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Water Resources of Indian Himalayan Region (IHR): A Synthesis in the Context of Climate Change

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Abstract
Water next to air is one of the most crucial elements in our national developmental planning for the 21st century.Proper management of our limited water resources is essential for ensuring enhanced food security for our growing population and to maintain ecological health at its best. So, efforts are essentially needed to map, monitor and assess the water resources of IHR in changing climate and socio-economic scenarios. Regular time bound physical assessment of surface and ground water and water derived from snow and ice, physical infrastructure of water resources, institutional arrangements and water governance system is of prime importance to identify impact of climate change in the Himalayan region. Through this review paper we tried to take stock of water resources of IHR to collect the information, status and projected impacts on water resources due to changing climate and presented selected facts regarding water availability, groundwater development, glacier melt, trends of temperature over IHR and their cascading impacts on river discharge, springs and hydropower generation. Aim of this paper is to identify potential changes in water resources system of IHR which will help in framing possible response strategies to conserve and manage water resources of IHR in coming future.

Introduction

Indian Himalayan Region (IHR) (Figure 1 and Table 1) spans over 5.37 lakh km^2 between 21^{o}57'– 37^{o}5'N and 72^{o}40'– 97^{o}25'E, and isprosperous with water resources and biodiversity. It covers nearly 16.2% of the total geographical area of the country and houses nearly 4% of the country's population (G-SHE 2018). Nearly 17% area of IHR is under permanent snow cover and glaciers, and about 30-40% under seasonal snow cover. As per the inventory, there are 9,575 glaciers in the Indian part of Himalaya, out of which the Indus basin houses 7,997 and the Ganga Basin (including the Brahmaputra basin) has 1,578 glaciers located across five states of India, namely Uttarakhand,Himachal Pradesh, Jammu and Kashmir, Sikkim and Arunachal Pradesh (Joshi *et al.,* 2015). Every year around 12,00,000 million m^3 water flows through the Himalayan rivers (Singh, 2006). This region not only holds a key strategic position but also regulates climate of the South-Asian region (Sharma *et al.,* 2015).

The Himalaya, in recent decades, experienced a high population pressure (local as well as floating population), unsustainable changes in land use and over-exploitation of natural resources, e. g. water resources (Viviroli and Weingartner 2003; Tiwari and Joshi 2005). Perhaps, all the IPCC reports predict large-scale changes in temperature and precipitation over the IHR region and therefore IHR and its dependent ecosystem is highly vulnerable to the impacts of climate change in near future. Impacts that have broader regional implications are food security, livelihood improvement, poverty alleviation and even civil security (Xu*et al*., 2007). It is therefore imperative to take stock of water resources of IHR and other interdependent entities and to identify potential response strategies to improve the sustainable development and management of water resources of IHR in the context of changing climate and socio-economic scenarios. The synthesis may be add-on in achieving the targets under 'SDG 6 - Clean Water and Sanitation'.

