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Witnessing Change:

Glaciers in the Indian Himalayas

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GLACIERS IN THE INDIAN HIMALAYAS

Witnessing Change: Glaciers in the Indian Himalayas

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This report is a part of the study at Gangotri and Kafni glaciers being carried out by WWF - India in collaboration with the Birla Institute of Technology, Extension Centre, Jaipur. The report presents the findings of the study and observations between 2006 and 2009. In subsequent years we aim to bring out more comparative analyses as further data is generated and compiled.

This study is part of a project which is a joint initiative of WWF India and WWF Nepal, supported by WWF Netherlands, focusing on 'Climate Change Impacts on Freshwater Ecosystems in the Himalayas (CCIFEH)'. Through this project, WWF aims to study and understand climate change impacts on freshwater ecosystems, livelihoods and economy. The programme involves a range of actions towards understanding future climate change impacts on Himalayan river systems and vulnerable communities. In India, the study areas under this project cover diverse ecosystems such as the glaciers of Gangotri and Kafni in Uttarakhand, the fertile plains of the Ganga, High Altitude Wetlands of Ladakh and the Sunderbans delta.

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Cover Page Photo Credit: **Anne – Marie P. Singh, WWF India**
Cover page photograph shows the snout of the Gangotri Glacier with fresh snow cover in October 2007 and the photograph on page 10 shows crevasses and cracks on the surface of the snout in October 2009.

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1
CHAPTER

Introduction

The mankind 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, 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, the youngest and one of the most fragile mountain systems in the world, 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

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 (km^2)	Number of glaciers	Glacierised area (km^2)	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

and alluvium are found in between the Himachal and Shivalik ranges (Jain *et al.*, 2007).

The Himalayas comprise approximately 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 drinking water, irrigation, hydropower, fishery, inland navigation and other needs of more than 1.3 billion people living downstream. With about 9,575 small and large glaciers in the Himalayas (Singh *et al.*, 2009), they hold the largest reserves 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 spread over different river basins including 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 their orographic characteristics (high altitudes exceeding above 0°C isotherms), and local and regional climatic conditions. In addition to these, the 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 is concurrently taking place while some other glaciers are nurtured only by the westerlies (in winter) during the accumulation period. A 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 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

The freshwater melt from the glacierised basins is a vital element in regulating the dry season flows of perennial Himalayan river systems.

Being closer to the Tropic of Cancer, the Himalayan glaciers receive more heat than the Arctic and temperate climate mountain glaciers, and hence they are 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.

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, possibly 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, climatic variability and growing impacts of climate change is posing pressure on our natural water supply. A holistic approach is required to manage the freshwater resources in the Himalayas and ensure environmental security in the region.

For this, knowledge of glacial melt characteristics and their subsequent impacts on freshwater availability is essential. However, the current knowledge about the behaviour of glaciers in the Himalayan region is still limited (Anthwal *et al*., 2006).

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 earth's total land area 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

An 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 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 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

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

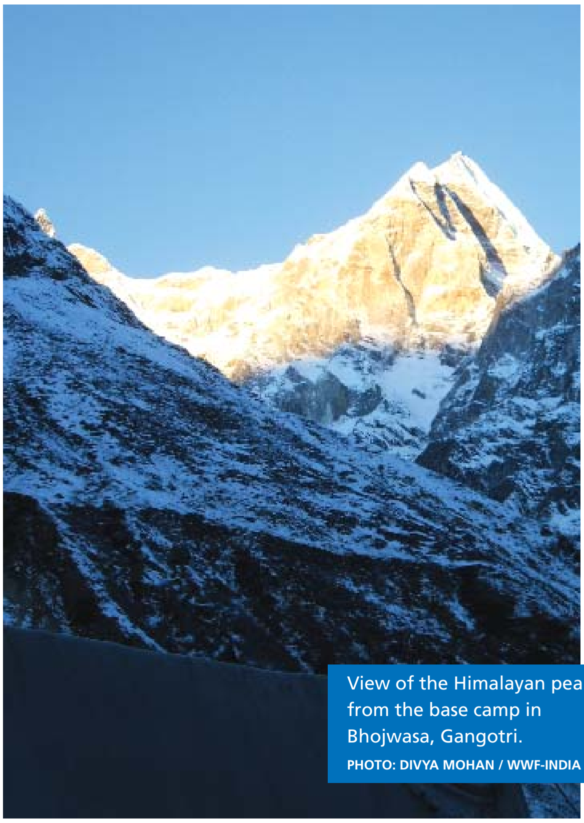
Source: UNEP, 2007; WWF, 2005; Mote and Kaser, 2007; UNEP, 2008; WGMS, 2008

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 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 rates 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 Patagonia, north-west USA and south-west Canada, and Alaska demonstrate strong 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*).



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*

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, 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 for long term monitoring or documented in terms of glacial retreat (*see table: 2.2*).

The climatology and the topography of the Himalayan region have wide variations all across the arc (Dobhal *et al*., 2004). Owing to these variations different parts of this region have been exhibiting diverse responses to the variability in climate. Singh and Bengtsson (2005) studied changes in climate in the Himalayan region. They found that 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.

The dynamics of a glacier are influenced by climatic factors including temperature, precipitation, amount of snowfall and wind. However, establishing

Studies on some important glaciers in the Himalayas

Dokriani

The Dokriani glacier (5.5 km) 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 records 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 m (with the average rate being 19.1 m/year). Since 1906, the glacier has vacated an area of 0.893 sq km in its pro- glacial realm. The increased rate of recession in the second half of the twentieth century is being attributed to global warming (Shukla and Siddiqui, 2001).

firm linkages between climatic variability due to anthropogenic factors and glacier retreat requires long-term studies and monitoring. Mass balance and glacier snout monitoring have been important methods 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 generated an important debate on the role of climate change in the extent of glacier loss (WWF, 2005; GoI, 2009).

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 WWF's and BIT's research on the Gangotri glacier, which shows that the average rate of retreat for this glacier declined substantially (6.02 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 accumulation zones. On the other hand large glaciers

Crevasses and cracks at the snout of the Gangotri Glacier. As the snout ice is fragile, large chunks of ice some times 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.

PHOTO: RAJESH KUMAR/ BIT

might sustain the impacts for a longer time due to their larger ice volume and bigger accumulation zone. Any changes in climate will take a long time to get reflected in the structure of larger glaciers in the form of retreat or advance because of their slow movement (~ 40-50 m/year). The impact observed at the snout for larger glaciers does not properly reflect the change in climate of the same year because it is the combined impact of several years' variations in weather patterns. Hence there is need for further investigation of the snowfall variability in the glacier region under climate change scenarios.

3
CHAPTER

Understanding the changes: Study of Gangotri and Kafni Glaciers 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 a 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 would help in developing regional climate projection models which are more accurate in providing information on future impacts.

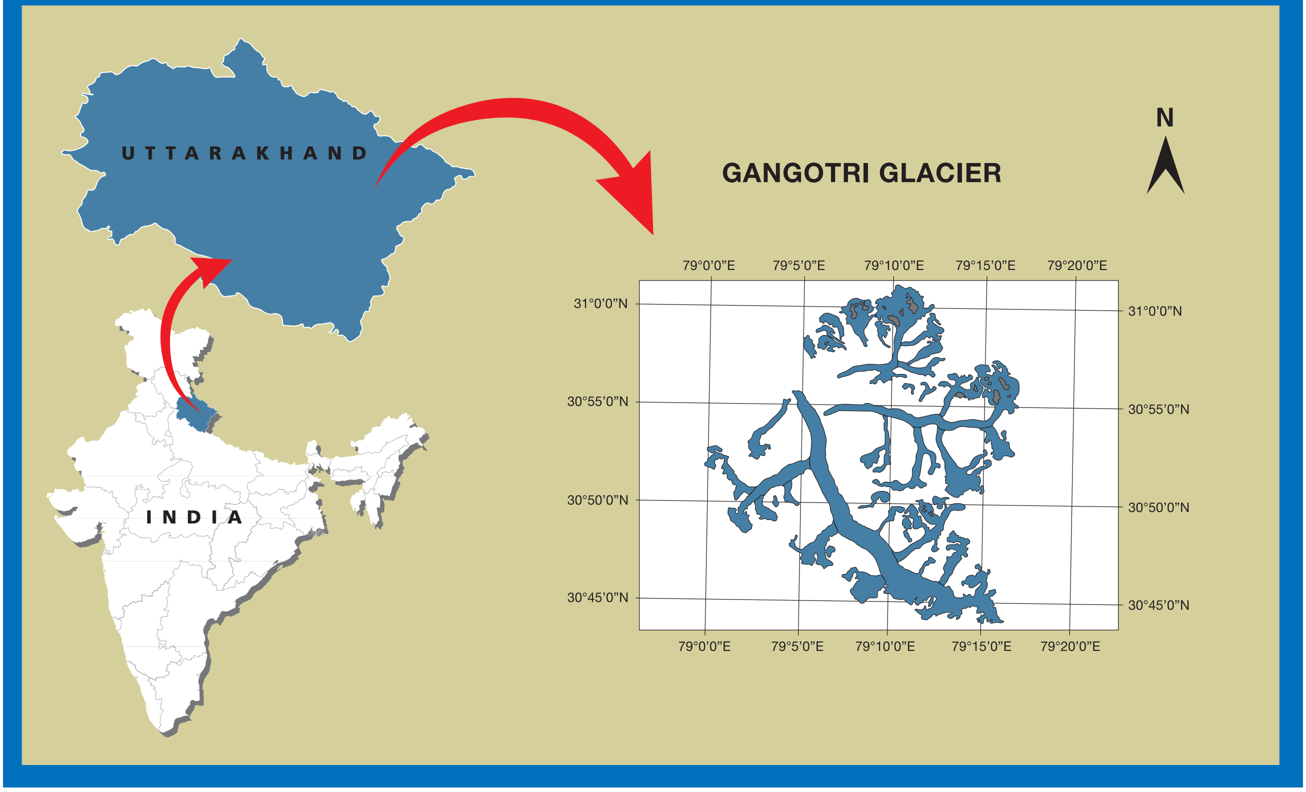
WWF India has been raising awareness about climate change and the impacts on Himalayan ecosystem since 2005 (WWF, 2005). In order to generate a deeper understanding of the potential impacts of glacial melt in the Himalayas, WWF initiated a project in 2006 which focused on studying two key glaciers from a climate change perspective and the subsequent impacts on freshwater availability. These glaciers were the 30 km long Gangotri glacier and the 4.2 km long Kafni glacier, 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, with 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 impacts on these glaciers are likely to affect this large river system (Singh *et al.*, 2009).

