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Vulnerability of Water Resources to Climate Change in Indian Himalayan Region

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Abstract: Climate change has become a proven threat to humanity. The unprecedented increases in the climate-related phenomenon and its impacts on nature, people, and animals are glaring examples of it. Water resources and the agriculture sector are going to be hit hard. The Indian Himalayan Region (IHR) is the most vulnerable region to climate change due to its peculiar geographical location, threatening food and nutritional security of millions of people whose livelihood options are primarily agriculture-based. This paper reviews the current status of water resources in IHR, the indicators of climate change in the region, and the implications of climate change on water resources. There are several issues that challenge the acquisition of data and sharing information concerning climate change, water resources, and agriculture in IHR. Various researchable, developmental, and policy issues have been raised to address the challenges associated with the vulnerability of water resources to climate change.

Keywords: Climate change, Indian Himalayan Region, Water resource, Vulnerability

The unprecedented increases in climate-related phenomenon such as warming of atmosphere and oceans, intense and frequent heat waves, declining snow in the Arctic region, reduced or lost permafrost, rising sea levels, increased glacial lake outburst floods (GLOF), torrential rainfall events, hurricanes, typhoons, storms, cloud bursts and flash floods, alarming forest fires, severe droughts, new insect pests and diseases, etc. are the strong evidence of climate change (Tiwari et al 2015, Dimri et al 2021). In addition, the impacts of climate change on nature, people, animals and marine life have become increasingly visible. Climate change brings different interactions with the water stored in the mountain cryosphere that even bring shifting of dominant communities in agro-ecosystems. This sometimes leads to threats and new opportunities in some areas, but the overall impacts in the long term are negative. The Intergovernmental Panel on Climate Change (IPCC) also discussed the long-term impacts of climate change that have also been given in the report on mountain ecosystem on Hindu Kush Himalayan Monitoring and Assessment Programme (HIMAP) (IPCC 2014, Cramer et al 2014, HIMAP 2019). Water insecurity will increase, leading to increased water conflicts among states and nations. It threatens economic growth and stability worldwide (Boretti and Rosa 2019). Recognizing the seriousness of climate change impacts, several countries worldwide have joined under Sustainable Development Goals (SDG) (Target 13.3) to establish climate forecasting systems, improve coverage of meteorological warnings, disaster prevention, and reduction systems, and strengthen climate resilience. It has also been recognized that coupling local and national mechanisms with appropriate communication and coordination systems, vitalizing local institutions, and appropriate policy instruments are necessary to achieve the desired goal of disaster risk reduction. The Indian Himalayan Region (IHR) is highly vulnerable to climatic disturbances due to its typical geographical location, lack of adequate infrastructure and poverty (Upgupta et al 2015).

Agriculture is the mainstay of people in this region. The risks of food and nutritional security and farming-based livelihood options for millions of people in the region have, thus, multiplied. According to a climate assessment report released by the International Centre for Integrated Mountain Development (ICIMOD), the IHR is warming much faster than the global average rate, resulting in significant changes in agro-ecology of the region (Anonymous 2020). The most glaring example is the disappearance of apple cultivation in the Kullu valley of Himachal Pradesh, where the rapid temperature rise has resulted in the inadequate chilling requirement for apple crop (Sahu et al 2020). Apple cultivation has shifted from lower altitudes (Kullu valley) to higher altitudes (Lahaul & Spiti districts) in Himachal Pradesh. NITI (National Institution for Transforming India) Aayog (Indian government's think tank) in 2018 expressed serious concern about social and environmental damages of economic activities in the IHR and future demands on the IHR rivers. A need has been felt to assess future water availability to the dependent highly densely populated areas downstream. Such assessments in the Himalayan range are a real challenge. Understanding of hydrology in IHR, with all threats and potentials, is needed for policy planning and initiating action to sustain agro-ecology and livelihood security in the region. This paper reviews the extent and pace of climate change and its possible threats to hydrology, water resources, agriculture, and livelihood options of the local people in IHR. Necessary steps for mitigating threats of climate change on water resources have also been discussed. Although due care has been taken to compile data only from IHR, few data from Hindu Kush Himalayas (HKH) have also been referred to understand the impact trends. The climate change studies conducted in IHR are few and sporadic.

