CHAPTER 6

IMPACT OF CLIMATE CHANGE ON HIMALAYAN CRYOSPHERE

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6.0 Introduction

The mountains cover about 35% geographical area of India, out of which 58% is envelopes by mighty Himalayas, which is almost 21% of India's total geographical area. The permanent snow and glacier fields of the Himalaya act as a critical fresh water reservoir that release large quantity of freshwater throughout the year. The water yield from high Himalayan basin is considered as a dependable source of water supply for drinking, irrigation, hydroelectric power generation and for other miscellaneous purposes like recreation etc. All the major south Asian rivers originating from the Himalayas are fed by the snow and glaciers melt water. Geographically from west to east, the Himalaya has been categorized in three parts, i.e., Western Himalayas, the Central Himalayas and the Eastern Himalayas, on the basis of their latitudes and topographic features. The Indian part of Himalaya has three main river systems namely; Ganges, Indus and Brahmaputra, which are the lifeline of millions of people of northern India. The streamflow in these rivers is induced by a combined form of rainfall and snowfall and glacier-melt runoff. The brief description of these river systems is stated later in this note.

Himalaya has a large area under seasonal snow cover during wintertime which plays a significant role to sustain the regional ecology. The snow cover in the Himalaya varies from western to eastern Himalaya and subsequently affect the flow regime of the rivers. The northern part of western Himalaya receives more snowfall and less rainfall as compared to eastern Himalaya, where the rainfall contribution is significant. Along with the seasonal snow Himalayan glaciers are also have huge storage and very important source of fresh water. In the Himalaya, approximately 33,000 km^2 area is covered by the glaciers (Dyurgerov and Meier, 1997, GSI, 2009) of varying shapes and sizes. With a total number of 9,600 glaciers, the Indian Himalaya (Raina and Srivastava, 2008) has one of the largest concentrations of glaciers after the Polar Regions (Bolch et al., 2001). Such a high concentration of ice has aptly designated the Himalayan region as the 'Third Pole' (Dyhrenfurth, 1955).

Melting from high Himalaya snow cover during early summer is a paramount source of water for many rivers originating from the Himalaya. It is roughly estimated that approximately 10 to 20% Himalayan area is covered by glacier ice, and about 30 to 40% area is covered by seasonal snow cover (Singh and Singh 2001; Singh et al. 2011, Thakur et al., 2013). The runoff from partially glaciered basin is characterized by extended lean flow season from October to February. The flow gradually increases during March and April with the snowmelt and advent of summer, and reaches higher levels of discharge during July and August. The rain and snowmelt contribution for three major basins i.e. Indus, Ganga and Brahmaputra are given in Table 6.1. (Khan et al., 2017)

Table 6.1 Relative percent contributions calculated with respect to sum of Rain (Aphrodite V1101R2), and modeled melt from: snow on land (SOL), snow on ice (SOI), and exposed glacier ice (EGI), for elevations above 2000 m

Basin	Gauge name	Lat (DegN)	Long (DegE)	Elevation (m)	Basin area (km^2)	Basin area>2000 m	Rain %	SOL melt %	SOI melt %	EGI melt (%)

						(km^2)				
Indus	Kotri	25.35	68.33	14	820,659	349,972	23	67	6	3
Ganges	Paksey	24.08	89.02	5	943,244	123,483	52	43	4	<1
Brahmaputra	Bahadurabad	25.18	89.70	13	514,383	344,977	26	66	7	1

It is found that the total annual glacier melt contribution from three major rivers namely; Ganges, Indus and Brahmaputra comes out to be about 16 km3, 41 km3 and 17 km3, respectively for the period of 1961-1990.However, the total glacier melt runoff was decreased to 15 km3, 36 km3 and 16 km3, respectively for these three basins, recent last decade (2001-2010)and shown in Table 6.2 (IWMI report, 2013).Table 6.2 shows that the Indus and Brahmaputra basins have similar percentage of snow and glaciered area, however the decrease in the snow and glacier area are more prominent in Indus basin. Also, the decrease in glacier area in all the three basins is more prominent than the snow cover area. However, the contribution from snow and glacier melt to the total run-off of Indus basin is much higher than the Brahmaputra basin, this is because of the higher contribution of monsoonal rainfall in Brahmaputra basin. Seasonal snow covers about 28% of the total basin area in case of Indus basin, which is much greater than the 2.6% occupied by the glaciers during 1961-90, the contribution of two sources to Mean Annual Flow is more or less same.

Table 6.2: Recent changes in the glaciers and seasonal snow and their contributions to MAF

Basin	**Part of basin area (%) covered by**		**Contribution to MAF (%)**	
	Glaciers	Seasonal Snow	Glacier runoff	Seasonal Snowmelt
1961-1990				
Indus	2.6	28	18	19
Ganges	1.2	6	4	2
Brahmaputra	2.7	27	2	2
2001 -2010				
Indus	1.8	25	15	16
Ganges	0.9	6	3	1
Brahmaputra	2.2	26	2	2

For the Ganges basin, as per the report high precipitation in summer season solely determines MAF volume for the basin. It is almost similar in the Brahmaputra basin while the lower parts of the basin i.e., Southeastern Tibet and Eastern Himalayas, observes the high monsoon rains. The report does an analysis of assessments done on impact of climate change on water availability in Himalayas and concludes that many assessments rely on poorly verified sources.

Using the Table 6.2 given above, the report states that the contribution from the glaciered region in the Ganges and Brahmaputra basins is very low to the annual water budgets. The report says, "The climate change impact was found to be more prominent on seasonal rather than annual water availability". Also, the increase percentage in nonrenewable glacier runoff components is highest among all three basins during the years 2001-2010, which imply that the glaciers of Ganga basin are melting rapidly

Table 6.3: Contribution of renewable and non-renewable components to glacial runoff.

Basin	Glacier runoff components		Total Glacier runoff (km^3)	Total Glacier runoff contribution to MAF (%)
	Renewable (km^3)	Nonrenewable (km^3)		
1961-1990				
Indus	33	8.14	41.2	18
Ganges	11	4.74	15.7	4
Brahmaputra	12.7	4.29	17	2
2001 -2010				
Indus	24.5	11.62	36.1	15
Ganges	8.1	6.95	15	3
Brahmaputra	10.6	5.05	15.7	2

6.1 Climate Change

Mountainous regions in general and Himalayas in particular have been identified as one of the most vulnerable regions to climate change (Bajracharya et al., 2015). Himalayas have varied climate from one region to another with elevation ranges varying from 1000 m to 8000 m above mean sea level (Azam et al., 2018). The complex terrain and general inter-dependency of mountain environment and socio-economic systems offer significant difficulties for climate change impacts studies. Different climate models such as General Circulation Model (GCM) and Regional Climate Model (RCM) are used to highlight the climate change impacts on Himalayas (Singh and Goyal, 2016; Bajracharya et al., 2015; Chang I. C., 2013; Jain et al., 2010), however, they are characterized by large amount of uncertainty in their projections. GCMs and RCMs may carry uncertainties due to coarser spatial resolutions and uncertainty involved with their complex physical processes and therefore, sometimes they are less applicable.

