Zhang, S., & Yang, X. (2021). Water and sediment yield response to extreme rainfall events in a complex large river basin: A case study of the Yellow River Basin, China. *Journal of Hydrology*, 597, Article 126183. <https://doi.org/10.1016/j.jhydrol.2021.126183>
- Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S. U., Hoelzle, M., Paul, F., Haeberli, W., Denzinger, F., Ahlstrøm, A. P., Anderson, B., Bajracharya, S., Baroni, C., Braun, L. N., Cáceres, B. E., Casassa, G., Cobos, G., Dávila, L. R., Delgado Granados, H., Demuth, M. N., ... Vincent, C. (2015). Historically unprecedented global glacier decline in the early 21st century. *Journal of Glaciology*, 61(228), 745–762. <https://doi.org/10.3189/2015JoG15J017>
- Zhang, F., Thapa, S., Immerzeel, W., Zhang, H., & Lutz, A. (2019). Water availability on the Third Pole: A review. *Water Security*, 7, Article 100033. <https://doi.org/10.1016/j.wasec.2019.100033>
- Zhang, G., Yao, T., Xie, H., Wang, W., & Yang, W. (2015). An inventory of glacial lakes in the Third Pole region and their changes in response to global warming. *Global and Planetary Change*, 131, 148–157. <https://doi.org/10.1016/j.gloplacha.2015.05.013>
- Zhang, S., Zhang, L. M., & Glade, T. (2014). Characteristics of earthquake- and rain-induced landslides near the epicenter of Wenchuan earthquake. *Engineering Geology*, 175, 58–73. <https://doi.org/10.1016/j.enggeo.2014.03.012>
- Zhang, T., Wang, W., Gao, T., An, B., & Yao, T. (2022). An integrative method for identifying potentially dangerous glacial lakes in the Himalayas. *Science of The Total Environment*, 806, Article 150442. <https://doi.org/10.1016/j.scitotenv.2021.150442>
- Zheng, G., Allen, S. K., Bao, A., Ballesteros-Cánovas, J. A., Huss, M., Zhang, G., Li, J., Yuan, Y., Jiang, L., Yu, T., Chen, W., & Stoffel, M. (2021). Increasing risk of glacial lake outburst floods from future Third Pole deglaciation. *Nature Climate Change*, 11(5), 411–417. <https://doi.org/10.1038/s41558-021-01028-3>
- Zheng, G., Mergili, M., Emmer, A., Allen, S., Bao, A., Guo, H., & Stoffel, M. (2021). The 2020 glacial lake outburst flood at Jinwuco, Tibet: Causes, impacts, and implications for hazard and risk assessment. *The Cryosphere*, 15, 3159–3180. <https://doi.org/10.5194/tc-15-3159-2021>
- Zheng, H., Chiew, F. H. S., Charles, S., & Podger, G. (2018). Future climate and runoff projections across South Asia from CMIP5 global climate models and hydrological modelling. *Journal of Hydrology: Regional Studies*, 18, 92–109. <https://doi.org/10.1016/j.ejrh.2018.06.004>
- Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C., Horton, R. M., van den Hurk, B., AghaKouchak, A., Jézéquel, A., Mahecha, M. D., Maraun, D., Ramos, A. M., Ridder, N. N., Thiery, W., & Vignotto, E. (2020). A typology of compound weather and climate events. *Nature Reviews Earth & Environment*, 1(7), 333–347. <https://doi.org/10.1038/s43017-020-0060-z>

CHAPTER 4

RECOMMENDED CITATION

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Effects of a changing cryosphere on biodiversity and ecosystem services, and response options in the Hindu Kush Himalaya

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Chapter overview

KEY FINDINGS

The cryosphere of the Hindu Kush Himalaya (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*).

However, 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, both increasing the vulnerabilities of biodiversity and people and affecting their wellbeing (*high confidence*).

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*).

POLICY MESSAGES

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.

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.

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.

CHAPTER SUMMARY

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 on 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 sharing, and the implementation of multidisciplinary approaches are needed for coordinated responses that are ultimately more effective (*very high confidence*).

KEY KNOWLEDGE GAPS

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.

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.

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.

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4.1. Introduction

The Hindu Kush Himalayan (HKH) region is exceptionally rich in biodiversity¹ at the ecosystem, species, and genetic levels (Allen et al., 2010; Chaudhary et al., 2022; Rana et al., 2022; Xu et al., 2019). This rich biodiversity is the result of high levels of climatic variability, rugged topography, and altitude variations (Sathyakumar et al., 2020; Zomer & Oli, 2012). The Hindu Kush Himalaya is one of the youngest mountain ranges on Earth, the formation of which commenced some 60 million years ago with the start of the collision between the Indian Plate and the Eurasian Plate, which resulted in twisted strata of biogeography, extreme variabilities in topography, and variations in vegetation (Jaegar, 2021; Sathyakumar et al., 2020; Xu et al., 2019). The dominant land cover of the region is characterised by high-elevation grassland (38.23%), bare rocks and soil (30.69%), forests (14%), snow and glacier areas (4%), and water bodies and riverbeds (2%) (Uddin et al., 2021). The major ecosystems include tropical and subtropical rainforests; temperate broadleaf, deciduous, and temperate coniferous forest; high-elevation cold shrub or steppe; and cold desert (Chen, 2002). The cryosphere, which consists of ice, snow, glacier, permafrost, and glacial lakes, is an important part of the HKH as it has the largest accumulation of ice and snow outside the polar regions (Bolch et al., 2019). The HKH is the source of 12 major river basins (Amu Darya, Helmand, Indus, Tarim, Ganges, Interior Tibetan Plateau, Brahmaputra, Irrawaddy, Salween, Mekong, Yangtze, and Yellow) and hosts all or parts of four global biodiversity hotspots (the Himalaya, South-West China Mountains, Indo-

Burma, and Central Asia Mountains) offering ideal habitats for endemic and rare species (Wu et al., 2013) (Figure 4.1).

The region contains 575 protected areas (Chaudhary et al., 2022), 12 of the Global 200 Ecoregions (Olson & Dinerstein, 2002), 335 Important Bird and Biodiversity Areas (IBAs), and 348 Key Biodiversity Areas (Donald et al., 2019). These ecosystems support a high level of biodiversity and provide a congenial environment for a range of flora and fauna often endemic to the region (Myers et al., 2000). Mountains are considered as ideal places to study species richness because of large environmental gradients over short distances at small spatial scales. The spatial pattern of species richness in mountains can be generally grouped into three types: (1) a monotonic decline; (2) high richness at lower elevations and decline at higher elevations; and (3) a “hump-shaped” distribution with high richness at intermediate elevations (Liang et al., 2020). Climatic factors are the dominant drivers of these observed spatial patterns. HKH is home to a significant share of the global plant and animal diversity, in particular the Himalaya, Indo-Burma, and southwest China biodiversity hotspots (Allen et al., 2010). Among the most charismatic and iconic species found in high-elevation HKH ecosystems are the snow leopard (*Panthera uncia*), Tibetan brown bear (*Ursus arctos pruinosus*), giant panda (*Ailuropoda melanoleuca*), red panda (*Ailurus fulgens*), semi-domesticated yak (*Poephagus grunniens*), and Marco Polo sheep (*Ovis ammon polii*).

¹“Biodiversity” is the diversity of life on earth at ecosystem, species, and genetic levels (CBD, 1992).

FIGURE 4.1

RIVER BASINS AND GLOBAL BIODIVERSITY HOTSPOTS IN THE HINDU KUSH HIMALAYA



Note: A map showing the four global biodiversity hotspots of the Hindu Kush Himalaya: Mountains of Central Asia, Himalaya, Indo-Burma and Mountains of South-west China

4.2. Drivers of change

Biodiversity and ecosystem services in the region are threatened by a range of drivers of change. Among them are climate change, land use and land cover change, increasing human footprints, and invasive species (Wang et al., 2019). The region has been modified and altered by humans for thousands of years (Ives & Messerli, 1989) through interventions such as cattle and crop farming, and cultural practices (Chen et al., 2015; Gurung, 2004; Pandit & Kumar, 2013). HKH has also experienced significant changes in climate during the past decades, with the region subject to higher variabilities and changes in temperature and precipitation. The mean temperature is increasing significantly across the HKH, and warming is likely to be higher in the region in the future with the higher elevations experiencing more warming than the lower (Krishnan et al., 2019). Likewise, changes in precipitation patterns, too, are

highly likely, particularly in higher elevation areas (Bolch et al., 2019) (see Chapter 2 for more details).

In the HKH, climate change impacts on the cryosphere are well established – evident in the rapid retreating of glaciers, shrinking of mountain ice, thawing of permafrost, and changing patterns in snow cover (Bolch et al., 2019). The outcome has been a shrinking cryosphere due to losses in glacier mass, snow cover, and permafrost area as well as changes in hydrology and an increase in natural hazards and disasters (IPCC, 2019). The rate of warming is slightly higher than the global average in the HKH cryosphere, with significant impacts on streams and river flows (Lutz et al., 2016) (see Chapter 3), and ecosystems and species of the region (Gaire et al., 2022; Shrestha et al., 2015; Singh & Samant, 2020). Even a 1.5°C temperature rise in the HKH would seriously impact most ecosystems, including forest, rangeland, and wetlands, because of changes in

species abundance, composition, and productivity (Mayewski et al., 2020; Negi et al., 2012). The non-climatic anthropogenic drivers of change such as land use and land cover change, invasive species, solid waste and atmospheric pollution, habitat degradation, and over-exploitation of resources are exacerbating the impacts of climate change on ecosystems and their services (Xu et al., 2019). The interactions between the various drivers of change amplifies the impacts on biodiversity and people (Wang et al., 2019).

While our knowledge about the physical science of the cryosphere and changes in it have developed considerably in recent years, our understanding of the interactions between components of the cryosphere (such as glaciers, ice, snow, permafrost, and glacial lakes), and their impacts on high-elevation biodiversity is very limited. This chapter assesses the scientific literature on the impacts of the changing cryosphere on biodiversity and ecosystem services in the HKH as well as response options. It

focuses on the observed impacts at the ecosystems and species level and discusses the response options reported in the literature. In doing so, the chapter highlights the key knowledge gaps and provides recommendations for better understanding the impacts as well as adaptation actions to enhance socio-ecological resilience. The assessment adopted the ‘state-of-the-art’ method proposed by Grant & Booth (2009) to conduct a review of relevant literature. The method focused on specific subject matter to gain a holistic understanding of the issue at hand. Deploying Scopus, we used specific keywords related to the cryosphere (snow, glaciers, permafrost, lakes, and ice), biodiversity (such as species, ecosystem, genetic, and alpine), region (HKH), and language. Relevant literature was selected through a quick scanning of the title and abstract. We also carefully reviewed the *HKH assessment* report (Wester et al., 2019) and the recent IPCC Cross-Chapter Paper on Mountains (Adler et al., 2022).

4.3. Cryosphere and ecosystem services

The biodiversity of the HKH provides a wide range of ecosystem services and contributes, thereby, to the wellbeing of the people living in the region and beyond. The major ecosystems that are spatially connected to the cryosphere are rangeland, freshwater (rivers and wetlands), high-elevation peatlands, and barren land (gravel, stones, and boulders) but the cryosphere also indirectly contributes to other ecosystems in lowland areas such as forest and agriculture. All these ecosystems provide a wide variety of services. However, this chapter will primarily focus on high-elevation ecosystems that are directly linked to the cryosphere (see Figure 4.2).

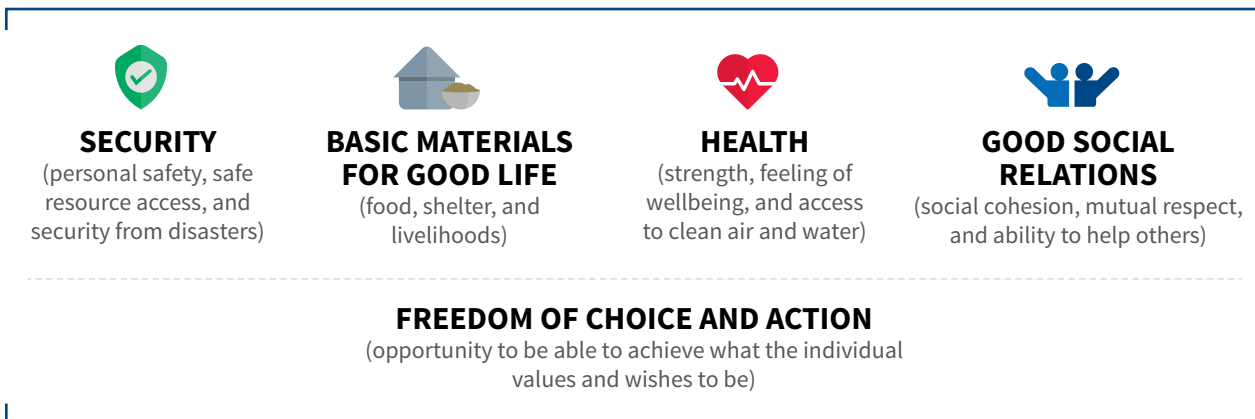
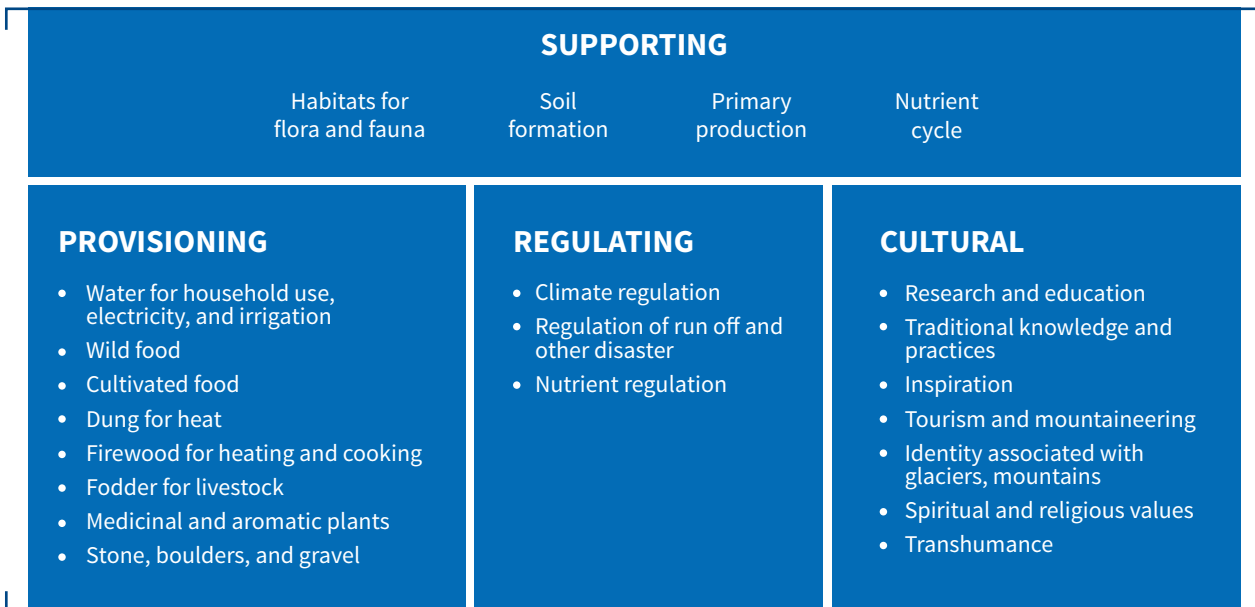
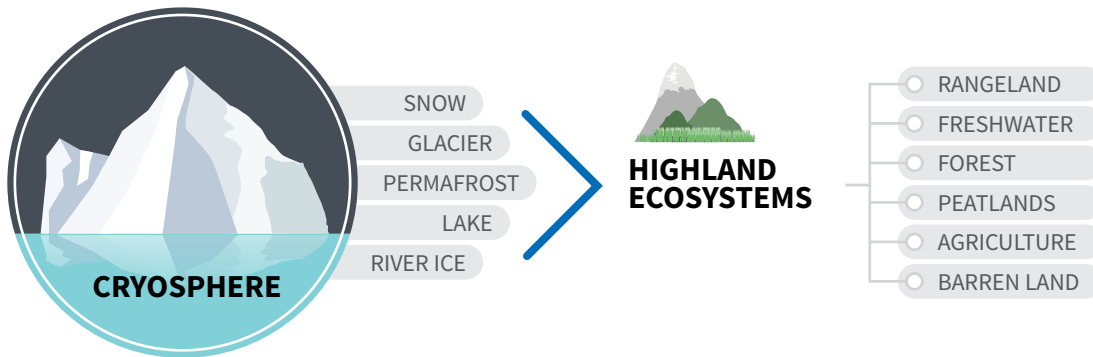
The major provisioning services reported in the HKH region are water for household use, irrigation, and electricity; wild and domesticated food, firewood, and forage; medicinal plants; and materials such

as stones, minerals, metal ore, coal, gravel, and boulders (Chaudhary et al., 2017; Murali et al., 2017). Countries of the HKH region are heavily dependent on these services. For example, about 80% of the population of Nepal is dependent on forests and agriculture for their livelihoods while around 26–39% of the country’s Gross Domestic Product comes from agriculture, forestry, and fisheries (Government of Nepal & UNDP Nepal, 2010). Similarly, the economy and culture are intricately linked to forests. The Bhutanese economy depends significantly on natural resources such as wood, non-timber forest products, minerals, agricultural land, and water. Tourism, festivals, and trekking, which are important for the country’s economy and cultural practices, too, are largely dependent on natural ecosystems (Sears et al., 2017). Among the other provisioning services from the high-elevation ecosystems are minerals, coals, metal ores, and salt (Govil et al., 2021).

In addition to the contributions to society and economy, the provisioning of freshwater from glaciers, snow, ice, and permafrost also play a

FIGURE 4.2

MAJOR SERVICES PROVIDED BY ALPINE ECOSYSTEMS



Source: Scopus-based literature review by the authors (2021). The dataset is available on request.

critical role in the function, growth, and survival of biodiversity at high elevations (Mukherji et al., 2015). As part of the ecosystem function, nutrients such as nitrogen, phosphorous, potassium, calcium, manganese, and sulphur are supplied, which are required for metabolic activity in organisms at higher elevations as well as nutrients cycling and soil formation (Su et al., 2019). The availability of such nutrients forms the basis of primary production, which determines vegetation types (Tian et al., 2019). This activity is largely supported through the flow of ecosystem services, including water. In the HKH, sources of water also play a significant role in the energy sector, especially hydropower. Permafrost and frozen ground, moreover, regulate and determine the types, composition, structure, and distribution pattern of ecosystems (Kaplan & New, 2006).

Alpine ecosystems are unique in terms of their role in regulating climate and nutrients, and disaster risk reduction as well as providing habitats and food for flora and fauna. Called supporting services, cryosphere components are important for the sustainability of biodiversity. The cryosphere strongly affects ecosystems in terms of structure, composition, and functions, which provide habitats for a range of flora, fauna, and micro-organisms (O'Connor et al., 2020). There are diverse ice-associated organisms, including bacteria,

fungi, microalgae, unicellular animals, birds, and mammals, which photosynthesise, forage, reproduce, and grow in cryosphere habitats and form unique food chains (Su et al., 2019). As such, the HKH cryosphere supports high biodiversity including diverse micro-organisms, plants, and animals such as the snow leopard (Lambeck, 1997; Mukherji et al., 2019).

Cultural services are important in the HKH in terms of wellbeing, social capital, and the economy. Some of the major cultural services in the region are transhumance, tourism and mountaineering, inspiration, social cohesion, spirituality and religious values, traditional ecological knowledge and practices, indigenous local knowledge and practices, and research and education (Chaudhary et al., 2017; Chettri et al., 2021; Kandel et al., 2021; Tuladhar et al., 2021). People regard some high mountains with snow, lakes, and rivers as the physical manifestations of God (Winters, 2022). The interactions between the cryosphere and biodiversity also provide opportunities for research as these cultural services, in the form of beliefs and practices, provide opportunities to advance science, shape contemporary and traditional knowledge about the high-elevation regions, and directly and indirectly contribute to the conservation of biodiversity at all levels.

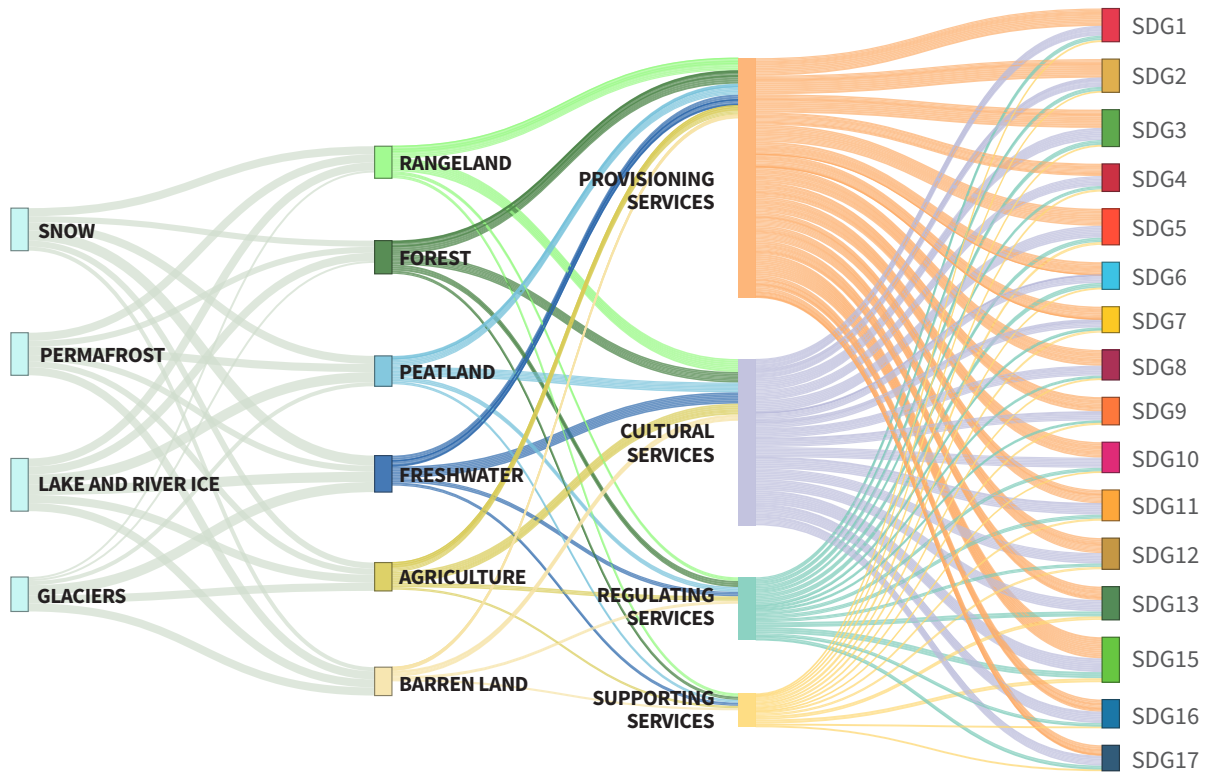
4.4. Cryosphere services and sustainable development goals

Figure 4.3 provides a conceptual overview of the flows of ecosystem services from the cryosphere towards the sustainable development goals (SDGs).

Services from the cryosphere substantially contribute towards SDG 1 (no poverty), SDG 2 (zero hunger), SDG 3 (health and wellbeing), SDG 6 (clean water and sanitation), SDG 7 (clean energy), SDG 8 (decent work and economic growth), SDG 11 (sustainable cities and communities), SDG 12 (sustainable consumption and production), SDG 13 (climate action), and SDG 15 (life on land).

FIGURE 4.3

LINKS BETWEEN CRYOSPHERE, HIGHLAND ECOSYSTEMS, ECOSYSTEM SERVICES, AND SUSTAINABLE DEVELOPMENT GOALS



- | | | |
|----------------------------------|--|---|
| SDG1: NO POVERTY | SDG7: AFFORDABLE AND CLEAN ENERGY | SDG13: CLIMATE ACTION |
| SDG2: ZERO HUNGER | SDG8: DECENT WORK AND ECONOMIC GROWTH | SDG15: LIFE ON LAND |
| SDG3: GOOD HEALTH AND WELLBEING | SDG9: INDUSTRY, INNOVATION, AND INFRASTRUCTURE | SDG16: PEACE JUSTICE, AND STRONG INSTITUTIONS |
| SDG4: QUALITY EDUCATION | SDG10: REDUCED INEQUALITIES | SDG17: PARTNERSHIP FOR THE GOALS |
| SDG5: GENDER EQUALITY | SDG11: SUSTAINABLE CITIES AND COMMUNITIES | |
| SDG6: CLEAN WATER AND SANITATION | SDG12: RESPONSIBLE CONSUMPTION AND PRODUCTION | |

Source: Scopus-based literature review by the authors (2021); dataset available on request.

Although, provisioning services of the cryosphere are crucial and directly contribute to the 16 goals of the SDGs, they contribute more particularly to SDG 1 (no poverty), SDG 2 (zero hunger), SDG 3 (good health and wellbeing), SDG 6 (clean water and sanitation), and SDG 15 (life on land), as shown in Figure 4.3. For instance, income from the trade of caterpillar fungus contributed 53–64% of the total household income annually in Dolpo, Nepal (Shrestha et al., 2019), and 40% on average of the rural cash income in Bhutan (Laha et al., 2018). In fact, ecosystem services contribute to the direct attainment of 12 SDGs in Nepal (Adhikari et al., 2022). Similarly, numerous cryosphere services, mainly, provision of freshwater, climate regulation, habitat for biodiversity, and run-off regulation have been found to be critical in promoting multiple goals including agricultural

development (SDG 2), eradication of extreme poverty (SDG 1), conservation of terrestrial biodiversity (SDG 15), economic growth (SDG 8), access to clean drinking water (SDG 6), and renewable energy (SDG 7) in Afghanistan, Bhutan, China, India, Nepal, and Pakistan (Zhang et al., 2022). Cultural services, including traditional ecological knowledge and practices, also indirectly contribute to multiple SDGs in the region. For example, spiritual and religious values, indigenous culture, and aesthetic and recreational values of the high mountains that are part of mountain tourism contribute to sustainable tourism and income generation (SDG 1), improving food security (SDG 2) and improving health and wellbeing (SDG 3) (Zhang et al., 2022) (see Chapter 5, section 5.3).

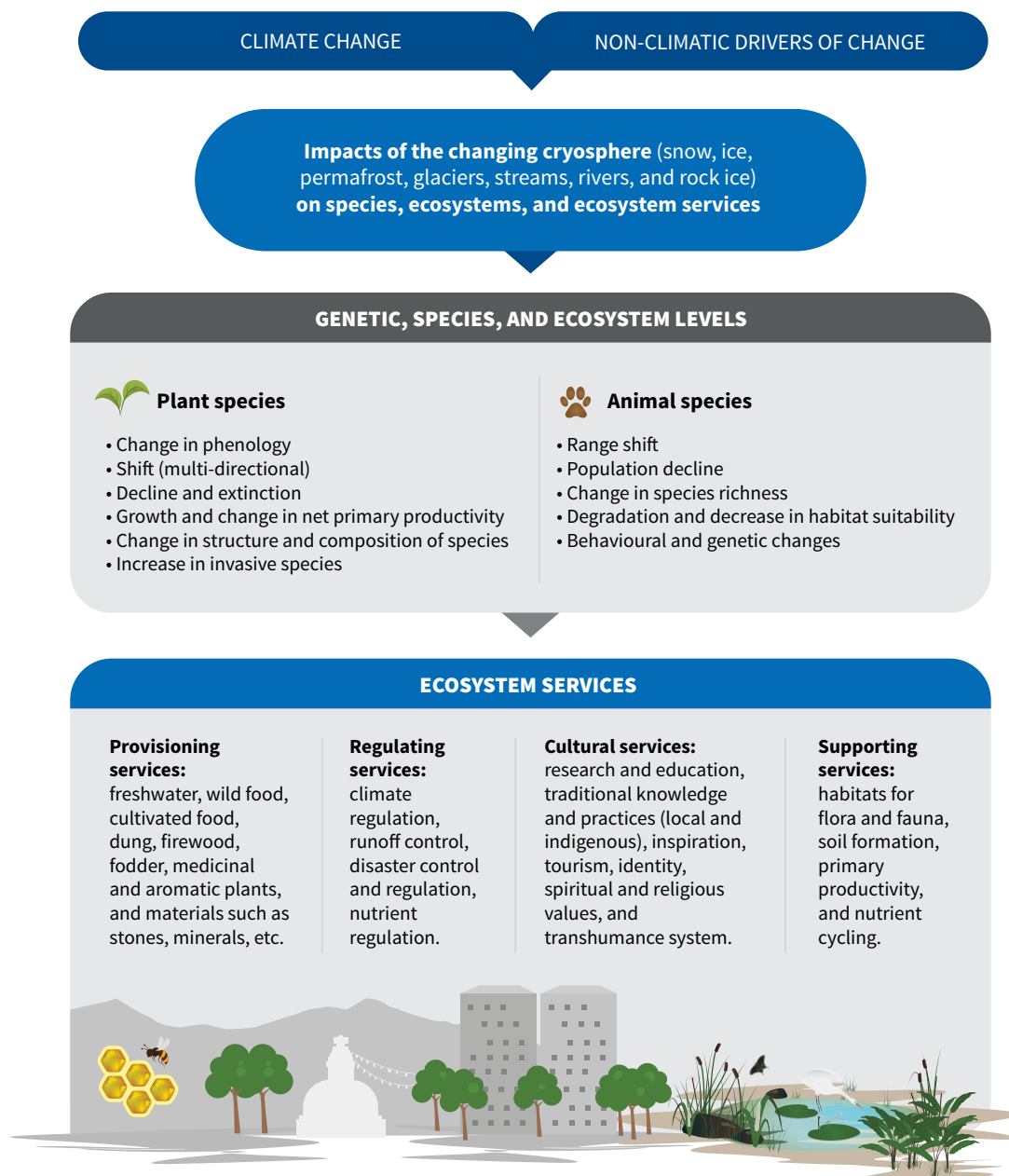
4.5. Impacts on biodiversity at genetic, species, and ecosystem levels

The cryosphere, a barometer of climate change, has been affected by different drivers of change. Some of the observed climate-related changes such as the ones in snow fall patterns, permafrost thaw, and

glacier melt are well established (Bolch et al., 2019). These climate-induced changes in the cryosphere have profound impacts on biodiversity at ecosystem, species, and genetic levels (Xu et al., 2019). The following section highlights the major impacts observed at ecosystem, species (both individual and population), and genetic levels, where such information is available (Figure 4.4).

FIGURE 4.4

OBSERVED CHANGES AND IMPACTS AT THE GENETIC, SPECIES, AND ECOSYSTEM LEVELS



4.5.1. Mountain flora

The impacts of and responses to climate and non-climatic changes are not uniform and are often shaped by the degree of vulnerability based on exposure, sensitivity, and adaptive capacity (Weiskopf et al., 2020). Increase in global temperatures, changes in precipitation patterns, glacial retreat, snowmelt, and permafrost thaw are instigating a series of changes in high-elevation species across the HKH region. While some species in certain regions are benefiting from warming temperatures and changes in precipitation levels, an overwhelming majority of animal and plant species are negatively affected by these changes. These changes, which often interact with other anthropogenic changes, have significant impacts on biodiversity and ecosystem services, and ultimately on the people who inhabit the region.

The major effects that cryospheric changes have on plants at species and ecosystem levels are changes in phenology, upslope habitat shifts, changes in structure of populations and communities, densification, growth enhancement, physiological changes, and changes in biochemical processes. Besides these, changes in soil stoichiometry characteristics (Zhang et al., 2019), increase in incidences of invasive alien species, species redundancy, and shift in dominance between species (Behera et al., 2019) are among the other impacts observed. In some cases, regions that were inhospitable due to colder climatic conditions at higher elevations have now become suitable for various monoculture plantations, which pose a threat to the habitats of endemic species through encroachment (Zomer et al., 2014).

CHANGES IN PHENOLOGY

Climate-induced changes in the cryosphere are causing profound changes in plant phenology across the HKH. The reported changes include the timing of leaf-fall and fruiting (Borogayary et al., 2018), changes in cambial activity, and flowering phenology (Hassan et al., 2021; Robbie et al., 2014). This is leading to a decrease in survival rates and increase in vulnerability of endemic and threatened species across the HKH.

Changes in flowering phenology have been reported

for a range of species, including alpine ginger *Roscoea* species in the central Himalaya (Mohandass et al., 2015), early onset of flowering of yellow amaryllis (*Sternbergia vernalis*) in the Kashmir Himalaya (Hassan et al., 2021), and the Ghizer valley of Pakistan, and contrasting phenological responses of Himalayan rhododendron where annual warming leads to advanced flowering and fall warming leads to delayed flowering (Robbie et al., 2014). The literature has also reported a lengthening of the overall average growing season of vegetation in Nepal and the adjacent HKH region (Shrestha et al., 2012). In northeast China, the start date and the length of land surface phenology are reported to have advanced by one day per year (Zhang et al., 2017). In the Qinghai-Tibet Plateau, increase in temperature led to a prolongation of the length of the growing season by about one to two days per decade between 1982 and 2005 (Zhang et al., 2018). Vegetation phenology has also advanced in the Qinghai-Tibetan Plateau in terms of greening, withering, and the growing season with an average advancement of 15–18 days (Zhang et al., 2018). Furthermore, extreme drought led to significant changes in the start and end dates of the growing season in the in the Yungui Plateau (Ge et al., 2021). These changes in phenology also have consequences for the migratory patterns of species such as birds, butterflies, mammals and others dependent on nectar, fruits, and seeds (Adhikari et al., 2018; Joshi et al., 2018; Shi et al., 2021).

MULTI-DIRECTIONAL SHIFTS

Shifts due to a rise in temperature and changes in snowfall patterns at higher elevation areas have been observed across the HKH. Most plant species demonstrate multi-directional shifts across the region. Upward or elevational range shift of multiple species has been recorded in different parts of the HKH (Dolezal et al., 2021; Hamid et al., 2020; Telwala et al., 2013). Singh et al. (2021) have reported an upward shift of the treeline from a few metres to 30 metres per decade in the Indian Himalaya. For example, the Himalayan pine (*Pinus wallichiana*) treeline has been reported to shift towards the upper elevations at the rate of 11 to 54 metres per decade in the monsoon and monsoon-shadow zones in the western Himalaya of India (Yadava et al., 2017). According to Singh et al. (2018), the *Rhododendron campanulatum* krummholz has expanded by 1.4

metres per year in Tungnath, Garhwal Himalaya with recent stabilization in the treeline ecotone. In India, the shrub species *Juniperus polycarpus* has been observed above the treeline at 4,000 m (Singh & Samant, 2020). Ninety percent of endemic plant species in the Sikkim Himalaya have been observed to undergo a warming-driven geographical range shift of 23–998 m with a mean upward displacement rate of 27.53 ± 22.04 m per decade (Telwala et al., 2013). Several species including *Potentilla pamirica* in eastern Ladakh of the northwest Himalaya have shifted upward about 150 metres above the limit of plant distribution (Dolezal et al., 2021).

Upward shifts have also been reported in Nepal. The average rate of the upward shift of the forest line in Nepal is 0.46 m per year at a rate of 0 to 2.6 m per year with site- and species-specific differences (Chhetri & Cairns, 2015; Gaire et al., 2014, 2017, 2022; Gaire et al., 2023; Sigdel et al., 2018; Tiwari et al., 2017). Researchers have attributed shifts in the east Himalayan fir (*Abies spectabilis*) and bell

rhododendron (*Rhododendron campanulatum*) in the Nepal Himalaya to increasing temperature in the region (Gaire et al., 2017; Mainali et al., 2020). *Abies spectabilis*, found between 2,500 and 4,100 m, has reportedly shifted by approximately 239 m to a higher elevation over a 150-year time period (1851–2009) in the Manaslu Conservation Area of Central Nepal (Gaire et al., 2014). Species-specific shifts have also been reported in the Everest region (Figure 4.5). Similarly, an overall advancement of the treeline in the Tibetan Plateau and adjacent mountain regions in China has also been reported (Wang et al., 2022). Wang et al. (2022) have recorded rapid advancement (>10m) of the treeline across the Tibetan Plateau for 50.8% of the sites studied over the past century while they have recorded slow advancement (0–10m) for 16.9% of the sites, and a stable treeline for 32.2% of the sites. Researchers have also observed an advancement of tree species including *Pinus wallichiana* in glacier-retreated sites in the HKH (Sigdel et al., 2020).

FIGURE 4.5

TREELINE DYNAMICS IN RESPONSE TO ENVIRONMENTAL CHANGE IN THE EVEREST REGION, NEPAL



Source: Gaire et al. (2017)

Variations in the rate of advancement regarding site, species, and climatic patterns have also been noted. The average rate of the upward treeline shift in Nepal is 0.46 m per year with differences in the rate ranging from 0 to 2.6 m per year (Gaire et al., 2023) when site- and species-specific differences are factored in.

An increasing trend in greening has been observed across the HKH. While most of the alpine pasture is greening (a positive trend) (Zheng et al., 2022), browning has been simultaneously observed in some areas exposed to high frequency of drought events and anthropogenic pressure such as population increase, urbanisation, and shifting cultivation (Kumar et al., 2022). In the eastern Himalaya, browning (a negative trend), especially at higher elevations (likely due to pre-monsoonal drought), has been observed while the lower and middle elevations of vegetation in the eastern Himalaya are predominantly greening. In Nepal, Baniya et al. (2018) have observed an overall increasing trend of greening between 1982 and 2015 with precipitation and temperature both contributing to the greening process (Mainali et al., 2015). Greening is also driven by increased CO₂ fertilisation, Nitrogen deposition, and anthropogenic activities such as irrigation and agricultural fertilisation (Mishra & Mainali, 2017).

Shrub encroachment is also apparent in the alpine meadows of different parts of the HKH region. For instance, around 39% of the alpine meadows converted to woody shrubs between 1990 and 2009 in northwest Yunnan, China (Brandt et al., 2013). A region-wide analysis of the changes in the spatial extent of subnival vegetation in the HKH from 1993 to 2018 using remote sensing data indicated that there has been an increase in subnival vegetation from 1993 with a rapid increase between 5,000 and 5,500 m (Anderson et al., 2020). Densification of shrubs just above the treeline has also been reported (E. Liang et al., 2016; Schickhoff et al., 2015).

DECLINE AND EXTINCTION

Species decline and even extinction are among the negative consequences of the changes in the cryosphere. A decreasing trend in tree growth has been observed in the western HKH while it has been relatively stable in central-eastern HKH (Zheng et al., 2021). The negative consequences are mostly mediated by increasing moisture stress and

temperature increases. For example, increasing degradation of the permafrost can lead to a decrease in soil surface moisture and soil nutrient supply capacity, which in turn can negatively affect the diversity of alpine plant species, as reported in the Qinghai-Tibetan Plateau (Yang et al., 2013). Endemic species, in particular, are at increased risk as even a slight change in the optimal combinations of temperature and precipitation can lead to a sharp decline in their survival rate and, ultimately, extinction. Species at relatively low-elevation areas in the HKH that are not flexible enough to make niche shifts in response to climate change risk possible extinction (Upadhyay et al., 2021).

GROWTH AND PRODUCTIVITY

Tree species respond to climate change in several ways. An increase in growth has been observed for several species across the HKH. While some species have shown significant growth enhancement, it has been slight for others (Camarero et al., 2021; Panthi et al., 2020; Thapa et al., 2017). The east Himalayan fir (*Abies spectabilis*) has shown growth enhancement in the high-elevation regions of Nepal (Thapa et al., 2017). A similar trend has been observed for *Androsace tapete*, an endemic cushion species found in the Tibetan Plateau. Rapid growth enhancement has also been observed since 1982 in three dominant genera (*Abies*, *Juniperus*, and *Picea*) in the southern and southeastern Tibetan Plateau (Zheng et al., 2021). A long-term growth study of dominant high-elevation species such as *Abies spectabilis*, *Juniperus indica*, and *Picea* species that are found above 3,000 m using regional datasets of tree-ring chronologies has shown little variation in growth of the species across the HKH in response to climate change since the 1950s (Zheng et al., 2021).

According to Mirzabaev et al. (2019), trees from the humid regions are more sensitive to temperature change while those from the dry and arid regions are more sensitive to moisture availability (precipitation and drought). Tree growth has been found to be more responsive to temperature than to precipitation at high-elevation areas indicating that the minimum temperature rather than the mean temperature is the main climate variable that influences tree growth in the HKH (Zheng et al., 2021). Tree growth has been positively correlated with winter and

spring precipitation in the drier western part of the HKH, and with winter temperature and spring precipitation in the humid southeastern Tibetan Plateau (Cheng et al., 2019). Moisture availability, especially during the spring season, is crucial for the growth of diverse tree species as evident from the positive relationship between several tree species in the region with precipitation of the spring season (N. Gaire et al., 2019).

Increase in temperature has also been reported to lead to an increase in aboveground net primary productivity in some locations without a permafrost presence and to a decrease in the same in other locations (Yang et al., 2018). Similarly, net primary productivity in the Source Region of Yangtze River also increased by 0.18 TgC per year from 2000 to 2014 as a result of the increase in temperature and precipitation due to climate change (Yuan et al., 2021). There has also been an increase in plant productivity in the alpine wetlands due to increase in temperature and precipitation (Kang et al., 2020). According to Chatterjee et al. (2010), direct warming of the lakes in high-elevation areas have altered the circulation patterns with continuous impacts on the biogeochemistry and functioning of the wetland ecosystem.

STRUCTURE AND COMPOSITION OF SPECIES

Changes in the composition, distribution, and abundance of species are reported across the region (Schwab et al., 2022; Singh et al., 2021). Early snowmelt instigated by warming temperatures has been linked to the increased diversity and density of herb communities in the Uttarakhand Himalaya (Adhikari et al., 2018). Similarly, phenological changes have been reported to lead to changes in plant community interactions, thereby changing their structures. For example, the rhododendron species, which were reported to be flowering earlier as a response to warming temperatures in Mount Yulong of Tibetan Plateau, were found to dominate “non-flexible” species of rhododendron. This has changed the plant community compositions and structure, thus threatening the existence of some species of rhododendron (Hart & Salick, 2018).

Changes in species composition are also happening in the mountain summits of the Kashmir Himalaya of India with increasing species richness on the lower

summits, which decrease towards the summits in the nival zone (Hamid et al., 2020). There has also been an increase in the cover of dominant shrubs, graminoids, and forbs as well as thermophilization (Hamid et al., 2020). In the Sikkim Himalaya and Tibetan Plateau, Hamid et al. (2020) and Telwala et al. (2013) observed an increase in species richness in the upper alpine zone with changes in snowfall and decrease in permafrost.

Peatlands are also impacted by changing weather patterns in the HKH. Peatlands in the HKH region have shrunk significantly, which has weakened its capacity to sink carbon (Wang et al., 2016). The change in carbon emissions from peatlands caused by frozen ground degradation will increase the uncertainty of the regional soil carbon pools and the GHG budget (IPCC, 2019), posing thereby a threat to the overall ecological security of the entire HKH region. Peatlands overlies permafrost and seasonal frozen ground across the HKH (Wang et al., 2016; Zou et al., 2017). Thus, there is strong interaction between peatland and permafrost as the latter forms an isolation layer that reduces hydrological conductivity in the vertical profile of soil while maintaining the water-table that favours the formation and development of peatland. When peat has accumulated in the surface soil, the thermal exchange between the atmosphere and deep soil is attenuated, as a result of which the permafrost is preserved (Zhang, 1993). Most of the peatlands are distributed in high-elevation areas where the seasonal freeze-thaw is a typical surface process (Zhang & Armstrong, 2001). The intensive diurnal freeze-thaw cycles (FTCs) during the seasonal freeze-thaw periods of autumn freeze and spring thaw are called the “shoulder season” (Arndt et al., 2019; Pirk et al., 2015).

Researchers have reported considerable methane emissions during the spring thaw (Song et al., 2012; Tokida et al., 2007) and autumn freeze (Bao et al., 2021; Mastepanov et al., 2008; Pirk et al., 2015). Methane emissions during the FTCs account for 11–27 % of emissions annually, while methane emissions during the autumn freeze are higher than that of the spring thaw in the peatland of the Qinghai-Tibet Plateau (Chen et al., 2021). Thick peat accumulation has also been reported in the Tibetan Plateau due to the warm and humid climate (H. Chen et al., 2014). In high-elevation regions, due to the stronger diurnal

temperature variations in the cold season (Dong & Huang, 2015), the seasonal freeze-thaw processes are influenced by a brief period of freeze up and long shoulder season of ground freezing and thawing (Yang et al., 2006). A recent study found increased methane emissions after simulated FTCs from peat soils of a high-elevation peatland on the QTP. The methane emission peak occurs after the first FTC. The longer duration of the FTCs appears to have a profound effect on elevating methane emission levels compared to the shorter duration FTCs of the low-elevation peatlands. The incubated soils with mild freeze-thaw intensity and higher water content thus had higher cumulative methane emissions. Under future climate scenarios, higher methane emissions were observed during the seasonal freeze-thaw process from high-elevation peatlands, as both longer and warmer shoulder seasons could be expected (Yang et al., 2022). Frequent flooding and irregular waterflow in the wetlands may also degrade the wetlands and their ecological parameters and species (Singh et al., 2021).

INVASIVE SPECIES

The introduction, establishment, and spread of invasive species in terrestrial ecosystems is widely recognised as one of the most serious threats to the health, sustainability, and productivity of native ecosystems. It has been identified as one of the five major drivers of change and biodiversity loss (IPBES, 2019). In the region, there are reports of new and

invasive species that were not observable 10–15 years ago (Khan & Dhani, 2017). There is evidence of increase in the number of invasive species and faster colonisation and infestation of protected areas, agricultural lands, freshwater ecosystems, and high-elevation rangelands (Everard et al., 2018; Khan et al., 2014; Pathak et al., 2019; Thiney et al., 2019).

