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Abstract

The Indian Himalayan Region (IHR) which is a domicile ~4 % of the country's population is a rich depository of biodiversity, a natural habitat of ~8000 species of flowering plants, over 816 tree species, 675 edibles and nearly 1740 species of medicinal plants. The region encompasses over several states of India, i.e., JK, HP, UK, Sikkim, and Arunachal Pradesh and the hill regions of Assam and West Bengal. This vast region is important in global atmospheric circulation and is vulnerable due to its unique geology, rich natural resources, and socioeconomic milieu. Climate change may cause a significant impact on this region. Water resources in this region are one of the vital inputs for the survival of mankind and rich biodiversity. Climate change can affect significantly in the quantum of flow as snow and glacial melt is the major contributor of the rivers' flow in this region. The serious challenge is related to frequency and magnitude of extreme weather events like rainfall which may lead to flash floods, landslides and debris flow. There will be both short- and long-term implications due to climate change in this region. A large knowledge gap exists in the present scenario regarding the climate change implications on water resources and related hazards in the Himalayas and their downstream river basins. Primary data generation and its utilization in developing scenarios taking into account water demand and socio-economic development as a whole are required. Establishment of monitoring system for snow, ice, and water and use of latest hydrological model are the keys. Climate change may have a detrimental effect on the present socio-economic structure in the region also. Society will also have to adapt to

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the stresses of the climate change on the livelihood. Participation of people in their general welfare backed by institutional support and updated knowledge base will be important in the changed climate scenario.

Keywords

Indian Himalayan Regions (IHR) • Climate change • Hydrology • Hydropower • Indian rivers • Monsoon • Modeling

19.1 Preface: The Himalayan Region

Himalaya, ‘the abode of snow’, is a Sanskrit term. Literally the whole Himalayan region is a home of extensive mountain ranges like the Himalaya, the Karakoram, the Hindu Kush and many more minor ranges extending from the Pamir Knot. The Himalayan mountain range in South Asia separates the Indo-Gangetic Plain (IGP) from the Tibetan Plateau. The region extends to five nations which include India, Nepal, Bhutan, Pakistan, and China. Himalayan mountain system is the largest in the world, and to name a few, Mount Everest, Kanchenjunga, Makalu, Cho Oyu, Dhaulagiri, Manaslu, Annapurna, and Naga Parbat are among the significant peaks (Figs. 19.1 and 19.2).

Physically the Himalayas are divided into three parallel zones, i.e., the Great Himalayas, the inner Himalayas (also known as middle or lesser Himalaya), and the Sub-Himalayan foothills with the adjacent Terai and Duar plain. The Great Himalayas consists of a great line of snowy peaks with an average height of more than 6100 m. Most of the highest peaks are in the Nepal and Sikkim followed by Kumaon section and then Punjab and Bhutan section. Peaks in the Assam portion are of least heights. Ranges like Karakoram, Kailas, Ladakh, and Zaskar come under the Great Himalayan region. The inner Himalaya is characterized by uniform height, between 6000 and 10,000 ft. The significant ranges in this region include Nag Tibba, Dhauladhar, Pir Panjal, North Kashmir, Mahabharata, Mussoorie, and Ratanpur. In the outermost and lowest zone, the Sub-Himalaya is characterized by the large number of longitudinal flat-bottomed valleys and plains known as Terai and Duars.

This region is having the third largest deposit of ice and snow in the world after Antarctica and the Arctic. There are about 15,000 glaciers which prominently include Gangotri, Yamunotri, Khumbu, Langtang, Zemu and many more. These glaciers provide storage of about 12,000 km³ of fresh water (IPCC 2007). The permanent snow line of the IHR is among the highest in the world at typically around 5500 m (Shi et al. 1978). The higher regions of the Himalayas are snowbound throughout the year and serve as sources of several large **perennial rivers** like Indus, Ganges, Brahmaputra, Yamuna, and Ayeyarwady (or Irrawaddy). Mountain lakes or **tarns**, formed due to glacial activity, are found mostly in the upper reaches of the Himalayas, i.e., above 5500 m. Below this altitude, snow-fed lakes are found. **Tilicho Lake** in Nepal in the Annapurna



Fig. 19.1 Origin and expansion of major Indian river systems (Source: Publication titled ‘Himalayan Glaciers: Climate Change, Water Resources, and Water Security’, National Academic Press 2012)

Massif is one of the highest lakes in the world. Some of the important lakes are [Yamdruk Tso](#) in Tibet, [Shey Phoksundo Lake](#) in Nepal, [Gurudongmar lake](#) in North Sikkim, [Gokyo Lakes](#) in Nepal, and [lake Tsomgo](#), near the Indo-China border in Sikkim (Figs. 19.2 and 19.3).