The Himalayas: Himalayas are the highest and the youngest mountain chain on the planet Earth which is still evolving and is known as the 'water tower of Asia'. The Himalayas, formed about 50 million years ago (Kious and Tilling1996), are the world's third-largest storehouse of ice and snow. They account for 70 percent of the world's non-polar glaciers (Nandy et al 2006). Himalaya is the source of the 10 largest rivers in Asia, viz. Ganges, Brahmaputra, Indus, Irrawady, Mekong, Amu Darya, Salween, Tarim, Yangtze, and Yellow Rivers. These rivers cover an area of more than 4,192,000 km^2 (Fig. 1) (Wester et al 2019). They serve as a source of fresh water for drinking, irrigation, and power for over 1.3 billion people across eight South Asian territories of Afghanistan, Pakistan, China, India, Nepal, Bhutan, Bangladesh, and Myanmar, which is nearly 23.7 percent of the world's population (Hirji et al 2017).

The Indian Himalayan region: The Indian Himalayan Region (IHR) refers to the Indian part of the Himalaya. It stretches about 2,400 km across the northern border of India, between the eastern border of Pakistan in the west and the frontiers of Myanmar in the east. The geo-dynamically complex young mountains of the IHR occupy a special place in the world's mountain ecosystems (Singh 2006). Geographically, the IHR between Indus and Brahmaputra river systems covers about 5,33,604 km^2 area (16.2% of the total geographical area of the country) and is inhabited by about 40 million people (about 3.5% of the total population of the country) in a little over the 73,000 villages and nearly 500 towns (Singh 2013). The IHR covers partially or fully twelve states in the country viz., Jammu & Kashmir, Himachal Pradesh, Uttarakhand, Sikkim, Arunachal Pradesh, Nagaland, Manipur, Mizoram, Tripura, Meghalaya and hill regions of two states i.e., Assam (Karbi Anglong and Dima Hasao) and West Bengal (Darjeeling and Kalimpong) (Table 1). As per a recent FAO report (IMI-FAO Report 2019), nearly 70 and 30 percent population in IHR is rural and urban, respectively. Around half of the water needs of people in IHR are met through three major rivers, viz., Indus, Ganga and Brahmaputra, fed by snow-melt and glacier-melt waters. The Planning Commission of India (1989) has divided IHR into five agro-climatic zones (Table 2).

The hydrology in IHR: The hydrology in IHR is complex and

Table 1. The geographical distribution of states in IHR (adapted from: Wastelands Atlas of India 2000 & FSI 2000)

States/Regions	Geographical area (km^2)	Percent (%) of area under		
		Agricultural land	Wastelands	Forest lands
Jammu and Kashmir	222,236[a]	4.7	64.6	9.6
Himachal Pradesh	55,673	14.5	56.9	25.8
Uttarakhand	55,483	12.5	30.1	44.8
Sikkim	7076	16.1	50.3	45.0
West Bengal hills	3149	43.5	2.2	69.7
Meghalaya	22,429	48.2	44.2	69.5
Assam hills	15,322	10.5	56.6	79.8
Tripura	10,486	29.6	12.2	67.4
Mizoram	21,081	21.2	19.3	83.0
Manipur	22,327	7.3	58.0	75.8
Nagaland	16,579	38.4	50.7	80.5
Arunachal Pradesh	83,743	3.5	21.9	81.3
India	3,287,263	55.8	20.2	20.6

Source: Kumar et al (2021)

highly variable, dominated by precipitation (rains and snow), glaciers, rivers, and springs. The significance and contribution of each of these components vary with the location in the region.

Precipitation: Two weather systems operate in the Himalayan region:

i. Indian Summer Monsoon (ISM) system (June-September) (Fig. 2) (Hodges 2006), and

ii. The winter westerly disturbances (WD) (December to March).

Both the systems show a significant impact on water resources in the region. A downward gradient exists in rainfall from the east to the west and in snowfall from west to east in IHR. A wide variation exists in the amount of rainfall received. Mawsynram of Khasi Hills in Meghalaya (NE India) is the wettest place in India and the world, with the highest annual rainfall recorded as 11,872 mm. It is closely followed by Cherrapunji, also on the slopes of Khasi Hills, with a record annual rainfall of 11,619 mm. Only 75 to 150 mm of rainfall is received at places such as Skardu, Gilgit, and Leh in the Kashmir portion of the Indus valley in the North of the Great Himalaya. The average annual rainfall in IHR varies between 1,530 mm in the western Himalaya and 3,050 mm in the eastern Himalaya. The sustainability of glaciers and the replenishment of water resources in IHR largely depend on the snowfall input by WD. Important glaciers in IHR are enlisted in Table 3. The cryosphere -snow, ice, and permafrost is an important part of the water supply in the extended Hindu Kush Himalayan region including IHR. The changes in the cryosphere affect the timing and magnitude of stream-flows across the region, with proportionally more significant impacts upstream. Cryospheric change is expected to have modest impacts on total annual stream-flows in large river systems but will strongly affect the timing and seasonal distribution of runoff, which is relevant for both ecology and economy of the region.

