Snow and Glacier Studies in Indian Himalayas: A joint Project of Ministry of Environment and Forests and Department of Space, Govt. of India

Technical Report · May 2010

DOI: 10.13140/RG.2.1.5167.5049

6 authors, including:

Shakil Ahmad Romshoo
Islamic University of Science and Technology

Ajai Prof
Space Application Center

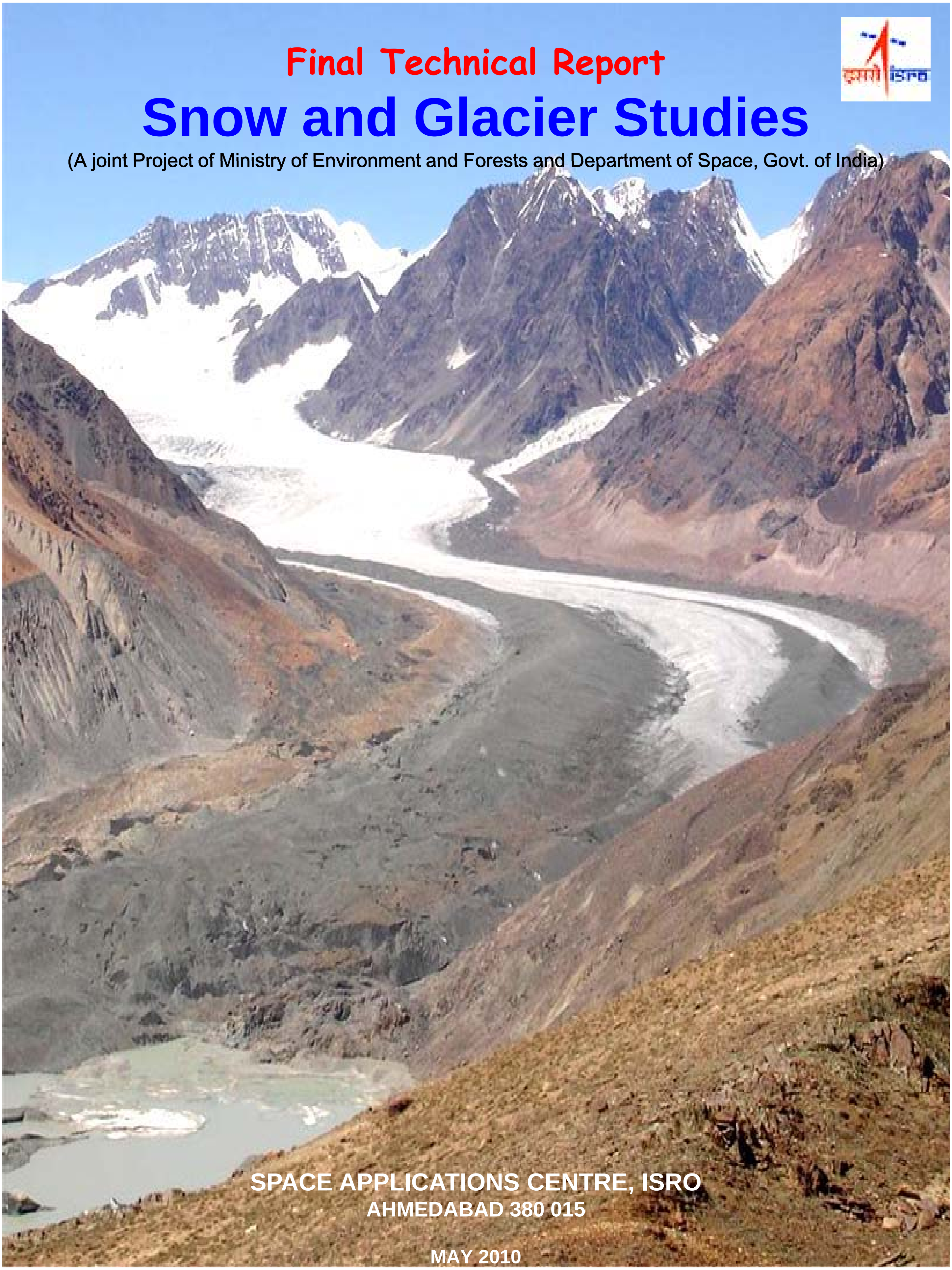
Milap C Sharma
Jawaharlal Nehru University

R.K. Ganjoo
University of Jammu

Final Technical Report

Snow and Glacier Studies

(A joint Project of Ministry of Environment and Forests and Department of Space, Govt. of India)



SPACE APPLICATIONS CENTRE, ISRO

AHMEDABAD 380 015

MAY 2010

Snow and Glacier Studies

(A joint Project of Ministry of Environment and Forests and Department of Space, Govt. of India)

SPACE APPLICATIONS CENTRE, ISRO
AHMEDABAD 380 015

भारत सरकार
अन्तरिक्ष विभाग
अन्तरिक्ष उपयोग केन्द्र
आंबावाडी विस्तार डाक घर,
अहमदाबाद - 380 015. (भारत)
दूरभाष : 6761188, 6740256
फैक्स : 079-6765410, 6767708

सत्यमेव जयते

GOVERNMENT OF INDIA
DEPARTMENT OF SPACE
SPACE APPLICATIONS CENTRE
AMBAWADI VISTAR P. O.
AHMEDABAD-380 015. (INDIA)
PHONE : 6761188, 6740256
FAX : 079-6765410, 6767708

Rangnath R. Navalgund
Director

Foreword

Himalayan mountains contain important natural resources of frozen fresh water in the form of snow and glaciers. These glaciers are unique as they are located in tropics, high altitude regions, predominantly valley type and many are covered with debris. The great northern plains of India sustain on the perennial melt of snow and glaciers meeting the water requirements of agriculture, industries, domestic sector even in the months of summer when large tracts of the country go dry. Therefore, it is important to monitor and assess the state of snow and glaciers and to know the sustainability of glaciers in view of changing global scenarios of climate and water security of the nation. Any information pertaining to Himalayan glaciers is normally difficult to be obtained by conventional means due to its harsh weather and rugged terrains.

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 the Himalayas. 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. 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 occurring in inaccessible regions.

A national project on “Snow and Glacier Studies” was taken up by the Space Applications Centre and executed in collaboration with 14 research organizations and academic institutions of the country, at the behest of the Ministry of Environment and Forests, Govt. of India. Snow cover for the entire Indian Himalaya has been monitored for four consecutive years starting from 2004 - 05. Inventory of the glaciers carried out on 1:50,000 scale reveals the total number of glaciers to be 32392 with a total glaciated area of 78040 sq km. More than two thousand glaciers have been monitored to study the advance/retreat of their extent. Glacier mass balance, based on Accumulation Area Ratio method, as derived from satellite images, has also been studied.

I compliment the entire team of scientists from both ISRO and other organizations for carrying out this task diligently. I do hope, the findings of the project presented in this document will be of interest and use to the researchers working in the field of environment, glaciology, hydrology and climate change.

July 9, 2010

(Rangnath R. Navalgund)

भारत सरकार
अन्तरिक्ष विभाग
अन्तरिक्ष उपयोग केन्द्र
आंबावाडी विस्तार डाक घर,
अहमदाबाद - 380 015. (भारत)
दूरभाष : 6761188, 6740256
फैक्स : 079-6765410, 6767708

सत्यमेव जयते

GOVERNMENT OF INDIA
DEPARTMENT OF SPACE
SPACE APPLICATIONS CENTRE
AMBAWADI VISTAR P. O.
AHMEDABAD-380 015. (INDIA)
PHONE : 6761188, 6740256
FAX : 079-6765410, 6767708

Dr. Ajai
Group Director
Marine & Earth Sciences Group

Acknowledgement

The Himalayas has one of the largest concentrations of glaciers outside the polar regions. Himalayan glaciers in the Indian subcontinent are broadly divided in to three river basins, namely, Indus, Ganga and Brahmaputra. These glaciers are important source of fresh water for northern Indian rivers and water reservoirs. For water resources planning and management in North-India, it is essential to study and monitor Himalayan glacier & snow cover. More ever the glaciers are important indicators of climate change. Space Applications Centre (SAC) has developed techniques for mapping and monitoring of Himalayan glaciers using satellite data.

In view of the above, Ministry of Environment and Forests (MoEF), Govt. of India has identified mapping and monitoring of Himalayan glaciers and snow cover as one of the thrust area under standing committee on Bio-resources and environment (SC-B), NNRMS. Thus a project on "Snow and Glacier studies" was taken up by Space Applications Centre at the behest of MoEF with joint funding by DOS and MoEF. The present report is the final technical report of this project which has been executed by SAC in collaboration with 14 research organizations and academic institutions of the country.

We would like to place on record our deep sense of gratitude to Dr. R.R. Navalgund, Director, SAC for his encouragement and guidance in carrying out this national project. We express our thanks to the Director's and Scientific team of each of the collaborating agencies for their valuable contributions in carrying out the project. We are thankful to Dr. V.S. Hegde, Scientific Secretary ISRO and Director, EOS and Dr. J.S. Parihar, Dy. Director, RESA, SAC and Dr. K. Ganesh Raj, Dy. Director (Applications), ISRO H.Q., for their support and help.

We are very much thankful to Dr. G.V. Subrahmanian, Advisor, Dr. Jag Ram, Director and Dr. Harendra Kharakwal, Scientist, MoEF for their continuous support in executing this project.

Secretarial support provided by Mr. KDM Menon and Ms. Shweta Solanki, MESG, SAC is thankfully acknowledged.

Ahmedabad
25th May, 2010

Ajai
(Ajai)

SPACE APPLICATIONS CENTRE (ISRO), AHMEDABAD-380015

DOCUMENT CONTROL AND DATA SHEET

Report Number	SAC/RESA/MESG/SGP /TR / 59 /2010
Month and Year of Publication	May 2010
Title	Final Technical Report - Snow and Glacier Studies
Type of Report	Technical Report
Number of Pages	268
Number of Figures and Tables	209 and 59
Authors	Team members
Number of References	16
Originating Unit	Marine and Earth Sciences Group, Remote Sensing Applications Area, Space Applications Centre (ISRO), Ahmedabad- 380015
Abstract	Himalayas has one of the largest resources of snow and ice, which act as a freshwater reservoir for all the rivers originating from it. Monitoring of these resources is important for the assessment of availability of water in the Himalayan rivers. Therefore, a project on Snow and Glacier studies was taken up with four objectives; i) Snow cover monitoring, ii) Glacier inventory, iii) Glacier retreat and iv) Glacier mass balance. Snow cover was monitored for 33 Himalayan basins for four consecutive years beginning from 2004 by using an algorithm based on Normalized Difference Snow Index. Glacier inventory was carried out in the Indus, Ganga and Brahmaputra basins on 1: 50,000 scale by using satellite data of the period from 2004 to 2007. Under this inventory, mapping of features of glaciers was carried out based on 37 parameters defined by UNESCO/TTS and 11 other parameters added by Space Applications Centre, Ahmedabad. Under the third component, glaciers were monitored for advance/retreat. Glaciated region of fourteen basins distributed in different climatic zones of the Himalayas were taken up for this work. Seven to thirty percent loss in glacier area was observed from 1962. Glacier mass balance was carried out for glaciers of ten basins using AAR approach.
Key Words	Snow cover, glacier inventory, mass balance and retreat / advance
Security Classification	Unrestricted
Distribution	Among concerned

PART - I

1 Title of the Project:

Snow and Glacier Studies

2 Name of Members of Research Team and their Designation:

Dr. Ajai, Group Director, MESG and Principal Investigator- Snow and Glacier Studies Project
Dr. Shailesh Nayak, Group Director, MWRG and Principal Investigator- Snow and Glacier Studies Project (upto April 2006)
Dr A.V. Kulkarni, Project Co-ordinator and Principal Investigator-Snow Cover Monitoring
Mr. Arun Sharma, Principal Investigator - Glacier Inventory
Dr. I. M. Bahuguna, Principal Investigator-Glacier Monitoring and Mass Balance
Mr. B. P. Rathore, Co-investigator- Snow Cover Monitoring, Glacier Monitoring and Mass Balance
Mr. Sushil Kumar Singh, Co-investigator-Snow Cover Monitoring and Glacier Inventory
Mr. J. G. Patel, Project Manager (Budget Coordination)

3 Number and Date of Sanction Letter

13-12/2003-EI Dated 28/03/2005

4 Duration of the Project:

Four years

5 Total Outlay of the Project

996 lakhs

6 Date of Start of Project

February 2006

7 Date of Completion of Project

31 March 2010

COLLABORATING AGENCIES

Serial Number	Institution	Work component
1	Snow and Avalanche Study Establishment, Chandigarh	Snow cover monitoring using NDSI for Beas & Parbati basin.
2	GB Pant Institute of Himalayan Environment and Development, Almorah	Glacier retreat / advance monitoring in Dhauliganga, Goriganga & Tista basin, ground validation of snout.
3	GB Pant Institute of Himalayan Environment and Development, Gangtok	Glacier retreat / advance monitoring in Dhauliganga, Goriganga & Tista basin, ground validation of snout.
4	Jawaharlal Nehru University, New Delhi	Glacier retreat / advance monitoring in Miyar basin , ground validation of snout and field mass balance for Chota Shigri glacier
5	Department of Science and Technology, Government of Sikkim, Gangtok	Snow cover monitoring using NDSI for Tista & Rangeet basin, Glacier retreat / advance monitoring for Tista & Rangeet basin
6	State Remote Sensing Applications Centre, Government of Arunachal Pradesh, Itanagar	Snow cover monitoring using NDSI for Subansiri, Tawang & Dibhang basin
7	M G Science Institute, Ahmedabad	Glacier retreat / advance monitoring and mass balance in Bhut & Warwan basin, ground validation of snout and Glacier inventory for Brahmaputra basin
8	Indian Institute of Technology-Bombay, Mumbai	Glacier retreat / advance monitoring in Bhaga basin and ground validation of snout.
9	Birla Institute of Technology, Mesra (Ranchi)	Glacier retreat / advance monitoring in Zanskar basin, and ground validation of snout., glacier inventory for Indus and Ganga basin, and field mass balance for

		Suru glacier
10	H.P. Remote sensing Cell, Shimla	Glacier retreat / advance monitoring in Spiti basin and ground validation of snout.
11	HNB Garhwal University, Srinagar, Uttrakhand	Glacier retreat / advance monitoring in Alaknanda basin and ground validation of snout.
12	Government college, Dharamshala	Glacier retreat / advance monitoring in Chandra basin and ground validation of snout.
13	Jammu University, Jammu	Glacier retreat / advance monitoring in Nubra basin and ground validation of snout.
14	University of Kashmir, Srinagar	Glacier retreat / advance monitoring in Suru basin and ground validation of snout.

PART - II

1. ABSTRACT

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. Himalayan region is difficult to study by conventional methods due to tough terrain and extreme weather conditions. Therefore, remote sensing methods are developed to monitor Himalayan snow and glacier cover.

A project on snow and glacier studies was taken up by Space Applications Centre (SAC). The project was jointly sponsored by Ministry of Environment and Forests, and Department of Space, Govt. of India. The project has four major objectives: i) Monitoring of Snow Cover in 33 basins, ii) Inventory of Himalayan Glaciers on 1:50,000 scale, iii) Monitoring retreat /advance of glaciers in selected basins, and iv) Glacier mass balance in selected basins of Himalayas. The project has been executed by Space Applications Centre in collaboration with 14 organisations.

To monitor seasonal snow cover, an algorithm based on Normalized Difference Snow Index was developed at Space Applications Centre using visible and short wave infrared data of AWiFS sensor of Resourcesat satellite. Snow cover was monitored for 33 sub-basins distributed in different climatic zones of Himalaya for four consecutive years starting from 2004. The results of snow cover monitoring show variations in patterns of snow accumulation and ablation for different basins falling in different climatic zones. For example, snow accumulation and ablation pattern for Ravi and Bhaga basins is discussed here. Ravi and Bhaga basins are located in south and North of Pir panjal range, respectively. These basins are located in different climatic zones. Ravi basin has altitude range between 630 m to 5860 m. Bhaga basin is located in altitude range between 2860 to 6352 m. In Ravi basin, snow accumulation and ablation is a continuous process throughout winter. Even in middle of winter large snow area was observed melting. In January, snow area was observed to be reduced from 90 % to 55 %. This is significant reduction in snow extent in winter season. In Bhaga basin, no significant amount of

melting was observed between January and April. However, snow melting was observed in early part of winter i.e. in the month of December. In the Eastern Himalaya, snow cover monitoring was carried out in Tista river basin. Data suggests accumulation of snow during North-East monsoon and in Winter-time. Winter time accumulation is major source of snow than monsoon time.

To understand distribution and extent of glaciers in the Himalayas, glacier inventory was carried out in the Indus, Ganga and Brahmaputra river basins on 1: 50,000 scale using images of Indian Remote Sensing Satellite for the period 2004-2007. Glacier inventory maps using multi temporal IRS LISS III and ancillary data were prepared. Specific measurements of glacier features with 37 parameters as per the UNESCO/TTS format and 11 additional parameters associated with the de-glaciated valley were carried out. The data sheet provides details for each glacier on various parameters like morphology, dimensions, orientation, elevation, etc. for both the active glacier component as well as the associated de-glaciated valley features. Mainly these comprise glacier identification in terms of number and name, glacier location in terms of coordinate details, information on the elevation above mean sea level, measurements of dimensions like length width of ablation and orientation, etc. of glacier. The inventory map shows 16197, 6237 and 9958 no of glaciers in Indus, Ganga and Brahmaputra Basins. The glaciated areas in these basins are 38375, 18393 and 21272 sq km respectively. Total number of glaciers and the total glaciated area in these three basins put together are 32392 and 78040 sq km respectively. The investigation has also shown presence of 823 moraine dammed and glacier lakes covering an area of 156.20 sq km. For the first time glaciers of the entire Indian Himalaya and also glaciers located outside but draining into India have been mapped on 1:50,000 scale using satellite data.

Monitoring of glaciers of selected fourteen basins was carried out. The basins are distributed in different climatic zones of the Himalaya. The glaciers were monitored for two time periods as: i) long term changes by using SOI topographical maps and satellite data; ii) Short term changes by using satellite images. Many Himalayan glaciers are covered by debris on ablation zones. On those glaciers emergence of channels helps in the identification snouts. The glaciers which have been monitored include large valley glaciers and small permanent snow/ice fields. On an average the loss in area has been found between 7 and 30 % using SOI maps as the reference data. Specifically in Bhaga basin, the loss in glacier area has been found to be approximately 30 %. The basins which are located in semi-arid to arid regions are relatively less debris covered and therefore show large retreat. For a period between 1990 and 2001 retreat was observed to be high in Spiti and Alaknanda basins, though located in different climatic zones. This indicates that in addition to local climatic variations, many other factors 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 more than 15 sq km, for a period 1962 and 2001/2002. Similar trend was also observed for a period between 2001/2002 to 2007, indicating influence of glacier size on retreat. In addition to moraine cover, area-altitude distribution may also influence glacier retreat/advance.

Glacier mass balance was carried out for ten basins using Accumulation Area Ratio (AAR) method for three consecutive years. Snow line during at the end of ablation (melting) season on the glaciers is indicative of mass balance. The mass balance data indicates upward movement of snowline at the end of ablation season.

2. INTRODUCTION

Today there are about 30 million cubic km of ice on our planet and cover an almost 10 percent of the World's land area. In addition, during northern hemispherical winter, snow covers almost 66 per cent of land cover. In the Himalayas, the glaciers cover approximately 33,000 sq. km. area and this is one of the largest concentrations of glacier-stored water outside the Polar Regions. Melt water from these glaciers forms an important source of run-off into the North Indian rivers during critical summer months. However, this source of water is not permanent as geological history of the earth indicates that glacial dimensions are constantly changing with changing climate. During Pleistocene the earth's surface has experienced repeated glaciation over a large landmass. The maximum area during the peak of glaciation was 46 Million sq. km. This is three times more than the present ice cover of the earth. Available data indicates that during the Pleistocene the earth has experienced four or five glaciation periods separated by an interglacial periods. During an interglacial period climate was warmer and deglaciation occurred on a large scale. This suggests that glaciers are constantly changing with time and these changes can profoundly affect the runoff of Himalayan rivers. This change in glaciers can be further accelerated due to green house effect and due to man-made changes in the earth's environment. Therefore, a proper understanding of glaciers is necessary. In view of the above, a joint program of DOS and MoEF was undertaken for snow and glacial investigations.

NNRMS Standing Committee on bio-resources in its meeting on Jan 21, 2003 has identified four major thrust areas namely 1) Forest type mapping on 1:12500 scale; (ii) Mapping of wildlife sanctuaries and national parks on 1:12500 scale; (iii) Coastal studies (including mangroves and coral reefs) and (iv) Snow and glaciers for taking up during the 10th five year plan in view of the recommendations of the peer review committee of remote sensing and GIS applications in the area of Environment and Forest. In view of above the Ministry of Environment and Forest, Government of India has constituted four task teams for each of the above-mentioned themes. The task teams have been given the mandates to identify the priority areas for detailed investigations and also to prepare detailed documents / project proposals highlighting the methodology, data, manpower, equipment requirement, study areas, project execution plans, time frame, budget requirement, output result and expected end-use etc. Accordingly the task team on 'Snow and Glaciers' had a brainstorming meeting on May 7, 2003 at Space Applications Centre, Ahmedabad. Subsequently, detail project proposal was prepared and submitted to Ministry of Environment and Forest. This proposal was discussed in detail during National level one-day workshop on August 6, 2004 at Space Applications Centre, Ahmedabad. Based on this, the project was sanctioned by Ministry of Environment and Forest on March 28, 2005.

3. OBJECTIVES AND STUDY AREA

Snow Cover Monitoring: To map and monitor seasonal snow cover of the Himalayas during year 2004- 05 to 2007-08. Snow cover maps at an interval of 5 and 10 days were prepared for 33 sub-basins of Himalayas. The sub-basins identified for snow cover monitoring are given in Table 1.

Table 1: Sub-basins for snow cover monitoring

Sr. No.	Basin	Sub-basins
1	Ganga	Alaknanda, Bhagirathi, Yamuna
2	Satluj	Spiti, Pin, Baspa, Jiwa, Parbati, Beas
3	Chenab	Ravi, Chandra, Bhaga, Miyar, Bhut, Warwan
4	Indus	Jhelum, Kishanganga, Astor, Suru, Dras, Shigo, Zaskar Nubra, Shyok, Hanza, Gilgit, Shasgan, Shigar
5	Brahmaputra	Tista, Rangit, Tawang, Dibang and Subansiri

Glacier Inventory: To carry out systematic inventory of the glaciers occurring in the Indus, Ganga and the Brahmaputra basins and draining into India by using Indian Remote Sensing Satellite data for the period 2004-2007. The area covered under glacier inventory is shown in figure 1.

Figure 1: Study area for Glacier Inventory

The study area comprises of glaciated sub-basins of Indus, Ganga and Brahmaputra river basins. The three rivers are mighty rivers that are originating from the glaciated Himalayan region where these rivers are fed by seasonal snow and glacier melt water. The Indus river originates in the Tibetan plateau near Lake Mansarovar and Mount Kailash and flow westward, south of Karakoram range and north of the Great Himalayas to Mt. Naga Parbat where it turns sharply to the south flowing through Pakistan into the Arabian sea near Karachi after traveling for 2880 km. In India the length of Indus river is 1114 km. The Ganga river originates from the Gangotri Glacier where it is known as Bhagirathi which is joined by Alaknanda at Deoprayag and combined together it is called as Ganga. The total length of the river is about 2525 km. The Brahmaputra river (Yalu Zangbu or Tsang po) rises in the glacier of the Kailash range, just south of the Lake Konggyu Tsho in Tibet. The Brahmaputra with a length of 2880 km ranks amongst the longest rivers of the world. It traverses its first 1625 km in Tibet, 918 km in India and the remaining 337 km in Bangladesh before it drains into the Bay of Bengal. The average width of Brahmaputra valley is about 86 km of which the river itself occupies 15-19 km. The Brahmaputra river system drains almost the entire eastern Himalaya. Middle and lower Himalayan hills account for the central part of this basin. In the Indian part very heavy rainfall is received in the entire Brahmaputra basin from early June to early September. Winters are very cold and snowfall occurs in the higher reaches. Dense evergreen and semi-evergreen forests are found along the Brahmaputra river in its course through Indian territory.