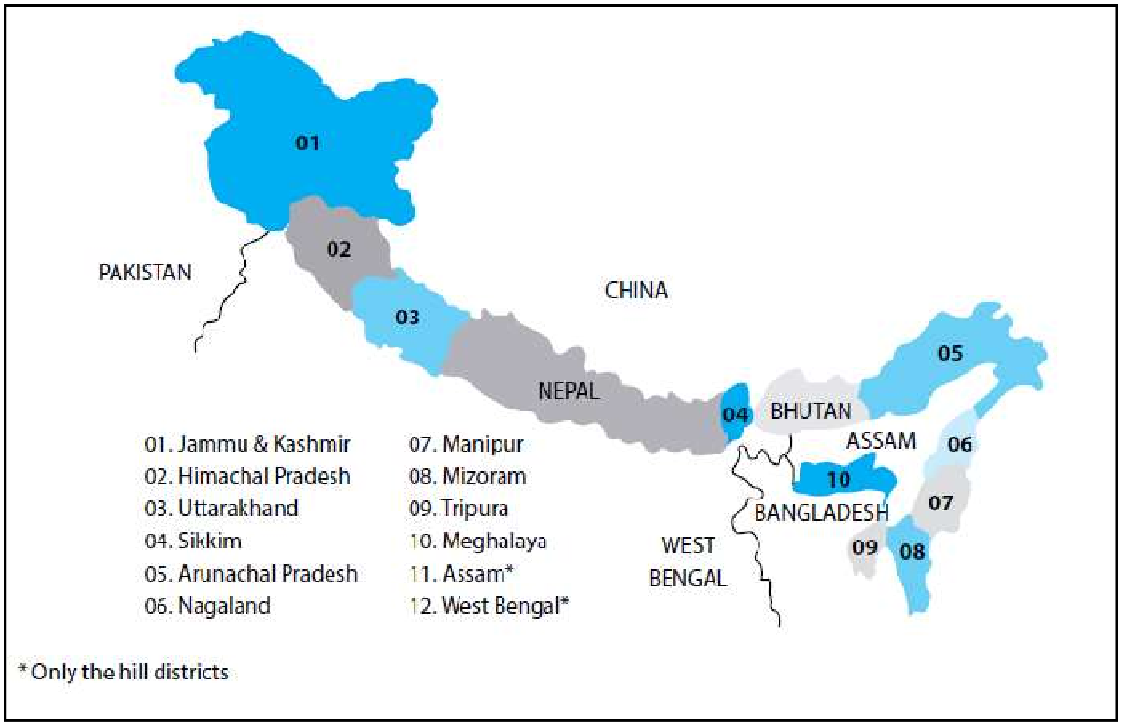

Figure 1 Indian Himalayan Region (IHR)(*Source*: http://nmhs.org.in/IHR_The_Target_Area.php)

Water Resources of IHR

Water resources and its availability are quintessential and hold the key for sustainable socio-economic development of mountain regions along with maintaining ecological balance of the nature.The water resources regime of IHR is diverse and ranges from ice-related components such as glaciers, snow, and to wetlands, watershed, river system, groundwater and springs. There is very limited scientific assessment available for water resources of entire IHR. This is partly due to insufficient network of observations for hydro-meteorology and bio-physical measurements and sectoral/fragmented studies on specific subjects and further absence of data sharing policy.

Glaciersof IHR regulate the water supply from mountains to the plains throughout the year and help in maintaining hydrological cycle and ecosystem stability. Some of the important glaciers of IHR and principal glacier-fed river system of Indian Himalaya are enlisted in Table 2 & 3 respectively.The snow and glacial melt contribution to the discharge of major rivers in the region ranges from 2% to 50% of their average flow (ICIMOD 2009).According to Bajracharya and Shresta (2011) the glacier covered area in the Himalaya is approximately 60,054 km^2. However, as per one estimation, *i.e.*25,041±1726 km^2,is the areal extent of glaciers and 3600 to 4400 Gt is total glaciated water stored in Indian part of the Himalaya (Kulkarni and Karyakarte 2014). The majority of glacier area is found in Indus river system followed by Ganga and Brahmaputra river system in Indian Himalaya.

Table 1 Important feature of states falling within IHR

Sr. No.	State	Geographical area - GA (km^2) (Year 2013)	Decennial Population (Year 2011)	Forest cover (% of GA (Year 2011)	Forest cover (% of GA (Year 2013)	Decadal growth rate (2001-2011)
1	Jammu & Kashmir	2,22,236	12,540	22,539 (10.14)	22,538 (10.14)	23.64
2	Himachal Pradesh	55,673	6864	14,679 (26.37)	14,683 (26.370	12.94
3	Uttarakhand	53,483	10,117	24,496 (45.80)	24,508 (45.82)	18.81
4	Sikkim	7096	608	3359 (47.34)	3358 (47.32)	12.89
5	Arunachal Pradesh	83,743	1383	67,410 (80.5)	67,321 (80.39)	26.03
6	Nagaland	16,579	1980	13,318 (80.33)	13,044 (90.38)	-0.58
7	Manipur	22,327	2700	17,090 (76.54)	16,990 (76.10)	24.50
8	Mizoram	21,081	1091	19,117 (90.68)	19,054 (90.38)	23.48
9	Tripura	10,486	3671	7977 (76.07)	7866 (75.01)	14.84
10	Meghalaya	22,429	2964	17,275 (77.02)	17,288 (77.08)	27.95
11	Assam hills	19,153	5517	12,985 (67.80)	13,024 (68.000	NA
12	West Bengal hills	3149	1847	2289 (72.69)	2378 (75.52)	14.77
13	India	32,87,263	12,10,193	6,92,027 (21.05)	6,97,898 (21.23)	

(*Source*: Economic Survey 2012-13, GoI; India State of Forest Report, 2013 and G-SHE 2018)

River: Water resource system of IHR mainly comprises of mighty river basins viz. Indus, Ganges and Brahmaputra.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. More than 50% of average water resources potential of India is shared by various tributaries of these river systems (Table 3 and 4). Observations of annual hydrographs for the Ganges and Indus rivers show strong seasonal pattern in river discharge, leading to seasonal differences in the water availability in the basin region (Hoekstra and Mekonnen 2011).

