Hydrology of the Himalayas

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Chapter 21
Hydrology of the Himalayas

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Abstract The Himalayan Mountain chain is the third-largest deposit of ice and snow in the world, serves as an important source of freshwater for the 1.3 billion population living in the lowlands of river basins of Indus, Ganga and the Brahmaputra (IGB) covering eight countries (Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan). Influence of Himalayan cryosphere is very significant in headwater tributaries of these river basins and also plays a significant role in the livelihood of the people through river runoff. Understanding of the timing and relative contribution of individual components of the hydrological cycle and water resources characteristics across the Himalayas is limited and is due to inadequate investigations and lack of synthesis of existing information. This chapter presents outcome of an extensive review of available knowledge and discuses knowledge gaps in the current understanding of hydrology of IGB river basins. Many factors that are considered important in managing Himalayan water resources have been identified and discussed in this chapter.

21.1 Introduction

High mountain areas around the world have served as an important source of freshwater for the population living in the adjacent lowlands, center of biodiversity, source regions for important natural resources and ecosystem services (Bandyopadhyay et al. 1997; Barnett et al. 2005; Schickhoff et al. 2016). The Himalayan mountain is one of the largest mountain chains on Earth, serving as a source of fresh water for the major river systems (Ganges, Brahmaputra, Indus, Irrawady, Mekong, Amu Darya, Salween, Tarim, Yangtze, and Yellow rivers) of the world, extends from 15.95° to 39.31° N and 60.85° to 105.04° E, covering an area of more than 4,192,000 km^2 (Bajracharya and Shrestha, 2011). Together these rivers support the drinking water, irrigation, energy, industry and sanitation needs of 1.3

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billion people living in the mountains and downstream (Shrestha et al. 2015). Himalayan mountain range directly influences the economic prospect of eight countries; Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan. It contains the third-largest deposit of ice and snow in the world, after the Antarctica and the Arctic (Ibsen 2018) and aptly called as 'Third Pole' or 'Water Tower of Asia' (Bajracharya and Shrestha 2011).

Three major river systems, trans-boundary in nature, originate from the Himalayas. Discussion in this chapter is limited to the Indus, Ganga and Brahmaputra (IGB) river systems, which are flowing into the Indian sub-continent. The Indus river basin (IRB) is distributed across Pakistan, India, China and Afghanistan. Ganga river basin (GRB) occupies the central part of the Himalayas and outspreads in India, Tibet (China), Nepal and Bangladesh. The third, the Brahmaputra river basin (BRB) covers China, India, Bangladesh and Bhutan.

Influence of Himalayan cryosphere is very significant in headwater tributaries of all the three river basins. A major share of the Himalayan glaciers lies in the IRB covering an area of 18,195 km^2 followed by BRB, 10,593 km^2 and GRB,7939 km^2. While glaciers occupy high elevation un-inhabited areas and water runs through deep gorges, seasonal snow cover spread over a much large mountain area also plays a significant role in the livelihood of the people through river runoff. Maximum snow cover in the IRB could extend up to 2,74,686 km^2, 67,708km^2 in the GRB and 1,22,905 km^2 in the BRB. Figure 21.1 and Table 21.1 illustrate the glacier and snow cover distribution in these basins.

Our understanding of the timing and relative contribution of individual components of the hydrological cycle across the Himalayas is limited (Bookhagen 2012) and water resources characteristics in the Himalayan region have many knowledge gaps (Bajracharya and Shrestha 2011). For example, many studies conducted in the IGB only focused on the downstream parts of the basin (e.g. Hirabayashi et al. 2013; Gain et al. 2011) and did not take into account the processes that are relevant in mountainous basins (e.g. ice and snowmelt). In the upstream domains of the IGB, where mountain-hydrological processes are important, the number of studies on extremes is very limited. The study conducted by Lutz et al. (2016); is only about high flows and does not take the effects of climate change on low flows into consideration. Available estimates of the ice volume and thickness showed large difference in the IGB region (Azam et al. 2018). Advances in knowledge of Himalayan springs, geology, sediment transfer etc. is limited due to inadequate investigations and lack of synthesis of existing information in published and gray literature. Therefore, the present chapter presents outcome of an extensive review of available knowledge of hydrology of Indus, Ganges and Brahmaputra river basins and has identified gaps in the current understanding of hydrology of these basins. Many factors that are considered important in managing Himalayan water resources have been identified.

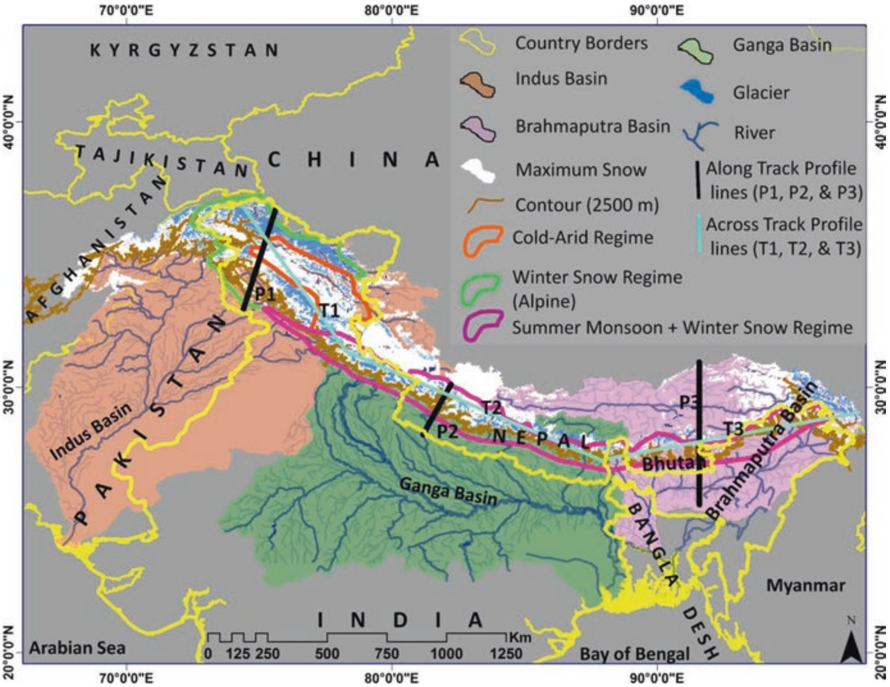

Fig. 21.1 Indus, Ganga and Brahmaputra basins with political boundaries of the countries, glacier distribution and maximum snow cover. Glacier area is based on Randolph Glacier Inventory, RGI6.0

Table 21.1 Country wise distribution of Indus, Ganga and Brahmaputra basin area, its glaciers and corresponding maximum snow cover areas

Basin	Country	Glacier Area	Max. Snow cover area	Total basin area	
		km^2	km^2	km^2	%
Indus	China	1216	46,480	83,669	08.85
	India	14,880	165,284	321,289	34.00
	Pakistan	1892	31,268	469,355	49.67
	Afghanistan	207	31,655	70,687	07.48
	Total	**18,195**	**274,687**	**945,000**	**100**
Ganga	China	2613	17,189	34,992	03.33
	Nepal	3099	33,566	147,181	14.02
	India	2227	16,953	861,452	82.04
	Bangladesh	0	0	6375	0.61
	Total	**7939.2**	**67,708**	**1,050,000**	**100**
Brahmaputra	China	8770	95,604	289,609	49.93
	Bhutan	1019	6461	46,500	8.02
	India	805	20,840	194,413	33.52
	Bangladesh	0	0	49,478	8.53
	Total	**10,594**	**122,905**	**580,000**	**100**

21.2 Hydrology of the Himalayas

Hydrology of the Himalayas is complex because of the impact of two circulation systems, the Asian Summer Monsoon (ASM) and Western Disturbances (WD) (Bookhagen and Burbank 2010). ASM declines in strength from east to west along the Himalayas, whereas WDs decline as they move from west to east (Gautam et al. 2013). To the west (Indus), there is general pattern of winter accumulation and summer melt, similar to glaciers of North America and Europe. However, part of IRB (Western Himalaya) is a transition region receiving precipitation from both the ASM and WD (Azam et al. 2016). Conversely, in east (Ganges and Brahmaputra), where glaciers experience maximum accumulation in the summer due to high monsoonal precipitation and high elevations, periods of summer time ablation punctuate overall summer-long snow accumulation (Ageta and Higuchi 1984). Further, the Himalaya is a barrier to monsoon winds, causing maximum precipitation on southern slopes with a regional east to west decrease in the monsoon intensity (Shrestha et al. 1999) and hence, large local orographic control on climate. For instance, ASM provided low precipitation (21% of the annual sum) on the leeward side of the orographic barrier at Chhota Shigri Glacier (western Himalaya) and high precipitation (51% of annual total) on the windward side at Bhuntar city (~50 km south from Chhota Shigri) (Azam et al. 2014). Depending on their geographical position and regional orography, the glaciers in the Himalaya (IGB) are subjected to different climates. This variability of precipitation regimes along the Himalaya begets varying types and behaviors of glaciers over short distances (Maussion et al. 2014).

