Chapter 3
Climate Change Impact on Major River Basins in the Indian Himalayan Region: Risk Assessment and Sustainable Management

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Abstract Billions of people relay on water resources of the Himalayan region for drinking, irrigation, and other domestic purposes. Abundance of natural resources makes this region suitable for human settlements, despite the fact that the area experiences frequent natural hazards. Water resources including major rivers are one of the important components, responsible for high biodiversity of the Himalayas and its role in global atmospheric circulation. Recent climate changes have proved to affect the precipitation pattern and ice cover of the Himalayas, causing variations in the dynamics of rivers in the area. Climate change–induced variation in river flow quantity, timing, and unpredictability raises the danger of ecological changes and has a negative impact on aquatic life and the ecosystem depending on rivers. Agriculture is one important sector that is at highest risk due to climate change. This is a serious concern as the runoff patterns of the rivers are mainly determined by the precipitation pattern and ice cover in the upper reaches. Reduction in ice cover reduces the water storage capacity of the Himalayas, and fluctuations in the precipitation pattern cause floods and droughts. The increased frequency of natural hazards including floods and droughts affects the economy and is a threat to people's life. Climate change effects on water resources, namely, Himalayan snow and ice reservoirs and lake and river systems and the risk associated with it, can be monitored using different hydrological models. To cover vast geographical areas of the Himalayan region, adequate hydrological observatories need to be installed in order to monitor and record time series data of the hydrological parameters. Systematic monitoring will

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help to predict how climate change will affect water resources in the future. Sustainable management of local resources based on suitable practices, adaptation strategies, and need-specific policies relevant to basin climate can further reduce frequent climate change-related impacts, risk, and vulnerability.

Keywords Climate change · Himalaya · Major rivers · Hydrological observatories · Risk assessment · Sustainable management

1 Introduction

Water resources in the Himalayan region include over ten of the largest rivers in Asia (Eriksson et al., 2009). Major rivers in the Indian Himalayan region (IHR) are distributed in the Indus basins, Ganga basins, and Brahmaputra (IGB) basins, and it possesses high water resource potential. Himalayas host large resources of snow, ice, and glaciers forming water tower of Asia (Xu et al., 2009). Large snow and ice cover are the source of fresh water to IGB rivers and their tributaries (Schild, 2008). The glacier coverage in Himalayas is estimated to be about 33,000 km^2, and it provides around 88×10^6 m^3 of water annually (NMSHE, 2010). Glacial melting impacts the water availability and seasonal flow of IGB basins. It provides many ecosystem services to people in the form of hydropower, water for agriculture, and household purposes and aid transport and tourism. Additionally, the biodiversity and global atmospheric circulation are significantly influenced by water resources. However, water-induced natural disasters including flash floods and riverine floods predominate in the Himalayan river basins. Increase in floods, droughts, landslides, endangered species, threat to biodiversity, food security, and people's livelihood are some of the impacts of climate change in the Himalayas (Xu et al., 2009; Mir et al., 2019). Climate change thereby affects the region socioeconomically, ecologically, and culturally. Although the Himalayas are hotspot for natural disasters due to frequent seismic activity and tectonic features like faults and thrusts, the frequency and severity of catastrophic disasters have grown due to recent climatic changes, posing a serious threat to people and their way of life, agriculture, infrastructure, and ecosystem. Understanding the behavior of IGB basins to climate change will help in studies related to disaster risk assessment and sustainable management.

Increase in air temperature, specific humidity, ocean heat, sea level rise, sea-surface temperature, decrease in extent of snow cover and glacier volume, and sea ice are some of the general climate change indicators (NOAA, 2009). Variations in temperature, precipitation patterns, water availability of IGB basins, fluctuations in streamflow, and extent and volume of glaciers are considered to be some of the important climate change indicators in the Himalayan region (IPCC, 2013).

In recent times, the IGB river basins have been affected by rising temperature, variation in precipitation trends, glacial retreat, and changes in runoff over time and space. Change in the strength and timing of the Monsson, winter westerlies, and high-pressure systems impact river flows and groundwater recharge, leading to natural hazards and damage to ecosystem and livelihood of people (ICIMOD, 2010). Reduction in water storage capacity due to decrease in the snow and ice is a major concern here (ICIMOD, 2010). However, the impacts may vary basin-wise in terms of rate, intensity, and direction. Rising temperature might affect the high altitude areas more than the low latitude areas as the rising temperature causes the melting of snow and ice in the region (Shrestha et al., 1999).

