CHAPTER 3

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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% ± 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.

Contents

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 (km^2), 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 km^2) 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)

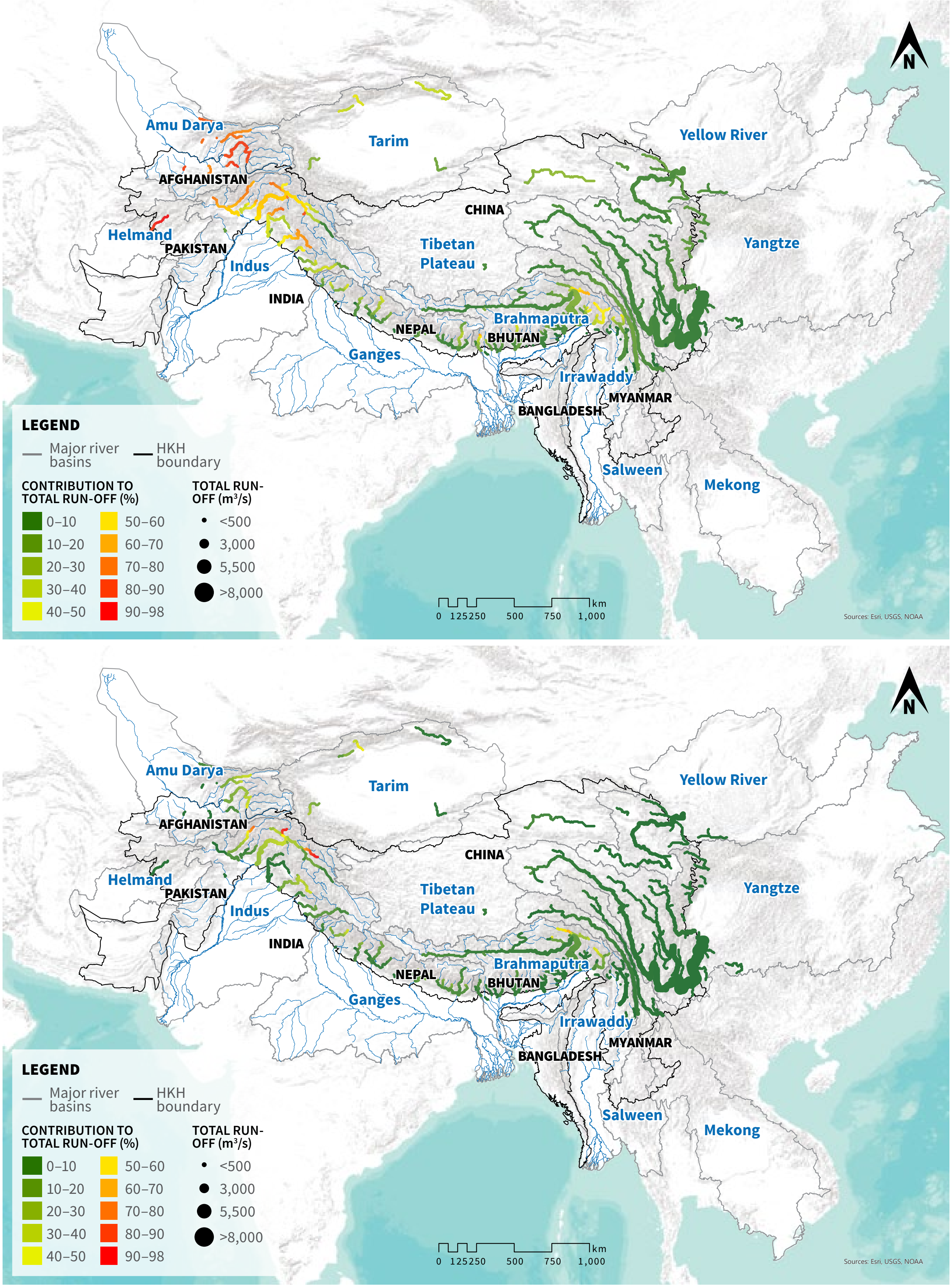
region, snowmelt contributes 41% and glacier melt 46% of the total streamflow (Mimeau et al., 2019). For the same basin downstream, with a catchment area of 3,712 km^2, the snowmelt contribution decreases to about 29% (Nepal et al., 2014). Similarly, in the small catchment of Langtang (360 km^2), the contribution of snowmelt varies between 20% and 30% while glacier melt varies between 13% and 62% (Immerzeel et al., 2013; Racoviteanu et al., 2013; Ragettli 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 km^2), Marsyangdi (4,062 km^2), and Tamor (3,990 km^2) (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).