Global surface air temperature is projected to keep rising, while the snow and ice fields are reducing, in all assessed climatic scenarios during the 21st century (IPCC, 2014). Therefore, glacier component in the annual runoff in glacier-dominated catchments is increasing to a certain maximum and then starts dropping as the glacier surfaces start shrinking. The timing of the peak of the glacier component depends on the characteristics and location of the catchment. During the past 100 years, the Himalayan region (including Tibetan Plateau) has shown a constant trend in the global warming (Yao et al. 2007). Several studies suggest that warming in the Himalayas is much greater than the global average of 0.74°C over the last 100 years (IPCC, 2007). During 20th century, Bhutiyani et. al. (2007) carried out a detailed study on long-term trends in the minimum, maximum and mean temperatures over the north western Himalaya and reported a significant rise in air temperature with a faster rate of winter warming. Future changes in precipitation are more uncertain and of varying nature across the Himalayas depending on the climate model, season and sub-region, with a general indication of increasing annual precipitation (Nepal and Shrestha, 2015). Long term projections indicate increased precipitation during monsoon season by up to 17%, with precipitation rising up to 12% in winter (Christensen et al., 2013).

The temperature warming due to climate change has brought significant changes in monsoon and precipitation over Asia and other parts of the world. Himalayan ranges are the youngest and belong to extreme high elevation ranges. Himalayas consisted with large amount of fresh water reserves in the form of glaciers, temporary and permanent snow covers, permafrost, lakes, wetlands, and hence it is called as "the water tower of India" (Bolch et al., 2012). The high mountainous regions, especially under Indian Territory, also named as Indian Himalayan Regions (IHR), are under the threat of accelerated anthropogenic greenhouse gas emissions as well as climate change (Singh et al., 2016). The effect of climate change over Himalayas has not only affected its physical processes but it also affects the economy and livelihood of the local communities (Azam et al., 2018). Due to poor availability of quality climatological datasets for IHR, a very few studies highlighted the effect of climate change for the region (Singh and Goyal, 2016; Jain et al., 2010). This has led to number of uncertainties and thus sometime climatic observations are less helpful in this region (Goyal, 2016; Jain et al., 2010).

A study done by Minder et al. (2018) discovered the characteristics and causes of elevation dependent warming in the high hilly Rocky Mountains using high resolution Weather Research and Forecasting Model (WRF) and observed a very complex patterns of warming with elevation, together with cases of warming nearly independent of height. In this study it is found that warming was maximum in regions of maximum snow loss and albedo reduction. As per the study conducted by Jain et al. (2009), the elevation-based fluctuations in temperature may affect the snowmelt process, especially over Himalayan regions. The elevation dependent warming may have significant influence for the mass balance of the high altitude and low altitude glacial areas. Himalayas have complex topography and climate variations and thus many factors make it difficult to analyse the rate of warming in high elevation areas (Pepin et al., 2015). Many studies suggested that warming is higher at higher elevations, but most of studies failed to provide a relationship or showed complex situation (Singh and Goyal, 2016; Jain et al., 2009). The reason could be lack of consistency in the data and methods utilized to determine the rate and patterns of warming. Yan and Liu (2014) showed a striking evidence of elevation dependent warming trends over Tibetan Plateau while using observations from 139 stations. Any temperature change to earth's surface affects the energy balance and along with other climate factors it may increase the net flux of energy; with an elevation changes it may further lead to accelerate warming as a function of elevation (Pepin et al., 2015).

Several studies highlighted that shifting of the permanent snow line across many glaciers in Himalayas are due to climate change (Das and Sharma, 2018; Salerno et al., 2017). The relationship between snow cover duration and elevation is nonlinear; therefore, snowline may change/retreat as temperature increase. This will enhance the absorption of solar radiation over the retreated snow line areas and the warming will be enhanced at that elevation region (Hantel et al., 2000). You et al. (2017) summarized the factors which could be responsible for the recent climate warming in the Himalayas such as acceleration in anthropogenic greenhouse gas emissions, the snow/ice-albedo feedback, and changes of environmental elements (e.g. cloud amount, Asian brown clouds, land use changes and specific humidity etc.). However, the perfect explanation for driving mechanisms accountable for elevation dependent warming need further investigation. The GCM and RCM outputs are found helpful to build a mechanism deriving elevation dependent warming, asmodel outputs can be run to produce both past and future climatic variables (Palazzi et al., 2018).

A study over Tibetan Plateau Himalayas (Palazzi et. al, 2018) identifies the thermal radiation as the most influencing factor for elevation dependent warming. Another study based on Sikkim eastern Himalayas, Singh and Goyal (2016) reported a strong correlation in elevation dependent warming and elevations, this relationship can be either positive or negative. Singh and Goyal (2016) utilized CMIP5 GCMs and computed precipitation lapse rates (gradient changes) based on elevation difference over Sikkim Himalayan catchments and found significant changes in precipitation lapse rates (during 2006-2100) due to the effect of climate change. Precipitation lapse rate has been recognized as an important component for determining snowmelt under varying conditions (Singh and Goyal, 2016; Jain et al., 2008). Though the GCMs and RCMs provide an effective way to examine the mechanisms by which elevation dependent warming occurs in response to increased CO_2 and climate change; an improved and finer resolutions parameterization schemes in climate models are essential to provide accurate observations.

6.2 Snow-Glacier Induced Himalayan Hydrology under Changing Climate

The above-mentioned changes will affect the water resources generated in the Himalayan catchments, modifying flow extremes and seasonal discharge patterns due to changes in rainfall amounts and seasonality, as well as snow and glacier accumulation and melt (Bolch et al., 2012). Thus, a robust spatio-temporal understanding of impacts on water requirements and availability is necessary for informed adaptation planning, which is of crucial importance for the regional economy and the livelihoods and well-being of the inhabitants (Kumar et al., 2015; Soundharajan et al., 2016). Hydrological models are a vital tool to support this analysis (Kour et al., 2016), as they translate the understanding of future climate and land use changes into impacts on river discharge and water availability in time and space.

Runoff at the basin scale is mainly sensitive to precipitation and temperature. Few studies have shown that due to increase in temperature, streamflow in melt season is reduced (Pelto, 1996, 2008; Barnett et al., 2005; Nolin et al., 2010); whereas other studies report that increasing temperature tends to induce glacier retreat and increased runoff through a rise in snow melt amount (Liu et al., 2003; Li et al., 2010; Zhang et al., 2011). The opposite conclusions can be attributed to the different length of analysis periods as the change in runoff volume is not correlated with increasing temperatures. In a warmer climate, runoff will increase first due to higher temperatures and more snowmelt. However, this phenomenon will reduced gradually as the glacier area will begin to decline as a result of continued glacier mass loss (Ye et al., 2003; Rango et al., 2007; Huss, 2011) causing streamflow to initially increase for a given period before declining in glacier basins.