Figure 3.1: The location map of Gangotri glacier system



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. The complete Gangotri glacier system along with its tributaries covers an area of 210.60 sq km (ETM+1999). 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, lies between 79°4′ 46.13″ E-79°16′ 9.45″ E and 30°43′ 47.00″ N-30°55′ 51.05″ N (ETM+1999). It has varying elevation of 4,015–6,145 metres above sea level (SRTM data analysis).

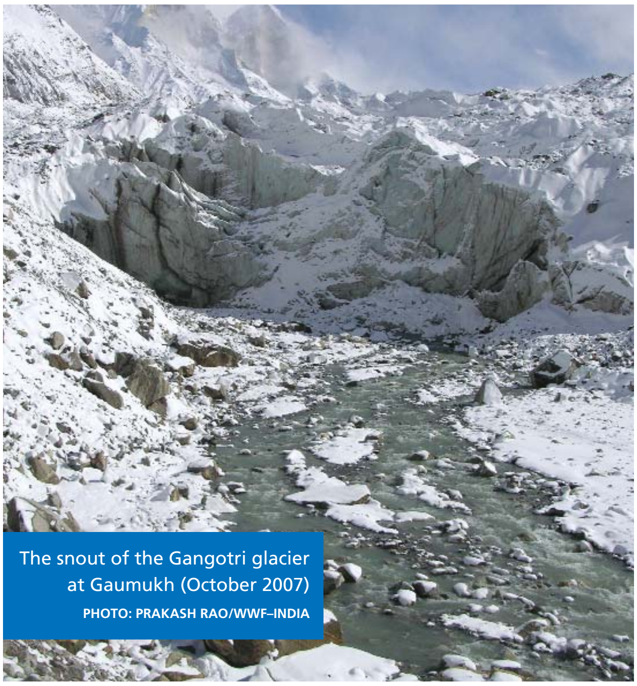

The snout of the Gangotri glacier at Gaumukh (October 2007)

PHOTO: PRAKASH RAO/WWF–INDIA

The snout of the glacier 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.

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 terminal and lateral moraines (GSI, 2001). In the past century, the retreat rate of the glacier has

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: Srivastava et al., 2004 (GSI, 2004); GSI, 2001

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*).

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. Meteorological analysis of long-term data becomes a fundamental aspect in determining the structural changes taking place in 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 times 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 a 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 night time 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 night time 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 maintains a high flow during June to August with maximum average discharge in August. The discharge starts reducing from September onwards. Singh *et al*., (2006) have also reported similar results in the discharge flows from the glacier.

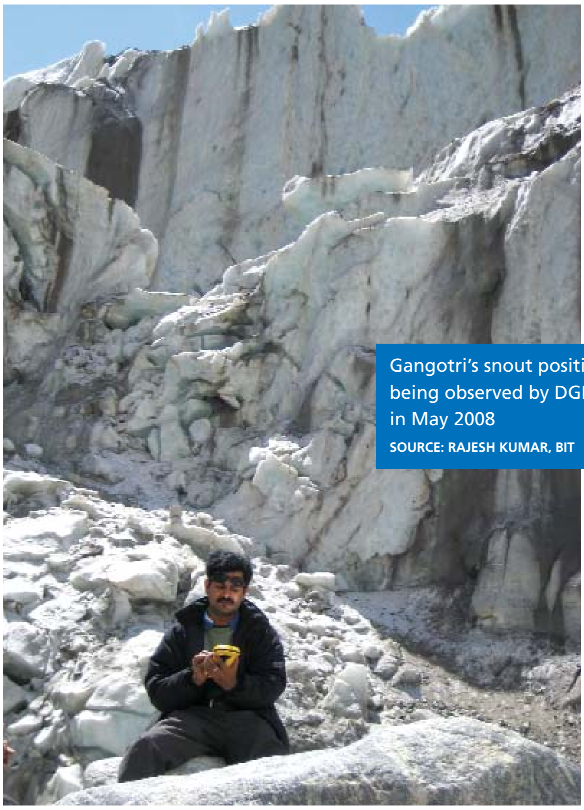
3.1.3 Understanding changes – methodology

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. Snout position was recorded in the months of September and October of each year since 2006. 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. The glacial area was calculated using satellite imageries of 1976, 1990, 1999 and 2006 by delineating the glacier boundary using ERDAS 9.0 and auto calculating the area using GIS methodology.

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. Satellite imageries available since 1976 formed the baseline for the analysis of the fluctuations in snout position together with DGPS

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



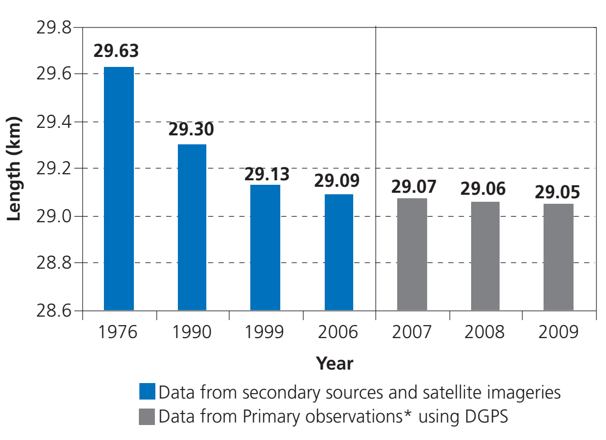
Gangotri's snout position being observed by DGPS in May 2008

SOURCE: RAJESH KUMAR, BIT

observations since 2006.

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 and fragmentation 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 about 0.59 km in 33 years, from 1976-2009, with an average retreat rate of 17.59 m/year (*see figure 3.2*).

Figure 3.2: Length of the Gangotri glacier in different years

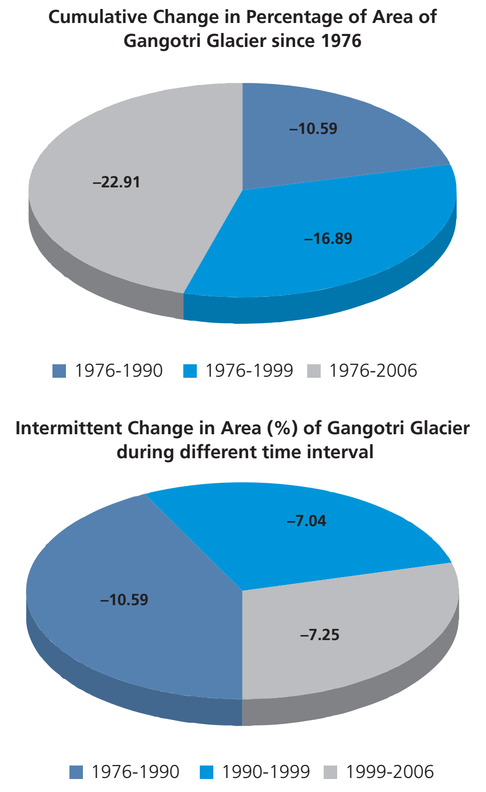


**Observations taken as part of study on glaciers by WWF-India and BIT*
Source: WWF/BIT, 2009

Based on the comparison of satellite imageries of the Gangotri glacier for the years 1976, 1990, 1999 and 2006, our analysis shows that 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. Analysis shows that between 1976 and 2006, the glacier area has reduced by 15.5 km^2, with an average loss of 0.51 km^2 per year. This reduction in glacier area is 22.9% over 1976 (*see figure 3.3*). The glacier area reduced by 7.2 Km^2 between 1976 and 1990 , in fourteen years, with a 10.6% reduction in the glacial area. In nine years, between 1990 and 1999, the glacial area reduced by 4.3 km^2 and resulting in 7% reduction in area when compared to 1990. However, the rate has increased between 1999 and 2006, with glacial area reducing by 4.1 km^2 and a 7.25% reduction in area over 1999.

