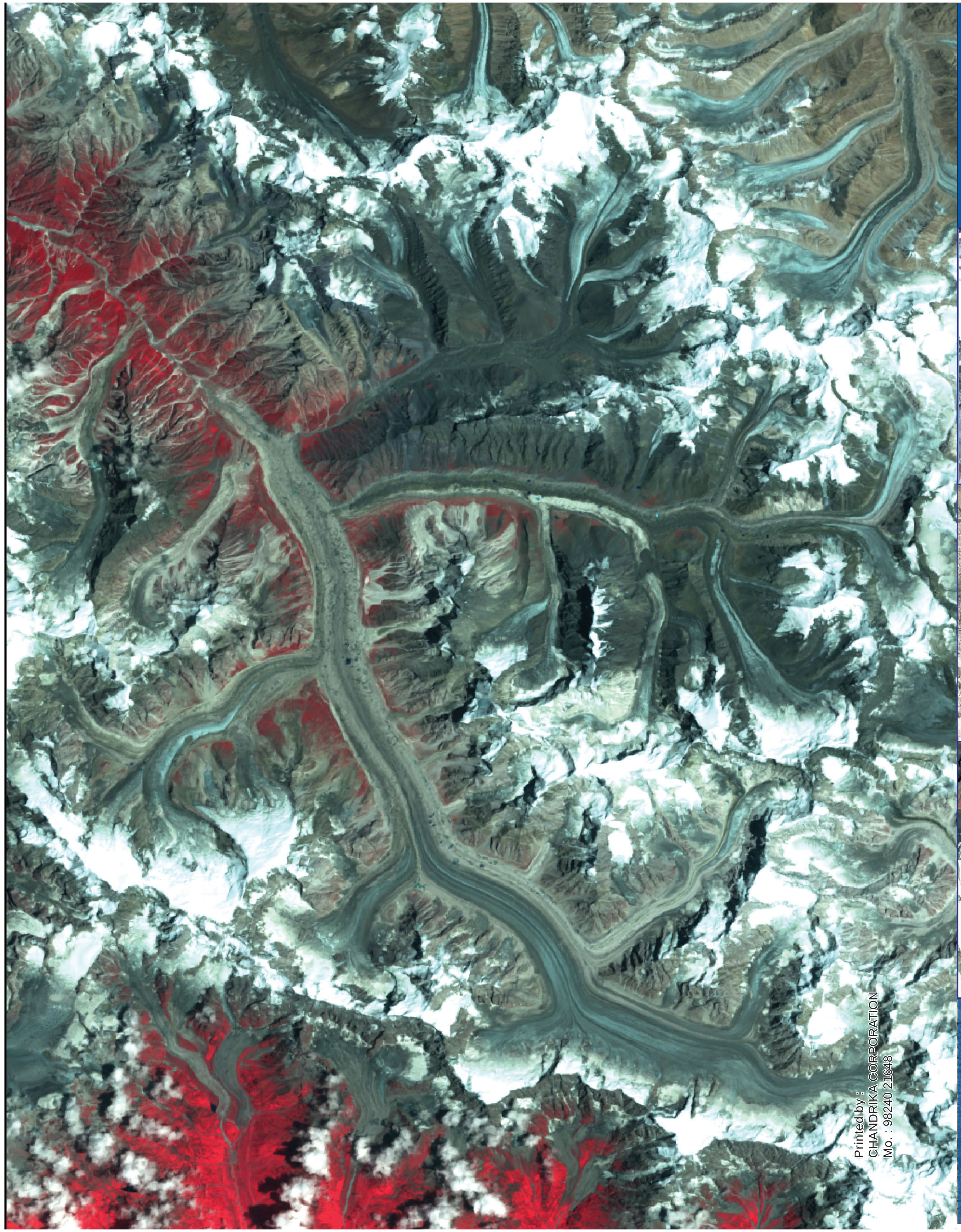

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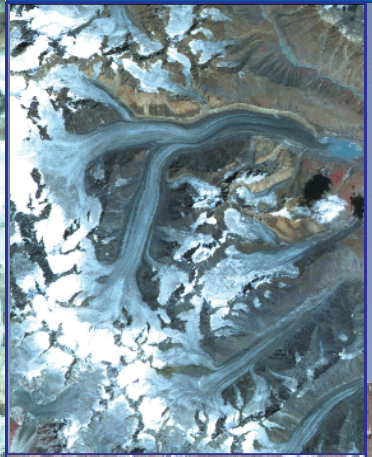
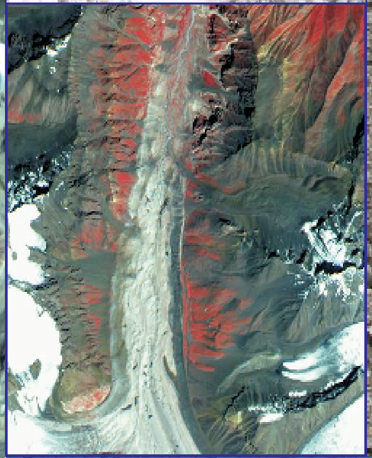
SNOW AND GLACIERS OF THE HIMALAYAS : INVENTORY AND MONITORING

(Work carried out by Space Applications Centre, ISRO in Collaboration with other Organisations)





Discussion Paper II

Space Applications Centre
Indian Space Research Organisation
Ahmedabad - 380015.

Ministry of Environment and Forests
New Delhi

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JAIRAM RAMESH

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GOVERNMENT OF INDIA
NEW DELHI - 110 003

FOREWORD

I am delighted to introduce the Discussion Paper on snow and glacier studies prepared by the Space Applications Centre (SAC), ISRO, Ahmedabad based on the work carried out by them. This is the second of what promises to be a stimulating working paper series that we aim to put in the public domain for informed science-based discussions and debates on critical environmental issues. This paper provides the perspective of the SAC on the subject based on the work carried out by them over a period of last 25 years.

The views expressed in this paper are not meant to represent the views of the Ministry of Environment & Forests or Government of India instead, we hope to gain useful lessons for public policy from the discussion contained in the paper and feed back received on it.

The Himalayan glaciers are valuable national and global resource and possess the largest concentration of ice outside polar regions. They are an important source of water, especially for our perennial north Indian rivers during the critical summer period. With fluctuating glacial dimensions, the source of our water which has helped sustain and flourish civilizations along the banks of the Ganga and Indus rivers, no longer remains permanent.

It is in this context, that I feel systematic monitoring is urgently required to understand future changes in the Himalayan snow and glacier cover and the downstream influences on stream runoff. This document provides an overview of the work carried out in Himalayas on the inventory and monitoring of the snow and glacial cover.

I strongly believe that rigorous scientific work on the Himalayas must be an urgent and important priority for our country. I congratulate the team of scientists from SAC and other national organizations for carrying out this important endeavour. I hope, they will continue to work on these issues. I am confident that this document will be useful to the scientific community, environmentalists and resource managers and will inspire critical debate on this important issue.

16th December, 2010

(Jairam Ramesh)

Dr. Ranganath R. Navalgund
Director

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PREFACE

Permanent snow fields and glaciers located in high altitudes of Himalayan mountain chains are very important natural resources of frozen fresh water for our nation's development, planning and growth. The great northern plains of India sustain on the perennial melt of snow and glaciers meeting the water requirements of agriculture, industries, domestic sector. It is of paramount importance to assess the state of glaciers and to know the sustainability of glaciers in view of changing global scenarios of climate and water security of the nation.

Space Applications Centre (SAC) has been contributing to the development of methods/techniques for extraction and dissemination of reliable and quick information from remote sensing data pertaining to snow and glaciers of Himalayas for the last more than two and half decades. The centre has been instrumental in developing remote sensing based techniques, models and methods to generate a large amount of digital database and maps to understand the state of Himalayan cryosphere. These techniques are validated through field observations. SAC has conceptualized and developed techniques, models and methodology for Himalayan glacial inventory, glacial mass balance, to assess effect of global warming on Himalayan glacial extent and stream runoff, algorithm to monitor seasonal snow cover, snow pack characterization, snow and glacier-melt runoff modeling and assessment of flash flood from glacial lakes.

The results of the work done by SAC have been presented in key national and international forums. This work has now assumed greater significance when the nation needs to address a large number of questions about the health and state of glaciers. There is no contemporary technique which provides this information to the nation in a very short span of time and for a large number of glaciers. SAC has trained more than hundred professionals across the country on the processing and use of remote sensing based information of Himalayan glaciers.

The results and findings of the work carried out by Space Applications Centre in collaboration with other organizations are presented in this discussion paper. I hope, this document will be useful to the scientists/Researchers for proper understanding of Himalayan cryosphere.

Ahmedabad
December 6, 2010

(R. R. Navalgund)

INDIA SPACE RESEARCH ORGANISATION

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Acknowledgement

Glaciers and snow fields together form one of the most crucial freshwater resources for Indian economy. Animal and plant life of the Himalayas and foothills depends on the melt water of these frozen reservoirs. There are several thousand of glaciers in Himalayas which feed to Indus, Ganga and Brahmaputra river systems but glaciers studies have been very limited due to the efforts and logistics required to carry out the field studies. A few glaciers (approximately 15) have been studied for mass balance in India which is important parameter for monitoring glacier's health and the impact of climate change. Remote sensing technique has proved to be most viable alternative to monitor snow and glaciers. Since repetitive satellite data from high to medium resolution of Indian Remote Sensing Satellite is available for the last two decades, it has become simpler to monitor snow and map glaciers of Himalayas with limited validation on the ground. In India, first glacier inventory using satellite images available from Landsat and IRS 1A & 2B satellite was carried out at 1,250,000 scale during early 90's. Detailed glacier inventory for Satluj basin, Dhauliganga basin, Tista basins and Chenab basin at 1,50,000 scale was followed up. Recently, inventory of all the glaciers in Indus, Ganga and Brahmaputra basins which feed into India has been carried out. The experience has led to expand the activity from inventory to snow cover monitoring, glacier retreat/advance studies glacier mass balance studies, hydropower potential estimation from snow and glaciers melt runoff and study of moraine-dammed lakes.

The present document on “Snow and glaciers of Himalaya; Inventory and monitoring” highlights the work carried so far out at Space Applications Centre, Ahmedabad along with other organizations/institutions of the country. Beginning with development of methodologies for extraction of information from satellite images to bringing this subject to operational level, it has been a long way towards the important issues related to Himalayan cryosphere.

There are many important organizations/institutions of the country which has worked with SAC for more than two decades in carrying out the studies reported in the report. We would like to acknowledge efforts made by the team and head of the organizations involved. We would like to place on record our deep sense of gratitude to Dr. R.R. Navalgund, Director, Space Applications Centre (SAC) for his guidance and keen interest in this work. We are also thankful to Dr. Shailesh Nayak, the then Group Director, Marine and Water Resources Group, for his contributions and guidance. Dr. J.S. Parihar, Deputy Director, EPSA has not only supported but strenthened this activity in EPSA. We express gratefulness to him. We are also thankful to Dr. V.S. Hegde, Director, EOS and Scientific Secretary ISRO and to Dr. K. Ganeshraj for discussions and help. Our team at SAC comprising Dr. A.V. Kulkarni, Dr. I.M. Bahuguna, Shri A.K. Sharma, Shri B.P. Rathore, Shri Sushil Singh and Shri Anish Mohan and Scientists from other participating institutions of the country has put in dedicated efforts to carry out these activities.

Ahmedabad
December 13, 2010

Ajai
(Ajai)

Executive Summary

Snow and ice have distinct spectral signatures in VNIR and SWIR region of Electromagnetic Spectrum which makes this landcover distinctly amenable to remote sensing data acquired from orbiting satellites. Moreover due to limitations of implementing field methods in rugged and harsh climatic conditions of Himalayas for assessing health of large number of glaciers, remote sensing has occupied a pivotal role in generating quick and reliable information on glaciers. The use of satellite images for glacier monitoring has increased manifold in the last one decade in view of climate change debates. There are now many aspects of remote sensing which can be applied for snow and glacier studies. The multi-resolution and multi-temporal data in optical region is operationally being used for monitoring of snow and glacier cover using this potential, Space Applications Centre (SAC) has executed many projects aimed at monitoring of snow cover, glacier inventory, monitoring of retreat and advance, monitoring of snow line for estimation of mass balance and mapping of moraine-dammed lakes. The highlights of the major projects under taken are presented as following :

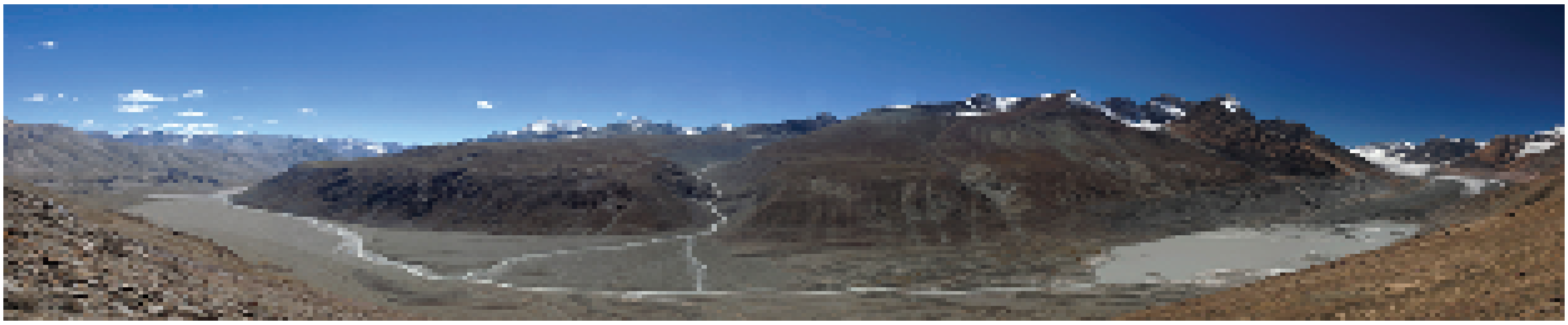
Glacier Inventory at 1: 250, 000 scale

A glacier inventory on 1:250,000 scale using satellite images of 1987 was carried out for entire Indian Himalayas. Inventory had shown 1702 glaciers covering an area 23,300 km^2. This estimate does not include features such as permanent snowfields, ice apron, hanging glaciers and rocky glaciers.

Glacier Inventory at 1: 50,000 scale

First glacier inventory at 1:50,000 scale using satellite images was carried out for Satluj basin. The study had indicated the presence of 334 glaciers in the Satluj basin covering an area 1515 km^2. This is in addition to the 1987 permanent snow fields having an area of 1182 km^2. The total area under glaciers and the permanent snow cover is distributed in 169 sub basins and amount to 2697 km^2. Inventory of glaciers in Dhauliganga basin was undertaken at 1:50,000 scale using IRS-LISS-II images of 1995. Results obtained during this investigation suggest presence of 48 glaciers. The 48 glaciers cover an area of 197.38 km^2. In addition, permanent snow fields were also mapped. The total areal extent of permanent snow fields were measured as 31.70 km^2. This makes total area under glaciers and permanent snow fields as 229.08 km^2 in Dhauliganga including Lesser Yankti basin.

For Tista basin eleven glacier inventory maps at 1: 50,000 scale were prepared. Maps were prepared based on interpretation of IRS LISS III geocoded FCC data. These have been presented in the form of an Atlas. Results obtained during Tista basin suggest presence of 84 glaciers in the Tista basin. This covers an area of 440.30 km^2. Total permanent snowfields have been measured as 251.22 km^2. For Chenab basin, twenty four glacier inventory maps were prepared. Maps have been prepared based on interpretation of IRS LISS III geocoded FCC data. Results obtained during this investigation suggest presence of 454 glaciers in the Chenab basin. This covers an area of 1174.5 km^2. The permanent snowfields were also mapped. The total number of permanent snow fields is 1186 carrying an area of 1419.5 km^2 in the Chenab basin. The permanent snow cover and glaciers are distributed in 55 sub-basins. The total glacial and permanent snow cover stored water in the Chenab basin is estimated as 93.03 cu km.



**Joint programme of Department of Space and Ministry of Environment and Forests.
(2006-2010)**

Snow Cover Monitoring

The snow cover mapping has been carried out in Indus, Ganga, Satluj, Chenab, Tista and Brahmaputra basins covering Western and Eastern Himalayan region. These basins are subdivided into 33 sub-basins. AWiFS sensor of RESOURCESAT-1 satellite has been used to monitor seasonal snow cover. AWiFS data covers an areal extent of 5,47,600 km^2 at an interval of 5-days. Approximately 1500 AWiFS scenes from October to June of years 2004-05, 2005-06, 2006-07 and 2007-08 have been analyzed in this investigation. An algorithm based on Normalized Difference Snow Index (NDSI) is used to map snow cover. NDSI is calculated using the ratio of green (band 2) and SWIR (band 5) channel of AWiFS sensor. NDSI is established using the following method.

$$Normalized\ Difference\ Snow\ Index(NDSI) = (band\,2 - band\,5)\,/(band\,2 + band\,5)$$

For each basin ablation and accumulation curves have been generated for the all the four years of monitoring.

Glacier Inventory

The main objective of this component was to carry out inventory of the glaciers occurring in the Indus, Ganga and the Brahmaputra basins on 1:50,000 scale and draining in to India. The study area also covers some parts of Nepal, Bhutan, Tibetian Plateau and China from where these rivers either originate or have major tributaries which flow into India. Geocoded IRS LISS III data on 1:50,000 scale, from period July to end of September seasons is procured in the form of FCC paper prints and digital format. The hard copy geocoded FCC's of standard band combination such as 2 (0.52-0.59 m), 3 (0.62-0.68 m) and 4 (0.77-0.86 m) and in digital data the standard bands with additional SWIR band (1.55-1.70 m) is used for mapping.

A glacier inventory datasheet with 37 parameters is prepared for each glacier. The three basins put together have 71182.08 km^2 of glaciated area with 32392 numbers of glaciers. The Indus basin has 16049 glaciers occupying 32246.43 km^2 of glaciated area. The 18 glaciated sub-basins in Indus basin are mapped. The Ganga basin has 6237glaciers occupying 18392.90 km^2 of glaciated area. There are 7 glaciated sub-basins in Ganga basin. The Brahmaputra basin has 10106 glaciers occupying 20542.75 km^2 of glaciated area. The 27 glaciated sub-basins in Brahmaputra basin are mapped. Basin wise glacier summary for Indus, Ganga and Brahmaputra basin is provided in table 1.

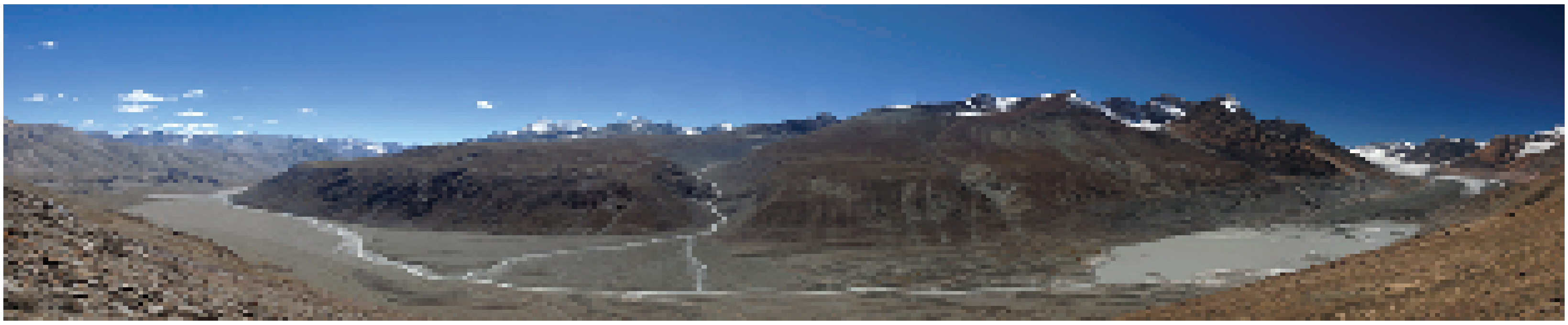
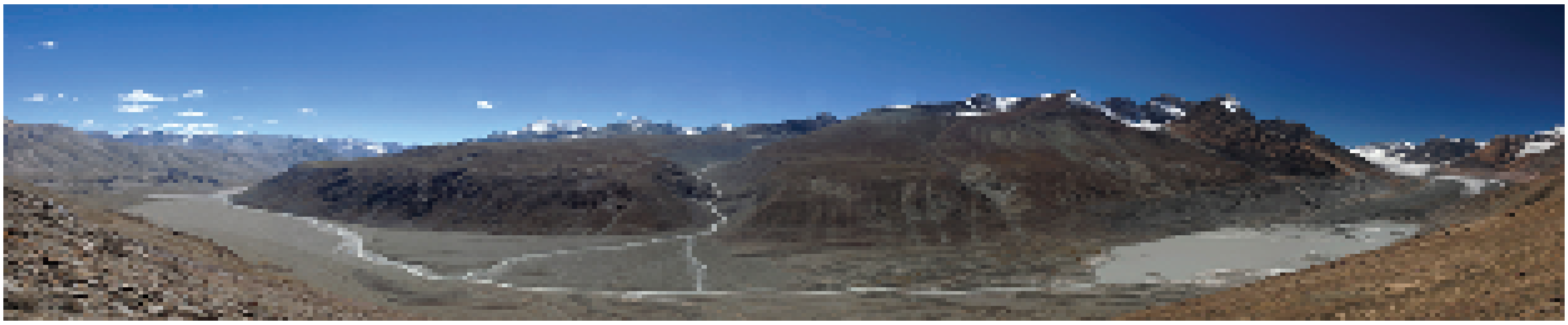


Table 1 : Summary of glacier inventory of Indus, Ganga and Brahmaputra basins.

Sr. No.	Basin Characteristics	Indus Area in km^2	Ganga Area in km^2	Brahmaputra Area in km^2	All basin total Area in km^2
1	Sub-basins (Nos.)	18	7	27	52
2	Accumulation Area	19265.98	10884.6	12126.35	42276.94
3	Ablation Area Debris	6650.95	4844.7	5264.90	16760.55
4	Ablation Ice Exposed	6310.58	2663.5	3081.48	12055.56
5	Total no. of glaciers	16049	6237	10106	32392
6	Total glaciated area	32246.43	18392.9	20542.7	71182.08
7	No. of Permanent Snow fields and Glacierets	5117	641	3651	9409
8	Area under of Permanent Snow fields and Glacierets	991.68	198.70	1282.9	2474.3
9	No. of Supra-glacier lakes	411	87	474	972
10	Area of Supra-glacier lakes	18.92	15.20	70.0	104.13
11	No. of Moraine dam /Glacial lakes	469	194	226	889
12	Area of Moraine dam /Glacial lakes	33.82	64.10	70.2	168.07

Monitoring Changes in Glacier Extent

Advance/Retreat of glaciers has been found for glaciers of 15 sub-basins of Himalayas. For long term change monitoring, Survey of India (SOI) topographical maps of 1962 at 1:50 000 scale have been used as reference maps. In some glaciers fragmentations have also been observed and therefore the numbers of glaciers in a specific range of area are also changing. Retreat/advance has also been estimated based on glacier extent mapped from IRS data available from 1997 to 2008 and Landsat TM data of 1989-90 time frames(table 2). In order to validate the retreat/advance in the field one



glacier in each basin has been visited and snout position has been noted using GPS receivers. Table 3 gives an account of glaciers showing retreat, advance or showing no change.

Glacier Mass Balance

The mass balance of the glacier is usually referred as the total loss or gain in glacier mass at the end of

Table 2 : Loss/gain in area of glaciers in different basins based on satellite images.

S.N.	Basin	No. of glaciers monitored	Year	Area (km^2)	Year	Area (km^2)	Loss/ Gain %
1.	Chandra	3	1989	107	2002	104	3
2.	Bhaga	10	1990	90	2001	88	2
3.	Warwan	180	2001	513	2007	510	1
4.	Bhut	28	1989	217	2002	203	6
5.	Alaknanda	119	1990	393	2005	355	10
6.	Bhagirathi	153	1989	867	2005	851	1.8
7.	Gauriganga	29	1990	272	2005	261	4
8.	Suru	355	1990	506	2001	459	9
9.	Zanskar	463	2001	775	2006	709	9
10.	Parbati	10	1998	113	2004	107	5
11.	Spiti	722	2001	718	2007	622	13.4
12.	Nubra	84	1989	3159	2001	3163	0*
13.	Tista	34	1990	305	2004	301	1
	TOTAL	**2190**					

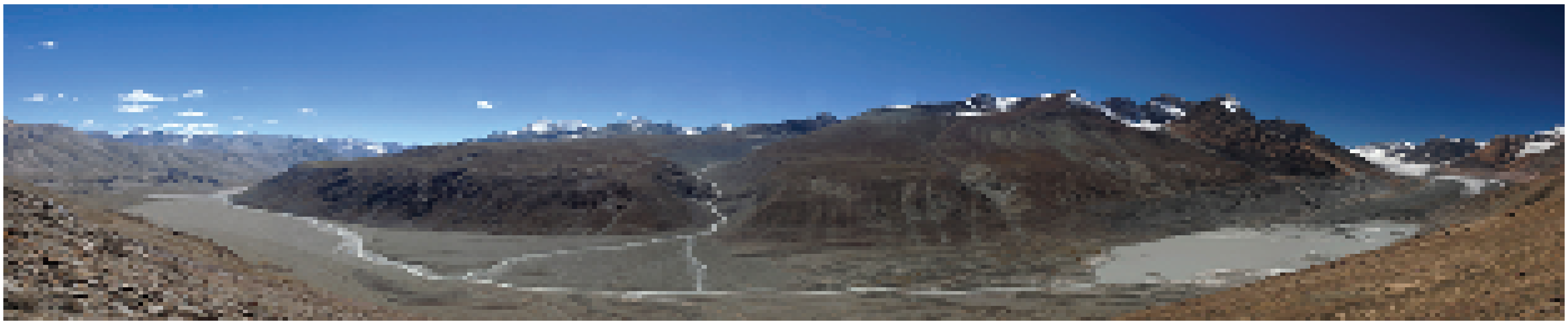
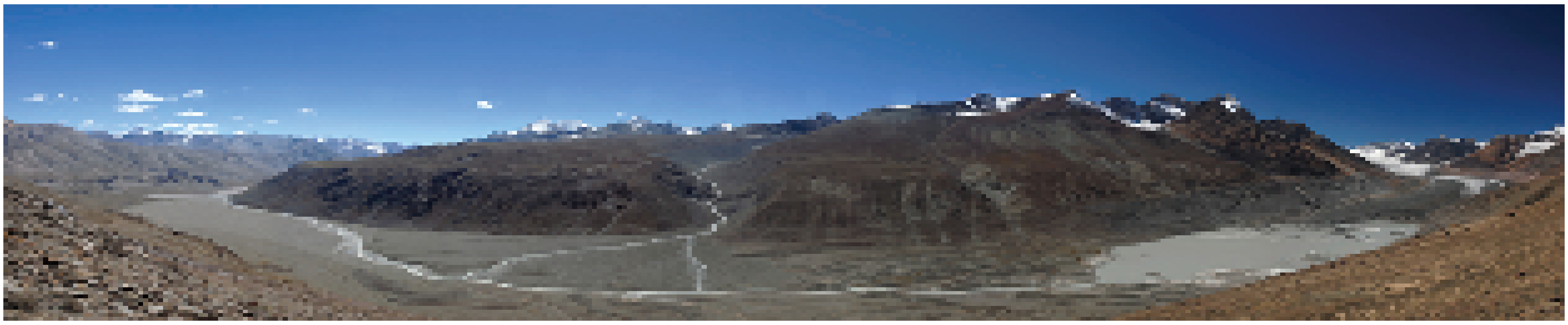


Table 3 : Status of glaciers advance/retreat in different basins based on satellite images.

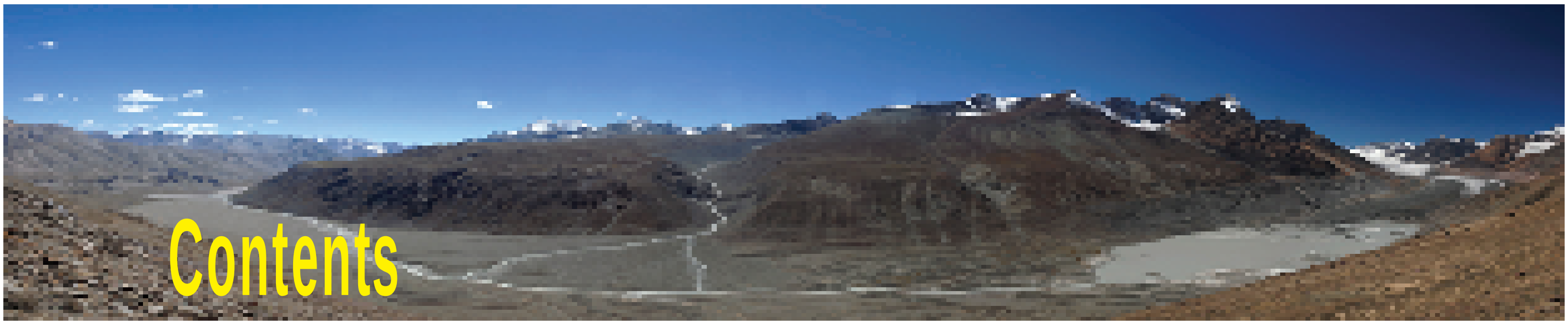
S.N.	Basin	No. of glaciers monitored	Retreat	Advance	No change
1.	Chandra	3	3	-	-
2.	Bhaga	10	10	-	-
3.	Warwan	180	32	-	148
4.	Bhut	28	17	-	11
5.	Alaknanda	119	119	-	-
6.	Bhagirathi	153	44	6	103
7.	Gauriganga	29	20	-	9
8.	Suru	355	299	39	17
9.	Zanskar	463	422	41	-
10.	Parbati	10	10	-	-
11.	Spiti	722	648	39	35
12.	Nubra	84	26	25	33
13.	Tista	34	23	8	3
Total		**2190**	**1673**	**158**	**359**

the hydrological year. It is estimated by measuring the difference in total accumulation of snow and ablation of snow and ice over glacier. The method based on computing Accumulation Area Ratio (AAR) is an alternate method to assess mass balance at reconnaissance level. A relationship between AAR and mass balance has been developed using field mass balance data of Shaune Garang and Gor Garang glaciers. On the basis of accumulation area ratio mass balance in terms of gain or loss can be estimated. This work has been carried out for glaciers of ten basins of Himalayas.



Collaborating agencies

1.	Snow and Avalanche Study Establishment, Chandigarh
2.	GB Pant Institute of Himalayan Environment and Development, Almorah
3.	Jammu University, Jammu
4.	University of Kashmir, Srinagar
5.	Department of Geology, Goverment college Dharamshala
6.	HNB Garhwal University, Srinagar
7.	Department of Science and Technology, Gangtok
8.	Jawaharlal Nehru University, New Delhi
9.	State Remote Sensing Applications Centre, Itanagar
10.	H. P. Remote sensing Cell, Shimla
11.	M. G. Science Institute, Ahmedabad
12.	Indian Institute of Technology-Bombay, Mumbai
13.	Birla Institute of Technology, Ranchi



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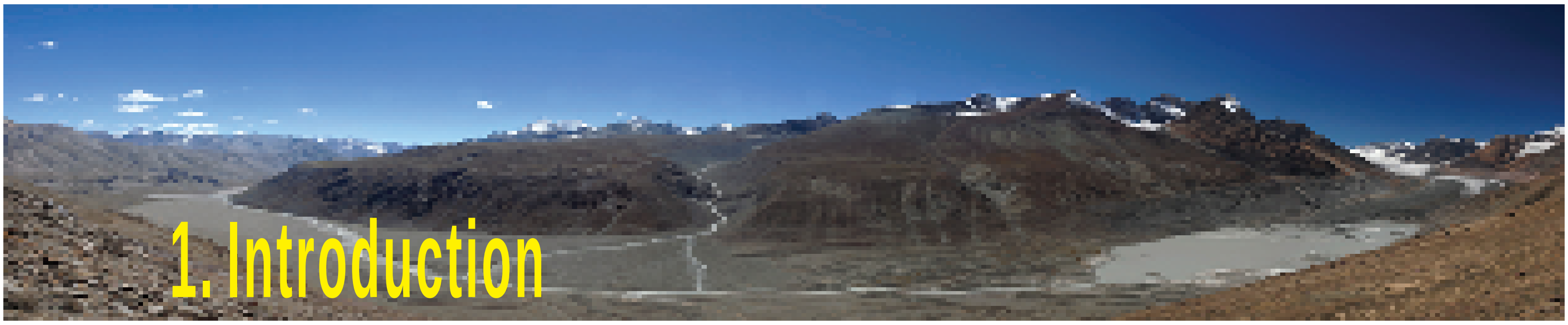


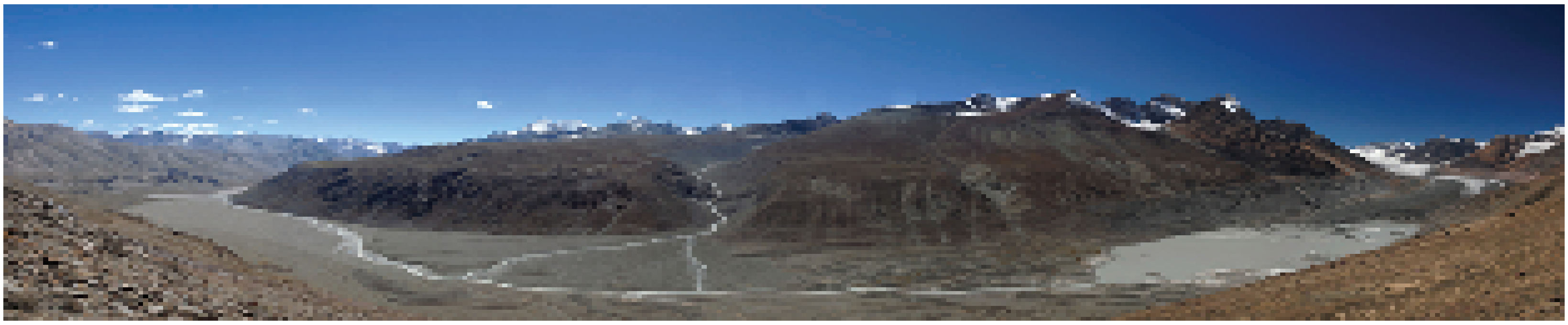
1. Introduction

1.1 Snow

Snow is a type of precipitation in the form of crystalline ice, consisting of a multitude of snowflakes that fall from clouds. Snow is composed of small ice particles. It is a granular material. The density of snow when it is fresh is 30-50 kg/m^3. When it becomes firn the density becomes about 400-830 kg/m^3. Snow becomes glacier ice when density is 830-910 kg/m^3. Snow becomes firn when it survives for minimum one summer and becomes glacier ice in many years(GP1.1). Density increases due to remelting and recrystallization and reduction in air spaces within the ice crystals.

The required atmospheric conditions for snow fall are met at higher latitudes and altitudes of the earth. There are three major classes of snow cover i.e. temporary, seasonal and permanent. Snow covers almost 40 per cent of the Earth's land surface during Northern Hemisphere winter. This makes albedo and areal extent of snow as important component of the Earth's radiation balance. Monitoring accumulation and ablation of seasonal snow cover is an important requirement for various applications. In addition, large areas in the Himalayas are also covered by snow during winter. Area of snow can change significantly during winter and spring. This can affect stream flow for rivers originating in the higher Himalayas. All the rivers originating from higher Himalayas receive almost 30-50 % of annual flow from snow and glacier melt run off. In addition, snow pack ablation is highly sensitive to climatic variation. Increase in atmospheric temperature can influence snowmelt and stream runoff pattern. Therefore, mapping of the areal extent and reflectance of snow are important parameter

Ground Photograph (GP1.1) A view of Panchinala glacier. Snow on accumulation zone and debris on ablation zone. (Bhaga basin)



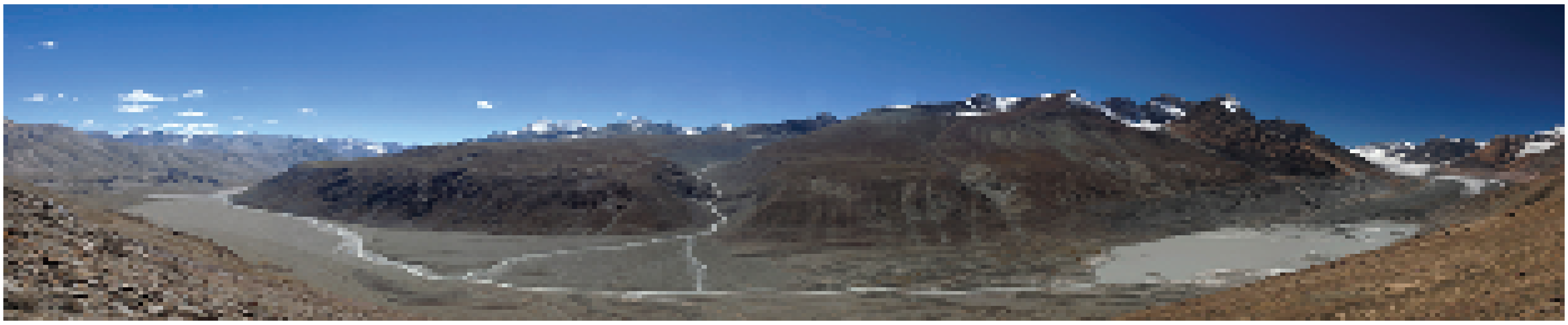
for various climatological and hydrological applications. In addition, extent of snow cover can also be used as input for numerous other applications. It is also needed for strategic application, as arrival of snow can significantly affect mobility of man and machine.

Mapping and monitoring of seasonal snow cover can be best done by remote sensing because a large area is covered, high temporal frequency data are available and snow has distinct signatures in optical remote sensing data which makes it easily identifiable and mappable. Therefore remote sensing can provide faster information on accumulation or ablation of snow cover than any other conventional means. This even becomes much more useful in a terrain like Himalayas where accessibility to remote areas is highly difficult and hazardous.

1.2 Glaciers

Glaciers are formed due to recrystallization and metamorphism of naturally fallen snow on land surface. It is permanent snow cover which gives rise to formation of glaciers. Glaciers are formed on the earth when rate of accumulation of snow is higher than rate of ablation and falling snow gets enough time and space to get metamorphosed to form ice. Nonetheless the glacier ice must move down under the influence of gravity to be called as glacier. The glaciers are mass of snow, ice, and water and rock debris (GP 1.2) slowly moving down a gradient. Out of these ice is an essential component. Presently, ice is distributed either in polar regions of earth or in high mountainous regions. There are two parts of glaciers: accumulation zone and ablation zone separated by snow line. In the accumulation zone the total accumulation from winter snowfall is more than the summer ablation. In ablation zone, total summer melting is more than the winter snow accumulation.

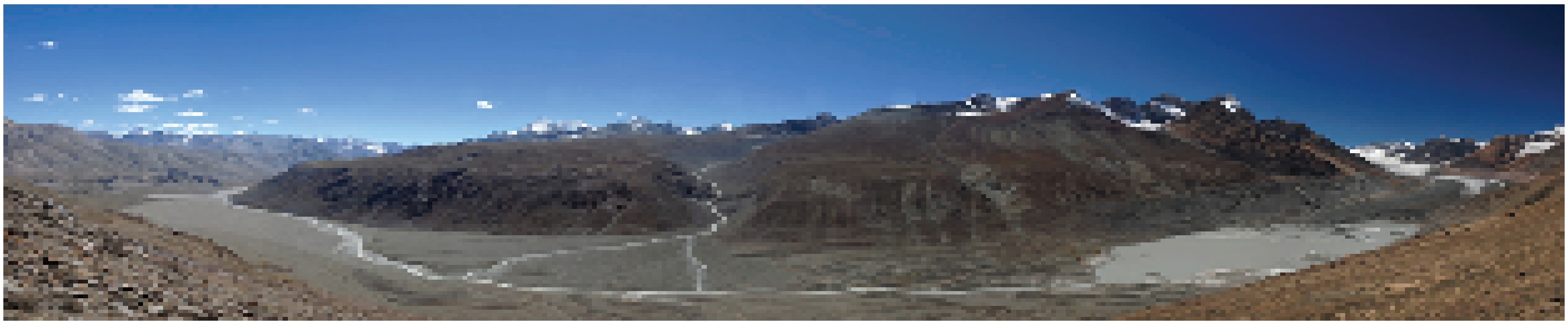
GP1.2 : Debris cover on ablation zone of Samudra Tapu glacier(Chandra basin).



Therefore, glacier ice along with debris gets exposed on the surface during summer. The frontal most part of ablation zone of the glacier from where river or stream appears on the surface is its terminus or snout. To determine the thickness of glacier ice Ground Penetrating Radar(GPR) can be used (GP 1.3).

The distribution of glaciers as what we see today is the result of last glaciation. Glaciation and deglaciation are the alternate cycles of cold and warm climate of earth. During Pleistocene, the earth's surface had experienced repeated glaciations over a large land mass. The most recent glaciations reached its maximum advance about 20,000 years ago due to fall of temperatures by 5º to 8º C. A Little ice age has been also recognized during 1650-1850 AD. During peak of glaciations approximately 47 million km^2 area was covered by glaciers, three times more than the present ice cover of the earth. Based upon morphological characteristics of glaciers, the glaciers can be grouped into classes such as ice sheet, ice cap, and glacier constrained by topography. Ice sheet and ice cap are formed when underlying topography is fully submerged by ice and glacier flow is not influenced by topography. On the other hand, when glaciers are constrained by the surrounding topography and the shape of valley influences their flow, then such glaciers are classified as valley glaciers, cirque glaciers and ice fields. Mountain glaciers as in Himalayas, Alps, Andes are basically constrained by topography and are predominantly of valley type. In Himalayas glaciers are distributed from West in Kashmir to East in Arunachal Pradesh, covering parts of Himachal Pradesh, Uttarakhand, Nepal Sikkim and Bhutan. The distribution and intensity of glaciation is governed by latitude and altitude of the mountains. The map showing glacier boundaries in Himalayan mountains are available with Survey of India for 1962.

GP1.3 : GPR reading on Chota Shigri to measure ice glacier thickness.



Glaciers are very vital to human kind as these natural resources are (i) reservoirs of freshwater (ii) control global climate as the albedo over snow and glaciers is very high, (iii) sensitive indicators of climatic variations. Since glaciers of Himalaya constitutes the largest concentration of freshwater reserve outside the polar region, a great significance is attached to the fact that these natural resources are the source of fresh water to almost all minor and major rivers of northern India and sustain the civilization for irrigation, hydroelectricity and drinking water. Concentration of glaciers in Himalaya varies from northwest to northeast according to the variation in altitude and latitude of the region. Siachin glacier in Kashmir, Gangotri glacier in Uttarakhand, Bara Shigri glacier in Himachal, Baltoro glacier in Karakoram and Zemu glacier in Sikkim are a few famous glaciers of Himalayas. The retreat or advance of glaciers of individual glaciers depends upon the variations in mass balance. The retreat depends upon static and dynamic factors. The static parameters are latitude, slope, orientation, width and size of the valley and altitude distribution of glaciers. The dynamic parameters are annual accumulation and ablation of snow and ice. These factors further depend upon daily and yearly variations in temperature, solid/liquid precipitation, heat flow from earth crust, debris cover and cloud cover.

