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CHAPTER

Introduction

The world has entered the 21st century in the midst of social, economic, developmental and environmental challenges that need to be addressed at a global scale. One of the most important issues confronting the planet is undoubtedly the threat of global warming.

The Fourth Assessment Report of the Inter Governmental Panel on Climate Change (IPCC) compiles current knowledge on various aspects of climate change, including the key indicators, based on research conducted during the last few years (IPCC, 2007). One of the most prominent indicators of climate change highlighted in the report is the melting of ice mass and glaciers worldwide.

Over the last few decades, changes in climate and local weather conditions have impacted the world's glaciers both in terms of structure and characteristics, reflected in the form of advancement or retreat of glacial snouts (UNEP, 2007). The changes in the length, width, area, volume and mass balance of the glaciers are among the most directly visible signals of global warming and these changes are the primary reasons why glacial observations have been used for climate system monitoring for many years (Haeberli, 1990; Wood, 1990), especially in areas where time series data on climate (mainly temperature and precipitation) is difficult to get and where climate change signals are not yet clear (Yadav *et al.*, 2004; Roy and Balling, 2005). Thirty reference glaciers that have been studied in detail since 1975 show an average annual mass loss of 0.58 metres (m) water equivalent in the past decade, which is four times the rate for the period 1976-85 (UNEP, 2007).

Unnatural rates of glacial melting can have serious implications on the hydrology of the associated river systems and consequently on the livelihoods of millions of people who are dependent on these rivers and their ecosystems.

As is the case with glaciers worldwide, notable changes have been recorded in glaciers of the Garhwal and Kumaon Himalayas as well as other parts of this Himalayan range. Warming has caused the snowline in the Himalayas to shift upwards, thus indicating an increase in the ablation area of the glaciers. This receding phenomenon has gathered pace in the past few years. Recent studies from 466 glaciers of the

Indian Himalayas indicate that there has been a 21% reduction in the glacierised area - from 2,077 square kilometers (sq km) in 1962 to 1,628 sq km in 2004 (Kulkarni *et al.*, 2007). Smaller glaciers of less than one sq km have reduced in area by as much as 38% compared to a 12% retreat of the larger glaciers.

These glaciers have left behind imprints of their unnatural retreat, which is in tandem with the discrete but well defined phases of global warming. The melting process has two key adverse impacts on the environment. One is the loss in the reserve of freshwater and the other is a significant rise in sea levels (Kaser *et al.*, 2006).

These ecosystems have an intricate web of interaction and therefore changes in any one of their components can have a chain of impacts on the other elements. The right approach, thus, in addressing these impacts is to have a better scientific understanding through long-term observations and analysis of the interactions of the different components of the mountain ecosystems with their climate, and then utilise this information to formulate effective adaptation and management strategies. There is also a pressing need for disaster management and rehabilitation policies in areas affected by the glacial retreat, particularly focussing on agriculture, meadows and other livelihood support structures of the local people.

Acknowledging the fact that a complex set of impacts are projected to occur as a result of climate change, scientists, academics, civil society organisations and policymakers have come together in the past two to three decades to assess the impacts of global warming. Strategies are being planned and implemented at the national and local levels and concerted efforts are being made to address the issue.

The present document is an attempt to compile the state of knowledge and research on glaciers in the Himalayas and its subsequent impacts on the freshwater resources and other key sectors.

1.2 Himalayan Glaciers – An overview

The Himalayas derive their name from a Sanskrit word which means 'abode of snow'. The mountain ranges of the Himalayas stretch for a distance of about 2,400 kilometres (km) in an east-west direction in the shape of an arc along the northern border of India covering an area of about 500,000 square kilometres (km^2). The Himalayas have three parallel running series of mountains – the greater Himalayas or the *Himadri* range, which has some of the highest peaks of the world; the middle Himalayas or *Himachal* and the lower Himalayas or the *Shivalik range*. Plateaus and flat bottom valleys of thick gravel and alluvium are found in between the Himachal and Shivalik ranges (Jain *et al.*, 2007).

View of a small glacier with moraine dammed lake in Baralacha Region, Himachal Himalaya

PHOTO: RAJESH KUMAR / BIT

Table 1.1: **Glaciers in India - basin-wise distribution**

Basin/sub basin	Total basin area (km²)	Number of glaciers	Glacierised area (km²)	Glacierised area (in %)	Largest glacier in the basin
Jhelum	12,362	133	94.18	0.76	Kolahoi
Satluj (Partly)	2,831.47	224	420.60	14.85	Baspa-Bamak
Bhagirathi	7,502.07	238	755.43	10.06	Gangotri
Tista	7,172.21	449	705.54	9.84	Zemu
Brahmaputra	5,4421.77	161	223.37	0.41	Subansari

Source: Kaul, 1999

Himalayas, the youngest and one of the most fragile mountain systems of the world, are an abode to thousands of glaciers spread between 27°-36° N. The Himalayas comprise around 33,000 sq km of glacierised area (Kaul, 1999; Dyurgerov and Meier, 2005) and its glaciers are a source of 10 of the largest rivers in Asia. The rivers flow trans-boundary and meet the needs of drinking water, irrigation, hydropower, fishery, inland navigation and others purposes of more than 1.3 billion people living downstream. With about 9,575 small and large glaciers in the Himalayas (Singh *et al.*, 2009), it has the largest reserve of water in the form of ice and snow outside the Polar Regions (GSI, 2001). The Himalayas are thus also referred to as the water towers of Asia and a third pole of the Earth.

The glaciers of the Indian Himalayas are divided into different river basins such as the Indus, Ganga and Brahmaputra. Inventories of the Himalayan glaciers by the Geological Survey of India (GSI) indicate that the Bhagirathi sub-basin has the largest glacierised area of about 755 sq km with as many as 238 glaciers including the Gangotri glacier (26-30 km). In comparison, the Brahmaputra basin has nearly 161 glaciers although it occupies a much smaller glacierised area of about 223 sq. km (*see table 1.1*). Some of the other important glaciers found in the Himalayas include Siachen (72 km), Zemu (26 km), Milam (19 km), Kedarnath (14.5 km) and Dokriani (5.5 km) (WWF, 2005).

The existence of the glaciers in the Himalaya is due to its orographic characteristics (high altitudes exceeding above 0°C isotherms), and local and regional climatic conditions. In addition to these, Himalayas are influenced by both the Indian summer monsoon and the westerlies, though not homogeneously. Some of the Himalayan glaciers are nourished only by the Indian summer monsoon (in summer) when accumulation and ablation are concurrently taking place while some other glaciers are nurtured only by the westerlies (in winter) during the accumulation period. Few glaciers are nourished by both the monsoon and the westerlies. The dynamic monsoon system in turn is also influenced by the complex orographic characteristics of the Himalayas, coupled with the snow and glacial environments. The radiation balance due to snow/ice cover provides feedback mechanisms for advection of water vapour from the surrounding oceans and maintains the seasonal cycles of monsoon. The Himalayas also play a critical role in the tropical summer monsoon climate in the Indian sub-continent by functioning as an effective meteorological barrier. They obstruct the advancement of the monsoon towards the north, thereby resulting in more rainfall on the southern slopes.

1.3 Himalayan glaciers – Understanding changes

Knowledge of glacial melt characteristics and its subsequent impacts on freshwater availability in rivers is an important aspect of understanding Himalayan ecosystems. The freshwater melt from the glacierised basins is a vital element in regulating the dry season flows of perennial Himalayan river ecosystems. Providing water to millions of people, these ranges are potentially one of the most critical parts of the world. However, the current knowledge about the behaviour of glaciers in the Himalayan region is limited (Anthwal *et al.*, 2006). Being closer to the Tropic of Cancer, the Himalayan glaciers receive more heat than the Arctic and temperate climate mountain glaciers, and hence they have become very sensitive to the rising temperature or climate variability both at regional and global levels. The responses of various glaciers are different due to variations in mass balance and the climate change impacts they face. Both a short-term perturbation in inputs as well as a long-term change in precipitation are said to affect glacial retreat.

Glacier lake outburst floods (GLOF) and other associated hazards are more common in recent times possibly due to climate change. Some of the studies carried out in the Indian Himalayas clearly point out an increase in glacial melt (Kumar *et al.*, 2007). For instance, the Baspa basin of Himachal Pradesh has shown an increase in the winter stream flow by 75% as compared to the rate in 1966. This is in tandem with the rise in average winter temperatures in the area, thus illustrating the impacts of global warming in the form of increased snow ablation, which in turn has augmented the stream flow (Kulkarni and Bahuguna, 2002; Kulkarni *et al.*, 2002). Climate change impacts are also visible in the mass balance study of the Chhota Shigri glacier in the Chandra valley of Himachal Pradesh. The study shows that there has been a decrease in the Accumulation Area Ratio (AAR) of the glacier and it has had a negative mass balance in the years 2002-2005 (Kumar *et al.*, 2007, Berthier *et al.*, 2007).

Thus, global climate change is posing pressure on our natural water supply. It is also leading to changes in the occurrences of extreme weather events and therefore needs to be addressed before the situation becomes out of control. A holistic approach is required to manage the freshwater resources in the Himalayas and ensure environmental security in the region.

2

CHAPTER

Glacier Retreat and Climate Change

Historically, glaciers all over the world are known to undergo changes over long periods. During the glacial age there was a huge accumulation of snow and ice cover due to increased snowfall in winters and less melting in summers. These glacial or ice ages occur alternatively with warmer periods called the inter-glacial periods which usually continue for about 10,000 years before the next glacial period starts. These cyclical glacial processes are dependent on the amount of solar radiation received by the earth. The shape of the earth's orbit around the sun, tilt of the earth's axis to the orbit and the precession effect determining the direction of earth's axis of rotation are the key factors which govern the amount of solar radiation falling on the earth's surface (Lerner and Lerner, 2008). Variations in these factors bring about changes in the atmosphere of the earth which in turn influences ecosystems.

2.1 Historical trends

The most recent glacial age occurred about 70,000 years ago and after reaching its peak about 20,000 years ago and ended around 10,000 years ago. About 32% of the total land area on the Earth was covered with ice during that period. Currently, this figure has been revised to 10% due to the continuing warm period (WWF, 2005; Lerner and Lerner, 2008). Traditionally, these processes of glacier advancement and retreat have been a feature in the history of the earth's evolutionary processes. This fact is supported by deposits of moraines left behind by the retreating glaciers on land, and the analysis of sea floor sediments and ice core samples taken from ice sheets. The advancement and recession of glaciers causes many structural changes in the glacier as well as the surrounding area.

Apart from the periodical cycles of glacial and interglacial ages, short periods of localised cooling and warming also occur, which brings in some changes in the glacier structure. The most recent cooling, known as the 'Little Ice Age', occurred from the 14th to the 19th century (UNEP, 2007). Since then almost all the glaciers worldwide have been facing retreat as a result of various factors including increasing temperatures.

Calving glaciers in the summer in Arctic waters. Kongsfjord, Svalbard, Norway

PHOTO: © PETER PROKOSCH / WWF-CANON

2.2 Glacier retreat in the 21st century

In recent times, the issue of concern for glaciologists and climate scientists has been the rate of retreat which has accelerated in the past few decades (Dyurgerov and Meier, 2005). There are two schools of thought around this issue of retreating glaciers - many consider the retreat pattern of the glaciers across the earth as a natural phenomenon. On the other hand, several other studies establish that anthropogenic climate change and accelerated global warming are responsible for this trend.

