Chapter 12
The Great Glacier and Snow-Dependent Rivers of Asia and Climate Change: Heading for Troubled Waters

David J. Molden, Arun B. Shrestha, Walter W. Immerzeel, Amina Maharjan, Golam Rasul, Philippus Wester, Nisha Wagle, Saurav Pradhananga, and Santosh Nepal

Abstract The glacier- and snow-fed river basins of the Hindu Kush Himalaya (HKH) mountains provide water to 1.9 billion people in Asia. The signs of climate change in the HKH mountains are clear, with increased warming and accelerated melting of snow and glaciers. This threatens the water, food, energy and livelihood security for many in Asia. The links between mountains and plains and the differential impacts of climate change on societies upstream and downstream need to be better established to improve adaptation measures. This chapter sheds light on climate change impacts on the cryosphere and mountains, the impact on river systems and the social consequences of such changes in mountains, hills and plains. In high mountains and hills, the impact of climate change is clear, as seen in changes in agropastoral systems and the increasing occurrence of floods and droughts, with losses and damages already high. Moving downstream, the climate change signal is harder to separate from other environmental and management factors. This chapter outlines how climate change in the mountains will impact various sectors in the hills and plains, such as hydropower, irrigation, cities, industries and the environment. It discusses how climate change will potentially lead to increased disasters and out-migration of people. The chapter concludes by highlighting necessary actions, such as the need to reduce emissions globally, build regional cooperation between HKH countries, increase technical and financial support for adaptation, and more robust and interdisciplinary science to address changing policy needs.

Keywords Climate change · HKH mountains · River basins · Environment · Adaptation · Disasters · Agriculture · Hydropower · Cities

---

D. J. Molden (✉) · A. B. Shrestha · A. Maharjan · G. Rasul · P. Wester ·
N. Wagle · S. Pradhananga · S. Nepal
International Centre for Integrated Mountain Development (ICIMOD),
Kathmandu, Nepal
e-mail: djmolden@gmail.com

W. W. Immerzeel
Utrecht University, Utrecht, The Netherlands

A. K. Biswas and C. Tortajada (eds.), *Water Security Under Climate Change*,
Water Resources Development and Management,
https://doi.org/10.1007/978-981-16-5493-0_12

12.1 Introduction

Images of melting glaciers have become iconic representations of the impacts of climate change, whether in the Arctic or the high mountains of the world. While these images are striking and emotive, they tell only part of the story about the impacts on people, biodiversity and the environment. For countries in Asia that share high mountains, the concern about melting glaciers is largely related to water supply and hazards. We also recognise there are many other factors impacting our water systems, such as snow melt and precipitation as well as rising demand for water in the region. This is a major concern for the 240 million people living in the mountains and hills of the Hindu Kush Himalaya (HKH) as well as people living downstream, as 1.9 billion people live in the ten river basins that have their source in the HKH mountains (Wester et al. 2019).

While the relation between climate change and melting glaciers and snow is clear and supported by outstanding science (IPCC 2019), the impacts of cryospheric change on water, people and the environment are less clear, although the evidence is growing. A few key questions arise: How will the hydrology of water systems change? How will these changes affect water-dependent sectors like hydropower, agriculture, cities and industries? What are their implications for key ecosystems and for people? What kinds of actions and policies will help societies to respond in the short and long run?

This chapter explores the impact of climate change on water resources and subsequent impacts on people and the environment in the Hindu Kush Himalaya region. It starts by identifying climate change impacts on the hydrology of river systems. Since changes in hydrology and precipitation have differing impacts and consequences moving downstream, we use an organising framework that discusses impacts on mountains, hills and plains separately. The chapter concludes with a range of potential responses for adapting to hydrologic changes in these river basins.

12.2 Warming in the HKH Mountains

The HKH, like other mountain systems of the world, is highly sensitive to climate change. Over the past six decades, mean temperature in the HKH has increased at a rate of 0.2°C/decade, while the global temperature increase for the same period was 0.13°C/decade. At the same time, extreme warm events have increased, and extreme cold events have decreased (Krishnan et al. 2019). In mountains, temperatures rise faster than at sea level, a phenomenon known as elevation-dependent warming (e.g. Hock et al. 2019; Pepin et al. 2015). From historic measurements, we see that the temperature in the mountains, including in the HKH, has already risen faster than the global average (DHM 2017; Diaz and Bradley 1997; Krishnan et al. 2019; Liu and Chen 2000; Shrestha et al. 1999).

The warming in the HKH is projected to continue and intensify in the future. With the Paris Agreement (NRDC 2017), the global community set the goal to limit temperature rise by 2100 to well-below 2°C, and ideally to 1.5°C, compared to pre-industrial levels. A special report by the IPCC highlighted the importance of limiting global warming to 1.5°C for adaptation and poverty alleviation (IPCC 2018). However, unless rapid action is taken to lower emissions, or new technologies deployed to remove carbon from the atmosphere, we are not likely to hit this mark. However, even if global warming is contained at 1.5°C, the HKH is likely to warm by 1.8 ± 0.4°C by the end of the century due to elevation dependent warming (Krishnan et al. 2019). In some specific mountain ranges such as the Karakoram, the warming is projected to be 2.2°C ± 0.4°C. Climate projections using Representative Concentration Pathway (RCP) 4.5 yield a warming of 2.2–3.3°C, while for RCP 8.5, which is close to the current emission trends, warming is likely to be 4.2–6.5°C by 2100 (Krishnan et al. 2019).

12.3 Changes in Precipitation

While snow and ice melt are significant factors in the hydrology of HKH rivers, rainfall is in many areas the most significant input to land and water systems. The monsoon and westerly climatic systems and their rhythms are major determinants of river flow hydrology, but also terrestrial ecosystems. Ecological composition and patterns are highly dependent on rain, which influences the density of flora, time of flowering and migration of animals. Agricultural patterns are based largely on these weather phenomena, which determine the timing of planting and harvesting, and what can be cultivated. High variability of rainfall in terms of timing and amount increases uncertainty for water system management. Drastic changes would disrupt the functioning of these ecosystems as we know them.

In spite of the importance of rainfall, we know less about the impact of climate change on rainfall patterns than we do about glacier melt. This is because rainfall patterns in the HKH are innately highly variable, making it hard to differentiate a climate change signal from normal variability of rainfall patterns. The addition of aerosols from air pollution to the atmosphere is also known to impact weather and longer-term climatic patterns. For example, it has been observed that winter fog across the Indo-Gangetic Plains has increased substantially over the last 35 years, with a threefold increase in the number of days with fog, due in part to these aerosols (Saikawa et al. 2019). In addition, there are important feedback loops between land use changes, in particular irrigated agriculture, moisture recycling and precipitation, that further complicate detecting the impact of climate change on rainfall (de Kok et al. 2020; Tuinenburg et al. 2012).

Long-term trends in precipitation have been difficult to discern (Krishnan et al. 2019), but there is some evidence that annual precipitation and annual mean daily precipitation intensity in past decades have increased. Also, annual intense precipitation days (frequency) and annual intense precipitation intensity are experiencing increasing trends (Ren et al. 2017). Looking to the future, there is a divergence among models in projecting changes in precipitation in the HKH. In general, it is projected to increase, but with strong regional differences. Precipitation projection over the HKH region is subject to larger uncertainties both in the global circulation models (GCMs) and RCMs (e.g. Choudhary and Dimri 2017; Hasson et al. 2013, 2015; Mishra 2015; Sanjay et al. 2017). Similar results are shown by Krishnan et al. (2020), although the latter shows that the projected increase is greater in RCMs compared to GCMs. Increasing extremes in precipitation in the HKH was also suggested by Panday et al. (2014), with more frequent extreme rainfall during the monsoon season in the Eastern Himalaya region and a wetter cold season in the Western Himalaya region. The region is naturally prone to water-induced hazards owing to the climate, topography and geological formations. The projected increase in extreme precipitation is likely to exacerbate this situation in the future (Vaidya et al. 2019). In summary, more evidence is needed, and there is still a high degree of uncertainty. Models point to more rainfall in the future, but more importantly, high variability in rainfall patterns with more intense rain and more drought periods.

12.4 Impact on the Cryosphere

While glaciers in High Mountains of Asia (HMA) have been retreating since the end of the Little Ice Age in the late nineteenth century (Bräuning 2006; Kayastha and Harrison 2008; Kick 1989; Mayewski and Jeschke 1979), this retreat has become much faster over the last few decades (Bolch et al. 2019; Maurer et al. 2019; Shean et al. 2020). Despite scattered studies of HKH glaciers, not much was known about the overall glacier status in the HKH 20 years ago. Studies on a handful of glaciers were not enough to draw conclusions about the 54,000 glaciers in the region (Bajracharya and Shrestha 2011).

However, over the last decade there has been an increasing number of studies on glaciers, and the picture is now becoming clearer. Aided by more fieldwork, remote sensing and modelling, we now know that the majority of glaciers in the region are wasting in area and volume at different rates (Zemp et al. 2019). Figure 12.1 shows the rate of loss of glaciers across the HKH between 2000 and 2018. In contrast to this general trend, a more complicated picture emerges in the Karakoram, where some glaciers have shown advances (Bhambri et al. 2013; Hewitt 2011; Paul 2015). This contrast between the Karakoram and the rest of the HKH region has been termed the ‘Karakoram anomaly’ (Hewitt 2005). While several hypotheses have been put forward (de Kok et al. 2018; Forsythe et al. 2017; Wiltshire 2014), there is not yet a convincing explanation of why this happens. Farinotti et al. (2020) suggest that under the projected climate change it is unlikely that the anomaly will persist in the long term. It is projected that under the 1.5° scenario, which is RCP 2.6 for some climate models, about 30–35% of the volume of HKH glaciers will be lost by the end of the century, while under current emission trends, which is close to

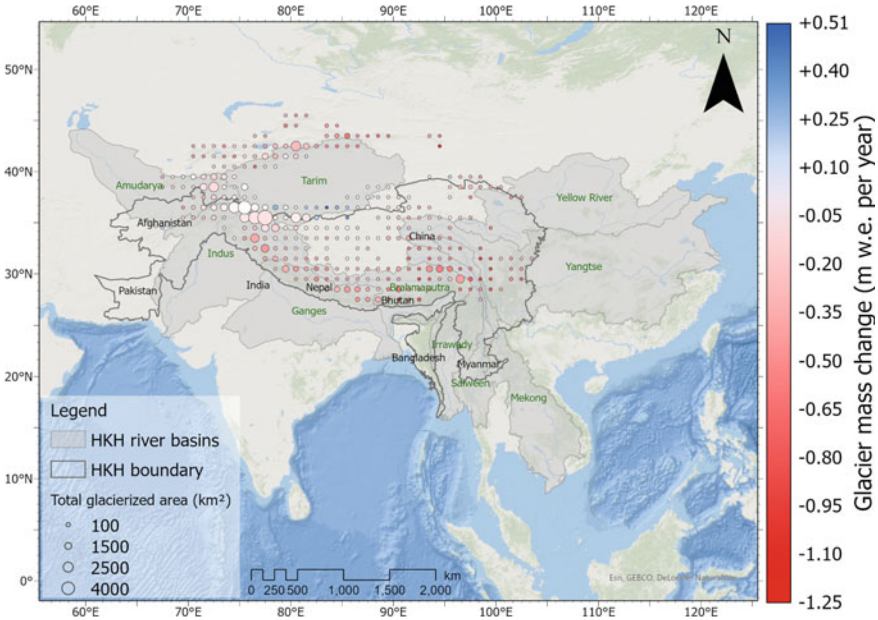

Fig. 12.1 Specific glacier mass balance change in metres of water equivalent per year (m w.e. yr^{-1}) for the period 2000–2018, based on data from Shean et al. (2020). The size of the circle represents the total glacierised area

RCP 8.5, this loss could be as high as 65% (Kraaijenbrink et al. 2017; Rounce et al. 2020).