Rivers: In the Himalayan region, the river basins are characterized into three types viz., (1) rainfed basins, which exclusively depends upon the rainfall (2) snowfed basins, where the runoff is generated through both rainfall–runoff as well as snowmelt and the (3) glacierfed basins, runoff is primarily generated from the melting of snow and glaciers. The rivers flow in the Himalayan region is highly sensitive to climatic conditions, precipitation and evapotranspiration. Climate change effect the hydrological regime of the river basin. Three major rivers, viz., the Indus, Ganga and the Brahmaputra, originate in the IHR. They cover a basin area of around 321,289 km^2 (34%), 861,452 km^2 (82%) and 194,413

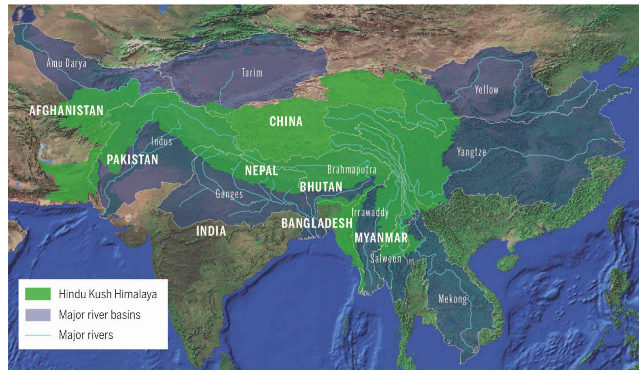

Fig. 1. Major Himalayan rivers (Wester et al 2019)

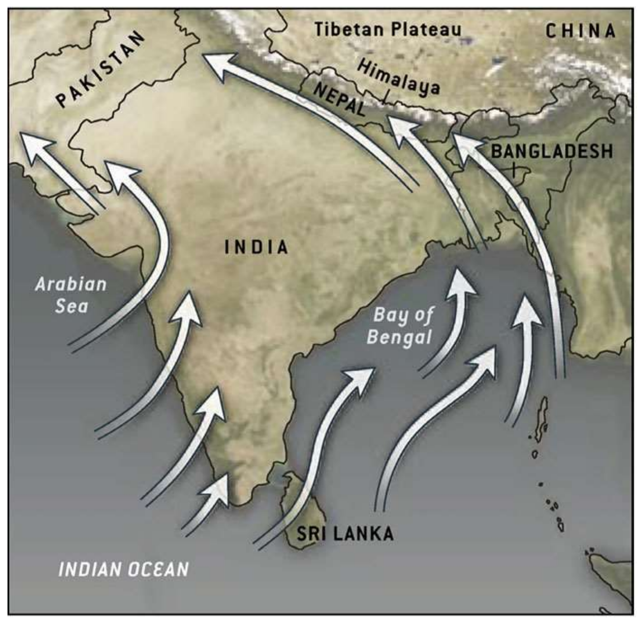

Fig. 2. Indian summer monsoon system in Himalaya (Hodges 2006). Monsoon flow from the Arabian Sea carries moisture to Indian subcontinent indicated by white arrows

Table 2. Agro-climatic zones of IHR

Agroclimatic zone	Climate	Rainfall (mm)	State/regions
Zone I	High altitude temperate (humid to cold arid)	<1200	Jammu and Kashmir
Zone I	Hill temperate (per humid to subhumid)	1200-1800	Himachal Pradesh and Uttrakhand
Zone II	Per humid to humid	1800-2200	Nagaland, Mizoram, Manipur and Tripura
Zone II	Per humid to humid	2200-2800	Sub-Himalayan West Bengal, Sikkim, Assam and Meghalaya
Zone II	Per humid to humid	>2800	Arunachal Pradesh

Source: Agro-climatic Regional Planning, Planning Commission (1989) km^2 (34%), respectively (Qazi et al 2020). The glacial and snow melt waters feed these rivers. Around 50% of country's total utilizable surface water resources are contributed by these three rivers (Srivastava and Misra 2012). The climate models project reductions in annual snowfall by 30–50 percent in the Indus Basin, 50–60 percent in the Ganges Basin, and 50–70 percent in the Brahmaputra Basin by 2071–2100 (Viste and Sorteberg 2015). It has been associated with the upward shift of mean elevation where rain changes into the snow (the rain-snow line).