In the HKH, an increasing number of invasive species with faster expansion and range shifts at higher elevation areas has been observed (Table 4.1). The global rise in temperature and elevation-dependent warming coupled with prevailing anthropogenic activities, it is predicted, will provide more favourable conditions for invasive species in the high-elevation areas.

For example, under a Representative Concentration Pathway (RCP) 8.5 scenario, *Ageratina adenophora* and *Lantana camara* are predicted to increase their coverage by 45.3% and 29.8%, respectively, than at present and reach up to elevations above 3,000 metres in the Kailash Sacred Landscape, India (Chaudhary et al., 2021). Similarly, according to the projections on the distribution of 26 invasive plants under the RCP6.0 scenario, 75% of the species range will expand and 25% of the species range will contract due to climate change (Shrestha & Shrestha, 2019). Similarly, it is projected that *Parthenium hysterophorus* will reach higher elevation protected areas such as Langtang, Annapurna, and Manaslu of Nepal in the future (Maharjan et al. 2019).

Species	Scenarios	Predicted spread area (%)	Predicted new elevation	Citations
<i>Ageratina adenophora</i>	RCP8.5	45.3%	3,029 m	Chaudhary et al., 2021
<i>Lantana camara</i>	RCP8.5	29.8%	3,018 m	Chaudhary et al., 2021
<i>Tithonia diversifolia</i>	RCP2.6, 8.5	23%–53%	2,700 m	Dai et al., 2021
<i>Parthenium hysterophorus</i>	RCP2.6, 8.5	NA	3,000 m	Maharjan et al., 2019

The aggressive and rapid expansion of invasive species at higher elevations is posing challenges to biodiversity and food security with significant economic costs (Sheergojri et al., 2022). For example, Nepal is among the topmost countries in the world facing invasive threats to the agricultural sector, the estimated annual cost of which is USD 1.4 billion (Paini et al., 2016).

4.5.2. Mountain fauna

Impacts of the changing cryosphere on mountain fauna in the HKH are significant. Elevational shifts, sharp population decline, decrease in species richness and habitat suitability, behavioural and genetic change, and emergence of new species are the identified impacts on the six categories of mountain fauna, namely, mammals, insects, microbes, birds, amphibians, and fishes (Table 4.2).

MAMMALS

Mammals in the HKH have been reported to experience distribution range changes, new species assemblages, genetic change, local population changes, and extinction. The changes in the snowline and shift in vegetation have led to movement of species. The upward shift of the snowline has

negatively impacted the snow leopard habitats (Li et al., 2016) and, according to Farrington & Li (2016), their suitable habitats are likely to be reduced in Bhutan, Nepal, India, and Myanmar by 2080. Snow leopard (*Panthera uncia*), golden snub-nosed monkey (*Rhinopithecus roxellana*), Himalayan musk deer (*Moschus chrysogaster*), and Himalayan grey langur (*Semnopithecus entellus*) are already experiencing range shifts across the HKH. For instance, the range shift of the golden snub-nosed monkey in the Tibetan Plateau has resulted in a dramatic decline in its population size (Luo et al., 2012).

The major driver of the range shift and population decline for most mammal species is decreased food availability and habitat change along with high fragmentation. Loss of suitable habitats due to upslope range shifts have also been reported for other species such as the giant panda (*Ailuropoda melanoleuca*), blue sheep (*Pseudois nayaur*), and Asiatic brown bear (*Ursus thibetanus*). The range of habitats of Tibetan antelope (*Pantholops hodgsonii*), Tibetan wild ass (*Equus kiang*), and wild yak (*Bos mutus*), which are endemic to the HKH, has also decreased by 44%, 7%, and 20%, respectively. Even genetic changes have been reported in the Arunachal macaque (*Macaca munzala*) because of climate and anthropogenic changes (D. Chakraborty et al., 2015).

TABLE 4.2

OBSERVED IMPACTS OF THE CHANGING CRYOSPHERE ON ANIMAL SPECIES IN THE HINDU KUSH HIMALAYA

VERTEBRATES	OBSERVED IMPACTS
Mammals	Decreased habitat suitability, genetic change, population decline, range shift
Birds	Range shift, extinction probability, habitat decline
Fish	Range shift, richness of benthic invertebrates (population increase)
Reptile	Range shift, likely extinction
Amphibian	Genetic diversity affected, likely extinction
INVERTEBRATES	OBSERVED IMPACTS
Insects	Range shift upward, species decline, extinction, abundance, new species
Microbes	Increase in microbial activity increase, upward range shift

Source: Scopus-based literature review (2021)

BIRDS

Changes in the patterns of the snow forming period and snow melting period of the cryosphere impact the distribution of species. Upslope range shifts, decline in suitable habitats, and increased possibility of extinction are the reported impacts on birds with the changing cryosphere. For instance, with climate warming, pheasants such as satyr tragopan (*Tragopan satyra*) have shifted their habitats to higher elevations and are predicted to further shift to even higher elevation areas therefore shrinking their range (Chhetri et al., 2021). Under extreme future climatic scenarios, the species could become restricted to sky islands in the Himalayan region (Chhetri et al., 2018, 2021). There has also been a significant decline in habitat suitability as well as range shift for the Chinese grouse (*Tetrastes sewerzowi*) (Lyu & Sun, 2014). The black-necked crane (*Grus nigricollis*) in the alpine environment has also been found to adjust its behaviour in relation to incubation based on weather conditions and the thermal requirements of its eggs (Zhang et al., 2017).

AMPHIBIANS, REPTILES, AND FISHES

The amphibians are among the species most impacted by the changing climate. The Kashmir paa frog (*Allopaa hazarensis*) and Himalaya paa frog (*Nanorana vicina*), which are endemic to Pakistan, face likely extinction due to metamorphosis, reduction in body size, more frequent developmental complications, deformities such as edema and tail kinks, lower fitness, and higher mortality at elevated temperatures (>26°C) (Saeed et al., 2021). The genetic diversity of the high Himalaya frog (*Nanorana parkeri*) has been affected by both climatic and non-climatic changes (Hu et al., 2019). Higher elevation shifts from 1,000 m to 1,700 m have been reported among the monocled cobra (*Naja kaouthia*) and king cobra (*Ophiophagus hannah*) in the Sikkim Himalaya (Bashir et al., 2010). Advanced breeding among the frogs in the region has also been reported. For instance, the Sikkim paa frog (*Nanorana liebigii*), has been reported to have advanced breeding by three months in Sikkim, India (Acharya & Chettri, 2012). Similarly, the richness of benthic invertebrates has been depleted and a range shift has been observed among warm dweller fishes to higher elevations along with losses in cold dweller fishes (Li et al., 2016). Range

extension of four agama lizards to higher elevations in Pakistan is partly attributed to the changing snow cover of high-elevation areas in the western Himalaya of the HKH (Khan et al., 2012).

INSECTS

Population decline and change, upward shifts, and emergence of new species are some of the changes reported for insects at higher elevation areas in the region. The Apollo butterfly (*Parnassius apollo*), endemic to China, has experienced a sharp decline in its population (Yu et al., 2012) while a constant monotonic decline of ants (*Hymenoptera: Formicidae*) has been reported in the eastern Himalaya (Wu et al., 2017). The decline is widely attributed to changes in weather and habitat conditions. In recent years, a sharp decline in caterpillar fungus (*Ophiocordyceps sinensis*) has also been reported across the region. The caterpillar fungus is threatened by the combined pressures of climate change and over-exploitation (Wei et al., 2021).

Similarly, a decrease in species richness and local extinctions are also apparent. For instance, a total of 14 species of butterflies have disappeared from the coniferous forests of Murree Hills and its adjacent areas in Pakistan (Saadat et al., 2016). Changes in weather patterns over decades (precipitation decrease and temperature increase), extreme weather events, and emergence of new species were found to be the contributory factors to the disappearance of some butterfly species in the area. Similarly, a decreasing species richness pattern along the elevational gradient has been observed in the Langtang National Park of Nepal where butterfly families were reportedly present in the past in the high, medium, and low elevational zones (Pandey et al., 2017).

An upward shift of the Chinese three-tailed swallowtail (*Bhutanitis thaidina*) and the Himalayan relict dragonfly (*Epiophlebia laidlawi*), which are endemic to the HKH, to a suitable altitudinal range due to changes in temperature and precipitation has been reported. There are also reports of an upward shift of forest pests, such as the tea shot-hole borer *Euwallacea fornicatus* (Eichhoff). Similarly, insects, pests, and mosquitoes have emerged in Everest region (Sherpa, 2014).

MICROBES

The changing cryosphere has impacts on microbial activity and related biogeochemistry (Bourquin et al., 2022). The impacts take the form of high microbial activity in some areas and low to no change in other areas. The high soil microbial activity influences the soil carbon dynamics resulting in a reduction in soil carbon loss (Li et al., 2019). There has also been a shift in micro-invertebrates and lichen such as the epiphytic foliose lichen (*Lobaria pindarensis*) to higher elevations with the vegetation shift (Sahu et al., 2019). For instance, significant changes in the lichen community structure have been observed in response to anthropogenic factors and climate change in Darjeeling, India (Bajpai et al., 2016).

4.5.3. Predicted future changes

Changes in the cryosphere have already affected ecosystems and biodiversity and will continue to affect them in the coming decades in the high mountains of the HKH.

RANGE SHIFTS

Range shifts of plants and animals are one of the major concerns. Glacier retreat and decreasing snow cover allow species to increase their abundance and extend their range (He et al., 2019; Liang et al., 2018; Yang et al., 2018). For example, Liang et al. (2018) used ecological niche modelling to predict the distribution of 151 species in the Hengduan Mountains since the Last Glacial Maximum. They found that all the species will expand their range size and shift upslope. Wang et al. (2011) employed forest gap models to predict the potential changes in subalpine forest over the eastern Tibetan Plateau and found a distribution shift to higher and colder regions (Xiaodan et al., 2011).

Predictions by Naudiyal et al. (2021) regarding the potential distribution of *Abies*, *Picea*, and *Juniperus* species in the subalpine forest of the Minjiang headwater region under current and future climate scenarios indicated changes in their future distribution range with possible implications for the supply of ecosystem services such as fuelwood and timber.

The Maxent model, which is one of the ecological niche-based models, indicates a regional increase in suitable habitats for three tree species (*Abies spectabilis*, *Betula utilis*, and *Pinus wallichiana*), predicting a possible northward and upslope advance (Chhetri et al., 2018). Another model study on the distribution of *B. utilis* across the HKH region for the present and future (RCP's 2.6–8.5 covering 2050 and 2070) indicated that the highly suitable area for *B. utilis* is predicted to shift towards the eastern parts of the Himalaya in the future, with suitability declining towards the western part of HKH (Hamid et al., 2020).

As forests play a vital role in the provision of goods and services and the function of mountain ecosystems, the potential distribution range shift of forests has critical implications for the supply of these ecosystem services. Material services such as timber, non-wood forest products, and freshwater as well as non-material services such as recreation, carbon sequestration, hydrological cycle maintenance, and erosion control obtained from forest ecosystems are fundamental to sustaining and supporting the wellbeing of the people. The range shift pressures therefore raise serious concerns regarding the continued supply of essential ecosystem services necessitating immediate attention from forest managers and conservation planning agencies. Further research and investigation into the overall supply of ecosystem services are also urgently needed.

Similar trends in range shifts towards the northern latitudes and higher elevations are observed in the case of animal habitats. For example, Thapa et al. (2021) applied Maxent to predict the occurrence of five species of bats under different climate scenarios (present and RCPs 4.5 and 8.5 for 2050 and 2070, respectively) and found similar trends in range shifts towards the northern latitudes and higher elevations for all five species. Using a multi-scale Random Forest model under all four RCPs, Dar et al. (2021) found that the habitat of the Himalayan brown bear (*Ursus arctos isabellinus*) would decrease by more than 90% under the high emission scenario with a significant percentage of the species shifting range to higher elevations. Another Maxent study under RCP4.5 and 8.5 for 2050 and 2070 found range shifts for the Himalayan ibex (*Capra sibirica hemalayanus*) and blue sheep (*Pseudois nayaur*) due to a significant loss in habitat for both species (Ali et al., 2022).

MOVEMENT, DECLINE, AND LOSS

Range shifts do not always mean expansion. Liao et al. (2020) applied ecological niche modelling to project the climatically suitable areas for six fir species in southwest China. Their results showed a northward and westward migration of the species to the interior Qinghai-Tibet Plateau. But as this migration cannot compensate for the range loss, it would result in a declined distribution of most fir species. Also using ecological niche modelling, Naudiyal et al. (2021) drew maps of the potential distribution of *Abies*, *Picea*, and *Juniperus* species in the subalpine forest of the Minjiang headwater region under current and future climate scenarios. They found that precipitation in the wettest month is the key environmental variable for determining habitat suitability for the three species. Climate change and associated precipitation changes will, therefore, likely lead to a clear decline in potentially suitable habitats for all three species according to all the RCP scenarios, with a shift downward of the mean elevation and a decrease in the elevation range of suitable habitats (Naudiyal et al., 2021).

In addition to a shift in the vegetation range, Wei et al. (2021) found significant shrinking in suitable habitats for the Chinese caterpillar fungus, an important fungus grown in the southwestern Tibet Plateau, under RCP4.5 and RCP8.5 climate scenarios. Similarly, projections of habitat suitability under future climate change scenarios for all concentration pathways using RCPs for two time periods (2050s and 2070s) showed a clear decline in potentially suitable habitats for all four ecologically and economically dominant forest tree species (*Quercus leucotrichophora*, *Q. semecarpifolia*, *Q. floribunda*, and *Pinus roxburghii*) in the central region of Nepal (A. Chakraborty et al., 2016). These results show both increase and decrease in suitable habitat range across all future climate change scenarios.

Future projections also showed that animal habitats in the Himalaya are under threat due to cryospheric change (Farrington & Li, 2016). For example, the suitable habitat for the Himalayan grey langur (*Semnopithecus entellus*) was predicted to decline by more than 60% in 2050 under both RCP4.5 and RCP8.5 scenarios (Bagaria et al., 2020). In addition, the current suitable habitats are likely to get further

fragmented in future scenarios, which would reduce the quality of the habitat.

Similarly, the suitable habitats of the snow leopard, too, are likely to be reduced in Bhutan, Nepal, India, and Myanmar by 2080 (Farrington & Li, 2016). Using the multi-scale Random Forests machine-learning algorithm, Dar et al. (2021) also predicted a habitat range shift for the Asiatic black bear towards higher latitudes in Asia under climate change. Similarly, the Himalayan and Tibetan brown bears' dispersal paths would also shift to higher latitudes. The study predicted that the habitats of the Himalayan and Tibetan brown bears would lose over 34% and 32%, respectively, of the current habitats under the most severe climate change scenario (Y. Dai et al., 2021).

Another study reported a 56–58% range reduction in the currently available suitable habitat for the blue sheep (*Pseudois nayaur*) and a 33.7–64.8% range reduction for the Himalayan ibex (*Capra sibirica hemalayanus*) in the extreme climate scenario (RCP8.5 of 2070) of Gilgit-Baltistan in the Pamir-Karakoram of Pakistan (Ali et al., 2022). This is consistent with Aryal et al. (2016) who predicted a decrease in suitable habitat for blue sheep in the future due to climate change in Nepal.

Inhabitants residing in the glacier-fed river basins which originate in the HKH, including the Indus, Ganges, Brahmaputra, Salween, Yangtze, and Yellow, have observed the impacts of climate change on native wildlife habitats. The snow-shrinking has led to catastrophic snow avalanches, flash floods, landslides, and erosions (Arora et al., 2016) resulting in short- to long-term damages to habitats. The acceleration in snow melting and changes in precipitation patterns can potentially change stream channel width, water velocity, bed roughness, nitrogen and phosphorus processing, dissolved organic matter processing, and net stream metabolism, ultimately changing the functioning of ecosystem and habitat support services (Sweeney et al., 2004) in the region.

CHANGES IN SPECIES POPULATION

Another observation regarding the impact of cryospheric change on the ecosystem is change in species numbers (Fell et al., 2017). Li et al. (2016) have predicted significant increases in benthic

invertebrate taxonomic richness in the Himalayan rivers in future decades under climate change. But the increasing rates were different in the three elevational bands. In the eastern region of the HKH, the rate of change was stable overall at lower elevations while slowing down considerably at higher elevations. This indicates higher climate-induced stress compared to the other regions of HKH as well as the general vulnerability of mountain inhabitants, albeit with regional variations, to future climate warming. On the contrary, Klein et al. (2004) predicted that warming caused a 26–36% decrease in species richness in the north-eastern Tibetan Plateau and higher species loss towards the more northward locations due to lack of nitrogen nutrients. Some cold-tolerant diatom species will be lost due to the loss of critical habitat for wildlife that depend on snow and ice cover.

IMPACTS OF INCREASED EXTREME EVENTS

Increase in wildfire as well as other climate extremes such as drought, storms, and cyclones can fundamentally alter species distribution, composition, phenology, and forest structure (Mirzabaev et al., 2019). Habibullah et al. (2022) observed an increase in the magnitude and frequency of extreme weather events under climate change with negative impacts on biodiversity at global scale including HKH. Vilà-Vilardell et al. (2020) applied a spatially explicit wildfire simulation model to predict forest fire hazards in blue pine (*Pinus wallichiana*) ecosystems. The results show a two-fold increase in the fire hazard occurrence by the end of this century for both the study areas of the wildland-urban interface in Bhutan under the RCP8.5 climate scenarios. Studies reveal that climate change and increased human activities have caused massive forest fires in Pakistan (Krebs et al., 2010). Prediction maps also indicate that 22% of Pakistan's natural forests are highly vulnerable (>0.65) to forest fires (Tariq et al., 2021). Chitale & Behera (2019) predicted and quantified wildfire impacts on forest distribution. They used four endemic tree species in the western part of the HKH under the A1B balanced future emissions scenario for this purpose. The model results showed a significant reduction in the geographic distribution of the indicator species under the “with wildfire” scenario in comparison with

the “no wildfire occurrence” scenario. The future distribution range is also projected to shift towards the northern and north-eastern regions of the study area oriented by higher moisture availability.

SPECIES RICHNESS

Cryospheric change is predicted to affect regional biodiversity too (Fell et al., 2017). Results from Peter & Sommaruga (2016) indicate increased diversity. They predicted that the reduced glacier run-off in the summer season would improve water clarity in many mountain lakes, thereby increasing biotic diversity and the abundance of bacterial and algal communities and, in turn, primary production. There is strong agreement that summer run-off will decline in the 21st century in many basins for all emission scenarios in the HKH (Engelhardt et al., 2017; Prasch et al., 2012) due to less snowfall and decrease in glacier melt after peak water discharge, thus indicating potentially long-lasting enhanced water clarity and increased aquatic biotic diversity. However, another study in the Yarlung Zangbo-Brahmaputra River found an overall increase in sediment deposition that could indirectly lead to regional wetland degradation and declined riparian biotic diversity (Wang et al., 2020).

Species-specific responses to the warming climate might eventually transform the subalpine *Abies* fabric forest in the mountainous areas of the eastern Tibetan Plateau into *Betula utilis* forest while subalpine forests could move to higher and colder areas, which are currently tundra (Xiaodan et al., 2011).

Modelling simulations of forest vegetation along the elevation gradient in the Gongga mountain in response to IPCC's different emission scenarios indicated that the vertical belts of mountainous vegetation will shift upward by approximately 300 m, 500 m and 600 m in the B1, A1B and A2 scenarios, respectively (Chen et al., 2020). The high-elevation ecoregions (3,000–8,585 m) will either shrink or shift to higher elevations while the mid-elevation ecoregions situated between 500–3,000 m will expand and the low-elevation ecoregions (0–500 m) will shrink substantially.

4.6. Impacts on ecosystem services

People living in the mountains and lowlands are highly dependent on ecosystem services. Ecosystem services from the HKH support around 240 million people residing in the region as well as 1.6 billion people residing in the downstream river basins (Xu et al., 2019). However, both climate and non-climatic changes are impacting the ecosystems and their services. Whether the ecosystems are managed or remain in their pristine natural state, they have been observed to be already impacted and will likely be impacted significantly in the future, too, by climate change (Malhi et al., 2020) and other anthropogenic changes. The changes reported are often negative as well as heterogeneous depending on the context, management system, and ecosystem conditions as also noted by Mina et al. (2017). Although some positive changes have also been reported, negative impacts far outweigh the positive impacts across the HKH.

The major impacts reported relate to provisioning services, followed by cultural services, and supporting and regulating services (Figure 4.6). Food, fibre, and ecosystem products, both wild and domesticated, are the provisioning services from forests, lakes/streams, agriculture lands, and rangelands that are impacted. The medicinal and aromatic plants are likely to lose their existing habitats by 2050 and 2070 due to phenological changes and shifts in habitats in a northerly and upward direction (Gaire et al., 2014; Manish, 2022). Species that have a limited habitat range are highly vulnerable and likely to face extinction (Manish, 2022). According to Manish (2022), 13–16% of the medicinal plant species in the Sikkim Himalaya will be lost. The collection of and trade in NTFPs and MAPs have not only supported the subsistence living of people but has dramatically changed livelihoods due to the diversified economies in the mountain regions of the HKH (Gurung et al., 2021; Kandari et al., 2012). The collection and sale of *Ophiocordyceps* in Nepal is a case in point. It has not only helped to support livelihoods but also created opportunities for business investments while bringing about improvements in the overall quality of education (Childs & Choedup, 2014). Pest attacks and diseases relating to apple production in Nepal and Himachal

Pradesh of India have also been reported with production declining by 9.4 ton per hectare over the last two decades in Himachal (Das, 2022). Similarly, the size of the fruits of box myrtle (*Myrica esculenta*) is reportedly decreasing in the HKH (Shah & Tewari, 2016).

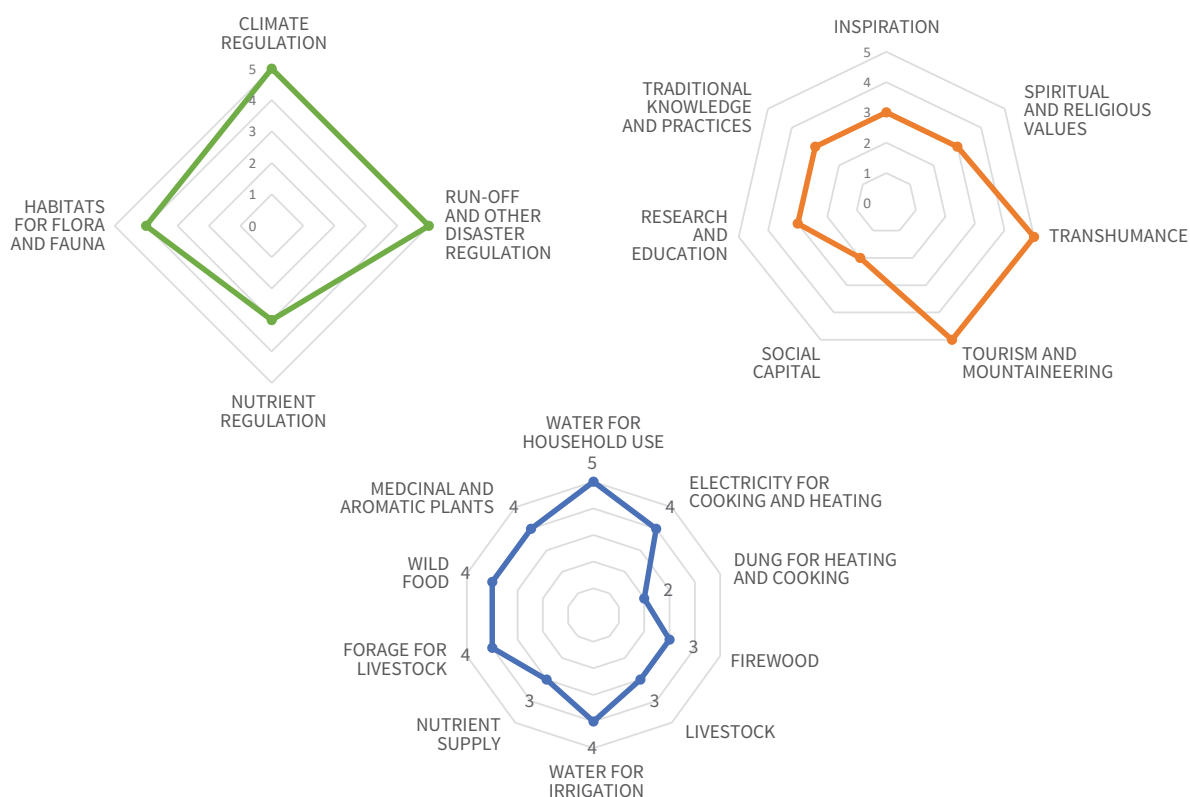
High-elevation wetlands, which provide a variety of services, face severe degradation from changing weather patterns, cryospheric changes (glacier melting/disappearance, permafrost thawing), and soil erosion (Chatterjee et al., 2010). As such, the quality and quantity of water, habitat functions of biodiversity, cultural and spiritual values, and local livelihoods linked to the wetlands are impacted. Mountain communities depend on glacier melt for drinking, cooking, and other household uses (Rasul & Molden, 2019) and these communities are facing a shortage of water because of reduced glacier melt (Rasul et al., 2020). Areas that were once covered by glaciers and snow are now dried up and exposed allowing vegetation growth (Molden et al., 2022). The increased occurrence of floods, debris flow, and droughts also degrade wetlands with high sedimentation, losses, and damages.

Climate change may also affect tourism and mountaineering significantly. The intensity and frequency of disasters and hazards like avalanches, landslides, debris flow, flooding, and GLOFs may negatively impact both access and destinations (K. C. & Parajuli, 2015). Climate change may also impact spirituality, cultural identity, and aesthetic values (Palomo, 2017). In the HKH, snow-capped mountains and glaciers are considered both symbolic and sacred (Allison, 2015). The identities of monks and highlanders, for instance, are linked with glaciers and mountains.

Among the livelihood options impacted are small-scale mountain agriculture and pastoral systems which are the major livelihoods of mountain communities (Molden et al., 2022). The melting of snow and ice, and permafrost thawing as well as extreme events such as floods, disasters, and debris flow significantly impact the pastoral and agriculture systems. Snow and glacial melt water are the only options for irrigation and, therefore, agricultural activity will be significantly impacted by changes in the melting patterns (Rasul & Molden, 2019). Mountain agriculture is also impacted by pest

FIGURE 4.6

AN INDICATIVE FIGURE SHOWING IMPACTS ON ECOSYSTEM SERVICES ACROSS THE HKH



Source: Scopus-based literature review by the authors (2021); dataset available on request

infestations and diseases, which have a direct impact on people’s livelihoods. According to Basnet et al., (2021), pests and diseases have caused a rapid decline in large cardamom production in the eastern part of the HKH.

At highest risk is biodiversity of the HKH, especially the endemic and threatened species that have a limited and specific habitat range and are already impacted by land use change and other pressures (Zomer et al., 2014). It has been found that the temperate and alpine areas are especially at risk. Zomer et al. (2015) has predicted an upward shift of bioclimatic zones by 2050 with significant impacts on biodiversity of high value in the Yunnan province of China. Changes in the vegetation composition, community structure, and conditions will affect wildlife habitats as well as cultural and religious values associated with high-elevation lands including rangelands (McCollum et al., 2017). Johnson et al. (2022) has drawn attention to the implications of the ecoregion shift of umbrella species like the

snow leopard, red panda, and Asian elephant in the transboundary Kangchenjunga landscape across Bhutan, India and Nepal.

Forests are the storehouse of goods and services, providing fuelwood, timber, fodder, MAPs, NTFPs, carbon sequestration, air, water, nutrients cycling, and species and genetic diversity which are fundamental to life (Joshi & Joshi, 2019; Joshi & Negi, 2011). The increased wildfires in the forests and grasslands across the HKH may impact the diversity and density of both plant and animal species. For instance, forest fire frequency has reduced the richness and density of floristic diversity due to poor regeneration processes in the forests of Uttarakhand, India (Bargali et al., 2022). Fires may also reduce the ability of forests and grassland to provide provisioning, regulating, cultural, and supporting services, thereby impacting people’s livelihoods significantly. This may ultimately affect the faunal diversity.

Rangelands in the HKH provide services to enhance food security, household survival, and community-wellbeing. Climate change leading to increased disasters and risks in the higher elevation areas, however, have posed risks to rangelands and their resources and practices including pastoralism (Caplins et al., 2018). Drought-induced degradation has accelerated erosion and natural hazards while disaster-induced degradation and upward shifts can have a negative impact on livestock rearing, productivity, and food security of pastoral communities (Rasul et al., 2014; Tiwari et al., 2020).

The increased number and frequency of disasters in the high mountains have been affecting people, their

cultural practices, and overall wellbeing (Stäubli et al., 2018). For instance, the avalanche following the earthquake of 2015 in the Langtang valley of Nepal not only destroyed most of the Langtang village, forests, and grassland but also claimed the lives of more than 380 local inhabitants, tourists, and over a hundred heads of livestock (Government of Nepal, 2015).

In terms of positive impacts, Hussain et al. (2016) reported higher productivity and favourable growing conditions for fruits and vegetables in Gilgit-Baltistan of Pakistan while S. Thapa & Hussain (2021) reported higher productivity for traditional crops in the Karnali region of Nepal. Higher grass productivity has also been reported in some areas of HKH (McCollum et al., 2017).

4.7. Adaptation options

Adaptation to climate change is challenging in the mountains due to its geography coupled with existing socio-economic and political conditions (Gioli et al., 2014). Despite the challenges, people and nature have been adapting to changes induced by climate and non-climatic drivers of change. Adaptation, like impacts, is heterogenous and context-specific depending on the issue(s), condition, and context.

In the HKH, ecosystem-based adaptation (EbA) has been reported to be effective. They have been reported to be effective not only for human adaptation but also to reduce risks from landslides and floods and to restore ecosystems (Klein et al., 2019; Lavorel et al., 2019). In China, the EbAs focus on restoration of degraded lands, urban forestry, and agrobiodiversity while, in India and Nepal, ecosystem-based disaster risks reduction (Eco-DRR), traditional knowledge for ecosystem management, EbA, and resilience building as well as ground water recharge are practiced (Chaudhary et al., 2021). These strategies have been reported to be successful in restoring landscape functions, sustain ecosystem services, and conserve biodiversity (Chong, 2014).

Among other EbA practices are sustainable water management practices such as recharging groundwater and adopting rainwater harvesting to improve soil moisture. In India, wetland protection

and rehabilitation has been reported to increase water retention capacity, conserve wetland biodiversity, and improve ecosystem services (Dhyani et al., 2018). Diversification of crop species, agroforestry practices, and agrobiodiversity are also in practice across the HKH to adapt to the changing climate, enhance sustainability against pests and diseases, and retain soil biodiversity (Chaudhary et al., 2021).

Looking at transboundary landscapes beyond country borders to increase connectivity for biodiversity conservation is an ideal way to adapt to climate change (Johnson et al., 2022; Zomer et al., 2014). Elsen et al. (2018) have also highlighted the importance of protecting areas along the elevational gradients. Corridors and connectivity are important, particularly for species with limited habitat range and range shifts, to move to higher elevations. These strategies may help to halt population decline or even extinction (Thomas et al., 2014). Similarly, regenerating fire-adapted species and rehabilitating fire-damaged forest ecosystems have been recommended to protect the diversity and density of flora for a healthy ecosystem (Bargali et al., 2022). Moreover, improvements in ecosystem health and quality can significantly reduce the impacts of climate change (Choi et al., 2021). What is more, land management systems play an important role in enhancing the capacity of ecosystems through promoting sustainable practices like integrated

watershed management (Thapa et al., 2021) and reducing anthropogenic impacts (Tchebakova et al., 2016). For instance, agriculture and infrastructure development are among the major reasons for peatland degradation in Pakistan (A. Khan et al., 2020). Halting such activities and restoring

such lands can help protect and conserve peatlands. Finding ways to combat increased pest infestation and invasive species on agriculture and agroforestry practices is another feasible option (Gurung et al., 2021).

4.8. Key knowledge gaps

Major knowledge gaps exist regarding the impacts of the changing cryosphere on biodiversity and ecosystem services as well as response options. These knowledge gaps can be categorised into linkages gaps, impact gaps, and response gaps as in Chapter 3.

4.8.1. Gaps in linkages

The cryosphere and biodiversity at species, genetic, and ecosystem levels are highly interconnected (Qin et al., 2017). However, understanding of the links between the cryosphere and biodiversity across the HKH with regard to the processes involved, connections, and feedback is limited. Some of the knowledge gaps with regard to the linkages are given below:

1. Knowledge of the treeline shift in the HKH region has advanced since the last decade. However, these studies have been confined to the high mountain regions of Nepal, China and India, while few studies are available on treeline dynamics in Afghanistan, Bhutan, Myanmar and Pakistan (Gaire et al., 2014).
2. Permafrost, an important component of, and contributor to, the alpine ecosystems has been less studied. The interactions and links between permafrost and alpine ecosystems remain under explored in the region (Wang et al., 2022).
3. Similarly, linkages between cryospheric changes and different ecosystems such as rangelands, peatlands, and high-elevation wetlands remain relatively less explored. For example, evapotranspiration is a key hydrologic process linked to ecosystems but thus far there is limited understanding on the relationship between evapotranspiration and high-elevation vegetation

(Wang et al., 2020), as also mentioned in Chapter 3.

4. There is limited understanding of the role that steep environmental heterogeneity can play in maintaining high diversity and endemism to fight against climate change;
5. There is also limited understanding of the two-way interaction between the cryosphere and biodiversity at species, genetic, and ecosystem levels;
6. Knowledge is limited on the response of fauna to changes in floral communities and vice-versa.

4.8.2. Gaps in impacts

This chapter has reported on the observed impacts of the changing cryosphere on biodiversity. We summarise the major gaps in knowledge below:

1. Although climate-driven extinctions and range retractions are already widespread, they are poorly reported due to failure to survey the distribution of species at sufficiently fine resolutions in order to detect declines and to attribute such declines to climate change (Thomas et al., 2006).
2. The impacts of cryospheric changes on high-elevation wetlands and peatlands need urgent attention (Bhatta et al., 2018; Zhu et al., 2021).
3. The impacts of hazards and disasters on biodiversity and their cascading impacts on society and their wellbeing need more careful study.
4. The impacts of a changing cryosphere on biodiversity at all levels and its cascading impacts on society and their wellbeing need further study.

4.8.3. Response gaps

How ecosystems or species respond to the changing cryosphere remains little explored. However, to better adapt, it is necessary to understand the process, degree, and type of responses. The identified knowledge gaps are as follows:

1. Knowledge of the ecosystem's sensitivity to extreme climate events is still limited. Hence, studies need to be conducted to understand the resistance, recovery, and resilience of ecosystems at higher elevations to such weather events as well as the extent and magnitude of ecosystem responses across the HKH (A. Chakraborty et al., 2018).

2. More studies to understand how biodiversity at ecosystem and species level adapt to changes including climate change are needed.
3. Long-term monitoring of the interrelationships between the cryosphere and biodiversity and studies of their climatic responses are still insufficient. Experimental studies are either insufficient or have narrow spatial/temporal coverage.
4. There is a need to standardise the methodology for purposes of reproducibility, comparability, and generalisation of the findings, something largely still lacking in the available studies.
5. A powerful model on the past and future simulations of cryo-biosphere linkages is lacking.

4.9. Recommendations

Several recommendations for better understanding the impacts of the changing cryosphere on biodiversity and ecosystems are given below:

Science

1. Long-term research and monitoring are required to better understand the linkages, interactions, changes, and responses across different ecosystems and ecotones at higher elevations in relation to a changing cryosphere. To do so, multi- and inter-disciplinary studies should be conducted to arrive at a holistic understanding of the complex issues around the cryosphere, biosphere, and society. Forest-water interactions and permafrost-grassland links are among subjects that need to be studied in detail.
2. An assessment of the nexus between the cryosphere, biosphere, and society needs to be undertaken to arrive at a holistic understanding of the central issues and their synergies.
3. Modern geospatial and information technologies and artificial intelligence such as geotagging, sensors, and bioacoustics should be used in studies to arrive at accurate assessments.
4. Research on contemporary issues need to be prioritised and strengthened in the region

through collaboration and partnership at all levels which include local people and organisations. Participatory approaches like citizen science and participatory Geographic Information System are among possible methodologies.

Policy and practice

1. EbA, nature-based solutions, and nature-climate solutions should be mainstreamed into policy, plans, and practices at the local, national, and regional scales.
2. Regional cooperation for science, policy, and practice across the HKH is important to understand and address the impacts, and it should be given priority.
3. Prediction and projection studies should be prioritised to understand issues and to plan for evidence-based solutions.
4. South-South cooperation and collaboration among HKH countries for research and practice should be prioritised.
5. Corridors as well as connectivity between protected areas should receive serious consideration to enable species movement upwards and northwards.

References

- Acharya, B. K., & Chettri, B. (2012). Effect of climate change on birds, herpetofauna and butterflies in Sikkim Himalaya: A preliminary investigation. In M. L. Arawatia & S. Tambe (Eds.), *Climate change in Sikkim: Patterns, impacts and initiatives* (pp.141-160). Government of Sikkim. <http://www.sikkimforest.gov.in/climate-change-in-sikkim/climate-change-in-sikkim-patterns-impacts-and-initiatives.htm>
- Adhikari, B., Prescott, G., Urbach, D., Chettri, N., & Fischer, M. (2022). Nature's contributions to people and the sustainable development goals in Nepal. *Environmental Research Letters*, 17(9), 1–16. <https://doi.org/10.1088/1748-9326/ac8e1e>
- Adhikari, B. S., Kumar, R., & Singh, S. P. (2018). Early snowmelt impact on herb species composition, diversity and phenology in a western Himalayan treeline ecotone. *Tropical Ecology*, 59(2), 365–382. https://www.researchgate.net/profile/Rahul-Kumar-358/publication/329128763_Early_snowmelt_impact_on_herb_species_composition_diversity_and_phenology_in_a_western_Himalayan_treeline_ecotone/links/604c6deb92851c2b23c5f3b2/Early-snowmelt-impact-on-herb-species-composition-diversity-and-phenology-in-a-western-Himalayan-treeline-ecotone.pdf
- Adler, C., Wester, P., Bhatt, I., Huggel, C., Insarov, G. E., Morecroft, M. D., Muccione, V., & Prakash, A. (2022). Cross-chapter paper 5: Mountains. In H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegria, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama (Eds.), *Climate change 2022: Impacts, adaptation and vulnerability* (pp. 2273–2318). Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. <https://doi.org/10.1017/9781009325844.022>
- Ali, H., Din, J. U., Bosso, L., Hameed, S., Kabir, M., Younas, M., & Nawaz, M. A. (2022). Expanding or shrinking? Range shifts in wild ungulates under climate change in Pamir-Karakoram mountains, Pakistan. *PLOS ONE*, 16(12), e0260031. <https://doi.org/10.1371/journal.pone.0260031>
- Allen, D. J., Daniel, B. A., & Molur, S. (2010). *The status and distribution of freshwater biodiversity in the Eastern Himalaya*. Cambridge University Press. <https://www.semanticscholar.org/paper/The-status-and-distribution-of-freshwater-in-the-Allen-Daniel/36321d4f76818f07659af8e1d0e414f1fe556b4c>
- Allison, E. A. (2015). The spiritual significance of glaciers in an age of climate change. *WIREs Climate Change*, 6(5), 493–508. <https://doi.org/10.1002/wcc.354>
- Anderson, K., Fawcett, D., Cugulliere, A., Benford, S., Jones, D., & Leng, R. (2020). Vegetation expansion in the subnival Hindu Kush Himalaya. *Global Change Biology*, 26(3), 1608–1625. <https://doi.org/10.1111/gcb.14919>
- Anup, K. C. & Thapa Parajuli, R. B. (2015). Climate change and its impact on tourism in the Manaslu conservation area, Nepal. *Tourism Planning and Development*, 12(2), 225–237. <https://doi.org/10.1080/21568316.2014.933122>
- Arndt, K. A., Oechel, W. C., Goodrich, J. P., Bailey, B. A., Kalthori, A., Hashemi, J., Sweeney, C., & Zona, D. (2019). Sensitivity of methane emissions to later soil freezing in Arctic tundra ecosystems. *Journal of Geophysical Research: Biogeosciences*, 124(8), 2595–2609. <https://doi.org/10.1029/2019JG005242>
- Arora, M., Kumar, R., Singh, R. D., Malhotra, J., & Kumar, N. (2016). Analysis of unusual meteorological conditions that led to recent floods in Bhagirathi basin (Uttarakhand Himalayas). *Hydrological Sciences Journal*, 61(7), 1238–1243. <https://doi.org/10.1080/02626667.2014.951362>
- Aryal, A., Shrestha, U. B., Ji, W., Ale, S. B., Shrestha, S., Ingty, T., Maraseni, T., Cockfield, G., & Raubenheimer, D. (2016). Predicting the distributions of predator (snow leopard) and prey (blue sheep) under climate change in the Himalaya. *Ecology and Evolution*, 6(12), 4065–4075. <https://doi.org/10.1002/ece3.2196>
- Bagaria, P., Sharma, L. K., Joshi, B. D., Kumar, H., Mukherjee, T., Thakur, M., & Chandra, K. (2020). West to east shift in range predicted for Himalayan langur in climate change scenario. *Global Ecology and Conservation*, 22, e00926. <https://doi.org/10.1016/j.gecco.2020.e00926>
- Bajpai, R., Mishra, S., Dwivedi, S., & Upreti, D. K. (2016). Change in atmospheric deposition during last half century and its impact on lichen community structure in Eastern Himalaya. *Scientific Reports*, 6(1), 30838. <https://doi.org/10.1038/srep30838>
- Baniya, B., Tang, Q., Huang, Z., Sun, S., & Techato, K. (2018). Spatial and temporal variation of NDVI in response to climate change and the implication for carbon dynamics in Nepal. *Forests*, 9(6), 329. <https://doi.org/10.3390/f9060329>

- Bao, T., Xu, X., Jia, G., Billesbach, D. P., & Sullivan, R. C. (2021). Much stronger tundra methane emissions during autumn freeze than spring thaw. *Global Change Biology*, 27(2), 376–387. <https://doi.org/10.1111/gcb.15421>
- Bargali, H., Calderon, L. P. P., Sundriyal, R. C., & Bhatt, D. (2022). Impact of forest fire frequency on floristic diversity in the forests of Uttarakhand, western Himalaya. *Trees, Forests and People*, 9, 100300. <https://doi.org/10.1016/j.tfp.2022.100300>
- Bashir, T., Poudyal, K., Bhattacharya, T., Sathyakumar, S., & Subba, J. B. (2010). Sighting of king cobra ophiophagus hannah in Sikkim, India: A new altitude record for the northeast. *Journal of Threatened Taxa*, 2(6), 990–991. <https://doi.org/10.11609/JoTT.o2438.990-1>
- Basnet, B., Yadav, P. K., & Devkota, A. R. (2021). Insect pests infestation, diseases and management practice of large cardamom in Nepal: A review. *I Tech Mag*, 3, 33–42. <https://doi.org/10.26480/itechmag.03.2021.33.42>
- Behera, M. D., Behera, S. K., & Sharma, S. (2019). Recent advances in biodiversity and climate change studies in India. *Biodiversity and Conservation*, 28(8), 1943–1951. <https://doi.org/10.1007/s10531-019-01781-0>
- Bhatta, L. D., Wu, N., Udas, E., Agrawal, N. K., Ranabhat, S., & Basnet, D. (2018). Wetlands in the Himalaya: Securing services for livelihoods. ICIMOD. <https://lib.icimod.org/record/33727>
- Bhattarai, S., Regmi, B. R., Pant, B., Uprety, D. R., & Maraseni, T. (2021). Sustaining ecosystem-based adaptation: The lessons from policy and practices in Nepal. *Land Use Policy*, 104, 105391. <https://doi.org/10.1016/j.landusepol.2021.105391>
- Bolch, T., Shea, J. M., Liu, S., Azam, F. M., Gao, Y., Gruber, S., Immerzeel, W. W., Kulkarni, A., Li, H., Tahir, A. A., Zhang, G., & Zhang, Y. (2019). Status and change of the cryosphere in the extended Hindu Kush Himalaya region. In P. Wester, A. Mishra, A. Mukherji, & A. B. Shrestha (Eds.), *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability and people* (pp. 209–255). Springer International Publishing. https://doi.org/10.1007/978-3-319-92288-1_7
- Borogayary, B., Das, A. K., & Nath, A. J. (2018). Vegetative and reproductive phenology of *Aquilaria malaccensis* Lam. (agarwood) in Cachar District, Assam, India. *Journal of Threatened Taxa*, 10(8), 12064–12072. <https://doi.org/10.11609/jott.3825.10.8.12064-12072>
- Bourquin, M., Busi, S. B., Fodelianakis, S., Peter, H., Washburne, A., Kohler, T. J., Ezzat, L., Michoud, G., Wilmes, P., & Battin, T. J. (2022). The microbiome of cryospheric ecosystems. *Nature Communications*, 13(1), 3087. <https://doi.org/10.1038/s41467-022-30816-4>
- Brandt, J. S., Haynes, M. A., Kuemmerle, T., Waller, D. M., & Radeloff, V. C. (2013). Regime shift on the roof of the world: Alpine meadows converting to shrublands in the southern Himalayas. *Biological Conservation*, 158, 116–127. <https://doi.org/10.1016/j.biocon.2012.07.026>
- Camarero, J. J., Gazol, A., Sánchez-Salguero, R., Fajardo, A., McIntire, E. J. B., Gutiérrez, E., Batllori, E., Boudreau, S., Carrer, M., Diez, J., Dufour-Tremblay, G., Gaire, N. P., Hofgaard, A., Jomelli, V., Kirdyanov, A. V., Lévesque, E., Liang, E., Linares, J. C., Mathisen, I. E., ... Wilmking, M. (2021). Global fading of the temperature–growth coupling at alpine and polar treelines. *Global Change Biology*, 27(9), 1879–1889. <https://doi.org/10.1111/gcb.15530>
- Caplins, L., Halvorson, S. J., & Bosak, K. (2018). Beyond resistance: A political ecology of cordyceps as alpine niche product in the Garhwal, Indian Himalaya. *Geoforum*, 96, 298–308. <https://doi.org/10.1016/j.geoforum.2018.08.019>
- Chakraborty, A., Joshi, P. K., & Sachdeva, K. (2016). Predicting distribution of major forest tree species to potential impacts of climate change in the central Himalayan region. *Ecological Engineering*, 97, 593–609. <https://doi.org/10.1016/j.ecoleng.2016.10.006>
- Chakraborty, A., Shukla, R., Sachdeva, K., Roy, P. S., & Joshi, P. K. (2018). The climate change conundrum and the Himalayan forests: The way forward into the future. *Proceedings of the National Academy of Sciences India. Biological Sciences*, 88(3), 837–847. <https://doi.org/10.1007/s40011-016-0788-x>
- Chakraborty, D., Ramakrishnan, U., & Sinha, A. (2015). Quaternary climate change and social behavior shaped the genetic differentiation of an endangered montane primate from the southern edge of the Tibetan Plateau. *American Journal of Primatology*, 77(3), 271–284. <https://doi.org/10.1002/ajp.22343>
- Chatterjee, A., Blom, E., Gujja, B., Jacimovic, R., Beevers, L., O’Keeffe, J., Beland, M., & Biggs, T. (2010). WWF initiatives to study the impact of climate change on Himalayan high-altitude wetlands (HAWs). *Mountain Research and Development*, 30(1), 42–52. <https://doi.org/10.1659/MRD-JOURNAL-D-09-00091.1>
- Chaudhary, A., Sarkar, M. S., Adhikari, B. S., & Rawat, G. S. (2021). *Ageratina adenophora* and *Lantana camara* in Kailash Sacred Landscape, India: Current distribution and future climatic scenarios through modeling. *PLOS ONE*, 16(5), e0239690. <https://doi.org/10.1371/journal.pone.0239690>