Although downstream hydrology is influenced by various components such as rainfall, permafrost, snow and glaciers and human interventions, glaciers receive most attention in climate change discussions in the scientific community and the media. For a complete picture, we need to know more about all of these components. Snow is important for water supply in the region (Bookhagen and Burbank 2010; Lutz et al. 2014), as well as for the influence it has on atmospheric circulation and the Asian monsoon (Bansod et al. 2003; Qian et al. 2011; Wu and Zhang 1998; Zhang et al. 2019). Ice cores (Kang et al. 2015; Thompson et al. 2000) and remote sensing-based studies (Gurung et al. 2011) indicate generally decreasing snow cover but with differences between the sub-regions. There is evidence of receding snowlines and of areas receiving increasing amounts of rainfall and less snowfall. This implies that storage from snowpack and retention of water in snow will be reduced, which will impact hydrologic patterns.

Less is known about permafrost, with most permafrost studies concentrated in the Tibetan Plateau (Gruber et al. 2017). The review conducted by Gruber et al. (2017) suggested that the area of permafrost in the HKH largely exceeds the area of glaciers. While detailed studies are lacking, as a general trend, most permafrost in the HKH is likely to have undergone warming and thaw during the past decades

(Zhao et al. 2010). Studies on the Tibetan Plateau suggest multiple impacts of permafrost thaw, such as release of carbon to the atmosphere, desertification and damage to infrastructure (Wang et al. 2008; Yang et al. 2010). As permafrost decreases, there is a major concern that mountain slope stability will be weakened, leading to more landslides (e.g. Gruber and Haeberli 2007).

Air pollution including black carbon can reach high mountain areas. In their assessment of the literature, Saikawa et al. (2019) conclude that air pollutants originating near and within the HKH amplify the effects of global warming and accelerate the melting of the cryosphere through the deposition of black carbon and dust. Sources of black carbon and air pollution emissions include forest fires, coal burning, rubbish burning, diesel fumes, dust and a number of other factors and often come from across borders to reach mountain areas. Clearly, a way to reduce temperature rise and glacier and snow melt is to reduce air pollution and black carbon emissions in the region.

12.5 Cumulative Impact on River Hydrology

The combination of changes in the cryosphere and rainfall, together with changing groundwater patterns, will result in changing river flow patterns over time. In glacier- and snow-fed river basins in many regions, it is projected that melt water yields from glaciers will increase for decades but then decline (IPCC 2019). As glaciers shrink, annual glacier runoff typically first increases till it reaches a turning point, often called ‘peak water’, after which the runoff declines. The timing of peak water is positively correlated with extent of glaciation in the basin. In most basins in the HKH with major contributions of glacier melt, annual glacier melt runoff is projected to increase until roughly the middle of the century under RCP 4.5 and later in the century under RCP 8.5, followed by steadily declining glacier runoff thereafter (Huss and Hock 2018; Nie et al. 2021). In the Upper Indus Basin (UIB), the peak water is projected to occur around 2045 ± 17 years under RCP 4.5 and around the middle of the century in most headwaters of the Ganges, while it is suggested that peak water has already occurred, or is close to doing so, in the headwaters of the Brahmaputra (Huss and Hock 2018; Nie et al. 2021). For more extreme scenarios (e.g. RCP 8.5), the peak water is further delayed due to intensified melting.

The change in basin runoff, however, depends on contributions of cryosphere melt and precipitation. Figure 12.2 shows the present contribution of rainfall runoff and melt runoff to total discharge in the upstream basins of HKH rivers (Khanal et al. 2021). The Upper Indus and Amu Darya located in more arid areas have a higher percentage of melt runoff contribution to their flows, while the rivers in the eastern and central region such as the Mekong, Salween and the upper Ganges have a higher contribution from rainfall. In the Upper Indus basin, melt runoff contributes about 45% of the total discharge compared to 13 and 15% in the Ganges and the Brahmaputra at the outlet (Khanal et al. 2021). In some rivers of the Upper Indus, the melt contribution

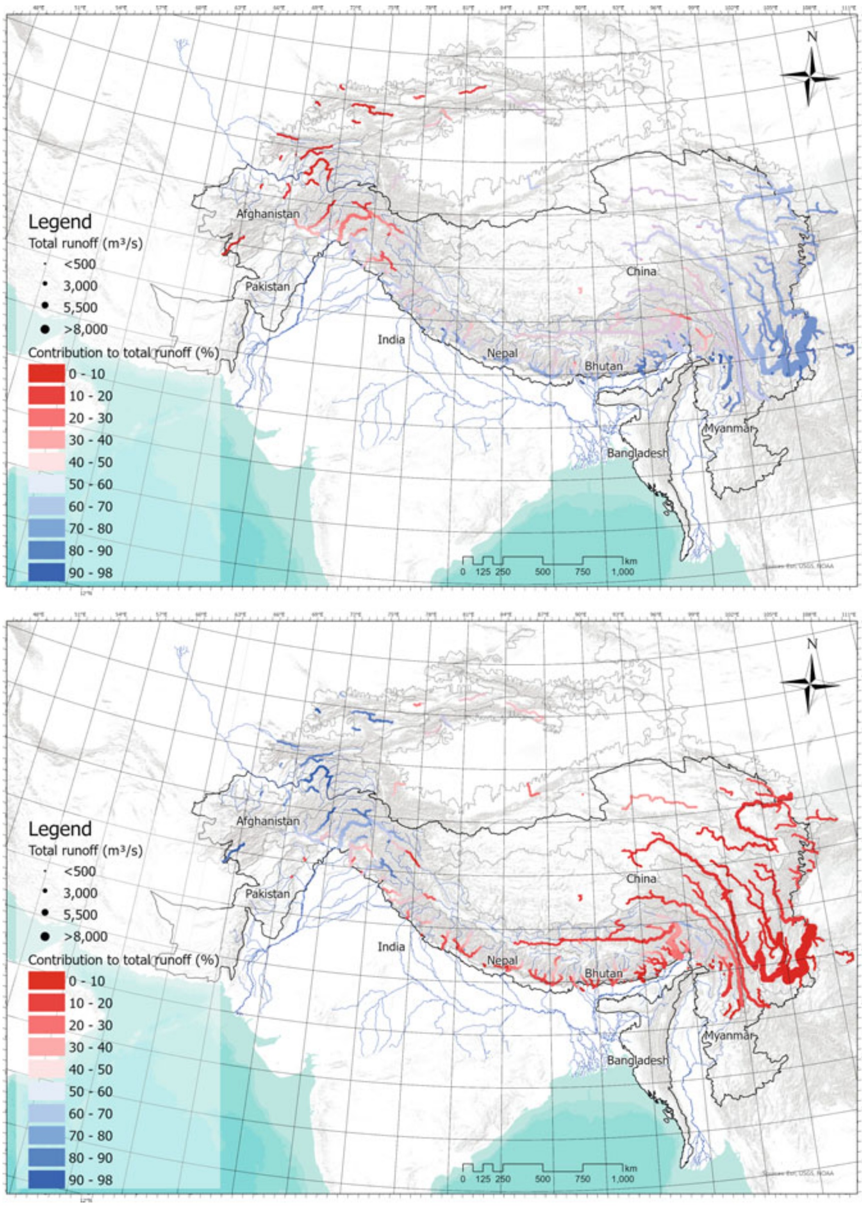

Fig. 12.2 Contributions of rainfall runoff (top) and snow and glacier melt runoff (bottom) to total river flow coming from the mountains from 1985 to 2014 (Khanal et al. 2021)

to total discharge is as high as 90%. In the eastern basin of the HKH like the Yellow and the Yantze, rainfall runoff contributes up to 80% of the total discharge. Table 12.1 shows the rainfall runoff and melt runoff contribution to total discharge in the ten river systems originating from the Hindu Kush Himalayan region.

However, by 2050, the total runoff in the Upper Indus Basin is likely to change by −5 to 12% based on discharge simulations performed using eight GCM runs (four each for RCP 4.5 and RCP 8.5) (Lutz et al. 2014). Most of the changes in the total runoff are directly related to changes in precipitation. In the Upper Ganges, the total runoff will likely increase by ~1–27% by 2050. The share of melt water is projected to decrease, while the share of rainfall runoff in the total runoff is projected to increase as the rising temperature is most likely to change the rainfall–snowfall dynamics. The case of the Upper Brahmaputra is quite interesting, as it picks up a lot of glacier and snow melt on the Tibetan Plateau, but as it turns to the Bay of Bengal, rain becomes more dominant. In the Upper Brahmaputra, too, the total runoff will likely increase by 2050 (0–13%). The share of melt water is decreasing, while the share of rainfall runoff increases here as well. The trends are in general similar for RCP 4.5 and RCP 8.5 although the spread between the GCM runs is large, especially for the Upper Ganges, mainly due to the larger spread in precipitation projections in the GCM runs used for RCP 8.5 compared to RCP 4.5.

HKH rivers in the west, like the Indus, receive more contribution from snow and glaciers than those in the east, like the Ganges, Brahmaputra, Salween and Mekong, where rainfall runoff contribution is higher. In all basins, the contribution of meltwater decreases, and rainfall becomes more significant as we move downstream. This implies that high mountain ecosystems, agriculture and people will most likely be impacted most by changes in glacier and snow melt. Moving downstream, as contributions from rain become larger, changes in the timing and amount of all flow components will be important when considering impacts of climate change. Contributions to flow vary across the annual cycle, and meltwater contribution during April and May is important when rainfall contribution is low and temperatures are high.