Water springs: Seasonal and perennial water springs, are the primary water source for rural households in the IHR. Human settlements in the inaccessible regions in IHR are found nearby the spring sources. In the non-snow fed and rain-shadow watersheds, springs are the only potable water source. Nearly 80-90 percent of the population in Meghalaya, Sikkim, and Uttarakhand depends on springs for freshwater (Tambe et al 2009). Around 64 percent of irrigated areas in India are fed by springs (Rana and Gupta 2009). Further, springs also play a crucial role in generating streamflow for non-glaciated catchments and in maintaining winter and dry-season flows across numerous IHR basins. The base flow of many rivers in the region is contributed by mountain springs. A few studies conducted in small and scattered areas in IHR suggest a strong relationship among precipitation, recharge and spring discharge (Negi and Joshi 2004, Vashisht and Sharma 2007, Tambe et al 2012, Tarafdar 2013, Sharma et al 2016). However, the results are variable across the region. While spring-discharge variation appeared to be consistent with rainfall in Sikkim in the east (Tambe et al 2012) and Uttarakhand in the central-western Himalaya, it showed an inverse pattern with monthly rainfall in the western Himalayan springs of Kashmir (Negi et al 2012). The groundwater aquifers also play an important role in charging the water springs (Mahamuni and Kulkarni 2012). A case study in the western Himalaya shows that spring discharge during the rainy season is very high for *Karst* springs and much lower for alluvium (fluvio-lacustrine) and *Karewa* (glacio-fluvio-lacustrine) springs (Jeelani 2008). Several other factors, such as human activities, changes in land use, soil erosion, and other causal local factors also significantly impact spring water flows (Valdiya and Bartarya 1989, Panwar 2020).

Table 3. Important glaciers in IHR

Glaciers	Location
Siachin	Indus basin, Karakoram
Rulung	Indus basin, Trans-Himalaya
Neh-Nar	Sind basin, Great Himalayan range
Thanak-Lungpa	Suru basin, Zansakar range
Braham Sar	Pir Panjal range
Harmukh	Sind basin, North Kashmir range
Gara	Tirung Khad basin
Gor Garang	Baspa basin
Bara Shigri	Chenab basin, Great Himalayan range
Shaune Garang	Baspa basin
Gangotri	Alaknanda basin, Kumaon Himalaya
Pindari	Alaknanda basin, Kumaon Himalaya
Chorabari	Alaknanda basin
Dunagiri	Alaknanda basin
Shangme-Khangpu	Sikkim Himalaya
Zemu	Sikkim Himalaya

Source: ENVIS Monograph 3

Climate change indicators in IHR

Warming of air and earth surface: The Himalayas are continuously warming faster than the nearby Indian landmass (Sabin et al 2020). The western and eastern Himalayan river basins in IHR are showing progressive warming, with rise in minimum temperatures slightly higher than the maximum temperatures (Rajbhandari et al 2015). The IHR has warmed at a rate of about 0.1-0.7°C per decade depending on elevation during the last four decades (Singh et al 2018). The warming rate has been slower (<0.2°C per decade) at low-elevation sites (<500 m) than at high elevations (>2000 m) (Liu et al 2009, Ren et al 2017). According to the Ministry of Earth Sciences (MoES), even with the Indian government's commitment to mitigate greenhouse gases by 2030, the Indian Himalaya could warm by 2.6–4.6°C by 2100. By the end of the 21st century, the average temperature over India is projected to rise by approximately 4.4°C compared with the 1976–2005 average. The temperature rise accelerates the melting of glaciers, in addition to the increased frequency of heat waves and more severe droughts, severe cyclonic storms, and floods in Himalayan river basins.

Changing precipitation patterns: Although visible changes in the amount and pattern of precipitation have been observed during past few years, the precipitation data are too scarce to conclude any particular precipitation trends in IHR. Studies conducted by Snow and Avalanche Study Establishment (SASE) indicated a decrease in the snowfall with a concurrent increase in the rainfall, but the total precipitation showed a decreasing trend in NW Himalaya during 2001-2015. Bhutiyani et al (2010) observed a statistically significant downward trend in monsoon rains in the western IHR from 1866 to 2006. A similar downward trend in winter precipitation in Jammu and Kashmir and Uttarakhand of Himalayan region during 1901–2003 (Guhathakurta and Rajeevan 2008). The monsoon rains are delayed and their typical characteristic feature of 7-10 days of continuous downpour has almost disappeared. Similarly, the winter rains have also become unpredictable and declined in quantity. Negi et al (2012) reported extreme drought events and shifts in the rainfall regime in Kullu valley, resulting in failure of crop germination and fruit set.