Despite the observed changes in the monsoon precipitation and temperature, the impact of future climate change on the hydrological regime of major river basins in the Himalayan region is not well studied (Gosain et al., 2011). One of the important challenges in understanding the hydrological response of IGB river basins is lack of availability of sufficient data on these basins as it remains classified (Mishra & Lilhare, 2016). Dam construction and river water diversion also complicate understanding climate change-induced hydrological variation in the river system. IGB river basins being one of the major basins with a lot of rivers in the Himalayan region are crucial to assess how susceptible their hydrological systems are to climate change and comprehend how these river systems are expected to react in the future.

2 Regional Setting of the Himalayan River System

The Indus Ganga and Brahmaputra (IGB) river systems broadly constitute the Himalayan river system. It supports ~700 million people in Asia (Nepal & Shrestha, 2015) and covers >50% area of the country (Khan et al., 2015). The water resource in Indus, Ganges, and Brahmaputra (IGB) river systems are the major source of water for drinking, irrigation, navigation, industry, and hydropower purposes (Mirza et al., 2003). The basin extends between 21°–37° N latitude and 66°–97° E longitude and covers India, Bangladesh, Pakistan, Nepal, and Bhutan. The Indus river flows into the Arabian Sea forming a delta of about 41,440 km^2 and Ganga river along with Brahmaputra falls into the Bay of Bengal (Patel et al., 2021). Distribution of these basins covers a large geomorphic area covering high elevated mountain areas, plains, and sea level. Indus and Brahmaputra river systems have a trans-Himalayan origin, and Ganga river system originates from the Himalayas. Indus river originates from Lake Ngangla rainfall-runoff (China); Ganga originates from Gangotri Glacier, Uttarakhand (India); and Brahmaputra river originates from Angsi Glacier (China) (India-WRIS, 2012). Jhelum, Ravi, Chenab, and Sutlej are the main tributaries of Indus; Yamuna, Rama Ganges, Gomti, Ghagra, Son, Gandak, Burhi Gandak, Koshi, and Mahananda are the major tributaries of Ganga; and the important tributaries of Brahmaputra are Dibang, Lohit, Dhansiri, Kolong, Kameng, Manas, Raidak, Jaldhaka, Teesta, and Subansiri (Shrestha et al., 2015).

The overall discharge from the IGB basins is affected differently by snowfall, glacial melt, surface runoff, and groundwater. Mean discharge of Brahmaputra river is higher than the Ganges, whereas Indus has the lowest mean discharge (Table 3.1). The total river discharge in the upper Indus basins is constituted by glacier meltwater

Table 3.1 Key geographical and hydrological features of the Indus-Ganga-Brahmaputra basins

Basin	India	Area (km^2)	Length (Km)	Annual discharge (m^3/s)	Annual basin precipitation (mm)	Glaciated area (Km^2)	Mean discharge (m^3/s)
Indus	39%	1,120,000	3180	5533	434	21,193	5533
Ganges	79%	1,087,300	2515	12,037	1094	9012	18,691
Brahmaputra	36%	543,400	2840	21,261	2143	14,020	19,824
Reference		Nepal & Shrestha et al. (2015) and references therein			Khan et al. (2015)	ICIMOD report (2005)	Mirza (2004)

(~41%), snowmelt (~22%), and rainfall runoff (~27%). However, the Ganga and Brahmaputra basin's streamflow is dominated by rainfall runoff (66% and 59%, respectively), followed by meltwater contribution of approximately 20% and 25% to the total runoff, respectively (Shrestha et al., 2015). Though the relative contribution of these sources is debatable, surface runoff controlled by precipitation including snowfall is the major contributor to the total discharge of the basin (Maurya et al., 2011). In Indus basins, the annual rainfall is higher in the mountain region (up to 2000 mm), and low lands experience a rainfall ranging from 100 mm to 500 mm (Aquastat, 2011). This is an important factor that contributes to mild weather in the southern parts and snowfall in the northern parts (Nepal & Shrestha, 2015).

The total discharge of the basin is the main source of water downstream, where only ~40% of water available can be utilized due to topographical constraints and uneven distribution of water resources (CWC, 2015). IGB river supports the agricultural sector in a vast geographical area; further, Indus basins alone constitute the largest irrigation network in the world, where the water is regulated by Tarbela Dam on the Indus river and Mangla Dam on the Jhelum (Laghari et al., 2012). About 144,900 ha of land is irrigated by Indus, 156,300 ha is irrigated by Ganges basins, and 6000 ha of land is irrigated in the Brahmaputra basins (Immerzeel et al., 2010) (Fig. 3.1).