- Chaudhary, S., Adhikari, B. R., Chaudhary, P., Dorji, T., & Poudel, R. (2021). Ecosystem-based adaptation (EbA) in the Hindu Kush Himalaya: Status, progress and challenges. In M. Mukherjee & R. Shaw (Eds.), *Ecosystem-based disaster and climate resilience: Integration of blue-green infrastructure in sustainable development* (pp. 29–51). Springer Singapore. https://doi.org/10.1007/978-981-16-4815-1_2
- Chaudhary, S., Tshering, D., Phuntsho, T., Uddin, K., Shakya, B., & Chettri, N. (2017). Impact of land cover change on a mountain ecosystem and its services: Case study from the Phobjikha valley, Bhutan. *Ecosystem Health and Sustainability*, 3(9), 1–12. <https://doi.org/10.1080/20964129.2017.1393314>
- Chaudhary, S., Uddin, K., Chettri, N., Thapa, R., & Sharma, E. (2022). Protected areas in the Hindu Kush Himalaya: A regional assessment of the status, distribution, and gaps. *Conservation Science and Practice*, 4(10), e12793. <https://doi.org/10.1111/csp2.12793>
- Chen, F. H., Dong, G. H., Zhang, D. J., Liu, X. Y., Jia, X., An, C. B., Ma, M. M., Xie, Y. W., Barton, L., Ren, X. Y., Zhao, Z. J., Wu, X. H., & Jones, M. K. (2015). Agriculture facilitated permanent human occupation of the Tibetan Plateau after 3600 B.P. *Science*, 347(6219), 248–250. <https://doi.org/10.1126/science.1259172>
- Chen, G. (2002). *Biodiversity in the Eastern Himalayas: Conservation through dialogue. Summary reports of workshops on biodiversity conservation in the Hindu Kush-Himalayan ecoregion*. ICIMOD. <https://lib.icimod.org/record/22102>
- Chen, H., Liu, X., Xue, D., Zhu, D., Zhan, W., Li, W., Wu, N., & Yang, G. (2021). Methane emissions during different freezing-thawing periods from a fen on the Qinghai-Tibetan Plateau: Four years of measurements. *Agricultural and Forest Meteorology*, 297, 108279. <https://doi.org/10.1016/j.agrformet.2020.108279>
- Chen, H., Yang, G., Peng, C., Zhang, Y., Zhu, D., Zhu, Q., Hu, J., Wang, M., Zhan, W., Zhu, E., Bai, Z., Li, W., Wu, N., Wang, Y., Gao, Y., Tian, J., Kang, X., Zhao, X., & Wu, J. (2014). The carbon stock of alpine peatlands on the Qinghai-Tibetan Plateau during the Holocene and their future fate. *Quaternary Science Reviews*, 95, 151–158. <https://doi.org/10.1016/j.quascirev.2014.05.003>
- Chen, J., Yang, Y., Wang, S., Sun, H., & Schöb, C. (2020). Shrub facilitation promotes selective tree establishment beyond the climatic treeline. *Science of The Total Environment*, 708, 134618. <https://doi.org/10.1016/j.scitotenv.2019.134618>
- Cheng, X., Lyu, L., Büntgen, U., Cherubini, P., Qiu, H., & Zhang, Q.-B. (2019). Increased El Niño–Southern oscillation sensitivity of tree growth on the southern Tibetan Plateau since the 1970s. *International Journal of Climatology*, 39(8), 3465–3475. <https://doi.org/10.1002/joc.6032>
- Chettri, N., Aryal, K., Thapa, S., Uddin, K., Kandel, P., & Karki, S. (2021). Contribution of ecosystem services to rural livelihoods in a changing landscape: A case study from the Eastern Himalaya. *Land Use Policy*, 109, 105643. <https://doi.org/10.1016/j.landusepol.2021.105643>
- Chhetri, B., Badola, H. K., & Barat, S. (2018). Predicting climate-driven habitat shifting of the near threatened satyr tragopan (*tragopan satyra; galliformes*) in the Himalayas. *Avian Biology Research*, 11(4), 221–230. <https://doi.org/10.3184/175815618X15316676114070>
- Chhetri, B., Badola, H. K., & Barat, S. (2021). Modelling climate change impacts on distribution of Himalayan pheasants. *Ecological Indicators*, 123, 107368. <https://doi.org/10.1016/j.ecolind.2021.107368>
- Chhetri, P. K., & Cairns, D. M. (2015). Contemporary and historic population structure of *Abies spectabilis* at treeline in Barun valley, eastern Nepal Himalaya. *Journal of Mountain Science*, 12(3), 558–570. <https://doi.org/10.1007/s11629-015-3454-5>
- Chhetri, P. K., Gaddis, K. D., & Cairns, D. M. (2018). Predicting the suitable habitat of treeline species in the Nepalese Himalayas under climate change. *Mountain Research and Development*, 38(2), 153–163. <https://doi.org/10.1659/MRD-JOURNAL-D-17-00071.1>
- Childs, G., & Choedup, N. (2014). Indigenous management strategies and socioeconomic impacts of Yartsa Gunbu (*ophiocordyceps sinensis*) harvesting in Nubri and Tsum, Nepal. *Himalaya*, 34(1), 8–22. <https://digitalcommons.macalester.edu/himalaya/vol34/iss1/7/>
- Chitale, V., & Behera, M. D. (2019). How will forest fires impact the distribution of endemic plants in the Himalayan biodiversity hotspot? *Biodiversity and Conservation*, 28(8), 2259–2273. <https://doi.org/10.1007/s10531-019-01733-8>
- Choi, C., Berry, P., & Smith, A. (2021). The climate benefits, co-benefits, and trade-offs of green infrastructure: A systematic literature review. *Journal of Environmental Management*, 291, 112583. <https://doi.org/10.1016/j.jenvman.2021.112583>
- Chong, J. (2014). Ecosystem-based approaches to climate change adaptation: Progress and challenges. *International Environmental Agreements: Politics, Law and Economics*, 14(4), 391–405. <https://doi.org/10.1007/s10784-014-9242-9>

- Dai, G., Wang, S., Geng, Y., Dawazhaxi, Ou, X., & Zhang, Z. (2021). Potential risks of *tithonia diversifolia* in Yunnan Province under climate change. *Ecological Research*, 36(1), 129–144. <https://doi.org/10.1111/1440-1703.12182>
- Dai, Y., Peng, G., Wen, C., Zahoor, B., Ma, X., Hacker, C. E., & Xue, Y. (2021). Climate and land use changes shift the distribution and dispersal of two umbrella species in the Hindu Kush Himalayan region. *Science of The Total Environment*, 777, 146207. <https://doi.org/10.1016/j.scitotenv.2021.146207>
- Dar, S. A., Singh, S. K., Wan, H. Y., Kumar, V., Cushman, S. A., & Sathyakumar, S. (2021). Projected climate change threatens Himalayan brown bear habitat more than human land use. *Animal Conservation*, 24(4), 659–676. <https://doi.org/10.1111/acv.12671>
- Das, P. V. (2022). People's climate knowledge versus scientists' climate knowledge: A study of apple farming communities in Western Himalayas, India. *GeoJournal*, 87(3), 2227–2238. <https://doi.org/10.1007/s10708-021-10371-z>
- Dhyani, S., Lahoti, S., Khare, S., Pujari, P., & Verma, P. (2018). Ecosystem based disaster risk reduction approaches (EbDRR) as a prerequisite for inclusive urban transformation of Nagpur City, India. *International Journal of Disaster Risk Reduction*, 32, 95–105. <https://doi.org/10.1016/j.ijdr.2018.01.018>
- Dolezal, J., Jandova, V., Macek, M., Mudrak, O., Altman, J., Schweingruber, F. H., & Liancourt, P. (2021). Climate warming drives Himalayan alpine plant growth and recruitment dynamics. *Journal of Ecology*, 109(1), 179–190. <https://doi.org/10.1111/1365-2745.13459>
- Donald, P. F., Fishpool, L. D. C., Ajagbe, A., Bennun, L. A., Bunting, G., Burfield, I. A. N. J., Butchart, S. H. M., Capellan, S., Crosby, M. J., Dias, M. P., Diaz, D., Evans, M. I., Grimmett, R., Heath, M., Jones, V. R., Lascelles, B. G., Merriman, J. C., O'Brien, M., Ramirez, I., ... Wege, D. C. (2019). Important bird and biodiversity areas (IBAs): The development and characteristics of a global inventory of key sites for biodiversity. *Bird Conservation International*, 29(2), 177–198. <https://doi.org/10.1017/S0959270918000102>
- Dong, H., & Huang, G. (2015). Relationship between altitude and variation characteristics of the maximum, minimum temperature and diurnal temperature range in China. *Chinese Journal of Atmospheric Sciences*, 39(5), 1011–1024.
- Elsen, P. R., Monahan, W. B., & Merenlender, A. M. (2018). Global patterns of protection of elevational gradients in mountain ranges. *Proceedings of the National Academy of Sciences*, 115(23), 6004–6009. <https://doi.org/10.1073/pnas.1720141115>
- Engelhardt, M., Leclercq, P., Eidhammer, T., Kumar, P., Landgren, O., & Rasmussen, R. (2017). Meltwater run-off in a changing climate (1951–2009) at Chhota Shigri Glacier, Western Himalaya, Northern India. *Annals of Glaciology*, 58(75pt1), 47–58. <https://doi.org/10.1017/aog.2017.13>
- Everard, M., Gupta, N., Chapagain, P. S., Shrestha, B. B., Preston, G., & Tiwari, P. (2018). Can control of invasive vegetation improve water and rural livelihood security in Nepal? *Ecosystem Services*, 32(July), 125–133. <https://doi.org/10.1016/j.ecoser.2018.07.004/>
- Farrington, J. D., & Li, J. (2016). Climate change impacts on snow leopard range. In T. Mccarthy & D. Mallon (Eds.), *Snow leopards: Biodiversity of the world: Conservation from genes to landscapes* (pp. 85–95). Academic Press. <https://doi.org/10.1016/B978-0-12-802213-9.00008-0>
- Fell, S. C., Carrivick, J. L., & Brown, L. E. (2017). The multitrophic effects of climate change and glacier retreat in mountain rivers. *BioScience*, 67(10), 897–911. <https://doi.org/10.1093/biosci/bix107>
- Gaire, N., Dhakal, Y., Shah, S. K., Fan, Z., Bräuning, A., Thapa, U. K., Bhandari, S., Aryal, S., & Bhujju, D. R. (2019). Drought (scPDSI) reconstruction of trans-Himalayan region of central Himalaya using *Pinus wallichiana* tree-rings. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 514, 251–264. <https://doi.org/10.1016/j.palaeo.2018.10.026>
- Gaire, N., Koirala, M., Bhujju, D. R., & Borgaonkar, H. P. (2014). Treeline dynamics with climate change at the central Nepal Himalaya. *Clim. Past*, 10(4), 1277–1290. <https://doi.org/10.5194/cp-10-1277-2014>
- Gaire, N., Koirala, M., Bhujju, D. R., & Carrer, M. (2017). Site- and species-specific treeline responses to climatic variability in eastern Nepal Himalaya. *Dendrochronologia*, 41, 44–56. <https://doi.org/10.1016/j.dendro.2016.03.001>
- Gaire, N., Fan, Z.-X., Chhetri, P. K., Shah, S. K., Bhujju, D. R., Wang, J., Sharma, B., Shi, P., & Dhakal, Y. R. (2023). Treeline Dynamics in Nepal Himalaya in a Response to Complexity of Factors. In S. P. Singh, Z. A. Reshi, & R. Joshi (Eds.), *Ecology of Himalayan Treeline Ecotone* (pp. 519–563). Springer Nature Singapore. https://doi.org/10.1007/978-981-19-4476-5_22
- Gaire, N., Zaw, Z., Bräuning, A., Sharma, B., Dhakal, Y., Timilsena, R., Shah, S. K., Bhujju, D. R., & Fan, Z. (2022). Increasing extreme events in the central Himalaya revealed from a tree-ring based multi-century streamflow reconstruction of Karnali River Basin. *Journal of Hydrology*, 610, 127801. <https://doi.org/10.1016/j.jhydrol.2022.127801>

- Ge, W., Han, J., Zhang, D., & Wang, F. (2021). Divergent impacts of droughts on vegetation phenology and productivity in the Yungui Plateau, southwest China. *Ecological Indicators*, 127, 107743. <https://doi.org/10.1016/j.ecolind.2021.107743>
- Ge, X., Jiang, C., Chen, L., Qiu, S., Zhao, Y., Wang, T., and Zong, S. (2017). Predicting the potential distribution in China of *Euwallacea fornicates* (Eichhoff) under current and future climate conditions. *Scientific Reports*, 7(1). <https://doi.org/10.1038/s41598-017-01014-w>
- Gioli, G., Khan, T., Bisht, S., & Scheffran, J. (2014). Migration as an adaptation strategy and its gendered implications: A case study from the Upper Indus Basin. *Mountain Research and Development*, 34(3), 255–265. <https://doi.org/10.1659/MRD-JOURNAL-D-13-00089.1>
- Government of Nepal. (2015). *Nepal earthquake 2015: Rapid environmental assessment*. Government of Nepal. https://d20uvy59p0dg6k.cloudfront.net/downloads/rea_2.pdf
- Government of Nepal & UNDP Nepal. (2010). *Poverty-environment initiative (PEI) Nepal: Programme framework*. Government of Nepal. https://www.unpei.org/files/sites/default/files/e_library_documents/nepal_final_pei_programme_framework_january_2010.pdf
- Govil, H., Mishra, G., Gill, N., Taloor, A., & Diwan, P. (2021). Mapping hydrothermally altered minerals and gossans using hyperspectral data in Eastern Kumaon Himalaya, India. *Applied Computing and Geosciences*, 9, 100054. <https://doi.org/10.1016/j.acags.2021.100054>
- Grant, M. J., & Booth, A. (2009). A typology of reviews: An analysis of 14 review types and associated methodologies. *Health Information and Libraries Journal*, 26(2), 91–108. <https://doi.org/10.1111/j.1471-1842.2009.00848.x>
- Gurung, H. (2004). *Mountain reflections: Pattern and development*. Mandala Book Point. <https://lib.icimod.org/record/6328>
- Gurung, L. J., Miller, K. K., Venn, S., & Bryan, B. A. (2021). Climate change adaptation for managing non-timber forest products in the Nepalese Himalaya. *Science of The Total Environment*, 796, 148853. <https://doi.org/10.1016/j.scitotenv.2021.148853>
- Habibullah, M. S., Din, B. H., Tan, S.-H., & Zahid, H. (2022). Impact of climate change on biodiversity loss: Global evidence. *Environmental Science and Pollution Research*, 29(1), 1073–1086. <https://doi.org/10.1007/s11356-021-15702-8>
- Hamid, M., Khuroo, A. A., Malik, A. H., Ahmad, R., Singh, C. P., Dolezal, J., & Haq, S. M. (2020). Early evidence of shifts in Alpine summit vegetation: A case study from Kashmir Himalaya. *Frontiers in Plant Science*, 11, 421. <https://doi.org/10.3389/FPLS.2020.00421/BIBTEX>
- Hart, R., & Salick, J. (2018). Vulnerability of phenological progressions over season and elevation to climate change: Rhododendrons of Mt. Yulong. *Perspectives in Plant Ecology, Evolution and Systematics*, 34, 129–139. <https://doi.org/10.1016/J.PPEES.2018.09.001>
- Hassan, T., Hamid, M., Wani, S. A., Malik, A. H., Waza, S. A., & Khuroo, A. A. (2021). Substantial shifts in flowering phenology of *sternbergia vernalis* in the Himalaya: Supplementing decadal field records with historical and experimental evidences. *Science of The Total Environment*, 795, 148811. <https://doi.org/10.1016/J.SCITOTENV.2021.148811>
- He, X., Burgess, K. S., Gao, L.-M., & Li, D.-Z. (2019). Distributional responses to climate change for alpine species of cyananthus and pimula endemic to the Himalaya-Hengduan mountains. *Plant Diversity*, 41(1), 26–32. <https://doi.org/10.1016/j.pld.2019.01.004>
- Hu, J., Huang, Y., Jiang, J., & Guisan, A. (2019). Genetic diversity in frogs linked to past and future climate changes on the roof of the world. *Journal of Animal Ecology*, 88(6), 953–963. <https://doi.org/10.1111/1365-2656.12974>
- Hussain, A., Rasul, G., Mahapatra, B., & Tuladhar, S. (2016). Household food security in the face of climate change in the Hindu-Kush Himalayan region. *Food Security*, 8(5), 921–937. <https://doi.org/10.1007/s12571-016-0607-5>
- IPBES. (2019). *The global assessment report on biodiversity and ecosystem services*. IPBES secretariat. <https://doi.org/10.5281/zenodo.3553579>
- IPCC. (2019). IPCC, 2019: Summary for policymakers. In 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, & N. M. Weyer (Eds.), *IPCC special report on the ocean and cryosphere in a changing climate* 3–36. Cambridge University Press. <https://doi.org/10.1017/9781009157964.001>
- Ives, J. D., & Messerli, B. (1989). *The Himalayan dilemma: Reconciling development and conservation*. Routledge. <https://doi.org/10.4324/9780203169193>
- Jaegar, T. (2021). *Leveraging the world heritage convention for conservation in the Hindu Kush Himalaya: An independent assessment of natural world heritage potential*. IUCN. <https://doi.org/10.2305/IUCN.CH.2021.18.en>

- Johnson, E., McDonald, K., & Spero, L. (2022). *Climate change impacts on ecoregions in the Kangchenjunga landscape of India, Bhutan, and Nepal*. University of Michigan. <https://dx.doi.org/10.7302/4360>
- Joshi, A. K., & Joshi, P. K. (2019). Forest ecosystem services in the Central Himalaya: Local benefits and global relevance. *Proceedings of the National Academy of Sciences, India. Biological Sciences*, 89(3), 785–792. <https://doi.org/10.1007/s40011-018-0969-x>
- Joshi, G., & Negi, G. C. S. (2011). Quantification and valuation of forest ecosystem services in the western Himalayan region of India. *International Journal of Biodiversity Science, Ecosystem Services & Management*, 7(1), 2–11. <https://doi.org/10.1080/21513732.2011.598134>
- Joshi, K. D., Das, S. C. S., Pathak, R. K., Khan, A., Sarkar, U. K., & Roy, K. (2018). Pattern of reproductive biology of the endangered golden mahseer *tor putitora* (Hamilton 1822) with special reference to regional climate change implications on breeding phenology from lesser Himalayan region, India. *Journal of Applied Animal Research*, 46(1), 1289–1295. <https://doi.org/10.1080/09712119.2018.1497493>
- Kandari, L. S., Phondani, P. C., Payal, K. C., Rao, K. S., & Maikhuri, R. K. (2012). Ethnobotanical study towards conservation of medicinal and aromatic plants in upper catchments of Dhauri Ganga in the central Himalaya. *Journal of Mountain Science*, 9(2), 286–296. <https://doi.org/10.1007/s11629-012-2049-7>
- Kandel, P., Chettri, N., Chaudhary, S., Sharma, P., & Uddin, K. (2021). Ecosystem services research trends in the water tower of Asia: A bibliometric analysis from the Hindu Kush Himalaya. *Ecological Indicators*, 121, 107152. <https://doi.org/10.1016/j.ecolind.2020.107152>
- Kang, X., Li, Y., Wang, J., Yan, L., Zhang, X., Wu, H., Yan, Z., Zhang, K., & Hao, Y. (2020). Precipitation and temperature regulate the carbon allocation process in alpine wetlands: Quantitative simulation. *Journal of Soils and Sediments*, 20(9), 3300–3315. <https://doi.org/10.1007/s11368-020-02643-x>
- Kaplan, J. O., & New, M. (2006). Arctic climate change with a 20C global warming: Timing climate patterns and vegetation change. *Climatic Change*, 79(3), 213–241. <https://doi.org/10.1007/s10584-006-9113-7>
- Khan, A. H., & Dhani, A. (2017). Impact of climate change on the proliferation of invasive alien plant species in Almora district of Uttarakhand Himalaya. *Indian Journal of Ecology*, 44(2), 295–299.
- Khan, A., Said, A., & Ullah, I. (2020). Landsat-based distribution mapping of high-altitude peatlands in Hindu Kush Himalayas – a case study of Broghil Valley, Pakistan. *Journal of Mountain Science*, 17(1), 42–49. <https://doi.org/10.1007/s11629-019-5384-0>
- Khan, B., Ahmed, W., Ablimit, A., Fakhri, S., & Ali, H. (2012). Range extension of four highland agamid lizards in Shimshal Pamir, Pakistan. *Journal of Arid Land*, 4(1), 77–847. <https://doi.org/10.3724/SP.J.1227.2012.00077>
- Khan, H., Marwat, K. B., Hassan, G., Khan, M. A., & Hashim, S. (2014). Distribution of parthenium weed in Peshawar valley, Khyber Pakhtunkhwa - Pakistan. *Pakistan Journal of Botany*, 46(1), 81–90. <https://www.cabi.org/ISC/abstract/20143089171>
- Klein, J. A., Harte, J., & Zhao, X.-Q. (2004). Experimental warming causes large and rapid species loss, dampened by simulated grazing, on the Tibetan Plateau. *Ecology Letters*, 7(12), 1170–1179. <https://doi.org/10.1111/j.1461-0248.2004.00677.x>
- Klein, J. A., Tucker, C. M., Steger, C. E., Nolin, A., Reid, R., Hopping, K. A., Yeh, E. T., Pradhan, M. S., Taber, A., Molden, D., Ghate, R., Choudhury, D., Alcántara-Ayala, I., Lavorel, S., Müller, B., Grêt-Regamey, A., Boone, R. B., Bourgeron, P., Castellanos, E., ... Yager, K. (2019). An integrated community and ecosystem-based approach to disaster risk reduction in mountain systems. *Environmental Science & Policy*, 94, 143–152. <https://doi.org/10.1016/j.envsci.2018.12.034>
- Krebs, P., Pezzatti, G. B., Mazzoleni, S., Talbot, L. M., & Conedera, M. (2010). Fire regime: History and definition of a key concept in disturbance ecology. *Theory in Biosciences*, 129(1), 53–69. <https://doi.org/10.1007/s12064-010-0082-z>
- Krishnan, R., Shrestha, A. B., Ren, G., Rajbhandari, R., Saeed, S., Sanjay, J., Syed, M. A., Vellore, R., Xu, Y., You, Q., & Ren, Y. (2019). Unravelling climate change in the Hindu Kush Himalaya: Rapid warming in the mountains and increasing extremes. In P. Wester, A. Mishra, A. Mukherji, & A. B. Shrestha (Eds.). *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability and people* (pp. 57–97). Springer International Publishing. https://doi.org/10.1007/978-3-319-92288-1_3
- Kumar, R., Nath, A. J., Nath, A., Sahu, N., & Pandey, R. (2022). Landsat-based multi-decadal spatio-temporal assessment of the vegetation greening and browning trend in the Eastern Indian Himalayan Region. *Remote Sensing Applications: Society and Environment*, 25, 100695. <https://doi.org/10.1016/j.rsase.2022.100695>

- Laha, A., Badola, R., & Hussain, S. A. (2018). Earning a Livelihood from Himalayan caterpillar fungus in Kumaon Himalaya: Opportunities, uncertainties, and implications. *Mountain Research and Development*, 38(4), 323–331. <https://doi.org/10.1659/MRD-JOURNAL-D-17-00063.1>
- Lambeck, R. J. (1997). Focal species: A multi-species umbrella for nature conservation. *Conservation Biology*, 11(4), 849–856. <http://www.jstor.org/stable/2387320>
- Lavorel, S., Colloff, M. J., Locatelli, B., Gorrard, R., Prober, S. M., Gabillet, M., Devaux, C., Laforgue, D., & Peyrache-Gadeau, V. (2019). Mustering the power of ecosystems for adaptation to climate change. *Environmental Science & Policy*, 92, 87–97. <https://doi.org/10.1016/j.envsci.2018.11.010>
- Li, F., Shah, D. N., Pauls, S. U., Qu, X., Cai, Q., & Tachamo Shah, R. D. (2016). Elevational shifts of freshwater communities cannot catch up climate warming in the Himalaya. *Water*, 8(8). <https://doi.org/10.3390/w8080327>
- Li, J., McCarthy, T. M., Wang, H., Weckworth, B. V., Schaller, G. B., Mishra, C., Lu, Z., & Beissinger, S. R. (2016). Climate refugia of snow leopards in High Asia. *Biological Conservation*, 203, 188–196. <https://doi.org/10.1016/j.biocon.2016.09.026>
- Li, Y., Lv, W., Jiang, L., Zhang, L., Wang, S., Wang, Q., Xue, K., Li, B., Liu, P., Hong, H., Renzen, W., Wang, A., Luo, C., Zhang, Z., Dorji, T., Taş, N., Wang, Z., Zhou, H., & Wang, Y. (2019). Microbial community responses reduce soil carbon loss in Tibetan alpine grasslands under short-term warming. *Global Change Biology*, 25(10), 3438–3449. <https://doi.org/10.1111/gcb.14734>
- Liang, E., Wang, Y., Piao, S., Lu, X., Camarero, J. J., Zhu, H., Zhu, L., Ellison, A. M., Ciais, P., & Peñuelas, J. (2016). Species interactions slow warming-induced upward shifts of treelines on the Tibetan Plateau. *Proceedings of the National Academy of Sciences*, 113(16), 4380–4385. <https://doi.org/10.1073/pnas.1520582113>
- Liang, J., Ding, Z., Lie, G., Zhou, Z., Singh, P. B., Zhang, Z., & Hu, H. (2020). Species richness patterns of vascular plants and their drivers along an elevational gradient in the central Himalayas. *Global Ecology and Conservation*, 24, e01279. <https://doi.org/10.1016/j.gecco.2020.e01279>
- Liang, Q., Xu, X., Mao, K., Wang, M., Wang, K., Xi, Z., & Liu, J. (2018). Shifts in plant distributions in response to climate warming in a biodiversity hotspot, the Hengduan Mountains. *Journal of Biogeography*, 45(6), 1334–1344. <https://doi.org/10.1111/jbi.13229>
- Liao, Z., Zhang, L., Nobis, M. P., Wu, X., Pan, K., Wang, K., Dakhil, M. A., Du, M., Xiong, Q., Pandey, B., & Tian, X. (2020). Climate change jointly with migration ability affect future range shifts of dominant fir species in Southwest China. *Diversity and Distributions*, 26(3), 352–367. <https://doi.org/10.1111/ddi.13018>
- Luo, M., Liu, Z., Pan, H., Zhao, L., & Li, M. (2012). Historical geographic dispersal of the golden snub-nosed monkey (*rhinopithecus roxellana*) and the influence of climatic oscillations. *American Journal of Primatology*, 74(2), 91–101. <https://doi.org/10.1002/ajp.21006>
- Lutz, A. F., Immerzeel, W. W., Kraaijenbrink, P. D. A., Shrestha, A. B., & Bierkens, M. F. P. (2016). Climate change impacts on the Upper Indus hydrology: Sources, shifts and extremes. *PLOS ONE*, 11(11), e0165630. <https://doi.org/10.1371/journal.pone.0165630>
- Lyu, N., & Sun, Y.-H. (2014). Predicting threat of climate change to the Chinese grouse on the Qinghai-Tibet plateau. *Wildlife Biology*, 20(2), 73–82. <https://doi.org/10.2981/wlb.13024>
- Maharjan, S., Shrestha, B. B., Joshi, M. D., Devkota, A., Muniappan, R., Adiga, A., & Jha, P. K. (2019). Predicting suitable habitat of an invasive weed *parthenium hysterophorus* under future climate scenarios in Chitwan Annapurna landscape, Nepal. *Journal of Mountain Science*, 16(10), 2243–2256. <https://doi.org/10.1007/s11629-019-5548-y>
- Mainali, J., All, J., Jha, P. K., & Bhujju, D. R. (2015). Responses of montane forest to climate variability in the Central Himalayas of Nepal. *Mountain Research and Development*, 35(1), 66–77. <https://doi.org/10.1659/MRD-JOURNAL-D-13-00101.1>
- Mainali, K., Shrestha, B. B., Sharma, R. K., Adhikari, A., Gurarie, E., Singer, M., & Parmesan, C. (2020). Contrasting responses to climate change at Himalayan treelines revealed by population demographics of two dominant species. *Ecology and Evolution*, 10(3), 1209–1222. <https://doi.org/10.1002/ece3.5968>
- Malhi, Y., Franklin, J., Seddon, N., Solan, M., Turner, M., Field, C., & Knowlton, N. (2020). Climate change and ecosystems: Threats, opportunities and solutions. *Philos Trans R Soc Lond B Biol Sci*, 375(20190104), 1–8 <https://doi.org/10.1098/rstb.2019.0104>
- Manish, K. (2022). Medicinal plants in peril due to climate change in the Himalaya. *Ecological Informatics*, 68, 101546. <https://doi.org/10.1016/j.ecoinf.2021.101546>

- Mastepanov, M., Sigsgaard, C., Dlugokencky, E. J., Houweling, S., Ström, L., Tamstorf, M. P., & Christensen, T. R. (2008). Large tundra methane burst during onset of freezing. *Nature*, 456(7222), 628–630. <https://doi.org/10.1038/nature07464>
- Mayewski, P. A., Perry, L. B., Matthews, T., & Birkel, S. D. (2020). Climate change in the Hindu Kush Himalayas: Basis and gaps. *One Earth*, 3(5), 551–555. <https://doi.org/10.1016/j.oneear.2020.10.007>
- McCollum, D. W., Tanaka, J. A., Morgan, J. A., Mitchell, J. E., Fox, W. E., Maczko, K. A., Hiding, L., Duke, C. S., & Kreuter, U. P. (2017). Climate change effects on rangelands and rangeland management: Affirming the need for monitoring. *Ecosystem Health and Sustainability*, 3(3), e01264. <https://doi.org/10.1002/ehs2.1264>
- Mina, M., Bugmann, H., Cordonnier, T., Irauschek, F., Klopčič, M., Pardos, M., & Cailleret, M. (2017). Future ecosystem services from European mountain forests under climate change. *Journal of Applied Ecology*, 54(2), 389–401. <https://doi.org/10.1111/1365-2664.12772>
- Mirzabaev, A., García-Oliva, F., Hussein, I. A. G., Iqbal, M. M., Kimutai, J., Knowles, T., Meza, F., Nedjraoui, D., Tena, F., Türkeş, M., Vázquez, R. J., & Weltz, M. (2019). Desertification. In P. R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, ... J. Malley (Eds.), *Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* (pp. 250–343). <https://www.ipcc.ch/srccl/>
- Mishra, N. B., & Mainali, K. P. (2017). Greening and browning of the Himalaya: Spatial patterns and the role of climatic change and human drivers. *Science of The Total Environment*, 587–588, 326–339. <https://doi.org/10.1016/j.scitotenv.2017.02.156>
- Mohandass, D., Zhao, J.-L., Xia, Y.-M., Campbell, M. J., & Li, Q.-J. (2015). Increasing temperature causes flowering onset time changes of alpine ginger *roscoea* in the Central Himalayas. *Journal of Asia-Pacific Biodiversity*, 8(3), 191–198. <https://doi.org/10.1016/j.japb.2015.08.003>
- Molden, D. J., Shrestha, A. B., Immerzeel, W. W., Maharjan, A., Rasul, G., Wester, P., Wagle, N., Pradhananga, S., & Nepal, S. (2022). The great glacier and snow-dependent rivers of Asia and climate change: Heading for troubled waters. In A. K. Biswas & C. Tortajada (Eds.), *Water security under climate change* (pp. 223–250). Springer Singapore. https://doi.org/10.1007/978-981-16-5493-0_12
- Mukherji, A., Molden, D., Nepal, S., Rasul, G., & Wagnon, P. (2015). Himalayan waters at the crossroads: Issues and challenges. *International Journal of Water Resources Development*, 31(2), 151–160. <https://doi.org/10.1080/07900627.2015.1040871>
- Mukherji, A., Sinisalo, A., Nüsser, M., Garrard, R., & Eriksson, M. (2019). Contributions of the cryosphere to mountain communities in the Hindu Kush Himalaya: A review. *Regional Environmental Change*, 19(5), 1311–1326. <https://doi.org/10.1007/s10113-019-01484-w>
- Murali, R., Redpath, S., & Mishra, C. (2017). The value of ecosystem services in the high altitude Spiti Valley, Indian Trans-Himalaya. *Ecosystem Services*, 28, 115–123. <https://doi.org/10.1016/j.ecoser.2017.10.018>
- Myers, N., Mittermeier, R. A., Mittermeier, C. G., da Fonseca, G. A. B., & Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature*, 403(6772), 853–858. <https://doi.org/10.1038/35002501>
- Naudiyal, N., Wang, J., Ning, W., Gaire, N. P., Peili, S., Yanqiang, W., Jiali, H., & Ning, S. (2021). Potential distribution of *Abies*, *Picea*, and *Juniperus* species in the sub-alpine forest of Minjiang headwater region under current and future climate scenarios and its implications on ecosystem services supply. *Ecological Indicators*, 121, 107131. <https://doi.org/10.1016/j.ecolind.2020.107131>
- Negi, G., Samal, P., Kuniyal, J., Kothiyari, B., Sharma, R., & Dhyani, P. (2012). Impact of climate change on the western Himalayan mountain ecosystems: An overview. *Tropical Ecology*, 53(3), 345–356. https://hero.epa.gov/hero/index.cfm/reference/details/reference_id/2515352
- O'Connor, B., Bojinski, S., Rösli, C., & Schaepman, M. E. (2020). Monitoring global changes in biodiversity and climate essential as ecological crisis intensifies. *Ecological Informatics*, 55, 101033. <https://doi.org/10.1016/j.ecoinf.2019.101033>
- Olson, D. M., & Dinerstein, E. (2002). The global 200: Priority ecoregions for global conservation. *Annals of the Missouri Botanical Garden*, 89(2), 199–224. <https://doi.org/10.2307/3298564>
- Paini, D. R., Sheppard, A. W., Cook, D. C., De Barro, P. J., Worner, S. P., & Thomas, M. B. (2016). Global threat to agriculture from invasive species. *Proceedings of the National Academy of Sciences*, 113(27), 7575–7579. <https://doi.org/10.1073/pnas.1602205113>
- Palomo, I. (2017). Climate change impacts on ecosystem services in high mountain areas: A literature review. *Mountain Research and Development*, 37(2), 179–187. <https://doi.org/10.1659/MRD-JOURNAL-D-16-00110.1>

- Pandey, R., Khadka, K. K., Ghimire, A., Jha, P., & Pathak, U. (2017). Elevational distribution of butterflies in the Himalayas: A case study from Langtang National Park, Nepal. *Journal of Mountain Science*, *14*(7), 1384–1390. <https://doi.org/10.1007/s11629-017-4360-9>
- Pandit, M. K., & Kumar, V. (2013). Land-use change and conservation challenges in the Indian Himalaya. In N. S. Sodhi, L. Gibson, & P. H. Raven (Eds.), *Conservation biology: Voices from the tropics* (pp. 121–133). John Wiley & Sons, Ltd. <https://doi.org/10.1002/9781118679838.ch15>
- Panthi, S., Fan, Z.-X., van der Sleen, P., & Zuidema, P. A. (2020). Long-term physiological and growth responses of Himalayan fir to environmental change are mediated by mean climate. *Global Change Biology*, *26*(3), 1778–1794. <https://doi.org/10.1111/gcb.14910>
- Pathak, R., Negi, V. S., Rawal, R. S., & Bhatt, I. D. (2019). Alien plant invasion in the Indian Himalayan Region: State of knowledge and research priorities. *Biodiversity and Conservation*, *28*(12), 3073–3102. <https://doi.org/10.1007/s10531-019-01829-1>
- Peter, H., & Sommaruga, R. (2016). Shifts in diversity and function of lake bacterial communities upon glacier retreat. *The ISME Journal*, *10*(7), 1545–1554. <https://doi.org/10.1038/ismej.2015.245>
- Pirk, N., Santos, T., Gustafson, C., Johansson, A. J., Tufvesson, F., Parmentier, F.-J. W., Mastepanov, M., & Christensen, T. R. (2015). Methane emission bursts from permafrost environments during autumn freeze-in: New insights from ground-penetrating radar. *Geophysical Research Letters*, *42*(16), 6732–6738. <https://doi.org/10.1002/2015GL065034>
- Prasch, M., Mauser, W., & Weber, M. (2012). Quantifying present and future glacier melt-water contribution to runoff in a central Himalayan river basin. *The Cryosphere*, *7*, 889–904. <https://doi.org/10.5194/tc-7-889-2013>
- Qin, J., Ding, Y., Han, T., & Liu, Y. (2017). Identification of the factors influencing the baseflow in the permafrost region of the northeastern Qinghai-Tibet Plateau. *Water*, *9*(9), 666. <https://doi.org/10.3390/w9090666>
- Rana, S. K., Dangwal, B., Negi, V. S., & Bhatt, I. D. (2022). Scientific research in the Himalaya: Current state of knowledge, funding paradigm and policy implications. *Environmental Science & Policy*, *136*, 685–695. <https://doi.org/10.1016/j.envsci.2022.07.030>
- Rasul, G., Hussain, A., Khan, M. A., Ahmad, F., & Jasra, A. W. (2014). *Towards a framework for achieving food security in the mountains of Pakistan*. ICIMOD Working Paper 2014/5, ICIMOD. <https://lib.icimod.org/record/30041>
- Rasul, G., & Molden, D. (2019). The global social and economic consequences of mountain cryospheric change. *Frontiers in Environmental Science*, *7*(91), 1–18. <https://www.frontiersin.org/articles/10.3389/fenvs.2019.00091>
- Rasul, G., Pasakhala, B., Mishra, A., & Pant, S. (2020). Adaptation to mountain cryosphere change: Issues and challenges. *Climate and Development*, *12*(4), 297–309. <https://doi.org/10.1080/17565529.2019.1617099>
- Robbie, H., Jan, S., Sailesh, R., & Jianchu, X. (2014). Herbarium specimens show contrasting phenological responses to Himalayan climate. *Proceedings of the National Academy of Sciences*, *111*(29), 10615–10619. <https://doi.org/10.1073/pnas.1403376111>
- Saadat, H. Bin, Nawaz, C. M., Manzoor, F., & Nasim, G. (2016). Effect of climate change on butterfly population of selected coniferous forests of Murree Hills and adjacent areas, Pakistan. *Pakistan Journal of Zoology*, *48*(6), 1963–1969. https://www.researchgate.net/publication/310619804_Effect_of_climate_change_on_butterfly_population_of_selected_coniferous_forests_of_Murree_Hills_and_adjacent_areas_Pakistan
- Saeed, M., Rais, M., Gray, R. J., Ahmed, W., Akram, A., Gill, S., & Fareed, G. (2021). Rise in temperature causes decreased fitness and higher extinction risks in endemic frogs at high altitude forested wetlands in northern Pakistan. *Journal of Thermal Biology*, *95*, 102809. <https://doi.org/10.1016/j.jtherbio.2020.102809>
- Sahu, N., Singh, S. N., Singh, P., Mishra, S., Karakoti, N., Bajpai, R., Behera, S. K., Nayaka, S., & Upreti, D. K. (2019). Microclimatic variations and their effects on photosynthetic efficiencies and lichen species distribution along elevational gradients in Garhwal Himalayas. *Biodiversity and Conservation*, *28*(8), 1953–1976. <https://doi.org/10.1007/s10531-019-01782-z>
- Sathyakumar, S., Mungee, M., & Pal, R. (2020). Biogeography of the mountain ranges of South Asia. In M. I. Goldstein & D. A. DellaSala (Eds.), *Encyclopedia of the world's biomes* (pp. 543–554). Elsevier. <https://doi.org/10.1016/B978-0-12-409548-9.12462-5>
- Schickhoff, U., Bobrowski, M., Böhner, J., Bürzle, B., Chaudhary, R. P., Gerlitz, L., Heyken, H., Lange, J., Müller, M., Scholten, T., Schwab, N., & Wedegärtner, R. (2015). Do Himalayan treelines respond to recent climate change? An evaluation of sensitivity indicators. *Earth System Dynamics*, *6*(1), 245–265. <https://doi.org/10.5194/esd-6-245-2015>

- Schwab, N., Bürzle, B., Böhner, J., Chaudhary, R. P., Scholten, T., & Schickhoff, U. (2022). Environmental drivers of species composition and tree species density of a near-natural Central Himalayan treeline ecotone: Consequences for the response to climate change. In U. Schickhoff, R. B. Singh, & S. Mal (Eds.), *Mountain landscapes in transition* (pp. 349–370). Springer International Publishing. https://doi.org/10.1007/978-3-030-70238-0_13
- Sears, R., Phuntsho, S., Dorji, T., Choden, K., Norbu, N., & Baral, H. (2017). *Forest ecosystem services and the pillars of Bhutan's Gross National Happiness*. Center for International Forestry Research. <https://doi.org/10.17528/cifor/006631>
- Shah, S., & Tewari, A. (2016). Limited impact of climate change on seed maturation time in *Myrica esculenta* Buch-Ham. Ex. D. Don in Himalayan region. *International Journal of Environment, Agriculture and Biotechnology*, 1(4), 0713–0717. <https://doi.org/doi:10.22161/ijeab/1.4.13>
- Sheergojri, I. A., Rashid, I., Rehman, I. U., & Rashid, I. (2022). Invasive species services-disservices conundrum: A case study from Kashmir Himalaya. *Journal of Environmental Management*, 309, 114674. <https://doi.org/10.1016/j.jenvman.2022.114674>
- Sherpa, P. Y. (2014). Climate change, perceptions, and social heterogeneity in Pharak, Mount Everest region of Nepal. *Human Organization*, 73(2), 153–161. <http://www.jstor.org/stable/44148749>
- Shi, X. U., Xiao, X., Zhao, X., Sun, R., Zhao, X., Choi, C.-Y., & Lin, W. (2021). Raptor migration at Guantouling, south-west China: Phenology, weather influence and persecution pressure. *Bird Conservation International*, 33(2023), e2. <https://doi.org/10.1017/S0959270921000356>
- Shrestha, K. B., Hofgaard, A., & Vandvik, V. (2015). Recent treeline dynamics are similar between dry and mesic areas of Nepal, central Himalaya. *Journal of Plant Ecology*, 8(4), 347–358. <https://doi.org/10.1093/jpe/rtu035>
- Shrestha, U. B., Dhital, K. R., & Gautam, A. P. (2019). Economic dependence of mountain communities on Chinese caterpillar fungus *ophiocordyceps sinensis* (yarsagumba): A case from western Nepal. *Oryx*, 53(2), 256–264. <https://doi.org/10.1017/S0030605317000461>
- Shrestha, U. B., Gautam, S., & Bawa, K. S. (2012). Widespread climate change in the Himalayas and associated changes in local ecosystems. *PLOS ONE*, 7(5), e36741. <https://doi.org/10.1371/journal.pone.0036741>
- Shrestha, U. B., & Shrestha, B. B. (2019). Climate change amplifies plant invasion hotspots in Nepal. *Diversity and Distributions*, 25(10), 1599–1612. <https://doi.org/10.1111/ddi.12963>
- Sigdel, S. R., Wang, Y., Camarero, J. J., Zhu, H., Liang, E., & Peñuelas, J. (2018). Moisture-mediated responsiveness of treeline shifts to global warming in the Himalayas. *Global Change Biology*, 24(11), 5549–5559. <https://doi.org/10.1111/gcb.14428>
- Sigdel, S. R., Zhang, H., Zhu, H., Muhammad, S., & Liang, E. (2020). Retreating glacier and advancing forest over the past 200 years in the Central Himalayas. *Journal of Geophysical Research: Biogeosciences*, 125(9), e2020JG005751. <https://doi.org/10.1029/2020JG005751>
- Singh, A., & Samant, S. S. (2020). Population and community structure pattern of *juniperous polycarpus* K. koch with climate change effect in the cold desert Trans Himalayan Region, India. *Arid Ecosystems*, 10(1), 17–26. <https://doi.org/10.1134/S2079096120010102>
- Singh, C., Madhavan, M., Arvind, J., & Bazaz, A. (2021). Climate change adaptation in Indian cities: A review of existing actions and spaces for triple wins. *Urban Climate*, 36, 100783. <https://doi.org/10.1016/j.uclim.2021.100783>
- Singh, P., Arya, V., Negi, G. C., & Singh, S. P. (2018). Expansion of *Rhododendron campanulatum* krummholz in the treeline ecotone in Tungnath, Garhwal Himalaya. *Tropical Ecology*, 59(2), 287–295. https://www.gbpihed.gov.in/PDF/Publication/Expansion_of_Rhododendron_2019.pdf
- Singh, S. P., Singh, R. D., & Gumber, S. (2021). *Interpreting mountain treelines in a changing world*. ICIMOD. <https://doi.org/10.53055/ICIMOD.787>
- Song, C., Xu, X., Sun, X., Tian, H., Sun, L., Miao, Y., Wang, X., & Guo, Y. (2012). Large methane emission upon spring thaw from natural wetlands in the northern permafrost region. *Environmental Research Letters*, 7(3), 034009. <https://doi.org/10.1088/1748-9326/7/3/034009>
- Stäubli, A., Nussbaumer, S. U., Allen, S. K., Huggel, C., Arguello, M., Costa, F., Hergarten, C., Martínez, R., Soto, J., Vargas, R., Zambrano, E., & Zimmermann, M. (2018). Analysis of weather- and climate-related disasters in mountain regions using different disaster databases. In S. Mal, R. B. Singh, & C. Huggel (Eds.), *Climate change, extreme events and disaster risk reduction: Towards Sustainable Development Goals* (pp. 17–41). Springer International Publishing. https://doi.org/10.1007/978-3-319-56469-2_2
- Stuart, S. N., Chanson, J. S., Cox, N. A., Young, B. E., Rodrigues, A. S. L., Fischman, D. L., & Waller, R. W. (2004). Status and trends of amphibian declines and extinctions worldwide. *Science*, 306(5702), 1783–1786. <https://doi.org/10.1126/science.1103538>