Melting of glaciers: Receding glaciers is one of the most reliable indicators of climate change. During the Pleistocene era (2 million years ago) glaciers occupied about 30 percent of the total area of the Earth, which presently has reduced to around 10 percent due to glacial melt (Bahadur 1998). Thinning and squeezing glaciers at increased rates since the mid-19th century has been observed globally and the Himalayas are no exception. Due to climate change, Himalayan mountain glaciers have been experiencing a significant decline over the past several decades, although detailed information is available only for a few glaciers (Rai and Gurung 2005). Kulkarni and Karyakarte (2014) have reported large-scale melting of snow and retreat of glaciers in IHR during the past five decades. Kulkarni and Pratibha (2018), based on remote sensing data and *in situ* observations from 83 glaciers, reported a loss in glacier extent by 12.6 ± 7.5 percent for the past 40 years. Mass balance studies of Singh et al (2018) in IHR (Gor Garang and Shaune Garang of Baspa Basin and Chhota Shigri glacier of Chandra Basin) have revealed continuous negative mass balance (with few exceptions for a year or two) with an increasing trend in recent decades. This has coordination with a continuous increasing pattern of temperature and decreasing pattern of precipitation.

The 'First-ever Assessment of Climate Change' report of ICIMOD, Kathmandu, Nepal indicated an increase in the number of glaciers in the Himalayan area during the last five decades due to the fragmentation of larger glaciers into smaller ones. Studies indicate that the melting of small glaciers is faster than the large glaciers. The Eastern Himalayan glaciers are shrinking faster than glaciers in the central or western Himalaya (ICIMOD 2011). The average glacial retreat has been between 0.1 and 1.0 percent per year. Studies on selected glaciers in IHR indicate that glaciers have been retreating discontinuously since post-glacial time. The 25 km long Gangotri glacier in 1930s, one of the major and important Glaciers in the Himalaya, has shrunk to about 20 km during the last six decades (Hasnain 1999). The average recession rate of this glacier between 1985 and 2001 has been around 23 m/y (Hasnain 2002), which increased to around 30 m/y during the recent decade (Rai and Gurung 2005). The Siachen & Pindari Glaciers retreated at the rates of 31.5 m/y and 23.5 m/y, respectively (Vohra 1981). Dobhal et al (1999) observed shifting of snout of Dokriani Bamak Glacier in the Garhwal Himalaya at a rate of 17.2 m/y during 1962-1997. Geological Survey of India studied the Gara, Gor Garang, Shaune Garang, Nagpo Tokpo Glaciers of Satluj River Basin and observed an average retreat of 4.2-6.8 m/y (Vohra 1981). The Bara Shigri, Chhota Shigri, Miyar, Hamtah, Nagpo Tokpo, Triloknath and Sonapani Glaciers in Chenab River Basin retreated at the rate of 6.8-29.8 m/y. A massive glacial retreat rate of 178 m/y was observed in Parbati Glacier in Kullu District from 1962 to 2000 (Kulkarni et al 2004). The Indian Space Research Organization (ISRO) recently monitored the glacial advance and retreat of 2,018 glaciers in IHR, using satellite data from 2000-2001 and 2010-2011. This study further concluded that 12 percent of glaciers retreated, 1 percent glaciers advanced and 87 percent glaciers remained unchanged. Glaciers in Sikkim are melting faster than in other parts of Himalayan region. The melting of snow and glaciers feeds river and spring flows, but if not compensated by matching/increased snowfall may lead to loss of water reserves in the Himalayas. Maximum runoff from snowmelt occurs of June and July. The increased glacial melt is also projected to increase flood frequencies in Indus, Ganges, and Brahmaputra rivers in the 21st century, risking the livelihood security of 220 million people (Hirabayashi et al 2013, Wijngaard et al 2017, Wester et al 2019).

Formation of glacial lakes and rising GLOF threats: The glacial melt waters may accumulate in natural depressions in hills giving rise to glacial lakes. The fast melting and retreating (at rates between a few meters to hundreds of meters per year) of Himalayan glaciers have been resulting in an increase in the number and size of glacial lakes and a concomitant increased threat of glacial lake outburst floods (GLOFs) (Chalise et al 2006, Bajracharya et al 2007). Some glacial lakes are expanding at a dangerous rate (Bajracharya et al 2008). Studies indicate that glacial lakes were almost non-existent in Nepal prior to the late 1950s, when they started forming and rapidly increasing in number and size (Chalise et al 2006). The investigation carried out by ICIMOD between 1999 and 2005 documented 8790 glacial lakes covering a total of 801.83 km^2 in the HKH, out of which 203 lakes were potentially dangerous for the GLOF in future (Ives et al 2010, Bolch et al 2019).

