IDENTIFICATION OF GLACIAL FEATURES BY USING SATELLITE REMOTE SENSING DATA IN GANGA HEADWATER

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MEENAKSHI YADAV

SCHOOL OF ENVIRONMENTAL SCIENCES
JAWAHARLAL NEHRU UNIVERSITY
NEW DELHI- 110067
INDIA
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जवाहरलाल नेहरू विश्वविद्यालय
JAWAHARLAL NEHRU UNIVERSITY
SCHOOL OF ENVIRONMENTAL SCIENCES
NEW DELHI-110067

CERTIFICATE

The research work embodied in this dissertation entitled "Identification of Glacial Features by Using Satellite Remote Sensing Data in Ganga Headwater" has been carried out at the school of Environmental Sciences, Jawaharlal Nehru University, New Delhi. This work is original and has not been submitted in part or full for any other degree or diploma in any other university/institution.

Meenakshi Yadav.
MEENAKSHI YADAV
(CANDIDATE)

PROF. KASTURI DUTTA
(DEAN)

PROF. S.I. HASNAIN
(SUPERVISOR)
22-7-2002

Gram : JAYENU Tel. : 6107676, 6167557 /Ext. 2302, 03, 04 Telex : 031-73167 JNU IN
Fax : 91-011-6165886 and 91-011-6172438

"A scarf of pure white snow
Hangs down from its head to its feet,
Cascades like strings of pearls
Glisten on its breast,
A net of drizzling cloud
Encircles its waist like a gray woolen shawl:
An astounding sight, still and bright,
Our blessed Himalaya.

Yaks graze fine grass on its steepest slopes,
And musk deer spread their scent divine,
Each day it receives the sun's first embrace:
A pillar of fortune, deep and still,
Our blessed Himalaya.

It endures the blows of tempest and storm,
And bears the tumult of rains;
Onto its head it takes the burning sun's harsh fire,
For ages past it has watched over Creation,
And now it stands smiling, an enlightened ascetic,
Our blessed Himalaya.

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CHAPTER I

INTRODUCTION

INTRODUCTION

1.1 HIMALAYAN GLACIERS: AN OVERVIEW

A glacier is defined as an aggregated snow and ice body located on land and which continuously flows down the slope under the force of gravity. The higher altitude range of Himalayas consists of a number of small and large glaciers. Their occurrence is controlled by climatic conditions, which are responsible for accumulation of snow during the winter and ablation during summer season. All important glaciers are located approximately above 4000m in the Himalayan region.

It is estimated that 33,200 sq. km (Flint, 1971) of the Himalaya is glaciated and glaciers occupy about 17% of the total mountainous area of the Himalaya (Vohra, 1978). They form the largest body of ice outside the polar caps. The Himalayan Glaciers form a unique reservoir, which supports mighty perennial rivers such as Indus, Ganga and Brahmaputra, which are lifeline of millions of people. Recently the Geologists of Geological Survey of India have counted 5,218 glaciers in the Himalaya (Puri, 1994).

Glaciers form in any area in which a year-to-year surplus of snow occurs. Under such conditions, successive layers of snow are slowly compacted until the loose snowflakes form a monomineralic (frozen H_2O) sedimentary deposit that gradually becomes more and more dense with increasing depth and age. When a density of 830 to 910 kg/m^3 is reached, formation of ice occurs. As the effect of gravity slowly deforms this mass of ice, a glacier is formed. A glacier, therefore, represents an unusual type of metamorphic rock, being the result of deformation of what was originally a sedimentary rock. Glaciers are of considerable scientific interest because of the extensive record of variations in atmospheric gases and aerosols contained within a vertical column of glacier ice. Snow falls in the highest part of the glacier, which is known as the *accumulation area*, adds to its mass. As the snow slowly turns to ice, the glacier grows in mass, forcing glacial movement. Further down the glacier is the *ablation area* where most of the melting and evaporation occurs. Between these two areas a balance is reached where snowfall equals snowmelt, the glacier is then in equilibrium. Whenever this equilibrium is disturbed, either by increased snowfall or by excessive melting, the glacier advances or retreats at more than its normal pace.

In the Himalaya, the storage of precipitation in the form of snow and ice over a long period provides a large water reservoir that regulates annual water distribution. The role of snow and glaciers into water resource management is well understood from the recent scientific studies (Singh et al., 1994a, 1994b, 1996). The majority of rivers originating in Himalayas have their upper catchments in snow & ice-covered areas and flow through steep mountains. This factor and the perennial nature of rivers provide excellent conditions for the development of hydropower resources despite the temporal variability in the sources of run-off for Himalayan rivers. In some semiarid areas, glaciers are of considerable economic importance in the irrigation of crops.

Glaciers are a peculiar type of landform because they can in turn modify the existing (preglacial) landscape, producing both erosional and depositional landforms. The process by which a glacier modifies the subglacial and adjacent landscape is by the action of moving ice and by the deposition of till beneath and adjacent to the glacier. Glaciers also affect areas peripherally by discharging large amounts of sediment-laden meltwater.

1.2 GLOBAL WARMING AND GLACIERS

The Quaternary period is well known for its repeated climatic changes. One of the most prominent features of Quaternary times is the periodic glacier activity during cold periods that have given rise to a rich record of glacial landforms. Therefore, by studying the landforms of the glacier, it is possible to reconstruct the environmental conditions and processes responsible for creating the glacial topography. However, there are several processes that cause and affect the existing landscape and modify it. The floods, rock falls, rock slides, debris flow, mass movement and small channels coming from the tributary glaciers are significant processes that are not directly related to the glacial processes but occur in glaciated terrain and are important in affecting the glacial processes. These are Paraglacial processes.

Present glacier ice cover is the remnant ice of Pleistocene glaciation when the ice cover was much larger and glaciers descended to lower altitudes. Global warming has caused significant glacier ice loss since the Little Ice Age (100-150 yrs. ago) resulting in both glacier retreat and thinning. Some recent variations in environmental conditions are related to drastic glacial advances and retreats, which can cause catastrophic slope failures and flooding. Therefore, glaciers have already significantly impacted settlements, communications, natural resources, and mountain economies.

However, little is known about glacial dynamics in the Himalaya (Shroder et al., 1993).

Climatic conditions in Uttaranchal Himalaya have experienced warming up since the last ice age some 18,000 years back. The glaciers, snow and ice fields have all experienced the impacts of global warming and have left behind the imprints, generated in consonance to the well-defined phases of global warming. These glaciogeomorphic features are a telltale to the paleogeographic reconstruction of the glaciated terrain of the Himalayas Glaciers and have long been known to be sensitive indicators of climate change (Sharp, 1960). Information regarding glacier characteristics and change is particularly crucial now, while anthropogenically induced global warming may already be in progress (Hansen et al., 1988).

Glacier retreats and advances are natural cyclical phenomena that occur during glacial and interglacial periods respectively. The world is now in an interglacial warm phase, the previous glacial advance having occurred during the last phase of the last glacial period (15^{th}-19^{th} century), which has come to be called " The Little Ice Age" (LIA). Since then, as a result of the subsequent warming phase, all glaciers have been retreating.

As global climate changes there is an accordant trend toward global recession and wasting of glaciers (Oerlemans, 1994; Dyurgerov and Meier, 1997; Oerlemans et. al., 1998). These changes are thought to be more rapid in Himalaya than many other places and are expected to continue this century (Ageta and Kadota, 1992; Nakawo et.

al., 1997; Hasnain, 1999; Naito et. al., 2000). Retreat of Himalayan glaciers near our study area has been linked to climate warming. The particular vulnerability of Himalayan glaciers to climate warming is due to the facts that (1) they are "summer accumulation types" dependent on summer monsoonal precipitation and cool summer temperatures (Ageta and Higuchi, 1984); (2) consequently, the summer mass balance of these glaciers nearly equals the annual mass balance. (Kadota et. al., 1993).

According to climatologists, alpine glaciers, such as those in the Himalaya, are particularly sensitive indicators of climate change. Most glaciers are more sensitive to temperature than to other climatic factors. The glaciers in Western Himalaya are fed by winter and summer precipitation. But those in the Eastern and Central Himalayas get their nourishment only from summer precipitation. With only the summer precipitation to depend on, the glaciers in these Himalaya have the dual problem of receding snowline and decreased precipitation due to global warming. *Unlike glaciers of Europe and other higher latitudes, both accumulation and ablation in these parts occur during summer months, making them very sensitive to temperature changes.*

Glacier recession impacts long-term and seasonal patterns and annual availability of fresh water and hydropower generating capacity (Johannesson, 1997). These changes are for the short-term, not all deleterious, though for the long-term they may cause major economic disruptions. Retreat of glaciers in a heavily glaciated watershed characteristically causes increased water flow during the ablation season for several more decades. The rate of retreat in the recent times has been much more rapid than the gradual retreat expected in an inter-glacial warming phase. This is perhaps due to global warming. This climate change brought about by human activity has already resulted in a global increase in the average surface temperature by 0.6 °C.

The fears now being felt over the receding Gangotri glacier should probably be attributed to its distancing itself away from its present location and the likelihood of the flow of melting water extending over a much longer stretch for feeding the rivers. The moving away of the glacier, estimated at 800 meters during the last 25 years, is causing concern because of its having been much faster than it had been during the last 200 years when its regression had been 2000m

1.3 ROLE OF REMOTE SENSING IN GLACIOLOGY

Glaciers and snowfields normally exist in remote and inaccessible areas and locations. In the normal course to collect data in such circumstances is quite difficult and hazardous. The availability of satellite remote sensing imagery for such areas is of immense value for identifying various features of glaciers and snowfields.

Satellite remote Sensing has been inducted to show surveying as early as 1960, when the initial picture taken by first weather satellite TIROS-1 was used to delineate snow cover in Eastern Canada. Since then a number of orbiting and geostationary satellites with improved spectral, spatial and temporal resolution have been put into orbit and data sensed by them were used for weather monitoring and earth resources studies like snow mapping. During this period quite a few snow studies were undertaken all over the world.

Remote sensing has played a significant role in assessing modern-day glaciers and estimating glacial denudation rates. Spatial analysis of multispectral satellite imagery can be used to assess the structural characteristics on alpine glaciers in the Himalaya (Bishop et. al., 1998a) Similarly the integration of data and information generated from image analysis and field work enable accurate mapping, assessment of sediment load variability and transfer efficiency and the estimation of glacier denudation rates. (Bishop et. al., 1995; Bishop et. al., 1998b; Shroder et. al., 1998b). Remote sensing methods are increasingly used for the study of seasonal snow extent and glaciers in the areas that are normally inaccessible. In order to classify the various glacial features from multispectral remote sensing data, it is important to first know the spectral reflectance properties of these features. In general, it is found that snow related features have higher reflectance than the ones of ice. It is also seen that debris plays an important role in modifying the reflectance values.

Snow cover was the Earth Resource readily identifiable in the early weather and remote sensing satellites. The areal extent of snow could be calculated and was utilized for developing snowmelt models. With the improvement of the spatial resolution of remote sensors, glaciers could also be identified and their inventory can be prepared. However, snow and glacier features have high reflectance value and so saturating the input systems of sensors in the present remote sensing satellites. Until the launches in 1972, 1975, 1978, 1982, and 1984 of the five spacecraft in the Landsat series of Earth-resources satellites, glaciologists had no accurate means of measuring the areal extent of glacier ice on a global basis. Only Multispectral Scanner (MSS) images provided the worldwide coverage needed for global geomorphological investigations. Landsat images provide a means for delineating the areal extent of ice sheet and ice caps, for determining the position of the termini of valley, outlet, and tidal glaciers, and for measuring the average speed of flow of some glaciers by a time-lapse method of sequential images on a common base of data for the entire globe. To take advantage of the vast amount of Landsat data of the glacierised regions of the planet, the U.S. Geological Survey (USGS), in association with more than 50 United States and foreign glaciologists and glacial geologists, is working on a project to prepare a satellite image atlas of glaciers of the world (Williams and Ferrigno, 1981). If Landsat - type surveys of the Earth are continued for several decades, a means of monitoring long-term changes in glacier area will also become possible, thereby providing means for monitoring one potential effect of global climatic change (Williams, 1986). In the erosional process of modifying the preglacial landscape by glacier ice and running water, glaciers pick up, carry, and deposit vast quantities of fragmental material derived from the underlying surficial deposits, including deposits from previous glaciation, and bedrock. This fragmented material ranges from large blocks, often several to tens of meters in dimension, that are directly transported by glacier ice to very fine-grained material, called rock flour, that is transported in glacial streams or deposited directly from the glacier as a till matrix.