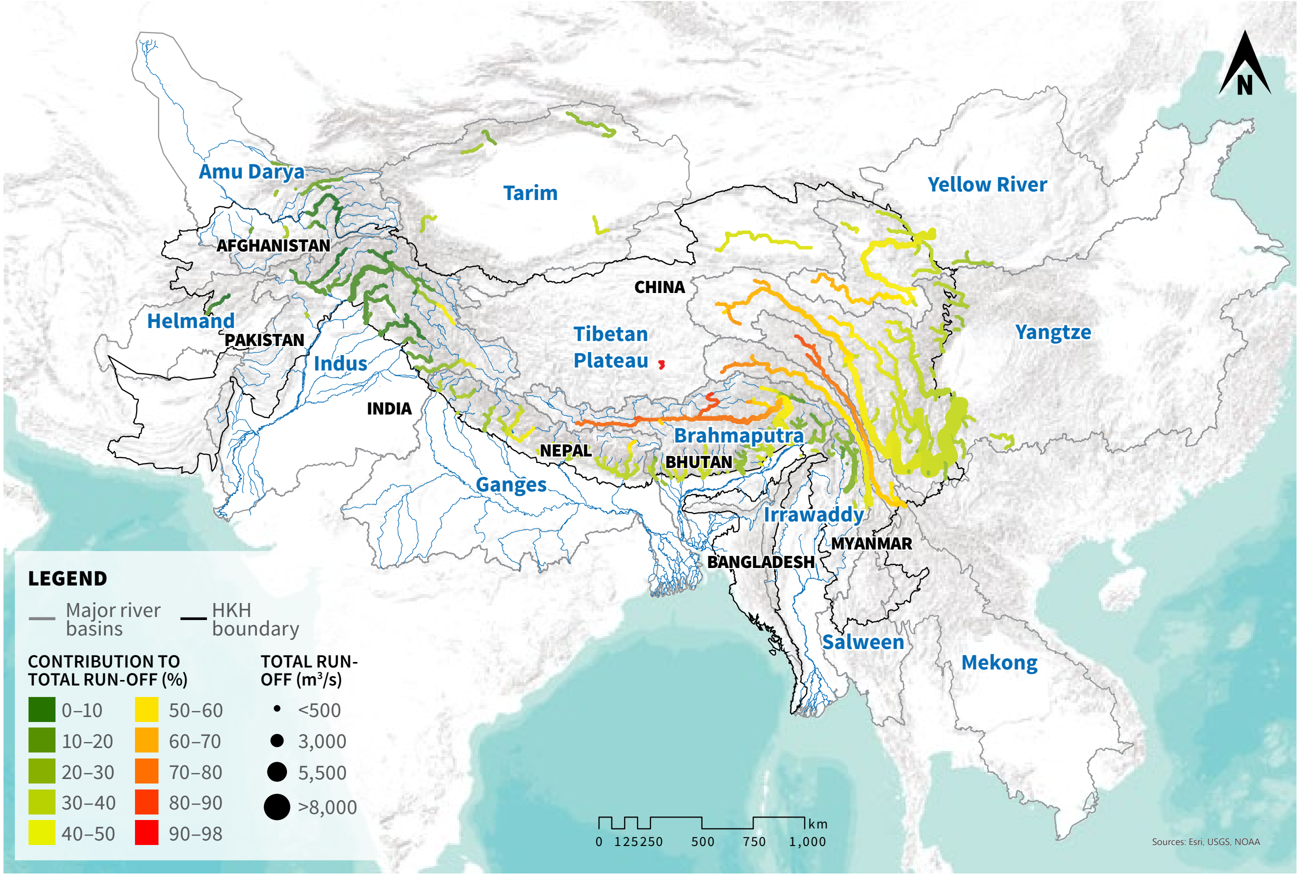
Meltwater is most important in high-elevation, proximal reaches of the HKH river basins. Meltwater volumes are greatest during the spring, summer, and early autumn, when snowmelt and ice melt typically are at their highest due to the higher temperatures in those seasons. In the monsoon-dominated basins, 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.