Abandoned moraines form the majority of the glacial lakes in Himalaya. (A moraine is generally soil and rock material left behind by a moving glacier). The moraine-dammed lakes are highly unstable and susceptible to outburst, triggered by ice or debris falls, strong earthquake tremors, internal piping or overtopping waves that exceed the shear resistance of the dam (Richardson and Reynolds 2000, Westoby et al 2014). As a result, they breach suddenly and release huge volumes of sediment-laden floods at rates

>100 km downstream within minutes to hours (Richardson and Reynolds 2000, Bajracharya et al 2007). The GLOFs are independent of hydrometeorological floods and are a potential threat downstream to lives (humans and livestock) and property (cultivated lands, forests, buildings, bridges, dams, hydro-power projects, roads, etc.). Studies have shown that the occurrence of GLOFs in the Eastern Himalayas is about 3 times higher than in any other Himalayan region (Veh et al 2020).

Changes in river flows: The river flows are linked with snow and glacier melt and rainfall events in the mountain regions. The river basins in the eastern and central IHR (i.e. Ganges and Brahmaputra Rivers) are primarily fed by the summer monsoon rains (ISM), while snow and glacial-melt during winter-time western disturbances (WD) feed river basins originating in the western Himalayan region (i.e. Indus River). Thus, rainfall contributes more to the flows of the Ganga and Brahmaputra, while snow and glacier melt contribute more to Indus flow (Alford and Armstrong 2010, Immerzeel et al 2010, Mukhopadhyay and Dutta 2010). The contribution of snow and glacial melt in Ganga, Brahmaputra, and Indus river flows was observed to be around 9, 19, and 60 percent, respectively. Therefore, a consistent increase in streamflow at large scales has been projected for the upstream reaches of the Indus, Ganges, and Brahmaputra rivers until at least 2050; in the Indus river due to increased glacial melt, and in Ganges and Brahmaputra rivers due to increased precipitation (Immerzeel et al 2013, Lutz et al 2014).

Studies also indicate that the average annual downstream flows in Ganga and Brahmaputra Rivers are unlikely to show change for quite some time, and it is unlikely that these rivers shall become seasonal rivers (Miller et al 2012). In case of the Indus River, however, increased glacier melt will provide short-term increases in river flow, but in the long run, the river flow is likely to decrease due to a decline in the potential melt-water stores (Miller et al 2012).

Receding mountain springs: There is increasing evidence of springs drying, reducing discharge and deteriorating water quality in many parts of the Himalayan region. Springs in IHR are reported to be drying up, although the status of most springs in the region is still unknown due to paucity of data. According to Rana and Gupta (2009) around 50 percent of perennial springs in the IHR have dried up or become seasonal. Around 30 percent of springs in one of the mid-hills districts in Nepal have been reported to be completely dried up in the last decade due to a combination of biophysical, technical, and socio-economic factors (Sharma et al 2016). Spring discharges have also significantly declined (Sharda 2005). Valdiya and Bartarya (1989) reported around 25 percent spring flow decrease by late 1980s in Gaula river basin; over 35 percent decrease during 2000s in Sikkim was reported by Tambe et al (2012). Several factors have been responsible for the drying up of springs or decrease in spring flows including, climate change, deforestation, grazing, exploitative land use, depletion of shallow water table because of reduced infiltration due to crust formation and high-intensity rainstorms, etc (Vashisht and Bam 2013, Scott et al2019). Spring flows are also impacted by rapid socio-economic growth, demographic changes, and infrastructural developments, such as dams and road construction (Mahamuni and Kulkarni 2012, Vashisht and Bam 2013).

Deposition of black carbon on glaciers: Black carbon (BC) has been deposited on snow and glaciers in the Himalayan region due to atmospheric pollution by CO (particulate pollution) and CO_2 (biomass pollution). The forest fires have also been responsible for it. The first historical record of BC deposition of about 80 ng m^{-3} was found in Mt. Qomolangma (Everest) in the high Himalaya from 1951 to 2001 (Ramanathan and Carmichael 2008). The increasing levels of BC in South Asia caused BC deposition in Tibetan Plateau. Kuniyal (2010) observed BC concentration as high as 15,657 ng m^{-3} hourly at Mohal-Kullu (H.P.) in the northwestern IHR. Deposition of BC cover on glaciers increases the rate of snow and glacial melting by decreasing albedo and increasing absorption of solar radiation (Ming et al 2008). According to Ramanathan and Carmichael (2008), solar heating from BC at high elevations in the Himalayan region may be as important as carbon dioxide in melting snow packs and glaciers.