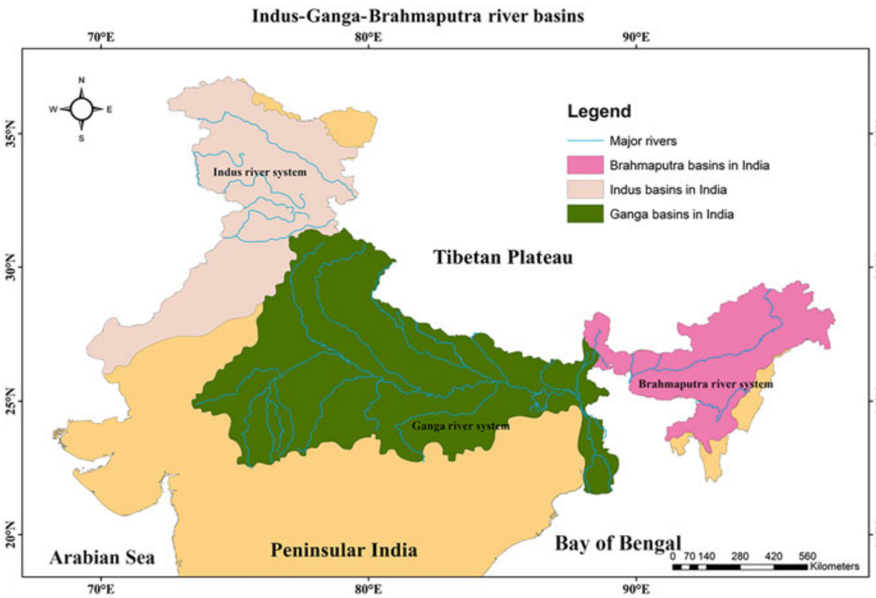

Fig. 3.1 Indus-Ganga-Brahmaputra river basins. (Modified after Patel et al., 2021)

3 Impact of Climate Change on Indus-Ganga-Brahmaputra River Basins

Temperature, precipitation, the amount of glacier/snow, and its melt are the common components studied to assess the impact of climate change on IGB river basins. Variations in precipitation, fluctuations in the amount of glacier/snow along with temperature changes, and seasonal extremes affect the life and chemistry of river basin (Bolch et al., 2012; Lutz et al., 2014). As temperatures rise, evapotranspiration increases, and glacial storage declines. This results in an increased glacier melt in short term and decreased amount of glacier melts in long term (Bolch et al., 2012; Milner et al., 2017). Fluctuating glacier volume leads to extreme weather events such as floods, droughts, flash floods, landslides, etc. (Nepal & Shrestha, 2015). Extreme weather conditions have become more common in India in recent years. For example, historical flood records from Alaknanda river in Uttarakhand, India, show an increase in extreme flood events (Goswami et al., 2006).

Himalayas being geologically dynamic, steep terrain with high seismicity and major thrust plains is highly vulnerable to natural hazards. Moderate to large magnitude earthquakes cause rock and ice avalanches and landslides, one of the major natural hazards of the region (Vaidya et al., 2019). Heavy rainfall with cloud bursts also activates landslides and debris flow. Unsustainable development and overuse of resources have a negative impact on slope stability and raise the risk of landslides. Sudden and unpredictable climatic change has made mountain ecosystems more susceptible to natural disasters, and it is one of the significant effects of climate change on the Himalayan river basins.

Depending on the basin location, the impact of climate change on glacier response and water supply varies. Eastern Himalaya witnessed a decrease in glacier volume due to decreased snowfall and increased ablation (Wiltshire, 2014). Continuous decrease in glacier volume causes increase in runoff for short term and a decrease in upstream water supply and annual runoff (Sharma et al., 2000). There can be up to 17% reduction in upstream water supply for Ganga river alone (Immerzeel et al., 2010). However, the river runoff is determined by both precipitation and snow/glacier melt. The southwest Indian Monsoon intensity and its seasonal changes determine the majority of precipitation (Bookhagen & Burbank, 2006). In Ganga basins, the reduced runoff due to decrease in glaciers is compensated by increase in precipitation (Immerzeel et al., 2013). However, an increase in rainfall during monsoon may not increase the water availability of the region but may result in increased flooding in the region. Shrinking of glaciers due to rise in temperature may result in an increase in meltwater volume initially, followed by water scarcity in some rivers in the long term (Bolch et al., 2012; Milner et al., 2017). Understanding the effects of climate change on the streamflow in the IGB river system is difficult, because of the spatial and temporal unpredictability of these changes, as well as practical constraints and a lack of monitoring of changes in river basins. As temperature and precipitation are primary driving factors, these data can be used for climate models to know the prospective impacts of climate change on the water supply in a river basin.