Determination of other periglacial features common in a cold-climate environment is generally inferential, being derived from pre-existing ancillary knowledge of the area encompassed by the Landsat image. Mountain environments are very complex due to interaction of tectonic, geomorphological, ecological and climatic agents (Walsh et al., 1997). Many problems cannot be solved without remote sensing information science and technology as spatial data are required to account for the spatial and temporal scale dependencies associated with the phenomena and processes (Davis et al., 1991). The morphology and hypsometry (frequency distribution of altitude) of mountain environments is a result of complex interaction of tectonics, climate and erosional processes (Masek et. al., 1994; Avouac and Burov, 1996; Pinter and Brandon, 1997).

Geoscience investigations of landscape evolution are best achieved with the use of remotely sensed data and GIS technology for data inventory and management, spatial analysis and quantitative modeling. DEMs and satellite multispectral data are necessary for studying the structural geology and surface geomorphology. In the Himalaya, where rapid uplift and denudation produce extreme topographic relief, remote sensing and GIS technologies play a crucial role in assessing and understanding this complicated and dynamic system. Satellite remote sensing is the only practical way to obtain detailed spatial information about the landscape, as logistical and physical limitations restrict access. Satellite multispectral imagery and DEM data must be integrated to assess topographic complexity and map landforms.

Analysis of relationships between uplift and denudation in complex mountain environments requires integrated approaches using remote sensing and GIS analyses in combination with field investigations. Remote Sensing of landscape includes satellite image acquisition, multispectral analysis, geomorphometric analysis of a satellite derived DEM, and the application of GIS and pattern recognition procedures to analyze topographic complexity and geomorphology of the mountain massif. Numerous investigators have found that the integration of DEM data, other sources of spatial data, and spatial features are essential for quantification and mapping of complex patterns in alpine environments (Allen and Walsh, 1996; Gong 1996).

1.4 OBJECTIVES AND SCOPE OF PRESENT WORK

The present study is mainly about the geomorphological analysis of Gangotri Glacier. As we all know that the various natural and anthropogenic processes have resulted in an increase in global temperature. This rise in global temperature has changed the global climate. The major effect of climate change is on Himalayan glaciers resulting in their recession.

Gangotri Glacier has been selected for this work because in last couple of years it has shown major signs of recession.

The main aims of this study are as follows:

- Use of Satellite Data and different Remote Sensing Techniques in Glaciology.
- Identification of various geomorphic features in Gangotri Glacier.
- Analysis of surfacial characteristics of Gangotri Glacier.

This study is expected to prove the utility of Remote Sensing in glacier research.

It might be helpful in assessing the glacier recession rate. DEM used in this study can also be used for snow melt-water runoff modeling. The glaciated area coverage in a glacier basin can also be calculated which can be of great significance to evaluate the present status of glaciers. It might be helpful for researchers interested in further studies in glaciers.

CHAPTER 2

REVIEW OF LITERATURE

2.1 STUDIES ON HIMALAYAN GLACIERS

The glaciers and snowfields normally exist in remote and inaccessible areas and the data collection on a regular basis becomes quite difficult and hazardous. The advent of satellite remote sensing has opened up the possibility of data acquisition in such terrains at regular intervals. Earlier the glaciers because of their remoteness didn't attract much attention of the researchers. In the recent years, glaciological studies have attracted much attention for two specific reasons:

- They hold large water reserves.
- Their studies afford an insight to the climatic changes in the past.

An impetus was given to glaciological studies with the initiation of International Hydrological Decade (1965-1974) and organization of several international symposia, the proceedings of which have appeared in the International Association of Hydrological Sciences publications Nos. 95 (1973), 104 (1975) and 138 (1982).

In India, the glaciological studies started with the occasional field visits by officers of Geological Society of India during the last century. However, regular monitoring of the snout of some important glaciers started only by the middle of this century. Glaciology division of Geological Survey of India has conducted several studies on Himalayan Glaciers. Realizing the importance of glaciers in the field of water resources, hydro-electricity generation, climatic fluctuations and pollution monitoring, an integrated project on Himalayan Glaciers covering geology, glacier dynamics, mass balance studies, isotopic dating, discharge measurements and chemical and sediment load, was launched by the Department of Science and Technology involving several research laboratories and Universities in the year 1985.

After eighteen years painstaking efforts the Glaciology Division, Geological Survey of India, has compiled the inventory of the glaciers in the India part of Himalaya. According to *Padmashri C.P. Vohra,* former Director General of Geological Survey of India, the glaciers cover an area of 38,039 km2, broadly divided into three river basins- Indus, Ganga and Brahamputra on the Indian side of Himalaya.The Indus basin has the largest number of glaciers-3538, followed by the Ganga basin (1,020) and Brahamputra (662). It has been estimated by researchers that about 17% of the Himalaya and 37% of Karakoram is presently under permanent ice cover. The principal glaciers of the Himalaya are Siachen 72km; Gangotri 26km; Zemu 26km; Milam 19km and Kedarnath 14.5 km.

Himalayan glaciers have been in a state of general retreat since 1850 (Mayewski and Jeschke, 1979). The period 1850-1910 is marked by a complexity of movements: retreats, fluctuations and advances in some areas. The period 1900-1920 is marked by general retreat of glaciers, since 1950's the glaciers in the Garhwal, Kumaon and Karakoram have been showing all indications of retreat. The response of the the transverse glaciers is more complex than of the longitudinal glaciers, and may be due to the fact that these are shorter, flow perpendicular to the oncoming atmospheric circulation patterns, and have steeper gradients (Mayewski & Jeschke, 1979).

The Himalayan Glacier fluctuations records are only 150 years old. Mayeswki and Jeschke (1979) have studied some 122 glaciers fluctuation records of Himalaya and concluded that most of the glaciers are retreating. Jangpangi and Vohra (1962), Kurien and Munshi (1972), Srikanta and Pandi (1972), Vohra (1981), and many others have made significant studies on the glacier snout fluctuation of almost all the Himalayan glaciers.

A perceptible impact of global warming has been in evidence in the Himalayan glaciers over the last few decades. A 1999 report by the Working Group on Himalayan Glaciology (WGHG) of the International Commission for Snow and Ice (ICSI), constituted in 1995, said: "Glaciers in the Himalyas are receding faster than in any other part of the world and, if the present rate continues, the likelihood of them disappearing by the year 2035 is very high".

The Gangotri glacier in the Garhwal Himalaya is the source of river Ganga. Grieshbach (1891) sketched the snout during the course of his geological traverses in the region. Macro Pallis (1933) was the first to climb the peak within the Gangotri basin. Evidence from a study of terminal moraines of the Gangotri points to the snout having been nearly 3 km downstream from its present position near the place called Bhujbasa before the post-LIA retreat began around the turn of the 19th century.

The findings of Naithani and his associates are based on investigations over three and a half years, between May 1996 and October 1999. The aim of Garhwal University group was to establish evidence for the increased rate of retreat seen in the earlier datasets of other research groups in terms of the geomorphological characteristics of the glacier. They found that during this period the snout had retreated by 76 m. They have, however, refrained from making any such statement about the possible cause of swift recession seen in their research paper, which appeared in the January 10, 2001 issue of the journal, *Current Science*, "Our findings clearly indicate that there is an increase in the rate of retreat. There can be various causes for the retreat including tectonic movements as the glacier sits right on the Bhagirathi Thrust Plane and is north of the main central thrust (MCT) in the Himalayas. Global Warming is only one of the factors. But a consistent trend of high retreat rate over the years, together with other morphological changes that are seen, is suggestive of a forcing like global warming".

Observations on the retreat of the Gangotri go back to 1842, and between 1842 and 1935 the snout of the Gangotri glacier was receding at an average rate of 7.3 m a year. According to data of the Geological Survey of India (GSI), between 1935 and 1996 it retreated by 1,147 m, which amounts to an average rate of 19 m a year. This implies that the rate of retreat more than doubled during a good part of the last century.

But a dramatic increase in the rate seems to have occurred in last three decades. In 1996, researchers L.A. Owen and M.C. Sharma showed, by studying the longitudinal profiles of the river, that between 1971 and 1996, the Gangotri glacier had retreated by about 850 m. This would yield a post-1971 retreat rate of 34 m a year. For the post-1971 period, the 61-year (1935-1996) data of GSI too shows that the retreat rate is about 28 m a year, indicating a clear increase in the rate after 1971. The 1996-1999 data of Naithani and associates too matches this general trend of an increased rate.

Survey of India under the leadership of *Mr. J.C. Ross* mapped the snout alongwith J.B. *Auden* in 1934.Auden stated that the Glacier must have receded by 740m during the last century and in the earlier times might have descended to at least Gangotri town and may be even as far as Jangla. The glacier has been since then visited by various expeditions by the Geological Survey of India namely, Jangpang, 1958; Vohra, 1971; Puri, 1974-75, 1975-76, 1976-77, 1989-90. These expeditions focussed on the geomorphology, mass balance, ice flow movement, sedimentological studies and the retreat of the glacier.

2.2 RECESSION OF GANGOTRI GLACIER

The observation conducted by the Geological Survey of India since 1835 has reported the recessional trend of this glacier.

Table2.1 Recession of Gangotri Glacier since 1935.

Period between Observations	No. of Years	Area vacated by the glacier (m^2)	Average recession per Year (m^2)
1935-1956	21.0	52,500	2,500
1956-1962	5.6	36,500	6,158
1962-1971	9.5	1,20,000	12,631
Sept. 1971 to July 1975	3.8	9,500	2,500

Sahai (1992) has reported that the glacier vacated an area of 0.243 km2 during the last fifty years (1935-1990). The annual rate of area vacated by the glacier between 1935 and 1971 (36 years) was 8.77% and in the next six years (1971-1977) this value went up to 10.4%. In the last thirteen years (1977-1990) the area vacated was exceptionally high i.e. 80.8%. Perhaps serious ecological imbalances coupled with increased human activity have caused its recession during the last three decades.

Geological Survey of India has carried out glaciological studies pertaining to mass balance on Tipra Bank (1980-1988) and Dunagiri glacier (1984-1991) in Ganga Basin. Mention of similar studies on Gangotri glacier is also found in the available literature. Mass balance is an important glaciological parameter as the deviation from steady state mass balance conditions causes a dynamic response of the glacier, resulting in a change of flow rate, leading finally to an advance or retreat of the glacier terminus. These effects also induce the formation of moraines and other morphological features, which allow delineation of former extent of glaciers.

Table. 2.2 Retreat of Important Glaciers in the Himalaya

Glacier	Period	Year	Retreat in meters
Milam	1849-57	108	1350 - after C.P.Vohra
Pindari	1845-66	121	2840 - after C.P.Vohra
Gangotri	1935-76	41	600 - Vohra (1981)
Gangotri	1985 – 2001	16	345 - Present study

Bada Shigri	1890-1906	16	320 - after Mayewski & Jeschke , 1979.
Rakhiot	1930-1950	20	600 – after Mayewski & Jeschke, 1979.

In Table 2.2, the retreat rate of the various glaciers in the Indian Himalayas shows that for the last five decades, a dramatic snow cover change has been recorded in the Himalayan territory. It resulted in rapid recession of various glaciers in Himalayas.

Numerous investigators have evaluated the use of remotely sensed data for the study of alpine glaciers and glacier terrain (e.g., Bayr et al., 1994; Hall et al., 1990; Herzfeld et al., 1993; Krimmel and Meier, 1973; Singhroy et al., 1992; Ventura et al., 1987; Williams et al., 1981). Much of this work focusses on comparing in situ and satellite derived reflectance (e.g., Gratton et al., 1993; Nakawo et al., 1993; Ostrem, 1975; Paterson, 1981), glacier mapping of ice and snow facies (e.g., Dozier and Marks, 1987, Hall et al., 1987; Parrot et al., 1993); and glacier inventory and change detection (e.g., Espizua and Bengochea, 1990; Ferrigno et al., 1993; Hastenrath, 1993; Lucchitta et al., 1993; Scambos et al., 1992; Shroder, in press). The work to date indicates that satellite digital data can be used to produce ice velocity estimates, and delineate and measure the snow line, glacier extent, and surfacial expression of some snow and ice facies at the end of the balance year.