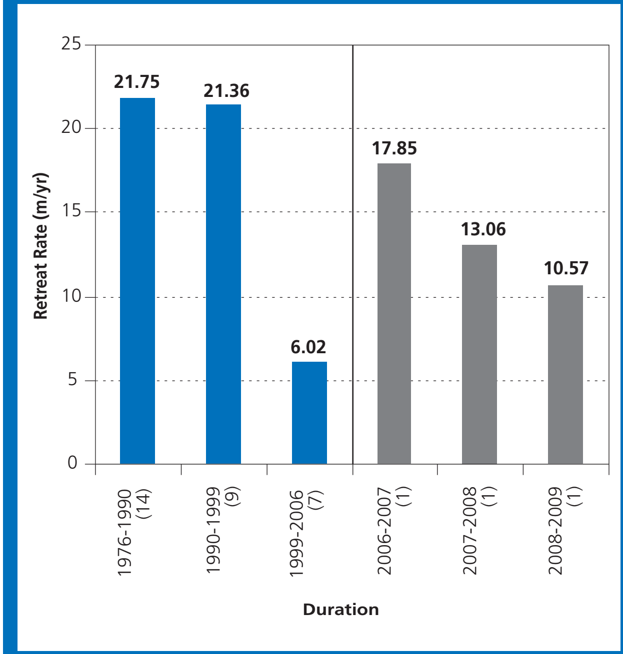
With a reduction in the area and length of the Gangotri glacier, there has also been a retreat in the snout position. Data collected from various sources shows that this has been a continuous process;

Figure 3.3: The cumulative and intermittent reduction in the area of Gangotri Glacier since 1976



Source: WWF/BIT, 2009

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

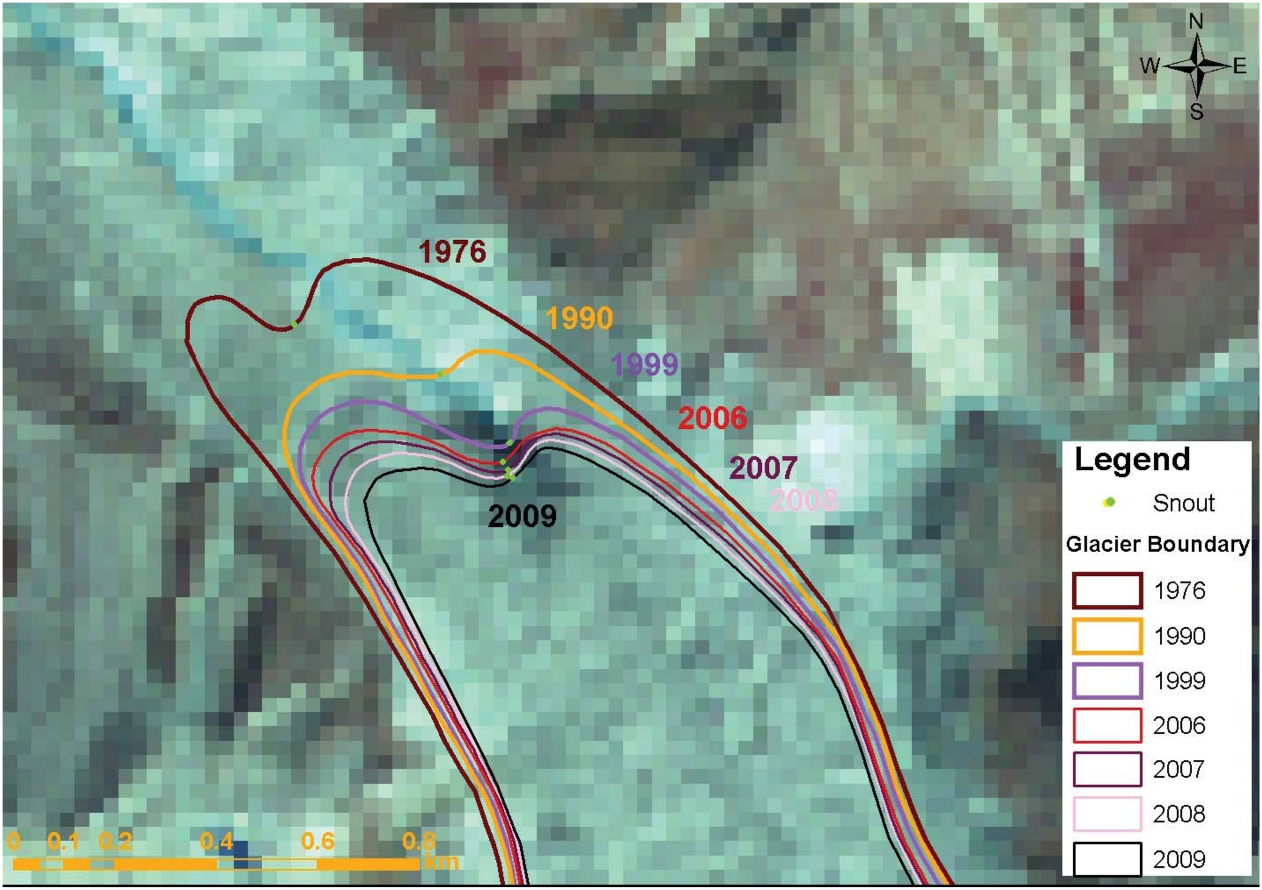


Source: WWF/BIT, 2009

however, there have been fluctuations in the rate of retreat for different time intervals.

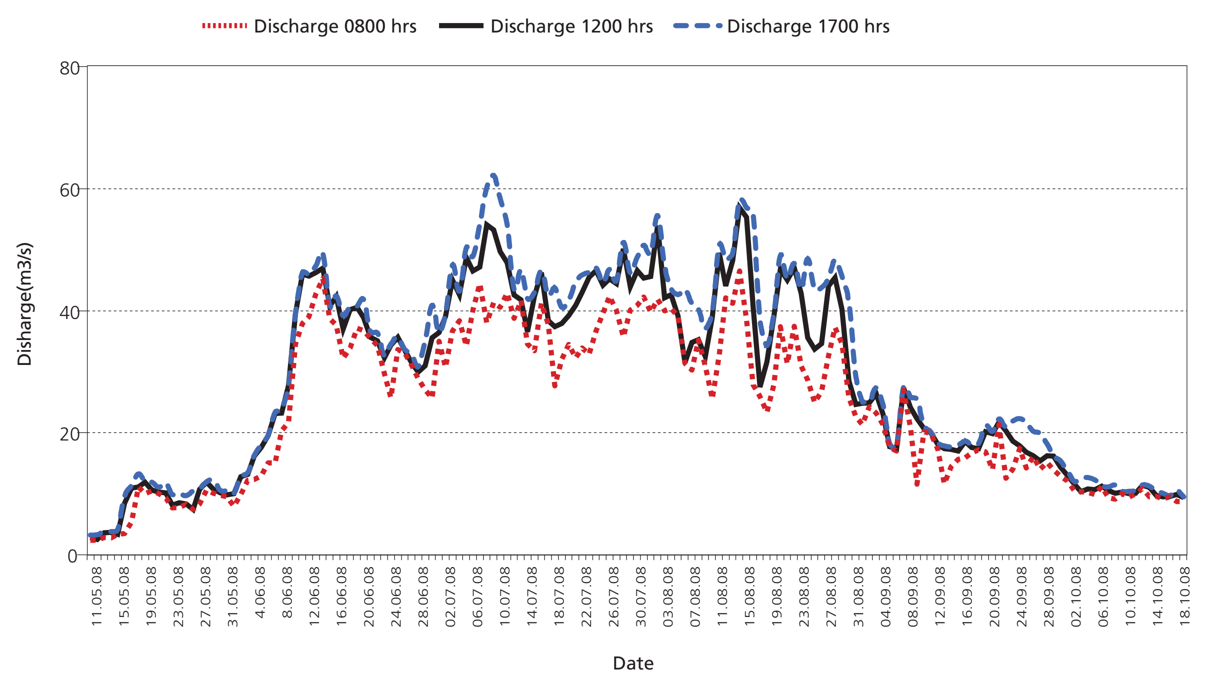
The calculation of the snout retreat by DGPS observation is made from point to point that gives the straight line distance of the two points that may include the shift of the water outlet point (left/right) in the curvilinear shape of the larger snout. The other way of measuring shift of the snout position 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 17.85 m when compared to snout position of 2006. In the subsequent years, the retreat rate has reduced - 13.06 m in 2007-08 and 10.57 m in 2008-09. It can be said that retreat has taken place between 2007 and 2009, however, it is lower than the long term average. Our observation from the glacier indicates that while there is a retreat, it is the fragmentation of the

Figure 3.5: Snout position of the Gangotri glacier from 1976 to 2009



Source: BIT

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



Source: WWF/BIT, 2009

Gangotri glacier is of larger concern. 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*).