Moraine cover, consists of dust, silts sands, gravel, cobbles and boulders. It is one of the most important components of a glacier system in view of the control it exercises on rate of glacier melting. Its areal cover and thickness should be known in order to estimate effect of climate on retreat of glaciers. An example of debris free ablation zone is shown in GP 1.4.

GP1.4 : Ablation zone of Chota Shigri glacier.

2. Remote Sensing in Snow and Glacier Studies

2.1 Snow

Mapping and monitoring of seasonal snow cover can be best done by remote sensing because snow has distinct signatures in optical remote sensing data which makes it easily identifiable and mappable on satellite images (figure 2.1). Satellite data views a large area and multi temporal data helps in monitoring the changes in snow cover. Therefore remote sensing can provide faster information on accumulation or ablation of snow cover than any other conventional means. This even becomes much more useful in a terrain like Himalayas where accessibility to remote areas is highly difficult and hazardous.

The potential of remote sensing for Snow cover monitoring using satellite images was first demonstrated by using the TIROS-1 satellite in April 1960. Since then, the potential for operational satellite-based mapping has been enhanced by the development of higher temporal frequency and satellite sensors with higher spatial resolution. In addition, satellites with better radiometric resolutions, such as NOAA have been used successfully for snow mapping.

India has launched series of Indian Remote Sensing Satellite (IRS) to study the different earth resources. The satellites carried many sensors with different spectral temperal and spectral resolutions. WiFS (Wide Field Sensor) data have been extensively used for assessing snow pack accumulation and ablation pattern in the parts of Himalayas. RESOURCESAT-1 satellite has three different sensors namely LISS III, LISS IV & AWiFS with different spatial, temporal and spectral resolutions as desired for different applications. AWiFS (Advanced Wide Field Sensor) is an advanced version of earlier Indian satellite sensor WiFS with improved spectral and spatial resolutions maintaining the same repetivity. There are a series of other polar

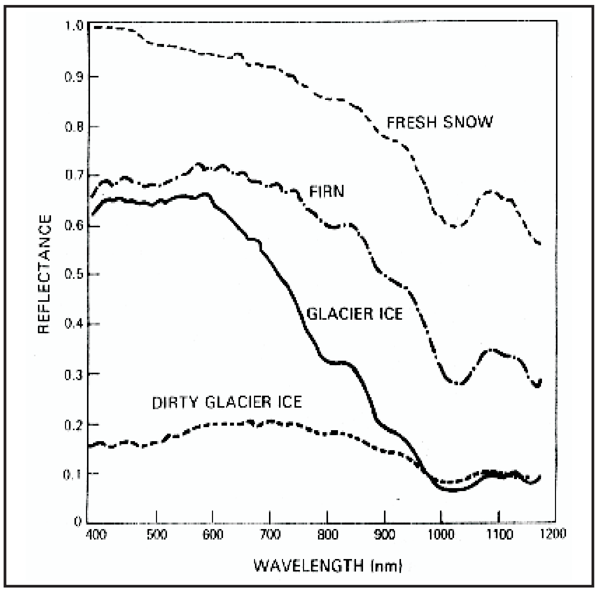
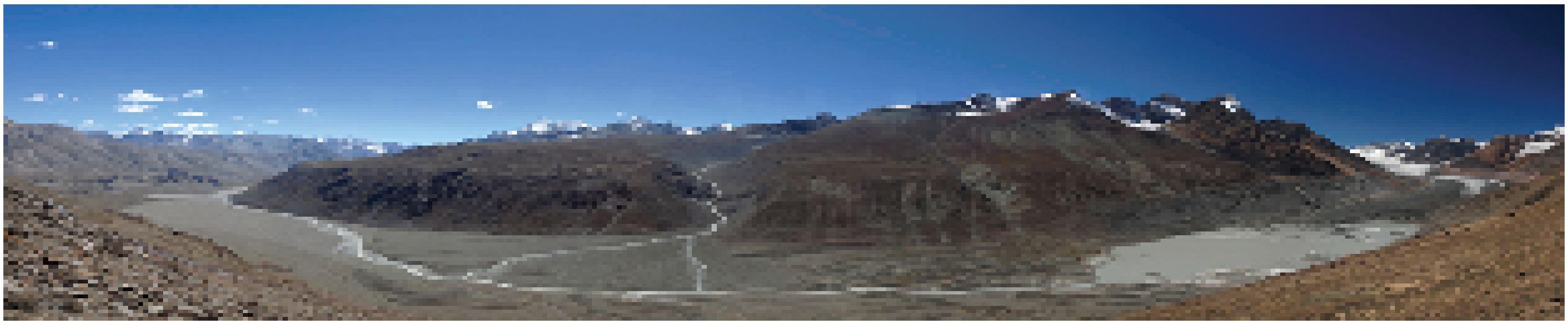


Figure 2.1 : Spectral reflectance characteristics of snow firn & ice.



orbiting satellites, like Landsat, NOAA and MODIS etc., which have provided information on different aspects of snow.

2.2 Glaciers

False Color Composites (FCCs) prepared from three bands in visible and near infrared region have been used successfully to map glacier boundary, snow/equilibrium line, accumulation and ablation zone(figure 2.2). These areas are possible to be mapped on satellite images due to significant difference in spectral reflectance between glacier and non-glacier areas. One of the earliest studies was carried out by using Landsat multi-spectral scanner (MSS) imagery, where extents of glaciers were mapped. Field and satellite obtained values suggest that spectral reflectance of accumulation area are high in bands 2, 3 and 4 in Landsat TM and IRS LISS-II images. On the other hand, in ablation areas, reflectance in band 2 and 3 are higher than surrounding terrain but are lower than vegetation in band 4; therefore this gives blue-green tone on FCCs. These spectral characteristics are useful to differentiate between glacial and non-glacial features as following:

Glacier Boundary

Differentiation between glacial and non-glacial areas is easily possible on the FCC, except where glaciers are covered by debris. Sometime during August-September season, grass appears on the lateral and terminal moraine. This gives a red tone on the FCC around glacier snout and makes it easy to delineate lower boundary of glacier. In upper part of ablation area, glacier edges are characterized by dirty snow, which gets accumulated due to avalanches from adjoining cliffs. This gives a distinctly higher reflectance along the edges.

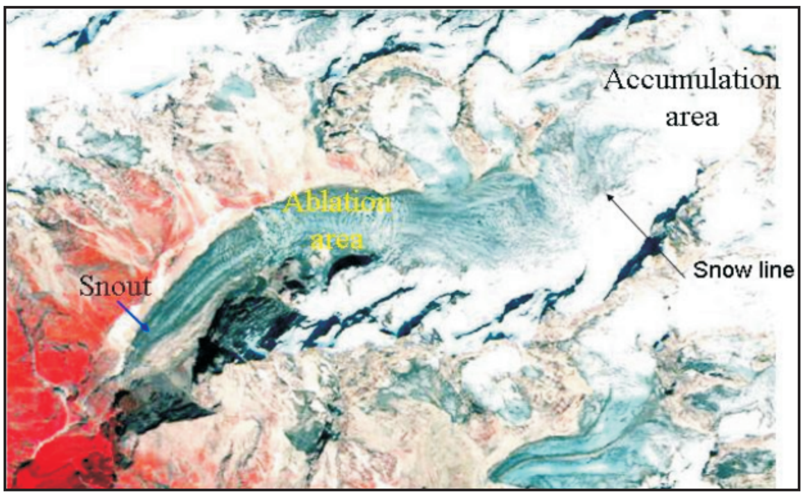
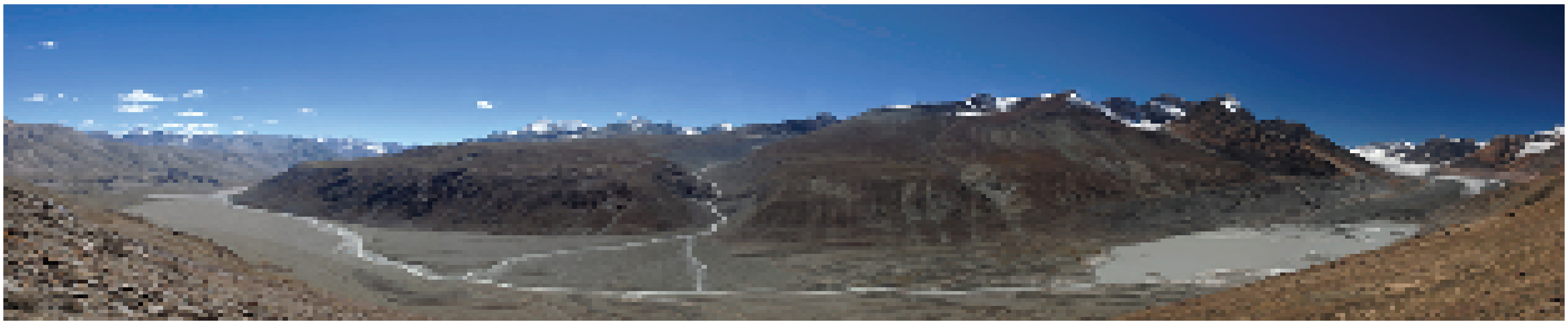


Figure 2.2 : Various features of a glacier seen on IRS LISS IV image.



Ice-divide

Ice movement in two different directions characterizes a line of division between two adjacent glaciers, the ice-divide. Normally, ice-divide cannot be easily demarcated by using satellite images. In the Himalayas, ice-divide is normally associated with mountain cliffs and hence could be easily delineated using cliff shadow. The amount of cliff shadow depends upon solar elevation and azimuth. In addition, cliff direction is also important, maximum shadow can be observed when cliff is perpendicular to the azimuth of the sun.

Accumulation Area

In this region total accumulation from winter snowfall is more than summer ablation; therefore, it is characterized by snow and gives higher reflectance. Spectral reflectance is higher in all three bands. Hence, it appears white on the FCC and can be easily demarcated.

Ablation Area

In ablation area, total summer melting is more than winter snow accumulation. Therefore, glacier ice along with debris gets exposed on the surface. Glacier ice has substantially lower reflectance than snow, but higher than rocks and soil of the surrounding area. Therefore, it

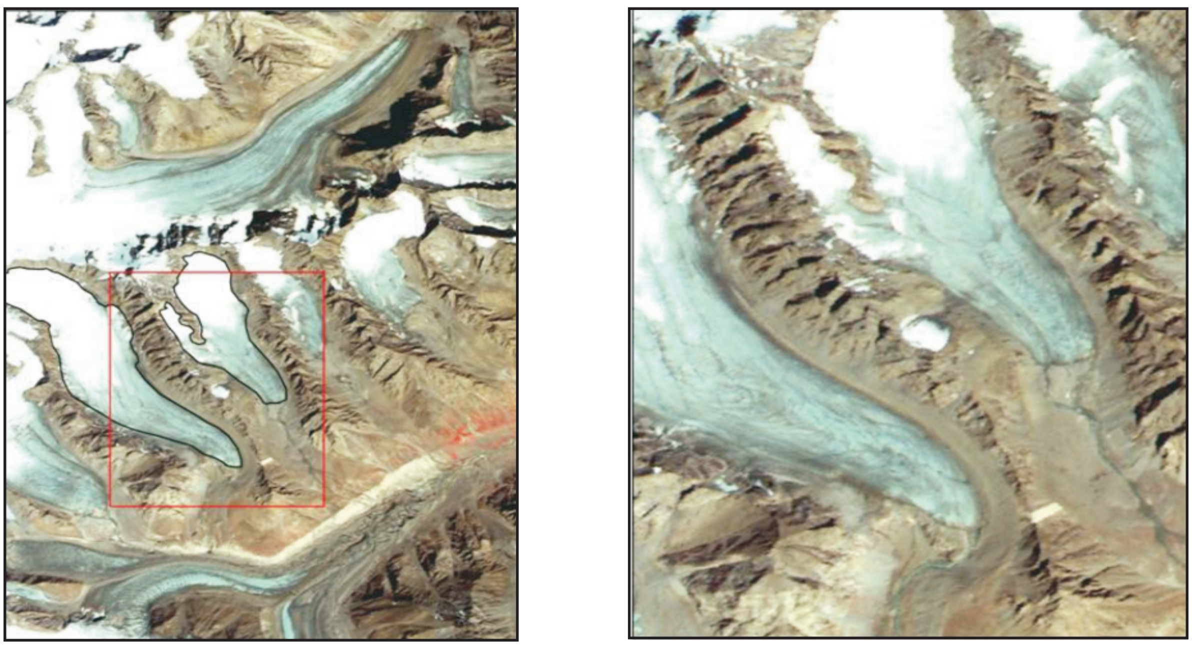
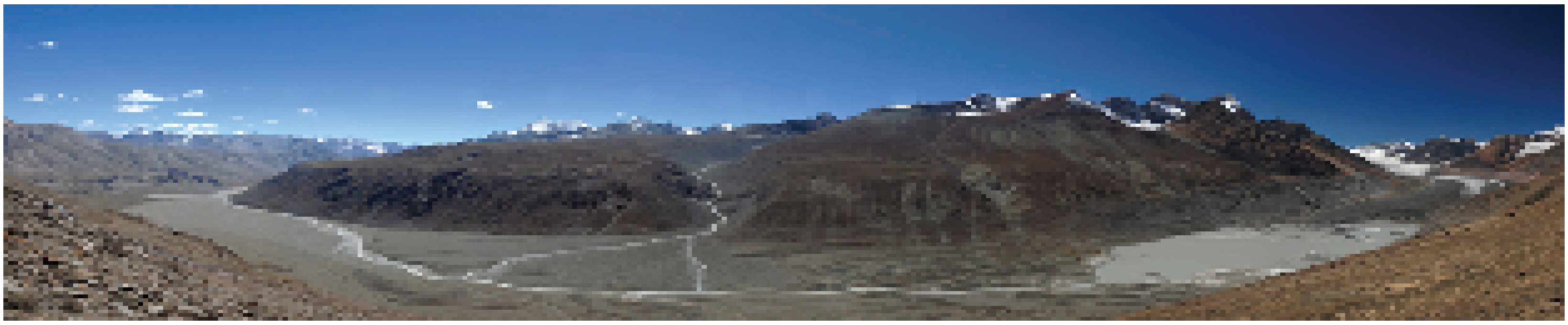


Figure 2.3 : Identification of snout of debris free.



gives green-white tone on FCC and can easily be differentiated from the accumulation area and surrounding rock and soil. The lowest part of ablation area is called terminus or snout. It is identified easily on glaciers with ice exposed(figure 2.3), whereas on debris covered glaciers, origin of stream is taken as clue to identify snout (Figure 2.4, 2.5 & 2.6).

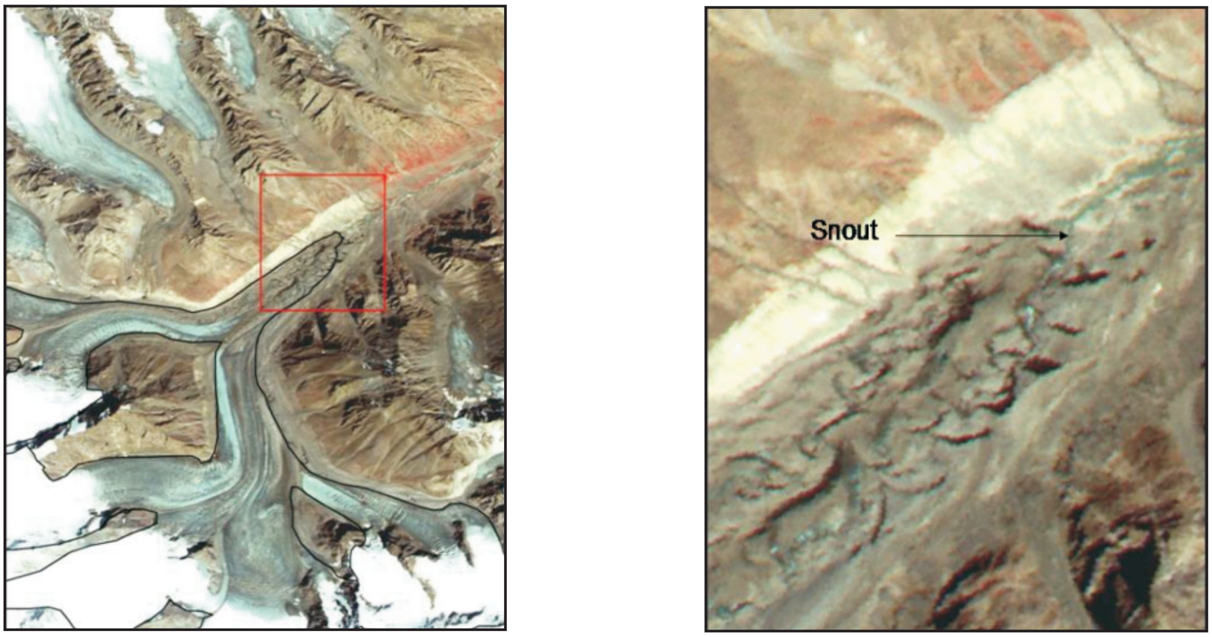


Figure 2.4: Identification snout of a debris covered glacier based on origin of stream

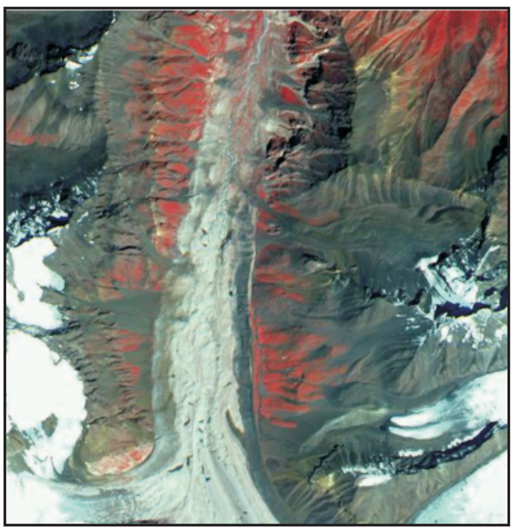


Figure 2.5: Snout of Jorya Garang glacier (Basapa basin) seen on IRS LISS IV image.

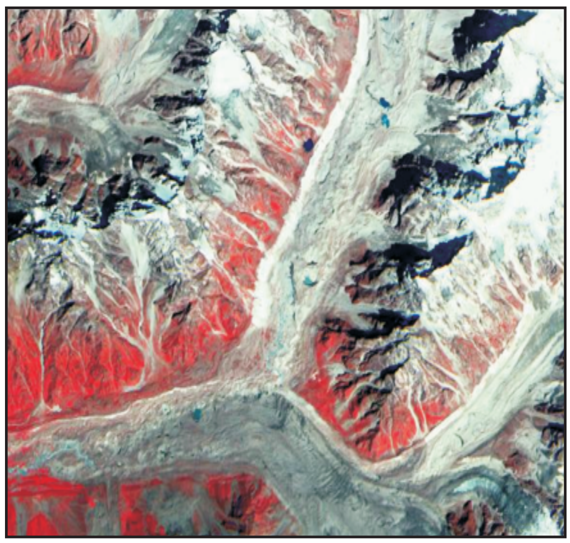


Figure 2.6: Snout of Jamdhar glacier on IRS LISS IV image(Tons basin)

3. Snow Cover Monitoring

3.1 Approach

AWiFS sensor of RESOURCESAT-1 satellite has been used to monitor seasonal snow cover. AWiFS data covers an areal extent of 5,47,600 km^2 at an interval of 5-days. Approximately 1500 AWiFS scenes from October to June of years 2004-05, 2005-06 and 2006-07, 2007-08 have been analyzed in this investigation. Snow cover monitoring is not carried out after month of June due to cloud cover in Monsoon season. The mapping is being done in the Western, Central and Eastern Himalaya basins including Ganga, Satluj, Chenab Indus, Tista and Bramhputra. These basins are subdivided into 33 sub-basins(table 3.1). The basins in Western Himalaya are shown in figure 3.1.

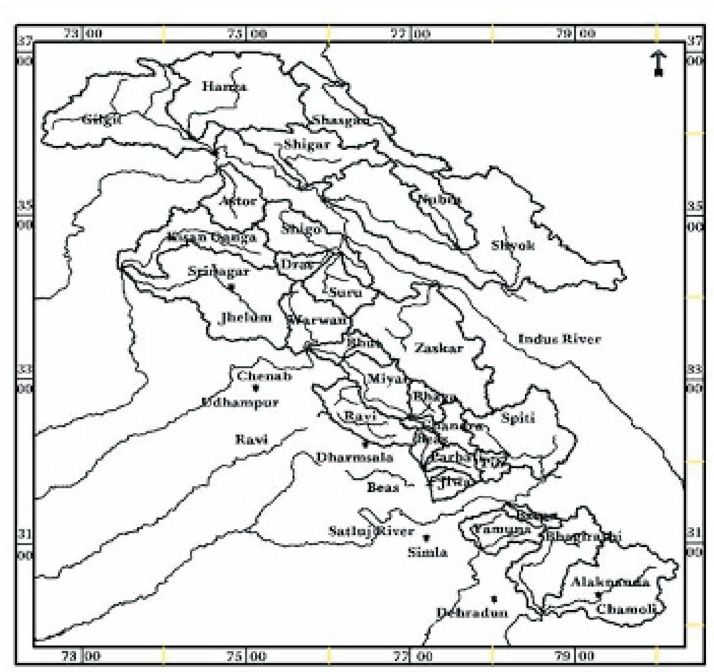


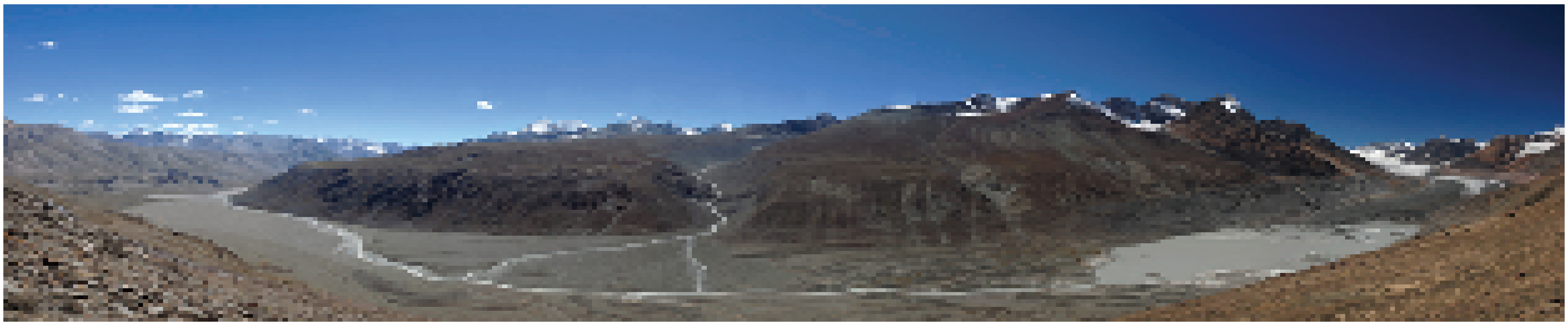
Figure 3.1: Location map of sub-basins in the Western Himalayas taken up snow cover monitoring.

Initially master template is generated using control points from 1:250,000 scale maps and then basin boundaries are delineated using drainage map. The master template is used for registration of all satellite data.

An algorithm based on Normalized Difference Snow Index (NDSI) is used to map snow cover (figure 3.2). NDSI is calculated using the ratio of green (band 2) and SWIR (band 5) channel of AWiFS sensor. NDSI is established using the following method.

$$\textit{Normalized Difference Snow Index (NDSI)} = (\text{band } 2 - \text{band } 5) / (\text{band } 2 + \text{band } 5)$$

To estimate NDSI, DN numbers are converted into top-of-atmosphere (TOA) reflectance. This involves conversion of digital numbers into the radiance values, known as sensor calibration, and then reflectance is estimated. Various parameters needed for estimating

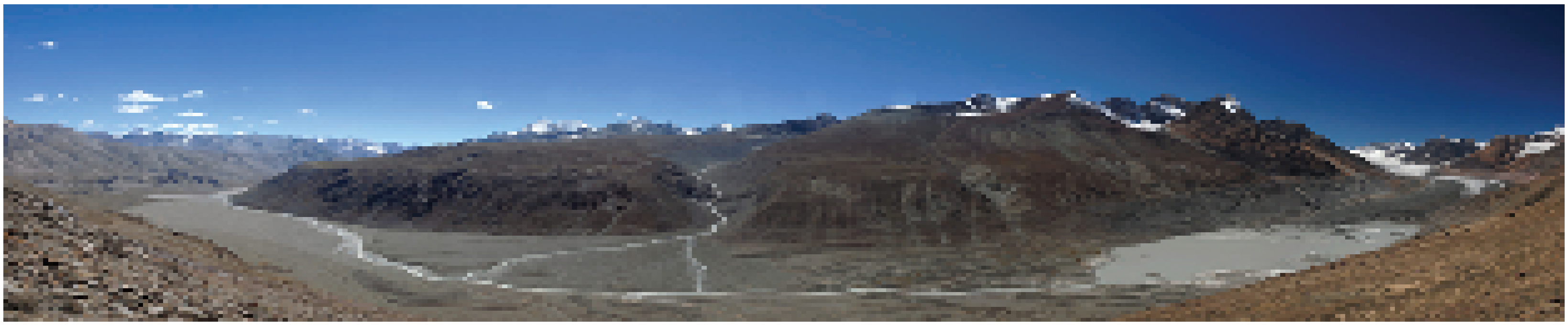


spectral reflectance are maximum and minimum radiances and mean solar exo-atmospheric spectral irradiances in the satellite sensor bands, satellite data acquisition time, solar declination, solar zenith and solar azimuth angles, mean Earth-Sun distance etc. Sensitivity analysis has shown that a NDSI value of 0.4 can be taken as a threshold to differentiate snow/non-snow pixels. Exo-atmospheric reflectance of band 2 and band 5 of AWiFS sensor are used to compute the NDSI. Field investigations have suggested that NDSI values are independent of illumination conditions i.e. snow/non-snow pixels can be identified under different slopes and orientations, even under mountain shadow region.

Validation of snow cover mapping algorithm has been carried out in Beas basin. Three locations were selected in Beas basin and respective GPS locations were taken. Total 69 AWiFS scenes were processed from December, 2004 to October 2005. Each pixel was classified as completely snow covered or snow free. Out of 207 points, 73 points were excluded due to presence of ice cloud which gives similar signature of snow and removed from final validation exercise. The 132 of 134 points were correctly classified as snow/non-snow pixels.

In second method, a geographical area around Beas basin was selected. AWiFS data of September 01, 2005 was used to classify region in 3 classes as snow/ice, barren land/soil and vegetation, when most of the area was snow free. ISODATA technique was used for classification. Then to estimate accuracy of snow products, satellite imagery of February 26, 2006 was selected, when region was completely snow covered. This assessment was made based on field observations on snow fall. The snow product suggests an error less than 1% for all three classes.

However, this error will significantly increase, if region is covered by ice clouds. Many times ice clouds have similar signature as snow and can be misclassified. This can significantly add error into final results. For example, in Parbati river basin in Himachal Pradesh in 2004-05 year out of 58 scenes in 18 scenes clouds were misclassified as snow. Present algorithm, due to lack of thermal band in AWiFS, has little potential to correct this problem. Therefore, satellite



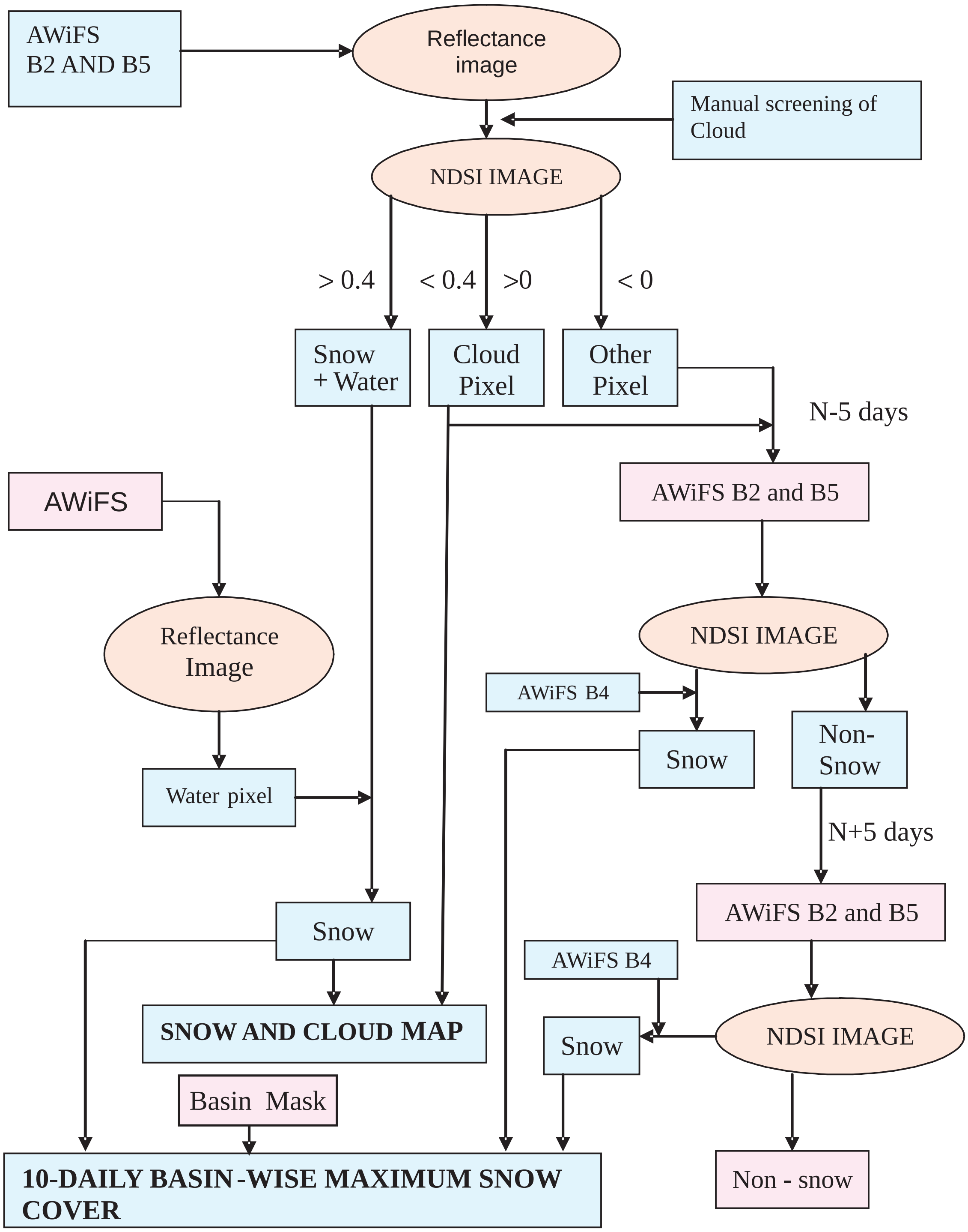
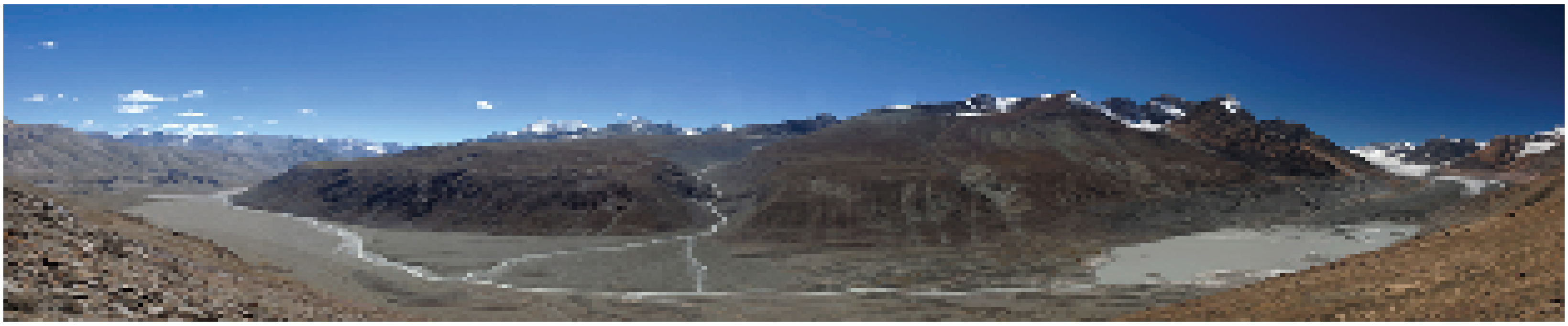


Figure 3.2 : Algorithm for snow cover mapping using AWiFS data.



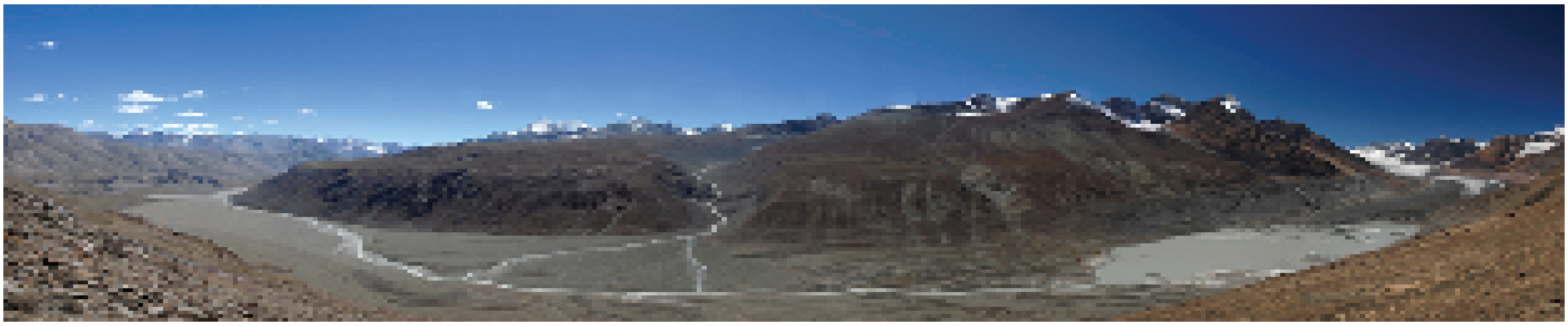
data was checked manually after geocoding and scenes were rejected if ice clouds were observed in the basin area. Manual separation between snow and ice cloud is possible due to textural differences.

3.2 Snow cover products

Snow extent is estimated at an interval of 5-days and 10-days, depending upon availabilities of AWiFS data. Cloud over snow covered region is a critical issue and it can introduce significant errors. In 10-daily product, three scenes are analyzed, if available. For example, for 10 March product data of 5, 10 and 15 March are used. If any pixel is identified as snow on any one date then it is classified as snow on final product. If three consecutive scenes are not

Table 3.1 : Major river basins and sub-basins

Basin	Sub-basin	Area (sq km)	Sub-basin	Area (km^2)	Sub-basin (km^2)	Area
Ganga	Alaknanda	11090	Bhagirathi	7438	Yamuna	3527
Satluj	Spiti	8871	Pin	1667	Jiwa	1445
	Beas	1132	Baspa	1096	Parbati	1773
Chenab	Ravi	4907	Chandra	2433	Bhaga	1680
	Miyar	4449	Bhut	2218	Warwan	4670
Indus	Jhelum,	14472	Kishanganga	7451	Astor	4008
	Suru	3575	Dras	1683	Shigo	5539
	Zaskar	14914	Nubra	4258	Shyok	27120
	Hanza	13711	Gilgit	13615	Shasgan	7613
	Shigar	7050				
Brahmputra Tista	Dibang	9158	Subansiri	25345	Tawang	6721
	Tista	5466	Rangit	1630		



available, then all available scenes in 10 days window are used in the analysis. This is used to generate basin-wise 10 daily product information (figure 8) and is expected to have at least one scene under cloud free condition for each pixel. In the present algorithm, water bodies are marked in pre-winter season and masked in the final products during winter, as separation of snow and water is difficult using reflectance, due to mountain shadow.

SRTM data are used to generate contours at an interval of 500 and 1000 m and then area within each contour is estimated using GIS software. The area-altitude information is

Table 3. 2 : Mean monthly snow line altitude for Western Himalaya (28 sub-basins)

Month	Snow areal extent (km^2)			Snow line altitude			Mean snow line altitude (m)
	2004-05	2005-06	2006-07	2004-05	2005-06	2006-07	
October	91595	63597	57161	4198	4726	5006	4578
November	80425	67973	79641	4383	4625	4439	4474
December	103070	82083	127119	4008	4355	3539	3998
January	146713	131309	117477	2903	3414	3757	3412
February	154619	141708	125474	2563	3098	3579	3138
March	145895	139531	140099	2930	3176	3152	3096
April	137761	133094	107061	3166	3350	3935	3532
May	104990	92607	68156	3983	4183	4624	4246
June	88293	68902	58409	4266	4616	4859	4551

generated for all 33 sub-basins in the Western and Central Himalayas and then mosaic is prepared to estimate area altitude distribution for the study area. The combination of area altitude distribution and snow map are used to estimate distribution of snow cover in each altitude zone for the individual basin. Area altitude distribution is also used to develop Hypsographic curve. This curve gives areal extent of the study area below any given altitude. Hypsographic curve and snow free area of the Western and Central Himalayas in each month is used to estimate monthly elevation of snow line.

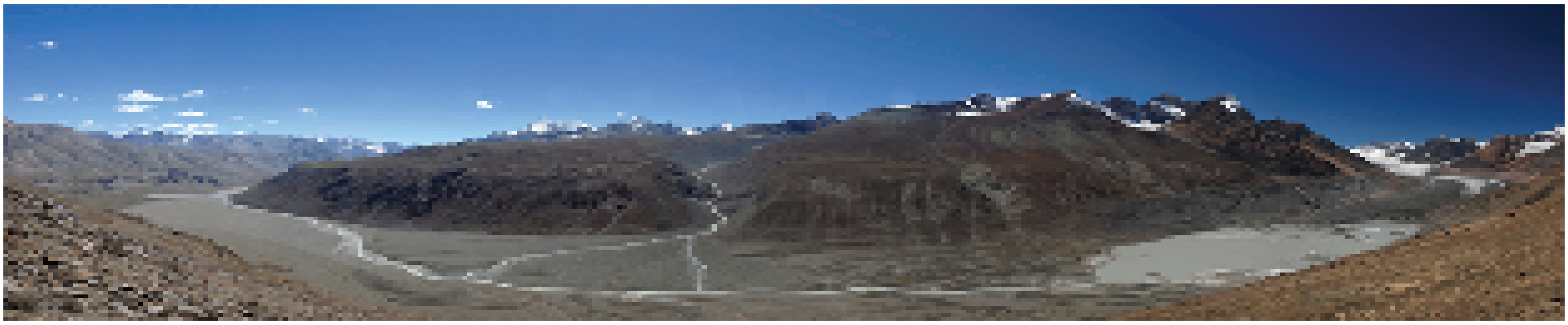
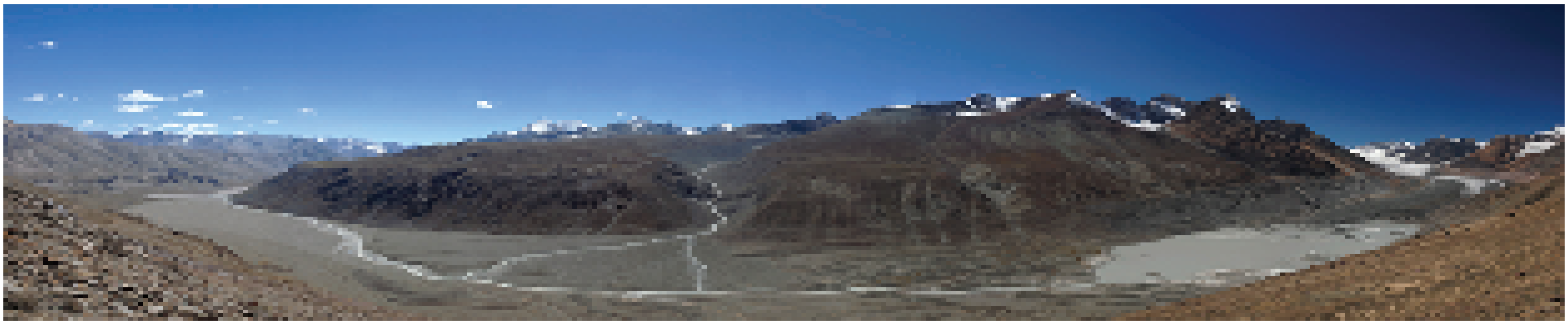


Figure 3.3 shows one of the products generated for Alaknanda basin. Snow accumulation and depletion curve for this basin is shown in figure 3.4. Figure 3.5 shows snow cover product and figure 3.6 shows the accumulation and ablation curves for Zanskar basin. Snow cover of different basins is combined to estimate snow cover of Central and Western Himalaya (table 3.2). In the winter of 2004 and 2005, for a period between October and mid-December, snow cover was less than 50 percent and increased to 82 percent by the end of January. Snow extent remained more than 80 percent till beginning of April and retreat of snow cover continued till the end of June. By the end of June snow cover was only 37 percent. The similar trends were observed for years 2005-06 and 2006-07.

Area altitude distribution can also influence snow accumulation and ablation. In the study area, maximum geographical area is located between 4000 and 5000 m altitude and a small area beyond altitude 6000 m. Hypsographic curve in combination with 10-daily snow cover product was used to estimate lowest snow line altitude at an interval of 10 days for 3 years between October and June. Lowest altitude of snow line in winter of 2004-05 was observed at 2482 m on February 25, 2005. Snow line altitude has remained below 3000 m for a period between January 5, 2005 and April 15, 2005. The highest altitude of snow line was estimated at 4617 m by June end. Three 10-daily snow cover products were used to estimate mean monthly snow cover. Mean monthly snow cover and hypsographic curve were used to estimate mean monthly snow line altitude. The lowest mean monthly snow line was lower in year 2004-05 as compared to other two years. This is due to higher snow fall for the same year. The lowest and highest mean monthly snow lines of 3 years were observed for the month of February and October, respectively.