Gleorsen and Solomonson (1975) showed that Landsat Multispectral Scanner imagery could be used for the purpose of calculating the aerial extent of snow and ice features. Krimmel and Meier (1975) have used similar data to determine glacier surface movement by observing certain surface features and comparing these with the topographical information in the earlier surveys. Later using sequential Landsat imageries, Lucchitta and Ferguson (1986) determined surface velocity of 780 m/yr for Byrd Glacier in Antarctica. Ostrem (1975) determined the transient snowline of Norwaian glaciers from Landsat imagery and established its relationship with the equilibrium line for calculating their AAR. This information was then to establish relationship with glacier mass balance.

Rundquist et al. (1978) have shown how Landsat digital data can be utilized for assessing glacier inventory parameters. Preparation of an atlas of world glaciers has been proposed from the global coverage of satellite imagery data (Williams and Ferringo, 1981). In an extensive review of the application of various satellite systems, Meier (1980) has shown their utility for glacier and snow studies. Williams (1986) has pointed out the use of satellite data for identifying various glacial landform systems in glaciated areas for alpine glaciers. Ventura et al (1987) have shown the use of satellite data for determining glacier parameters and indicating certain specific digital data techniques.

A study by Srinivasan and Raman (1972) on the snow hydrology of Himalayan region, utilizing the API satellite photographs for one winter season of 1969-70, showed that by the peak of summer the total snow cover in Himalayan region is reduced to about 1/10th of the maximum snow cover during the peak of winter season.

Geomorphological and paleoglacial studies have been carried out by Kar (1972), Ahmed and Saxena (1963), Ahmed and Hashmi (1974), Chaujar (1977), Sharma

(1977), Kaul et al (1982), Kaul (1990), Bose (1966), Janpangi and Vohra (1962), Srivastava et al. (1996), Bhandari et al.(1981) and Nizampurkar et al.(1982) have carried out radiometric dating of Nehnar glacier. Remote Sensing technique has been effectively used for the estimation of snow and ice cover for the Himalayan glaciers by Chansarkar (1983), Jeyram et al. (1983) and Danju & Buch (1989). Tangri and Srivastava (1989) assessed the spatial and temporal distribution of glaciers around Badrinath using satellite imageries. Hasnain et al (1969), Hasnain & Thayyen (1996) and Chauhan & Hasnain (1983) have worked out chemical characteristics and suspended sediment load of meltwater of different glaciers of Ganga basin. Recently Mukherjee & Sangewar (1996) have correlated the Accumulation Area Ratio (AAR) & ELA with mass balance of Gora, Gorgarang & Schaunegarang glaciers of Himachal Pradesh.

CHAPTER 3

STUDY AREA

STUDY AREA

3.1 LOCATION AND EXTENT

Gangotri glacier, the longest valley glacier in Garhwal Himalayas, is located in the Uttarkashi district of Uttaranchal, India. It extends from longitude 79° 04′ E to 79° 15′ E and latitude 30° 44′ N to 30° 56′ N. The total length of glacier is 26 Km and its width varies from 0.5 to 2.5 Km and covers an area of about 75 km^2 (SOI, 2000). The total ice cover is approx. 200 km^2 and has about 20 km^3 of ice in volume (Vohra, 1981). Gangotri lies at 10,300 feet above sea level on the right bank of river Ganga. It originates at an altitude of 7143m on the North-Western slopes of Chaukhamba peaks and descends to 4000m at Gaumukh where it forms a snout. It is a 100m (328 ft) high wall of gray snow. It is 30 km (18.85 miles) long and 2 to 4 km wide. At this point the Ganga river flows north giving its name, Gangotri, which means "Ganga turned north". The Bhagirathi river originates at the snout of glacier located at Gaumukh in Northernmost end of the glacier (Auden, 1937) (Fig.3.1). Sub-terrain channels also feed the Bhagirathi river at Gaumukh, below the glacier (Thakur et al, 1991).

The glacier is easily approachable and, is well connected by motorable road from Rishikesh to Gangotri town (250 km) and from there a 18 km long bridle path follows along the right bank of the Bhagirathi river to Gaumukh, the snout of the glacier. This 18 km is non-motorable and one has to trek along the right bank of Bhagirathi valley taking a narrow footpath maintained by government department during the tourist season (mid May to October). Chirbasa is located halfway between the two places and Bhojbasa is 5 km from Chirbasa. The snout is about 4 km from Bhojbasa. From a

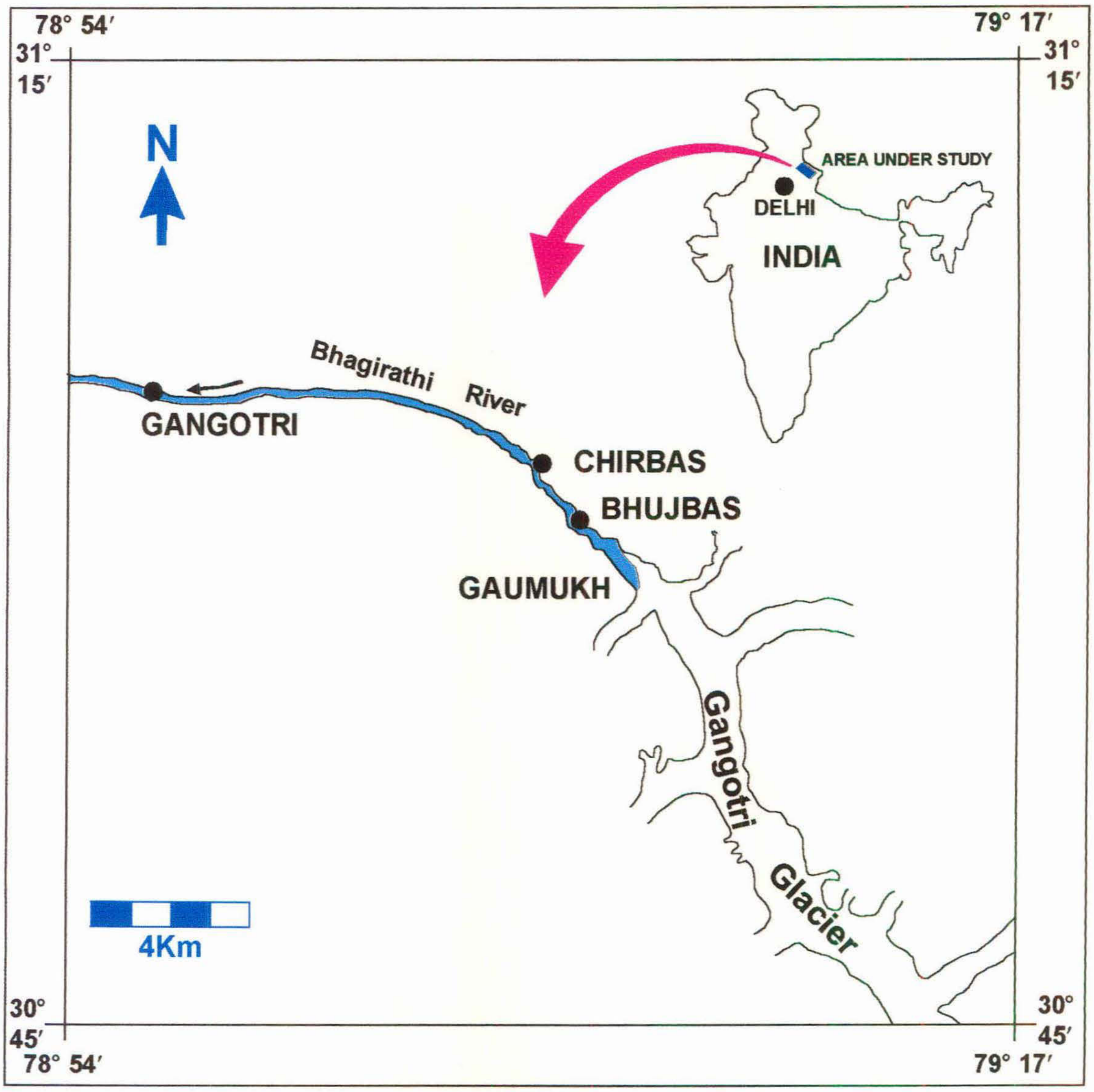


Fig.: 3.1 Location Map of the Study Area

massive cave in Gaumukh, meltwater emerges and form the main stream of River Ganga.

3.2 TRIBUTARY GLACIERS IN GANGOTRI BASIN

Satellite data (IRS-1D) shows that there are numerous small- sized glaciers, which feed and contribute into the main glacier to form Gangotri Group of Glaciers (Fig.3.2) These small-sized glaciers, named as tributary glaciers, are generally transverse to the main glacier and vary from NE-SW and NW-SE in orientation (Table 3.1). Miandi, Swachand and Chaturangi Bamak Glaciers meet Gangotri on the east rim. Chaturangi Bamak is the longest tributary glacier (16 km) of the Gangotri group of glaciers. Nandanvan is a meadow formed at the confluence of Chaturangi Bamak and Gangotri glacier. Another glacier on the east rim, namely, Raktavarn glacier is not connected to the Gangotri glacier but it discharges water into the main glacier. Ganohim and Kirti bamak are on the west rim of Gangotri. Meru glacier is also on the west rim but it is not connected to the main glacier and its meltwater meets the Bhagirathi River just in front of Gaumukh (Fig. 3.3)

Table 3.1 Tributary glaciers between Gangotri and Gaumukh.

TRIBUTARY GLACIERS	RIM OF THE GLACIER
Miandi	East
Swachand	East
Chaturangi	East
Raktavarn	East
Ganohim	West
Kirti	West
Meru	West

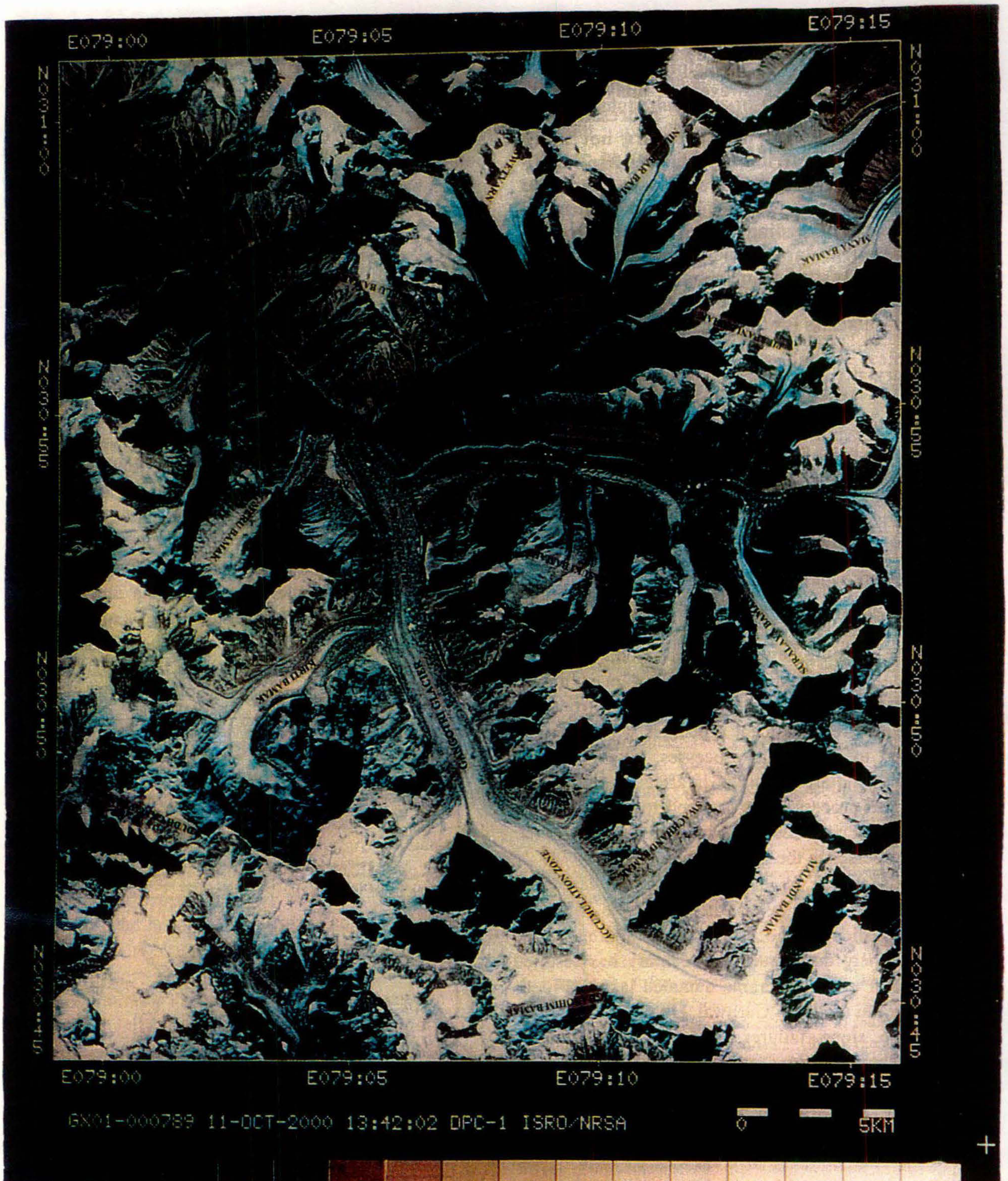


Fig. 3.2 Gangotri and its Tributary Glaciers as seen in Satellite Image (IRS – 1D)