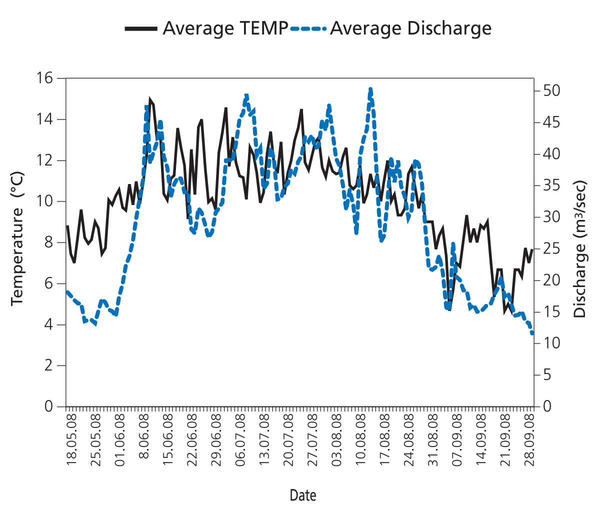
Hydro-meteorological study

Trends emerging from the analysis of summer season discharge data for Gangotri show that there are variations on a 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 rates 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 temperatures 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.

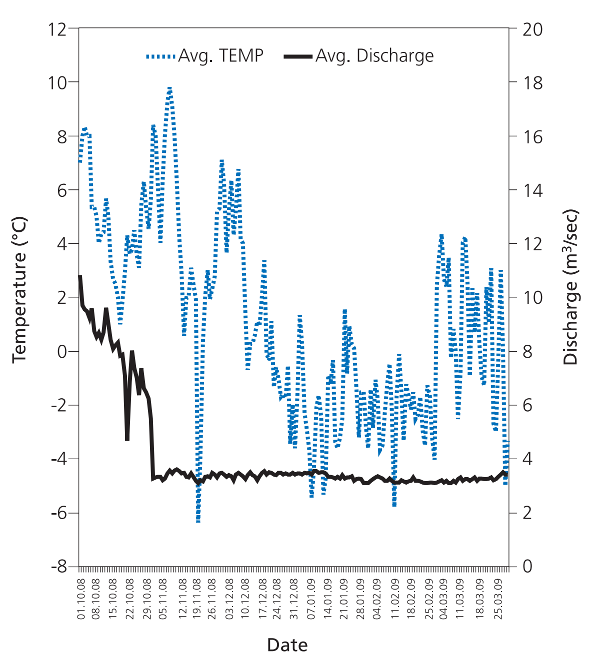
The daily average temperature and average discharge for the ablation and accumulation season at Bhojwasa are shown through figures 3.7 and 3.8 respectively. A good correlation of 0.73 has been found to exist between the average temperature and average discharge in the ablation season. However, these parameters are not well correlated (0.46) in the accumulation season, which shows a lower influence

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



Source: WWF/BIT, 2009

Figure 3.8: The average temperature and discharge during the accumulation season at Bhojwasa on Bhagirathi river



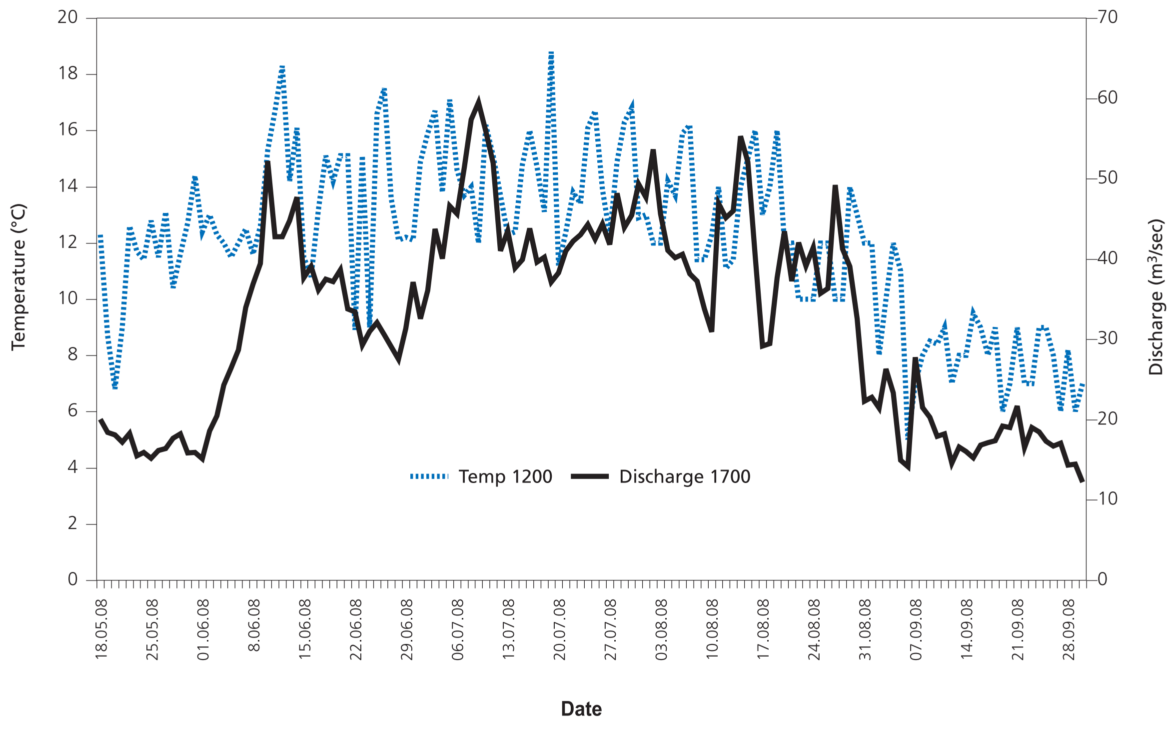
Source: WWF/BIT, 2009

of 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 . While these are initial results, comparisons 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 mid-day 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 the Bhagirathi river (*see figure 3.9*). In the month of October the discharge rate falls as the average temperature starts reducing (*see figure 3.9*).

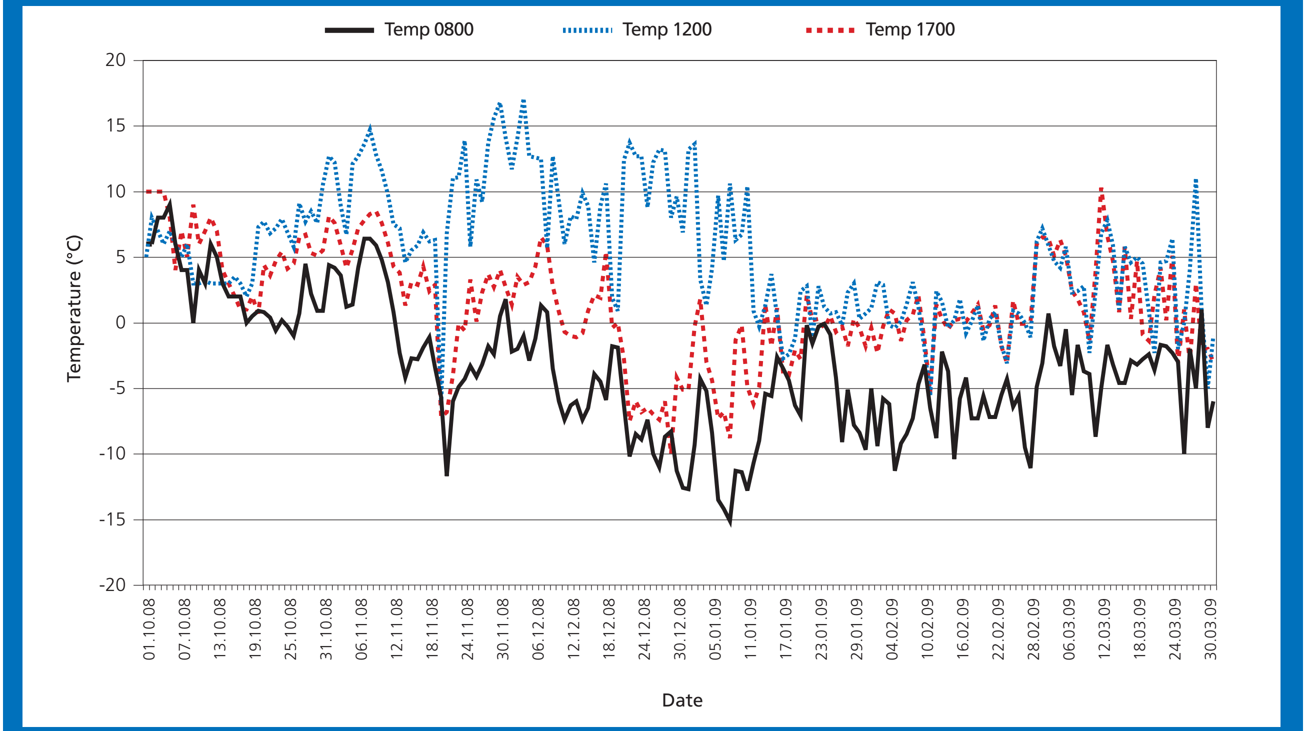
Trends in the Gangotri region (*see figure 3.10*) reflect that temperature start falling with the arrival of September. The maximum temperature reaches up to 18 degrees Celsius in June and July and remains