Glacier Monitoring: To monitor advance/retreat of Himalayan glaciers in selected sub-basins in Jammu and Kashmir, Himachal Pradesh, Uttarakhand and Sikkim. The list of basins for monitoring glacial advance/retreat is given in Table 2.

Table 2: List of basins used for glacial monitoring

Basins				
Chandra	Bhaga	Warwan	Bhut	Miyar
Alaknanda	Bhagirathi	Dhauliganga	Suru	Zaskar
Parbati	Basapa	Sptiti	Nubra	

Mass Balance Estimation: To estimate mass balance based on accumulation area ratio method for glaciers of selected sub-basins and mass balance using glaciological method for selected glaciers. List of basins is given in Table 3.

Table 3 List of basins used for glacier mass balance

Basins				
Warwan	Bhut	Chandra	Bhaga	Dhauliganga
Goriganga	Miyar	Alaknanda	Mandakini	Bhagirathi

4. DETAIL REPORT OF WORK DONE INCLUDING METHODOLOGY

4.1 Snow Cover Monitoring

The AWiFS data of Resourcesat satellite was analyzed to estimate snow extent. The snow cover was monitored for a period between October and June for 4 years from year 2004-05. A total 1500 AWiFS scenes were analyzed. Snow cover was not monitored during June-September due to cloud cover.

To generate snow cover products, initially master template was prepared using control points from 1:250,000 scale maps and then basin boundaries were delineated using drainage map. The master template was used for registration of all satellite data. Then algorithm based on Normalized Difference Snow Index (NDSI) was used to map snow cover (Kulkarni et al, 2006). NDSI was calculated using the ratio of green (band 2) and SWIR (band 5) channel of AWiFS sensor. NDSI is established using following method as given in equation 1.

$$Normalized\ Difference\ Snow\ Index(NDSI) = (band2 - band5)/(band2 + band5) \qquad ..(1)$$

To estimate NDSI, DN numbers were converted into top-of-atmosphere (TOA) reflectance. This involves conversion of digital numbers into the radiance values, known as sensor calibration, and then reflectance was estimated. The various parameters as maximum and minimum radiances, 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 was used to estimate reflectance (Markham and Barker, 1987; Srinivasulu and Kulkarni, 2004). Sensitivity analysis has shown that a NDSI value of 0.4 can be taken as a threshold to differentiate between snow and non-snow pixels. Exo-atmospheric reflectance of band 2 and band 5 of AWiFS sensor were used to compute the NDSI and no atmospheric correction has been applied at present. 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 (Kulkarni et. al., 2006). The flow diagram of NDSI based algorithm is given in Figure 2.

Validation of snow cover mapping algorithm was 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 2003 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. 132 out of 134 points were correctly classified as snow/non-snow pixels (Table 4).

Table 4: Validation NDSI to detect snow pixels

Sr. No.	Validation points	Nos.
1	Match	132
2	Unmatched	2
3	Excluded due to cloud	73
	Total	207

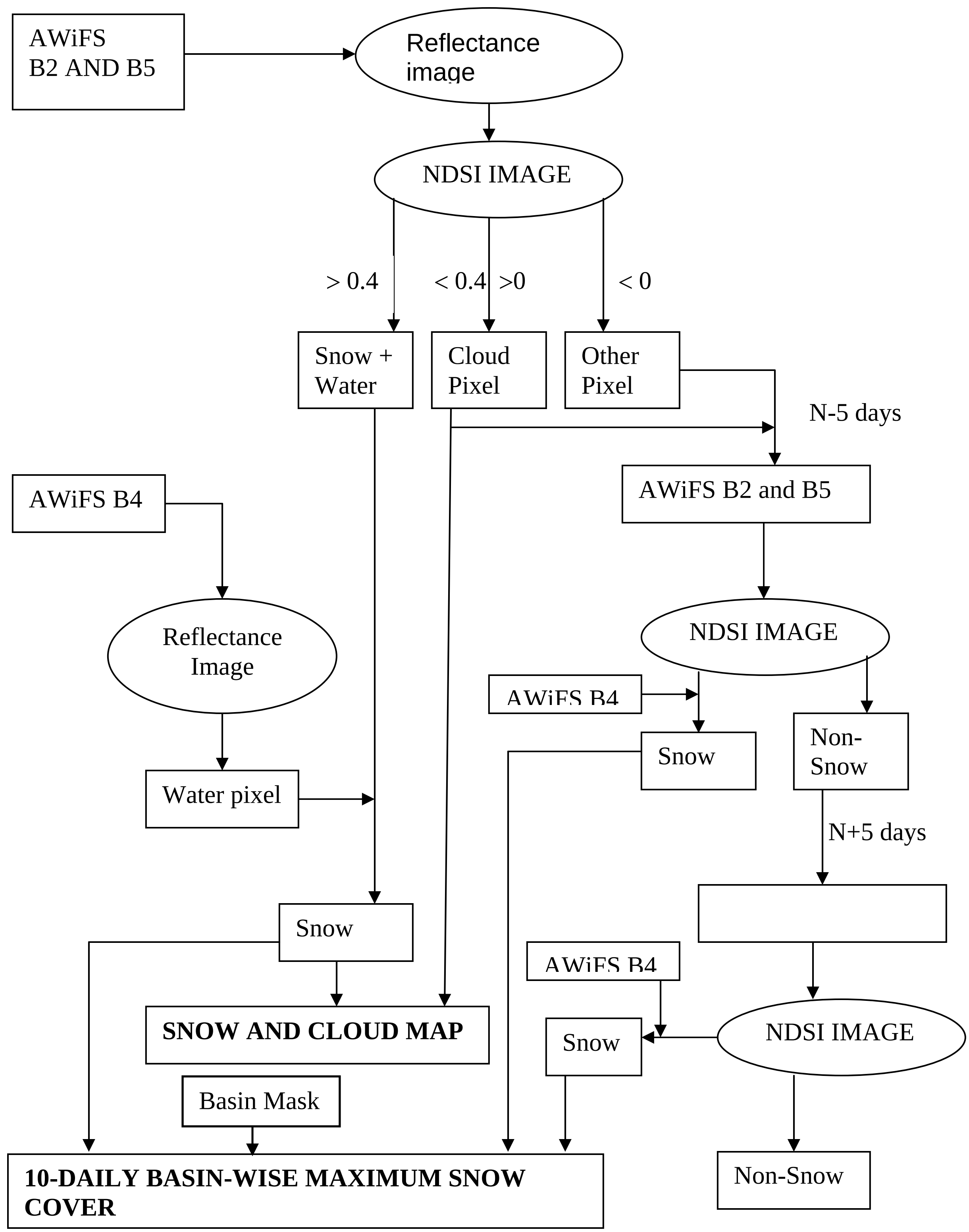


Figure 2: Algorithm for snow cover mapping using AWiFS data

In second method for validation of snow products, an area around Beas basin was selected. AWiFS data of 1 September 2005 was used to classify the region into 3 classes as snow or ice, barren land or 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 26 February 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 corresponding pixels can be misclassified. This can significantly add error to final results. For example, in Parbati river basin in Himachal Pradesh in the year 2004-05 in 18 out of 58 scenes, clouds were misclassified as snow. The present algorithm, due to lack of thermal band in AWiFS, has little potential to correct this problem. Therefore, satellite data were 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 (Kulkarni and Rathore, 2003).

Another possible source of error in snow areal extent is identification and mapping of snow under mixed pixel category. To understand influence of mixed pixels due to vegetation and soil, spectral reflectance studies were carried out in the Himalaya. The studies were carried out at Dhundi observatory of Snow and Avalanche study Establishment, Manali. A field photograph taken during observations is given in Figure 3.

Figure 3: A field photograph showing spectral reflectance observations

Snow extent is estimated at an interval of 5 and 10 days, depending upon availability 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 depending on its availability. For example, for 10 March product data of 5, 10 and 15 March were used. If any pixel is identified as snow on any one date then it was classified as snow on final product. If three consecutive scenes are not available, then all available scenes in the 10-day window were used in the analysis. This will be used to generate basin-wise 10-daily product information 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 discrimination of snow and water is difficult using reflectance due to mountain shadow.

This procedure was modified in Sikkim, due to extensive cloud cover. Cloud free images was difficult to get, therefore, two consecutive images were used to make composite product.

4.2. Glacier Inventory

The main aim of this work is to generate a glacier morphological map using multi temporal IRS LISS III and ancillary data. Specific measurements of mapped glacier features are the inputs for generating the glacier inventory data sheet (Annexure-1) with 37 parameters as per the UNESCO/TTS format and 11 additional parameters associated with the de-glaciated valley. The data sheet provides glacier wise details for each glacier on the significant glacier parameters like morphology, dimensions, orientation, elevation, etc. for both the active glacier component as well as the associated de-glaciated valley features. Mainly these comprise glacier identification in terms of number and name, glacier location in terms of coordinate details, information on the elevation above mean sea level, measurements of dimensions like length width of ablation and orientation, etc. of glacier. A table showing statistics summarizing the essential glacier features is then generated.

The sub-basin wise glacier inventory summary statistics provides a means to compare the glacier characteristics among the glaciated sub-basins. Analysis of inventory data is carried out to understand the broad distribution of glaciers across various sub-basins. Critically analyzed glacier inventory data can provide an insight to the behavior as well as the over all health of glaciers and the glaciated basins. For this each of the glacier features is studied independently as well as in conjunction with other associated glacier features. The glacier features of significance that are studied and analyzed are the accumulation area, ablation area (both ice exposed and debris covered), supra-glacier lakes, snout or terminus, de-glaciated valley and moraine dam lake. The analysis is carried out mainly in terms the glacier dimension, elevation, orientation, association, etc. The accumulation and ablation areas of glaciers are susceptible to subtle changes in atmospheric variability. These changes can put glaciers in changed environment which results in retreat/advance or thinning/thickening of glacier. This will depend on the response time of glacier which is a function of glacier geometry and other factors.

The relative size of various glacier features is significant as it indicates the characteristics of glacier in a given basin. As compared to large glaciers the smaller glaciers are relatively more prone to rapid melting depending on position and orientation of the glacier valley. The number and size of lakes particularly the moraine dam lakes and supra-glacier lakes indicate the glacier melt pattern in the glacier sub-basins. The information on such lakes is important as it indicates the possible hazard due to sudden breach or bursting of such lake dams. Similarly the de-glaciated valley number and size are also indicators of past glacier melt patterns among the sub-basins.

Description of each of these glacial features and its significance in glacial studies is given below;

Accumulation area

The region where snow falls on a glacier more commonly on a snowfield or cirque and where the glacier ice accumulates by the precipitation of snow and other forms of ice at the glacier surface is the accumulation area. The most important primary source of ice on most glaciers is snowfall, although amounts vary a great deal from place to place and throughout the year. On a more local scale, accumulation rates are strongly influenced by redistribution processes such as wind-blowing or avalanching. In accumulation area winter snowfall is more than summer ablation and is characterized by snow with high reflectance in visible and NIR region of electromagnetic spectrum. The accumulation area is significant glacier feature that indicates that the snow feed received is accumulated over a period of time and is not getting melted across seasons. The variation of accumulation area over time indicates the melt pattern of glaciers. The ratio of accumulation area and total area of a glacier when measured over a period of time is useful for estimating the variation in mass balance of glacier.

Ablation area

The region of a glacier where more glacier mass is lost by melting or sublimation than is gained is called as the ablation area. In ablation area the loss from a glacier ice could be due to wind ablation, avalanching, calving into water, melting, etc. Melting is the dominant process of ablation on many glaciers specially if the temperature exceeds 0 degree C for a part of year. This process looses winter snow accumulation, therefore, glacier ice gets exposed and has lower reflectance in visible and NIR region giving green-white tone on False Colour Composite (FCC) which can easily be differentiated from the accumulation area. The information on ablation area is significant as it indicates the area that is exposed to active seasonal ablation effect. The glacier ice in the ablation area is believed to be relatively protected from effective melting if it is covered by a layer of debris. The exposed ice on glacier in ablation area is prone to more rapid melting as compared to glacier ice in debris covered ablation area.

De-glaciated valley

The de-glaciated valley is one of the indicators of retreat of valley glaciers by vacating the valleys in lower reaches beyond the snout region. The dimensions of the de-glaciated valley and the elevation at which these occur along with the various types of moraines are significant in glacial studies related to the glacier retreat pattern.

Moraine dam lakes

The water bodies or glacial lakes are formed due to accumulation of glacier melt water at the lower elevation of the glaciers in the de-glaciated valleys and are still associated with the glacier. In majority of the cases the water bodies are resultant from the dam effect due to moraines. The moraine dam lakes are prone to dam bursts and sudden breaches leading to flooding in down stream areas.

Glacieret and snow fields

The small glaciers that cannot be morphologically further divided and the snow fields that occur in two consecutive years of satellite data are classified as glacieret and snow fields. Snow cover throughout the year and perennially under the snow covers these areas. Such areas can be mapped at the end of hydrologic year, when seasonal snow cover is fully melted. However, some confusion can arise if amount of seasonal snowfall is abnormally higher for a year. Then it can lead to mapping of seasonal snow cover into this category. To avoid this confusion, multi-year satellite images to be used for permanent snow mapping.

Methodology for generation of Glacier Inventory Maps and datasheets

Geocoded IRS LISS III data on 1:50,000 scale, from period July to end of September for the glacier inventory 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 μm), 3 (0.62-0.68 μm) and 4 (0.77-0.86 μm) and in digital data the standard bands with additional SWIR band (1.55-1.70 μm) is procured from National Data Centre (NDC), National Remote Sensing Centre (NRSC), Hyderabad. IRS AWiFS data with five day repeativity has also been used for glacier inventory as the possibilities of obtaining good quality cloud free data with less snow cover is high. In general satellite data for the period 2004-2007 has been used. For few map sheets where 2004-07 IRS satellite data were not available, other satellite data as well as the data for period 2002-03 were also used. In addition, collateral data as Drainage maps from Irrigation Atlas of India, basin Boundary maps from Watershed Atlas of All India Soil and Land Use Survey (AIS&LUS), available Snow and Glacier maps (at 1:250,000) and other scales from internet. (Bahuguna et. al. 2001, Kulkarni et. al. 1999 and 2005, Kulkarni and Buch. 1991), elevation information from DEM generated from SRTM data, road, trekking routes and guide maps, Political and Physiographic maps and Published literatures on Himalayan glaciers are used.

The glacier inventory map with details of the glacier features is prepared by visual on screen interpretation by using soft copy of multi-temporal IRS LISS III 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 (Dozier, 1984).

The broad approach for the preparation of glacier inventory map, data sheet and digital data base is given in flow chart below in Figure 4 (Sharma et al, 2006).

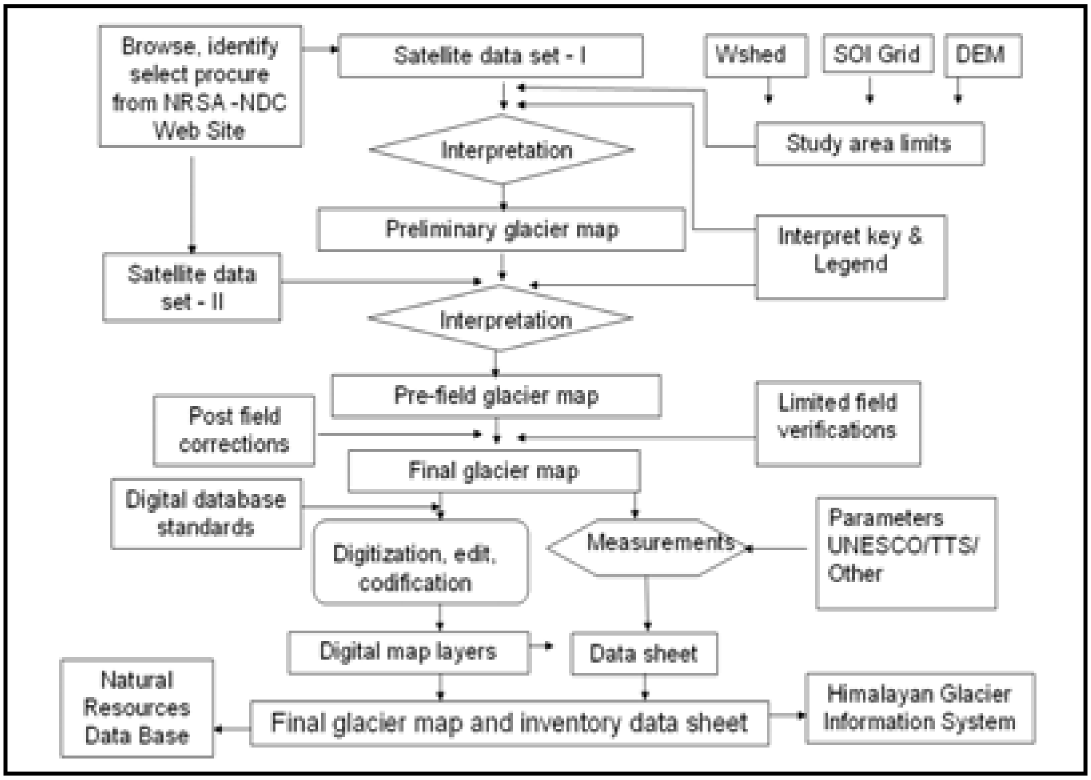


Figure 4: Broad approach for glacier inventory map and data sheet preparation

In practice the preparation of glacier inventory map involves preparation and integration in GIS of primary theme layers. The primary theme layers are grouped into three categories i) Base information ii) Hydrological information iii) Glacier and De-glaciated valley features as shown in Table 5 (Sharma et al, 2008).

Table 5: Theme layers for glacier inventory map and data sheet creation

Sr. No.	Theme	Remarks/ Contents
A] Base Map		
1	Frame work	5’ * 5’ latitude-longitude tic points (background for all layers)
2	SOI map reference	15’*15’ latitude-longitude grid and SOI reference no.
3	Country Boundaries	Country (not authenticated)
4	Roads	Metalled/unmetalled road, foot-path, treks, etc.
5	Settlement extent	Extent of habitation
6	Settlement location	Location of habitation
7	Elevation DEM*	Image grid
B] Hydrology		
8	Drainage lines	Streams with nomenclature
9	Drainage poly	Water body, river boundary with nomenclature
10	Watershed Boundary	Watershed boundary and alphanumeric codes
C] Glacier		
11	Glacier boundary	Ablation, accumulation, snow cover areas, supra-glacial lake, de-glaciated valley, moraine dammed lake, etc
12	Glacier lines	Ice divide, transient snow line, centre line, etc.
	Glacier point	Point locations representing coordinates for glacier, glacier terminus/snout, moraine dam lake, supra-glacier lakes, etc.
13	Glacier elevation point locations	Glacier elevation point locations. Highest/lowest values for glacier, moraine dam lake, supra-glacier lakes.

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.

Preliminary glacier inventory maps have been prepared using the first set of satellite data. Subsequently, they are modified as pre-field glacier inventory maps 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.

Preparation of theme layers

The published Irrigation Atlas, Watershed Atlas, small and large scale maps like political/ physical maps from reliable source have been identified for utilization 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:-

Base map layers

The base map comprises of the four types of layers like the administrative boundary layer, transportation network, settlement locations and elevation information (DEM) layer.

Administrative boundary layer

Major administrative boundaries like the national is obtained from published Political maps (or SOI open series maps). In digital data base these boundaries are identified, delineated, codified and are stored as separate layers with corresponding look-up tables (Table 6 and Table 7). The country codes as identified by UNESCO/TTS /Muller are followed.

The satellite data does not have any role in creating these administrative layers. However, these are significant reference layers essential for understanding the distribution of glaciers within the political boundaries. The layers are directly procured from SOI as open series digital maps. The administrative maps are directly incorporated in the data base at SAC.

Table 6: Attribute tables for Country: COUNTRY.LUT

COUNTRY-CODE	**COUNTRY-NAME**
IN	India
CH	China
NP	Nepal
BH	Bhutan
TB	Tibet

Table 7: Structure of table-COUNTRY.LUT

Field Name	**Field Type**	**Key Field-Y/N**
COUNTRY-CODE	2,2,C	Y
COUNTRY-NAME	10,10,C	N

Transportation network

As majority of the glaciated areas in the Himalayas are not easily assessable, the meager transportation features that are available become all the more significant for any glacier related study. The information on the transportation features occurring in the area is represented in a separate layer called the Roads layer.

The road maps published by the state or other transportation network maps like road atlas, tourist/track maps, etc., containing the required information on various types of roads are used. The road network comprising of various types of metalled, un-metalled roads, foot paths, cart tracks, track on glacier, etc. leading to the glacier or across the glacier, if any, are identified and delineated on to the vector layer. This information is then compared and updated based on satellite data and field visit. The layer is digitized and appropriately codified to create a final ROADS layers. The corresponding look up tables (ROADS.LUT) and structure of the table are as given in Tables 8 and 9 given below.

Table 8: Attribute Table for Roads: ROADS.LUT (Anonymous, 2000)

RD- CODE	ROAD TYPE	SUB-TYPE
01-00	Metalled Black Topped (BT) or Bitumen Roads	
01-01	National Highway	
01-02	State Highway	
01-03	District Road	
01-04	Village Road	
02-00	Unmetalled Water Bound Macadam (WBM) or Concrete/ Cement Roads	
02-01	National Highway	
02-02	State Highway	
02-03	District Road	
02-04	Village Road	
03-00	Tracks	

03-01		Pack Track in Plains
03-02		Pack Track in hills
03-03		Track follows stream
03-04		Cart Track in plains
03-05		Cart track in desert/ wooded/ hilly area
03-06	Footpath	
03-07	Footpath in hill	
04-00	Route Over glacier	
05-00	Pass	
06-00	Pass in permanent snow	
07-00	Road on dry river bed	
08-00	Road under construction	
08-01		National Highway
08-02		State Highway
08-03		District Road
08-04		Village Road
09-00	Others	Earthen/Gravel, Flyover etc.

Table 9: Structure of the table - ROADS.LUT (Anonymous, 2000)

Field Name	**Field Type**	**Key Field - Y/N**	**Remarks**
RD-CODE	4, 4, C	Y	Feature Code
TYPE	30,30, C	N	Road Type
SUB-TYPE	30,30, C	N	Sub-Type

Settlement location

The lower reaches of the basins are inhabited and presence of small settlements common. The extents of such village/town are first delineated based on available published maps and stored as a polygon (SETTLEA) layer or the habitation mask. The village/town settlement extent (polygon) is updated using multi-date satellite data and corresponding codification is done as per look-up table SETTLEA.LUT (Table 10 and Table 11). The centeroid of the delineated polygon for settlement is marked as the settlement location point (SETTLEP) and all relevant information is attached with this point in the look-up table SETTLEP.LUT (Table 12). The SETTLEP codification for each of the village is as per the codes given in Census (2001).

The settlement layers is used as habitation location mask that are overlaid on the glacier inventory map while generation of the hardcopy output during the preparation of the A3 size Atlases for each of the three basins.