The snow accumulation and ablations curves are different for each basin, depending upon climatologically sensitive zones and altitude distribution of the basin. The Himalayan region is classified into three regions namely Lower, Middle and Upper Himalayan Zones with normal snow fall between 1990 and 2004 varies as 1178, 537 and 511 cm, respectively. For comparative analysis Ravi and Bhaga basins are selected, as located in south and north of Pir-Panjal Range, respectively. Ravi basin is located in lower altitude zones. For example, at



AWIFS Image of Alkananda Basin

10 Daily Snow cover maps of Alkananda Basin

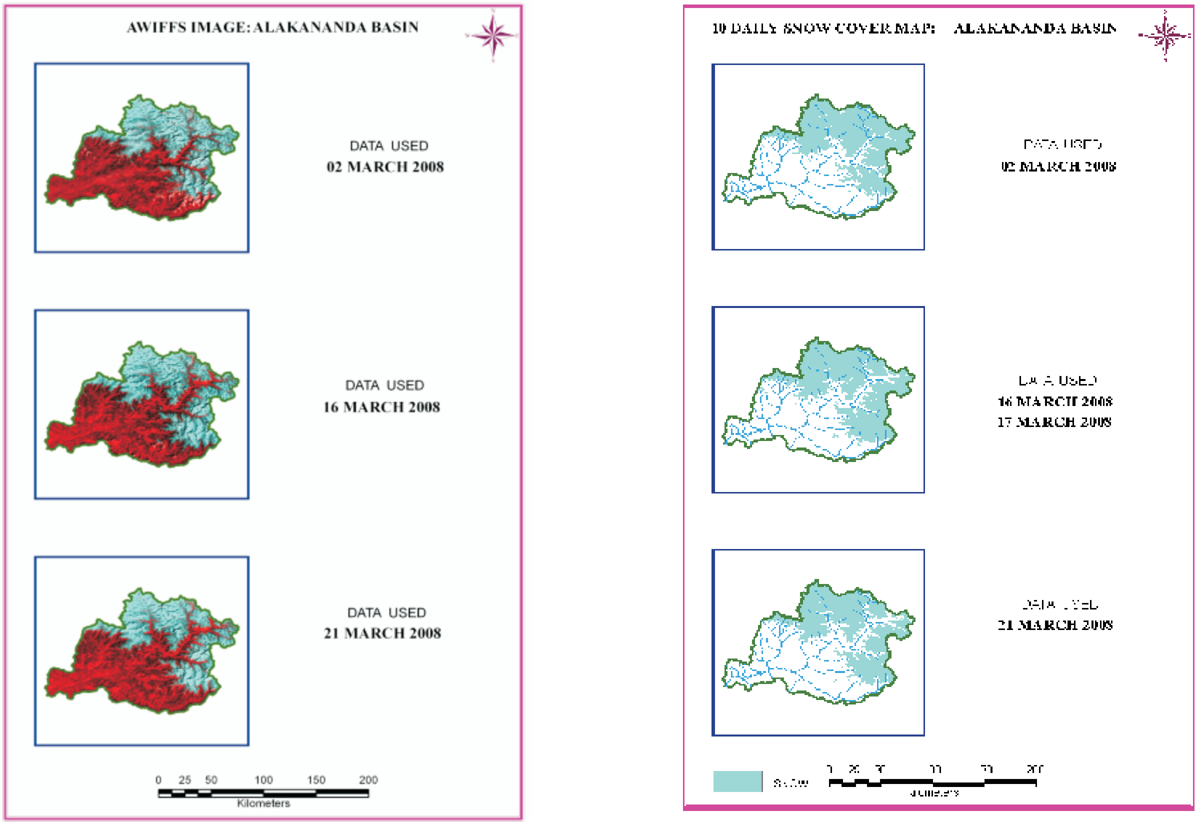


Figure 3.3 : Snow cover products of Alaknanda basin.

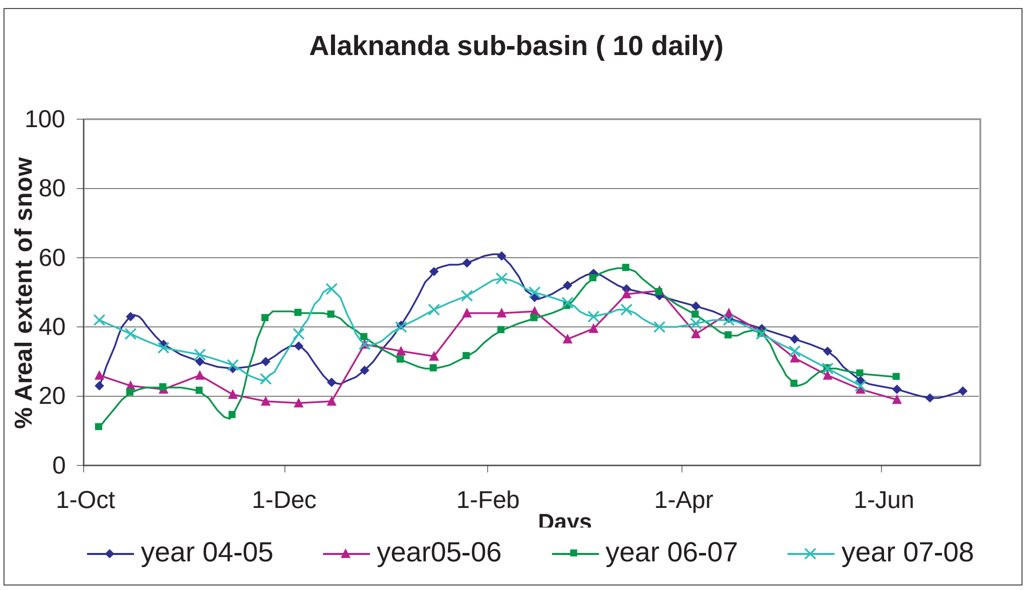
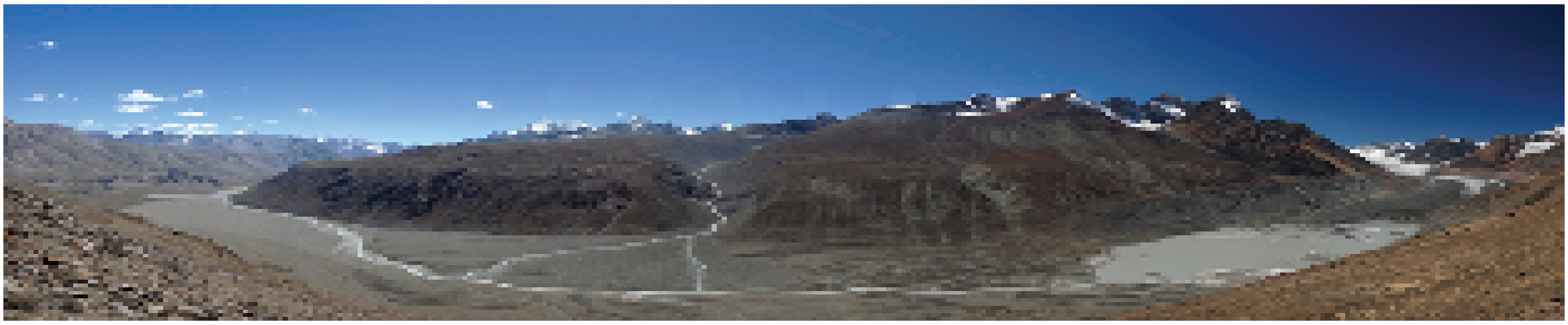


Figure 3.4 : Snow cover accumulation and ablation curves for Alaknanda basin



AWIFS Image of Zaskar Basin

10 Daily Snow cover maps of Zaskar Basin

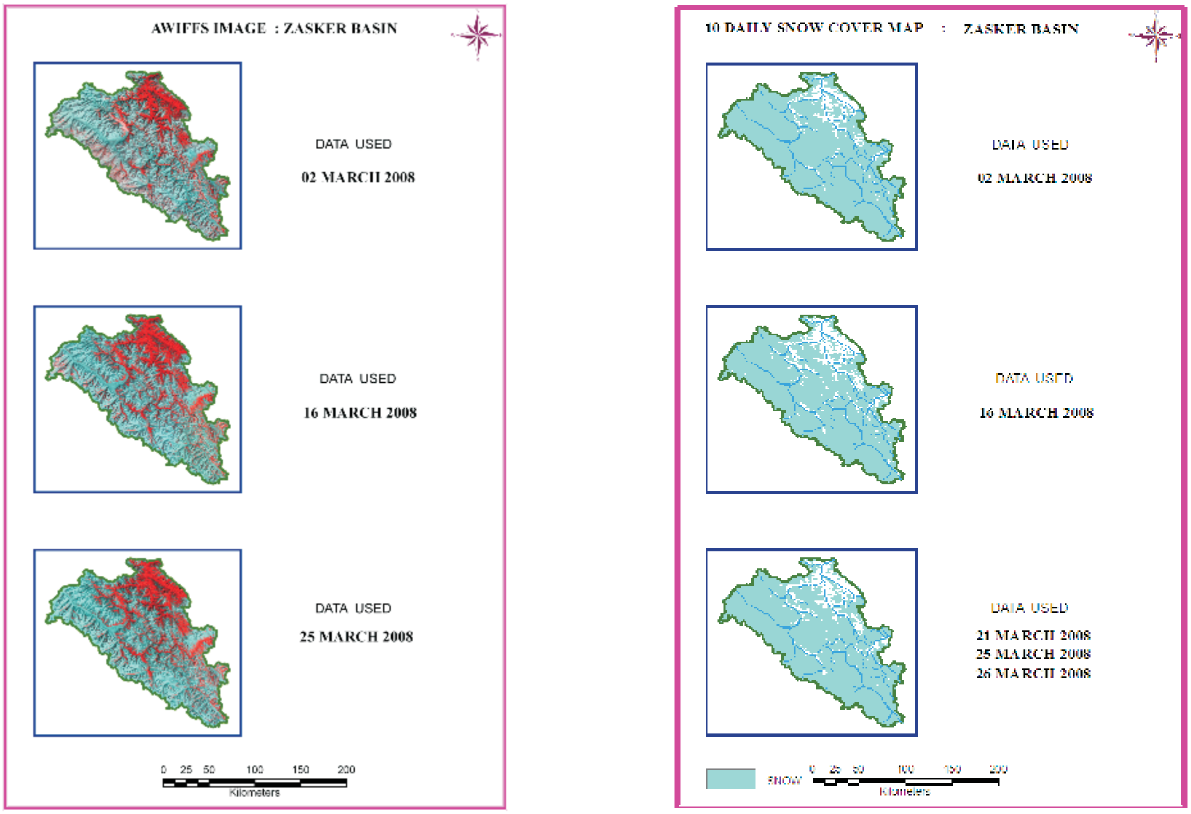


Figure 3.5 : Daily Snow cover maps of Zasker Basin

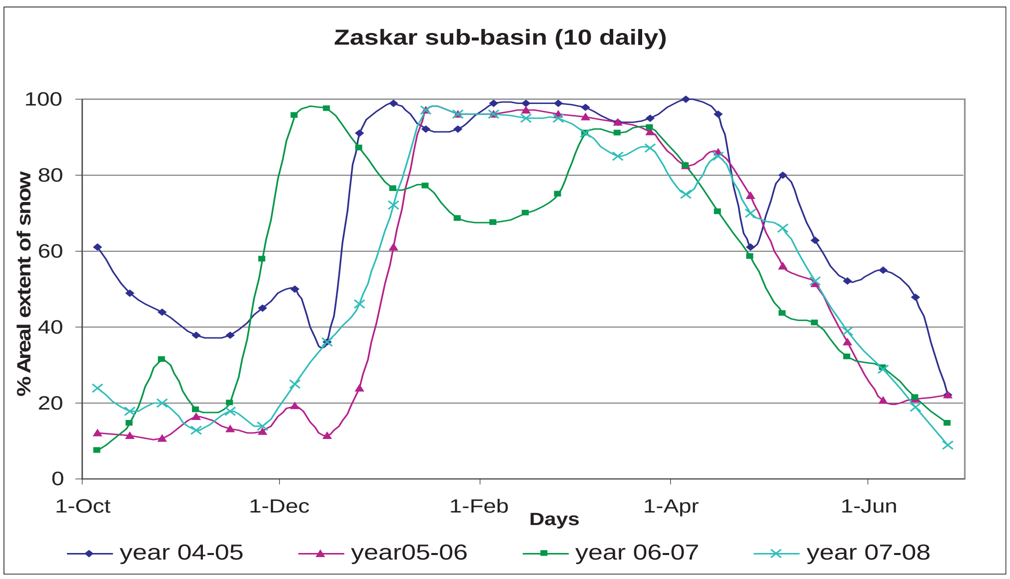
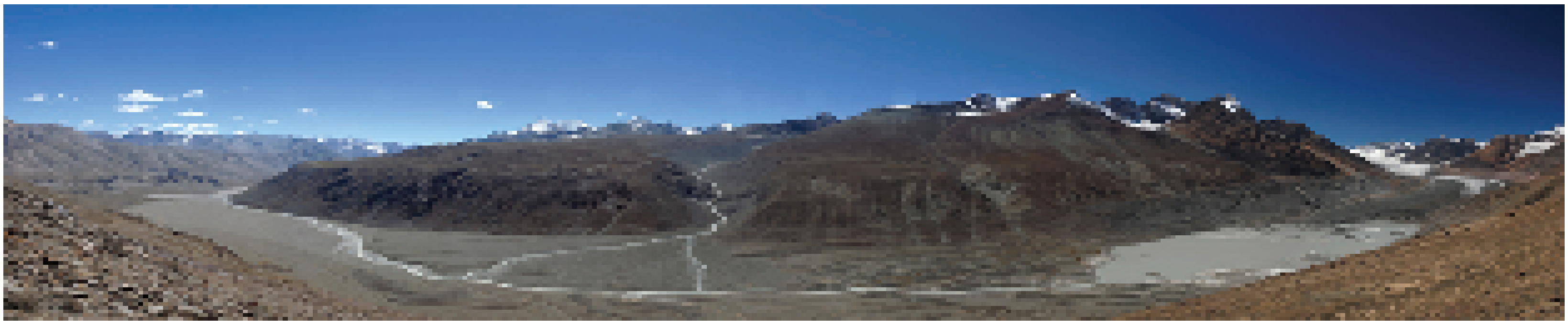


Figure 3.6 : Snow cover accumulation and ablation curves for Zaskar basin.



altitude below 4000 m, 90 percent of Ravi basin and only 20 percent of Bhaga basin area is located. Altitude range of the Ravi and Bhaga basins are between 630 and 5860 m, 2860 - 6352 m, respectively.

In Ravi basin(figure 3.7), snow accumulation and ablation are continuous process throughout winter. Even in middle of winter melting of large snow area was observed. In January 2005, snow area was observed to be reduced from 90 percent to 55 percent. Similar trends were observed for year 2005-06 and 2007-08. This is significant reduction in snow extent in winter season. In summer, snow ablation was fast and almost 50 percent snow cover was melted in a period of one month and by June end almost 80 percent of the snow cover was melted.

In the Bhaga basin, snow melting was observed in early part of winter i.e. in the month of December. Snow pack was stable from middle of January to end of April. This observation is consistent with earlier observations made in Baspa basin. Baspa is also a high altitude basin and also located in Northern side of the Pir-Panjal range. In this basin, significant melting of snow was observed in December, influencing stream runoff[3]. These observations suggest that river basins are responding to climate change depending upon its geographical locations and altitude distribution.

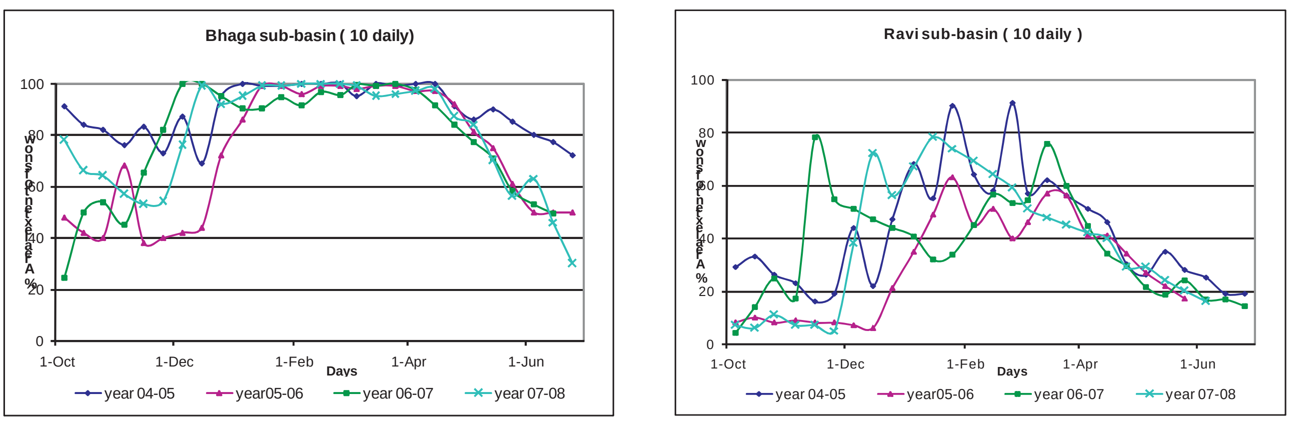
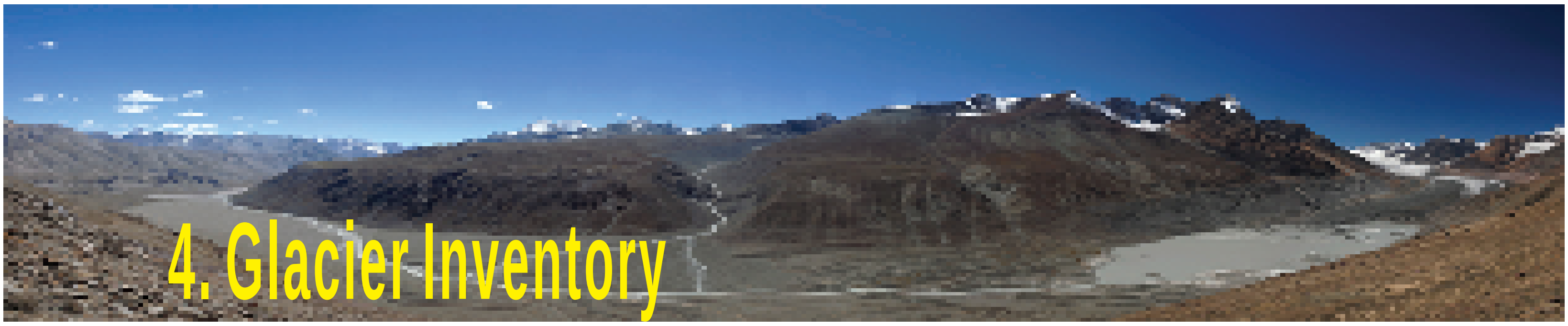


Figure 3.7 : Snow cover accumulation and ablation curves for Bhaga and Ravi basins.



4. Glacier Inventory

4.1 Introduction

Systematic inventory of glaciers is required for a variety of applications such as a) planning and operation of mini and micro hydroelectric power stations, b) disaster warning and c) estimation of irrigation potential, etc. needed for the overall development of the Himalayan region. But glaciological studies in high altitude terrains and under inclement weather conditions as in higher Himalayas become difficult by conventional means. Thus remote sensing techniques play much greater role in mapping and monitoring of permanent snowfields and glaciers. Therefore, use of satellite data is finding wide acceptance in glacial inventory. Inventory data is generated for individual glaciers in a well-defined format as suggested by United Nations Temporary Technical Secretariat (UNESCO/TTS) and later modified with few additional parameters. Additional parameters contain information related to de-glaciated valleys and glacier lakes.

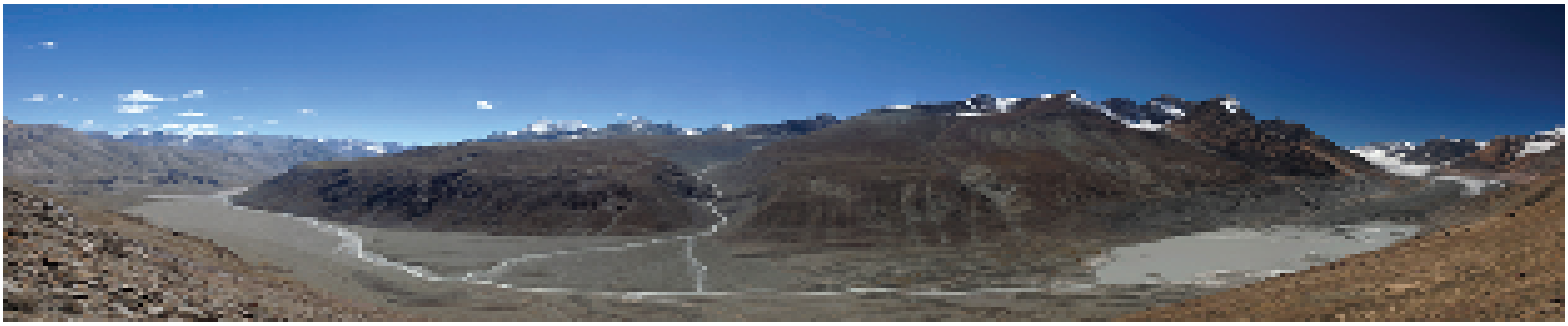
A period of the year i.e. from July to end of September, when seasonal snow cover is at its minimum and permanent snow cover and glaciers are maximum exposed, is selected for the glacier mapping using remote sensing data. Available Regional/Local maps and corresponding multi-temporal geocoded FCC's of standard band combination such as 2 (0.52-0.59 μm), 3 (0.62-0.68 μm) and 4 (0.77-0.86 μm) of IRS LISS III sensors at 1:50,000 scale are used for interpretation. Following sections describe work undertaken at SAC, Ahmedabad on Inventory of glaciers.

4.2 Glacier inventory of Indian Himalaya at 1: 250 000 scale

In India, remote sensing has been extensively used for glacier investigations. A glacier inventory of Indian Himalaya on 1:250,000 scale using satellite images of 1987 was carried out for entire Indian Himalayas during 1988-1991. Investigations have shown 1702 glaciers covering an area 23,300 km^2. This estimate does not include features such as permanent snowfields, ice apron, hanging glaciers and rocky glaciers.

4.3 Glacier inventory of Satluj basin

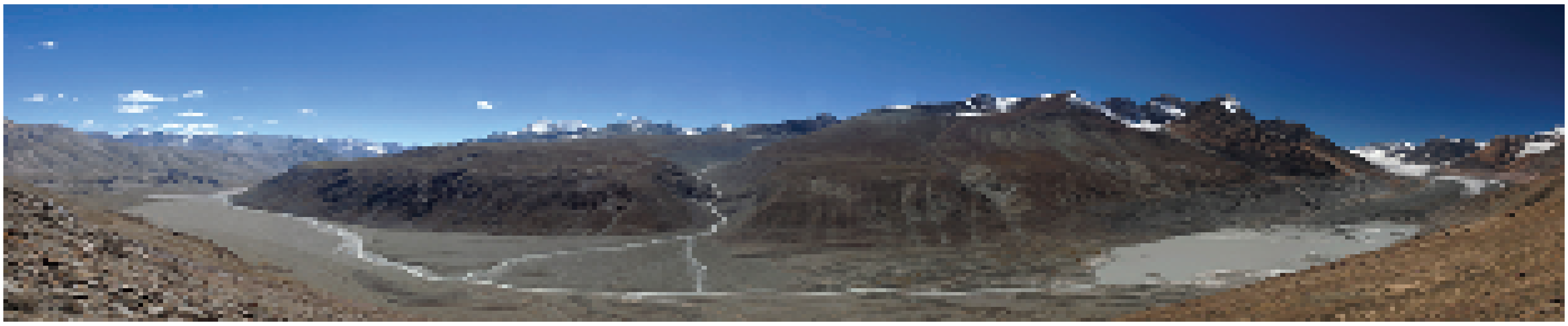
Inventory of glaciers on 1:50,000 scale was carried out for Satluj basin using satellite images during 1991-1995. The study indicates the presence of 334 glaciers in the Satluj basin



covering an area 1515 km^2 which is in addition to the number of permanent snow fields (total 1987) cover having an area of 1182 km^2. The total area under glaciers and the permanent snow cover is distributed in 169 sub basins and amount to 2697 km^2. The distribution of

Table 4.1 : Basin wise results of inventory of glaciers Indian Himalaya at 1: 250 000

Basin Name	UNESCO/TTS Number	Number of Glacier	Glacier covered Area (km^2)
Alaknanda	IN5O122	44	1036.30
Beas	IN5Q221	12	379.25
Bhagirathi	IN5O121	33	882.90
Brahmaputra	IN5O140	25	223.00
Chenab	IN5Q213	161	2567.25
Indus	IN5Q130	742	8081.11
Jhelum	IN5Q210	38	157.72
Ravi	IN5Q214	9	104.67
Satluj	IN5Q222	37	296.17
Alaknanda	IN5O122	44	1036.30
Beas	IN5Q221	12	379.25
Sharada	IN5O102	48	771.80
Shyok	IN5Q131	333	5652.01
Siang	IN5O145	5	57.30
Tista	IN5O130	25	430.80
Yamuna	IN5O116	7	136.20
Shaksgam	IN5Y***	134	2198.15
Sulmar	IN5Z***	49	339.60
		1702	23314.93



glaciers has been shown in 5 major river sub-basins (table 4.2 and 4.3) and their areal extent has also been estimated. While most of the small glaciers are located in the Trans Himalayan region, the smallest glacier mapped is of 0.1km².

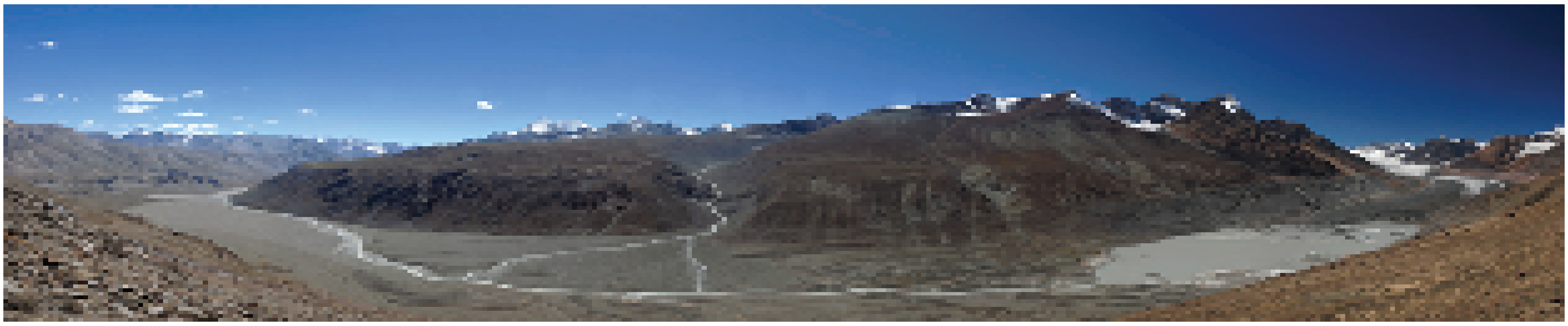
Table 4.2 : Basin wise distribution of glaciers and snowfields with areal extent for selected sub basins of Satluj basin

Basin Name	Number of Glaciers	Areal Extent (km^2)	Number of snow Fields	Areal extent (km^2)
Beas basin	6	15.84	47	72.44
Parbati basin	36	450.63	131	188.19
Sainj basin	9	37.26	59	51.93
Spiti basin	71	258.24	597	368.37
Baspa basin	25	203.30	66	64.96

For the Beas sub-basin, the lowest glacier mapped is of 0.281 km^2. This observation is significant considering 3mm X 3mm mappable size of the satellite data product where the smallest mappable area is 0.0225 km^2 on 1: 50,000 scale provided they are not covered by debris. In addition, the number of glaciers less than 1 km^2 are 88 though their contribution into total glacier extent is only 4.41km. This is very small (3%) as compared to the total glacial extent in the Satluj basin.

Table 4.3 : Glacial distribution in different ranges of areal extent in Satluj basin

Range of areal extent (km^2)	Number of glaciers	Total area of glaciers (km^2)
0.5	41	10.25
0.5 - 1	47	37.17
1.0 - 2.0	75	108.64
2.0 - 5.0	92	296.21
5.0 - 10.0	51	377.65
10	28	687.20
Total	334	1517.12



The altitude of glacial snout, or the transient snow line was estimated by comparing the inventory maps with topographic maps of the Survey of India.

Table 4.4 : Basin wise altitude for snout, snowline and moraines for selected sub-basins of Satluj basin.

Basin Name	Average Elevation (m)		
	Glacier Snout	Snowline	Moraines lowest
Beas	3912	4392	3866
Parbati	4446	4937	404 2
Sainj	4177	4797	4025
Spiti	5004	5211	4859
Satluj	4799	5149	4585

The altitude of snow/equilibrium line was delineated by using satellite images of September 1987. Altitude information is available for 205 glaciers out of a total of 334 glaciers. Average altitude of transient snowline/ Equilibrium line is 5093m after taking the average of snow line for 205 glaciers (table 4.4). It is observed that an average altitude of transient snow line/ equilibrium line is 85 m lower than the average mid altitude.

In order to asses the effect of altitude on Accumulation Area Ratio (AAR), accumulation and total areas were added together for all the glaciers falling in a particular range of altitude. The result is given in table 4.5.This suggests that with increasing altitude, AAR also increases and has a profound effect on mass balance. Then mid latitude of less than 4500m can cause AAR of less than 0.42, indicating negative mass balance. Therefore, very few glaciers have been found in this region and most of them, except one, are northern facing. As the mid altitude range increase from 4000 to more than 5500m, AAR also increases 0.333 to 0.840.

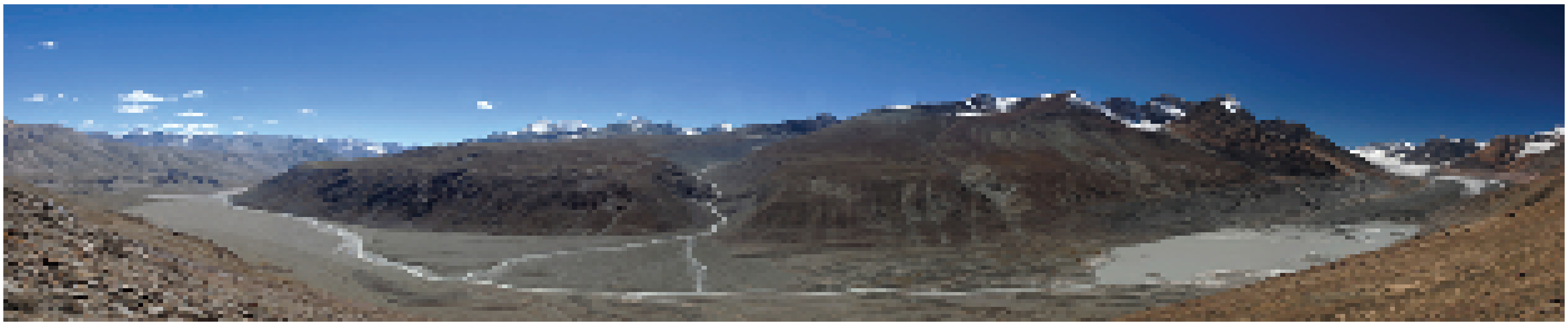


Table 4.5 : Distribution of glaciers in different altitude Zones of Satluj basin.

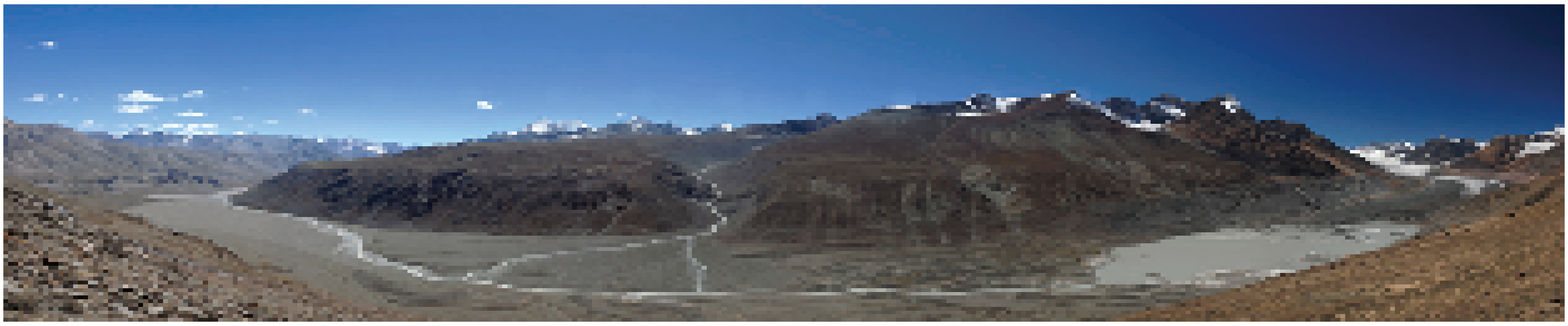
Mid altitude Range (m)	Number of glaciers	Accumulation Area (km^2)	Total area (km^2)	Transient AAR
< 4000	02	000.45	001.35	0.33
4000 - 4500	05	004.58	011.96	0.38
4500 - 5000	49	249.05	392.46	0.63
5000 - 5500	105	337.31	447.62	0.75
> 5500	44	109.81	130.28	0.84

Information regarding deglaciated valleys was also obtained. This has been included as a part of standard data sheet. In all 164 deglaciated valleys could be mapped in the basin. The total areal extent of all deglaciated valleys is 231 km^2. Orientation of glacier is also important aspect for glacier ablation, runoff and mass balance since the insolation and orographic impact are crucial for glacier melt. In glacial inventory program orientation is estimated in eight different directions. In Himalayas generally the southerly facing glaciers since they receive maximum insolation. At the same time the fast rate of melting results to poor preservation of glacier features. On the contrary the slow melting gives a wealth of information about the glacier features indicative of the palaeo-climatic signatures. In the Satluj basin most of the glaciers have northerly facing orientation. Considerable amount of information therefore could be extracted from the deglaciated valleys, which are indicative of past climate.

4.4 Glacier inventory of Dhauliganga basin

Inventory of glaciers in Dhauliganga basin was carried out on 1:50,000 scale using IRS-LISS of 1995. Results obtained during this investigation suggest presence of 48 glaciers in the Dhauliganga river basin including Lesser Yankti river basin. This covers an area of 197.377 km^2. In addition, permanent snow fields were also mapped. The total areal extent of permanent snow fields were measured as 31.70 km^2. This makes total area under glaciers and permanent snow fields as 229.077 km^2.

The lowest glacier of 0.475 km^2 was mapped in the basin. Number of glaciers less than 1 km^2 are 11, however their contribution into total glacial extent is only 7.875 km^2. Large number of glaciers; more than 50 % of total glaciers are located in areal extent range between 1 and 5 km^2.



4.5 Glacier inventory of Tista basin

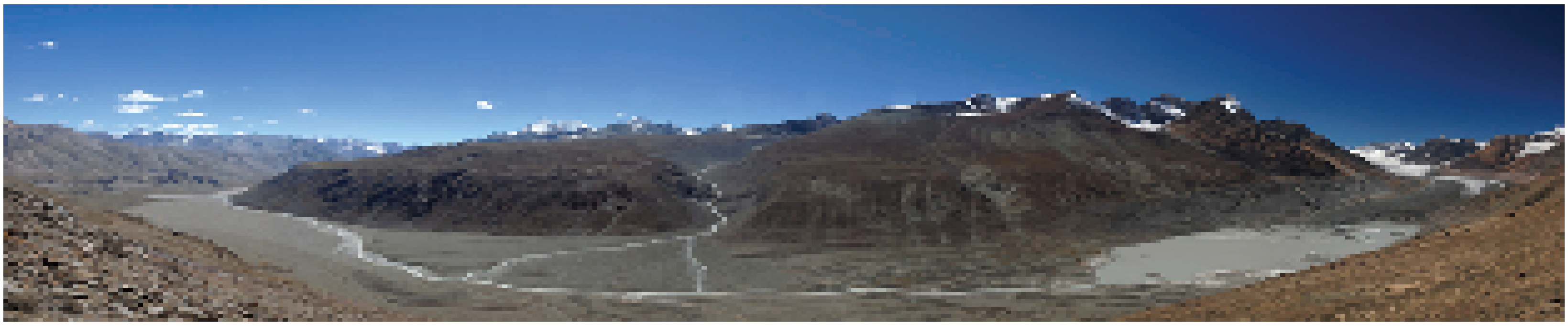
Eleven glacier inventory maps at 1: 50,000 scale were prepared for inventory of glaciers of Tista basin. Maps have been prepared based on interpretation of IRS LISS III geocoded FCC data. These have been presented in the form of an Atlas. Results obtained during this investigation suggest presence of 84 glaciers in the Tista basin. This covers an area of 440.30 km^2. Total permanent snowfields have been measured as 251.22 km^2. This makes total area under glaciers and permanent snowfields as 691.52 km^2. In the Tista basin the permanent snow cover and glaciers are distributed in 12 sub basins. The total glacial and permanent snow cover stored water in the Tista basin is estimated as 145.05 cu km. Most of the glaciers of Tista basin have an area less than 20 km^2. Analyzing permanent snow fields in various ranges of areal extent it has been seen that most of the permanent snowfields have an area of less than 1 km^2.

In Sikkim Himalayas seven moraine dammed lakes were also mapped. Largest lake has an area of about 1.55 km^2. This lake is formed in the glacier no. 78A13012 in Lachung Chu sub basin. The smallest lake has an area of about 0.13 km^2. It has been observed in Sebuzung Chu sub-basin. In addition to moraine dammed lakes three deglaciated valleys were also mapped. Deglaciated valleys cover an area of 8.659 km^2.

Altitude of snow/ equilibrium line has been delineated using satellite images of 01 January 1997. This is available for all glaciers of the Tista basin. Average altitude of snow line is 5093m. This is 342 m lower than average middle altitude for the glaciers of the basin.

4.6 Glacier inventory of Chenab basin

Twenty four glacier inventory maps were prepared for inventory of glaciers of Chenab basin on 1:50,000 scale. Maps have been prepared based on interpretation of IRS LISS III geocoded FCC data. Results obtained during this investigation suggest presence of 454 glaciers in the Chenab basin. This covers an area of 1174.5 km^2. The permanent snowfields were also mapped. The total number of permanent snow fields is 1186 carrying an area of 1419.5 km^2 in the Chenab basin. The permanent snow cover and glaciers are distributed in 55



sub-basins. The total glacial and permanent snow cover stored water in the Chenab basin is estimated as 93.033 cu km. Most of the glaciers of Chenab basin have an area less than 5 km^2. There are 43 glaciers having an area of more than 5 to 10 km^2. There are only 8 glaciers having an area between 10 and 20 km^2. There are only 6 glaciers having an area of more than 20 km^2. (Table 4.6). Analyzing permanent snow fields in various ranges of areal extent, it has been seen that most of the permanent snowfields have an area of less than 1 km^2.

Table 4.6 : Distribution of glaciers in different area range of Chenab basin.

Glacier Area (km^2)	No. of Glaciers	Total Area (km^2)
< 1	244	113.83
1-5	165	394.59
5-10	34	211.28
> 10	14	335.61

In Chenab basin 46 moraine-dammed and 5 supraglacial lakes were mapped. The largest lake has an area of about 1.053 km^2. This lake is formed in the glacier no. 52H11001 in 12448 sub-basin. Smallest lake has an area of about 0.002 km^2. It has been observed near glacier No. 52C12S52 in 12200 sub-basins. In addition to moraine dammed lakes 301 deglaciated valleys were also mapped. Deglaciated valleys cover an area of 269.013 km^2. Altitude of snow/equilibrium line has been delineated using satellite images of 27 August 2001. This is available for all glaciers of the Chenab basin. Figure 4.1 shows one of the IRS LISS III image used in inventory. Figure 4.2 shows one of the glacier inventory maps corresponding to the image shown in figure 4.1.