The intensity, timing, and magnitude of the monsoon precipitation vary from east to west, with the longest duration of monsoon and greatest amounts of precipitation in the east. In the eastern part of the region, more than three-quarters of all precipitation falls during the summer monsoon months from June to September (Nepal 2012), whereas the western area receives more than one-third of total precipitation in winter (Shrestha 2008). Snow is an important component of the hydrology of the Himalaya. Snow-cover dynamics in the high Himalayas and on the Tibetan Plateau, influence the water availability and timing in downstream basins, specifically in the spring at the onset of the growing season, but also in the fall after the monsoon season (Barnett et al. 2005; Kundzewicz et al. 2007; Lemke et al. 2007; Viviroli et al. 2007; Immerzeel et al. 2009; Bookhagen and Burbank 2010). Hydrological characteristics of IGB is presented in Table 21.2.

21.2.1 Glaciers and Snow

Himalayan mountains contain important natural reserves of frozen fresh water in the form of glaciers and snow. These glaciers are unique as they are located in tropics, high altitude regions, predominantly valley type and many are covered with debris. Today there are about 30 million km^3 of ice on our planet that covers an almost 10% of the World's land area. In the Himalayas, the glaciers cover

Table 21.2 Hydrological characteristics of Indus, Ganga and Brahmaputra

Parameter	Indus	Ganges	Brahmaputra
Catchment area (km$^{2)}$	**945,000**	**1,050,000**	**580,000**
River length (km)	3200	2500	2900
Average annual rainfall (mm)	415	1125	1350
Average annual discharge (m^3/sec)	7610	11,600	19,300
Annual sediment load at river mouth (million tons/year)	291	599	580–650
Sediment yield (million tons/km^2/year	0.3	0.61	0.85–1.12
No. of glaciers/area (km^2)	18,495/21000	7963/9000	11,497/14000
Snow coverage (annual Avg. %)	13.5	5	20
Contribution of snow melt (%)	>50	22	<25
Snow and glacier melt index	150	10	27

Source: Modified from Hasson et al. (2013), Sinha and Tandon (2014), and others

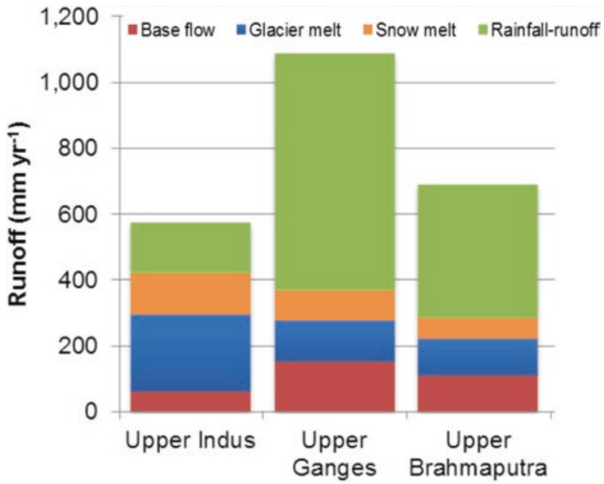

Fig. 21.2 Hydrological regime 1998–2007 in the upper IGB. (Lutz and Immerzeel 2013)

approximately 33,000 km^2 area and this is one of the largest concentrations of glacier-stored water outside the Polar Regions. IGB are originating from the glaciated Himalayan region where these rivers are fed by seasonal snow- and glacier- melt water. IGB is having 18,495, 7963 and 11,497 glaciers covering an area of 21,000 km^2, 9000 km^{2}and 14,000 km^2 (Bajracharya and Shrestha 2011) and 13.5%, 5% and 20% of average snow coverage (Gurung et al. 2011). Model suggested that Indus has the highest meltwater index as compared to Ganges and Brahmaputra (Table 21.2), (Immerzeel et al. 2010). The total annual glacier runoff (IGB) for the period of 1961–1990 was 41 km^3, 16 km^3 and 17 km^3, respectively. However, in the recent periods of 2001–2010, total glacier runoff was reduced to 36 km^3, 15 km^3 and 16 km^3, respectively (Savoskul and Smakhtin 2013). As is clear from the Fig. 21.2, glacier melt has highest importance in the upper Indus basin, while the contribution of glacier melt to total flow is very small in the upper Ganges and upper Brahmaputra. GRB and BRB are dominated by rainfall-runoff, followed by baseflow, however, baseflow contribution is just 10.8% of total flow in IRB. Continuous changes in surface temperatures and precipitation may have serious consequences glacier melt and rainfall-runoff relationships, e.g. drought and floods.

Role of glaciers in basin hydrology varies significantly in different mountain hydrological systems. Most of the interpretations are based in the conceptual framework of ‘Alpine catchment’ where most of the annual precipitation occurs as snow in the winter months. The melting of the winter snow persists through the summer season and together with the glacier melt, produces the seasonal high discharges. In such systems, glaciers are critical for the river flow, especially during the peak summer months (Fig. 21.3a). A ‘Himalayan catchment’ is significantly different from ‘Alpine catchment’ with the presence of monsoon coinciding with the temperature, melt and discharge peaks of the annual hydrograph. Hence the ‘Himalayan catchment’ is characterized by the peak glacier runoff contributing to the crest of the annual stream flow hydrograph from monsoon in July and August months (Thayyen and Gergan 2010), (Fig. 21.3b). Consequently, higher discharges in the headwater streams of the monsoon catchment could occur during the positive mass balance regimes of the glacier and reduced discharges associated with the negative glacier mass balance regimes. Third important glacio-hydrological regime of the Himalaya is the cold-arid systems, geographically situated in the Ladakh region of the trans-Himalaya (Fig. 21.3c). The seasonal precipitation distribution of these three dominant hydrological regimes of the Himalaya is shown in Fig. 21.4.

21.2.2 Discharge Characteristics of IGB Basins

The *discharge* of the *IGB rivers* are governed by a strong precipitation. The mean annual discharge of the Ganges at Bay of Bengal is more than 51,176 $m^3 s^{-1}$ and thus, occupies ninth position among the world’s largest rivers. Whereas annual discharge of Indus and Brahmaputra are 6600 $m^3 s^{-1}$ and 21,261 $m^3 s^{-1}$, respectively. Almost 80% of the mean annual flows of Indus and Ganges are confined to the summer months (April–September) with a peak in the month of August, due to snow and glacier melt as well as the monsoonal rainfall. However, the analysis of the observed discharge of Brahmaputra shows that more than 90% of the flows are confined to the high flow period (April-early November) with a mean maximum during mid-July. During the winter (October–March), the rivers of IGB experiences low flow conditions, because contributions mainly come from the snowmelt, winter rainfall and base flow. Water availability of different tributaries of IGB basins is shown in Table 21.3.