According to the Fifth Assessment Report of Intergovernmental Panel on Climate Change(IPCC), the earth will be warmer by 1.5°C to 4.5°C by the end of 21st century (IPCC 2013), this would accelerate the melting of glaciers and snow covers and will also affect the natural equilibrium from precipitation-to-rain and precipitation-to-snow in mountains. There are two drivers identified by Foster et al. (2016) that can be affected by temperature increase and will have significant impact on snow hydrology over mountains: (i) precipitation phase that can be shifted and (ii) available energy at the land surface which may increase. Foster et al. (2016) also showed the reduction in streamflow between 11 to 18% over semi-arid mountains due to shift in precipitation pattern from snowfall to rainfall. Similar observations were made by Liu et al. (2018) in Upper Yellow River Basin (USA) where due to enhanced warming and wetter conditions, more precipitation was reported in the form of rainfall and thus more flow added in the total runoff. Nevertheless, several studies found that it is critical to understand the impact of these two drivers (shift in precipitation phase and changes in available energy at the land surface) on hydrologic partitioning vis-à-vis preparedness against climate change in snow-dominated regions (Liu et al. 2018; Foster et al. 2016). Several efforts have been made in this direction reveal the relative sensitivity of mountains to changes in precipitation phase and surface energy fluxes (Barnhart, 2018; Foster et al. 2016).

Snow cover and glaciers are important components of Himalayan hydrology and are expected to be vulnerable to accelerated global warming and climate change (IPCC 2013). These are the key hydrological components that benefit various sectors such as agriculture, hydropower production, sanitation and drinking water supply, especially in IHR. Many studies have highlighted that temperature and precipitation significantly changed over Himalayan regions due to climate change (Singh and Goyal, 2016; Bolch et al., 2012). The permanent snowpack (or snowfall) and glaciers are reported to be reducing their masses and more snowmelt is entering the streams (Shukla et al., 2017; Jain et al., 2009). Many studies utilized remote sensing applications for the characterization of glaciers (Singh and Goyal, 2018) and calculation of snow cover areas and their changes (Shukla et al., 2017; Jain et al., 2010; Jain et al., 2009; Kulkarni et al., 2007), however, due to the limitation of the temporal data availability from remote sensing it is found less applicable for analysing long term changes. An increased global annual average temperature is reported as the primary cause of changes in precipitation pattern and magnitude in the Himalayas (IPCC, 2013; Bolch et al., 2012). The retreat in glacier and variations in snowmelt due to climate change may influence water storage and, thus, affecting the sustainability of human activities. The equilibrium between precipitation-to-rain/snow is changing. Spatial distribution and temporal variability of rainfall and snowfall across the Himalayas in spatio-temporal domain is attributed to climate change (Jain et al., 2008). While snowpack and glaciers influence stream flows in high elevation, rainfall is considered a predominant factor in low elevations (Jain et al., 2009). As an example, Satluj River, one of tributaries of Indus. Higher melting will result in an increase in runoff downstream before the monsoon season (Jain et al., 2010) leading to increased vulnerability to floods in downstream channel. The variability in Temperature Lapse Rate (TLR) and Precipitation Lapse Rate (PLR) due to observed climate change can be the major cause of reduced snowpack at high elevations of the Himalayas (Singh and Goyal, 2016).

Snowmelt which is highly sensitive to temperature change and precipitation pattern is particularly significant for flow in the Himalayan basins. Immerzeel et al. (2013) forecasted reduction in glacier area and volume by 33% and 50% by 2100 with peak glacier melt in 2044 or 2065 in the Baltoro catchment of upper Indus basin. It will lead to 7-12% increase in annual runoff by 2050 due to accelerated melt with increase in precipitation (Lutz et al., 2014). At present Snow and glacier melt contributes 10% and 27% to upstream water flow overall in the Ganges and Brahmaputra basin, respectively. It may decrease by ~17% in Gnaga and ~20% in Brahmaputra basin by 2046-2065 as per the projections made in A1B emission scenario (Immerzeel et al., 2010). This reduction in upstream melt runoff may partially compensated by the increased upstream rainfall by more than 8% and 25% in upstream of Ganges and Brahmaputra. Immerzeel et al., (2013) forecasted 54% reduction in glacier area by the end of the century in Lang tang catchment of Ganga basin under projected climate change scenario.

The capability or strength of any hydrological model to simulate and project snowmelt and glacier melt runoff depends on how well the model accounts the complexities that are associated with multiple snow-hydrology parameters and their processes (Fontaine et al., 2002). Many studies incorporated the temperature index model based on the degree-day-factor (e.g. SWAT Model, HMS Model, NAM model, HBV model etc.) for the assessment of snowmelt runoff (Goyal and Goswami, 2018; Kumar et al., 2017; Azamat et al., 2016). Temperature index model generates snow water equivalent (SWE) or the amount of snowmelt (liquid water) using a constant snowmelt factor which is a function of mean surface air temperature (Fontaine et al., 2002), however, in unstable climate conditions like Himalayas where elevation variations are frequent this approach is found less acceptable (Kumar et al., 2017; Fontaine et al., 2002). The snowmelt factor or degree-day factor directs the snow-glacier melt process, and it is defined as the function of temperature. The temperature is dependent on elevation, and thus, it alters the degree-day parameter significantly (Fontaine et al., 2002), however, an elevation dependent warming in Himalayas due to climate change can enhance uncertainties in their simulations (Kumar et al., 2017; Azamat et al., 2016). Therefore, the role of elevation bands must be addressed when computing snowmelt and snowpack, especially over Himalayan catchments.

Stigter et al. (2017) utilized remotely sensed snow cover with the seNorge snow model to estimate snow water equivalent and snowmelt runoff over Nepalese Himalayan catchment and a decrease in snow water equivalent (SWE) due to higher air temperature at high elevations is observed. Shukla et al. (2016) utilized remotely sensed MODIS snow cover dataset to find out the snow cover area-based changes in western Himalaya and revealed 44% to 56% variations in snow cover area over Satluj river Himalayan catchment during 2001 to 2014. Several studies highlighted that since last two decades Himalaya has warmed greatly (IPCC 2013). Engelhardt et al. (2017) utilized mass balance model for the computation of meltwater runoff from a glaciered catchment of western Himalaya and revealed that mass balance approaches are more compatible for accounting melt contributions especially from glaciers. Jain et al. (2010) used elevation band approach for accounting snowmelt runoff from satellite snow covers in Satluj river Himalayan catchment and incorporated GCMs for analysing snowmelt runoff changes in future time domain. The results showed that snowmelt runoff occurred earlier due to increased snow melting, a shift is observed, however, reduced in the monsoon months. Ahluwalia et al. (2017) utilized hydrological model SNOWMOD coupled with isotope analysis to characterize and compute the snowmelt runoff in western Himalayan catchment. The coupled approach is found more suitable to analyse snowmelt and glacier melt runoff separately. A very few studies applied energy balance approach for the computation of snowmelt runoff over Himalaya due to less data available and harsh climatology of Himalaya. Energy balance approach could be more accurate but it requires large amount of dataset. However, a study done by Datt et al. (2008) used energy balance approach over North-West Himalaya for snowmelt runoff computations show significant improvements in the results.