- Su, B., Xiao, C., Chen, D., Qin, D., & Ding, Y. (2019). Cryosphere services and human well-being. *Sustainability*, *11*(16), 4365. <https://doi.org/10.3390/su11164365>
- Sweeney, B. W., Bott, T. L., Jackson, J. K., Kaplan, L. A., Newbold, J. D., Standley, L. J., Hession, W. C., & Horwitz, R. J. (2004). Riparian deforestation, stream narrowing, and loss of stream ecosystem services. *Proceedings of the National Academy of Sciences*, *101*(39), 14132–14137. <https://doi.org/10.1073/pnas.0405895101>
- Tariq, A., Shu, H., Siddiqui, S., Mousa, B. G., Munir, I., Nasri, A., Waqas, H., Lu, L., & Baqa, M. F. (2021). Forest fire monitoring using spatial-statistical and geo-spatial analysis of factors determining forest fire in Margalla Hills, Islamabad, Pakistan. *Geomatics, Natural Hazards and Risk*, *12*(1), 1212–1233. <https://doi.org/10.1080/19475705.2021.1920477>
- Tchebakova, N. M., Parfenova, E. I., Korets, M. A., & Conard, S. G. (2016). Potential change in forest types and stand heights in central Siberia in a warming climate. *Environmental Research Letters*, *11*(3), 35016. <https://doi.org/10.1088/1748-9326/11/3/035016>
- Telwala, Y., Brook, B. W., Manish, K., & Pandit, M. K. (2013). Climate-induced elevational range shifts and increase in plant species richness in a Himalayan biodiversity epicentre. *PLOS ONE*, *8*(2), e57103. <https://doi.org/10.1371/journal.pone.0057103>
- Thapa, S., Baral, S., Hu, Y., Huang, Z., Yue, Y., Dhakal, M., Jnawali, S. R., Chettri, N., Racey, P. A., Yu, W., & Wu, Y. (2021). Will climate change impact distribution of bats in Nepal Himalayas? A case study of five species. *Global Ecology and Conservation*, *26*, e01483. <https://doi.org/10.1016/j.gecco.2021.e01483>
- Thapa, S., & Hussain, A. (2021). Climate change and high-altitude food security: A small-scale study from the Karnali region in Nepal. *Climate and Development*, *13*(8), 713–724. <https://doi.org/10.1080/17565529.2020.1855099>
- Thapa, U. K., St. George, S., Kharal, D. K., & Gaire, N. (2017). Tree growth across the Nepal Himalaya during the last four centuries. *Progress in Physical Geography: Earth and Environment*, *41*(4), 478–495. <https://doi.org/10.1177/0309133317714247>
- Thiney, U., Banterng, P., Gonkhamdee, S., & Katawatin, R. (2019). Distributions of alien invasive weeds under climate change scenarios in mountainous Bhutan. *Agronomy*, *9*(8), 442. <https://doi.org/10.3390/agronomy9080442>
- Thomas, C. D., Franco, A. M. A., & Hill, J. K. (2006). Range retractions and extinction in the face of climate warming. *Trends in Ecology & Evolution*, *21*(8), 415–416. <https://doi.org/10.1016/j.tree.2006.05.012>
- Thomas, F., Sabel, C. E., Morton, K., Hiscock, R., & Depledge, M. H. (2014). Extended impacts of climate change on health and wellbeing. *Environmental Science & Policy*, *44*, 271–278. <https://doi.org/10.1016/j.envsci.2014.08.011>
- Tian, L., Zhao, L., Wu, X., Hu, G., Fang, H., Zhao, Y., Sheng, Y., Chen, J., Wu, J., Li, W., Ping, C.-L., Pang, Q., Liu, Y., Shi, W., Wu, T., & Zhang, X. (2019). Variations in soil nutrient availability across Tibetan grassland from the 1980s to 2010s. *Geoderma*, *338*, 197–205. <https://doi.org/10.1016/j.geoderma.2018.12.009>
- Tiwari, A., Fan, Z.-X., Jump, A. S., Li, S.-F., & Zhou, Z.-K. (2017). Gradual expansion of moisture sensitive *Abies spectabilis* forest in the Trans-Himalayan zone of central Nepal associated with climate change. *Dendrochronologia*, *41*, 34–43. <https://doi.org/10.1016/j.dendro.2016.01.006/>
- Tiwari, M. P., Devkota, B. P., Jackson, R. M., Chhetri, B. B., & Bagale, S. (2020). What factors predispose households in Trans-Himalaya (Central Nepal) to livestock predation by snow leopards? *Animals*, *10*(11), 2187. <https://doi.org/10.3390/ani10112187>
- Tokida, T., Mizoguchi, M., Miyazaki, T., Kagemoto, A., Nagata, O., & Hatano, R. (2007). Episodic release of methane bubbles from peatland during spring thaw. *Chemosphere*, *70*(2), 165–171. <https://doi.org/10.1016/j.chemosphere.2007.06.042>
- Tuladhar, S., Pasakhala, B., Maharjan, A., & Mishra, A. (2021). Unravelling the linkages of cryosphere and mountain livelihood systems: A case study of Langtang, Nepal. *Advances in Climate Change Research*, *12*(1), 119–131. <https://doi.org/10.1016/j.accre.2020.12.004>
- Uddin, K., Matin, M. A., Khanal, N., Maharjan, S., Bajracharya, B., Tenneson, K., Poortinga, A., Quyen, N. H., Aryal, R. R., Saah, D., Lee Ellenburg, W., Potapov, P., Flores-Anderson, A., Chishtie, F., Aung, K. S., Mayer, T., Pradhan, S., & Markert, A. (2021). Regional land cover monitoring system for Hindu Kush Himalaya. In B. Bajracharya, R. B. Thapa, & M. A. Matin (Eds.), *Earth observation science and applications for risk reduction and enhanced resilience in Hindu Kush Himalaya Region* (pp. 103–125). Springer International Publishing. https://doi.org/10.1007/978-3-030-73569-2_6

- Upadhyay, K. K., Shah, S. K., Roy, A., & Tripathi, S. K. (2021). Dendroclimatology of teak indicates prevailing climatic conditions of tropical moist forests in India. *Ecological Indicators*, 129, 107888. <https://doi.org/10.1016/j.ecolind.2021.107888>
- Vilà-Vilardell, L., Keeton, W. S., Thom, D., Gyeltshen, C., Tshering, K., & Gratzer, G. (2020). Climate change effects on wildfire hazards in the wildland-urban-interface – Blue pine forests of Bhutan. *Forest Ecology and Management*, 461, 117927. <https://doi.org/10.1016/j.foreco.2020.117927>
- Wang, G., Bai, W., Li, N., & Hu, H. (2011). Climate change and its impact on tundra ecosystem in Qinghai-Tibet Plateau, China. *Climatic Change*, 106(3), 463–482. <https://doi.org/10.1007/s10584-010-9952-0>
- Wang, J., He, G., Fang, H., & Han, Y. (2020). Climate change impacts on the topography and ecological environment of the wetlands in the middle reaches of the Yarlung Zangbo-Brahmaputra River. *Journal of Hydrology*, 590, 125419. <https://doi.org/10.1016/j.jhydrol.2020.125419>
- Wang, Y., Li, D., Ren, P., Ram Sigdel, S., & Camarero, J. J. (2022). Heterogeneous responses of alpine treelines to climate warming across the Tibetan Plateau. *Forests*, 13(5), 788. <https://doi.org/10.3390/f13050788>
- Wang, Y., Wu, N., Kunze, C., Long, R., & Perlik, M. (2019). Drivers of change to mountain sustainability in the Hindu Kush Himalaya. In P. Wester, A. Mishra, A. Mukherji, & A. B. Shrestha (Eds.), *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability and people* (pp. 17–56). Springer International Publishing. https://doi.org/10.1007/978-3-319-92288-1_2
- Wang, Z., Wang, Q., Zhao, L., Wu, X., Yue, G., Zou, D., Nan, Z., Liu, G., Pang, Q., Fang, H., Wu, T., Shi, J., Jiao, K., Zhao, Y., & Zhang, L. (2016). Mapping the vegetation distribution of the permafrost zone on the Qinghai-Tibet Plateau. *Journal of Mountain Science*, 13(6), 1035–1046. <https://doi.org/10.1007/s11629-015-3485-y>
- Wei, Y., Zhang, L., Wang, J., Wang, W., Niyati, N., Guo, Y., & Wang, X. (2021). Chinese caterpillar fungus (*Ophiocordyceps sinensis*) in China: Current distribution, trading, and futures under climate change and overexploitation. *Science of The Total Environment*, 755, 142548. <https://doi.org/10.1016/j.scitotenv.2020.142548>
- Weiskopf, S. R., Rubenstein, M. A., Crozier, L. G., Gaichas, S., Griffis, R., Halofsky, J. E., Hyde, K. J. W., Morelli, T. L., Morissette, J. T., Muñoz, R. C., Pershing, A. J., Peterson, D. L., Poudel, R., Staudinger, M. D., Sutton-Grier, A. E., Thompson, L., Vose, J., Weltzin, J. F., & Whyte, K. P. (2020). Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. *Science of The Total Environment*, 733, 137782. <https://doi.org/10.1016/j.scitotenv.2020.137782>
- Wester, P., Mishra, A., Mukherji, A., & Shrestha, A. B. (Eds.). (2019). *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability and people*. Springer International Publishing. <https://doi.org/10.1007/978-3-319-92288-1>
- Winters, D. A. (2022). Landscape and divinity spoken in the same breath. *Religions*, 13(1), 27. <https://doi.org/10.3390/rel13010027>
- Wu, N., Rawat, G. S., Joshi, S., Ismail, M., & Sharma, E. (2013). *High altitude ecosystem interfaces in the Hindu Kush Himalayan region*. ICIMOD. <https://lib.icimod.org/record/28840>
- Wu, X., Dong, S., Liu, S., Su, X., Han, Y., Shi, J., Zhang, Y., Zhao, Z., Sha, W., Zhang, X., Gao, F., & Xu, D. (2017). Predicting the shift of threatened ungulates' habitats with climate change in Altun Mountain National Nature Reserve of the northwestern Qinghai-Tibetan Plateau. *Climatic Change*, 142(3), 331–344. <https://doi.org/10.1007/s10584-017-1939-7>
- Xiaodan, W., Genwei, C., & Xianghao, Z. (2011). Assessing potential impacts of climatic change on subalpine forests on the eastern Tibetan Plateau. *Climatic Change*, 108(1), 225–241. <https://doi.org/10.1007/s10584-010-0008-2>
- Xu, J., Badola, R., Chettri, N., Chaudhary, R. P., Zomer, R., Pokhrel, B., Hussain, S. A., Pradhan, S., & Pradhan, R. (2019). Sustaining biodiversity and ecosystem services in the Hindu Kush Himalaya. In P. Wester, A. Mishra, A. Mukherji, & A. B. Shrestha (Eds.), *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability and people* (pp. 127–165). Springer International Publishing. <https://doi.org/10.1007/978-3-319-92288-1>
- Yadava, A. K., Sharma, Y. K., Dubey, B., Singh, J., Singh, V., Bhutiyani, M. R., Yadav, R. R., & Misra, K. G. (2017). Altitudinal treeline dynamics of Himalayan pine in western Himalaya, India. *Quaternary International*, 444, 44–52. <https://doi.org/10.1016/j.quaint.2016.07.032>
- Yang, M. X., Ya, T. D., Hirose, N., & Hideyuki, F. (2006). The daily freeze-thaw cycle of the surface soil on the Qinghai-Tibet Plateau. *Chinese Science Bulletin*, 51, 1974–1976. <https://link.springer.com/article/10.1007/s11434-007-0004-8>
- Yang, Y., Hopping, K. A., Wang, G., Chen, J., Peng, A., & Klein, J. A. (2018). Permafrost and drought regulate vulnerability of Tibetan Plateau grasslands to warming. *Ecosphere*, 9(5), e02233. <https://doi.org/10.1002/ecs2.2233>

- Yang, Z., Gao, J., Zhao, L., Xu, X., & Ouyang, H. (2013). Linking thaw depth with soil moisture and plant community composition: Effects of permafrost degradation on alpine ecosystems on the Qinghai-Tibet Plateau. *Plant and Soil*, 367(1), 687–700. <https://doi.org/10.1007/s11104-012-1511-1>
- Yang, Z., Zhu, D., Liu, L., & Liu, X. (2022). The effects of freeze-thaw cycles on methane emissions from peat soils of a high-altitude peatland. *Frontiers of Earth Science*, 10. <https://doi.org/10.3389/feart.2022.850220>
- Yu, F., Wang, H., Wang, S., Zhang, Q., & Ji, R. (2012). Response of *Parnassius apollo* population and vertical distribution to climate warming. *Acta Ecologica Sinica*, 32(19), 6203–6209. <https://doi.org/10.5846/stxb201107281107>
- Yuan, Z., Wang, Y., Xu, J., & Wu, Z. (2021). Effects of climatic factors on the net primary productivity in the source region of Yangtze River, China. *Scientific Reports*, 11(1), 1–11. <https://doi.org/10.1038/s41598-020-80494-9>
- Zhang, J., Zhang, W., Liu, S., Kong, W., & Zhang, W. (2022). Cryosphere services to advance the national SDG priorities in Himalaya-Karakoram region. *Sustainability*, 14(5), 2532. <https://doi.org/10.3390/su14052532>
- Zhang, L., An, B., Shu, M., Zhao, C., Yang, X., Suo, Y., Se, Y., & Dabu, X. (2017). Incubation strategies of the black-necked crane (*Grus nigricollis*) in relation to ambient temperature and time of day. *Avian Research*, 8(1), 1–9. <https://doi.org/10.1186/s40657-017-0076-3>
- Zhang, Q., Kong, D., Shi, P., Singh, V. P., & Sun, P. (2018). Vegetation phenology on the Qinghai-Tibetan Plateau and its response to climate change (1982–2013). *Agricultural and Forest Meteorology*, 248, 408–417. <https://doi.org/10.1016/j.agrformet.2017.10.026>
- Zhang, T., & Armstrong, R. L. (2001). Soil freeze/thaw cycles over snow-free land detected by passive microwave remote sensing. *Geophysical Research Letters*, 28(5), 763–766. <https://doi.org/10.1029/2000GL011952>
- Zhang, Y., Li, C., & Wang, M. (2019). Linkages of C: N: P stoichiometry between soil and leaf and their response to climatic factors along altitudinal gradients. *Journal of Soils and Sediments*, 19(4), 1820–1829. <https://doi.org/10.1007/s11368-018-2173-2>
- Zhang, Y., Lin, L., Wang, H., Zhang, Y., Wang, N., & Chen, J. (2017). Land surface phenology of Northeast China during 2000–2015: Temporal changes and relationships with climate changes. *Environmental Monitoring Assessment*, 189(11), 1–13 <https://doi.org/10.1007/s10661-017-6247-1>
- Zhang, Z. Y. (1993). The formation characteristics of frozen area bogs in China. *Journal of Glaciology and Geocryology*, 15, 225–229.
- Zheng, L., Gaire, N., & Shi, P. (2021). High-altitude tree growth responses to climate change across the Hindu Kush Himalaya. *Journal of Plant Ecology*, 14(5), 829–842. <https://doi.org/10.1093/jpe/rtab035>
- Zheng, L., Li, D., Xu, J., Xia, Z., Hao, H., & Chen, Z. (2022). A twenty-year remote sensing study reveals changes to alpine pastures under asymmetric climate warming. *ISPRS Journal of Photogrammetry and Remote Sensing*, 190, 69–78. <https://doi.org/10.1016/j.isprsjprs.2022.06.001>
- Zhu, D., Wu, N., Bhattarai, N., Oli, K. P., Chen, H., Rawat, G. S., Rashid, I., Dhakal, M., Joshi, S., Tian, J., Zhu, Q., Chaudhary, S., & Tshering, K. (2021). Methane emissions respond to soil temperature in convergent patterns but divergent sensitivities across wetlands along altitude. *Global Change Biology*, 27(4), 941–955. <https://doi.org/10.1111/gcb.15454>
- Zomer, R. J., & Oli, K. P. (2012). *Kailash Sacred Landscape Conservation and Development Initiative (KSLCDI)*. ICIMOD. <https://lib.icimod.org/record/26968>
- Zomer, R. J., Trabucco, A., Metzger, M. J., Wang, M., Oli, K. P., & Xu, J. (2014). Projected climate change impacts on spatial distribution of bioclimatic zones and ecoregions within the Kailash Sacred Landscape of China, India and Nepal. *Climatic Change*, 125(3–4), 445–460. <https://doi.org/10.1007/s10584-014-1176-2>
- Zomer, R. J., Trabucco, A., Wang, M., Lang, R., Chen, H., Metzger, M. J., Smajgl, A., Beckschäfer, P., & Xu, J. (2014). Environmental stratification to model climate change impacts on biodiversity and rubber production in Xishuangbanna, Yunnan, China. *Biological Conservation*, 170, 264–273. <https://doi.org/10.1016/j.biocon.2013.11.028>
- Zomer, R. J., Xu, J., Wang, M., Trabucco, A., & Li, Z. (2015). Projected impact of climate change on the effectiveness of the existing protected area network for biodiversity conservation within Yunnan Province, China. *Biological Conservation*, 184, 335–345. <https://doi.org/10.1016/j.biocon.2015.01.031>
- Zou, D., Zhao, L., Sheng, Y., Chen, J., Hu, G., Wu, T., Wu, J., Xie, C., Wu, X., Pang, Q., Wang, W., Du, E., Li, W., Liu, G., Li, J., Qin, Y., Qiao, Y., Wang, Z., Shi, J., & Cheng, G. (2017). A new map of permafrost distribution on the Tibetan Plateau. *The Cryosphere*, 11(6), 2527–2542. <https://doi.org/10.5194/tc-11-2527-2017>

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Cryospheric change, adaptation, and sustainable development in the mountain societies of the Hindu Kush Himalaya

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Chapter overview

KEY FINDINGS

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*).

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*).

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

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 Hindu Kush Himalaya (HKH).

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.

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.

CHAPTER SUMMARY

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.

Impacts of non-climatic drivers of change

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.

Impacts of cryospheric change on society

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 to cryospheric change

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

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.

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.

Both the effectiveness and inclusiveness of existing 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.

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 examine 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.

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5.1. Introduction

The Hindu Kush Himalayan (HKH) region, which is part of the Asian Water Tower and widely regarded as the Third Pole, is home to the largest cryospheric systems outside the Antarctic and Greenland (Yao et al., 2020). The region is also the most densely populated mountain range in the world (see Figure 5.1), with an estimated 240 million (E. Sharma et al., 2019) people comprising hundreds of ethnic groups and living languages. A further 1.65 billion people living in the 12 river basins – including 10 major transboundary rivers that flow through 16 countries – depend directly or indirectly on the natural resources and ecosystem services (i.e., food, water, energy) provided by the mountains (E. Sharma et al., 2019; also see Chapter 4, section 4.4). Accordingly, changes in the mountains of the HKH region, including changes in the mountain cryosphere – glaciers, snow cover, permafrost, and river and lake ice – have the potential to impact lives and livelihoods in mountain and downstream communities. Meanwhile, mountain people often live in poverty; one-third of the region's mountain population live below the poverty line, a figure considerably higher than the national average for the respective countries of the HKH region (Gioli et al., 2019). This makes both the mountain ecosystems and people living therein more likely to be vulnerable to changes occurring in the HKH, where multiple spheres interact with each other (Y. Wang et al., 2019).

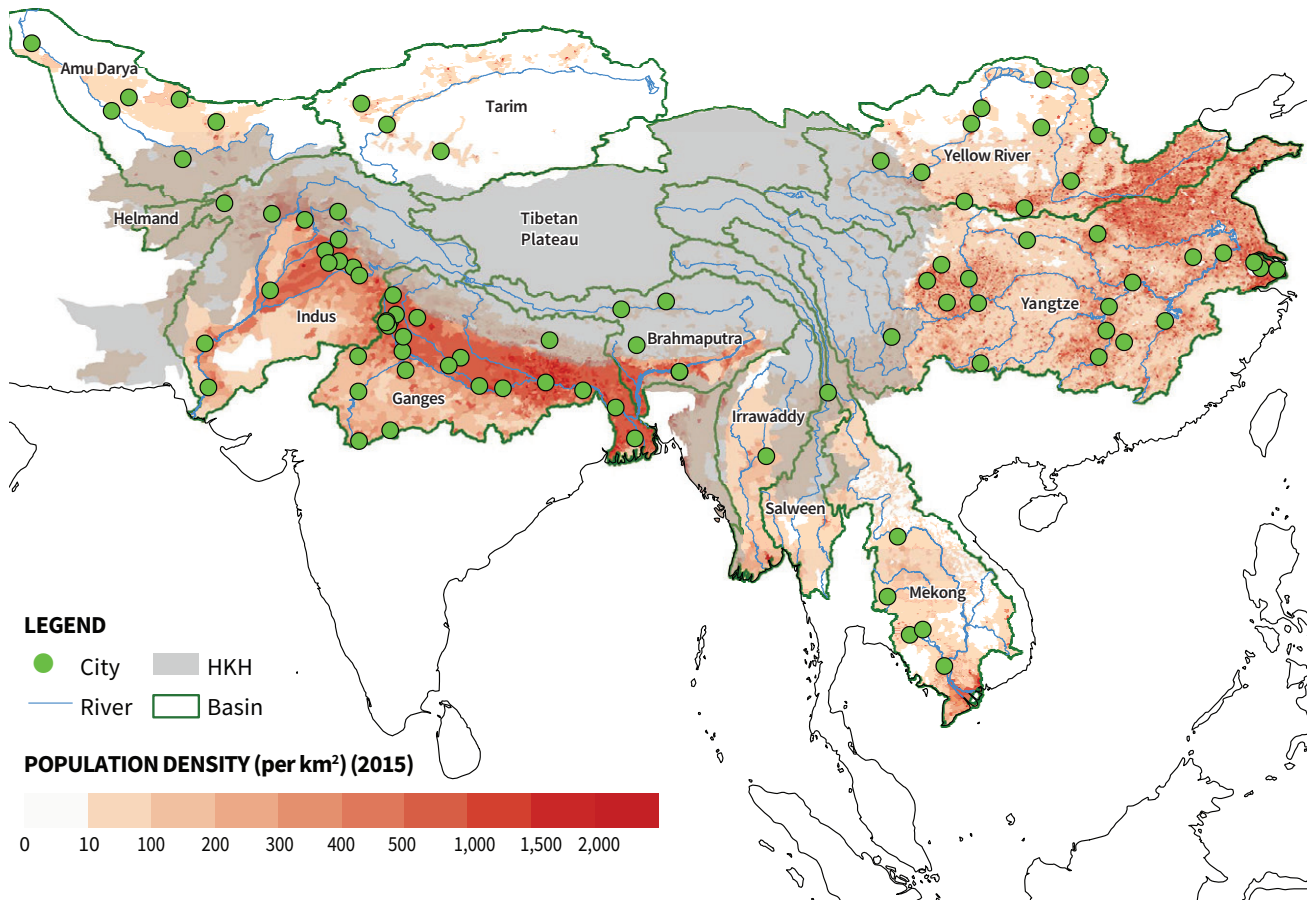
The physical dimension of interactions between the cryosphere and hydrosphere are routinely studied in the HKH region. However, less is known about connections between the social conditions and environmental processes and changes, in particular, how cryospheric change interacts with mountain livelihoods, cultures, economies, and institutions. This relative knowledge deficit impedes the development and implementation of robust responses to changes in mountain systems and could undermine efforts to address the vulnerability of mountain populations across the HKH region (C. Singh et al., 2022).

In general, while the high mountains supply crucial freshwater, maintain biodiversity, and deliver essential goods and services to mountain societies¹, the difficult topography and remoteness mean that mountain communities are often isolated – economic and infrastructural development in the mountains are hindered and there is limited access to quality education. The impacts of cryospheric change exacerbate these challenges, making already difficult livelihoods more precarious. Traditional practices, although often ingenious and time tested, still struggle to keep pace with the rapid pace of climate change (Orr et al., 2022). Furthermore, existing adaptations are mostly reactive and incremental (Adler et al., 2022), hindering progress towards sustainable development in the HKH. This situation highlights

¹ While HKH societies refer to the population and their activities as a whole in the HKH basins (including mountain areas and the downstream), mountain societies refer only to the population in the mountain areas and their activities.

FIGURE 5.1

POPULATION DENSITY MAP OF THE HKH REGION



Data source: WorldPop (2018).

the importance of understanding the linkages between cryospheric change, human adaptation, and sustainable development in the region.

The importance of sustainable development in mountain areas such as the HKH is well established. For example, the 13th chapter of Agenda 21 is focused on sustainable mountain development (SMD), which is defined as “a regionally-specific process of sustainable development that concerns both mountain regions and populations living downstream or otherwise dependent on these resources” (Price & Kim, 1999, p. 205). Furthermore, the 2012 UN Convention on “The future we want”, recognises mountains as playing an essential role in overall sustainable development; it also calls for strengthened multi-stakeholder cooperative actions and the inclusion of mountains in national sustainable development agendas (UN,

2012). Finally, in the 2030 Agenda for Sustainable Development (UN, 2015), three targets are explicitly associated with mountains:

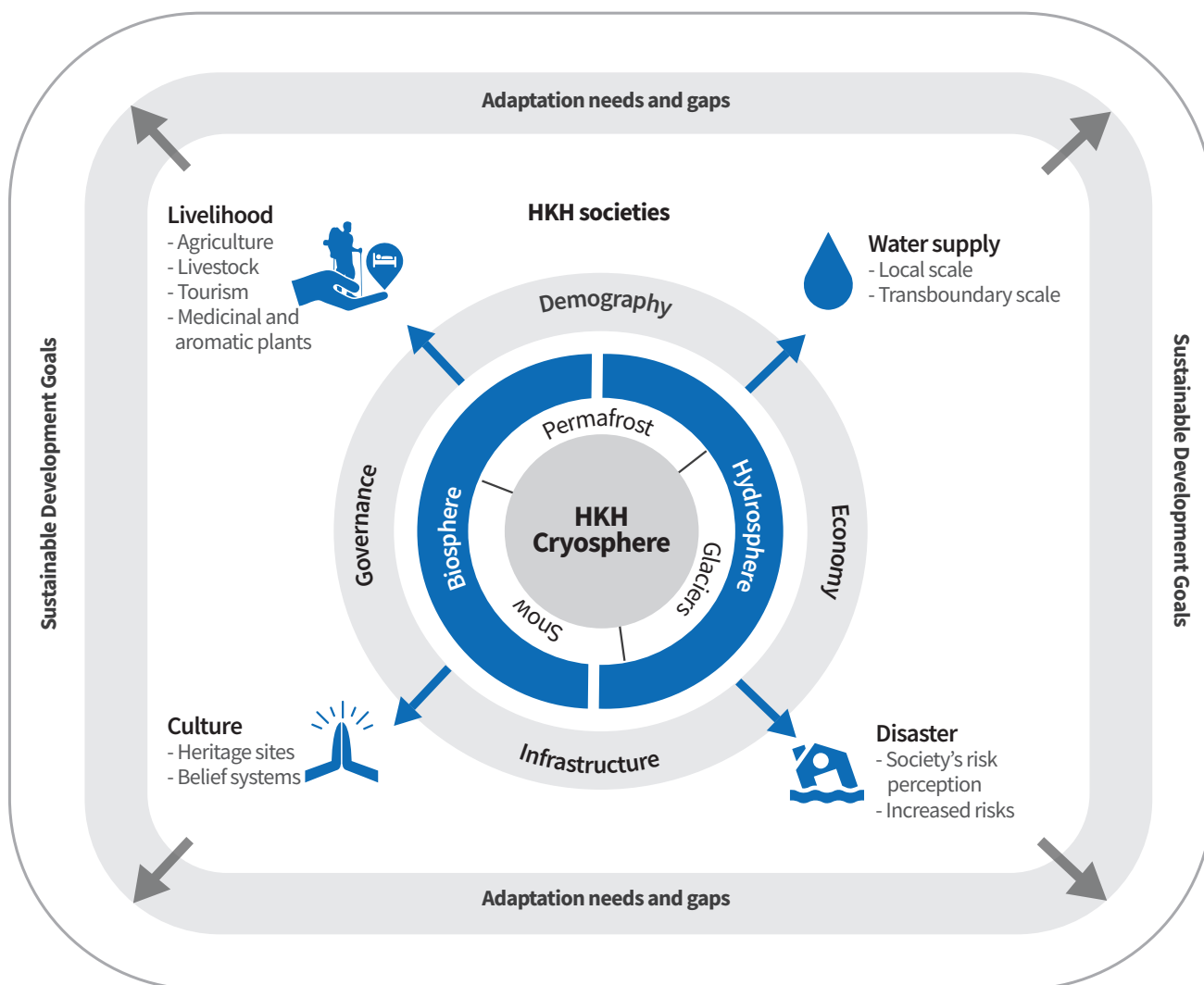
- Target 6.6: By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers, and lakes.
- Target 15.1: By 2020, ensure the conservation, restoration, and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular, forests, wetlands, mountains, and drylands, in line with obligations under international agreements.
- Target 15.4: By 2030, ensure the conservation of mountain ecosystems, including their biodiversity, in order to enhance their capacity to provide benefits that are essential for sustainable development.

In high mountains such as the HKH, mountain specificities require a better understanding of the linkages between the remote and more disadvantaged mountain societies and the highly interwoven nexus of the high mountain cryosphere, hydrosphere, and biosphere. This would help in addressing the concerns of mountain communities (Figure 5.2) and identify effective ways to meet SMD goals. More recently, there has been a growing emphasis on connections between cryospheric change, human adaptation, and sustainable development (Adler et al., 2022; Hock et al., 2019; McDowell et al., 2020 & 2021a; Rasul et al., 2020; Wester et al., 2019), a topic that this chapter examines in the context of mountain societies in the HKH region.

It is important to note that role of adaptations in supporting SMD depends considerably on the approaches to adaptation, which can include autonomous or planned, reactive or anticipatory, and incremental or transformational. Contextually appropriate approaches can improve the resilience of natural and socioeconomic systems, reduce the overall vulnerability and risks of high mountain societies, and advance levels of sustainable development. For example, incremental or autonomous adaptations by high mountain societies may no longer be effective in the context of the increasing magnitude and complexity of cryospheric change and persistent socioeconomic challenges (see Chapter 3, section 3.1.2). In this context, proactive

FIGURE 5.2

IMPACTS OF CRYOSPHERIC CHANGE, ADAPTATION, AND SUSTAINABLE DEVELOPMENT IN THE HKH SOCIETIES



responses informed by the tenets of SMD are needed to secure the well-being of mountain communities affected by a changing cryosphere (Adler et al., 2022).

This chapter presents the current state of knowledge regarding the impacts of cryospheric change on high mountain societies as well as observed adaptations to associated challenges and the contributions these responses make to SMD. It then identifies knowledge and action gaps, before presenting options for advancing sustainable development in the HKH region.

The chapter first identifies cryospheric impact drivers (CrIDs), which are the cryospheric conditions or changes that can influence high mountain societies, such as changes to glacier mass, meltwater, and snow cover. We identify the effects of CrIDs on four key dimensions of mountain societies:

- Livelihoods: agriculture, livestock, tourism, and medicinal and aromatic plants;
- Water security: water resource availability, scarcity, and quality;
- Culture: cultural heritage and mountain sacredness;
- Disaster risk: loss and damage, exposure, vulnerability.

The effects of CrIDs on high mountain societies are mediated by societal factors or non-climatic impact drivers (nCIDs), such as socioeconomic factors, land use, and governance. The chapter will, therefore, address the following questions:

- What are the primary CrIDs and nCIDs relevant to mountain societies in the HKH, and what are their effects on the four key dimensions of mountain societies as described above?
- Who is vulnerable to the effects of CrIDs and nCIDs, and how are they impacted?
- What adaptations are being undertaken to address vulnerabilities, how are these responses integrated with tenets of sustainable development, and are limits to adaptation constraining necessary progress towards SMD?

The chapter began with a short introduction to cryospheric change, mountain societies, and adaptation in the HKH region. It also discussed the importance of sustainable mountain development in a changing climate and outline the chapter objectives. The second section of the chapter explains key CrIDs and nCIDs, and their association with increasing vulnerability in mountain societies of HKH. Observed impacts of CrIDs and nCIDs on the four key dimensions of mountain societies are explained in section 3. This section also examines CrIDs and nCIDs in a transboundary context, particularly as they relate to the potential for transboundary water conflicts and disasters. Adaptations to such impacts and important limits to adaptation are presented in section 4. Section 5 discusses how the effects of CrIDs and nCIDs hamper progress towards SDGs despite considerable adaptation efforts. The last section (6) summarises the chapter's major findings and identifies key knowledge gaps that must be addressed to better integrate adaptation with sustainable development in the region.

5.2. Changes in cryospheric and non-climatic impact drivers in the region

5.2.1. Cryospheric impact drivers

CrIDs are part of climatic impact drivers (CIDs) introduced in the Working Group I Assessment Report 6 of the Intergovernmental Panel on Climate Change (IPCC) as the “physical climate system conditions (e.g., means, events, extremes) that affect an element of society or ecosystems” (Chen et al., 2021; p. 201). They are more specifically linked to the cryosphere and their changes can have a detrimental, beneficial, neutral, or mixed effect on mountain societies. CIDs are value-neutral in characterisation as opposed to hazards – understood as adverse conditions – for the purpose of highlighting the beneficial outcomes of some impacts (Chen et al., 2021).

In the HKH, the CrIDs signify glacial retreat, which is more significant in the Central and the Eastern Himalaya than in the Karakoram and West Kunlun regions (see Chapter 2, section 2.3). Rapid glacial retreat led to an increasing number and area of glacial lakes during 1990, 2000, and 2020, while increasing the risk of GLOFs, particularly in the Eastern Himalaya (see Chapter 2, section 2.4). Meanwhile, barring a few exceptions in the Karakoram, CrIDs have also led to a widespread decline in the extent of snow cover and snow days across the region (see Chapter 2, section 2.4). Furthermore, the rise in average permafrost temperature has led to permafrost degradation, putting more pressure on ongoing environmental changes and increasing the risks of hazards (see Chapter 2, section 2.5). Similarly, as a consequence of the warming climate, the contribution of cryospheric meltwater to the annual streamflow is increasing in the high-altitude areas. It is the highest during the snow- and ice-melting seasons, namely, spring, summer, and early autumn. Moreover, it is higher in the western river basins than in the eastern river basins (see Chapter 3, section 3.1). Though the number of studies is limited, they indicate that the contribution of meltwater and permafrost thaw to groundwater recharge and spring discharge is high, particularly in high-altitude areas (see Chapter 3, section 3.1.2).

Apart from scientific findings, understanding how people perceive and comprehend climate change and its impacts is important for identifying and implementing suitable adaptation measures in order to enable them to transit to a better state in the midst of the ongoing changes (Negi et al., 2017; A. Sharma et al., 2020). While the geophysical changes in the cryosphere have been monitored and extensively analysed, less is known about how people and communities live through these changes and how they perceive the changes and associated risks (Carey et al., 2021). This chapter emphasises the importance of the lived experiences of the HKH communities and explores these experiences in the context of cryospheric change.

One of the most visible signs of climate change in the HKH and among the most documented is the rapid melting of glaciers (Kargel et al., 2011; National Research Council [NRC], 2012; A. B. Shrestha & Aryal, 2011). The disappearance of glaciers has exposed the underlying rocks and darkened the peaks that embody cultural framings and attributions (Adler et al., 2022; Orlove, 2009). Perceptions of high mountain communities in the HKH about the snow cover also attest to its decline both temporally and spatially (Bacha et al., 2021; HI-AWARE, 2018).

In a context of increasing climatic variability and uncertainty, people make decisions based on available information and alternatives to reduce risks and secure their lives and livelihoods (Berkes, 2007). Although weather-related information and scientific evidence of climate change are disseminated by external sources, communities’ social memory of climatic events (such as avalanches, floods, and droughts), their traditional ecological knowledge, and cultural values and belief systems are also equally important when it comes to making decisions (T. Byers et al., 2019; Butcher, 2013). Moreover, oral narratives of individuals who have survived past hazard events can add value to remotely sensed data and complement scientific hazard assessments (T. Byers et al., 2019; Lennartz, 2013). Such shared cultural knowledge and rules have been key to survival and adaptive strategies in this high mountain region that has been historically influenced by a set of socioeconomic, cultural, political, and institutional factors spanning from the household to the global scale (Nüsser et al., 2012; Nüsser and Schmidt, 2017).

5.2.2. Non-climatic impact drivers

Apart from cryospheric change, the region is also facing important changes in the sociocultural, economic, and political realms with direct and indirect impacts on the lives and livelihoods of mountain communities as well as the sustainability of mountain systems. These non-climatic changes that can influence the impact of CrIDs are referred to as non-climatic impact drivers or nCIDs. Some changes in nCIDs are global in nature (e.g., globalisation) whereas others are regional (e.g., air pollution) and local (e.g., infrastructure growth) in nature.

It is well established that the effects of CrIDs are shaped by the nature of the climatic or cryospheric conditions as well as changes in the socioeconomic and political dynamics or nCIDs. Such understanding has been shaped by existing literature that has focused on the idea that experience of climate change is always mediated by pre-existing social constraints and opportunities with differential consequences for different segments of the population, namely, women (Goodrich et al., 2019; Resurrección et al., 2019), the poor (Dilshad et al., 2019; Gentle et al., 2014), and other marginal groups such as migrants (Samui & Sethi, 2022).

ECONOMIC GROWTH

Economic growth is a major policy goal for all countries and more so for developing nations. At present, five of the eight countries in the HKH region fall under the least developed country category based on their low levels of income and structural impediments to growth. Out of these three countries – Bangladesh, Bhutan, and Nepal² – are in the process of graduating to low middle-income countries status (UNCTAD, 2021). Although monetary poverty is declining across the HKH countries except Afghanistan, signifying thereby betterment of life, around 15% of the population continues to remain

in poverty, with almost 260 million people living in extreme poverty³ (Islam et al., 2021). Poverty is also linked with age, gender, caste, ethnicity, education, and access to services and accessibility. Thus, understanding multidimensional poverty⁴ is vital because it remains high in the mountainous areas of the HKH countries (Gerlitz et al., 2015; Hunzai et al., 2011; Mohanty et al., 2018) due to mountain specificities (Jodha, 2007). Multidimensional poverty constitutes a major bottleneck to sustainable mountain development, and adaptation to climate and cryospheric change in the mountains.

Despite economic growth, food security is still a concern in the HKH countries with about 12% of the population (390 million) suffering from undernourishment (FAO et al., 2022). The severity of food insecurity is higher among the mountain population than among those in the lowlands. In the HKH countries, around one-third of the population is food insecure, and half is suffering from malnutrition with children (under 5 years of age) and women among the most nutrition-insecure groups (Rasul et al., 2019). The need for rapid economic growth to meet the target of poverty and food insecurity reduction has increased the demand for natural resources, often leading to their overexploitation, significant land use and land cover changes, and unsustainable socioeconomic activities (Ali et al., 2021; Rasul et al., 2019).

DEMOGRAPHIC SHIFTS

The HKH region is one of the most populated mountainous areas of the world. The overall population in the region is still increasing though the population growth rate is decreasing due to decline in fertility rates. Within the region, China has a lower population density than Pakistan, India, Nepal, and Bangladesh.

Another observable demographic shift in the region is the growing concentration of the population in towns and cities, leading to rapid urbanisation (Dame et al., 2019; Mukherji et al., 2018), including in the

² The Committee for Development Policy (CDP) is a group of independent experts that report to the Economic and Social Council (ECOSOC) of the United Nations. CDP's 2021 triennial review considered some countries including Bangladesh, Nepal, and Myanmar for graduation from LDC status and recommended Bangladesh and Nepal for graduation from the LDC category. Taking into consideration the special conditions created by the COVID-19 pandemic, the Committee recommended an extended preparatory period as well as careful monitoring and analysis of the impacts of the pandemic, with specific transition support. The Committee decided to defer its decision on Myanmar to the CDP's 2024 triennial review. Bhutan is already scheduled for graduation in 2023 (UNCTAD, 2021).

³ 'Poor' refers to those who earn less than USD1.90 a day (2011 PPP).

⁴ The multidimensional poverty index (MPI) measures poverty in terms of three broad dimensions of human development: education, health, and living standards. However, to capture the geographical dimension (mountain specificities), the two dimensions of accessibility and resource endowment are added to the calculations.

sparse populated Tibetan Plateau range (Qi & Yi, 2021). Lack of access to basic services such as education and health care as well as economic opportunities are major reasons for the migration of people from rural to urban areas (Dame, 2018; Pathak et al., 2017). Cryospheric change, both slow-onset and extreme events, also contribute to out-migration from the high mountain areas (Prasain, 2018; Rasul & Molden, 2019). Often, male members of households migrate outside the village for work purposes, leaving the immobile populations, namely, women, children, and the older generation behind (Maharjan et al., 2020). Multilocality and translocal livelihoods have become an integral part of household livelihood strategies (Benz, 2016; Dame, 2018). But the ability to migrate to towns/cities or international destination is dependent on the socioeconomic situation of households. Households with better education and economic opportunities, and of higher social classes find it easier to move as compared to vulnerable groups. This has resulted in changes in the social composition and vulnerability of immobile populations (Pathak et al., 2017). These changes leading to depopulation in rural areas and urbanisation in selected pocket areas have had an impact on land use and land cover changes (Dame et al., 2019; Maharjan et al., 2020; Parveen et al., 2015).

INFRASTRUCTURE AND TECHNOLOGICAL DEVELOPMENT

The mountain communities are becoming increasingly accessible, both physically and virtually. Governments have focused on connecting remote mountain areas with national road networks, thereby meeting aspirations of the local communities as well (Lennartz, 2013; A. Pandey et al., 2021). In addition, rapid growth in road networks in the Tibetan Plateau has improved transboundary connections easing the trade in goods and services and enabling economic development in the mountain areas (Ali et al., 2022; Saxer, 2017; Zhao et al., 2022). Increase in access to information technology has virtually connected mountain communities with other areas although disparities exist in accessibility and quality of connections. Table 5.1 shows access to electricity, roads, and information and communication technology in the HKH countries, which clearly illustrates rural–urban disparities in accessibility and quality of services. As most mountain areas continue to remain rural, not only is access to services poor but also the quality of service, with implications for the adaptive capacities of mountain communities.