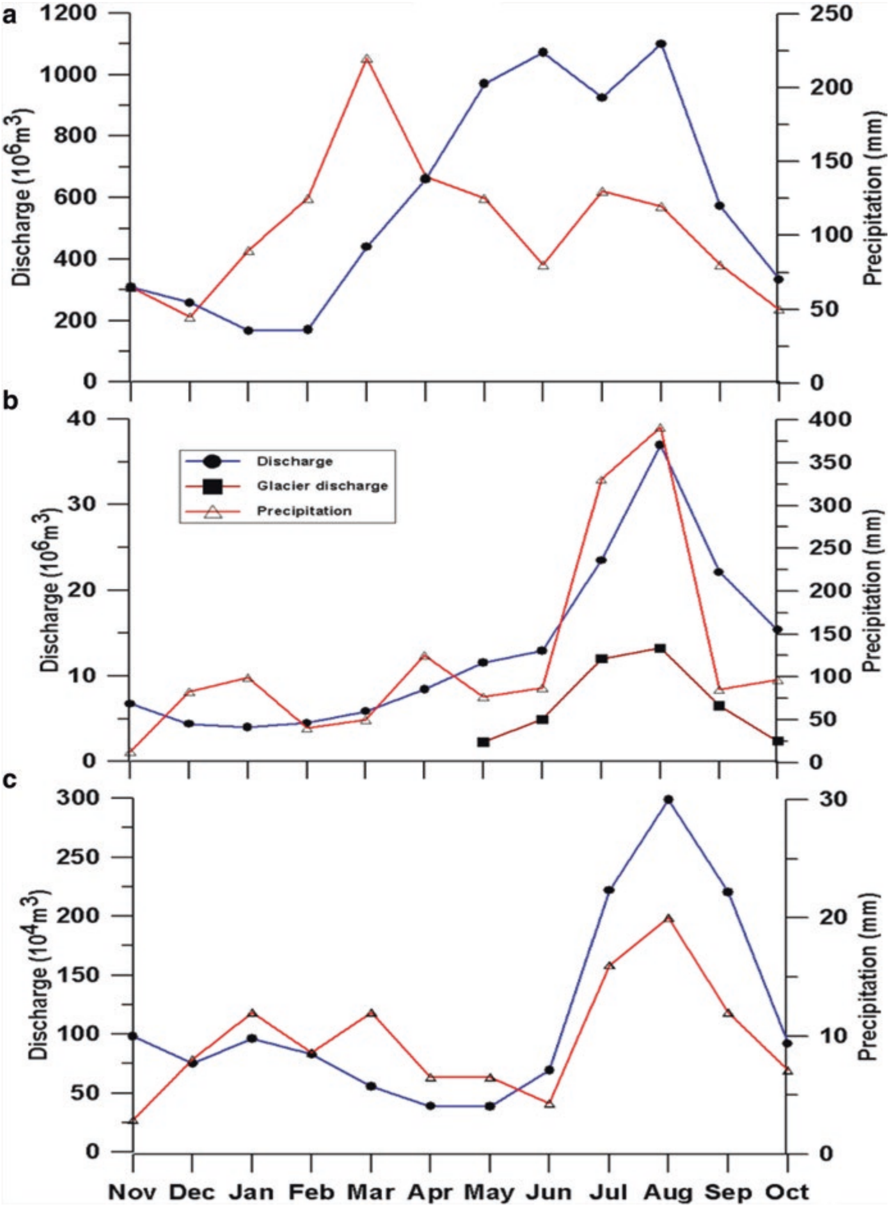

Fig. 21.3 Seasonal distribution of runoff in three hydrological regimes (**a**) Alpine catchment (peak glacier runoff contributes to other wise low flow period of annual stream hydrograph governed by lower precipitation in summer), (**b**) Himalayan catchment (characterized by the peak glacier runoff contributing to the crest of the annual stream flow hydrograph from monsoon in July and August months) and (**c**) Cold-arid catchment (annual discharge peak occurs in the month of July and August mainly from glacier/permafrost/snow melting at higher reaches during the period e.g. Ladakh region

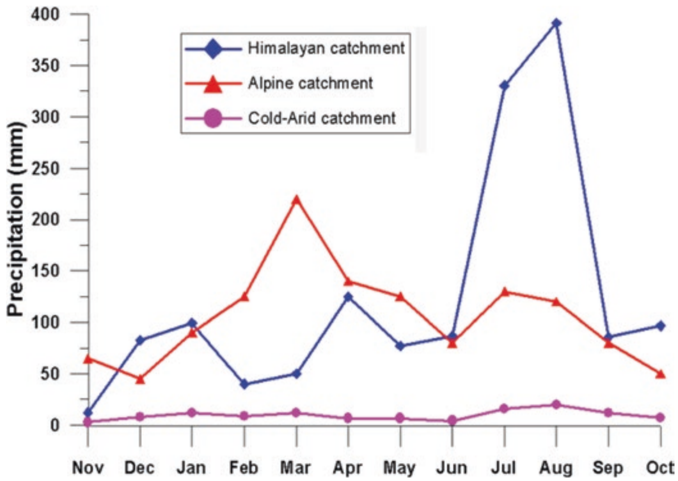

Fig. 21.4 Seasonal distribution of precipitation in the major hydrological regimes of the Himalaya. (Thayyen and Gergan 2010)

21.2.3 Sediment Transfer Characteristics of IGB Basins

Rivers and streams in the Himalayas carry sediment in their flows and transports from one part of the system to other (Lupker et al., 2012). Table 21.3 presents quantitative estimation of erosional budget/sediment yield for individual tributary of IGB and are useful in understanding the dynamics of movement, storage, or removal of water and sediment in systems. These estimates provide a framework for scientific analysis and a basis for policy decision and management. In case of a vast and dynamic alluvial river like the Brahmaputra, which exhibits a high variability in flow and sediment yield, changing boundary conditions of the channel, complex river morphology, and recurrent seismic instability in the basin region, the uncertainties involved in the estimation are significantly high. Yet, the studies compiled (Table 21.3) indicate useful results and prospects for further development.

Sediment in the Indus system is preferentially eroded from the western Tibetan Plateau and Karakoram (Clift et al. 2000, 2001). During summer, when snow melts, water discharge increases by 20–50 times and sediment load by 500–1000 times (Ferguson 1984). Eastern portion of the Himalayan Range is eroding faster than the western portion, which contributes to the Brahmaputra having a higher suspended load than the Ganges (Galy and France-Lanord 2001). The higher erosion in the eastern region is likely caused by higher precipitation in the eastern region (Fluteau et al. 1999; Galy and France-Lanord 2001). The sediment budget mentioned in Table 21.3 is mainly based on sediment yields at selected reaches on the main stem and at confluence points of tributaries. The Table 21.3 indicate that the Indus carries the highest amount of sediment per unit drainage area followed by Brahmaputra.

Table 21.3 Characteristics of annual average discharge and sediment yield of different tributaries of Indus, Ganga and Brahmaputra basin

Basin	Rivers/Station	Basin Area (km^2)	Avg. Annual discharge (m^3/s)	Sediment Yield (tons/km^2/year)
INDUS	Shyok (Yugo)	33,670	347.1[a]	754
	Shigar (Shigar)	6610	NA	2547
	Hunza (Dainyor)	13,157	338.6[a]	3375
	Gilgit (Gilgit)	12,095	281.9[a]	1008
	Gilgit (Alam Br.)	26,159	644[a]	2108
	Astore (Doyian)	4040	136.8[a]	401
	Gorband (Karora)	635	NA	1406
	Indus (Kharmong)	67,858	489.1[a]	496
	Indus (Kachura)	112,665	1069.1[a]	705
	Indus (Parlab Br.)	142,709	1775.8[a]	973
	Indus (Shatial Br.)	150,220	NA	709
	Indus (Besham Q.)	162,400	2412.2[a]	1345
	Kabul (Kabul City)	NA	247	4700
	Jehlum (Chinari)	13,775	330[b]	NA
	Jehlum (Kohala)	25,000	828[b]	NA
	Chenab (Akhnoor)	NA	8001	NA
	Ravi (Muksar)	NA	268	NA
	Beas (Mandi plain)	NA	499	NA
	Satluj (Ropar)	NA	500	NA
GANGES	Ganga (Garhmukteshwar)	29,709	660	766
	Ganga (Fatehgarh)	40,096	576	444
	Ganga (Ankinghat)	82,209	1015	366
	Ganga (Kanpur)	87,650	895	376
	Ramganga (Dabri station)	23,919	274	213
	Garra (Husepur)	6155	82	1262
	Ganga (Farraka barrage)	907,000	16,648	1235
	Gomti (Saidpur)	NA	234	NA
	Ghaghara (Revelganj)	NA	2990	NA
	Gandak (Sonepur)	NA	1760	NA
	Koshi (Kursela)	NA	2166	NA
	Tons (Dehradun)	NA	2827	NA
	Sone (Indrapuri)	NA	33,045	NA

(continued)

Table 21.3 (continued)