Climate change is now recognized as one of the most prominent threats facing civilisation. According to the Fourth Assessment Report of the IPCC (2007), climate change brought about by anthropogenic activities has resulted in the average surface temperature increasing by 0.74°C in the last 150 years. This warming has directly impacted the temperature sensitive snow and ice cover, resulting in rapid glacial melt, which in turn has caused variations in flow and discharge of the rivers downstream and also a rise in sea levels (Bates *et al.*, 2008). The Greenland and Antarctic ice sheets have both shrunk in area and mass, with major losses occurring in the last few decades. Data from the Jet Propulsion Laboratory of NASA shows that Greenland lost 150 to 250 cubic kilometers of ice per year between 2002 and 2006, while Antarctica lost about 152 cubic kilometers of ice between 2002 and 2005 (JPL, NASA, 2008). Mass balance measures of all glaciers globally indicate that the retreat rates have been increasing rapidly specially during the last couple of decades. For instance, the tropical Andes have observed significantly increased glacier retreat in the recent decades. According to the Fourth Assessment Report of the IPCC smaller glaciers are more vulnerable to a warmer world and climate change (Rosenzweig *et al.*, 2007).

The projections made by IPCC clearly state that the increase in global surface temperatures will continue to shrink glaciers and ice caps and it may lead to the disappearance of glaciers from many mountain regions in the coming decades. The increased melting of glaciers would initially increase the runoff. However, in the long-run this runoff is projected to decrease. Decline in the stored water supplies from glaciers and snow cover will reduce the water availability in regions which are dependent on the melting snow water. Such reduction is likely to affect more than one-sixth of the world's population living in glacier or snowmelt fed river basins (IPCC, 2007). Trends indicate an increase in sea level rise due to glacier melt from a rate of 0.51 millimetres/yr (1961-2003) to 0.93 millimetres/yr for the period 1994-2003 (Dyurgerov and Meier, 2005). Shrinking glaciers are also likely to increase the vulnerability of people and ecosystems in the

Table 2.1: **Regional trends of glacier retreat**

Region	Glacierised area	Observed changes	Key sectors impacted
Africa	Rwenzori Mountains, Mount Kenya, Kilimanjaro	82% reduction in glacier area over the last century, 50% glaciers disappeared, larger ones fragmented	Water resources, agriculture
New Zealand	Southern Alps	11% net ice volume lost in the last three decades	Irrigation, hydropower generation
South America	Tropical Andes, Patagonian ice fields	3.4 % of area lost in the last 50 years. Recent thinning rates observed to be around 30m/yr	Water resources
Tibetan plateau	Tibetan Plateau, surrounding regions in China	Loss of 20% area since the 17th century with 90% of the glaciers retreating	Mountain forest ecosystems, biodiversity, hydropower
Central Asian Tien Shan and Pamirs	Tien Shan, Pamirs	25-30% reduction in glacier area in Tien Shan during the last century, 30-35% reduction in the Pamirs, and more than 50% reduction in northern Afghanistan	Agriculture, water resources
Russia	Arctic islands, mountain ranges	50% retreat in the North Caucasus over the last 50 years	Water resources, biodiversity
European Alps	Caucasus mountains	50% area loss in the last 150 years	Tourism, water resources
North America	Ice fields in Canada, Alaska	25% area lost in western Cordillera	Water resources, biodiversity, agriculture

Source: UNEP, 2007; WWF, 2005; Mote and Kaser, 2007; UNEP, 2008; WGMS, 2008

associated river systems and basins of the Himalayas, necessitating the introduction of appropriate adaptation strategies and response measures.

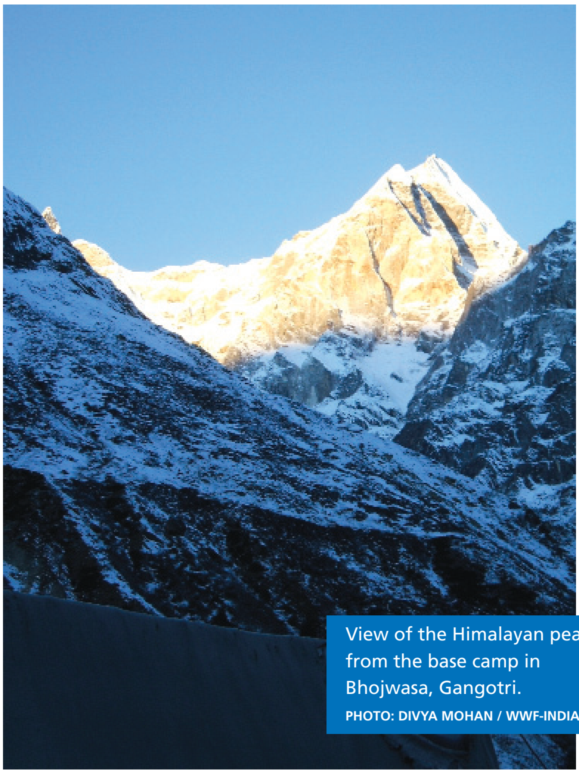
2.3 Regional variations

Globally, there has been a steady increase in the mean winter accumulation and summer melting of almost all glaciers in the later part of the 20th century (Lemke *et al.*, 2007). However, there have been inter-regional variations in glacial melt patterns. The trend has been more prominent in the Northern Hemisphere though many glaciers in the Southern Hemisphere have also shown high rate of retreat. This corresponds to a warmer and more humid climate observed in the last decades of the 20th century (Dyurgerov and Meier, 2005). Long-term observational records of 300 glaciers and about 49 primary systems throughout the world suggest a marked negative mass balance and acceleration of glacier volume losses in the late 1980s and 1990s (Dyurgerov and Meier 2005), which coincides with the unusually high mean temperatures in these years.

Studies in regional variations point out that the Patagonia, the North-west USA and South-west Canada, and Alaska demonstrate strongest negative mean specific mass balances of glaciers with accelerated losses after the mid 1990s (Dyurgerov and Meier, 2005, Lemke *et al.*, 2007) (*see table 2.1*).

2.4 Glacier retreat in the Himalayas

In the Himalayan region, glaciers and snow cover have been thinning since the end of 19th century in line with the global trends. With significant snout fluctuations,



View of the Himalayan peaks from the base camp in Bhojwasa, Gangotri.

PHOTO: DIVYA MOHAN / WWF-INDIA

Table 2.2: **Recession of some glaciers in Uttarakhand**

Glacier	Period of observation	Years	Retreat (in metres)	Average retreat (metre/year)	Source
Milam	1848-1996	148	2,472	16.70	Vohra
Pindari	1845-1966	121	2,840	23.47	Vohra
Gangotri	1935-1996 1996-1999	61 3.5	1,147 76	18.80 22.24	Vohra Naithani *et al*
Shanklup	1881-1957	76	518	6.82	Vohra
Poting	1906-1957	51	262	5.14	Vohra
Dunagiri	1992-1997	05	15	3.00	Swaroop *et al*
Burphu	1966-1997	31	150	4.84	Srivastava *et al*
Chorabari	1992-1997	05	55	11	Swaroop *et al*
Bhrigupanth	1962-1995	33	550	16.67	Srivastava *et al*
Tipra Bank	1960-1987	27	100	3.70	Vohra
Dokriani	1962-1991 1991-2000	29 09	480 164	16.5 18.2	Dobhal Gergan
Meru	1997-2000	32	395	17.17	Chitranshi *et al*

Source: Nainwal et al.*, 2008*

most of the glaciers in the Himalayan mountain ranges have been retreating at accelerated rates in the last three decades (WWF, 2005) and their rate of retreat is much faster than that of glaciers in other parts of the world (Cruz *et al*., 2007). These changes correspond to the rising surface temperature trends in the Himalayas which have been reported to be higher than the global average warming (UNESCO, 2007; Jianchu *et al*., 2007; Barnett *et al*., 2005). A study of the temperature trends in the North West Himalayan region (Bhutiyani *et al*., 2007) shows that a significant warming of 1.6°C has occurred over the last century with warming in winter taking place at a faster rate, with the highest warming rates recorded in the period 1991-2002. This warming has been due to a rise in both maximum and minimum temperatures, though the maximum temperatures have gone up more rapidly. Apart from warming, other factors like high human population density near these glaciers, deforestation and land use changes have also been responsible for the decline and shrinkage of glaciers (Cruz *et al*., 2007). At current rates of retreat, the smaller valley type glaciers are more likely to decline at a faster rate in the future, with uncertain impacts on the downstream areas. In India, although high mountain glaciers occur across all the Himalayan range states of Jammu and Kashmir, Himachal Pradesh, Uttarakhand, Sikkim and Arunachal Pradesh, only a few have been studied or documented in terms of glacial retreat. For example, in India, several small and larger glaciers have been monitored on a long-term basis in the state of Uttarakhand, with the Gangotri glacier being among the prominent ones (*see table: 2.2*).

The climatology and the topography of the Himalayan region have wide variations all across the arc (Dobhal *et al*., 2004). Slope, climate, physical features and sources of run-off are the vital governing features for hydrological responses in a river basin. According to a study on the changes in climate in the Himalayan region, under a warmer climate, the melting from the seasonally snow covered part of the basin was reduced while, in contrast, it increased from the glacier-fed basin (Singh and Bengtsson, 2005). Owing to the variations in the Himalayan basins and local climate, these areas have been exhibiting different responses to the variability in climate.

Research studies on glacial recession indicate that the changing atmospheric conditions due to anthropogenic climate change play a major role in influencing changes in the glacier structure. However, establishing firm linkages between these two phenomena requires long-term studies and monitoring. Mass balance and glacier snout monitoring have been important tools for the assessment of the volumetric and geometric changes in the glaciers brought about by advancement or recession (Dobhal *et al.*, 2007). In the Indian Himalayas, studies on snout recession/mass balance measurements have been carried out on a few glaciers and some studies have been able to generate long-term monitoring data (Kumar, *et al.*, 2007; Dobhal *et al.*, 2007; Wagnon *et al*, 2007, Kulkarni, 2007). While studies by various institutions on the changing characteristics of glaciers in the Himalayas may be limited (see box: *Studies on some important glaciers in the Himalayas*), this has interestingly generated a debate amongst various sections of the society on the role of climate change in the extent of glacier loss (WWF, 2005).

While the global view (IPCC 2007) suggests that a large percentage of glaciers are declining worldwide, there are conflicting views also on the rate of retreat in the post industrial era. Some studies suggest that a few glaciers in the Himalayas may be showing reduced retreat patterns. For instance, the reduction in the retreat rate of Gangotri Glacier for 2004-05 was obtained by Kumar *et al.* (2008). Similar results have been observed by our on going research on Gangotri glacier, which shows that the average rate of retreat for this glacier declined substantially (5.6 m/yr) during 1999 to 2006. On the basis of several observations, it can be said that the affects of climate change have variable impacts on glaciers depending on their size. Small glaciers are more likely to face the brunt of the changes in climate owing to their smaller and less snowfall receiving accumulation zones. On the other hand large glaciers might sustain the impacts for a longer time due to their larger ice volume and bigger accumulation zone. Any changes in the climate will take a long time to get reflected in the structure of larger glaciers in the form of retreat or advance

Studies on some important glaciers in the Himalayas

Dokriani

The Dokriani glacier (5.5 km) located in Uttarakhand has been continuously retreating with slight increases in the retreat rates by 1 m/yr in the 1990s as compared to the average rate in the previous years. This has led to a reduction in thickness from 55 m in 1962 to 50 m in 1995 (Dobhal *et al.*, 2004). Field observations and recording indicate that the annual thinning in the ablation zone is higher than the net accumulation, leading to significant reduction in the ice volume (Dobhal *et al.*, 2007).

Chhota Shigri

The Chhota Shigri glacier in Himachal Pradesh, which is about 10 km long, is one of the well documented glaciers in India. Long-term studies show increased negative net mass balance (Dobhal, 1995, Kumar *et al.*, 2007) and an accelerated retreat in the snout position in the last two decades (Wagnon *et al.*, 2007). This has led to more thinning of the glacier at lower altitude (Kumar, *et al.*, 2007). An upward shift in the Equilibrium Line Altitude (ELA) has also been observed (Wagnon *et al.*, 2007).