The unique flora and fauna is the wealth of the Himalayan region. Variations are basically due to wide range of climatic condition in different parts of this region. The region also supports a strong ethnicity of several cultures and religions. Based on the general spatial differentiation with associated geographic elements and broad pattern of human occupancies, the entire Himalayas was divided into three major realms, i.e., Western Himalayas, Central Himalayas, and Eastern Himalayas (Karan 1966). Each of these three realms possesses some unifying physical and cultural traits along with a certain measure of geographic homogeneity. The Western Himalayan realm may be divided into the Sub-Himalayan Kashmir (Poonch and Jammu), Pir Panjal, Vale of Kashmir, Ladakh and Baltistan, and the Kohistan and Gilgit regions. This realm is dominated by Afghan-Iranian culture and Hinduism and Lamaistic Tibetan cultures. The Central Himalayan realm between Kashmir and Sikkim may be divided into three major geographic regions, i.e., Himachal and Punjab Himalayas, Garhwal and Kumaon Himalayas, and Nepal Himalayas. The

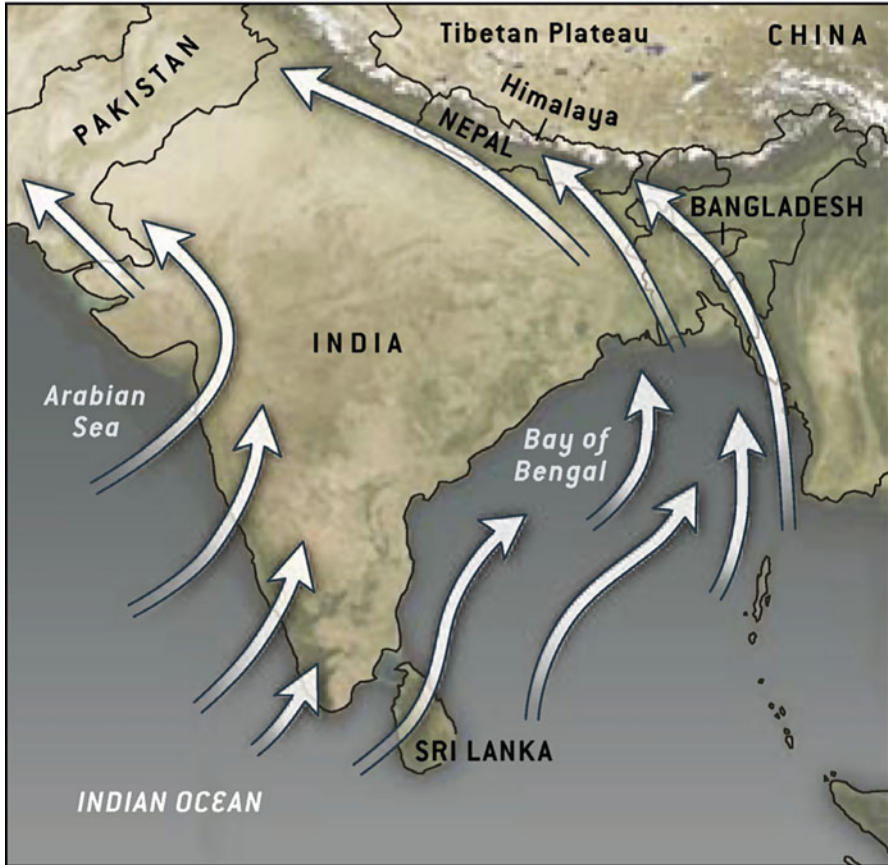


Fig. 19.2 The moist air currents that drive the South Asian Monsoon are indicated by *white arrows*. Monsoon flow transports moisture from the Arabian Sea to the Indian subcontinent, resulting in heavy monsoon rain over the Indo-Gangetic Plain and the Bay of Bengal (Source: Hodges 2006)

realm is dominated by Hinduism and Buddhism. Eastern Himalayan realm may be divided into three geographic regions, i.e., Darjeeling and Sikkim Himalayas and Bhutan and Assam Himalayas. The realm is dominated by Hindu and Tibetan culture.

Since this region is sensitive to its unique ecology, environment and culture and religion and climate change may have serious consequences altogether. Studies (Kothawale et al. 2010; Basistha et al. 2009; Bhutiyan et al. 2007; Arora et al. 2005; Meena et al. 2015d, e) have suggested for temperature variations in either direction (Figs. 19.1, 19.2, and 19.3). This will have an impact on the flora and fauna base, snow and glacial base and culture and environment base. The impact on the snow and glacial base and effect on the major river systems