Basin	Rivers/Station	Basin Area (km^2)	Avg. Annual discharge (m^3/s)	Sediment Yield (tons/km^2/year)
Brahmaputra	Subansiri	27,400	755,771	959
	Ranganadi	2941	74,309	1598
	Burai	791	20,800	5251
	Bargang	550	16,000	1749
	Jia Bharali	11,300	349,487	4721
	Gabharu	577	8450	520
	Belsiri	51	9300	477
	Dhansiri (north)	10,240	26,577	379
	Noa Nadi	907	4450	166
	Nanoi	860	10,281	228
	Bamadi	739	5756	323
	Puthimuri	1787	26,324	2887
	Pagladiya	383	15,201	1887
	Manas-Aie-Beki	36,300	307,947	1581
	Chamramati	1038	32,548	386
	Gaurang	1379	22,263	506
	Tipkai	1.364	61,786	598
	Gadadhar	610	7000	272
	Burhi Dehang	4923	1,411,539	1129
	Disang	3950	55,101	622
	Dikhow	3610	41,892	252
	Jhanzi	1130	8797	366
	Bhogdoi	920	6072	639
	Dhansiri (south)	10,240	68,746	379
	Kopili	13,556	90,046	230
	Kulsi	400	11,643	135
	Krishnai	1615	22,452	13 I
	Jinari	594	7783	96

Note: [a]daily mean, [b]monthly mean

The conjoined Ganges-Brahmaputra River carries 80% of the sum of the loads and remaining 20% of sediment is diverted from the main river by the tributaries and deposited along the main river channel (Rice 2007). Sediment that reaches the Bay of Bengal is dominated by silt and clay, with 15–20% of the total discharge being fine to very fine sand (Thorne et al. 1993). An additional study shows that more than 76% of the bed sediments are within the fine to very fine sand class, and have a mean grain size between 177 μm and 62.5 μm (Datta and Subramanian 1997). The suspended load of a river carries the majority of the sediment, while bedload transport accounts for approximately 10% of the suspended load (Walling 1987).

21.3 Topography

The Himalayas are not a single continuous chain of mountains, but a series of several more or less parallel, or converging ranges, intersected by enormous valleys and extensive plateaus. Their width is between 250 km and 300 km (Sorkhabi 2010) and these comprise of many minor ranges. The individual ranges generally present a steep slope towards the plains of India and a more gently inclined slope towards Tibet. The Eastern Himalayas of Nepal and Sikkim rise very abruptly from the plains of Bengal and Uttar Pradesh and suddenly attain their great elevation above the snow-line within strikingly short distances from the foot of the mountains. But in the Western Himalayas, the rise in elevation is gradual across many cascading mountain ranges of lesser altitudes.

The topography of the Himalayas in the upper IGB is characterized by sudden rise of Shivalik from the Ganga plains which further rise up to Lesser Himalayas and connect to the Great Himalayan range with a steep slope. Some of the highest peaks of Earth such as the Mount Everest (8848 m), K2 (8611 m), Kanchenjunga (8586 m), Dhavalagiri (8167 m), Nanga Parbat (8126 m), Gasherbum (8035 m), Gosainthan (8013 m), Nanda Devi (7816 m), etc. are situated in the Great Himalayan belt with average elevation extending to about 7000 m. The average elevation in the Lesser Himalayas lies between 3500 m and 4600 m whereas lower foothills of Himalayas seldom exceeds the elevation range 900–1200 m (Fig. 21.5).

The varying elevations and slope profiles of each basins play significant role in determining the regional climate and hydrological responses as it critically influences both air and water circulations. As climate and hydrology of the Himalayas is dictated by the orographic nuances of the Asian monsoon in summer and westerly disturbances in winter months, precipitation dominant and shadow zones lay interspersed in the Himalayas. Sudden rise in elevation facilitates lifting of the moist air along the frontal band of Lesser and Great Himalayas resulting in excessive orographic precipitation. As a result, two discrete bands of monsoon precipitation exist which stretches along the length of Great Himalayan Range. The first orographic barrier is created through southward thrusting of Lesser Himalayas over the northernmost proximal edge of the Himalayan foreland basin resulting in a zone of high rainfall at a mean elevation of 0.9 ± 0.4 km and a relief of 1.2 ± 0.2 km (Bookhagen and Burbank 2006). A steep slope front along the boundary of the lesser and Greater Himalayas controls the location of another inner rainfall band at an average elevation of 2.1 ± 0.3 km and relief of 2.1 km.

There are numerous rain shadow zones in the Himalayas and the complex topography of that region create wet and dry regions side by side. Several studies (e.g., Bookhagen and Burbank 2006; Bookhagen and Strecker 2008; Shrestha et al. 2012) conducted on the distribution of rainfall with elevation in various regions of the Himalayas indicate a strong relationship between rainfall and elevation. Some studies (Dhar and Rakhecha 1981) show that no linear relationship exists between rainfall and altitude. However, other studies (e.g., Singh et al. 1995; Singh and Kumar 1997) have reported that there may be a continuous increase in precipitation with

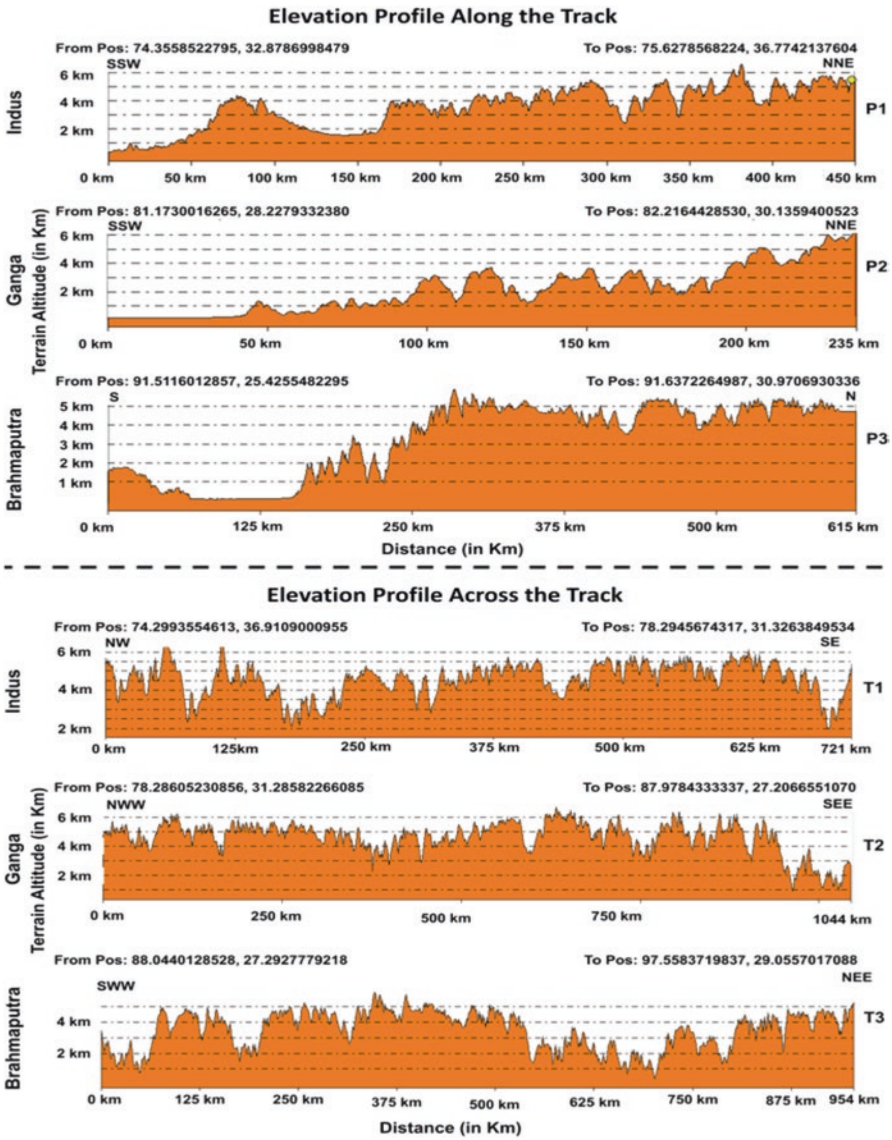

Fig. 21.5 Cross sectional slope progression of the Himalayas from the southern front of Indus, Ganga and Brahmaputra basins. (Slope progressions were extracted using hydrologically conditioned 3 arc-second SRTM DEM freely downloadable from HydroSheds (Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales) website (https://hydrosheds.cr.usgs.gov/dataavail.php)

altitude in the Himalayan region but precipitation begins to decrease above a certain altitude. Clearly, this relationship varies considerably with time and place.