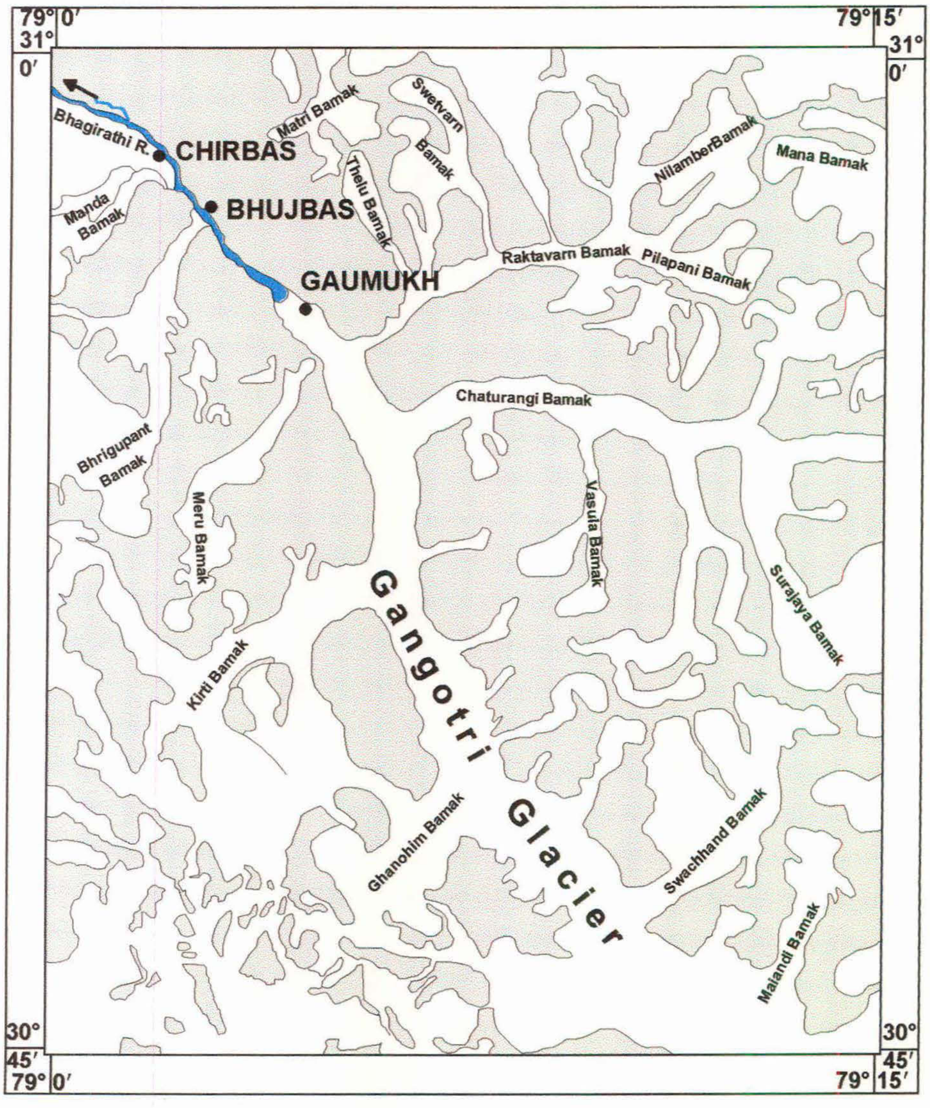


Fig.: 3.3 Gangotri Glacier along with Its Tributary Glaciers

3.3 CLIMATE

Summer is cool during daytime and cold at night. Winter is snow-bound. The best time to visit is between June to September. Before June and after the second week of October there is too much ice and snow.

3.4 PEAKS IN THE AREA

There are several high peaks in this area. Some of them are: Shivling (6543m), Kedar Dome (6940m), Bhrigupanth (6772m), Meru (6660m), Sumeru (6350m), Chaukhamba group of peaks (7138m, 7068m, 6973m, 6853m), Satopanth (7075m), Vasuki Parbat (6795m), Bhagirathi group of peaks (6856m, 6512m, 6454m) and Sudarshan Parbat (6507m).

3.5 GEOLOGY

Gangotri region is a part of Garhwal neppe (Auden, 1937). The area consists of tourmaline-rich granite intruded into older metamorphic rocks. Potash feldspar, Quartz, muscovite and tourmaline are the major minerals found in granites. The older metamorphic rocks, mainly consisting of mica-schists, sericite-schists, phyllites and quartizites are found to form caps of several peaks in the area.

3.6 FLORA AND FAUNA

The Gangotri glacier and its adjoining areas offer unparallel natural beauty and rare panoramic close-up views of mountain peaks, lakes and thermal springs, as well as exhilarating trekking opportunities. Near the snout of Gangotri, hardly there are any traces of vegetation. But thick grass and flowering plants can be seen at Nandanvan and Tapovan meadows located much above the snout. A kind of flowering plant, locally known as Brahma Kamal, is found in these areas. About one and a half kilometers downstream of the snout, some trees of Bhojpatra can be seen. Conifers can be seen near Chirbasa. Sheep-sized wild animal, locally known as Berd, is seen in the area. This animal moves in groups along the slope of the glacier. Black coloured Mina with bright yellow beaks and black colored rats are also seen in the area.

3.7 HUMAN INTERFERENCE

With the improved transport facilities to reach the Gangotri town and increasing facilities to stay near the glacier, a large number of pilgrims are visiting the snout of the glacier as they consider the birthplace of Bhagirathi a sacred place. Gangotri town is full of tourists and local people during peak tourist season (May to October). Himalaya as loftiest mountain system in the world also attracts several trekking and mountaineering teams. With the increasing flow of tourists in the area, several local people started moving upwards during the summer months to open canteens, which can provide both food as well as facilities for night stay. The pilgrims, who have established ashrams in Tapovan have further aggravated the situation by giving fillip to the tourists to travel across the glacier and climb over the left lateral moraine to visit the beautiful meadow and the Shivling peak. The increasing traffic in the area is also showing its effects. One can find heaps of tins, plastics and other undesirable materials left by the tourists in such remote places as Nandanvan Meadow. As the winter approaches most of the locales move down to their permanent villages. In winters, the fresh snowfall covers the entire region and the area is closed for traffic.

CHAPTER 4

METHODOLOGY

4.1 DATA USED

As a rule, winter imagery is better for discriminating larger glacial features because the low Sun angle affords a natural enhancement as shadows call attention to small topographic differences. Although snow cover may inhibit recognition of some smaller glacial landforms, in some instances it aids in highlighting certain features.

A period of the year when seasonal snow cover is at its minimum and the permanent snow cover and the glaciers are fully exposed is selected for the glacier mapping. The type of satellite data to be used basically depends upon the resource information requirements of the study. In the present study, IRS PAN data of October 2001 (Source: National Remote Sensing Agency) (Fig. 4.1) and ASTER data (Source: United States Geological Survey) were analyzed. The IRS PAN image having spatial resolution 5.8m and ASTER image with spatial resolution of 15m were used. Visual interpretation of the images based on standard photo interpretation methods and subsequently Digital Image Processing has been carried out to identify and delineate various glacial features. The features so identified were confirmed thorough a reconnaissance survey of the study area. Finally, the features have been traced and compared with the toposheet (1985) of 1:250,000 scale.

4.2 MAPPING OF GLACIAL FEATURES

In this study, only those areas, which show distinct shape of valley glaciers, were identified and various glacier features were mapped. These are as follows:

Fig. 4.1 Gangotri Basin as Seen in IRS PAN Image of Oct. 2001
(Source : NRSA)

- Glacier boundary
- Snout position
- Accumulation Zone
- Ablation Zone.
- Supraglacial lakes
- Crevasses
- Moraines
- Equilibrium Line Altitude (ELA).

Demarcation of Glacier Boundary

The line of division between two adjacent glaciers is characterized by ice movement in two different directions. Normally it's not so easy to demarcate the ice-divide line but in Himalayas due to its peculiar topography, ice-divide is associated with mountain cliffs. Therefore, by using the tonal variation on the basis of shadows approximate glacier boundaries have been marked on the image.

Snout

Geomorphological features as origin of stream, shadow due to snout cave, moraine-dammed lake is used to mark snout in Image In PAN image the snout is shown as near meandering of the stream.

Accumulation Zone

It is characterized by snow and gives higher reflectance than ablation area. Therefore, it appears white in the image and can be easily demarcated.

Ablation Zone

In this zone, glacier ice along with debris is exposed on surface. Glacier ice has substantially lower reflectance than snow, but higher than that of rock and soil of the surrounding area. Therefore it gives gray tone in the image and can be easily differentiated from accumulation zone.

Supraglacial Lakes

Principal Component Analysis (PCA) of ASTER data (September, 2001) in 3 VNIR bands was done, 3 factors were extracted. As maximum variance was associated with the 1^{st} factor, it was then visualized to calculate the number and size of lakes in various zones.

Moraines

To identify the moraines, the edge enhancement spatial filtering was carried out using convolution windows. The Laplacian edge enhancement was carried on PAN Image

Equilibrium Line Altitude (ELA)

This line separates yearly accumulation from ablation. This can be easily marked on the image because of the difference in spectral reflectance of accumulation and ablation zones.

4.3 GENERATION OF DEM

Any digital representation of the continuous variation of relief over space is known as Digital Elevation Model (DEM). The instrument ASTER attached to Earth Observation Satellite TERRA offers the stereo images with minimizing temporal changes and sensor modeling errors. The stereo image data can be used to generate the DEM of any region on the globe. Band 3B and 3N of the VNIR sensor Nadir looking scene and a Backward looking scene those provides stereo coverage from which a DEM is automatically extracted. For the present study, DEM prepared by Dr. Rick Wessels, US Geological Survey, Flagstaff, Arizona, USA was used (Fig. 4.2). This DEM was generated from ASTER stereo image (September 9, 2001) using two stereo bands (3B & 3N). 500 points were used in both these bands for Orthorectification and automatic DEM was extracted using Geometica Orthoengine.

4.4 ANALYSIS OF DEM

Hypsographic analysis of DEM was done by selecting our area of interest (Gangotri basin) out of total image. This basin was stretched to 0-255 classes and then cell wise analysis in different elevation bands was carried out using IDRISI® 2.0 software.

Fig. 4.2 DEM of Gangotri Basin Prepared from ASTER Stereo Image of Sept. 2001
(Source : US Geological Survey)

CHAPTER 5

RESULT AND DISCUSSION

RESULTS AND DISCUSSION

Glacial Geomorphology examines the formation and development of landforms created by the glaciers. Visual interpretation of Remote Sensing Satellite imagery in conjunction with Digital Image Processing of IRS data has enabled us to identify various geomorphological features.