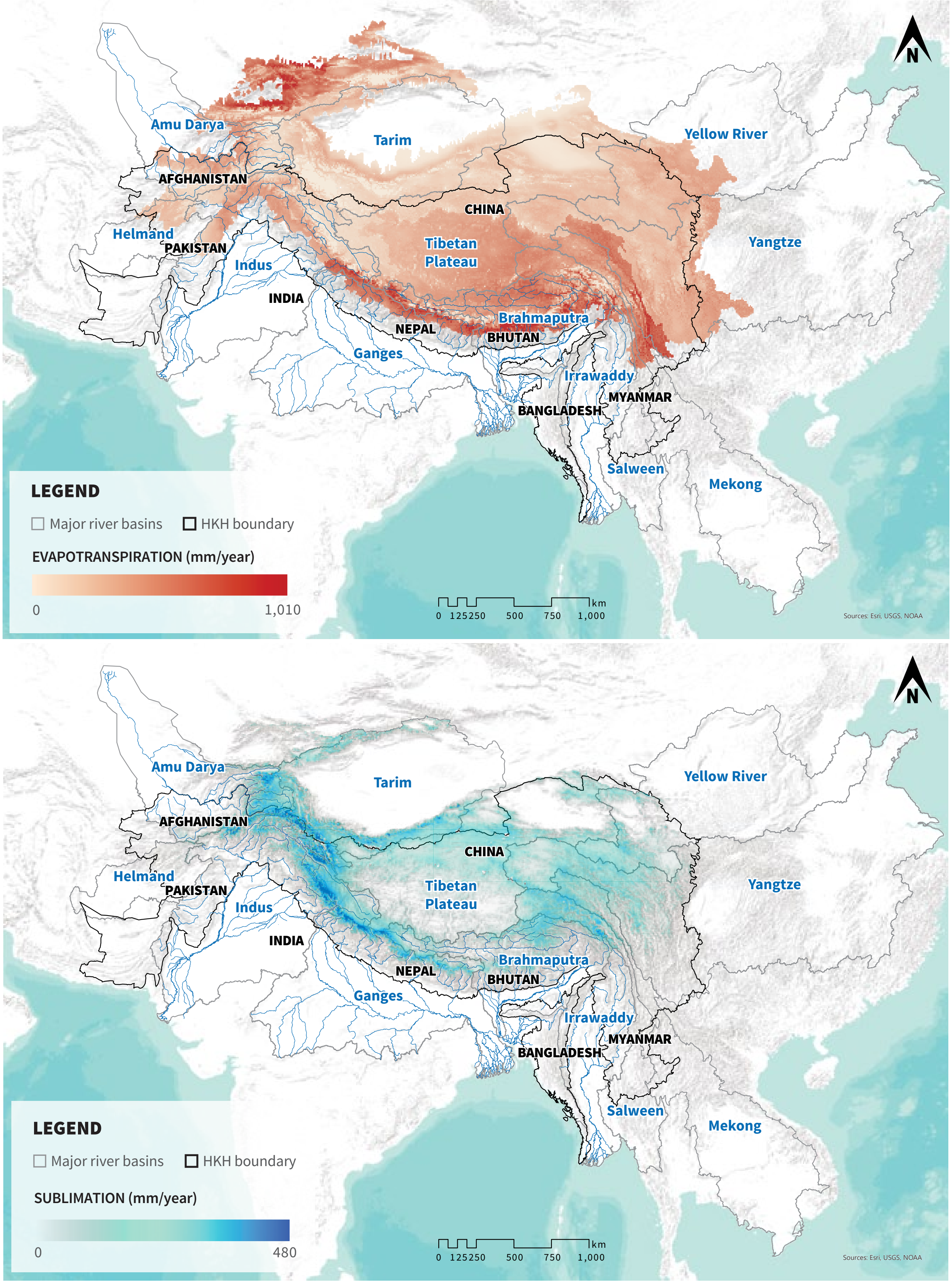
Studies of the Tibetan Plateau have investigated evapotranspiration on a regional scale using satellite data or reanalysis products (Shenbin et al., 2006; Song et al., 2017) as well as climate data of multiple weather stations (W. Wang et al., 2013), or as part of regional hydrological models (Khanal 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 km^3 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)

