Advanced Review

Changing climate and glacio-hydrology in Indian Himalayan Region: a review

Shaktiman Singh,[1] Rajesh Kumar,[1*] Anshuman Bhardwaj,[1,2] Lydia Sam,[1,3] Mayank Shekhar,[4] Atar Singh,[1] Ramesh Kumar[1] and Akhilesh Gupta[5]

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This study presents a comprehensive review of the published literature on the evidences of a changing climate in the Indian Himalayan Region (IHR) and its impacts on the glacio-hydrology of the region. The IHR serves as an important source of fresh water for the densely populated areas downstream. It is evident from the available studies that temperature is significantly increasing in all parts of the IHR, whereas precipitation is not indicative of any particular spatiotemporal trend. Glacio-hydrological proxies for changing climate, such as, terminus and areal changes of the glaciers, glacier mass balance, and streamflow in downstream areas, highlight changes more evidently in recent decades. On an average, studies have predicted an increase in temperature and precipitation in the region, along with increase in streamflow of major rivers. Such trends are already apparent in some sub-basins of the western IHR. The region is particularly vulnerable to changing climate as it is highly dependent on snow and glacier melt run-off to meet its freshwater demands. We present a systematic review of key papers dealing with changing temperature, precipitation, glaciers, and streamflow in the IHR. We discuss these interdisciplinary themes in relation to each other, in order to establish the present and future impacts of climatic, glaciological, and hydrological changes in the region.

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INTRODUCTION

Climate is the long-term average of the weather condition (temperature, precipitation, humidity, wind speed, and direction) observed in a given location. Climate change refers to any long term deviation in these climate parameters caused by natural variability or human activities.[1] The phrase ‘long term’ is consistent with the definition of climate as an average of its parameters over a duration of 30 years. All the available records of temperature and climate models show near-surface rise in temperature, particularly in recent decades.[2] Studies suggest an increased rate of warming, particularly in the minimum temperatures of the mountainous regions (the Swiss Alps, the Colorado Rocky Mountains, the Tibetan Plateau/Himalayas, and the Tropical Andes), as compared to the nearby low land areas.[3] The rising temperature has a negative impact on the glacio-hydrology of snow/ice-fed river catchments.[4] *Glacio-hydrology* is

*Correspondence to: rajesh.kumar@sharda.ac.in

[1]Department of Environmental Science, School of Basic Sciences and Research, Sharda University, Greater Noida, India

[2]Division of Space Technology, Department of Computer Science, Luleå University of Technology, Kiruna, Sweden

[3]Defence Terrain Research Laboratory, Defence Research and Development Organisation, New Delhi, India

[4]Birbal Sahni Institute of Palaeobotany, Lucknow, India

[5]Department of Science and Technology, Technology Bhavan, New Delhi, India

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an integrated term using the words 'hydrology' and 'glaciology.' Hydrology refers to the science that incorporates the occurrence, distribution and movement of water, and their relationship to the physical factors in each phase of the hydrological cycle.[5] Therefore, the term hydrology also includes the glaciological processes as part of hydrological cycle, but due to distinguishing behavior of glaciers and its importance in hydrological regime, it has been separately termed as glaciological process and its study is referred to as glaciology. The term *glacio-hydrology* defines both the glaciological processes as well as the hydrological processes within a catchment. The form of precipitation coupled with snow- and glacier-melt are the most important hydrological processes in a glacierized catchment. Therefore, to understand the hydrology of a glacierized catchment, one needs to understand the processes like snow and glacier melt, glacier dynamics, surface and subsurface hydrology, and energy and mass balance mechanisms.

Glacio-hydrology of mountainous catchments has significant implications on socioeconomic aspects as well with changing climatic trends. Mountains cover around 24% of the global surface area and sustain about 12% of the world's population.[6] Nearly 10% of the global population is dependent on mountains directly for its livelihood while another 40% depends indirectly on mountain ecosystems for timber and nontimber forest products, fresh water, and river valley projects for industrial, agricultural, and domestic purposes.[7,8] The Himalayan mountain range is the youngest and highest mountain range. It has enormous fresh water storage in the form of snow, glaciers, permafrost, natural lakes, wetlands, and natural springs and hence is known as the water tower of Asia. The mountains of High Asia (Figure 1) or Hindu Kush-Himalaya (HKH) have around 50% (by area) of all the glaciers falling outside the polar realm.[10] There are approximately 54,000 glaciers in the HKH region, covering an area of about 60,000 km^2 with nearly 6000 km^3 of ice volume reserves.[9] The rivers originating from these mountains provide freshwater to support livelihood of people (~1.3 billion) living in densely populated downstream regions.[11–13] Because of latitudinal and altitudinal positions, the Himalayan glaciers are vulnerable to even minute changes in temperature and patterns of precipitation.[12] Several studies have shown that the changing climate will have a negative impact on snow and glacier melt, ultimately affecting the water supply and storage capacity of the region.[4,12,14] Various studies propose that most of the Himalayan glaciers are retreating, though the rate of retreat varies both spatially and temporally, depending upon the topography and local climate.[4,15–21] In fact, contrary to the general retreats, Hewitt[22] observed expansion of a few debris-covered glaciers in the Karakoram region.

The high mountain ecosystems in the Indian territory, also known as Indian Himalayan Region (IHR), need significant study and exploration due to their vulnerability toward anthropogenic and climatic factors. The ever-increasing population in this region marks an era of mankind's dominance on ecosystem services and life supporting systems.[23] Excessive use and encroachment of the land resources have led to extensive degradation of natural landscapes, extinction of species, and loss of ecosystem functions and services.[24–26] Glacier retreat in these high mountains is not just a physical process but it also affects the livelihood and economy of the downstream regions with implications on the traditional knowledge and beliefs of the local communities.[27,28] Because of the difficult terrain and harsh weather conditions, the availability of observed data is scarce and fragmented, and the studies carried out in the IHR are very few. This has increased the uncertainties and restricted the understanding of probable impacts of changing climate in the region. Therefore, it is important to carry out studies helpful in generating a database and reducing the uncertainties about the changes observed in the IHR. This scientific approach is more important in case of the complex glacier systems which are the ultimate source of water in the Himalayan rivers. Such studies can further help in assessing the relationship between climate parameters, contribution of glacier discharge, and the impact of climate change on the hydrology of glacierized basins. In addition, they can provide the future scenarios of variation of streamflow in river basins, defining the prospective economy of this region. The studies on changes in the biodiversity and ecosystem are also important as they serve as important ecological and economic resources for communities at local and regional scales.