Satopanth and Bhagirath Kharak

The snouts of the Satopanth and Bhagirath Kharak glaciers in Uttarakhand have undergone continuous recession. Compared to the Bhagirath Kharak glacier, the Satopanth glacier is receding at a higher rate. During the period 1962–2006, the Satopanth glacier registered a net recession of 313,923.14 sq m (7.134×10^{-3} sq km/yr), while the Bhagirath Kharak glacier registered a net recession of 129,369.16 sq m (2.940×10^{-3} sq. km/yr). Data for 2005–06 indicates that recession of snouts of the Bhagirath Kharak and Satopanth glaciers is 1.5 m/yr and 6.5 m/yr respectively (Nainwal *et al.*, 2008).

Milam

Milam is one of the largest valley type glaciers in the Kumaon Himalaya and it has been monitored since 1906. Recent studies suggest that the glacier is in a continuous state of recession. Since 1906 it has retreated by about 1740 metres (with the average rate being 19.1 metres/year). Since 1906, the glacier has vacated an area of 0.893 sq km in its pro-glacial realm. Increased rate of recession in the second half of the twentieth century is being attributed to global warming (Shukla and Siddiqui, 2001).

Crevasse and cracks at the snout of the Gangotri Glacier showing its vulnerability towards glacier retreat. As the snout ice is fragile, some times large chunks of ice break off from the glacier mass, causing the backward movement of the snout. Even the snout cave which used to be near the central flow has taken a rightward shift (NNW) with respect to its earlier position. These kinds of features have also been observed in other glaciers which have broader snout.

PHOTO: RAJESH KUMAR/ BIT

because of their slow movement (~ 40-50 m/year). The impact observed at the snout for larger glaciers doesn't properly reflect the change in climate of the same year because it is the combined impact of several years' variations in the weather pattern. Hence there is need for further investigation of the snowfall variability in the glacier region under climate change scenarios. The next chapter of this report details the findings of the study on two glaciers – Gangotri and Kafani – which indicates that the retreat of the Gangotri glacier as observed in the recent few years is relatively slower as compared to the past observed trends, whereas, the retreat has gained acceleration in the Kafani glacier in recent years.

The Himalayan region has one of the most diverse systems, with a multitude of cultures, diversity and unique ecological character, which are all complexly interwoven with the elements of the cryosphere, and the temperate and alpine ecological systems. The Himalayas also harbour some of the most remote settlements on earth where many traditional mountain communities and cultures have thrived for centuries. The impacts of glacial retreat is already affecting the lives of millions of these mountain communities living upstream and downstream of the Himalayan rivers in terms of variations in water flows, increased summer time temperatures, and biodiversity loss.

The future consequences of climate change in the Greater Himalayan region is a matter of concern to all stakeholders. Thus, we need to increase our understanding of the relationship between climate and various other parameters such as glacial melt, water flows and the adaptive capacity of communities. The change in glaciers is now regarded as a suitable climate change indicator and a valuable element in the early detection strategies of many international climate monitoring programmes. However, the lack of regular and continuous baseline data on Himalayan glaciers has often been a major obstacle in understanding the glaciers.

3
CHAPTER

Understanding the changes: Study of Gangotri and Kafani Glacier in the Himalayas

A growing body of scientific knowledge solidly indicates that carbon concentrations are changing the global climate and that there would still be significant changes to the global climate even if emissions would drastically reduce and fall to zero. The world is anticipating 2°C warming above the pre-industrial level, and this will result in some unavoidable changes, the effects of which need to be understood, especially in fragile and endangered ecosystems. Generating a deeper understanding of the climate impacts on critical indicators such as glaciers are needed as there is inadequate documented scientific evidence within India on the impact of climate change on the Himalayan ecosystems. This is critical as there is need for developing regional climate projection models which are more accurate in providing information on future impacts and kinds of adaptation response mechanisms that need to be developed.

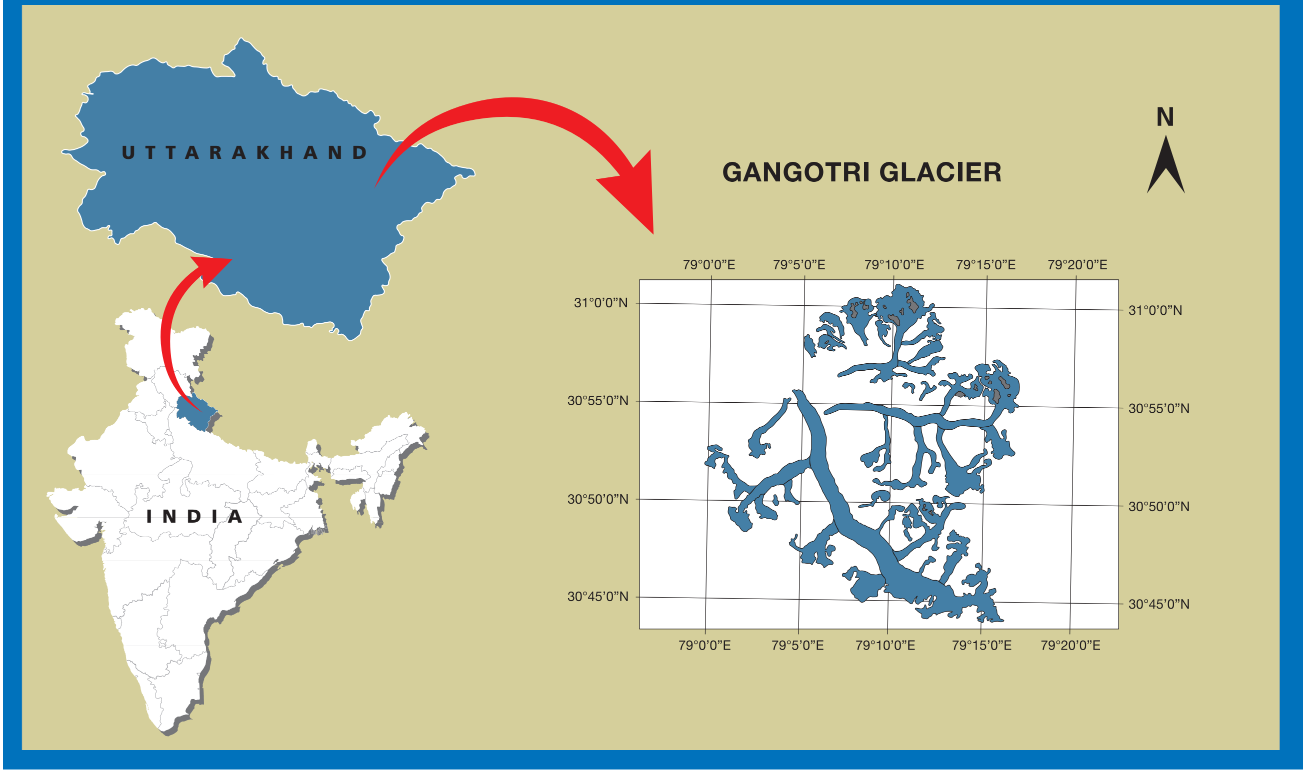
WWF India has been focusing on raising awareness about climate change and the impacts on Himalayan ecosystem since 2005 (WWF, 2005). In order to generate a deeper understanding of the potential impacts of glacial melt in the Himalayas, WWF initiated a project in 2006 which focused on studying two key glaciers from a climate change perspective and the subsequent impacts on freshwater availability. These glaciers were the 30 km long Gangotri glacier and the Kafani glacier having a length of 4.2 km, both located in the state of Uttarakhand.

3.1 Gangotri glacier

3.1.1 Study area

The Gangotri glacier, one of the largest ice bodies in the Garhwal Himalayas, is located in the Uttarkashi district of the state of Uttarakhand in India *(see figure 3.1)*. It is one of the most sacred shrines in India, having immense religious significance. Being the main source of the river Ganga, it attracts thousands of pilgrims every year. The Gangotri glacier is a vital source of freshwater storage and water supply especially during the summer season for a large human population living downstream. The discharge from the glacier flows as the river Bhagirathi initially before meeting the Alaknanda river at Devprayag to form the river Ganga. Snow and glaciers contribute about 29% to the annual flows of the Ganga (up to Devprayag) and hence any

Figure 3.1: The location map of Gangotri glacier system



impacts on these glaciers are likely to affect this large river system (Singh *et al.*, 2009).

The north-west facing Gangotri glacier is a valley type glacier originating in the Chaukhamba group of peaks. Numerous smaller glaciers join the main stem of the main glacier to form the Gangotri group of glaciers. As per satellite imagery (ETM+, 1999), the complete Gangotri glacier system along with its tributaries covers an area of 210.60 sq km. The area and length of the main trunk of the glacier is 56.59 sq km and 29.13 km respectively. The average width of the glacier is 1.85 km. The glacier, as per the satellite imageries (ETM+) of year 1999, lies between 79°4′ 46.13″ E-79°16′ 9.45″ E and 30°43′ 47.00″ N-30°55′ 51.05″ N. It has varying elevation of 4,015–6,145 metres above sea level (as per the SRTM data analysis).

The snout of the glacier known as *Gaumukh* (meaning mouth of a cow) occurs at an altitude of about 3,949 m above sea level, and this is the place from where the Bhagirathi originates (GPS observation, 2008). Its snout position (2008) is at 73°4′ 47.26″ E and 30°55′ 36.45″ N. Table 3.1 provides an overview of the characteristics of the glacier system.

The snout of the Gangotri glacier at Gaumukh (October 2007)
PHOTO: PRAKASH RAO/WWF-INDIA

3.1.2 Gangotri glacier retreat – a historical perspective

The Gangotri glacier has been receding since the last ‘Little Ice Age’, which ended in the 19th century. The tributary glaciers have also shrunk and some of them have even got separated from the main trunk of the glacier. This fact is evident by systematic studies going on since 1935 on the movement of the glacier snout, and by the presence of recessional features such as the terminal and lateral moraines (GSI, 2001). In the past century, the retreat rate of the glacier has shown a rising trend. It has been observed by glaciologists that the snout of the Gangotri glacier has retreated by about two km in the last 100 years. Both the snout retreat and area vacated by the Gangotri glacier have been documented by several scientists (*see table 3.2*).

Table 3.1: **Gangotri glacier inventory**

Glacier Coordinates	30°43”22” - 30°55’49” N 79°4’41” - 79°16’34” E
GSI identification number	5O131 06029
Highest elevation (m asl)	7138
Lowest elevation (m asl)	4000
Surface area (km^2)	143.58
Ablation (km^2)	92.48
Accumulation (km^2)	51.11
Mean width (km)	1.50
Maximum length (km)	30.20
Ablation zone length (km)	26
Accumulation zone length(km)	4.20
Mean depth(km)	0.20
Ice volume (km^3)	28.716
Tributaries:	
Chaturangi Glacier	length 22.45 km; area 67.70 km^2
Raktvarn Glacier	length 15.90 km; area 55.30 km^2
Kirti Glacier	length 11.05 km; area 33.14 km^2

Source: (GSI), 2001; Naithani et al., 2001; Singh et al., 2006)

Table 3.2: **Snout retreat and area vacated by the Gangotri glacier (1935-96)**

Period	**Annual Snout retreat (m)**	**Average annual surface area vacated (sq m/year)**	**Reference**
1935- 1956	4.35 (small cave) 10.16 (large cave)	2,500	Jangpani (1958)
1956-1971	27.33	10,032	Vohra (1971)
1971-1974	27.34	594	Puri and Singh (1974)
1974-1975	35	13975	Puri (1984)
1975-1976	38		Puri (1984)
1976-1977	30	14875	GSI, 2001
1977-1990	28.08	15096	Puri (1991)
1990-1996	28.33	22370	Sangewar (1997)

Source: (GSI), 2001; Naithani et al., 2001; Singh et al., 2006)

Meteorological conditions around the Gangotri glacier

Meteorological conditions play a pivotal role in governing the state of glaciers and their associated hydrological features such as water storage in downstream areas. In the light of the changing local weather conditions due to global warming, meteorological analysis of the long-term data becomes a fundamental aspect in determining the structural changes which have taken place in the glaciers. Scientific institutions like the Roorkee-based National Institute of Hydrology (NIH) have been studying the Gangotri glacier for the past few years and have collected extensive data on the meteorological parameters (rainfall and temperature) through standard meteorological observatories installed near the glacier snout.