Temperature Even though the extreme topography and complex response of the Himalayas to greenhouse effect make climate change projections difficult, climate models predict that by 2100, the Indian subcontinent will heat up and the temperature will rise between 3.5 and 5.5 °C (Kumar et al., 2006). The glaciers in the Himalayas are retreating faster than the world average glacier retreat rate (Dyurgerov & Meier, 2005). Global warming is one of the important reasons for this. Global warming causes snowmelt to occur earlier causing shorter winter, and a large proportion of precipitation fall as rain (ICIMOD, 2010). This shows the interrelationship between temperature, glaciers, and runoff. Climate models based on different climate change scenario suggest that as a result of global warming, by 2050, 35% of the glaciers will retreat, and there will be a sudden increase in runoff between 2030 and 2050 (Qin, 2002). This might result in disappearance of smaller glaciers also. Increase in temperature can also affect the aquatic ecosystem by disturbing the environment suitable for their survival.

Precipitation Precipitation trends over the IGB basins have varied spatially and over time. Time period from 1998 to 2007 shows a decreasing trend in annual rainfall over IGB river basins where the mean annual rainfall has a heterogenous pattern at different locations (Patel et al., 2021). Interannual and interseasonal increase and decrease have been reported from the Himalayan region. Decreasing trend of both annual and seasonal rainfall is observed in the eastern Himalayan region (Brahmaputra basins), whereas Indus basins in the western region show an increasing trend. However, the middle part of the IGB basins shows complex pattern as both Indian summer Monsoon and westerlies contribute differently. This fluctuation in temperature and rainfall has an impact on the water storage in this region, causing water stress over time. Rainfall pattern and temperature can be correlated to the runoff of IGB basins (Patel et al., 2021). The intensity, amount, and distribution of total precipitation determine the river runoff and impact the downstream flow of river. Over the last years, overall rainfall in Indus basins shows an increasing trend, whereas Brahmaputra has a decreasing trend, and the Ganga basins experience both increasing and decreasing rainfall trend (Patel et al., 2021) (Table 3.2).

4 Impact of Future Climate Change on Himalayan River Basins

Himalayan region is very sensitive to climate change, which experiences more warming than the global average, very high variability in precipitation with increased frequency of precipitation events, and shrinking of glaciers (ICIMOD, 2010). Climate change might greatly impact the water supply of the IGB river basins causing potential threat to food security, energy security, environmental quality, livelihoods, and quality of life of people (Dahal et al., 2020). There is an increased occurrence of climate extremes in the past years, and it is likely to be more prominent in the future (Mishra et al., 2015; Easterling et al., 2000). One of the projected effects

Table 3.2 Overview of impact of climate change on water resources

Climate	Trend	Impacts on IGB river basins	Risk associated	Sustainable practices
Rainfall	Increase in rainfall intensity	Increased runoff with increased sediment load, flooding, and reduced ground water discharge	Groundwater exploitation, affect agriculture, human settlements, and infrastructure	Disaster preparedness and management, groundwater management, proper planning on urban drainage system and land use planning, soil and water conservation
	Decrease in rainfall intensity	Drying up of small tributaries and springs, reduction in seasonal flow of water, drought	Groundwater exploitation	Water harvesting
	Variation in rainfall pattern	Unpredictable river flow patterns	Affect agriculture	Efficient management of irrigation and water supply system
Temperature	Increase in temperature	Increase in temperature of water resources	Changes or imbalance in aquatic ecosystem	Proper monitoring of temperature changes
Glacier volume	Decrease in glacier volume	Unpredictable river flow patterns	Affects perennial water sources	Efficient management of irrigation and water supply system

Source: Climate change adaptation in Himachal Pradesh; Sustainable strategies for water resources (2010)