The present study is an attempt to analyze the existing glacio-hydrological research carried out across IHR. It provides an overview of the patterns and the effects of changing climate in IHR; changes observed or predicted for different indicators, namely, temperature and precipitation, and their impact on glaciers and river systems of the region are emphasized upon. The study first discusses the study area and its significance in terms of high population density and glacio-hydrological systems. In the following sections, the results of various studies on the changes observed and predicted in temperature and precipitation are discussed. The article further

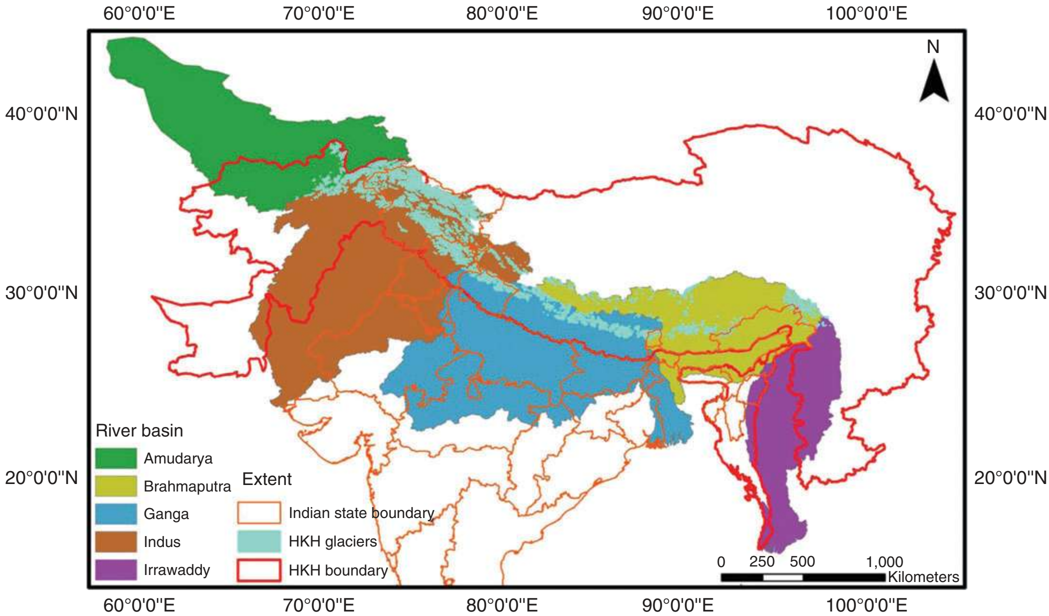

FIGURE 1 | Major river basins and glaciers in Hindu Kush-Himalaya (HKH) adjoining Indian Himalayan Region (boundary after Bajracharya and Shrestha[9]).

highlights the impact of changing climate on the glaciers and streamflow regimes and their interrelationships in the IHR. The study also attempts to point out the areas of high uncertainty in the climatic and physical proxies which require further investigation to draw any conclusion with confidence.

Study Area: IHR

India is a densely populated country with total population of 1210 million, which grew from 1028 million in 2001 with a decadal growth rate of 17.46%.[29] The population density has increased from 325 persons per km^2 in 2001 to 382 persons per km^2 in 2011.[29] Thus, land is a scarce natural resource in India, even though the country has total area of about 3.28 million sq. km, the seventh largest in the world.[30] The Indian part of the Himalaya, that is, IHR covers an area of about 0.67 million km^2 (about 20% of country's total geographical area) and forms the northern boundary of the country.[30] The IHR is inhabited by 44 million people.[29] Thus, even the IHR boasts a high population density of 66 persons per km^2. The IHR separates the plains of the Indian subcontinent from the Tibetan Plateau and extends between latitudes 26°20′ and 35°40′ North, and longitudes 74°50′ and 95°40′ East. This part of the Himalaya has around 14 peaks with elevation more than 8000 m and many more within a range of 6000–8000 m.[31]

Indus and Ganges are the two river basins originating from the Himalaya, covering large part of the IHR. The Geological Survey of India, in 2008, estimated 9575 glaciers in IHR, of which 7997 glaciers covering an area of 33,679 km^2 are in the Indus river basin, and 1578 glaciers spread across an area of 3787 km^2 are in the Ganges river basin.[32] Another glacier inventory by Space Application Centre (SAC), Indian Space Research Organization (ISRO) in 2011, suggested the existence of around 32,392 glaciers covering an area of 71,182 km^2 in Indus, Ganges, and Brahmaputra basins.[33] Apart from having enormous fresh water reserves, the IHR serves as an orographic insulator, as well as an elevated thermal heat source, largely influencing the Indian Summer Monsoon (ISM)[34] and thus, serving as an important factor in determining the regional climate. There are studies demonstrating the relationship between the strength of ISM and the snow cover in the Himalayan region.[35,36]

Temperature

Change in air temperature is considered as a good indicator of changing climate globally, because of its capacity to represent energy exchange (long-wave downwelling and absorbed shortwave radiation) over the earth's surface.[37] The meteorological (instrumental) data worldwide show a systematic increase of 0.85°C from 1885 to 2012, following a decadal rise of 0.05°C in global mean temperature.[2,38–41] However, the warming pattern has not been globally uniform.[2] The unavailability of sufficient long-term *in situ* observations and complex topographic conditions pose major problems in quantifying the magnitude of climatic trends in mountainous regions.[42] Studies based on instrumental data suggest that the Himalayan region has experienced warming trend with a rate that is more than twofold higher than the global average.[43] Studies in some parts of the Indian subcontinent[20,37,44,45] and the Tibetan Plateau region[46–48] have reported a similar warming trend. During the last few decades, a sharp rise has been observed in this trend. The reason for this unusual local climatic warming has been attributed to the anthropogenic greenhouse gas (GHG) emission and deforestation, which are suggested to be dominant climate forcing agents.[20,37,45]

Temperature is the most studied climate parameter with the longest series of observations available. Even in case of the data-deficient IHR, observations date back to 1901 for some stations.[37,49] Results from various studies undertaken in the IHR, based on both reanalysis datasets as well as station data, have been summarized in Figure 2. These results show warming in IHR in general with varying trends, both spatially and seasonally. The analysis of temperature data from ten stations in the northwestern IHR shows warming trends with elevated rates of rising temperature, particularly the mean winter temperature and the annual maximum temperature, in recent decades.[37] The study by Bhutiyani et al.[37] suggest an increase in the average annual temperature (1.6°C) and in the average annual maximum temperature (1.6°C) during the last century. This increase is several folds higher than the rise in the global average temperature.[37] Another basin-wise study using century-long station data from lower regions of the basins suggests the rise by 0.50 and 0.44°C in lower Indus and Ganges basin, respectively.[50] Kothawale et al.[44] suggested that the western IHR has warmed at a rate (0.46°C per decade) higher than rest of the India (0.20°C per decade) during 1971–2007. In addition, several studies using reanalysis dataset for the northwestern IHR also conclude an increased rate of warming in recent decades.[51,52] A study undertaken for the central part of IHR using temperature data from one meteorological station suggests an increase in the annual mean temperature by 0.49°C during the period 1967–2007.[53] Like the central part, the eastern part of IHR also lacks available scientific literature discussing the temperature variations. A study using station data of around 35 years for the eastern IHR shows increasing trend in temperature but the statistical significance of the trend is low.[54]