Table 12.1 Rainfall runoff and melt runoff contribution to total discharge of ten major river basins of the HKH region from 1985 to 2014 (Khanal et al. 2021)

Basin	Area (km^2)	Glacier area (%)	Rainfall runoff (%)	Melt runoff (%)
Amu Darya	268,280	4.4	5.4	78.8
Brahmaputra	400,182	2.7	62.1	15
Ganges	202,420	4.4	64.7	13.4
Indus Basin	473,494	6.3	43.9	44.8
Irrawaddy	49,029	0.2	78.2	5.1
Mekong	110,678	0.3	55.1	7.7
Salween	119,377	1.5	55.7	16.1
Tarim	1,081,663	3.1	47.3	27.0
Yangtze	687,150	0.4	71	5.7
Yellow	272,857	0.1	63.9	9.7

12.6 Impact of Hydrological Changes on the Uses of Water

Knowing the possible impacts of these hydrologic changes on uses of water is essential for developing responses for different sectors. While we are getting a clearer picture of what will happen to river flows in the future, the implication of these changes is less clear, as only a few scattered studies have explored the downstream impact in detail. Carey et al. (2017, p. 350) argue that people are aware of the potential impact with 1.9 billion people living in HKH river basins, but often conclude, that… 'Unfortunately, research focusing on the human impacts of glacier runoff variability in mountain regions remains limited, and studies often rely on assumptions rather than concrete evidence about the effects of shrinking glaciers on mountain hydrology and societies.' According to a review by Rasul and Molden (2019), a growing number of field-based local studies, both observation and perception based, report that many high-elevation areas of the HKH region are already experiencing water shortages and uncertainties that are considerably impacting agriculture, livelihoods, economy and society.

This knowledge gap is partly attributable to a lack of work across different disciplines. While glaciologists and hydrologists predict changes in river flow patterns, understanding the impacts of these changes on various sectors requires engagement with water management specialists, economists and social scientists. The situation in mountains is very different from that on the plains, so a combined mountain to plain perspective considering multi-scale upstream–downstream linkages is needed.

In a recent important study linking mountain water supply and dependence of societies on mountain water, Immerzeel et al. (2020) developed a water tower index and applied it in 78 watersheds globally to assess the role of mountains in supplying water and the downstream dependence on water for ecosystems and society. Of the river basins they assessed, they found the Indus Basin most vulnerable and most of the ten HKH river basins to be highly vulnerable due to high population densities, high dependence of their populations on water for irrigation, industries and cities and their vulnerability to climate change. Another reason that made the situation in the Indus River Basin most critical was the high dependency of the downstream population on meltwater. Moreover, eight of the ten HKH rivers are transboundary in nature, in a geopolitically sensitive region. The study clearly showed the importance of mountain water for societies around the world and the importance of mountains for HKH rivers.

To discuss impacts, we use a simple framework of water flowing from the mountains to the hills and downstream to the plains (Fig. 12.3). Water use patterns are distinctly different in these three zones. In the high mountains, people are heavily dependent on cryospheric resources. Moving downstream to the hills, river beds cut deep into valleys. Because of the hill topography, this is the location for dams, reservoirs and hydropower projects. The hills receive little snow compared to the high mountains, so people in the hills use water from rivulets and springs. Most

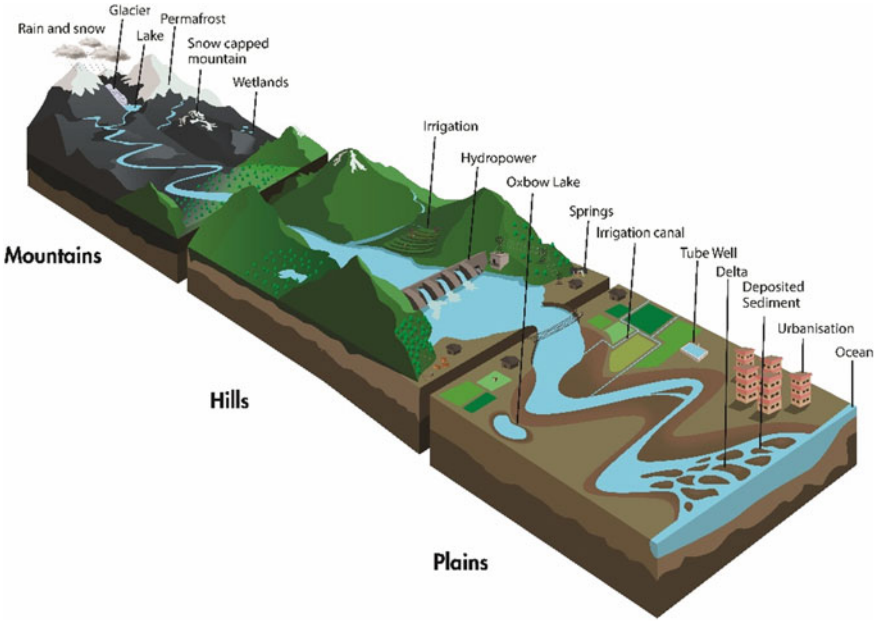

Fig. 12.3 Flow of water from mountains to hills to plains to oceans. Each zone has its unique physiographic and climate change characteristics and is discussed separately in the chapter (adapted from Nepal et al. 2018)

of the HKH population lives in the hills and depends less on glacier and snow melt, rather from rainfed springs. In spite of this, the cryosphere receives much more attention than climate change impacts on water resources in hill region. Population densities increase in the plains, where water is used intensively by cities, the agricultural sector and industries. People depend on water mainly for floodplain agriculture and fishing. Rainfall becomes the primary contributor to river flows, and groundwater use is prevalent. This shows strong upstream–downstream linkages in the HKH river basins (Molden et al. 2016; Nepal et al. 2018), and these linkages may be affected by environmental and socioeconomic changes across different scales.

In high mountains where people rely on glacier and snow melt, changes in the cryosphere will have direct impact on water use, and the climate signal is direct—glaciers and snow melt, and the supply of water changes. Moving downstream, long-term changes in runoff could also be a result of anthropogenic changes such as changes in land use patterns, agricultural practices and upstream water infrastructure like dams. The hills are also intensively used for hydropower development due to year-round availability of river flow (originating from high mountains) along with elevation differences. Then moving to the plains there is considerable human influence on hydrologic patterns with the diversion and use of water, effluent flows, groundwater pumping and reuse of water. Hydrologic changes are due to a number of factors including climate change, and it is more difficult to separate out the climate change signal.

12.7 Societal Impacts in Mountains

The mountains are dominated by alpine ecosystems, including steep slopes, snow- and ice-covered lands, grasslands and forests. Human systems include villages, small-scale agriculture and pastoral systems. Snow and ice melt and permafrost thaw can significantly influence water systems used by people for pastoral activities and crop cultivation. Changes in melt patterns can disrupt these systems. Mountain agriculture and pastoralism are impacted by changes in both temperature and water regimes (Rasul and Molden 2019). In high mountain areas in Afghanistan, northern Pakistan and western and central India, snow and glacial melt water is used for irrigation and helps retain soil moisture on pastures and grasslands. People living in high mountain areas of the HKH region also depend on glacial melt water for drinking and other domestic uses (Rasul and Molden 2019). It is reported that people in such areas have been facing a shortage of water for drinking and domestic uses, partly due to reduced glacier and snow melt (McDowell et al. 2013; Rasul and Molden 2019; Rasul et al. 2020). In some cases, communities have lost their water source, and in extreme cases, this has led to displacement of communities. Interestingly, some areas previously covered by glaciers, and snow are growing new vegetation and have become potential grazing grounds.

A number of field-based studies indicated that subsistence agriculture, the main source of livelihood in high mountain areas of Bhutan, India, Nepal, and Pakistan, is being impacted by melting glaciers, thinning snow cover and changing precipitation patterns (Dame and Nüsser 2011; Rasul et al. 2020; Rasul 2021). Agriculture and agro-pastoralism in high mountain areas of the HKH depends heavily on cryospheric resources, and in particular, the spring and summer melt runoff is a vital source of water for plant growth. People in those areas are thus highly vulnerable to changes in the cryosphere (Rasul 2021). In northwestern India, for example, farmers have been impacted by a shortage of irrigation water and soil moisture due to the gradual recession of low-lying glaciers and changing patterns of snowfall (Grossman 2015). In Ladakh, India, agricultural production almost entirely relies on meltwater for irrigation. Farmers divert snow meltwater and channel glacial meltwater to farm fields and settlements where topography allows. It is reported that faced with water shortage, farmers are taking many adaptation measures including changing cropping patterns across the western Himalaya region (Clouse 2016; Dame and Nüsser 2011; Rasul et al. 2019).

Livestock is an integral part of farming systems and livelihoods in high mountain areas of the HKH. Animal husbandry and agropastoral livelihoods are also impacted by cryosphere change in the HKH region, though less visibly. Changes in snowfall patterns and overall decline in snow cover result in fodder and water shortages that affect livestock production, food security and livelihoods. For instance, it is reported that plant density in meadows has declined in Nagqu Prefecture in the Tibet Autonomous Region of China, in part due to global warming and cryospheric change, as well as increasing intensity of grazing, which affects yak and sheep herders who depend on it for their livelihood (He and Richards 2015; Rasul et al. 2020).

In mountains, life has always been risky, but now it is even more so as avalanches, landslides, floods and glacier lake outburst floods have increased, in part due to climate change. When glaciers melt, lakes often form downstream, dammed by moraines which are often unstable. As the lakes grow with increased melt, the danger of glacial lake outburst floods (GLOF) increases (Byers et al. 2019; ICIMOD 2011; Rounce et al. 2017). In the Koshi Basin, there have been six GLOF events since 1990, and four of these occurred since 2015. In addition, 42 lakes in the Koshi, three in the Gandaki and two in the Karnali basins were identified as potentially dangerous lakes (Bajracharya et al. 2020). Likewise, permafrost thaw tends to destabilise steep slopes actually held together by frozen water, leading to an increase in hazards from landslides.

In the mountains, disaster and its cascading events are common and dangerous. For instance, the Kedarnath flood of 2013 was caused by a rainfall triggered landslide into a glacier lake. The avalanche that destroyed the Langtang village in Nepal in 2015 was the result of an earthquake in combination with a 1:100-year spring snow pack. The recent Chamoli disaster led to over 70 deaths, with 134 missing. A few days before the disaster a strong westerly disturbance caused heavy rain, leading to rising water levels. Then, a massive rockfall mixed with ice and snow occurred on Ronti peak. This melted the ice below, causing a flood wave to surge down the already swelled river and mix with previously deposited sediments and debris. Infrastructure in the flood path, in particular hydropower plants, exacerbated the damage. The unfinished Tapovan Vishnugad hydropower project was destroyed, and the flood inflicted substantial damage on the Rishi Ganga hydropower project (Shrestha et al. 2021a). Disaster can be considered one reason why people migrate away from their homes, a topic that will be discussed in detail in another section.