The present work deals mainly with the geomorphological studies around Gangotri glacier including glacial action and landforms made by it. The main glacial landforms in Gangotri basin are lakes, debris cover, moraines and crevasses.

Important geomorphological features noted around the Gangotri glacier are detailed below:

5.1 SURFACIAL CHARACTERISTICS OF THE GANGOTRI BASIN

Quantitative and qualitative analysis of the Gangotri glacier surface and various features has been carried out by using various Imageries (Panchromatic and ASTER stereo images) and field studies. The surface of the Gangotri glacier is heavily covered by debris as a result of various factors such as high relief, a good degree of diurnal variations in temperature, young mountains and high seismicity. This debris cover changed into various geomorphological features such as lateral moraine, medial moraine and terminal moraine, etc. because of glacial activity. The main glacier is associated with numerous tributary glaciers (Table. 5.1).

Table 5.1 Major Tributary Glaciers and their Area in Gangotri Basin

Name of the glacier	Area in km^2
Chaturangi Bamak	14.8
Meru Bamak	8.3
Pilapani Bamak	6.1
Kirti Bamak	24.7
Ghanohim	14.2
Maiandi Bamak	6.3
Swachand Bamak	16.4

In present study, the area of the glaciar and debris is derived from Panchromatic IRS 1D image. The area of the main Gangotri glacier is about 77 Km^2 in present PAN image, while this area is 87 km^2 in the toposheet surveyed in 1985. This implies that the glacier has vacated about 12% in last 16 years.

On the basis of surfacial characteristics, the Gangotri glacier has been divided into various zones. The zonal characteristics of Gangotri glacier are shown in Table 2.

Table 5.2 Zonal Characteristics of Gangotri Glacier.

Glacier Zones	Elevation range (msl)	Zonal Characteristics	Ice covered area (Km^2)	Percentage of total ice cover
Zone 1 (lower ablation)	3975 - 4507	Non-uniform thick debris cover, highly fractured ice	8	11
Zone 2 (upper ablation)	4507 - 4875	Uniform debris cover Non fractured ice	9	12
Zone 3 (accumulation)	4875 - 7068	Fresh snow and ice	59	77

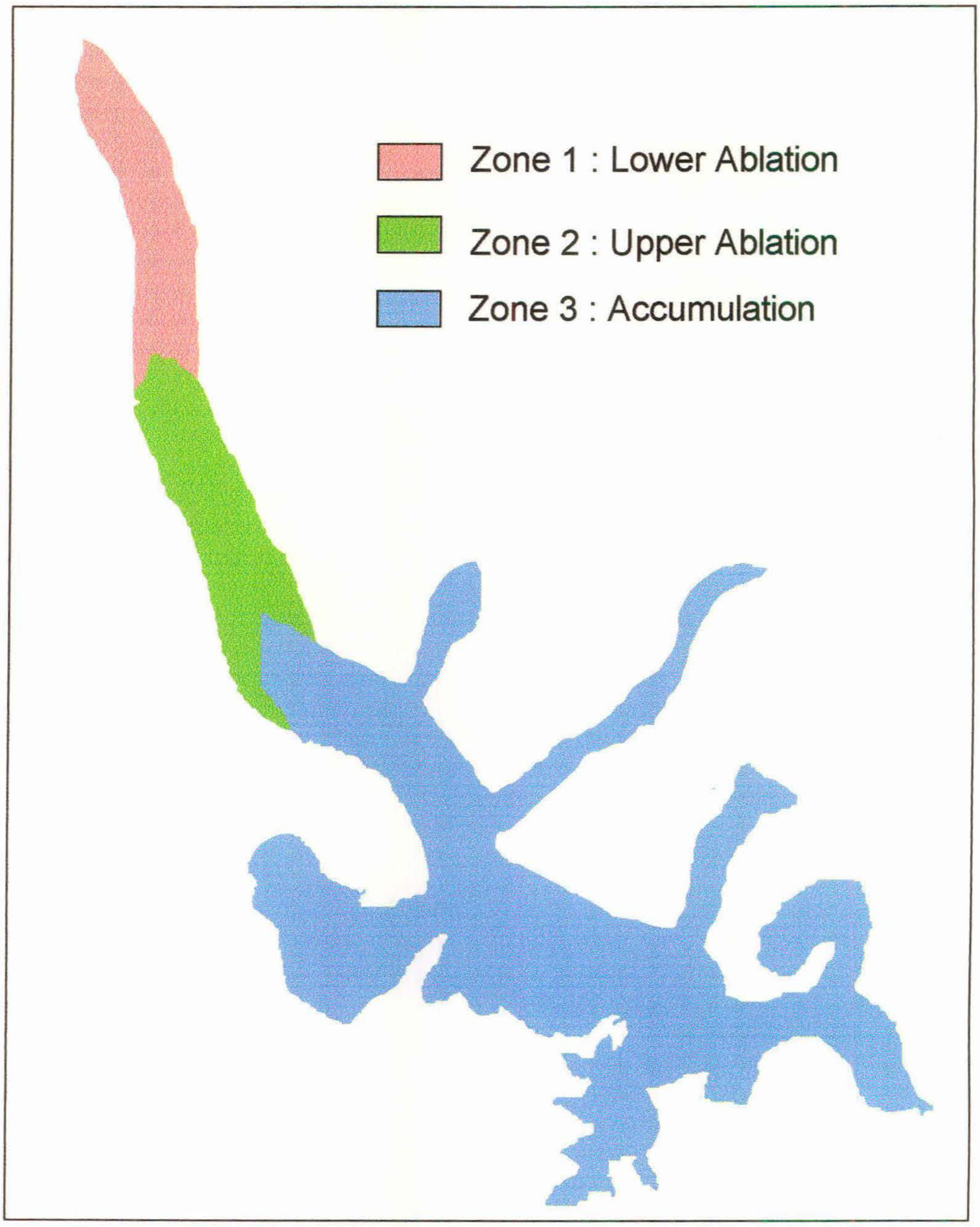


Fig. 5.1 Zonal Categorisation of Gangotri Glacier

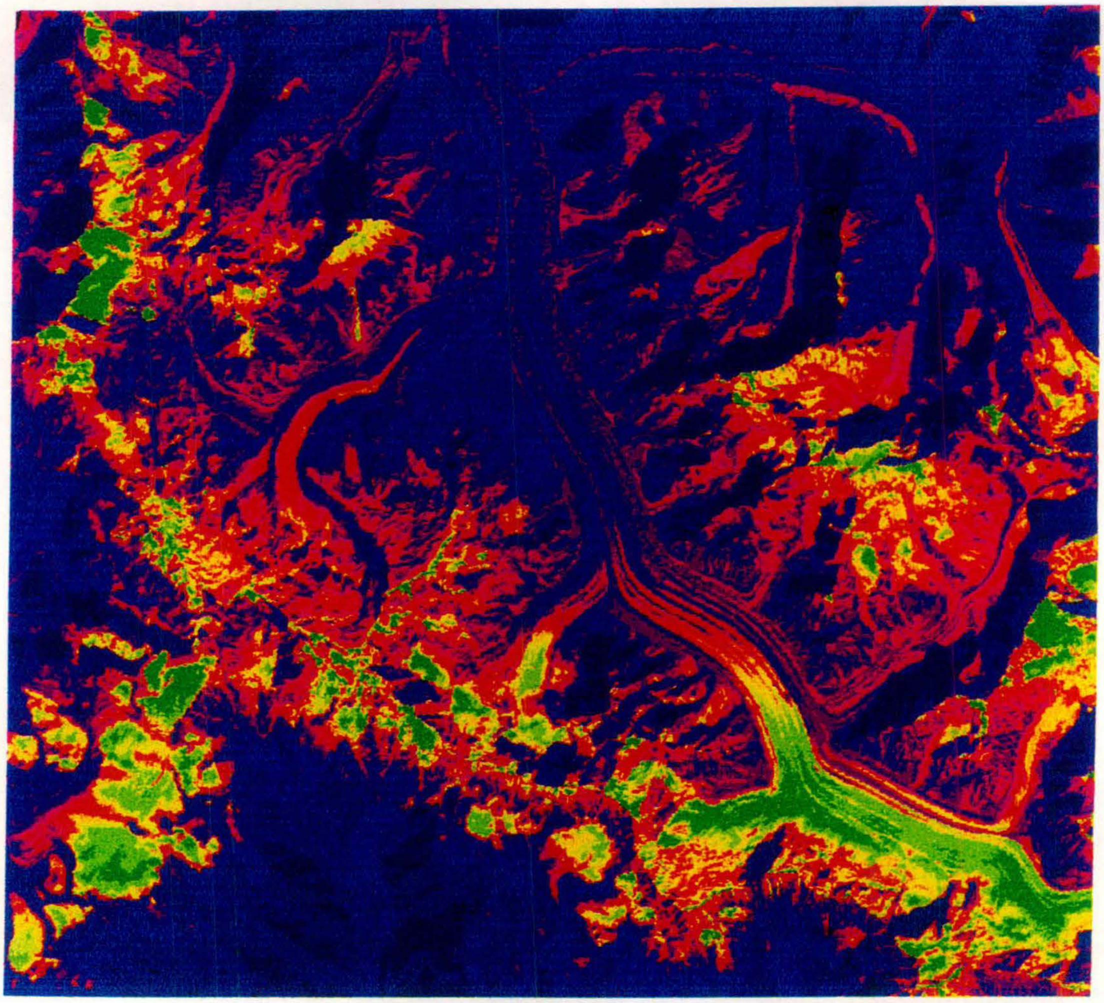
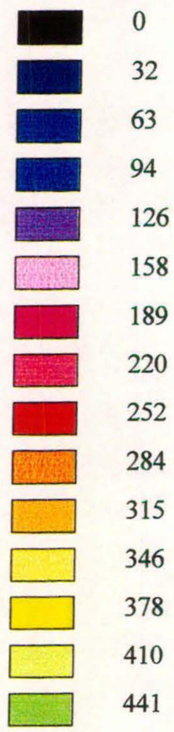


Fig. 5.2 Pseudo-Colour Image of IRS PAN Showing Debris, Snow and Ice cover in Gangotri Basin



The ablation area of Gangotri is divided into two zones. The zone 1 ranges from 3975m to 4507m. This zone has highly fractured ice with non-uniform thick debris cover. The thickness of debris cover varies from 0.5m to 2m. About 8 km^2 of this zone is ice-covered which is 11% of the total ice cover. A uniform debris cover characterises the zone 2 with elevation ranging from 4507m to 4875m. Non-fractured ice covers about 9km^2 area and this represents 12% of total ice-covered area in upper ablation zone. The accumulation zone lies between 4875m to 7068m and accounts for 77% of total ice cover in Gangotri glacier (Figs. 5.1 and 5.2).

5.2 SUPRAGLACIAL ICE-DAMMED LAKES

When glaciers melt fast and heavy debris cover accumulates in the terminus region it results in the development of supraglacial lakes. Supraglacial ice-dammed and moraine-dammed lakes abound on many glaciers in Himalaya and elsewhere (Konovalov 2000) and lending a chaotic potential for Glacier Lake Outburst Floods (GLOFs) and destruction of property and loss of human life in areas downstream. (Mool 1995, Rana and others 1999, Reynolds 2000, Ageta and others 2000, Raymond and Nolan 2000, Richardson and Reynolds 2000a). Even if catastrophic outbursts are absent, supraglacial lakes and lakeshore ice cliffs are important for the thermal and mass balance of glaciers (Chikita and others 1999, Ageta and others 2000) and are important components of the hydrology- related dynamical behaviour of glaciers (Humphrey and others 1986, Fountain and Walder 1998).

Rapid glacier melting in Himalayas resulting into increase in development of supraglacial lakes near the ablation area. If current negative mass balance continues, more potentially dangerous ice-dammed lakes can be expected to develop. Supraglacial lakes are well developed in Eastern Himalaya where melting is expected faster than in Western Himalaya. Because the glaciers situated in Eastern Himalayas receive more rainfall. Also the rise in air temperature has strong negative effect on mass balance of these summer accumulation type glaciers.. In the present study, the ASTER (VNIR) 321 bands were used to delineate the supraglacial lakes. A PCA module was runned using 3, 2 and 1 bands and three factors were extracted. 1st factor had the maximum co-variance and was visualized and the area of such features was also calculated using IDRISI® 2.0 software. The observations are shown in Table 5.3.