Apurv et al. (2015) studied over eastern Himalayas and reported a significant increase in the amount of discharge from the Brahmaputra River utilizing CMIP5 GCMs. Most of the modeling-based approaches incorporated the melt contributions in streamflow only from the snowfalls (or snow cover areas). Studies using GCMs revealed the impact of climate change on the variability of precipitation over the Himalayas (Singh and Goyal, 2016; Apurv et al., 2015; Jain et al., 2010). Several studies utilized GCMs and RCMs for the assessment and projections of snowmelt and snowpack in Himalayas and revealed that in future snowpack will be reduced, while snowmelt volume will be enhanced due to warming (Palazzi et al., 2017; Jain et al., 2010). However, the accuracy of these predictions is still not very clear because of the uncertainty involved in coarser resolution GCMs and RCMs and also due to uncertainties associated with hydrological models (Singh and Goyal, 2016; Apurv et al., 2015; Jain et al., 2010).

Observed discharge variations in the Himalayan head Water Rivers and tributaries, with substantial snow and glacier ice contribution show a mixed response with majority of them showing a declining or a steady trend. In the Ganga basin, flow of the Kali Gandaki at Setibeni declined by 12% over 20 years, while the runoff from the bigger Narayani basin basin remained stable. Discharge of Sutlej at Khab decreased by 32% over 20 years, influenced by declining monsoon precipitation over the north-west watershed of the Ganges basin (Collins et al., 2013). Reducing discharge in the Sutlej in the downstream reaches, at the Bhakra dam, confirms weakening monsoon conditions reducing summer precipitation in the late twentieth century (Thayyen and Gergan, 2010). Similar to the Sutlej river, Beas river also shows declining trend in the discharge (Bhutiyani et al., 2008). Moving further west, Chenab, Jhelum and Indus, rivers show lower discharge during 2000-2016 period as compared to 1985-1998 period (Wescoat et al., 2017). The observed discharge variations of western Himalayan rivers have an overriding trend of reducing discharge which is not entirely in tune with the results obtained from modelling studies. This points towards large uncertainty of modelling studies which call for greater improvement in climate modelling of Himalayan region.

6.3 Status and Mass Changes of Indian Himalayan Glaciers

A considerable impact on the glaciers of Himalayan Region has been seen due to change in climate in recent decades. It is believed that the changes in glaciers are a consequence of climatic changes. The response of climate change on glacier is different which depends on size, area-altitude distribution, orientation, and moraine cover. Change is glacier extent is important to study as it will have profound effect on water availability. For estimation of retreat it is important to identification and mapping of glacier boundary and terminus. The identification of snow, ice and rock on satellite images is possible in case there is no debris because of the difference in spectral reflectance signature of different surfaces. A map of glacier in three major basins of Himalayan region i.e. Indus, Ganges and Brahmputra are shown in Figure 6.1 (Sharma et al., 2013)