Cryosphere change has significant impacts on local economy and society, and a few studies have demonstrated this. The IPCC Special Report on Ocean and Cryosphere suggest that economic losses are incurred through two pathways—due to climate-induced disasters, and through additional risks and loss of potential opportunities brought about by cryopsheric changes (Hock et al. 2019). Hock et al. (2019) reported that cryosphere-induced disasters such as flood, landslides and avalanches are increasing in the HKH region and projected to increase in the future, and additional costs will be required for risk reduction measures. These have already incurred huge economic, social and environmental cost to society. It is reported that over the period 1985–2014, economic losses in mountain regions from all flood and mass movements (including those not directly linked to the cryosphere) were highest in the HKH region (USD 45 billion), followed by the European Alps (USD 7 billion) and the Andes (USD 3 billion) (Stäubli et al. 2018). For instance, the Zhangzangbo glacier outburst flood of 1981 in Tibet killed 200 people and caused extensive damage to infrastructure and property, with an estimated economic loss of USD 456 million (Mool et al. 2001). Similarly, the Dig Tsho flood in the Khumbu region of eastern Nepal in 1985 damaged a hydropower plant and other properties, with estimated economic losses of USD 500 million (Shrestha et al. 2010). As an adaptation measure, a channel was dug in Tsho Rolpa glacier in Nepal in 2002 to lower a glacial lake, an initiatve that costs USD 3 million (Bajracharya 2010).

12.8 Societal Impacts in Hills

People living in hills, especially those in rural areas, have a very close relation with ecosystems. They often rely directly on forests for food, fodder and medicinal goods. Changing rainfall patterns impact forest and other ecosystems and threaten livelihoods. Traditionally, most hill and mountain communities reside on hill slopes or hill tops, not on river valley bottoms. This is changing as more roads are being built and more towns and urban centres are springing up. People are moving to valley bottoms to take advantage of increased connectivity. Changing river flow patterns including discharge and timing of water will have an impact on the amount and timing of hydropower production. This movement to valley bottoms makes people and infrastructure vulnerable in different ways. People on hill slopes are quite susceptible to landslides, and this risk gets aggravated with increasing intensity of rain driven by climate change. There are many causes of landslides besides climate change, such as road building and land cover change including deforestation, but the hazard of landslides will increase in the future.

Of rising concern is the situation of springs in the hills, which are a major contributor to river flows and a source of domestic water and small-scale irrigation (Scott et al. 2019). Springs are drying up all across the countries of the HKH. There are several site-specific reasons, such as changes in land use reducing recharge capacity; increased extraction of water from springs with pipes and pumps and possibly changes in rainfall, runoff and recharge patterns due to climate change, though the latter is not well established. Climate change research and development activities should pay more attention to springs given their important role in rural and urban water supply (Scott et al. 2019).

Rivers grow in size as they move downstream, receiving contributions from the cryosphere and increasingly rainfall-driven flows from the land. Changes in land use such as changes in forest cover influence these patterns. Artisanal fisheries and floodplain agriculture are common across the hills, and both are impacted by changing flows and flood flows.

The HKH is now witnessing a hydropower boom, with an increasing number of hydropower dams being built in the hills on the tributaries of the great HKH rivers (Vaidya et al. 2021). Hydropower could significantly help countries move towards less carbon intensive energy, reduce GHG emissions and increase energy security. Hydropower already produces almost 100% of Bhutan's electricity, 93% in Nepal and 33% in Pakistan (Shrestha et al. 2016; Vaidya et al. 2021) and contributes considerably in India. All the countries of the HKH region have taken the initiative to increase hydropower generation. While river runoff is not expected to reduce until the second half of this century, changes in glacier and snow melt patterns will affect hydropower production in the HKH due to changes in the seasonality of river flows to increased variability of flows. The exact impact of cryospheric change is difficult to determine because the effects vary greatly across the region and even within each country. The impact is likely to be greatest on small-scale 'run of the river' hydropower plants with little or no storage, of the type common in the Himalayan region (Boehlert et al. 2016; Turner et al. 2017). Reduction in dry season runoff can reduce or even halt hydropower production from these plants. Even if there is an initial increase in annual flow from glaciers as they recede (Rees et al. 2004), such increase will occur in the warm wet season and will not compensate for decreased water availability during the dry season. For instance, hydropower generation in the Khulekhani project in Nepal is projected to decrease in future by 0.5–13% (Shrestha et al. 2020).

Hydropower plants in the mountains are susceptible to disasters such as floods, GLOFs and landslides. The disastrous cryosphere-related flood of February 2021 in Uttarakhand, which destroyed two hydropower installations, was a stark reminder of the power of floods. Bajracharya et al. (2020) show that the number of potentially dangerous glacier lakes is rising, which has increased risks for hydropwer plants and other infrastructure. For instance, a hydropower plant in Nepal was destroyed by the Dig Tsho GLOF in Nepal in 1985. Similarly, a hydropower project in Uttarakhand, India, was damaged by a cryosphere-related disaster linked with a cloudburst near Chorabari glacier in June 2013 (Schwanghart et al. 2016). A hydropower plant on the Bhote Koshi near the Nepal–China border was severely damaged in 2016 by a GLOF (Liu et al. 2020), and in 2014, a landslide in the Jure area of central Nepal destroyed hydropower projects (Bhatt 2017).

12.9 Climate-Induced Migration in Hills and Mountains

Human mobility and migration are integral to mountain livelihoods. For centuries, mountain people have moved from one place to another to avoid extreme winters, access more productive land and respond to agricultural seasonality (Macfarlane 1976; Pathak et al. 2017). By successfully adopting multi-local livelihoods, mountain communities have flourished in harsh climatic and topographic conditions. There are three major types of migration in the HKH region—transhumance mobility, labour migration and permanent migration. Human mobility and migration in the region are impacted by climate change and cryospheric changes as they have changed the availability of water and increased the frequency of hazards (Carey et al. 2017; Rasul and Molden 2019; van der Geest and Schindler 2016). In high mountains, transhumance mobility and associated herding activities are affected by the changes in snow and glaciers (Gentle and Thwaites 2016; Namgay et al. 2014; Nyima and Hopping 2019). Prolonged winter snow resulting in food and water shortages and increasing hazard events like avalanche resulting in death of livestock in large numbers makes herding a highly risky livelihood option (Shaoliang et al. 2012; Tuladhar et al. 2021).

For a long time, communities in the mountains, hills and plains have adopted labour migration as a livelihood diversifying strategy and also as a response to agricultural seasonality (Adger et al. 2015; Tuladhar et al. 2021). Climate change influences labour migration through its adverse impact on local livelihoods (Foresight 2011). There is a growing body of evidence that attributes migration to the impacts of droughts, floods, landslides, erratic precipitation and its impact on agriculture and other nature-based livelihoods (Hugo 1996; Viswanathan and Kavi Kumar 2015). Apart from climate change and cryospheric changes, other major drivers of migration are economic and employment opportunities, better access to education and health facilities (Gioli et al. 2014; Hugo 1996; Maharjan et al. 2020; Rigaud et al. 2018; Warner and Afifi 2014) and the younger generation's desire to move away from farm-based livelihoods (Carling and Schewel 2018). Labour migration, in turn, helps households to better adapt to climate change impacts through spatially diversifying household livelihood sources and spreading risks (Gemenne and Blocher 2017; Le De et al. 2013; Maharjan et al. 2021). In the last two decades, there has been a growing trend of permanent out-migration of entire households, leading to a decline in mountain population. There is anecdotal evidence that drying up of springs in the mid-hills, as a result of climate change and development interventions, is resulting in out-migration of entire villages in the HKH region. In the Upper Ganga basin, drying springs and rising floods have disrupted local agriculture-based livelihoods resulting in large-scale migration, particularly of youth, to urban centres in search of alternative livelihoods (Bhadwal et al. 2017). In the last population census, 36 out of 55 mountain and hill districts in Nepal reported a negative population growth rate (CBS 2012). Similar trend of depopulation and a rise in 'ghost villages' (villages without inhabitants) is also seen in Uttarakhand, India, that has led to a loss of traditional livelihoods and cultures (Pathak et al. 2017).

However, while there are many intertwined factors for migration, climate change could serve as a tipping point in people's decision to move. There is new evidence that often people's migration decisions are influenced by their perception of changes in climate (Koubi et al. 2016a, b). As the HKH region is highly vulnerable to the impacts of climate change due to its high dependence on nature-based livelihoods, this region is likely to see an increase in migration in future. If no action is taken, climate change is expected to result in 40 million internal climate migrants in South Asia (Rigaud et al. 2018).

12.10 Societal Impacts in the Plains

The plains of the great rivers of Asia, which emanate from the HKH mountains, are home to dense populations, major cities, industries, high economic activity and intense agricultural production. The plains depend on mountains for fertile soil, abundant water supplies and other mountain resources like forests. The Indo-Gangetic Plains is the food basket of India and Pakistan, similarly, the Yangtze is known as China's rice bowl, and the Yellow River Basin also significantly contributes to China's food production. China Water Risk (Hu and Tan 2018) reported that in 2015 the ten HKH river basins generated a total GDP of USD 4 trillion. However, there is growing concern that climate change impacts might threaten economic activities in the plains.

It is not easy to disentangle climate change impacts from other impacts. For example, dams placed at the mouth of rivers where rivers meet the plains (e.g. Tarbela and Tehri dams) exert significant influence on flow regimes. Diversions for cities and agriculture influence river flows, and groundwater dependence has made a huge difference to water supply over the last decades. Water management itself makes a tremendous difference. Where water is poorly managed, even with ample supplies, people can experience water scarcity; in contrast, where it is well managed, people can get enough water even with minimal supply (Molden 2020). It is hard to single out the impact of climate change as it is mixed with many other factors. Nevertheless, changes in flow patterns will present an additional water management challenge in areas that are already stressed by a situation where demand outstrips supply.

With climate change and increased rainfall, monsoon season river flows are likely to increase further, and the likelihood of floods will increase. However, as glaciers shrink and snow melt diminishes, water supply will gradually reduce, especially in the dry season when more water is needed for irrigation. This may affect agriculture and food security in large parts of South Asia, including the Indo-Gangetic Plains, where the lion's share of water is used for food production. Declining runoff, due to a combination of decreasing ice mass and early snow melt, is expected to reduce the productivity of irrigated agriculture in the Indo-Gangetic Plains and other plain areas unless preventive measures are taken (Siderius et al. 2013; Biemans et al. 2019).

Using a coupled cryosphere-hydrology-crop modelling approach, Biemans et al. (2019) analysed the impacts of glacier and snow melt on agricultural production in the the Indus, Ganges and Brahmaputra River basins. The study showed that there is strong spatial and temporal variability of impacts with more dependence on meltwater in the arid Indus Basin and with meltwater being more critical during the pre-monsoon dry season. The contribution of glacier and snow melt to river flows is very high in the Indus. Overall 37% and in the pre-monsoon season up to 60% of total irrigation withdrawals originate from mountain snow and glacier melt, and it contributes an additional 11% to total crop production. In contrast, in the Ganges plains, there is significant contribution in the pre-monsoon from March to May, where snow and glacier melts contribute 20% of supply, but negligible amounts during the monsoon, and in the Brahmaputra Basin, the contribution is much smaller. The authors estimated that meltwater contributes to wheat production for 64 million people and rice production for 52 million people. With climate change, it is expected that the modulating role of meltwater will diminish, and in the long term, an important source of supply would diminish.