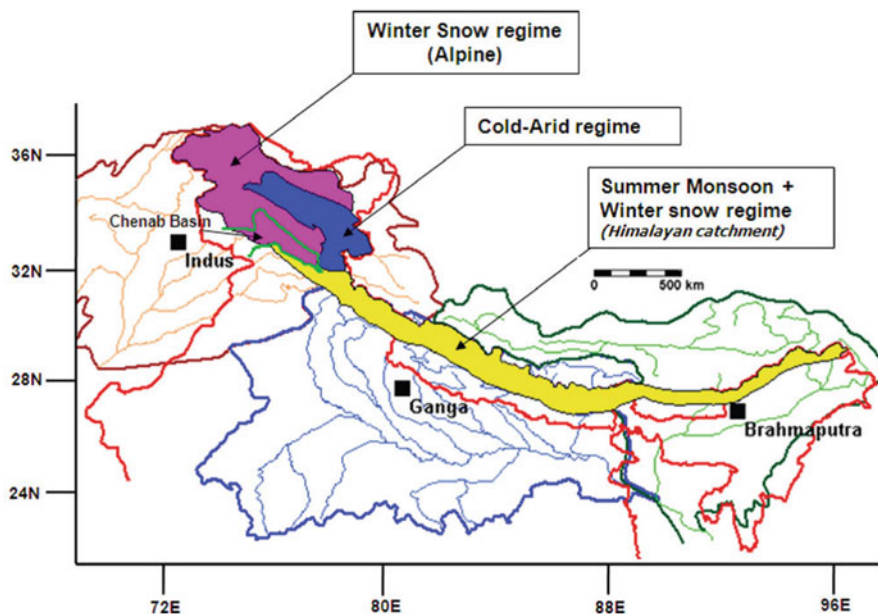


Fig. 19.3 The climate varies across the HKH region. In the west, indicated by *purple* in the figure, the climate is alpine and dominated by the mid-latitude westerlies. Most precipitation takes the form of winter snow. This area adjoins a cold arid climate regime, indicated by *blue* in the figure. In the east, indicated by *yellow* in the figure, the climate is dominated by the summer monsoon, with most of the precipitation coming during the summer months. The Indus, Ganges, and Brahmaputra watersheds are also shown in the figure (Source: Thayyen and Gergan 2010)

originating from this region, in the context of Indian subcontinent, would be the focus in the subsequent sections of this chapter.

19.2 Indian Himalayan Region (IHR)

The IHR extends from Kashmir in the west to Arunachal Pradesh in the east and is almost 2500 km long, and its breadth is about 80–300 km and rising from low-lying plains to over 8000 m above msl. The region spreads between $21^{\circ} 57' - 37^{\circ} 5' N$ latitudes and $72^{\circ} 40' - 97^{\circ} 25' E$ longitudes and covers 12 states of India, viz., Jammu and Kashmir, Himachal Pradesh, Uttaranchal, Sikkim, Arunachal Pradesh, Nagaland, Manipur, Mizoram, Tripura, Meghalaya, and hills of Assam and West Bengal of a total geographical area around 5, 33,604 km². The region is full of peaks and lakes, which feed the river system originating from this region (Table 19.1).

This region is a repository of diverse natural resources and habitat of about 40 million people of different cultures and beliefs. Multiple ethnic compositions are a striking feature of the region, where more than 171 out of 573 scheduled tribes of

Table 19.1 Major peaks and lakes of Indian Himalayan Region

Peaks	Altitude (m asl)	High altitude lakes	Altitude (m asl)
K2	8611	Suraj Tal	4950
Kangchenjunga	8598	Tso Moriri	4524
Nanga Parbat	8128	Panggon	4350
Masher Bram (East)	7821	Hemkund Sahib	4329
Nanda Devi	7817	Vasuki Tal	4300
Rakaposhi	7788	Chandra Tal	4300
Kamet	7756	Daiya Tal	4275
Saser Kangri	7672	Dashir lake	4270
Chaukhamba (Badrinath Shikhar)	7138	Manimahesh	4080
Trisul (west)	7138	Gandhi Sarovar	3970
Noonkonn	7135	Nako lake	3662
Phaunari	7128	Tsongo (Changu)	3658
Kaunto	7090	Tulian lake	3353
Dunagiri	7066	Deoria Tal	3255

Source: ENVIS Monograph 3

India inhabit the region (Samal et al. 2000). Varied climatic conditions have been the reason for the rich flora and fauna base in the region. Three major Indian river systems, i.e., Indus, Ganges, and Brahmaputra (Fig. 19.1), provide for the economic and cultural development of the whole region in particular and for the country in general (Fig. 19.1).

19.2.1 Climate and Meteorology

The climate of the IHR ranges from subtropical (<800 m) at the foothills to arctic zone (>3500 m) at the highest altitude (Tibetan Plateau). During the late spring and early summer, the plateau surface heats up quickly and serves as an elevated heat source, which draws warm and moist air from the Indian Ocean toward the Himalayas and Tibetan Plateau region. As the monsoon flow transports moisture from the Arabian Sea to the Indian subcontinent, it causes heavy monsoon rain over the Indo-Gangetic Plain (IGP) and the Bay of Bengal (Fig. 19.2). During the winter, the low-level monsoon flow reverses to northeasterly, with prevailing large-scale subsidence and relative dry conditions over India (NAP 2012).

The climatic gradient is strong not only across but also along the arc of the Himalayas. The Sutlej valley serves as a rough dividing line between the climate regimes of the Western and Eastern Himalayas (Bookhagen and Burbank 2010). In the west (Fig. 19.3), the climate is alpine and dominated by the mid-latitude westerlies (indicated by purple) where most of the precipitation takes the form of winter snow. This area adjoins a cold arid climate regime (indicated by blue). However in the east, the climate is dominated by the summer monsoon, and most of

the precipitation comes during the summer months (indicated by yellow) (NAP 2012).