Figure 3.9: Influence of midday temperature (1200 hours) on evening discharge 1700 hours at Bhojwasa, Gangotri



Source: WWF/BIT, 2009

Figure 3.10: Temperature patterns at Gangotri Glacier site during the summer season



Source: WWF/BIT, 2009

mostly around 14 degrees Celsius during May to August. The morning temperature (at 0800 hours) remains at around 9 degrees Celsius till August and falls to zero in the mid of September. The winter temperature is quite low especially in December when the morning temperature is always sub-zero and can dip down to -15 degrees Celsius. The noon temperature remains at around 10 degrees 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 varies around 5 degree Celsius (*see figure 3.10*).

3.2 Kafni glacier

3.2.1 Study area

The Kafni 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 Kafni glacier originates from the southern slope of Nanda Kot - a major peak in the region. The glacier is the source of river Kafni 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 Kafni glacier consists of two tributary

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

Figure 3.11: Location Map of Kafni glacier

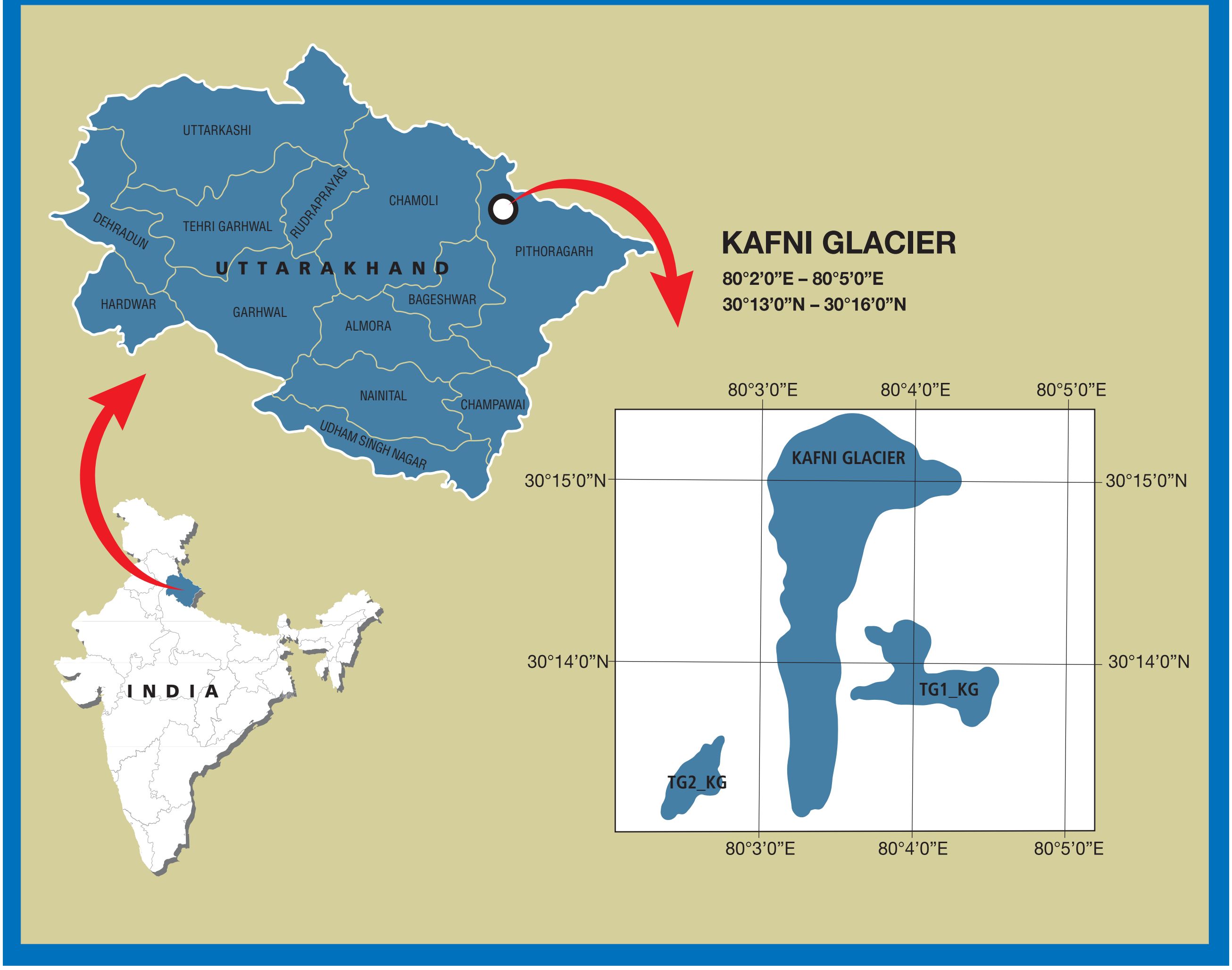


Table 3.3: **Kafni glacier inventory**

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: BIT

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 Kafni Glacier.

3.2.2: Understanding changes – methodology

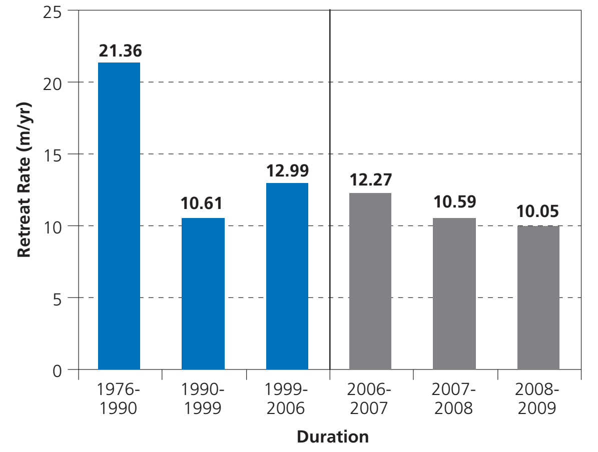
The objective of selecting the Kafni glacier was to understand the impacts of the changing local climate on small glaciers. The glacier is being monitored for changes in length, area and volume using satellite imageries and DGPS. The recession pattern of the glacier has been studied by comparing the 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 Kafni 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 Kafni glacier have also been monitored to find the linkages between meteorological parameters and the glacial melt. Hydrological discharge data has been collected using float techniques.