21.4 Geology of IGB Basins

Active tectonics in any basin is an important forcing factor affecting the river channel dynamics, its sediment load, and morphology. Himalayas have common geological history but sharply varying geology across the elevations and latitudes. The geology of the Indus drainage is largely shaped by the collision between the Indian Plate with mainland Asia, starting at around 50 million years ago (Inam et al. 2007). Continued tectonic activity and erosion from the valleys has allowed the surrounding ranges to be uplifted to great heights. The drainage of the Indus is dominated by the Western Tibetan Plateau, Karakoram and tectonic units of the Indus Suture Zone. The Indus basin has variety of rock formations, which are continuously undergoing disintegration through glacio-fluvial action. Main central thrust separates lesser Himalayan rocks from higher Himalayas in north and main boundary thrust separates it from Siwalik in the south. Fracture zones, which are developed due to thrust, faults and other lineaments, are good locations for springs and promote groundwater recharge as well as control the drainage pattern. The Ganga basin in the Himalayan foreland forms one of the largest plains of the world over with ~450 million people dwelling in it. The plain evolved by deposition of huge piles of sediments over the basement within the down-warp between Himalayan Orogenic Belt in the north and Precambrian rocks of the Indian craton in the south (Shukla and Raju 2008; Sinha et al. 2009). The basement is marked with linear furrows, ridges and faults, lying obliquely to the Himalayan structural grains (Thakur et al. 2009; Jayangondaperumal et al. 2010; Goswami 2012). These oblique trending basement structures divide the basin into several tectonic blocks (Hazarika et al. 2010; Dasgupta et al. 2013). In many cases, the blocks act as half-grabens with differential uplift and bending. BRB shows significant difference in fluvial dynamics. The vast tract of Brahmaputra valley developed between the Arunachal Himalaya, the Naga-Patkai range of hills and the Shillong plateau is a typical fluvial terrain with a mosaic of numerous minor fluvial landform features. The valley has developed through alleviation over a sequence of Cenozoic sediments which again overlie a basement that has developed a structural high nearly coinciding the flow path of the Brahmaputra. The BRB consists mainly of Holocene floodplain deposits, underlain by poorly consolidated or unconsolidated tertiary and quaternary sediments.

21.5 Major Landuse in the IGB Basins

The forest cover in the IGB Basins are only 4%, 8% and 15% whereas major part of basins are covered with snow and glacier (75%, 53% and 74%), respectively. Moreover, second major part of the IRB and GRB are agriculture, however, forest cover is the second landuse in BRB (Table 21.4). Forest cover is declining in all three basins; overgrazing and deforestation to make room for cultivation and human settlements are common in Indus and Ganges Basin, however, shifting cultivation, is widely being practiced in the hills and foot hill regions of Brahmaputra basin. Nowadays, some part of land in Indus and Ganges are used for other economic uses which consists of mineral exploitation or construction of human settlements, industrial structures, roads, railways, airports and other civil works. On the other hand, grasslands are today broken up by vast tracts of tea plantations and human habitation in Brahmaputra basin.

Quantifying effect of land-use change on water resources is a challenge in hydrological science. The land use/cover changes from forest to other uses have been widespread in the past several decades in the Himalayan region (Batar et al. 2017). Such changes in land use/cover lead to environmental degradation through soil erosion, change in discharge, evapotranspiration etc. Agricultural land area has increased considerably over the past four decades in the Himalaya at the costs of other land uses, particularly forests (Sharma et al. 2007). The forest-dominated watersheds are consequently converted into agrarian watersheds where discharge, sediment and nutrient losses are accelerated. The study conducted by Younis and Ahmad (2017), concluded that as built-up area increase up to 40% from the year 2000 to 2010, which also increases the discharge to 33%, and confirms that LULC change affects discharge values of watersheds of Indus basin. Similarly, Chawla and Mujumdar (2015), analyzed the change in landuse land cover in the Ganges basin and observed that from 1973 to 2011, there was an increase in crop land and urban area by 47% and 122% and decline in dense forest from 14% in 1973 to 11% in 2000), a slight increase in dense forest (11.44–14.8%) between 2000 and 2011, respectively. The results showed that the change in landuse significantly increased

Table 21.4 Landuse landcover distribution of IGB

	Indus		Ganga		Brahmaputra	
Landuse	km^2	%	km^2	%	km^2	%
Built up land	6701	0.6	36,908	2.1	3163	0.4
Agricultural	115,005	10.1	564,866	31.4	50,375	6.9
Forest	48,481	4.2	137,817	7.7	107,854	14.7
Grassland	13,473	1.2	7324	0.4	8531	1.2
Wasteland	91,651	8.0	76,604	4.3	10,117	1.4
Waterbodies	5935	0.5	29,877	1.7	11,266	1.5
Snow/glacier	860,160	75.4	944,978	52.5	543,725	74.0
Total	1,141,406	100.0	1,798,374	100.0	735,031	100.0

Source: CWC and NRSC (2014)

peak discharge and evapotranspiration by 77% and 42% from 2011 to 1973. Likewise, Tsarouchi et al. (2014), also found effect of land cover change in change in hydrology of Ganges basin from 1984 to 2010. On the other hand, the Brahmaputra basin (especially upper Brahmaputra basin) is one of the worst flood-affected areas in India. River dynamics of Brahmaputra basin changes landuse land cover (LULC) significantly especially agriculture due to flooding, leads to changes in the sediment flux and other hydrology of the basin (Hazarika et al. 2015). Therefore, number of studies on forested watersheds provided situations from macro to micro scales of IGB. Sustenance of watershed functioning in the IGB needs substantial support from various approaches and promotion of forests and agroforestry practices in combination with rehabilitation of degraded lands and better land husbandry could provide hydrological benefits for both upstream and downstream users.

21.6 General Climate of the IGB Basins

The climate of IGB ranges from tropical at the base of the mountains to permanent ice and snow at the highest elevations. The average annual precipitation in the IGB basins are 415 mm year^{-1}, 1125 mm year^{-1} and 1350 mm year^{-1}, respectively (CRU 2012; Hasson et al. 2013). Variation in rainfall across the basins are considerable, particularly between the upper and lower basins (Turner and Slingo 2009; Bera 2017). The upper IRB receives nearly 500 mm year^{-1}, whereas the lower basin receives just under 300 mm year^{-1}. Although there is not much difference between the annual amount of precipitation in the lower and upper parts of the GRB. In contrary to IRB, the lower BRB receives approximately 2216 mm year^{-1} of rain annually, which is over three times more than the upper basin. Overall, the upper IRB and GRB basin experience more rainy days (132 and 179) in a year, compared to their lower basins (84 and 152 days). However, upper Brahmaputra basin experiences less number of rainy days (164) in a year as compared to lower basin (214 days). There are two sources of precipitation in the IGB; monsoon (July–September) and westerly (December–March), (Bookhagen and Burbank 2006). The hydrological regimes of the IGB is dominated by the monsoon system and its contribution is about 55% (I), 84% (G), and 70% (B) (Kripalani et al. 2007; Sabade et al. 2011; Hasson et al. 2013; CWC-NRSC 2014) and westerly contributes about 45% (I), 16% (G) and 30% (B), respectively. Deka et al. (2013), Bera (2017), Latif et al. (2018), observed large spatial and temporal variability in the annual and seasonal rainfall trends in IGB. The increase in rainfall intensity, changes in rainfall patterns, and greater frequency of extreme rainfalls (Turner and Slingo 2009) likely to aggravate flooding problems within IGB whose early signs are visible now.

Temperature plays important role in IGB in several ways. Over the past decades and across the IRB, winters are getting warmer, but summers are getting cooler. However, extreme hot days are getting hotter and extreme cold days are getting milder. On the other hand, in GRB, winters are getting warmer, but summer average temperatures have remained constant. Summer extremes are becoming more intense, while winter extremes are showing mixed trends across the basin. Nevertheless, in BRB, temperatures are changing over time and showing mixed trends across the seasons and in different areas of the basin. The average maximum temperatures of IGB are about 30 °C, 30.3 °C and 19.6 ° C in summer and 13 °C, 21.1 °C and 9.2 °C in winter. Average minimum temperatures range from 18 °C, 21.5 °C and 18.3 °C in summer to −0.3 °C, 6.4 °C and − 0.3 °C in winter. Over last decades, average maximum temperatures of Indus basin have slightly decreased (0.5 °C), while minimum temperatures have increased (1.2 °C) in the winter. On the other hand, there has been no significant trend in terms of changes in maximum temperatures, but there has been rise of 0.7 °C and 0.5 °C in average minimum winter temperature across the GRB and BRB.