The areas in Indus basin have a relatively dry climate, with annual precipitation of 400–600 mm, primarily from winter time storms associated with the mid-latitude westerlies. In the cold arid regions of Ladakh, though the precipitation is somewhat higher in summer, but the mean annual precipitation is as low as 115 mm (Thayyen and Gergan 2010). Rainfall is higher in the east, mostly from summer monsoon rain. Based on 10 years data (1998–2007), Bookhagen and Burbank (2010) showed that mean annual rainfall ranges from ~1 to more than 4 m (1000–4000 mm) in the monsoon-precipitation-dominated portions of the region (Figs. 19.2 and 19.3).

19.2.2 Glaciers

Glaciers play an important role in maintaining hydrological cycle and ecosystem stability as they act as buffers and regulate the runoff water supply from mountains to the plains in both dry and wet spells. On the basis of the mode of occurrence and dimensions, glaciers have broadly been classified as valley glaciers, piedmont glaciers and continental glaciers. Himalayan glaciers which amount to about 70 % of world non-polar glaciers (Nandy et al. 2006) fall in the category of valley glaciers. It has been estimated that an area of about 32,000 km² is under permanent cover of ice and snow in the Himalaya (Negi 1991). Some of the important glaciers are enlisted in Table 19.2.

The committee on Himalayan glaciers, hydrology, climate change, and implications for water security has calculated the proportion of glacier area in

Table 19.2 Important glaciers of Indian Himalayan Region

Glaciers	Location
Siachen	Indus basin, Karakoram
Rulung	Indus basin, Trans-Himalaya
Neh-Nar	Sind basin, Great Himalayan range
Thanak-Lungpa	Suru basin, Zaskar 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
Changme-Khangpu	Sikkim Himalaya
Zemu	Sikkim Himalaya

Source: ENVIS Monograph 3

different elevation bands for the Indus, Ganges, and Brahmaputra basin (NAP 2012). In all the three basins, the majority of glacier area is in the 5000–6000 m band, and a significant amount lies in the 4000 to 5000 m band. The Indus basin has a slightly greater proportion of its glacier area below 4000 m than the Ganges/Brahmaputra basin, whereas the latter has a slightly greater proportion of its glacier area above 6000 m. The calculation suggests that glacial retreat would be more significant to changes in climate in the Indus basin than in the Ganges/Brahmaputra basin. This also qualifies the evidence that glaciers are more stable in the Western Himalayas.

Based on the model study, it was reported that as much as 70 % of the summer flow in the river Ganges and 50–60 % of the flow in other major rivers are contributed from melting glaciers (Barnett et al. 2005). Although a large variation in the reported percentage figures was observed (Alford and Armstrong 2010; Racoviteanu 2011; Armstrong 2010), it has been generally accepted that the percent contribution increases from east to west across the IHR (Immerzeel et al. 2010). However, there is an ambiguity over the glacial and snow contribution. It is worth to mention that snowmelt is a renewable resource that is replenished every year, in contrast to the glacial melt (Barnett et al. 2005). Considering the widely varied climatic regime alone in the IHR, it can be anticipated that there will be variation in the relative contributions of rain, snowmelt, and melt of glacier ice toward the discharge of different rivers of the IHR.

19.2.3 Water Resources

The main sources of water in this mountain chain are primarily rainfall from southwest monsoon, winter rains and heavy snowfall in the winter season. A significant contribution of the water resources in this region comes from snow and ice melt. Even a part of the groundwater and natural springs in the IHR are also recharged from the snowmelt water. An estimated water flow of about 8634 million m³ occurs down the Himalayan rivers every year (Negi 2003). The catchment of Indus river system in Western Himalaya forms part of Jammu and Kashmir and Himachal Pradesh, while Ganges river rising from the snout of Bhagirathi drains very large catchment of Himachal Pradesh and entire Uttarakhand. In the eastern most part, the Brahmaputra river system drains a considerable area of the North Bengal, Sikkim, and Arunachal Pradesh in the IHR (Table 19.3).

There are total 19 rivers in the Indus basin, 67 in the Ganges basin and 31 in the Brahmaputra basin besides many small rivulets, streams and tributaries which altogether contribute in a large way to the sustenance of diversified flora and fauna of this region. More than 50 % of average water resources potential of our country is shared by various tributaries of these river systems (Table 19.4).