Rainfall: Precipitation data collected from the region indicates that the area around Gangotri usually receives less than 15 mm of daily rainfall during the summer season (Singh *et al.*, 2005). There are only few unusual days when the rainfall patterns vary due to a storm or some unusual heavy rainfall event. The study also shows that August and September usually receive higher rainfall as compared to the other months. A similar kind of trend in precipitation has also been observed in recent years by our weather station installed at Bhojwasa. It has also been found that early morning and late evening are the most probable time for the occurrence of rainfall (Singh *et al.*, 2005).

Temperature: Temperature in the ablation season increases for a few months after which it starts decreasing. July has been found to be the warmest month on the basis of the mean-maximum and minimum temperatures. Diurnal variations in temperature show that the maximum temperature is observed around 1400 hours, while the minimum is observed in the early morning hours (Singh *et al.*, 2005). Changes in minimum temperature have been seen to be more significant than those in the maximum temperature. It has also been found that the ‘maximum diurnal temperature range’ occurs in May and October while August shows the least variation in temperature range. This is probably due to the presence of a cloud cover during the rainy season.

Hydrological characteristics of the Gangotri glacier

For the Gangotri glacier, the major sources of runoff are melting snow and ice. Since this area receives less rainfall, it does not contribute much to the runoff. Stream flow at the Gangotri glacier shows wide variation depending on various factors. In the beginning and at the end of the ablation season, there is not much difference in the day and nighttime flow volume; however as the peak melting time approaches there is a comparative reduction in the nighttime flow. Still, a significant flow is observed at nighttime in spite of very little or no melting taking place at that time. This reflects the fact that the Gangotri glacier has strong meltwater storage characteristics. Monthly variation of flow shows that the discharge starts rising from May and after reaching a maximum in July it reduces from September onwards (Singh *et al.*, 2006). Similar results have also been observed in our study during the last couple of years; it has been found that the discharge increases in May and it maintains a high flow during June to August with maximum average discharge in August. The discharge starts reducing from September onwards.

3.1.3 Understanding changes – methodology

The methodology for field studies at Gangotri involved a combination of primary field data through the use of Differential Global Positioning System (DGPS) and Remote Sensing Applications along with the existing secondary data. DGPS measurements have been extensively used for locating the snout position of the glacier during various field visits starting from 2006. Long-term observations are an important factor for accuracy in any glacial research as the snout position is quite dynamic and inter-seasonal changes are seen in the exact position of the snout. For the collection of meteorological data, an automatic weather station (AWS) has been installed at Bhojwasa near the snout of the glacier. Apart from the glacial and meteorological monitoring, data has also been collected about the discharge patterns of the glacial meltwater.

3.1.4 Results and analysis

A comparative analysis of the glacier's snout position was carried out using data from secondary sources and interpretations from various satellite imageries over the past three decades. The snout position markings as indicated on rocks and other physical structures are an important source of data especially for the first half of the century. Satellite imageries available since 1976 formed the baseline for the analysis of the snout fluctuations. Since 2006, DGPS observations of the snout position have been recorded regularly through field visits.

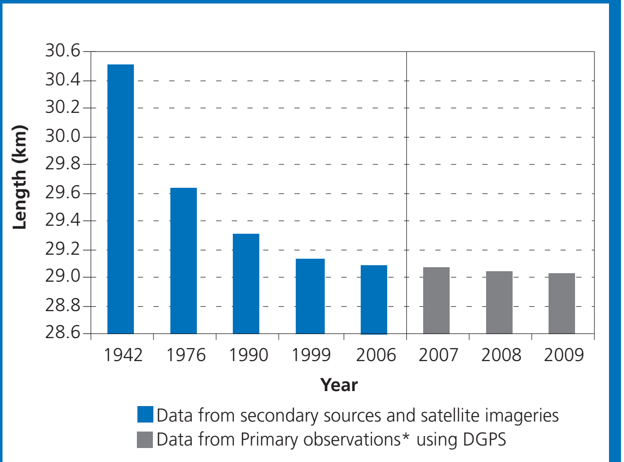
Automatic weather station installed at Bhojwasa near the snout of Gangotri glacier (May, 2008)
PHOTO: RAJESH KUMAR/BIT

Gangotri's snout position being observed by DGPS in May 2008

SOURCE: RAJESH KUMAR, BIT

A study of data from all available sources illustrates that the main trunk of the Gangotri glacier has been in a continuous state of recession during the past century. The length of the glacier has been computed for different years based on available data. The trend shows that the length of the glacier has reduced by almost 1.5 km in 67 years with an average retreat rate of 22.1 m/year. Consequently, there has been a gradual decline in the length of the glacier from 1942 to 2009 (*see figure 3.2*).

Figure 3.2: Length of the Gangotri glacier in different years



**Observations taken as part of study on glaciers by WWF-India and BIT*

The glacier is not only receding in length but also in terms of glaciated area from all the sides. The possible reasons behind this retreat may be linked with two main factors: (a) reduction in snowfall and (b) an increase in the temperature of the region. With an average loss of 0.279 km^2 per year, the glacier's area has reduced by 17.84 km^2, which comes to 25.33% of its area in 64 years since 1942 (*see figure 3.3*). It is evident that the reduction in the area was much slower between 1942 and 1976, with a loss of 3.19% in 35 years. However, the rate has increased subsequently and the glacier lost around 10.6% of its area in just 15 years (1976–1990). In the last two decades another 14.5% of the glacial area has been reduced.

With a reduction in the area and length of the Gangotri glacier, there has been an obvious retreat in the snout position. Data collected from all the sources shows that this has been a continuous process; however, there have been fluctuations in the rate of retreat for different time intervals. The Gangotri glacier's snout has retreated by about 1.5 km in the last 67 years (1942 to 2009) at an average rate of 22.21 m/yr. However, the actual retreat rates for different years vary

Figure 3.3: The cumulative and intermittent reduction in the area of Gangotri Glacier since 1942

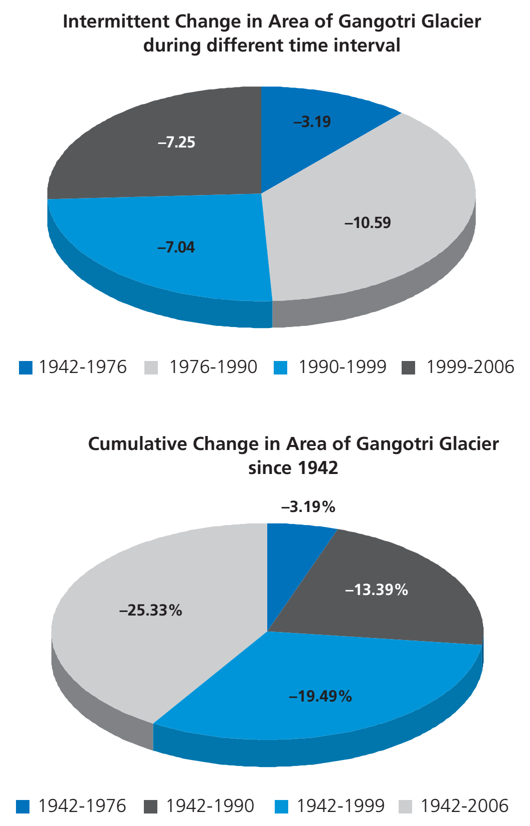
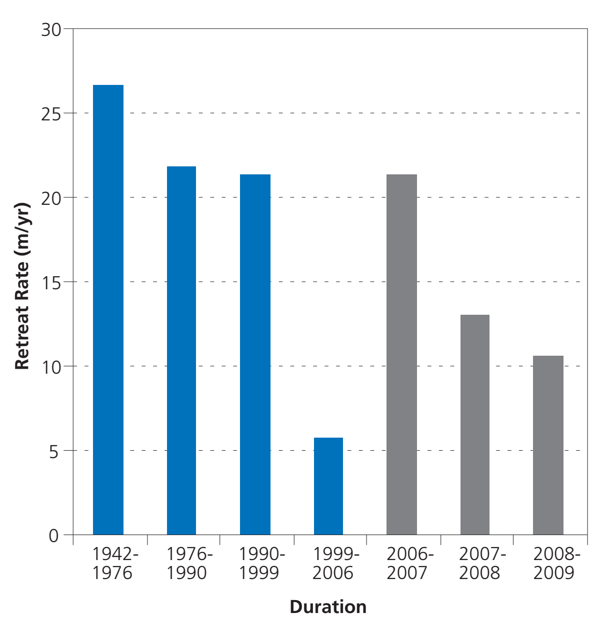


Figure 3.4: Retreat rate of Gangotri snout in different interval of time



considerably (*see figure 3.4*). During 1999-2006, the retreat rate came down to 5.6 m/yr, which may be due to an increase in snowfall during winters throughout this period as well as in earlier years because the glacier response time of Gangotri glacier is higher due to its larger size.

The retreat rate for the duration 2006 – 2009 is based on DGPS observations. The calculation of the snout retreat by DGPS observation is made from point to point that gives the straight line distance of the two points that may include the shift of the water outlet point (left/right) in the curvilinear shape of the larger snout. The other way of measuring shift of the snout position in the glacier flow direction is to measure the perpendicular distance on the curvilinear shape of the snout. This measurement normally gives a lesser value if the snout point has moved either left or right rather than in the glacier flow direction as compared to the previous position. Based on this measurement we have observed that the snout retreat during 2006-07 was 21.59 m when compared to snout position of 2006 (based on satellite imagery). In the subsequent years,