of climate change is the decrease in availability and access to freshwater by 2050 (ICIMOD, 2010). The "National Commission for Integrated Water Resources Development" (NCIWRD) reports that by the year 2050, the demand for water is expected to be 973–1180 billion cubic meters (BCM). Agriculture sector will dominate the demand share (70%) followed by households (9%) and industries (7%) (NCIWRD, 1999). The mismatch between the present availability and projected demand for water in the coming years explains the need to study the major river basins and factors controlling their discharge and/ recharge. Regular water scarcity and flooding, deteriorating water quality, and excessive dependence on groundwater in past years have increased the concern that water resources may be vulnerable to global climate change (IPCC, 2007). The hydrological regime of IGB can be affected by factors such as seasonal changes in rainfall onset, its intensity, amount, and duration causing fluctuations in the precipitation pattern over IGB basins (Anja du, 2019; Berger et al., 2019). Rising temperature has resulted in overall increase of total runoff in IGB basins, where the runoff changed by −5% to +12% for Upper Indus, 1–27% for Upper Ganga, and 0–13% for the Upper Brahmaputra basins by 2050 (Lutz et al., 2014). Increase in runoff also predicts the possibility of future flood events (Gain et al., 2011). Global circulation models (GCMs) predict an increase in mean peak discharge in Brahmaputra river (Mirza, 2002), and along with the precipitation, accelerated melt runoff causes increase in runoff up to 2050 (Lutz et al., 2014). There will be ~20% reduction in upstream water supply in Brahmaputra river, and the glacier ice melt will accelerate up to 2040, followed by a decrease (Immerzeel et al., 2010; Prasch et al., 2011). Overall, the river basins experience a decrease in the amount of water availability in upstream, higher peak flow, and reduced volume and area of glaciers and snow. Along with surface runoff, soil erosion and sediment yield of a river basin also get affected by climate change (Lilhare et al., 2015). According to Lutz et al. (2014), the Indus basin's annual discharge may rise by 7–12% by 2050 as a result of increased precipitation and rapid melt. Reduction in snowfall and a decrease in annual snowmelt runoff were associated with an increase in temperature, and a decrease in glacier area might decrease the river discharge drastically (Singh & Bengtsson, 2004; Akhtar et al., 2008). Projected impact of climate change on the hydrology of Indus basins shows that by 2100, glacier area might reduce by 33% and glacier volume by 50%, and there will be glacier melt peak in 2044 or 2065 followed by a decline in glacier volume (Immerzeel et al., 2013).

5 Risk Assessment

Natural hazards like flash floods and landslides are caused by an increase in the frequency of high-intensity rainfall (ICIMOD, 2002), which adversely affects human settlements. River runoff, which is dependent on the total precipitation, variation in intensity, and quantity and type of precipitation, will disturb the high latitude wet lands, water flow, and sediment transport in the rivers. Disaster risk assessment is an interplay between hazard, exposure, and vulnerability (Wester et al., 2019). Risk assessment starts with awareness about risks such as the intensity of existing and anticipated risk. It is important to identify, quantify, and characterize the hazards toward people's life and the environment for disaster risk assessment. This information forms the base of practices and policies related to disaster risk reduction. While risk analysis has both political and scientific dimensions, public perception on risk also has an important role in disaster risk analysis (Slovic, 1999). Impact of climate change on the hydrologic sensitivity of rivers can be monitored through precipitation trends, temperature changes, surface runoff data, rate of evapotranspiration, and streamflow data (Mishra & Lilhare, 2016). The Himalayan mountain system is very susceptible to global warming (Bandyopadhyay & Gyawali, 1994). Even though climate change is affecting the whole IGB basins, the effect is not uniformly distributed. Since the Western Himalayas are dominated by the westerlies and the eastern end is dominated by the southwest monsoon, global warming affects differently from west to east of the Himalayas. Each basin has a different and /unique response to climate change; hence, its impact varies within a basin from upstream to downstream and also in different catchment areas.

Monitoring of climatic variables such as temperature and rainfall and their influence on water availability over the IGB basins shows a decrease in terrestrial water storage (-12.6 mm year^{-1}) with increase in mean annual temperature (0.02 °C year^{-1}), and there is a positive correlation between terrestrial water storage ($r = 15.8$) (Patel et al., 2021). Variations in temperature and precipitation cause water stress over different part of IGB basins. Glaciers in Ganga river basins are sensitive to global warming; the contribution of glacier to water resources in the Indus basins is higher than that in the Ganges Basins (Immerzeel et al., 2012). Sensitivity analysis in Ganges Basins shows that the effect of warming may be higher in the northern, upstream region of Ganga river basins due to the presence of snow and glaciers (Mishra & Lilhare, 2016). Hence, the overall streamflow in the basin is controlled by the monsoon system. This shows that even within the Ganges Basins, the risk associated with future climate change has to be done locally to develop a robust mitigation program. Reduced river flow adversely affects the agricultural production, hydroenergy generation and agricultural production, and physical infrastructure of the area (Mirza 2011; Rupper et al., 2012).

Glacier retreat can destabilize the surrounding slopes causing landslides (Dadson & Church, 2005). Outbreak floods, flash floods, and debris flows are also some of the consequences of glacier retreat and excessive rain. Excessive meltwater formed as a result of glacial melt formed glacial lakes in the Eastern and central Himalayas. Most of these high-altitude lakes are moraine-dammed, which are weak and prone to sudden breach (ICIMOD, 2010). Floods due to this glacial outburst can cause serious damage to life, property, and ecosystem downstream. However, the impacts of glacial retreat are pronounced in basins, which are highly glaciated and receive less precipitation (Rees & Collins, 2006). Warming climate is the major reason for precipitation extremes. Human-induced global warming also contributes to the intensification of extreme precipitation events (Min et al., 2011).