Table 10: Attribute Table for Settlement (Polygons): SETTLEA.LUT (Anonymous, 2000)

SETA-CODE	SET-TYPE
01	Towns/ Cities (Urban)
02	Villages (Rural)

Table 11: Structure of the Table DRAINL.LUT (NRIS)

Field Name	Field Type	Key (Y/N)	Remarks
SETA-CODE	4,4, C	Y	Feature Code
SET-TYPE	30,30,C	N	Code Description

Table 12: Attribute Table for Settlements (Points): SETTLEP.LUT (Anonymous, 2000)

Field Name	Field Type	Key Field Y/N	Remarks
SCODE	8,8,C	Y	
LOCATION	25,25,C	N	Village Name
V –TYPE	25,25,C	N	
SCODE is the system link CODE			
SCODE	V -TYPE		
00009000	Village		
00009001	Forest		
00009002	Town		
9004	Others		

Elevation information (DEM) layer

The DEM generated based on Shuttle Radar Terrain Mapping (SRTM) Mission with vertical resolution of 30 m is used for collecting the elevation information. The point location layer is overlaid on the DEM and significant elevation measurements required as input for the data sheet is obtained.

Hydrology

The hydrology layer with information on all the minor, major drainage, water bodies and watershed 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).

Drainage line layer

The drainage line layer is prepared to represent all the streams arising from the snow and glacier feed area and which is represented only as single line due to mapping scale (DRAINL.LUT) as given in Table 13 and Table 14.

Table 13: Attribute Table for Water Body Polygons: DRAINL.LUT (Anonymous, 2000**)**

DRNL-CODE	**DISCR**
01	Perennial
02	Dry
03	Tidal*
04	Undefined/ Unreliable
05	Perennial - Unreliable
06	Tidal creek*
07	Water channel in dry river
08	Broken Ground/ ravines

*may not exist in glacier areas.

Table 14: Structure of the Table DRAINL.LUT (Anonymous, 2000**)**

Field Name	**Field Type**	**Key (Y/N)**	**Remarks**
DRNL-CODE	2,2,C	Y	Feature Code
DISCR	30,30,C	N	Code Description
STREAM ORDER	2,2,I	N	Stream Order

Drainage poly layer

This layer provides information on all the major streams and the water bodies which are mapped as polygons at this scale. The dry and wet parts of the drainage are identified and delineated with appropriate codification. The sand area, which is seasonally under water during occasional flooding caused by snow melt, should also be appropriately identified and mapped.

The moraine dammed lakes and the supra-glacial lakes are delineated and appropriately classified (DRAINP.LUT) (Table 15 and Table 16). Names of large water bodies and rivers are identified from published maps and stored in the associated record in look-up table.

Both the preliminary drainage line and polygon layers prepared using small scale maps as input are updated using multi-date satellite data. All changes in stream/river courses and presence of new water bodies are incorporated in the final drainage layers.

Table 15: Attribute Table for Water Body Polygons: DRAINP.LUT (Anonymous, 2000**)**

DRNP-CODE	**DISCR**
01	River
02	Canal*
03	Lakes/ Ponds
04	Reservoirs
05	Tanks
06	Cooling Pond/ Cooling Reservoir*
07	Abandoned quarries with water*
08	Bay*
09	Cut-off Meander*
10	Supra-glacial lake
11	Moraine dammed lake

* may not exist in glacier areas

Table 16: Structure of the Table DRAINP.LUT (Anonymous, 2000**)**

Field Name	**Field Type**	**Key (Y/N)**	**Remarks**
DRNP-CODE	2,2,C	Ŷ	Feature Code
DISCR	30,30,C	N	Code Description

Watershed (Basin / Sub-basin) boundary layer

The hierarchical (preliminary) watershed boundary information as delineated from the small scale watershed maps as available in the Watershed Atlas. The delineated boundaries in the preliminary map are modified using multi-date satellite data. The ridges, ice divide and stream/river features representing the watershed boundaries as seen on the image are carefully interpreted and are refined at 1:50,000 scale to prepare the final watershed ***(Basin / Sub-basin)*** map layer.

Glacier

The glaciers in the Himalayas are mainly of the Mountain and valley glacier type. The available archive information on glaciers in the form of glacier maps / Atlas on the Himalayan Glacier Inventory at 1:250,000 scale (Kulkarni and Buch, 1991) is referred before the mapping is initiated to get an idea of the glacier occurrences and distribution in the past.

Using multi-date satellite data the required glacier morphological features are mapped. However, for convenience of generating statistics from digital layers, these morphological features are stored separately as line point and polygon layers.

The glacier inventory map is prepared in two steps; first the preliminary glacier inventory map is prepared using the first set of satellite data and all glacier features (Figure 5) are mapped. Later, the dynamic features like snow line, permanent snow covered area, moraine extent, etc., are modified and new glacier features, if any, are appended based on the subsequent year satellite data to prepare the pre-field glacier inventory map. The pre-field glacier inventory map is then verified in the field wherever possible and final glacier inventory map is prepared after including the modifications if any.

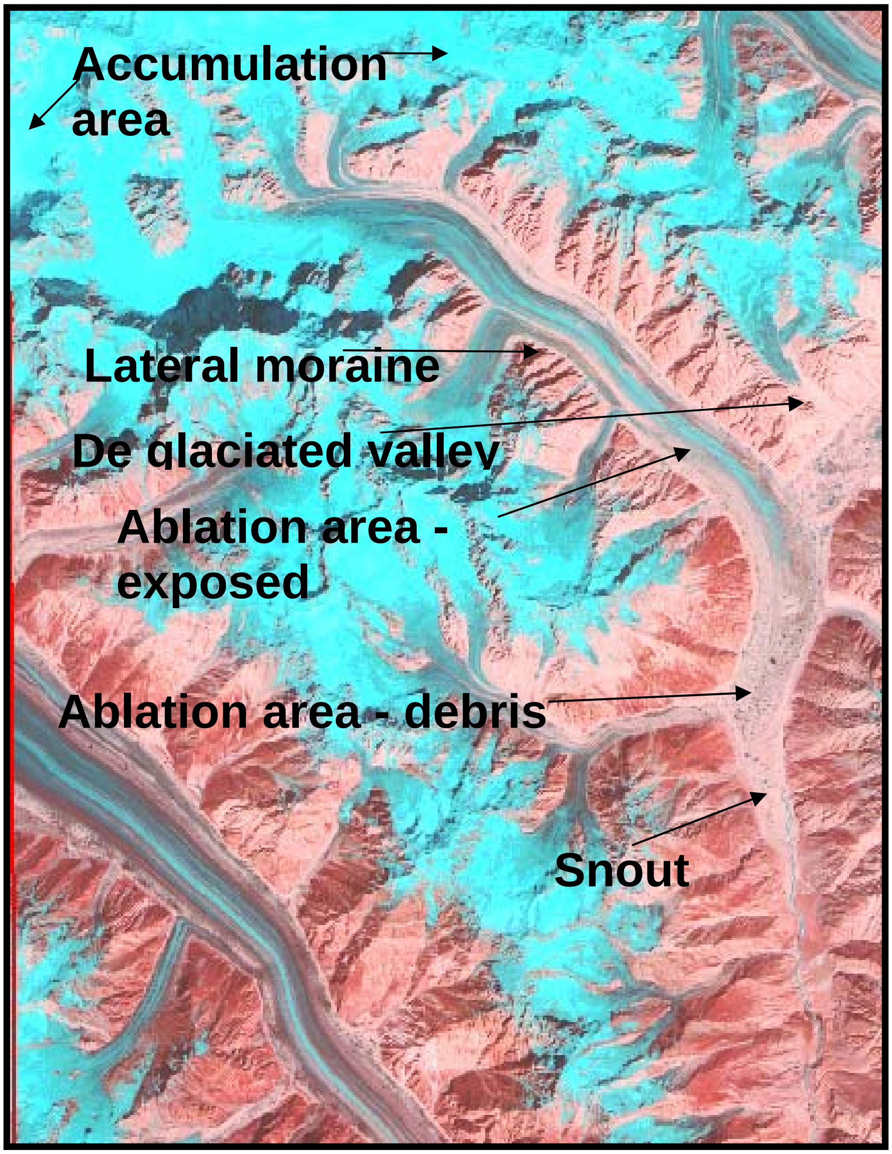


Figure 5: Glacier Features as seen on IRS LISS III FCC (Sep. 2005)

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 lateral and medial moraine features associated with the ablation areas are delineated. The supra-glacier lakes if any are delineated.

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.

Glacier features layers

Using multi-date satellite data, the extent of the perennial snow covered areas, the glacieret, the glacier accumulation and ablation area, etc., associated with the glacier are delineated as polygon features (GLACIER) and appropriately codified (GLACIER.LUT).

The transient snow line which separates the accumulation and ablation areas and the ice divide line at the margins of two or more glaciers are identified and delineated as line features in a separate cover. The centre line running along the maximum length/longitudinal axis of the glacier and dividing it into two equal halves is delineated and stored as line feature (GLACIERL). The position of the glacier terminus or snout is delineated as point feature in a separate cover (GLACIERP). The associated look-up tables for the glacier poly, line and point features are created as GLACIER.LUT, GLACIERL.LUT and GLACIERP.LUT along with corresponding structure for each of these are respectively given in Tables 17, 18, 19, 20, 21 and 22.

As per the TTS format the glacier positions as represented by the latitude /longitude and coordinate system are essential. Similarly, various point locations representing the coordinate point for de-glaciated valley, supra-glacier lake, snout, moraine dam lake, etc. are essential for tabular representation and future reference. The layer GLACIERP with point location (coordinates in latitude /longitude) is created for this purpose.

De-glaciated valley feature

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, medial, lateral moraine, outwash plain, moraine dammed lake, etc. (Figure 6). 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 (GLACIER) layer. Some of the lateral and terminal moraines which are delineated only as the lines are separately kept in a line vector layer the de-glaciated valley line (GLACIERL) layer.

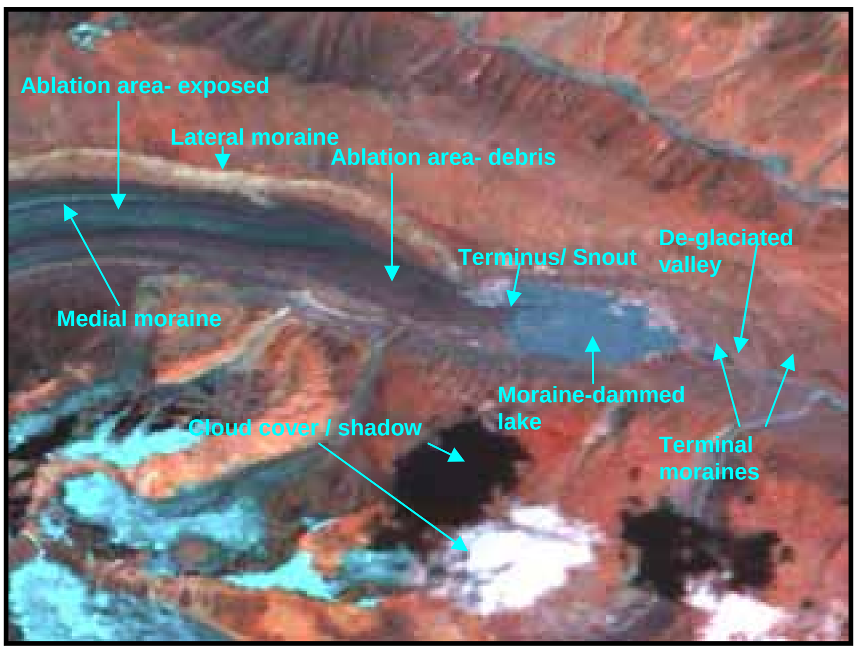


Figure 6: Glacier and De-glaciated valley features on IRS LISS III FCC (Samudra Tapu Glacier, Indus Basin)

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 attribute table and the structure of the ELEVP is given in Table-23. The elevation information for these locations is obtained by intersecting this layer with the DEM layer created using SRTM data.

Table 17: Attribute Code Table for Glacier Polygon Layer: GLACIER.LUT

GL-Code	Discr-L1	Discr-L2	Discr-L3
01-00-00	Glacier		
01-01-00		Accumulation area	
01-02-00		Ablation area	
01-02-01			Ablation area: debris cover
01-02-02			Ablation area: exposed
01-03-00		Moraine	
01-03-01			Terminal moraine
01-03-02			Medial moraine
01-03-03			Lateral moraine
01-04-00		Supra glacier lakes	
02-00-00	De glaciated valley		
02-01-00		Moraine	
02-01-01			Terminal moraine
02-01-02			Lateral moraine
02-02-00		Outwash plain	
02-03-00		Moraine dammed lake	
03-00-00	Glacieret & Snow field		
88-88-88	Non glaciated area		

Table 18: Structure of the Table GLACIER.LUT

Field Name	Field Type	Key Field - Y/N	Remarks
GL-Code	6, 6, C	Y	Feature Code
GLAC_ID	15, 15, C	Y	Glacier identification number
Discr-L1	50,50, C	N	Glacier Unit at very small scale
Discr-L2	50,50, C	N	Glacier Unit at large (1:50k) scale
Discr-L3	50,50, C	N	Glacier Unit at large (1:50k) scale with next level of (hierarchy) details

Table 19: Attribute Code Table for Glacier Line Layer: GLACIERL.LUT

GLL-Code	Discr-L1
01	Ice divide line
02	Lateral Moraine glaciated area (trace)
03	Median Moraine in glaciated area (trace)
04	Terminal Moraine in glaciated area (trace)
05	Lateral Moraine in de-glaciated area (trace)
06	Terminal Moraine in de-glaciated area (trace)
07	Transient snow line
08	Centre line of total glacier (max. length)
09	Centre line of glacier (2) smallest (min. length)
10	Centre line of total de-glaciated valley (max. length)
11	Centre line of exposed glacier (max. length-exposed)
12	Centre line of ablation area (max. length)
13	Mean width line for ablation area – maximum length
14	Mean width line for ablation area – minimum length

Table 20: Structure of the Table GLACIERL.LUT

Field Name	Field Type	Key Field - Y/N	Remarks
GLL-Code	2, 2, C	Y	Feature Code
GLAC_ID	15, 15, C	Y	Glacier identification number
Discr	50,50, C	N	Glacier line feature at large (1:50k) scale

Table 21: Attribute Code Table for Glacier Point Layer: GLACIERP.LUT

GLP-Code	DESCRIPTION
01	Terminus / snout
02	Glacier coordinate point
03	Supra-glacial lake coordinate point
04	De-glaciated valley coordinate point
05	Moraine dam lake coordinate point
06	Snowline coordinate point

Table 22: Structure of the Table - GLACIERP.LUT

Field Name	Field Type	Key Field - Y/N	Remarks
GLP-Code	2, 2, C	Y	Feature Code
GLAC_ID	15, 15, C	Y	Glacier identification number
Discr	50,50, C	N	Glacier co-ordinate point location

Glacier elevation point layer (ELEVP)

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 attribute table and the structure of the ELEVP are given in Table 23 and Table 24. The elevation information for these locations is obtained by intersecting this layer with the DEM layer created using SRTM data.

Table 23: Attribute Code Table for Elevation Point Layer: ELEVP.LUT

ELEV-CODE	**DESCRIPT**
01	Highest glacier elevation point
02	Lowest glacier elevation point (same as snout location)
03	Lowest supra-glacial lake elevation point
04	Lowest moraine dam lake elevation point
05	Snowline elevation point / high elevation ablation area / low elevation of accumulation area
06	Lowest De-glaciated valley elevation point

Table 24: Structure of the Table - ELEVP.LUT

Field Name	**Field Type**	**Key Field - Y/N**	**Remarks**
ELEV-CODE	2, 2, C	Y	Feature Code
GLAC_ID	15, 15, C	Y	Glacier identification number
ELEV-VAL	5,5,I	N	Glacier elevation value in meters
Discr	50,50, C	N	Various glacier elevation point

Steps in preparation of glacier inventory map and data sheet

For preparing the glacier inventory map and data sheet, onscreen analysis of satellite data is carried out using FCC digital image. Along with the satellite data following thematic layers prepared earlier are also used.

- Frame work (FRAME) comprising of tic marks at interval of 5' x 5' representing the latitude and longitude for the study area with WGS 84 and projection in WGS84 corresponding to open series maps (OSM) is created and provided. The codification for the tic ids is DDMMSSDDMMSS (12 digits) corresponding to the longitude and latitude for the tic location.

- SOI layer comprising of polygons Grid obtained by joining the tics located at interval of 15' x 15' and representing the boundary of 1:50,000 scale map sheet. The information of the map sheet number the minimum and maximum values of latitude and longitude associated with the sheet is stored in the associated look-up table (SOI.LUT) Table 25.

- Watershed (Basin / Sub-basin) boundary (WSHED) based on small scale maps and codification as per AIS&LUS procedure.

- DEM based on SRTM data. Raster image with elevation information.

Table 25:.Attribute Table for Survey of India Toposheets: SOI.LUT

Field Name	**Field Type**	**Key Field- Y/N**
SOI-CODE	6,6,C	(Y)
SOI-NAME	8,8,C	N
LAT-MIN	10,10,C	N
LONG-MIN	10,10,C	N
LAT-MAX	10,10,C	N
LONG-MAX	10,10,C	N
Explantation for SOI-CODE (nn-qq-ss)		
Nn	Toposheet Number at 1:1million level i.e. 01, 02.....	
Qq	Quadrant number	
	01	A
	02	B
	----------	-----------
Ss	16	P
	Segment Numbers from 01 to 16	
	For Example SOI-CODE for Toposheet 56/E/2 is 56-05-02	

- The administrative boundary of COUNTRY is generated and is finally integrated with the data base. The corresponding look-up tables is prepared for these layers COUNTRY.LUT
- The details of steps involved in the preparation of the glacier inventory map given in Figure 7 and data sheet in Annexure-2.

The geocoded satellite data and the vector layers are appropriately loaded on to the computer system.

A new vector layer is created with the projection and datum system standards.

Copies of this layer are made and appropriately renamed as DRAINL, DRAINP, WSHED, GLACIER, GLACIERL, GLACIERP, etc. The coverage topology is built as poly, line or point as required.

DRAINL

The available scanned small scale drainage map is used and all the drainage features as seen on the map are delineated as a line. The courses of drainage are modified as seen on the satellite data to finalize the drainage line layer. The lines are suitably codified as given in DRAINL.LUT.

DRAINP

The boundary of streams /rivers and water body features as seen on the map are delineated as double line. Modifications based on satellite data are carried to include the changed courses of drainage features. The extent of dry sections of channel / water body is also appropriately delineated and all features are codified.

WSHED

The small scale preliminary watershed map is used and correlated with the features on satellite data like the ridges or courses of major stream, ice divide, etc. which represents watershed / basin limits. The refinement is done to follow distinctly seen watershed (Basin) features on the satellite data.

ROADS

The preliminary small scale ROADS layer is superimposed on the satellite data and the road features on map and satellite data are correlated. The new road features are delineated and any other changes with respect to road features as seen on the satellite data are incorporated on to the map. The delineated road features are codified as per the codification scheme. All map sheets do not have roads layer.

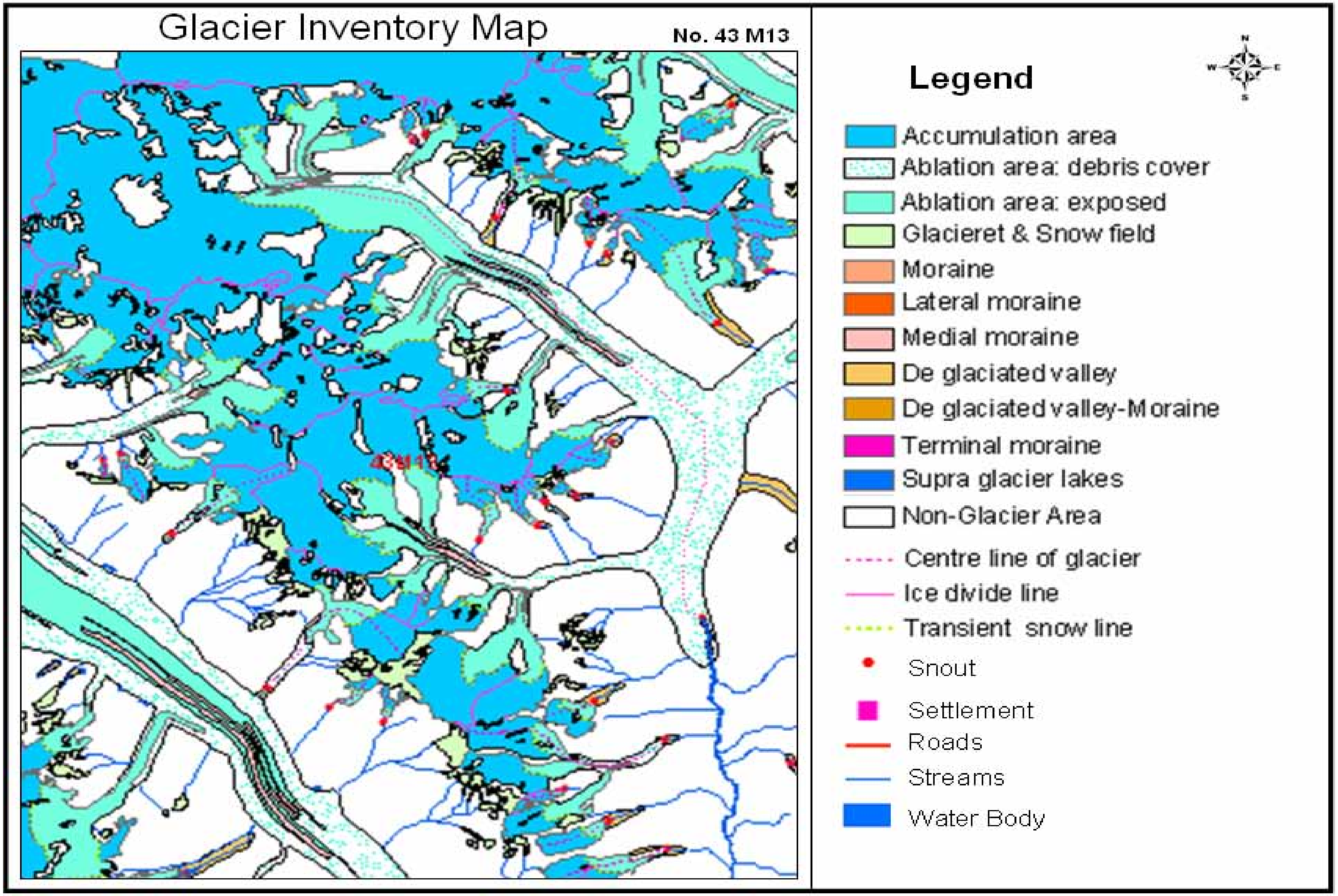


Figure 7: Glacier Inventory Map

GLACIER:

The glacier inventory map is prepared in two stages using two set of satellite data. The preliminary layers which are intermediate layers are stored in the database.

First the preliminary glacier inventory map is prepared using the first set of satellite data by superimposing the glacier poly layer on the satellite data and delineating the area features like the extent of the snow fields and glacierets. The glacier boundary with separate accumulation and ablation area are delineated as polygon features and appropriately codified (GLACIER.LUT) and stored.

The line vector layer for glacier (GLACIERL) contains the line features like the transient snow line which separates the accumulation and ablation areas and the ice divide line at the margins of two or more glaciers are identified and delineated as line features. The centre line running along the maximum length/longitudinal axis of the glacier and dividing it into two approximately equal halves is identified, delineated, codified and stored as line feature in the database. Besides these, other line features are also delineated as required to fill the standard TTS glacier inventory data sheet. These lines mostly are drawn to represent width of the glacier (mean width line) for ablation and accumulation areas. In practice, two lines are drawn for width estimation, one representing the maximum width and other representing the minimum width of the feature (viz. ablation area / accumulation area). These lines are only meant for recording the measurements for the purpose of the TTS data sheet.

Similarly the point vector glacier layer GLACIERP is created by delineating the glacier terminus or snout as point feature. The coordinate point for glacier features such as glacier, de-glaciated valley, supra-glacier lake, moraine dam lake, etc. are delineated. The corresponding latitude and longitude values are obtained against these locations for further use in TTS form and others. These points are appropriately codified and stored as GLACIERP layer in the database.