Figure 3.5: Snout position of the Gangotri glacier from 1942 to 2008

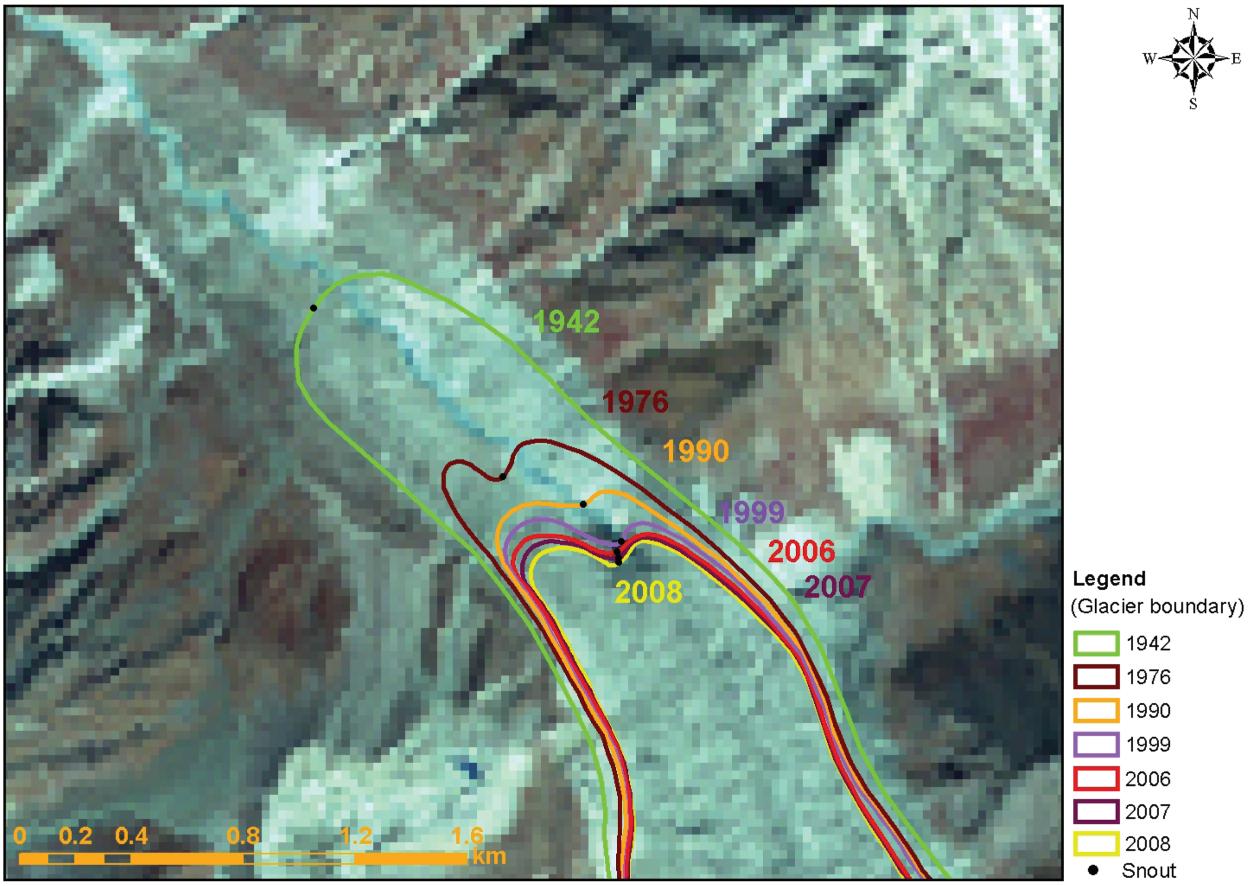
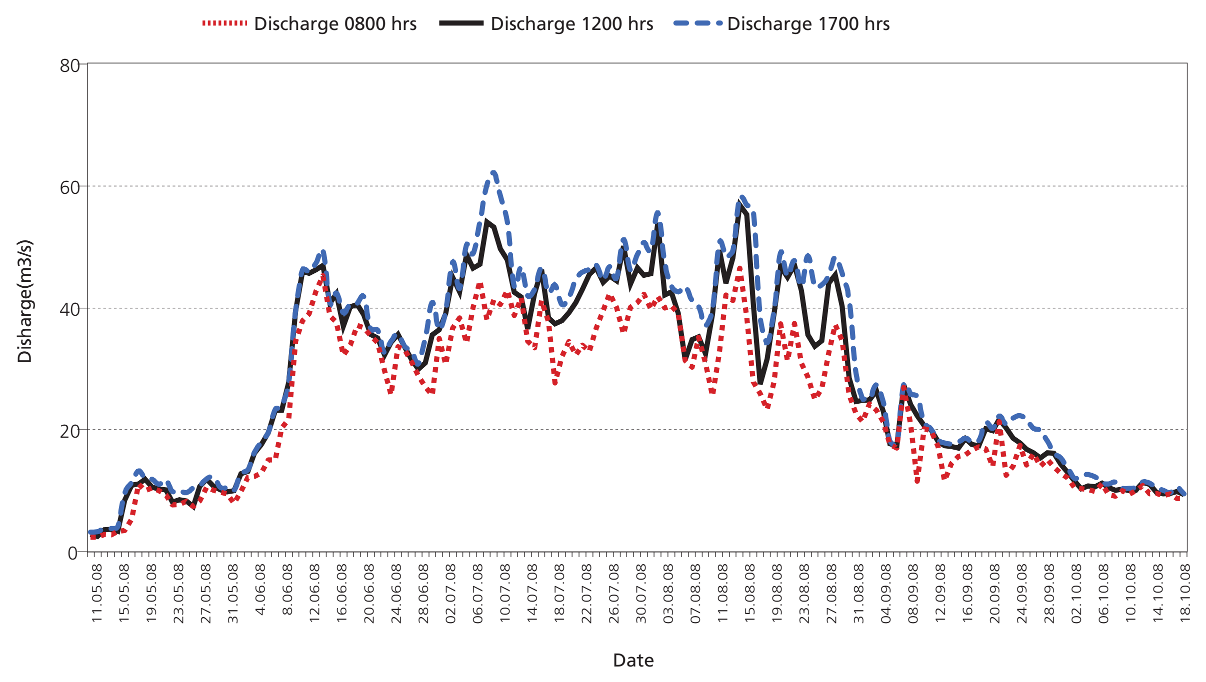


Figure 3.6: Diurnal variation in discharge at Bhojwasa, Gangotri 2008



retreat rate has slowed down – 9.25 m in 2007-08 and 8.91 m in 2008-09. It can be said that retreat has taken place in the last couple of years but still it was below the long term average observed from 1942 to 2009. This also reflects the fluctuating trend in the retreat pattern of the Gangotri snout in recent time. The retreat of the Gangotri Glacier snout is shown by overlaying the glacier boundary on the Enhanced Thematic Mapper(ETM)+ 1999 imagery (*see figure 3.5*).

Hydro-meteorological study

Trends emerging from the analysis of summer season discharge data for Gangotri show that there are variations on diurnal and monthly basis. Flows recorded at different times of the day were found to be highest during the evening hours (1700 hours). The discharge is lowest during the morning hours (*see figure 3.6*). These results are also in agreement with the findings of an earlier study by Singh *et al.*, (2006) in which they observed a high discharge rate during daytime and low during the nighttime for the Bhagirathi river at Bhojwasa.

On a monthly scale, flows increase with the commencement of the summer season reaching a peak during July and August due to the combined impact of more melting of ice, which is driven by higher average temperature and rainfall in the catchments. The discharge starts reducing in September and reaches a very low level throughout the accumulation season. During winters, the flow is reduced and keeps almost at a constant value. The combined impact of low winter temperature (sub zero) and higher albedo (90-95 % for fresh snow) reduces the winter discharge rate to quite a low level.

The daily average temperature and average discharge for ablation and accumulation season at Bhojwasa are shown through figures 3.7 and 3.8 respectively. A good correlation of 0.73 has been found to exist between the average temperature and average discharge in the ablation season. However,

Figure 3.7: The average temperature and discharge during the ablation season at Bhojwasa

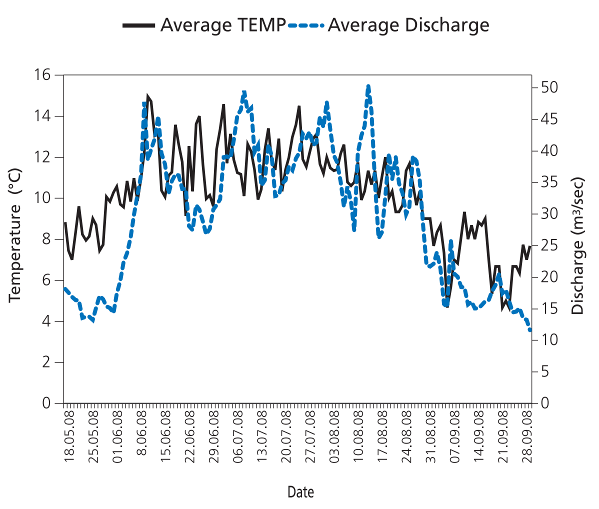
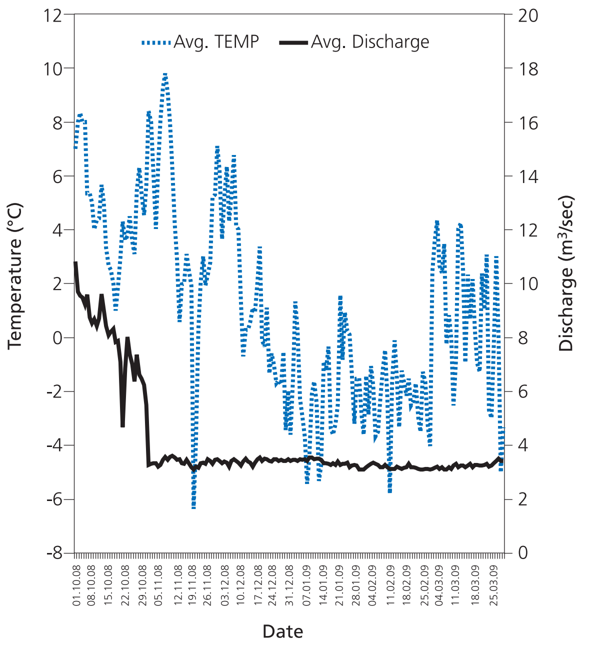


Figure 3.9: The average temperature and discharge during the accumulation season at Bhojwasa on Bhagirathi river



these parameters are not well correlated (0.46) in the accumulation season, which shows less influence of the temperature on melting because most of the solar energy is reflected back to the atmosphere due to the snow-covered valley that has a high albedo. The preliminary trends observed during the study in 2008 seem to suggest that the volume of discharge and flow patterns is also being influenced by the temperature variations in the valley. This is in consonance with results obtained by other studies (Singh *et al.*, 2006) over the past decade or so. While these are initial results, comparison with similar studies indicate a consistent pattern in the rate of discharge and temperature increase for the region.

Where the general trend of the impact of midday temperature on evening discharge in the glaciated basin is concerned, we have found a correlation of 0.63 between the 1200 hours temperature and the 1700 hours discharge at Bhojwasa on Bhagirathi river (*see figure 3.9*). In the month of October the discharge rate falls down as the average temperature starts reducing (*see figure 3.9*).