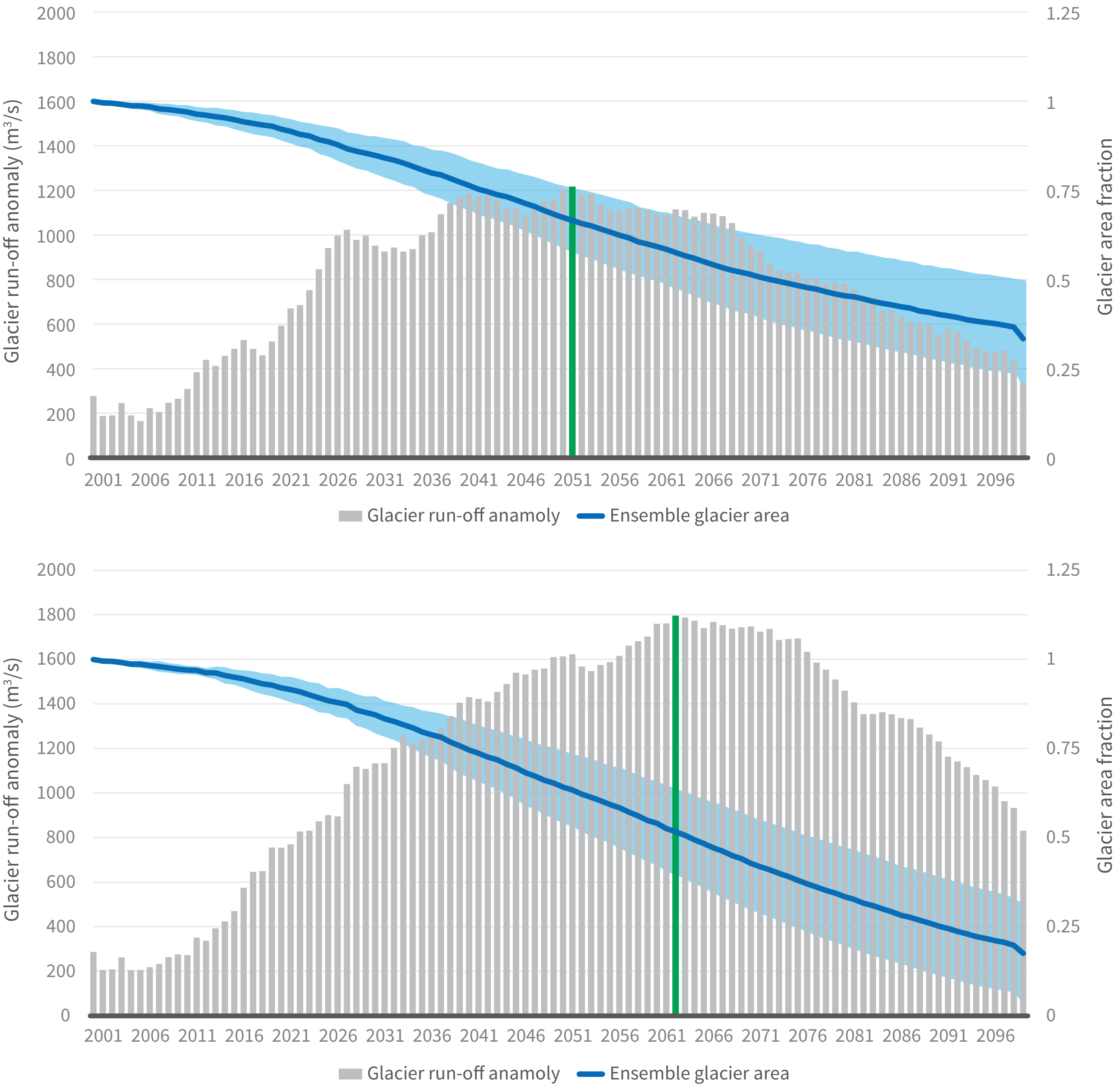
3.2.4. Future changes in melt run-off

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).

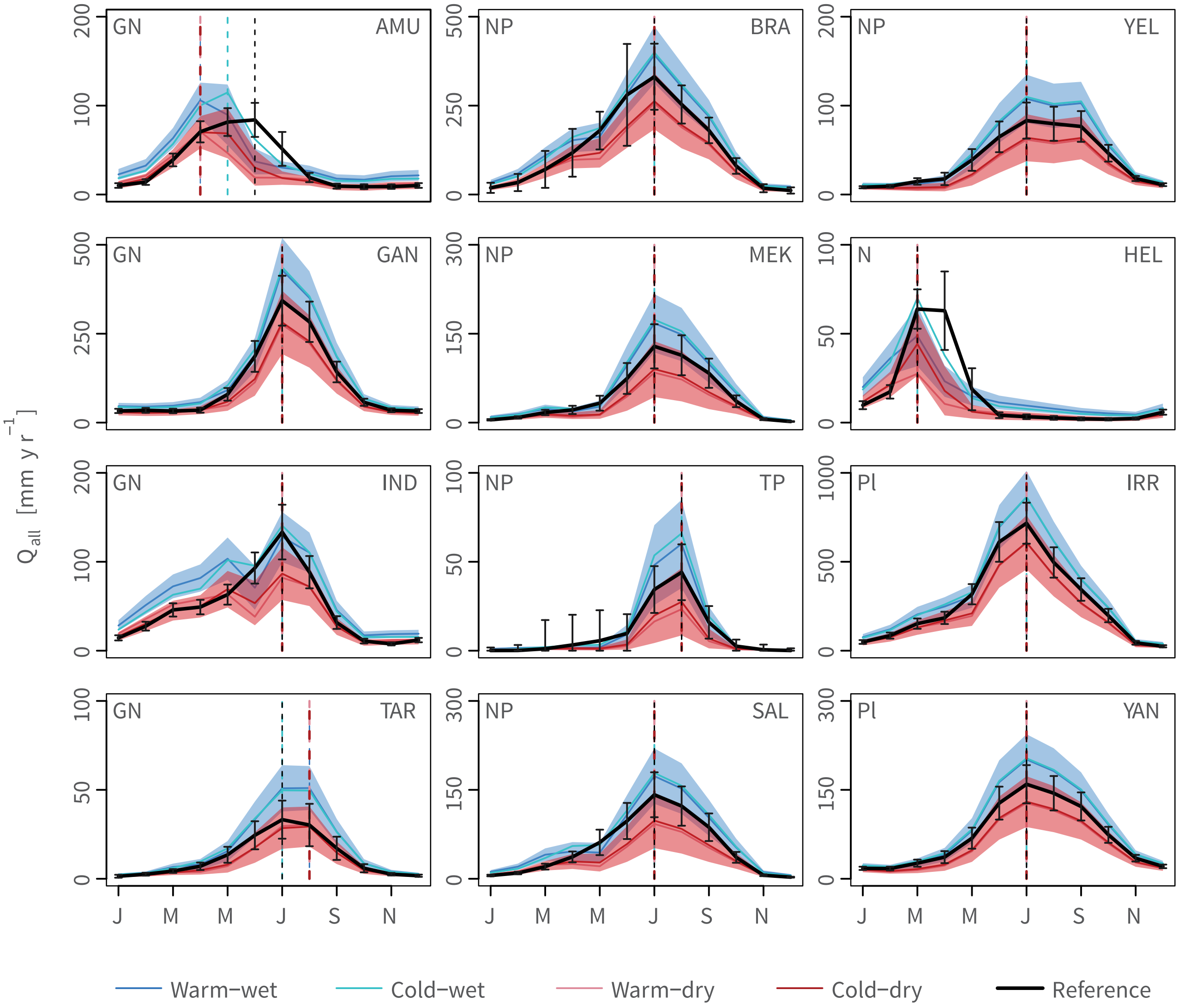
In the HKH, the changes in future total water availability are larger at higher elevations compared to lower elevations for the different hydrological regimes (Khanal et al., 2021). At higher elevations, the total water availability increases either due to an increase in the melt contribution until 'peak 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 (Qall) 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, Pl – 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