The various elevation points like the lowest/highest glacier elevation are identified using the SRTM - DEM within the glacier boundaries (ELEVP). It is important to note that some of the point features as required for the TTS form may be common during digitization. Like the lowest glacier elevation point may be lowest elevation point for ablation area and may also represent the location for the snout position. The same point representing more than one feature may also occur in both the GLACIERP as well as the ELEVP layers. But these are essential for the analysis purpose and hence are repeated in more than one layer.

To finalize the glacier layer the second date (subsequent year) satellite data is used to verify and, if necessary, modify the previously delineated boundaries of glacier features. The snout position is taken as in the latest data set. The snow extent and snow line is taken as the minimum extent of the two set of data.

The associated look-up tables for the glacier poly, line and point features are created as GLACIER.LUT, GLACIERL.LUT and GLACIERP.LUT respectively. The maps are edge matched/ mosaicked and stored in database. The final outputs are prepared basin-wise.

Field verification

The final glacier inventory map layer is prepared only after limited field verification exercise is carried out for few specific glaciers that are approachable.
The specific glaciers are selected judiciously from among a set of basins geographically well distributed and showing definite variation of observed geomorphological parameters.
The accessibility to the regions is ascertained while identifying the glaciers for field validation.
Based on the field expeditions to different glaciers, the glacier inventory map is verified and corrections, if any, are incorporated.

ELEVP

The elevation locations mainly represent the highest glacier elevation, lowest glacier elevation, lowest supra-glacial lake elevation, lowest moraine dam lake elevation, snowline elevation, etc. All elevations measurements (as applicable) are taken along the centre line of the glacier. The point locations are provided codes/attributed as given in ELEVP.lut. The actual elevation values are obtained by overlaying the ELEVP on the DEM layer in GIS using identity function for the points.

Integration of Layers and Preparation of Final Glacier Inventory Map

The various layers prepared by interpretation of multi-date satellite data are digitized, appropriately codified and stored in the digital database in GIS environment. These layers are then systematically integrated in GIS to prepare the final glacier inventory map (pre-field). Limited field verification is carried out to verify the delineated features. The post-field modifications, if any, are incorporated in the map to prepare the final glacier inventory map. Cartographic maps are composed by overlaying the various layers in GIS and by using appropriate symbology for each of the features related to the base map, hydrology and glacier features layers.

The Index map showing India and environs comprising of parts of major basins Indus, Ganga and Brahmaputra that flow into India are given in Figure 8. The Basin maps for Indus, Ganga and Brahmaputra basin showing the locations of Sub-basins are given in Figure 9, Figure 10 and Figure 11. Sub-basin wise sample glacier inventory maps one each for Indus, Ganga and Brahmaputra represented by Chenab, Alaknanda and Tista respectively are given in Figure 12 to 14. The remaining sub-basin wise maps are given in Annexure-2.

Figure 8: Index map - India and Environs (Indus, Ganga and Brahmaputra basins)

Figure 9: Index map showing Indus sub-basins

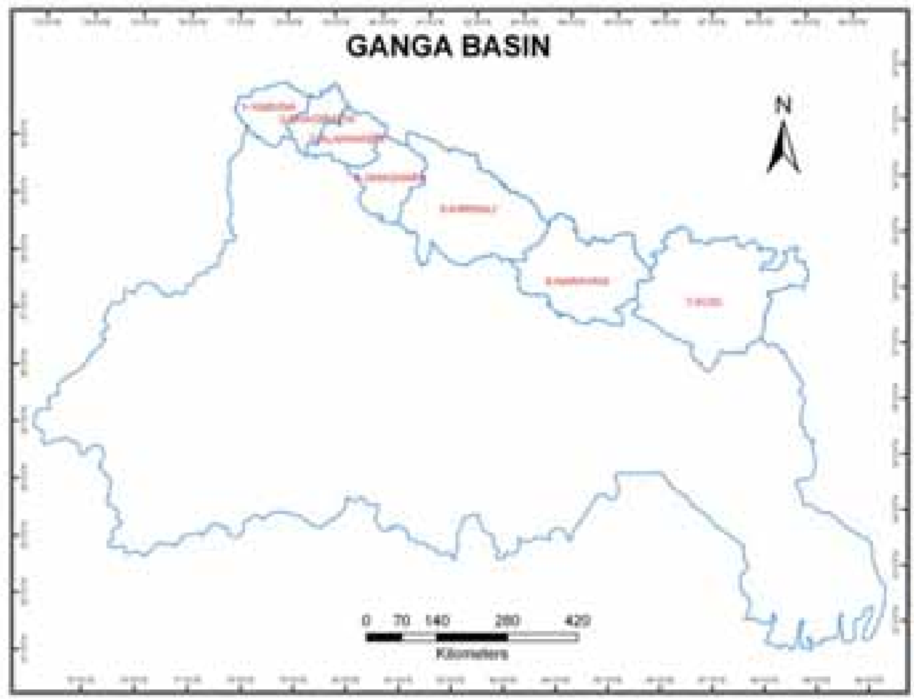


Figure 10: Index map showing Ganga sub-basins

Figure 11: Index map showing Brahmaputra sub-basins

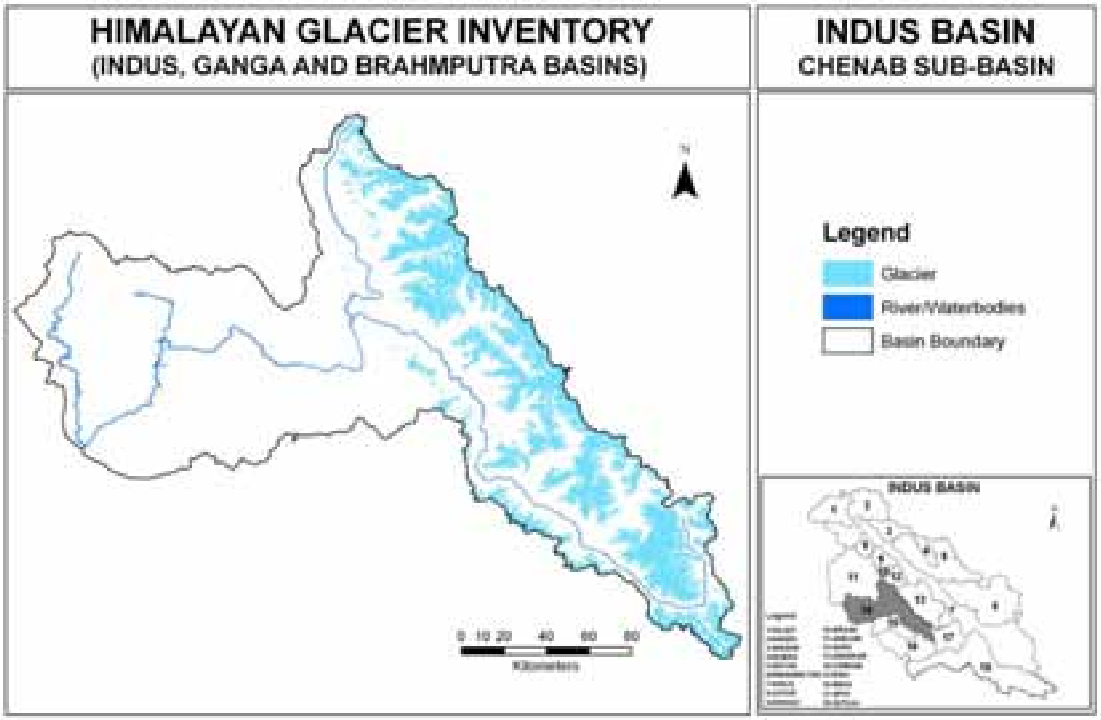


Figure 12: Glaciated area of Chenab Sub-basin (Indus Basin)

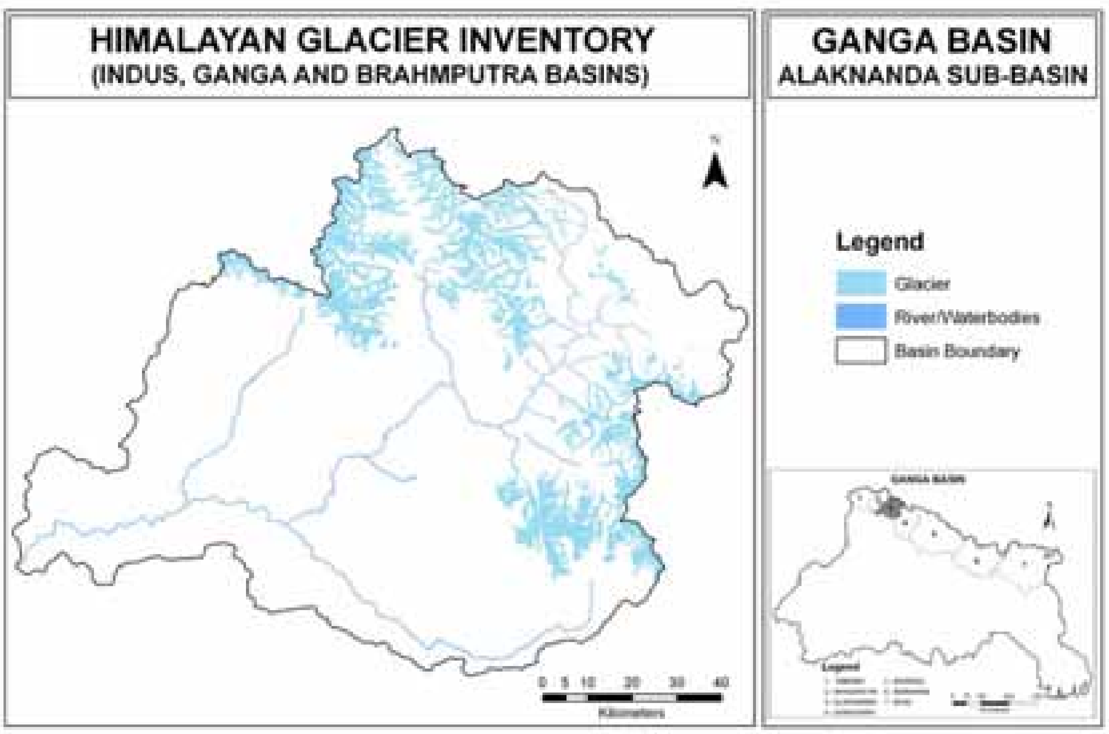


Figure 13: Glaciated area of Alaknanda Sub-basin (Ganga Basin)

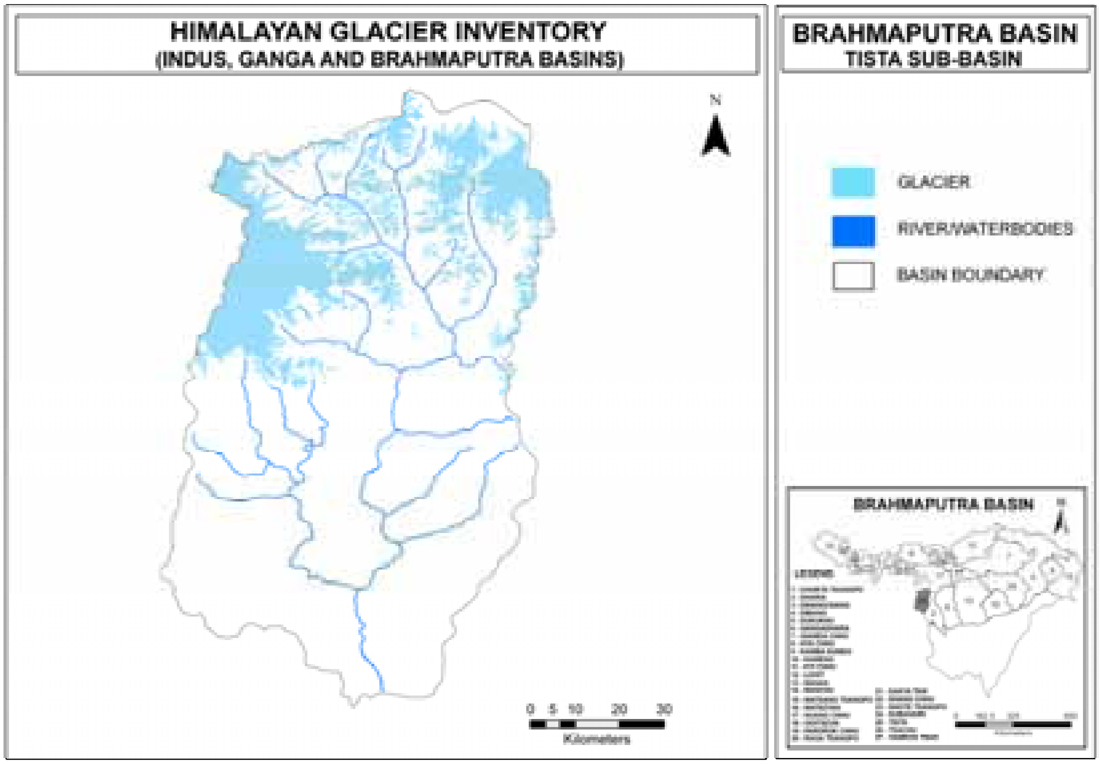


Figure 14: Glaciated area of Tista Sub-basin (Brahmaputra Basin)

Generation of glacier inventory data sheet

Inventory data (Annexure-2) 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 of 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 present 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 are 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 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 Ganga 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 the 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. To facilitate this, smallest stream is given, by definition, order eight, instead of four as given by UNESCO/ TTS. This can cause change in number from order five to eight and no change is necessary for positions between four and one. This makes data completely compatible with UNESCO/ TTS data base. To get number for stream order between eight and five; the map of watersheds is taken from Watershed Atlas of India (Anon., 1990).

2. Glacier name: Every glacier does not have 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 (or other nationally determined format)

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.

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) as detailed in Table 26.

Table 26: Classification System for Glaciers

	Classification					
	Digit 1	**Digit 2**	**Digit 3**	**Digit 4**	**Digit 5**	**Digit 6**
	Primary Classification	**Form**	**Frontal Characteristics**	**Longitudinal Profile**	**Major Source Of Nourishment**	**Activity Of Tongue**
0	**Uncertain or Misc.**	**Uncertain or Misc.**	**Normal or Misc.**	**Uncertain or Misc.**	**Uncertain or Misc.**	**Uncertain**
1	Continental ice sheet	**Compound basins**	**Piedmont**	Even; regular	Snow and/or drift snow	Marked retreat
2	**Ice field**	**Compound basin**	**Expanded foot**	Hanging	Avalanche ice and /or avalanche	Slight retreat

					snow	
3	Ice cap	**Simple basins**	Lobed	Cascading	Superimposed ice	Stationary
4	Outlet glacier	**Cirique**	**Calving**	Ice-fall		Slight advance
5	**Valley glacier**	**Niche**	**Coalescing, non-contributing**	Interrupted		Marked advance
6	**Mountain glacier**	**Crater**				Possible surge
7	**Glacieret and snow field**	Ice apron				Known surge
8	Ice shelf	**Group**				Oscillating
9	**Rock glacier**	**Remnant**				

Descriptions of each of the above classification are given below

Digit 1 Primary classification

0 Uncertain or Misc. - Any not listed

1 Continental ice sheet - Inundates areas of continental size

2 Ice field - Ice masses of sheet or blanket type of a thickness not sufficient to obscure the surface topography

3 Ice cap - Dome shaped ice mass with radial flow

4 Outlet glacier - Drains ice sheet or ice cap, usually of valley glacier form; the catchment area may not be clearly delineated

5 Valley glacier - Flows down a valley; the catchment area is well defined

6 Mountain glacier - Cirque, niche or crater type; includes ice aprons and groups of small units

7 Glacieret and snow field - Glacieret is a small ice mass of indefinite shape in hollows, river beds and on protected slopes developed from snow drifting, avalanching and / or especially heavy accumulation in certain years; usually no marked flow pattern is visible and therefore no clear distinction from snow fields is possible. Exists for at least two consecutive summers.

8 Ice shelf - A floating ice sheet of considerable thickness attached to a coast, nourished by glaciers (s); snow accumulation on its surface or bottom freezing

9 Rock glacier - A glacier-shaped mass of angular rock in a cirique or valley either with inertial ice, firn and snow or covering the remnants of a glacier, moving slowly down slope

Digit 2 Form

1 Compound basins - Two or more individual valley glaciers issuing from tributary valleys and coalescing (Figure 15a and Figure 17).

2 Compound basin -Two or more individual accumulation basins feeding one glacier system (Figure 15b and Figure 18).

3 Simple basin - Single accumulation area (Figure 15c and Figure 19a).

4 Cirque - Occupies a separate, rounded, steep walled recess which it has formed on a mountain-side (Figure 15d and Figure 19b).

5 Niche - Small glacier formed in initially V-shaped gulley or depression on mountain slope; generally more common than the genetically further developed cirque glacier (Figure 15e).

6 Crater - Occurring in extinct or dormant volcanic craters which rise above the regional snow line.

7 Ice apron - An irregular, usually thin, ice mass plastered along a mountain slope or ridge.

8 Group - A number of similar small ice masses occurring in close proximity and too small is assessed individually.

9 Remnant -An inactive, usually small ice mass left by a receding glacier.

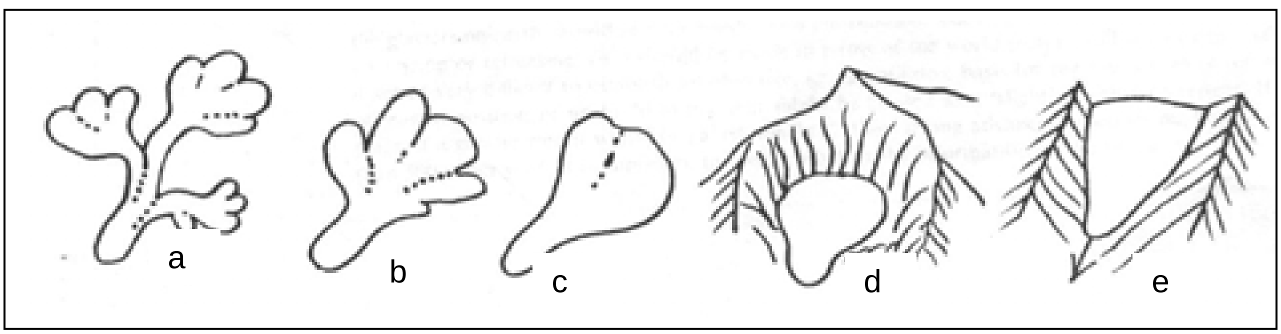


Figure 15: Glacier Classification- Form a) Compound basins, b) Compound basin c) Simple basin d) Cirque e) Niche (After Muller, 1977)

Digit 3 Frontal characteristics *(Figure 16)*

1 Piedmont (glacier) -Ice-field formed on lowland by the lateral expansion of one or the coalescence of several glaciers. (Figure 16a and 16b)

2 Expanded foot - Lobe or fan of ice formed where the tower portion of the glacier leaves the confining wall of a valley and extends on to a less restricted and more level surface (Figure 16c and Figure 20).

3 Lobed - Part of an ice sheet or ice cap, disqualified as outlet or valley glacier.

4 Calving - Terminus of glacier sufficiently extending into sea or occasionally lake water to produce icebergs; includes-for this inventory-dry land calving, which would be recognizable from the ‘lowest glacier elevation.

5 Coalescing, non contributing (Figure 16d).

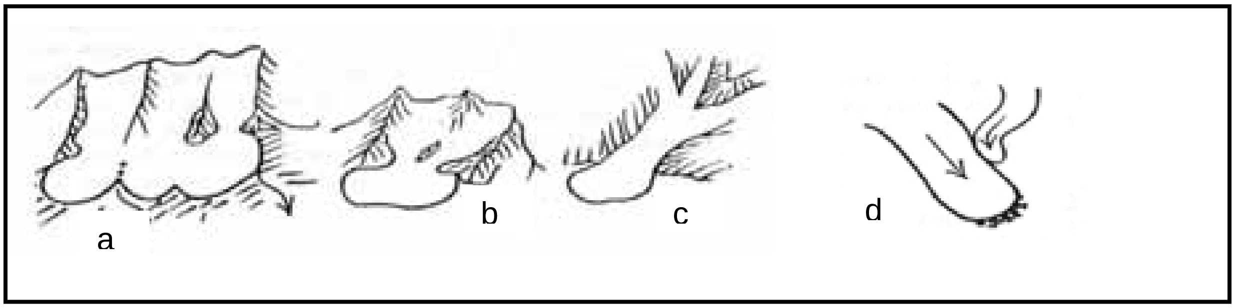


Figure 16: Glacier Classification - Frontal characteristics

Digit 4 Longitudinal profile

1 Even -Includes the regular or slightly irregular and stepped longitudinal profile.

2 Hanging (glacier) - Perched on a steep mountain-side or issuing from a hanging valley.

3 Cascading - Descending in a series of marked steps with some crevasses and seracs.

4 Ice-fall - Break above a cliff, with reconstitution to a cohering ice mass below.

Digit 5 Nourishment

Source of nourishment for glacier mostly comprises of seasonal snow and avalanche snow & ice.

Digit 6 Tongue activity

A simple-point qualitative statement regarding advance or retreat of the glacier tongue in recent years, if made for all the glaciers on earth, would provide most useful information. The assessment for an individual glacier (strongly or slightly advancing or retreating, etc.) should be made in the context of the region and not just that of the local area; however, it seems very difficult to establish an objective, i.e. quantitative basis for the assessment of the tongue activity. A change of frontal position of up to 20 m per year might be classed as a ‘advance or retreat. If the frontal change takes place at a greater rate it would be called ‘marked’. Very strong advances or surges might shift the glacier front by more than 500 m per year. It is important to specify whether the information on the tongue activity is documented or estimated. As data used is for short duration of two years only assessment of tongue activity is not taken in to consideration in the current study.