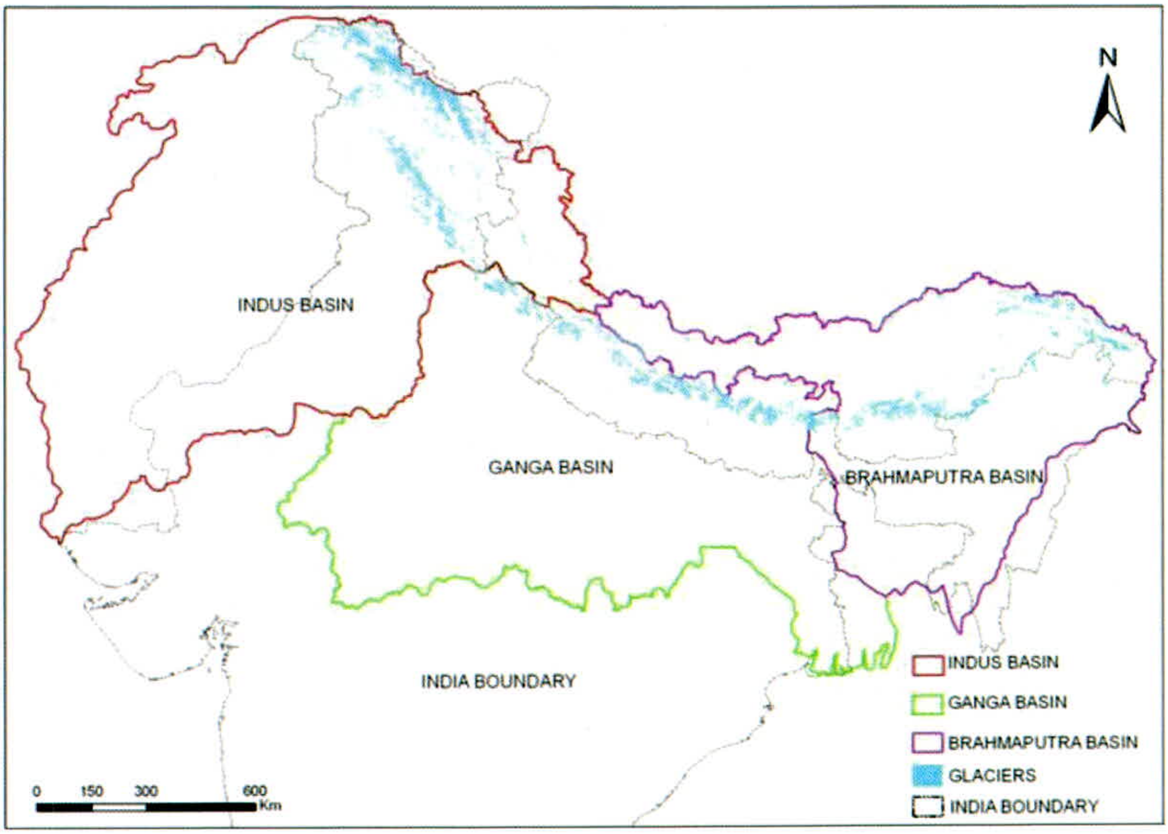


Figure.6.1 *Indus, Ganges and Brahmputra with glacier covered area*

Studies highlighted that glaciers in Himalayan regions are retreating since 1850s (Azam et al., 2018), however, a very few studies highlighted opposite trends such as Karakoram glaciers gained mass and found stable during 1998-2008 (Gardelle et al. 2012). Several studies based on field measurements highlighted that ice flow of land-terminating glaciers varies with mass changes at decadal scales (Dehecq et al., 2018; Vincent et al., 2009; Span and Kuhn, 2003). In other study, ice velocity changes analysed in recent decades using single satellite image pairs from few numbers of glaciered regions in the world (Heid and Kaab, 2012). In these studies, with negative mass balance ice flow found slower in regions but also represented no clear relation between mass balance and velocity change. A study by Wagon et al. (2007) over Chhota Shigri Glacier, a part of western Himalaya, found evidences of retreat which could be influencing by the effect of incoming solar radiation. It was further observed that melting rate varies as per elevation variations and thus, they suggested an energy-balance approach to analyse the effects of heat fluxes. More recent studies clearly highlighted that most of glaciers in Himalayas including large size glaciers are under threat to climate change (Azam et al., 2018; Kaushik et al., 2018; Mukhopadhyay, 2012). Kaushik et al. (2018) studied western Himalayan ranges and analyse the climate change driven impacts on glaciers. Bhaga river basin demonstrated that the total area of glaciers was lost by reduction rate of 12 m/year from 1979 to 2017. Glaciers situated at low elevations and smaller in sizes are reducing faster than large size glaciers (Kaushik et al., 2018; Mukhopadhyay, 2012).

Most of studies conducted over smaller size of glaciers showed enormous changes, while only few studies showed significant retreating in large size of glaciers (Thakuri et al., 2013; Nainwal et al., 2008). Several site-specific studies provided significant information about various glacial parameters such as glacier orientation, hypsometry, topography, morphology and other glacier dynamics (Mukhopadhyay, 2012; Kulkarni and others, 2007). Debris cover is an important factor for analysing glacier retreating and studies highlighted that glaciers having thick debris covers which are responsible to reduce melting rates found less prone to retreat (Singh and Goyal, 2018; Huss et al., 2011). However, the thickness of debris covers is mainly controlled by elevation (Singh and Goyal, 2018) and therefore, elevation dependent warming could be crucial to understand the glacier retreating (Murtaza and Romshoo, 2017). The ice-covered area of Satopanth Glacier part of Alaknanda basin reduced by 313.9 m^2 mainly at the snout area from 1962 to 2006.In other glacier such as Bhagirathi Kharak Glacier around 129.4 m^2 area has been during a similar time period (Nainwal et al., 2008). While these two glaciers having same climatic and topographical conditions and also situated in the same river basin, their recession rates were recorded to be different. This could be happened because of the sensitivity of the thickness of debris covers with respect to elevation changes. Bhambri et al. (2011) concluded that the south- and southwest facing glaciers shrank at higher rates and average shrinkage rate mainly is influenced by glacier size. Huss (2011) noticed that when glaciers shrunk, their relative contribution decreased and the annual runoff peak shifted toward spring. However, shifting in the runoff is expected to be higher in the western Himalaya than the eastern Himalayas due to shifts in snowmelt, where monsoon and melt seasons overlapped (Azam et al., 2018).

Glacier change studies have been carried out in two sub-basins of Satluj basin and Beas basin by National Institute of Hydrology (NIH), Roorkee. A glacier inventory has been prepared using Survey of India (SOI) topographical maps (1966) and Landsat datasets as ETM+ (2000, 2006) and TM (2011) to study glacier changes in Tirungkhad basin (Fig. 6.1a). This basin, a part of Satluj basin, is located in western Himalaya. Glacier areal changes showed a deglaciation of 26.1% (29.1 km^2) from 1966 to 2011. Smaller glaciers (area <1 km^2) lost more ice (34%) compared to large glaciers (area >10 km^2) for which the ice loss is reported around 20%. Glacier volume loss was found to be 32% (2.9 km^3) from 1966 to 2011. The north facing and low altitude glaciers showed high percentage of loss. A trend analysis of temperature, rainfall and snow water equivalent (SWE) was also carried out. During a period of 24 years (1984 to 2008), the mean annual maximum temperature has increased by 1.1°C and minimum temperature has increased by 1°C, whereas snowpack and rainfall has decreased. SWE data from Purbani meteorological station within the basin also showed a decreasing trend. This observation indicates that the warming of the climate is probably one of the reasons for the glacier retreat in the basin.

Using the Landsat data (MSS, ETM+ and TM), the changes in glacier area, length and debris cover have been delineated in the Baspa basin (Fig. 6.2)., which is a highly glacierised sub-basin of Satluj River in the western Himalaya. A total of 109 glaciers have been inventoried and it is found that 36 glaciers were found to be heavily debris covered. The clean, small sized, low altitude glaciers with south to southwest aspect and relatively steep slope have lost maximum area which indicates a major control of these factors on the glacier changes.

The mass balance of glaciers has been determined using the geodetic method (Pratap et al., 2016; Zemp et al., 2013), glaciological method (Pratap et al., 2016; Dobhal et al., 2013; Paterson 1994), accumulation-area ratio (AAR)/equilibrium line altitude (ELA) method (Pratap et al., 2016; Brahmbhatt et al., 2012; Kulkarni 2004) and hydrological method (Pratap et al., 2016; Bhutiyani et al., 1999). Glaciological mass balance is an in-situ measurement of ablation and accumulation for the entire glacier in a balance year which generally utilize to compute glacier mass and volume changes