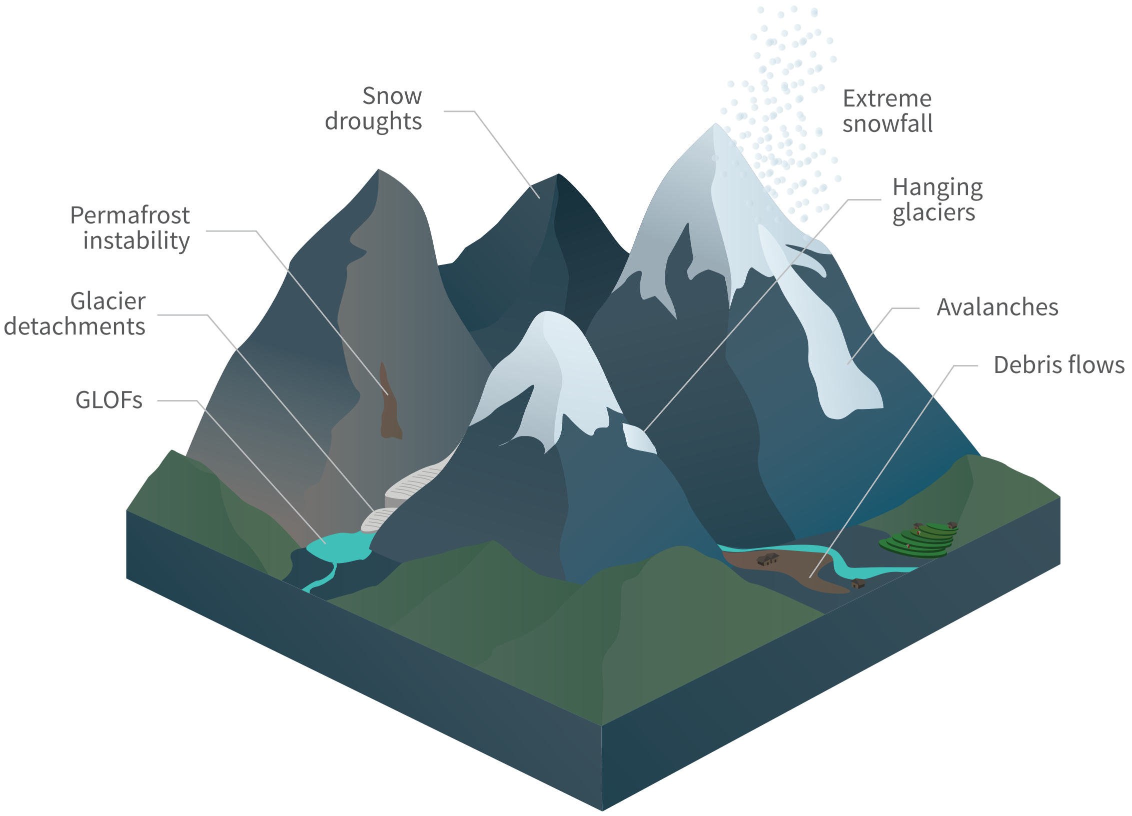
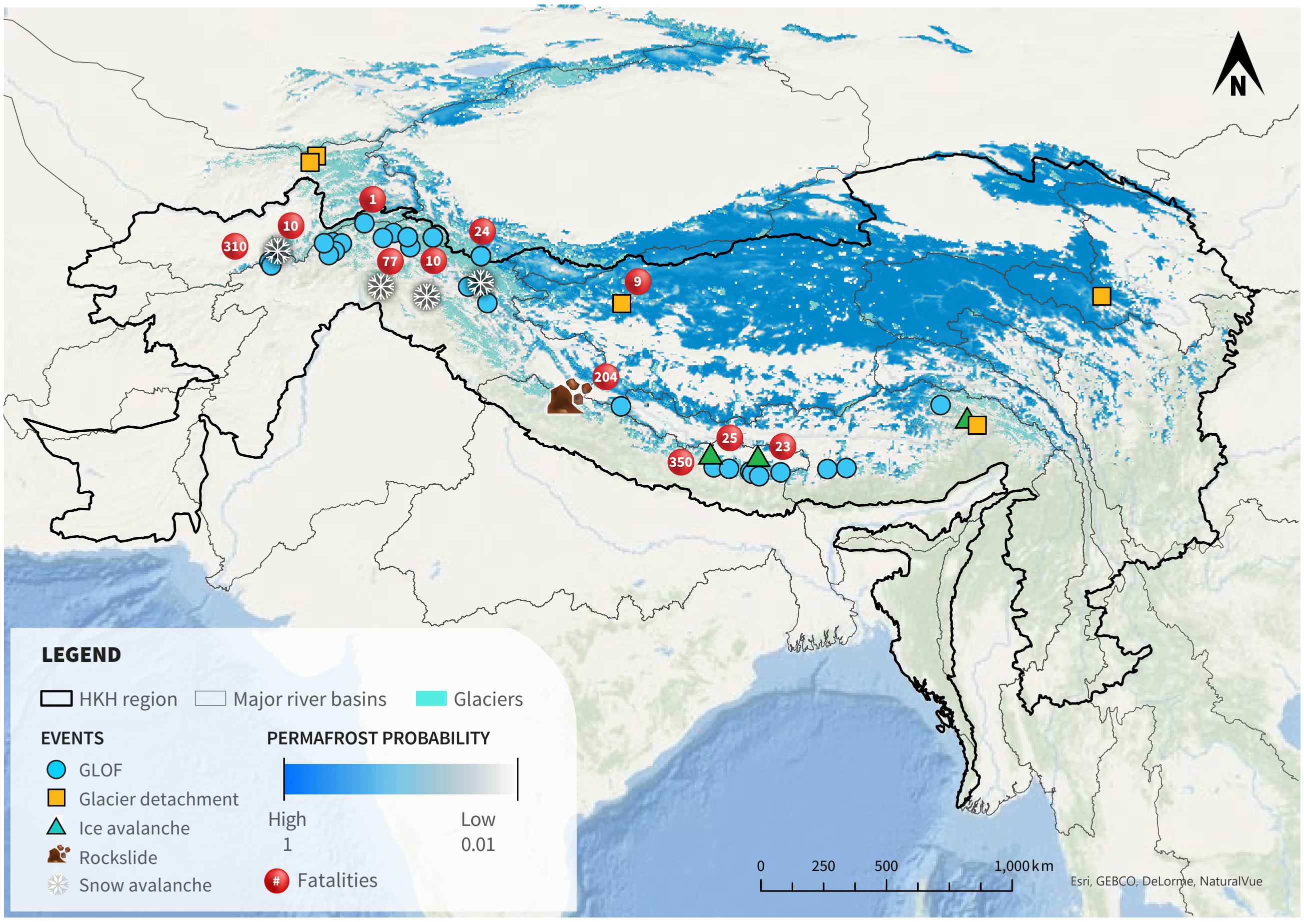