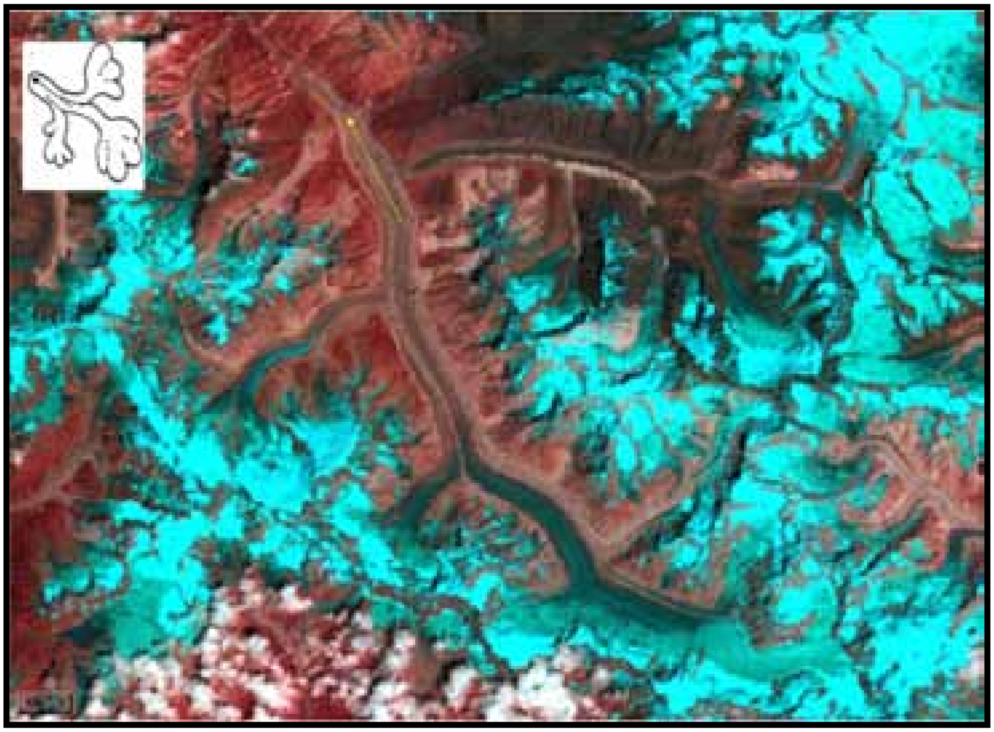


Figure 17: Glacier Classification – Compound Basins as seen on satellite data

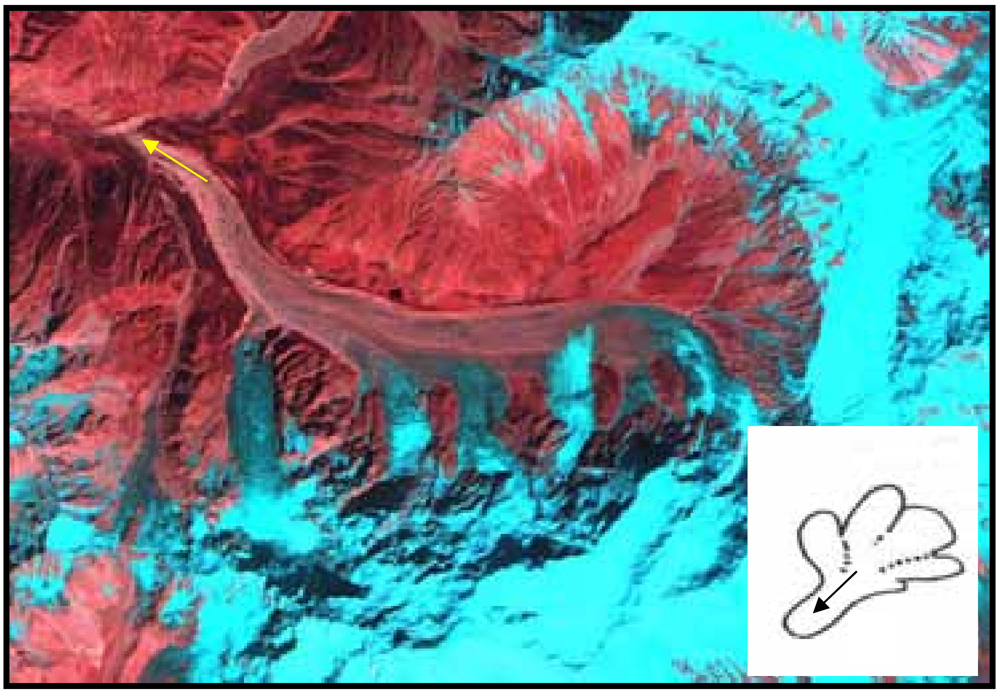


Figure 18: Glacier Classification – Compound Basin as seen on satellite data

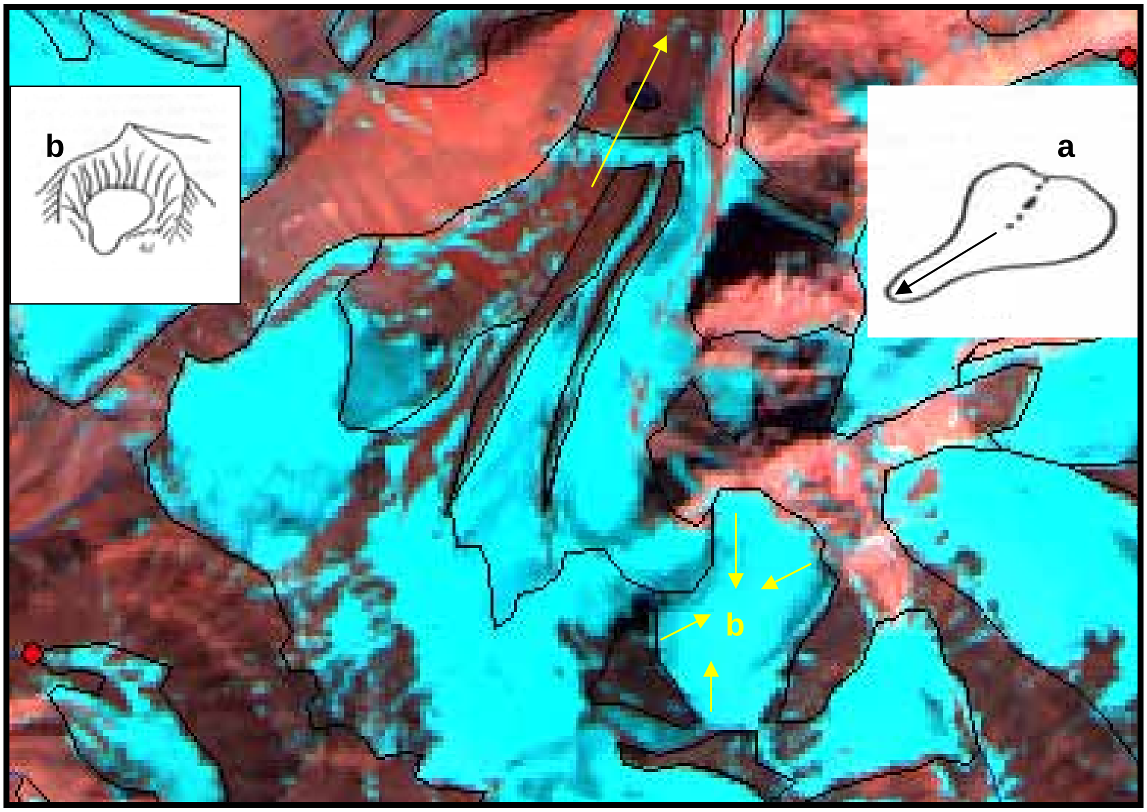


Figure 19: Glacier Classification - a) Simple Basin b) Cirque as seen on satellite data

Figure 20: Glacier Classification - Frontal Characteristics-Expanded Foot as seen on satellite data

31. Period for which tongue activity assessed*: Period of activity for which the tongue activity was assessed.*

32. Moraine code: 1st digit refers to moraines in contact with present-day glacier. The 2nd digit refers to moraines farther downstream. Both the above digits use the same coding system Table 27.

Table 27: Coding Scheme for Moraine

Code	**Description**		**Code**	**Description**
0	**No moraines**		5	Combinations of 1 and 3
1	**Terminal moraine**		6	Combinations of 2 and 3
2	**Lateral and/or medial moraine**		7	Combinations of 1, 2, and 3
3	Push moraine		**8**	**Debris, uncertain if morainic**
4	**Combinations of 1 and 2**		**9**	**Moraines, type uncertain or not listed**

33. Snow line elevation: The observed or calculated location of the snow line for the total glacier in meters above mean sea level (masl).

34. Snow line accuracy: The snow line accuracy rating is high as snow line based on the two set of satellite data (SAT_DATA) are entered in the Proforma.

35. Snow Line Date: The date of observation of the snow line or the method of calculation of the snow line. The date of observation can range from a precise day (e.g. 1/7/06) to an individual year (e.g. 2006).

36. Mean Depth: The physical depth of the glacier, in meters. This is estimated based on Table 28.

Table 28: Mean glacier depth estimates (after Muller, 1970)

<table>
<tr><th colspan="2">Glacier Type</th><th>Area km^2</th><th>Depth (m)</th></tr>
<tr><td rowspan="12">Valley glaciers</td><td rowspan="4">Compound basins</td><td>1-10</td><td>50</td></tr>
<tr><td>10-20</td><td>70</td></tr>
<tr><td>20-50</td><td>100</td></tr>
<tr><td>50-100</td><td>100</td></tr>
<tr><td rowspan="5">Compound basin</td><td>1-5</td><td>30</td></tr>
<tr><td>5-10</td><td>60</td></tr>
<tr><td>10-20</td><td>80</td></tr>
<tr><td>20-50</td><td>120</td></tr>
<tr><td>50-100</td><td>120</td></tr>
<tr><td rowspan="3">Simple basins</td><td>1-5</td><td>40</td></tr>
<tr><td>5-10</td><td>75</td></tr>
<tr><td>10-20</td><td>100</td></tr>
<tr><td rowspan="5">Mountain glacier, cirque</td><td></td><td>0-1</td><td>20</td></tr>
<tr><td></td><td>1-2</td><td>30</td></tr>
<tr><td></td><td>2-5</td><td>50</td></tr>
<tr><td></td><td>5-10</td><td>90</td></tr>
<tr><td></td><td>10-20</td><td>120</td></tr>
<tr><td rowspan="3">Glacieret and snow fields</td><td></td><td>0-0.5</td><td>10</td></tr>
<tr><td></td><td>.05-1</td><td>15</td></tr>
<tr><td></td><td>1-2</td><td>20</td></tr>
</table>

37. Depth Accuracy rating: The accuracy rating of the depth measurement on a percentile basis is given as shown in Table 29.

Table 29: Accuracy rating of the depth measurement

Index [A]	Area, length % [B]	Altitude (m)
1	0-5	0-25
2	5-10	25-50
3	10-15	50-100
4	15-25	100-200
5	> 25	> 200

Derivation of dimensions (length / width / area), altitude and azimuth information of glacier features in GIS

The glacier polygon, line and point layers are designed for providing easy access to important information for filling the glacier inventory data sheet. The glacier inventory map layers are used to obtain various details for filling the datasheet as per modified UNESCO/TTS format and additional parameters. Using standard GIS tools, area is found out for the polygon features like total glacier, the ablation zone, accumulation zone, de-glaciated valley, moraine-dammed lakes, etc. By measurement in GIS of various stored line features information for length and width is obtained. By using GIS function the altitude information is derived from DEM generated by SRTM data of corresponding scale. The data thus generated is stored in a structured digital data sheet (GLACIER.DAT) with 65 entries corresponding to the modified UNESCO/TTS format. A sample data sheet with the defined database structure (GLACIER.DAT) is given in Annexure-2.

4.3 Estimation of changes in glacier extent

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.

The retreat/advance of glaciers is therefore determined by mapping glacier boundaries of different time frame. In this project, satellite images have been used to map glacier boundaries in different basins to find out the status of retreat/advance of glaciers. Following two major steps have been followed while carrying out this study.

(i) Georeferencing of the satellite data

The IRS LISS III data (band 1, band 2, band 3 and band 4) is georeferenced with Survey of India (SOI) topographical maps covering the study area. Prior to this the data had already being processed for radiometric and first order geocorrections. First order geocorrections are usually carried out using five corner coordinates given along with IRS scene in leader file. The georeferencing with topographical maps is carried out by identifying a set of ground control points on the maps and images. The topographical maps used for this georeferencing is at 1:50,000 scale. Normally, the GCPs are those locations where either drainages intersect or there is sharp bends of drainages. The point accuracy of topographical map is 12.5 m. Ideally GCPs are normally, collected in the field using high precision GPS in differential mode. But due to remote locations of glaciers in the Himalayan region this method can not be employed therefore topographical maps with fairly good amount of accuracy are considered to be the best alternative as a source of GCPs. One of the other purposes of using topographical map is that the glaciers extent in a given basin (in toposheets) are required to be compared with the extent mapped from IRS images. A comparison of glacial extent of two different time period can be done when the two source of glacial boundaries are properly registered. In the present case approximately 100 points are used to georeference the satellite dataset of two basins. The registration is based on polynomial model. The ERDAS imagine version 9.1 has been used for this work.

(ii) Delineation of glacial boundaries from SOI maps and satellite data

Monitoring changes in glacial extent and advance/retreat is carried out using satellite images/maps of two or more time frame. In the present work, monitoring of glacier extent and retreat/advances has been done by extracting glacier boundaries using the recent satellite images (year 2001, 2004) as well as the topographical sheets of 1962.It has been observed while taking boundaries from maps that sometimes the boundary of the accumulation zone matches with the ridge boundary but in many other instances glacier boundary at the head is a few meters lower than the ridge boundary. This point is matched with glacial extent is interpreted and extracted on screen from any satellite image.

To extract glacial boundary from satellite image false color composite (FCCs) are interpreted in different combination of band 1 to band 4. The SWIR band is used to discriminate cloud and snow because clouds are often observed on the upper region of the glaciers. The distinction of non-glaciated and glaciated region is sharper in SWIR band. The unique reflectance of snow-ice, shape of the valley occupied by the glacier, the flow lines of ice movement of glaciers, the rough texture of the debris on the ablation zone of the glaciers, the shadow of the steep mountain peaks and presence of vegetated parts of the mountains help in clear identification of a glacier on the satellite image. The understanding of reflectance curve of various glacier features helps to vectorize the glacial boundary on satellite data.

The snout of the glacier is a vital element of interpretation of glacial extracts. The glacier terminus is identified on satellite data using multiple criterions such as:

a) Sometimes the river originates from the snout and river can be easily identified on the image.
b) The peri-glacier area downstream of the snout has distinct geomorphological set up then the glacier surface.

c) In many instances the frontal portion of the glaciers which are retreating has convex shape therefore it helps identification of the terminus.
d) When interpretation becomes more complex sometimes DEM is used in the background to confirm the snout as there is a chance of change in the slope of glacier profile near the snout and 3d view help to identify the lateral and terminal boundary of glacial extent.
e) Extreme care is taken while delineating glacier boundary that boundaries are marked in the inner side of the lateral moraines.

(iii) Estimating loss in area of glaciers

To estimate change in glacial area, the glacier boundaries of two time frame data of glacier extent are overlaid on each other. The two time frame data/glacier boundaries are brought to common scale. While matching the boundary, the scale of the map and image is kept at 1:50,000 because the mapping depends on the scale. Increase or decrease in the evacuated area from glaciers can be measured.

(iv)Validation on ground

In order to validate the retreat in the field one glacier in each basin has been visited and snout reading has been taken using GPS.

4.4 monitoring snowline at the end of ablation season for mass balance

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 mass 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.

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.

Geodetic Method

A volume change can be estimated by subtracting the surface elevation of a glacier and the glacier 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.

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.

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.

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.

Accumulation Area Ratio Method

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 snow line can be defined as the location where there is enough snowfall and energy available to balance accumulation and ablation. 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 21). 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.

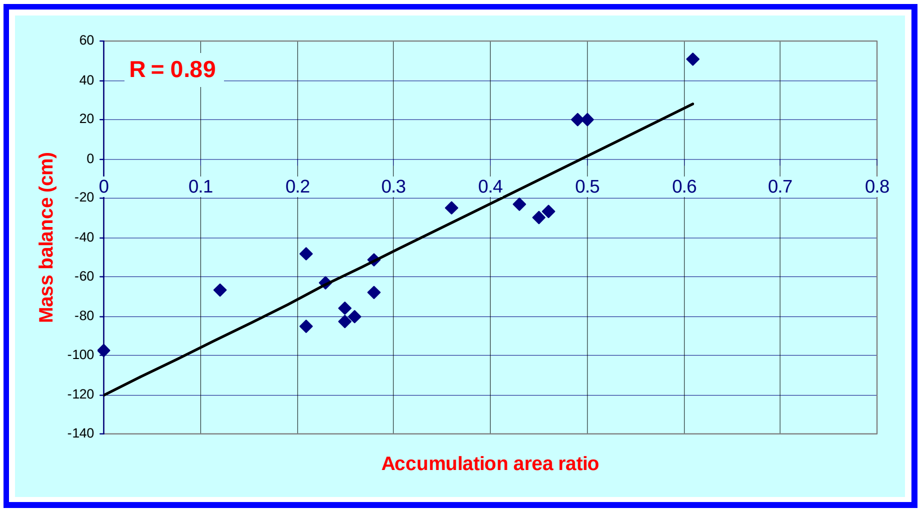


Figure 21: Relationship of AAR and Specific mass balance (Kulkarni et al., 2004)

A snow line separated from bare ice by an area of old firn indicates a more negative balance than the preceding few years. AWiFS data from IRS P-6 (Resourcesat-1) satellite is the main source of information in the present study. Its repeativity of 5 days has been exploited for monitoring of snow line.

This method of estimating mass balance has been employed in this project. The steps which are followed to extract AAR for each glacier under study have been enumerated as below.

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 was digitized and overlayed on the images. Image to map registration was carried out to match basin boundary.
3) All the glaciers boundaries were digitized 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 overlaid 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 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.
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.

5. RESULTS AND DISCUSSION

5.1 Snow Cover monitoring

NDSI Algorithm was used to generate snow cover products. 10 daily products along with satellite images for selected 5 basins are given in Fig. 22 to 31. These basins are selected on the basis of different climatic zones and distributed from Jammu and Kashmir to Sikkim. For the remaining basins images and products are given in Annexure 1. For the same five basins snow accumulation and ablation curves are given in Figure 32 to 36 and for remaining basins curves are given in annexure 1. 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 average snow fall (1990-2004) of 1178 cm, 537 cm and 511 cm, respectively (Sharma et al, 2000; Gusain et al, 2004). For comparative analysis Ravi and Bhaga basins are selected, as located in south and north of Pir Panjal Range, respectively. The area altitude distributions of these basins has shown that Ravi basin is located in lower altitude zone. For example, 90% of Ravi is located at an altitude below 4000 m, whereas this portion is only 20% for the Bhaga basin. Altitudes of the Ravi and Bhaga basins range from 630 m to 5860 m, and from 2860 m to 6352 m, respectively.

In Ravi basin, snow accumulation and ablation are continuous processes throughout the winter. Even in the middle of winter melting of large snow area was observed. In January 2005, snow area was observed to be reduced from 90% to 55%. Similar trends were observed for the year 2005-06 and 2007-08 (Figure 33). This is a significant reduction in snow extent in the winter season. In summer, snow ablation was fast and almost 50% of the snow cover was melted within a period of one month and by the end of June almost 80% of the snow cover was melted.

In the Bhaga basin, snow melting was observed in the early part of the winter i.e. in the month of December. Snowpack was stable from the middle of January to the end of April (Annexure 1). This observation is consistent with earlier observations made in Basapa basin (Kulkarni and Rathore, 2003). Basapa is a high altitude basin and located on the Northern side of the Pir Panjal range. In this basin, significant melting of snow was observed in December influencing stream runoff. These observations suggest that river basins are responding to climate change depending on geographical location and altitude distribution.