There is a wide variation of precipitation pattern in different parts of this region. In the eastern and central part of the region experiences more rainfall than snow falls, whereas in the western part snowfall is predominant. Therefore the nature of river flows in the western part is different from the eastern and central part. Due to a

Table 19.3 Principal glacial-fed river systems of the Himalaya

River	Mountain area (km ²)	Glacier area (km ²)
Indus	268,824	7890
Jhelum	33,670	170
Chenab	27,195	2944
Ravi	8092	206
Sutlej	47,915	1295
Beas	12,504	638
Yamuna	11,655	125
Ganges	23,051	2312
Ramganga	6734	3
kali	16,317	997
Karnali	53,354	1543
Gandak	37,814	1845
Kosi	61,901	1281
Tista	12,432	495
Raikad	26,418	195
Manas	31,080	528
Subansiri	81,130	725
Brahmaputra	256,928	108
Dibang	12,950	90
Lohit	20,720	425

Source: ENVIS Monograph 3

Table 19.4 Potential of major water resources in India

River basin	Catchment area (km ²)	Average water resources potential (BCM)
Indus (up to border)	321,289	73.31
Ganges	861,452	525.02
Brahmaputra	194,413	537.24
Total (20 river basins of India)		1869.35

Source: CWC Publication 1993

lack of data and the inaccessibility of the region, the contribution of glacier to the river flow is not well established in the IHR.

Glacial melt and snowmelt are reported to play an extremely important role in the Indus basin followed by the Brahmaputra basin, but play only a modest role for the Ganges rivers (Immerzeel et al. 2010). Wulf et al. (2011) quantified the water resources and discharge components for the Sutlej river, a major tributary of the Indus River, for the period 2004–2009. Results indicated that the discharge of the Sutlej river at Bhakra located at low elevation and situated at the base of the mountains is sourced predominately by snowmelt (48 %) followed by an effective share of rainfall (evapotranspiration, 39 %) and glacial melt (13 %).

There is a strong seasonality observed in annual precipitation as well. Annual hydrographs for the Ganges and Indus rivers clearly show strong seasonality pattern in the amount of discharge, leading to seasonal differences in the water availability. The Ganges river exhibits a significant discharge during the summer months, resulting in a water surplus that can maintain streamflows and recharge groundwater storage in some areas. However, water consumption exceeds natural runoff in the late winter months (February and March) seems to have some reliance on groundwater and/or storage (Hoekstra and Mekonnen 2011). The Indus river has a lower peak discharge and lower annual discharge than the Ganges river. The Indus river discharge also varies seasonally and interannually (NAP 2012).

19.2.4 Land Use and Land Cover

In the IHR, about 52 % of the total area is covered with forest, followed by wastelands, whereas arable land cover is about 11 % (Nandy et al. 2006).

The land use/land cover changed from forest to other land uses in the past several decades in the region (Rai et al. 1994); this may lead to environmental degradation through massive soil erosion and nutrient loss. For example, Jhum cultivation in the Eastern Himalayan region showed to disrupt ecological balance due to soil erosion resulting from reduction of Jhum cycle (Nandy et al. 2006). Agricultural land area has also found to increase considerably over the past four decades in the Himalaya replacing the other land uses, particularly forests (Sharma et al. 1992). Understanding the relationship between land use/land cover and hydrology is critical for the prediction of soil fertility, nutrient budgets and local water recharges for the functioning of watershed (Sharma et al. 1992; Meena et al. 2013, 2015a, 2016; Singh et al. 2014; Kumar et al. 2015; Ghosh et al. 2016). Geographical distribution of states covering IHR is given in Table 19.5.

19.2.5 Agriculture

The Himalayan people have traditionally practiced integrated agriculture, balancing cultivation of agroforestry, animal husbandry, and forestry. Mountain geography and inaccessibility have helped to maintain agro-biodiversity; however commercial agriculture is not as high yielding and profitable like plains (Nandy et al. 2006). Dependency on its limited arable land is marginally higher in the IHR as cultivators and agricultural laborers together comprise about 59 % of total workforce in the region (Nandy and Samal 2005; Meena et al. 2015b, c; Verma et al. 2015a, b).

Table 19.5 Geographical distribution of states covering Indian Himalayan Region

States/regions	Geographical area (km ²)	% of area under		
		Agricultural land	Wastelands	Forest cover
Jammu and Kashmir	222,236 ^a	4.7	64.6	9.6
Himachal Pradesh	55,673	14.5	56.9	25.8
Uttaranchal	53,483	12.5	30.1	44.8
Sikkim	7096	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

^aIncluded 78,114 and 37,555 km² occupied by Pakistan and China, respectively, and 5180 km² handed over by Pakistan to china (Source: Wastelands Atlas of India and FSI 2000)

19.2.6 Agroclimatic Zonation

Considering the commonality of factors like soil type, rainfall, temperature, water resources, etc., Indian subcontinent has been divided into 15 agroclimatic regions (zones). The IHR represents two prominent agroclimatic zones (Table 19.6), viz., Zone I, the Western Himalayan region, and Zone II, the Eastern Himalayan region. Zone I characteristically covers the low altitude subtropical region of south to mid to high temperate region in the mid-hills and extended to high hills on the north. The northern part of Zone I belongs to cold arid regions of Himachal Pradesh and Jammu and Kashmir. Zone II is the hills and mountains of folded topography (Table 19.6) with near tropical to alpine climatic conditions (Nandy et al. 2006).