Global warming intensifies the extreme precipitation events causing variability in occurrences of droughts and floods (Sheffield & Wood, 2008) and hazards like landslides. Large-scale landslides can lead to damming of river flow upstream resulting in the formation of landslide dam, which can subsequently result in outburst flood (Reynolds, 2014). Intense rainfall or/and breaching of natural dams cause flash floods. Though riverine floods and flash floods are common in IGB river basins, flash floods often occur rapidly without giving much time to provide warning.

Risk associated with natural hazards can be assessed in different dimensions such as physical, social, environmental, and economic dimensions. Damage to physical assets such as infrastructure, suffering of human life, and economic loss come under physical, social, and economic dimensions, respectively. While natural hazards disrupt the balance of ecosystem, poor environmental management, overexploitation of natural resources, ecosystem degradation, and climate change make people more susceptible to disasters and cause more damage (ISDR & UNEP, 2007). Climate change increases the vulnerability to disaster and leads to greater destruction. Environmental degradation can also bring on anthropogenic interventions like massive construction projects. Extreme temperature changes such as heat wave and cold wave itself are hazardous to human and natural systems and can be classified as climatological hazards (IPCC, 2012).

An important part of risk assessment is identifying the triggers for natural hazards and assessing its exposure to formulate a disaster risk management strategy according to geographical and geopolitical scales (Reynolds, 2014). Risk assessment is reliable when it is used to support practical risk management, the gathering of historical damage data to support evidence-based risk management, land use and urban planning, risk-informed decision, and policy making. Regular risk assessment can reduce the vulnerability to natural hazards. Lack of risk assessment, unplanned and unscientific developmental works, and lack of disaster mitigation programs worsen the impact of disaster. Sharing information related to scientific and indigenous knowledge, infrastructure, institutions, and insurance can enhance resilience, and government needs to adopt a regionally standardized, multihazard risk assessment approach (Wester et al., 2019). It is crucial to include watershed features such as land cover and land use, hydrological parameter, soil type, landscape, anthropogenic activities, and agricultural practices while assessing the implications of future climate change. Coupling the principles of climate change, hydrology, and cryosphere science with economic analysis might help in identifying economic impacts of climate change, which is one of the important risks associated with climate change (Mishra et al., 2020). Though these areas have been reported to have experienced increase in the frequency of glacial lake outburst floods, the distinction between climate-induced events and anthropogenic influences is still not clear (Sud et al., 2015).

6 Sustainable Practices, Adaptation Strategies, and Policies

Considering the long-term impact, risk, and vulnerability of climate change on societies, it calls for more planned adaptations along the river basins. This includes strengthening of the local knowledge, practices, and functioning of the institutions, which are trying to cope with the climate change. Studies show that there are many sustainable adaptation methods that have been practicing in the Himalayan region. In the early 1960s, local villagers residing near the upper Ganga region collectively prepared a traditional recharge structure “Chahal” to maintain the springs of the region. In the downstream area, villagers are mostly cultivating potato, maize, chilly, and pumpkin on sandy soil, which is a popular adaptation practice. Sharing livestock or Adhi system is also an important adaptation mechanism followed by poor people in this region. In Indus basins, people use drip irrigation and sprinkler irrigation along with several off-farm activities, which are very effective adaptation strategies. The spring shed management by Sikkim people is also a good example of adaptation according to climate changes (Dilshad et al., 2019). Toward efficient planning of climate change adaptation, a holistic understanding of the different components of the river systems focusing on sustainable management alternatives for ecosystems and healthy rivers is essential. Impacts of climate change at all three levels (local, downstream, and global level) should be thoroughly studied in connection to each other, and accordingly, adaptive strategies should be developed from each of these perspectives. Local adaptive strategies can be planned by taking into account of local effects, whereas adaptation at downstream level needs to evaluate the downstream effects and model accordingly. Adaptive methods should be based on future projections, on the global level, and on the possible feedback mechanism of the environmental changes in the Himalayas to global warming (Eriksson et al., 2009). It would be quite useful if the trends of all possible hydrological and hydrometeorological variables are assessed for concurrent years to draw meaningful inferences and cause-effect relationships between key variables, and based on the inferences, adaptive strategies should be designed. Since the Himalayan basins are international basins and some of their data are in classified domain, integration of all the relevant information for effective planning and management of climate change adaptation for this region would require a transboundary approach and multilateral collaboration across the regions. Policies for such river basin should be based on an interdisciplinary method and an integrated governance policy.