3.2.3: Results and analysis

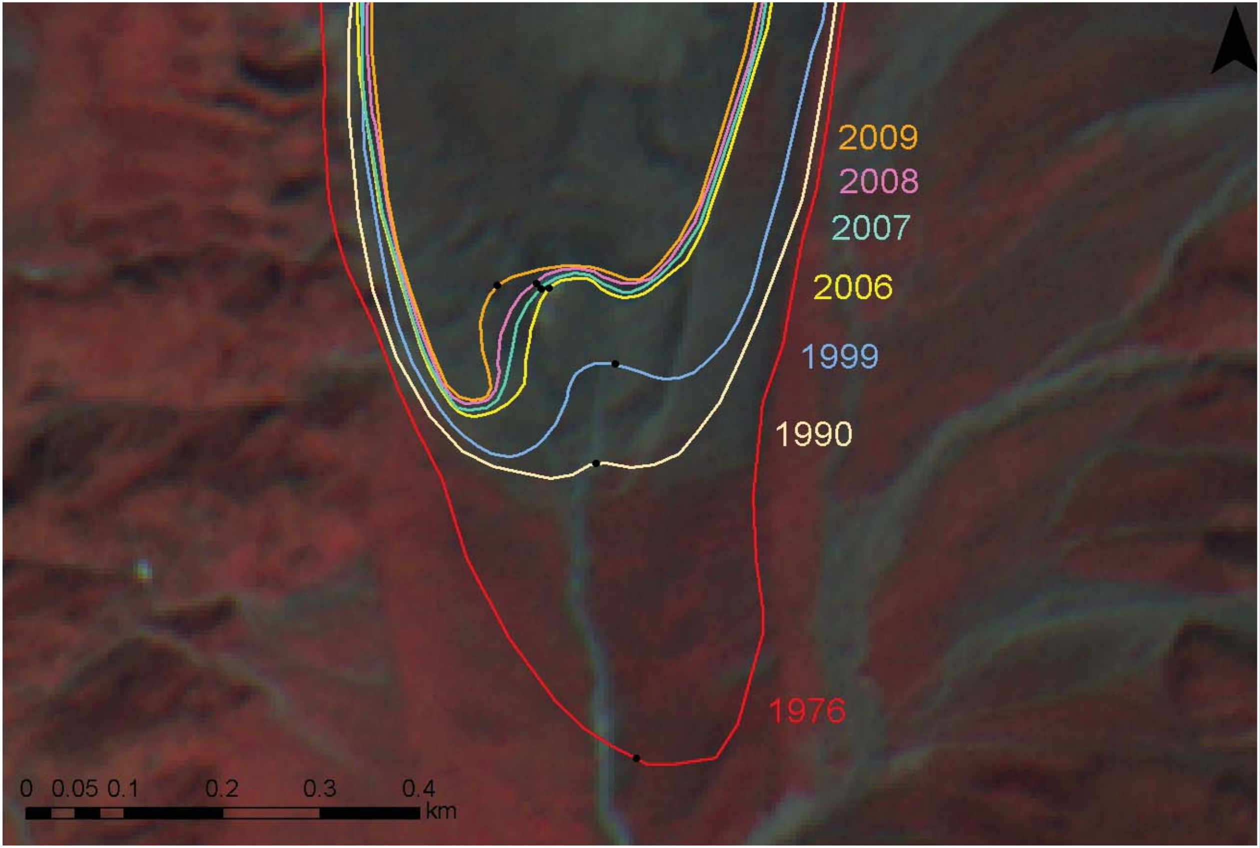
A combination of data from primary and secondary sources indicates that the average retreat rate of the Kafni glacier has been 15.7 m/year between 1976 and 2009. However, the snout position of the glacier in different years shows a variation in the retreat rate during different time periods, i.e. between 1976 and 2009 (*see figure 3.12*). It is apparent from the analysis that the average retreat rate was higher at 21.36 m/yr from 1976-1990 but reduced to 10.61 m/yr during 1990-99. The average retreat increased to 12.99 m/yr between 1999 and 2006. Annual observations since 2006 shows that the Kafni snout retreated by 12.27 m/yr between 2006-07 and it continues to show a reducing trend – 10.6 m/yr in 2007-08 and 10.05 m/yr in 2008-09. While the retreat rate of the glacier shows a reducing trend, however, it is important to note that given that Kafni is a smaller glacier, even a small retreat has a significant impact on the mass balance of the glacier (*see figure 3.13*).

Figure 3.13: Retreat Rate of Kafni snout in different intervals of time



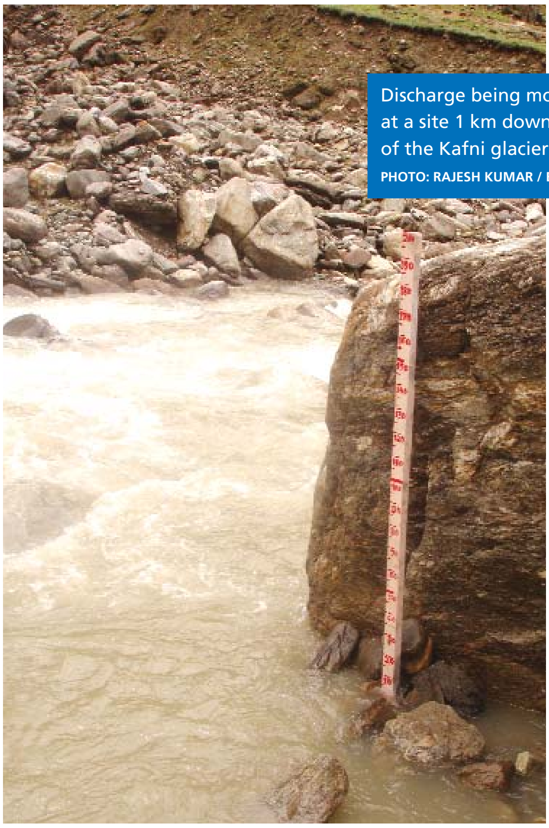
Source: WWF/BIT, 2009

Figure 3.12: The snout recession of Kafni glacier during 1976-2009 (the results of 2007-09 are based on DGPS observation)



Source: BIT

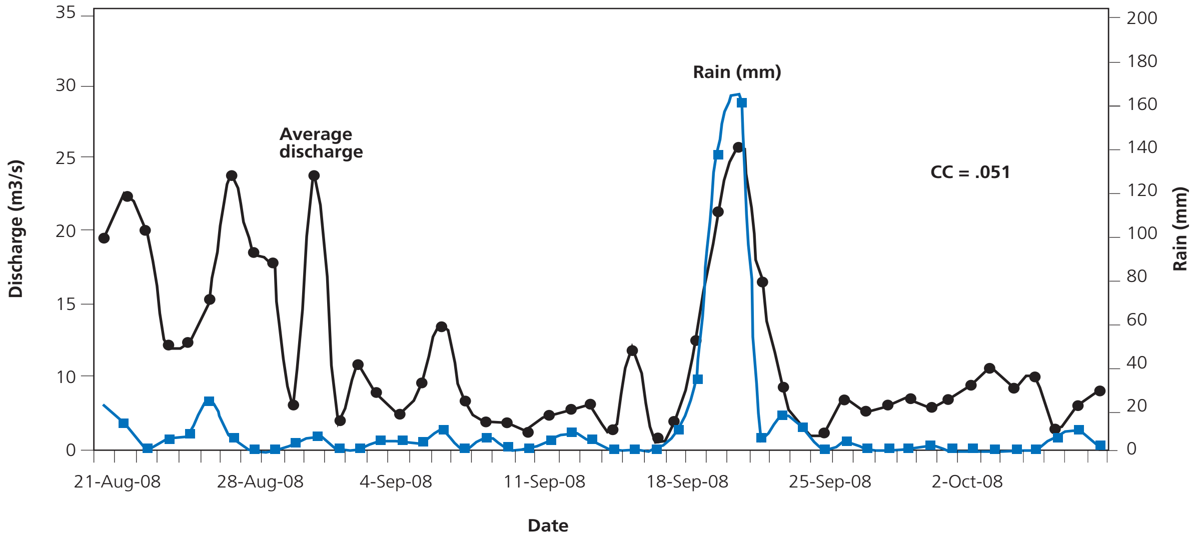
AWS established near the snout of the Kafni glacier
PHOTO: RAJESH KUMAR / BIT



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

The characteristics and condition of the upper ablation area – rock exposed at several places and reduction in ice thickness – will show its impact in a few years 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. Kafni, being a smaller glacier has a lower accumulation zone and therefore is more sensitive to the variations in snowfall and any change in the equilibrium line. The tributary glacier of the Kafni (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 Kafni. This indicates the loss of a huge ice volume in the glaciated catchment of Kafni. The glacier

Figure 3.14: Rainfall and discharge correlations at Kafni in 2008



Source: WWF/BIT, 2009

has vacated 14.76% of its area during 1976-1990 (16 years) and another 4.06% during 1990-1999 (9 years) as per analysis of this study taking the base area and year as 1976. The overall loss in the glaciated area of Kafni and its tributaries during 1976 to 1999 is 17.5% (main trunk), 29% (TG1) and 23% (TG2) respectively. For quick referencing, the results of the Kafni glacier's snout retreat have been shown in *Figure 3.14.*

Hydro-meteorological study

Initial trends about correlating meltwater discharge at Kafni 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 3.14*) 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° for the same month. In October, with the onset of the winter, discharge rates tapered off to around 10 m^3/s in relation to average temperatures of about 4-8 °C. 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 of the Kafni glacier.