FIGURE 3.6 **OVERVIEW OF ALL RECORDED CRYOSPHERE-RELATED EVENTS IN THE HKH SINCE 2015**



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; Kääb 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 overlaying 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, *snowfall*	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	*Surging glacier, snow accumulation*	–	(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, *snowmelt*	–	
Darmander/ Rogheli/ Badswat GLOFs	2018/2019	Compound + cascading	GLOF, debris flows	Snow and glacier melt, *high intensity rainfall*	–	
Chamoli rockslide	02/2021	Compound + cascading	Ice and rockslide, debris flow	*Ice melt, permafrost thaw*	204	(Shugar et al., 2021)
Melamchi debris flow	06/2021	Compound + cascading	GLOF, LLOF, debris flow	Intense precipitation, *snowmelt, permafrost thaw*	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% ± 5% (mean ± standard error) increase in sediment load, and that a 1°C increase in air temperature results in a 32% ± 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.

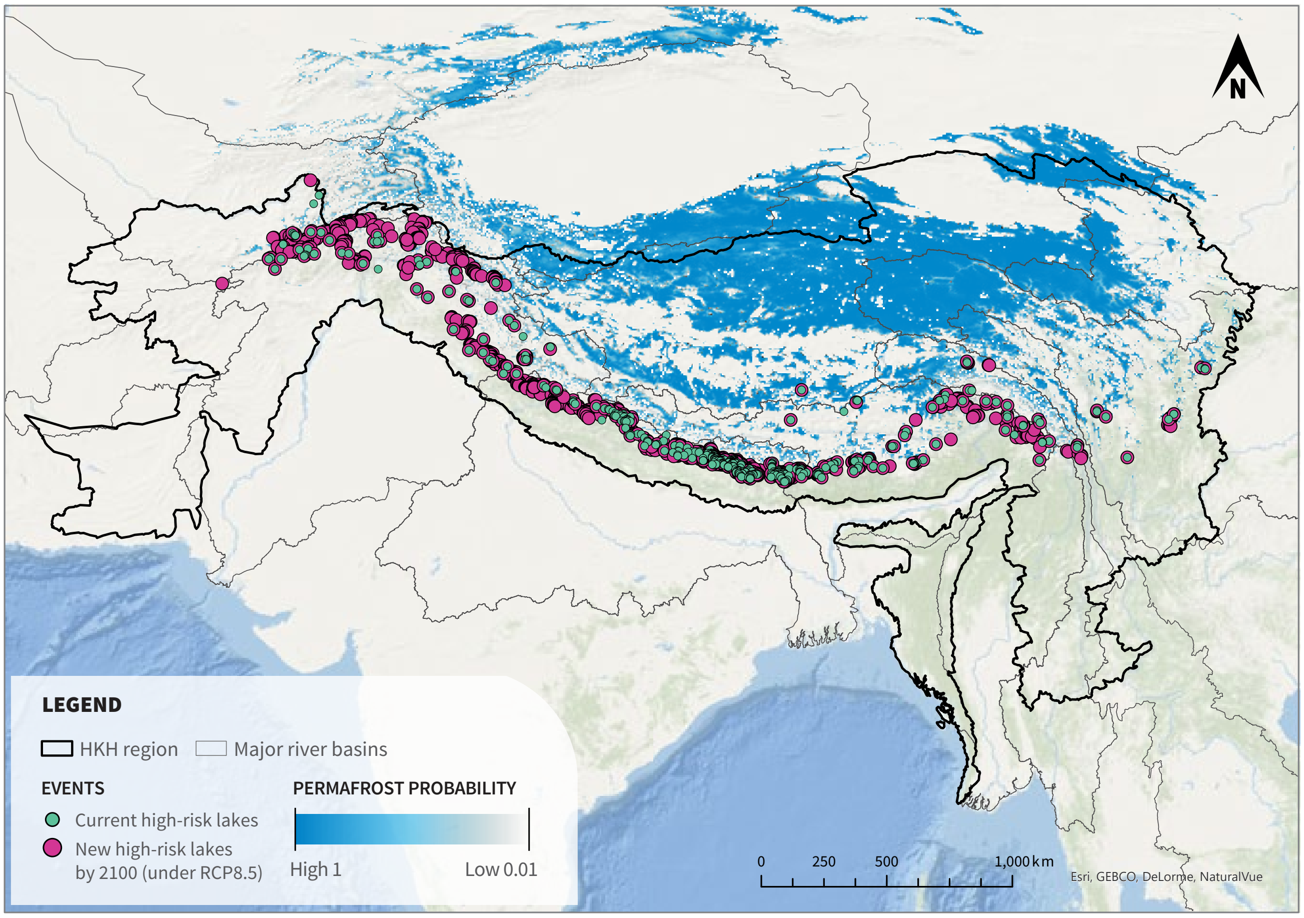
3.3.5. What to expect: Projected changes for mountain hazards

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 (Haeberli 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 disproportionally 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).

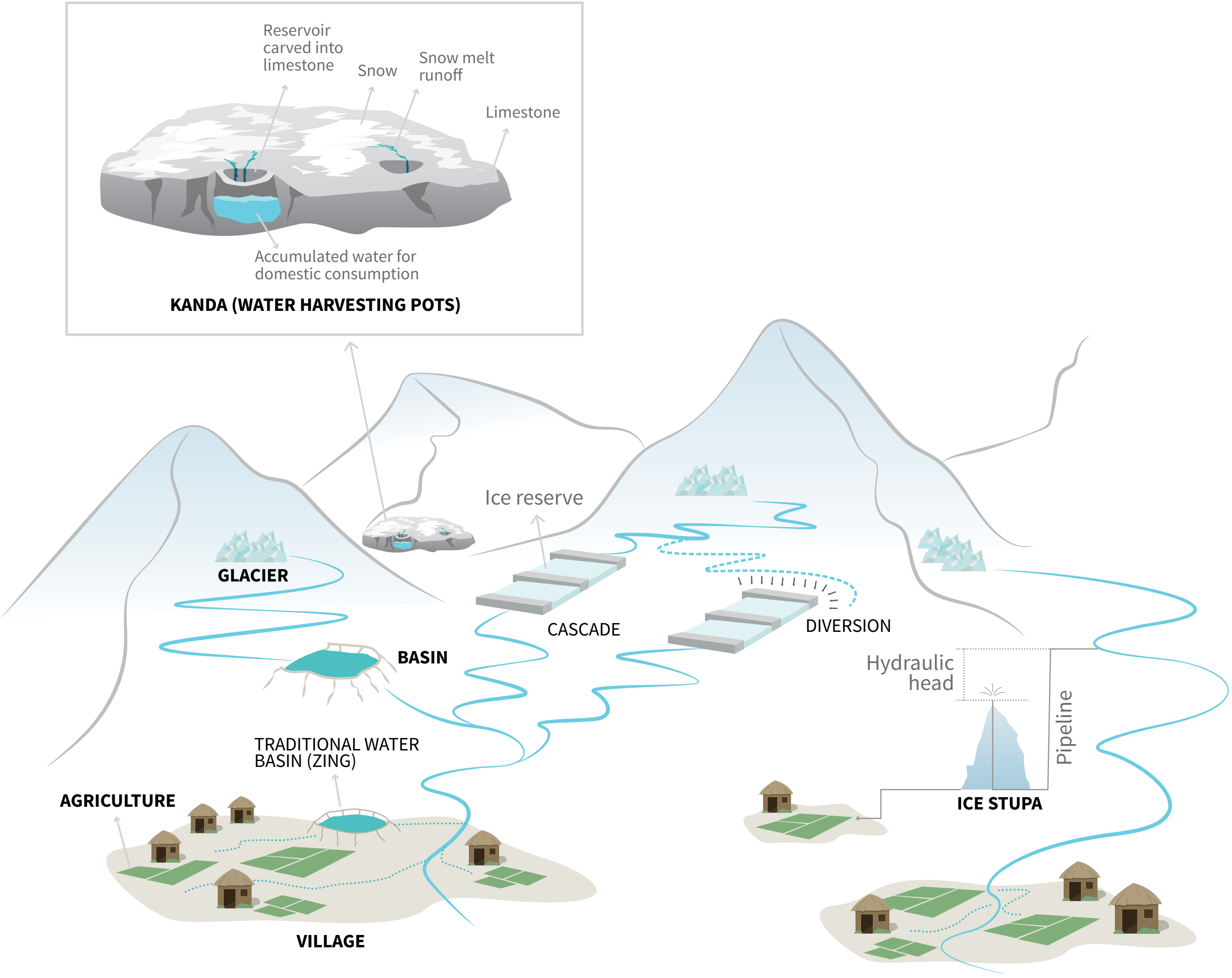
A recent study describing a similar analysis focusing on the Indus, Ganges, and Brahmaputra basins presented a slightly different picture, with a lower decrease in meltwater's contribution to irrigation (Lutz et al., 2022). The study combined both snowmelt and glacier melt – the latter releasing water 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 Melachmi 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 km^2 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