To facilitate such policy integration, climate change adaptation should be mainstreamed into integrated river basin plans rather than treated as an isolated activity. Successful river basin management requires participatory and equitable decision-making and an effective coordinating institution with adequate authority and mandate to act. It should be accountable to all relevant stakeholder groups (Oglethorpe et al., 2015) and should be able to coordinate across geographical boundaries. Policies should be coordinated to avoid contradictions and overlaps among prevailing plans that already exist. The need of putting science-based policies in the conservation of the whole riverine ecosystems is important. The policy interventions should be based on an integrated knowledge base. The key to sustainability and sustainable management of resources for climate change adaptation lies in effective utilization of multidisciplinary scientific knowledge. As a starting point for policymaking, flows in rivers need to be studied in a holistic manner. Volume of flow per unit time, its constituents and composition, energy content of the river flow, biodiversity, and sediment budget are a few parameters that need to be considered other than simple hydraulic quantities. The occurrence of floods in the river basins should be duly considered at the time of policy development. The longitudinal, lateral, and vertical river flows must be integrated and should be the basis of any new policy related to this area. A holistic analysis of the upstream-downstream properties in the IHR river basins is important in planning for watershed management and cost assessment for ecosystem services. Basin-level governance should be a priority during policymaking, which urgently needs to be put in practice. Plans for adaptation should include built-in flexibility and scenario planning that takes future uncertainties into account. Water management strategies need to be developed to utilize the predicted water availability during monsoon season in future, and it is crucial to have policies and practices that can manage the uncertainty in precipitation pattern. In light of growing climatic unpredictability, uncertainty, and extreme events, coordinating institutions must be adaptable enough to allocate water and natural resources while also being able to adopt novel strategies as and when necessary. Policy and institutional solutions must adequately address the structural and underlying causes of climate vulnerability. By establishing monitoring programs for snow, ice, and water, downscaling climate models, using hydrological models to forecast water availability in various regions and localities, and creating basin-wide scenarios that take socioeconomic development and water demand into account, the related knowledge gap can be reduced (Eriksson et al., 2009). Policy pushes to research on developing informed data instruments is essential in this context.

Water from rivers is used by a variety of parties and sectors as it flows from upstream to downstream. Climate change-related risks like landslides, floods, and droughts would affect significantly those individuals who reside within the basin area and/or live further downstream. The unique needs and goals of these vulnerable groups should therefore be taken into account in adaptation policies and programs. An integrated management system along the basins with the goals of catastrophe risk management, resilience building, and fair benefit sharing is crucial for the long-term sustainability of the river ecosystem and its communities. In this regard, managing urban and industrial growth along the basin areas with respect to water supplies, efficient use of catchment area, discharge management, identifying key environmental assets (protected areas, critical habitats such as wetlands and floodplains, sensitive ecosystems) and some of the crucial elements in basin planning to enable sustainable management, which must be included in IHR river basin policy, include identifying the special demands of basin populations and appreciating the value of the eco-services they give to people and their livelihoods (Eriksson et al., 2009; Dilshad et al., 2019; Pradhan et al., 2021). Effective public participation and regional and cross-border cooperation hold the key to successful policy implementation. To do this, cross-sectoral coordination between the government, local communities, community-based organizations, NGOs, and research agencies is required in the formulation of adaptation and livelihood measures. Effective utilization of traditional knowledge locally can significantly reduce community's vulnerability and will contribute socially inclusive economic development as per Sustainable Development Goals. One such strategy is integrated water resources management (IWRM), which encourages the coordinated development and management of water, land, and related resources in order to maximize the resulting economic and social benefits in a fair way without risking the sustainability of crucial ecosystems (Global Water Partnership, 2000). This might be helpful in creating adaptive management strategies across geographic ranges in the Himalayan region by deliberately focusing on the connections between upstream and downstream regions at the macro (river basin), meso (catchment), and micro (local) scales (Pradhan et al., 2021). Recognizing the climate change threat to these basins, different countries have adopted policy measures in their respective government as National Communications and National Adaptation Programs of Action. These policies place a strong emphasis on utilizing the human and infrastructure resources at hand to increase people's capacity for adaptation and decrease vulnerabilities (Sud et al., 2015).