A recent study[52] using the reanalysis dataset from GIOVAANI, acronym for Geospatial Interactive Online Visualization and Analysis Infrastructure (Goddard Earth Sciences Data Information Services Center, 2013), downloaded for the Baspa river basin in Himachal Pradesh and calibrated using the observed data of two stations at two different elevations in the basin, suggests rise in the average maximum and minimum temperatures annually in contrast to other studies. The period of this study is 25 years which is smallest duration of all the studies referred here (Figure 2). However, it is interesting to see that the gradient of increase in the temperature per annum is comparatively higher in the studies considering only recent decades than the studies which have analyzed data of longer time period.[51,52] Although, Fowler and Archer[49] suggests a lower rate of warming in recent decades. Also, the analysis of the minimum temperature in both these studies undertaken for the western IHR suggests its higher rate of increase in comparison to the average and maximum temperatures.[51,52] On the contrary, in the eastern IHR the maximum temperature is observed to have maximum rate of increase.[54] Several studies predict a continuous rise also in the future temperature.[12,55,56]

Conclusively, temperature in the IHR has been observed to be increasing in the last century with rates higher than those in other parts of the globe, along with several spatial and seasonal variations, and has further been projected to increase in the future. This rate has been observed to be increasing in recent decades. The minimum temperature is one of the key parameters which directly affect the type of precipitation in mountainous regions.[57] It is the least studied parameter in the IHR and the temporal coverage of such studies is also relatively smaller except for the study undertaken by Bhutiyani et al.[37] (Figure 2). The rate of increase of the minimum temperature is highest in the studies for the western IHR and this alarming trend needs further investigation using long term instrumental data.

Precipitation

The Himalayan mountain region is influenced by two major weather systems (precipitation sources) namely the ISM or the southwest summer monsoon and the mid-latitude westerlies also known as the western disturbances.[58–61] These weather systems show wide spatiotemporal variations. The northeastern and

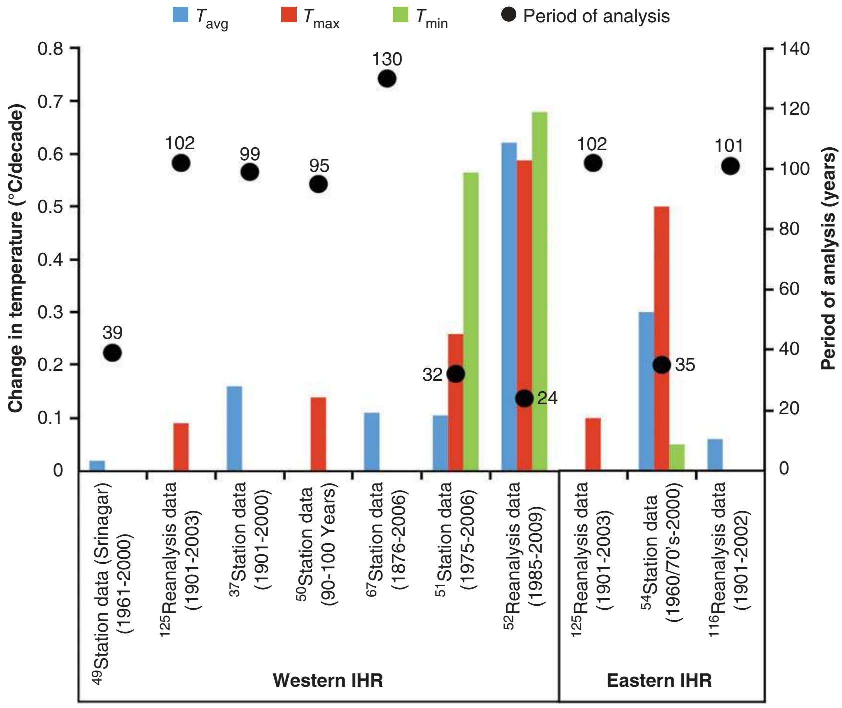

FIGURE 2 | Summary of temperature trend observed by several studies in different parts of IHR. T_{avg}, T_{max}, and T_{min} represent average temperature, maximum temperature, and minimum temperature, respectively. The numbers given in superscripts on the *X*-axis represent corresponding references.

central parts of IHR experience prominent summer precipitation in the form of rainfall at lower altitudes and snowfall at higher altitudes, under the influence of the ISM. However, the summer precipitation gradient is orographically controlled; hence the region north of the higher Himalaya receives scanty monsoon precipitation compared to its southern counterpart during summer. On the contrary, the mid-latitude westerlies are dominant in the northwestern IHR as the main source of snowfall and their influence keeps on decreasing toward the southeast regions.[62] The analysis of precipitation in three stations (Srinagar, Skardu, and Gilgit) in the northwestern part of IHR during 1893–1999 shows that almost 37% of the total annual precipitation occurs during the months of January to March, another 31% occurs during April to June, while the rest of 32% occurs during the months of July to December.[63]

Although a conceptual understanding of the weather system in the IHR is available, we have found that precipitation is a relatively lesser-studied parameter for observing the changing climate. Using the limited available data, it can probably be suggested that the precipitation across the IHR does not show any specific trend unlike temperature. Few studies suggest that the extreme rainfall events in the Indian subcontinent have increased significantly, along with a significant decrease in the moderate rainfall events[64,65] and a similar pattern has been observed for the IHR as well.[66] Significant increasing trend of precipitation has been observed in the upper Indus basin in the northwestern part of IHR.[60] In another study, Bhutiyani et al.[67] have suggested a significant decrease in the annual and monsoon precipitation and an insignificant increase in the winter precipitation in the northwestern part of IHR after analysis of observations from around 10 weather stations (Figure 3). In contrast, a rather insignificant decrease in the winter precipitation in western IHR has been reported by Dimri and Dash.[51] In a detailed study of precipitation pattern for the entire country, a significant decrease in annual precipitation of Uttarakhand and Himachal Pradesh, while an increase in annual precipitation of Jammu and Kashmir and other eastern Himalayan states (Figure 3) was observed.[68] Analysis of the longest time series of gridded reanalysis datasets, namely, Asian Precipitation Highly Resolved Observational Data Integration Toward Evaluation of Water Resources (APHRODITE), Climate Research Unit (CRU), and Global Precipitation Climatology Centre (GPCC) show statistically significant decrease in summer precipitation in the IHR while earth system model EC-