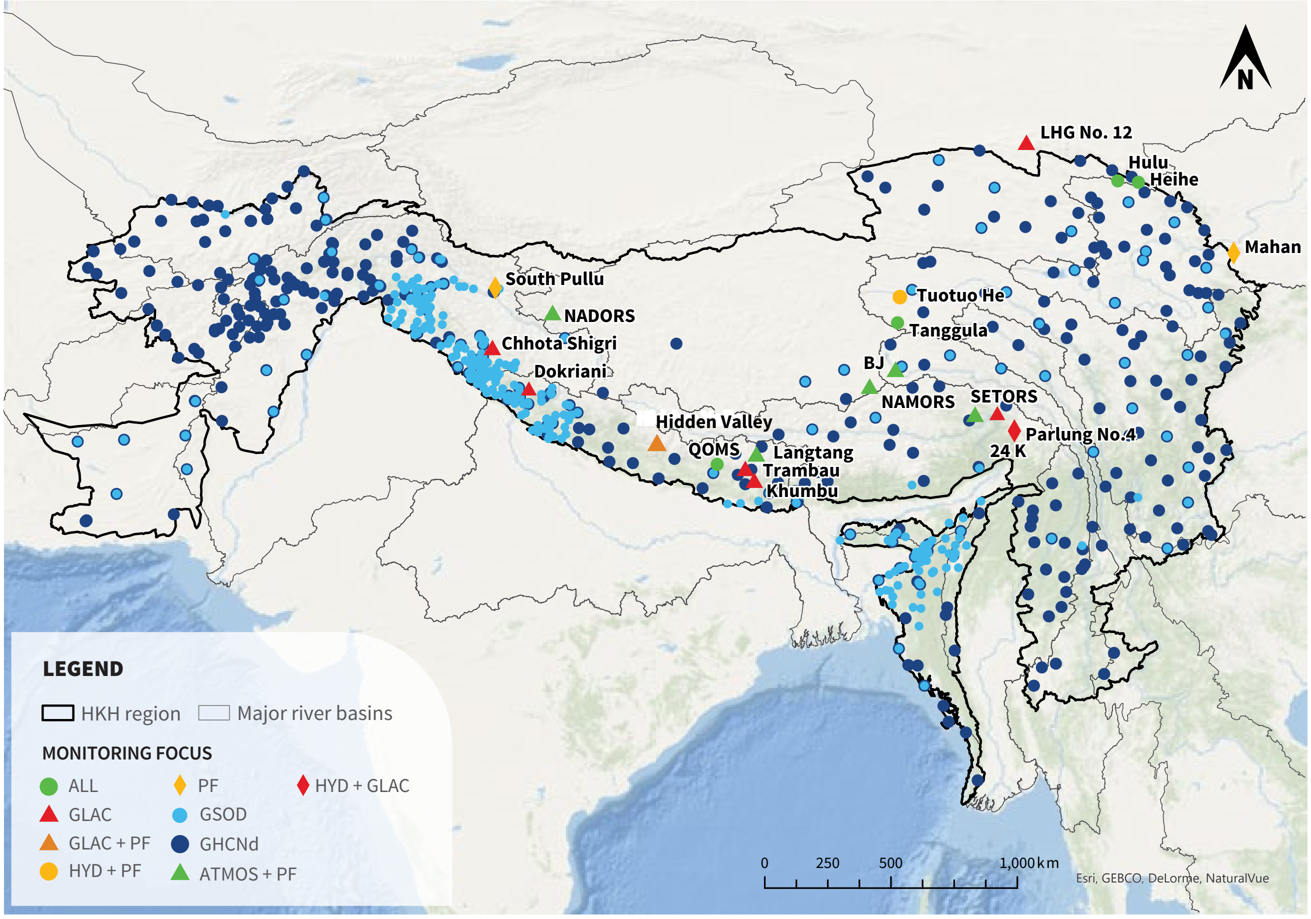
Develop institutional and political mechanisms to ensure long-term and stable support for these activities, as well as data access.

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.

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