TABLE 5.1 INFRASTRUCTURE DEVELOPMENT IN THE HKH COUNTRIES

Infrastructure	Electricity				Rural roads		Information and communication (country level)	
	Access				Access %	Quality	Internet use ^a	Mobile subscription ^b
	Urban %	Rural %	Total %	Quality				
Afghanistan	99.5	97.1	97.7	Poor	20.3		18	58
Bangladesh	99.5	81.3	88	3.7	47	3.1	25	107
Bhutan	99.1	96.8	97.7	5.8	34.2		86	100
China	100	99.9	100	5	57.4	6	73	122
India	99.2	89.3	92.6	4.7	42.8	4.4	43	82
Myanmar	92.5	59.9	69.8	Poor	38.3		35	126
Nepal	98.7	94.7	95.5	2.8	51.7	2.6	38	130
Pakistan	100	54.1	70.8	2.9	39.9	3.9	25	82

Notes:

Access to electricity: Percentage of population (total, rural, urban) with access to household electricity services; Access to rural roads: Percentage of rural population with access to all-season roads (within two kilometres); Quality of infrastructure: 1-7 (from worst to best); Internet use: Percentage (%) of population using internet; Mobile cellular subscription (per 100 people)

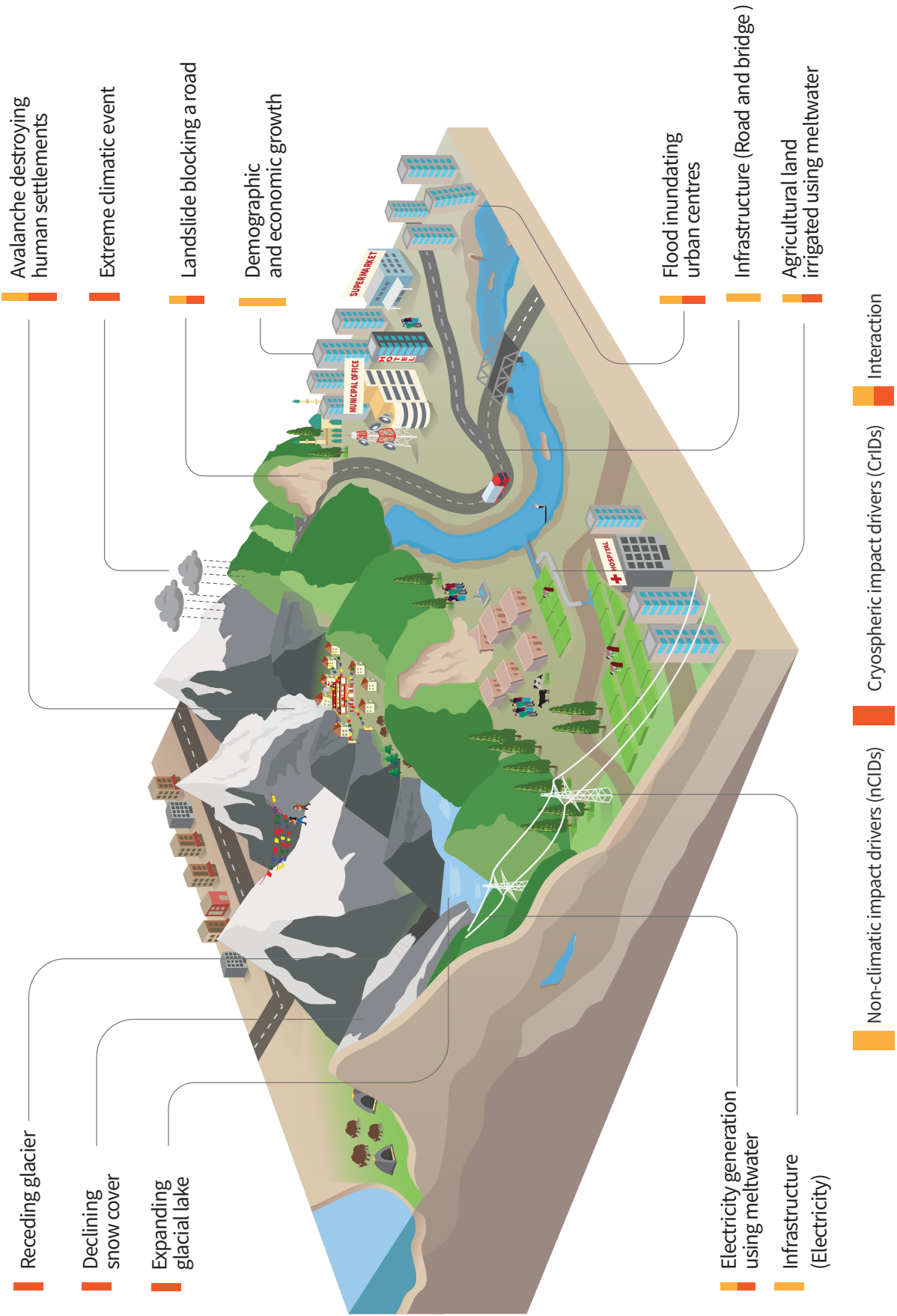
^aAfghanistan, Bangladesh, India, Myanmar, Nepal & Pakistan (2020), Bhutan & China (2021)

^bAfghanistan & Nepal (2020), Bangladesh, Bhutan, China, India, Myanmar & Pakistan (2021)

Source: World Bank (2020); World Bank (2022)

FIGURE 5.3

CrIDs, nCIDs AND THEIR INTERACTIONS IN THE HKH SOCIETIES



GOVERNANCE SYSTEMS AND INSTITUTIONS

Historically, high mountainous communities have remained disconnected from and beyond the reach of formal governmental institutions. Local communities have, therefore, followed traditional customary laws to govern their natural resources as well as social relations (Ojha et al., 2019). But the local communities' access to governmental institutions and their services is improving with growing physical and virtual connectivity as well as the implementation of decentralised policies by countries in the region (Shah & Thompson, 2004). Despite the growing reach of formal governmental institutions, public service delivery has not met the locals' expectations due to lack of human, financial, and technical resources (Ehsan, 2021; Khan, 2021; Kharel & Pasa, 2021). Moreover, the introduction of formal institutions has undermined customary institutions, sometimes even leading to clashes between them.

In other instances, traditional customary governance mechanisms have been recognised and integrated into formal governance mechanisms (Chhetri, 2008). Overall, a shift towards decentralisation and community participation in natural resource management (i.e., forest and water) is evident in the region (Ojha et al., 2019). While this is a positive development in meeting the needs and aspirations of local communities, the decentralisation processes still face multiple challenges such as a deep-rooted centralised governance mindset, high central dependency, inadequate resource mobilisation, absence of coherent legal frameworks, sub-national conflicts, and the limited capacity of local institutions (Ehsan, 2021; Nixon et al., 2013).

In sum, rapid economic growth, technological and infrastructure development, and newer forms of governance have increased the connectivity of mountain societies to other parts of their respective countries as well as the rest of the world. With the commercialisation of the agriculture sector, changes in land use, and more intense use of natural resources, rural mountain societies are gradually shifting from subsistence to market economies, and are being increasingly integrated into regional, national, and global markets (Kreutzmann, 1991;

Mizushima, 2016; Y. Wang et al., 2019). This has contributed to a general rise in income levels and enhanced livelihoods, although not uniformly, across the region and across all population groups. On the other hand, it has also led to a decline in traditional livelihood practices, ways of life, social structures, and local knowledge systems (Dame & Mankelow, 2010).

5.2.3. Intersection of CrIDs and nCIDs

As highlighted in the earlier sections, the HKH is undergoing changes in both CrIDs and nCIDs. When they intersect, the result can be either exacerbated vulnerabilities, albeit differentiated, or increased opportunities for mountain societies. With improved access alongside other infrastructure development, tourism has increased leading to improvements in the local economy although also leading to increased food imports and decreased social bonding (Tuladhar et al., 2021). On the other hand, cryospheric change have also increased the risks of cryospheric hazards (see Chapter 3, section 3.2). These simultaneous socioeconomic and cryospheric changes have increased the overall vulnerability of the mountain inhabitants (see Chapter 3, section 3.2). Similarly, the decline in caterpillar fungus production across four HKH countries (China, India, Nepal, and Bhutan) is attributed to climate change, habitat degradation, and overexploitation (Hopping et al., 2018), which highlights the intersection between CrIDs and nCIDs. Figure 5.3 shows how the CrIDs and nCIDs interact and influence mountain societies, particularly mountain livelihoods, water security, culture, and disaster risk.

Adaptation to impacts of cryospheric change occurs mostly in the form of behavioural changes, infrastructure and technology access, and institutional, financial, and regulatory support (Rasul et al., 2020). Therefore, the adaptive capabilities of communities are directly linked with their socioeconomic situation and locality. All this highlights the importance of looking into the combined effect of both CrIDs and nCIDs when it comes to impacts and adaptations.

5.3. Implications of cryospheric impact drivers on mountain societies

Both CrIDs and nCIDs influence mountain livelihoods such as agriculture, livestock, tourism, water security, and culture (Biemans et al., 2019; Carey et al., 2017; Mukherji et al., 2019; Pasakhala et al., 2021; Tuladhar et al., 2021). The population living in the HKH as well as downstream are directly and indirectly dependent on meltwater run-off to meet their water needs (Nie et al., 2021; Rasul & Molden, 2019; Xiao et al., 2015). Therefore, cryospheric change will have an impact on the supply of water (see Chapter 3, section 3.1.5) for several sectors (Rasul et al., 2019; 2020) while also increasing the disaster risk (Allen et al., 2019; Stäubli et al., 2018; Vaidya et al., 2019). This will, in turn, have a cascading effect on the social, economic, cultural, and environmental dimensions at multiple spatial and temporal scales (Pasakhala et al., 2022; Rasul & Molden, 2019). Water-induced hazards and other

climatic stressors are estimated to have caused losses to the tune of USD 45 billion in the HKH region during the 1985–2014 period (Stäubli et al., 2018).

5.3.1. Impacts on livelihoods

Agriculture, livestock production, tourism, and the collection and trading of medicinal and aromatic plants (Figure 5.4) are the major income sources closely connected with the cryosphere. Cryospheric change will, therefore, carry implications for these livelihood options. For example, in the Kashmir Valley of India, the decreasing trend in snowfall, along with increasing temperature, poses a challenge to the social and economic development of the valley (A. K. Mishra & Rafiq, 2017). Labour migration is the other major income source in the mountains. Although not directly affected by cryospheric change, it is a result of CrIDs on traditional livelihoods, which have been adversely impacted by them (R. Pandey, 2021; Sati, 2021).

FIGURE 5.4

ADVERSE IMPACTS OF CRYOSPHERIC CHANGE ON LIVELIHOODS IN THE HKH



AGRICULTURE

Agriculture is the primary source of livelihoods in the HKH region, providing food, nutrition, and employment opportunities to people. Despite the rising importance of non-farm income opportunities, more than 80% of the mountain people in the region still partially or significantly depend on agriculture (Hussain et al., 2016).

Glacier and snow meltwater are the major water sources of irrigation as well as soil moisture in the high mountain areas (Nüsser et al., 2019; Parveen et al., 2015). Farmers drain glacier and snow meltwater through irrigation channels to agricultural fields and settlements (Nüsser & Schmidt, 2017; see Chapter 3, section 3.3.1). In Gilgit-Baltistan (Pakistan), glacier and snow meltwater irrigate more than 85% of the agricultural land through traditional and improved irrigation systems (Ashraf & Akbar, 2020). Destruction of such traditional irrigation systems could result in large-scale agricultural land abandonment (see Chapter 3, section 3.3.1). Many irrigation systems in the downstream also rely on the glacier- and snow-fed rivers (Kreutzmann, 2012; Molden et al., 2022; Mukherji et al., 2015) as Indus, Jhelum, and Chenab rivers feed the Indus Basin Irrigation System (Qureshi, 2011), Satluj and Beas rivers the Indira Gandhi Nahar Paryojana (Amarasinghe et al., 2012), and Bhagirathi river the Tehri dam (R. C. Sharma et al., 2008).

About 129 million farmers in the Indus and Ganges river basins are dependent on glacial and snow melt (Biemans et al., 2019). In the Indus Basin, meltwater contributes to 9% of the ~46 megatons (MT) of wheat, 15% of the 19 MT of rice, 28% of the 4 MT of cotton, and 17% of the 53 MT of sugarcane (Biemans et al., 2019). Besides irrigation, the snow coating on agriculture and tree debris helps in-situ decomposition adding to soil fertility. Winter climate change can thus influence nitrogen cycling in soils by changing the freeze-thaw cycles in the temperate forest ecosystems (Urakawa et al., 2014).

Changes in the cryosphere are also likely to impact the hydrological regimes of major river systems in the HKH region (Immerzeel et al., 2010; see Chapter 3) as well as the irrigation systems fed by those rivers. Erratic snowfall patterns (i.e., timing, duration, and amount) have been reported to cause

crop failure and loss (Aggarwal, 2008; Dilshad et al., 2019; Sujakhu et al., 2016; Tuladhar et al., 2021). In 2018, an early snowfall (late September) in Himachal Pradesh, India, adversely impacted the summer harvest of potatoes, cauliflower, cabbage, apples, pears, plums, and cherries causing losses in the range of USD 4 million (Pinto, 2018).

Increasing temperature also affects crop phenology. Most highland horticulture crops require low temperatures to be maintained for a long period of time, during which the plants remain dormant only to emerge when the conditions are favourable for growth (Rautela & Karki, 2015). Studies have reported phenological changes such as early sprouting and maturation of seeds (Deng et al., 2011), flowering, and fruiting of cereal (rice and wheat) and fruit crops (apple and cherry) (Sujakhu et al., 2016; Vedwan, 2006) as a result of increasing temperature. Temperature increase, together with water scarcity, have been reported to result in changes in land use practices and cropping patterns (Aggarwal, 2008; Rashid et al., 2020). For instance, in Jammu and Kashmir, summer varieties of rice and traditional Kashmiri apples have vanished, and paddy land has been converted to rainfed dry land in some areas due to increasing temperature and untimely snow and rainfall (R. C. Sharma et al., 2017). In Mustang and Manang, Nepal, higher temperatures and increased meltwater availability have created a conducive environment for growing fruits, vegetables, and other cash crops (Manandhar et al., 2011; Konchar et al., 2015), which were hitherto unsuitable given climatic conditions.

The adverse impacts of cryospheric change can be devastating for food production in the long run. In the downstream areas of the river basins – the food basket for a large population – decline in water availability may result in drastic reductions in food production, putting the food and nutrition status of poor people in jeopardy (Molden et al., 2022). Similarly, in upstream areas, the food and livelihood security of people is under threat due to impacts of cryospheric change, such as glacier retreat, and thinning and changing snow dynamics, on cryosphere-fed irrigation systems (Nüsser et al., 2019a; also see Chapter 3, section 3.3.1). This might increase dependency on imported food. In the mountains, characterised by remoteness, political marginalisation, low market integration,

and limited agricultural land, availability and access to food for purposes of food security remains a challenge (Dame & Nüsser, 2011). The decline in consumption of nutritious traditional crops, abandonment of farmlands, and the limited capacities of the immobile population (women and older generation) are bound to adversely impact the food and nutrition security of the mountain communities (Rasul et al., 2019; P. C. Tiwari et al., 2018).

LIVESTOCK

Livestock production plays an integral role in the livelihoods of 25 to 30 million agro-pastoralists and pastoralists living in the region (Shaoliang & Sharma, 2009). Livestock contributes to food production and food security and provides a wide range of services, among them, buffering against climatic and economic shocks (Godde et al., 2021). Sedentary, transhumance and nomadism are the major livestock production systems in the region, which are dependent on cryospheric services.

Snow meltwater is a major source of moisture and nutrients for vegetation in the high altitudes (Walker et al., 1993). The timing of snowfall and snowmelt and the depth of snow cover play vital roles in vegetation distribution, growth, and productivity (Walker et al., 1993) as well as the seasonal mobility of transhumance herders and their livestock (Ahmad et al., 2021; Namgay et al., 2013; R. Singh et al., 2020).

Studies on the perceptions of local communities, particularly herders, in the region have reported a decrease in the amount of snowfall and an upward shift of the snowline (Aryal et al., 2014; Klein et al., 2014; Luxom et al., 2022; Negi et al., 2017; Pasakhala et al., 2021; Y. Wang et al. 2014). Rapid melting of snow and glaciers as well as permafrost degradation have caused an expansion in high-altitude lakes in the Tibetan Plateau, resulting in the loss of grazing areas for livestock (Hopping et al., 2016; Nyima & Hopping, 2019). Increase in temperature and shifting of the snowline have also provided a conducive environment for shrub encroachment in the alpine meadows, which further shrink the grazing areas for animals (Dong et al., 2011). With the decrease in the amount of snowfall, the number of watering points for animals has also reduced, leading to a higher concentration of animals and increased grazing pressure around the remaining water points (Paudel & Andersen,

2010). These cryospheric changes in conjunction with temperature increase and overgrazing have led to rangeland degradation (Wu et al., 2015), adversely affecting the quality and amount of forage available for livestock (Gentle & Thwaites, 2016; Rayamajhi & Manandhar, 2020). The changes listed above have combined to create a reduction in livestock productivity (Manandhar et al., 2011).

Decrease in snow cover and snowfall has allowed herders to access previously unavailable pastures for grazing their animals (Pasakhala et al., 2021). In the short-term, access to new pastures compensates for reduction in forage quality and quantity. However, continual decline in snowfall and frequent occurrence of snow drought will shorten the growing season, degrading rangelands further in the long-term (Paudel & Andersen, 2013; Shang et al., 2012).

Livestock production in the region is also vulnerable to cryosphere-related disasters. Heavy snowfall and snowstorms that bury rangelands for prolonged periods of time deprive livestock of food as well as water (Shang et al., 2012). These snow-related disasters also impair the mobility of animals in search of food. The erratic snowfall pattern has disrupted the movement of herders and their animals and increased the risk of losses due to snowstorms (Luxom et al., 2022; Namgay et al., 2013). These weather-related occurrences have led to mass death of livestock from both starvation and severe cold in several areas of the HKH (Dollfus, 2013; Joshi et al., 2013; Luxom et al., 2022; Tuladhar et al., 2021; Yeh et al., 2014). For example, snow-related disasters between 1974 and 2009 killed 18 million animals in the eastern Tibetan Plateau (Y. Wang et al., 2014). Avalanches, too, cause heavy loss of animals as in the case of Manang, Nepal, in 2018, which killed 250 animals (K. R. Tiwari et al., 2020). These deaths incurred huge economic losses to the herding community (Shang et al., 2012; K. R. Tiwari et al., 2020). In conjunction with other socioeconomic drivers of change, the growing adverse impacts of cryospheric change and forage shortages have discouraged herders from continuing with livestock production (Luxom et al., 2022; Pasakhala et al., 2021).

Under observed and projected cryospheric change, livestock-based livelihoods are likely to become more vulnerable in the future, and hence, untenable. As livestock is a form of liquid asset for mountain communities, these changes can have significant

implications for poverty in the region. Livestock products (diary and meat) are also an important source of protein for the households. Thus, decrease in or abandonment of livestock keeping, because of fodder shortage and loss of interest in the younger generation, might have implications for the nutritional security of household members.

MEDICINAL AND AROMATIC PLANTS

Medicinal and aromatic plants (MAPs) play an important role in the health and livelihoods of the communities in the region. Plants are traditionally used for treating various ailments of humans as well as livestock and is often a cheap alternative to costly medicines (Applequist et al., 2019; Bergmann et al., 2008). In remote mountain villages, access to modern medicines and medical services is limited and the traditional knowledge of medical plants is often the only option available for local communities (M. Kumar et al., 2021; Phondani et al., 2014). Moreover, the harvesting of and trading in these plants is a major source of cash income (Pradhan et al., 2020; U. B. Shrestha & Bawa, 2014; Wallrapp et al., 2019).

Soil moisture is an important limiting factor in the distribution of high-altitude plant species (M. Müller et al., 2016). Snow meltwater provides soil moisture for vegetation, including MAPs, growing in the subalpine and alpine meadows (Paudel & Andersen, 2013). But the decrease in snowfall and receding of glaciers threaten water availability for plant species that grow in cool and moist conditions. For example, the rapid melting of the Braga glacier and the Gangapurna glacier in Manang, Nepal, threatens water availability for *Neopicrorhiza scrophulariiflora* (B. B. Shrestha & Jha, 2009). Decrease in snowfall has been perceived as a major factor in the decrease in availability of MAPs such as the highly valued *Ophiocordyceps sinensis*, colloquially referred to as the caterpillar fungus (Hopping et al., 2018; U. B. Shrestha & Bawa, 2013). Untimely heavy snowfalls during April and May have, moreover, begun to disrupt and delay its collection season in Bhutan, India, and Nepal (A. C. Byers et al., 2020), with serious adverse impacts on mountain livelihoods.

Studies have also reported changes in plant phenology and growing seasons due to shifts in snowfall patterns and warming conditions (Zeng & Jia, 2013). The decline in snow cover favours the growth of shrubs in

alpine conditions (Brandt et al., 2013; Wipf & Rixen, 2010) which, in conjunction with decreased meltwater, will lead to habitat alterations of ecologically sensitive medicinal plant species (Choden et al., 2021). All these are likely to have negative implications on the livelihoods of communities dependent on the collection and trading of MAPs.

TOURISM

Tourism is an important contributor to the national as well as the local economy of countries in the region (Ingty, 2017; Tuladhar et al., 2021). International tourism contributed about 4% of the total Gross Domestic Product (GDP) of Nepal in 2017 (Khanal, 2020) and 10% of that of Bhutan in 2019 (Tourism Council of Bhutan [TCB], 2022). The majority of international tourists arriving in Nepal have stated their purpose as mountaineering and holiday/pleasure (Ministry of Culture, Tourism & Civil Aviation [MoCTCA], 2020). In Solukhumbu, Nepal, the gateway to Mount Everest, the number of seasonal tourists doubled between 1994 and 2014 (Aubriot et al., 2019). Similarly, the Yolung Snow Mountain range of Yunnan province in China, which is a popular destination for glacier tourism (offering sightseeing by train, car and helicopter as well as hiking, skiing, ice cave tourism, ice climbing, etc.), attracted a large number of tourists, the recreational value of which ranges from 1.97 to 8.17 billion CNY (1 USD=6.93 CNY as of August 2020) (Shijin et al., 2020).

Cultural and spiritual services of the cryosphere also attract hundreds of thousands of tourists to the region every year (Hong-Min et al. 2021; Mukherji et al. 2019; Nepal & Chipeniuk 2005). There is an abundance of sacred sites for different religious groups, among them, Hindus, Jains, Sikhs, and Bons, who travel across the HKH to visit them (Pathak, 2016; Piasecki, 2019). Culture and spirituality are important determiners of the satisfaction levels of the tourists visiting the Himalaya (Bagri & Kala, 2015). In the Indian Himalaya of Garhwal, the spiritual *char dham yatra* circuit received around 2.2 million tourists in 2017 alone (Nath, 2018). Cultural and spiritual tourism centred on people, places, and events can be marketed as niche high-mountain tourism products in the international tourism market and would contribute significantly to economic and social development goals (Haq & Medhekar, 2020). Along with cultural and

spiritual tourism, adventure tourism (winter sports, mountaineering, and trekking) is a major attraction related to the cryosphere (MoCTCA, 2020; Shijin et al., 2020; Zhang et al., 2022).

Cryospheric change has both positive and negative impacts on the tourism industry. From a positive angle, cryospheric change has improved access to formerly inaccessible areas due to the melting of glaciers generating ice-free routes (Lama, 2010; Palomo, 2017). Access is also a major concern in the transit destinations leading to high mountain areas (Apollo, 2017). In Qinghai Tibetan Plateau, increase in the annual cumulative number of thermally favourable days has had a positive impact on tourism (L. E. Wang et al., 2017). Tourist arrivals are likely to increase in colder areas as they become warmer (Bigano et al., 2008; Ramasamy & Swamy, 2012) while a lengthened summer season has the potential to expand domestic and international tourism markets, thereby increasing tourist receipts (D. Scott et al., 2004). However, these positive impacts are likely to be short-lived, while the negative impacts will likely be long-lasting. The loss of glaciers and snow cover on the mountains not only spoil their aesthetically pleasing appearance (Becken et al., 2013; Mukherji et al., 2019) but also affect the cultural and belief systems of the local inhabitants and decreases the number of tourists, resulting in low employment and revenue generation for locals from the tourism sector (Shi-Jin & Lan-Yue, 2019). Moreover, warmer temperatures may restrict access to various high passes due to the thinning of the glacier surface, and the development of surface ponds and glacial lakes (Apollo, 2017; Watson & King, 2018). In Ladakh, the freezing of the Zaskar River creates a route that is popularly known as the Chadar trek, which is used by both locals and tourists. This route is now experiencing early melting and a shorter frozen period, hampering, thereby, access (Apollo, 2017; Raina & Koul, 2011; Shaheen et al., 2013).

Tourism is also affected by the fragile nature of mountain geography which makes it highly unstable and prone to numerous disaster events such as avalanches and snowstorms, landslides, and glacial lake outburst floods that endanger the lives of both locals and tourists as well as infrastructure. Cryosphere-related disasters claimed the lives of 372 mountaineers, guides, and locals between 1922 and 2020 in Nepal (Schweizer et al., 2003; Thakuri et

al., 2020). Similarly, the 2013 mega-flood event, also referred to as the Himalayan Tsunami, in Kedarnath, one of the four most holy places in India for Hindus, caused a loss of over 4,000 human lives and affected about 1 million people, while damaging roads and other infrastructure (Bhambri et al., 2016). Such devastating disaster events adversely affect the number of tourist arrivals (NITI Aayog, 2018) as safety is of paramount importance to tourists (Šimková 2014; Hock et al., 2019).

Changes in temperature also influence mountain tourism by affecting water availability for tourists' use. In the Khumbu region of Nepal, cryospheric change has resulted in a decrease in stream flow, affecting water availability and impacting local ability to meet the demands for amenities of a growing number of tourists (Lama, 2010; McDowell et al., 2013). The rapid increase in the number of tourists in the high mountains has created competition for water between the traditional uses of water for water mill operations and new uses of water to host tourist operations (Aubriot et al., 2019). Similarly, in the Indus Basin, the changing cryosphere (loss of glacier mass and area) and resultant water scarcity are expected to carry implications for socioeconomic development, including tourism (Kulkarni et al., 2021; Romshoo et al., 2015).

5.3.2. Impacts on water security and their implications: Local to transboundary

IMPACTS AT LOCAL SCALE

The high mountain settlements are dependent upon water sources like springs, lakes, and streams fed by glaciers and/or snow meltwater for drinking and domestic use (Mukherji et al., 2019; Nüsser et al., 2019b; Parveen et al., 2015; C. Scott et al., 2019). They have been harnessing drinking water through local and traditional methods such as canals and pipes, or a complex array of channels from the source (Gagné, 2016; Lal & Verma, 2008; J. Müller et al., 2020; Prasad & Sharma, 2019; Rawat & Sah, 2009; Tuladhar et al., 2021).

The meltwater from glacier, snow, and permafrost contributes significantly to rivers in the region (Kaser et al., 2010; Prakash & Molden, 2020), which gradually reduces with decrease in elevation and increase in

distance from the cryosphere (Siderius et al., 2013). High mountain communities are not the only ones dependent on snow and glacier meltwater. The water security of densely populated urban areas in the downstream are also dependent on this water, which is utilised for domestic and commercial purposes (R. Kumar & Sharma, 2019; Rasul & Molden, 2019). For instance, the Melamchi River in Nepal, fed by snow and glacier melt, provides 170 million litres of water for residents of the Kathmandu valley. Not only does it offer water security but it also prevents excessive groundwater extraction (Khadka & Khanal, 2008; Chinnasamy & Shrestha, 2019). The water supply systems in cities such as Haridwar, Varanasi, Patna, Delhi, and Islamabad are also partially dependent on meltwater (Rasul & Molden, 2019).

Although the warming climate is associated with an increase in meltwater that flows into downstream rural and urban settlements, these settlements are also facing scarcity in drinking water, mostly due to the decline in the available water supply sources such as springs, traditional spouts, etc. This is compounded by the rapidly growing demand for water, poor water management, and inadequate infrastructure in the region (Ranjan & Pandey, 2019; A. Sharma et al., 2020; Synder, 2014), particularly in the urban areas (Mondal & Roychowdhury, 2019; J. Müller et al., 2020; Ranjan & Pandey, 2019; Synder, 2014). Both the growth in population and economic activities such as tourism are aggravating water scarcity (Narain & Singh, 2019). For instance, in the Everest region, pressure on water is generated not only by domestic and agricultural use but also by the demand for water for electricity generation (Faulon & Sacareau, 2020). Water scarcity increases the workload of women and, consequently, the health risks as women are mostly responsible for fetching water from distant water sources for their families (Khanduri & Rawat, 2003; Prakash & Molden, 2020; Prasad & Sharma, 2019; Resurrección et al., 2019; Sidh & Basu, 2011).

The water quality of glacier and snow meltwater are usually within the safe limits for drinking (Nicholson et al., 2016; R. C. Sharma & Kumar, 2017). However, the rapid melting of glaciers and permafrost is releasing stored pollutants and pathogens into the river systems fed by meltwater (Kang et al., 2019; Yarzabal et al., 2021), which poses serious health risks for humans. Mercury and organic pollutants

have already been detected in meltwater of the Bhagirathi and Alaknanda river basins and the Tibetan Plateau (Mu et al., 2020; B. M. S. Sharma et al., 2015; Sun et al., 2017).

IMPACTS AT TRANSBOUNDARY SCALE

The challenges posed by change in the water supply can have repercussions at the transboundary basin scale. The term transboundary is understood as an area that extends across the international political borders of two or more countries (Albrecht et al., 2017; Lorenz et al., 2001). As the rivers flow from upstream to downstream across different spatial scales, they create hydrosocial territories of people, institutions, and biophysical environments revolving around the control of water (Boelens et al., 2016; A. Pandey et al., 2020). In the HKH region, water resources and services are shared by eight countries. The water originating in the HKH is a lifeline for the economies of the region, which have been adversely impacted by cryospheric change. While the Tarim is largely an endorheic basin in China, other basins such as the Indus, Ganges, Brahmaputra, Amu Darya, and Syr Darya are all transboundary in nature.

Globally, it is understood that the river discharge in many basins will be impacted by future glacier mass loss under climate change, especially when glacier meltwater reaches a peak (Huss & Hock, 2018). In the meantime, the increasing demand for freshwater for rapidly growing economies and the rising dependence of the downstream on mountain water (A. Pandey et al., 2020; Viviroli et al., 2020) will lead to more imbalance between supply and demand. Often, the most vulnerable are those residing in transboundary basins such as the Indus Basin where there is dense population and large irrigation areas (Immerzeel et al., 2020). The rising imbalance between demand and supply leads to scarcity of freshwater while competition for the limited freshwater often leads to disputes (De Stefano et al., 2010) increasing, thereby, hydro-political tensions among countries of the transboundary river basins (Bernauer et al., 2012; Dinar et al., 2015; Vorosmarty et al., 2000).

Freshwater is now often considered as a strategic resource, for which countries in transboundary basins would be willing more and more to extend their special protection and to compete for at international fora, even resorting to armed confrontation (Baghel

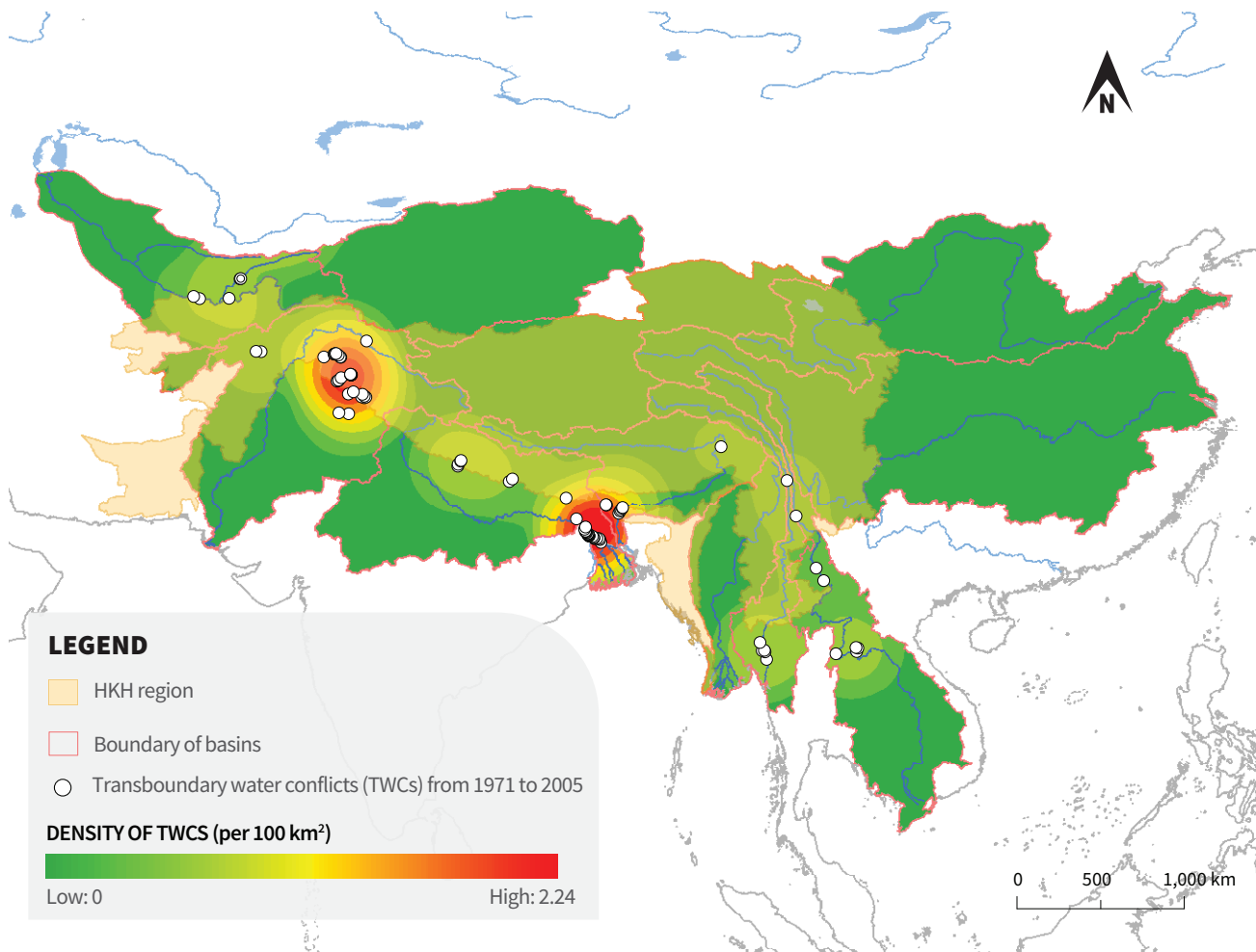
& Nüsser, 2015; Toset et al., 2000). Coupled with the lack of effective transboundary cooperation between upstream and downstream countries, these disputes could soon escalate into transboundary water conflicts (TWCs) (Brochmann & Gleditsch, 2012). In fact, there has been a rising risk of global TWCs in the latter part of the 20th century after World War II (De Stefano et al., 2010; Yoffe et al., 2003) with water crises ranked as one of the highest risks to world peace during the next decade (World Economic Forum, 2019).

A similar trend is observable in the HKH, especially in the Indus and Ganges-Brahmaputra basins where disputes over water have occurred during the 1971–2005 period as illustrated in Figure 5.5, based on the number of water conflicts recorded in the International Water Event Database in the

Transboundary Freshwater Dispute Database (TFDD). According to the records, the disputes at Baglihar Dam, Wullar Barrage, and Kishan Ganga Dam of the Indus Basin located in Jammu-Kashmir all revolved around the issue of sharing river water. Similarly, in the Ganges-Brahmaputra basins, there have been frequent disputes over water between India and Bangladesh.

The causes of TWCs are complicated involving political, social, and economic factors, but one of the fundamental triggers is the increasing imbalance between freshwater supply and demand, or water stress, as defined by the ratio between water demand and supply in transboundary basins.

FIGURE 5.5 HOTSPOTS OF TRANSBOUNDARY WATER CONFLICTS IN THE HKH FROM 1971 TO 2005



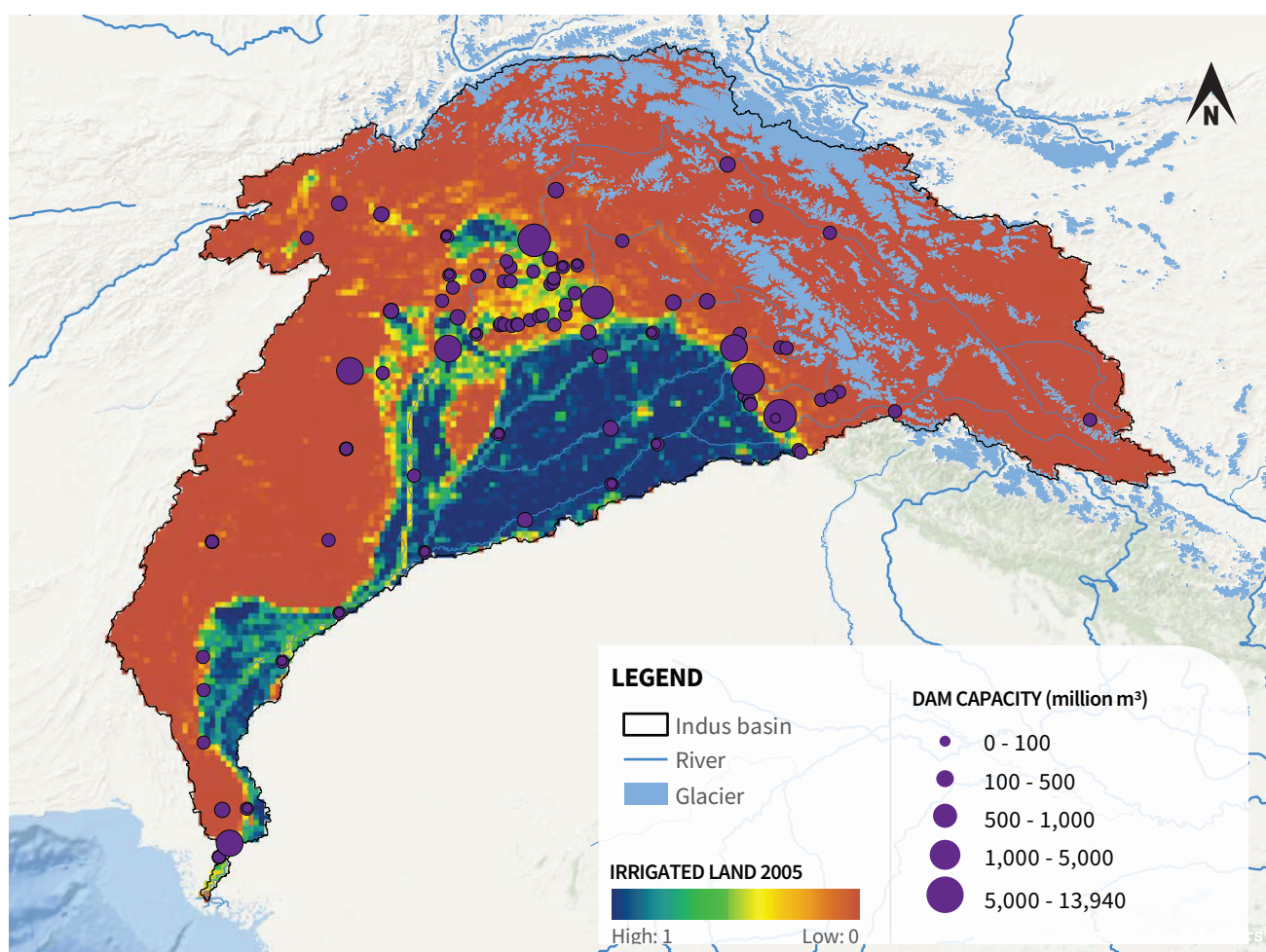
Data source: Transboundary Freshwater Dispute Database (n.d.)

Considering the reliance on the freshwater of the Indus Basin for irrigation in both India and Pakistan, (Figure 5.6), the importance of regional collaboration for sharing freshwater resources becomes paramount. The Indus Water Treaty, which was signed by India and Pakistan in 1960, is considered as one of successful cooperation to avoid severe conflicts between nations. According to the treaty, India has rights over the three eastern rivers, namely, Satluj, Beas and Ravi while Pakistan has control over the western rivers, Chenab, Jhelum, and Indus.

The Indus Basin Irrigation System (IBIS) is the largest contiguous irrigation system in the world, irrigating over 2.5 million acres and running over 90,000 km of watercourses (Muhammad et al., 2016). The irrigated land fraction for 2005 was extracted from ESACCI-LC dataset (Lamarche et al., 2017) based on the linear

resample method as shown in Figure 5.6. It shows that about 77% of crop land was irrigated while the rest was rainfed. According to Simons et al. (2020), 76% of the annual average evapotranspiration for crop land in the Pakistani part of the IBIS was replenished by irrigation. The mountain water from the upstream high-mountain areas of the HKH is the main water source for irrigation (Biemans et al., 2019; Immerzeel et al., 2010; 2020; see also section 5.3.1.1). Notably, the Indus Basin shows high dependence on mountain water, not only due to the significant run-off contribution from mountain water but also due to the insufficient water supply in the lowland for the growing population (Viviroli et al., 2020). It has also been reported that the immense irrigation system leads to unsustainable use of local blue water resources because of heavy reliance on the mountain water surplus.

FIGURE 5.6 IRRIGATION AREA AS PERCENTAGE OF THE TOTAL AREA IN THE INDUS BASIN



Data source: ESA (2017)

When irrigation relies heavily on mountain water in transboundary basins, the importance of geo-collaboration to share the freshwater resources among the countries in the basins cannot be overemphasised. This is particularly true in the case of the Indus Basin. The issue is further compounded by ground water depletion, which comes to about 300 mm per year in the north-eastern Indus (Wijngaard et al., 2018). It is projected that both renewable and non-renewable groundwater abstraction would increase in the future (Lutz et al., 2022). Notably, the decline in the groundwater table could possibly be exacerbated by the transboundary impacts of extensive groundwater pumping on the Indo-Pakistan border (Cheema et al., 2014; Iqbal et al., 2017; Simons et al., 2020). In Pakistan, nearly half of the labour force is engaged in agriculture and one-fifth of the GDP is generated from agricultural production (Kreutzmann, 2011). Hence, the stakes involved in obtaining enough freshwater are high. It is even more critical when its cascading impacts, not only on the economy but also on poverty eradication, food security, and other aspects associated with sustainable development goals, are considered.

5.3.3. Impacts on cultural heritage

The physical changes in the cryosphere due to CrIDs and their impacts are described in the previous chapters. But the cryosphere is also inextricably linked with human societies as it provides material and non-material services towards societal well-being (Mukherji et al., 2019; Su et al., 2019) and, hence, cryospheric change also impacts these services. While the material services, especially the impacts on human lives, livelihoods, housing, and other infrastructure have received much attention, the impacts on non-material services such as culture and spirituality are not well understood and are hardly incorporated into the global knowledge generation process (Chakraborty & Sherpa, 2021). This is a significant lacuna in knowledge production as climate change also influences the cultural landscape and affects ethno-climatic rituals and the religious and symbolic relationships that societies form with the mountains around them (Allison, 2015; Becken et al., 2013; Brautigam, 2011). In Mustang Nepal, for instance, women especially have been found to be confused by the observed weaker

correlations between religious rituals and climatic conditions and made anxious by the perceived indifference of the weather gods to their prayers (Becken et al., 2013).

The HKH, with its abundance of water and ice, and richness in flora and fauna have shaped human civilisation for millions of years (Tan, 2015), and the mountain systems have played a significant role in it (Zurick, 2014; Allison, 2015b). In all these cultures, snow- and glacier-covered mountains, for instance, have carried powerful mystical and symbolic meanings, attracting spiritual visitors on auspicious occasions from ancient times (Allison, 2015; S. Singh, 2004). The cryosphere components are seen as the sacred abode of deities and spirits protecting the local socio-ecological systems (Ikeda et al., 2016; Mukherji et al., 2019). For instance, *Lü* (the underwater spirits) of the Khumbu Valley (Bjønness, 1986; Spoon & Sherpa, 2008) and *Klu* in Ladakh (Gagné, 2019) protect the water bodies (lakes and rivers) while Mt. Langtang-Lirung in the Langtang Valley is the local protector deity (Pasakhala et al., 2022). In Bhutan, only religious monuments are allowed to be built in places believed to be the abode of the local deities while other land use and commercial or residential constructions are prohibited in those locations (Allison, 2015). These spiritual beliefs and the tendency to regard the cryosphere and mountains as sacred have directed the mountain societies towards the protection of geology, geography, and the natural environment, including flora and fauna (Ghimire et al., 2020). Moreover, spiritual practices in the high Himalaya have had positive impacts on people's mental, emotional, and social well-being (Arya et al., 2017). Generations of local inhabitants as well as artists and poets from elsewhere have regarded various elements of the cryospheric system as symbols of vibrant life and as sources of creative inspiration.

But the exposure of rocks due to the decrease in snow and glaciers has caused a darkening of the peaks, which locals perceive as a loss of honour and pride (Orlove, 2009; Diemberger et al., 2015). At the same time, the cryospheric disasters also threaten aspects of the tangible cultural heritage such as monasteries and temples (Bhambri et al., 2016). The recurring GLOFs in the Limi valley in northwestern Nepal threaten the eleventh-century Rinchenling Monastery (Kropacek et al., 2015). Therefore,

the impact of cryosphere degradation on human well-being extends to the aesthetic, inspirational, religious, and spiritual as well as the educational, recreational, and cultural spheres (Su et al., 2019).

The discussion on the cultural impacts of cryospheric change in the HKH has also explored the question of morality and the ethics of care where the geophysical and cultural landscapes are perceived as an assemblage of people's intricate and interdependent relations with animals, plants, and lands (Butcher, 2017; Gagné, 2019 & 2020). It is widely believed in mountain societies that when people disregard the sanctity and sacredness of these natural bodies believed to be protected by the deities and spirits (e.g., glaciers, summits, lakes, and forests) and pollute them, these entities would, in return, avenge and punish those committing the infractions (Butcher, 2013; Gagné, 2019; Sherry & Curtis, 2017; Spoon & Sherpa, 2008). This moral and ethical viewpoint also recognises the value of tending to and caring for the non-human members as well as the other dharma in one's life and livelihood, which includes farming, herding, conservation, and avoidance of pollution. The observed cryospheric changes have been framed and interpreted by many societies as the consequence of diminished morality and ethics, mainly the result of irresponsible human actions against nature and the loss of the values of reciprocity and morality (Gagné et al., 2014; Pasakhala et al., 2022). Although the connections between the two may seem abstract or even superstitious, especially to outsiders, these moral and ethical perspectives guide local interpretations and influence perceptions and responses – to either adjust or shift adaptive measures, for example – of communities living in the glacierised region (Spoon & Sherpa, 2008).