Trends in the Gangotri region (*see figure 3.10*) reflect that temperature starts falling with the arrival of September. The maximum temperature reaches up to 18 degree Celsius in June and July and remains mostly around 14 degree Celsius during May to August. The morning temperature (at 0800 hours) remains at around 9 degree Celsius till August and falls to zero in the mid of September. The winter temperature is quite

Figure 3.10: Influence of midday temperature (1200 hours) on evening discharge 1700 hours at Bhojwasa, Gangotri

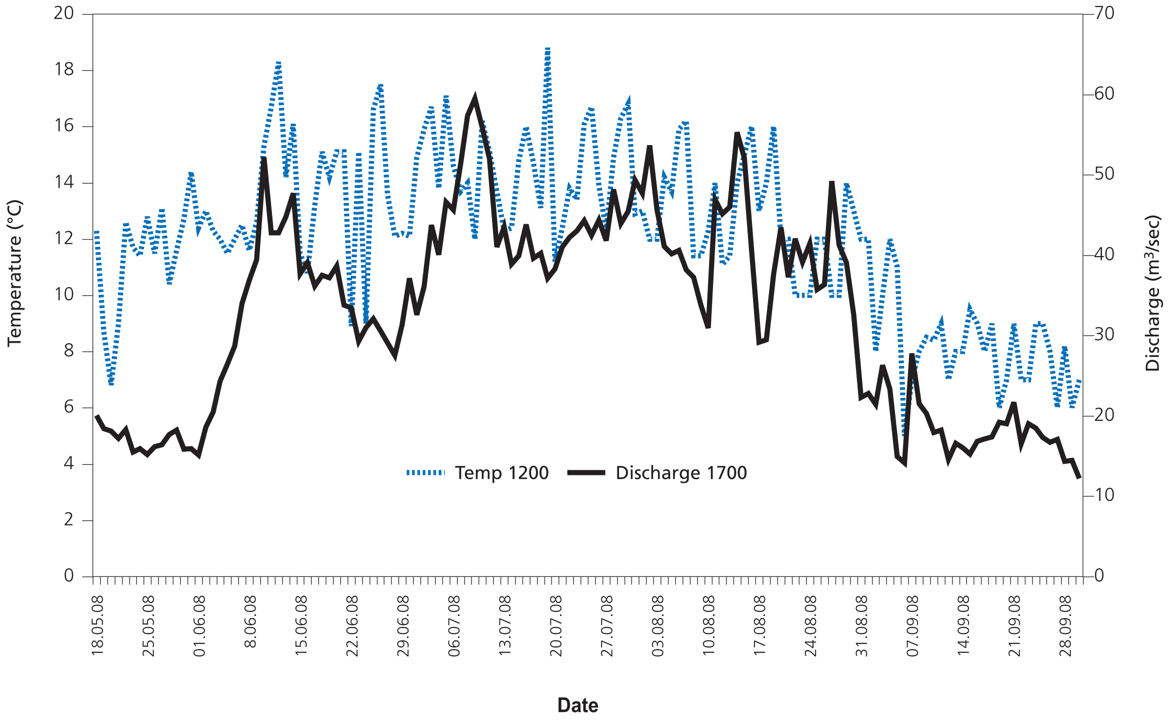
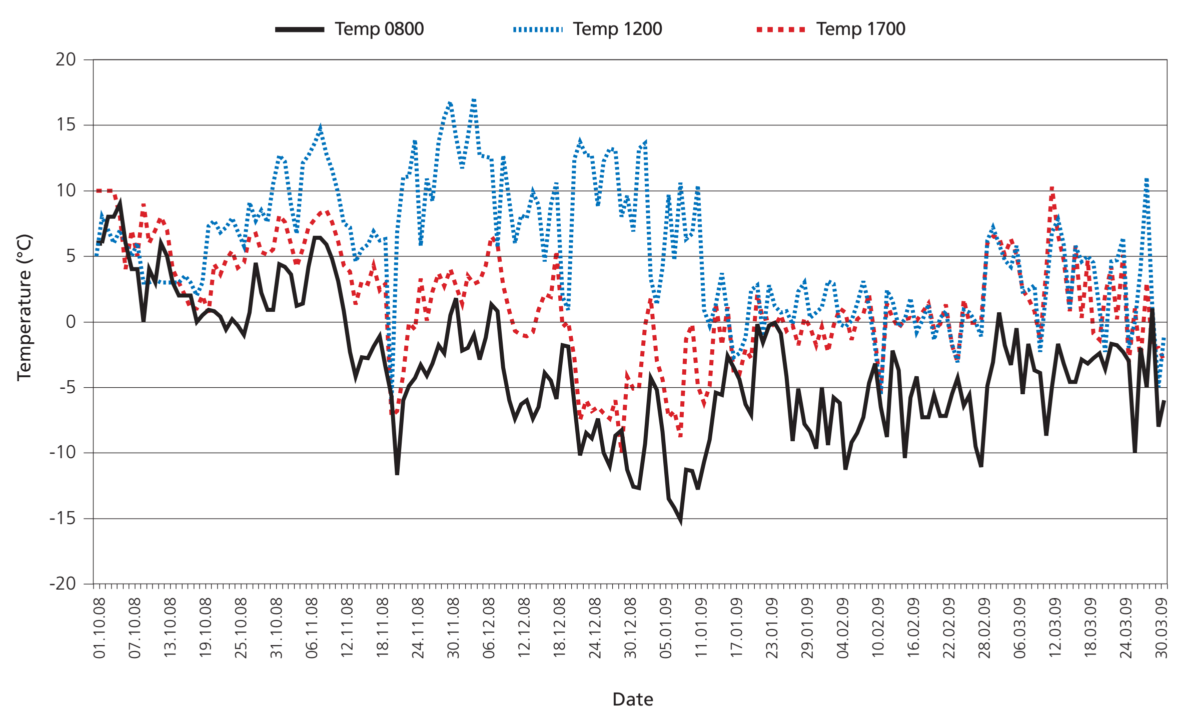


Figure 3.11: Temperature patterns at Gangotri Glacier site during the summer season



low especially in December when the morning temperature is always sub-zero and can dip down to -15 degree Celsius. The noon temperature remains at around 10 degree Celsius. During January and February, the morning and evening temperature is always below zero while in the noon it just crosses the zero degree mark. During March, the morning temperature remains at below zero, while the noon and evening temperature gets its value above zero and varies around 5 degree Celsius (*see figure 3.10*).

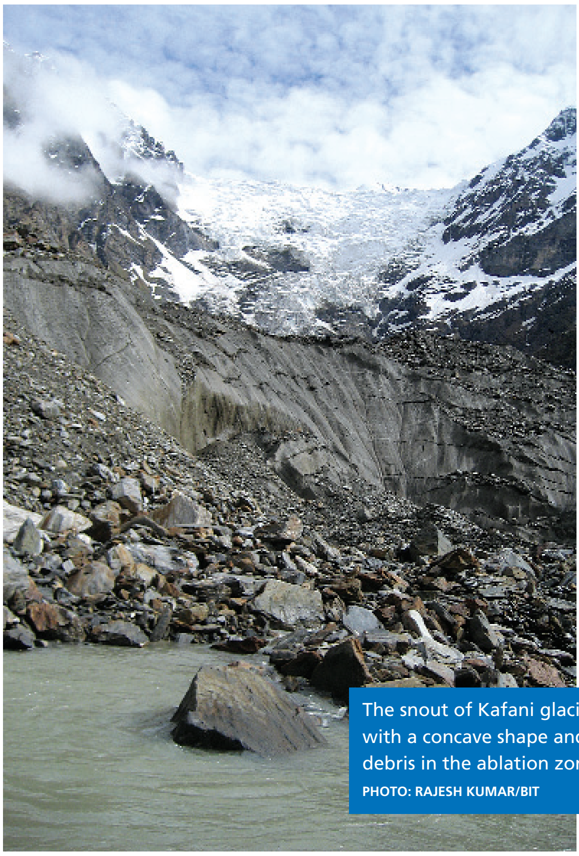
3.2 Kafani glacier

3.2.1 Study area

The Kafani glacier is located in the Pindar basin of the Kumaon Himalayas at the border of Bageshwar and Pithoragarh districts in Uttarakhand (*see figure 3.11*). The current snout position of the glacier lies at 30°13' 12" N and 80°03'14"E.

The north-south extending Kafani glacier originates from the southern slope of Nanda Kot - a major peak in the region. The glacier is the source of river Kafani which originates from the ice cave formed at the snout. This river is a tributary of the Pindar River which flows into the Alaknanda river system.

The Kafani glacier consists of two tributary glaciers that are no longer connected with the main trunk. They now exist in the form of hanging glaciers and contribute to the river flow through their meltwater. Table 3.3 encapsulates the major features of the Kafani Glacier.



The snout of Kafani glacier with a concave shape and debris in the ablation zone.
PHOTO: RAJESH KUMAR/BIT

Figure 3.11: Location Map of Kafani glacier

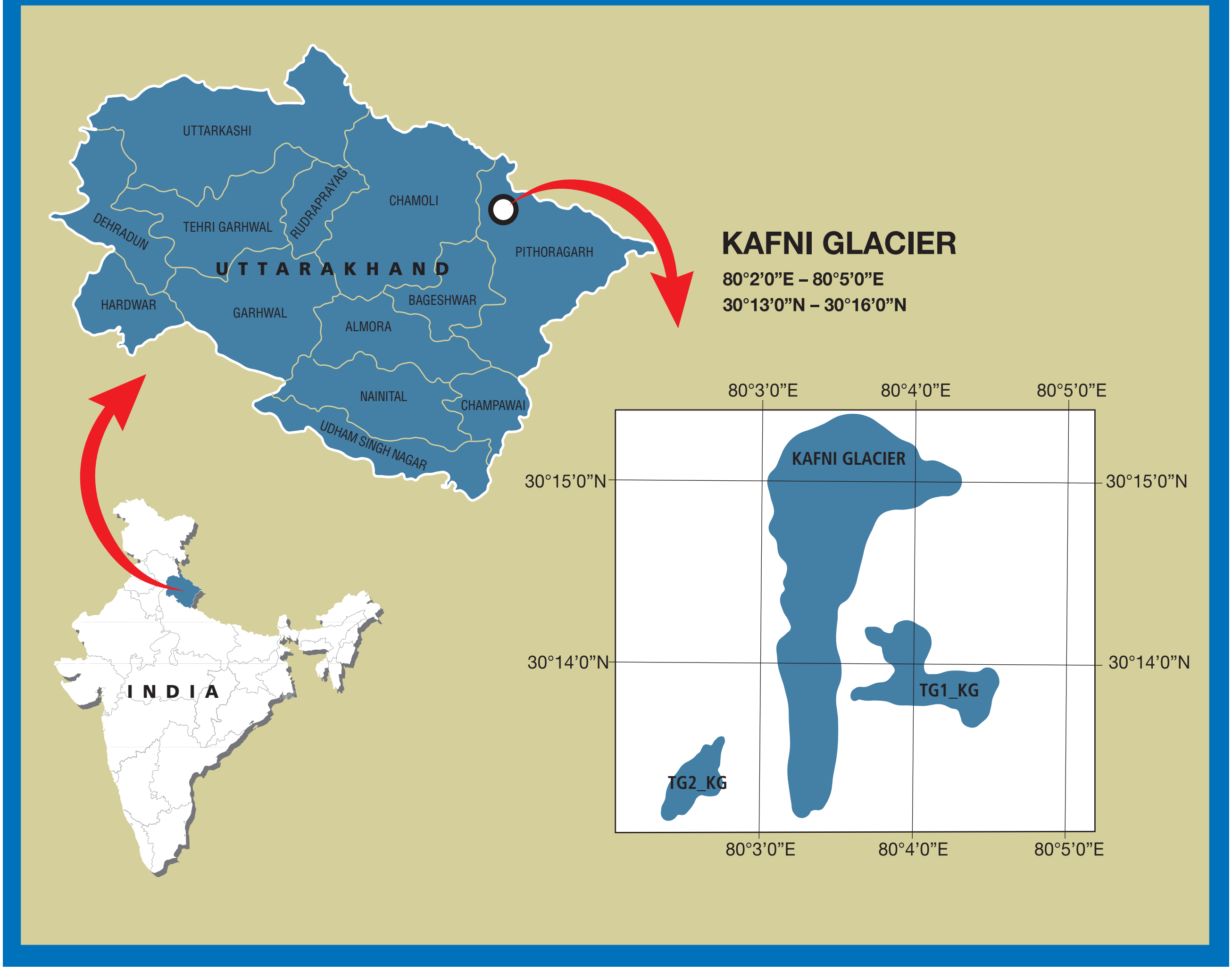


Table 3.3: **Kafani glacier inventory**	
Glacier Coordinates	80° 3′ 3.80″ E - 80° 4′ 18.26″ E 30° 13′ 10.14″ N - 30° 15′ 22.46″ N
Highest elevation (m asl)	5447.00
Lowest elevation (m asl)	3930.00
Surface area (km^2)	3.35
Ablation (km^2)	2.03
Accumulation (km^2)	1.32
Mean width (m)	775.33
Maximum length (km)	4.21
Ablation zone length (km)	3.21
Accumulation zone length(km)	0.99

Source: Rajesh Kumar, BIT

3.2.2: Understanding changes – methodology

The objective of selecting the Kafani glacier was to understand the impacts of the changing local climate on small glaciers. The glacier is being monitored for changes in length, area and volume using satellite imageries and DGPS. The recession pattern of the glacier has been studied by comparing the past satellite data (LANDSAT series of satellite imageries, 1976-1999) with the present data collected through DGPS during field visits in 2007 and 2008. The analysis has proved helpful in giving an overview of the changes in the snout position and glacierised area of the Kafani glacier in the last 30 years.