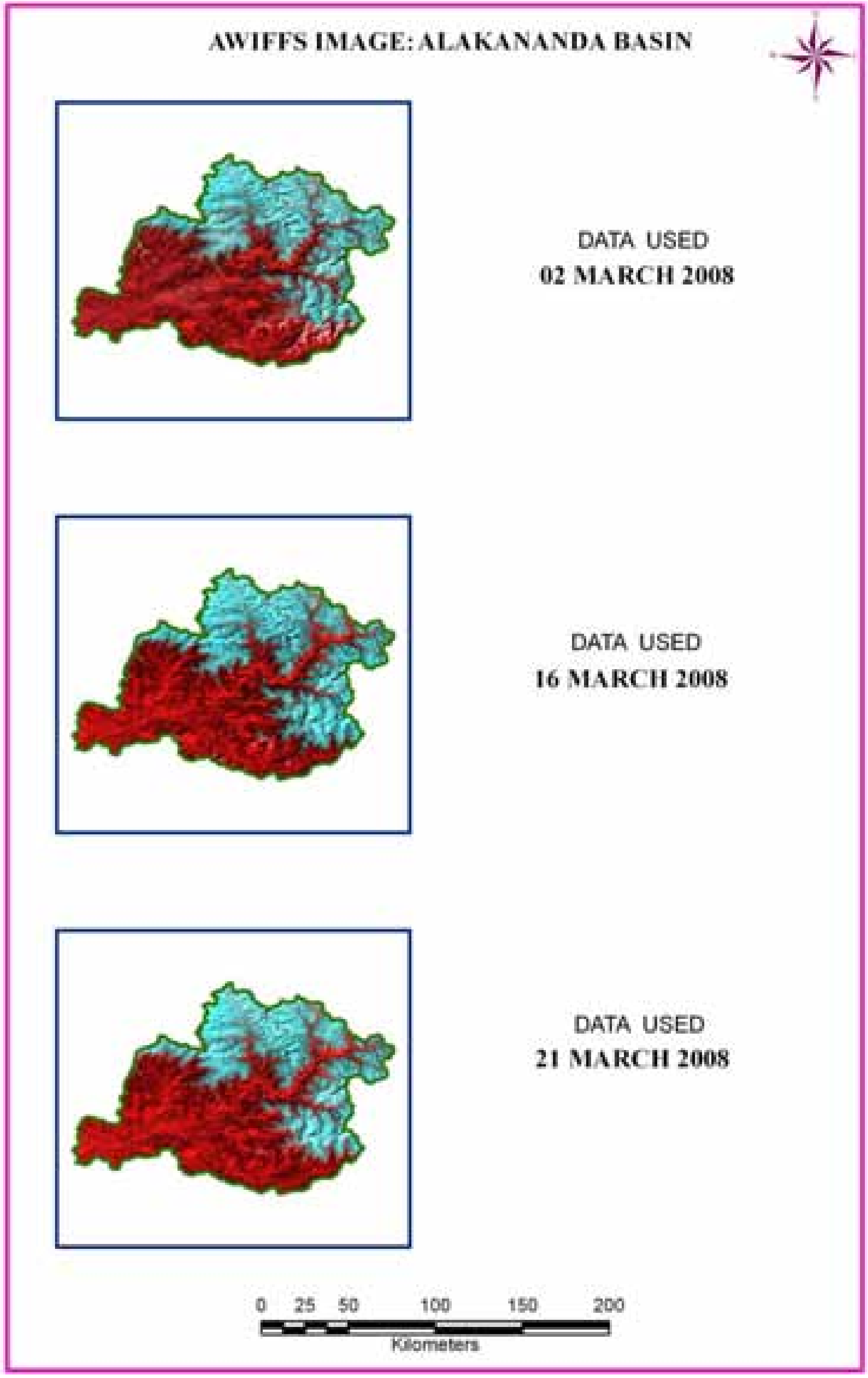


Figure 22: AWIFS Image of Alkananda Basin

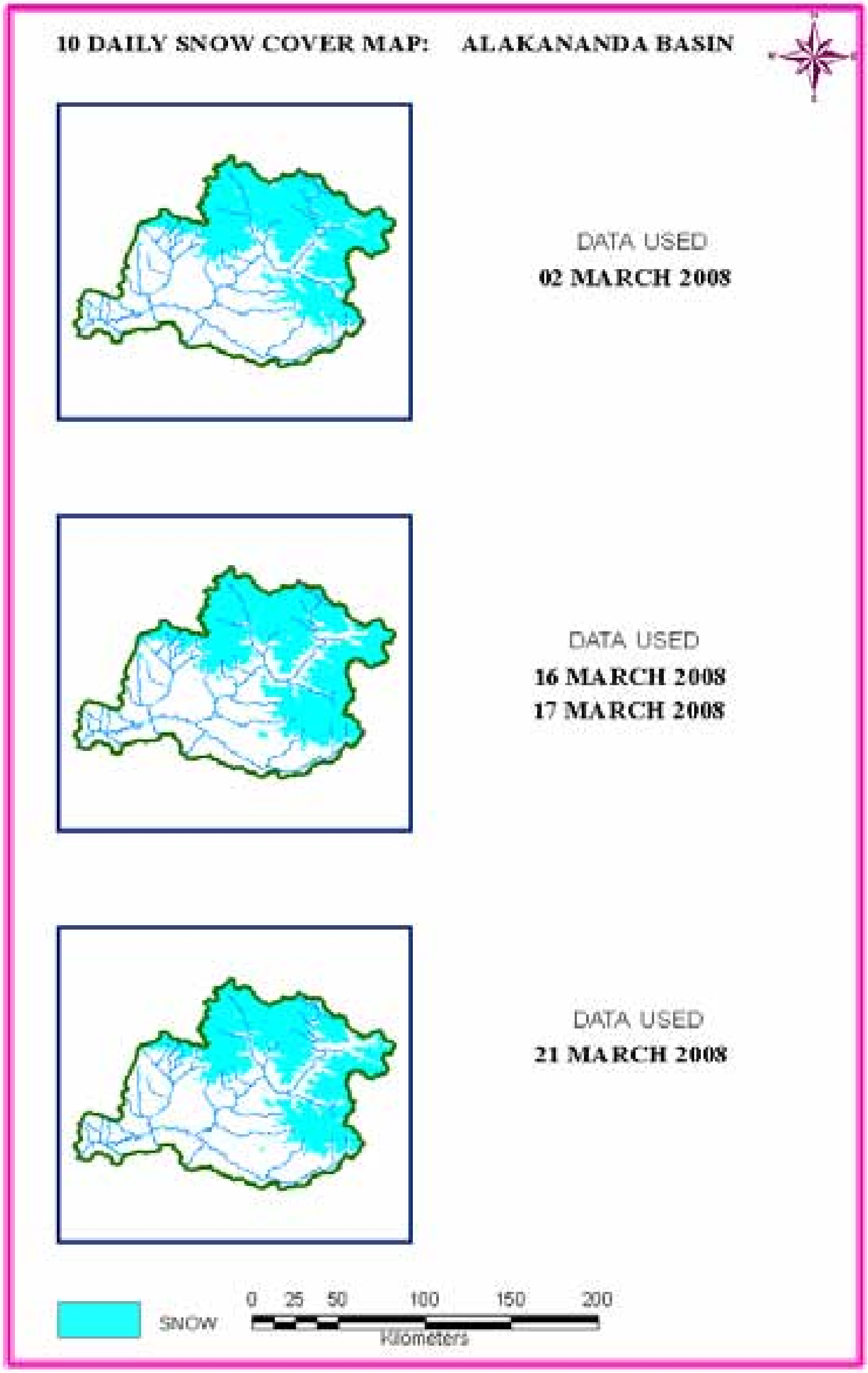


Figure 23: 10 Daily Snow cover maps of Alkananda Basin

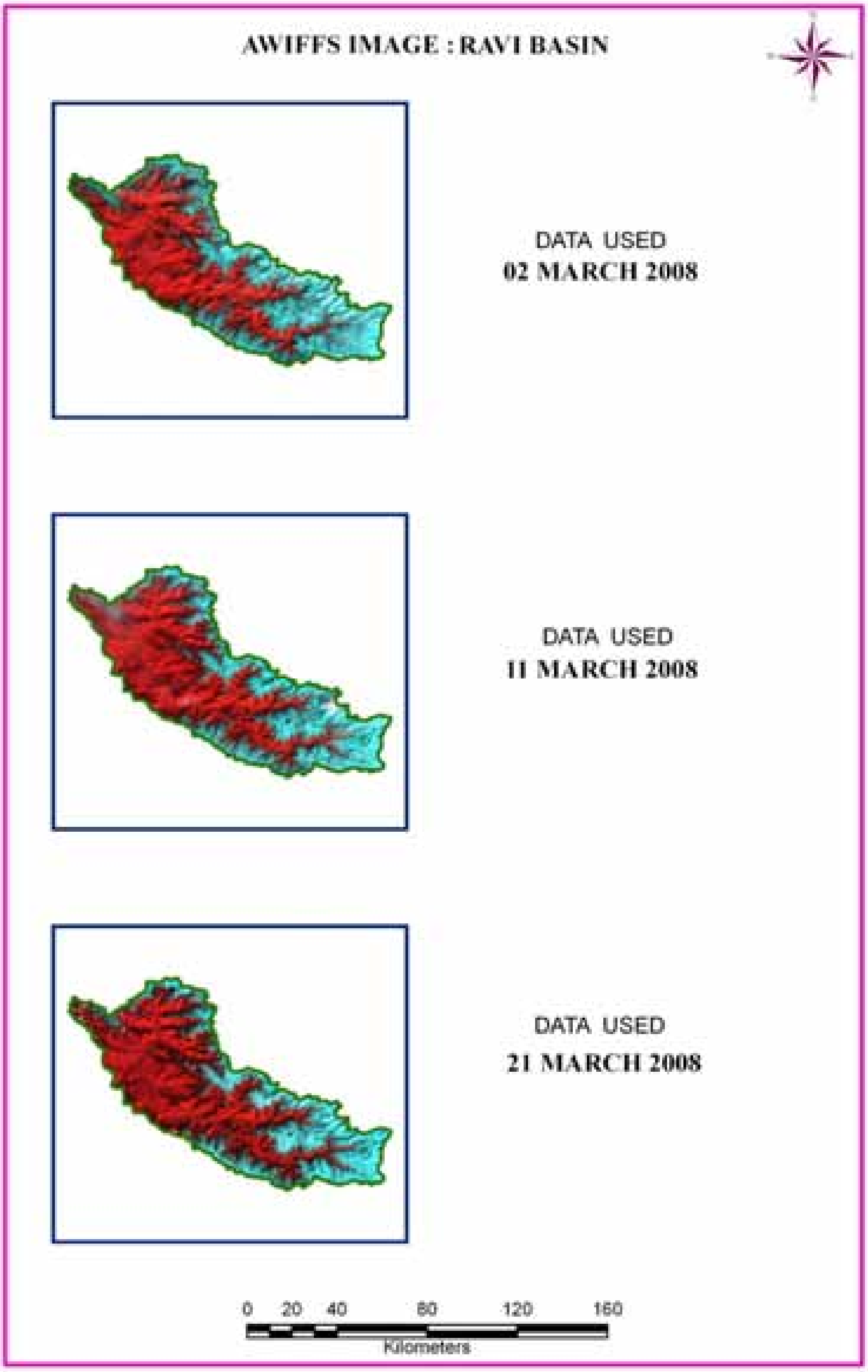


Figure 24: AWIFS Image of Ravi Basin

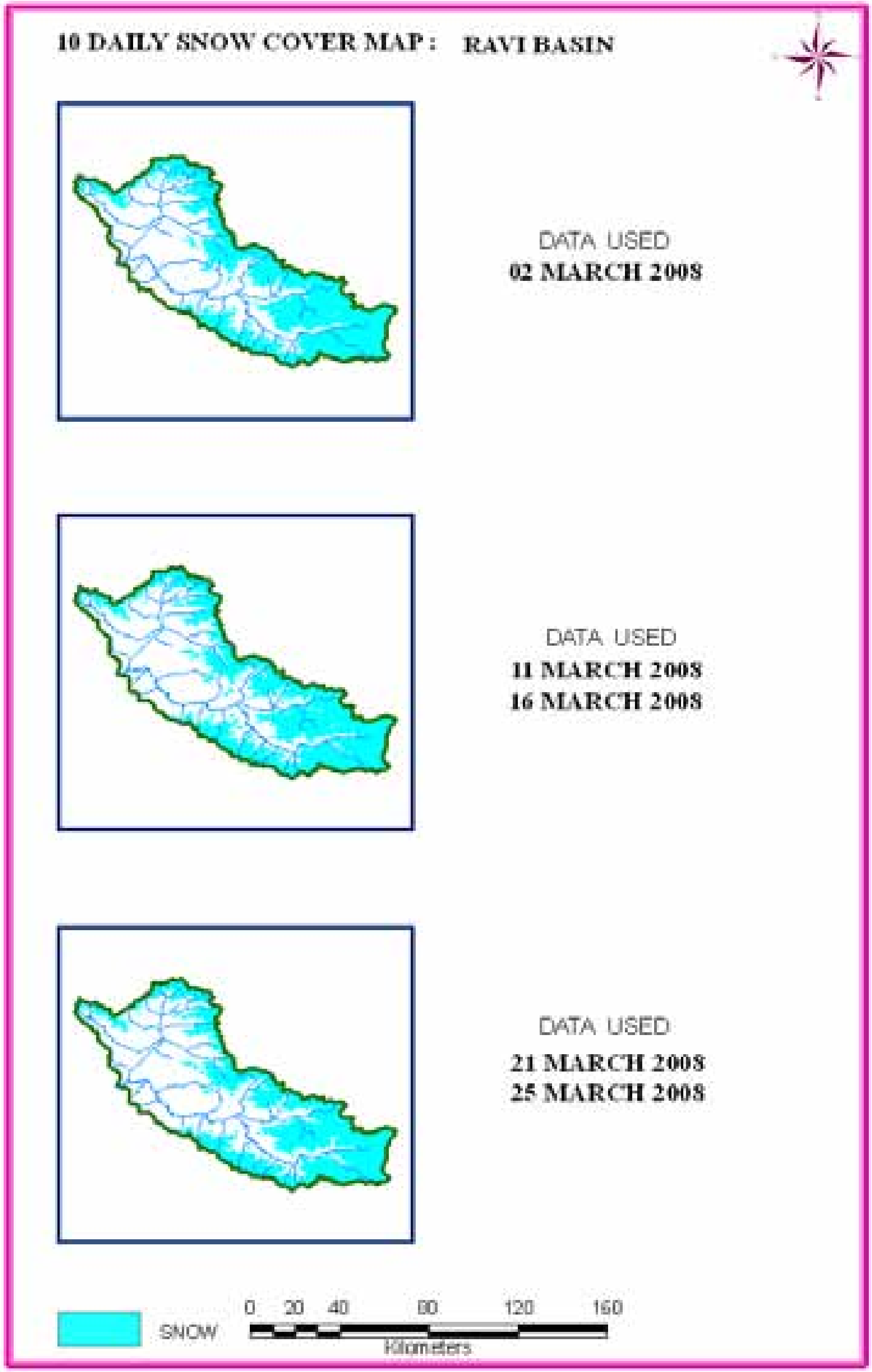


Figure 25: 10 Daily Snow cover maps of Ravi Basin

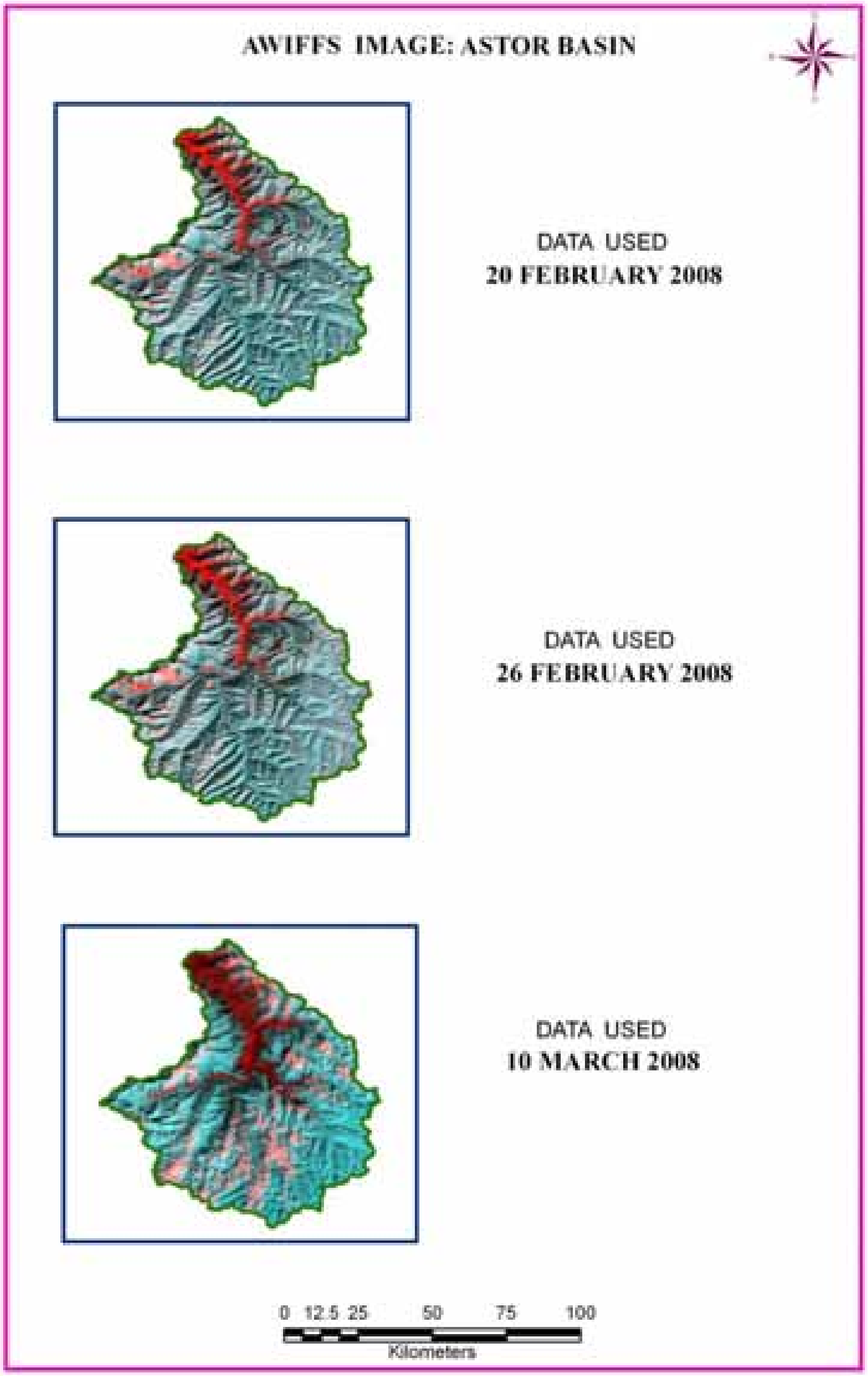


Figure 26: AWIFS Image of Astor Basin

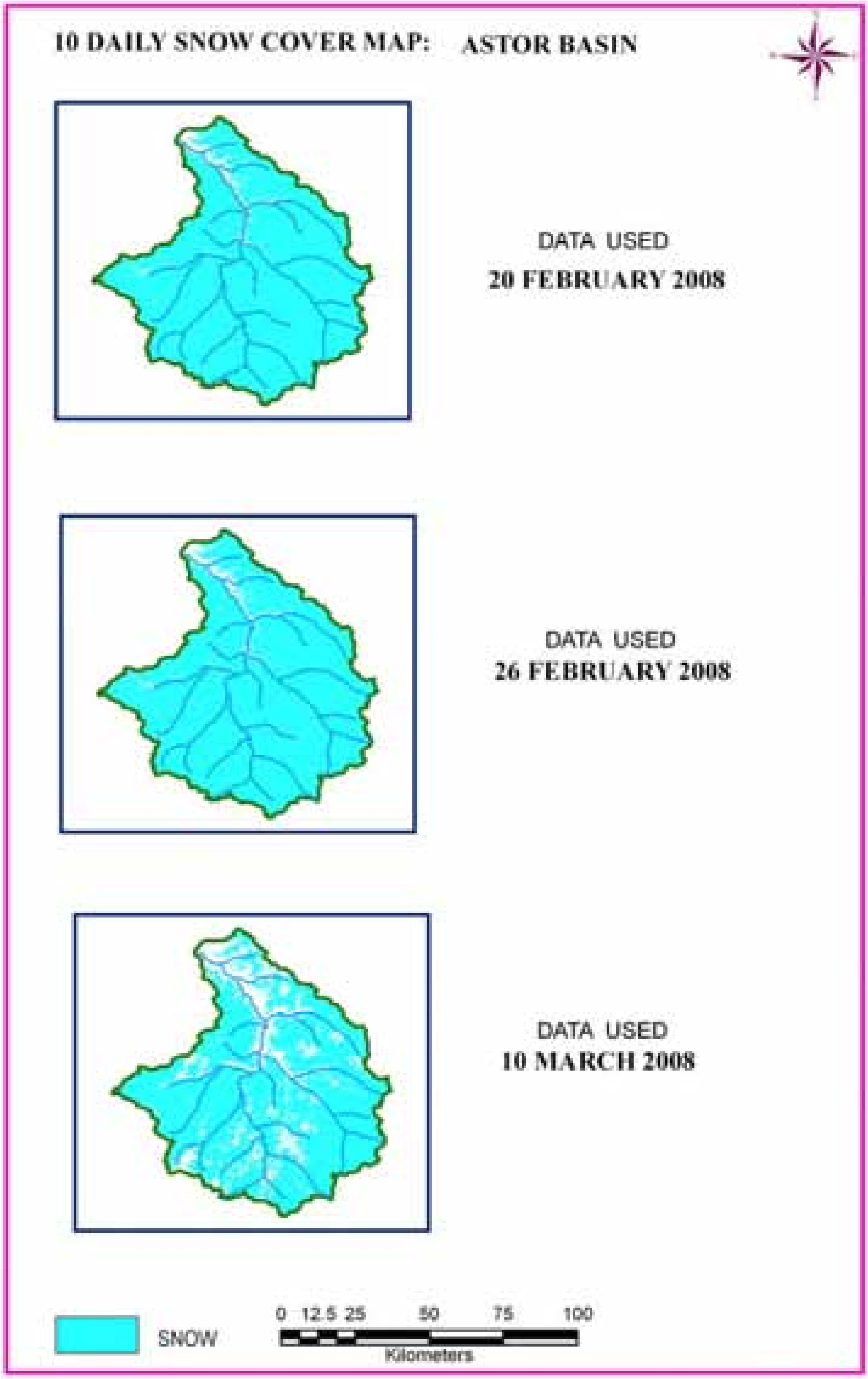


Figure 27: 10 Daily Snow cover maps of Astor Basin

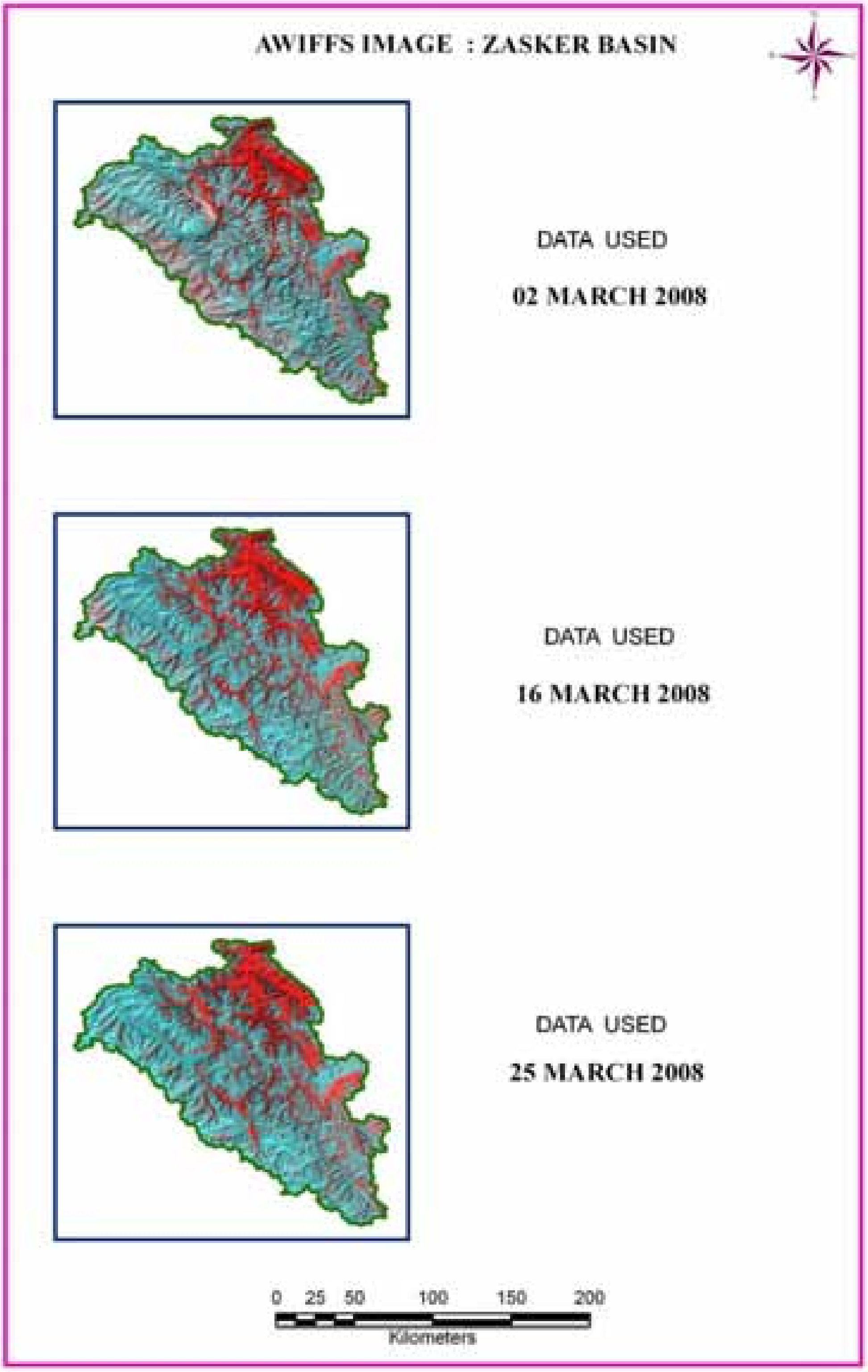


Figure 28: AWIFS Image of Zasker Basin

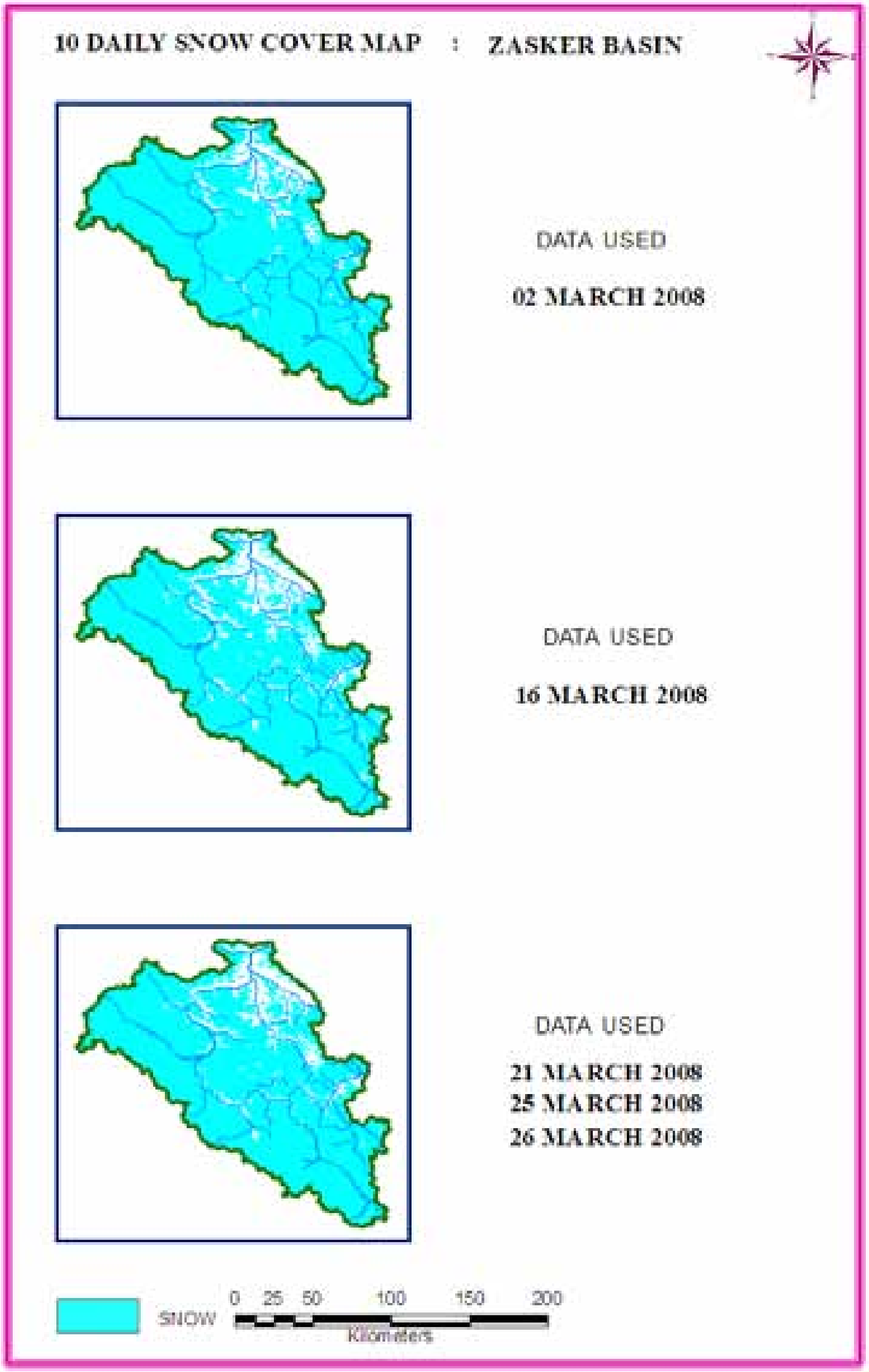


Figure 29: 10 Daily Snow cover maps of Zasker Basin

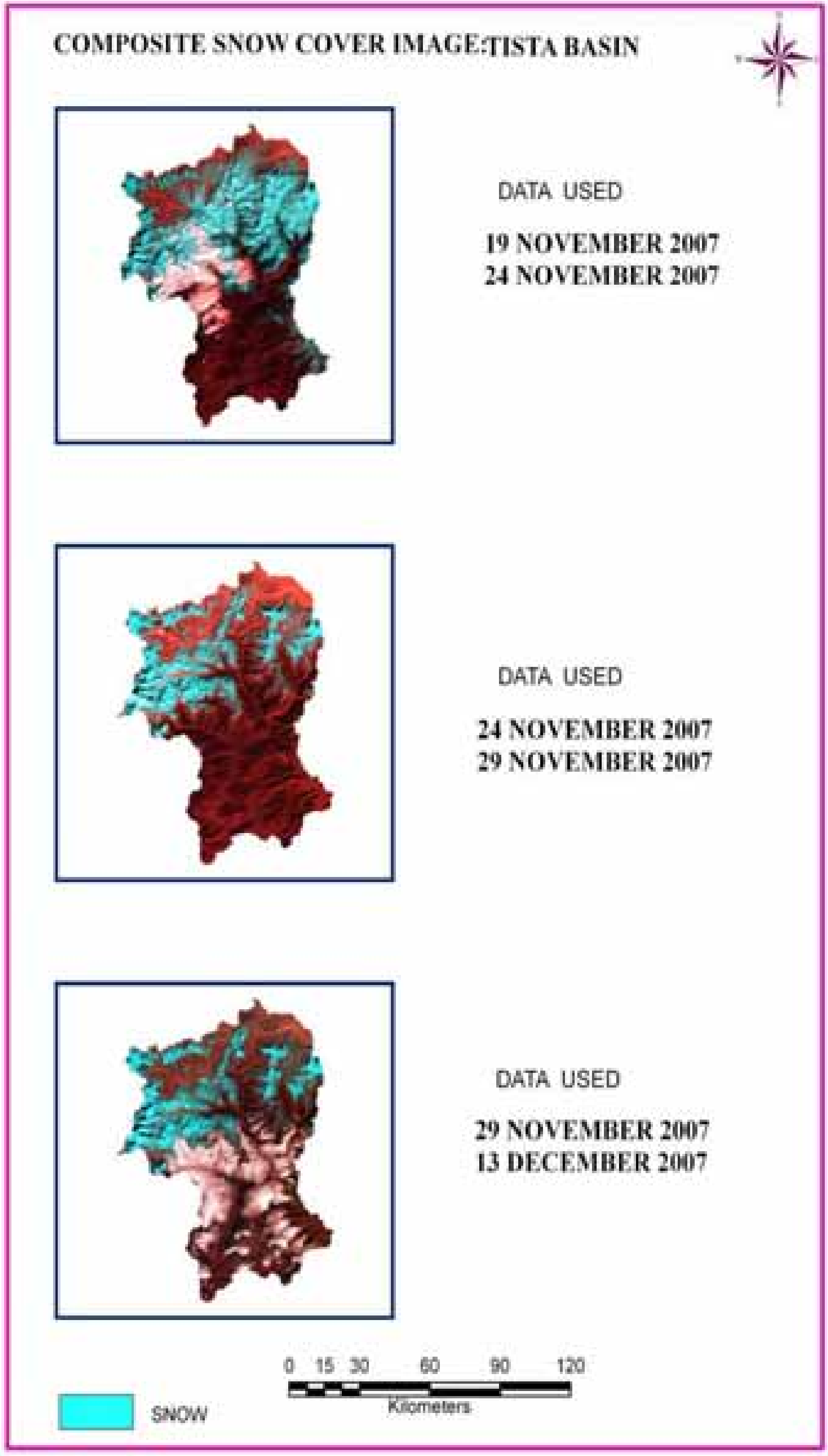


Figure 30: AWIFS Image of Tista Basin