5.3.4. Cryosphere-related disasters and society's perception of risks

CRYOSPHERE-RELATED DISASTERS

Cryospheric hazards such as glacial lake outburst floods, heavy snowfall, avalanches, rockfalls, and blizzards are common phenomena in the HKH (Vaidya et al., 2019; also see Chapter 3, Figure 5.3, for

an overview of water-induced hazards in the HKH region since 2015). The growing population and infrastructure development in the mountainous area have increased the exposure of communities to cryospheric hazards. These developments are also likely to increase the magnitude of cryosphere-related disasters (Hewitt & Liu, 2013; Hewitt & Mehta, 2012; Vaidya et al., 2019). For decades, glacial lake outburst flooding (GLOF) received much of the attention as the ever-increasing size of glacial and supra-glacial lakes in the region have caught the attention of scientists and policy makers (Carrivick & Tweed, 2016; Hewitt & Liu, 2013). But there are other smaller and relatively unknown glacier-related floods that have not received as much attention. Only in recent years have some of these been documented (A. C. Byers et al., 2018; 2022; Veh et al., 2018). But if the recent episodes of devastating flood disasters such as the Chamoli and Kedarnath floods of India (Bhambri et al., 2016; Shugar et al., 2021), Melamchi, Seti, and Bhotekoshi River floods of Nepal (A. C. Byers et al., 2022; Cook et al., 2018), and the recent floods in Pakistan (Waqas, 2022) are any indication, cryospheric hazards in the region have grown more complex and devastating. The risks posed by the cryosphere-related disasters are becoming more unpredictable, costly, and deadly as the cryospheric elements (namely, snow melt, glacial lake outburst floods, and avalanches) are increasingly interlinked with and often compounded by other environmental extremes (namely, landslides, rockfalls, seismic activity, and heavy rains), often creating cascading hazards (A. C. Byers et al., 2017; Kirschbaum et al., 2019) and catastrophic disasters (see Chapter 3, section 3.2.1). In this section, we examine how changes in the HKH cryosphere have increased disaster risk in the region.

As shown in the chapter on high mountain areas in a recent IPCC special report (Hock et al., 2019), cryosphere-related disasters are projected to increase in the future requiring additional expenditure on risk-reduction measures, along with expenditure on the protection of infrastructure and possible relocation of communities to safer places. The societal costs of these cryospheric disaster risks are enormous as the exposure of people and

infrastructure to cryospheric hazards and risks has also increased due to population growth, tourism, and socioeconomic development (Hock et al., 2019). Tourism, infrastructure (e.g., roads and hydropower plants), and other human activities have intensified in the high mountains, causing more disturbances to the already fragile mountain slopes, and increasing cryospheric disaster risks. All these in turn have increased the vulnerability of mountain people as well as their infrastructure.

The HKH region has experienced several GLOFs and other significant cryospheric hazards and risks, with long-term implications for the regional economy (Rasul et al., 2020; Richardson & Reynolds, 2000). Some of the major episodes are presented here to emphasise the intricate intersection between cryospheric change and associated disaster risks and their social implications. For instance, the Zhangzangbo GLOF in Tibet, China, killed 200 people and incurred an estimated economic loss of USD 456 million in 1981. It caused severe damage to the Nepal–China Highway, which cost USD 3 million to rebuild (Mool et al., 2001). Similarly, the Dig Tsho GLOF in the Khumbu Himal of Nepal damaged a hydropower plant and other properties in 1985, the estimated economic loss of which was USD 500 million (A. B. Shrestha et al., 2010). The GLOF risk in the Imja Tsho alone has been estimated to be over USD 11 billion as a major GLOF from this lake could significantly affect the tourism industry – the main source of revenue – as well as potentially damage roads, highways, several bridges, and three major hydropower stations, in addition to causing damage to dozens of settlements in flood zones (Bajracharya et al., 2007). Due to several GLOFs and the disruptions to irrigation canals, the entire village of Passu and the communities of Northern Borith and Ghulkin in northern Pakistan were forced to migrate to higher ground (Ashraf et al., 2012; Parveen et al., 2015). There have been other such forced relocations of populations due to GLOF hazards in several areas such as Uttarakhand, India (Jha & Khare, 2016; Maikhuri et al., 2017) and the Nagchu Prefecture in China (Diemberger et al., 2015).

Avalanches are another source of fatal hazards in the HKH. Snow and ice avalanches that occur at higher elevations can cause considerable loss of life as well as damage to property and infrastructure. Among such documented disasters are the following: the snow avalanches that caused 65 casualties in the Nepal

Himalaya during the period of 2011–2019 (Thakuri et al., 2020), the two co-seismic avalanches which killed nearly 400 people after the Gorkha Earthquake in 2015 (Kargel et al., 2016), the rock and ice avalanche that killed more than 200 in Chamoli (Uttarakhand, India) in 2021 (Shugar et al., 2021), and the glacier detachment on the Tibetan Plateau that killed 9 people in 2016 (Kääb et al., 2018). A major avalanche from Mt Pumori into the Everest Basecamp, which was triggered by the Gorkha Earthquake in 2015, virtually closed the climbing season, bringing the local tourism industry to a virtual standstill (Moore et al., 2020; Thakuri et al., 2020).

SOCIETY'S RISK PERCEPTION

The above-mentioned disasters are only a few of the major disaster impacts recorded in the HKH region but they represent a much broader trend discernible in the region in recent decades and years. There is one area of the discourse on disasters that is relatively understudied in studies on the intersection between cryospheric hazards and society. It is societal perceptions and responses to hazards and risks. For people and communities experiencing cryospheric change, their decisions regarding risks can be influenced by their perceptions of the sources of risk. While scientific studies have helped tremendously to reduce objective uncertainty (e.g., mass balance, rate of glacier recession, and trigger factors of glacial lake outburst floods), more complicated (and less understood) are the ways people tend to view and calculate their exposure, and ability to adapt, to cryospheric hazards and risks (A. C. Byers et al., 2014; S. F. Sherpa et al., 2019). Among the key barriers and constraints in the way of the decision-making process are the structural biases (e.g., confirmation biases, cognitive dissonance) that people tend to live with in their lives, which either prompt them to overestimate or underestimate the risk they face. These would, in turn, depend on the socioeconomic, cultural, and political contexts of the people under reference (Slovic & Peters, 2006). For example, earthquakes and glacial lake outburst floods are often perceived to be more dangerous than landslides and droughts which occur more frequently and may not be perceived as catastrophic as the former even though the latter may cause more damage (S. F. Sherpa et al., 2019). In Khumbu, people's perceptions of cryospheric hazards were found to be influenced by livelihood

sources, age, prior experiences of hazardous events, and geography (S. F. Sherpa et al., 2019). As this was the same area where a major GLOF event from the Dig Tsho occurred in 1985, which destroyed a newly built small hydropower station, farming land, and trails along the Dudh Koshi River Basin (Vuichard & Zimmermann, 1987), there has been a heightened sense of urgency, of late, among both scientists and the residents regarding the rapid expansion of the nearby Imja Tsho (A. C. Byers et al., 2017; Somos-Valenzuela et al., 2014).

Similar studies focusing on the Tsho Rolpa have also highlighted how people's perceptions of GLOF risks are shaped by socioeconomic, cultural/religious, and political factors that are not adequately articulated by outsiders such as government agents and researchers. The adverse implications of this disconnect are evident in the level of participation of the locals in the disaster risk mitigation measures in the Tsho Rolpa

(Dahal & Hagelman, 2011; Sherry & Curtis, 2017), which is similar in nature to other such instances elsewhere in the region (S. P. Singh & Thadani, 2015). They also show that peoples' risk perceptions – whether underestimation or overestimation of the potential hazard and disaster risk – play a significant role in identifying and prioritising adaptation measures to address cryospheric change and associated risks (Thompson et al., 2020). All in all, this only underscores the need to move beyond the tendency to frame cryospheric changes and their risks as something to be solved by experts and expert (engineering) solutions and to develop an integrated and interdisciplinary understanding of and approach to disaster risks and hazards in which people's perceptions and complex local realities are given their due place, and complemented with scientific monitoring and assessments (Carey et al., 2021; S. P. Singh & Thadani 2015).

5.4. Adaptation measures: Successes and limits

The nexus of significant climate-related changes in the cryosphere and prevalent socioeconomic difficulties are leading to appreciable negative impacts for people living across the HKH (Adler et al., 2022; Carey et al., 2017; McDowell et al., 2013; A. Mishra et al., 2019).

These challenges, however, are not decisive in shaping the fate of mountain communities as mountain people are displaying agency in adapting to the changes in diverse ways across the HKH. In fact, more adaptation actions have been recorded in the HKH than in any other mountain region globally (McDowell et al., 2014, 2019, & 2021a).

In this section, we examine the characteristics of the responses of mountain communities to the combined CrID and nCID impacts across four dimensions. The results presented here are based on the analysis of recent adaptation-focused systematic reviews that include the HKH region (McDowell et al., 2019 &

2021a; Rasul et al., 2020) as well as literature reviews by the chapter authors. Here, adaptations reported in the literature are used as a proxy to assess the adaptation actions in the region. However, because many adaptations go undocumented, the results below likely underrepresent the actual extent of adaptations taking place across the HKH region.

5.4.1. Adaptation to maintain livelihoods

AGRICULTURE

Most adaptation measures in the agricultural sector are being carried out at the household level by local communities (Table 5.2). Most of these responses are autonomous, in that they are carried out without a formal adaptation plan or specific adaptation support. Formal policies or programmes are rare in the region. Instead, behavioural, and technological responses are

the most common adaptation measures in response to growing water scarcity due to the decline in snowfall and the receding of glaciers.

Responding to increasing uncertainty of snowfall, farmers have changed their crop sowing seasons and planted drought-resistant crops such as buckwheat (Chaudhary et al., 2011; Hussain et al., 2016; Onta & Resurrección, 2011). Crop failures due to delayed snowfall or snow drought have led farmers to organise themselves and advocate for compensation and support against crop failures, as seen in the case of the Apple Growers' Association in Himachal Pradesh (Vedwan, 2006). In a few areas, increased water availability due to increasing temperature and snowmelt have favoured the growth of vegetables as well as other new crops (Ingty, 2017; Macchi et al., 2014; Maikhuri et al., 2017; Manandhar et al., 2011; Negi et al., 2017; Nüsser and Schmidt, 2017; Nüsser et al., 2019a).

LIVESTOCK

Adaptations in the pastoralism sector follow a similar pattern as in agriculture, with most actions being carried out at the household level or community scale, with behavioural and technological responses being the most common (Table 5.3). However, in this sector, a modest number of responses is institutional in form.

Behavioural adaptations were observed amongst pastoral communities, who have changed their grazing locations and timing of animal movement to cope with snowfall uncertainty (Fu et al., 2012; Gentle & Thwaites, 2016; Rayamajhi & Manandhar, 2020). Fodder plantation, seeding of pastures, and purchasing of livestock feed are some of the measures adopted to improve food availability for livestock (Suberi et al., 2018; Wang et al., 2014; Wu et al., 2015). In response to impacts of cryospheric change on water and food shortages as well as other drivers of

Form	Scale	Measures
Behavioural	Household	Planting new crops at higher elevations (Macchi et al., 2014); Planting less water-consumptive crops (Kelkar et al., 2008); Shifting to alternative livelihood options (Tuladhar et al., 2021)
	Single community	Agricultural diversification (Ingty, 2017)
	Multiple communities	Changes in the sowing season (Hussain et al., 2016)
Technological	Household	Replacement of traditional cultivars with high yielding ones (Maikhuri et al., 2017)
	Single community	Shifting from traditional crops to vegetables (Negi et al., 2017)
Institutional	Single community	Formation of the Apple Growers' Association to advocate for compensation and support against crop failure (Vedwan, 2006)

Form	Scale	Measures
Behavioural	Household	Reduction in the number of animals (Hussain et al., 2016)
	Single community	Changes in the timing of animal movement (Fu et al., 2012; Gentle and Thwaites, 2016; Rayamajhi and Manandhar, 2020)
	Multiple communities	Replacing large-sized animals with small ones (Macchi et al., 2014)
Technological	Household	Purchase of livestock feed (Suberi et al., 2018); Plantations of fodder species (Suberi et al., 2018)
	Multiple communities	Reseeding of pastures (Wu et al., 2015)
Institutional	Single community	Pooling of resources and labour (Fu et al., 2012; Y. Wang et al., 2014)
	Multiple communities	Formation of herders' committees to regulate grazing (Joshi et al., 2013)
Infrastructural	Single community	Construction of sheds for the animals (Hussain et al., 2016)
	Multiple communities	Construction of sheds and fencing (Wu et al., 2015)

change, communities have reduced the number of animals they own (Hussain et al., 2016; Y. Wang et al., 2014) while some have abandoned livestock keeping altogether and shifted to other livelihood options (Negi et al., 2017; Tuladhar et al., 2021).

For ecological restoration of the rangelands affected by permafrost degradation, the provincial government of the Qinghai-Tibet Plateau has implemented ‘Returning to grasslands from grazing’ and ‘Ecological protection in the Three Rivers’ sources’ (Huijun et al., 2009). Communities have also built sheds and fences to protect their animals against snowstorms (Hussain et al., 2016; Y. Wang et al., 2014; Wu et al., 2015).

TOURISM

Responding to the impacts of change to traditional livelihoods such as agriculture and pastoralism, as well as new income generation opportunities, many mountain communities have been gradually diversifying their activities to include tourism (Ingty, 2017; Tuladhar et al., 2021). However, the tourism sector is threatened by cryospheric change, complicating the livelihood diversification efforts for mountain societies. A few adaptive measures have been taken to safeguard against cryospheric risks albeit mostly by the private sector (Table 5.4).

In the case of the Yulong Snow Mountain in southwestern China, the government and the private sector have jointly developed and implemented an environmental protection plan, which includes restricting the number of tourists visiting the area, along with financial incentives to tourism entrepreneurs, to avoid damage to Baishui Glacier No. 1 (S. Wang et al., 2010). In Langtang Nepal, the local communities and the private sector have come together to promote ‘disaster tourism’ to support the recovery of the village devastated by the earthquake-triggered avalanche (Kunwar et al., 2019). Installation of hazard signposts and construction of shelters for tourists along the trekking routes, weather forecasting, and early warning communication are among the major measures undertaken to reduce risks in Nepal (Ziegler et al., 2021). Countries in the region have also introduced regulatory measures and guidelines to control the number of visitors, limit the tourist season, implement rescue operations, and introduce other disaster risk preparedness measures (Burtscher, 2012).

MEDICINAL AND AROMATIC PLANTS

There is limited documentation about the adaptation measures adopted with regard to the collection of MAPs (Table 5.5). Delayed collection of MAPs,

Form	Scale	Measures
Infrastructure	Single region	Construction of shelters (Ziegler et al., 2021)
Technological	Single region	Use of environment-friendly vehicles (S. Wang et al., 2010)
Financial	Single region	Diversification of tourism products and use of financial measures to restrict the number of tourists (S. Wang et al., 2010)
Regulatory	Single community	Implementing environmental protection rules and guidelines for controlling the number of visitors (Burtscher, 2012; Ingty, 2017)
	Single region	Implementing environmental protection rules (S. Wang et al. 2010)
Informational	Single region	Establishing a glacier museum and educating tourists about the need for glacier protection (S. Wang et al., 2010); Installation of signposts (Ziegler et al., 2021)

Form	Scale	Measures
Behavioural	Single community	Changes in the timing of collections (A. C. Byers et al., 2020) Conservation of MAPs (Koul et al., 2005)
Technological	Multiple communities	Propagation of MAPs (Koul et al., 2005; Rokaya et al., 2017)

particularly caterpillar fungus, has been reported in response to delayed snowfall (A. C. Byers et al., 2020). There have also been efforts to conserve and propagate high-altitude MAPs such as *Hedychium spicatum*, the habitats of which have been destroyed as a result of climatic and anthropogenic factors (Koul et al., 2005).

5.4.2. Adaptation to ensure water security

Adaptation efforts in the water sector are more widespread as well as more diverse than in the other sectors (Table 5.6). For example, while community members are still the most active in leading adaptations, local, regional, and national government-affiliated entities as well as non-governmental organisations are also active in leading adaptations in irrigation and water supply. In a similar vein, while autonomous responses are more numerous, formal policies and adaptation plans are also more commonly observed here than in the other sectors.

Technical measures were commonly adopted to maintain water availability for irrigation and water supply. For irrigation, innovative water infrastructure

such as artificial glaciers, ice stupas, and snow barrier bands have been devised through a collaborative approach between engineers and local communities (Clouse, 2016; Nüsser et al., 2019a). Such innovative approaches were also in evidence many decades ago, as recalled by the elders in Ladakh, India, when ice cultivation was practiced by spreading charcoal over the glacier to decrease the melting process (Gagné, 2016). Rainwater harvesting and installation of water tanks are other common measures adopted at the household and village levels (McDowell et al., 2013; Nüsser and Schmidt, 2017; Spies, 2016).

5.4.3. Adaptation to impacts on cultural heritage

The literature on cultural adaptations to cryospheric change in the HKH region is limited. Some efforts have been made to preserve structures constituting tangible cultural heritage, such as monasteries, against the impacts of cryospheric disasters (Table 5.7). For example, in the Limi valley, gabion walls have been constructed along the riverbank to protect the Rinchenling Monastery. Similarly, in the state of Uttarakhand in India, after the devastating floods

TABLE 5.6 ADAPTATION IN WATER SUPPLY

Form	Scale	Measures
Behavioural	Household	Water rationing, fetching water from distance sources, and hiring assistants to collect water (McDowell et al., 2013)
Technological	Household	Installing rooftop water collection systems (McDowell et al., 2013), and installing water efficient irrigation systems (Kelkar et al., 2008)
	Single community	Constructing ice stupas, snow barrier bands, and artificial glaciers for irrigation and water conservation purposes (Clouse, 2016)
Institutional	Single community	Adjusting and regulating irrigation timing (Clouse, 2016; Kelkar et al., 2008)
Informational	Single community	Community outreach activities to design artificial glaciers (Clouse, 2016; Nüsser et al., 2018)
Infrastructure	Household	Installing water storage tanks (Kelkar et al., 2008; McDowell et al., 2013)
	Multiple communities	Constructing, repairing, and rehabilitating irrigation canals (Parveen et al., 2015; Spies, 2016)

TABLE 5.7 ADAPTATION TO IMPACTS ON CULTURAL HERITAGE

Form	Scale	Measures
Technological	Single community	Construction of gabion walls (Kropacek et al., 2015)

of 2013, the government constructed double flood retaining walls to minimise the impacts of future flooding on culturally important infrastructure to protect the cultural heritage (Bharaj, 2018).

5.4.4. Adaptation to cryosphere-related disaster risks

Adaptations to cryosphere-related disaster risks aim to (1) prevent hazard occurrence, (2) reduce exposure, and (3) minimise vulnerability (Table 5.8). A wide range of stakeholders have been engaged in designing and implementing adaptation measures to address and minimise cryosphere-related disaster risks. Similarly, various types of adaptation measures, ranging from behavioural, technological, and institutional to infrastructural changes, have also been adopted in the region. Among measures taken are collaborations between governmental, non-governmental, and community-based institutions to drain out water from the glacial lakes, install early warning systems, build gabions, and monitor glacier lakes to minimise cryosphere-related disaster risk (Cuellar & Mckinney, 2017; Meenawat & Sovacool, 2011; Orlove, 2009; Schimdt et al., 2020; Somos-Valenzuela et al., 2015). Hydrological models,

scenarios, and maps, too, have been developed to forecast cryosphere-related disaster risks such as GLOFs and debris flow (Maskey et al., 2020) in order to support better disaster risk preparedness. But many of these technological measures are confined to a few sites.

Considering the threat of disaster-related risks, some local communities have voluntarily abandoned their agricultural lands and settlements (Kreutzmann, 2011; Maikhuri et al., 2017); government agencies have provided support for resettlement at other safer sites. For example, this was the case with communities from Kumik village in Jammu and Kashmir, India (Grossman, 2015), and the Nagchu Prefecture in Tibet, China (Deimberger et al., 2015).

Cryosphere-related disasters are projected to increase in the future and will therefore require additional investments to secure the safety of mountain societies. For instance, the cost of digging a canal into the Tsho Rolpa glacier in Nepal to lower the glacial lake in 2002 was USD 3 million (Bajracharya, 2010). A similar disaster mitigation measure was implemented in 2016 in the Imja Tsho glacial lake, Nepal, which needed over USD 5 million (CFGORRP, 2017). And costs can be much greater when communities need to be relocated to safer locations.

TABLE 5.8 ADAPTATION TO CRYOSPHERE-RELATED DISASTER RISKS

Form	Scale	Measures
Behavioural	Single community	Relocation of settlements (Maikhuri et al., 2017)
Technological	Single region	Draining of water from the glacial lakes and installation of early warning systems (Meenawat & Sovacool, 2011)
Institutional	Single region	Formulation of disaster management plans and policies at sub-national and national levels (Kaul & Thornton, 2014; Meenawat & Sovacool, 2011; P. Y. Sherpa, 2015)
Infrastructure	Single community	Construction of gabion walls (Kropacek et al., 2015)

5.5. Adaptation to cryospheric change and links to sustainable development

The adaptation responses of communities to cryospheric change illustrated in section 5.4 are mostly reactive and autonomous – the use of available skills, resources, and opportunities to address experienced adverse conditions – and carried out at household/community scale. They are also primarily incremental, maintaining the essence of relevant systems or processes without driving fundamental changes in existing practices (A. Pandey, 2019; Adler et al., 2022). The autonomous nature of adaptations can be indicative of resilient mountain communities who are able to act without the need or desire for external support (Ingty, 2017; McDowell et al., 2014). However, such responses may arise from either the lack of, or lack of access to, relevant social safety nets (Gentle & Maraseni, 2012). Insofar as this is the case, there appears to be a significant gap between the adaptation needs of mountain communities and access to necessary adaptation support (McDowell et al., 2019).

Even when the adaptation actions are planned, they remain inadequate to address the negative consequences. For example, the increase in the number and extent of glacier lakes in the region (see Chapter 2, section 2.4) is endangering the lives and livelihoods of the populations living within the vicinity of the lakes and downstream when GLOFs occur (Bajracharya et al., 2020; Dimri et al., 2021). Early warning systems are often considered an important adaptation measure against GLOFs. Although such systems can save lives, both livelihoods as well as the ability to regenerate effective economic and sociocultural outcomes are still massively impacted, leading directly to an increase in poverty and hunger, which carry other broader social and economic implications. The lack of scope and depth in the adaptation response to address systematically the fundamental issues related to the exposure, sensitivity, and vulnerability of mountain societies to GLOFs poses a barrier to long-term sustainable development.

Adaptation deficit also persists for many high mountain livelihoods. For instance, the local communities dependent on medicinal products like

the caterpillar fungus, have witnessed decline in their harvest under warming climate conditions compounded by unsustainable harvesting (Hopping et al., 2018), but lack any adaptation measures. Deficits in adaptation are also evident in the responses to the decline in rearing of mountain-suited livestock like yak (Joshi et al., 2020) as well as agrobiodiversity (Rasul et al., 2022; Hussain & Qamar, 2020). Such instances constitute barriers to advancing sustainable development.

Furthermore, a high number of reactive responses is concerning in the context of trajectories of climate change and, especially, non-linear processes of change such as peak water (Huss & Hock, 2018; McDowell et al., 2021b). Such dynamics call attention to the need for anticipatory responses that are attentive to novel climate futures in mountain areas. In addition, formal evaluations of adaptation in the HKH region are very rare, making it difficult to determine how, where, under what conditions, and for whom/what adaptations are (or are not) effective and equitable. Consequently, this makes it difficult to determine the extent to which adaptations are contributing to the advancement of SMD. However, even without formal evaluation, there are several bright spots reported in the literature which are presented here.

While autonomous approaches to adaptations appear to be common, it should be stressed that there are at present a wide variety of adaptation support programmes that are of relevance to advancing adaptation efforts in mountain communities, including those of the United Nations, multi- and bi-lateral aid organisations, government programmes, NGOs, and the private sector (McDowell et al., 2021a). However, ensuring that HKH communities benefit from such resources depends on addressing the underlying socioeconomic and political conditions as well as marginalisation that make it difficult for mountain communities to identify, apply for, and secure adaptation support (McDowell et al., 2020). This also requires overcoming biases on the part of supporting institutions and agencies regarding mountain specificities that result in the under-allocation of state support and resources to highland areas compared to lowland regions (Debarbieux & Rudaz, 2015; Romeo et al., 2020). In addition, ensuring that mountain communities can utilise the available adaptation support requires understanding the ways in which specific globalised discourses relating to climate change may conflict with the material and symbolic

ways in which mountain communities understand climate-related changes (Gagné et al., 2014; Jurt et al., 2015; Mills-Novoa et al., 2017; McDowell et al., 2020). Here, bringing traditional and local knowledges into conversation with the approaches and findings of climate researchers and adaptation planners on equal grounds is crucial although this has proved to be very difficult in practice to date (Ericksen et al., 2021; Haag et al., 2021; Nightingale, 2017; Ojha et al., 2016).

Ultimately, adaptation aims to reduce risks by minimising exposure and vulnerability of societies when facing future changes (Y. Wang et al., 2019). Securing a desirable adaptation future across the HKH hinges on addressing soft limits to adaptation such as financial, institutional, governance, and policy constraints that impede sufficient adaptation action. For example, it will also be necessary to move towards deeply collaborative approaches to adaptation that are rooted in local needs, aspirations, and knowledges while being supported by external adaptation support (McDowell et al., 2020; Muccione et al., 2019).

In addition to addressing the limits, the success of adaptation measures also depends on depth, scope, and speed. Sustainable development would be able to build adaptive capacity (Munasinghe & Swart, 2005; R. P. Shrestha et al., 2019). It is therefore important to bring adaptation in line with sustainable development (Robinson & Herbert, 2001). Effective adaptation is key to meeting SDGs and to reducing the economic gap between mountain societies and those living in less marginalised geographies. In fact, as indicated above, there are three SDG targets that are explicitly related to the mountain region. However, a much broader development plan has to be implemented to address the social, economic, and environmental challenges in countries of the HKH region. Although each country has its own priorities in sustainable development, they share in common their desire to eradicate

poverty (SDG1) and hunger (SDG2), to improve public health and well-being (SDG3), to provide decent work and economic growth (SDG8), and to develop partnerships for the goals (SDG17). In addition, the HKH Assessment Report (Wester et al., 2019) has identified and linked the SDGs that are relevant to the HKH through nine mountain priorities (ICIMOD, 2020; Jodha, 2007).

Changes in the cryosphere also have important direct and indirect implications for meeting the SDG 2030 targets in the region (Table 5.9). Cryospheric services are central to achieving the mountain priorities and specific targets and will enhance the adaptation capabilities of mountain communities. Cryospheric services (see also Chapter 4) benefit the mountain communities mainly through the provisioning, regulating, cultural, and supporting services (X. Wang et al., 2019; Zhang et al., 2022). The provisioning services with regard to the cryosphere include freshwater supply, clean energy, and snow and ice materials; the regulating services are run-off, climate, environment, and hydrothermal regulations; the cultural services are aesthetic, recreational, research and educational, and religious and spiritual; and supporting services are habitation and infrastructure, and engineering.

More specifically, provisioning service in terms of the freshwater supply and the regulating service in terms of run-off and climate play important roles in the eradication of poverty (SDG1), especially extreme poverty, for all people everywhere. They reduce the number of people living under the poverty line (Target 1.1, 1.2) through opportunities for land ownership (Target 1.4) and ensures food security by increasing agriculture production (Target 2.3), which also assists in ending hunger (SDG2). This combination of services also contributes to SDG15 (Targets 1, 2, 3, and 4), which includes two targets (Targets 15.1 and

TABLE 5.9 LINKAGES OF CRYOSPHERIC SERVICES WITH SUSTAINABLE DEVELOPMENT GOALS

Cryospheric services	Components	Linkages with the four dimensions	SDGs
Provisioning services	Freshwater supply, clean energy, snow/ice material	Livelihoods, water supply, culture	1, 2, 3, 5, 6, 7, 12, 13, 14, 16
Regulating services	Climate, run-off, environment, and hydrothermal regulations	Livelihoods, water supply, disasters	1, 2, 3, 13, 15
Cultural services	Aesthetics, recreation, religious and spiritual, research and education	Livelihoods, culture	1, 2, 3, 4, 5, 16
Supporting services	Habitation, infrastructure, and engineering	Livelihoods, disaster	1, 2, 3, 4, 7, 8, 9, 11

15.4) that are directly associated with mountains, their primary aims being the conservation of terrestrial ecosystems and sustainable use of natural resources. Run-off, climate, and hydrothermal regulation as well as habitation supporting services enhance the resilience of disadvantaged communities (Targets 1.5 and 13.1), agricultural practices, and ecosystems (Target 2.4) so as to minimise disaster displacement (Target 10.7). Similarly, the freshwater provisioning service together with the run-off and hydrothermal regulation service and habitation support service contributes to the goal of access to affordable, reliable, sustainable, and modern energy for all (SDG7). This would eventually help in decoupling economic growth

from environmental degradation (Target 8.4). In the meantime, economic growth (Target 8.1) and good health and well-being (SDG 3) benefit from cultural services, which are likely supported by an enhanced tourism industry and spiritual/religious belief systems. Such linkages between cryospheric services and the SDGs suggests that adaptation must be highly sensitive to, and supportive of, broader socio-cryospheric dynamics that support the well-being of mountain societies. Similarly, advances in sustainable development should be seen as having the co-benefit of enhancing adaptive capacity amongst mountain communities (Munasinghe & Swart, 2005).

5.6. Conclusions, key messages, and knowledge gaps

The HKH is undergoing changes in multiple aspects of the society-cryosphere interface, but the region lags behind in terms of generating attention in global forums concerned with climate change. One of the reasons is the lack of research on the various drivers at play, particularly the human dimensions. This is highly consequential, as changes in the cryosphere directly impact the lives and livelihoods of some 240 million people living within the mountains of the HKH, while indirectly affecting approximately 1.65 billion people living on the floodplains of the rivers stemming from mountain watersheds. Such impacts include the destruction of traditional irrigation channels, crop losses and failures, rangeland degradation, land use changes, and an overall decline in crop and livestock production. In some instances, these changes have resulted in the abandonment of farming and livestock herding in subsistence farming villages and resettlement of entire villages.

In this chapter, four key dimensions of the society-cryosphere interface were assessed in relation to the interactions and interdependencies between CrIDs and nCIDs: livelihoods, water security, culture, and disaster risk. The review of the intersections between the CrIDs and nCIDs yielded valuable insights into the

mosaic of lived experiences of cryospheric change impacts in the HKH region. Mountain societies in the HKH are highly dependent on the provisioning, regulating, cultural, and supporting services associated with mountain ecosystems. However, given the large number of people living both upstream and downstream of the HKH, their high dependence on natural resources from the mountain areas, and shortcomings in accessing basic services and support for adaptation, climate-related changes are manifesting themselves in largely negative ways for those who call the region home.

Despite these challenges and adversities, mountain people are displaying agency and adapting in diverse ways across the HKH region, drawing on their rich traditional knowledge and practices. Adaptation responses to date have been mostly autonomous, and have taken behavioural, technological, financial, regulatory, institutional, and infrastructural forms. However, these autonomous measures may prove to be insufficient in the long run with the rapid CrID and nCID changes taking place in the region. This exacerbates fears about the safety of the local inhabitants and the habitability of their locations. This realisation is complicating efforts at meeting SDG targets by 2030 and is raising concerns about possible transboundary water conflicts.

The mosaic of lived experiences of climate-change-induced cryospheric change in the HKH documented in this chapter will help to clarify the state of

knowledge regarding the CrIDs, nCIDs, and their interactions in the region. But it has also brought to light significant knowledge gaps, which must be addressed to secure more sustainable and equitable futures for those living in the HKH. The chapter points to several key messages:

KEY MESSAGES

- Life in mountains of the HKH is generally improving, but this progress is being jeopardised by cryospheric change and the increasing pressures that these place upon mountain communities.
- Cryospheric change have mostly adverse implications for mountain societies as major mountain livelihoods such as agriculture, livestock, MAPs, and tourism are directly and indirectly dependent on cryospheric services.
- Risk perception within mountain societies – whether they underestimate or overestimate potential cryospheric hazards and disaster risks – plays a significant role in identifying and prioritising responses to cryospheric change and the associated adverse consequences.
- Mountain societies have been resorting to adaptations that are mostly autonomous and incremental in nature and largely limited to household and community scales. But limits to adaptation make mountain livelihoods highly precarious in the changing cryosphere.
- Effective adaptation is key to advancing SMD, while SMD can mobilise the capacity of mountain societies to achieve more effective adaptation.
- Cryospheric change has significant implications for societies in areas that rely on high mountain freshwater. Thus, collaborative efforts through mutual agreements are required among the relevant countries to share water resources, mitigate disaster risks, and explore options to counteract common threats to derive co-benefits. Regional and global cooperation would be needed for technical and financial assistance to facilitate adaptation and mitigation and to advocate on matters of common interest.

KNOWLEDGE GAPS AND POTENTIAL RESPONSES

Despite advances in the extent of understanding about the societal impacts of cryospheric change, existing adaptation efforts, and associated implications for

sustainable development in the HKH, critical knowledge and action gaps remain. This section summarises several of these gaps and provides insights into potential pathways forward.

Gap 1

There is poor understanding about the interactions between cryospheric and non-climatic drivers of socio-ecological change and their respective influence on the lives and livelihoods of mountain societies. This knowledge gap hampers informed responses that are essential for minimising vulnerability and enhancing the capacity of mountain societies for effective and sustainable adaptation to a rapidly changing and complex mountain system.

Response

Increasing the number of case studies examining interactions between cryospheric and non-climatic drivers of change, the impact of the nexus of multiple drivers of change on mountain societies, and the responses of the communities to the interlinked challenges and opportunities. It will also require greater involvement with the local and traditional communities (including greater respect for diverse knowledge systems). Such studies should identify the context-specific as well as generalisable aspects of community-level experiences of the interlinked processes of change. The findings thus elicited should inform policies on adaptation that attend to the myriad pressures faced by mountain societies.

Gap 2

There is little understanding of the cascading consequences of cryospheric change as well as the extent of actual or potential maladaptation and responses that shift the burden of addressing cryospheric change to other places (downstream), systems (ecosystems), or times (future). Without greater understanding of such system-level dynamics, it would be difficult to anticipate and avoid undesirable regime shifts in socio-cryospheric systems across the HKH.

Response

Undertaking interdisciplinary observations and studies to explore the nexus of the spheres (cryosphere–hydrosphere–biosphere–society) that lead to mountain cryospheric change and its influences on the livelihoods and economy, which will help in addressing this knowledge gap. An in-depth study is a prerequisite to

generate holistic knowledge and understanding about the multiple facets of the nexus involving upstream–downstream natural linkages, hazards and disasters, ecosystem services, livelihoods, and social behaviour pertinent to cultural and spiritual beliefs in order to represent the various interactions at different scales.

Gap 3

There is little knowledge on the impact of cryospheric change on the intangible cultural heritage such as spiritual practices and belief systems that generate societal well-being. Cultural/spiritual tourism is a growing livelihood opportunity in the region and that, too, is likely to be impacted by cryospheric change.

Response

Increasing the number of studies exploring the nexus of cryospheric change, intangible cultural heritage, and tourism, and identifying the contextually appropriate opportunities for protecting the cultural and spiritual practices and belief systems that are critical for the people's well-being as well as for cultural tourism.

Gap 4

The effectiveness and inclusiveness of adaptation remain poorly understood.

Response

Increasing efforts to monitor the effectiveness of adaptation activities bearing in mind that the criteria for 'effectiveness' should be informed by tenets of social and environmental justice and sustainable development more broadly. Such efforts can increase understanding of who is vulnerable (or adaptable) to which stresses, how, and with what implications. This is knowledge that is essential for generating durable responses to cryospheric change.

Gap 5

Too little is known about the transboundary implications of adaptation actions in glaciated river basins. Cultivating cooperation in knowledge generation, exchange, and sharing among global, regional, national, and local actors in the common interest and for co-benefits is urgently required.

Response

Undertaking studies exploring the transboundary implications of cryospheric change with the collaboration of research teams from the respective

countries will not only help in filling the knowledge gap but also facilitate cooperation with regard to data/information sharing, cross-learning, and scaling of adaptation options from one country to another.

Gap 6

Disasters are complex socio-environmental events, often with upstream–downstream linkages as well as transboundary impacts. There is not enough understanding about the complex nature of hazards and their potential for loss and damage as well as appropriate management measures at different scales to mitigate risks and enhance resilience.

Response

Increasing the number of studies exploring the cascading and compounding hazards, their processes, and exposure to such hazards and vulnerability of mountain societies as well as infrastructure will help in better understanding this new phenomenon. It will also help policy makers and communities to better prepare for such emerging complex disasters in the HKH countries, with a more regional approach to finding and establishing effective solutions.

Gap 7

At present, adaptation is mostly autonomous and incremental in nature with investment in adaptation efforts low in mountain areas. This raises concerns about what warming beyond 1.5°C means for socio-cryospheric systems in the HKH, including the relationship between limits to adaptation and warming that exceeds 1.5°C.

Response

Increasing social scientific work that examines the nature, extent, and implications of the hard limits to adaptation associated with warming beyond 1.5°C, with the aim of shaping anticipatory responses to potentially transformative changes in the cryosphere of the HKH.

Despite existing knowledge gaps, this chapter demonstrates that, currently, there is sufficient understanding to address the many timely issues related to the societal impacts of cryospheric change in the HKH. Attending to the gaps listed above will enhance efforts to secure sustainable and desirable futures for the people living in (and beyond) the HKH.

References

- Adler, C., Wester, P., Bhatt, I., Huggel, C., Insarov, G., Morecroft, M., Munnione, V., & Prakash, A. (2022). Cross-Chapter Paper 5: Mountains. In 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.), *IPCC climate change 2022: Impacts, adaptation, and vulnerability*. Contribution of Working Group II to the sixth assessment report of the intergovernmental panel on climate change (pp. 2273 – 2318). Cambridge University Press. https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_CCP5.pdf
- Aggarwal, P. K. (2008). Global climate change and Indian agriculture: Impacts, adaptation, and mitigation. *Indian Journal of Agricultural Sciences*, 78, 911–919. <http://www.indiaenvironmentportal.org.in/files/Global%20Climate%20Change.pdf>
- Ahmad, Z., Postigo, J. C., Rahman, F., & Dittmann, A. (2021). Mountain pastoralism in the Eastern Hindu Kush: The case of Lotkuh Valley, Pakistan. *Mountain Research and Development*, 41(4), R16-R28. <https://doi.org/10.1659/MRD-JOURNAL-D-21-00007.1>
- Albrecht, T. R., Varady, R. G., Zuniga-Teran, A. A., Gerlak, A. K., & Staddon, C. (2017). Governing a shared hidden resource: A review of governance mechanisms for transboundary groundwater security. *Water Security*, 2, 43-56. <https://doi.org/10.1016/j.wasec.2017.11.002>
- Ali, A., Ali, G., Shah, G. M., Shah, A., Karim, R., Joshi, S., Ali, K., & Khan, B. (2021). Factors shaping economics of land use change in Gilgit Baltistan, Pakistan. *GeoJournal*, 87, 3951-3966. <https://doi.org/10.1007/s10708-021-10478-3>
- Ali, T., Huang, J., & Xie, W. (2022). Bilateral economic impacts of China–Pakistan economic corridor. *Agriculture*, 12(2), 143. <https://doi.org/10.3390/agriculture12020143>
- Allen, S. K., Zhang, G., Cuaresma, J. C., & Bolach, T. (2019). Potentially dangerous glacial lakes across the Tibetan Plateau revealed using a large-scale automated assessment approach. *Science Bulletin*, 64, 435–445. <https://doi.org/10.1016/j.scib.2019.03.011>
- Allison, E. A. (2015). The spiritual significance of glaciers in an age of climate change. *WIREs Climate Change*, 6(5), 493-508. <https://doi.org/10.1002/wcc.354>
- Amarasinghe, U. A., Palanisami, K., & Singh, O. P. (2012). Improving canal irrigation performance with on-farm water storage: Evidence from the Indira Gandhi Nahar Pariyojana project in India. *Irrigation and Drainage*, 61(4), 427-435. <https://doi.org/10.1002/ird.689>
- Apollo, M. (2017). The true accessibility of mountaineering: The case of the High Himalaya. *Journal of Outdoor Recreation and Tourism*, 17, 29-43. <https://doi.org/10.1016/j.jort.2016.12.001>
- Appelquist, W. L., Brinckmann, J. A., Cunningham, A. B., Hart, R. E., Heinrich, M., Katerere, D. R., & van Andel, T. (2019). Scientists' warning on climate change and medicinal plants. *Planta Medica*, 86(1), 10-18. <https://pubmed.ncbi.nlm.nih.gov/31731314/>
- Arya, N. K., Singh, K., & Malik, A. (2017). Impact of five days' spiritual practice in Himalayan Ashram of Sahaj Marg on well-being-related parameters and selected physiological indicators. *The International Journal Indian Psychology*, 4(2), 36-51. <https://doi.org/10.25215/0402.064>
- Aryal, S., Maraseni, T. N., & Cockfield, G. (2014). Climate change and indigenous people: Perceptions of transhumant herders and implications to the transhumance system in the Himalayas. *Journal of Geology and Geophysics*, 3(4), 162. <https://www.longdom.org/open-access/climate-change-and-indigenous-people-perceptions-of-transhumant-herders-and-implications-to-the-transhumance-system-in-t-39271.html>
- Ashraf, A., & Akbar, G. (2020). Addressing climate change risks influencing cryosphere-fed kuhl irrigation system in the Upper Indus Basin of Pakistan. *International Journal of Environment*, 9(2), 184-203. <https://doi.org/10.3126/ije.v9i2.32700>
- Ashraf, A., Naz, R., & Roohi, R. (2012). Glacial lake outburst flood hazards in Hindukush, Karakoram and Himalayan ranges of Pakistan: Implications and risk analysis. *Geomatics, Natural Hazards and Risk*, 3(2), 113-132. <https://doi.org/10.1080/19475705.2011.615344>
- Aubriot, O., Faulon, M., Sacareau, I., Puschiasis, O., Jacquemet, E., Smadja, J., André-Lamat, V., Abadia, C. & Muller, A. (2019). Reconfiguration of the water–energy–food nexus in the Everest tourist region of Solukhumbu, Nepal. *Mountain Research and Development*, 39(1), R47-R59. <https://doi.org/10.1659/MRD-JOURNAL-D-17-00080.1>
- Bacha, M. S., Muhammad, M., Kılıç, Z., & Nafees, M. (2021). The dynamics of public perceptions and climate change in Swat Valley, Khyber Pakhtunkhwa, Pakistan. *Sustainability*, 13(8), 4464. <https://doi.org/10.3390/su13084464>