An automatic weather station has also been installed near the snout to understand the hydro-meteorological characteristics in the region and their linkages with the glacial melt (*see photo*). Along with weather monitoring, discharge patterns of the Kafani glacier have also been monitored to find the linkages between meteorological parameters and the glacial

AWS established near the snout of the Kafani glacier
PHOTO: RAJESH KUMAR / BIT

Discharge being monitored at a site 1 km downstream of the Kafani glacier
PHOTO: RAJESH KUMAR / BIT

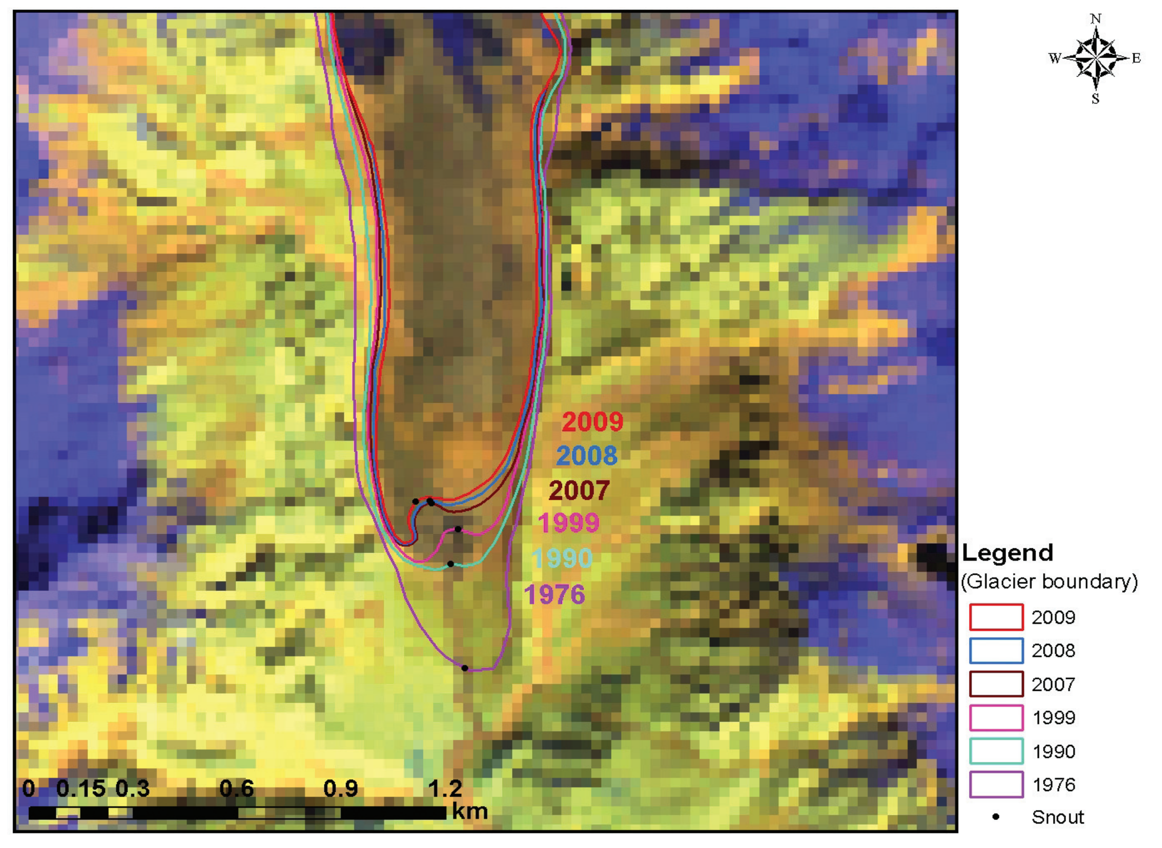
melt. Hydrological discharge data has been collected using float techniques.

3.2.3: Results and analysis

A combination of data from primary and secondary sources indicates that the average retreat rate of the Kafani glacier has been 16.15 m/year in the last three decades. However, the snout position of the glacier in different years shows a variation in the retreat rate during different time periods, i.e. between 1976 and 2008 (*see figure 3.12*). It is apparent from the analysis that the average retreat rate was higher at 21.64 m/yr from 1976-1990 but came down to 12.83 m/yr during 1990-99. It further reduced to 10.48 m/yr in the subsequent years from 1999-2007. However, in the last couple of years the rate has again increased and reached 14.99 m/yr in 2007-08 and 15.55 m/yr in 2008-09.

In spite of the bad condition of the upper ablation area (rock exposed at several places, showing reduction in ice thickness) the current retreat rate of the snout is nearly equal to the three decadal averages. The deteriorating condition will take a few years to reflect its impact on the snout and the total length of the glacier. The equilibrium in the retreat rate may be due to the thick debris on the lower to middle portion of the glacier, which reduces the solar energy transfer to the ice surface and hence a reduction in the melting. But this doesn't mean that this glacier is in good health. Smaller glaciers have a lower accumulation zone and therefore are more sensitive to the variations in snowfall and any change in the equilibrium line. The tributary glacier of the Kafani (being quite small in size) is now hanging, meaning that it is not directly connected any more through ice mass to the main trunk of the Kafani. This indicates the loss of huge ice volume in the glaciated catchment of Kafani. The glacier has vacated 14.76% of its area during 1976-1990 (16 years) and another 4.06% during 1990-1999 (9 years) as per an analysis conducted taking the base area as 1976. The overall loss in the glaciated area of Kafani and its tributaries during 1976 to 1999 is 17.5% (main trunk), 29% (TG1) and 23% (TG2) respectively. This loss clearly signifies that the smaller the area of a glacier, the greater is the loss under varying climate and snowfall patterns. For quick referencing, the results of the Kafani glacier's snout retreat have been shown in Figure 3.13. The analyses are based on satellite imageries (1976, 1990 and 1999) and DGPS observation during field visits (2007, 2008 and 2009).

Figure 3.12: The snout recession of Kafani glacier during 1976-1999 (the results of 2007-09 are based on DGPS observation)



Hydro-meteorological study

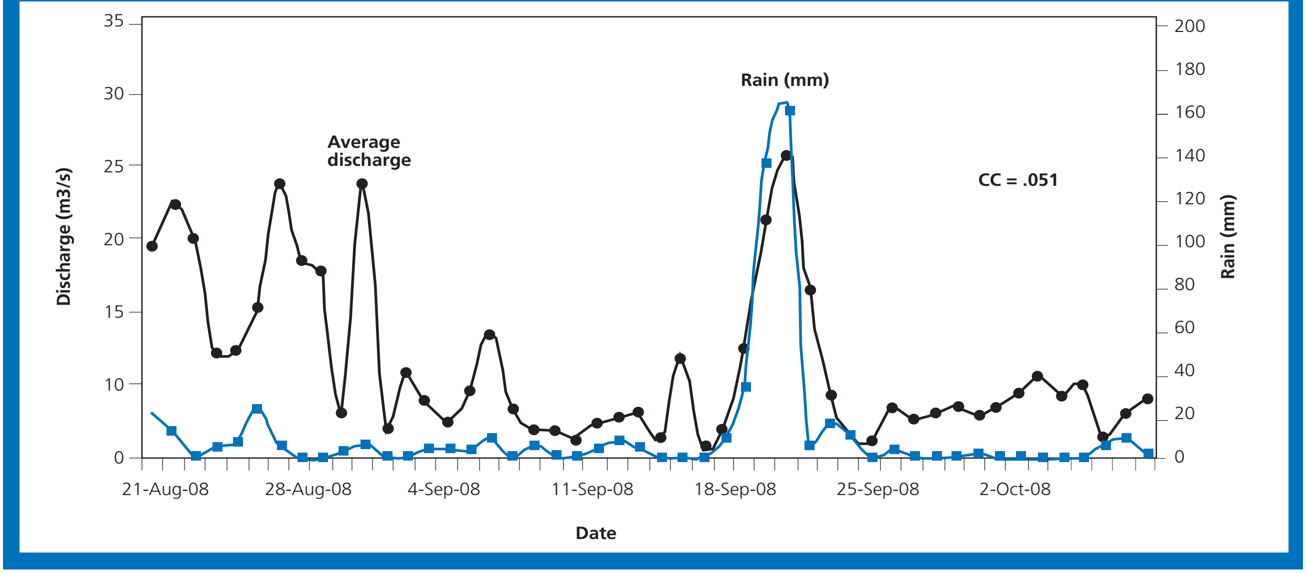
Initial trends about correlating meltwater discharge at Kafani with rainfall and temperature were established in 2008. Discharge data collected at the glacial snout in 2008 indicates a correlation of 0.51 between discharge and rainfall (*see figure 3.13*) which followed a uniform pattern throughout the entire summer season except for one extreme weather event during late September when high rainfall (about 165 mm) caused increase in discharge rate to ~30 m^3/s. Towards October trends indicated that the discharge rates dropped to 15 m^3/s.

Similarly, a clear correlation was observed between increase in temperature and discharge rates although the relation does not appear to be as strong as in the case of rainfall and discharge. This shows the importance of rainfall in this valley. Usually the valleys in the Kumaon Himalayas get more rain during the monsoon season as compared to the Garhwal Himalayas. With higher average temperatures in August during peak discharge season, actual discharge rates vary between 18-25 m^3/s, corresponding with the temperature range of 25-30°C for the same month. In October, with the onset of the winters, discharge rates tapered off to around 10 m^3/s in relation to average temperatures of about 4-8 °C. The upcoming data for the year 2009 will help us in understanding more about the behaviour of this region. Since this region was never equipped with a meteorological observatory, no analysis could be done from a hydro-meteorological point of view. This is for the first time that an attempt has been made in this part of the Himalayas to understand the hydro-meteorological characteristics near the Kafani glacier.

3.3 Conclusion

The initial results from our field study indicate that smaller glaciers like Kafani are retreating at a faster rate, and are not only loosing more glaciated portion but also their tributary glaciers – a trend which has been observed across the Himalayas for many other smaller glaciers. These glaciers are perhaps more vulnerable to local climate variations and hence long-term and continuous assessment is required to monitor the hydro-meteorological parameters existing in their vicinity to develop predictive model for future

Figure 3.13: Rainfall and discharge correlations at Kafani in 2008



water resource scenarios.

The current observations at the Gangotri glacier region will strengthen the existing observations; for the Kafani glacier region, this is the beginning of the hydro-meteorological observations. This data base will encourage researchers in future to conduct studies in the region of Gangotri, Kafani as well as other glaciers. This will further help in accurate assessments of the glacial melt and water flows based on long-term data. Better use of these technologies could provide an efficient and scientifically sound method to study different patterns and changes in the glacier systems on various spatial and temporal scales.

Though glacial retreat is a natural phenomenon with the earth moving towards a warming phase, the accelerated rate of retreat forces us to think of the other factors having an impact on it at present. Based on some of our studies and past scientific data, it is clear that climate change has a visible impact on the status and condition of some of studied glaciers as is evident through the increase in the net loss of mass year after year. It is worthwhile to note that the phenomenon of global warming and climate change will impact not only temperature but also the other variables like intensity and quantity of precipitation, cloud cover, wind and radiation. These variables will respond in complex mode through their impacts on glacier fluctuations. Hence, it becomes difficult to predict the glacier retreat or advance scenarios with confidence. Different glaciers in the same climatological set up respond differently to the changes in climate. In addition, the India Himalayas are lacking in meteorological records which makes it further difficult to establish the climate change linkages with the glacier fluctuations. Undoubtedly, the glaciers are retreating, but not at a catastrophic rate and the larger glaciers (like Gangotri ~ 30 km) are not going to disappear in near future. In view of these factors it is recommended to carry out a long term study on glacier mass balance and glacier dynamics to understand the impact of climate change in the Himalayas.