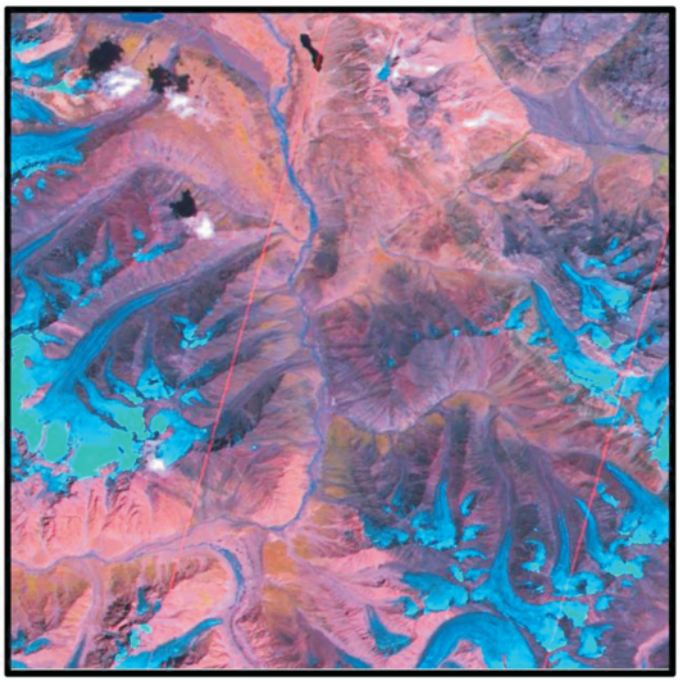
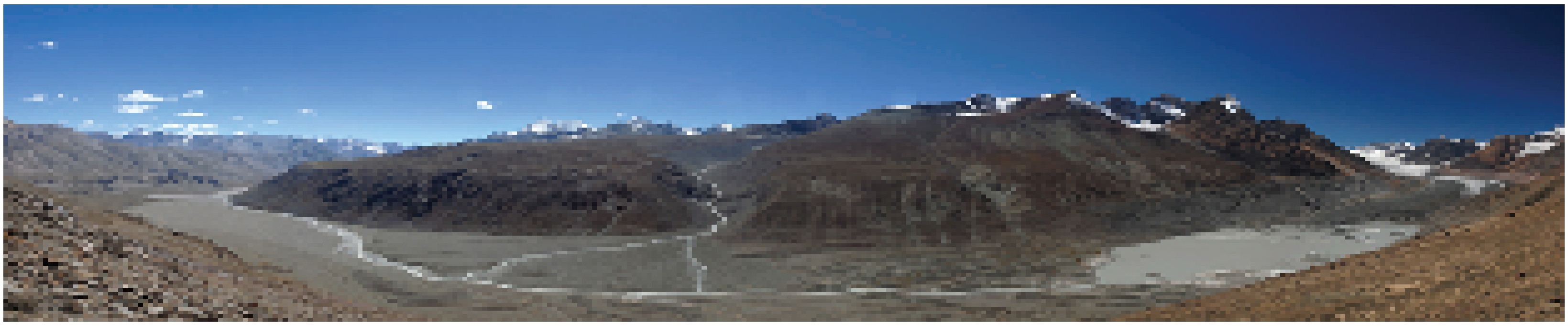


Figure 4.1: IRS LISS III FCC image showing glaciers in Chenab basin



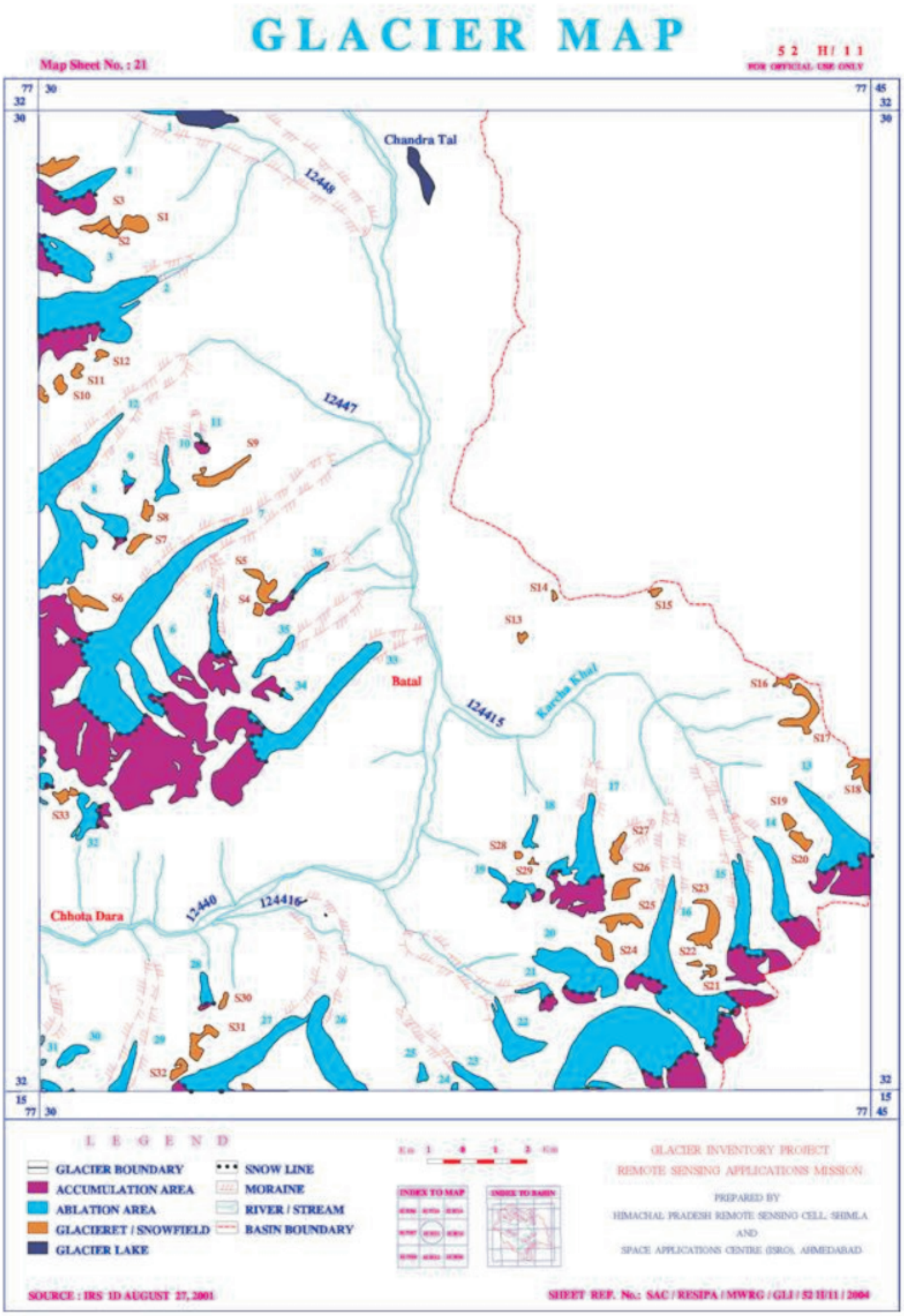
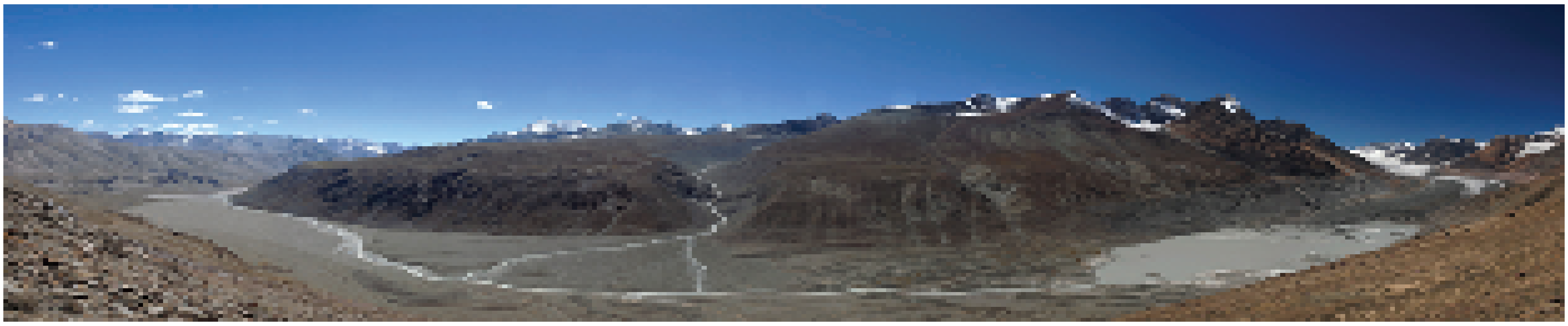


Figure 4.2 : Glacier inventory map for a part of Chenab basin



4.7 Glacier Inventory of Indus, Ganga & Brahmputra basins

The main objective of this inventory aims at :

- Preparation of glacier inventory maps at 1:50,000 scale for glaciers of Indus, Ganga & Brahmputra basins draining in to Indian territory.
- Preparation of glacier inventory data sheet.
- Creation of (spatial / non spatial) digital database in GIS.

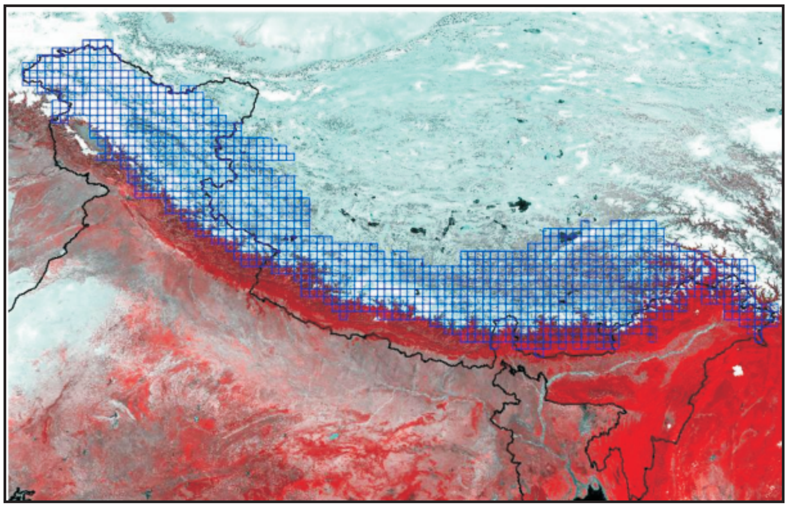
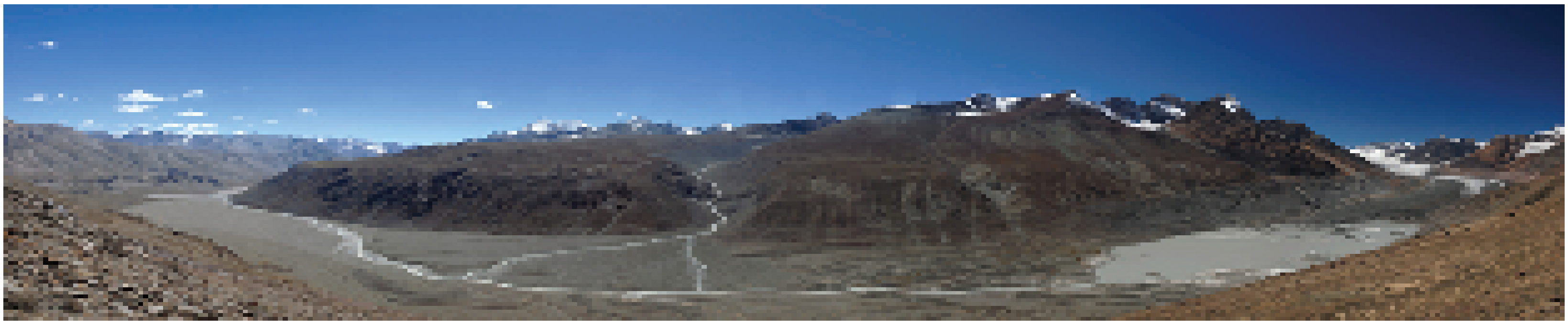


Figure 4.3 : Grid showing maps covering Himalayan region for glacier inventory

The study area also covers some parts of Nepal, Bhutan and China(Tibet) from where these rivers either originate or have major tributaries which flow into India. Geocoded IRS LISS III data on 1:50,000 scale, from period July to end of September season is procured in the form of FCC paper prints and digital format(of years 2003-2007). The hard copy geocoded FCC's of standard band combination such as 2 (0.52-0.59µm), 3 (0.62-0.68µm) and 4 (0.77-0.86µm) and in digital data the standard bands with additional SWIR band (1.55-1.70µm) is procured from National Remote Sensing Centre (NRSC), Hyderabad.

4.7.1 Approach

The main aim is to generate a glacier morphological map based on multi temporal IRS LISS III satellite data and ancillary data. Specific measurements of mapped glacier features is the input for generating the glacier inventory data sheet with 37 parameters as per the UNESCO/TTS format and 11 additional features associated with the de-glaciated valley. The data sheet provides glacier wise details mainly related to the glacier identification in terms of



number and name, glacier location in terms of coordinate details, information on the elevation, measurements of dimensions and orientation, etc. A table showing statistics summarizing the essential glacier features is also generated.

The glacier inventory map with details of the glacier features under this inventory project has been prepared by visual on screen interpretation using soft copy of multi-temporal IRS LISS III / AWiFS satellite data and ancillary data. Earlier field studies and results derived using satellite data suggest that spectral reflectance's of the accumulation area are high in bands 2, 3 and 4 of IRS LISS II and TM data. On the other hand, reflectance in band 2 and 3 are higher than the surrounding terrain but lower than vegetation in band 4. These spectral characteristics are useful to differentiate between glacial and non-glacial features. The broad approach for the preparation of glacier inventory map, data sheet and digital data base is given in flow chart below (figure 4.4).

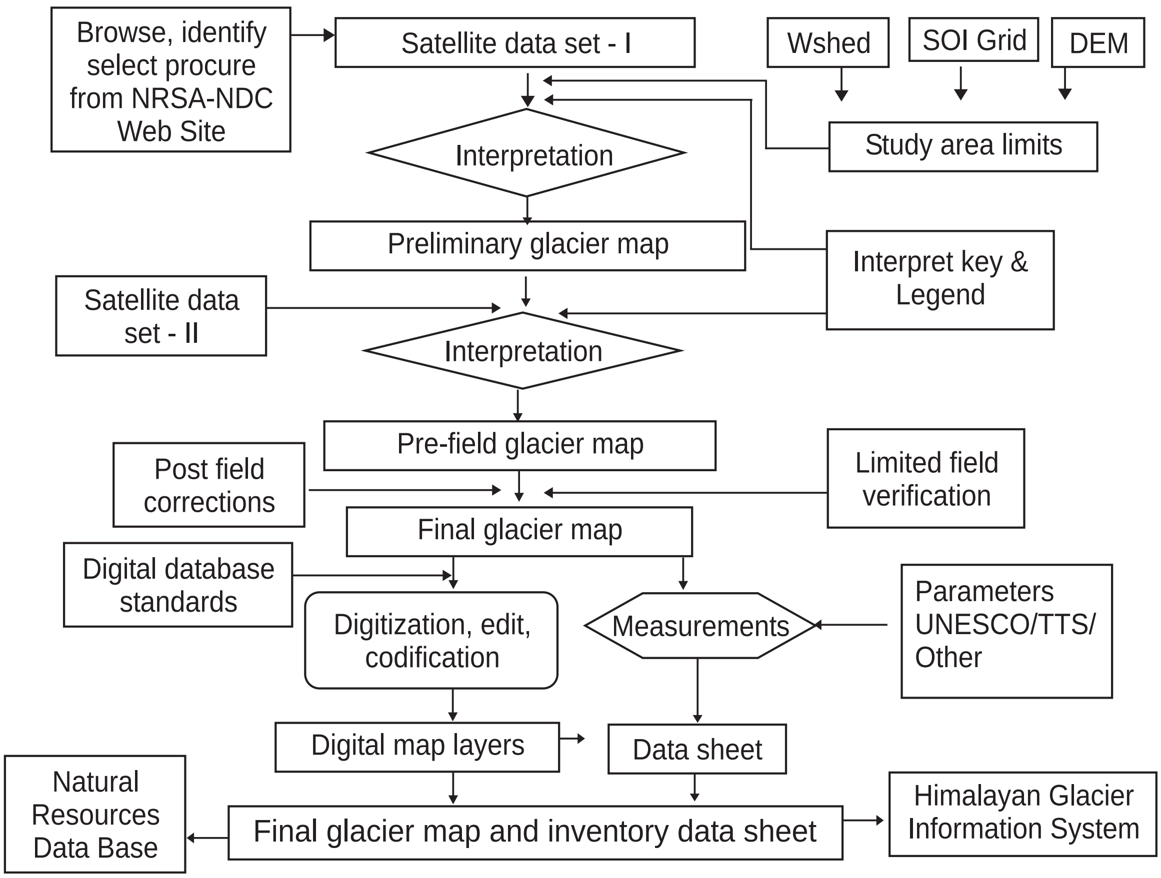
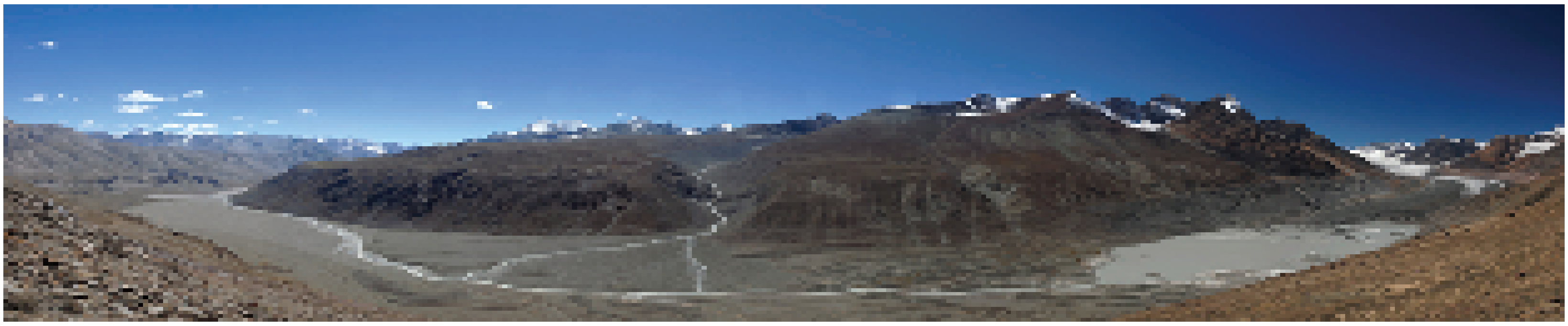


Figure 4.4 : Broad approach for glacier inventory map and data sheet preparation



Initially the small scale ancillary data (drainage, watershed, roads, settlements, etc.) is used to prepare preliminary digital maps corresponding to the base and hydrology themes. These preliminary theme layers are modified and finalized by using multi-temporal satellite data. A preliminary glacier inventory map is prepared using the first set of satellite data. Subsequently, it is modified as pre-field glacier inventory map using second set of satellite data to include all the essential glacier features. Limited field visits are carried out to verify the pre-field glacier inventory map. Corrections, if any, are incorporated to prepare the final glacier inventory map. Measurements carried out on the glacier inventory map result in generating the glacier data sheet.

4.7.2 Preparation of theme layers

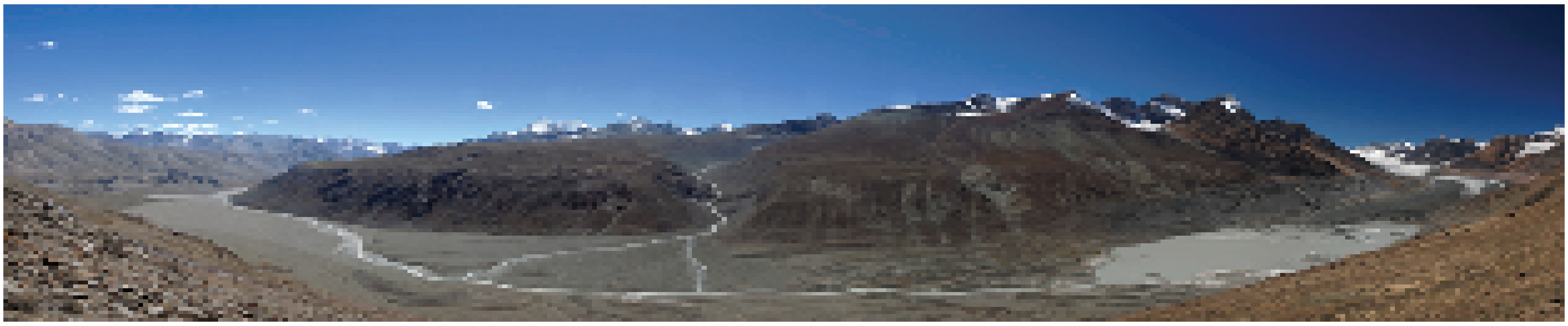
The published Irrigation Atlas, Watershed Atlas, small and large scale maps like political/ physical maps from the reliable sources have been used for base map and hydrology theme layers. The information like administrative boundary, transportation features and settlement locations, drainage, watershed, etc., are identified on these maps. The maps are then scanned as raster images and registered / projected with the satellite data based on common control features. These scanned images are used in the background for extracting the base information on separate vector layers. The information content of each of the primary theme layers and the procedure for their preparation is discussed below:-

Hydrology

The hydrology layer with information on all the minor, major drainage, water bodies and watershed (Basin/Sub-basin) with their corresponding identification numbers and names is created. The published small scale Irrigation Atlas of India is used as input for generating the preliminary drainage line and water bodies layers. The watershed Atlas of India is used as input for generating the preliminary watershed (Basin/Sub-basin) layer. The drainage layer is generated as two separate layers the *drainage line layer* (DRAINL) and the drainage polygon layer (DRAINP).

Glaciers

The mapped glacier features comprise of the permanent (for 2 or more glacial inventory season) snow covered areas/snow fields, the boundary of smaller glacieret, the glacier boundary for accumulation and ablation area with the transient snow line separating the two areas. The ice divides line at the margin of glaciers and other features like Cirque, horn, the



glacial outwash plain areas, the glacier terminus / snout, etc. are delineated. The ablation area is further classified as ice exposed or debris covered. The extent of the de-glaciated valley and the associated various types of moraines and moraine dammed lake features are delineated. These features are appropriately stored in GIS as point line and polygon layers.

De-glaciated valleys

The de-glaciated valley and associated features are significant to determine the health of the glacier. The dimensions of the valley and the type of moraines deposits reflect upon the retreat pattern of the glacier. The multi-date satellite data is used to identify and delineate the extent of the de-glaciated valley features. Mainly the de-glaciated valley and associated features that are mapped include the glacial valley, moraines like the terminal, lateral moraine, outwash plain, moraine dammed lake, etc. The moraines can occur both as polygon as well as line features depending upon their width at the mapping scale. The information is stored in polygon vector layer. Some of the lateral and terminal moraines which can be delineated only as the lines are separately kept in a line vector layer the de-glaciated valley line layer. A sample map is shown in figure 4.5.

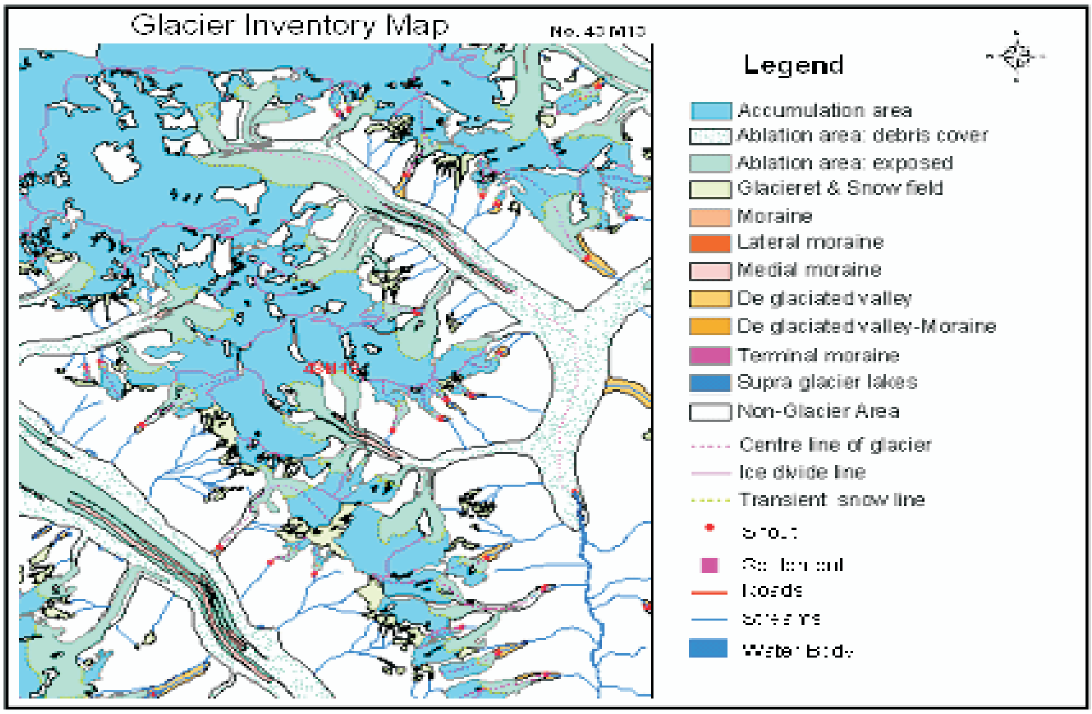
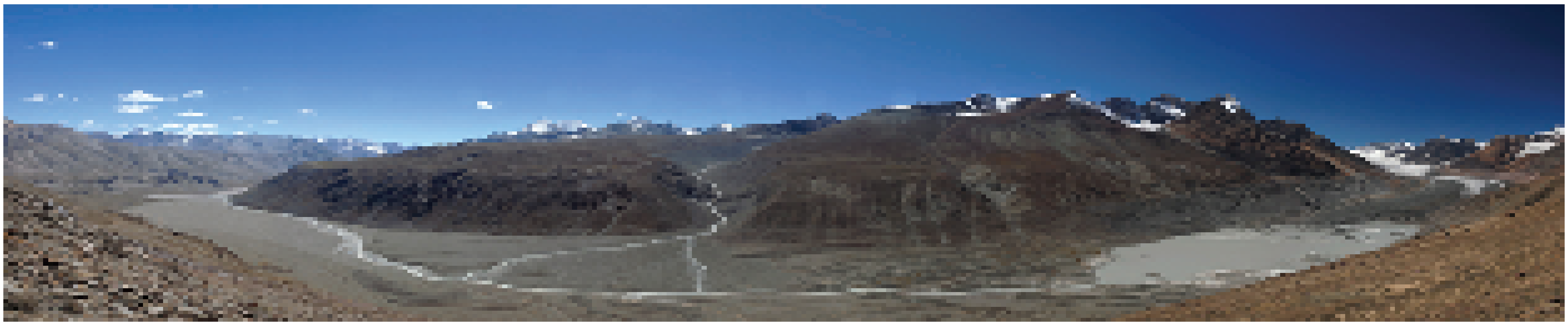


Figure 4.5 : Glacier inventory map



The elevation information, particularly the highest and lowest elevation of glaciers, de-glaciated valley, the supra-glacial and moraine dam lakes are significant as these are incorporated in the TTS format. A point layer (ELEVP) is created to store all the locations of these elevation points and their elevation values. The elevation information for these locations is obtained by intersecting this layer with the DEM layer created using SRTM data.

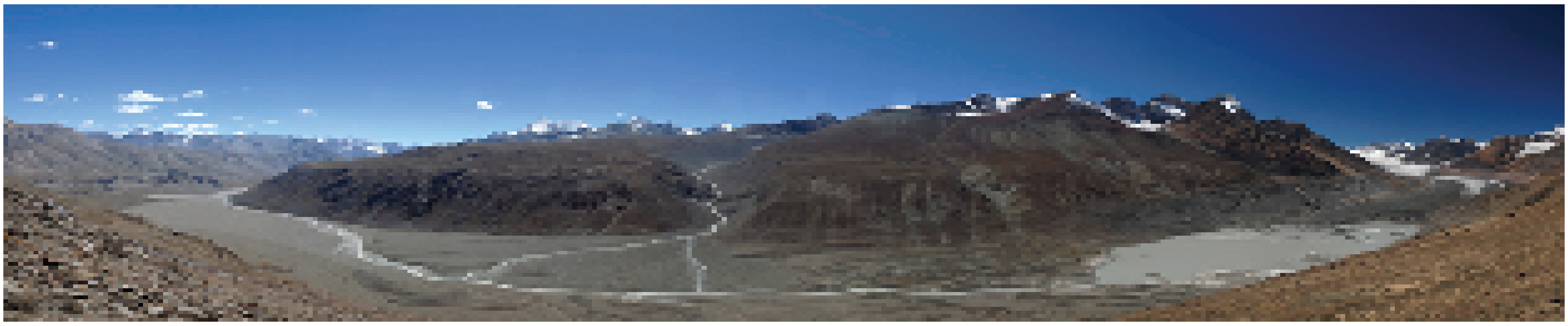
4.7.3 Generation of glacier inventory data sheet

Inventory data is generated for individual glaciers in a well-defined format as suggested by UNESCO/TTS and later modified. It is divided into two parts. First part comprises all 37 parameters recommended by UNESCO/TTS. Second part contains additional information on 15 parameters related to remote sensing and de-glaciated valleys and glacier lakes. These parameters are not recommended by UNESCO/TTS. However, by considering usefulness of this information in glaciological studies, these are also included in the investigation. By using the glacier inventory map layers in GIS environment, systematic observations and measurements are made on the glacial feature and recorded in tabular form in the inventory data sheet The observations and features measured and recorded are mainly related to the data (age / year) used, location, dimensions, elevations and directions, etc. for the glacier. Majority of the measurements can be directly obtained through GIS functions. The table thus generated is linked to corresponding glacier inventory map feature in GIS through the unique glacier identification number.

Data fields description

The World Glacier Inventory data sheet contains the following data fields. Not all glaciers have entries in every field. Explanations for various Data fields in the standard Data Sheets are as below :

1. Glacier identification number: The glacier identification number as defined by the World Glacier monitoring Service's convention. It is based upon inverse STRAHLER ordering of the stream. To achieve uniform classification a base map of 1:20,000 scale was used. On this map the smallest river gets, by definition, order five and when two rivers of the same order meet



together; they make a lower order river. Each order is assigned a fixed position in the numbering scheme, which has a total of 12 positions. First three positions are reserved for apolitical and continent identification; fourth position for first order basin and code Q and O is assigned for Indus and Gang rivers, respectively. Next three positions are reserved for 2nd, 3rd and 4th order basins, respectively. In order to identify every single glacier, remaining five positions from 8 to 12 are kept at the disposal of local investigators. In the local system of identification, glaciers are first identified with map number and then numbered in the individual basins.

In present investigation the identification of major basin is done by using map supplied by UNESCO/TTS. Present investigation is done on large scale maps; therefore, to make full utilization of inventory information it would be necessary to further subdivide major basin into smaller sub basins. This will make it possible to provide glacier inventory information for small stream and thus improving utility in water resources management.

2. Glacier name: The name of the glacier. Note that not every glacier has a name within the database. Often the name is the glacier's numerical position within its particular drainage sub-region.

3. Latitude: The latitude of the glacier, in decimal degrees North.

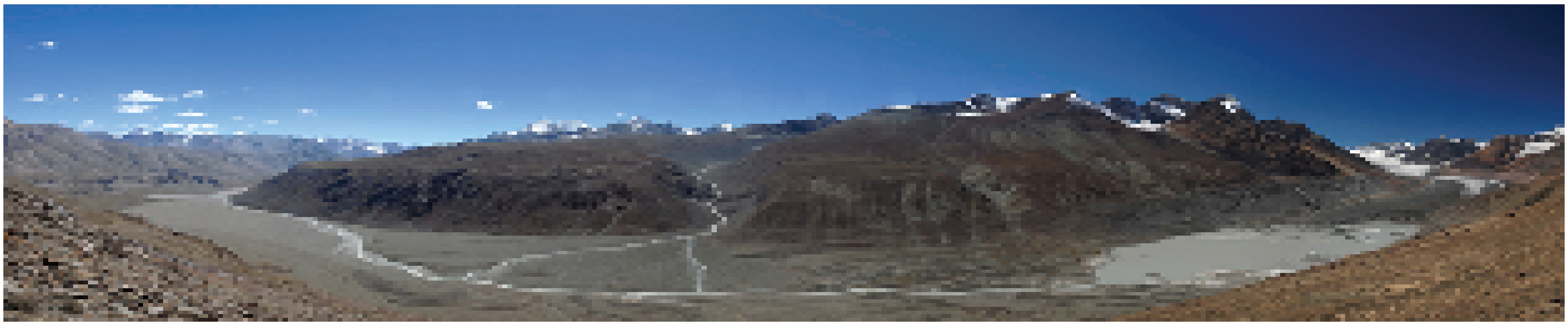
4. Longitude: The longitude of the glacier, in decimal degrees East.

5. Coordinates: Local coordinates in UTM

6. Number of drainage basins: Number of drainage basins

7. Number of independent states: The number of independent states

8. Topographic scale: The scale of the topographic map used for measurements of glacier parameters.



9. Topographic year: The year of the topographic map used for measurements of glacier parameters.

10 Photo / image type: The year of the photograph/image used for measurements of glacier parameters.

11. Photo year: The year of the photograph/image used.

12. Total area: The total surface area of the glacier, in square kilometers.

13. Area accuracy: The accuracy of the area measurements on a percentile basis.

14. Area in state: The total area in the political state reporting.

15. Area exposed: The area of open ice, in square kilometers.

16. Area of ablation (total): The total surface ablation area of the glacier, in square kilometers.

17. Mean width of glacier : The mean width of the glacier, in kilometers.

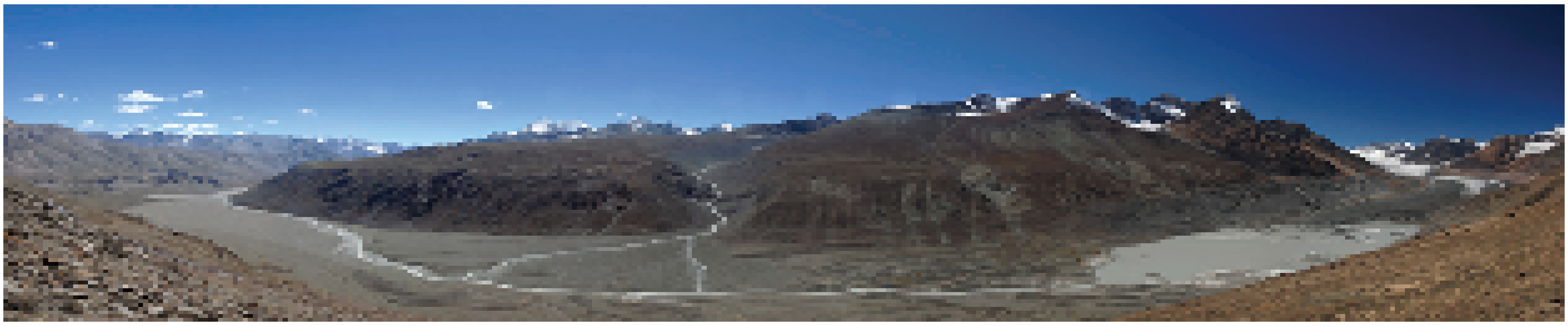
18. Mean length (total): The mean glacier length, in kilometers

19. Max length: The maximum glacier length, in kilometers.

20. Max length exposed: The maximum length of exposed ice, in kilometers.

21. Max length ablation: The maximum length of ablation area, in kilometers

22. Orientation of the accumulation area: The aspect of the accumulation area in degrees in direction of flow. The value -360 indicates an ice cap.



23. Orientation of the ablation area: The aspect of the ablation area in degrees in direction of flow. The value -360 indicates an ice cap.

24. Max / highest glacier elevation: The maximum glacier elevation, in meters. Altitude information is generated from standard Digital Elevation Model (DEM) available from satellite data of Shuttle Radar Terrain Mapping Mission (SRTM).

25. Mean elevation: The mean glacier elevation, in meters.

26. Min / lowest elevation: The minimum glacier elevation, in meters.

27. Min / lowest elevation exposed: The minimum elevation of exposed ice, in meters.

28. Mean elevation-accumulation: The mean elevation of accumulation area, in meters (along the centre line mean of max. elevation and min. elevation)

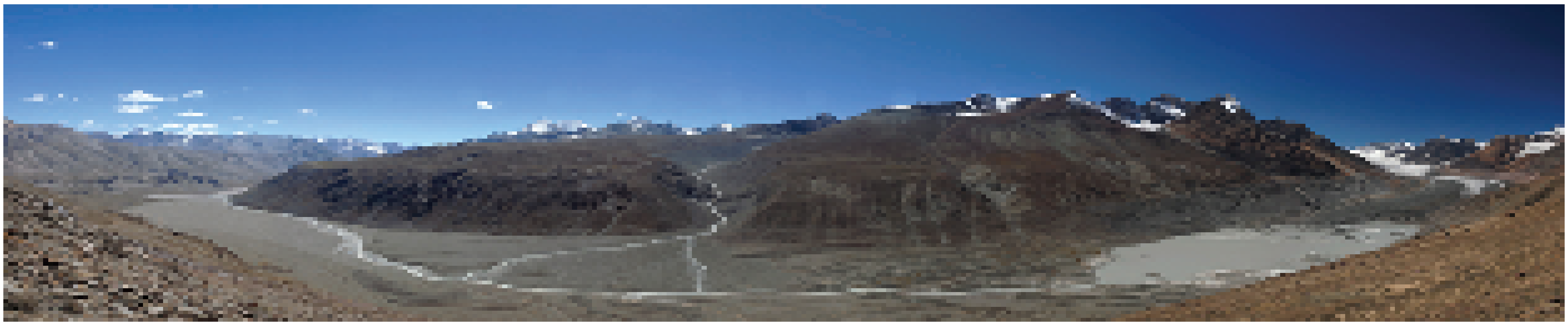
29. Mean elevation ablation: The mean elevation of the ablation area, in meters. (along the centre line mean of max_elevation_ablation and min. elevation_ablation)

30. Classification: Is the six digit form morphological classification of individual glaciers (UNESCO/IASH guidelines).

4.7.4 Results

The glacier inventory data primarily deals with the occurrence and distribution of glaciers and also provides details for each glacier on the more significant glacier parameters like morphology, dimensions, orientation, elevation, etc. for both the active glacier component as well as the associated de-glaciated valley. The sub-basin wise glacier inventory data provides a means to compare the glacier characteristics among the glaciated sub-basins.

For the three basins 1152 glacier inventory maps sheets have been prepared at 1:50,000 scale for the glaciated area of the Himalayas that drain into India. The Indus Ganga and Brahmaputra Basins are covered in 483, 203 and 544 number of map sheets respectively with an overlap in 78 map sheets. The inventory maps and datasheets are prepared to cover all glaciers in the three basins draining into India.



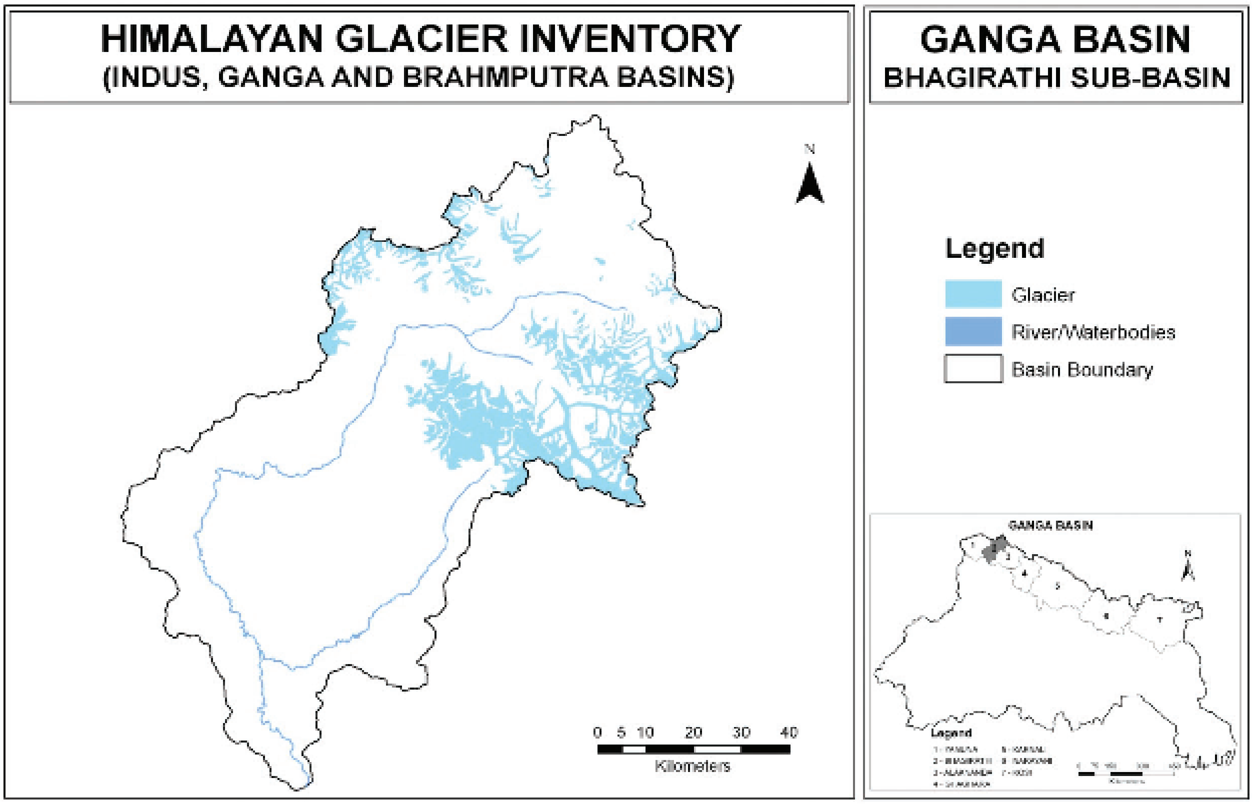
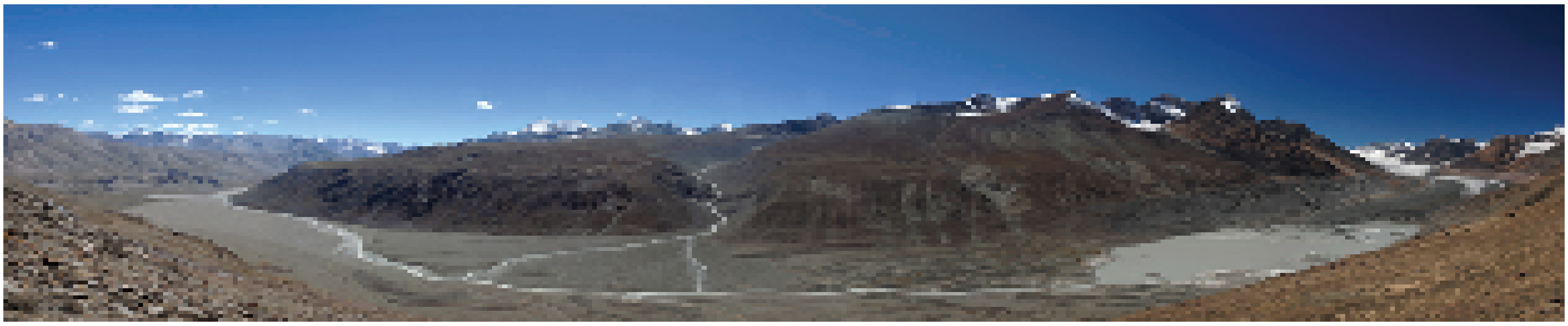


Figure 4.6 : Glaciated region of Bhagirathi sub-basin

The glacier inventory map depicts the presence of glaciers and their distribution in space. The significant glacier morphological features for each of the glacier are mapped and appropriately represented on the map by a pre-defined colour scheme. The mapped glacier features comprise of glacier boundary with separate accumulation area and ablation area. The ablation area is further divided into ablation area ice exposed and ablation area debris covered. The Moraines like median, lateral and terminal moraines present on the glacier are separately mapped and delineated. The supra-glacier lakes occurring on the glaciers are also delineated. The snout is marked as a point location depicting the end of the glacier tongue. The de-glaciated valley associated with the glacier is also delineated along with the associated moraines both lateral and terminal moraines and the moraine dam lakes. Figure 4.6, 4.7 & 4.8 show glaciated region of different sub-basins.