19.2.7 Forest Types and Forest Ecosystems of IHR

Forests in Western and Eastern Himalayas are typically different depending on the factors like altitude, climate, topography, soil, etc. The Western Himalayan forests are diverse both in content and composition, whereas Eastern Himalayan forests are very rich both in flora and fauna (Dhar et al. 1997).

Table 19.6 Agroclimatic zones of Indian Himalayan Region

Agroclimatic zone	Climate	Rainfall (in 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 Uttaranchal
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)

19.2.8 Biodiversity

IHR, as a whole, supports nearly 50 % of the total flowering plants of India, of which 30 % are endemic to the region. The IHR supports about 8000 species of angiosperms (40 % endemics), 44 species of gymnosperms (16 % endemics), 600 species of pteridophytes (25 % endemics), 1737 species of bryophytes (33 % endemics), 1159 species of lichens (11 % endemics) and 6900 species of fungi (27 % endemics) (Singh and Hajra 1996). There are over 816 identified tree species found in the IHR, of which 675 are edible and nearly 1743 species are of medicinal value (Samant et al. 1998). The diversity of plant species used in various ailments is dispersed all across the IHR (Samal et al. 2002, 2004).

19.2.9 Hydropower

The IHR is suitable for hydroelectric power development because of availability of perennial sources of water in rivers. At present this region has been estimated to produce electricity more than 1.10 lakh MW (Table 19.7) (Slariya 2013). Brahmaputra subbasin has the largest hydropower potential among three basins with Indus basin and Ganges basin in the second and third positions. Considering the completed and under construction projects, Brahmaputra subbasin, Indus, and Ganges have harnessed about 11 %, 48 %, and 31 % of the assessed potential, respectively (<http://india-wris.nrsc.gov.in>). Therefore, a large chunk of the hydro-power potential of the basin is yet to be exploited. Some of the major running hydropower stations in this area are Tehri; Koteshwar; Rihand; Raj Ghat; Bhakra; Pong; Dehar; Ranjit Sagar; Chamera stages I, II, and III; Nathpa Jhakri; Uri; Salal; etc. (Table 19.7).

Table 19.7 Status of hydropower projects situated in Indian Himalayan Region

Indian Himalayan State	Status	Capacity (MW)	
Himachal Pradesh	Projects under operation	6370.12	
	Projects under execution/allotted	5744.10	
	Projects under the process of allotment	5615.50	
	Projects to be re advertised	1481.00	
	Abandoned projects	0435.00	
	Projects under investigation	0046.50	
	Himurja projects proposed/under execution	0723.40	
	Total	20,415.00	
Jammu and Kashmir	Existing projects	Jhelum River basin (total = 6)	0252.60
		Chenab basin (total = 5)	0483.80
		Ravi basin (total = 1)	0009.00
		Indus basin (total = 8)	0013.03
		Central sector	1560.00
	Under construction	State sector	0453.61
		Central sector	0449.00
	Total	3221.31	
Uttarakhand	Power projects under operation	3164.75	
	Power projects under construction	5509.40	
	Projects under development	1,7540.93	
	Total	2,6214.68	
Sikkim	Upper part of Sikkim (total = 9 projects)	2823.00	
	Lower part of Sikkim (total = 11 projects)	1402.00	
	Total	4225.00	
Arunachal Pradesh	Central (total = 4)	05870.00	
	State (total = 8)	1,4785.00	
	Private (total = 74)	2,7512.00	
	Total (total = 86 projects)	4,8167.00	
Nagaland	State	0075.00	
Manipur	To be implemented by NHPC (total = 7)	0037.75	
	Under capital subsidy program (total = 3)	0800.00	
	Under state sector (total = 3)	0560.84	
	Under center sector (total = 2)	1590.00	
	Mini/micro projects (total = 5)	3900.00	
	Total (total = 20 projects)	6888.59	
Mizoram	Central sector (total = 3)	0876.00	
Tripura	State/center (total = 2)	0184.00	
Meghalaya	State (total = 1)	0090.00	
	Grand total	110,281.25	

Source: Slariya (2013)

19.3 Climate Change in IHR

The increasing human activities due to industrial revolution have led to unprecedented changes in the earth's delicate climate system. There is now established evidence that the earth's surface has warmed during the past 100 years, which is mainly attributed to the anthropogenic activity. Changes in many components in the climate system, like precipitation, snow cover, sea ice, extreme weather events, etc., have also been observed. These changes, however, showed remarkable regional variations around the globe.

19.3.1 Climate Change Models

Studies on climate change in mountain areas remained incomplete and scattered (IPCC 2007; Nogués-Bravo et al. 2007), although certain studies from the Hindu Kush Himalayas (HKH) (Shrestha et al. 1999) do indicate that climate change has an undesirable impact on Himalayan biodiversity and its services. The Himalayan region, including the Tibetan Plateau, has shown consistent warming trends during the past 100 years (Yao et al. 2006). Specific knowledge on IHR with respect to climate change indicators are lacking due to both inaccessibility of the location and the insufficient theoretical attention given to the complex interaction of spatial scales in weather and climate phenomena in mountain areas. The analysis in the Eastern Himalayan region estimated for widespread warming, and the rate is generally greater than 0.01 °C per year or more (Shrestha and Devkota 2010). The highest rates of warming are in the winter and the lowest, or even cooling, are in summer. It has also been reported that more warming may be the reality in the higher elevation.