Implications of climate change on water resources: The implications of climate change on the availability of water resources-spatial distribution, temporal dynamics and water security, in general, are extremely significant. Important ones are briefly described below:

Shrinkage of water resources: The changes in precipitation coupled with the continuous melting of glaciers is expected to reduce the storage of snow and ice in the region with the future implication of shortage of fresh water availability in the snow-glacier fed river systems. The recent review of the past literature reveals a huge cumulative loss of glacial ice equivalent to the 443±136 Gt out of the total 3600–4400 Gt stored glacial water in the IHR (Kulkarni and Buch 1991, Kulkarni and Karyakarte 2014). Local communities start to relocate as the water resources decline in many villages of HKH (Kulkarni et al 2021). This has threatened regional water security and livelihood of the local inhabitants.

Change in river flows: A consistent increase in stream flow is expected at large scales in all three major rivers viz. Indus, Ganges, and Brahmaputra in IHR, until at least 2050.

Increased glacier melt will provide short-term increases in the contribution to discharge but will likely lead to decreased water supply in the future, impacting the water availability downstream (https://www.ipcc.ch/srocc/about/faq/faq-chapter-2/).

Drying of mountain springs: Drying of springs or progressive decline in spring flows is a matter of grave concern to hill people who mainly depend on spring waters for their household needs and irrigation. The drying of mountain springs can also lead to an environmental crisis in the loss of indigenous flora, fauna and human migration.

Formation of glacial lakes: The IHR is also vulnerable to natural disasters viz., landslide, flash flood and cloudburst, while the impact of climate change increases the intensity and frequency of such disasters. Retreating glaciers contribute to the formation of glacial lakes and increased threats of glacial lake outburst floods (GLOFs). The Chorabari Lake outburst flood, Kedarnath, caused disaster in 2013, and the more recent Chamoli Glacier outburst on 7th Feb., 2021, are the glaring example that resulted in losses of life and property. Such events are expected to increase in IHR due to fragile geology, active tectonics and peculiar hydrometeorology.

Increased frequency of cloud bursts and flash floods: The orographic lifting of air due to unstable inclines resulted in unexpected heavy precipitation in IHR. Many researchers reported occurrence of cloudbursts mainly in monsoonal period around the southern rim of the Himalaya and along the Gangetic plains (Sah and Mazari 2007; Dimri et al. 2017). The frequency of cloud bursts and resultant flash floods is projected to increase due to climate change. It would escalate soil erosion hazards, degradation of agricultural lands, damage to irrigation structures, economy and service sectors, and threats to human life and livestock etc.

Increased frequency of droughts: Droughts are expected to increase, resulting in the decreased number of rainy days and a shrinking of cropping seasons. It would seriously impact agriculture, especially in rainfed areas. More than 60 percent of cultivated lands in IHR are rainfed. Climate change signatures are also visible in the fragile landscape of the Himalaya, causing abnormal floods and droughts (Tewari et al 2017). There is increasing concerns about current and potential climate change impacts that need to be mitigated by adopting resource–conservation technologies (RCTs), conservation agriculture (CA) practices and agro–meteorological analysis of climate–soil–crop relationship.

Increased threats to water security – demand and supply issue: Water security is threatened by increased water demand associated with improved socio-economic conditions in the downstream region. The impacts of climate change are also visible in the IHR, putting enormous stress to the hydrological system (Matthew et al. 2013). Water stress often manifests drought and flood that need to address through systematic management measures.

Challenges

- The information concerning changing climate scenarios in IHR and its implications on water resources and the related threats are yet not thoroughly investigated and understood.
- Research on climate change vis-à-vis its impact on ecosystems (e.g., forests, water, agricultural resources, etc.) is still in the infancy stage in IHR.
- As such, there is a paucity of long-term climate data in the region. There is a lack of reliable micro-level data. The climate data collection network is presently insufficient to meet the requirement of climate change research.
- Current generation climate models and downscaling methodologies have limitations in capturing the observed hydro-climatic variations of the Himalayan river basins (Hasson et al 2019).
- The climatic effects of black carbon on the Himalayan glaciers are not adequately understood, partly due to the large spatio-temporal variability of black carbon in the region (Kopacz et al 2011).
- Each IHR river basin has its characteristic ecological complexity, endowment and water needs, creating diverse governance challenges.
- The assessment of the water flowing in the IHR river basins suffers from great uncertainty (Kattelman 1987).

What needs to be done?