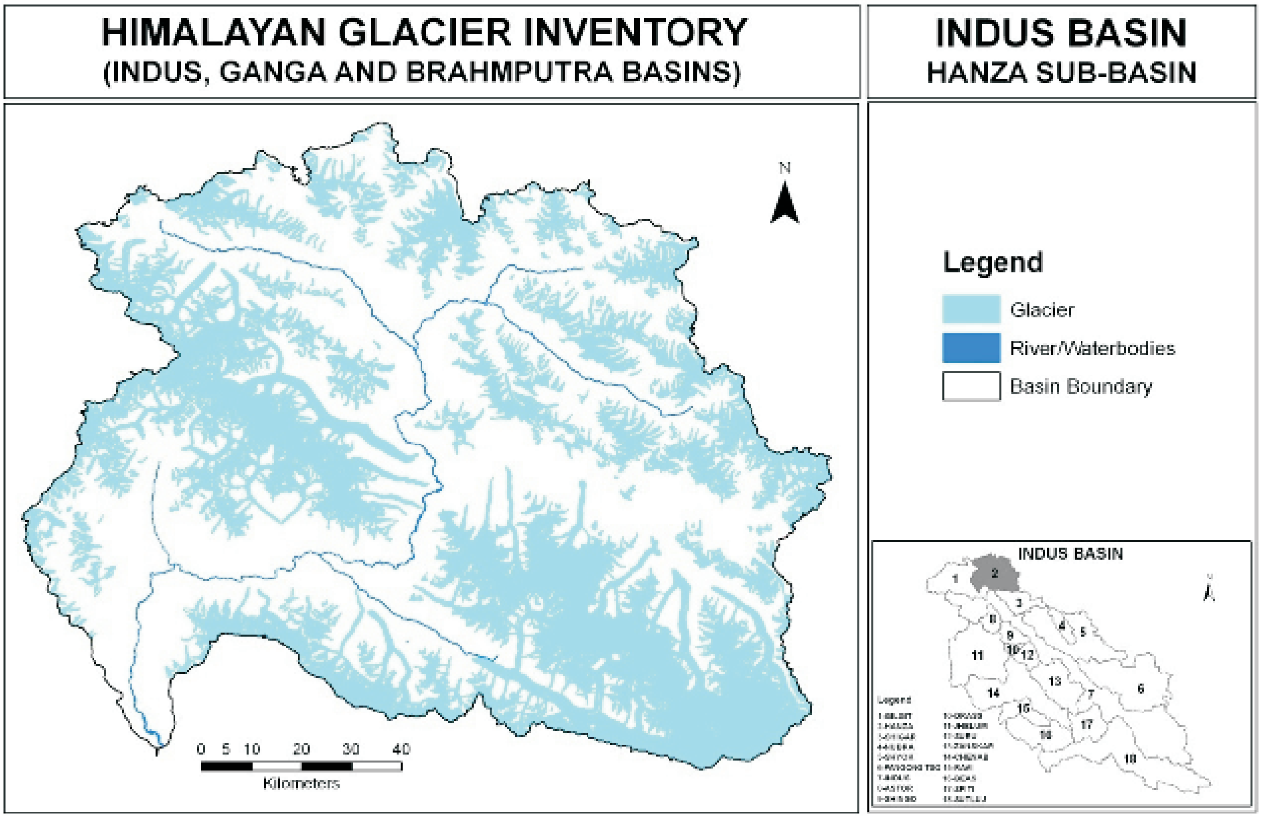


Figure 4.7 : Glaciated region of Hanza sub-basin

The glacier inventory datasheet with 37 parameters is prepared for each glacier. The three basins put together have 71182.08 km^2 of glaciated area with 32392 numbers of glaciers. The Indus basin has 16049 glaciers occupying 32246.43 km^2 of glaciated area. The 18 glaciated sub-basins in Indus basin are mapped. The Ganga basin has 6237glaciers occupying 18392.90 km^2 of glaciated area. There are 7 glaciated sub-basins in Ganga basin. The Brahmaputra basin has 10106 glaciers occupying 20542.75 km^2 of glaciated area. The 27 glaciated sub-basins in Brahmaputra basin are mapped. Basin wise glacier summary for Indus, Ganga and Brahmaputra basin is provided in table 4.6.

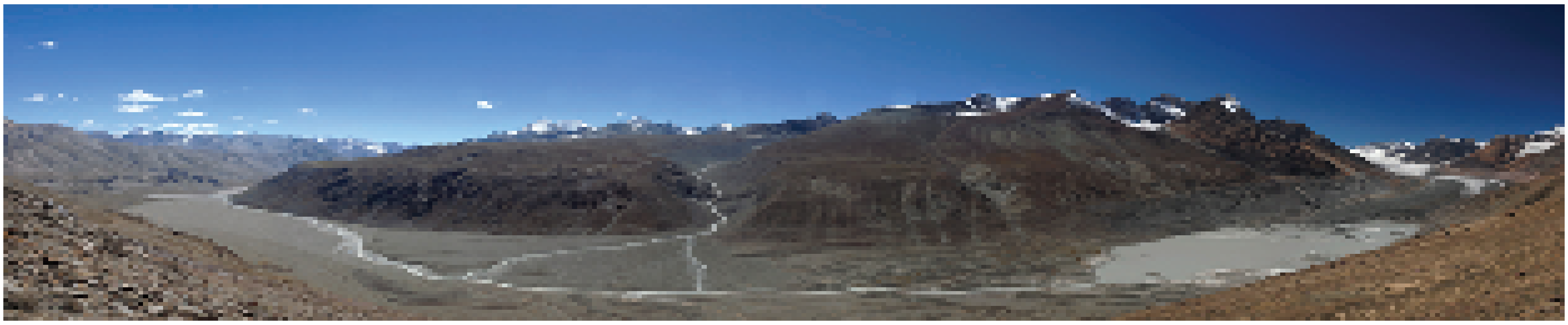
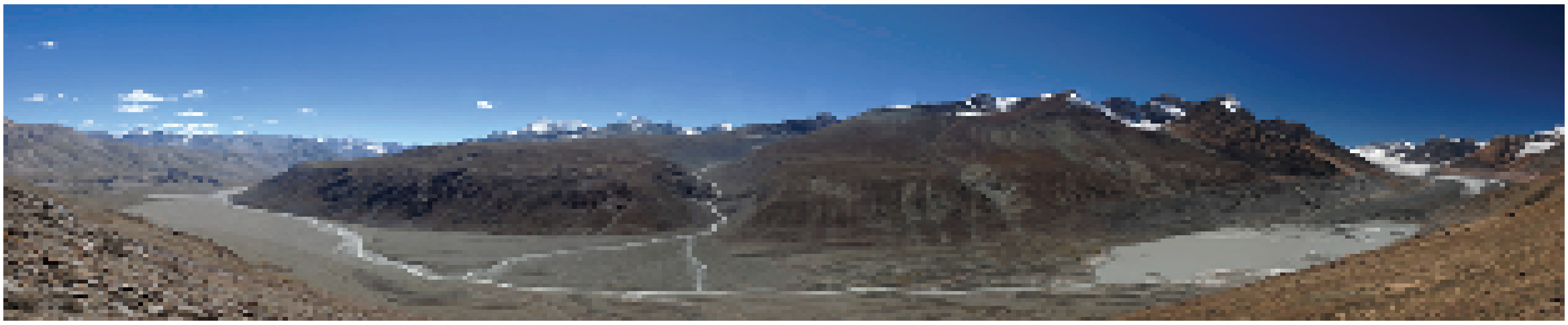


Table 4.6 : Summary glacier inventory results for Indus, Ganga and Brahmaputra basins

Sr. No.	Basin Characteristics	Indus Area in km^2	Ganga Area in km^2	Brahmaputra Area in km^2	All basin total Area in km^2
1	Sub-basins (Nos.)	18	7	27	52
2	Accumulation Area	19265.98	10884.6	12126.36	42276.94
3	Ablation Area Debris	6650.95	4844.7	5264.90	16760.55
4	Ablation Ice Exposed	6310.58	2663.5	3081.48	12055.56
5	Total no. of glaciers	16049	6237	10106	32392
6	Total glaciated area	32246.43	18392.9	20542.7	71182.08
7	No. of Permanent Snow fields and Glacierets	5117	641	3651	9409
8	Area under Permanent Snow fields and Glacierets	991.68	198.70	1282.9	2474.3
9	No. of Supra-glacier lakes	411	87	474	972
10	Area of Supra-glacier lakes	18.92	15.20	70.0	104.13
11	No. of Moraine dam /Glacial lakes	469	194	226	889
12	Area of Moraine dam /Glacial lakes	33.82	64.10	70.2	168.07

It is observed that the percent accumulation area is highest in the Indus basin as compared to the other two basins. The percent accumulation area is almost similar among Ganga and Brahmaputra basin. The ratio of accumulation to ablation area is also high in Indus basin. The ratio of accumulation to ablation area is almost similar among Ganga and Brahmaputra basins. This indicates that the glaciers of the Indus basin are having larger feed area and hence are relatively more stable as compared to the other two basins. The percent ablation area debris cover is almost similar among Ganga and Brahmaputra basin and is low in the Indus basin. The ablation area ice exposed is highest in Indus basin. The ablation area ice



exposed is almost equal among Ganga and Brahmaputra basin. For the Brahmaputra and Ganga basin the accumulation - ablation area ratios are low and most of the glaciated areas are having varying amounts of debris cover. The thick debris cover plays an important role by stopping the heat from sun rays in reducing the melting of glacier ice. However, the status of these glacier features depends on its altitude and latitudinal distribution.

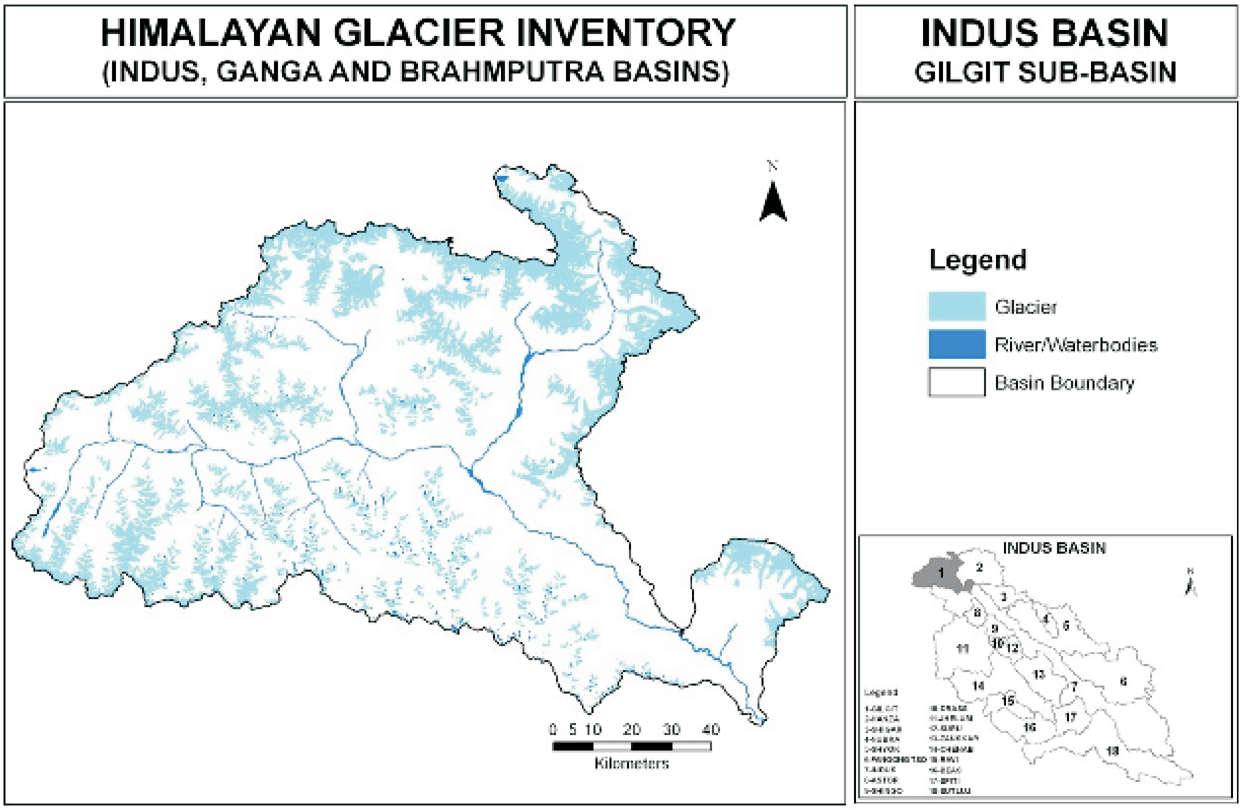


Figure 4.8 : Glaciated region of Gilgit sub-basin

The above input is being used for the creation of Himalayan Snow and Glacier Information System (HGIS). The database will also be used for the Natural Resources Data Base (NRDB).

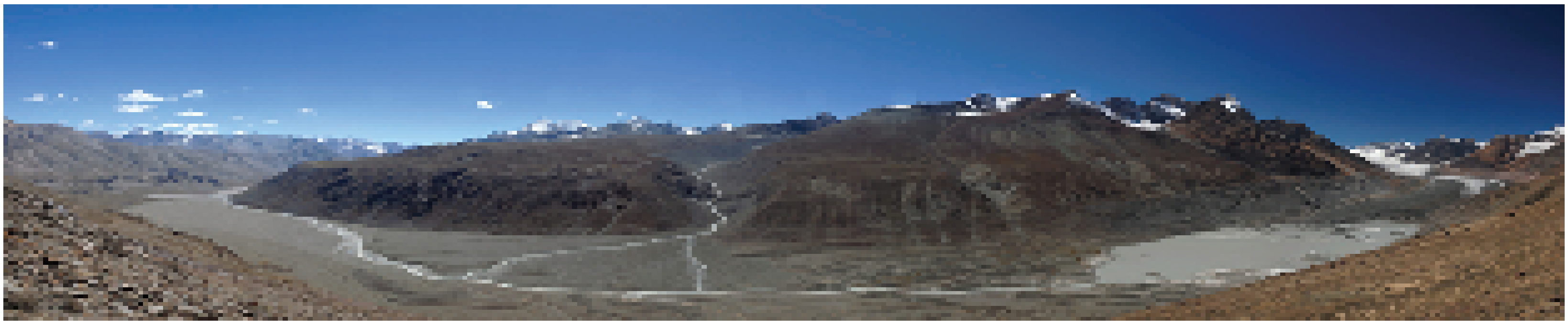
5. Monitoring Changes in Glaciers

5.1 Introduction

There is a pertinent relationship between retreat and advance of glaciers and variations in the mass balance of glaciers. It is the climate which is the driving forces controlling the mass balance of glacier in space and time and resulting in recession and advancement of glacier. Climatic ice fluctuations cause variation in the amount of snow and ice lost by melting. Such changes in the mass initiate a complex series of change in the flow of glacier that ultimately results in a change of the position of terminus.

As glaciers descend from the mountain or plateaus, a part of the matter composing them is expended for melting and evaporation, which become more intense as they descend into the region of higher temperatures. Finally, they reach a level at which the amount of ice arriving from the accumulation area is balanced completely by ablation. In case of equilibrium between replenishment and ablation, the position of the lower boundary of a glacier is stationary and the dimensions of the glacier remain more or less constant. If the supply by the accumulation increases, while melting and evaporation remain unchanged, the glacier advances and its dimensions increase. Such glacier is said to be advancing. The picture is reversed when replenishment diminishes and wastage increases. In that case, the glacier will grow shorter until the snout (the front end of glacier) reaches a stationary position, corresponding to new equilibrium of replenishment and ablation. This is known as retreat of glacier. Thus advancement and retreat of glacier closely depend on the conditions of replenishment of an accumulation area and the intensity of ablation i.e. faster melting due to climatic changes. On one hand the study is an important indicator of climatic variations, it is also useful in understanding changes in glacier mass fluctuation resulting in variation of stream run-off originating from the glacier. Stream run-off in Himalayan region is the basic resource for water resource development and micro and mini hydel projects which has direct implications in fluvioglacial geomorphological process and ecological balance of the region.

The adjustment of a glacier to a change in its mass balance continues for many years. Thus a glacier may advance or retreat as a result of past balance changes even though it's net balance for the current year might be zero. However if the net balance remains zero for many years the dimensions of the glacier will eventually remain constant. The glacier is then said to be in a steady state. If the glacier experiences a change in input (usually as an increase or decrease in the amount of snow accumulating on the surface) it must respond accordingly. But because glacier stores material, there is always a lag before the response becomes easily



discernible at the snout. This is called response time. The flow of ice through a glacier system varies according to how much material is being added or lost.

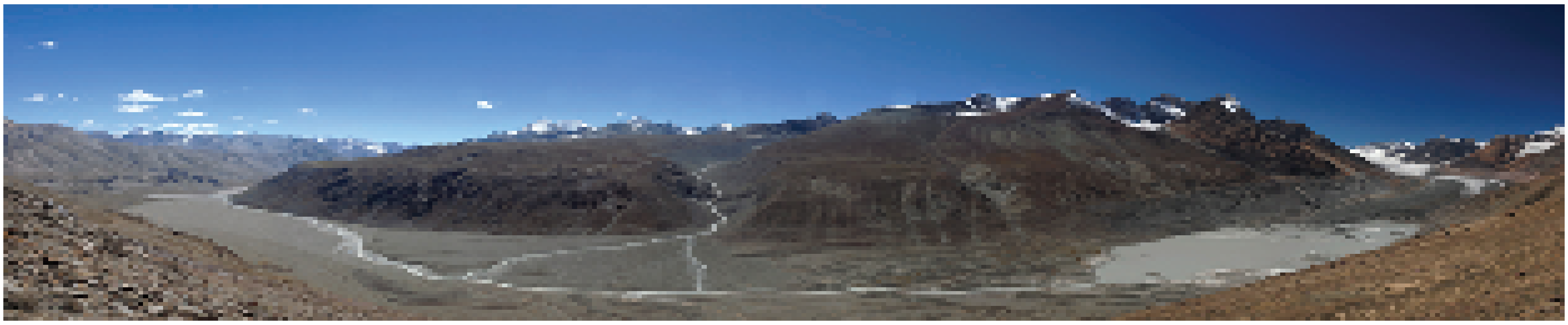
During its geological history, the earth has experienced alternate cycles of warm and cold climates. During cold climate, glaciers and ice sheets had formed on the surface of the earth. Geological evidence suggests that the earth had experienced glaciations during, Permo-Carboniferous and in the Pleistocene period. Precambrian tillites and boulder-beds are also reported from many parts of the world, such as Scotland and U.S.A. Clear evidence of Permo-Carboniferous ice age is also established in India and South Africa. The Permo-Carboniferous glaciation was followed by Mesozoic era, during which the world temperature was higher than that of today and no evidence of glaciation was observed in the geological formations of that period. In Cenozoic era, large-scale glaciation was experienced, which includes glaciation during Pleistocene and Quaternary periods. It has also influenced the present distribution of glaciers on the earth's surface.

In the following sections glacier advance/retreat studies carried out for different glaciers/basins are being discussed

5.2 Basapa basin

The investigation was carried out in the Baspa Basin, tributary of the Satluj River. The basin is located in Kinnaur District of Himachal Pradesh. The river is northern flowing and most of the glaciers are located in the northern slope of the Pir-Panjal mountain range. The basin is located in high altitude region. Basin area up to Sangla is 1050 km^2 and out of this 88 % area is located above 3600 m. Due to high altitude, the stream flow is mostly generated from snow and glaciers melt runoff. Annual average discharge for a period between 1970 and 1990 is varying from 62 to 31 cumecs. Annual mean snowfall from 1976 to 1988 at Chitkul (3841 m) in the basin was observed as 380 mm. Economically this basin is also important, as a hydroelectric power project of 300 MW is under construction.

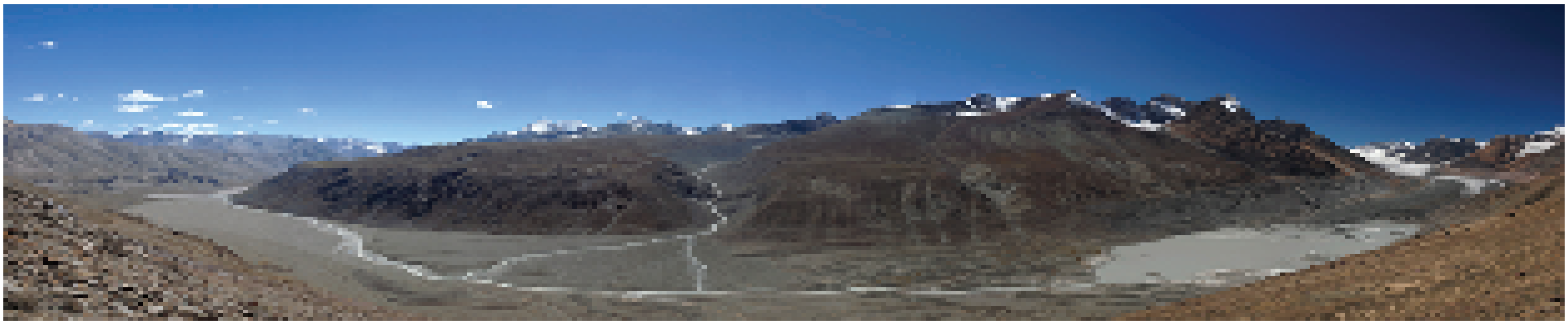
The glaciers of Baspa Basin were identified using topographic maps of the Survey of India (1:50,000 scale) surveyed in 1962. Mapping of Glacial extent in 2001 was carried out using Indian Remote Sensing Satellite (IRS) LISS III images. LISS III sensor has spatial resolution of 23.5 m in visible and near infrared bands and 70 m in SWIR band. Images of July-



September season (25 August 2001 and 11 September 2000) were selected, because during this period snow cover is at its minimum and glaciers are generally fully exposed. Glacier boundary was initially delineated using topographic maps and then it was digitized using Geographic Information System. On satellite images, glacial boundary was mapped using standard combinations of bands such as band 2 (0.52-0.59 m), band 3 (0.62-0.68 m) and band 4 (0.77-0.86 m). Image enhancement technique was used to enhance difference between glacial and non-glacial area. Position of Shaune Garang Glacier snout was verified by the field investigations. Snout position was marked using GPS and by comparing relative position of snout with geomorphological features as moraines, origin stream and moraine-dammed lakes.

Table 5.1 : Retreat of glaciers in the Baspa basin, Himalayas from 1962 to 2001

Glacier number	Data base number	Mid-Altitude (m)	Glacier area (km^2)			Glacier volume (km^3)		
			1962	2001	Loss %	1962	2001	Loss
1	53I07001	4920	10.5	8.7	17	1.01	0.79	0.23
2	53I07002	4960	4.6	4.3	7	0.34	0.33	0.002
3	53I07003	5040	2.2	2.0	9	0.13	0.11	0.02
4	53I07004	5160	4.6	4.1	11	0.34	0.29	0.05
5	53I07005	4840	1.7	1.2	29	0.09	0.06	0.03
6	53I11013	5520	3.2	3.2	0	0.21	0.21	0
7	53I11014	5320	1.5	0.8	47	0.07	0.03	0.04
8	53I12001	5440	5.9	5.6	5	0.47	0.33	0.14
9	53I12002	5240	38.4	33.5	13	5.66	4.73	0.93
10	53I12003	5080	2.7	2.2	19	0.17	0.12	0.04
11	53I11009	5120	7.1	5.0	30	0.60	0.38	0.22
12	53I11010	5320	6.9	5.8	16	0.57	0.45	0.12
13	53I11011	5360	8.7	4.5	48	0.79	0.33	0.47
14	53I07006	5240	35.2	30.4	14	5.06	4.16	0.89
15	53I07007	5120	11.6	9.9	15	1.15	0.94	0.21
16	53I07008	5000	5.5	4.1	26	0.42	0.28	0.14
17	53I07009	4680	3.9	1.9	51	0.27	0.10	0.17
18	53I07010	4720	8.0	7.0	13	0.71	0.59	0.12
19	53I07011	5120	10.8	6.1	44	1.05	0.49	0.56

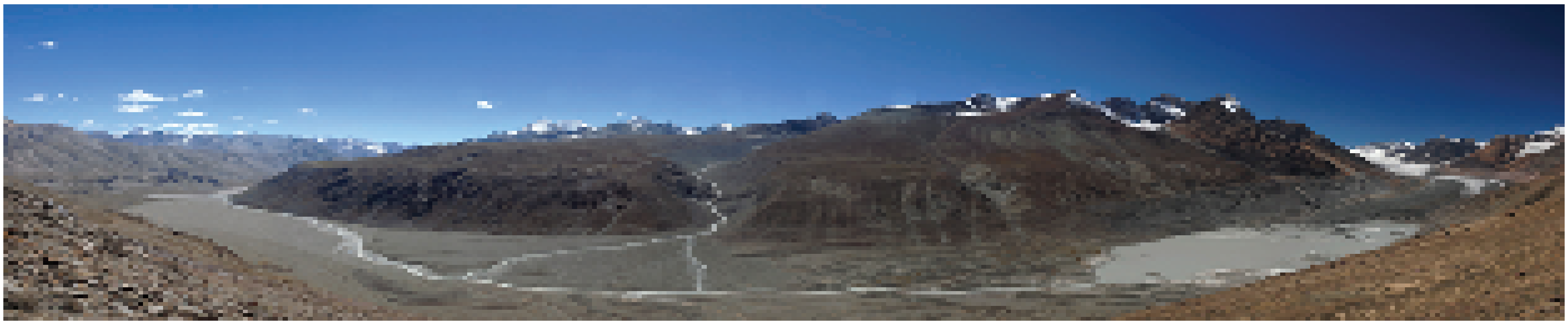


Using satellite data, 30 glaciers were mapped in the Baspa Basin, which cover an areal extent of 167 km^2. Out of these, 19 glaciers, covering an area of 140 km^2 were selected for detail analysis, depending upon availability of topographic maps (table 5.1). These are mountain glaciers and represent many types. Compound (Glacier number 15 and 18) and simple (Glacier number 10 and 11) glacier basins are represented. Glaciers are also well distributed in various altitude ranges starting from 4660 m (Glacier number 17) to 5340 m (Glacier number 2). Areal extents of glaciers are also widely distributed. Minimum areal extent is 1.5 sq. km. (Glacier number. 7) and maximum areal extent is 38.4 sq. km. (Glacier number. 9). In addition, distribution of debris on glacier are also varying, as some are having very heavy debris cover on the glaciers, as in case of glacier number 9. Many of these factors as glacier size, area-altitude distribution and debris cover normally influence the glacier retreat.

The present results suggest that all studied glaciers, except (Glacier number 6), are retreating in this basin. Mid altitude of Glacier number 6 is 5520 m, much above snow line at the end of ablation season. This may be influencing glacial mass balance and retreat. Glacial area obtained from topographic map (1962) and satellite imagery of 2001 is 173 and 140 km^2, respectively. Overall 19 % deglaciation has occurred in last 39 years. In addition, average altitude of snout is also shifted from 4482 to 4570 m, i.e. 88 m. The loss in glacial extent is varying from 0 to 51 %. A change in glacial boundary from 1962 to 2001 suggests retreat of glacier from snout and overall reduction in glacier width in the ablation areas, indicating significant reduction in glacier depth.

Table 5.2 : Influence of altitude on glacial retreat for Basapa basin

Mid-altitude range (m)	Number of glaciers	Glacier area extent (km^2)		Loss in %
		1962	2001	
< 5000	5	28.7	23.1	20
5000-5200	7	44.6	33.4	25
5200-5400	5	90.7	75	17
> 5400	2	9.1	8.8	03



To understand influence of altitude on glacier retreat (table 5.2), glaciers are classified on the basis of mid-altitude ranges. Mid-altitude is the altitude, which divides the glacier in two halves. In general, glaciers located in lower altitude ranges are showing higher retreat, except many glaciers located in altitude range lower than 5000 m. This is possibly because many small, low altitude glaciers are well protected due to extensive debris cover. Heavy debris cover can retard melting and protect glaciers from retreat. The low altitude glaciers, which were covered by debris, were less sensitive to climatic change. In high altitude large size glaciers also showed a less retreat. However glaciers of southern orientation occupied only 17% area compared to 83 % area of north oriented. The south facing glaciers are located in deep narrow valleys, which made them to survive in spite of its orientation, whereas northern facing glaciers located in broader valleys. Large flat glaciers react to a given climatic change more slowly than do short steep ones.

5.3 Parbati basin

Parbati basin is a tributary basin of the Beas basin in Himachal Pradesh. Parbati river originates from Parbati glacier and flows eastward from its origin before joining Beas River.

Saraugma glacier is the largest glacier with an approx. area of about 49.56 sq km followed by Parbati glacier with an area of about 35 sq km. These two glaciers are among the ninety glaciers of this sub-basin. The loss in area of Parbati glacier from 1962 is estimated to be of the order of 10.62 sq km. The Parbati glacier of this sub-basin has been validated on ground for secular retreat during the expedition in September 2004. The glaciers on the left bank of this river mostly have their ablation zone towards north, whereas most of the glaciers on its right bank have ablation zone oriented towards south. Glacier melt feeds Parbati river in addition to permanent snowfields of the sub-basin. Table 5.3 summarizes the loss in change in number of glaciers from 1962 but has been classified in different area ranges. Table 5.4 highlights the percent loss and number of glaciers corresponding to it.

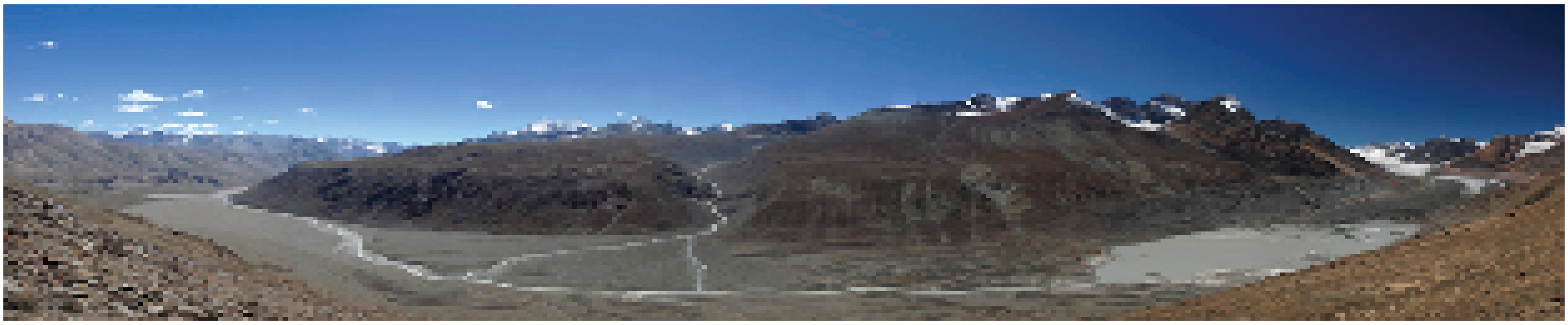


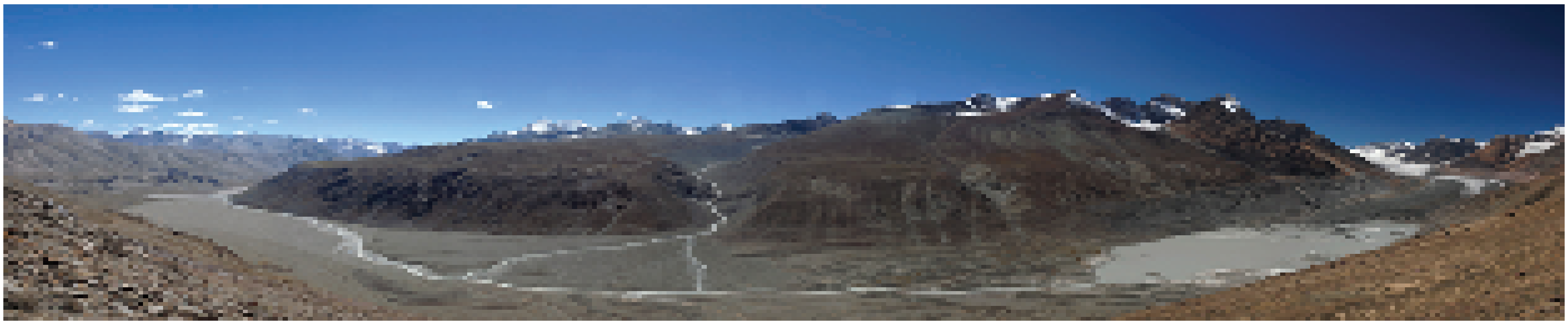
Table 5.3 : Statistical summary of number of glaciers in the year 1962 and 2004 under different classes of their size in Parbati sub-basin

Glacier Area (sq km)	No. of glaciers in 1962	No. of glaciers 2004
<1	42	49
1-3	23	18
3-5	8	6
5-10	5	3
10-20	4	6
20-40	5	5
>40	3	1
Total	90	88

Table 5.4 : Statistical summary of loss in area of glaciers expressed in percentage from 1962 and 2004 in Parbati sub-basin

Loss in area (%)	Number of glaciers
100	6
>75	5
50-75	12
25-50	19
0-25	43

There are 42 glaciers, which lie in the areal range of 0-1 sq km in 1962 as compared to 49 in 2004. The increase in number is due to fragmentation of tributary glaciers from the main glacier. There are 6 glaciers, which have vanished completely followed by 5 glaciers, which have lost area between 75 to 100 %. The no. of glaciers, which have lost area ranging between 0 to 25 percent, is 43. There are two glaciers, which indicate no loss in area. Another two glaciers of the sub-basin could not be checked because of cloud cover. One glacier is also estimated to have increased its area although very small.

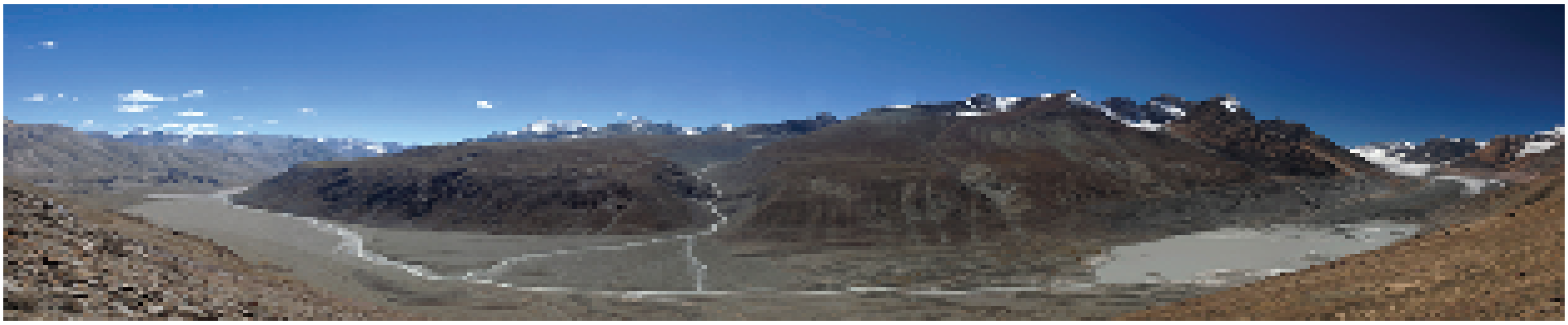


5.4 Parbati glacier

The Parbati glacier (GP 5.1) is one of the largest glaciers in the Parbati river basin, a major tributary of river Beas and fed by almost thirty-six glaciers, covering an areal extent of 188 sq km. Melt water from these glaciers form an important source into runoff of the Parbati basin. In terms of economics, the Parbati basin is very important because 800-MW-power project is under construction and another 520-MW-power project is being planned. In addition, many micro and mini hydroelectric projects are planned in the basin. Therefore, knowledge of the changes in glacial extent is important to assess future changes in stream runoff.

The boundary of Parbati glacier was delineated from the topographic maps of the Survey of India (1:50,000 scale). This region was surveyed using vertical air photograph taken in 1962. The boundary was superimposed on satellite images of 1990, 1998, 2000 and 2001 obtained using Landsat and Indian Remote Sensing Satellite images. Images of August-September season were selected, because during this period snow cover is at minimum and glaciers are fully exposed. Delineation of glacial boundary was carried out using standard band combination as 2 (0.52-0.59m), 3 (0.62-0.68m) and 4 (0.77-0.86m). Debris cover on the glacier was estimated using band combination as 2 (0.52-0.59m), 4 (0.77-0.86m) and 5 (1.55-1.75 m). Reflectance of rock in band 5 is higher than ice; therefore debris cover on glacier gives red tone. In year 1998, IRS PAN and LISS-III data were available. Therefore, this data was merged to improve interpretation capability. Various types of techniques can be used to merge data. However, Bovey technique was found more suitable for glaciated region. Geographic Information System (GIS) technique was used to analyze changes in glacial parameters. In order to verify position of glacier snout, an expedition was organized to Parbati glacier in October 2003. Snout position was obtained using GPS and by comparing relative position of snout in comparison with other geomorphological features.

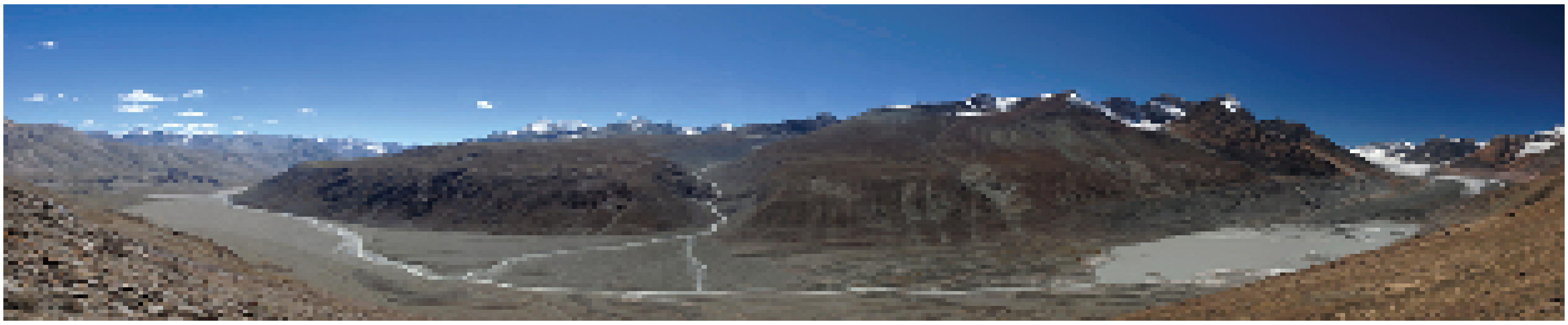
Initially, map of the Parbati glacier was prepared using topographic map of Survey of India. In 1962, the glacial areal extent was 48.44 sq. km and it was fed by two major tributary glaciers.



The main and tributary glaciers are facing northwest and northeast, respectively. In a period between 1962 and 1990, the glacier has experienced large retreat. Therefore, main and tributary glaciers got completely detached from each other, forming two independent glaciers. The areal extent of Parbati glacier was estimated from large number of satellite data, starting from year 1990 to 2001. In all four data sets were collected and analyzed. The satellite data is available for five years from 1990 to 2001. However, data is of different spatial resolution. Therefore, glacial retreat for analysis purpose is taken from data 1962, 1990, 1998 and 2001 (table 5.5). The total loss in glacial extent of 8.3 sq km was observed from 1962 to 1990. In addition, 1.93 and 1.32 km^2 loss in extent was observed for a period between 1990-1998 and 1998-2001, respectively. This suggests a total loss of 11.55 km^2 between 1962 and 2001. The loss in glacial length is also estimated and overall of glacial retreat was estimated as 5991 m from 1962 to 1990 and 578 m from 1990 to 2001. This suggests a total loss of 6569 m from 1962 to 2001. The amount of retreat is very high in a period between 1962 and 1990, possibly because of gentle topography of the deglaciated region. From year 1990 to 2001, systematic satellite data suggests large variations in amount of retreat from year to year. For example, for a period between 1998 and 2000 glacier was retreated by only 22 m and glacier was retreated by 97 m between 2000 and 2001.

In order to verify satellite observations, field investigation was carried out to assess position of glacier terminus. Position of glacier snout was estimated by comparing its relative position with other geomorphological features in field and in satellite images. In

GP 5.1 : Glacier snout of Parbati glacier in field.



addition, position of snout was also estimated using Global Positioning System. Field investigation suggests that lower portion of glacier tongue is broken in to independent ice mound. These are covered by fine sand and separated from each other by valleys. These ice mounds are not attached with active glacier and therefore, can be considered as dead ice. Dead ice mounds will slowly convert in to ice cored moraines and ice will melt independently of main glacier body. The transition of ice mound into ice-cored moraine can be clearly seen in the field. The zone of ice mounds and ice-cored moraines can be easily identified on high-resolution satellite images. This is because each ice mound is separated by valley and this topographic variation is causing mountain shadow.

For the Parbati glacier, the amount of retreat from 1962 to 1990 and from 1990 to 2001 was 5991 m and 578 m, respectively. This rate of retreat is very high and alarming in nature (table 5.6). In order to assess possible reasons for the unusual retreat, area altitude distribution of glacier was studied. The investigation suggests that entire glacier is located in low altitude zone. Cumulative percent area below each altitude zone is given. It suggests, almost 90 percent of glacier is located in altitude range lower than 5200 m. This is almost equal to the average altitude of snow line at the end of ablation season of year 2001. In addition, mid-altitude of glacier in 1962 was 4800 m. This is low as compared to mid-altitude of 5500 m and 5300 m in Beas and Satluj basins, respectively.

Table 5.5 : Satellite data used in the analysis

Satellite	Sensor	Spatial resolution (m)	Date of acquisition
Landsat	TM	30	18-09-1990
IRS	LISS-II	36.25	18-08-1993
IRS	PAN and LISS-III	5.8 and 23	05-09-1998
IRS	PAN and LISS-III	5.8 and 23	11-09-2000
IRS	LISS-III	23	27-08-2001

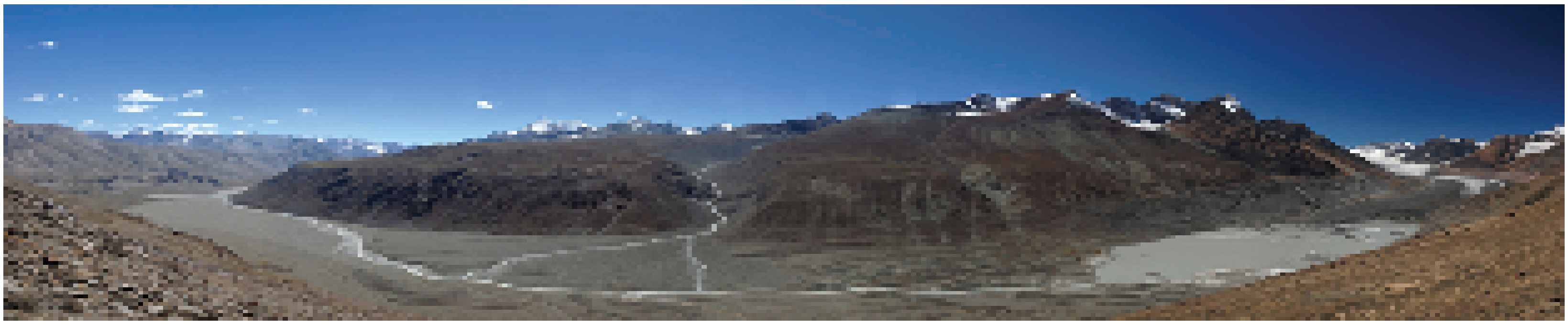
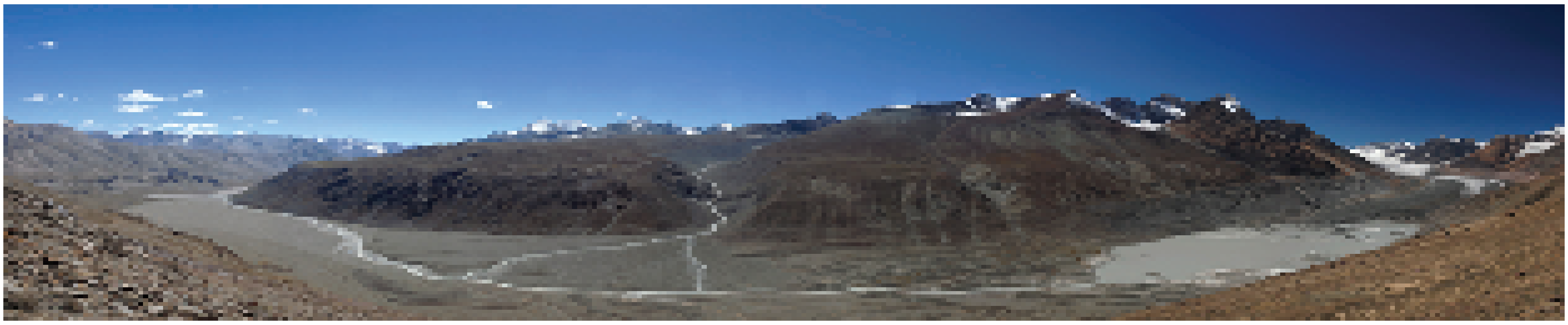


Table 5.6 : Changes in Parbati glacier between 1962 and 2001.