The spatial distributions of maximum temperature trends in Nepal (Central Himalayan region) showed high warming in most of the Himalayan region and the middle mountains, while low warming or even cooling trends are observed in most of the Terai and the Siwalik regions (Shrestha et al. 1999). Analyses of maximum temperature data from 49 stations in Nepal over a period of 1971–1994 revealed annual warming trends after 1977 varied from 0.068 to 0.128 °C in most of the middle mountain and Himalayan regions, while the Siwalik and Terai (southern plains) regions seemed to be less affected and showed warming trends of less than 0.038 °C year⁻¹.

19.3.2 Climate Change Impact on Water Resources in IHR

19.3.2.1 Glaciers

Since glaciers are contributing significantly in river flow, the impact of climate change on glacier is the most important from the point of view of water availability and ecosystem balance. Data that has been generated from the glacier studies, in the Himalayas, over the last 100 years or so, indicates that the glaciers, in the

Himalayas, have been, by and large, shrinking and retreating continuously, barring a flip here and there, but the rate of retreat cannot be considered as alarming/abnormal, especially in the last decade or so (Raina, MoEF discussion paper 2009).

Glacier monitoring in the Indian Himalayas started in the early twentieth century, when 20 odd glaciers in the Himalayas, located across the Indian Himalayas, from Jammu and Kashmir in northwest to Sikkim in northeast, began to be monitored by the Geological Survey of India (GSI). Observations had revealed that the degeneration of the glacial mass has been highest in the northwest side and declined toward the northeast side (Raina, MoEF discussion paper 2009).

The Ministry of Environment & Forest (MoEF) discussion paper has revealed that glaciers in the Himalayas, over a period of the last 100 years, behaved in contrasting ways. As an example, Sonapani glacier has retreated by about 500 m during the last hundred years. On the other hand, Kangriz glacier has practically not retreated even an inch in the same period. Siachen glacier is believed to have shown an advance of about 700 m between 1862 and 1909, followed by an equally rapid retreat of around 400 m between 1929 and 1958, and hardly any retreat during the last 50 years. Gangotri glacier, which had hitherto been showing a rather rapid retreat, along its glacier front, at an average of around 20 m per year till up to 2000 AD, has since slowed down considerably and between September 2007 and June 2009 is practically at a standstill (NAP 2012). The same is true of the Bhagirath Kharak and Zemu glaciers. The paper highlighted 'It is premature to make a statement that glaciers in the Himalayas are retreating abnormally because of the global warming. A glacier is affected by a range of physical features and a complex interplay of climatic factors'.

19.3.2.2 Major Rivers

Given the difference in climate between the drier western and monsoonal eastern ends of the region, future warming is unlikely to affect river flow uniformly throughout. Impacts of declining glacier area on river flow will be greater in smaller and more highly glacierized basins in both the west and east and in the west, where precipitation is scarce, for considerable distances downstream (Rees and Collins 2006). Glacier shrinkage and the relative contribution of glacier melt to the region's river discharge are lower than reported in the Fourth Assessment Report of IPCC, 2007 (Miller et al. 2012). There has been some research on the water availability in three basins of IHR.

Indus

Snow and glacier melt both are considered as the primary drivers of the hydrological regime (Mukhopadhyay and Dutta 2010). Modeling of the upper Indus indicated that some 34 % of total streamflow in this area is generated by snowmelt, while 26 % is from glacier melt (Immerzeel et al. 2010; Bookhagen and Burbank 2010). A decrease in the observed average annual and summer monsoon discharge data from the river Sutlej was also reported (Bhutiyan et al. 2008; Tahir et al. 2011). Impacts of declining glacial mass on river discharge as a result of climate change will be more substantial in the Indus basin because of the high proportion of discharge

derived from melt water (Rees and Collins 2006). Increased glacier melt as a result of climate change will provide short-term increases in the contribution to discharge of the Indus river, but is likely to lead to decrease in the future (Miller et al. 2012).

Ganges

Considering the changes to the meteorological variable, Arora and Boer (2001) has reported 5% increases in mean annual runoff for the Ganges by 2070–2100. Immerzeel et al. (2010) projected a decrease in mean runoff of 17.6% at higher elevation (>2000 mean sea level) with a likely scenario of declining precipitation and glacier melt. However, in small high-altitude catchments a contrasting pattern was projected (Immerzeel et al. 2012). Glacier retreat may not have a drastic influence on the flow of Ganges river (Jain 2008). Toward downstream its influence will be reducing but it is unlikely that the Ganges will become a seasonal river (Miller et al. 2012).