21.7 Precipitation (P), Evaporation (E) and Potential Evapotranspiration (PET) over the Basins

The mean annual cycle of the P, E, and PET over the IRB, GRB, and BRB is presented in Fig. 21.6. It can be observed that monthly P values from ERAI tend to be slightly greater than those computed from CRU, but the annual cycle is the same. These differences are best appreciated in the annual cycle of P over the BRB. In the IRB, the P annual cycle is characterized by two maximum peaks in February–March and July–August (Fig. 21.6a). The E approximately follows this cycle but with lower values. In IRB basin, the PET remains higher than the P and E across the year; in fact, Cheema (2012), argue that the major part of this basin is dry and located in arid to semiarid climatic zones. Laghari et al. (2012), also found for the climatology from 1950 to 2000 that PET exceeds P at the IRB across the year. PET is enhanced after maximum precipitation; maximum values occur in May–June. Over the GRB maximum P occurs between May and October and is greater than over the IRB (Fig. 21.6b, c). The PET and E annual cycles over this basin differ, and as expected, PET > E. The PET annual cycle is mainly like for the IRB. Indeed, both variables reflect close but different information. The E annual cycle agrees with that obtained by Hasson et al. (2014), for the three river basins. Over the BRB, the monthly average precipitation both from CRU (Climatic Research Unit) and ERA-I increases abruptly from March until a maximum (> 11.0 mm day^{-1}) in July and later falls until a minimum is reached in December (Fig. 21.6c). The PET and E are very close and do not surpass 4 mm day^{-1} in the annual climatology. In particular, the PET annual cycle is notable for being lower than what was obtained for the IRB and GRB. The annual cycles of P (from CRU and ERA-I) and E for the IRB, GRB, and BRB follow the same annual cycle as those obtained by Hasson et al. (2014). These authors analysed the seasonality of the hydrological cycle over the same basins for the twentieth century climate (1961–2000 period), utilizing PCMDI/CMIP3 general circulation models (GCMs) and observed precipitation data.

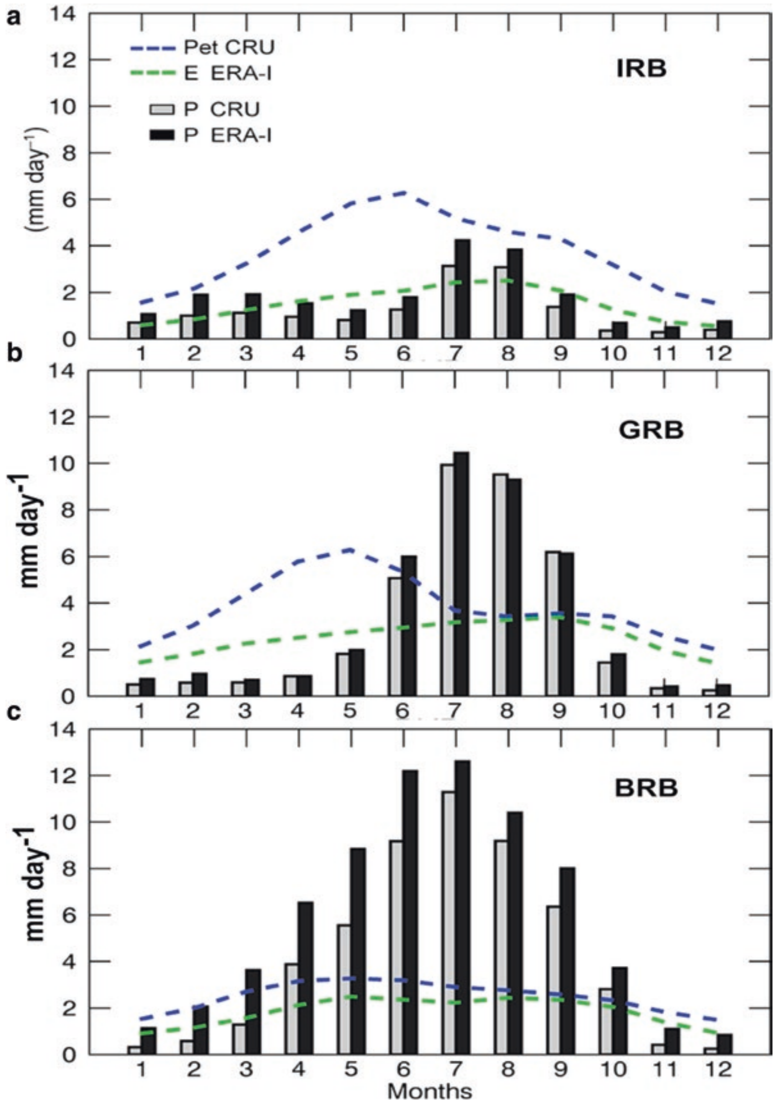

Fig. 21.6 The 1981–2015 annual cycle of precipitation (gray, black bars from CRU and ERA-I, mm day−[1]) and potential evapotranspiration (blue line from CRU, mm day−[1]) and evaporation (green line from ERA-I, mm day−[1]) over the Indus (**a**), Ganges (**b**), and Brahmaputra (**c**) river basins from CRU 3.24.01. (Sori et al. 2017)

21.8 Climate Change Impact on IGB Basins

Impacts of Climate change (CC) on hydrological regimes vary from basin to basin. CC have potential impact on hydrological processes including precipitation, evapotranspiration, overland flow, streamflow (volume, timing, frequency and magnitude), infiltration, groundwater flow, soil erosion and transport, water temperature, snow and glacier change. The results of such hydrological changes would affect almost every aspect of life i.e., agricultural productivity, water supply for urban and industrial use, power generation, wildlife and biotic ecosystems, sedimentation, plant growth and nutrient flow into water bodies (Zhang et al. 2007). Climate change is also expected to have significant consequences on snowmelt and glacier runoff across the Himalayan region. Our knowledge of high-altitude snow/ice and its response to climate is still incomplete (Azam et al. 2018; Brun et al. 2017). Understanding the present hydrological, climatological and glaciological processes of high elevation catchments is thus vital. This requires better insights into the present composition of runoff and interactions between climate, glaciers, snow and soil. Climate change impacts of IGB basins is divided into following two sections:

21.8.1 Observed Impacts

The cryosphere of the Karakoram and the Greater Himalayas, source of the headwaters of all major rivers of IGB, is highly susceptible to climate change. Degradation of perennial snow covers by thinning, retreat, and negative mass balance of glaciers or ice losses have been widely observed in the Himalayas (Azam et al. 2016, 2018; Brun et al. 2017). Compared to such prevalent losses of the cryosphere in the Himalayas, several reports suggest glacial stability or even positive glacier mass balance in the Karakoram (Hewitt 2005; Gardelle et al. 2012, 2013; Zhou et al. 2017; Bolch et al. 2017). However, glacial growth and stability is not ubiquitous throughout Upper Indus sub-basin (Kaab et al. 2012). Glacierized watersheds of upper IRB show that in the central and eastern Karakoram glacier, mass balance is negative whereas in the western Karakoram it is positive (Mukhopadhyay and Khan 2014a, b, 2015). Such findings have made the prediction and assessment of impacts of climate change on the future of the Upper IRB and associated flows downstream very uncertain.

Climate change is also altering ecosystems of the GRB largely through changes in water quantity, water quality as well as changes in biodiversity (Hosterman et al. 2009). Reduced flows to the Sundarbans wetland ecosystem have resulted in salinity intrusion in the south-western part of Bangladesh, loss of biodiversity, and loss of ecosystem functionality (Islam 2016). Due to increase in temperatures of GRB, resulting in retreat of glaciers, increase variability in precipitation, increased magnitude and frequency of droughts and floods; and leads to sea level rise (Hosterman et al. 2009). Droughts, floods and other extreme events results in scarcity of water and food which further leads to displacement of populations, loss of livelihoods, communicable disease and malnutrition (Menne and Bertollini 2000). Increased runoff from glacier retreat and ice/snow melt could increase annual discharge into the GRB in the short term, followed by the reduction of runoff in long term (Barnett et al. 2005). Changes in precipitation pattern, glacial retreat and increased sedimentation may adversely affecting dam storage capacity and hydropower generation in GRB and its tributaries (Hosterman et al. 2009). Climate change also has significant impact on fresh water storage (glacial snow covered regions) at high elevations and fresh water runoff to low elevations (Jianchu et al. 2007).