Table 5.3 Distribution of Ice-dammed Lakes in Gangotri Glacier

Glacier Zone	Elevation Range (msl)	Characteristics of Glacier ice	Glacier area (Km^2)	Number of lakes	Area of the lakes (m^2)	Gradient (%)
Zone 1 (lower ablation)	3975 – 4507	Highly fractured	8.0	None	-	210
Zone 2 (middle ablation)	4507 – 4663	Fractured with number of ice-dammed lakes	2.4	6	20 – 200	21
Zone 3 (upper ablation)	4593 - 4875	Surface water channels disappearing through moulins	10	-	-	15

Small curved fractures with dark tone were observed at the lower ablation zone of Gangotri glacier in Panchromatic image but field observations have proved that these are not the lakes. Instead these features are due to the shadow of debris hillock in the image. This lower ablation zone ranges from 3975m to 4507m. No lakes have been identified in this zone because the gradient of this area is very steep.

Most of the ice-dammed lakes are concentrated within the elevation range of 4507m to 4663m. This zone shows highly fractured ice. This zone is having gentle slope and about six lakes of size varying from 20 to 200m^2 have been identified in this region as confirmed by the field visit. Numerous surface water channels have been observed in upper part of ablation zone. These channels later on disappear through moulins.

The development of these lakes is in infant stage. This study shows that the supraglacial lakes are developing in front of Kirti Bamak. Extensive fracturing and heavy dumping of supraglacial sediments have created large number of ice - dammed lakes on Gangotri glacier (Plates. 5.1, 5.2, 5.3 and 5.4).

The supraglacial lake development is correlated with rise in global temperature. In present scenario global temperature has resulted in initiation and stagnation of supraglacial lakes in Gangotri region. If the present rate of global temperature anomaly continues as predicted by various models (IPCC hi, low, 2002), It may result in formation of new lakes and growth and expansion of lakes in this region (Fig. 5.3).

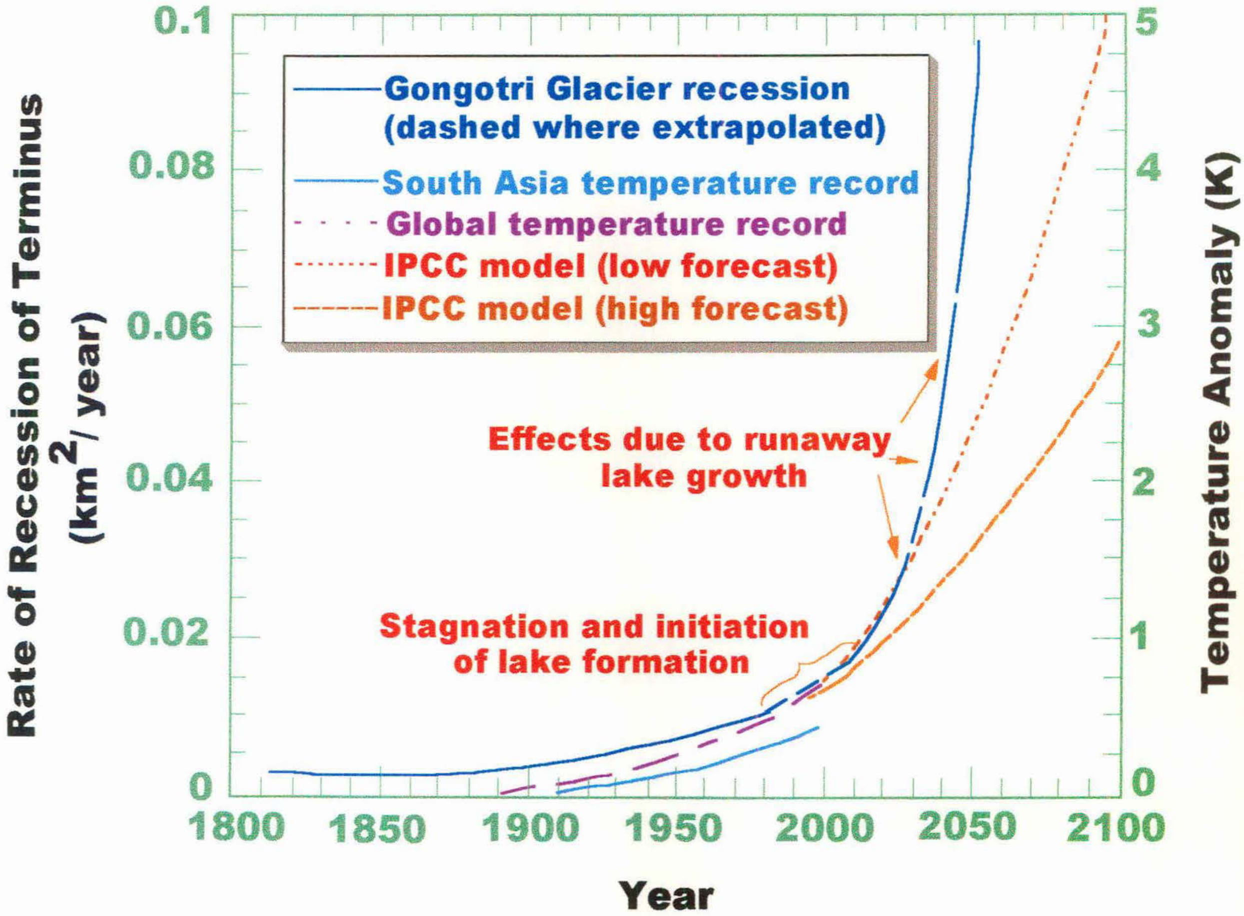


Fig. 5.3 Projection of Climate and Glacier Recession
(runaway lake growth, "Bhutan Mode")
(Source: Vohra, C.P., 1989)

Plate 5.1 Development of Lakes (Infant Stages) in Gangotri Glacier

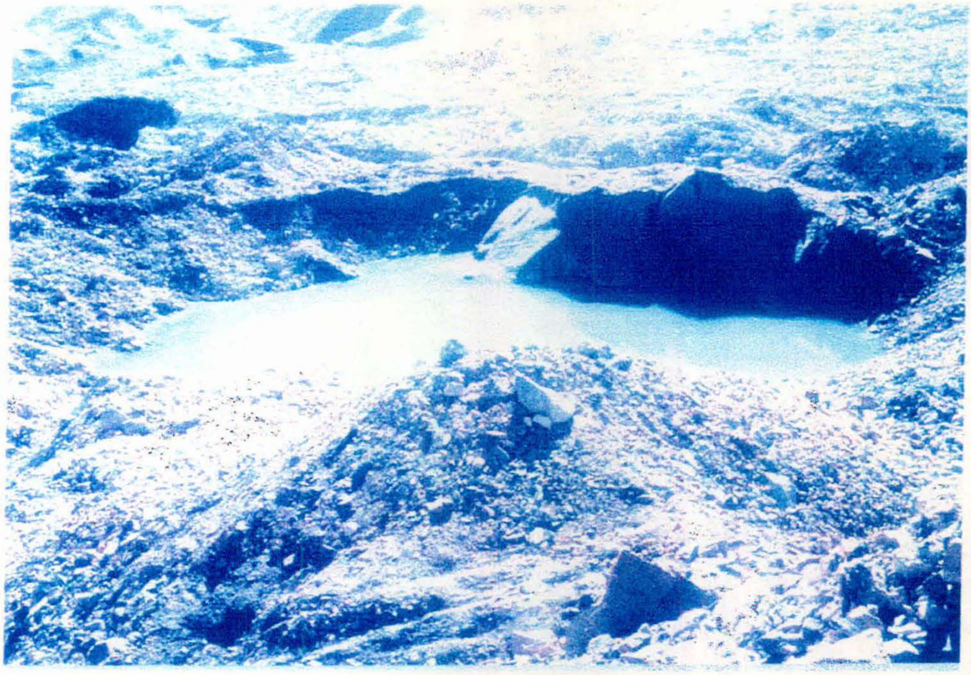


Plate 5.2 Ice-Dammed Lake Near Kirti Bamak

Plate 5.3 An Ice-Dammed Lake in the Upper Ablation Zone (Accumulation Zone is Seen in the Backdrop)

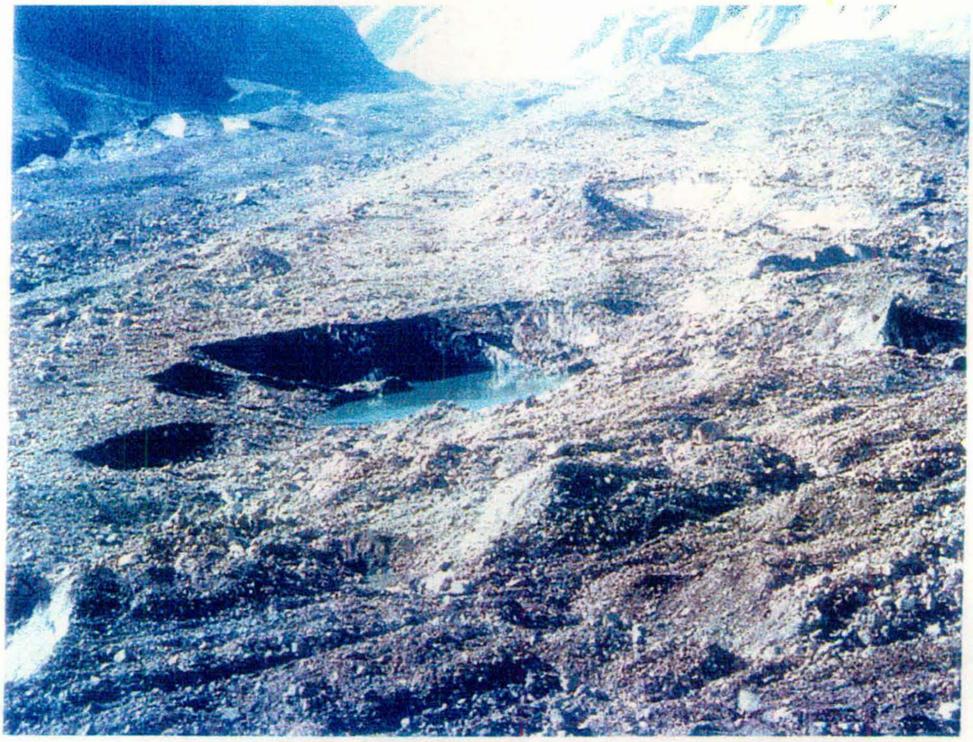


Plate 5.4 An Ice-Dammed Lake at the Confluence of Kirti Bamak and Gangotri Glacier

5.3 SNOUT

The snout of Gangotri glacier, i.e., "Gaumukh" is a vertical wall of ice at an altitude of approx. 3975 msl as observed by using Global Positioning System (GPS) during field study (Plate 5.5). In PAN image the snout is shown as near meandering of the stream. Average retreat rate of the Gangotri glacier has been determined by comparing the snout positions in 2001, 1971, 1964 and 1935 and result shows 20 meter per year retreat. The studies conducted by various researchers have been compiled by Jeff Kargil (Fig. 5.4). Vohra (1989) plotted the rates of terminus retreat against time (Fig. 5.5). In this figure, the rate of terminus recession shows a direct relationship with temperature anomaly. If the current temperature anomaly continues in future due to induced global warming, the rate of terminus recession may reach to 100 meter per year by the end of this century.