Brahmaputra

Comparatively a lesser studies were carried out regarding the impacts of climate change on the glacier hydrology, and discharge exists for the Brahmaputra basin compared to the Indus or Ganges (Miller et al. 2012). Glacier melt is not a significant component of downstream discharge in the Brahmaputra. There is no visible spring contribution from glacier and snowmelt (Immerzeel 2008). Despite the fact that there is considerable uncertainty in predicting changes to the South Asian monsoon, all global climate models (GCM) were found to indicate an increase in discharge in the lower Brahmaputra river owing to a projected increase in precipitation downstream (Miller et al. 2012).

19.3.2.3 Extreme Events

In recent decades, the hydrological characteristics of the watersheds in the Himalayan region seem to have undergone substantial changes as a result of extensive land use (e.g., deforestation, agricultural practices, and urbanization), leading to frequent hydrological disasters, enhanced variability in rainfall and runoff, extensive reservoir sedimentation, and pollution of lakes. Global warming and its impact on the hydrological cycle and nature of hydrological events have posed an additional threat to this mountainous region of the Indian subcontinent (Mall et al. 2006).

Climate change may induce physical hazards like flash flooding due to extreme precipitation, flooding due to monsoon rainfall, lake outbursts, landslides and avalanches (NAP 2012). Although the main reason behind the monsoon flood is heavy rain, other factors like snowmelt and change in land use may increase the flood volume, and the outcome may be disastrous. Major Himalayan rivers being intercountry rivers, such disasters may have ramifications on the political scenario of the neighboring countries. As an example, the flooding of the Kosi river led to a dispute between Nepal and India in 2008 (Malhotra 2010).

A glacial lake outburst flood (GLOF) occurs when water dammed by a glacier or a moraine is rapidly released by failure of the dam (Bajracharya et al. 2007; Hewitt 1982; Xin et al. 2008). Failure of the confining dam can have a variety of causes,

including earthquakes, catastrophic failure of slopes into the lake (avalanches, rockslides, icefall from a glacier into the lake), a buildup of water pressure, or even simple erosion of the confining dam over time.

Twenty-four GLOF events have been occurred in Nepal in the recent past, causing considerable losses of life and property. For example, the Sun Koshi GLOF in 1981 damaged the only road link to China and disrupted transportation for several months, and the Dig Tsho GLOF in 1985 destroyed the nearly completed Namche small hydroelectric project, in addition to causing other damages farther downstream (Bajracharya et al. 2007).

Landslide lake outburst flood (LLOF) is a catastrophic release of impounded water from behind a natural dam formed by a landslide. In the steep mountainous Himalayas, landslides are a common event, whether they are triggered by normal weathering and erosion processes, extreme rainfall events, or earthquakes. Gupta and Sah (2008) presented an example of a LLOF in the Sutlej catchment in Himachal Pradesh, India, well below the termini of any glaciers above it. Like GLOFs, LLOFs also pose a serious hazard to people, property, and infrastructure downstream from the landslide dams. LLOFs are even less predictable than GLOFs.

19.3.2.4 Hydropower

The response of hydrological systems, erosion processes and sedimentation of IHR could alter considerably due to climate change. Therefore the hydropower stations may face some kind of insecurity either due to uncertain water availability or the water quality issues. Increased sedimentation may certainly have implications on the available head to the power turbines. Therefore, the planning of hydropower stations should consider the climate change scenarios as the Himalayan regions are the available powerhouse for Indian subcontinent from which a significant share is yet to be exploited.

19.4 Conclusions

It has been ample clear that, although the outcome of the climate change scenarios from various circulation models varies in quantitative terms, there is an overall agreement for the rise in temperature and rainfall events in the Indian Himalayan Region. Realizing the importance of this region's high forest cover which acts as sink for carbon dioxide and provides major ecosystem services, the impacts of global warming, due to both natural causes and anthropogenic emissions, may cause serious consequences. Since the water availability is directly related to the forest cover, the impact on the water resources, sediment load in the rivers and its seasonal variability may have the potential to change the environmental, social and economic structure of this region. Climate change studies of IHR on several aspects have raised the awareness about the threats and possibilities. Depending on the model assumptions, the developed scenarios sometimes rule out the alarming forecast and sometimes make the comfort level disturbed. The most important areas in the context of water resources in the IHR, the glaciers, are either accessible

with utmost difficulty or completely inaccessible, and thereby the ground data collection in itself is many times not possible. Therefore mapping of the present and future scenarios mostly depends on the secondary data and assumptions. So, efforts are needed to standardize the assumptions and setting up observation stations for collection of primary data to encourage the scientific community to reduce the uncertainty associated with the research outcomes. Many organizations are putting their efforts to understand the possible effects of climate change in this region. Coordination among those organizations is also needed. This will help to formulate schemes which will be beneficial to the people of this region, to the preservation of forest land and to control of soil erosion. More emphasis is needed toward the adaptation strategies as the phenomenon of global climate change involves the solution from both local and global perspectives.

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