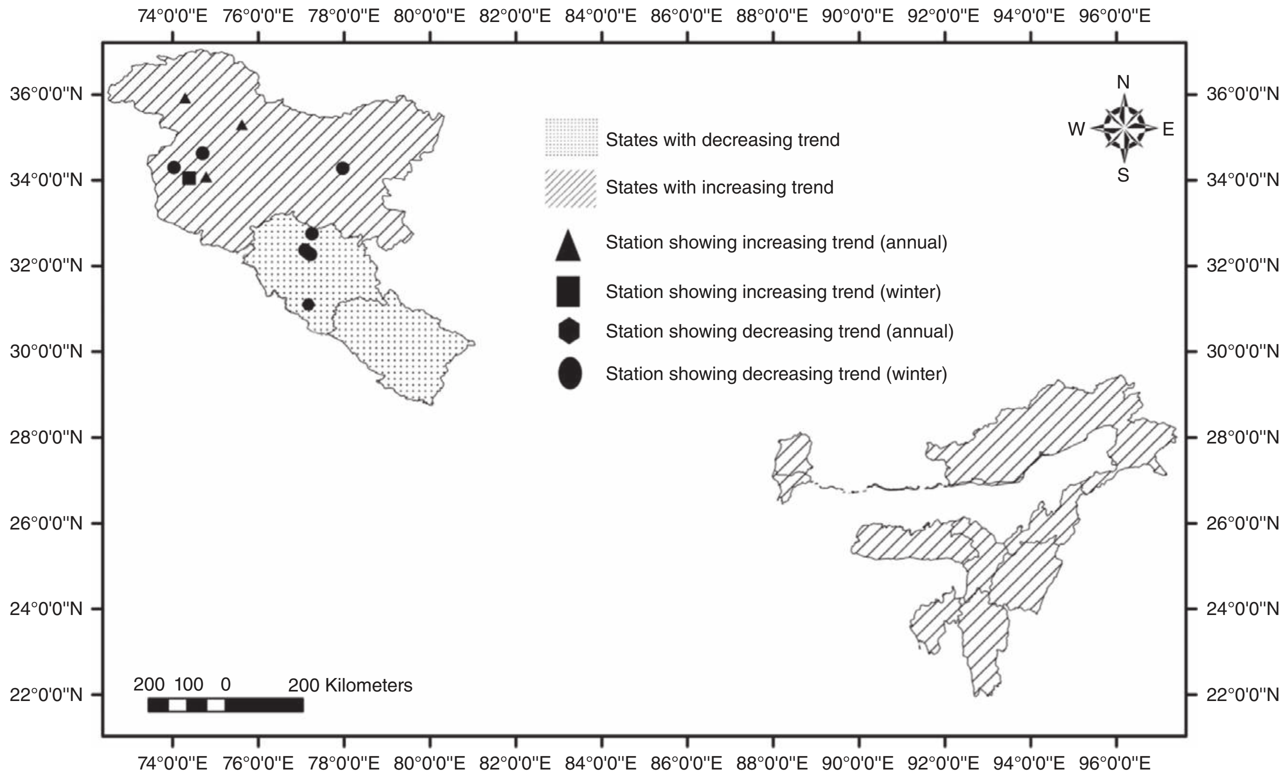

FIGURE 3 | Map of Indian Himalayan Region showing trends of precipitation in different parts. The boundary of Hindu Kush-Himalaya (after Bajracharya and Shrestha[9]) has been dissolved with the boundary of India. The station data have been shown after Archer and Fowler[63] and Bhutiyani et al.[67] and state-wise trend has been shown after Guhathakurta and Rajeevan.[68]

Earth estimates an increase in summer precipitation in this region.[69] The reason behind overestimation by EC-Earth model has been attributed to its inability to incorporate the increase in concentration of atmospheric aerosols.[69] The model estimates an increase in summer precipitation in the IHR in recent future. An increase in precipitation has also been predicted by Lutz et al.[56] in upper Ganges basin and upper Brahmaputra basin while decrease has been predicted for upper Indus basin. Similar trend of increasing precipitation has also been predicted by Immerzeel et al.[12,55]

Andermann et al.[70] evaluated performance of five different gridded precipitation dataset and suggested that the reanalysis dataset with interpolation of rain gauge data performs best in the Nepal Himalayas, with limitations during monsoon season and in areas of high elevation. It is evident from these studies that the precipitation data available for the IHR is scarce and fragmented to draw any significant conclusion with statistical confidence regarding the trend of change (Figure 3). This has also restricted the understanding to predict the trend of changes using different climate scenarios. Although the changes observed in temperature have direct impact on pattern, timings and the form of precipitation; ultimately, they have an impact on the hydrological regime of the entire region. Therefore, there is an urgent need to increase the density of rain gauge network in the IHR to create a database which will help to draw statistically significant conclusions on the patterns of changes in the precipitation and further the hydrology of the region.

Glacier Changes

The changes in temperature and precipitation have direct impact on ablation and accumulation of glaciers. Air temperature is a proxy for components of energy balance and hence controls snow and ice melt.[71] However, precipitation and its form controls the accumulation of glaciers. In recent years, the retreating glaciers globally have received much attention of the public and scientific community as a sensitive indicator of global warming. Parameters for observing changes in a glacier include length, area, and volume. The change in length of a glacier is one of the obvious parameters to observe the impacts of changing climate on glaciers. The snout of the glacier is the transition point between glacier ice and meltwater stream. Hence, any significant increase in temperature will drastically shift the snout toward higher altitudes. Glacier length is one of the most widely available data for the Himalaya. This can be easily reported using remote sensing observations. A mere photograph can act as a source of database and can be used for reporting the changes in the length of a glacier.

For three states of IHR, glacial length changes are mostly available. The data availability dates go back to around a century for some of the glaciers. The average glacier length changes, along with the corresponding years have been shown in Figure 4 for the states of Jammu and Kashmir, Himachal Pradesh, and Uttarakhand in the IHR.[72] Uttarakhand has the maximum number of glaciers observed for changes in glacier length. All the glaciers have been found to be retreating with an average rate of about 18 m/year throughout the observation window of four decades. Surprisingly, apart from the shrinkage reported by different glaciological studies using remote sensing, a recent study using the same method suggests that 86.8% of 2018 glaciers mapped in Karakoram, Himachal Pradesh, Zanskar, Uttarakhand, Nepal, and Sikkim regions of the HKH show stable or no-retreat condition from 2000/2001 to 2010/2011.[73]

Remote sensing has been used extensively for mapping changes in the area covered by glacier and snow in the IHR. The mapping of Chhota Shigri, Patsio, and Samudra Tapu glaciers in Chenab basin, Parbati glacier in Parbati basin and Shaune Garang glacier in Baspa basin, has reported an overall deglaciation of 21% from 1962 to 2001.[74] A study from western IHR suggests a loss of glacier area of 19 and 9% from two nearby river basins, Warwan and Bhut respectively; attributing the areal difference to factors such as, size of glaciers in the basin, less area covered by moraines, and glacier area distribution in higher elevation.[75] Another study of the Chandra-Bhaga basin in the western IHR shows a glacier area loss of 2.5% from 1980 to 2010.[76] Bhambri et al.[77] reported an overall reduction of the glacial area by $4.6 \pm 2.8\%$ from 1968 to 2006 in Garhwal Himalaya, which is a part of the central IHR, with an increased rate of reduction during 1990–2006. A recent study from the eastern IHR shows that glaciers in Teesta river basin lost an area of about $3.3 \pm 0.8\%$ from 1989/1990 to 2010.[78] Another study observed areal loss of $20.1 \pm 8\%$ from 1962 to 2000 in the Sikkim Himalaya.[79] The studies for different parts of the IHR suggest reduction in glacierized area with an increased rate after 1990s. As the changes in glacier length and area show only the horizontal variation and not the overall change in the amount of ice volume present in the glacier, they cannot be treated as conclusive indicators of the changing climate. In addition, there can be several other reasons which can cause change in the length of a glacier. These factors include bed topography, aspect, and slope which primarily control flow and dynamics of glaciers and hence the changes incurred in them. Apart from these factors, debris cover which is a characteristic of Himalayan glaciers can also be responsible for the anomalous behavior of snout position of the glaciers. The debris cover also restricts the applicability of remote sensing methods to map glacier terminus using satellite images.[80] However, there are several studies which have successfully mapped glacial features in glacierized catchments with debris cover.[80–84] Freely available remotely sensed data have recently been used to develop algorithms for mapping features,[85,86] and dynamics[87] of debris-covered glaciers.