7 Climate Change Adaptation Policies Associated with IGB River Basins

IGB river basins have a geographical spread in India, Bangladesh, Pakistan, Nepal, and Bhutan. These countries have formulated regulations, organizations, and networks to achieve climate change policies. India has National Ganga River Basin Authority (NGRBA) and Brahmaputra River Valley Authority (BRVA) focused on integrated water resource development and Draft National Water Policy 2012, which proposes a legal framework for water governance, giving emphasis on climate change impacts (Sud et al., 2015 and references therein). India's first National Action Plan on Climate Change (NAPCC) was released on June 2008. In this action plan, policies and programs related to climate mitigation and adaptation were addressed. The national action plan has been divided into eight national missions, namely, (1) National Solar Mission, (2) National Mission for Enhanced Energy Efficiency, (3) National Mission on Sustainable Habitat, (4) National Water Mission, (5) National Mission for Sustaining the Himalayan Ecosystem (NMSHE), (6) National Mission for a "Green India," (7) National Mission for Sustainable Agriculture, and (8) National Mission on Strategic Knowledge for Climate Change. There are two national missions, NMSHE and "National Water Mission" under NAPCC specifically deal with the Himalayan region and river climate. NMSHE targets the sustenance of the Himalayan ecosystem by developing different task forces dedicated for different themes such as natural and geological wealth, water, ice, snow resources, forest resources and plant biodiversity, microflora and fauna, wildlife and animal population, Himalayan agriculture, and traditional knowledge system of the Himalayas. These task forces concentrate on establishing databases, design monitoring systems, and do modelling and simulation and apply it in vulnerability assessment and policy research.

Under the National Mission on Himalayan Studies (NMHS), water resource management is a broad thematic area covering the states of Jammu and Kashmir, Himachal Pradesh, Uttarakhand, Arunachal Pradesh, Sikkim, Manipur, and Tripura. The Ministry of Environment, Forest and Climate Change (MoEF & CC) implemented this mission and have nearly 25 ongoing projects targeted on water resources in the Indian Himalayan Region. The objectives of projects range from spring rejuvenation in different states to development of low-cost water purification systems. Understanding climate change scenarios up to year 2100 in IHR states, groundwater augmentation, quantification of hydrological processes, policy recommendation on land use practices and water use, capacity, and awareness building of stakeholders are some of the overall objectives of the mission (NMSHE). The Mission targets to develop inventories of mountain spring in selected states of IHR, monitor and model prediction of water-induced disasters, and monitor water quality and ecological integrity of selected springs, lakes, and rivers. Under the mission, a decision support system is developed to support water demand in Jammu and Kashmir and Uttarakhand, low-cost landslide early warning system in

Uttarakhand, and natural hazard prediction models in Uttarakhand, and with the help of geospatial techniques and hydrological models, hydropower potential zones in Himachal Pradesh have been identified.

Similarly, Bangladesh has instituted different centers and national committee such as National Steering Committee on Climate change, Flood Forecasting and Warning Centre (FFWC), and National Disaster Management Council (NDMC), to address the issue related to water resources and impact of climate changes. In Afghanistan, National Climate Change Committee and Supreme Council for Water Resources Management coordinate and function toward the steering and coordination of water resource management. A small country like Bhutan has a government body called "Bhutan Water partnership" (BhWP), which is to coordinate programs related to water resource protection and development, and committee like "National Climate Change Committee," a technical-level task force for project implementation. In Pakistan, Indus River System Authority (IRSA) and Prime Minister's Committee on Climate Change focus on knowledge generation and management. Muti-Stakeholder Climate Change Initiatives Coordination Committee (MCCICC) in Nepal coordinates among government agencies and stakeholders to work toward climate change.

8 Conclusion

Urbanization, agriculture expansion, population explosion, and recent industrial and economic developments have affected the health of water resources. Changes in land use and cropping pattern and overexploitation of groundwater along with recent climate changes have significantly affected the freshwater resources in India. Himalayan river systems are reportedly affected by recent climate changes. Rapid reduction in glaciers and associated changes in the downstream of Himalayan river basins indicate the effect of climate change in the Himalayan river basins. Unpredicted and accidental disasters in the mountain region is one of the consequences of these changes. Hence, mountain settlements are more susceptible to natural disasters like earthquakes, floods, landslides, avalanches, and severe weather. The availability and accessibility of water resources in the downstream area are significantly impacted by climate change indicators like rising temperatures, abrupt changes in precipitation, glacial retreat, and related risks. However, due to complex topography of the Himalayas and lack of sufficient snow, ice, and water monitoring system, the information about impact of short- and long-term climate change on water resources in the Himalayan region is limited. Since climate change-induced natural hazards are difficult to predict, it is important to have more hydrological units to gauge the river flow, precipitation, and climate models required to be developed. These models need to be evaluated and updated regularly to predict the effect of climate change on Himalayan river basins. Society must adopt sustainable practices as part of disaster preparedness. Sharing meteorological information regionally and seasonal migration and restricting construction activities in landslide areas may reduce the risk associated. Even though there are several studies conducted on IHR, the policy development for climate change adaptation needs to be dealt with in a comprehensive manner and for different levels such as a general policy for the entire IHR river basin and also as separate policies for each basin.

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