4
CHAPTER

Conclusions

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 Kafni 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, ecological services generated by these ecosystems support the well-being of communities in the mountains and lower plains.

Smaller Glaciers – More Vulnerable

The initial results from our field study indicate that the Himalayan glaciers are retreating, but at a reduced rate and the larger glaciers like Gangotri are unlikely to disappear in near future, due to its large mass balance. The smaller glaciers like Kafni are retreating at a faster rate, and are not only losing more glaciated portion but also their tributary glaciers – a trend which has been observed across the Himalayas for many other smaller glaciers. At present, the rapid decline of smaller glaciers is of concern and the study at Kafni 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. 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 models for future water resource scenarios.

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. The movement of larger glaciers are dynamic and snout retreat is a delayed response, but the fragmentation of the larger glaciers needs to be continuously monitored.

The Climate Change Angle

While there is limited consensus amongst the scientific community and government on whether the Himalayan glaciers are retreating on account of climate change, through our study we can say that we are witnessing changes in the Himalayan glaciers. Not only climatic variations can be observed but there also are visible changes in the social and economic dimensions of the Himalayan region. Communities living closer to 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.

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 our study 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. Different glaciers in the same climatological set up respond differently to the changes in climate. Hence, it becomes difficult to predict the glacier retreat or advance scenarios with confidence.

Addressing the Data Challenge

The current observations at the Gangotri and Kafni glaciers strengthen the existing observations especially by providing the hydro-meteorological data. This database will encourage researchers in future to conduct studies in the region of Gangotri, Kafni 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.

Since region specific climate models are limited, a long- term monitoring of meteorological parameters is crucial before arriving at definitive conclusion regarding the impact of global warming and climate change. It is also important to study the impact of local pollutants and climate variables together with non-climatic stressors.

As a way forward it is essential that more data is generated over a longer time period and that new mechanisms need to be created to ensure sharing of data to enable more in-depth research and analysis. This will enable development of more region specific climate models to make projections for potential future impacts and preparation of appropriate response measures and mechanisms. It is also essential to carry out a long term study on glacier mass balance and glacier dynamics to understand the impact of climate change in the Himalayas.

Non-climatic Stressors

Non-climatic stressors, such as rapid economic growth, including tourism and infrastructure development 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. 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.

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 (WWF, 2009). 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.

Way Forward

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 the ground level parameters. 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 from our ongoing project in the Himalayan glaciers and WWF will continue to provide informed analysis of this critical issue which can affect the food, water and livelihood security of millions of people.

Annexures

I. About glaciers

Introducing glaciers

A glacier is a large, perennial accumulation of ice, snow, rock, sediment and liquid water, originating on land and moving downslope under the influence of its own weight and gravity. It can be classified on the basis of its size, location and thermal regime. Since a glacier forms as a result of accumulation and transformation of snowfall over several years, it can be found only in areas where such build-up of snow can exist (like the polar and mountain regions). Being a dynamic mass of ice and snow, a glacier experiences continuous downward movement due to the gravitational force. Atmospheric factors such as temperature, precipitation, snowfall, wind and solar radiation also govern the structure of a glacier.

Though a glacier is primarily made of ice and snow, but it also consists of sediments and rock debris which it carries along during the downward movement. Several topographic and climatic features together govern the existence and development of glaciers in a particular location. When a glacier moves back or retreats, it leaves behind these materials termed as moraines. These moraines take different shapes, and are designated as lateral, medial and terminal, depending on their position. Moraines are also helpful in understanding the earlier existence and the palaeo extent of any glacier.

Thr Durung Drung glacier, Zanskar basin , Jammu and Kashmir
PHOTO: RAJESH KUMAR/ BIT

Glacier formation and structure

Formation

Glacier ice formation starts with the falling of snowflakes that get deposited in the higher altitudes where accumulation of snow is favoured. New snow layers deposited during the subsequent years create pressure on the existing layers. Snow avalanches also contribute in shaping these layers. Constant deposition due to snowfalls, and repeated freezing and thawing turns the snow into grain sized ice called firn, and this process is known as firnification. Metamorphosis and compression of the deposited snow over the years result in the creation of glacial ice. As the snow slowly turns into ice, the glacier gets its final shape by gaining weight and when it gets large enough it begins to move under the force of gravity (Lerner and Lerner, 2008, Philander, 2008). The time taken for the formation of a glacier mainly depends on the local weather conditions, and thus the process varies from region to region. For instance, snow transformation happens more rapidly in temperate areas as compared to the Antarctica (Singh and Singh, 2001). Worldwide, glaciers also exhibit a wide variation in their areal extent and thickness.

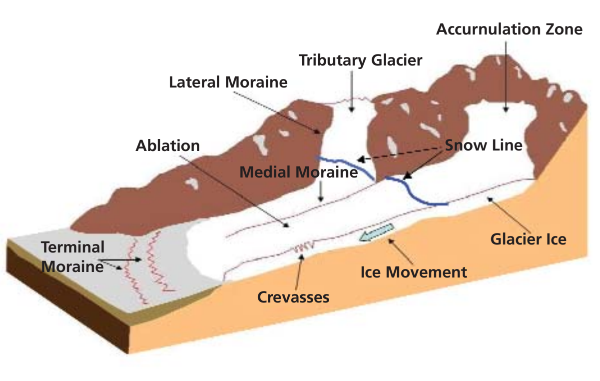
The Gangotri glacier snout and water gushing out from the ice cave (2009)
PHOTO: RAJESH KUMAR/ BIT

Glacier snout and frozen water in an ice cave (Glacier of J&K, 2009)
PHOTO: RAJESH KUMAR/ BIT

Structure

Structurally, a glacier is divided into two – the accumulation and the ablation zones (*see figure 1.1*). The accumulation zone, having round the year snow on its surface, is the upper area of the glacier where addition of snowfall each year intensifies its mass. This zone is crucial in causing positive or negative changes to the mass balance of any glacier. Snowfall and snow drifted by wind and avalanches mainly causes accumulation in this zone. The lower area of the glacier is the ablation zone where most of the ice loss occurs through melting, calving, and evaporation. Ice loss from the ablation zone greatly affects the mass balance of a glacier. In the middle of these two zones lies the equilibrium line where the amount of snowfall is equal to the snowmelt. Any disturbance in this balance triggers the advancement or retreat of a glacier.

Figure 1.1: A schematic diagram of a glacier



Source: Rajesh Kumar, BIT

The terminus of the glacier from where the meltwater starts flowing downstream is called the snout. The position of the snout with reference to time is a prominent indicator of the advancement or retreat of the glacier. The surroundings of a glacier, which are an integral part of the system, are equally important to trace its history. These surroundings mainly include moraines and glacial lakes.

Glossary of terms related to glacier environment

Ablation
The process of loss of ice and snow from a glacier system is called ablation. This occurs through a variety of processes including melting and runoff, sublimation, evaporation, calving, and wind transportation of snow out of a glacier basin.

Accumulation
The process of addition of ice and snow into a glacier system is termed as accumulation. This also occurs through a variety of processes including precipitation, firnification, and wind transportation of snow into a glacier basin from an adjacent area.

Crevasse
A crack or series of cracks that open on the surface of a moving glacier in response to differential stresses caused by glacier flow is a crevasse. They range in shape from linear to arcuate and in length from feet to miles. Their orientation may be in any direction with respect to the glacier flow. The deepest crevasses may exceed 100 feet.

Firn
Firn is an intermediate stage in the transformation of snow to glacier ice. Snow becomes firn when it has been compressed so that no pore space remains between flakes or crystals, a process that takes less than a year.

Glacier
A large, perennial accumulation of ice, snow, rock, sediment and liquid water originating on land and moving down slope under the influence of its own weight and gravity; a dynamic river of ice. Glaciers are classified by their size, location, and thermal regime.

Moraine
Moraine is a general term for unstratified and unsorted deposits of sediment which are formed through the direct action or contact with glacier ice. Many different terms are given to moraines on the basis of their position with respect to a glacier.

Retreat
A decrease in the length of a glacier compared to a previous point in time.

Terminus
The lower-most margin, end, or extremity of a glacier from where the glacier's melt water comes out.

Repeated freezing and thawing turns snow into firn.
PHOTO: RAJESH KUMAR/ BIT

Frozen crevasses on the glacier surface.
PHOTO: RAJESH KUMAR/ BIT

Source: U.S Geological Survey (http://pubs.usgs.gov/of/2004/1216/)

II: Techniques involved in glacier studies

Monitoring of glaciers is a pre-requisite requirement for establishing the links between climate change and glacial retreat, and thereafter designing response measures. Over the past two to three decades, various scientific institutions, academicians and mountaineers across the world have been documenting the existence of glaciers through meticulous field studies and mountaineering expeditions.