Glacier mass balance or surface mass balance is a reliable, direct, and an unfiltered indicator of determining the response of a glacier to changing climate. Glacier mass balance is the measurement of difference of mass gained or lost by a glacier within a hydrological year by carrying out *in situ* or *ex situ* measurements. It is affected by both climatic (temperature and precipitation) and nonclimatic [accumulation area ratio (AAR), elevation, debris-covered area, and avalanche contribution] factors. In addition, the mass balance of a glacier is also affected by its own properties such as velocity, slope, aspect, and basal features. Mass balance of a glacier can further regulate its own dynamics, mountain hydrology at local and regional scales, and the sea level as explained in Figure 5.[88] A recent study by Pratap et al.[89] presents a comprehensive review of mass balance studies undertaken for the IHR in the last four decades. Mass balance observations need to be made extensively for drawing valid conclusions for the IHR.

There are different methods used for the measurement of mass lost and gained by a glacier. These include geodetic, direct or glaciological, hydrological, and remote sensing-based methods to determine equilibrium line altitude (ELA) and AAR for a particular glacier. Of all these methods, direct or glaciological method of mass balance measurement is the only method which is based on direct *in situ* measurements and hence is comparatively difficult to apply in harsh environments such as high altitude Himalaya. There are 15 glaciers in the IHR with glaciological mass balance measurements, out of which, 11 glaciers have been monitored for more than 5 years (Figure 6). The annual specific mass balance in meter

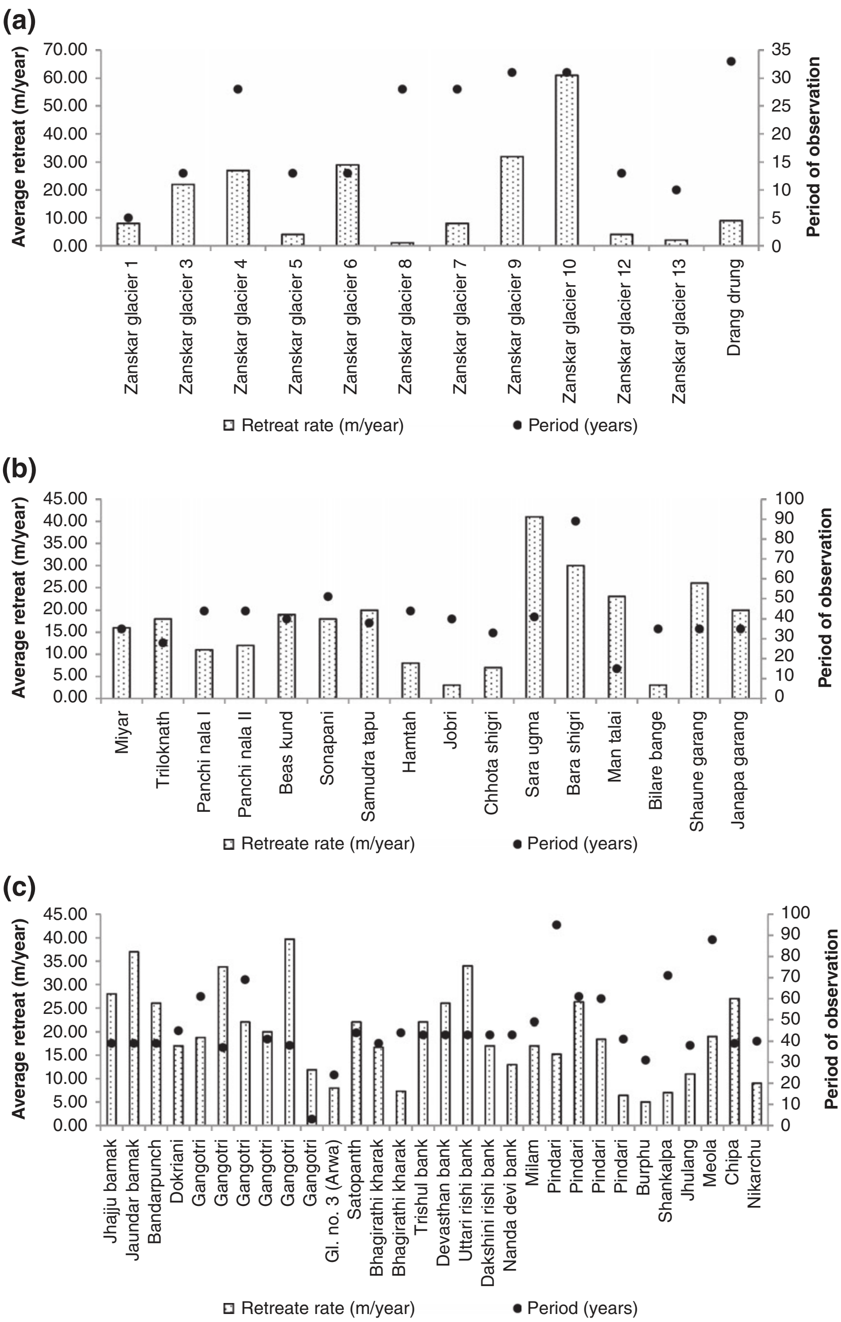

FIGURE 4 | Length changes observed in glaciers of (a) Jammu and Kashmir, (b) Himachal Pradesh, and (c) Uttarakhand in IHR. (Data source: Ref 72)

water equivalent per year (m w.e./year) for these 11 glaciers along with their surface areas have been summarized and represented in Figure 7. On an average, these glaciers show a specific mass loss of about 0.54 m w.e./year based on the data available during different periods of measurement. It is interesting to note that only few of these glaciers have shown positive mass balance and that too for a very short period. For example, Chhota Shigri glacier located in Himachal Pradesh, India has been observed to have gained mass during 2008–2010.[90] Contrary to this, the nearby Hamtah glacier has constantly lost mass.[92] The available data of specific mass balance for Chhota Shigri glacier and Hamtah glacier show a positive correlation of more than 75% for the same period of measurement. Similarly, nearby Gara and Gor Garang glaciers show a positive correlation of more than 90% for the observed specific mass