An estimated water flow of about 8,634 million m^3 occurs down the Himalayan rivers every year (Negi 2003). Glacial melt and snowmelt are reported to play a significant role in the Indus basin followed by the Brahmaputra and Ganges rivers and percent contribution of snow increases from eastern Himalaya to western Himalaya (Immerzeel*et al*., 2010). There is a wide variation of precipitation pattern in this river system. Eastern and central part of the region experiences more rainfall than snowfalls, whereas in the western part snowfall is predominant. Discharge of Sutlej river (tributary of Indus) at Bhakra is dominated by snowmelt (48 %) followed by an effective share of rainfall (39 %) and glacial melt (13 %) (Wulf*et al*., 2011). Whereas, 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).

Lakes/water bodies: National Remote Sensing Centre (NRSC) in 2011 made inventory of glacial lakes and water bodies in river basins of Indian Himalayan Region using satellite images which shows the presence of 2028 glacial lakes and water bodies. Out of these, 1525 are water bodies and 503 are glacial lakes. Brahmaputra basin part of the Himalayan region contains 294 glacial lakes and 1099 water bodies; 178 glacial lakes and 105 water bodies found in Ganges basin; whereas Indus basin has 31 glacial lakes and 321 water bodies. Details are shown in Table 5.

Table 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, Zanskar range
Braham Sar	PirPanjal range
Harmukh	Sind basin, North Kashmir range
Gara	TirungKhad basin
Gora Garang	Baspa basin
Bara Shigri	Chenab basin, Great Himlayan range
ShauneGarang	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, 2006)

Table 3 Principal Glacial-fed river systems of the Himalaya

Major River System	Mountain Area (km^2)	Glacier Area (km^2)	Glaciations (%)
Indus System	398218	13143	27.9
Ganga System	210826	8106	27.05
Brahmaputra System	441658	2566	13.5

(*Source*: Hasnain 1999)

Table 4 Potential & utilizable water resources of major river systems in Himalayan region

Sr. No.	Items	River Basins			
		Indus	Ganga	Brahmaputra	Meghna
1.	Water resource potential (km^3)	73.3	525	537.2	48.4
2.	Utilizable surface water (km^3)	46.0	250	24	-
3.	Groundwater potential (km^3)	25.5	171.7	27.9	1.8
4.	Per capita annual availability of water (m^3)	1757	1473	18417	7646
5.	Per hectare of cultural area annual availability (m^3)	7600	8727	44232	43447

(*Source*: Reassessment of Water Resources - CWC Publication March 1993)

Groundwater and springs

Groundwaterin IHR is most undiscovered subject. As on March 2009, the net ground water availability and the existing gross ground water draft for all uses in the Himalayas is 10,12,288.4 ha-m, and 2,47,466 h-m respectively. The overall stage of groundwater development in Himalayas is ~ 30%. However, there is significant variation in ground water development in the Himalayas. This variation ranges from 0.066% in Arunachal Pradesh to 66.33% in Uttarakhand (CGWB 2014).

Table 5 Basin wise details of glacial lakes and water bodies

Basin name	Glacial lakes		Water bodies		Total	
	Count	Area (ha)	Count	Area (ha)	Count	Area (ha)
Brahmaputra	294	11371.9	1099	194562.9	1393	205935
Ganga	178	8475.5	105	54247.7	283	62724
Indus	31	771.1	321	294791.3	352	295562
Total	503	20619	1525	543602	2028	564221

(*Source*: NRSC 2011)

Springs are very important and primary source of water for urban and rural population in Indian Himalayan Region. NITI Aayog (2018) reported that out of 5 millions springs of India, nearly 3 million springs are in the IHR alone and 50 million people of 12 states of IHR region are depend on these springs.Problem of drying spring is observed in recent times and nearly 50 per cent of the total springs are dried and this problem is more frequent in Himalayan region. The drying up of springs will affect the flow of spring-fed rivers and further add work burden of women since they are forced to manually fetch the water from far distance.Interested readers may refer NITI Aayog, 2018 report regarding detailed information on springs and its associated problems.