The combined effects of a growing population and increasing food demand, declining per capita land availability and crop yield, and reduced water availability threaten future food security for a large population in the HKH region (Aggarwal 2008; Immerzeel et al. 2010; Rasul 2010, 2014). People in the Indus Basin will likely be impacted more because of their high dependence on irrigated agriculture. More than 90% of all crops in the Indus Basin are irrigated, with glacier and snow melt a major source of irrigation water.

Cryospheric change and changes in rainfall patterns may also threaten urban water supply in the future. In the Himalayan region, many of the world's mega cities are situated along the banks and in the catchments of rivers that originate in the mountains, and a large number of major cities partly depend on glacier- and snow-fed surface water for their drinking water supply. A number of large cities in India such as Haridwar, Varanasi, Patna, Kanpur, Allahabad, Munger, Bhagalpur, Delhi, Agra, Mathura and Kolkata are situated along the mighty river Ganges and its tributaries and depend partly on glacier and snow meltwater that feeds the river. In Nepal, the government is developing an inter-basin water transfer project to supply 3.5 million litres of water per day to Kathmandu city from the glacier-fed Melamchi river (Khadka and Khanal 2008). Similarly, the Bhagirathi and Yamuna rivers are a major source of water for Delhi. In Pakistan, the Soan river supplies water to Simly Dam, a major reservoir of Islamabad, and in southern Punjab, water seepage from the glacier-fed Indus Basin Irrigation System is an important source of water (Jehangir et al. 1998). While the demand for water in urban areas is increasing with the growth of population, urbanisation and industrialisation, the reduction in water from glacier melt and snow melt is likely to exacerbate the challenge of urban water supply in many towns and cities in the HKH region.

Looking to the future, with rising populations and increased economic activity, there will be more demand for water from cities, agriculture and industries. At the same time, there is already significant ecosystem degradation. All of the great HKH rivers, except the Yellow and the Yangtze, are transboundary; yet cooperation between countries on rivers remains limited. Water sharing between states in India is also an issue. Even without climate change, the management of these river basins is an urgent challenge. Climate change will add more challenges including changes in hydrology and the threat of more floods and droughts.

12.11 Flooding in the Plains

The HKH Assessment Report provided a grim picture of disasters in the HKH and associated river basins, with 36% of all disaster events in Asia between 1980 and 2015 occurring in the HKH and 21% of events globally (Vaidya et al. 2019). The report stated that the number of disaster events, people killed and affected and economic losses increased by 143% from the ten-year period of 1990–2000 to the period of 2000–2010. Floods are the most common disaster in the HKH (Shrestha et al. 2015) accounting for 17% of people killed and 51% of damage.

Plains adjacent to mountains are prone to severe flooding due to increased climate and rainfall variability. The 2010 floods in Pakistan killed more than 2000 people with a loss of USD 10 billion; the 2013 Uttarakhand flood killed more than 5000 people; and Bangladesh, which lies at the intersection of three HKH rivers, is most vulnerable to floods (Vaidya et al. 2019). The increased intensity of rain in the mountains and plains plays a role, although the climate change attribution has not been adequately assessed. Wijngaard et al. (2017) projected that the 50-year return period flood is expected to increase by up to 305% relative to the current level with the largest increase in the upstream headwaters of the Upper Brahmaputra Basin. In contrast, in the Upper Indus Basin, the 50-year return level is expected to decrease by up to 25%. These changes are attributed to changes in rainfall and melt runoff patterns.

Disasters are a combination of the interplay between hazard, exposure and vulnerability (IPCC 2012) with climate change in the mix, so it is quite difficult to separate out climate change impacts from other human or environmental causes. Climate change will increase hazards, and unless preventative measures are taken to reduce vulnerabilities and exposure, the region is likely to experience more and larger disasters.

To reduce disaster risk, it is important to consider the links between mountains and plains and install flood early warning systems in downstream areas. It is also necessary to protect forests, empower communities and take collective action that transcends national boundaries.

12.12 Key Actions

The HKH mountains are a global resource, important for human survival and well-being and for biodiversity. The first global action required is to immediately reduce greenhouse gas emissions and slow the rise of temperatures in the mountains. While HKH mountain communities and downstream populations already feel the impact of climate change, the global community needs to become more aware of what is happening in the HKH. Located in a strategically important geopolitical region, countries that share the HKH mountains are prone to conflict. The global community has a responsibility to help HKH mountain communities, some of the poorest in the world, to adapt to the changing environment and build resilience. Even if the most drastic greenhouse mitigation measures are taken, changes will continue, and thus, adaptation is essential.

Adaptation and resilience building will be key for mountain communities and downstream communities. Local communities in different parts of the HKH region have already adopted a range of measures, including migration and mobility, in response to challenges posed by changes in the cryosphere. To cope with increasing water stress and uncertainty resulting from cryosphere shrinkage, farmers are increasing water storage and modifying livestock grazing patterns, constructing new water channels, storing water by creating artificial glaciers, shifting away from water intensive crops and growing new crops suited to water stress conditions. In some cases, communities have abandoned agriculture and livestock practices and undertaken new sources of livelihood such as tourism and labour migration. In cases where the impact of cryospheric changes is extreme, communities have been compelled to take the decision to relocate to more favourable areas. Many response measures are site-specific and carried out at a local scale and represent autonomous initiatives of local communities. With the changes in hydrology, downstream communities must adapt their water systems to cope with too much or too little water. Where possible, water augmentation will have to be combined with water demand management, and at all levels, institutions have to become much more adaptable and responsive to change.

Some responses are beyond the financial means of local communities—for example, building the infrastructure needed to deliver water to villages or fields. A key to building adaptation measures is to co-develop solutions with communities and local governments, taking advantage of indigenous knowledge and also strengthening institutions needed to sustain adaptation. Resilience building provides an important framework, as it is a forward-looking approach that also sees the inherent vulnerability of the system beyond climatic drivers and thus helps identify interventions necessary for positive transformation (Mishra et al. 2017).

Many of the impacts will be regional in the sense that impacts of climate change cross-national boundaries, and cooperation is required to deliver solutions. Countries share areas that are important to biodiversity, they share rivers and forested areas, and often disasters extend across borders. Moreover, there is a huge opportunity for countries to share knowledge to help in the adaptation process. However, the region is rife with political tension between countries. While this certainly hampers efforts to strengthen cooperation, the threat of climate change itself could be turned into an opportunity to promote cooperation. ICIMOD has taken important steps through its programmes on river basins and transboundary landscapes (Molden et al. 2017), river basin networks like the Upper Indus Basin Network (Shrestha et al. 2021b) and most recently through a Ministerial Declaration agreeing to work together on mountains (ICIMOD 2020).

A regional adaptation plan is required for the HKH region. A regional action plan supported by regional funding could deliver big impact and also provide measures of both adaptation and mitigation. Key elements of such a plan would include

- Efforts for increased cooperation on river basins, so that water supply, storage, transportation and energy generation and transmission could be developed more optimally, sharing benefits and costs.
- Managing cross-border disasters, improving flow of information and setting up regional responses to disasters when they happen.
- Efforts to build cooperation on important biodiversity hot spots; supporting local communities who live in these areas.

- Better linking of upstream and downstream activities, including compensating upstream communities for conservation efforts and supporting downstream communities in adaptive management of resources impacted by climate change. Focus should be on agriculture as it is the biggest user of water.

Infrastructure is a key concern, considering the need for development and also the need to do things differently in light of climate change. For example, hydropower project impacts the environment, but they are also impacted by the environment. Proper environmental risk assessment and implementation of environmental mitigation measures can ensure the sustainability of hydropower (Vaidya et al. 2021). Many hydropower plants were constructed based on historical meteorological and hydrological data and may need considerable modification to operate under a different hydrological regime.

Governments have a critical role to play in raising awareness about present and future impacts and vulnerabilities, building adequate capacity to cope with impacts, and to help build from the inherent adaptive capacity of local communities. Governments of the HKH region have to work closely with mountain and downstream communities to understand the changing situation and develop solutions. This will require financial and human resources, and these must be mobilised in different ways than before. Much more foresight is required, and there is a need to deal with a a high level of uncertainties. Plans and programs that worked in the past will not be sufficient now. It is necessary to improve research capacity to understand, assess and predict so that appropriate response measures can be developed. Now is also the time for governments to reach out beyond their boundaries to their neighbouring countries for ideas and inspiration, but also to address real and growing transboundary issues such as floods. The International Community has set up instruments like the Green Climate Fund, and this is a positive step, but more could be done to support regional and transboundary issues.

We need more robust science to back policy formulation, but we also need to do science in a different way, using more inter and transdisciplinary approaches involving many disciplines including social sciences and connecting research with communities and policy makers. More measurements and observatories are required in the mountains. Upstream and downstream linkages, including downstream impacts on the plains, need to be better quantified. More attention should be paid to key linkages such as the water–food–energy nexus and the role of air quality. Experts in the social sciences and physical sciences should work together to find ways to alleviate poverty, build institutions and build awareness of the complex political ecology in the region.

There is a lot to be done, and it is not too soon to start. This chapter has brought out some of the existing knowledge on climate change in the mountains and its impacts downstream. We feel that much more needs to be done to understand this critical link. The chapter also shows that we know enough to take action now—through investments, strengthening cooperation and institutions and expanding scientific knowledge and practice to improve our responses.

Acknowledgements and Disclaimer This study was partially supported by core funds of ICIMOD contributed by the governments of Afghanistan, Australia, Austria, Bangladesh, Bhutan, China, India, Myanmar, Nepal, Norway, Pakistan, Sweden and Switzerland.

The views and interpretations in this publication are those of the authors. They are not necessarily attributable to their institution and do not imply the expression of any opinion by their institutions concerning the legal status of any country, territory, city or area of its authority or concerning the delimitation of its frontiers or boundaries or the endorsement of any product.