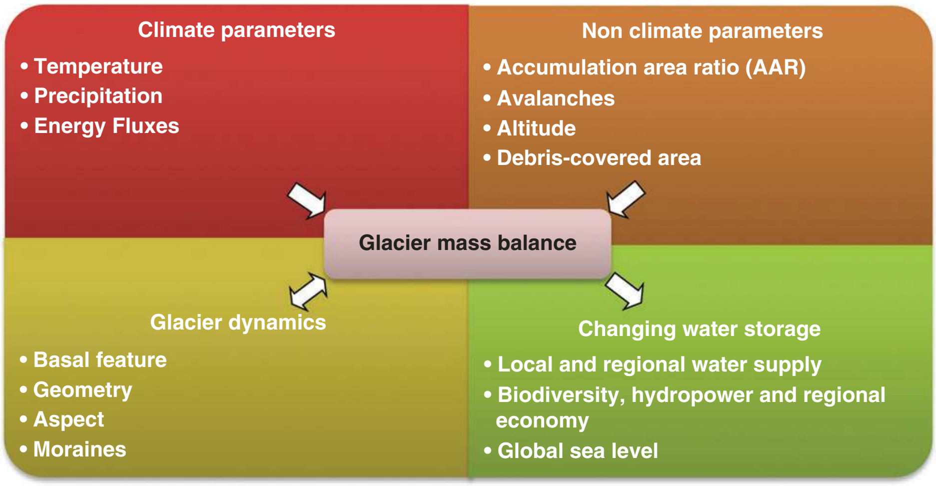

FIGURE 5 | The role of glacier mass balance and factors affecting it. (Information source: Ref 88)

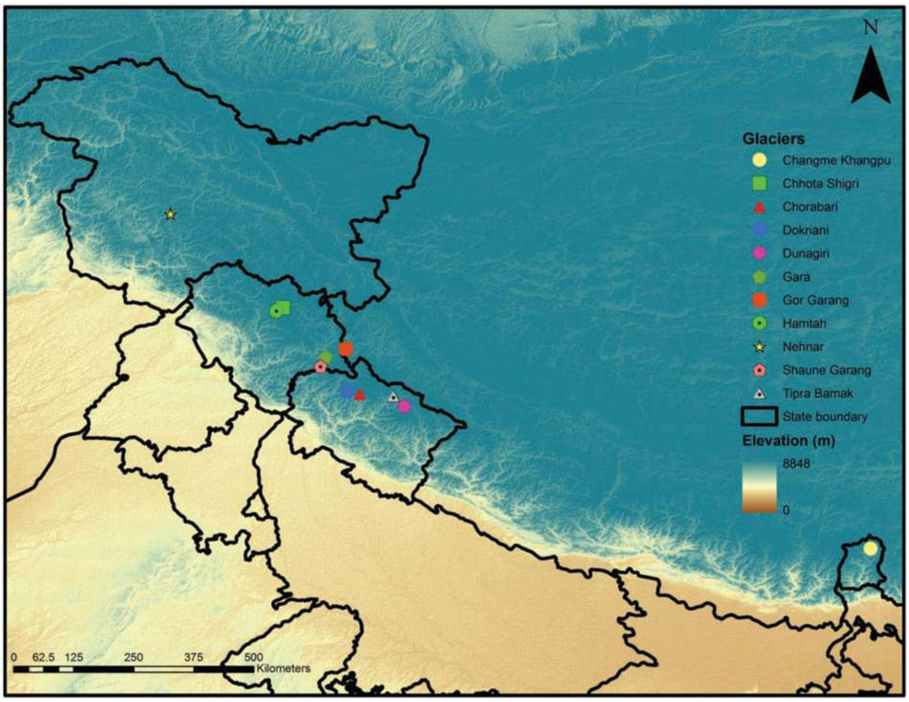

FIGURE 6 | Map of Indian Himalayan Region showing the location of glaciers for which glaciological mass balance measurements are available for at least 5 years.

balance. However, both Gara and Gor Garang glaciers have shown positive mass balance for the same period of observation. This gives an opportunity to explain the relationship between mass balance observations made for two nearby glaciers for which the mass input for a given hydrological year can be assumed to be almost similar. The maximum elevations of Chhota Shigri glacier and Hamtah glacier are 6263 and 5000 m a.s.l. respectively, whereas the minimum elevation of both the glaciers is almost same.[89] Moreover, the accumulation zone of Hamtah glacier is smaller in comparison to Chhota Shigri. These can be the probable reasons behind the difference between their mass balances. This observation further gets supported by the fact that the minimum and maximum altitudes of Gara and Gor Garang glaciers are almost same[89] and therefore these glaciers show mass balance with similar trend and values. Apart from the altitude, the differences in mass balance can be attributed to other nonclimatic factors

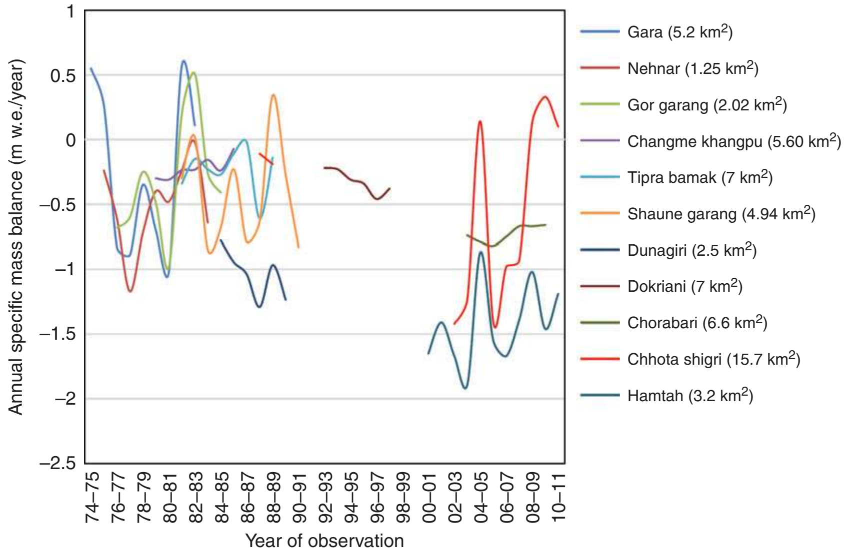

FIGURE 7 | Mass balance of glaciers in IHR with more than 5 years of observation. The values in bracket show the area of the corresponding glaciers. Source: Azam et al.[90]; Dobhal et al.[91]; Mishra et al.[92]; Pratap et al.[89]; Raina and Srivastava[30]; and Wagnon et al.[93]

such as AAR of the glacier, area under debris cover, aspect, slope, and glacier geometry (Figure 5).