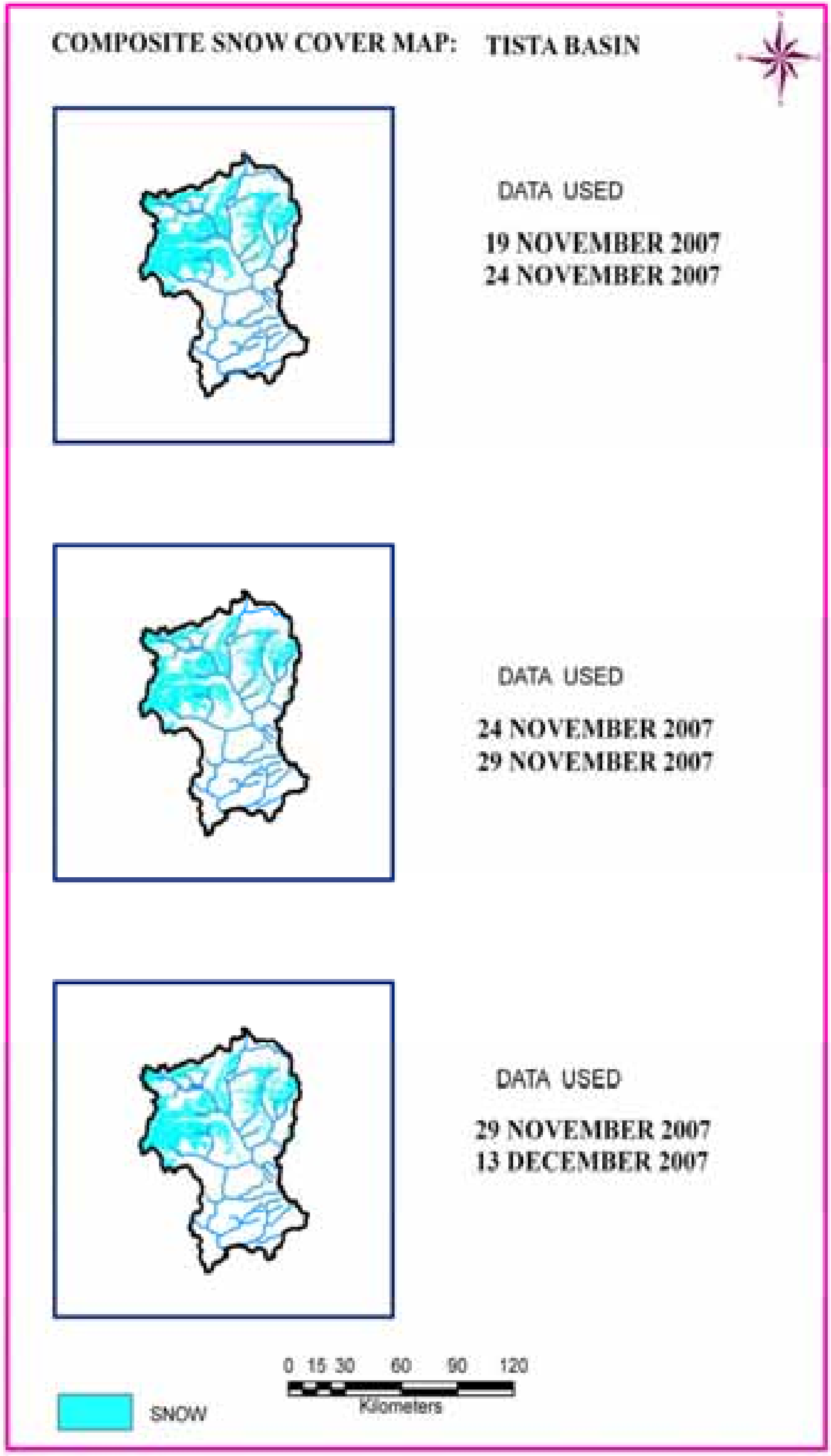


Figure 31: 10 Daily Snow cover maps of Tista Basin

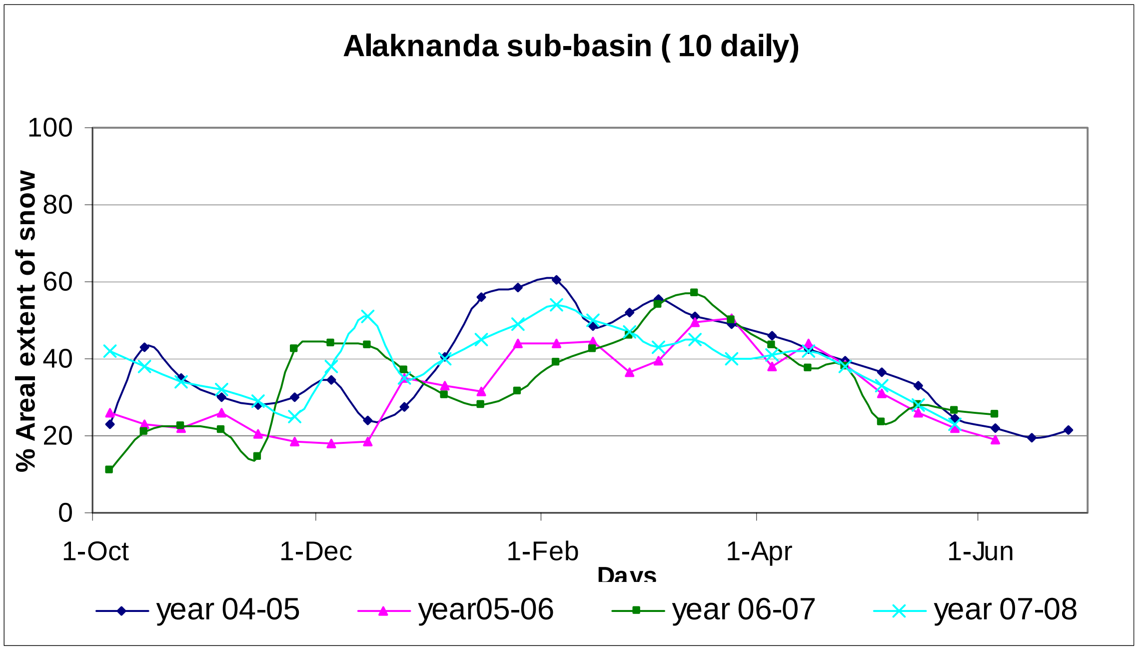


Figure 32: 10 Daily Snow Extent of Alaknanda Sub-Basin

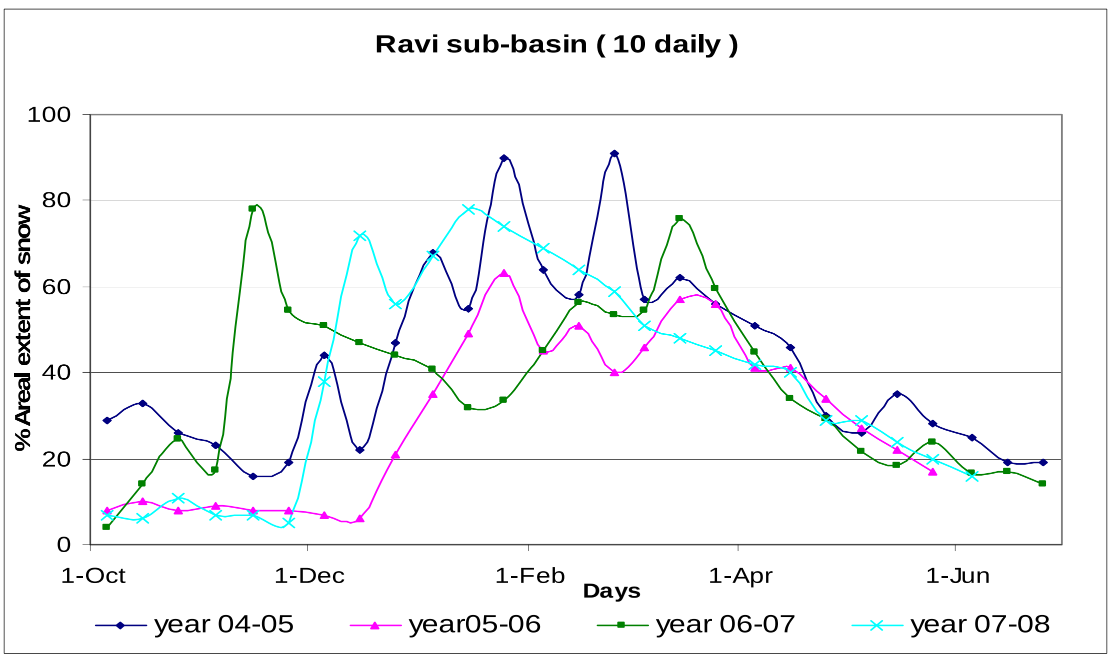


Figure 33: 10 Daily Snow Extent of Ravi Sub-Basin

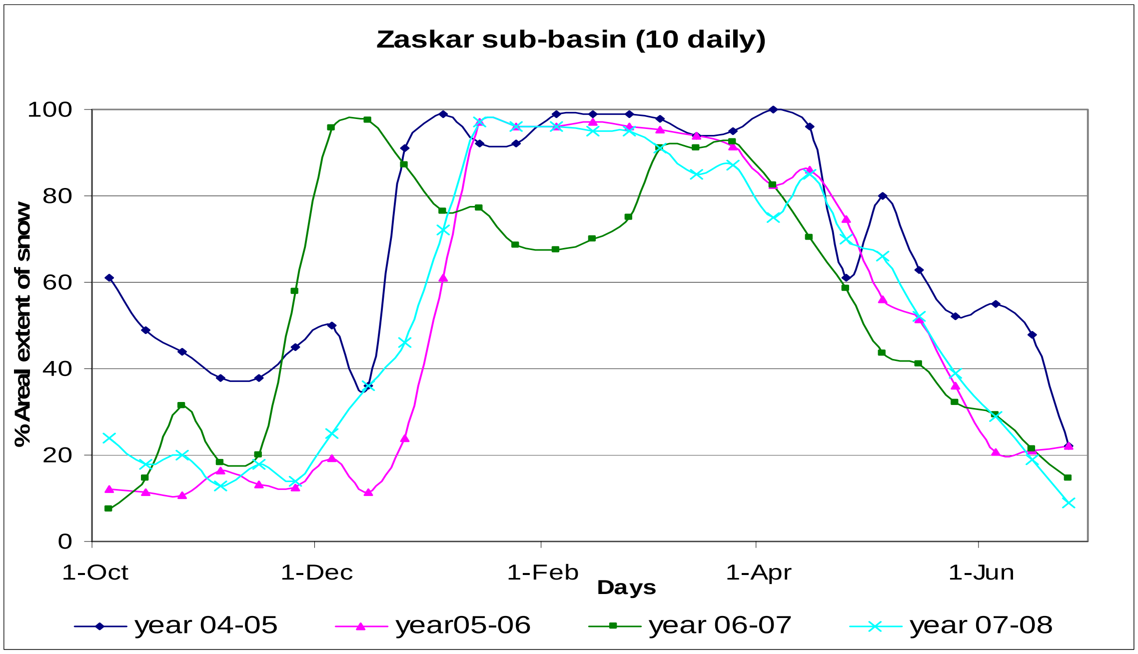


Figure 34: 10 Daily Snow Extent of Zasker Sub-Basin

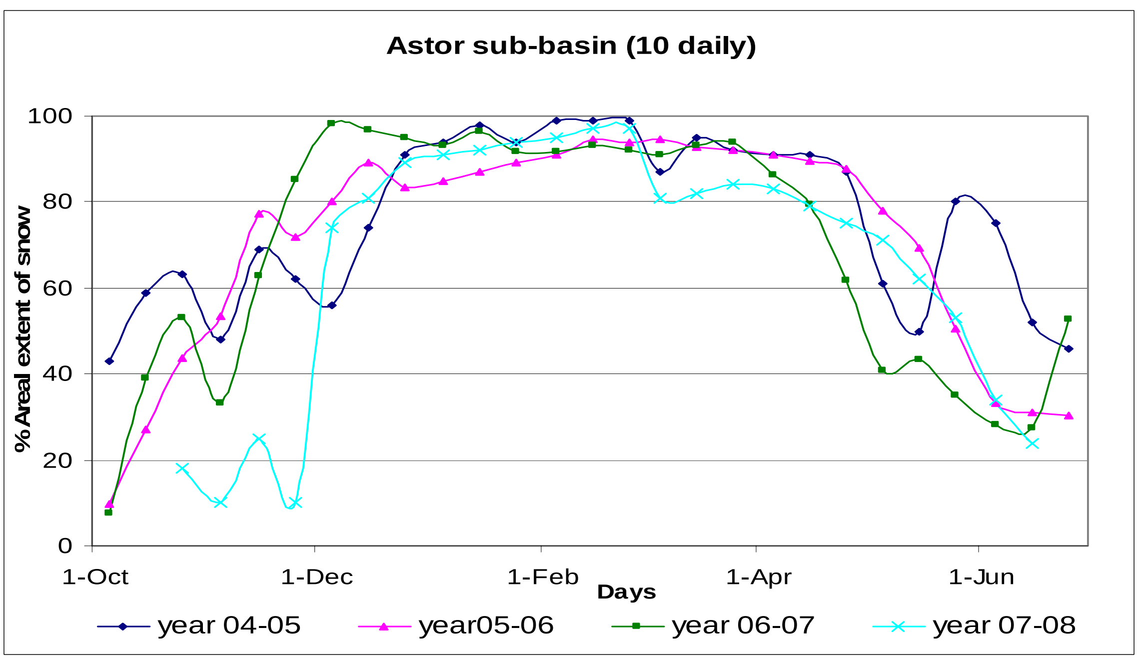


Figure 35: 10 Daily Snow Extent of Astor Sub-Basin

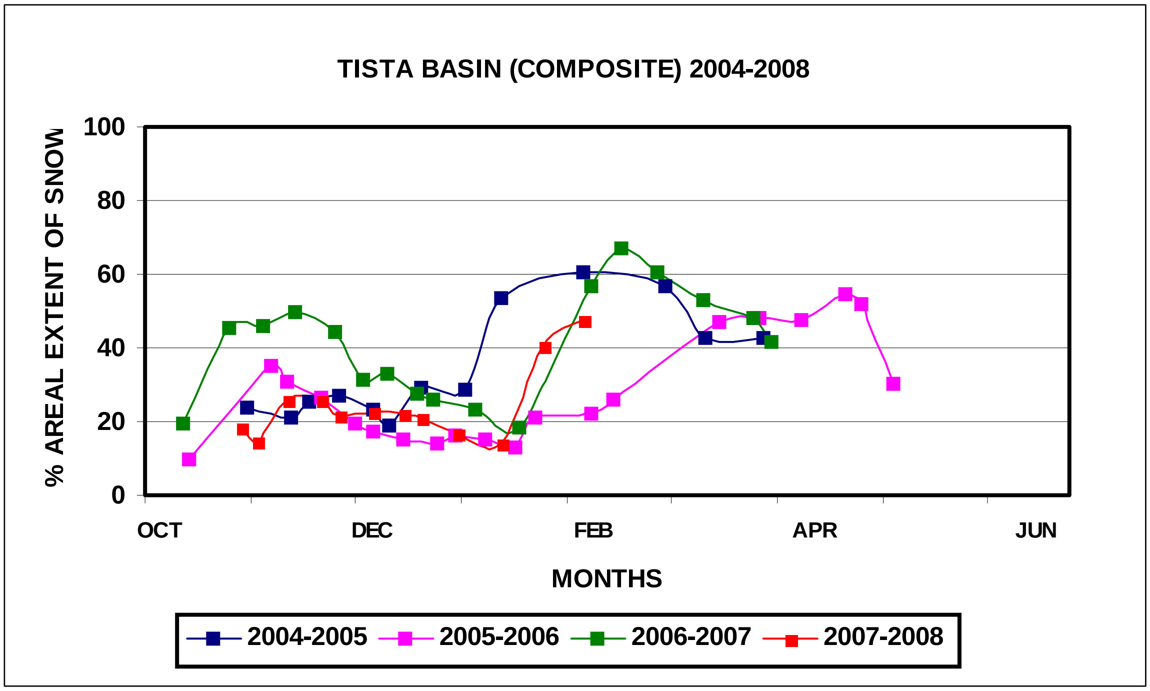


Figure 36: 10 Daily Snow Extent of Tista Sub-Basin

ANNEXURE – 3
Retreat and Advance of Glaciers

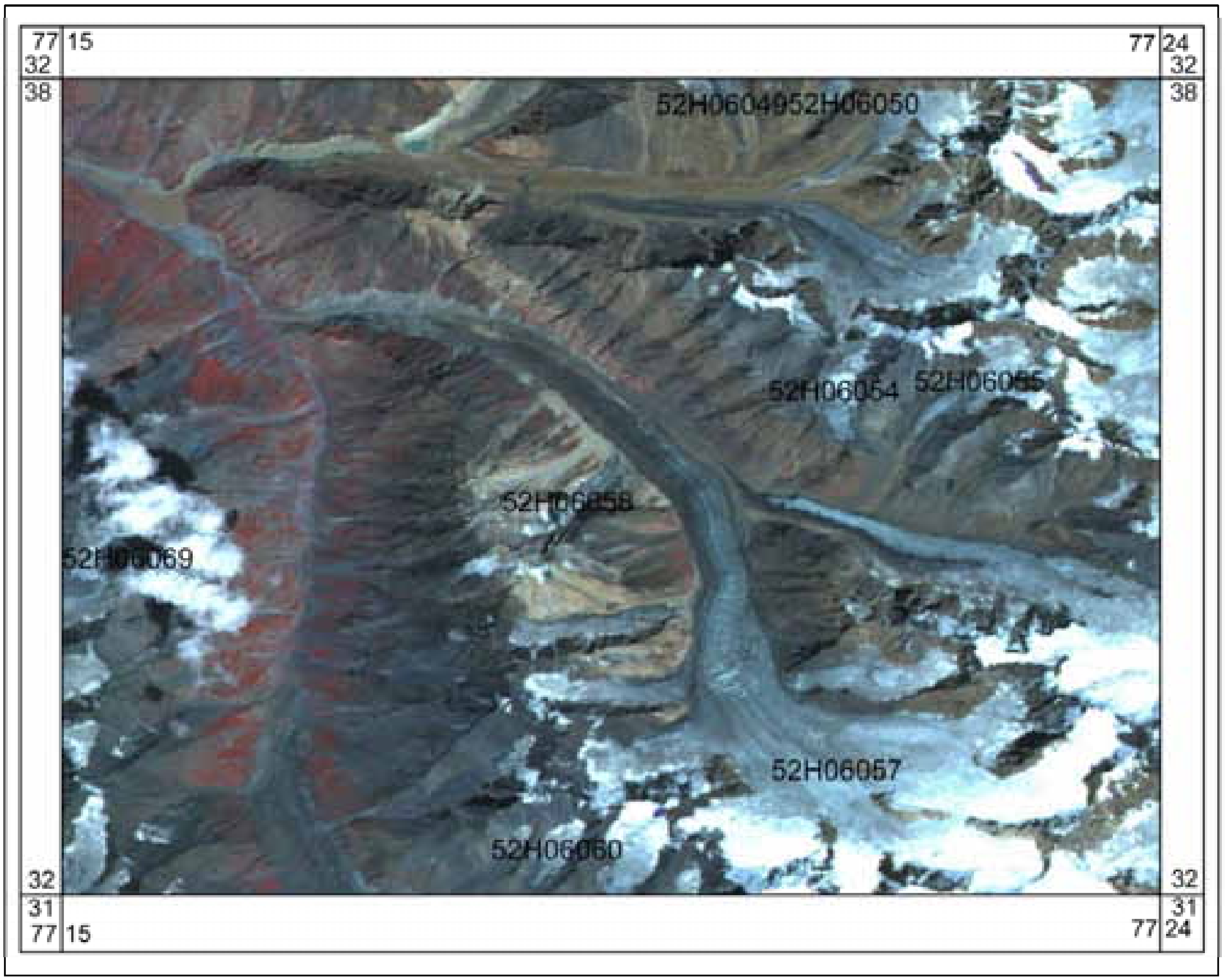


Figure 190: IRS 1C LISS III image of August 27, 2001 showing the glaciers of part of the Bhaga sub basin