Plate 5.5 Gaumukh - The Snout of Gangotri Glacier

Fig. 5.4 Snout Positions in Different Time Periods (After Kargil, J., 2001)

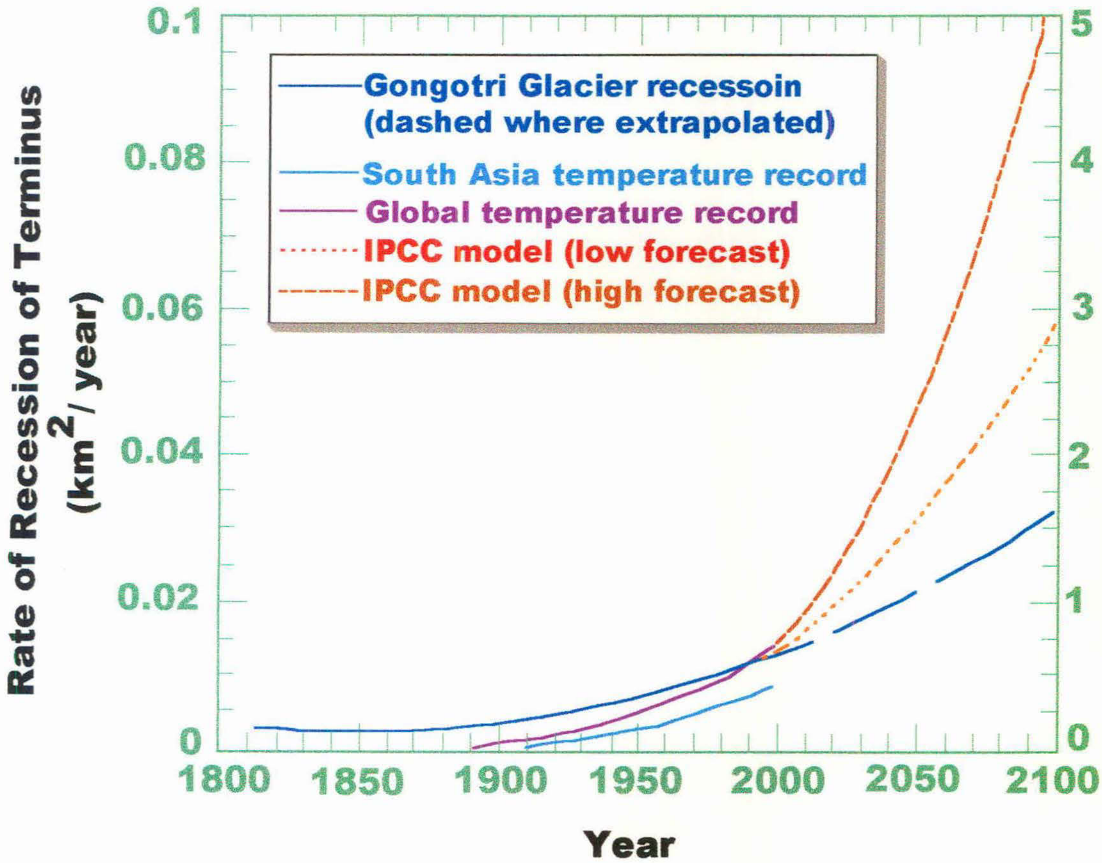


Fig. 5.5 Projection of Climate and Glacier Recession

("Normal Mode")

(Source: Vohra, C.P., 1989)

5.4 HYPSOGRAPHIC ANALYSIS OF DEM

The Instrument ASTER attached to Earth Observation Satellite TERRA offers the stereo images with minimizing temporal changes and sensor modeling errors. The stereo image data can be used to generate the DEM of any region on the globe. In present study the DEM of the Gangotri region is extracted by using the data downloaded from USGS, flagstaff, Arizona, USA. The Nadir looking and Backward looking images were used for extracting automatic DEM by Geomatica Orthoengine. The DEM image was visualized in gray 256 palette using IDRISI® 2.0 (Figs. 5.6 and 5.7) and percentage of area in various altitude bands is computed (Table 5.4).

Table 5.4 Hypsographic Analysis of DEM.

Elevation range msl	Basinal area in %	Gangotri glacier area in %
3800- 4400	5	1.602
4400-5000	27	14.418
5000-5600	31	33.464
5600-6200	34	43.61
6200-6800	0.9	6.764
6800-7000	0.7	0.0176
	99.6	**100.0**

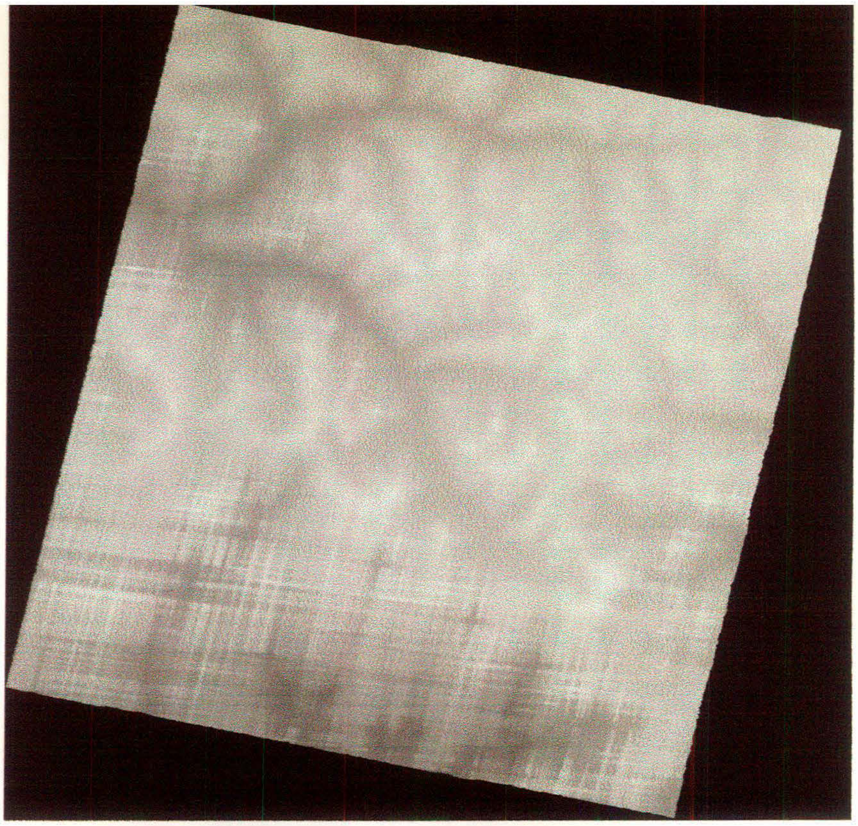


Fig. 5.6 DEM of Gangotri and its Tributary Glaciers (Source USGS)

Fig. 5.7 DEM of Gangotri Glacier (Source USGS)

The results showed that major part of the basin is concentrated within the elevation range of 4400 - 6200 m and this range contributes to about 98% of Gangotri basin and 92% of Gangotri glacier. The maximum 44% of the glacier area lies between 5600-6200m.

Regional gradient and altitude values were also measured by GPS and glacier thickness was calculated for the glacier body. The results show that the average thickness of the glacier in the ablation region is about 300 meter. It ranges from 150m at snout wall and 430 m near Raktavarn.

5.5 EQUILIBRIUM LINE ALTITUDE (ELA)

The term is used here to indicate snowline at the end of the snow ablation season, which is usually September in Himalaya. This line separates yearly accumulation from ablation. Therefore, it is perhaps the sole indicator having its genesis and configuration uniquely governed by the climatic parameters in the region. Climatic variability in the region often leads to fluctuations in Equilibrium Line Altitude (ELA). ELA is climate sensitive. As the ambient temperature changes, the ELA also varies and accordingly the glacier advances and retreats

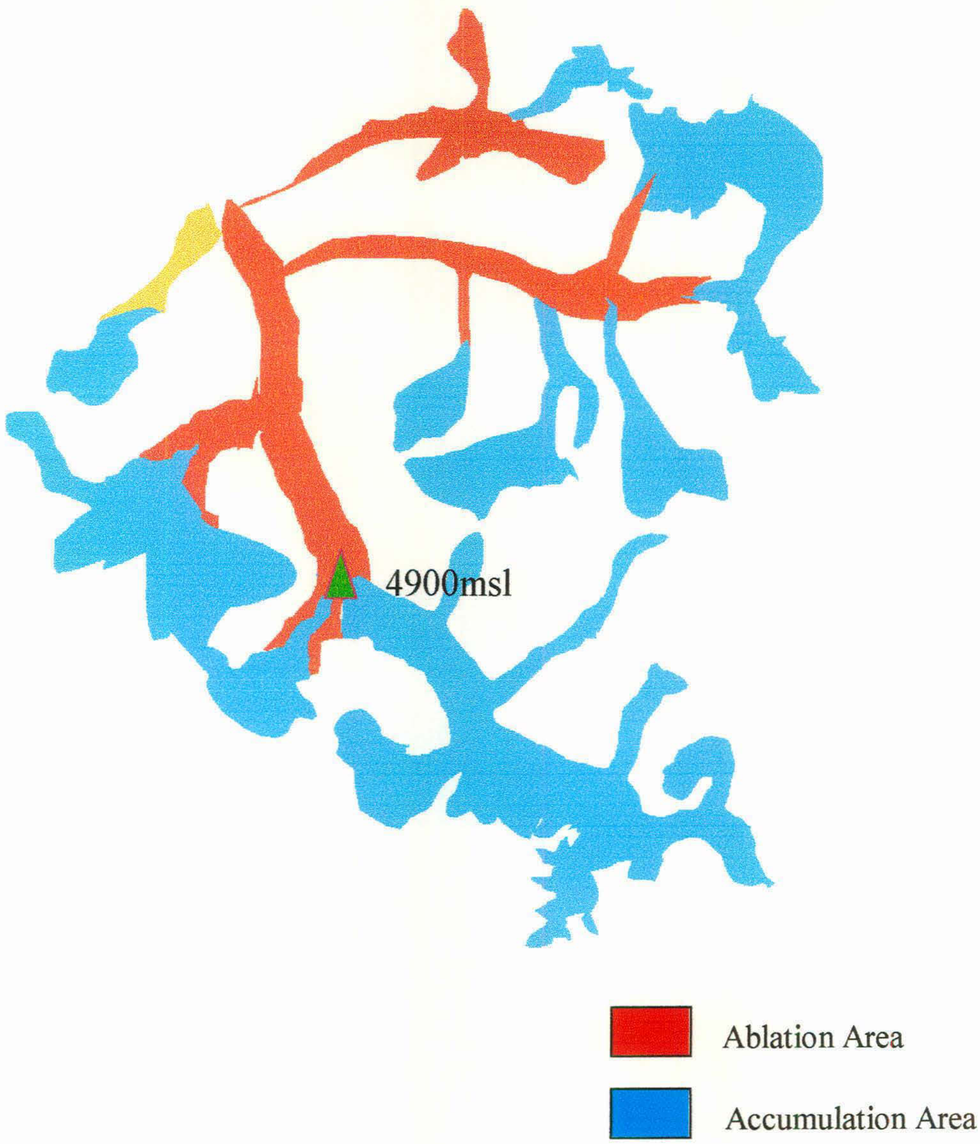
The recession rate of the glacier is well related to Mass balance studies, a rough estimate of the mass balance of the glacier was derived from AAR. The various studies have concluded that AAR can be used as proxy of Mass balance study on regional Level. AAR of zero mass balance glaciers is 0.5, the AAR less than 0.5 is related to negative mass balance. It has been delineated for the entire tributary and main glaciers.

Table 5.5 ELA of Major Himalayan Glaciers

REGION	PRESENT ELA (m)	SOURCE
Hindu Kush	4000-4600	Porter, 1970
Swat Kohistan	4100-4400	Porter, 1970
Nanga Parbat	3750-5200	Scott, 1992
Kashmir	3900-4300	Holmes & Perrott, 1989
Ladakh	5200-5400	Burbak & Fort, 1985
Zanskar	5200-5400	Burbank & Fort, 1985
N. Everest	5800	Williams, 1983
S. Everest	5200	Williams, 1983
Tibetan Plateau	5900	Kuhle, 1987
Tibetan Plateau	****	Burbank & Cheng, 1991
NW Garhwal	**4500-5400**	**This study**

The ELA of major Himalayan Glaciers is shown in Table 5.5.Higher ELA is for sun facing glaciers and the glaciers opposite to sun have lower ELA. ELA in the Himalaya varies from East to West and in North to South as a result of various Climatic and Geomorphological factors.

In the present study, it has been done with the help of the PAN and ASTER data. By filter method and multispectral analysis of various bands, different varieties of the snow and ice has been identified. The AAR of the Gangotri glacier and others in the basin is about 0.38. (Fig. 5.8).