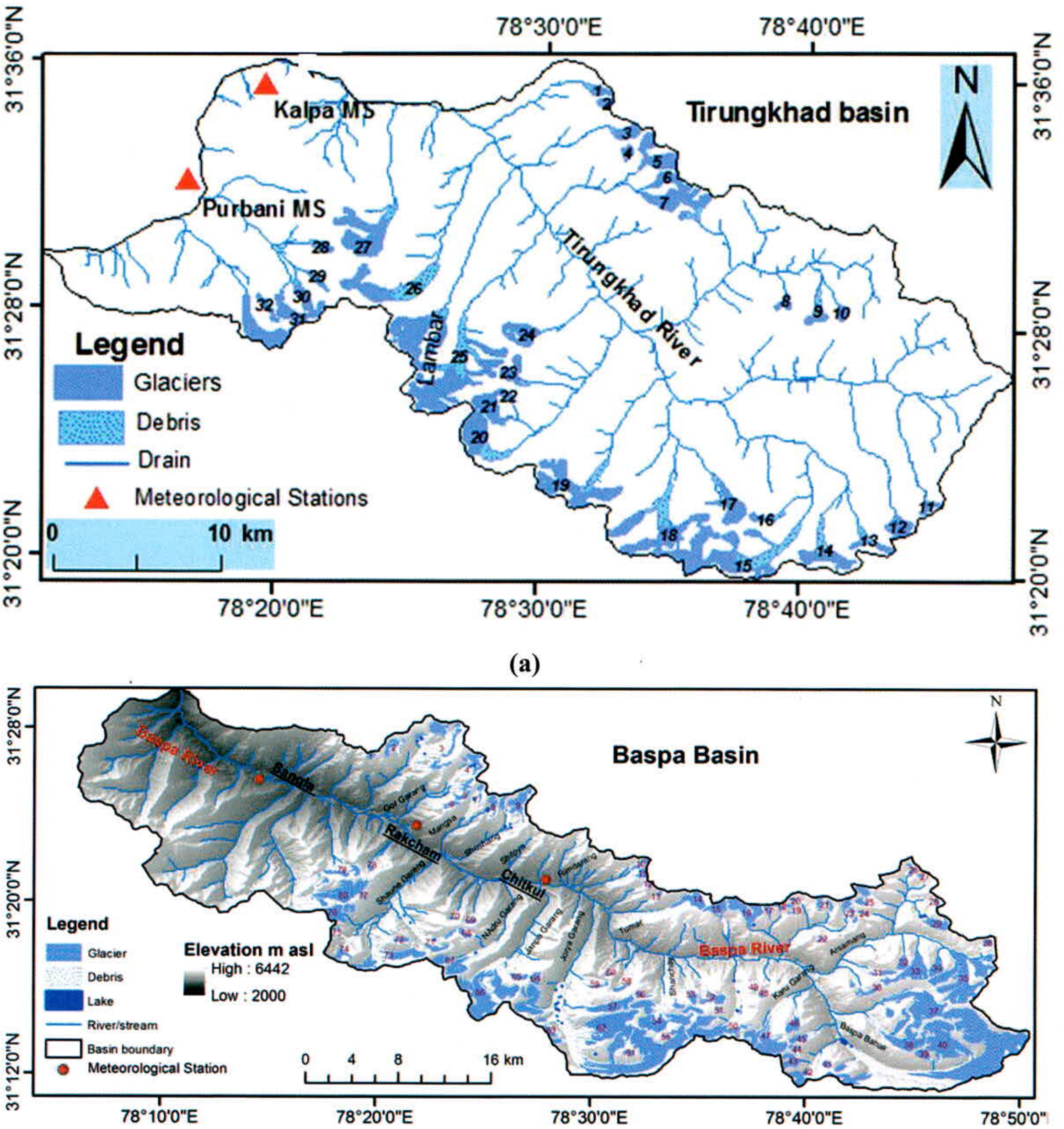
(Pratap et al., 2016; Paterson 1994). Geodetic method mostly utilizes to compute glacier thickness by generating Digital Elevation Model (DEM) of the glacier in two different times (Zemp et al., 2013). In the early seventeenth century, glacier boundaries and their characteristics (parameters) were denoted as rough sketches. Raina and Srivastava (2008) provided a glacier inventory and historical documentation of the glacier related studies in India, which gives detail for only few selected glaciers. The Survey of India (SOI) is the nodal agency in India involved in surveying the Himalayan regions and mapping glaciers since year 1767 when it was established. Few glacier inventories have been prepared for world glaciers and specific to Himalayan glaciers (Frey et al., 2012; Cogley, 2009).

A study by Bhushan et al. (2018) over Zanskar River basin analysed the prevent mass loss in glaciers, and emphasizes that mass budget and surface velocity of glaciers is important for characterizing heterogeneity in glacier dynamics. Thayyen and Gergan (2010) also reported that most of the glaciers are retreating due to warming, whereas glacier growth is also observed over few glaciers due to strong monsoon. In other study over central Himalaya, Xiang et al. (2018) utilized remote sensing techniques for the assessing glacier mass-balance (1975-2010) and reported that debris covered glaciers having area > 5km^2 retreated faster than debris free glaciers ofsame sizes. A study conducted by Mir et al. (2018) over Dalung Glacier and Padam Glacier, western Himalaya utilizing remote sensing satellite datasets of different temporal resolutions found significant reduction in the mass of both glaciers with different recession rates. Garg et al. (2018) found a degeneration of the frontal part of the Kangriz glacier situated in Jammu and Kashmir, western Himalaya, and resulted accelerated surface melting, thinning of debris cover and snout areas. The ablation data assimilated for 2016–2017 displays the lowering of the frontal part of the glacier to be ~148 ± 34 cm (mean). Thinning rates of the debris flows of Gangotri glacier have seen during the period 1968-2014. In many studies like for Gangotri glacier the reduction of length of glaciers is identified as a delayed response of climate change, while glacier mass balance is identified as a more direct and immediate response (Bhattacharya et al., 2016).

6.4 Status of Permafrost in the Himalaya

Permafrost is another cryospheric component critical for the Himalayan environment. Permafrost is unconsolidated sediment or bedrock that remains frozen for at least two consecutive years. Permafrost mainly occurs in the arctic (Westermann et al.,2015, Gartner-Roer et al.,2010) and high mountain areas (Haeberli et al., 1993; Cremonse et al.,2011, Gruber et al.,2012) and impact around 25% of the landmass of the northern hemisphere. Number of studies have shown permafrost thawing in the Northern Hemisphere during the past couple of decades (Nelson, 2003; Hinzman et al., 2005, Zhang et al., 2005; Romanovsky et al., 2010). However, Permafrost studies are sparse in the Hindu Kush Himalaya (HKH) region in general and IHR in particular (Gruber et al., 2017).

As water resources in the IHR region showing signs of stress, with the increasing population and unpredictable climate; there is a need to look into the finer details of the water resources dynamics in the Himalayas. Conclusive evidence of permafrost in the IHR was available from Tso Kar lake area way back in 1975-76 from a study conducted by the Geological Survey of India (GSI) (Rastogi and Narayan, 1999). Boreholes drilled up to 29m had many ice layers interspersed with sandy gravel layers with a temperature of -2^{o}C indicated permafrost area about 20 km^2. Initial modelling assessment on a regional scale suggests that the permafrost area in the HKH region could extent up to 1 million km^2, which roughly translate into 14 times the area of glacier cover of the region (Gruber et al., 2017).



(a)

(b)

Figure 6.2 *Location and glacier maps of the (a) Tirungkhad and (b) Baspa basins, which are sub-basins of the Satluj river basin. On the maps, the glaciers are labeled by numerical numbers only where as in the text; the prefix G is also indicated before the numerical number (such as G-1, G-2).*