Time-line studies of snout position and mass balance have been carried out on a number of glaciers globally for a long-term. With the advent of monitoring based on remote sensing, it has become possible to study even the most inaccessible glaciers. Usually individual glaciers have their own 'response time period' to any changes under the influence of climate, and this is regulated by topographic, local climatic, morphological and geometrical features.

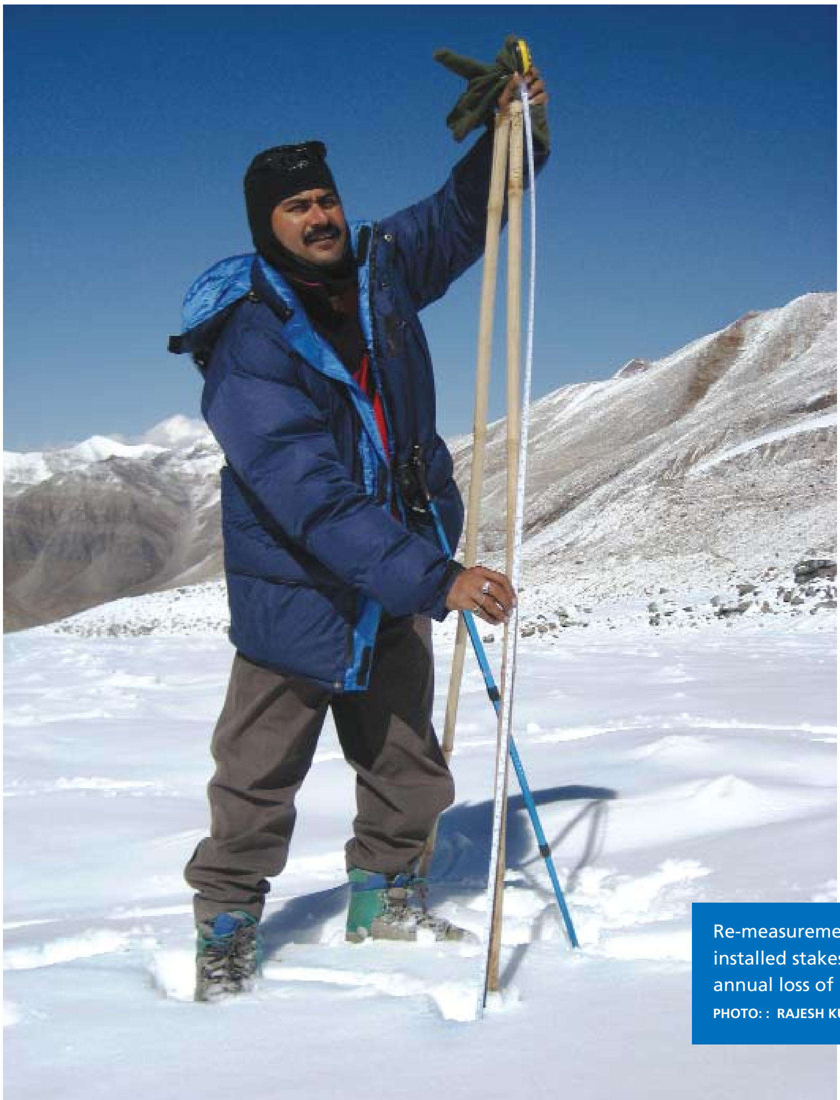
The task of studying glaciers is a time-consuming process and involves detailed methodological processes at different levels depending upon the extent and type of glaciers being studied. The accessibility, length and characteristics of glaciers often determine the methodologies that are adopted to determine the changes of the glacierised region. These methodologies help in monitoring various glacier characteristics, including snout position, surface area, volume elevation and ice mass.

The two commonly used methods are described as follows:

1. Mass balance method
2. Remote Sensing/GIS

Mass Balance method

The mass balance of a glacier reflects the direct link between climate and glacial characteristics. The overall



Re-measurement (in September) of installed stakes to determine the annual loss of ice mass

PHOTO: : RAJESH KUMAR/ BIT

mass balance of a glacier is measured to calculate the volume of a glacier and runoff characteristics. Mass balance measurements prove feasible for glacier whose size ranges anywhere between 2-10 sq km.

The mass balance of a glacier can be measured in a variety of ways including the geodetic techniques and direct glaciological methods. One of the most frequently used method for measuring glacial changes involves drilling into the ice and installing wooden stakes in the ablation zone to know the amount of melting; a pit is also dug in the accumulation zone to gauge the yearly input of snow. The network of ablation stakes and snow pits between two dates (e.g. summer and winter days) is then monitored. The difference in the elevation, i.e. gains or losses, is multiplied by the density of ice/snow and then extrapolated over the stake/pit representative area through a set of methods. The total gain/loss of the glacier mass (in terms of water equivalent) is then calculated, which helps to understand the health of the glacier. Depending on the amount of melted snow and ice and the input of snow in the accumulation zone, mass balance can be either positive or negative (gain or loss of glacier volume). The traditional stake method has been used frequently by scientists to measure mass balances and snout fluctuation of glaciers over a period of time (Dobhal *et al.*, 2004).

The measurements of glacier mass balance at times contain systematic and random errors, which need to be checked using geodetic methods which derive decadal volume change in glaciers based on constant mapping of the glacierised extent (Gerbaux *et al.*, 2005). The mass balance technique is now a widely accepted form of measuring glacier volume and area (Kaser *et al.*, 2003). Such measurements need to be carried out regularly on a long-term basis for effective monitoring.

Remote Sensing /GIS

The use of data derived with the help of remote sensing techniques is of great relevance and importance particularly for studying glacier. Remote sensing plays a crucial role in studying glaciers that are inaccessible. As a tool it is used for mapping area and length of a glacier, particularly the large ones for whom mass balance studies prove inadequate. Recent advances in satellite technology have enabled scientists to monitor changes in glacial and snout retreat patterns using remote sensing satellite imageries. By superimposing past satellite data on present maps (with the help of techniques like image enhancement), the area of recession of individual glaciers is estimated with a fair degree of accuracy. As is the case in other parts of the world, in India studies based on remote sensing techniques have provided valuable insights into the retreat pattern of glaciers (Kulkarni *et al.*, 2007).

The use of data from Differential Global Positioning Systems (DGPS) also helps in determining the snout position and the extent of a glacier. Such a dataset helps in achieving a higher degree of accuracy. GIS based technologies are also used in developing spatial databases of land use/land cover of a region which provide very useful information about the extent of glacial surface area/volume, etc.

III: Detailed results of area, length and average width of the Gangotri glacier system

Gangotri Glacier Inventory based on ETM+ satellite image (1999)

Glacier Name	Area (sq km)	Length (km)	Avg. Width (km)
Gangotri Glacier	56.59	29.13	1.85
Sumeru Bamak	6.69	3.15	1.54
Chaturangi Bamak (CB)	21.87	21.88	1.30
TG1_CB	5.73	5.27	0.75
TG2_CB	7.06	9.00	0.72
TG3_CB	0.86	2.13	0.29
TG4_CB	0.40	1.54	0.27
Seeta Bamak	4.49	3.16	1.23
Suralaya Bamak	10.69	6.58	1.44
Vasuki Bamak	4.13	5.51	0.64
Nilambar Bamak	3.38	4.72	0.70
Pilapani Bamak	2.71	4.24	0.57
Raktvarn Bamak (RB)	17.64	12.66	1.25
TG1_RB	5.90	4.67	1.02
TG2_RB	1.34	2.54	0.38
TG3_RB	2.44	3.47	0.65
Swetvarn Bamak1	1.91	2.60	0.62
Swetvarn Bamak2	1.04	2.96	0.27
Swetvarn Bamak3	2.06	3.13	0.57
Thelu Bamak	1.32	2.07	0.52
Kirti Bamak (KB)	10.38	9.77	0.99
TG1_KB	1.45	2.55	0.66
TG2_KB	2.36	2.80	0.81
TG3_KB	5.28	6.26	0.76
TG4_KB	0.32	1.01	0.32
Swachhand Bamak (SB)	11.30	8.17	0.71
TG1_SB	1.11	2.66	0.38
Meru Bamak	4.70	6.78	0.65
Miandi Bamak	5.12	4.80	0.91
Ghanohim Bamak	7.52	4.55	1.30
Bhagirathi Parbat_I	1.65	3.42	0.53
Bhagirathi Parbat _II	1.17	2.31	0.49
Total Area (Gangotri glacier system)	210.60		

Note: TG stands for the Tributary Glacier

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WWF-India is one of India's largest conservation organizations. Its mission is to stop the degradation of the planet's natural environment, which it addresses through its work in biodiversity conservation and reduction of humanity's ecological footprint. WWF-India engages multiple stakeholders in an inter-disciplinary approach to address the issues pertaining to mitigation of, and adaptation to, climate change.

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