Numerous studies also have assessed climate change impacts on hydrological processes in the BRB, e.g. temperature (Immerzeel 2008; Shi et al. 2011), precipitation (Kripalani et al. 2007), snow (Shi et al. 2011), streamflow (Gain et al. 2011; Jian et al. 2009), groundwater (Tiwari et al. 2009), runoff (Ghosh and Dutta 2012; Mirza 2002), extreme events (Rajeevan et al. 2008; Webster and Jian 2011), and even water quality (Huang et al. 2011). However, a few studies have assessed how projected changes in climate and land use and land cover could impact long-term patterns in the basin's hydrological components. Some studies e.g. Flugel et al. (2008) and Immerzeel (2008), suggests a consistent rise in average and seasonal temperatures over the last 50 years, and the projections indicate that the temperature will continue to rise, although the magnitudes of the projected changes differ depending on the driving models.

21.8.2 Future Implications/Changes

The potential impact of climate change will be more evident in future in the Himalayan region, where the runoff is dominated, largely, by glacier melt and snowmelt (Viviroli et al. 2007; Immerzeel et al. 2013; Lutz et al. 2014b). Climate change and rising temperature will increase annual runoff by 7–12% by 2050 due to accelerated melt in the upper IRB together with an increase in precipitation (Lutz et al. 2014a). However, the projected future hydrology depends on the precipitation projections which have a large uncertainty and large variation between annually averaged and seasonal projections among the General Circulation Models (GCMs). IRB may lose up to 8.4% of its total water resources by 2050 and Pritchard (2017), showed that glacier melt is a critical buffer at the time of drought in the whole Asia including all Himalayan basins. Nepal et al. (2014), estimated that the contribution of snow melt to river flow in the Dudh Koshi catchment would decrease by 31% with a 2 °C rise in temperature, and by 60% with a 4 °C rise, changing the river from 'snow-dominated' to 'rain-dominated'. Wiltshire (2014), suggested that under a warming climate, the volume of glaciers in the eastern Himalayas (Nepal and Bhutan) will decline over the twenty-first century, despite increasing precipitation, as a result of less precipitation falling as snow as well as increased ablation. Application of the water balance model in the Tamor catchment suggested an annual decrease in runoff up to 8% for a 5 °C temperature increase (Sharma et al. 2000), however, the study did not take glacier melt into account. All these studies suggest that a rise in temperature will affect the snow/glacier melt pattern and annual runoff. The predicted decrease in the water flows of the IRB will have serious consequences for India and Pakistan which receive 63% and 36% of its water. Per capita availability of water in the IRB has suffered a 70% decline during the past few decades.

Demographic trends in both India and Pakistan are fraught with ominous consequences for the water sector with serious impacts on their food and energy security. In India, per capita water availability stood at 1539 m^3 in 2011. Demographic changes during the future will further aggravate water scarcity.

A study by Immerzeel et al. (2010), projected a decrease of 17.6% in mean upstream water supply in the GRB, with the reduction in melt runoff partly compensated for by increased upstream rainfall (+8%). Immerzeel et al. (2013), suggested that under projected climate change, the glacier area in the Langtang catchment will be reduced by 54% by the end of the century and the ice volume by 60%. Initially, net glacier melt runoff will increase, with a peak in 2045 and 2048 for RCP 4.5 and RCP 8.5, respectively, after which it will decrease. However, water availability is not likely to decline during this century as the reduction in runoff will be offset by an increase in precipitation. Lutz et al. (2014b), found that the runoff (Koshi River basin, eastern Nepal) is likely to increase up to 2050, primarily due to an increase in precipitation in upstream areas, with the maximum increase during the pre-monsoon period, but the hydrograph remains unchanged. These studies indicate that the future reduction due to melt runoff of GRB will be offset by increased precipitation.

Many tributaries of BRB are flashy in nature, which increase the chance of significant damages due to extreme events. During the last 10 years, the river has seen some of the most destructive floods in its history. During 2009 and 2012 flooding, thousands of people died and 2.2 million people were forced to evacuate their homes as monsoon rains inundated large areas. Ghosh and Dutta (2012), revealed that although the number of flood events would decrease in future (2010–2100), the peak discharge and duration of the floods would increase. Gain et al. (2011), predicted a very strong increase in annual peak flow for the river, which may have severe impact on flooding. Immerzeel et al. (2010), estimated that the discharge generated by snow and glacier melt is 27% of the total discharge naturally generated in the downstream areas of the BRB. The study by Immerzeel et al. (2010), for 2046–2065 projected a decrease of 19.6% in mean upstream water supply, with the reduction in melt runoff partly compensated by increased upstream rainfall (+25%). Prasch, et al. (2011), suggested that glacier ice melt will accelerate from 2011 to 2040 due to the increase in air temperature and longer melting periods and that as the amount of glacier ice is reduced, ice melt will decrease. Lutz et al. (2014b), in their investigation projected an increase in total runoff in the upper BRB up to 2050, primarily due to an increase in precipitation and accelerated melt runoff, with the increase occurring throughout the year. Mirza (2002), projected a substantial increase in mean peak discharge in the BRB (although less than in the Ganges), based on climate change scenarios from four GCMs, which could lead to more frequent flooding of different magnitudes. Gain et al. (2011), indicated that there will be a strong increase in peak flows, both in size and frequency, although dry-season conditions are likely to increase. Thus, number of authors have looked at intra-annual variation and the impact of climate change on flooding and other negative impacts on basin. The results from various studies and their quantitative analysis (hydrological impact on climate change) are helpful for better understanding of potential hydrological risks for future water management planning.

21.9 Challenges in Water Resources Management in IGB Basins

21.9.1 Methodological Challenges

There are number of methods to analyze the runoff components from rainfall, melting of snow and glaciers including water balance analysis (Thayyen et al. 2005; Kumar et al. 2007), glacier degradation from observation or modelling as a contribution to runoff (Kotliakov 1996; Kaser et al. 2010), isotopic investigations (Dahlke et al. 2013) and hydrological modelling (Hagg et al. 2007; Naz et al. 2013). However, the water balance method can only estimate the effects of glacier and snow at monthly or larger time scales; additionally this method cannot separate snowmelt and ice melting on glaciers. Isotopic investigation cannot be widely used as it demands large financial and laboratory support. However, the application of hydrological models to understand the glacier effects in hydrology is relatively new (Hagg et al. 2007; Huss et al. 2008; Koboltschnig et al. 2008; Prasch 2010; Nepal et al. 2013). A practical challenge is the lack of long-term good quality data to represent the hydrological dynamics of Himalayan rivers. Moreover, the rainfall-runoff models rarely describe the snow and ice melting (Singh and Singh 2001) and glacier dynamics (Naz et al. 2013) at basin scale. Physically based models, are likely to produce more realistic results because they depend less on parameter calibration and their parameters have a physical basis. All models, including physically based ones, have parameters that need to be estimated or identified through calibration (Foglia et al. 2009). Appropriate calibration is a key issue in modern hydrological science, and much attention has been recently devoted to it.

In the Himalayas, fieldwork is difficult due to the tough terrain, remoteness of glaciers as well as logistical, financial and political obstacles. For this reason, in recent years the focus has been on remote sensing approaches used to reconstruct snow cover, frontal and areal changes of glaciers and ice volumetric changes (Gardelle et al. 2013; Kaab et al. 2012; Shangguan et al. 2014). However, in the light of possible changes in the snow-glacier-energy balance due to climatic changes, there is a strong call for more in-situ measurements across the Himalayas and models that integrate those data in space and time (Azam et al. 2018; Cogley 2012; Reid and Brock 2010). Local processes and effects that are difficult to study using remotely sensed data could explain regional differences and temporal changes in glacier mass balance across the region, such as the glacier expansion in the central Karakorum known as the ‘Karakorum anomaly’ (Hewitt 2005). Glacio-hydrological models are indispensable tools to study these effects and to understand the characteristics of a catchment and its response to climate change. Their applicability in high elevation regions is restricted due to: (i) the lack of representative data to force the models (Huss et al. 2014; Pellicciotti et al. 2014), (ii) simplifications in model structure due to insufficient process understanding and the scarcity of detailed information about glacio-hydrological processes (Huss et al. 2014) and (iii) parametric uncertainty due to insufficient quality or paucity of data for model calibration and validation (Ragettli et al. 2013).

21.9.2 Disaster Challenges

Due to its physical setting, the IGB region is prone to various water-induced hazards (landslides, floods, glacial lake outburst floods, and droughts). Every year, during the monsoon season, floods wreak havoc on the mountains and the plains downstream. These floods are often trans-boundary. Globally, 10% of all floods are trans-boundary, and they cause over 30% of all flood casualties and account for close to 60% of all those displaced by floods. The social and economic setting of the region makes its people more vulnerable to natural hazards. Lack of supportive policy and governance mechanisms at the local, national and regional levels, and the lack of carefully planned structural and non-structural measures of mitigation lead to increased vulnerability.