Larger glaciers like Gangotri show a continuous recessionary trend in recent years through this and other studies (Singh *et al.*, 2006). However, at present this trend may have a -limited influence on the water flows downstream primarily due to the large extent of the glacierised area. At present, the rapid decline of smaller glaciers is important and the study at Kafani compliments some of the earlier findings by other research (Dobhal *et al*, 2004). Regional climate variations could threaten the fragile nature of these glaciers which are likely to disappear at a much faster rate or be considerably reduced in length as compared to the larger ice bodies. The decline in glacial area and variations in annual runoff patterns in the future gains importance in the context of hydro power planning and development of the Himalayan states.

Emerging trends do not point out at a good omen for glaciers in Uttrakhand and need a detailed study based on more satellite imageries and ground research. The impact of climate change needs to be studied in context of enhanced rate of retreat as well as other fluctuations in the glacier terminus. A long-term monitoring of meteorological parameters is crucial before arriving at any conclusion regarding the impact of global warming, rather than the effect of local climate on glacier retreat.

4
CHAPTER

Adapting to Change

In this report we have made an attempt to present our understanding of the current changes in the Himalayan glaciers based on scientific evidence and analysis of observed data from the Gangotri and the Kafani glaciers. The science of climate change is complex as it is not only about temperature variations, but also the impact of local environmental factors; non-climate stressors play an equally critical role. The ecologically fragile Himalayan ecosystems harbour a diverse range of flora and fauna. Moreover, a range of ecological services generated by the Himalayan ecosystems support the well-being of communities in the mountains and lower plains. Changes in these will result in immediate long-terms impacts and requires development of appropriate adaptation responses.

While there is limited consensus amongst the scientific community and governments on the fact that the Himalayan glaciers are retreating, our study shows that changes are happening in the glacier. Climatic variations can be observed and are slowly but surely changing the social and economic dimensions of the vast Himalayan region through their manifold impacts. Communities living in the downstream of Gangotri have indicated changes in snowfall levels in the winter months resulting in less soil moisture, which in turn is changing cropping patterns and availability of water.

Non-climatic stressors, such as rapid economic growth, including tourism are equally increasing pressure on the Himalayan belt. Unplanned development has already resulted in severe pressures on both local ecology and communities. The impacts of climate change and changes in climate variability would further create additional stress.

Impacts on Forests and Biodiversity

The riparian ecosystems in the Himalayan belt comprising deciduous and temperate forests are likely to be affected (including shifts in forest boundaries) due to the projected changes in water flows (owing to unnatural rate of glacial melt). The rise in average surface temperatures in the region coupled with variations in melt water flows could lead to an upward movement of the tree line and significant impact on alpine ecosystems. The changing pattern of water and stream flows (due to glacial retreat) can lead to long-term impacts on forest vegetation and their economies. Various forest types are likely to get affected by not only reduced water flows but also variability in local precipitation. Similarly, the change in floral composition and resultant upward migration are likely to reduce the available habitat for several critical high altitude wildlife species such as wild sheep, goat and antelopes (Sukumar, 2000). In the Himalayan region, exposure of moraines to outside environs (due to glacial retreat) can also cause shifts in alpine species, particularly species like *Abies*, *Betula*, and *Acer* which are known to survive mainly under extremely low temperatures.

The consequence of changing forest types can also have far reaching impacts on the local communities of the region. The role of forests is critical in sustaining the local economy – for example, in the sub-alpine zones livestock rearing is a common economic activity particularly for the hill tribes along with other productive activities like animal husbandry, and fruit cultivation. The shifting pattern of forest vegetation will also lead to shrinkage of available grasslands in the sub-alpine zone that are traditionally used by local communities.

Impacts on Freshwater

The supply of freshwater resources in the Himalayas is likely to decrease as perennial snow and ice volume reduces over the years. In a uniform warming scenario of 0.06°C, impacts on river flows will be greater on small and highly glaciated basins, with flows in the sub-catchments attaining a peak of 150% of the initial flows by 2050 (Rees and Collins, 2006). Snow and glacial melt water runoff in the Himalayas have been highest in the summer months (May-August), and they play an important role in ensuring a continuous supply of freshwater for drinking and irrigation (Singh *et al*, 2006). Our observations on discharge patterns in summer months show similar trends.

One of the imminent impacts is changes in discharge patterns of rivers since these are directly linked to local temperature and precipitation. The unpredictable rate of discharge and its variability can influence the livelihoods, food security and energy security. For much of the Himalayan range, particularly in the headwaters, retreating smaller valley type glaciers could be a key indicator for future assessments. An understanding of snow and glacier melt processes as well as stream flow data will help in better investment and designing of infrastructure projects from a climate change perspective.

Linked to the issue of availability of freshwater is the aspect of energy security for the country through development of hydropower. There has been a manifold increase in the development of dams across some of the Himalayan states to tap the vast hydropower potential from Himalayan rivers and tributaries. However, changes in meltwater flows could impact energy security because of lack of enough water to run a hydropower plant at its full potential. The rapid development of such dams could also cause other indirect effects like environment impacts on fragile forest ecosystems as well as livelihood issues like rehabilitation and resettlement. It is evident that these projects often do not factor in long-term climate projections or extreme weather events.

A recent assessment of the impact of glacial melt waters and precipitation in Uttarakhand suggests that future hydrological flows could be very different when compared with current levels of flow (Iimi 2007). This would have implications on both energy outputs and to on the long-term viability of a project.

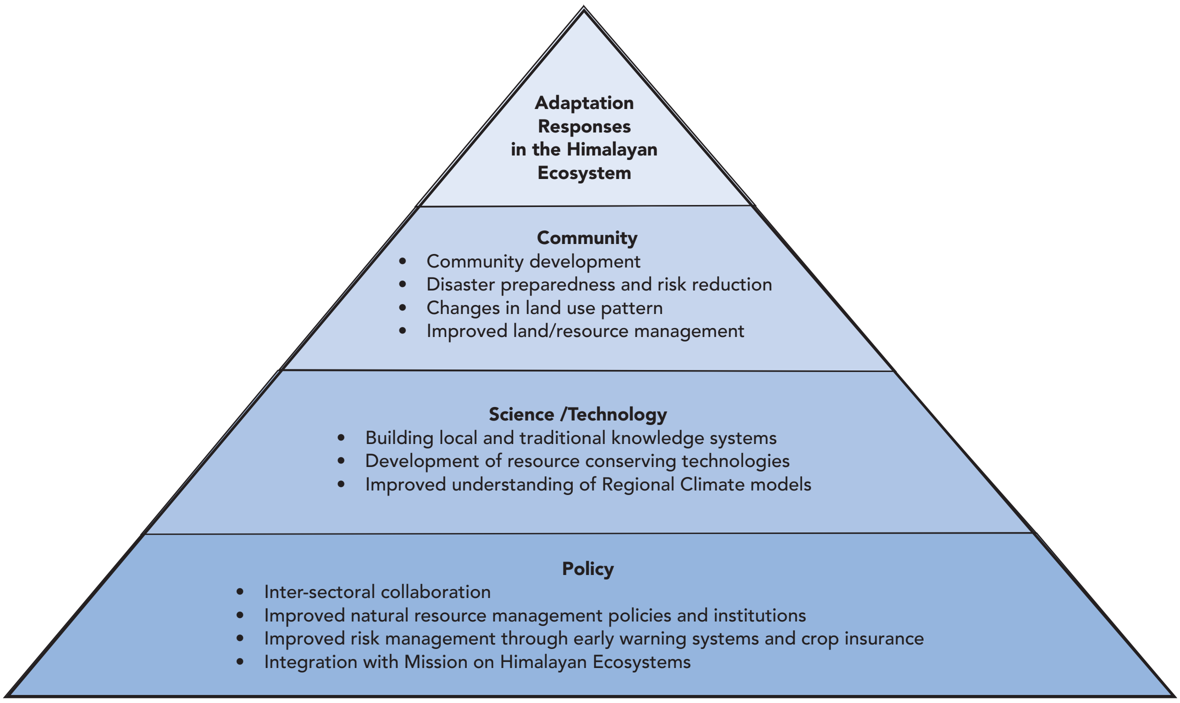
Adapting to the Change

Glacial retreat could pose the most far-reaching challenge in the Himalayan region. The dynamics of the monsoon are influenced by Himalayan systems which act as a reservoir to sustaining agriculture, providing freshwater and groundwater recharge, and are home to a unique ecosystem with many endemic species. Adaptation to climate change, therefore, requires not just local action but also trans-boundary cooperative arrangements.

Future efforts in building the resilience of the local community and the ecosystems should take into account a concerted and integrated approach. There is an urgent need by communities, scientists and policymakers to take a closer look at the linkages between local impacts, scientific research, policy interventions and the larger understanding of using resource conservation technologies and practices for promoting societal benefits. Given that climate change is a reality and India is vulnerable to its impacts, future directions for various states and the central government in addressing the issue needs to strongly focus on an ecosystems-based adaptation framework.

The impact of climate change affects the poor and the vulnerable in many ways, but the two major issues are – agriculture productivity and vulnerability to extreme events. In the rural Indian economy people are heavily dependent on agriculture as a source of income and sustenance. In an ecologically fragile

Figure 4.1: Adaptation responses in the Himalayan Ecosystem



Adaptation Responses in the Himalayan Ecosystem

Community

- Community development
- Disaster preparedness and risk reduction
- Changes in land use pattern
- Improved land/resource management

Science /Technology

- Building local and traditional knowledge systems
- Development of resource conserving technologies
- Improved understanding of Regional Climate models

Policy

- Inter-sectoral collaboration
- Improved natural resource management policies and institutions
- Improved risk management through early warning systems and crop insurance
- Integration with Mission on Himalayan Ecosystems

region, people live in areas that are acutely vulnerable to severe weather, and extreme events will continue to make their lives and livelihood more risk-prone.

As part of this process, different stakeholders at multiple levels need to come together to address the issue of climate change and environment security. Credible scientific observations interrelated with traditional ecological knowledge systems can be a step in promoting proactive policies for adaptation. There is a need for an integrated approach for development and growth without compromising on environmental sustainability. It would involve developing local climate scenarios and creating informed awareness among local communities to design and implement adaptation strategies for critical ecosystems.

The national level efforts should focus on building and strengthening the knowledge base of the impacts of climate change on our natural resources as well as developing suitable responses for tackling them. While developing and implementing management strategies (that are aimed at long-term conservation of the Himalayan glacier system) is critical, there is also a need for integrating remote sensing technologies with observed data for better monitoring of glaciers. Inventorisation of glaciers on a regional basis in close cooperation with other Himalayan countries is critical for understanding potential climate change impacts and building capacity within the region to find long-term solutions.

Science has provided evidence of changes happening in the glaciers, but probably not very accurately as there is inadequate recorded historical evidence. However, the growing body of anecdotal evidence and observations of the communities provide evidence of how communities are coping and managing with change. This needs to be supported with science and observed data. This study has provided data and information of what is happening at the ground level. In our view this aligns with the growing emphasis on regional cooperation between Himalayan countries on the impacts of glacial retreat as well as the national focus within India on the Himalayan ecosystems.

This report is first in a series of report from our on-going project in the Himalayan glaciers. In the subsequent years, we will continue to provide informed analysis of this critical issue which can affect the food, water and livelihood security of millions of people.