As water resources in the IHR region showing signs of stress, with the increasing population and unpredictable climate; there is a need to look into the finer details of the water resources dynamics in the Himalayas. Conclusive evidence of permafrost in the IHR was available from Tso Kar lake area way back in 1975-76 from a study conducted by the Geological Survey of India (GSI) (Rastogi and Narayan, 1999). Boreholes drilled up to 29m had many ice layers interspersed with sandy gravel layers with a temperature of -2°C indicated permafrost area about 20 km^2. Initial modelling assessment on a regional scale suggests that the permafrost area in the HKH region could extent up to 1 million km^2, which roughly translate into 14 times the area of glacier cover of the region (Gruber et al., 2017). Studies on the rock glaciers were also carried out in recent past suggested that the lower limit of permafrost in the region may lies within 3500-5500 m a.s.l. (Schmid et al., 2015). Allen et al., (2016) suggested a permafrost spread of 420 km^2 in Kullu district of Himachal Pradesh covering 9% of the district area.The cold-arid region of Ladakh has reported sporadic occurrence of permafrost and associated landforms (Gruber et al., 2017) with sorted patterned ground and other periglacial landforms such as ice-cored moraines. Catchment scale studies suggest that ground ice melt component may be a critical water source during dry years in the cold-arid regions of Ladakh (Thayyen et al., 2015). Ladakh has large areas of high altitude wetlands and lakes and the studies indicated phases of permafrost growth during low lake levels, especially after 5 kyr BP. Continuous development of permafrost mounds and thermokarst features are also inferred during the last 60 years as well (Wünnemann et al.2008). These studies have firmly established significant permafrost coverage in the high mountain areas of IHR. As glaciers and snow cover are shrinking in the most part of the IHR (Bolch et al., 2012, Immerzeel et al., 2013) in response to changing climate, the permafrost areas are also expected to respond in a comparable manner as evident from other similar cryospheric areas globally. Possible permafrost thaw related impacts also can be inferred from other areas which include changed frequency and unexpected location of landslides, changes to vegetation and runoff patterns, change in the water quality and sediment load in the rivers and could impact more on the population depended on these high altitude ecosystems (Gruber et al., 2017). World Meteorological Organization (WMO) describes the permafrost as an essential climate variable and growing appreciation of the permafrost thaw related issues are visible in the region during the recent past. Some firm steps are taken by the national and International agencies (Stumm et al., 2016; Thayyen et al., 2016) to promote permafrost research in the IHR.

6.5 Climate Change and Extreme Events

A study conducted over eastern Himalaya and western Himalaya based on CMIP3 and CMIP5 models showed a significant increase in Temperature (Panday et al., 2015). Singh and Goyal (2016) developed standard precipitation extreme indices over Sikkim Himalayas utilizing CMIP5 GCMs and revealed that extreme high intensity events and wet spells will increase after 2040s. In a similar area (Sikkim Himalayan catchments), Goswami et al. (2017) generated temperature extreme indices applying copula-based approach under CMIP5 GCMs and revealed that warmest night and day temperature are increased by 1.41°C to 1.83°C, respectively. Every of the main features of the Himalayan regions induced by snow, glaciers and ice-sheets may carry conditions that can pose threats to society under extreme climate conditions (Xu et al., 2007). For example; a large fluctuation in the melting of snow and ice may result in extreme or inadequate water supplies, heavy snowfalls can obstruct roads and other structures. Heavy snowfall on steep slopes, which are so frequent in Himalayan regions, and related conditions give rise to avalanches etc.

Nandargi and Dhar (2011) analysed precipitation extremes over Himalayan regions during 1871 to 2007 and concluded that the frequency of rainfall events has been significantly enhanced during 1951-2000 followed by a sudden decrease from 2001 to 2007. Another study based on precipitation extreme indices performed over HKH regions showed that light and moderate precipitation events have increased during 1961-2012 over Indian and Tibetan Plateau (Zhan et al., 2017). Several other studies have also shown an increase in precipitation over Tibetan Plateau (You et al., 2017; Singh and Goyal, 2016). Several precipitation gauges over the Karakoram regions have also measured a clear increase in the number of wet days and extreme precipitation events during the last few decades (Choi et al., 2009; Klein Tank et al., 2006). Studies highlighted that because of the positive correlation between changes in potential velocity of air near surface and precipitation along with the flow of western disturbances and topography of the western Himalaya complicated extreme weather events (e.g. Leh floods in 2010, Uttarakhand floods in 2013; Kashmir floods in 2014) (Zaz et al., 2019). As per IPCC (2013), in the Himalayas, every year there will be at least one extreme event. It may range from north-eastern India to Pakistan in the west. A glaicla lake inventory of three major basins is given in Table 6.4. (Maharjan et al., 2018)

A continuous glacier recession due to climate change and due to which formation of glacial lakes have been found behind the newly exposed unstable moraines in most of the glaciated regions of the world (Kaser et al., 2006; Zemp et al., 2009; Bolch et al., 2012; Mir et al., 2015).These lakes are made of poorly consolidated unstable glacial material and formed behind consolidated end-moraine dams. During recent past, a number of glacial lakes have been identified and found expanding in response to climate change and glacier thinning (Reynolds, 2000; Ageta et al., 2000; Benn et al., 2000). The moraines provide a physical barrier to glacial melt water drainage resulting in the creation of a moraine-dammed glacial lakes (Costa and Schuster, 1988) with a potential for a glacial lake outburst flood (GLOF) hazard (Benn et al., 2012; Westoby et al., 2014; Worni et al., 2014).

Table 6.4: Number, area (in km^2), and types of glacial lakes in three major river basins of Himalayan region

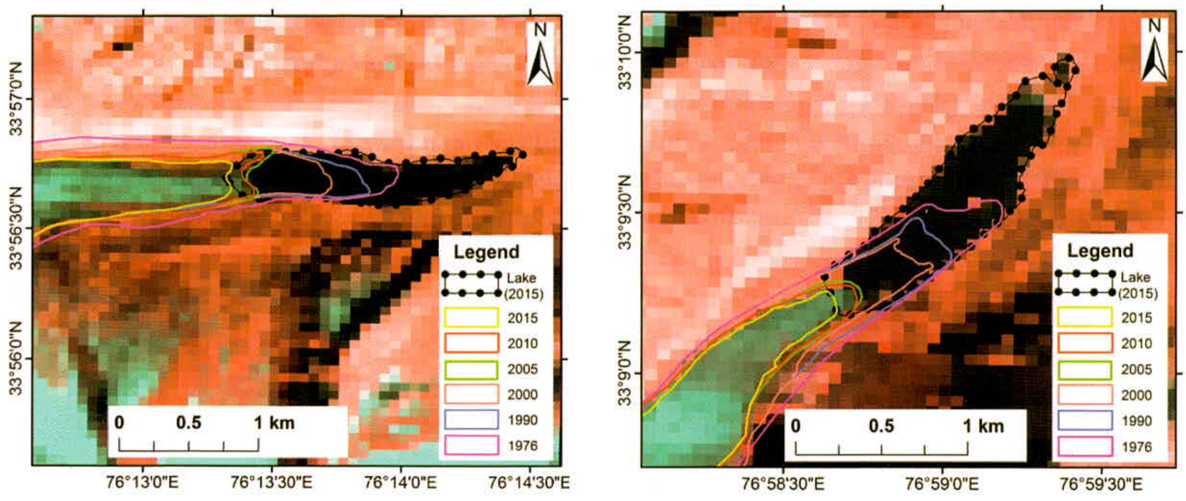
Major basin			Indus		Ganges		Brahmaputra	
Type			Number	Area (km^2)	Number	Area (km^2)	Number	Area (km^2)
Moraine-dammed lake (M)	End-Moraine	M(e)	587	25.02	587	103.28	1,241	170.93
	Lateral Moraine	M(l)	121	4.28	97	11.15	43	4.07
	Other Moraine-dammed lake	M(o)	1,215	39.07	1,482	31.00	1,973	51.48
Ice-dammed lake (I)	Supra-glacial lake	l(s)	461	4.75	539	5.58	196	2.07
	Glacier ice-dammed lake	l(v)	13	0.56	7	0.10	5	0.10
Bedrock-dammed lake (B)	Cirque	B(c)	378	40.83	299	14.70	1,976	173.48
	Other bedrock-dammed lake	B(o)	2,611	107.86	1,045	34.35	7,809	351.52
Others		0	303	38.17	26	8.43	399	129.90
Total			5,689	260.54	4,082	208.59	13,642	883.55