References

Adger W, Arnell N, Black R, Dercon S, Geddes A, Thomas D (2015). Focus on environmental risks and migration: causes and consequences. Environ Res Lett 10(60201). https://doi.org/10.1088/1748-9326/10/6/060201

Aggarwal PK (2008) Global climate change and Indian agriculture: impacts, adaptation and mitigation. India J Agric Stud 78(10):911–919

Bajracharya SR (2010) Glacial lake outburst flood disaster risk reduction activities in Nepal. Int J Erosion Control Eng 3(1):92–101. https://www.jstage.jst.go.jp/article/ijece/3/1/3_1_92/_pdf

Bajracharya SR, Shrestha B (2011) The status of glaciers in the Hindu Kush-Himalayan region. International Center for Integrated Mountain Development, Kathmandu

Bajracharya SR, Maharjan SB, Shrestha F, Sherpa TC, Wagle N, Shrestha AB (2020) Inventory of glacial lakes and identification of potentially dangerous glacial lakes in the Koshi, Gandaki, and Karnali River Basins of Nepal, the Tibet Autonomous Region of China, and India. Research report, ICIMOD and UNDP

Bansod SD, Yin ZY, Lin Z, Zhang X (2003) Thermal field over Tibetan Plateau and Indian summer monsoon rainfall. Int J Climatol 23(13):1589–1605. https://doi.org/10.1002/joc.953

Bhadwal S, Ghosh S, Gorti G, Govindan M, Mohan D, Singh P, Singh S, Yogya Y (2017) The Upper Ganga Basin—will drying springs and rising floods affect agriculture? HI-AWARE working paper 8. HI-AWARE, Kathmandu

Bhambri R, Bolch T, Kawishwar P, Dobhal DP, Srivastava D, Pratap B (2013) Heterogeneity in glacier response in the upper Shyok valley, northeast Karakoram. Cryosphere 7(5):1385–1398. https://doi.org/10.5194/tc-7-1385-2013

Bhatt RP (2017) Hydropower development in Nepal—climate change, impacts and implications. Renew Hydropower Technol. https://doi.org/10.5772/66253

Biemans H, Siderius C, Lutz AF, Nepal S, Ahmad B, Hassan T, von Bloh W, Wijngaard RR, Wester P, Shrestha AB, Immerzeel WW (2019) Importance of snow and glacier meltwater for agriculture on the Indo-Gangetic Plain. Nat Sustain 2:594–601. https://doi.org/10.1038/s41893-019-0305-3

Boehlert B, Strzepek KM, Gebretsadik Y, Swanson R, McCluskey A, Neumann JE, McFarland J, Martinich J (2016) Climate change impacts and greenhouse gas mitigation effects on U.S. hydropower generation. Appl Energy 183:1511–1519. https://doi.org/10.1016/j.apenergy.2016.09.054

Bolch T et al (2019) Status and change of the cryosphere in the extended Hindu Kush Himalaya Region. In: Wester P, Mishra A, Mukherji A, Shrestha AB (eds) The Hindu Kush Himalaya assessment—mountains, climate change, sustainability and people. Springer, Cham, pp 209–255. https://doi.org/10.1007/978-3-319-92288-1_7

Bookhagen B, Burbank DW (2010) Toward a complete Himalayan hydrological budget: spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge. J Geophys Res Earth Surf 115(3):1–25. https://doi.org/10.1029/2009JF001426

Bräuning A (2006) Tree-ring evidence of “Little Ice Age” glacier advances in southern Tibet. Holocene 16(3):369–380. https://doi.org/10.1191/0959683606hl922rp

Byers AC, Rounce DR, Shugar DH, Lala JM, Byers EA, Regmi D (2019) A rockfall-induced glacial lake outburst flood, Upper Barun Valley Nepal. Landslides 16:533–549. https://doi.org/10.1007/s10346-018-1079-9

Carey M, Molden OC, Rasmussen MB, Jackson M, Nolin AW, Mark BG (2017) Impacts of glacier recession and declining meltwater on mountain societies. Ann Am Assoc Geogr 107 (2):350–359. https://doi.org/10.1080/24694452.2016.1243039

Carling J, Schewel K (2018) Revisiting aspiration and ability in international migration. J Ethn Migr Stud 44(6):945–963. https://doi.org/10.1080/08941920.2019.1590667

CBS (2012) National population and housing census 2011. National report. National Central Bureau of Statistics, Government of Nepal, Kathmandu

Choudhary A, Dimri AP (2017) Assessment of CORDEX-South Asia experiments for monsoonal precipitation over Himalayan region for future climate. Clim Dyn 50:3009–3030. https://doi.org/10.1007/s00382-017-3789-4

Clouse C (2016) Frozen landscapes: climate-adaptive design interventions in Ladakh and Zanskar. Landsc Res 41:821–837. https://doi.org/10.1080/01426397.2016.1172559

Dame J, Nüsser M (2011) Food security in high mountain regions: agricultural production and the impact of food subsidies in Ladakh, Northern India. Food Secur 3:179–194. https://doi.org/10.1007/s12571-011-0127-2

De Kok RJ, Tuinenburg OA, Bonekamp PNJ, Immerzeel WW (2018) Irrigation as a potential driver for anomalous glacier behavior in High Mountain Asia. Geophys Res Lett 45:2047–2054. https://doi.org/10.1002/2017GL076158

De Kok RJ, Kraaijenbrink PDA, Tuinenburg OA, Bonekamp PNJ, Immerzeel WW (2020) Towards understanding the pattern of glacier mass balances in High Mountain Asia using regional climatic modelling. Cryosphere 14(9):3215–3234. https://doi.org/10.5194/tc-14-3215-2020

DHM (2017) Observed climate trend analysis in the districts and physiographic regions of Nepal (1971–2014). Department of Hydrology and Meteorology, Ministry of Population and Environment, Government of Nepal. Kathmandu, Nepal. http://www.dhm.gov.np/uploads/climatic/1935165359NAP_TrendReport_DHM_2017.pdf. Accessed 15 Apr 2021

Diaz HF, Bradley RS (1997) Temperature variations during the last century at high elevation sites. Clim Change 36:253–279

Farinotti D, Immerzeel WW, de Kok RJ, Quincey DJ, Dehecq A (2020) Manifestations and mechanisms of the Karakoram glacier anomaly. Nat Geosci 13:8–16. https://doi.org/10.1038/s41561-019-0513-5

Foresight (2011) Migration and global environmental change: future challenges and opportunities. Final project report. The Government Office for Science, London. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/287717/11-1116-migration-and-global-environmental-change.pdf. Accessed 15 Apr 2021

Forsythe N, Fowler HJ, Li XF, Blenkinsop S, Pritchard D (2017) Karakoram temperature and glacial melt driven by regional atmospheric circulation variability. Nat Clim Chang 7:664–670. https://doi.org/10.1038/nclimate3361

Gemenne F, Blocher J (2017) How can migration serve adaptation to climate change? Challenges to fleshing out a policy ideal. Geogr J 183:336–347. https://doi.org/10.1111/geoj.12205

Gentle P, Thwaites R (2016) Transhumant pastoralism in the context of socioeconomic and climate change in the mountains of Nepal. Mt Res Dev 36(2):173–182. https://doi.org/10.1659/mrd-journal-d-15-00011.1

Gioli G, Khan T, Bisht S, Scheffran J (2014) Migration as an adaptation strategy and its gendered implications: a case study from the Upper Indus Basin. Mt Res Dev 34:255–265. https://doi.org/10.1659/MRD-JOURNAL-D-13-00089.1

Grossman D (2015) As Himalayan Glacier melts, two towns face the fall out. Yale Environment 360. Yale school of Forestry and Environment Studies. http://e360.yale.edu/features/as_himalayan_glaciers_melt_two_towns_face_the_fallout. Accessed 15 Apr 2021

Gruber S, Haeberli W (2007) Permafrost in steep bedrock slopes and its temperature-related destabilization following climate change. J Geophys Res 112. https://doi.org/10.1029/2006JF000547

Gruber S, Fleiner R, Guegan E, Panday P, Schmid M-O, Stumm D, Wester P, Zhang Y, Zhao L (2017) Review article: Inferring permafrost and permafrost thaw in the mountains of the Hindu Kush Himalaya region. Cryosphere 11:81–99. https://doi.org/10.5194/tc11-81-2017

Gurung DR, Giriraj A, Aung KS, Shrestha B, Kulkarni AV (2011) Snow-cover mapping and monitoring in the HinduKush-Himalayas. International Center for Integrated Mountain Development, Kathmanud

Hasson S, Lucarini V, Pascale S (2013) Hydrological cycle over South and Southeast Asian river basins as simulated by PCMDI/CMIP3 experiments. Earth Syst Dyn 4(2):199–217. https://doi.org/10.5194/esd-4-199-2013

Hasson S, Böhner J, Lucarini V (2015) Prevailing climatic trends and runoff response from Hindukush–Karakoram–Himalaya, upper Indus basin. Earth Syst Dyn Discuss 6:579–653. https://doi.org/10.5194/esdd-6-579-2015

He S, Richards K (2015) Impact of meadow degradation on soil water status and pasture management: a case study in Tibet. Land Degrad Dev 26:468–479. https://doi.org/10.1002/ldr.2358

Hewitt K (2005) The Karakoram anomaly? Glacier expansion and the 'elevation effect', Karakoram Himalaya. Mt Res Dev 25(4):332–340. https://doi.org/10.1659/0276-4741(2005)025[0332:TKAGEA]2.0.CO;2

Hewitt K (2011) Glacier change, concentration, and elevation effects in the Karakoram Himalaya, Upper Indus Basin. Mt Res Dev 31(3):188–200. https://doi.org/10.1659/MRD-JOURNAL-D-11-00020.1

Hock R, Rasul G, Adler C, Cáceres B, Gruber S, Hirabayashi Y, Jackson M et al (2019) High mountain areas. In: Pörtner H-O, Roberts DC, Masson-Delmotte V, Zhai P, Tignor M, Poloczanska E, Mintenbeck K, Alegría A, Nicolai M, Okem A, Petzold J, Rama B, Weyer NM (eds) IPCC special report on the ocean and cryosphere in a changing climate. IPCC, Geneva, pp 131–202. https://www.ipcc.ch/srocc. Accessed 20 Apr 2021

Hu F, Tan D (2018) No water, no growth. Does Asia have enough water to develop? China Water Risk, Hong Kong. -https://www.chinawaterrisk.org/resources/analysis-reviews/no-water-no-growth-does-asia-have-enough-water-to-develop/. Accessed 20 Apr 2021

Hugo G (1996) Environmental concerns and international migration. Int Migr Rev 30(1):105–131. https://www.jstor.org/stable/2547462

Huss M, Hock R (2018) Global-scale hydrological response to future glacier mass loss. Nat Clim Chang 8:135–140. https://doi.org/10.1038/s41558-017-0049-x

ICIMOD (2011) Glacial lakes and glacial lake outburst floods in Nepal. International Center for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal

ICIMOD (2020) The Hindu Kush Himalaya ministerial mountain summit 2020. https://www.icimod.org/hkhmms. Accessed 20 Apr 2021

Immerzeel WW, van Beek LPH, Bierkens MFP (2010) Climate change will affect the Asian water towers. Science 328(5984):1382–1385. https://doi.org/10.1126/science.1183188

Immerzeel WW, Lutz AF, Andrade M, Bahl A, Biemans H, Bolch T, Hyde S et al (2020) Importance and vulnerability of the world's water towers. Nature 577(7790):364–369. https://doi.org/10.1038/s41586-019-1822-y

IPCC (2012) Managing the risks of extreme events and disasters to advance climate change adaptation. Special report of the intergovernmental panel on climate change. https://www.ipcc.ch/site/assets/uploads/2018/03/SREX_Full_Report-1.pdf. Accessed 20 Apr 2021

IPCC (2018) Summary for policymakers. In: Masson-Delmotte V, Zhai P, Pörtner H-O, Roberts D, Skea J, Shukla PR, Pirani A, Moufouma-Okia W, Péan C, Pidcock R, Connors S, Matthews JBR, Chen Y, Zhou X, Gomis MI, Lonnoy E, Maycock T, Tignor M, Waterfield T (eds) Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. In Press