AAR of the basin is 0.38 and ELA of the Gangotri region is about 4900msl

Fig. 5.8 AAR of Gangotri Basin

It indicates the negative mass balance glacier budget in the basin. The AAR of the various tributary glaciers in the Gangotri basin and particular main Gangotri is derived by differentiating the ablation and accumulation area in Panchromatic image on basis of ELA. This line differentiates the Ablation and Accumulation region on glacier surface. In present study The ELA of the main Gangotri region is about 4900-msl.

5.6 MORAINES

The term moraine covers a wide range of depositional features associated with glaciers and ice sheets activity. The movement of glacier leaves behind moraines, the dark bands of rocky debris pushed along by the glacier and deposited on its top and on its edges. The formation and the type of moraines, together with other landforms, provide the key morphological evidence of the previous positions of a glacier, particularly its snout, and provide indications of its advance or retreat.

Moraines are formed due to erosion and transportation of the rock material from the floor and sides of the valley during its movement from zone of accumulation to the zone of ablation. Besides weathering of rock faces above the glacier by frost shattering and erosion by snow, melt water supplies a considerable amount of debris carried by land sliding, avalanches, etc. on the glacier surface. Different types of moraines that have been identified in Gangotri glacier area are as follows

5.6.1 Recessional Moraine

These are formed when there are periodic advances by the glacier during the overall retreat of the glacier. There can be many recessional moraines formed during the overall retreating period. In present study, a continuous trail of the recessional moraine is observed from 2 Km away from present day snout position (Fig. 5.9). The old recessional moraines are covered by vegetation; hence reflection is lower than that of new surfaces. The differentiation between recessional moraine and avalanches deposited by inactive tributaries glacier confuse to identify the recessional moraine in the region. The trend of old and new recessional moraines is different. Old recessional moraine is shaped by the continuous action of the geological action, while new ones are developed in short span of time, therefore these are still very fresh. The shape of the recessional moraines is arcuate and valley facing.

5.6.2 Lateral Moraine

The remnants of previous glacial activity in the region are recorded in the form of lateral moraine in inactive zone. The major part of the sediment load transported near the surface which is located along the margin is known as lateral moraine. In the present area, previous stages of the glaciation have been identified on laplacian enhancement image. The lateral moraine height varies from few meters to 200m suggesting that the glacier remained stationary for quite a long time during the formation of this moraine. Lateral moraine is largely modified by the avalanches activity and glacial outburst lake developed in the catchment of tributaries glacier along lateral slope

The lateral moraines in the active glacier region are not well recognized in Panchromatic image as the debris and lateral moraines have same material. But the lateral moraines are easily identified on ASTER 321 image due to different spectral signature of the dry lateral moraine and ice covered debris (Fig. 5.10).

Fig. 5.9 Recessional Moraines

3 x 3 Laplacian Edge enhancement filter of subset1

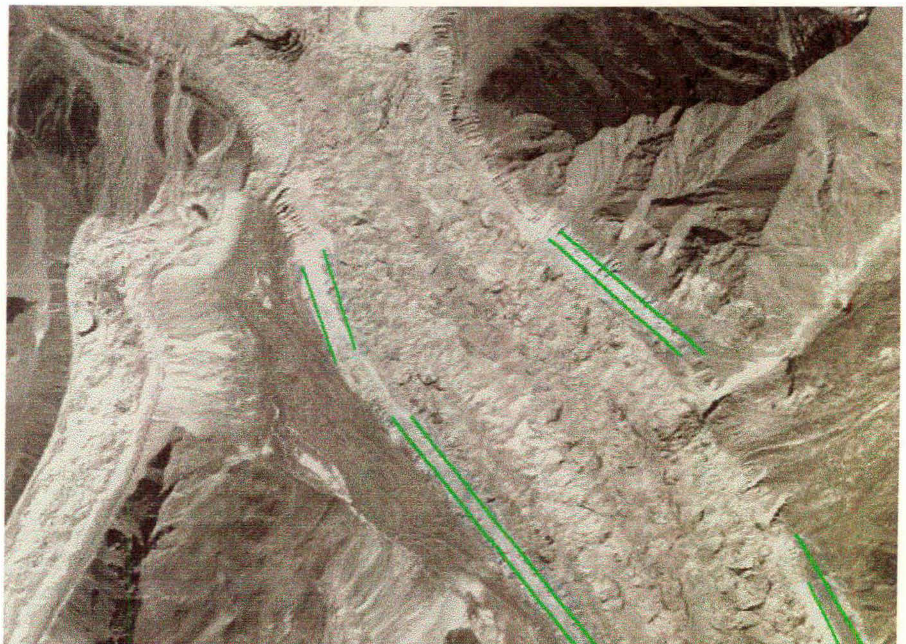


Fig. 5.10 Lateral Moraines (Prepared by 3 X 3 Laplacian Edge Enhancement Filter)

In the ASTER 321 image these lateral moraines are high running parallel to the glacier from accumulation zone to full length of the glacier. The right side lateral moraines are poorly preserved; however, left lateral images are well preserved. Because the sun illumination result into higher avalanches activity on left side and less avalanches activity on right side of the glacier. Lateral moraines are crossed by the crevasses in the high altitude due to high gradient, while in the lower ablation zone; these moraines are crossed by transverse crevasses.

5.6.3 Medial Moraine

Medial moraines are formed where lateral moraines of two glaciers (either two main glaciers or a main glacier and a tributary glacier) join each other and move down. The medial moraine is usually an entirely superficial feature consisting of coarse stony debris lying on the ice. These moraines are quite common in middle of the glacier, where tributary glaciers contribute the sediment to main glacier. Medial moraines are few in number and are not so thick. Sometimes these merge into the lower ablation zone near terminal moraine and form the thick uniform moraine lobate. A glacier having several medial moraines is likely to be transporting a volume of drift sufficient to cover almost completely the surface in the terminal zone. Individual medial moraines in turn lose their identity and merge into an irregular superglacial veneer of rock fragments referred to as an ablation moraine.

5.7 CREVASSES

Crevasses are the cracks on the glacier surface resulting from the movement of the glacier. Numerous crevasses of longitudinal and transverse types are found over the glacial surface. Analysis of PAN image depicts that the crevasses can be observed on the glacier surface starting from the snout and covering the whole accumulation area. Near the snout the crevasses are transverse type trending EW. These crevasses are filled with morainic material. Transverse crevasses are most prominent type of crevasses running almost at right angles to the length of the glacier. About 500m from snout towards glacier body numerous small cracks can be observed. These are not as such crevasses but these may result into crevasses if the present rate of regression continues.

On the basis of the trends of formation, crevasses may be categorized as :

1. Marginal crevasses: These develop at right angles to the margins of the glacier.
2. Longitudinal crevasses: These are found parallel to glacier margins and are formed where the width of the valley increases and the ice surface widen to fill the valley.
3. Radial crevasses: They are the result of spreading of ice into a lobe.

The melt water streams that are flowing over the ice surface mostly take a downward route via the crevasses into deeper parts of the glacier. Melt water from the Meru glacier is seen seeping into the Gangotri glacier through crevasses along the west rim. The life of an open crevasse is limited and soon closes with the movement of glacier when it moves to an area of less tension. Its place is taken by another more suitably oriented crevasse.

5.8 ROCK GLACIER

Rock glaciers form an important element of the coarse debris supply system in high mountains. In the high Indian Himalayas they are widely distributed in desert environment with an annual precipitation of 250mm. Both talus-derived and moraine-derived forms can be observed at altitude more than 40,000m. In the study area, small glaciers have been identified on the Northern slope of Shivling.

These are arcuate shape in images and face towords main valley (Fig. 5.11). The moraine material of rock glacier are clearly related to recent ice retreat, particularly of cirque glaciers, such that ice becomes buried by increasing amounts of supraglacial debris. However, talus-derived forms are also developed where there is a high sediment flux associated with mechanical disintegration of specific rock types.

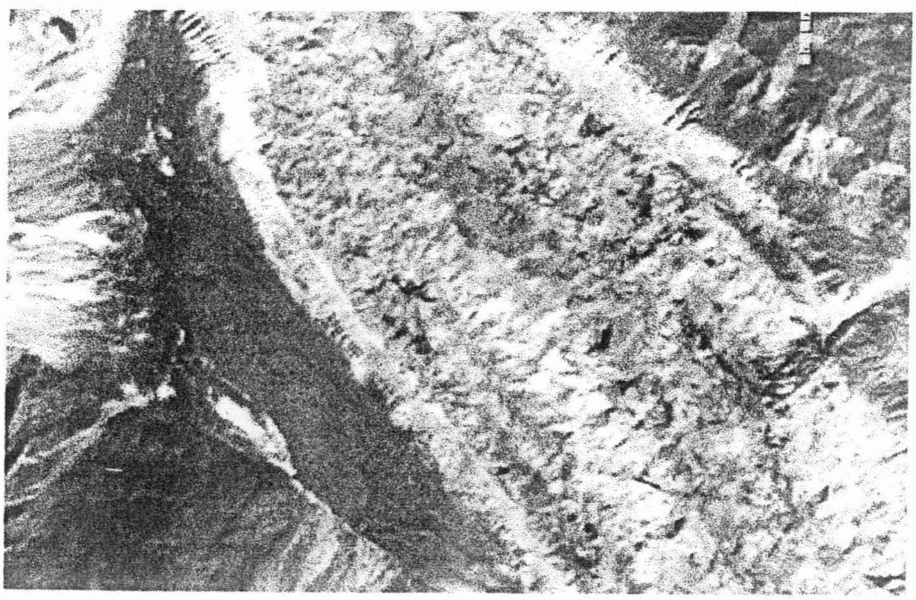


Fig. 5.11 Rock Glacier in Gangotri Basin

5.9 ALPINE MEADOWS

Morainic material deposited by the glacier during earlier periods much above the present position of the glacier form flat meadows near the base of some of the peaks. In Gangotri glacier area several of the alpine meadows are formed. Tapovan is the flat area formed at the base of the peak Shivling. Similarly Nandanvan is another meadow at the confluence of Gangotri and Chaturangi Bamak glaciers.

5.10 HANGING VALLEY

The tributary glaciers form these valleys, when the main glacier cuts comparatively deeper valley and tributary glaciers look like hanging over the main glaciers. Raktavarn, Meru and Chaturangi occupy the hanging valley. The Retreat of the hanging glacier leaves the boulder and pebbles & sometimes may result into avalanches. These avalanches obliterate the old glacio-fluvial geomorphological features.

CONCLUSION

This study has shown that the satellite images can be used in various glacier studies. Various features as boundary, equilibrium line, ablation and accumulation areas can be mapped, if images of proper season are available. The study of surfacial features indicates that the glacier is receding at a faster rate. In the middle ablation zone, the thick glacier sheet lies on steeper slope and exhibits features like crevasses associated with an active glacier. From this study it is concluded that geomorphological investigations do provide reliable estimates of glacial retreat.

23% of total glaciated area is debris-covered which confirm the occurrence of several periglacial processes over the surface of Gangotri glacier due to Global warming.

Terminus has retreated at a very fast rate in last couple of years and this change in snout position is correlated to temperature anomaly. AAR of Gangotri glacier is 0.38, which confirms negative mass balance in Gangotri glacier. ELA of Gangotri is 4900msl. This separates ablation and accumulation zones. Due to rapid weathering and deglaciation, a large amount of debris has been transported as moraines. Recessional moraines have also been identified in IRS PAN image near the snout of the glacier. These are formed because of the transport of glacial debris as the glacier advances during various periods of retreat. Small rock glaciers were identified near Northern slope of Shivling. These are formed when ice gets buried under morainic material formed during ice retreat. These glaciers represent recent ice retreat.

Numerous fractures have developed over the main glacier. In middle ablation zone (4507-4663m), six ice-dammed lakes have been identified. These lakes are now in infant stages of development. If the present rate of temperature rise continues, these lakes may result in Glacial Lake Outburst Flows (GLOFs), which may cause serious havocs.

This implies that Gangotri is receding at a faster rate. The immediate impact of receding Gangotri would be an increased risk of glacial hazards, such as incidents of landslips, changes in the courses of rivers and floods. The formation of glacial lakes on the main trunk of the glacier poses a hazard.

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