Strengthening resilience and adaptive capacity to climate-related hazards and natural disasters in all countries and integrating climate change measures into national policies, strategies and planning are the two major targets of SDG 13. Understanding the past and potential future of climate change in IHR based on robust scientific analysis is important to better comprehend the region's present and future risks. Evidence-based actions to reduce disaster risk, to mitigate and adapt to climate change, and adopt good governance, are central to ensuring prosperity in the IHR. Challenges and opportunities vary at different levels: micro (watershed and spring-shed), meso (river basin), and macro (regional), and so are the needed actions. Water-related decision-making is influenced by different stakeholders and interest groups across micro, meso and macro scales. At the micro level, informal local institutions are influential decision-makers. There should be greater synergy between the formal state and informal local institutions. At the meso level, the formal state institutions are the critical decision-makers. Their decisions should be evidence-based rather than politics-based, supported by science and local knowledge. At the macro level, different states at the national level (and different nations at the international level) play an important role in decision-making. Trust building among themselves and settling issues and conflicts wisely are important for the interest of humanity. Important researchable, developmental, and policy issues focusing on the mitigation or reduction in the impact of climate change on water resources in IHR are enlisted below:

Researchable and developmental issues

- Systematic data collection to understand the current status of climate and water resources in IHR should form the first step of the action plan. Understanding glaciers and snow cover is vital for water resources planning and management. The climate data collection efforts need to be strengthened and intensified.
- Rescuing a shrunk glacier is rather difficult. Therefore, it is important, to concentrate on mitigating the impact of the glacier melt and prepare at the societal and economic level.
- To address the water crisis caused by the dried-up springs, spring-shed management strategies and conservation measures should be developed by merging scientific and community knowledge. Few studies have established a relationship among precipitation, recharge and spring discharge, but in small and scattered areas with variable results (Negi and Joshi 2004, Sharma et al 2016, Kumar and Sen 2020).
- A workable and realistic management plan for spring-sheds needs hydrogeological and hydrological characterization of catchments and a reliable modelling approach (Kresic and Stevanovic 2010). Additional field investigations of declining springs and further research, about detailed geohydrology and modelling studies are required in spring catchments.

Policy issues

- India needs to reduce its greenhouse gas emissions and move on to renewable energy sources like wind, solar, and ocean waves, in addition to improving forest cover and other means to absorb the country's carbon dioxide emissions. India is committed to reducing its emission intensity (annual greenhouse gas emissions per unit gross domestic product) by up to 35 percent from 2005 levels.
- India's commitment to achieving Net Zero emissions by 2070 is revealed in the 26th Conference of Parties (CoP26) with a five-fold strategy named '*panchamrita*' by focusing on renewable energy and reducing carbon emission (https://pib.gov.in/PressReleasePage.aspx?PRID=1768712).
- Particular attention concerning the IHR needs to be given to the possible use of aquifers in the foothill regions.
- A two-tiered policy approach is required to manage hydrology in IHR. A framework policy for all the IHR river basins, and more specific policies and practices for individual basins within that framework are needed.
- The policy must recognize all constituents of flows (water and its composition, energy content of flows, biodiversity, and sediment budget in all parts of their basins) beyond simple hydraulic quantifications.
- Organized governance at the basin level is required by treating the IHR as a large catchment with land use zones designed basis on water as a product, along with crops, fruits, timber, flowers, minerals etc. The existing reductionist policy fails to address such an aspect of governance of river basins in IHR.
- The policy must integrate water demand and infrastructural development infrastructure for flood mitigation, irrigation, water supply, functioning of ecosystems, pollution control, etc.
- The spatio-temporal heterogeneity has varied impacts from climate change. The IHR also has many implications that require a holistic approach with the involvement of local communities to usher its long-term benefits to upcoming generations. The national mission for sustaining the Himalayan ecosystem also highlighted the importance of community participation in adapting and mitigating the climate change.

CONCLUSION

The Indian Himalayan Region (IHR) is the storehouse of fresh water for millions of people downstream. It stores water in the form of snow and glaciers. The three major rivers (Indus, Ganga and Brahamputra) and mountain springs which originate from melting snow and glaciers and rainfall events in IHR, meet more than half of the water requirement of people in India. However, water resources are under the increased threat of climate change. The precipitation is declining while snow and glacial melt is increasing, leading to loss of water storage, formation of glacial lakes and flash floods, endangering life and property. The challenges of managing water resources in IHR are enormous because of the paucity of databases, poor data-collecting network, uncertainties of assessing river flows, and uncertainties in climate models because of large hydro-climatic variability in the Himalayan region, etc. Nevertheless, India has the potential trained human resources, relevant infrastructure, and political willpower to convert these challenges into opportunities. Since water resource management in mountain ecosystems is a complex issue, it must be tackled by integrating the efforts of all the stakeholders holistically. All efforts must be made to minimize GHGs production to curb global warming and climate change.

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