Year	Areal extent (sq. km)	Loss in area from		Maximum length (m)	Loss in Length from (m)			Snout altitude (m)
		1962 (km^2)	Previous observation		1962	Previous observation		
						Total	Rate/yr	
1962	48.44	-----	-----	16689	----	----		4042
1990	40.14	8.3	8.3	10698	5991	5991	214	4297
1998	38.21	10.23	1.93	10239	6450	459	57	4324
2000	37.73	10.71	0.48	10217	6472	22	11	4326
2001	36.87	11.55	0.84	10120	6569	97	97	4331

5.5 Samudra Tapu glacier

Samudra Tapu is one of the largest glaciers in Chandra basin of district Lahaul and Spiti, Himachal Pradesh. Based on the field investigations and the remote sensing techniques, features such as accumulation area, ablation area snowline/equilibrium line, moraine-dammed lakes and permanent snowfields were mapped(figure 5.1). The glacial terminus was identified using moraine-dammed lake, as lake is located at down streamside of the terminus. The total recession of glacier during the period of 38 years (1962-2000) is about 742 m with an average rate of 19.5 m/yr. In addition, glacial extent is reduced from 73 to 65 km^2 between 1962 and 2000, suggesting overall deglaciation of 11%. During field investigation, three stages of glaciation using terminal moraine were identified(GP 5.2). These moraines were mapped by merging LISS-III and Pan Data. At the peak of glaciation, the glacial terminus was extended 3.18 km downstream of terminus position in year 2000. Total area during peak of glaciation period has been observed to be 77.67 km^2, which is 12.67 km^2 higher than the present glacier extent.



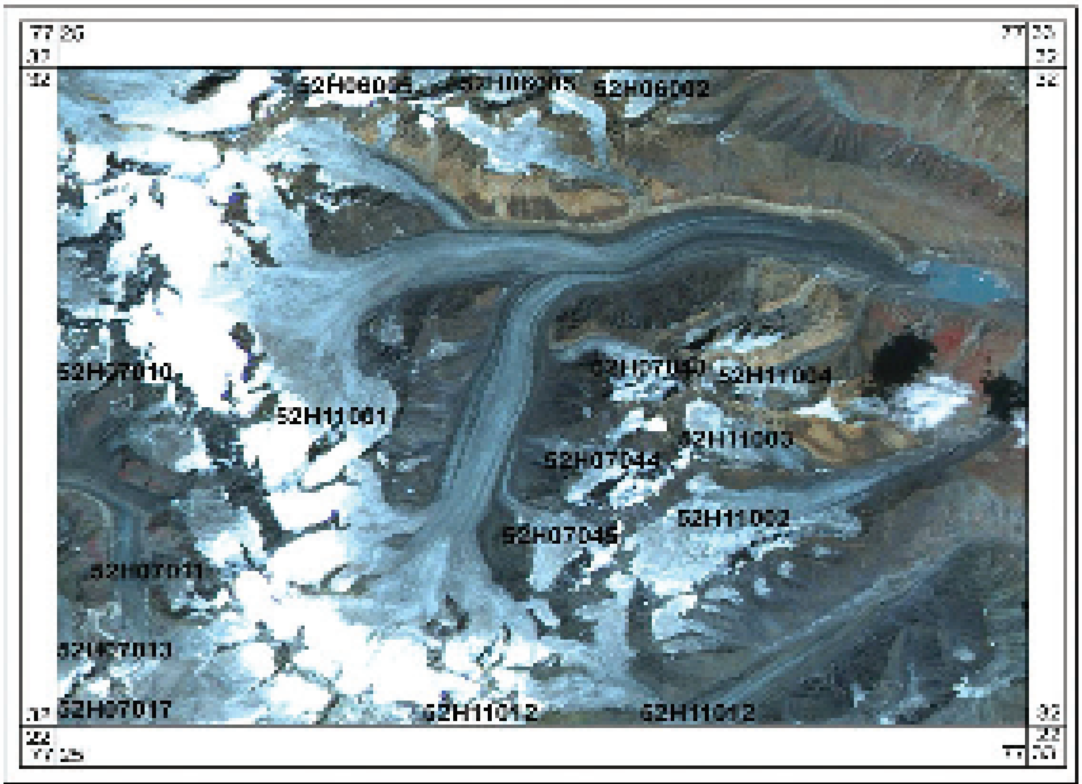
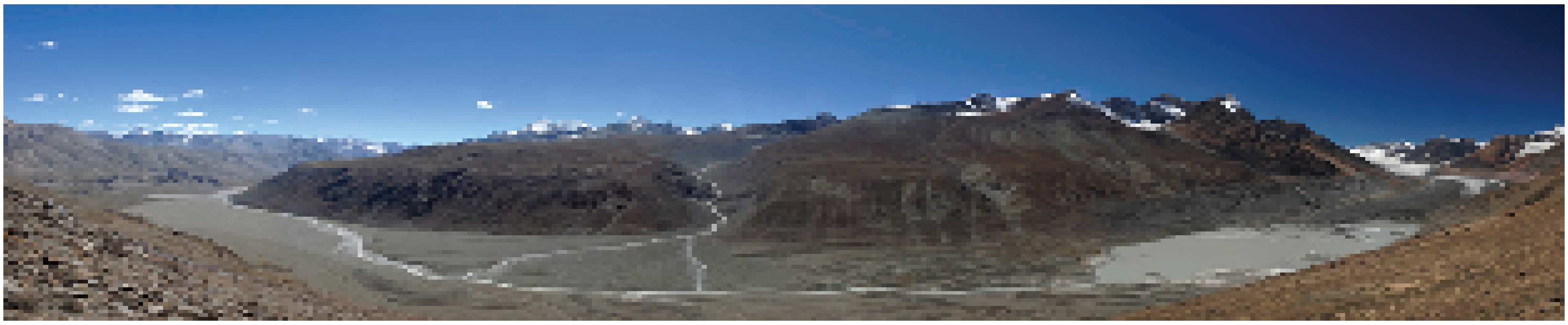


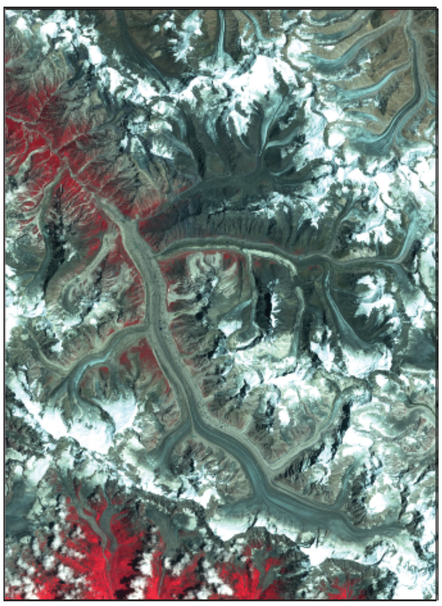
Figure 5.1 : IRS 1C LISS III Image of August 23, 2005
showing the Samudra Tapu glacier (Chandra Sub-Basin)

GP 5.2 : A view of snout of Samudra Tapu glacier



5.6 Gangotri glacier

Monitoring of glacier advance and retreat requires correct identification of the glacier snout. Many times identification of snout needs mapping of various peri and pro-glacial features such as ice, moraines, streams, lakes and vegetation in deglaciated valley. These features normally have unique reflectance characterists in different spectral bands. However, available multispectral satellite data has normally medium spatial resolution. Therefore finer details of these features are sometimes difficult to be interpreted. On the other hand panchromatic data is available in high resolution but lacks multispectral information. Therefore fusion of panchromatic images and multispectral data can provide unique characteristics of both the sensors. IRS LISS III and PAN images covering the Gangotri glacier have been merged through HIS and Brovey transformation to locate its snout. Investigation has shown that Brovey transformation is useful for better identification of snout of the Gangotri glacier. The snout has been validated in the field using GPS in differential mode. Identification of snout of Gangotri glacier on satellite images can be utilised in assessment of its tongue activity in recent past. The retreat of Gangotri glacier was found to be of the order of 1525 m between 1962 and 2001(figure 5.2).



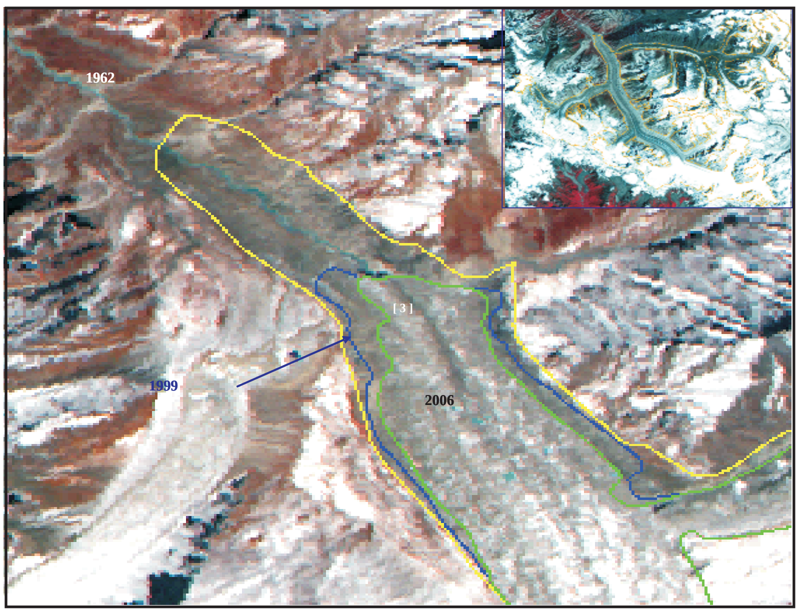
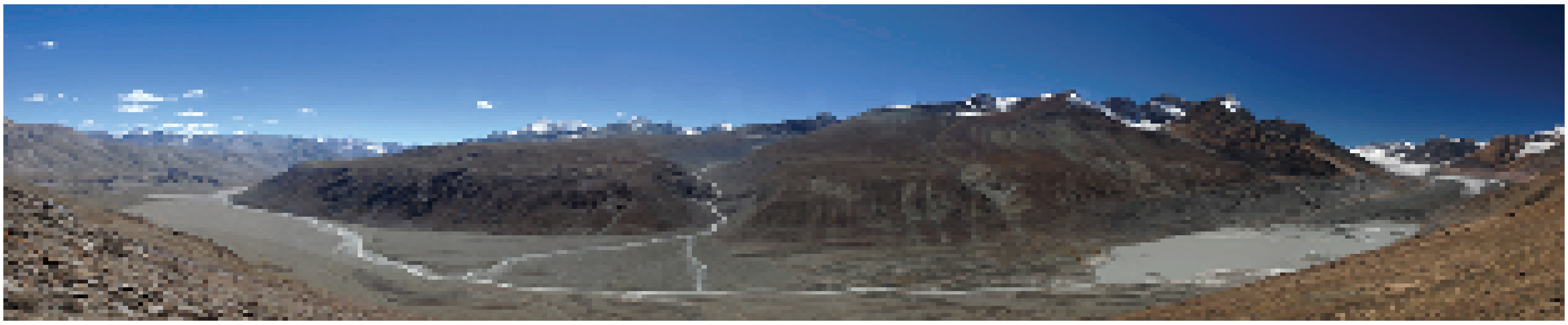
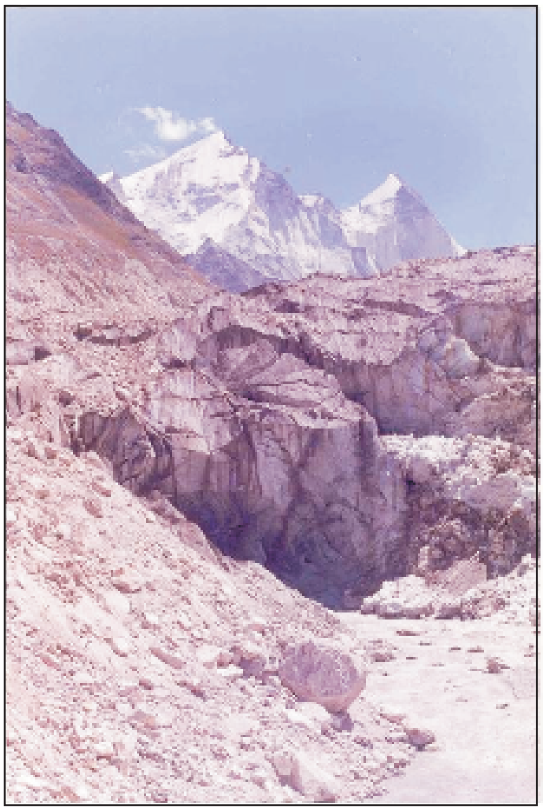


Figure 5.2 : IRS LISS III Image showing full view of Gangotri glacier(left) and retreat of its snout from 1962 to 2000.

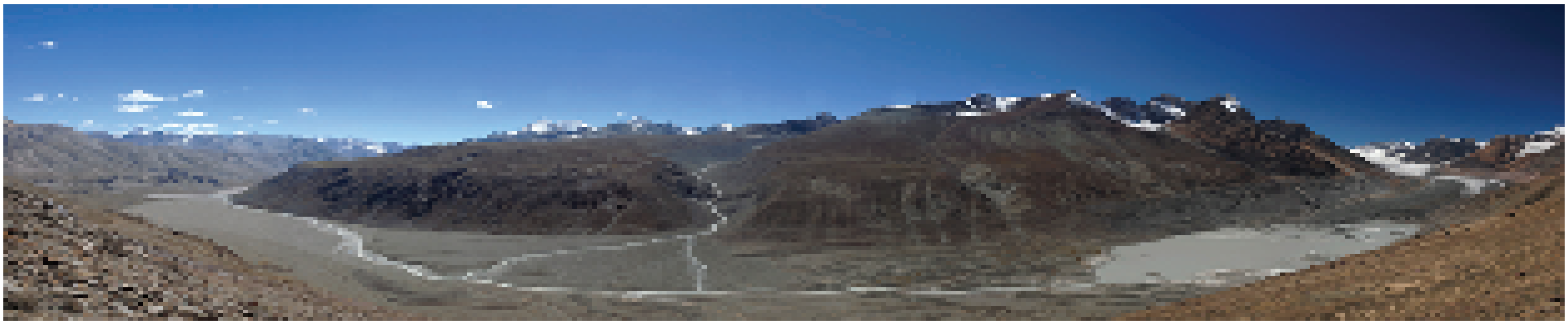




GP 5.3 : Snout of Gangotri glacier in the field (2001).

Digital data of PAN and LISS-III sensors were used. Field investigations were also carried out at the Gangotri glacier using hand held GPS and differential GPS. To use DGPS a permanent reference station has been identified near the glacier and rover station has been used to take reading of snout of glacier. Observation of hand held GPS have been noted down directly from instrument whereas data of DGPS has been processed using SKI software. Ground Control Points (GCP) near the snout of the glacier were identified based on mainly the intersections of streams and track and their co-ordinates were obtained using GPS. These were used to georeference and merge satellite data.

Field verification of glacial snout was carried out using GPS. The coordinates of glacial snout obtained by georeferenced-merged image are 79 4' 48.35” and 30 55' 40.879”. The coordinates of glacial snout obtained by using DGPS are 79 4' 48.75105” and 30 55' 40.55798”. This gives an accuracy of approximately 5-15m. The difference in coordinates is attributed to inaccuracy in the identification of GCPs and location of snout observed on the image. The coordinates are in close proximity, suggesting usefulness of technique for monitoring snout of Gangotri glacier and for many other glaciers in the region.



5.7 Glacier advance / retreat studies (selected 16 sub-basins under joint programme of DOS & MoEF)

The retreat or advance what is normally observed on the surface is the response of glaciers to adjust to change in its mass balance. The most conspicuous effect is seen on the movement of snout or terminus. The retreat can be measured in following two ways:

1. Linear or one dimensional based on movement of snout
2. Aerial or two dimensional based on change in glacier area

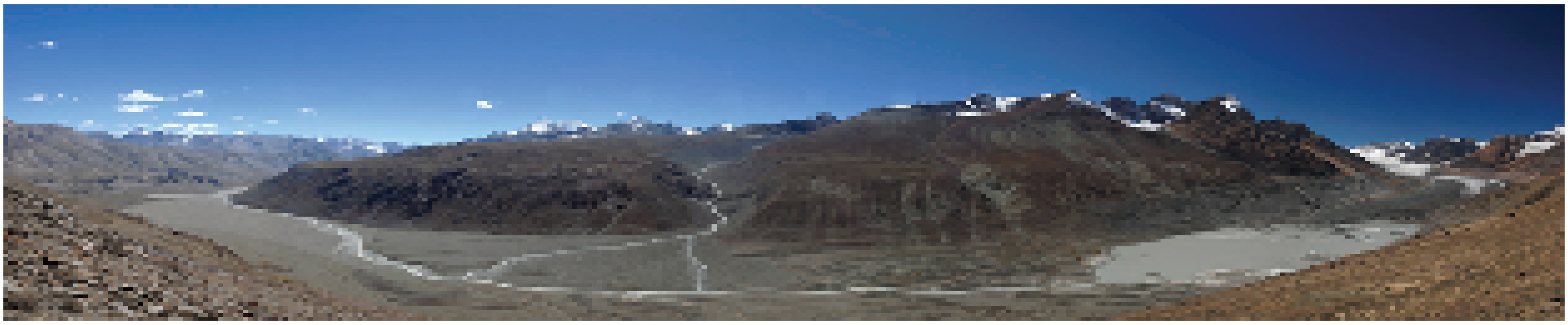
The approach adopted here is based on the areal extent measurements using topographical maps and satellite images. As discussed in methodology the work has been carried out in two parts.

(i) Measurements of changes in extent using topographical maps as reference maps and comparing the extent interpreted from IRS LISS III images covering the specific basin: The topographical maps of 1962 are used except in case of Suru and Nubra basin where maps are of 1969. The satellite data used is of year 2001 or 2004 or 2005 and 2007. The survey of India maps were also checked in the field for a few glaciers to ascertain the accuracy of glacier extents.

(ii) Measurements of changes in extent of glaciers interpreted using satellite images only: The satellite images used as reference are Landsat TM images of 1989/1990 and recent IRS images pertaining to 2001-07 time frame.

Glaciers of sixteen sub-basins were monitored. The work has been carried out in collaboration with twelve other organizations. The organizations include Universities, State Remote Sensing Centres and other government organizations.

Digital database for the areal extent of individual glaciers of each basin has been created in a GIS environment. These basins are located in different geographic, geologic and climatic conditions. The glaciers include valley glaciers and small permanent snow/ice fields. For example Chandra, Bhaga, Miyar, Warwan and Bhut basins are located in Himachal Pradesh or at the border of Jammu and Kashmir and Himachal Pradesh. They all are part of Chenab basin and occur in the region where wet precipitation is poor. Alaknanda, Bhagirathi, Dhauliganga and Goriganga basins are located in Garhwal and Kumaon Himalayas and lie at a lower latitude than Chenab basin. Suru and Zanskar basins belong to Zanskar range of



Ladakh and lie across northwards of Chenab sub-basin. Parbati sub-basin belongs to Beas and Beas is tributary of Satluj basin. This basin lies in relatively wet zones of Himachal Pradesh. Basapa is a part of Satluj basin and lies in wet zones of Himachal Pradesh. The Spiti basin is also a part of Satluj basin and bears a dry climatic condition. Within each basin also glaciers behave differently because the local inherent characters of valleys play important role in accumulation and ablation. The geologic, geomorphic and climatic conditions control the accumulation and ablation pattern of glaciers. These external forcing also has implication on debris cover on glaciers.

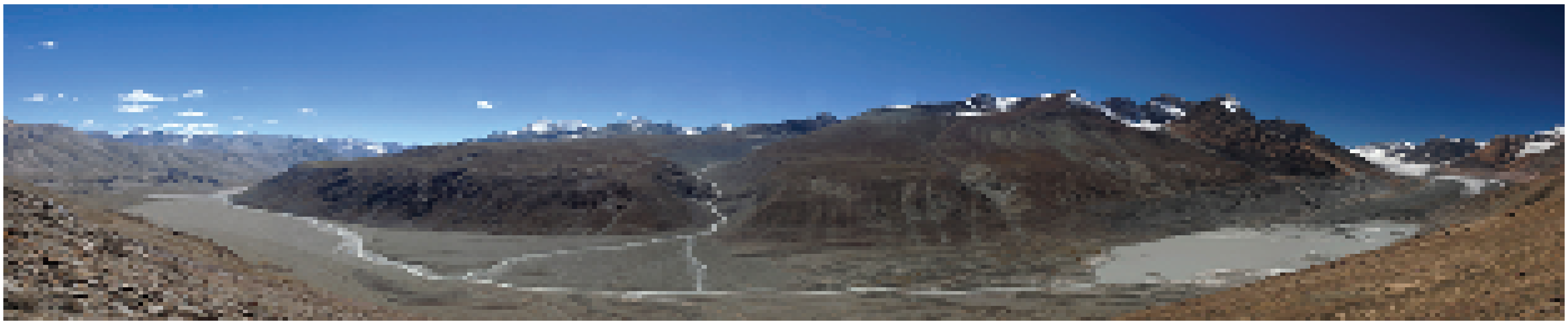
The results of retreat/advance have been presented in four tables. The results show the total gain or loss for an individual basin. The loss or gain is expressed as percentage of total initial area of glaciers. Table 5.7 shows the total loss in area of glaciers for each basin based on SOI topographical maps as reference maps. Small permanent snow fields and ice fields are also included as glaciers. Table 5.8 shows the statistics of number of glaciers showing retreat/advance or no change based.

Table 5.9 shows the change in glacier extents as mapped from satellite data of different periods for the same basins. Table 5.10 shows the statistics of number of glaciers showing retreat, advance or no change. Based on the data shown on these tables we discuss the results of each basin.

Chandra Sub-basin:

Bara Shigri, Chota Shigri, Hamta and Samudra Tapu glaciers are some of the large glaciers of this basin. Glacier boundaries of 116 glaciers were taken from topographical maps. The total area of these glaciers in 1962 and 2001 were 696 and 554 km^2 respectively. This gives a loss of 20% in glacier area. Number of glaciers which show retreat are 113 and the glaciers which do not show any change is 3. This shows that most of the glaciers in this basin show retreat.

Landsat images available of 1990 covering this basin show that most of the glaciers are snow covered. Therefore the comparison could not be done for most of the glaciers. The



snouts of three glaciers could be identified and mapped on 1999 data. The three glaciers having an area of 107 sq km show a decline of about 3 % during a period of 12 years.

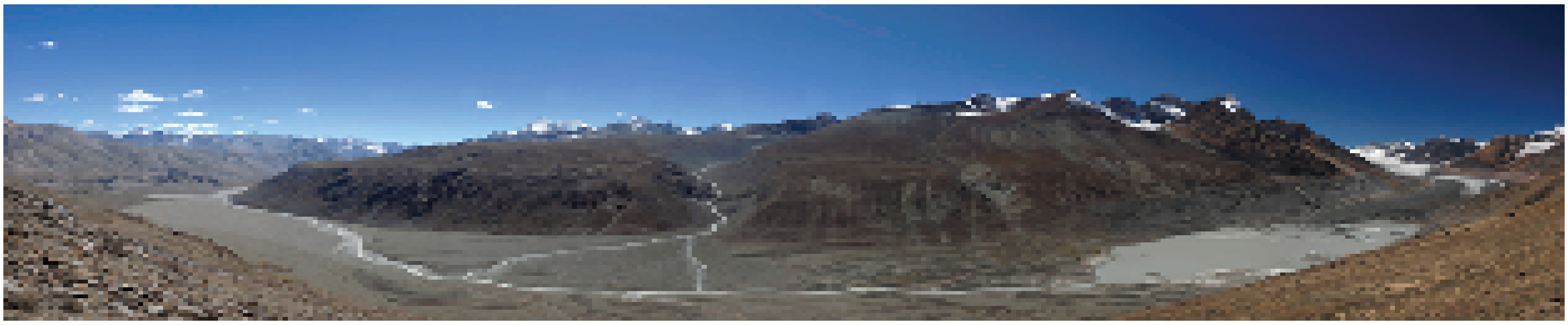
Bhaga sub-basin

Most of the glaciers of this basin are located on Manali Leh road along the river Bhaga. Glacier boundaries of 111 glaciers were adopted from topographical maps of this basin. The total area of 111 glaciers in 1962 and 2001 has been found to be 363 km^2 and 254 km^2 respectively. There is loss of 30 % during 1962-2001. Among these 108 glaciers show retreat and 3 glaciers do not show any change. Bhaga basin is located in similar climatic conditions as Chandra basin but glaciers of this basin show higher rate of retreat. This is possibly due to the fact that glaciers of this basin are mostly debris free. Glaciers with or without debris cover can be discriminated on FCCs. Another reason for this much retreat could be the size of the glaciers. Mean glacier area of this basin suggests that glaciers are smaller in size. Smaller size indicates the smaller depth of glaciers and short response time. Therefore retreat or advance is faster in smaller glaciers.

Landsat images of ablation season in 1990 covering this basin show that glaciers are mostly snow covered. However ten glaciers were observed to be exposed at their snouts in images of 1990. Glacier extents of these glaciers were compared using satellite images. The ten glaciers having an area of 90 sq km show a decline of about 2 % during a period of 12 years. This rate is relatively smaller than what has been found for duration of 1962-2001. A glacier named after Panchinala stream originating from it was also visited on ground. Another glacier near Patsio village called Patsio glacier has been visited for its snout position verification.

Warwan sub-basin

The number of glaciers mapped from topographical maps for this basin is 230. The total area of these glaciers is 740 km^2 in 1962 and 608 km^2 in 2001 respectively. This gives a loss of 18 %. No. of glaciers which show retreat is 180 and which do not show any change is 15.



Among these, 35 glaciers show even advance. This shows that about 78 % of the glaciers of this basin show retreat.

Glacier extents were also compared using satellite images available for 2001 and 2007. The number of glaciers which could be compared using the satellite images of the above time frames is 180. The total area declined from 513 to 510 sq km. This gives 1 percent loss during 2001-2007. This loss of 1 percent in 6 years is much less than 18 % loss during 1962-2001. This shows that there is decline in the trend of glacier retreat after 2001.

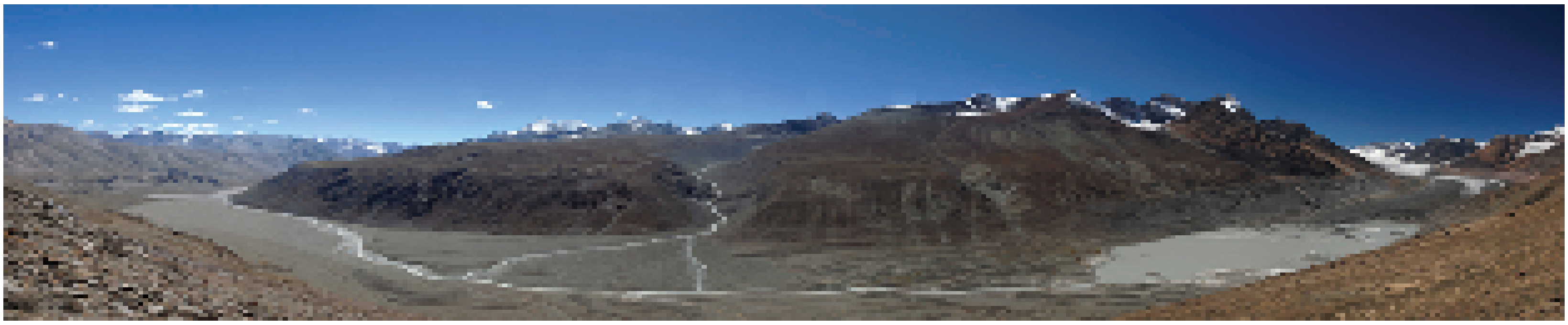
Bhut sub-basin

The number of glaciers mapped from topographical maps for this basin is 143. The total area of glaciers is 450 km^2 in 1962 and 417 km^2 in 2001 respectively. This gives a loss of 7 %. No. of glaciers which show retreat is 74 and 29 glaciers do not show any change. Among these, 40 glaciers show advance. This shows that 51.7 % of the glaciers show retreat.

Glacier extents were compared using satellite images available for 2001 and 2007. Twenty eight glaciers could be compared using the images. The total area declined from 217 to 203 sq. km. This gives 6 percent loss during 2001-2007. This loss of 6 percent is much higher than loss during 1962-2001. This shows that the glacier retreat after 2001 for this basin is much rapid than previous years. Though Bhut basin and Warwan basin are adjacent basins, the rate of retreat during 1962-2001 and 2001-2007 show a contrasting trend.

Alaknanda sub-basin

Satopanth and Bhagirath Kharak glaciers are some of the large glaciers of this basin. The number of glaciers which were mapped from topographical maps is 274. The total area of glaciers is 1047 km^2 in 1962 and 905 km^2 in 2004 respectively. This gives a loss of 14 %. No. of glaciers which show retreat is 243 and 4 glaciers do not show any change. Among these, 27 glaciers show even increase.



When glacier extents were compared using satellite images available for years 1990 and 2005 we find that there is a loss of 10 % in glacier area. The glacier area in 1990 and 2005 are 393 km^2 and 355 km^2 respectively for 119 glaciers. The loss after 1990 is 10 percent as compared to 14 percent during 1962-2005. This shows that the glacier retreat after 1990 for this basin is much rapid than previous years.

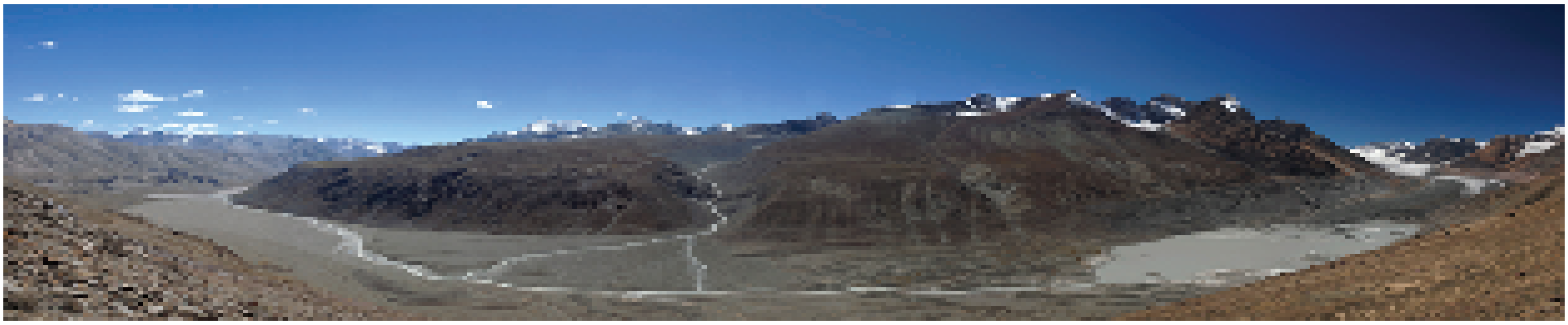
Bhagirathi sub- basin

Gangotri group of glaciers is largest glacier of this basin. There are 183 glaciers which have been mapped for this sub-basin. The total area of glaciers is 1218 km^2 in 1962 and 1074 km^2 in 2004 respectively. This gives a loss of 11 %. No. of glaciers which show retreat is 117 and 39 glaciers do not show any change. Among these, 27 glaciers show even advance.

When glacier extents were compared using satellite images available for 1990 and 2005 we find that there is a loss of 1.8 % in glacier area. The glacier area in 1990 and 2005 are 867 km^2 and 851 km^2 respectively for 153 glaciers. The loss after 1990 is 1.8 % than 11 % during 1962-2005. Among 153 glaciers only 44 show retreat, 6 show advance and 103 glaciers show no change. This shows that the glacier retreat after 1990 for this basin is much slower than in adjacent basins and also in comparison to period of 1962-2005. Though Alaknanda and Bhagirathi basin are adjacent basins the rate of retreat during 1962-2001 and 2001-2007 show a contrasting trend.

Gauri ganga sub-basin

Milam glacier is one of the largest glaciers of Kumaon Himalayas. The satellite images and corresponding map covering this glacier are shown in figure 5.5. The retreat was estimated for selected glaciers subject to the availability of topographical maps of this region. The comparison between satellite images of year 1990 and 2005 has also been carried out.



Twenty Nine glaciers with area of 272 km^2 in 1990 and 261 km^2 in 2005 indicating a loss of 4 percent were mapped. Most of the glaciers of this basin show retreat.

Dhauliganga sub-basin

Extents of a few glaciers of this basin have been taken from topographical maps. There are 104 glaciers shown in topographical maps. Among 104 glaciers 65 glaciers show retreat whereas 39 glaciers show no change. The loss found during 1962-2005 is 16 %. This loss is quite comparable to retreat of glaciers in other basin.

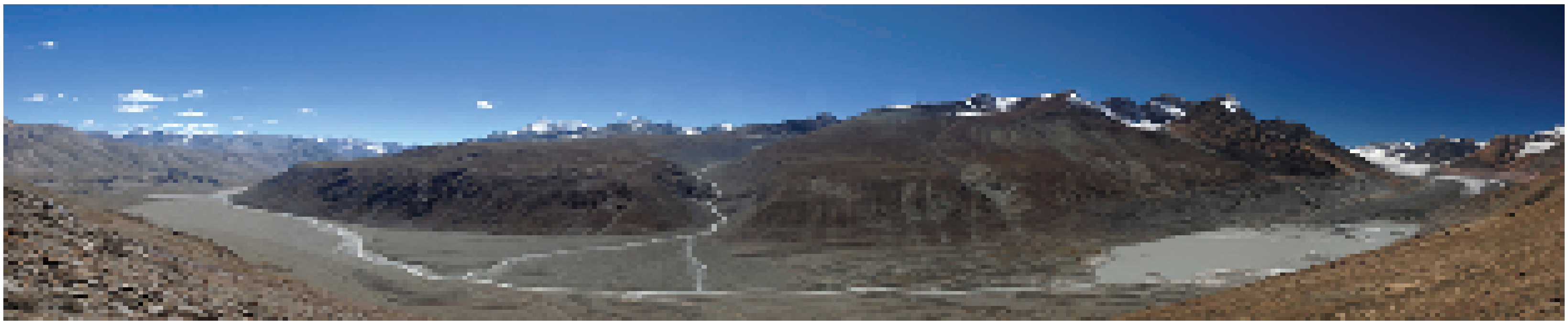
Suru sub-basin

215 glaciers were mapped for this basin. The total area of glaciers is 568 km^2 in 1969 and 474 km^2 in 2001 respectively. This gives a loss of 17%. All glaciers show retreat in this basin. 17% loss matches well with similar loss shown by many other basins though the duration of monitoring is smaller than with respect to monitoring carried out using topographical maps of 1962.

When glacier extents were compared using satellite images available for 1990 and 2001 we find that there is a loss of 9 % in glacier area. The glacier area in 1990 and 2001 are 506 km^2 and 459 km^2 respectively for 355 glaciers. All the 355 glaciers show retreat. The loss after 1990 is 9 %. This shows that there glacier retreat after 1990 for this basin is much rapid than in comparison to period of 1969-2001.

Zanskar sub-basin

The number of glaciers monitored in this basin is highest among all. Six hundread thirty one glaciers were mapped for this basin. The total area of glaciers is 1107 km^2 in 1962 and 940 km^2 in 2001 respectively. This gives a loss of 15%. No. of glaciers which show retreat is 578. Rest of glaciers either show no change or advance. 15 % loss in glacier area matches well with similar loss shown by many other basins.



When glacier extents were compared using satellite images available for 2001 and 2006 we find that there is a loss of 9 % in glacier area. The glacier area in 1990 and 2001 is 775 km^2 and 709 km^2 respectively for 463 glaciers. Among these, 422 glaciers show retreat. The loss after 2001 is 9 %. This shows that glacier retreat after 2001 for this basin is much rapid than in comparison to period of 1962-2001. The 9 % loss after 2001 in Zanskar basin is comparable to Spiti basin.

Spiti sub-basin

Three hundred thirty seven glaciers were monitored for this basin. The total area of glaciers is 474 km^2 in 1962 and 396 km^2 in 2001 respectively. This gives a loss of 16 %. No. of glaciers which show retreat is 169. Rest of glacier either show no change or advance. 16 % loss matches well with similar loss shown by many other basins.

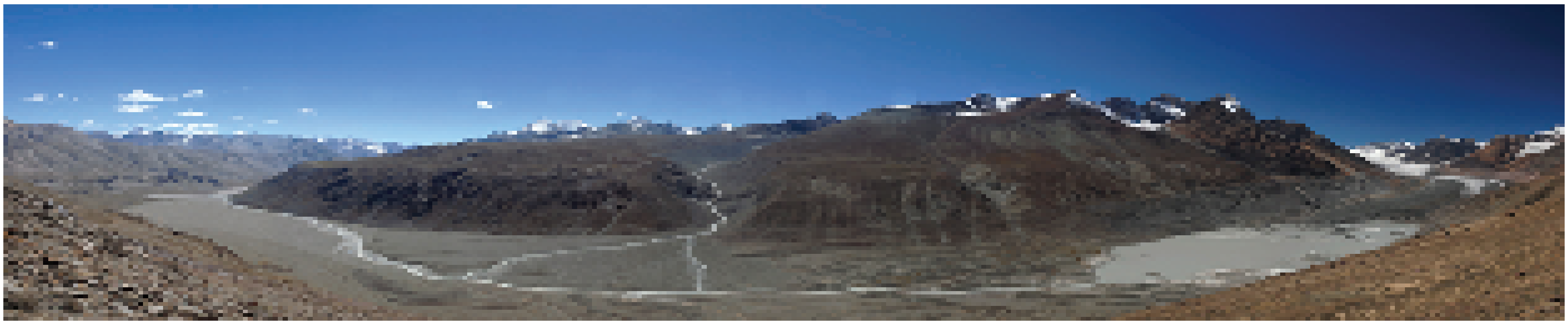
When glacier extents were compared using satellite images available for 2001 and 2007 we find that there is a loss of 13.4 % in glacier area. The glacier area in 2001 and 2007 are 718 and 622 respectively for 722 glaciers. Among all 648 glaciers show retreat. This shows that there glacier retreat after 2001 for this basin is much rapid than in comparison to period of 1962-2001. This rate is highest among all basins for a period after 2001.

Parbati sub-basin

The number of glaciers monitored during 1962- 2001 are 90. Eighty eight glaciers show loss in area. The loss for the basin comes out to be 20 %. Based on satellite images the loss is 5% during 1998-2004. This rate is also higher than what has been found during 1962-2001. Figures 5.3 & 5.4 show retreat of glaciers in Parbati basin.

Tista sub-basin

Since the topographical maps were not available for this basin the glaciers were only monitored using satellite images. 34 glaciers mapped from data of 1990. The total area of these glaciers in 1990 was 305 km^2 and decreased to 301 km^2 in 2004. This gives only 1 percent loss. Tista basin is located in much lower latitudes than other basins. Most of the



glaciers are covered with debris. There is almost no retreat in this basin. It shows that basins of eastern Himalaya show no or very less retreat than western Himalayas. Among 34 glaciers 23 glaciers show retreat and rest of them show either no change or advance.

Nubra Sub-basin

The number of glaciers monitored during 1962- 2001 are 31. Seventeen glaciers show loss in area. The loss for the basin comes out to be 6 %. The total area of glaciers in 1969 was 2150 km^2 and 2026 km^2 in 2001. This data shows that the glaciers of this basin are very large. The number of glaciers mapped in 1989 is 84 and cover 3159 km^2 area. The area increases to 3163 km^2 in 2001. The data indicates almost no change in glaciers after 1989. As we see that the number of glaciers of this basin occupy a very large area the response time is slow and retreat is very less. Figure 5.6 shows an advancing glaicer in Shyok basin.

Ground Photograph 5.4 shows snout of Panchinala glacier near Patsio. GP 5.5 shows a glacier covered with thin layer of snow near Bara Lacha Pass on Leh road. GP 5.6 is the ground picture of snout of a glacier near Zing Zing Bar(22 km. from Patsio). GP 5.7 shows the debris cover and crevasse on the Panchinala glacier.

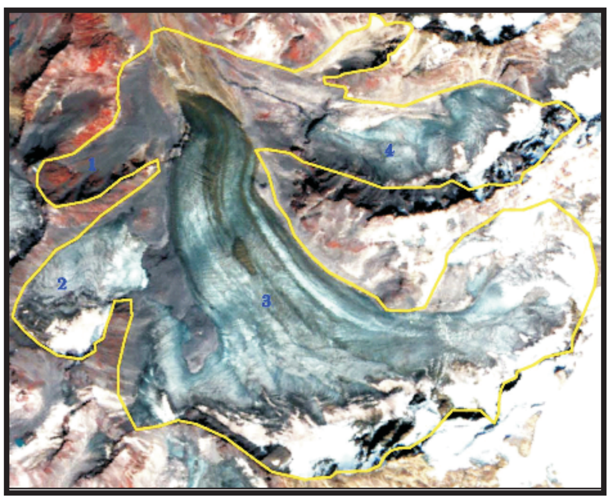


Figure 5.3 : Retreat and fragmentation shown on IRS LISS IV image covering glaciers of Parbati basin. The boundary of glacier is taken from SOI map of 1962.