IPCC (2019) IPCC special report on the ocean and cryosphere in a changing climate [Pörtner H-O, Roberts DC, Masson-Delmotte V, Zhai P, Tignor M, Poloczanska E, Mintenbeck K, Alegría A, Nicolai M, Okem A, Petzold J, Rama B, Weyer NM (eds)]. In press

Jehangir WA, Mudasser M, Hassan M, Ali Z (1998) Multiple uses of irrigation water in the Hakra-6/R distributary command area, Punjab, Pakistan. Pakistan National Program, International Irrigation Management Institute, Lahore. https://www.researchgate.net/publication/254425808_Multiple_Uses_of_Irrigation_Water_in_the_Hakra_6-R_Distributary_Command_Area. Accessed 25 Apr 2021

Kang S, Wang F, Morgenstern U, Zhang Y, Grigholm B, Kaspari S, Schwikowshi M et al (2015) Dramatic loss of glacier accumulation area on the Tibetan Plateau revealed by ice core tritium and mercury records. Cryosphere 9(3):1213–1222

Kayastha RB, Harrison SP (2008) Changes of the equilibrium-line altitude since the Little Ice Age in the Nepalese Himalaya. Ann Glaciol 48:93–99

Khadka RB, Khanal AB (2008) Environmental Management Plan (EMP) for Melamchi water supply project, Nepal. Environ Monit Assess 146(1–3):225–234. https://doi.org/10.1007/s10661-007-0074-8

Khanal S, Lutz AF, Kraaijenbrink PDA, van den Hurk B, Yao T, Immerzeel WW (2021) Variable 21st century climate change response for rivers in High Mountain Asia at seasonal to decadal time scales. Water Resour Res 57:e2020WR029266. https://doi.org/10.1029/2020WR029266

Kick W (1989) The decline of the Little Ice Age in high Asia compared with that in Alps. In: Oerlemans J (ed) Glacier fluctuation and climate change. Springer, Dordrecht, pp 129–140. https://doi.org/10.1007/978-94-015-7823-3_8

Koubi V, Spilker G, Schaffer L, Bernauer T (2016a) Environmental stressors and migration: evidence from Vietnam. World Dev 79:197–210. https://doi.org/10.1016/j.worlddev.2015.11.016

Koubi V, Spilker G, Schaffer L, Böhmelt T (2016b) The role of environmental perceptions in migration decision-making: Evidence from both migrants and non-migrants in five developing countries. Popul Environ 38(2):134–163. https://doi.org/10.1007/s11111-016-0258-7

Kraaijenbrink PDA, Bierkens MFP, Lutz AF, Immerzeel WW (2017) Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers. Nature 549:257–260

Krishnan R, Shrestha AB, Ren G, Rajbhandari R, Saeed S, Sanjay S, Syed MA, Vellore R, Xu Y, You Q, Ren Y (2019) Unravelling climate change in the Hindu Kush Himalaya: rapid warming in the mountains and increasing extremes. In: Wester P, Mishra A, Mukherji A, Shrestha AB (eds) The Hindu Kush Himalaya assessment—mountains, climate change, sustainability and people. Springer, Cham, pp 57–97

Krishnan R, Sanjay J, Gnanaseelan C, Mujumdar M, Kulkarni A, Chakraborty S (2020) Assessment of climate change over the Indian Region. A Report of the Ministry of Earth Sciences (MoES), Government of India. SpringerOpen, 242 pp. https://doi.org/10.1007/978-981-15-4327-2

Le De L, Gaillard JC, Friesen W (2013) Remittances and disaster: a review. Int J Disaster Risk Reduction 4:34–43. https://doi.org/10.1016/j.ijdrr.2013.03.007

Liu X, Chen B (2000) Climatic warming in the Tibetan Plateau during recent decades. Int J Climatol 20(14):1729–1742. https://doi.org/10.1002/1097-0088(20001130)20:14%3c1729::AID-JOC556%3e3.0.CO;2-Y

Liu M, Chen N, Zhang Y, Deng M (2020) Glacial lake inventory and lake outburst flood/debris flow hazard assessment after the Gorkha earthquake in the Bhote Koshi Basin. Water 12:1–21. https://doi.org/10.3390/w12020464

Lutz AF, Immerzeel WW, Shrestha AB, Bierkens MFP (2014) Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. Nat Clim Chang 4:587–592. https://doi.org/10.1038/nclimate2237

Macfarlane A (1976) Resources and population: a study of the gurungs of Nepal. Cambridge University Press, Cambridge

Maharjan A, de Campos RS, Singh C, Das D, Srinivas A, Bhuiyan MRA, Ishaq S et al (2020) Migration and household adaptation in climate-sensitive hotspots in South Asia. Curr Clim Change Rep 6:1–16. https://doi.org/10.1007/s40641-020-00153-z

Maharjan A, Tuladhar S, Hussain A, Bhadwal S, Ishaq S, Saeed BA, Sachdeva I, Ahmad B, Ferdous J, Hassan SMT (2021) Can labour migration help households adapt to climate change? Evidence from four river basins in South Asia. Clim Dev. https://doi.org/10.1080/17565529.2020.1867044

Maurer JM, Schaefer JM, Rupper S, Corley A (2019) Acceleration of ice loss across the Himalayas over the last 40 years. Sci Adv 5(6):eaav7266. https://doi.org/10.1126/sciadv.aav7266

Mayewski PA, Jeschke PA (1979) Himalayan and trans-Himalayan glacier luctuations since AD 1812. Arct Alp Res 11(3):267. https://doi.org/10.2307/1550417

McDowell G, Ford JD, Lehner B, Berrang-Ford L, Sherpa A (2013) Climate-related hydrological change and human vulnerability in remote mountain regions: a case study from Khumbu, Nepal. Reg Environ Change 13:299–310. https://doi.org/10.1007/s10113-012-0333-2

Mishra V (2015) Climatic uncertainty in Himalayan water towers. J Geophys Res Atmos 120 (7):2680–2705. https://doi.org/10.1002/2014JD022650

Mishra A, Ghate R, Maharjan A, Gurung J, Gurung CG, Dorji T, Wester P (2017) Building resilient solutions for mountain communities in the HKH region. ICIMOD position paper, Kathmandu

Molden D (2020) Scarcity of water or scarcity of management?. Int J Water Resour Dev 36:2–3, 258–268. https://doi.org/10.1080/07900627.2019.1676204

Molden DJ, Shrestha AB, Nepal S, Immerzeel WW (2016) Downstream implications of climate change in the Himalayas. In: Biswas AK, Tortajada C (eds) Water security, climate change and sustainable development. Springer, Singapore, pp 65–82

Molden D, Sharma E, Shrestha AB, Chettri N, Pradhan NS, Kotru R (2017) Advancing regional and transboundary cooperation in the conflict-prone Hindu Kush-Himalaya. Mt Res Dev 37 (4):502–508. https://doi.org/10.1659/MRD-JOURNAL-D-17-00108.1

Mool PK, Bajracharya SR, Joshi SP (2001) Inventory of glaciers, glacial lakes and glacial lake outburst floods, monitoring and early warning systems in the Hindu Kush Himalaya region. ICIMOD/UNEP, Kathmandu

Namgay K, Millar JE, Black R, Samdup T (2014) Changes in transhumant agro-pastoralism in Bhutan: a disappearing livelihood? Hum Ecol 42(5):779–792. https://doi.org/10.1007/s10745-014-9684-2

Nepal S, Pandey A, Shrestha AB, Mukherji A (2018) Revisiting key questions regarding upstream–downstream linkages of land and water management in the Hindu Kush Himalaya (HKH) region. HI-AWARE working paper 21. Himalayan Adaptation, Water and Resilience (Hi-AWARE) Research. Kathmandu, Nepal

Nie Y, Pritchard HD, Liu Q, Hennig T, Wang W, Wang X, Liu S et al (2021) Glacial change and hydrological implications in the Himalaya and Karakoram. Nat Rev Earth Environ 2:91–106. https://doi.org/10.1038/s43017-020-00124-w

NRDC (2017) The Paris agreement of climate change. Issue Brief. https://assets.nrdc.org/sites/default/files/paris-agreement-climate-change-2017-ib.pdf. Accessed 25 Apr 2021

Nyima Y, Hopping KA (2019) Tibetan lake expansion from a pastoral perspective: local observations and coping strategies for a changing environment. Soc Nat Resour 32(9):965–982. https://doi.org/10.1080/08941920.2019.1590667

Panday PK, Thibeault J, Frey KE (2014) Changing temperature and precipitation extremes in the Hindu Kush-Himalayan region: an analysis of CMIP3 and CMIP5 simulations and projections. Int J Climatol 35(10):3058–3077. https://doi.org/10.1002/joc.4192

Pathak S, Pant L, Maharjan A (2017) De-population trends, patterns and effects in Uttarakhand, India—a gateway to Kailash Mansarovar. ICIMOD working paper 2017/22. International Center for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal.

Paul F (2015) Revealing glacier flow and surge dynamics from animated satellite image sequences: examples from the Karakoram. Cryosphere 9(6):2201–2214. https://doi.org/10.5194/tc-9-2201-2015

Pepin N, Bradley RS, Diaz HF, Baraer M, Caceres EB, Forsyhe N, Greenood G (2015) Elevation-dependent warming in mountain regions of the world. Nat Clim Chang 5:424–430. https://doi.org/10.1038/nclimate2563

Qian Y, Flanner MG, Leung LR, Wang W (2011) Sensitivity studies on the impacts of Tibetan Plateau snowpack pollution on the Asian hydrological cycle and monsoon climate. Atmos Chem Phys 11(5):1929–1948. https://doi.org/10.5194/acp-11-1929-2011

Rasul G (2010) The role of the Himalayan mountain systems in food security and agricultural sustainability in South Asia. Int J Rural Manag 6(1):95–116. https://doi.org/10.1177/097300521100600105

Rasul G (2014) Food, water, and energy security in South Asia: a nexus perspective from the Hindu Kush Himalayan region. Environ Sci Policy 39:35–48. https://doi.org/10.1016/j.envsci.2014.01.010

Rasul G (2021) Twin challenges of COVID-19 pandemic and climate change for agriculture and food security in South Asia. Environ Challenges 2:100027. https://doi.org/10.1016/j.envc.2021.100027

Rasul G, Molden D (2019) The global social and economic consequences of mountain cryopsheric change. Front Environ Sci 7:91. https://doi.org/10.3389/fenvs.2019.00091

Rasul G, Saboor A, Tiwari PC, Hussain A, Ghosh N, Chettri GB (2019) Food and nutrition security in the Hindu Kush Himalaya: unique challenges and niche opportunities. In: Wester P, Mishra A, Mukherji A, Shrestha A (eds) The Hindu Kush Himalaya assessment—mountains, climate change, sustainability and people. Springer, Cham, pp 301–338

Rasul G, Pasakhala B, Mishra A, Pant S (2020) Adaptation to mountain cryosphere change: issues and challenges. Clim Dev 12(4):297–309. https://doi.org/10.1080/17565529.2019.1617099