In addition to the observed glaciological mass balance data, hydrological, geodetic, and modeled mass balance based on temperature index models and albedo changes are also available for the western part of IHR.[94–97] In different studies, the mass balance for glaciers of Lahaul and Spiti region has been calculated to be −1 to −1.1,[98] −0.48 ± 0.08,[97] and −0.45 ± 0.14 m w.e./year[99] using geodetic methods. These statistics indicate a balanced status of glaciers prior to 1990 and an increased rate of mass loss since late 1990s,[88] which is in accordance with the increased glacierized area loss observed in the central and eastern Himalaya.[77,78] Similar conclusions were drawn by Azam et al.[94] as they used a temperature index model to reconstruct the mass balance of Chhota Shigri glacier in Lahaul and Spiti region. The study suggests near zero mass loss (−0.01 m w.e./year) during 1986–2000, an increased rate of mass loss (−0.57 m w.e./year) during 2001–2012 and continuous loss of mass at the rate −0.30 m w.e./year for total reconstruction period which is 1969–2012. This is in agreement with other studies in the region,[17,99] which suggest that mass loss has increased in recent decades in Lahaul and Spiti region. The mass balance reconstruction using surface albedo of Chhota Shigri glacier shows significantly more negative value (−0.68 ± 0.10 m w.e./year) when compared to other mass balance data of the same glacier.[87] A valid reason for this disagreement can be the use of Moderate Resolution Imaging Spectroradiometer (MODIS) satellite images having too coarse of a spatial resolution (500 m)[100] to be compared with the point-based measurements of mass balance on the glacier. Categorically, glaciers of the IHR have lost mass with rates increasing in recent decades and are predicted to continue losing mass in future due to increased melting caused by rise in temperature predicted for the region.

Change in Streamflow of Major River Basins

As discussed earlier, fresh water supply is one of the major ecosystem services provided by the Himalaya. But due to recent warming trends, changes in the glacierized area and precipitation pattern have affected the streamflow in the downstream areas. Although, a change in precipitation has a direct impact on the change in streamflow in downstream areas, a change in temperature affects the contribution from snow and glacier melt, the form of precipitation (liquid or solid), and the timing of their contribution to the discharge. To understand the glacio-hydrological process in the IHR; we have compared, the mass balance and the discharge of, different glaciers in the IHR, with that of few polar glaciers[101] (Figure 8). Theoretically, the years with less negative mass balance should relate to the years with a decrease in discharge due to more water stored in glaciers within a hydrological year. This is clearly observed in the case of polar glaciers (Figure 8(b)). In contrast, though statistically insignificant but, except for two glaciers namely Chhota Shigri and Dunagiri, reverse patterns

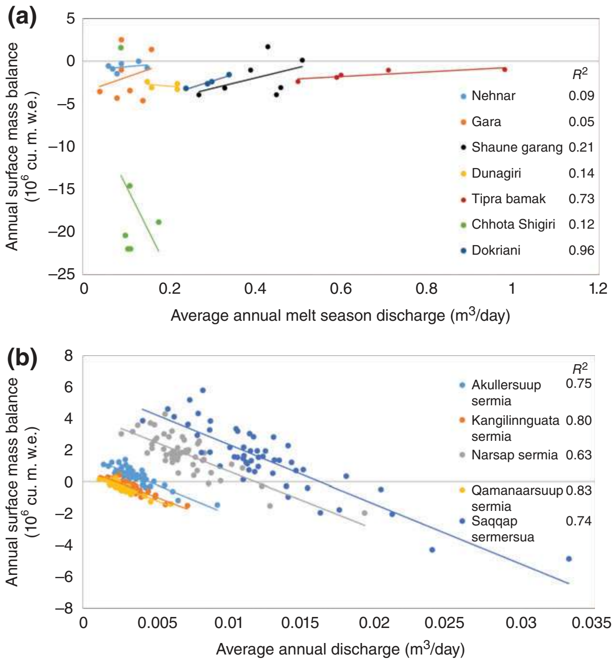

FIGURE 8 | Comparison of (a) annual mass balance measurement and average daily melt season discharge of glaciers in IHR (Azam et al.[90]; Dobhal et al.[91]; Mishra et al.[92]; Raina and Srivastava[30]; Ramanathan[102]); and (b) annual mass balance measurement and average annual discharge of glaciers in Greenland (Van As et al.[101]).

of high discharge during years of less negative mass balance and vice versa have been observed for most glaciers in IHR. Similar conclusions were also made by Thayyen and Gergan,[103] suggesting that this characteristic of the Himalayan catchments is different from glacierized catchments of other mountainous regions and the poles. The positive mass balance is caused by high solid precipitation during winter and low melting during summer. The solid precipitation in the nonglacierized part of the catchment contributes to an increased discharge during summer in a hydrological year of positive mass balance, which can explain such a characteristic.

The percentage contribution of glacier and snowmelt in the streamflow of a river is an important parameter which needs to be dealt with before analysis of the change in temperature and precipitation, on the streamflow. The percentage contribution of these components in the overall discharge from a basin has been summarized in Table 1. The proportion of contribution of snow and glacier melt in the overall discharge of a river increases with the increase in altitude.[110,111] It is evident from previous studies, that the contribution from glacier and snow melt plays very crucial role in the discharge of the Himalayan rivers in the upstream areas (Table 1). The contribution of snow and glacier melt in the downstream areas however, is significant in case of the Indus.[12] The Indus basin has relatively a larger proportion of the areas upstream (>2000 m) to the areas downstream (<2000 m). The contribution of total melt in the downstream areas of Indus, Ganges, and Brahmaputra river basins has been estimated to be 151, 10, and 27%, respectively[12] of the total discharge naturally generated in the downstream areas. The impacts of changing climate on the streamflow of basins cannot be generalized and its severity may vary from basin to basin, depending on the population inhabited, glacierized area and dominance of the southwest summer monsoon/westerlies as source of precipitation.[12] Xu et al.[112] present a systematic summary of the observed signals of future trends of streamflow in different river basins of the HKH region and suggest significant increase in streamflow in all major river basins. In a comprehensive manner, discharge data of four different sub-basins of the Indus basin in western IHR namely, Satluj, Beas, Chenab, and Ravi have been analyzed and compared with temperature and precipitation data.[113] The study suggests that there has been a decrease in the streamflow of Satluj and Beas (strong in recent decades), contrary to an increase in the streamflow of Chenab and Ravi (slight increase in case of Ravi). The scarcity of observed discharge data of river basins has restricted our understanding of the changes in streamflow.