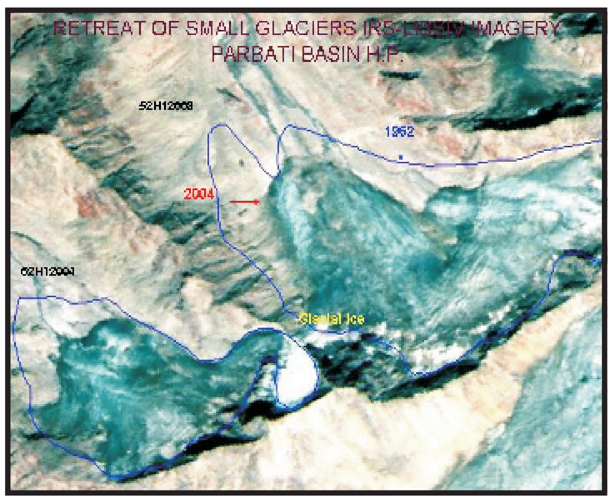


Figure 5.4 : Glacier retreat shown on IRS LISS III image covering glaciated region of Parabati basin. The blue colour boundary of glacier is taken from SOI map of 1962

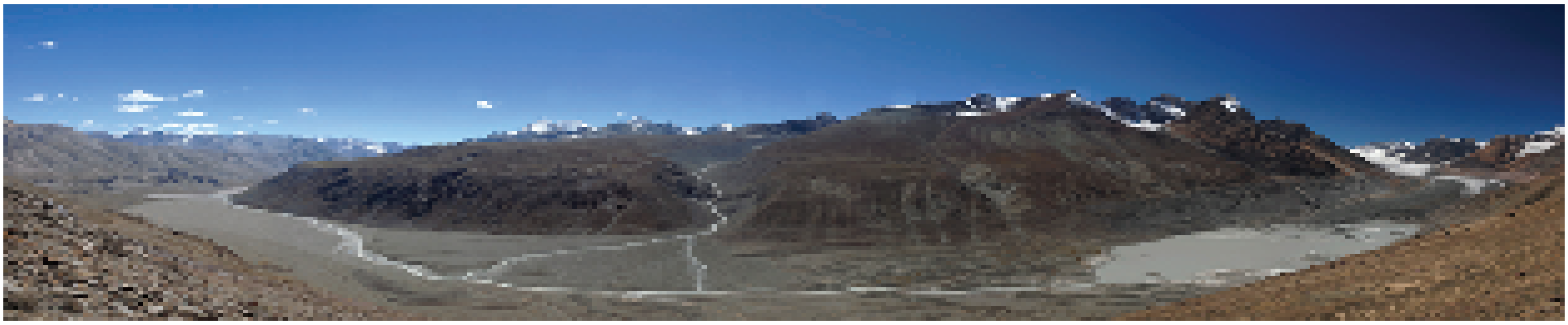
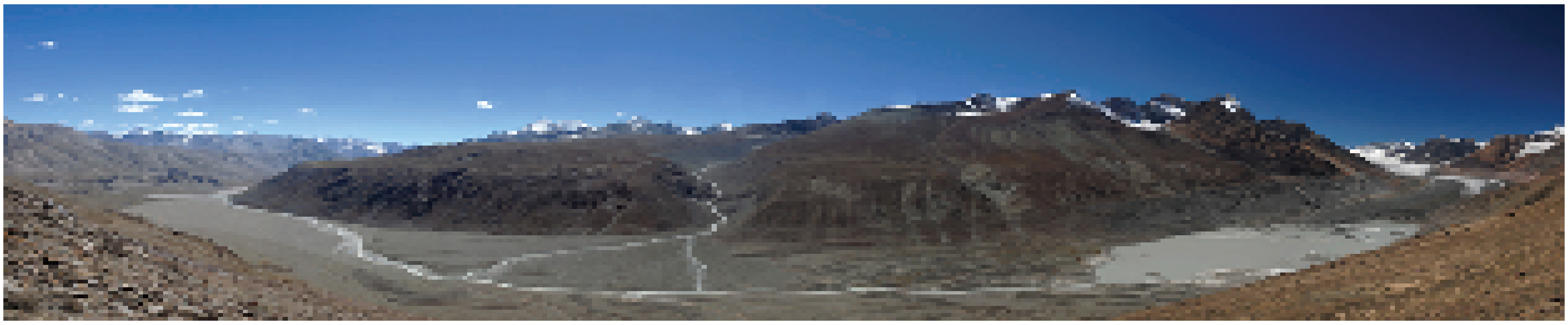
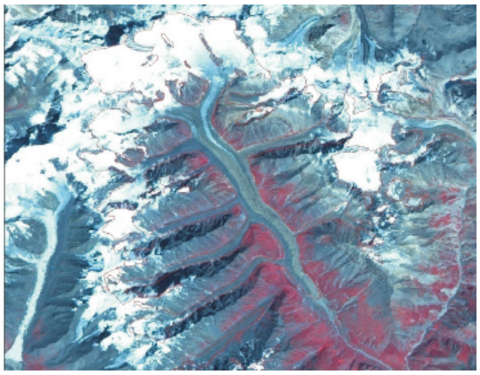


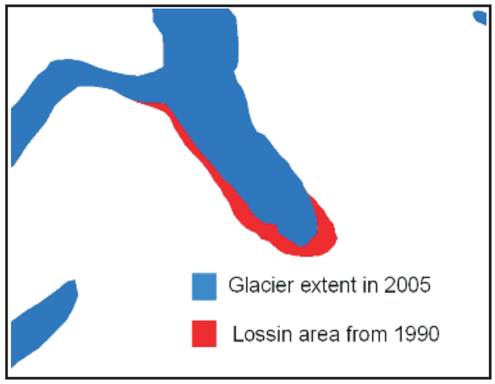
Table 5.7 : Loss/gain in area (km²) of glaciers in different basins based on Survey of India (SOI) maps and satellite images.

S.N.	Sub-Basin	No. of glaciers monitored	1962 /1969* (km^2)	2001/2004*/2005# (km^2)	Loss in area %
1.	Chandra	116	696	554	20
2.	Bhaga	111	363	254	30
3.	Warwan	230	740	608	18
4.	Bhut	143	450	417	7
5.	Miyar	165	568	523	08
6.	Alaknanda	274	1047	905#	14
7.	Bhagirathi	183	1218	1074#	11
8.	Dhauliganga	104	429	362#	16
9.	Suru	215	568*	474*	17
10.	Zanskar	631	1107	940	15
11.	Parbati	90	493	390	20
12.	Spiti	337	474	396	16
13.	Nubra	31	2150*	2026	6



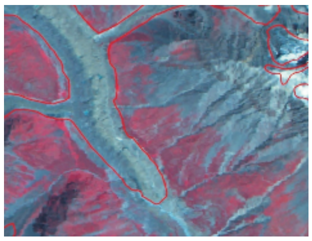


Milam Glacier on IRS LISS –III (2005)



Vector-map Showing Retreat of Glacier from 1990 to 2005

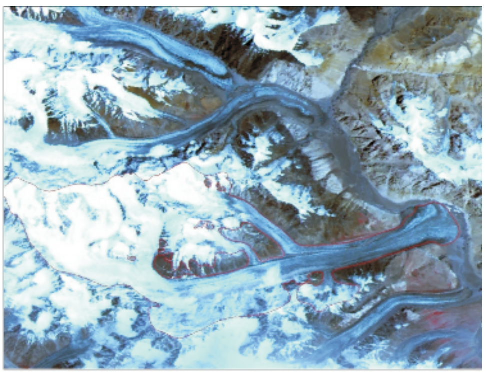
Snout in 1990 (Landsat -TM)



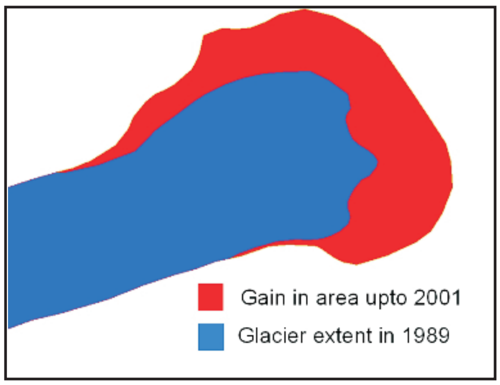
Snout in 2005 (IRS - LISS-III)

Area in 1990 (Sq.Km)	68.77
Area in 2005 (Sq.Km)	66.12
Change in Area (Sq.Km)	2.65

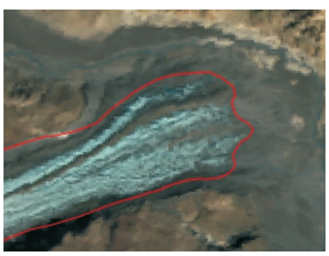
Figure 5.5 : A retreating glacier of Goriganga Sub-basin



Kichik Kumdan Glacier on IRS LISS –III (2001)



Vector-map Showing advance of Glacier from 1989 to 2001



Snout in 1989 (Landsat -TM)

Snout in 2001 IRS - LISS-III

Area in 1989 (Sq.Km)	65.44
Area in 2001 (Sq.Km)	67.38
Change in Area (Sq.Km)	1.94

Figure 5.6 : An advancing glacier of Indus Basin

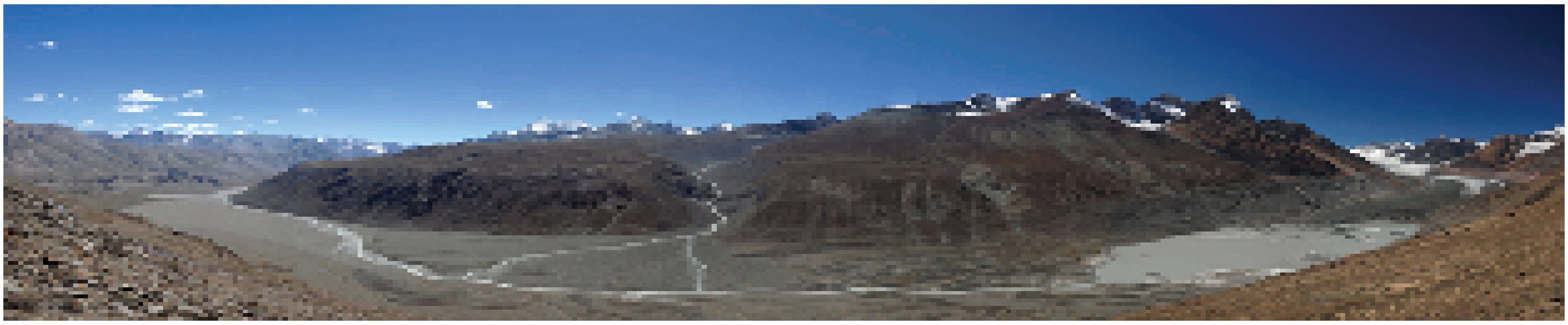


Table 5.8 : Status of glacier advance/retreat in different basins based on SOI maps and satellite images

S.N.	Sub-Basin	No. of Glaciers monitored	Retreat	Advance	No Change
1.	Chandra	116	113	-	3
2.	Bhaga	111	108	-	3
3.	Warwan	230	180	35	15
4.	Bhut	143	74	40	29
5.	Miyar	165	80	78	7
6.	Alaknanda	274	243	27	4
7.	Bhagirathi	183	117	27	39
8.	Dhauliganga	104	65	-	39
9.	Suru	215	215	-	-
10.	Zanskar	631	578	53	-
11.	Parbati	90	88	-	2
12.	Spiti	337	169	161	7
13.	Nubra	31	17	14	-
Total		**2630**	**2047**	**435**	**148**

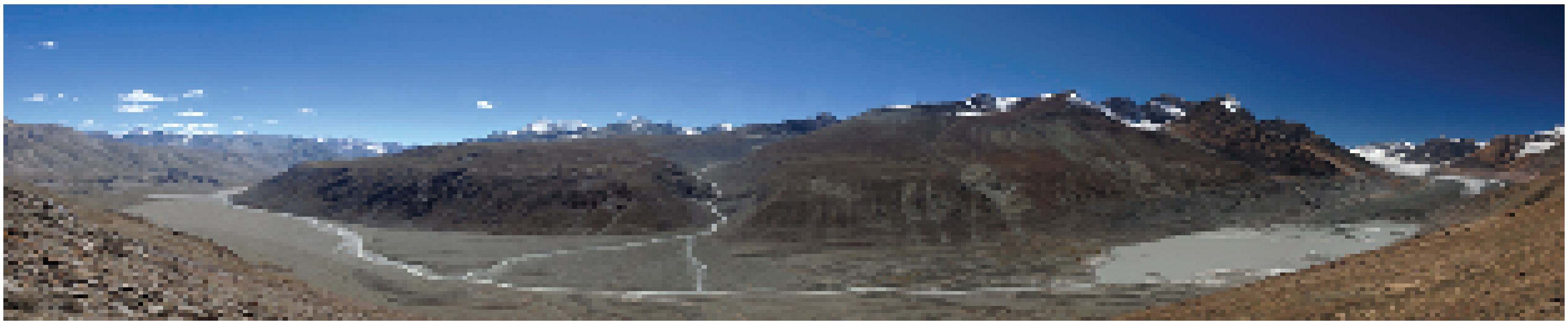


Table 5.9 : Loss/gain in area (km^2) of glaciers in different basins based on satellite images.

S.N.	Sub-basin	No. of Glaciers monitored	Year	Area (km^2)	Year	Area (km^2)	Loss Gain %
1.	Chandra	3	1989	107	2002	104	3
2.	Bhaga	10	1990	90	2001	88	2
3.	Warwan	180	2001	513	2007	510	1
4.	Bhut	28	1989	217	2002	203	6
5.	Alaknanda	119	1990	393	2005	355	10
6.	Bhagirathi	153	1989	867	2005	851	1.8
7.	Gauriganga	29	1990	272	2005	261	4
8.	Suru	355	1990	506	2001	459	9
9.	Zanskar	463	2001	775	2006	709	9
10.	Parbati	10	1998	113	2004	107	5
11.	Spiti	722	2001	718	2007	622	13.4
12.	Nubra	84	1989	3159	2001	3163	0.0
13.	Tista	34	1990	305	2004	301	1

GP 5.4 : Snout of Panchinala glacier(Bhaga basin).

GP 5.5 : Accumulation zone of Panchinala glacier near Patseo in Bhaga basin

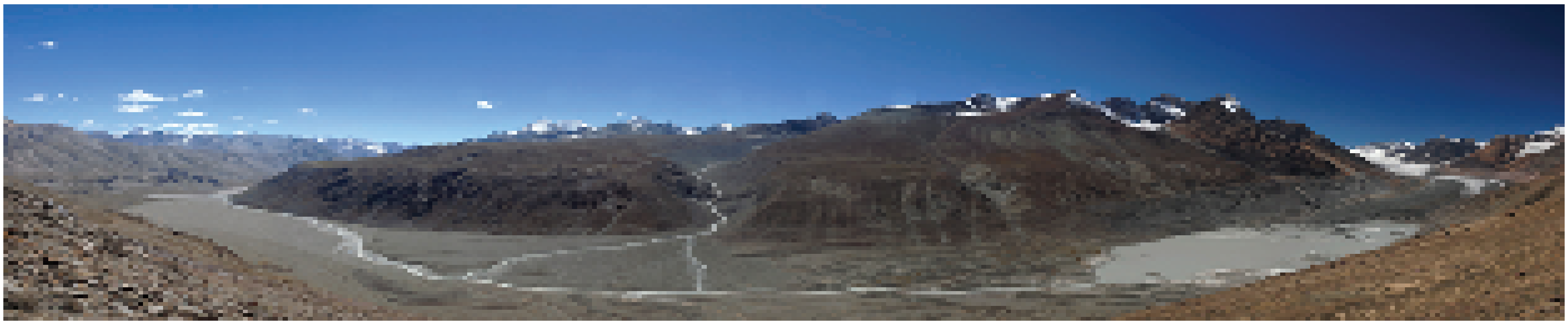


Table 5.10 : Status of glacier advance/retreat in different basins based on satellite images

S.N.	Sub-Basin	No. of Glaciers monitored	Retreat	Advance	No Change
1.	Chandra	3	3	-	-
2.	Bhaga	10	10	-	-
3.	Warwan	180	32	-	148
4.	Bhut	28	17	-	11
5.	Alaknanda	119	119	-	-
6.	Bhagirathi	153	44	6	103
7.	Gauriganga	29	20	-	9
8.	Suru	355	299	39	17
9.	Zanskar	463	422	41	-
10.	Parbati	10	10		
11.	Spiti	722	648	39	35
12.	Nubra	84	26	25	33
13.	Tista	34	23	8	3
Total		**2190**	**1673**	**158**	**359**

GP 5.6 : Snout of Patsio glacier (Bhaga Sub-basin)

GP 5.7 : Debris cover Panchinala glacier(Bhaga Sub-basin)

6. Monitoring Snowline for Mass Balance

6.1 Introduction

The mass balance of the glacier is usually referred as the total loss or gain in glacier mass at the end of the hydrological year. It is estimated by measuring the total accumulation of seasonal snow and ablation of snow and ice. Mass balance has two components, accumulation and ablation. The accumulation (input) includes all forms of deposition, precipitation mainly and ablation (output) means loss of snow and ice in the form of melting, evaporation and calving etc from the glacier. The boundary between accumulation and ablation is the Equilibrium line. The difference between net accumulation and net ablation for the whole glacier over a period of one year is net balance. The net balance for each glacier is different in amount and depends upon the size/shape of the glacier and climatic condition of the area. The net balance per unit area of glacier is specific balance, expressed in mm of water equivalent. There is wide variation in mass changes from time to time and place to place on the glacier due to the various factors. The process of mass balance of the glaciers over an entire region is complex, as it is irregular in amount, rate and time of occurrence. Therefore the ultimate aim to monitor mass balance is to match it with the changes in various parameters of the glaciers. These changed directly affect the flow of the glacier and its terminus position. i.e. advancement and recession of the frontal position of the glaciers. Table 6.1 shows the basis of estimation of mass balance.

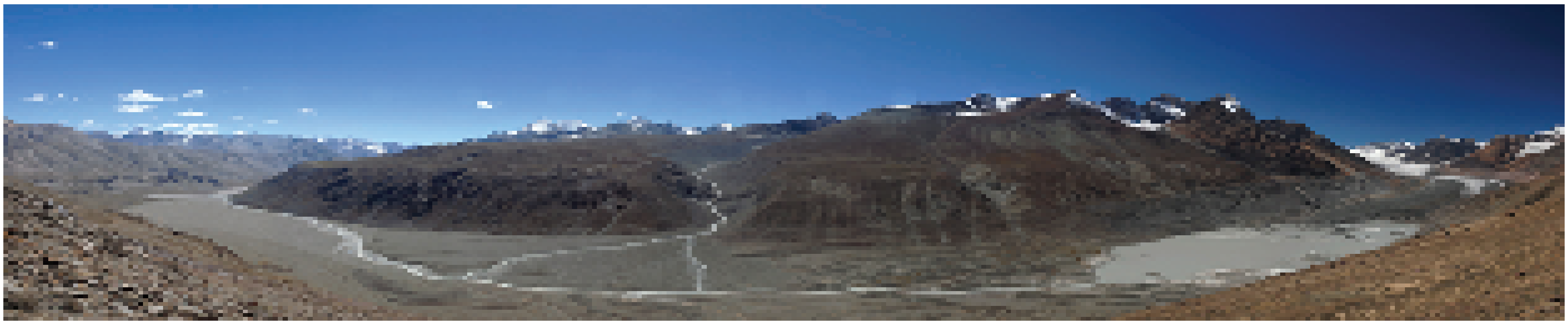
6. 2 Methods of mass balance studies

There are several methods for carrying out the mass balance studies of a glacier, which has been used world wide. Generally mass balance studies are carried out mainly by following methods.

6.2.1 The Geodetic Method:

A volume change can be estimated by subtracting the surface elevation of a glacier and theglacier extent at two different times. By measuring the density of snow at different parts of the glacier, the volume change can be converted into mass change. This method can be applied using topographic maps, digital elevation models obtained by aircraft, satellite imagery and by airborne laser scanning. The satellite imageries must be analysed for average mass balance of a glacier over a period of 5 - 10 years.

This method has some limitations; the geodetic method must be applied over the entire glacier surface, which is a difficult task. Surveying the surface by field methods require that all parts of



glacier is covered, including highly crevassed and steep regions. In addition the density of the firn and/or ice body must be approximated. This is rather easy for the ice portions but not easy for the firn areas. These major changes in the accumulation areas are difficult to determine accurately. Also this method does not yield point values of mass balance, such as its variation with elevation. For example, a glacier in steady state will yield a zero volume (mass) change over time, yet field measurement point values will yield positive values in the accumulation zone and negative values in the ablation zone.

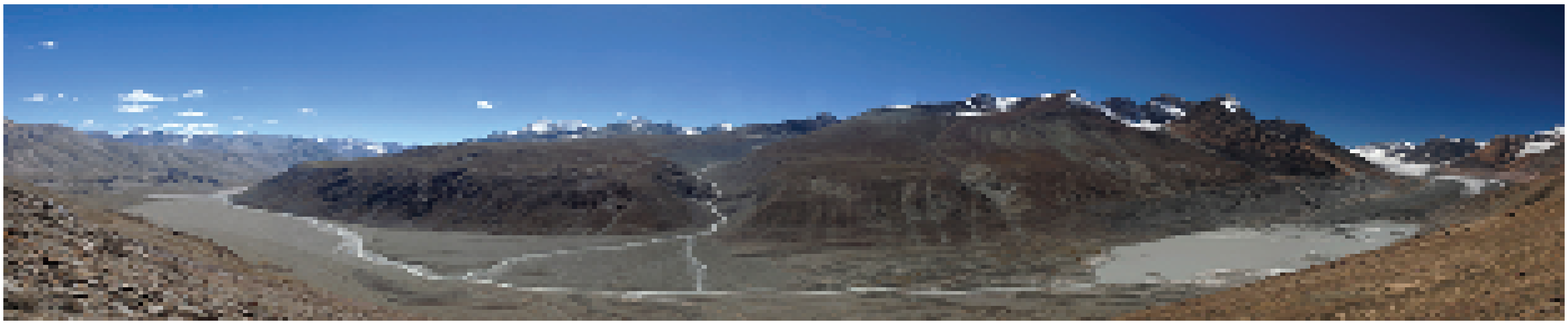
Table 6.1: Basis of mass balance estimation

Seasons	Spatial Variation	Mass balance Characteristics
Autumn	Snow accumulation at higher altitude. Ablation of ice continues at lower altitude	Snow mass increasing, ice mass decreasing. Total mass constant.
Winter	Snow accumulating over whole glacier, little ablation in lower altitude	Snow mass increasing, ice mass constant. Total mass increasing.
Spring	Snow accumulating at higher altitude, ablation of winter snow at lower	Snow mass constant, ice mass constant. Total mass constant
Summer	Little snow accumulation at higher altitude, ablation over whole glacier	Snow mass decreasing, ice mass decreasing. Total mass decreasing

This is a convenient method and time saving and this has been used worldwide. This method is simple and easy for monitoring of glacier mass balance and only applicable to determine the average mass balance of the entire glacier.

6.2.2 The Glaciological Method

Glaciological method is the only method that includes in-situ measurements. Glaciological method is a traditional method, which is accepted and used worldwide. This method includes accurate determination of mass balance by monitoring the stake network.The net accumulation/ablation data from each stake measurement within a time interval is taken. The difference in level (accumulation/ablation), when multiplied by the near surface density yields

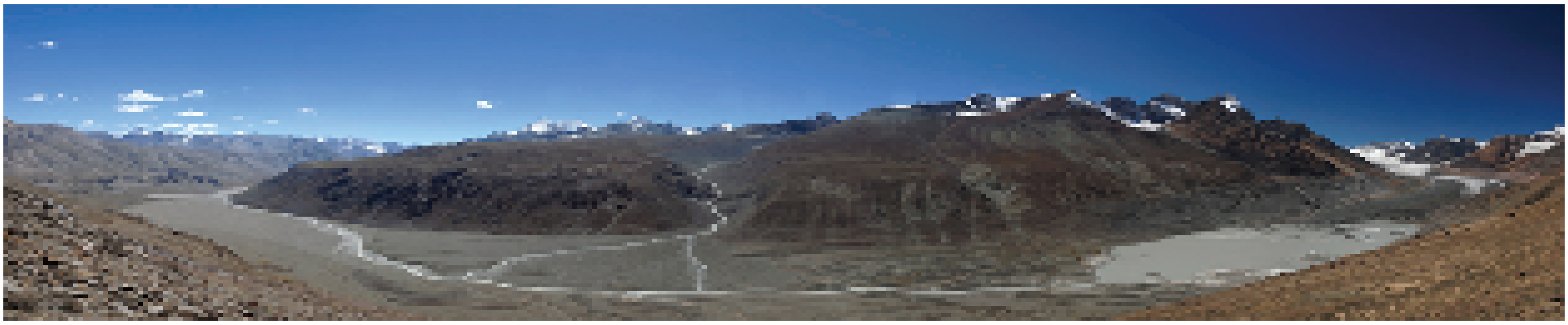


an estimate of the mass balance of that point. Changes in the levels are measured in a variety of ways, including stakes drilled into the glacier and snow depth relative to a known stratigraphic surface (e.g. previous summer surface). Density value for the ice is assumed constant at 900 kg m^{-3}. Snow density is measured in snow pits, which are dug down to a reference surface. Density can also be measured from cores taken with a drill or a cylinder of known volume.In this method, net balance is measured representative points on the glacier. The mass of snow and ice accumulated during the current balance year that remains during end of the year. This is the net balance at points in the accumulation area.

There are several ways to calculate total mass balance of a glacier. One way is to construct a plot of mass balance as a function of elevation and a plot of area of glacier with elevation. A regression equation can be applied to each plot. Multiplying the values of many mass balance and area for specific intervals of elevation and summing the product over all the intervals gives the mass balance. This method is considered to be the most accurate method till date and it provides the most detailed information on the spatial variation of mass balance magnitudes. Furthermore, confidence in the results increases after independent checking by the geodic method. However, although the glaciological method may achieve the greatest accuracy and provide the investigator with a feel for the field conditions, it is based on repeated field measurements, which have to be carried out every year.

6.2.3 The Hydrological method

When hydrology is concerned, the glacier acts as a reservoir with seasonal gains and losses. Thus mass balance of a glacier can also be calculated by estimating the annual accumulation and ablation from snow-accumulation and discharge data. This is generally used for confined drainage basin. Estimation of mass balance of a glacier by this method is extremely unreliable, as the adequate sampling of precipitation, runoff and evaporation of the glacier is difficult to record throughout the year. It takes lot of effort for unattended operation in high alpine basins. Maintaining a good gauging station for water discharge can be expensive and also time consuming.



6.2.4 Based on accumulation area ratio (AAR)

It is not feasible to study all the mountain glaciers in the field for every year, therefore it is important to replace the conventional method by some cost effective, fast and reliable techniques so that a quick assessment of mass balance of individual glaciers could be done. The method based on computing Accumulation Area Ratio (AAR) is an alternate method to assess mass balance at reconnaissance level. Delineation of Accumulation and ablation zone on high-resolution satellite images of ablation period is a well-established procedure. Accumulation and ablation zone are defined as zones of glacier above and below equilibrium line or snow line at the end of ablation season (melting season). The equilibrium can be defined as the location where there is enough snowfall and energy available to balance accumulation and ablation(GP 6.1). On temperate glaciers, this is typically taken as the boundary between snow and ice. The snow line at the end of ablation, which roughly corresponds to the equilibrium line on glaciers in mountainous region glaciers, can be identified on satellite images.

A relationship between AAR and mass balance is developed using field mass balance data of Shaune Garang and Gor Garang glaciers (figure 6.1). The model has shown AAR representing zero mass balance as 0.5 in comparison to 0.7 in the Alps and Rocky Mountains. On the basis of accumulation area ratio (area of accumulation divided by whole area of glacier) mass balance in terms of gain or loss can be estimated.

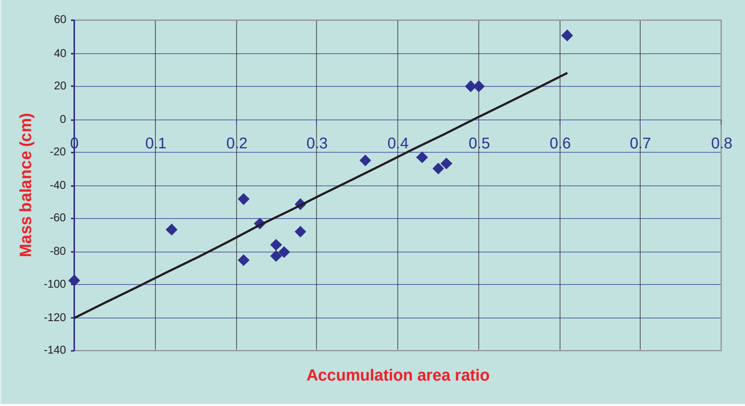
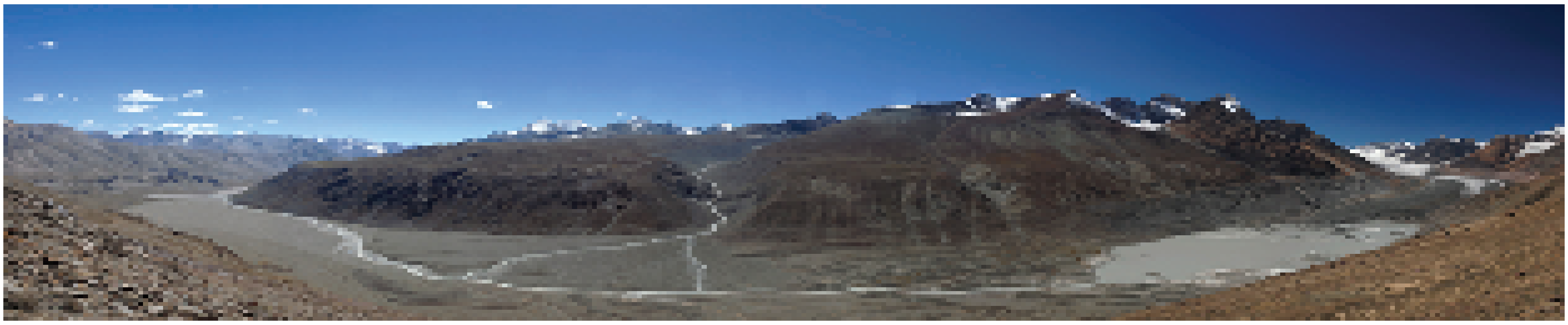


Figure 6.1 : Relationship of AAR and Specific mass balance

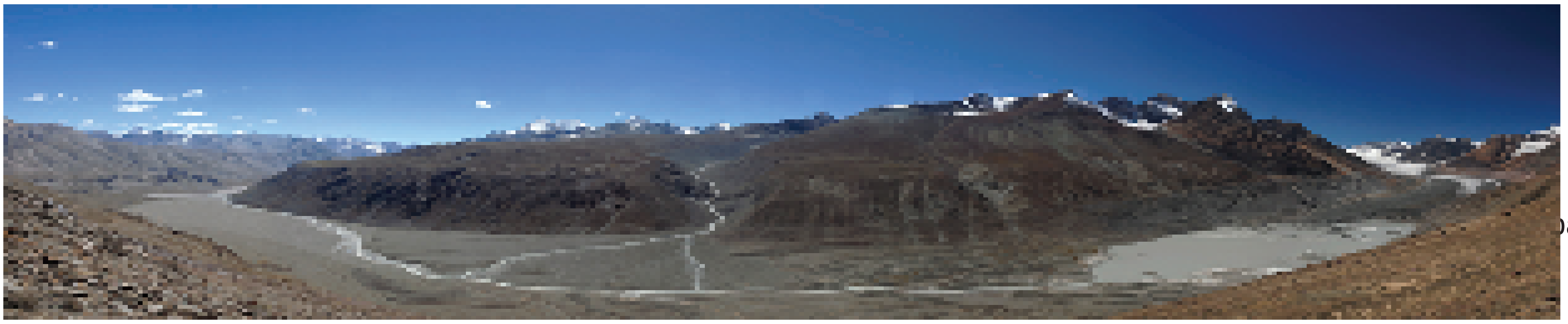
This method has been used extensively to find out the mass balance of glaciers in selected 10 basis of Himalaya. AWiFS data from IRS P6 (Resourcesat-1) satellite has been the main source of information in the present study. Its repeativity of 5 days has been used for monitoring of snow line.



The steps which were followed to delineate a snow line at the end of ablation season are discussed as following:

1) AWiFS images of the year 2005, 2006 and 2007 for the period from July to October were georeferenced with Survey of India maps (SOI).
2) Basin boundary were digitised and overlayed on the images. Image to map registration was carried out to match basin boundary.
3) All the glaciers boundaries were digitised on screen using IRS LISS III image to get area of glaciers. The LISS III scenes are used in order to ascertain the boundary of glaciers using higher resolution of the data. These boundaries are further confirmed using SOI maps. To match the boundary of glaciers from maps and satellite data part of accumulation zone is matched which is further matched with boundary created using shadow. The boundaries of retreating glaciers do not match with SOI maps near the snout of glaciers.
4) Glacier boundaries are overlayed on all AWiFS scenes sequentially. Band 4 is essentially used to discriminate snow and cloud on the image. Snowline of the date is created on the

GP 6.1 : A view of accumulation zone of Panchinala glacier(Bhaga basin)



glacier. AWiFS data has 10 bit radiometry therefore while delineating snowline the part of the glacier having fresh snow is identified based on highest reflectance.

5) The accumulation area is the area of glacier above equilibrium line or snow line at end of ablation season. Thus AAR is derived for each glacier based on location of snow line at the end of ablation season (figure 6.2 & 6.3).
6) A table is generated for AAR of each glacier corresponding to each scene. The least AAR is considered for estimation mass balance.
7) The mass balance for each glacier is estimated using relationship between AAR and mass balance.
8) Glaciers with no accumulation zone are confirmed using LISS III data.

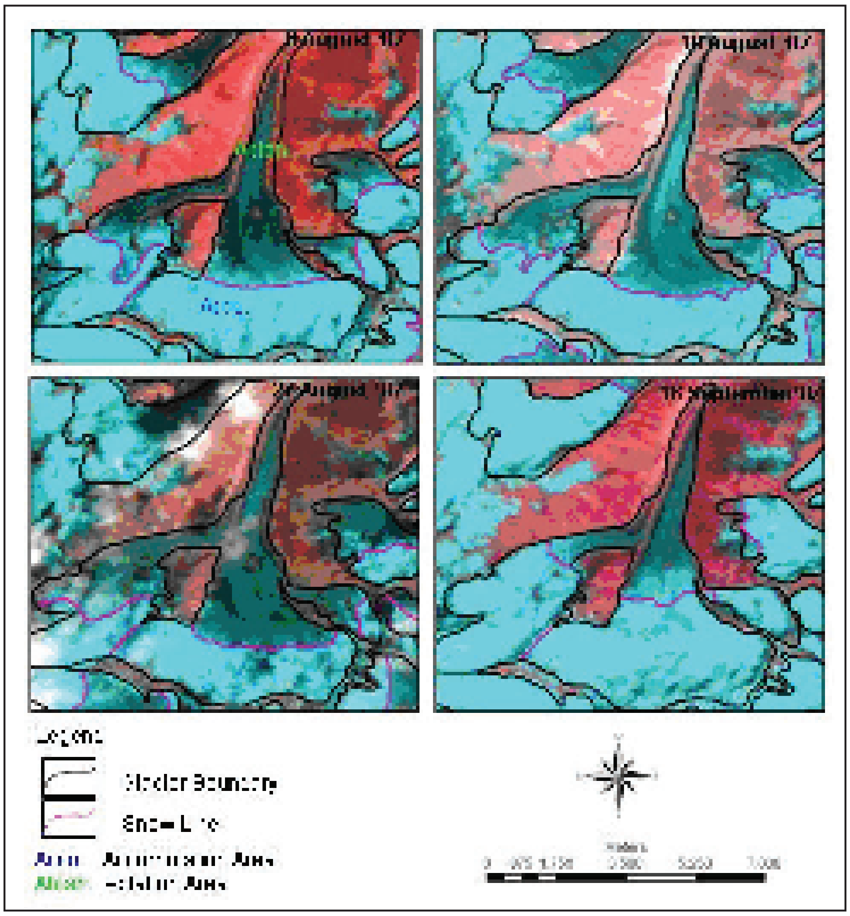
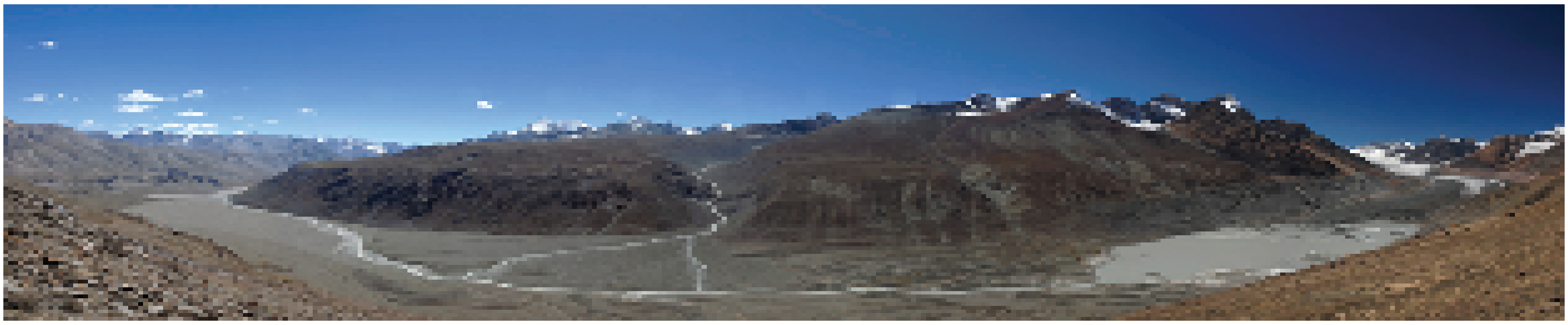
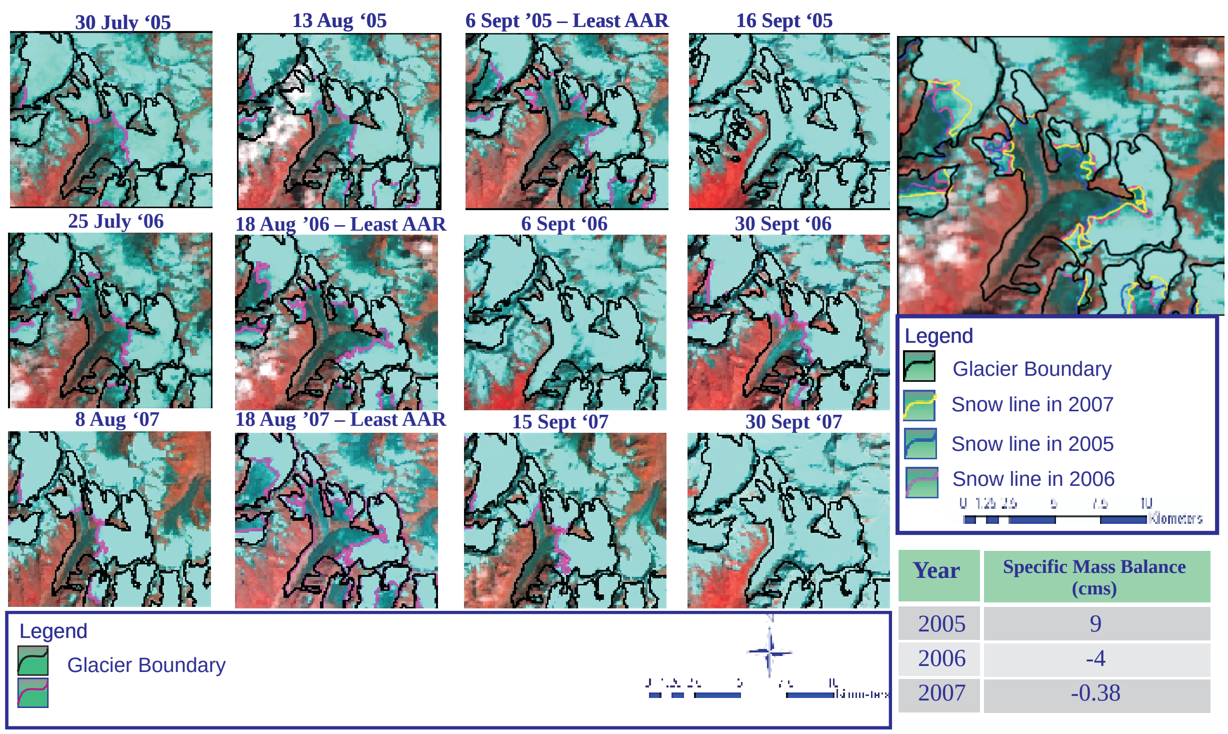


Figure 6.2 : IRS P6 Images showing fluctuation of snow line for 2007 glacier for Bhaga Sub-basin



6.2 Results

Table 6.1 to 6.16 describe the number of glaciers showing positive or negative mass balance using AAR approach for different basins for the year 2005, 2006 and 2007. The right column in each table shows significance of mass balance with respect to total area occupied by glaciers. Actual estimation of mass balance is done for each glacier. The mass balance is estimated only when it is certain that snow line is at the end of ablation period. The variation of snow line in each year is indicative of trend of mass balance. This method gives a rough estimate of increase or decrease of mass of the glacier. This method is also useful for inter and intra comparison of trend in mass balance among the entire basin.



Year	Specific Mass Balance (cms)
2005	9
2006	-4
2007	-0.38

Figure 6.3 : Snow line variation on glaciers for estimation of AAR.

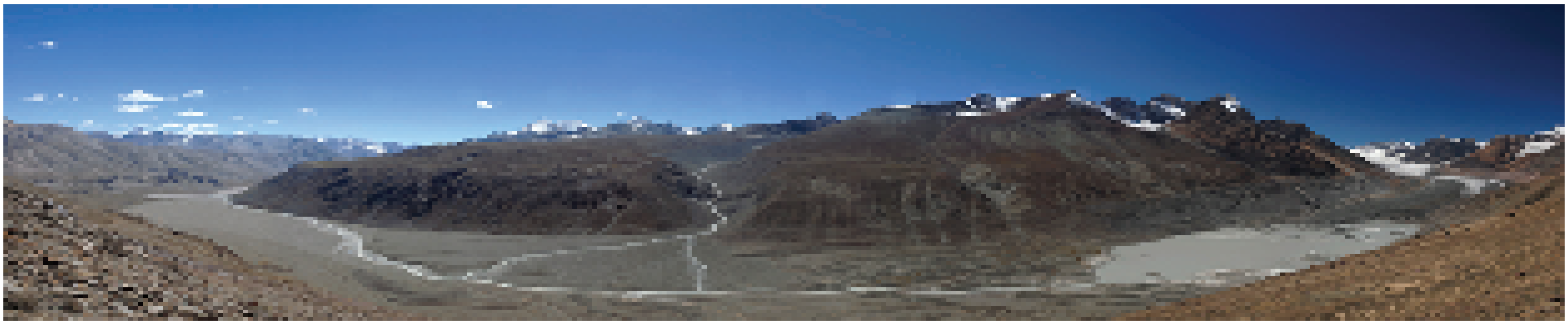


Table 6.1 : Salient results of mass balance estimation based on AAR approach using AWiFS data of 2005 ablation period for Warwan basin.