Rees HG, Holmes MGR, Young AR, Kansaker SR (2004) Recession-based hydrological models for estimating low flows in ungauged catchments in the Himalayas. Hydrol Earth Syst Sci 8:891–902. https://doi.org/10.5194/hess-8-891-2004

Ren Y-Y, Ren G-Y, Sun X-B, Shrestha AB, You Q-L, Zhan Y-J et al (2017) Observed changes in surface air temperature and precipitation in the Hindu Kush Himalayan region during 1901–2014. Adv Clim Change Res 8(3). https://doi.org/10.1016/j.accre.2017.08.001

Rigaud KK, de Sherbinin A, Jones B, Bergmann J, Clement V, Ober, K, Schewe J et al (2018) Groundswell: preparing for internal climate migration. World Bank, Washington, DC. https://openknowledge.worldbank.org/handle/10986/29461. Accessed 26 Apr 2021

Rounce DR, Byers AC, Byers EA, McKinney DC (2017) Brief communication: observations of a glacier outburst flood from Lhotse Glacier, Everest area, Nepal. Cryosphere 11:443–449. https://doi.org/10.5194/tc-11-443-2017

Rounce DR, Hock R, Shean DE (2020) glacier mass change in high mountain Asia through 2100 using the open-source python glacier evolution model (PyGEM). Front Earth 7:331. https://doi.org/10.3389/feart.2019.00331

Saikawa E, Panday A, Kang S, Gautam R, Zusman E, Cong Z, Somanathan E (2019) Air pollution in the Hindu Kush Himalaya. In: Wester P, Mishra A, Mukherji A, Shrestha A (eds) The Hindu Kush Himalaya assessment—mountains, climate change, sustainability and people. Springer, Cham, pp 339–377. https://doi.org/10.1007/978-3-319-92288-1_10

Sanjay J, Krishnan R, Shrestha AB, Rajbhandari R, Ren GY (2017) Downscaled climate change projections for the Hindu Kush Himalayan region using CORDEX South Asia regional climate models. Adv Clim Chang Res 8(3):185–198. https://doi.org/10.1016/j.accre.2017.08.003

Schwanghart W, Worni R, Huggel C, Stoffel M, Korup O (2016) Uncertainty in the Himalayan energy–water nexus: Estimating regional exposure to glacial lake outburst floods. Environ Res Lett 11(074005). https://doi.org/10.1088/1748-9326/11/7/074005

Scott CA, Zhang F, Mukherji A, Immerzeel W, Mustafa D, Bharati L (2019) Water in the Hindu Kush Himalaya. In: Wester P, Mishra A, Mukherji A, Shrestha A (eds) The Hindu Kush Himalaya assessment—mountains, climate change, sustainability and people. Springer, Cham, pp 257–292. https://doi.org/10.1007/978-3-319-92288-1_8

Shaoliang Y, Ismail M, Zhaoli Y (2012) Pastoral communities' perspectives on climate change and their adaptation strategies in the Hindukush-Karakoram-Himalaya. In: Kreutzmann H (ed) Pastoral practices in High Asia. Advances in Asian human-environmental research. Springer, Dordrecht, pp 307–322. https://doi.org/10.1007/978-94-007-3846-1

Shean DE, Bhusan S, Montesano P, Rounce DR, Arendt A, Osmangolu B (2020) A systematic, regional assessment of high mountain Asia glacier mass balance. Front Earth Sci 7(363):1–19. https://doi.org/10.3389/feart.2019.00363

Shrestha AB, Wake CP, Mayewski PA, Dibb JE (1999) Maximum temperature trends in the Himalaya and its vicinity: an analysis based on temperature records from Nepal for the period 1971–94. J Clim 12:2775–2786

Shrestha AB, Eriksson M, Mool P, Ghimire P, Mishra B, Khanal NR (2010) Glacial lake outburst flood risk assessment of Sun Koshi basin, Nepal. Geomat Nat Haz Risk 1(2):157–169. https://doi.org/10.1080/19475701003668968

Shrestha MS, Grabs WE, Khadgi VR (2015) The establishment of a regional flood information system in the Hindu Kush Himalayas: challenges and opportunities. Int J Water Resour Dev 31:238–252. https://doi.org/10.1080/07900627.2015.1023891

Shrestha P, Lord A, Mukherji A, Shrestha RK, Yadav L, Rai N (2016) Benefit sharing and sustainable hydropower: lessons from Nepal. International Center for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal

Shrestha A, Shrestha S, Tingsanchalia T, Budhathoki A, Ninsawat S (2020) Adapting hydropower production to climate change: a case study of Kulekhani Hydropower Project in Nepal. J Clean Prod 279:1–14

Shrestha AB, Shukla D, Pradhan NS, Dhungana S, Azizi F, Memon N, Mohtadullah K, Lotia H, Ali A, Molden D, Daming H, Dimri AP, Huggel C (2021b) Developing a science-based policy network over the Upper Indus Basin. Sci Total Environ 784:147067. https://doi.org/10.1016/j.scitotenv.2021.147067

Shrestha AB, Steiner J, Nepal S, Maharjan SB, Jackson M, Rasul G, Bajracharya B (2021a) Understanding the Chamoli flood: cause, process, impacts and context of rapid infrastructure development. International Center for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal. https://www.icimod.org/article/understanding-the-chamoli-flood-cause-process-impacts-and-context-of-rapid-infrastructure-development/. Accessed 26 Apr 2021

Siderius C, Biemans H, Wiltshire A, Rao S, Franssen WHP, Kumar P, Gosain AK et al (2013) Snowmelt contributions to discharge of the Ganges. Sci Total Environ 468–469:S93–S101. https://doi.org/10.1016/j.scitotenv.2013.05.084

Stäubli A, Nussbaumer SU, Allen SK, Huggel C, Arguello M, Costa F et al (2018) Analysis of weather-and climate-related disasters in mountain regions using different disaster databases. In: Mal S, Singh R, Huggel C (eds) Climate change, extreme events, and disaster risk reduction. Sustainable development goals series. Springer, Cham, pp 17–41. https://doi.org/10.1007/978-3-319-56469-2_2

Thompson LG, Yao T, Mosley-Thompson E, Davis ME, Henderson KA, Lin PN (2000) A high-resolution millennial record of the South Asian monsoon from himalayan ice cores. Science 289(5486):1916–1920. https://doi.org/10.1126/science.289.5486.1916

Tuinenburg OA, Hutjes RWA, Kabat P (2012) The fate of evaporated water from the Ganges basin. J Geophys Res 117(D1):D01107. https://doi.org/10.1029/2011jd016221

Tuladhar S, Pasakhala B, Maharjan A, Mishra A (2021) Unravelling the linkages of cryosphere and mountain liveihood systems: a case study of Langtang, Nepal. Adv Clim Chang Res 12(1):119–131. https://doi.org/10.1016/j.accre.2020.12.004

Turner SWD, Hejazi M, Kin SH, Clarke L, Edmonds J (2017) Climate impacts on hydropower and consequences for global electricity supply investment needs. Energy 141:2081–2090. https://doi.org/10.1016/j.energy.2017.11.089

Vaidya RA, Shrestha MS, Nasab N, Gurung DR, Kozo N, Pradhan NS, Wasson RJ (2019) Disaster risk reduction and building resilience in the Hindu Kush Himalaya. In: Wester P, Mishra A, Mukherji A, Shrestha A (eds) The Hindu Kush Himalaya assessment—mountains, climate change, sustainability and people. Springer, Cham, pp 389–419. https://doi.org/10.1007/978-3-319-92288-1_11

Vaidya RA, Molden DJ, Shresthat AB, Wagle N, Tortajada C (2021) The role of hydropower in South Asia's energy future. Int J Water Resour Dev 37(3):367–391. https://doi.org/10.1080/07900627.2021.1875809

van der Geest K, Schindler M (2016) Brief communication: loss and damage from a catastrophic landslide in Nepal. Nat Hazard 16(11):2347–2350. https://doi.org/10.5194/nhess-16-2347-2016

Viswanathan B, Kavi Kumar KS (2015) Weather, agriculture and rural migration: evidence from state and district level migration in India. Environ Dev Econ 20(4):469–492. https://doi.org/10.1017/S1355770X1500008X

Wang G, Yuanshou Li, Yibo W, Qingbo W (2008) Effects of permafrost thawing on vegetation and soil carbon pool losses on the Qinghai-Tibet Plateau, China. Geoderma 143(1–2):143–152. https://doi.org/10.1016/j.geoderma.2007.10.023

Warner K, Afifi T (2014) Where the rain falls: Evidence from 8 countries on how vulnerable households use migration to manage the risk of rainfall variability and food insecurity. Climate Dev 6(1):1–17. https://doi.org/10.1080/17565529.2013.835707

Wester P, Mishra A, Mukherji A, Shrestha AB (eds) (2019) The Hindu Kush Himalaya assessment—mountains, climate change, sustainability and people. Springer, Cham

Wijngaard RR, Lutz AF, Nepal S, Khanal S, Pradhananga S, Shrestha AB, Immerzeel WW (2017) Future changes in hydro-climatic extremes in the Upper Indus, Ganges, and Brahmaputra River basins. PLOS ONE 12(12):e0190224. s

Wiltshire AJ (2014) Climate change implications for the glaciers of the Hindu Kush, Karakoram and Himalayan region. Cryosphere 8:941–958. https://doi.org/10.5194/tc-8-941-2014

Wu G, Zhang Y (1998) Tibetan Plateau Forcing and the timing of the Monsoon onset over South Asia and the South China Sea. Mon Weather Rev 126(4):913–927. https://doi.org/10.1175/1520-0493(1998)126%3c0913:TPFATT%3e2.0.CO;2

Yang M, Frederick E, Nikolay IS, Guo D, Wan G (2010) Permafrost degradation and its environmental effects on the Tibetan Plateau: a review of recent research. Earth-Sci Rev 103(1–2):31–44. https://doi.org/10.1016/j.earscirev.2010.07.002

Zemp M, Huss M, Thibert E, Eckert N, McNabb R, Huber J, Barandun M, Machguth H, Nussbaumer SU, Gärtner-Roer I, Thomsan L, Paul F, Maussion F, Kutuzov S, Cogley JG (2019) Global glacier mass balances and their contributions to sea-level rise from 1961 to 2016. Nature 568:382–386. https://doi.org/10.1038/s41586-019-1071-0

Zhang T, Wang T, Krinner G, Wang X, Gasser T, Peng S, Piao S, Yao T (2019) The weakening relationship between Eurasian spring snow cover and Indian summer monsoon rainfall. Climatology 5(3):eaau8932. https://doi.org/10.1126/sciadv.aau8932

Zhao L, Wu Q, Marchenko SS, Sharkhuu N (2010) Thermal state of permafrost and active layer in Central Asia during the international polar year. Permafrost Piglacial Process 21(2):198–207. https://doi.org/10.1002/ppp.688