21.9.3 Energy Challenges

Energy is one of the most important pillars of sustainable development and hydropower is one of the most promising environmentally friendly sources of energy of the IGB. The varying estimated potential Hydro-electric Power (HEP) figures for India is 45, 635 MW, Nepal is 83,000 MW and for Bhutan is 21,000 MW. Moreover, innovative solutions such as electric transportation and a clean source of domestic and industrial energy supply would significantly improve the deteriorating environmental condition of the region. However, many countries in the region have been able to tap only a small fraction of their available potential. Still, people in these countries face many hours of scheduled power cuts. Major causes are lack of cooperation among nations, politicization of the water resource development and management aspects, prolonged negotiations, disagreements on the location of dams, reservoir safety, resettlement and rehabilitation issues, environmental concerns, cost and benefits sharing, etc.

21.9.4 Water Quality Challenges

Water quality has witnessed progressive deterioration due to growing urbanization and industrialization. The increased use of agrochemicals, discharge of untreated domestic sewage and poor sanitation facilities have aggravated the problem of water pollution. The optimum utilization of the water resource, effective management to meet the multi-sectoral uses, enhancing the efficiency of water utilization, technological modernization, checking pollution and inter countries cooperation are the major challenges for maintaining water quality in the IGB basins.

21.9.5 Environmental Challenges

Water plays a vital role in maintaining different ecosystem services in riparian areas. Freshwater ecosystems in particular largely depend on the specific flow regime of rivers passing through them. However, due to intervention of infrastructure development, the flow regime changes in the downstream areas, where, in many cases, communities depend on water resources for livelihoods such as fishing. A major concern is how to make sure that a certain minimum flow is maintained so as to sustain freshwater supply and support dependent ecosystems. There is very weak monitoring of the minimum flow requirement in the region.

21.9.6 Food Challenges

Water and food share a strong nexus, both being essential ingredients for human survival and development. Agriculture is a major contributor to many countries of IGB. The Indus river system is a source of irrigation for about 144,900 hectares of land, whereas the Ganges basin provides irrigation for 156,300 hectares of agricultural land. Access to water resources for food production and their sustainable management is a concern from the local to national level. Amid rapid environmental and socio-economic changes, the growing population will require more water and food, and equitable access to vital resources has become a major question. Sustainable solutions to these problems require efficient use of water resources for agricultural use in which technological innovation plays a vital role.

21.9.7 Other Challenges

Construction of new projects is becoming progressively more tedious due to concerns about submergence of forests, siltation of reservoirs, fragmentation of rivers, loss of biodiversity, displacement of population etc.

21.10 Floods and Droughts

Floods and drought have been observed to cause a gradual increase in human suffering and damage to property as well as increased loss of life and economic costs (Doocy et al. 2013). The frequent occurrence of droughts and floods in the IGB regions also has had huge impacts on regional food and energy security (Webster et al. 2011). During the summer monsoon months (June–September), the IGB experiences severe floods; and frequency and magnitude of floods generated in one country affect another country, and erosion in one country can deposit sediment in another. Therefore, floods are not only linked to single country/stateproblem but is also linked to trans-boundary internationally. Future hydrological extremes, such as floods and droughts, may pose serious threats for the livelihoods in the upstream domains of the IGB (Mirza 2011; Lutz et al. 2016). A recent study, assessing the impacts of climate change on hydrological regimes and extremes in the Upper IRB, showed that, in general, summer peak flow will likely shift to other seasons, and projected an increase in the frequency and intensity of extreme discharge conditions (Lutz et al. 2016). Another study projected increases in heavy precipitation indices during monsoon period, accompanied with extended periods of no precipitation during the winter months, in the GRB (Mittal 2014). Hence, the cited study (Mittal 2014) indicated an increase in the incidence of extreme weather events over the first half of the twenty-first century. Studies performed on global flood risk show similar patterns (Hirabayashi et al. 2008, 2013; Pechlivanidis et al. 2016). Significant increasing trends in high flows (i.e. 10 percentile exceedance discharge) were found in the GRB with relative increases up to about 100% (Pechlivanidis et al. 2016). Thereby, the changes in high flows were projected to be more significant than the changes in low flows (i.e. 90 percentile exceedance discharge). Assessments on future flood and drought frequencies shows that a future 100-year flood will occur once in 26.1 years and 3.8 years, respectively, at the end of the twenty-first century in the IGB basins (Hirabayashi et al. 2008). Furthermore, the average number of drought days were found to increase by a factor 1.17 and 4.05 in the IGB basins, respectively (Hirabayashi et al. 2008). It is difficult to compare the magnitude of absolute and relative changes in discharge levels because different studies have used different climate forcing and approaches to investigate impacts of climate change, precipitation, temperature, landuse cover etc. on hydrological extremes (i.e. floods and drought).

21.11 Research Gaps

- One of the greatest areas of uncertainty in Himalayan science remains how changes in glacier melt will affect river discharge over coming decades. Naturally, there will be variability within and between river systems in each basin; but these data are in agreement with previously published findings that allay water shortage fears, at least in the short term. Perhaps what they do less well, simply because of the broad-scale nature of the assessment, is to assess how these projections change with increasing distance from the source. This remains a major data gap for the discipline to address in coming years.
- The last decade has seen a proliferation of research focusing on Himalayan climate, glaciers, water resources, and related policy, but rarely these disciplines are considered together in a single volume.
- The need for more research in the Himalayas can hardly be overstated. It is known the mountain range is being badly affected by deforestation, habitat loss and global warming, and its ability to act as Asia's water tower over the long term is increasingly in doubt. But there are serious data gaps whenever scientists and policymakers look at the ecology of the world's highest mountain range.
- Research methodology is a way to systematically solve the research problem, but ongoing research gaps are also due to methodological challenges e.g. (a) lack of standardized image analysis, (b) limited field validation data (c) lack of accurate elevation data for remote glacierized areas (d) algorithms for automatically discerning debris-covered ice from non-ice areas with debris, etc.

21.12 Summary

The Himalayan Mountain chain which is the third-largest deposit of ice and snow in the world, serves as an important source of freshwater for the 1.3 billion population living in the lowlands of river basins of Indus, Ganga and the Brahmaputra (IGB) covering eight countries (Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan). Influence of Himalayan cryosphere is very significant in headwater tributaries of these river basins. While glaciers occupy high elevation uninhabited areas and water runs through deep gorges, seasonal snow cover spread over a much large mountain area also plays a significant role in the livelihood of the people through river runoff. Understanding of the timing and relative contribution of individual components of the hydrological cycle and water resources characteristics across the Himalayas is limited. In the upstream domains of the IGB, where mountain-hydrological processes are important, the number of studies on extremes is very limited. Although there are some studies conducted about high flows but they does not take the effects of climate change on low flows into consideration. Estimates of the ice volume and ice thickness is mostly lacking for the glaciers in this region. Advances in knowledge of Himalayan springs, geology, sediment transfer etc. is limited due to inadequate investigations and lack of synthesis of existing information. Therefore, this chapter presents outcome of an extensive review of available knowledge about the hydrology of IGB river basins. The chapter also identifies and discuss the knowledge gaps in the current understanding of hydrology for this region. Many factors that are considered important in managing Himalayan water resources have been identified and discussed. Observed and future implications of climate change impacts in IGB has also been discussed in detail. **Major findings discussed in the chapter are as:**

- Temperatures across the Himalayan region will increase by about 1–2 °C (in some places by up to 4–5 °C) which will result in increase of annual runoff by 7–12% and IRB may lose up to 8.4% of its total water resources by 2050.
- Glaciers will continue to suffer substantial ice loss, with the main loss in the Indus basin.
- Precipitation will change with the monsoon expected to become longer and more erratic.
- Extreme rainfall events are becoming less frequent, but more violent and are likely to increase in intensity.
- Communities living immediately downstream from glaciers are the most vulnerable to glacial changes.
- Despite overall greater river flow projected, higher variability in river flows and more water in pre-monsoon months are expected, which will lead to a higher incidence of unexpected floods and droughts, greatly impacting on the livelihood security and agriculture of river-dependent people.
- Changes in temperature and precipitation will have serious and far-reaching consequences for climate-dependent sectors, such as agriculture, water resources and health.

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