S.N.	Characteristics 2005	No.	Area (km^2)
1	Glaciers	43	414.6
2	Glaciers with no accumulation area	3	3.57
3	Glaciers with +mass balance	16	122.27
4	Glaciers with -mass balance	24	288.76

Table 6.2 : Salient results of mass balance estimation based on AAR approach using AWiFS data of 2006 ablation period for Warwan basin.

S.N.	Characteristics 2006	No.	Area (km^2)
1	Glaciers	43	414.6
2	Glaciers with no accumulation area	2	2.58
3	Glaciers with +mass balance	11	88.94
4	Glaciers with -mass balance	28	319.04

Table 6.3 : Salient results of mass balance estimation based on AAR approach using AWiFS data of 2007 ablation period Warwan basin.

S.N.	Characteristics 2007	No.	Area (km^2)
1	Glaciers	43	413.33
2	Glaciers with no accumulation area	1	2.18
3	Glaciers with +mass balance	13	119.13
4	Glaciers with -mass balance	29	294.2

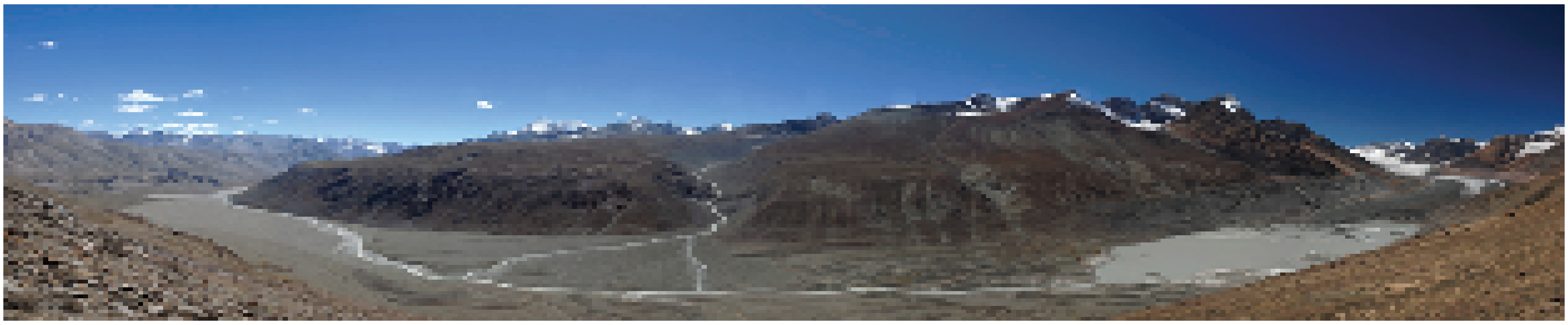


Table 6.4 : Salient results of mass balance estimation based on AAR approach using AWiFS data of 2005 ablation period for Bhut basin

S.N.	Characteristics 2005	No.	Area (km^2)
1	Glaciers	38	343.78
2	Glaciers with no accumulation area	0	0
3	Glaciers with +mass balance	24	139.68
4	Glaciers with -mass balance	14	204.10

Table 6.5 : Salient results of mass balance estimation based on AAR approach using AWiFS data of 2006 ablation period for Bhut basin

S.N.	Characteristics 2006	No.	Area (km^2)
1	Glaciers	38	343.78
2	Glaciers with no accumulation area	0	0
3	Glaciers with +mass balance	19	107.56
4	Glaciers with -mass balance	17	230.07

Table 6.6 : Salient results of mass balance estimation based on AAR approach using AWiFS data of 2007 ablation period for Bhut basin.

S.N.	Characteristics 2007	No.	Area (km^2)
1	Glaciers	38	343.78
2	Glaciers with no accumulation area	2	2.78
3	Glaciers with +mass balance	16	91.88
4	Glaciers with -mass balance	20	249.12

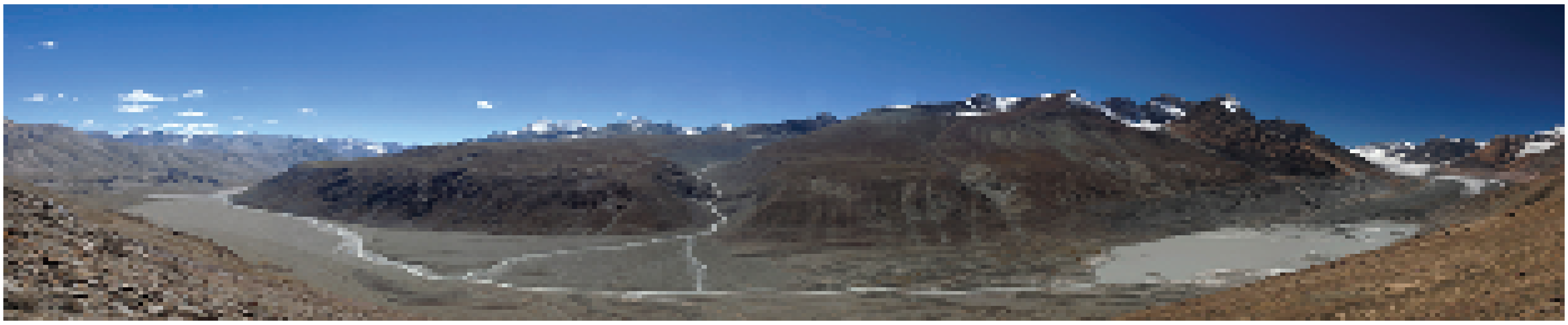


Table 6.7 : Salient results of mass balance estimation based on AAR approach using AWiFS data of 2005 ablation period for Chandra basin.

S.N.	Characteristics 2005	No.	Area (km^2)
1	Glaciers	106	586.109
2	Glaciers with +mass balance	67	293.639
3	Glaciers with -mass balance	37	292.470
4	Cloudy	2	4

Table 6.8 : Salient results of mass balance estimation based on AAR approach using AWiFS data of 2006 ablation period for Chandra basin.

S.N.	Characteristics 2006	No.	Area (km^2)
1	Glaciers	106	586.109
2	Glaciers with +mass balance	30	182.709
3	Glaciers with -mass balance	37	308.926
4	Cloudy	39	0

Table 6.9 : Salient results of mass balance estimation based on AAR approach using AWiFS data of 2007 ablation period for Chandra basin.

S.N.	Characteristics 2007	No.	Area (km^2)
1	Glaciers	106	586.11
2	Glaciers with +mass balance	15	133.85
3	Glaciers with -mass balance	90	447.79
4	Cloudy	1	0

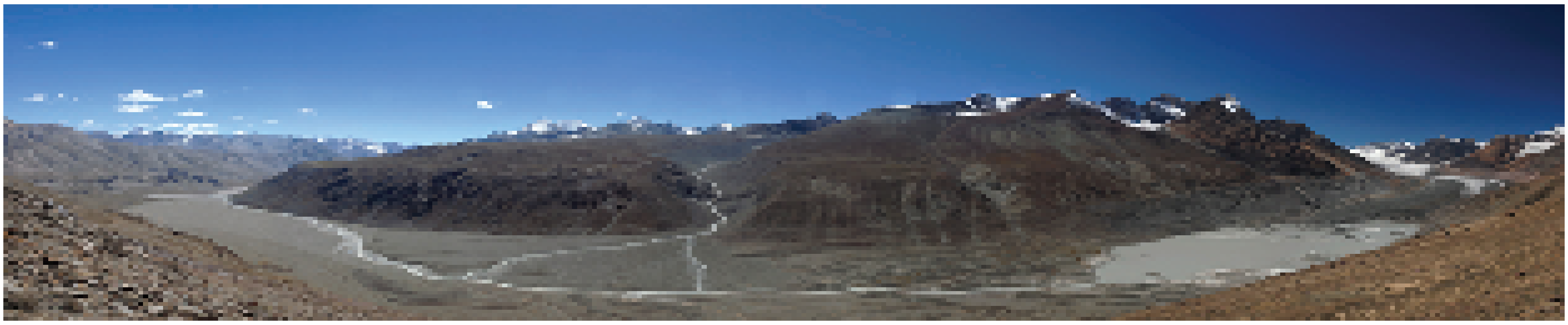


Table 6.10 : Salient results of mass balance estimation based on AAR approach using AWiFS data of 2005 ablation period for Bhaga basin.

S.N.	Characteristics 2005	No.	Area (km^2)
1	Glaciers	72	278.41
2	Glaciers with +mass balance	67	255.60
3	Glaciers with -mass balance	5	22.81
4	Cloudy	--	–

Table 6.11 : Salient results of mass balance estimation based on AAR approach using AWiFS data of 2006 ablation period for Bhaga basin.

S.N.	Characteristics 2006	No.	Area (km^2)
1	Glaciers	72	278.41
2	Glaciers with +mass balance	24	107.40
3	Glaciers with -mass balance	20	121.54
4	Cloudy	28	

Table 6.12 : Salient results of mass balance estimation based on AAR approach using AWiFS data of 2007 ablation period for Bhaga basin.

S.N.	Characteristics 2007	No.	Area (km^2)
1	Glaciers	72	278.41
2	Glaciers with +mass balance	34	172.73
3	Glaciers with -mass balance	37	103.66
4	Cloudy	1	

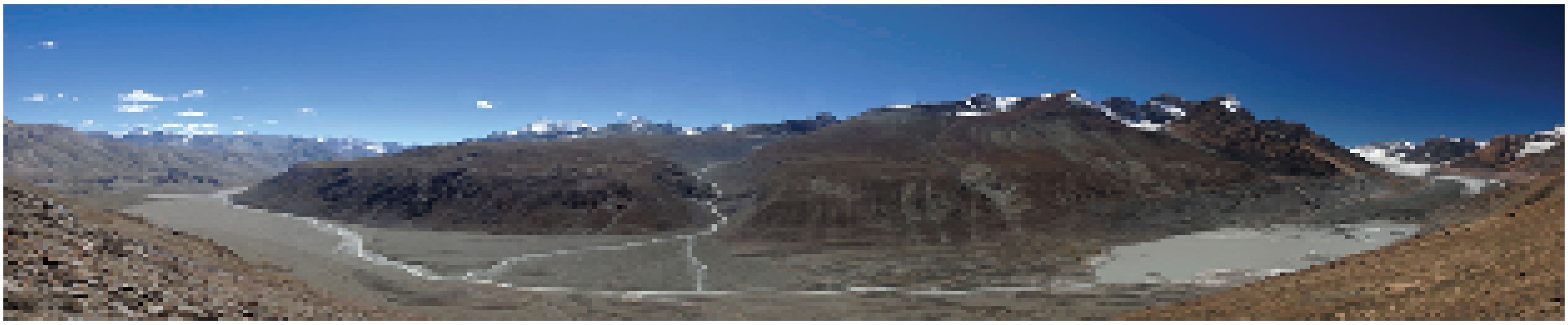


Table 6.13 : Salient results of mass balance estimation based on AAR approach using AWiFS data of 2006 ablation period for Dhauliganga basin.

S.N.	Characteristics 2006	No.	Area (km^2)
1	Glaciers	59	206.62
2	Glaciers with +mass balance	15	76.98
3	Glaciers with -mass balance	32	102.90
4	Cloudy	12	

Table 6.14 : Salient results of mass balance estimation based on AAR approach using AWiFS data of 2007 ablation period Dhauliganga basin.

S.N.	Characteristics 2007	No.	Area (km^2)
1	Glaciers	59	206.62
2	Glaciers with +mass balance	3	23.21
3	Glaciers with -mass balance	38	168.34
4	Cloudy	18	

Table 6.15 : Salient results of mass balance estimation based on AAR approach using AWiFS data of 2006 ablation period for Goriganga basin.

S.N.	Characteristics 2006	No.	Area (km^2)
1	Glaciers	42	318.85
2	Glaciers with +mass balance	26	236.83
3	Glaciers with -mass balance	5	65.48
4	Cloudy	11	

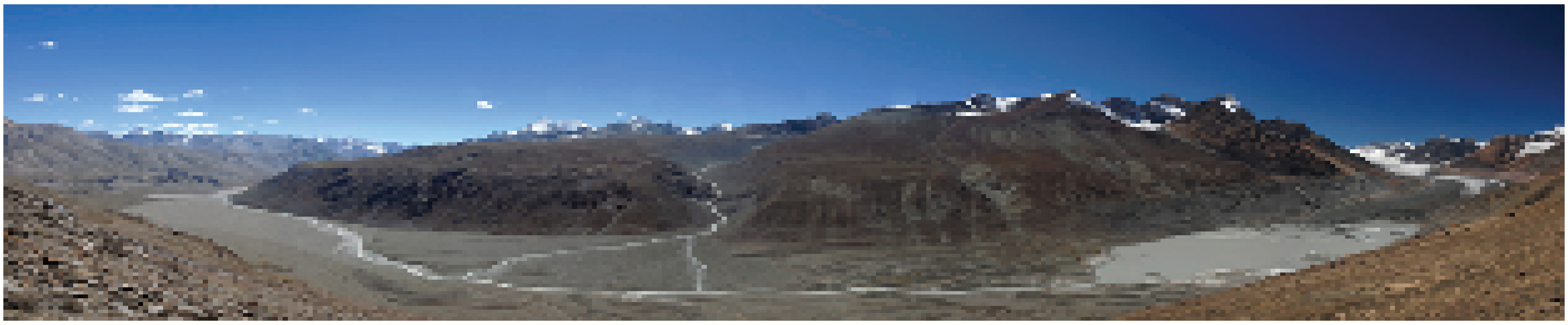


Table 6.16 : Salient results of mass balance estimation based on AAR approach using AWiFS data of 2007 ablation period for Goriganga basin.

S.N.	Characteristics 2007	No.	Area (km^2)
1	Glaciers	42	318.85
2	Glaciers with +mass balance	14	135.72
3	Glaciers with -mass balance	23	176.81
4	Cloudy	5	

7. Inventory of Moraine-Dam Lakes

7.1 Introduction

Among many types of naturally occurring lakes in the Himalayan region, some are formed by snow or glacier-melt runoff. Lakes formed by glacier-melt runoff include Supra-glacial lakes, Moraine-dam lakes and Pro-glacial lakes. The lakes which occur on the surface of the glaciers are called supra-glacial lakes. Moraine-dam lakes are formed when a large amount of debris (moraine) is transported to lower gradient, sometimes causing temporary damming at the terminus of the glacier. This type of damming gives rise to formation of moraine-dam lakes. It essentially happens during the ablation season of glaciers, which varies from west to east, as the latitude varies. The main source of such lakes is the glacial-melt runoff. The lakes remain under snow cover in winter season and get exposed when snowline is at higher altitude than the altitudes of lakes. As the volume of water in lakes increases, the pressure on temporary dams also does so this might result in the disruption of structure causing intense floods down the gradient. It is thought that some Himalayan lakes of glacial origin may get swollen due to rapid melting of glaciers under the effect of global warming. Therefore, monitoring of such lakes in Himalayan glaciated region is vital for disaster management and climate change studies.

Since the glaciers and associated lakes occur in very high altitude and rugged mountainous regions, it is very hazardous and requires enormous efforts to monitor the lakes on the ground. Therefore remote sensing is one of the most appropriate techniques to monitor the growth and decay of such lakes.

Space Applications centre has been carrying out mapping of moraine-dam lakes using data of varying spatial resolutions for the last two and half decades. These studies either have been carried out in conjunction with glacier inventory or specifically for the purpose of identification of hydro-electric projects in snow or glaciated terrains of Himalayan region.

The following sections deals with work carried out so far at SAC for mapping of moraine-dam lakes.

7.2 Satluj basin

During the glacier inventory of Satluj basin at 1:50 000 scale, moraine-dam lakes were also identified and mapped. The study had shown the presence of large number of moraine-dam lakes in Satluj basin. A total of 38 glacier lakes were identified and mapped in this basin. The mapping of these lakes is very useful if in future any project is to be undertaken in order to identify those lakes which can give rise to Glacial Lake Outburst Floods (GLOF). GLOF have been reported from many parts of Himalayas.

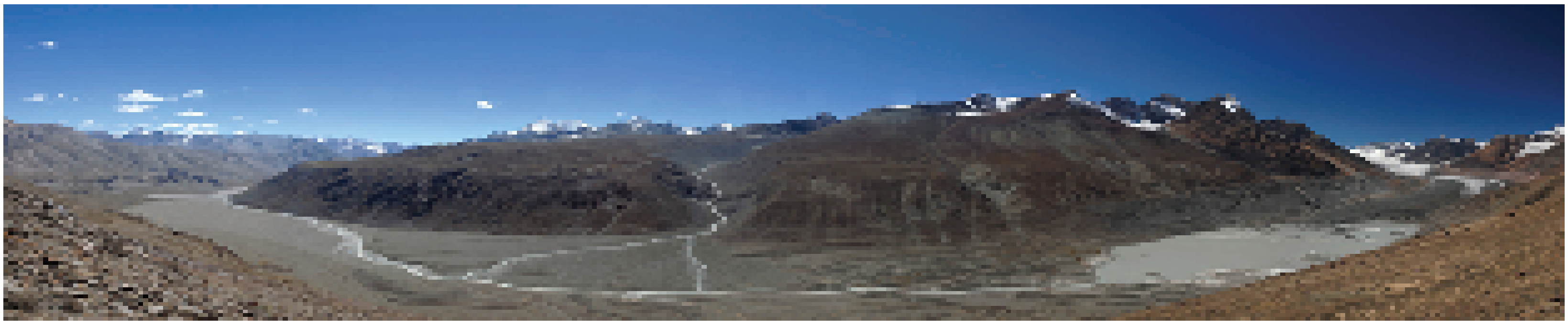


Table 7.1 : Distribution of Moraine dammed lakes in Satluj Basin and its tributary Beas basin

(The glacier nos. are taken from inventory of glaciers of Satluj basin carried out by SAC in collaboration with WIHG, Dehradun & HPRSAC, Shimla.)

Glacier Number	Basin Number	Area of Lake (km^2)
53E09013	2211314	0.2
53E09014	2211314	0.1
53E09018	2211521	0.075
53E09021	2211531	0.05
53I07013	2220012	0.025
53I07014	2220012	0.025
53M08001	2220028	0.05
53M08002	2220028	0.05
53I10024	2220060	0.05
53I14001	2220061	0.1
53I07017	2220308	0.025
53I107010	2220711	0.15
53I105001	2221000	0.075
52L16003	2221400	0.2
52I16005	2221400	0.025
52I16006	2221400	0.05
52P03004	2222010	0.025
52P03005	2222010	0.025

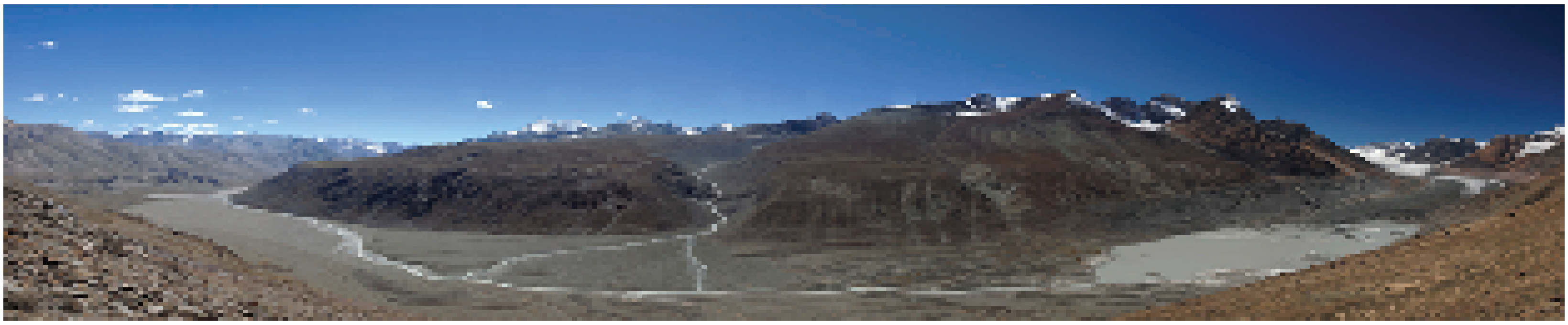
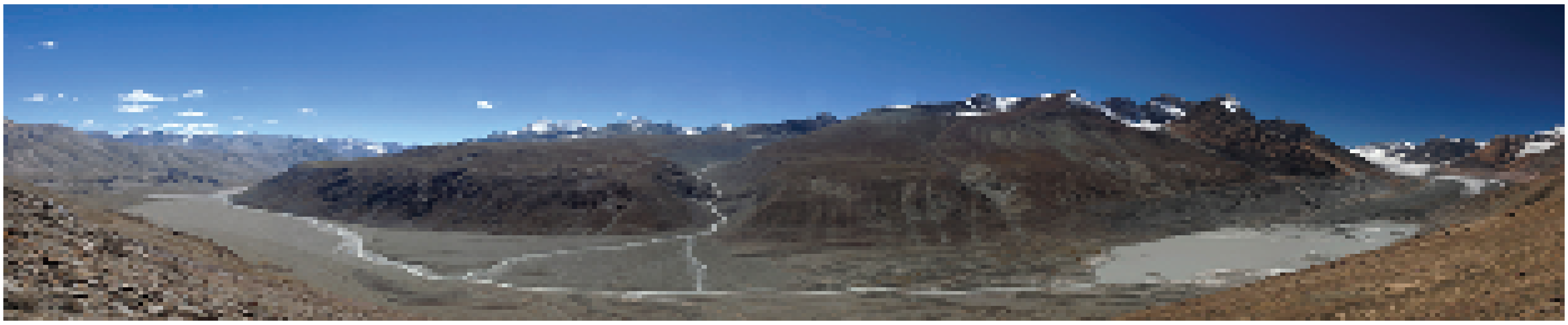


Table 7.1 : (Continued)

52P03007	2222010	0.05
52P06001	2222010	0.05
52P06002	2222010	0.025
52P06010	2222042	0.05
53M12001	2222051	0.05
53M12005	2222052	0.05
53M12006	2222052	0.1
53M12008	2222052	0.025
53M08004	2222053	0.05
62E04007	2222203	0.025
62E08001	2222230	0.05
62E08002	2222230	0.05
62F07001	2222266	0.05
62F07002	2222267	0.1
62F07003	2222267	0.075
62B10001	2222322	0.025
62B06001	2222410	0.05
62B06002	2222410	0.05
62B10007	2222410	0.025
62B06005	2222421	0.05



7.3 Dhauliganga basin

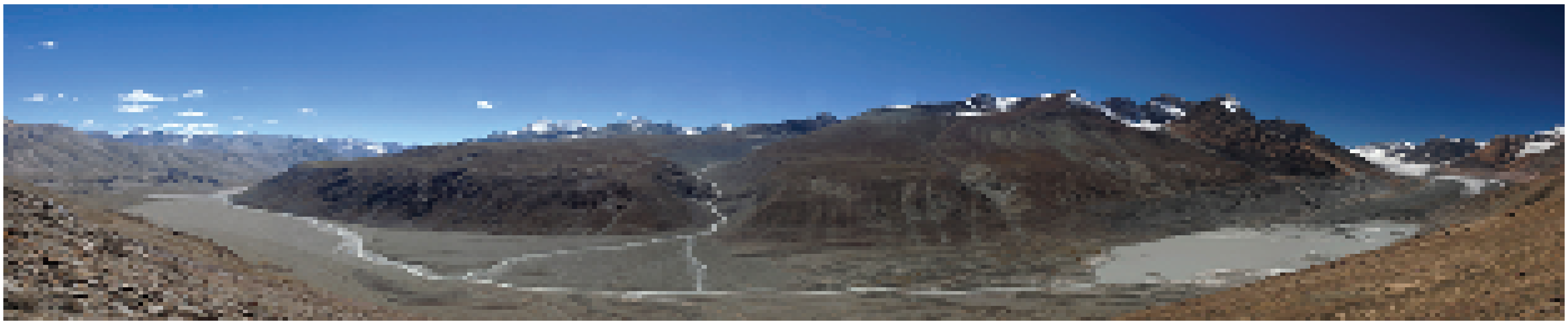
Inventory of glaciers in Dhauliganga basin was carried out on 1:50,000 scale using IRS-LISS of 1995. Results obtained during this investigation suggest presence of 48 glaciers in the Dhauliganga river basin including Lesser Yankti river basin. The inventory of Dhauliganga basin was taken up with an objective to identify the moraine-dam lakes. This work was undertaken as National Thermal Power Corporation wanted to know the occurrence of such lakes in view of any disaster arising out of GLOF and likely damage to proposed hydroelectric projects. Seven moraine-dam lakes were identified (table 7.2).

Table 7.2 : Moraine dam lakes in Dhauliganga basin

Glacier Number	Lake Area (km^2)
62BO7006	0.050
62BO7007	0.025
62BO7008	0.150
62B11001	0.050
62B11004	0.050
62B11005	0.075
62B11006	0.050

7.4 Nepal and Bhutan

In view of the large number of lakes formed by snow or glacier-melt runoff in Nepal and Bhutan Himalayas, a study was undertaken to find the change in area of lakes over period of about 15 years by using satellite images of 1990 and 2005. For the year 1990 the Landsat TM and for 2005 IRS AWiFS FCC (False Colour Composite) images were used. Normally, mapping of moraine-dammed lakes is possible when ablation zone of a glacier is exposed. It happens during October-December time-frame for central Himalayan region. The lakes have been categorized in two classes i.e. moraine-dammed lakes and glacier lakes (supra-glacial lakes and lakes fed by snow-melt run-off).

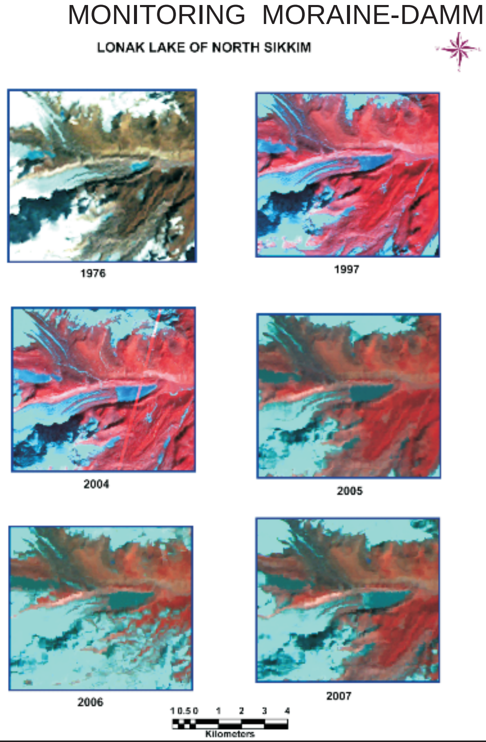


There are 21 moraine-dammed lakes which have been identified and mapped in Bhutan. In addition, 44 glacial lakes (supra-glacial lakes or lakes fed by snow-melt run-off) have been mapped. The area covered by largest moraine dammed lake is 584.1 ha in 2005 which was 567.5 ha in 1988. There are six moraine-dammed lakes which have area more than 100 ha. The maximum change of 81.2 ha area has been mapped. There are a few cases where lakes have been observed to be frozen during October November 2005 / 2007. Most of the supra-glacial lakes or lakes fed by snow-melt Run-off (shown as glacier lakes) are smaller than 50 ha.

7.5 Lakes in Tista basin

During the glacier inventory of Tista basin of Sikkim Himalayas few moraine-dammed lakes are observed. One of the moraine dammed lake was further monitored and mapped. This is shown in figure 7.1. The lake has been increasing in size and volume from 1965. Its area has increased 10 times in about 32 years and this indicates the lake is important from the disaster point of view and also in view of climatic variations in last three decades.

MONITORING MORAINE-DAMMED LAKES IN SIKKIM



Year	Area (ha)
1965	10.10
1976	23.42
1997	57.41
2004	81.71
2005	77.14
2006	96.21
2007	110.70

Figure 7.1 : A moraine dammed lake in Tista basin

8. Summary of Investigations

Himalayas possess one of the largest resources of snow and ice outside the polar regions, which act as a huge freshwater reservoir for all the rivers draining into Indo-Gangetic plains. This has helped to sustain the life for thousands of years. Therefore monitoring of these resources is important to assess availability of water in Himalayan river system. These regions are difficult to be studied by conventional methods due to tough terrain and extreme weather conditions. Therefore, remote sensing based methods have been developed to monitor snow and glacier cover of Himalayas.

8.1 Snow cover

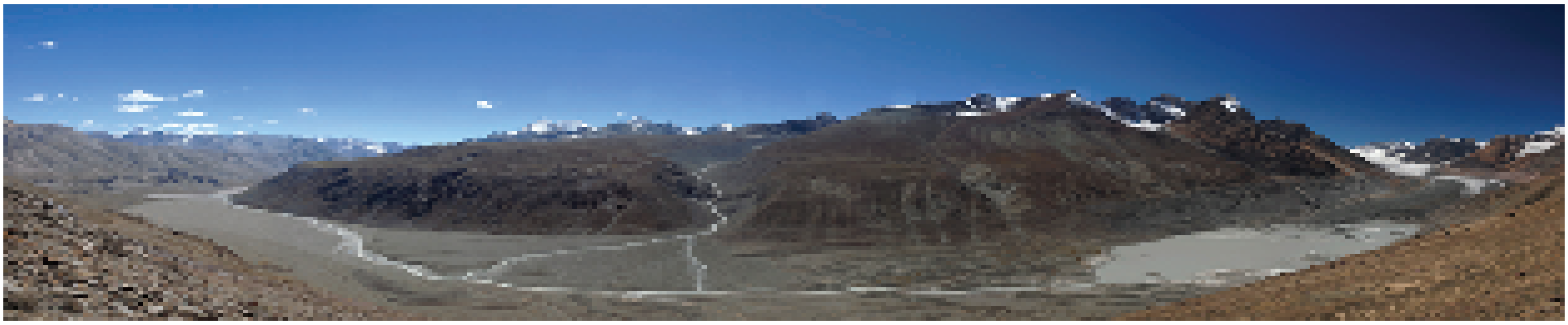
To monitor seasonal snow cover, an algorithm based on Normalized Difference Snow Index(NDSI) has been developed at Space Applications Centre(SAC), Ahmedabad using visible and short wave infrared data of AWiFS sensor of Resourcesat satellite. Using this algorithm snow cover was monitored for 33 basins distributed in all regions of Himalayas for four consecutive years starting from 2004.

8.2 Glaciers inventory

SAC has carried out inventory of glaciers using UNESCO/TTS procedures for Indian Himalayas at 1:250000 scale and later on for different basins at 1: 50000 scales. Areal extent of glaciers in Indian Himalaya was estimated as 23315 km^2 on 1:250,000 scale Sutluj etc.. This investigation did not include permanent snow fields and glacieretes, as data of one season was only used. The study was further extended to glaciated regions of Indus, Ganga and Bramhputra river basins. A total of 32392 numbers of glaciers are mapped in the three basins. Total glaciated area has been estimated as 71182.08 km^2. This investigation has been carried out on 1:50,000 scale and features such as permanent snow fields and glacieretes have aslo been mapped. The investigation has also shown presence of 889 moraine dammed and 972 Supra glacier lakes.

8.3 Monitoring of glacier advance/retreat

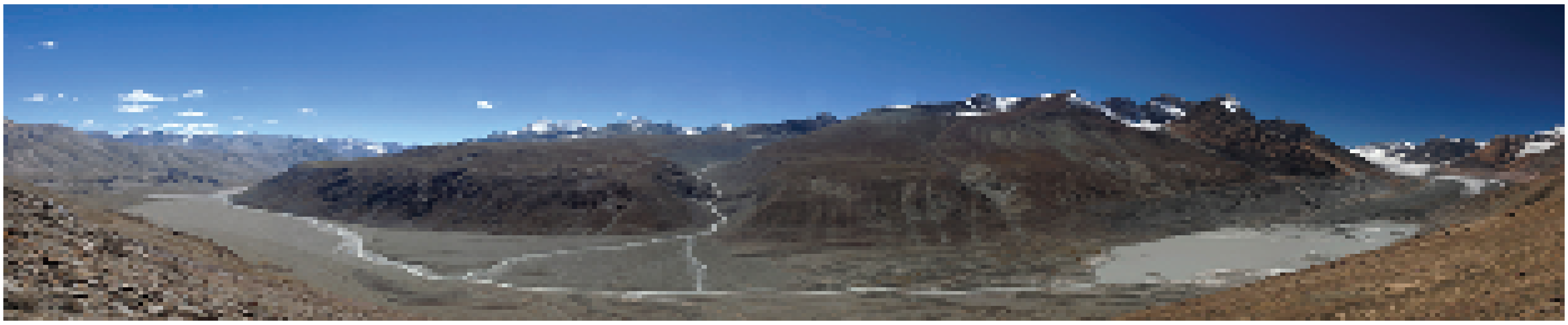
Retreat of individual glaciers depends upon the variations in mass balance. The retreat depends upon static factors and dynamic factors. The static factors are latitude, slope, orientation, width and size of the valley and altitude distribution of glaciers. The dynamic factors are annual accumulation and ablation of snow and ice. These factors further depend



upon Daily and yearly variations in temperature, solid/liquid precipitation, heat flow from earth crust, debris cover and cloud cover.

Glacier monitoring carried out at SAC covers the duration of 1962/1969 to 1989/1990 and 1989/2001/2004. The longer interval is based on the glacier extent as given in Survey of India topographical maps. The survey of India maps are checked in the field for location of features around glaciers to ascertain the accuracy of maps. Many Himalayan glaciers are debris covered on ablation zones. Sometime the debris covers the ice but emergence of channels helps in the identification snouts. Glaciers of sixteen basins were monitored. The glaciers include large valley glaciers and small permanent snow/ice fields. On an average the loss in area has been found to be ranging from 7 to 20 % for longer interval. In Bhaga basin the loss is high i.e.30 %. The basins which are located in semi arid to arid regions are relatively less debris covered and therefore show higher retreat. For a period between 1990 and 2001 retreat is found to be higher in Spiti and Alaknanda basins, even though both basins are located in different climatic zones. This indicates that in addition to local climatic variations many other factors can also affect glacial retreat. In Warwan and Bhut basins, 15 % loss in area was observed for glaciers having areal extent between 3 and 5 sq km and 10% loss were observed for glaciers having areal extent higher than 15 sq.km. for a period 1962 and 2001/2002. Similar trend was observed for a period between 2001/2002 to 2007, indicating influence of glacier size on retreat. In addition moraine cover and altitude distribution can also influence retreat.

We observe that out of 2767 glaciers monitored 2184 with respect to SOI maps are retreating 435 are advancing and 148 glaciers shows no change. This result indicates that approx. 79% of the total glaciers have shown retreat during 1962-2001/2003/2004/2005. In case of monitoring carried out by using only images 1673 glaciers out of 2193 have shown retreat. This is approx. 76 %. Twenty four percent glaciers either do not show any change or show advance. So it also confirms that monitoring using satellite images also indicate retreat of large number of glaciers.



8.4 Glacier mass balance

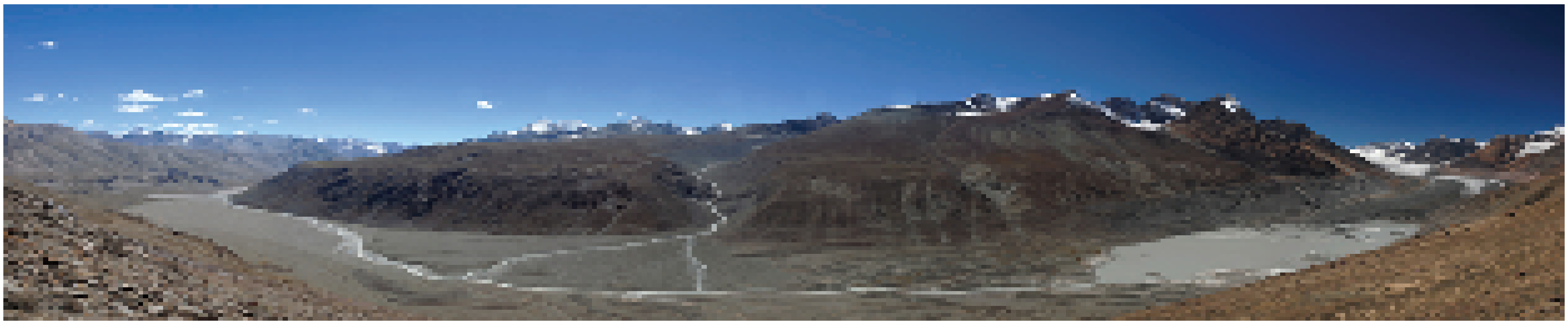
Variation of snow line at the end of melting season on the glaciers is indicative of mass balance. Methods based on Accumulation Area Ratio (AAR) have been developed and used to determine mass balance of glaciers of ten Himalayan basins for three consecutive years. The data indicates upward movement of snowline for more number of glaciers. The glaciers showing negative massbalance have larger area than showing positive mass balance.

8.5 Moraine dam lakes

Moraine dam lakes are an important component of glacier studies. These lakes are important in monitoring of disaster prone zones in high altitude regions. Moraine dam lakes have been mapped and monitored by using remote sensing data in almost all the regions of Himalayas while carrying out glacier inventory. The lakes have mapped and monitored even in parts of Nepal and Bhutan.

8.6 Glacial expeditions

Glacial expeditions were also organized to validate terminus position of glaciers interpreted from RS data. Jurya Sarang, Samudra Tapu, Parbati, Patsio, Panchi nala, East Rathong, Chhota Shigri, Parkichey, Bhagirathi Kharak, Satopanth and Gangotri glaciers have been visited during expeditions. Instruments such as GPS, Laser range finder, spectral radiometer and ground penetrating radar have been used to measure different glacial parameters .



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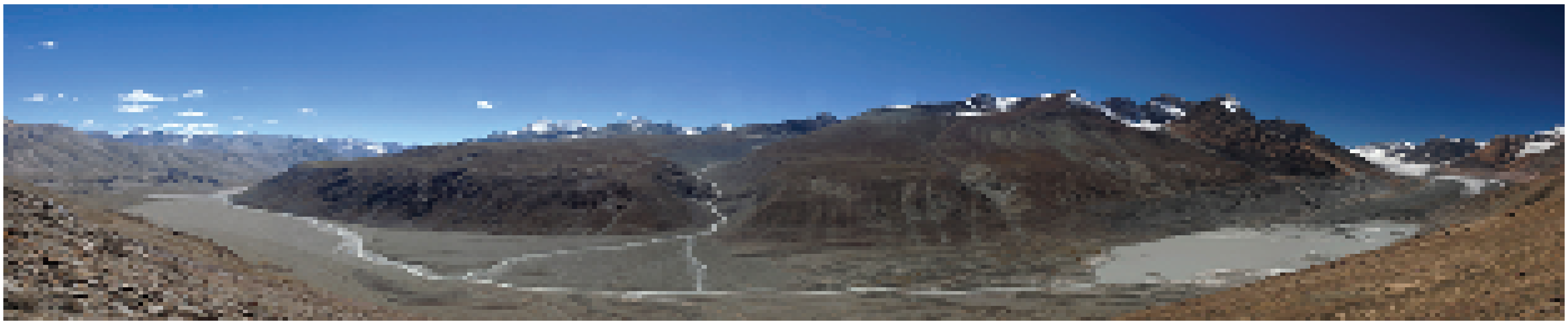

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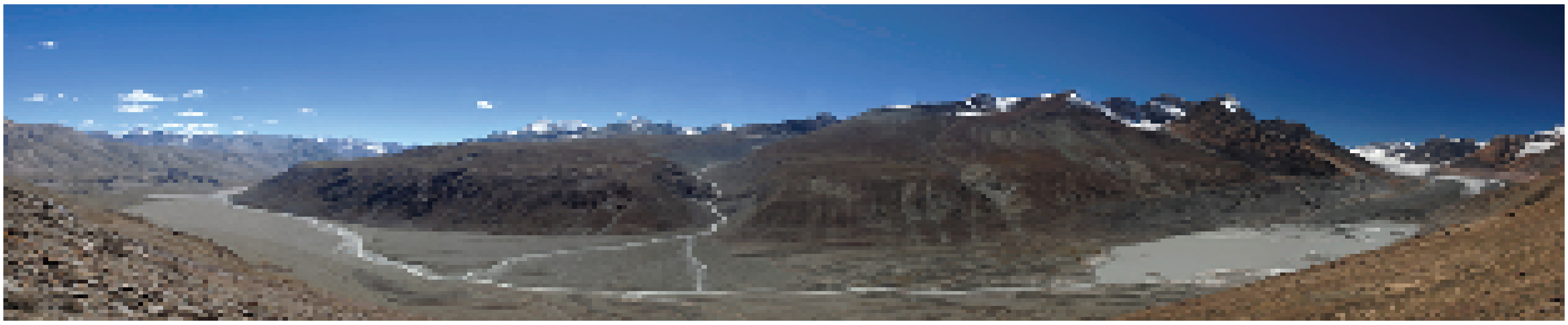

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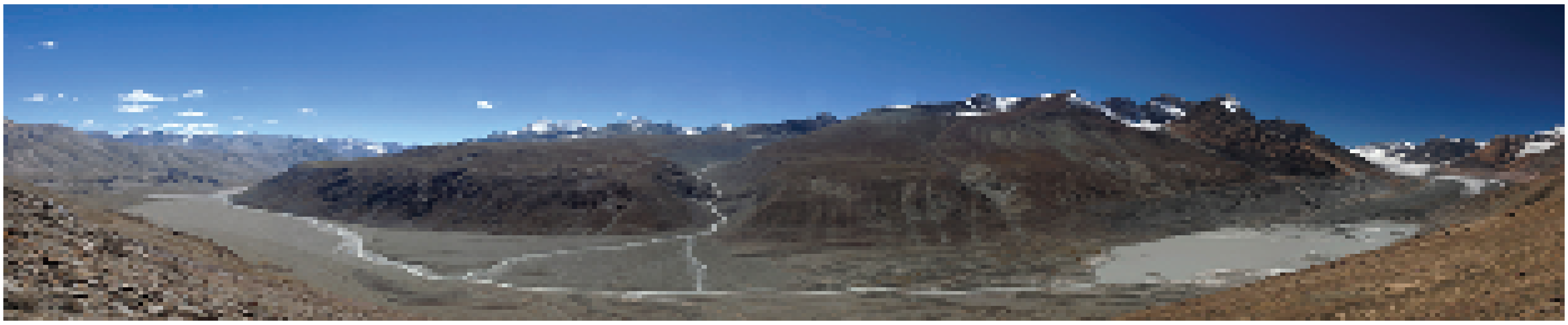

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