The glacial lakes closer to the glaciers are mostly fed by glacial melt and continuously changing size. The lakes that lie for ahead of the glaciers may or may not be fed by glacial melt but are instead formed in the paleo-glaciation landforms and are mostly constant in size. The lakes are categorized into 10 classes in terms of distance from the glaciers. Lakes on the glaciers comprise 4.8% of the total number of lakes and are mostly ice-dammed. The size and number of these lakes change frequently depending on seasons and time, and supra-glacial lakes especially appear to merge with maraine-dammed lakes or may develop contemporaneously as composite forms. Lakes in contact with the glaciers are mostly maraine-dammed and comprise about 2.5% of all lakes. The size of these lakes changes rapidly due to melting of glaciers, and so need to be monitored. Maharjan et al., 2018)

A first step for the assessment of GLOF hazards is the identification of Potentially Dangerous Glacial Lakes (PDGLs). However, this is difficult, cumbersome and time-consuming by conventional methods due to inaccessibility and harsh weather condition prevailing at high-altitude region such as Himalayas. Therefore, RS and GIS techniques are highly suitable as it allow rapid analysis of large areas and large number number of sites in economical way (Huggel et al., 2002; Kääb et al., 2005). Using such techniques, the vulnerable lakes can be easily identified and detailed studies (e.g., GLOF modeling) can be carried out if found to pose any potential risk to down lake communities or infrastructure (Bajracharya et al., 2007; Mergili and Schneider, 2011; Worni et al., 2012). It is to keep in mind that the modeling of GLOF is similar to the dam break study of the moraine dams (Jain et al., 2012, 2015).

The first GLOF event in the Indian Himalaya; has been reported in 1926 in which a flood was released from the Shyok glacier, Jammu and Kashmir destroying the Abudan village and the surrounding land at a distance of 400 km from the outburst source (Mason, 1929). Sangewar et al., (1999) has also reported sudden emptying of some of the moraine dammed lakes of Shaune Garang glacier in the Indian Himalayas based on high discharge measurements downstream during 1981 to 1988. During June, 2005 an outburst of landslide dammed lake at Parechu River (China) caused a transboundary flood in Himachal Pradesh, India. Chorabari Lake in Kedarnath was very disastrous event in the year 2013. As reported, the Himalayas have 9000 glacial lakes created from 15,000 glaciers (Bajracharya et al., 2006; ICIMOD, 2011) with total glacierised area around 33,200 km^2. Worni et al., (2012) has provided an inventory of 103 glacial lakes for Indian Himalayan region. In July 2016, a glacial lake outburst flood (GLOF) occurred in the Bhotekoshi/Sunkoshi River, Nepalese Himalaya that resulted insubstantial changes to the River channel bed, banks, and adjacent hill slopes, further causing at least 26 landslides (Cook et al., 2017). Several studies highlighted that Himalayan glacial lakes are under the threat of climate change and they are increasing their sizes and volume mainly due to faster melting of snow-covers and glaciers (Zaz et al., 2019; Mir et al., 2018; Cook et al., 2017, IPCC 2013). The comparatively recurrent occurrence of GLOFs relative to monsoon floods, or may be the effect of global warming causing monsoon disturbances, suggest that GLOFs could dominate the dynamics of fluvial systems.

A number of GLOF studies have been carried out by NIH for river basins of Teesta, Dhauliganga, Twang, and Bhutan. As per these studies, as such no lake is potentially dangerous in Dhaluiganga whereas some lakes are vulnerable in Teesta, Twang and basins in Bhutan. GLOF study has been carried out for two lakes located in Zanskar Himalays (Mir et al., 2018) and shown in Figure 6.3



(a) (b)

Figure 6.3: *Recession of (a) Dalung glacier (b) Padam glacier during different time periods between 1975-2015 and corresponding expansion of Lakes in Zanskar Himalaya. The back ground is represented by Landsat-TM image of October, 2010.*

6.6 Concluding Remarks and Way Forward

The livelihoods and wellbeing of billions of people rely on the water resources generated in the Himalayas. The above review and discussion clearly highlight that Indian Himalayan Region currently is under the threat of global climate change. Many studies showed that warming over the Himalayas has been enhanced since 1955, which is further accelerated since 1980s. Last two decades are found to be very critical for the Himalayan snow cover and glaciers changes and also for other mountains around the world which are induced by snow cover and glaciers. Studies have shown that though most of the Himalayan glaciers are retreating since 1850s, this retreat has accelerated since last four-five decades. The only reason is enhanced global average annual temperature due to anthropogenic acceleration of greenhouse gases emissions. Studies revealed that large size of glaciers are retreating slower than smaller size glaciers. The temperature and precipitation variations have been increased based on their altitudinal variations. Temperature lapse rate and precipitation lapse rate are changing due to accelerated warming, which may be crucial for accounting snowmelt. Many glaciers have been reduced their masses and permanent snow covers. However, few exceptions are also seen such as for Karakoram glacier which has gained mass and found to be stable. Various methods are successfully employed for the computation of glacier mass balance and snow-glacier induced hydrological modeling.

Based on findings as discussed above, it is assumed that contributions of melt water from glacierized and non-glacierized portions may be affected largely due to the increasing variability in temperature and precipitation. Previous studies did not highlight impacts of climate change and their severity on the snowmelt induced streamflow resulted from glacierized and non-glacierized portions separately. In a variable climatic condition, an accurate projection of snowmelt and snowpack through model-based approaches, especially in Himalayas under lot of data scarcity conditions, is a major challenge. Therefore, the severity of climate change over melting volume of water should be accounted separately for glacierized and non-glacierized portions, especially in Himalayas.

Understanding the evolution of the Himalayan snowpack and glaciers is necessary for projecting the impacts of future climate change on the hydrological behaviour of the major rivers originated in the Himalayas. Hydrological models and their application are a key supporting component for this. The review of relevant hydrological modelling studies applied in the Himalayas show that distributed, process-based hydrological models, coupled with temperature-index snowmelt models, are predominant in simulating the direct impacts of climate change. However, limitations in input data (particularly related to their availability and spatial resolution) lead to significant uncertainty in the ability of all models to confidently project climate change impacts on water resources and hydrological behaviour over medium and long timescales in the region. Therefore, there is a need to have extensive snow/glacier melt runoff modelling under future climate change scenarios in Himalayan region.

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