Hydropower:IHR is endowed with perennial water sources/rivers and thereforeis most suitable for hydropower development in terms of water availability but difficult in terms of geographical locations. Hydropower potential of Himalayan river systems is about 78% of the total Indian hydropower resources (Bahadur, 1998). The state-wise potential of hydropower in IHR region is given in Table 6.At present this region has been estimated to produce electricity of about 1.10 lakh MW (Slariya, 2013). Brahmaputra sub-basin has the largest hydropower potential among three basins followed by Indus basin and Ganges basin. However, considering the completed and under construction projects; Brahmaputra sub-basin, Indus, and Ganges have harnessed about 11 %, 48 %, and 31% of the assessed potential, respectively (http://india-wris.nrsc.gov.in).

Climate change in IHR

IHR being one of the most sensitive regions the world is also affected by impacts of global warming or climate change.Due to difficult terrain and harsh climatic conditions this region remains under-explored in terms of specific knowledge with respect to climate change indicators. At the same time, lack of specific attentions towards spatial and temporal scales interaction among the different climatic regime while modeling the global or regional climate models, plays hurdles in understanding the impacts of climate change on Himalayan ecosystem.

Through available literatures on Himalaya, in most Himalayan regions, temperature trends during 1880 and 2012considerably exceed the global average of 0.85°C, where it is found that trends of winter season temperature is higher than other seasons; and along the altitude - warming rate is found to be increased. During the period of 1866 - 2006, due to rapid increase in the maximum and minimum temperatures, average winter temperature increases at the rate of 1.4 °C/100 years in Northwestern (NW) Himalayan region; with the maximum temperature increasing much more rapidly than minimum (Bhutiyani, 2015). Eastern Himalayan region warming rate is generally greater than 0.01 °C per year or more (Shrestha and Devkota 2010). It has been observed that there is increase in temperature and decrease in snowfall inWestern Himalaya, thatsuggests the influence of climate change (Shekar*et al*., 2010). As per IPCC AR4, by the 2050s, there will be increase in average annual mean temperature by about 3°Cover the Asia, including the Himalayas, and by 2080s, average annual precipitation will increase by 10-30%. Further, in AR5 of IPCC, it is clearly indicated that the globe will warmer in between 1.5°C and 4.5°C by the period of 2085–2100, and specifically in regional projections (withprevailing emissions scenario) for South Asia and Tibetan Plateau,the expected increase in annual average surface temperature will be up to 3.1 – 6.0^{0}C and 3.9 – 8.4^{0}C respectively(Christensen *et al*., 2013).

Table 6 Hydropower potential in IHR region

State	Hydropowerpotential (Mega Watt, MW)	Actual hydropower developed (MW)	Actual generation (GWh)
Assam	680	430	1,011
Arunachal Pradesh	50,328	98	366
Himachal Pradesh	18,820	1,495	9,451.1
Jammu and Kashmir	14,146	2,274.4	4,798.7
Meghalaya	2,394	356.6	257
Mizoram	2,196	34	NA
Manipur	1,784	82	30
Nagaland	1,574	53	10
Sikkim	NA	270	910
Uttarakhand	25,000	3,756	NA
Tripura	NA	62	1,025
West Bengal	NA	1,328	1,199

(*Source*: Central Electricity Authority, CEA 2016)

Synthesis of climate change impacts on water resources

Climate change is affecting the temperatures (rise) and amount of snow and ice (loss) and likely to have significant impact on water resourcesespecially water availability (amount and seasonality)in the Himalaya (Buytaert, 2012 and Xu*et al*., 2009).A study of last 3 decades conducted by Negi*et al*., (2018) found that mean temperature in Himalayais higher than world average and decrease in winter time snowfall and increase in winter time rainfall has been observed over the region.

Glaciers: The rate of retreat of glaciers in Himalaya has been relatively faster than the world average and they are retreating at the rate of 0.3-1 m/year (Dyurgerov and Meier 2005). From 1960 to 2000, there is 13% glacier loss in the Himalaya(Kulkarni and Karyakarte 2014).In their study of western and eastern Himalayan ranges, Rees and Collins (2006) found that most of the glacier-fed sub-catchments i.e. glaciations greater than or equal to 50%, are likely to attain peak flows of 150% and 170% of initial flows around 2050 and 2070 respectively;and water discharge in decline trend until the respective glaciers vanish by 2086 and 2109. The western Himalayan glaciers are expected to retreat in the next 50 years as reported in IHCAP (2015) report, causing increase in river flow of Indus, and the glacial water reservoirs will be empty thereafter, which will results in30% to 40% decrease of flows.