Streamflow is one of the indicators of changes in the climate parameters of a glacierized river basin. Also, it is one of the important resources to be first affected as a result of the changing climate. The analysis of long-term precipitation data from different stations in Indus and Ganges river basins shows that both the river basins are experiencing an increasing trend in precipitation. The Ganges river basin is showing a slight increasing trend in comparison to the Indus river basin.[114] Therefore, both these basins are predicted to experience an increase in flow attributed mainly to the increasing trend of temperature and precipitation in future.[115] Brahmaputra basin covers the Eastern part of IHR. The basin is predicted to experience a sharp increase in temperature and precipitation leading to an increase in the number of occurrences of average and extreme discharge.[116] Immerzeel et al.[12] carried out an extensive study in the high altitude parts of major river basins of the HKH region. The streamflow in the Indus, Ganges, and Brahmaputra from year 2046–2065 is projected to decrease by 8.4, 17.6, and 19.6%, respectively in comparison to the streamflow from year 2000 to 2007.[12] Another study suggests an increase in the net streamflow of the Langtang river catchment, a part of the Ganges river basin in Nepal, by 4 mm/year due to the predicted increase

TABLE 1 | Summary of Results of Different Studies on Percentage Contribution of Different Components to the Total Discharge of a Basin

River/Basin/Glacier	Period of Study	Gauging Site	% Contribution to Annual Discharge		Method Used
			Total Melt	Rain	
Spiti[104]	1987/1988–1989/1990	Basin outlet	49	51	Water balance approach
Chenab[105]	1982–1992	Akhnoor	49	51	Water balance approach
Satluj[106]	1985/1986–1990/1991, 1996/1997–1998/1999	Bhakra Dam	59	41	Water balance approach
Beas[107]	1990–2004	Pandoh Dam	35	65	Water balance approach
Upper Indus basin (>2000 m altitude)[108]	2001–2005	Besham Qila	72	28	SRM based Hydrological Model
Bhagirathi river[109]	1999–2002	Loharinag Pala	70.5	16.3	Temperature index model
Dhauli Ganga[109]	1983–1984, 1987	Tapovan Vishnugad	77.3	10.3	Temperature index model

in temperature and precipitation.[117] A recent study predicts an increase in streamflow in upper catchments of all three river basins. The increase in the streamflow of Ganges and Brahmaputra is attributed to the predicted increase in rainfall while the increase in the streamflow of Indus is attributed to the accelerated melting process due to the predicted rise in temperature.[56] Contrary to these studies, another study predicts a decrease in the annual mean flow for Indus and Ganges river basins while an increase is predicted for Brahmputra river basin.[112] A recent study[118] highlighted the significant delayed impact of the groundwater system on the generation of streamflow, even in high altitude regions, indicating the need to distinguish the groundwater component from snow and glacier melt.[119] The study suggests discrepancy in other studies estimating the streamflow for the Himalayan river basins, as most of them have neglected the substantial contribution of groundwater. Therefore, it is recommended that the base flow which plays an important role in the hydrological regime of the Himalaya, must be considered while modeling the streamflow especially in case of large river basins.

CONCLUSION

Studies on the parameters of changing climate namely, temperature and precipitation, and their effects on changes observed and predicted for glacier length, area and mass balance, and river discharge in the IHR have been summarized in the present study. A very strong indication of warming has been observed in the studies carried out, with rates varying across the region and seasons. The rate of warming for the minimum temperature is more as compared to the average and maximum temperature. But the number of studies and data are very less to draw any conclusion with statistical significance. Any particular pattern of precipitation is missing in the IHR due to very low statistical significance all over the region. Specifically, there is a decline in monsoon precipitation in the western IHR while an increase in annual precipitation has been observed in the eastern IHR. As mentioned previously, the main reason behind the low statistical significance for precipitation pattern is the scarce observational network in the region. Glaciers in the IHR mostly show a reduction in area as well as volume. The data available for glacier length changes in different states of the IHR show an average reduction of 18 m/year in length for an average of four decades of observation. Glacier mass balance in the IHR shows a negative trend in general with few years of positive observation in case of some glaciers. The mass balance studies using nonglaciological methods in the region also show continuous loss of glacier mass with an accelerated rate during late 1990s. Unanimous conclusions of loss in glacier area have been made by several studies in the central and eastern IHR. Remote sensing has served as a very useful technique in monitoring glaciers. But results can be misleading if proper methodology is not adopted for mapping the glaciers. Therefore, it is strongly recommended that internationally accepted guidelines for delineating glacial features[120] must be adopted to reduce discrepancies in the results.

The comparison of discharge and mass balance for the same period of observation shows that most of the glaciers in the IHR show less discharge during more negative mass balance and vice versa. This observation distinguishes the response of Himalayan glaciers from that of glaciers in other parts of the globe. The changes observed in major river basins of the IHR can be described as an impact of the observed warming and change in the precipitation pattern. The streamflow of two major sub-basins in the western IHR has been observed to significantly increase especially in recent decades while the other two show slight increase. The prediction for changes in the streamflow has been widely studied for different basins of the IHR and is complicated. The warming reported in the region will cause increased rate of melting resulting increase in streamflow initially and then decrease. Though, the decrease in streamflow caused by increased temperature and decreased glacierized area can be compensated by predicted increase in precipitation. But the increased temperature will influence the form of precipitation and thus, the timings of its contribution to the discharge and the overall storage capacity of the region. Also, the impacts of changes in streamflow on the population inhabited downstream cannot be generalized, and widely depend on agricultural area, dependence on rainfall for irrigation, hydropower stations, and population density of the basin. Apart from this, the future predictions of the streamflow estimated by different studies for the region have not considered the base flow component and its resultant delay. The base flow plays an important role in the hydrological regime of the region and needs to be considered while modeling the future changes in streamflow.

The IHR is vulnerable to changing climate because of the population inhabited, its dependence on the ecosystem services and physiographic features. Ecosystem and biodiversity in the IHR are vulnerable to changing climate due to high endemism with limited ecological niche of the species inhabited. As agriculture is the main source of livelihood in the region, predicted warming and changes in precipitation patterns in the region will certainly affect the livelihood and economy. In addition, the changes in streamflow with the increasing sediment load during high flow months will have an effect on the performance of hydropower plants. The changing climate is also observed to affect the number of extreme rainfall events in the region, which will increase the number of disasters and natural hazards, making the region further vulnerable.[64,65,121]

There is lack of expertise, observed data, policy, and collaboration, in the region which increases the level of uncertainty in drawing any conclusion with statistical confidence. This also makes it difficult for the communities at the regional and local scale to develop a framework and strategy for adapting to the changing climate. Therefore, a political willingness and implementation of the existing policies is required at the earliest to avoid any delay in ensuring the sustainability of the IHR. However, recent development in availability of freely available remotely sensed data and reanalysis meteorological data provides an opportunity to develop understanding on glacio-hydrology of the region. A nationally coordinated mission named 'National Mission for Sustaining the Himalayan Mountain Ecosystem' under the National Action Plan on Climate Change was initiated by the Department of Science and Technology, Government of India in 2010.[122] The main objective of this mission is to develop the capacity to check the status of the Himalayan ecosystem and to establish policy bodies in accordance with the Himalayan states to support and practice sustainable development. This involves the introduction of capacity building programs and creating institutional network to carry out research. Several capacity building programs in glaciology and climate science have been organized since then.[123,124] Therefore, a better status of knowledge and understanding can be anticipated for the IHR in near future.

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