- Baghel, R., & Nüsser, M. (2015). Securing the heights: The vertical dimension of the Siachen conflict between India and Pakistan in the Eastern Karakoram. *Political Geography*, 48, 24-36. <https://doi.org/10.1016/j.polgeo.2015.05.001>
- Bagri, S. C., & Kala, D. (2015). Tourists' satisfaction at Trijuginarayan: An emerging spiritual and adventure tourist destination in Garhwal Himalaya India. *Turizam*, 19(4), 165-182. <https://doi.org/10.5937/Turizam1504165B>
- Bajracharya, S. R. (2010). Glacial lake outburst flood disaster risk reduction activities in Nepal. *International Journal of Erosion Control Engineering*, 3(1), 92-101. https://www.globalsupportprogramme.org/sites/default/files/downloads/glof_risk_reduction_activities_in_nepal_-_icimod_-_2011.pdf
- Bajracharya, S. R., Maharjan, S. B., Shrestha, F., Sherpa, T. C., Wagle, N., & Shrestha, A. B. (2020). *Inventory of glacial lakes and identification of potentially dangerous glacial lakes in the Koshi, Gandaki, and Karnali River Basins of Nepal, the Tibet Autonomous Region of China, and India*. ICIMOD and UNDP. <https://doi.org/10.53055/ICIMOD.773>
- Bajracharya, S. R., Mool, P. K., & Shrestha, B. R. (2007). *Impact of climate change on Himalayan glaciers and glacial lakes: Case studies on GLOF and associated hazards in Nepal and Bhutan*. International Centre for Integrated Mountain Development (ICIMOD). <https://lib.icimod.org/record/22442>
- Becken, S., Lama, A. K., & Espiner, S. (2013). The cultural context of climate change impacts: Perceptions among community members in the Annapurna Conservation Area, Nepal. *Environmental Development*, 8(4), 22-37. <http://dx.doi.org/10.1016/j.envdev.2013.05.007>
- Benz, A. (2016). Framing modernization interventions: Reassessing the role of migration and translocality in sustainable mountain development in Gilgit-Baltistan, Pakistan. *Mountain Research and Development*, 36(2), 141-152. <https://doi.org/10.1659/MRD-JOURNAL-D-15-00055.1>
- Bergmann, C., Gerwin, M., Nüsser, M., & Sax, W. S. (2008). Living in a high mountain border region: The case of the 'Bhotiyas' of the Indo-Chinese border region. *Journal of Mountain Science*, 5(3), 209-217. <https://doi.org/10.1007/S11629-008-0178-9>
- Berkes, F. (2007). Understanding uncertainty and reducing vulnerability: Lessons from resilience thinking. *Natural Hazards*, 41(2), 283-295. <https://doi.org/10.1007/s11069-006-9036-7>
- Bernauer, T., Böhmelt, T., & Koubi, V. (2012). Environmental changes and violent conflict. *Environmental Research Letters*, 7(1), 015601. <https://doi.org/10.1088/1748-9326/7/1/015601>
- Bhambri, R., Mehta, M., Dobhal, D.P., & Verma, A. (2016). Devastation in the Kedarnath (Mandakini) Valley, Garhwal Himalaya, during 16–17 June 2013: A remote sensing and ground-based assessment. *Natural Hazards*, 80(3), 1801-1822. <https://doi.org/10.1007/s11069-015-2033-y>
- Bharaj, V. (2018). Rising out of the wrath: The post-disaster religious landscape of Kedarnath valley, Uttarakhand, India [Master's thesis, Delft University of Technology]. <https://repository.tudelft.nl/islandora/object/uuid:6811bc45-8ad3-4847-a8ef-2bbb852106c7?collection=education>
- Biemans, H., Siderius, C., Lutz, A. F., Ahmad, B., Hassan, T., von-Bloh, W., Wijngaard, R. R., Wester, P., Shrestha, A. B., & Immerzeel, W. W. (2019). Importance of snow and glacier meltwater for agriculture on the Indo-Gangetic Plain. *Nature Sustainability*, 2(7), 594-601. <https://doi.org/10.1038/s41893-019-0305-3>
- Bigano, A., Hamilton, J. M., & Tol, R. S. (2008). *Climate change and tourism in the Mediterranean* (Working Papers FNU-157). Hamburg University and Centre for Marine and Atmospheric Science. https://www.researchgate.net/publication/24130111_Climate_Change_and_Tourism_in_the_Mediterranean
- Bjønness, I. M. (1986). Mountain hazard perception and risk-avoiding strategies among the Sherpas of Khumbu Himal, Nepal. *Mountain Research and Development*, 6(4), 277-292. <https://doi.org/10.2307/3673369>
- Boelens, R., Hoogesteger, J., Swyngedouw, E., Vos, J., & Wester, P. (2016). Hydrosocial territories: A political ecology perspective. *Water International*, 41(1), 1-14. <https://doi.org/10.1080/02508060.2016.1134898>
- Brandt, J. S., Haynes, M. A., Kuemmerle, T., Waller, D. M., & Radeloff, V. C. (2013). Regime shift on the roof of the world: Alpine meadows converting to shrublands in the southern Himalayas. *Biological Conservation*, 158, 116-127. <https://doi.org/10.1016/j.biocon.2012.07.026>
- Brautigam, M. (2011). *Above the Mukpa: This shifting ground of Khumbu sacred geography*. Independent Study Project (Collection 1234). SIT Digital Collections. https://digitalcollections.sit.edu/isp_collection/1234/
- Brochmann, M., & Gleditsch, N. P. (2012). Shared rivers and conflict – A reconsideration. *Political Geography*, 31(8), 519-527. <https://doi.org/10.1016/j.polgeo.2012.11.001>
- Burtscher, M. (2012). Climbing the Himalayas more safely. *BMJ*, 344(7863), e3778. <https://doi.org/10.1136/bmj.e3778>
- Butcher, A. (2013). Keeping the faith: Divine protection and flood prevention in modern Buddhist Ladakh. *Worldviews*, 17(2), 103-114. [10.1163/15685357-01702002](https://doi.org/10.1163/15685357-01702002)

- Butcher, A. (2017). Networks and practices of weather and climate in the Western Himalaya. *European Bulletin of Himalayan Research*, 49(49), 5-34. https://himalaya.socanth.cam.ac.uk/collections/journals/ebhr/pdf/EBHR_49.pdf#page=7
- Byers, A. C., Byers, E., Shrestha, M., Thapa, D., & Sharma, B. (2020). Impacts of yartsa gunbu harvesting on alpine ecosystems in the Barun Valley, Makalu-Barun National Park, Nepal. *Himalaya*, 39(2), 44-59. <https://digitalcommons.macalester.edu/himalaya/vol39/iss2/8/>
- Byers, A. C., Byers, E. A., McKinney, D. C., & Rounce, D. R. (2017). A field-based study of impacts of the 2015 earthquake on potentially dangerous glacial lakes in Nepal. *Himalaya*, 37(2), 26-41. <https://digitalcommons.macalester.edu/himalaya/vol37/iss2/7>
- Byers, A. C., McKinney, D. C., Thakali, S., & Somos-Valenzuela, M. (2014). Promoting science-based, community-driven approaches to climate change adaptation in glaciated mountain ranges: HiMAP. *Geography*, 99(3), 143-152. <https://doi.org/10.1080/00167487.2014.12094408>
- Byers, A. C., Rounce, D. R., Shugar, D. H., Lala, J. M., Byers, E. A., & Regmi, D. (2018). A rockfall-induced glacial lake outburst flood, Upper Barun Valley, Nepal. *Landslides*, 16(3), 533-549. <https://doi.org/10.1007/s10346-018-1079-9>
- Byers, A. C., Shugar, D. H., Chand, M. B., Portocarrero, C., Shrestha, M., Rounce, D. R., & Watanabe, T. (2022). Three recent and lesser-known glacier-related flood mechanisms in high mountain environments. *Mountain Research and Development*, 42(2), A12-A22. <https://doi.org/10.1659/MRD-JOURNAL-D-21-00045.1>
- Byers, T., Reist, J. D., & Sawatzky, C. D. (2019). *Compilation and synopsis of literature on the traditional knowledge of indigenous peoples in the Northwest Territories concerning Dolly Varden*. Canadian Manuscript Report of Fisheries and Aquatic Sciences 3177. Department of Fisheries and Oceans, Canada. <https://publications.gc.ca/site/eng/9.873211/publication.html>
- Carey, M., McDowell, G., Huggel, C., Marshall, B., Moulton, H., Portocarrero, C., Provant, Z., Reynolds, J. M., & Vicuña, L. (2021). A socio-cryospheric systems approach to glacier hazards, glacier runoff variability, and climate change. In W. Haeberli & C. Whiteman (Eds.), *Snow and ice-related hazards, risks, and disasters* (pp. 215-257). Elsevier. <https://doi.org/10.1016/B978-0-12-817129-5.00018-4>
- Carey, M., Molden, O. C., Rasmussen, M. B., Jackson, M., Nolin, A. W., & Mark, B. G. (2017). Impacts of glacier recession and declining meltwater on mountain societies. *Annals of the American Association of Geographers*, 107(2), 350-359. <https://doi.org/10.1080/24694452.2016.1243039>
- Carrivick, J. L., & Tweed, F. S. (2016). A global assessment of the societal impacts of glacier outburst floods. *Global and Planetary Change*, 144(9), 1-16. <https://doi.org/10.1016/j.gloplacha.2016.07.001>
- Chakraborty, R., & Sherpa, P. Y. (2021). From climate adaptation to climate justice: Critical reflections on the IPCC and Himalayan climate knowledges. *Climatic Change*, 167(3), 1-14. <https://doi.org/10.1007/s10584-021-03158-1>
- Chaudhary, P., Rai, S., Wangdi, S., Mao, A., Rehman, N., Chettri, S., & Bawa, K. S. (2011). Consistency of local perceptions of climate change in the Kangchenjunga Himalaya landscape. *Current Science*, 101(4), 504-513. <https://www.jstor.org/stable/24078981>
- Cheema, M., Immerzeel, W., & Bastiaanssen, W. (2014). Spatial quantification of groundwater abstraction in the irrigated Indus basin. *Groundwater*, 52(1), 25-36. <https://doi.org/10.1111/gwat.12027>
- Chen, D., Rojas, M., Samset, B. H., Cobb, K., Diongue Niang, A., Edwards, P., Emori, S., Faria, S. H., Hawkins, E., Hope, P., Huybrechts, P., Meinshausen, M., Mustafa, S. K., Plattner, G.-K., & Tréguier, A.-M. (2021). Framing, context, and methods. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (Eds.), *Climate change 2021: The physical science basis* (pp. 147-286). Contribution of Working Group I to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press. <https://www.ipcc.ch/report/ar6/wg1/chapter/chapter-1/>
- Chhetri, H. P. (2008). *Panchayat Raj system and development planning - the case of Sikkim*. Rawat Publications.
- Chinnasamy, P., & Shrestha, S. R. (2019). Melamchi water supply project: Potential to replenish Kathmandu's groundwater status for dry season access. *Water Policy*, 21(S1), 29-49. <https://doi.org/10.2166/wp.2019.080>
- Choden, K., Nitschke, C. R., Stewart, S. B., & Keenan, R. J. (2021). The potential impacts of climate change on the distribution of key tree species and Cordyceps in Bhutan: Implications for ecological functions and rural livelihoods. *Ecological Modelling*, 455, 109650. <https://doi.org/10.1016/j.ecolmodel.2021.109650>
- Clouse, C. (2016). Frozen landscapes: Climate-adaptive design interventions in Ladakh and Zaskar. *Landscape Research*, 41(8), 821-837. <https://doi.org/10.1080/01426397.2016.1172559>

- Community-based flood and glacial lake outburst risk reduction project (CFGORRP). (2017). *What we achieved so far*. United Nations Development Program (UNDP)/ Department of Hydrology and Meteorology, Nepal. <https://www.undp.org/nepal/projects/closed-community-based-flood-and-glacial-lake-outburst-risk-reduction-project>
- Cook, K. L., Andermann, C., Gimbert, F., Adhikari, B. R., & Hovius, N. (2018). Glacial lake outburst floods as drivers of fluvial erosion in the Himalaya. *Science*, 362(6410), 53–57. <https://doi.org/10.1126/science.aat4981>
- Cuellar, A. D., & McKinney, D. C. (2017). Decision-making methodology for risk management applied to Imja Lake in Nepal. *Water*, 9(8), 591. <https://doi.org/10.3390/w9080591>
- Dahal, K. R., & Hagelman, R. (2011). People's risk perception of glacial lake outburst flooding: A case of Tsho Rolpa Lake, Nepal. *Environmental Hazards*, 10(2), 154–170. <https://doi.org/10.1080/17477891.2011.582310>
- Dame, J. (2018). Food security and translocal livelihoods in high mountains: Evidence from Ladakh, India. *Mountain Research and Development*, 38(4), 310–322. <https://doi.org/10.1659/MRD-JOURNAL-D-18-00026.1>
- Dame, J., & Mankelov, J. S. (2010). Stongde revisited: Land-use change in Central Zangskar. *Erdkunde*, 64, 355–370. <https://doi.org/10.3112/erdkunde.2010.04.05>
- Dame, J., & Nüsser, M. (2011). Food security in high mountain regions: Agricultural production and the impact of food subsidies in Ladakh, Northern India. *Food Security*, 3, 179–194. <https://link.springer.com/article/10.1007/s12571-011-0127-2#citeas>
- Dame, J., Schmidt, S., Müller, J., & Nüsser, M. (2019). Urbanisation and socio-ecological challenges in high mountain towns: Insights from Leh (Ladakh), India. *Landscape and Urban Planning*, 189(9), 189–199. <https://doi.org/10.1016/j.landurbplan.2019.04.017>
- Debarbieux, B., & Rudaz, G. (2015). *The mountain: Political history from the enlightenment to the present*. University of Chicago Press. <https://doi.org/10.7208/chicago/9780226031255.001.0001>
- Deng, M., Zhang, H., Mao, W., & Wang, Y. (2011). Public perceptions of cryosphere change and the selection of adaptation measures in the Ürümqi River Basin. *Advances in Climate Change Research*, 2(3), 149–158. <https://doi.org/10.3724/SP.J.1248.2011.00149>
- De Stefano, L., Edwards, P., De Silva, L., & Wolf, A. T. (2010). Tracking cooperation and conflict in international basins: Historic and recent trends. *Water Policy*, 12(6), 871–884. <https://doi.org/10.2166/wp.2010.137>
- Diemberger, H., Hovden, A., & Yeh, E. (2015). The honour of the snow mountains is the snow. In C. Huggel, M. Carey, J. Clague, & A. Kaab (Eds.), *The high mountain cryosphere: Environmental changes and human risks* (pp. 249–271). Cambridge University Press. <https://www.cambridge.org/core/books/abs/highmountain-cryosphere/honour-of-the-snowmountains-is-the-snow/615905558C02A03FB4643139A092CA76>
- Dilshad, T., Mallick, D., Udas, P. B., Goodrich, C. G., Prakash, A., Gorti, G., Bhadwal, S., Anwar, M. Z., Khandekar, N., Tanvir Hassan, S. M., Habib, N., Abbasi, S. S., Syed, M. A., & Rahman, A. (2019). Growing social vulnerability in the river basins: Evidence from the Hindu Kush Himalaya (HKH) region. *Environmental Development*, 31(6), 19–33. <https://doi.org/10.1016/j.envdev.2018.12.004>
- Dimri, A. P., Allen, S., Huggel, C., Mal, S., Ballesteros-Canovas, J. A., Rohrer, M., Shukla, A., Tiwari, P., Maharana, P., Bolch, T., Thayyen, R. J., Stoffel, M., & Pandey, A. (2021). Climate change, cryosphere, and impacts in the Indian Himalayan Region. *Current Science*, 120(5), 774–790. <https://doi.org/10.18520/cs/v120/i5/774-790>
- Dinar, S., Katz, D., De Stefano, L., & Blankespoor, B. (2015). Climate change, conflict, and cooperation: Global analysis of the effectiveness of international river treaties in addressing water variability. *Political Geography*, 45, 55–66. <https://doi.org/10.1016/j.polgeo.2014.08.003>
- Dollfus, P. (2013). Transformation processes in nomadic pastoralism in Ladakh. *Himalaya*, 32(1), 61–72. <https://digitalcommons.macalester.edu/himalaya/vol32/iss1/15>
- Dong, S., Wen, L., Liu, S., Zhang, X., Lassoie, J. P., Yi, S., Li, X., Li, J., & Li, Y. (2011). Vulnerability of worldwide pastoralism to global changes and interdisciplinary strategies for sustainable pastoralism. *Ecology and Society*, 16(2), 10. <https://doi.org/10.5751/ES-04093-160210>
- Ehsan, S. M. A. (2021). The local government system in Bangladesh: An anatomy of perspectives & practices. *South Asian Journal of Policy and Governance*, 44(2), 1–22. <https://ssrn.com/abstract=3799533>
- European Space Agency (2017). *Land Cover CCI Product User Guide Version 2. Tech. Rep.* maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-Ph2-PUGv2_2.0.pdf
- FAO, IFAD, UNICEF, WFP, & WHO. (2022). *The state of food security and nutrition in the world 2022: Repurposing food and agricultural policies to make healthy diets more affordable*. FAO. <https://doi.org/10.4060/cc0639en>
- Faulon, M., & Sacareau, I. (2020). Tourism, social management of water, and climate change in an area of high altitude: The Everest Massif in Nepal. *Journal of Alpine Research*, 108(1), 1–16. <https://doi.org/10.4000/rga.6779>

- Fu, Y., Grumbine, R. E., Wilkes, A., Wang, Y., Xu, J. C., & Yang, Y. P. (2012). Climate change adaptation among Tibetan pastoralists: Challenges in enhancing local adaptation through policy support. *Environmental Management*, 50(4), 607-621. <https://doi.org/10.1007/s00267-012-9918-2>
- Gagné, K. (2016). Cultivating ice over time: On the idea of timeless knowledge and places in the Himalayas. *Anthropologica*, 58(2), 193-210. <https://www.jstor.org/stable/26350480>
- Gagné, K. (2019). *Caring for glaciers: Land, animals, and humanity in the Himalayas*. University of Washington Press. <https://uwapress.uw.edu/book/9780295744001/caring-for-glaciers/>
- Gagné, K. (2020). The materiality of ethics: Perspectives on water and reciprocity in a Himalayan anthropocene. *Water*, 7(4), e1444. <https://doi.org/10.1002/wat2.1444>
- Gagné, K., Rasmussen, M.B., & Orlove, B. (2014). Glaciers and society: Attributions, perceptions, and valuations. *Climate Change*, 5(6), 793-808. <https://doi.org/10.1002/wcc.315>
- Gentle, P., & Maraseni, T. N. (2012). Climate change, poverty, and livelihoods: Adaptation practices by rural mountain communities in Nepal. *Environmental Science & Policy*, 21, 24-34. <https://doi.org/10.1016/j.envsci.2012.03.007>
- Gentle, P., & Thwaites R. (2016). Transhumant pastoralism in the context of socioeconomic and climate change in the mountains of Nepal. *Mountain Research and Development*, 36(2), 173-182. <https://doi.org/10.1659/MRD-JOURNAL-D-15-00011.1>
- Gentle, P., Thwaites, R., Race, D., & Alexander, K. (2014). Differential impacts of climate change on communities in the middle hills region of Nepal. *Natural Hazards*, 74(2), 815-836. <https://ideas.repec.org/a/spr/nathaz/v74y2014i2p815-836.html>
- Gerlitz, J-Y., Apablaza, M., Hoermann, B., Hunzai, K., & Bennett, L. (2015). A multidimensional poverty measure for the Hindu Kush-Himalayas, applied to selected districts in Nepal. *Mountain Research and Development*, 35(3), 278-288. <https://doi.org/10.1659/MRD-JOURNAL-D-14-00027.1>
- Ghimire, T. R., Pant, P., Regmi, G. R., & Huettmann, F. (2020). Ethnobiology and indigenous regimes in the conservation of species, watersheds, and landscapes: Experiences and evidences from the Hindu Kush-Himalayan nations for a global application. In G. R. Regmi & F. Huettmann (Eds.), *Hindu Kush-Himalaya watersheds downhill: Landscape ecology and conservation perspectives* (pp. 249-281). Springer Nature. https://link.springer.com/chapter/10.1007/978-3-030-36275-1_13
- Giola, G., Thapa, G., Khan, F., Dasgupta, P., Nathan, D., Chhetri, N., Adhikari, L., Kumar Mohanty, S.K., Aurino, E., & Mapstone Scott, L. (2019). Understanding and tackling poverty and vulnerability in mountain livelihoods in the Hindu Kush Himalaya. In P. Wester, A. Mishra, A. Mukherji, & A. B. Shreshtha (Eds.), *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability, and people* (pp. 421-455). Springer Nature. https://link.springer.com/chapter/10.1007/978-3-319-92288-1_12
- Godde, C. M., Mason-D'Croz, D., Mayberry, D. E., Thornton, P. K., & Herrero, M. (2021). Impacts of climate change on the livestock food supply chain: A review of the evidence. *Global Food Security*, 28, 100488. <https://doi.org/10.1016/j.gfs.2020.100488>
- Goodrich, C. G., Udas, P. B., & Larrington-Spencer, H. (2019). Conceptualizing gendered vulnerability to climate change in the Hindu Kush Himalaya: Contextual conditions and drivers of change. *Environmental Development*, 31, 9-18. <https://doi.org/10.1016/j.envdev.2018.11.003>
- Grossman, D. (2015, March 24) As Himalayan glaciers melt: Two towns face the fallout. *Yale Environment*. https://e360.yale.edu/features/as_himalayan_glaciers_melt_two_towns_face_the_fallout
- Haag, I., Kassam, K. A., Senftl, T., Zandler, H., & Samimi, C. (2021). Measurements meet human observations: Integrating distinctive ways of knowing in the Pamir Mountains of Tajikistan to assess local climate change. *Climatic Change*, 165(1), 1-22. <https://doi.org/10.1007/s10584-021-02988-3>
- Haq, F. M., & Medhekar, A. (2020). The rise of spiritual tourism in South Asia as business internationalization. *Journal of Management and Research*, 7(1), 52-78. <https://doi.org/10.29145/jmr/71/070103>
- Hewitt, K., & Liu, J. (2010). Ice-dammed lakes and outburst floods, Karakoram Himalaya: Historical perspectives on emerging threats. *Physical Geography*, 31(6), 528-551. <https://doi.org/10.2747/0272-3646.31.6.528>
- Hewitt, K., & Mehta, M. (2012). Rethinking risk and disasters in mountain areas. *Journal of Alpine Research | Revue de géographie alpine*, 100(1), 1-13. <https://doi.org/10.4000/rga.1653>
- HI-AWARE. (2018). Climate change critical moments survey 2018 (unpublished). *Himalayan adaptation, water, and resilience (HI-AWARE) Initiative*. The consortium of the collaborative adaptation research initiative in Africa and Asia (CARIAA). https://lib.icimod.org/record/34382/files/HI-AWARE_FTRa.pdf
- Hock, R., Rasul, G., Adler, C., Cáceres, B., Gruber, S., Hirabayashi, Y., Jackson, M., Kääh, A., Kang, S., Kutuzov, S., Milner, A., Molau, U., Morin, S., Orlove, B., & Steltzer, H. (2019). High mountain areas. In 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, & N. M. Weyer (Eds.), *IPCC special report on the ocean and cryosphere in a changing climate* (pp. 131-202). Cambridge University Press. <https://doi.org/10.1017/9781009157964.004>

- Hong-Min, A., Cun-De, X., Yao, T., & Jie, F. (2021). Ice-and-snow tourism and its sustainable development in China: A new perspective of poverty alleviation. *Advances in Climate Change Research*, 12(6), 881-893. <https://doi.org/10.1016/j.accres.2021.09.004>
- Hopping, K. A., Chignell, S. M., & Lambin, E. F. (2018). The demise of caterpillar fungus in the Himalayan region due to climate change and overharvesting. *PNAS*, 115(45), 11489-11494. <https://doi.org/10.1073/pnas.1811591115>
- Hopping, K. A., Yangzong, C., & Klein, J. A. (2016). Local knowledge production, transmission, and the importance of village leaders in a network of Tibetan pastoralists coping with environmental change. *Ecology and Society*, 21(1), 25. <https://www.jstor.org/stable/26270331>
- Huijun, J., He, R., Cheng, G., Wu, Q., Wang, S., Lu, L., & Chang, X. (2009). Changes in frozen ground in the source area of the Yellow River on the Qinghai-Tibet Plateau, China, and their eco-environmental impacts. *Environmental Research Letters*, 4(4), 045206. <https://doi.org/10.1088/1748-9326/4/4/045206>
- Hunzai, K., Gerlitz, J. Y., & Hoermann, B. (2011). *Understanding mountain poverty in the Hindu Kush-Himalayas: Regional report for Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan*. ICIMOD. <https://doi.org/10.53055/ICIMOD.553>
- Huss, M., & Hock, R. (2018). Global-scale hydrological response to future glacier mass loss. *Nature Climate Change*, 8(2), 135-140. <https://doi.org/10.1038/s41558-017-0049-x>
- Hussain, A., & Qamar, F. M. (2020). Dual challenge of climate change and agrobiodiversity loss in mountain food systems in the Hindu-Kush Himalaya. *One Earth*, 3(5), 539-542. <https://doi.org/10.1016/j.oneear.2020.10.016>
- Hussain, A., Rasul, G., Mahapatra, B., & Tuladhar, S. (2016). Household food security in the face of climate change in the Hindu-Kush Himalayan Region. *Food Security*, 8(5), 921-937. <https://doi.org/10.1007/S12571-016-0607-5>
- ICIMOD. (2020). *The HKH call to action to sustain mountain environments and improve livelihoods in the Hindu Kush Himalaya*. ICIMOD. <https://lib.icimod.org/record/34934>
- Ikeda, N., Narama, C., & Gyalson, S. (2016). Knowledge sharing for disaster risk reduction: Insights from a glacier lake workshop in the Ladakh region, Indian Himalayas. *Mountain Research and Development*, 36(1), 31-40. <https://doi.org/10.1659/MRD-JOURNAL-D-15-00035.1>
- 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., Fernandez, A., Haritashya, U., Kargel, J. S., Koppes, M., Kraaijenbrink, P. D. A., Kulkarni, A. V., Mayewski, ... & Baillie, J. E. M. (2020). Importance and vulnerability of the world's water towers. *Nature*, 577(7790), 364-369. <https://doi.org/10.1038/s41586-019-1822-y>
- Immerzeel, W. W., Van Beek, L. P., & Bierkens, M. F. (2010). Climate change will affect the Asian water towers. *Science*, 328(5984), 1382-1385. <https://www.science.org/doi/10.1126/science.1183188>
- Ingty, T. (2017). High mountain communities and climate change: Adaptation, traditional ecological knowledge, and institutions. *Climatic Change*, 145, 41-55. <https://doi.org/10.1007/s10584-017-2080-3>
- IPCC. (2012). *Managing the risks of extreme events and disasters to advance climate change adaptation: A special report of Working Groups I and II of the Intergovernmental Panel on Climate Change*. [C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach, G.-K. Plattner, S. K. Allen, M. Tignor, & P. M. Midgley (Eds.)]. Cambridge University Press. <https://www.ipcc.ch/report/managing-the-risks-of-extreme-events-and-disasters-to-advance-climate-change-adaptation/>
- IPCC. (2022). Annex II: Glossary. [V. Möller, R. van Diemen, J. B. R. Matthews, C. Méndez, S. Semenov, J. S. Fuglestedt, & A. Reisinger (Eds.)]. In 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* (pp. 2897-2930). Cambridge University Press. https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_Annex-II.pdf
- Iqbal, N., Hossain, F., Lee, H., & Akhter, G. (2017). Integrated groundwater resource management in Indus Basin using satellite gravimetry and physical modelling tools. *Environmental Monitoring and Assessment*, 189(3), 1-16. <https://doi.org/10.1007/s10661-017-5846-1>
- Islam, T. T., Newhouse, D., & Yanez-Pagans, M. (2021). International comparisons of poverty in South Asia. *Asian Development Review*, 38(1), 142-175. https://doi.org/10.1162/adev_a_00161
- Jha, L. K., & Khare, D. (2016). Glacial lake outburst flood (GLOF) study of Dhauliganga basin in the Himalaya. *Cogent Environmental Science*, 2(1), 1249107. <https://doi.org/10.1080/23311843.2016.1249107>
- Jodha, N. S. (2007). Mountain commons: Changing space and status at community levels in the Himalayas. *Journal of Mountain Science*, 4(2), 124-135. <https://doi.org/10.1007/s11629-007-0124-2>

- Joshi, S., Jasra, A. W., Ismail, M., Shrestha, R. M., Shaoliang, Y., & Wu, N. (2013). Herders' perceptions of and responses to climate change in northern Pakistan. *Environmental Management*, 52(3), 639–648. <https://doi.org/10.1007/s00267-013-0062-4>
- Joshi, S., Shrestha, L., Bisht, N., Wu, N., Ismail, M., Dorji, T., Dangol, G., & Long, R. (2020). Ethnic and cultural diversity amongst yak herding communities in the Asian Highlands. *Sustainability*, 12(3), 957. <https://doi.org/10.3390/su12030957>.
- Jurt, C., Burga, M. D., Vicuña, L., Huggel, C., & Orlove, B. (2015). Local perceptions in climate change debates: Insights from case studies in the Alps and the Andes. *Climatic Change*, 133(3), 511–523. <https://doi.org/10.1007/s10584-015-1529-5>
- Kääb, A., Leinss, S., Gilbert, A., Buhler, Y., Gascoin, S., Evans, S. G., Bartlett, P., Berthier, E., Brun, F., Chao, W-A., Farinotti, D., Gimbert, F., Guo, W., Huggel, C., Kargel, J. S., Leonard, G. J., Tian, L., Treichler, D., & Yao, T. (2018). Massive collapse of two glaciers in western Tibet in 2016 after surge-like instability. *Nature Geoscience*, 11(2), 114–120. <https://www.nature.com/articles/s41561-017-0039-7>
- Kääb, A., Leinss, S., Gilbert, A., Buhler, Y., Gascoin, S., Evans, S. G., Bartlett, P., Berthier, E., Brun, F., Chao, W-A., Farinotti, D., Gimbert, F., Guo, W., Huggel, C., Kargel, J. S., Leonard, G. J., Tian, L., Treichler, D., & Yao, T. (2018). Massive collapse of two glaciers in western Tibet in 2016 after surge-like instability. *Nature Geoscience*, 11(2), 114–120. <https://www.nature.com/articles/s41561-017-0039-7>
- Kang, S., Zhang, Q., Qian, Y., Ji, Z., Li, C., Cong, Z., Zhang, Y., Guo, J., Du, W., Huang, J., You, Q., Panday, A. K., Rupakheti, M., Chen, D., Gustafsson, O., Thiemens, M. H., & Qin, D. (2019). Linking atmospheric pollution to cryospheric change in the Third Pole region: Current progress and future prospects. *National Science Review*, 6(4), 796–809. <https://doi.org/10.1093/nsr/nwz031>
- Karan, P. P., & Mather, C. (1976). Art and geography: Patterns in the Himalaya. *Annals of the Association of American Geographers*, 66(4), 487–512. <https://doi.org/10.1111/j.1467-8306.1976.tb01106.x>
- Kargel, J. S., Cogley, J. G., Leonard, G. J., Haritashya, U., & Byers, A. (2011). Himalayan glaciers: The big picture is a montage. *Proceedings of the National Academy of Sciences*, 108(36), 14709–14710. <https://doi.org/10.1073/pnas.1111663108>
- Kargel, J. S., Leonard, G. J., Shugar, D. H., Haritashya, U. K., Bevington, A., Fielding, E. J., Fujita, K., Geertsema, M., Miles, E. S., Steiner, J., Anderson, E., Bajracharya, S., Bawden, G. W., Breashears, D. F., Byers, A. C., Collins, B., Dhital, M. R., Donnellan, A., Evans, T. L. ... Young, N. W. (2016). Geomorphic and geologic controls of geohazards induced by Nepal's 2015 Gorkha earthquake. *Science*, 351(6269), aac8353. <https://www.science.org/doi/10.1126/science.aac8353>
- Kaser, G., Großhauser, M., & Marzeion, B. (2010). Contribution potential of glaciers to water availability in different climate regimes. *Proceeding of the National Academy of Sciences of the United States of America*, 107(47), 20223–20227. <https://doi.org/10.1073/pnas.100816210>
- Kaul, V., & Thornton, T. F. (2014). Resilience and adaptation to extremes in a changing Himalayan environment. *Regional Environmental Change*, 14(2), 683–698. <https://doi.org/10.1007/s10113-013-0526-3>
- Kelkar, U., Narula, K. K., Sharma, V. P., & Chandna, U. (2008). Vulnerability and adaptation to climate variability and water stress in Uttarakhand State, India. *Global Environmental Change*, 18(4), 564–574. <https://doi.org/10.1016/j.gloenvcha.2008.09.003>
- Khadka, R. B., & Khanal, A. B. (2008). Environmental management plan (EMP) for Melamchi water supply project, Nepal. *Environmental Monitoring and Assessment*, 146(1), 225–234. <https://doi.org/10.1007/s10661-007-0074-8>
- Khan, S. A. (2021). Decentralization and the limits to service delivery: Evidence from Northern Pakistan. *SAGE Open*, 11(1), 1–15. <https://doi.org/10.1177/2158244021994505>
- Khanal, B. P. (2020). Impact of the COVID-19 in tourism industry in Nepal and policy recommendation. *Journal of Tourism & Adventure*, 3(1), 76–91. <https://www.nepjol.info/index.php/jota/article/download/31357/24793>
- Khanduri, B. K., & Rawat, R. (2003). Role of women in sustaining life in Garhwal Himalaya, Uttaranchal. *Economic Affairs (Calcutta)*, 48(3), 152. <https://www.proquest.com/docview/1474329418?pq-origsite=gscholar&fromopenview=true>
- Kharel, S., & Pasa, R. J. (2021). Agriculture service delivery practices of local government in Nepal. *American Journal of Water Resources*, 9(2), 80–91. <http://www.sciepub.com/ajwr/abstract/13949>
- Kirschbaum, D., Watson, C. S., Rounce, D. R., Shugar, D., Kargel, J. S., Haritashya, U. K., Amatya, P., Shean, D., Anderson, E. R., & Jo, M. (2019). The state of remote sensing capabilities of cascading hazards over High Mountain Asia. *Frontiers in Earth Science*, 7, 197. <https://doi.org/10.3389/feart.2019.00197>
- Klein, J. A., Hopping, K. A., Yeh, E. T., Nyima, Y., Boone, R. B., & Galvin, K. A. (2014). Unexpected climate impacts on the Tibetan Plateau: Local and scientific knowledge in findings of delayed summer. *Global Environmental Change*, 28(1), 141–152. <https://doi.org/10.1016/j.gloenvcha.2014.03.007>
- Konchar, K. M., Staver, B., Salick, J., Chapagain, A., Joshi, L., Karki, S., Lo, S., Paudel, A., Subedi, P., Ghimire, S. K. (2015). Adapting in the shadow of Annapurna: A climate tipping point. *Journal of Ethnobiology*, 35(3), 449–471. <https://doi.org/10.2993/0278-0771-35.3.449>

- Koul, S., Raina, V., & Sharma, S. K. (2005). Conservation and propagation of high altitude medicinal and aromatic plant: *Hedychium spicatum*. *Journal of Plant Biochemistry and Biotechnology*, *14*(1), 57-59. <https://doi.org/10.1007/BF03263227>
- Kreutzmann, H. (1991). The Karakoram highway: The impact of road construction on mountain societies. *Modern Asian Studies*, *25*, 711-736. <https://doi.org/10.1017/S0026749X00010817>
- Kreutzmann, H. (2011). Scarcity within opulence: Water management in the Karakoram mountains revisited. *Journal of Mountain Science*, *8*(4), 525-534. <https://doi.org/10.1007/s11629-011-2213-5>
- Kreutzmann, H. (2012). After the flood: Mobility as an adaptation strategy in high mountain oases: The case of Pasu in Gojal, Hunza valley. *Die Erde, Journal of the Geographical Society of Berlin*, *143*(1-2), 49-73. <https://www.die-erde.org/index.php/die-erde/article/view/23/19>
- Kropacek, J., Neckel, N., Tyrna, B., Holzer, N., Hovden, A., Gourmelen, N., Schneider, C., Buchroithner, M., & Hochschild, V. (2015). Repeated glacial lake outburst flood threatening the oldest Buddhist monastery in northwestern Nepal. *Natural Hazards and Earth System Sciences*, *15*(10), 2425-2437. <https://doi.org/10.5194/nhess-15-2425-2015>
- Kulkarni, A. V., Shirsat, T. S., Kulkarni, A., Negi, H. S., Bahuguna, I. M., & Thamban, M. (2021). State of Himalayan cryosphere and implications for water security. *Water Security*, *14*, 100101. <https://doi.org/10.1016/j.wasec.2021.100101>
- Kumar, M., Rawat, S., Nagar, B., Kumar, A., Pala, N. A., Bhat, J. A., Bussman, R. W., Cabral-Pinto, M., & Kunwar, R. (2021). Implementation of the use of ethnomedicinal plants for curing diseases in the Indian Himalayas and its role in sustainability of livelihoods and socioeconomic development. *International Journal of Environmental Research and Public Health*, *18*(4), 1509. <https://doi.org/10.3390/ijerph18041509>
- Kumar, R., & Sharma, R. C. (2019). Assessment of the water quality of glacier-fed lake Neel Tal of Garhwal Himalaya, India. *Water Science*, *33*(1), 22-28. <https://doi.org/10.1080/11104929.2019.1631554>
- Kunwar, R. R., Aryal, D. R., & Karki, N. (2019). Dark tourism: A preliminary study of Barpak and Langtang as seismic memorial sites of Nepal. *Journal of Tourism and Hospitality Education*, *9*(2019), 88-136. <https://doi.org/10.3126/jthe.v9i0.23683>
- Lama, A.K. (2010). *Vulnerability of nature-based tourism to climate change: Stakeholders' perceptions of and response to climate change in the lower Mustang Region of the Annapurna Conservation Area* [Doctoral dissertation, Lincoln University]. Digital Thesis.
- Lamarche, C., Santoro, M., Bontemps, S., d'Andrimont, R., Radoux, J., Giustarini, L., Brockmann, C., Wevers, J., Defourny, P., & Arino, O. (2017). Compilation and validation of SAR and optical data products for a complete and global map of inland/ocean water tailored to the climate modelling community. *Remote Sensing*, *9*(1), 36. <https://doi.org/10.3390/rs9010036>
- Lennartz, T. (2013). Constructing roads—constructing risks? Settlement decisions in view of landslide risk and economic opportunities in Western Nepal. *Mountain Research and Development*, *33*(4), 364-371. <https://doi.org/10.1659/MRD-JOURNAL-D-13-00048.1>
- Lorenz, C. M., Gilbert, A. J., & Cofino, W. P. (2001). Indicators for transboundary river management. *Environmental Management*, *28*(1), 115-129. <https://doi.org/10.1007/s002670010211>
- Lutz, A., Immerzeel, W., Siderius, C., Wijngaard, R., Nepal, S., Shrestha, A. B., Wester, P., & Biemans, H. (2022). South Asian agriculture increasingly dependent on meltwater and groundwater. *Nature Climate Change*, *12*(6), 556-573. <https://doi.org/10.1038/s41558-022-01355-z>
- Luxom, N. M., Singh, R., Theengh, L., Shrestha, P., & Sharma, R. K. (2022). Pastoral practices, pressures, and human-wildlife relations in high altitude rangelands of eastern Himalaya: A case study of the Dokpa pastoralists of North Sikkim. *Pastoralism: Research, Policy, and Practice*, *12*(5), 1-19. <https://doi.org/10.1186/s13570-022-00252-6>
- Macchi, M., Gurung, A. M., & Hoermann, B. (2014). Community perceptions and responses to climate variability and change in the Himalayas. *Climate and Development*, *7*(5), 414-425. <https://doi.org/10.1080/17565529.2014.966046>
- Maharjan, A., de Campos, R. S., Singh, C., Das, S., Srinivas, A., Bhuiyan, M. R. A., Ishaq, S., Umar, M. A., Dilshad, T., Shrestha, K., Bhadwal, S., Ghosh, T., Suckall, N., & Vincent, K. (2020). Migration and household adaptation in climate-sensitive hotspots in South Asia. *Current Climate Change Reports*, *6*(1), 1-16. <https://doi.org/10.1007/s40641-020-00153-z>
- Maharjan, A., Kochhar, I., Chitale, V. S., Hussain, A., & Gioli, G. (2020). Understanding rural outmigration and agricultural land use change in the Gandaki Basin, Nepal. *Applied Geography*, *124*, 102278. <https://doi.org/10.1016/j.apgeog.2020.102278>
- Maikhuri, R. K., Nautiyal, A., Jha, N. K., Rawat, L. S., Maletha, A., Phondani, P. C., Bahuguna, Y. M., & Bhatt, G. C. (2017). Socio-ecological vulnerability: Assessment and coping strategy to environmental disaster in Kedarnath valley, Uttarakhand, Indian Himalayan Region. *International Journal of Disaster Risk Reduction*, *25*, 111-124. <https://doi.org/10.1016/j.ijdrr.2017.09.002>

- Manandhar, S., Vogt, D. S., Perret, S. R., & Kazama, F. (2011). Adapting cropping systems to climate change in Nepal: A cross-regional study of farmers' perception and practices. *Regional Environmental Change*, 11(2), 335–348. <https://doi.org/10.1007/s10113-010-0137-1>
- Maskey, S., Kayastha, R. B., & Kayastha, R. (2020). Glacial lakes outburst floods (GLOFs) modelling of Thulagi and lower Barun glacial lakes of Nepalese Himalaya. *Progress in Disaster Science*, 7, 100106. <https://doi.org/10.1016/j.pdisas.2020.100106>
- McDowell, G., Ford, J. D., Lehner, B., & Sherpa, A. (2013). Climate-related hydrological change and human vulnerability in remote mountain regions: A case study from Khumbu, Nepal. *Regional Environmental Change*, 13(2), 299–310. <https://doi.org/10.1007/s10113-012-0333-2>
- McDowell, G., Harris, L., Koppes, M., Price, M. F., Chan, K. M. A., & Lama, D. G. (2020). From needs to actions: Prospects for planned adaptations in high mountain communities. *Climatic Change*, 163, 953–972. <https://doi.org/10.1007/s10584-020-02920-1>
- McDowell, G., Huggel, C., Frey, H., Wang, F. M., Cramer, K., & Ricciardi, V. (2019). Adaptation action and research in glaciated mountain systems: Are they enough to meet the challenge of climate change? *Global Environmental Change*, 54, 19–30. <https://doi.org/10.1016/j.gloenvcha.2018.10.012>
- McDowell, G., Koppes, M., Harris, L., Chan, K. M., Price, M. F., Lama, D. G., & Jiménez, G. (2021b). Lived experiences of 'peak water' in the high mountains of Nepal and Peru. *Climate and Development*, 14(3), 268–281. <https://doi.org/10.1080/17565529.2021.1913085>
- McDowell, G., Stephenson, E., & Ford, J. (2014). Adaptation to climate change in glaciated mountain regions. *Climatic Change*, 126, 77–91. <https://doi.org/10.1007/s10584-014-1215-z>
- McDowell, G., Stevens, M., Lesnikowski, A., Huggel, C., Harden, A., DiBella, J., Morecroft, M. D., Kumar, P., Joe, E. T., Bhatt, I. D., Pant, G. B., & Global Adaptation Mapping Initiative. (2021a). Closing the adaptation gap in mountains. *Mountain Research and Development*, 41(3), A1–A10. <https://doi.org/10.1659/MRD-JOURNAL-D-21-00033.1>
- Meenawat, H., & Sovacool, B. K. (2011). Improving adaptive capacity and resilience in Bhutan. *Mitigation and Adaptation Strategies for Global Change*, 16(5), 515–533. <https://doi.org/10.1007/s11027-010-9277-3>
- Messerli, B., & Ives, J. D. (1997). *Mountains of the world: A global priority*. The Parthenon Publishing Group. <https://lib.icimod.org/record/4729>
- Mills-Novoa, M., Borgias, S., Crootof, A., Thapa, D., de Grenade, R., & Scott, C. A. (2017). Bringing the hydrosocial cycle into climate change adaptation planning: Lessons from two Andean Mountain water towers. *Annals of the American Association of Geographers*, 107(2), 393–402. <https://doi.org/10.1080/24694452.2016.1232618>
- Ministry of Culture, Tourism & Civil Aviation (2020). *Nepal tourism statistics 2020*. https://www.tourism.gov.np/files/NOTICE%20MANAGER_FILES/NTB_Statistics_2020%20_final.pdf
- 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., & Sharma, U. (2019). Adaptation to climate change in the Hindu Kush Himalaya: Stronger action urgently needed. In P. Wester, A. Mishra, A. Mukherji, & A. B. Shrestha (Eds.), *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability and people* (pp. 457–490). Springer Nature. https://doi.org/10.1007/978-3-319-92288-1_13
- Mishra, A. K., & Rafiq, M. (2017). Analysing snowfall variability over two locations in Kashmir, India in the context of warming climate. *Dynamics of Atmosphere and Oceans*, 79, 1–9. <https://doi.org/10.1016/j.dynatmoce.2017.05.002>
- Mizushima, K. (2016). The changes in regional structure and land use related to external factors in Hussaini Village, Northern Pakistan. In H. Kreutzmann & T. Watanabe (Eds.), *Mapping transition in the Pamirs* (pp. 215–227). Springer Nature. https://doi.org/10.1007/978-3-319-23198-3_14
- Mohanty, S. K., Rasul, G., Mahapatra, B., Choudhary, D., Tuladhar, S., & Holmgren, E.V. (2018). Multidimensional poverty in mountainous regions: Shan and Chin in Myanmar. *Social Indicators Research*, 138(3), 23–44. <https://doi.org/10.1007/s11205-017-1662-9>
- Molden, D. J., Shrestha, A. B., Immerzeel, W. W., Maharjan, A., Rasul, G., Wester, P., Wagle, N., Pradhananga, S., & Nepal, S. (2022). The great glacier and snow-dependent rivers of Asia and climate change: Heading for troubled waters. In A. K. Biswas & C. Tortajada (Eds.), *Water security under climate change: Water resources development and management* (pp. 223–250). Springer Nature. https://doi.org/10.1007/978-981-16-5493-0_12
- Mondal, T. K., & Roychowdhury, P. (2019). Water scarcity in Himalayan hill town: A study of Darjeeling Municipality, India. In B. Ray & R. Shaw (Eds.), *Urban drought. disaster risk reduction: Methods, approaches and practices* (pp. 363–383). Springer Nature. <https://www.springerprofessional.de/en/water-scarcity-in-himalayan-hill-town-a-study-of-darjeeling-muni/16367000>