Indian Himalaya constitutes 23,314 km^2 and stores 3,651 Giga-ton of glacier water. However, losing mass rate of Himalayan glaciers is 6.6 ± 1 Giga-ton per annum. According to Kulkarni and Karyakarte(2014) if the temperature in Himalaya rises by 2.36^{0}C (low GHG emission scenario) by the end of 21st century, the Himalaya would be losing 12 ± 2 Giga-ton of glacier every year that time onward. If the temperature in Himalaya rises by 5.51^{0}C (high-end GHG emissions scenario) by the end of 21st century, the Himalaya will lose 35 ± 2 Giga-ton of glacier every year that time onward.In past decade, almost 67 percent of the glaciers in the Himalaya have retreated (glacier loss and retreat rate of major river basins are given in Table 7) and will continue to retreat resulting in glacier mass loss, decrease in flows of glacier-fed rivers results in severe water shortages as well as potential food insecurity and energy security (hydropower generation) and GLOFs (IDSA 2008 andChaturvedi*et al*., 2014); and that eventually leads to imbalanced Water-Food-Energy (WFE) nexus.

Table 7 Glacier area loss and rate of retreat for glaciers in major river basins

Basin	Glacier area loss (% per decade)	Avg. retreat rate (meter per decade)
Indus	3.72 (±1.93)	178 (±138)
Ganga	3.03 (±2.25)	148 (±97)
Brahmaputra	3.22 (±1.83)	135 (±110)

(*Source*: Kulkarni and Pratibha, 2018)

Rivers: Out of total stream flow of Indus basin, 34% is by snowmelt and 26% is from glacier melt (Immerzeel*et al*., 2010). Due to this significant contribution of snowmelt and glacier melt, Indus basin will have severe impact of glacier retreat. At initial stage of climate change the glacier melt will results in short-term increases in the contribution to discharge, which is likely to decrease in the future of the Indus river (Miller *et al*., 2012). On same note, Arora and Boer (2001) reported 5% increases in mean annual runoff for the Ganges by 2070–2100. But with likely scenario of declining precipitation and glacier melt, there will be decrease in mean runoff of 17.6% at higher elevation (>2000 mean sea level) (Immerzeel*et al*., 2010). There are hardly any studies on Brahmaputra river basins, but through available literature and considerable impacts of climate change,projected increase in precipitation downstreamwill increase the discharge in the lower Brahmaputra river (Miller *et al*., 2012).

Allied water resources: Changes in air temperature, precipitation, snow-glacier melt will have profound impacts on high altitude lakes by reduction of lake levels.Spatial and temporal shift in rainfall and its extremity along with change in land use pattern affects spring discharge that eventually leads to drying of springs in some cases and in other case perennial spring flow becomes seasonal. Due to uncertainty in water availability or river flows in lean season, hydropower plants are facing problem of water shortage results in only about 30 % power generation of the total installed capacity in dry months (Chaulagain, 2015). Further in extreme events like flood, sedimentation is another problem for hydropower plants.

Way-forward

Himalaya is a data deficient region. There is a lack of well-developed hydro-meteorological and river gauging network for improving the knowledge on climate, hydrology, rainfall, sediment transport, floods and other aspects in IHR. The IPCC in its AR4 described the Himalayan region as data-deficient region (also described as a ‘white spot’ due to lack of sufficient data on natural ecosystems) in terms of climate monitoring. The NITI Aayog (2018) in its report also recognizes that there is a gap between data availability and their use for sustainable development of IHR. Further, unwillingness to share data is another major challenge which is hampering integration of data for conservation and developmental planning. Although this situation is now changing, showing positives signs of data generation and observations at acceptable spatial as well as temporal scale which will be very helpful in quantifying water resources and their planning in the context of changing climate.In context of present water resources situation of IHR and under the shadow of climate change as mentioned in above paragraphs more emphasis is needed towards synchronizing the research activities and doing coordinated efforts to generate and maintain the datasets with respect water resources of IHR. Robust datasets and frequent impact assessment will strengthen the decisions of policy makers in framing the strategies for sustainable development of water resources of IHR.

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