- Mool, P. K., Wangda, D., Bajracharya, S. R., Kunzang, K., Gurung, D. R., & Joshi, S. P. (2001). *Inventory of glaciers, glacial lakes and glacial lake outburst floods: Monitoring and early warning systems in the Hindu Kush-Himalayan Region, Nepal*. ICIMOD. <https://lib.icimod.org/record/21962>
- Moore, G. W. K., Cristofanelli, P., Bonasoni, P., Verza, G. P., & Semple, J. L. (2020). Was an avalanche swarm responsible for the devastation at Mount Everest base camp during the April 2015 Nepal earthquake? *High Altitude Medicine & Biology*, *21*(4), 352-359. <https://doi.org/10.1089/ham.2019.0069>
- Mu, C., Schuster, P. F., Abbott, B. W., Kang, S., Guo, J., Sun, S., Wu, Q., & Zhang, T. (2020). Permafrost degradation enhances the risk of mercury release in Qinghai-Tibetan Plateau. *Science of the Total Environment*, *708*, 135-127. <https://doi.org/10.1016/j.scitotenv.2019.135127>
- Muhammad, A., Haider, B., & Ahmad, Z. (2016). IoT enabled analysis of irrigation rosters in the Indus basin irrigation system. *Procedia Engineering*, *154*, 229-235. <https://doi.org/10.1016/j.proeng.2016.07.457>
- Mukherji, A., Molden, D., Nepal, S., Rasul, G., & Wagnon, P. (2015). Himalayan waters at the crossroads: Issues and challenges. *International Journal of Water Resources Development*, *31*(2), 151-160. <https://doi.org/10.1080/07900627.2015.1040871>
- Mukherji, A., Scott, C., Molden, D., & Maharjan A. (2018). Megatrends in Hindu Kush Himalaya: Climate change, urbanisation and migration and their implications for water, energy and food. In A. K. Biswas, C. Tortajada, & P. Rohner (Eds.), *Assessing global water megatrends: Water resources development and management* (pp. 125-146). Springer Nature. https://link.springer.com/chapter/10.1007/978-981-10-6695-5_8
- Mukherji, A., Sinisalo, A., Nusser, M., Garrard, R., & Eriksson, M. (2019). Contributions of the cryosphere to high mountain communities in the Hindu Kush Himalaya: A review. *Regional Environmental Change*, *19*(2), 1311-1326. <https://doi.org/10.1007/s10113-019-01484-w>
- Munasinghe, M., & Swart, R. (2005). Adaptation to climate change: Concepts and linkages with sustainable development. In *Primer on climate change and sustainable development: Facts, policy analysis, and applications* (pp. 172-206). Cambridge University Press. <https://doi.org/10.1017/CBO9780511622984>
- Müller, J., Dame, J., and Nüsser, M. (2020). Urban mountain waterscapes: The transformation of hydro-social relations in the Trans-Himalayan town Leh, Ladakh, India. *Water*, *12*(6), 1698. <https://doi.org/10.3390/w12061698>
- Müller, M., Schwab, N., Schickhoff, U., Böhner, J., & Scholten, T. (2016). Soil temperature and soil moisture patterns in a Himalayan alpine treeline ecotone. *Arctic, Antarctic, and Alpine Research*, *48*(3), 501-521. <https://doi.org/10.1657/AAAR0016-004>
- Namgay, K., Millar, J., Black, R., & Samdup, T. (2013). Transhumant agro-pastoralism in Bhutan: Exploring contemporary practices and socio-cultural traditions. *Pastoralism: Research, Policy and Practice*, *3*(3), 1-26. <https://doi.org/10.1186/2041-7136-3-13>
- Narain, V., & Singh, A. K. (2019). Replacement or displacement? Periurbanisation and changing water access in the Kumaon Himalaya, India. *Land Use Policy*, *82*, 130-137. <https://doi.org/10.1016/j.landusepol.2018.12.004>
- Nath, N. (2018). From pilgrim landscape to 'pilgrim road': Tracing the transformation of the Char Dham Yatra in colonial Garhwal. *Journal for the Study of Religion, Nature & Culture*, *12*(4), 419-437. <https://doi.org/10.1558/jsrc.34317>
- National Research Council. (2012). *Himalayan glaciers: Climate change, water resources, and water security*. The National Academies Press. <https://doi.org/10.17226/13449>
- Negi, V. S., Maikhuri, R. K., Pharswan, D., Thakur, S., & Dhyani, P. P. (2017). Climate change impact in the Western Himalaya: People's perception and adaptive strategies. *Journal of Mountain Science*, *14*(2), 403-416. <https://doi.org/10.1007/s11629-015-3814-1>
- Nepal, S. K., & Chipeniuk, R. (2005). Mountain tourism: Toward a conceptual framework. *Tourism Geographies*, *7*(3), 313-333. <https://doi.org/10.1080/14616680500164849>
- Nicholson, K., Hayes, E., Neumann, K., Dowling, C., & Sharma, S. (2016). Drinking water quality in the Sagarmatha national park, Nepal. *Journal of Geoscience and Environment Protection*, *4*(04), 43. <https://www.scirp.org/journal/paperinformation.aspx?paperid=65791>
- Nie, Y., Pritchard, H. D., Liu, Q., Hennig, T., Wang, W., Wang, X., Liu, S., Nepal, S., Samyn, D., Hewitt, K., & Chen, X. (2021). Glacial change and hydrological implications in the Himalaya and Karakoram. *Nature Reviews Earth & Environment*, *2*(2), 91-106. <https://doi.org/10.1038/s43017-020-00124-w>
- Niti Aayog. (2018). *Sustainable tourism in the Indian Himalayan Region*. Niti Aayog. <https://sdruk.in/wp-content/uploads/2020/03/Sustainable-Tourism-in-the-Indian-Himalayan-Region.pdf>
- Nixon, H., Joeline, C., Saw, K. P. C., Lynn, T. A., & Arnold, M. (2013). *State and region governments in Myanmar*. Myanmar Development Resource Institute – Centre for Economic and Social Development and the Asia Foundation. https://asiafoundation.org/wp-content/uploads/2016/09/State-Region-Government_Policy-Brief_ENG.pdf

- Nüsser, M., & Schmidt, S. (2017). Nanga Parbat revisited: Evolution and dynamics of socio-hydrological interactions in the Northwestern Himalaya. *Annals of the American Association of Geographers*, 107(2), 403-415. <https://doi.org/10.1080/24694452.2016.1235495>
- Nüsser, M., Dame, J., Kraus, B., Baghel, R., & Schmidt, S. (2019a). Socio-hydrology of artificial glaciers in Ladakh, India: Assessing adaptive strategies in a changing cryosphere. *Regional Environmental Change*, 19(2), 1327-1337. <https://doi.org/10.1007/s10113-018-1372-0>
- Nüsser, M., Dame, J., Parveen, S., Kraus, B., Baghel, R., & Schmidt, S. (2019b). Cryosphere-fed irrigation networks in the Northwestern Himalaya: Precarious livelihoods and adaptation strategies under the impact of climate change. *Mountain Research and Development*, 39(2), R1-R11. <https://doi.org/10.1659/MRD-JOURNAL-D-18-00072.1>
- Nyima, Y., & Hopping, K. A. (2019). Tibetan lake expansion from a pastoral perspective: Local observations and coping strategies for a changing environment. *Society & Natural Resources*, 32(9), 1-18. <https://doi.org/10.1080/08941920.2019.1590667>
- Ojha, H. R., Ghate, R., Dorji, L., Shrestha, A., Paudel, D., Nightingale, A., Shrestha, K., Watto, M. A., & Kotru, R. (2019). Governance: Key for environmental sustainability in the Hindu Kush Himalaya. In P. Wester, A. Mishra, A. Mukherji, & A. B. Shrestha (Eds.), *The Hindu Kush Himalaya assessment* (pp. 545-578). Springer Nature. https://link.springer.com/chapter/10.1007/978-3-319-92288-1_16
- Onta, N., & Resurreccion, B. P. (2011). The role of gender and caste in climate adaptation strategies in Nepal: Emerging change and persistent inequalities in the far-western region. *Mountain Research and Development*, 31(4), 351-356. <https://doi.org/10.1659/MRD-JOURNAL-D-10-00085.1>
- Orlove, B. (2009). Glacier retreat: Reviewing the limits of human adaptation to climate change. *Environment: Science and Policy for Sustainable Development*, 51(3), 22-34. <https://doi.org/10.3200/ENVT.51.3.22-34>
- Orr, A., Ahmad, B., Alam, U., Appadurai, A., Bharucha, Z. P., Biemans, H., Bolch, T., Chaulagain, N. P., Dhaubanjari, S., Dimri, A. P., & Dixon, H. (2022). Knowledge priorities on climate change and water in the Upper Indus Basin: A horizon scanning exercise to identify the top 100 research questions in social and natural sciences. *Earth's Future*, 10(4), p.e2021EF002619. <https://doi.org/10.1029/2021EF002619>
- Palomo, I. (2017). Climate change impacts on ecosystem services in high mountain areas: A literature review. *Mountain Research and Development*, 37(2), 179-187. <https://doi.org/10.1659/MRD-JOURNAL-D-16-00110.1>
- Pandey, A. (Ed.) (2019). Annex I: Glossary. In P. Wester, A. Mishra, A. Mukherji, & A. B. Shrestha (Eds.), *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability and people* (pp. 579-608). Springer Nature. <https://link.springer.com/content/pdf/bbm:978-3-319-92288-1/1?pdf=chapter%20toc>
- Pandey, A., Prakash, A., & Werners, S. E. (2021). Matches, mismatches and priorities of pathways from a climate-resilient development perspective in the mountains of Nepal. *Environmental Science & Policy*, 125(4), 135-145. <https://doi.org/10.1016/j.envsci.2021.08.013>
- Pandey, A., Prakash, A., Barua, A., Syed, A., & Nepal, S. (2020). Upstream-downstream linkages in Ganges-Brahmaputra-Meghna basin: The hydro-social imperatives. *Water Policy*, 22(6), 1082-1097. <https://doi.org/10.2166/wp.2020.231>
- Pandey, R. (2021). Male out-migration from the Himalaya: Implications in gender roles and household food (in) security in the Kaligandaki Basin, Nepal. *Migration and Development*, 10(3), 313-341. <https://doi.org/10.1080/21632324.2019.1634313>
- Parveen, S., Winiger, M., Schmidt, S., & Nüsser, M. (2015). Irrigation in Upper Hunza: Evolution of socio-hydrological interactions in the Karakoram, northern Pakistan. *Erdkunde*, 69(1), 69-85. <https://doi.org/10.3112/erdkunde.2015.01.05>
- Pasakhala, B., Ghate, R., Phuntsho, K., Gentle, P., Gurung, J., Shrestha, A., Gurung, K., & Thapa, S. (2021) Against the tide: The future of transhumant herders in the Kailash Sacred Landscape of Nepal. *Mountain Research and Development*, 41(4), R8-R15. <https://doi.org/10.1659/MRD-JOURNAL-D-20-00073.1>
- Pasakhala, B., Maharjan, A., Tuladhar, S., & Mishra, A. (2022). Cryosphere changes, cascading risks, and societies – a case in the Langtang Valley, Nepal. In P. K. Pradhan and W. Leimgruber (Eds.), *Nature, society, and marginality: Case studies from Nepal, Southeast Asia, and other regions* (pp. 49-64). Springer Nature. <https://link.springer.com/book/9783031213243>
- Pathak, S. (2016). Himalaya: Highest, holy and hijacked. In R. Chand & W. Leimgruber (Eds.), *Globalization and marginalization in mountain regions* (pp. 87-109). Springer Nature. https://link.springer.com/chapter/10.1007/978-3-319-32649-8_7
- Pathak S., Pant L., & Maharjan, A. (2017). Depopulation trends, patterns, and effects in Uttarakhand, India – a gateway to Kailash Mansarovar. Working Paper 2017/22. ICIMOD. <https://lib.icimod.org/record/32787>

- Paudel, K. P., & Andersen, P. (2010). Assessing rangeland degradation using multi temporal satellite images and grazing pressure surface model in Upper Mustang, Trans Himalaya, Nepal. *Remote Sensing of Environment*, 114(8), 1845-1855. <https://www.sciencedirect.com/science/article/abs/pii/S0034425710000994>
- Paudel, K. P., & Andersen, P. (2013). Response of rangeland vegetation to snow cover dynamics in Nepal Trans Himalaya. *Climatic Change*, 117(1-2), 149-162. <https://doi.org/10.1007/s10584-012-0562-x>
- Phondani, P. C., Maikhuri, R. K., & Saxena, K. G. (2014). The efficacy of herbal system of medicine in the context of allopathic system in Indian Central Himalaya. *Journal of Herbal Medicine*, 4(3), 147-158. <https://doi.org/10.1016/j.hermed.2014.05.004>
- Piasecki, S. (2019). A mountain as multiverse: Circumnavigating the realities and meta-realities of a Kailas Pilgrim. *Performance Research*, 24(2), 16-23. <https://doi.org/10.1080/13528165.2019.1626146>
- Pinto, A. (2018). *Climate change impacts on agriculture in the northern Himalayas*. Mongabay. <https://india.mongabay.com/2018/12/climate-change-impacts-agriculture-in-the-northern-himalayas/>
- Pradhan, B. K., Sharma, G., Subba, B., Chettri, S., Chettri, A., Chettri, D. R., & Pradhan, A. (2020). Distribution, harvesting, and trade of Yartsa Gunbu (*Ophiocordyceps sinensis*) in the Sikkim Himalaya, India. *Mountain Research and Development*, 40(2), R41-R49. <https://doi.org/10.1659/MRD-JOURNAL-D-19-00039.1>
- Prakash, A., & Molden, D. (Eds.). (2020). *Water in Himalayan towns: Lessons for adaptive water governance*. IWA Publishing. <https://www.iwapublishing.com/books/9781789061895/water-himalayan-towns-lessons-adaptive-water-governance>
- Prasad, C., & Sharma, R. C. (2019). Water resources and their traditional management in Kedarnath valley of Garhwal Himalaya, India. *International Journal of Hydrology*, 3(3), 194-203. <https://doi.org/10.15406/ijh.2019.03.00180>
- Prasain, S. (2018). Climate change adaptation measure on agricultural communities of Dhye in Upper Mustang, Nepal. *Climatic Change*, 148(2), 279-291. <https://doi.org/10.1007/s10584-018-2187-1>
- Price, M., & Kim, E. (1999). Priorities for sustainable development in Europe. *The International Journal of Sustainable Development & World Ecology*, 6(3), 203-219. <https://doi.org/10.1080/13504509909470011>
- Qi, W., & Yi, J. (2021). Spatial pattern and driving factors of migrants on the Qinghai-Tibet Plateau: Insights from short-distance and long-distance population migrants. *Journal of Geographical Sciences*, 31(2), 215-230. <https://doi.org/10.1007/s11442-021-1843-y>
- Qin, L. (2016). *Xinjiang ban on glacier tourism ignores the bigger problem*. Third Pole. <https://www.thethirdpole.net/en/climate/xinjiang-ban-on-glacier-tourism-ignores-the-bigger-problem/>
- Qureshi, A. S. (2011). Water management in the Indus Basin in Pakistan: Challenges and opportunities. *Mountain Research and Development*, 31(3), 252-260. <https://doi.org/10.1659/MRD-JOURNAL-D-11-00019.1>
- Raina, R. K., & Koul, M. N. (2011). Impact of climatic change on agro-ecological zones of the Suru-Zanskar valley, Ladakh (Jammu and Kashmir), India. *Journal of Ecology and the Natural Environment*, 3(13), 424-440. <https://academicjournals.org/journal/JENE/article-full-text-pdf/0120EBC10245>
- Ramasamy, R., & Swamy, A. (2012). Global warming, climate change and tourism: A review of literature. *CULTUR: Revista de Cultura e Turismo*, 6(3), 72-98. <https://dialnet.unirioja.es/descarga/articulo/5322623.pdf>
- Ranjan, P., & Pandey, P. K. (2020). Reviving development and protection of springs to increase water security in the Himalayan Region. *Proceedings of the 5th international conference on computers & management skills (ICCM 2019)*. Northeastern Regional Institute of Science & Technology (NERIST). https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3516630
- Rashid, I., Majeed, U., Aneaus, S., & Pelto, M. (2020). Linking the recent glacier retreat and depleting streamflow patterns with land system changes in Kashmir Himalaya, India. *Water*, 12(4), 1168. <https://doi.org/10.3390/w12041168>
- Rasul, G., Hussain, A., Adhikari, L., & Molden, D. J. (2022). Conserving agrobiodiversity for sustainable food systems in the Hindu Kush Himalaya. *International Journal of Agricultural Sustainability*. <https://doi.org/10.1080/14735903.2022.2057642>
- Rasul, G., & Molden, D. (2019). The global social and economic consequences of mountain cryospheric change. *Frontiers in Environmental Science*, 7(91), 1-18. <https://doi.org/10.3389/fenvs.2019.00091>
- Rasul, G., Pasakhala, B., Mishra, A., & Pant, S. (2020). Adaptation to mountain cryosphere change: Issues and challenges. *Climate and Development*, 12(4), 297-309. <https://doi.org/10.1080/17565529.2019.1617099>
- Rasul, G., Saboor, A., Tiwari, P. C., Hussain, A., Ghosh, N., & Chettri, G. B. (2019). Food and nutrition security in the Hindu Kush Himalaya: Unique challenges and niche opportunities. In P. Wester, A. Mishra, A. Mukherji, & A. B. Shrestha (Eds.), *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability, and people* (pp. 301-338). Springer Nature. https://link.springer.com/chapter/10.1007/978-3-319-92288-1_9

- Rautela, P., & Karki, B. (2015). Impact of climate change on life and livelihood of indigenous people at higher Himalaya in Uttarakhand, India. *American Journal of Environmental Protection*, 3(4), 112-124. [https://usdma.uk.gov.in/PDFFiles/Piyooosh_and_Bhavna_CC_1\[1\].pdf](https://usdma.uk.gov.in/PDFFiles/Piyooosh_and_Bhavna_CC_1[1].pdf)
- Rawat, A. S., & Sah, R. (2009). Traditional knowledge of water management in Kumaon Himalaya. *Indian Journal of Traditional Knowledge*, 8(2), 249–254. <http://nopr.niscpr.res.in/handle/123456789/3942>
- Rayamajhi, N., & Manandhar, B. (2020). Impact of climate change and adaptation measures on transhumance herding system in Gatlang, Rasuwa. *Air, Soil and Water Research*, 13, 1–10. <https://doi.org/10.1177/1178622120951173>
- Resurrección, B. P., Goodrich, C. G., Song, Y., Bastola, A., Prakash, A., Joshi, D., Liebrand, J., Shah, S. A. (2019). In the shadows of the Himalayan mountains: Persistent gender and social exclusion in development. In P. Wester, A. Mishra, A. Mukherji, and A. B. Shrestha (Eds.), *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability, and people* (pp. 491-516). Springer Nature. <https://lib.icimod.org/record/34398>
- Richardson, S. D., & Reynolds, J. M. (2000). An overview of glacial hazards in the Himalayas. *Quaternary International*, 65, 31-47. [https://doi.org/10.1016/S1040-6182\(99\)00035-X](https://doi.org/10.1016/S1040-6182(99)00035-X)
- Robinson, J. B., & Herbert, D. (2001). Integrating climate change and sustainable development. *International Journal of Global Environmental Issues*, 1(2), 130–149. <http://dx.doi.org/10.1504/IJGENVI.2001.000974>
- Rokaya, M., Muzbergova, Z., & Dostalek, T. (2017). Sustainable harvesting strategy of medicinal plant species in Nepal - results of a six-year study. *Folia Geobotanica*, 52, 239-252. <https://doi.org/10.1007/s12224-017-9287-y>
- Romeo, R., Grita, F., Parisi, F., & Russo, L. (2020). *Vulnerability of mountain peoples to food insecurity: Updated data and analysis of drivers*. FAO and UNCCD. <https://doi.org/10.4060/cb2409en>
- Romshoo, S. A., Dar, R. A., Rashid, I., Marazi, A., Ali, N., & Naz, S. N. (2015). Implications of shrinking cryosphere under changing climate on the streamflow in the Lidder catchment in the Upper Indus Basin, India. *Arctic, Antarctic, and Alpine Research*, 47(4), 627-644. <https://doi.org/10.1657/AAAR0014-088>
- Samui, S., & Sethi, N. (2022). Social vulnerability assessment of glacial lake outburst flood in a northeastern state in India. *International Journal of Disaster Risk Reduction*, 74(3), 102907. <https://doi.org/10.1016/j.ijdrr.2022.102907>
- Sati, V. P. (2021). Out-migration in Uttarakhand Himalaya: Its types, reasons, and consequences. *Migration Letters*, 18(3), 281-295. <https://migrationletters.com/index.php/ml/article/view/957/1008>
- Saxer, M. (2017). New roads, old trades: Neighbouring China in north-western Nepal. In J. Saxer & M. Zhang (Eds.), *The art of neighbouring: Making relations across China's borders* (pp. 73-92). Amsterdam University Press. <https://doi.org/10.4000/ebhr.396>
- Schweizer, J., Bruce Jamieson, J., & Schneebeili, M. (2003). Snow avalanche formation. *Reviews of Geophysics*, 41(4), 1016. <https://doi.org/10.1029/2002RG000123>
- Scott, C. A., Zhang, F., Mukherji, A., Immerzeel, W., Mustafa, D., & Bharati, L. (2019). Water in the Hindu Kush Himalaya. In P. Wester, A. Mishra, A. Mukherji, & A. B. Shrestha (Eds.), *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability, and people* (pp. 257-299). Springer Nature. https://doi.org/10.1007/978-3-319-92288-1_8
- Scott, D., McBoyle, G., & Schwartzentruber, M. (2004). Climate change and the distribution of climatic resources for tourism in North America. *Climate Research*, 27(2), 105-117. <https://doi.org/10.3354/cr027105>
- Shah, A., & Thompson, T. (2004). *Implementing decentralized local governance: Treacherous road with potholes, detours, and road closures*. Policy Research Working Paper 3353. World Bank. <https://doi.org/10.4337/9781845421656.00023>
- Shaheen, F. A., Wani, M. H., Wani, S. A., & Norphel, C. (2013). Climate change impact in cold arid desert of north--western Himalaya: Community based adaptations and mitigations. In S. Nautiyal, K. Rao, H. Kaechele, K. Raju, & R. Schaldach (Eds.), *Knowledge systems of societies for adaptation and mitigation of impacts of climate change* (pp. 239-256). Springer Nature. https://link.springer.com/chapter/10.1007/978-3-642-36143-2_15
- Shang, Z. H., Gibba, M. J., & Long, R. J. (2012). Effect of snow disasters on livestock farming in some rangeland regions of China and mitigation strategies – a review. *The Rangeland Journal*, 34(1), 89-101. <https://doi.org/10.1071/RJ11052>
- Shaoliang, Y., & Sharma, E. (2009). *Climate change and the Hindu Kush–Himalayan rangelands*. Information Sheet no. 8/09. ICIMOD. https://lib.icimod.org/record/26773/files/attachment_657.pdf
- Sharma, A., Batish, D. R., & Uniyal, S. K. (2020). Documentation and validation of climate change perception of an ethnic community of the western Himalaya. *Environmental Monitoring and Assessment*, 192(8), 1-22. <https://doi.org/10.1007/s10661-020-08512-x>
- Sharma, B. M. S., Nizzetto, L., Bharat, G. K., Tayal, S., Melymuk, L., Sanka, O., Pribylova, P., Audy, O., & Larssen, T. (2015). Melting Himalayan glaciers contaminated by legacy atmospheric depositions are important sources of PCBs and high-molecular-weight PAHs for the Ganges floodplain during dry periods. *Environmental Pollution*, 206, 588-596. <https://doi.org/10.1016/j.envpol.2015.08.012>

- Sharma, E., Molden, D., Rahman, A., Khatiwada, Y. R., Zhang, L., Singh, S. P., Yao, T., & Wester, P. (2019). Introduction to the Hindu Kush Himalaya assessment. In P. Wester, A. Mishra, A. Mukherji, & A. B. Shrestha (Eds.), *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability, and people* (pp. 1-16). Springer Nature. https://link.springer.com/chapter/10.1007/978-3-319-92288-1_1
- Sharma, R. C., Bahuguna, M., & Chauhan, P. (2008). Periphytonic diversity in Bhagirathi: Preimpoundment study of Tehri dam reservoir. *Journal of Environmental Science and Engineering*, 50(4), 255-262. <https://pubmed.ncbi.nlm.nih.gov/19697759/>
- Sharma, R. C., & Kumar, R. (2017). Water quality assessment of sacred glacial Lake Satopanth of Garhwal Himalaya, India. *Applied Water Science*, 7(8), 4757-4764. <https://doi.org/10.1007/s13201-017-0638-x>.
- Sherpa, P. Y. (2015). Institutional climate change adaptation efforts among the Sherpas of the Mount Everest region, Nepal. *Climate Change, Culture, and Economics: Anthropological Investigations*, 35, 3-23. <https://ideas.repec.org/h/eme/reanzz/s0190-128120150000035001.html>
- Sherpa, S. F., Shrestha, M., Eakin, H., & Boone, C. G. (2019). Cryospheric hazards and risk perceptions in the Sagarmatha (Mt. Everest) national park and buffer zone, Nepal. *Natural Hazards*, 96(6079), 607-626. <https://doi.org/10.1007/s11069-018-3560-0>
- Sherry, J., & Curtis, A. (2017). At the intersection of disaster risk and religion: Interpretations and responses to the threat of Tsho Rolpa glacial lake. *Environmental Hazards*, 16(4), 314-329. <https://doi.org/10.1080/17477891.2017.1298983>
- Shi-Jin, W., & Lan-Yue, Z. (2019). Integrated impacts of climate change on glacier tourism. *Advances in Climate Change Research*, 10(2), 71-79. <https://doi.org/10.1016/j.accre.2019.06.006>
- Shijin, W., Jia X., & Lanyue, Z. (2020). China's glacier tourism: Potential evaluation and spatial planning. *Journal of Destination Marketing and Management*, 18, 100506. <https://doi.org/10.1016/j.jdmm.2020.100506>
- Shrestha, A. B., & Aryal, R. (2011). Climate change in Nepal and its impact on Himalayan glaciers. *Regional Environmental Change*, 11(1), 65-77. <https://doi.org/10.1007/s10113-010-0174-9>
- Shrestha, A. B., Eriksson, M., Mool, P., Ghimire, P., Mishra, B., & Khanal, N. R. (2010). Glacial lake outburst flood risk assessment of Sun Koshi basin, Nepal. *Geomatics, Natural Hazards and Risk*, 1(2), 157-169. <https://doi.org/10.1080/19475701003668968>
- Shrestha, B. B., & Jha, P. K. (2009). Habitat range of two alpine medicinal plants in a trans-Himalayan dry valley, Central Nepal. *Journal of Mountain Science*, 6(1), 66-77. <https://doi.org/10.1007/s11629-009-0209-1>
- Shrestha, R. P., Pasakhala, B., & Qasim, S. (2019). Assessing household vulnerability to climate variability in far-west Nepal. *Journal of Sustainable Development Studies*, 12(2), 83-118. <https://www.infinitypress.info/index.php/jds/article/view/1813>
- Shrestha, U. B., & Bawa, K. S. (2013). Trade, harvest, and conservation of caterpillar fungus (*Ophiocordyceps sinensis*) in the Himalayas. *Biological Conservation*, 159, 514-520. <https://doi.org/10.1016/j.biocon.2012.10.032>
- Shrestha, U. B., & Bawa, K. S. (2014). Economic contribution of Chinese caterpillar fungus to the livelihoods of mountain communities in Nepal. *Biological Conservation*, 177, 194-202. <https://doi.org/10.1016/j.biocon.2014.06.019>
- 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., ... & Westoby, M. J. (2021). A massive rock and ice avalanche caused the 2021 disaster at Chamoli, Indian Himalaya. *Science*, 373(6552), 300-306. <https://doi.org/10.1126/science.abh4455>
- Siderius, C., Biemans, H., Wiltshire, A., Rao, S., Franssen, W. H. P., Kumar, P., Gosain, A. K., van Vliet, M. T. H., & Collins, D. N. (2013). Snowmelt contributions to discharge of the Ganges. *Science of the Total Environment*, 468-469, S93-S101. <https://doi.org/10.1016/j.scitotenv.2013.05.084>
- Sidh, S. N., & Basu, S. (2011). Women's contribution to household food and economic security: A study in the Garhwal Himalayas India. *Mountain Research and Development*, 31(2), 102-111. <https://doi.org/10.1659/MRD-JOURNAL-D-10-00010.1>
- Šimková, E. (2014). Psychology and its application in tourism. *Procedia - Social and Behavioural Sciences*, 114, 317-321. <https://doi.org/10.1016/j.sbspro.2013.12.704>
- Simons, G. W. H., Bastiaanssen, W. G. M., Cheema, M. J. M., Ahmad, B., & Immerzeel, W. W. (2020). A novel method to quantify consumed fractions and non-consumptive use of irrigation water: Application to the Indus Basin irrigation system of Pakistan. *Agricultural Water Management*, 236, 106174. <https://doi.org/10.1016/j.agwat.2020.106174>
- Singh, C., Iyer, S., New, M. G., Few, R., Kuchimanchi, B., Segnon, A. C., & Morchain, D. (2022). Interrogating 'effectiveness' in climate change adaptation: Eleven guiding principles for adaptation research and practice. *Climate and Development*, 14(7), 650-664. <https://doi.org/10.1080/17565529.2021.1964937>

- Singh, R., Sharma, R. K., Babu, S., & Bhatnaga, Y. V. (2020). Traditional ecological knowledge and contemporary changes in the agro-pastoral system of Upper Spiti landscape, Indian Trans-Himalayas. *Pastoralism: Research, Policy, and Practice*, 10(15), 1-14. <https://doi.org/10.1186/s13570-020-00169-y>
- Singh, S. (2004). Religion, heritage and travel: Case references from the Indian Himalayas. *Current Issues in Tourism*, 7(1), 44-65. <https://doi.org/10.1080/13683500408667972>
- Singh, S. P., & Thadani, R. (2015). Complexities and controversies in Himalayan research: A call for collaboration and rigor for better data. *Mountain Research and Development*, 35(4), 401-409. <https://doi.org/10.1659/MRD-JOURNAL-D-15-00045>
- Slovic, P., & Peters, E. (2006). Risk perception and affect. *Current Directions in Psychological Science*, 15(6), 322-325. <https://doi.org/10.1111/j.1467-8721.2006.00461.x>
- Somos-Valenzuela, M. A., McKinney, D. C., Byers, A. C., Rounce, D. R., Portocarrero, C., & Lamsal, D. (2015). Assessing downstream flood impacts due to a potential GLOF from Imja Tsho in Nepal. *Hydrology and Earth System Sciences*, 19(3), 1401-1412. <https://doi.org/10.5194/hess-19-1401-2015>
- Somos-Valenzuela, M. A., McKinney, D. C., Rounce, D. R., & Byers, A. C. (2014). Changes in Imja Tsho in the Mount Everest region of Nepal. *The Cryosphere*, 8(5), 1661-1671. <https://doi.org/10.5194/tc-8-1661-2014>
- Spies, M. (2016). Glacier thinning and adaptation assemblages in Nagar, Northern Pakistan. *Erdkunde*, 70(2), 125-140. <https://www.jstor.org/stable/24893170>
- Spoon, J., & Sherpa, L. N. (2008). Beyul Khumbu: The Sherpa and Sagarmatha (Mount Everest) national park and buffer zone, Nepal. In J. M. Mallarach (Ed.), *Protected landscapes and cultural and spiritual values* (pp.68-79). The World Conservation (IUCN), GTZ, and Obra Social de Caixa Catalunya. <https://portals.iucn.org/library/node/9310>
- Stäubli, A., Nussbaumer, S. U., Allen, S. K., Huggel, C., Arguello, M., Costa, F., Hergarten, C., Martínez, R., Soto, J., Vargas, R., Zambrano, E., & Zimmermann, M. (2018). Analysis of weather-and climate-related disasters in mountain regions using different disaster databases. In S. Mal, R. Singh, & C. Huggel (Eds.), *Climate change, extreme events, and disaster risk reduction* (pp. 17-41). Springer Nature. https://link.springer.com/chapter/10.1007/978-3-319-56469-2_2
- Su, B., Xiao, C. D., Chen, D., Qin, D., & Ding, Y. (2019). Cryosphere services and human well-being. *Sustainability*, 11(16), 4365. <https://doi.org/10.3390/su11164365>
- Suberi, B., Tiwari, K. R., Gurung, D. B., Bajracharya, R. M., & Sitaula, B. K. (2018). People's perception of climate change impacts and their adaptation practices in Khotokha Valley, Wangdue, Bhutan. *Indian Journal of Traditional Knowledge*, 17(1), 97-105. https://nmbu.brange.unit.no/nmbu-xmlui/bitstream/handle/11250/2586854/Sitaula_Peoples%2Bperception.pdf?sequence=2
- Sujakhu, N., M., Ranjitkar, S., Niraula, R. R., Pokharel, B. K., Schmidt-Vogt, D., & Xu, J. (2016). Farmers' perceptions of and adaptations to changing climate in the Melamchi Valley of Nepal. *Mountain Research and Development*, 36(1), 15-30. <https://doi.org/10.1659/MRD-JOURNAL-D-15-00032.1>
- Sun, X., Wang, K., Kang, S., Guo, J., Zhang, G., Huang, J., Cong, Z., Sun, S., & Zhang, Q. (2017). The role of melting alpine glaciers in mercury export and transport: An intensive sampling campaign in the Qugaqie basin, inland Tibetan Plateau. *Environmental Pollution*, 220, 936-945. <https://doi.org/10.1016/j.envpol.2016.10.079>
- Snyder, A. (2014). *Shortage in the mountains of plenty: Water supply in mountain and hill cities throughout the Hindu-Kush Himalayan Region*. ICIMOD and The World Food Prize. https://www.worldfoodprize.org/documents/filelibrary/images/youth_programs/2014_interns/2014_br_research_papers/SnyderAbigail_LONGReport_56ED38F157B76.pdf
- Tan, C. (2015). *Himalaya calling: The origins of China and India*. World Century Publishing Corporation.
- TFDD (n.d.). *Transboundary freshwater dispute database*. <https://transboundarywaters.science.oregonstate.edu/content/transboundary-freshwater-dispute-database>
- Thakuri, S., Chauhan, R., & Baskota, P. (2020). Glacial hazards and avalanches in high mountains of Nepal Himalaya. *Journal of Tourism Himalayan Adventures*, 2, 87-104.
- Thompson, I., Shrestha, M., Chhetri, N., & Agusdinata, D. B. (2020). An institutional analysis of glacial floods and disaster risk management in the Nepal Himalaya. *International Journal of Disaster Risk Reduction*, 47, 101567. <https://doi.org/10.1016/j.ijdrr.2020.101567>
- Tiwari, K. R., Sitaula, B. K., Bajracharya, R. M., Raut, N., Bhusal, P., & Sengel, M. (2020). Vulnerability of pastoralism: A case study from the high mountains of Nepal. *Sustainability*, 12(7), 2737. <https://doi.org/10.3390/su12072737>
- Tiwari, P. C., Tiwari, A., & Joshi, B. (2018). Urban growth in Himalaya: Understanding the process and options for sustainable development. *Journal of Urban and Regional Studies on Contemporary India*, 4(2), 15-27. <https://doi.org/10.15027/45582>

- Toset, H. P. W., Gleditsch, N. P., & Hegre, H. (2000). Shared rivers and interstate conflict. *Political Geography*, 19(8), 971-996. [https://doi.org/10.1016/S0962-6298\(00\)00038-X](https://doi.org/10.1016/S0962-6298(00)00038-X)
- Tourism Council of Bhutan (2022). 2019 Bhutan tourism satellite account. https://www.tourism.gov.bt/uploads/attachment_files/tcb_jP2NfOiM_Bhutan%20Tourism%20Satellite%20Account.pdf
- Tuladhar, S., Pasakhala, B., Maharjan, A., & Mishra, A. (2021). Unravelling the linkages of cryosphere and mountain livelihood systems: A case study of Langtang, Nepal. *Advances in Climate Change Research*, 12(1), 119-131. <https://doi.org/10.1016/j.accre.2020.12.004>
- UN. (2012). *The future we want*. Rio +20 United Nations Conference on Sustainable Development. <https://sustainabledevelopment.un.org/content/documents/733FutureWeWant.pdf>
- UN. (2015). *Transforming our world: The 2030 agenda for sustainable development*. United Nations. <https://sdgs.un.org/2030agenda>
- UNCTAD. (2021). *The least developed countries in the post-COVID world: Learning from 50 years of experience*. United Nations Conference on Trade and Development. <https://unctad.org/publication/least-developed-countries-report-2021>
- Urakawa, R., Shibata, H., Kuroiwa, M., Inagaki, M., Tateno, R., Hishi, T., Fukuzawa, K., Hirai, K., Toda, H., Oyanagi, N., Nakata, M., Nakanishi, A., Fukushima, K., Enoki, T., & Suwa, Y. (2014). Effects of freeze-thaw cycles resulting from winter climate change on soil nitrogen cycling in ten temperate forest ecosystems throughout the Japanese archipelago. *Soil Biology and Biochemistry*, 74, 82-94. <https://doi.org/10.1016/j.soilbio.2014.02.022>
- Vaidya, R. A., Shrestha, M. S., Nasab, N., Gurung, D. R., Kozo, N., Pradhan, N. S., & Wasson, R. J. (2019). Disaster risk reduction and building resilience in the Hindu Kush Himalaya. In P. Wester, A. Mishra, A. Mukherji, and A. B. Shrestha (Eds.), *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability, and people* (pp. 389-419). Springer Nature. <https://lib.icimod.org/record/34395>
- van der Geest, K., & Schindler, M. (2016). Brief communication: Loss and damage from a catastrophic landslide in Nepal. *Natural Hazards and Earth System Sciences*, 16(11), 2347-2350. <https://doi.org/10.5194/nhess-16-2347-2016>
- Vedwan, N. (2006). Culture, climate, and the environment: Local knowledge and perception of climate change among apple growers in Northwestern India. *Journal of Ecological Anthropology*, 10(1), 4-18. <https://digitalcommons.usf.edu/jea/vol10/iss1/1>
- Veh, G., Korup, O., Roessner, S., & Walz, A. (2018). Detecting Himalayan glacial lake outburst floods from Landsat time series. *Remote Sensing of Environment*, 207, 84-97. <https://doi.org/10.1016/j.rse.2017.12.025>
- Viviroli, D., Kumm, M., Meybeck, M., Kallio, M., & Wada, Y. (2020). Increasing dependence of lowland populations on mountain water resources. *Nature Sustainability*, 3(11), 917-928. <https://doi.org/10.1038/s41893-020-0559-9>
- Vorosmarty, C. J., Green, P., Salisbury, J., & Lammers, R. B. (2000). Global water resources: Vulnerability from climate change and population growth. *Science*, 289(5477), 284-288. <https://doi.org/10.1126/science.289.5477.284>
- Vuichard, D., & Zimmermann, M. (1987). The 1985 catastrophic drainage of a moraine-dammed Lake, Khumbu Himal, Nepal: Cause and consequences. *Mountain Research and Development*, 7(2), 91-110. <https://doi.org/10.2307/3673305>
- Walker, A., Halfpenny, J. C., Walker, M. D., & Wessman, C. A. (1993). Long-term studies of snow-vegetation interactions. *BioScience*, 43(5), 287-301. <https://www.jstor.org/stable/1312061>
- Wallrapp, C., Keck, M., & Faust, H. (2019). Governing the yarshagumba 'gold rush': A comparative study of governance system in the Kailash landscape in India and Nepal. *International Journal of the Commons*, 13(1), 1-24. <http://doi.org/10.18352/ijc.884>
- Wang, L. E., Zeng, Y., & Zhong, L. (2017). Impact of climate change on tourism on the Qinghai-Tibetan Plateau: Research based on a literature review. *Sustainability*, 9(9), 1539. <https://doi.org/10.3390/su9091539>
- Wang, S., He, Y., & Song, X. (2010). Impacts of climate warming on Alpine glacier tourism and adaptive measures: A case study of Baishui Glacier No. 1 in Yulong Snow Mountain, Southwestern China. *Journal of Earth Science*, 21(2), 166-178. <https://doi.org/10.1007/s12583-010-0015-2>
- Wang, X., Liu, S. W., & Zhang, J. L. (2019). A new look at roles of the cryosphere in sustainable development. *Advances in Climate Change Research*, 10(2), 124-131. <https://doi.org/10.1016/j.accre.2019.06.005>
- Wang, Y., Wang, J., Li, S., & Qin, D. (2014). Vulnerability of the Tibetan pastoral systems to climate and global change. *Ecology and Society*, 19(4), 8. <http://dx.doi.org/10.5751/ES-06803-190408>
- Wang, Y., Wu, N., Kunze, C., Long, R., & Perlik, M. (2019). Drivers of change to mountain sustainability in the Hindu Kush Himalaya. In P. Wester, A. Mishra, A. Mukherji, and A. B. Shrestha (Eds.), *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability, and people* (pp. 17-56). Springer Nature. https://doi.org/10.1007/978-3-319-92288-1_2

- Waqas, M. A. (2022). Pakistan's floods flow from climate injustice. *Science*, 378(6619), 482-482. <https://doi.org/10.1126/science.ade8490>
- Watson, C. S., & King, O. (2018). Everest's thinning glaciers: Implications for tourism and mountaineering. *Geology Today*, 34(1), 18-25. <https://doi.org/10.1111/gto.12215>
- Wester, P., Mishra, A., Mukherji, A., & Shrestha, A. B. (Eds.), (2019). *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability, and people*. Springer Nature. <https://link.springer.com/book/10.1007/978-3-319-92288-1>
- Wijngaard, R. R., Biemans, H., Lutz, A. F., Shrestha, A. B. Wester, P., & Immerzeel, W. W. (2018). Climate change vs. socio-economic development: Understanding the future South Asian water gap. *Hydrology and Earth System Sciences*, 22(12), 6297-6321. <https://doi.org/10.5194/hess-22-6297-2018>
- Wipf, S., & Rixen, C. (2010). A review of snow manipulation experiments in Arctic and alpine tundra ecosystems. *Polar Research*, 29, 95-109. <https://doi.org/10.3402/polar.v29i1.6054>
- World Bank (2022). *Infrastructure data*. [Data set]. <https://datacatalog.worldbank.org/infrastructure-data>
- World Economic Forum. (2019). *The global risks report*. World Economic Forum. https://www3.weforum.org/docs/WEF_Global_Risks_Report_2019.pdf
- WorldPop. (2018) *Global High Resolution Population Denominators Project* (the spatial distribution of population) [Data set, Res 1 km.]. WorldPop. Retrieved April 28, 2023, from <https://dx.doi.org/10.5258/SOTON/WP00647>
- Wu, X., Zhang, X., Dong, S., Cai, H., Zhao, T., Yang, W., Jiang, R., Shi, Y., & Shao, J. (2015). Local perceptions of rangeland degradation and climate change in the pastoral society of Qinghai-Tibetan Plateau. *The Rangeland Journal*, 37(1), 11-19. <https://doi.org/10.1071/RJ14082>
- Xiao, C. D., Wang, S. J., & Qin, D. H. (2015). A preliminary study of cryosphere service function and value evaluation. *Advances in Climate Change Research*, 6(3), 181-187. <https://doi.org/10.1016/j.accre.2015.11.004>
- Yao, T., Thompson, L., Chen, D., Zhang, Y., Wang, N., Zhao, L., Che, T., Xu, B., Wu, G., Zhang, F., Tang, Q., Immerzeel, W., Bolch, T., Pellicciotti, F., Li, X., Yang, W., Gao, J. & Wang, W. (2020). Third Pole climate warming and cryosphere system changes. *World Meteorological Organization*, 69(1). <https://public.wmo.int/en/resources/bulletin/third-pole-climate-warming-and-cryosphere-system-changes>
- Yarzabal, L. A., Salazar, L. M. B., & Batista-García, R. A. (2021). Climate change, melting cryosphere, and frozen pathogens: Should we worry? *Environmental Sustainability*, 4(3), 489-501. <https://doi.org/10.1007/s42398-021-00184-8>
- Yeh, E. T., Nyima, Y., Hopping, K. A., & Klein, J. A. (2014). Tibetan pastoralists' vulnerability to climate change: A political ecology analysis of snowstorm coping capacity. *Human Ecology*, 42(1), 61-74. <https://doi.org/10.1007/s10745-013-9625-5>
- Yoffe, S., Wolf, A. T., & Giordano, M. (2003). Conflict and cooperation over international freshwater resources: Indicators of basins at risk. *Journal of the American Water Resources Association*, 39(5), 1109-1126. <https://doi.org/10.1111/j.1752-1688.2003.tb03696.x>
- Zeng, H., & Jia, G. (2013). Impacts of snow cover on vegetation phenology in the arctic from satellite data. *Advances in Atmospheric Sciences*, 30(5), 1421-1432. <https://doi.org/10.1007/s00376-012-2173-x>
- Zhang, J., Zhang, W., Liu, S., & Kong, W. (2022). Cryosphere services to support SDGs in high mountains. *Sustainability*, 14(2), 791. <https://doi.org/10.1016/j.gloplacha.2022.103923>
- Zhao, J., Sun, G., & Webster, C. (2022). Does China-Pakistan economic corridor improve connectivity in Pakistan? A protocol assessing the planned transport network infrastructure. *Journal of Transport Geography*, 100(4), 103327. <https://doi.org/10.1016/j.jtrangeo.2022.103327>
- Ziegler, A. D., Wasson, R. J., Sundriyal, Y., Srivastava, P., Sasges, G., Ramchunder, S. J., Ong, C. E., Nepal, S. K., McAdoo, B. G., Gillen, J., Bishwokarma, D., Bhardwaj, A., & Apollo, M. (2021). A call for reducing tourism risk to environmental hazards in the Himalaya. *Environmental Hazards*, 1-28. <https://doi.org/10.1080/17477891.2021.1984196>
- Zurick, D. (2014). *Land of pure vision: The sacred geography of Tibet and the Himalaya*. University Press of Kentucky. <https://www.jstor.org/stable/j.ctt7zwdtp>

About ICIMOD

The International Centre for Integrated Mountain Development (ICIMOD), based in Kathmandu, Nepal, is the leading institute for the study of the Hindu Kush Himalaya (HKH). An intergovernmental knowledge and development organisation with a focus on climate and environmental risks, green economies, and sustainable collective action, we have worked in our eight regional member countries – Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan – since our foundation.

Entering our 40th year, ICIMOD is perfectly positioned to support the transformative action required for the HKH to face the challenges of the escalating effects of climate change, pollution, water insecurity, increased disaster risk, biodiversity loss, and widespread socioeconomic changes. We seek to raise our ambition to support the required transformative action to step up our engagement through to 2030.

REGIONAL MEMBER COUNTRIES



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