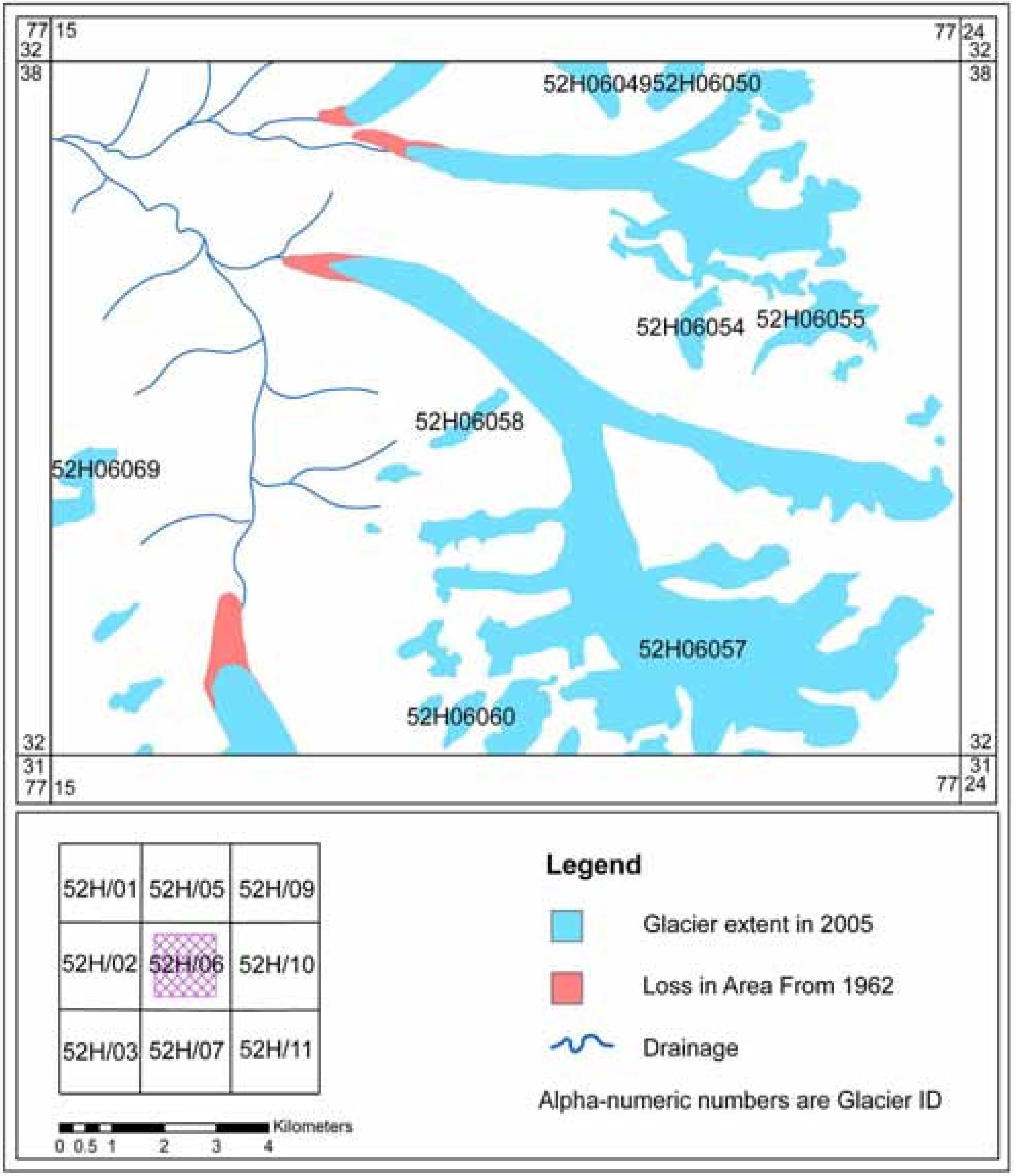


Figure191: Map showing loss in area of the glaciers of a part of the Bhaga sub-basin between 1962 and 2005

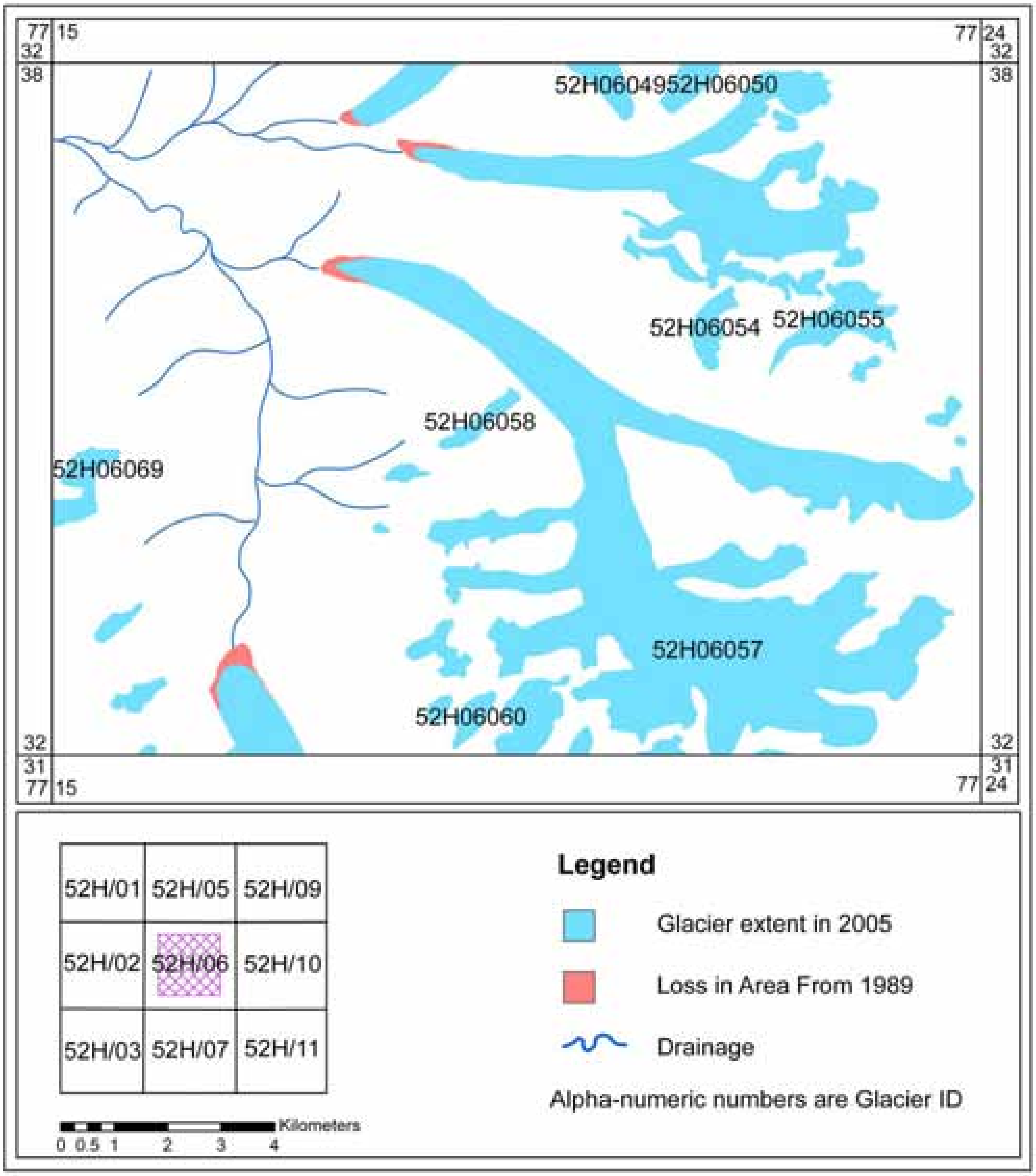


Figure 192: Map showing loss in area of the glaciers of a part of the Bhaga sub-basin between 1989 and 2005

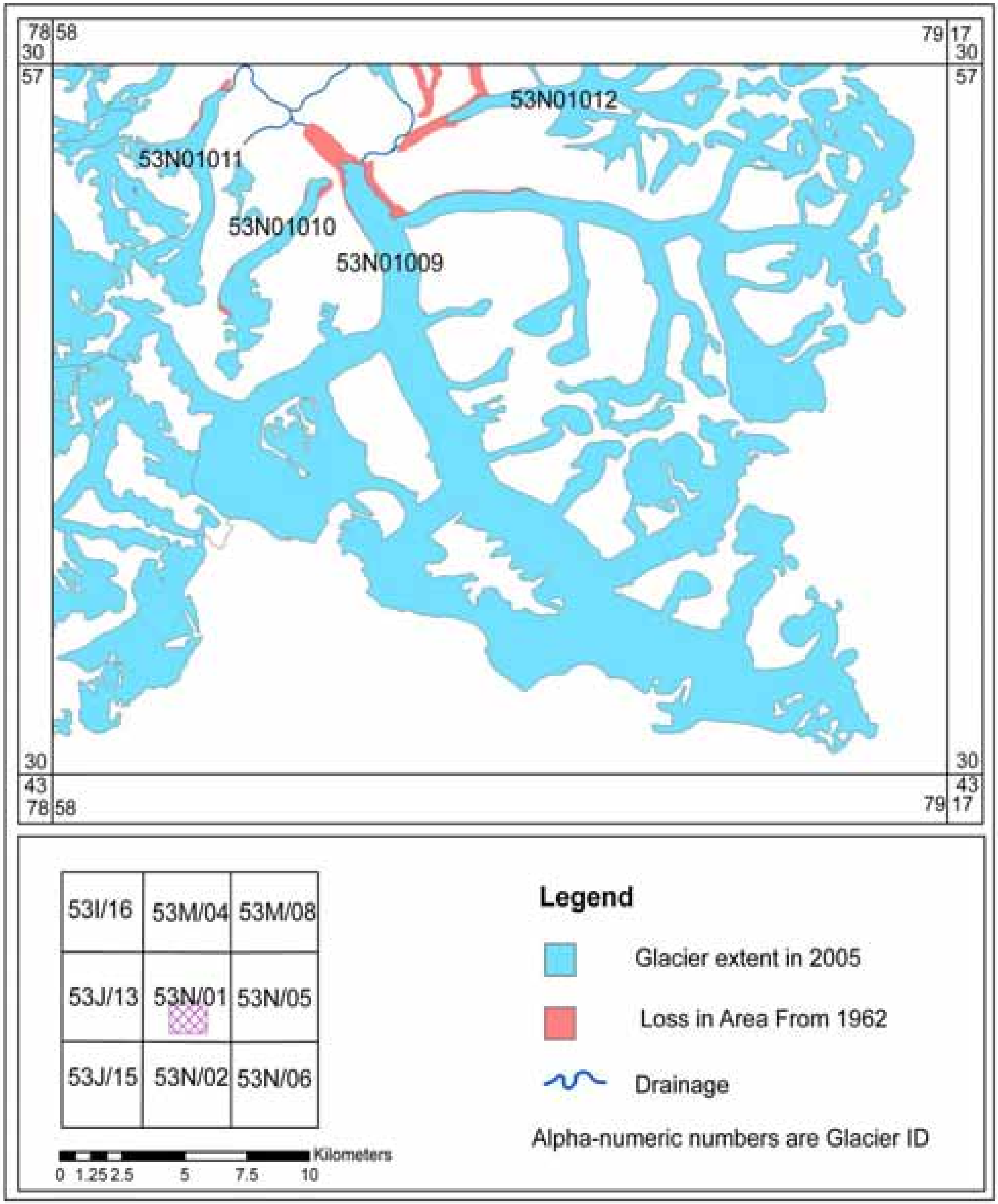


Figure 193: Map showing loss in area of the glaciers of a part of the Bhagirathi sub-basin between 1962 and 2005

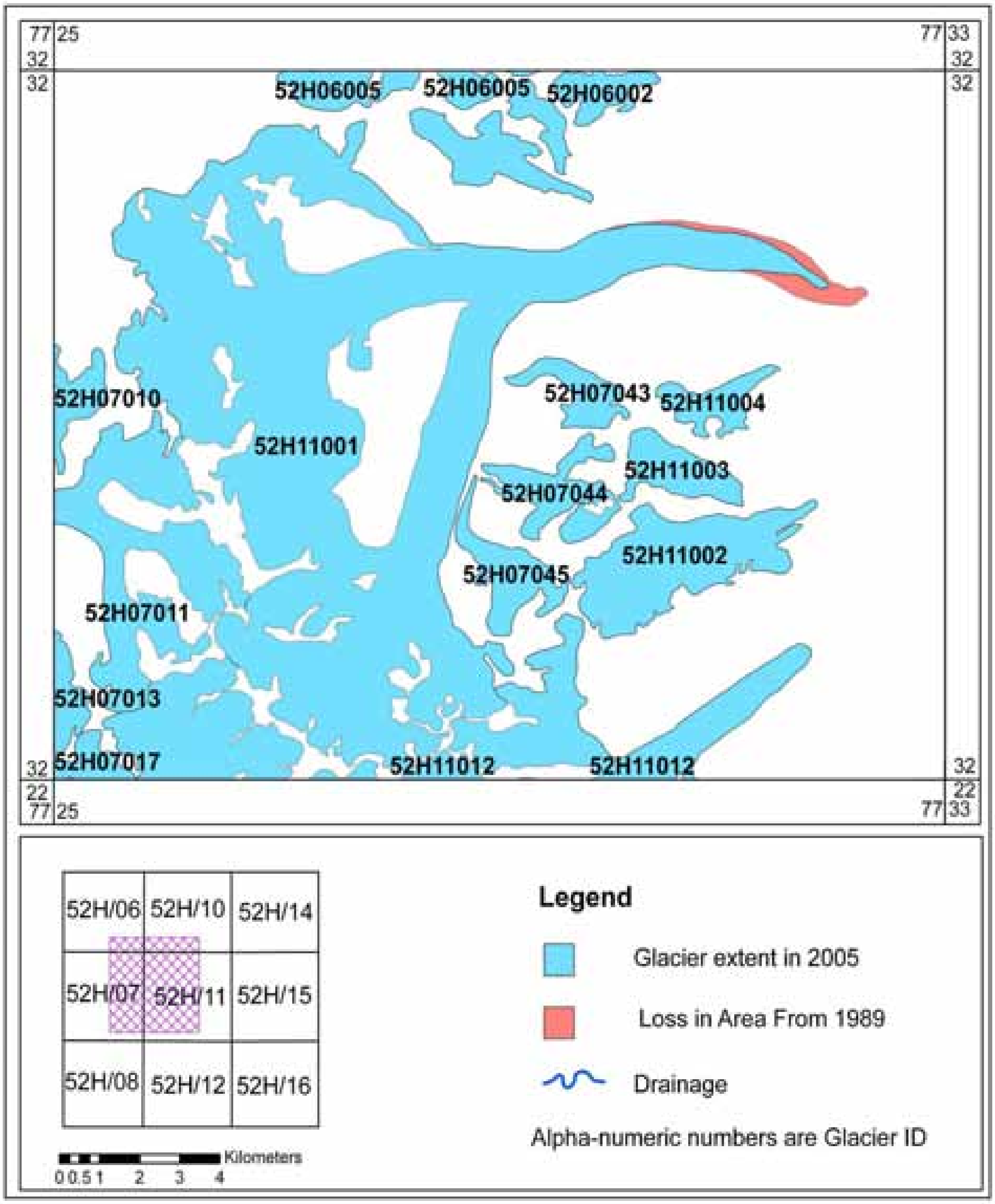


Figure 194: Map showing loss in area of the glaciers of a part of the Chandra sub-basin between 1989and 2005

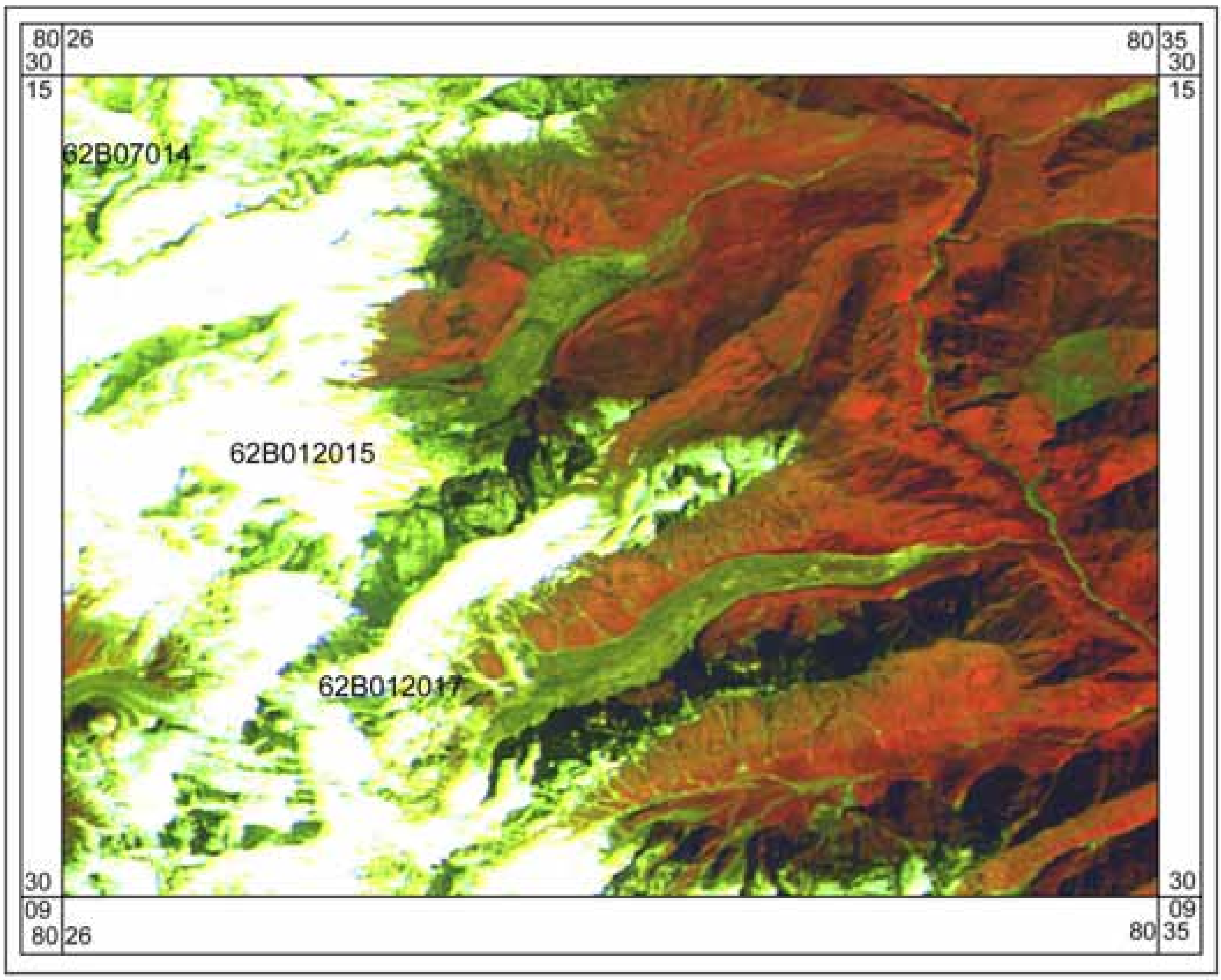


Figure 195 : IRS 1C LISS III image of September 7, 2005 showing the glaciers of part of the Dhauliganga sub basin

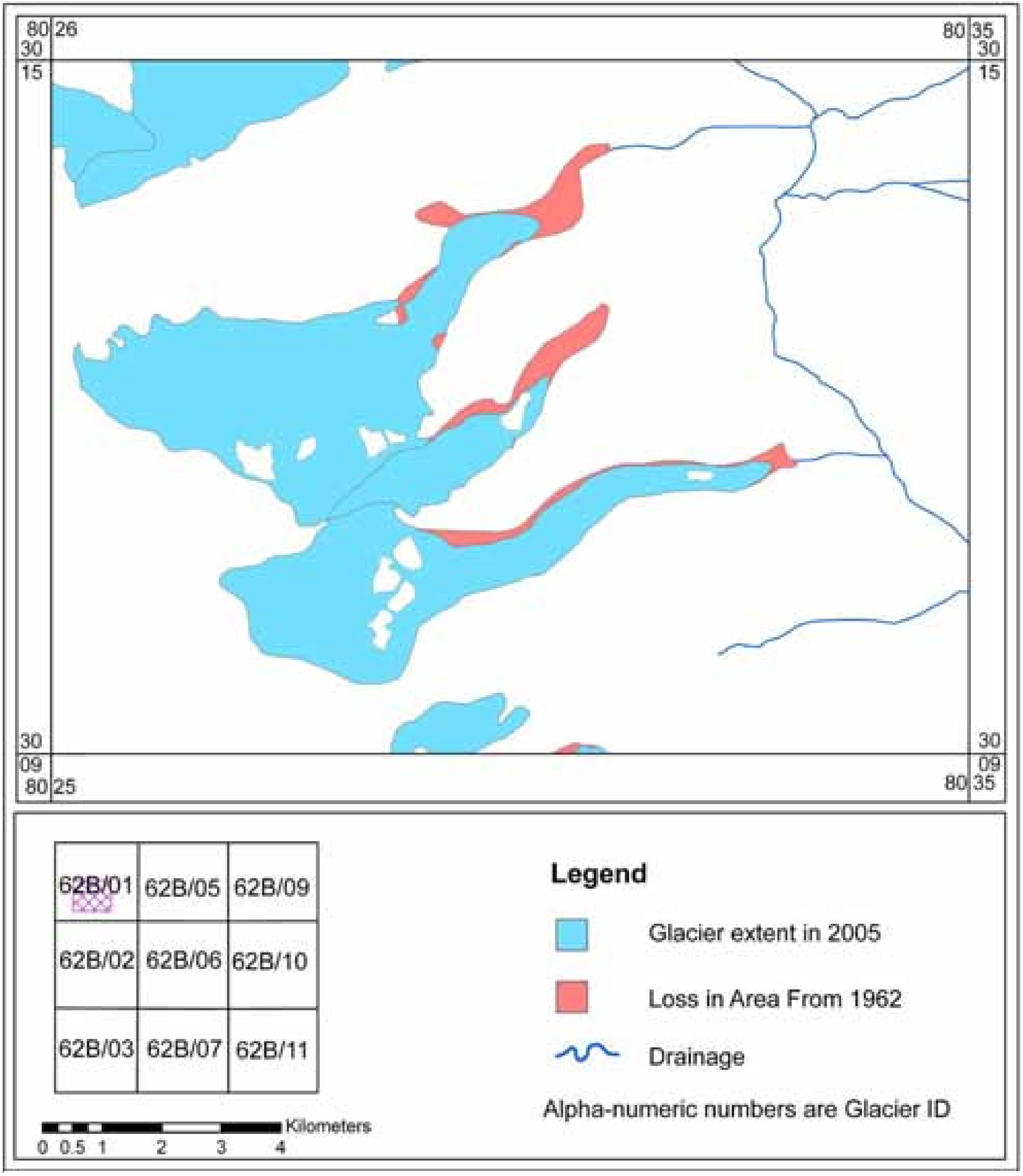


Figure 196: Map showing loss in area of the glaciers of a part of the Dhauliganga sub-basin between 1962 and 2005

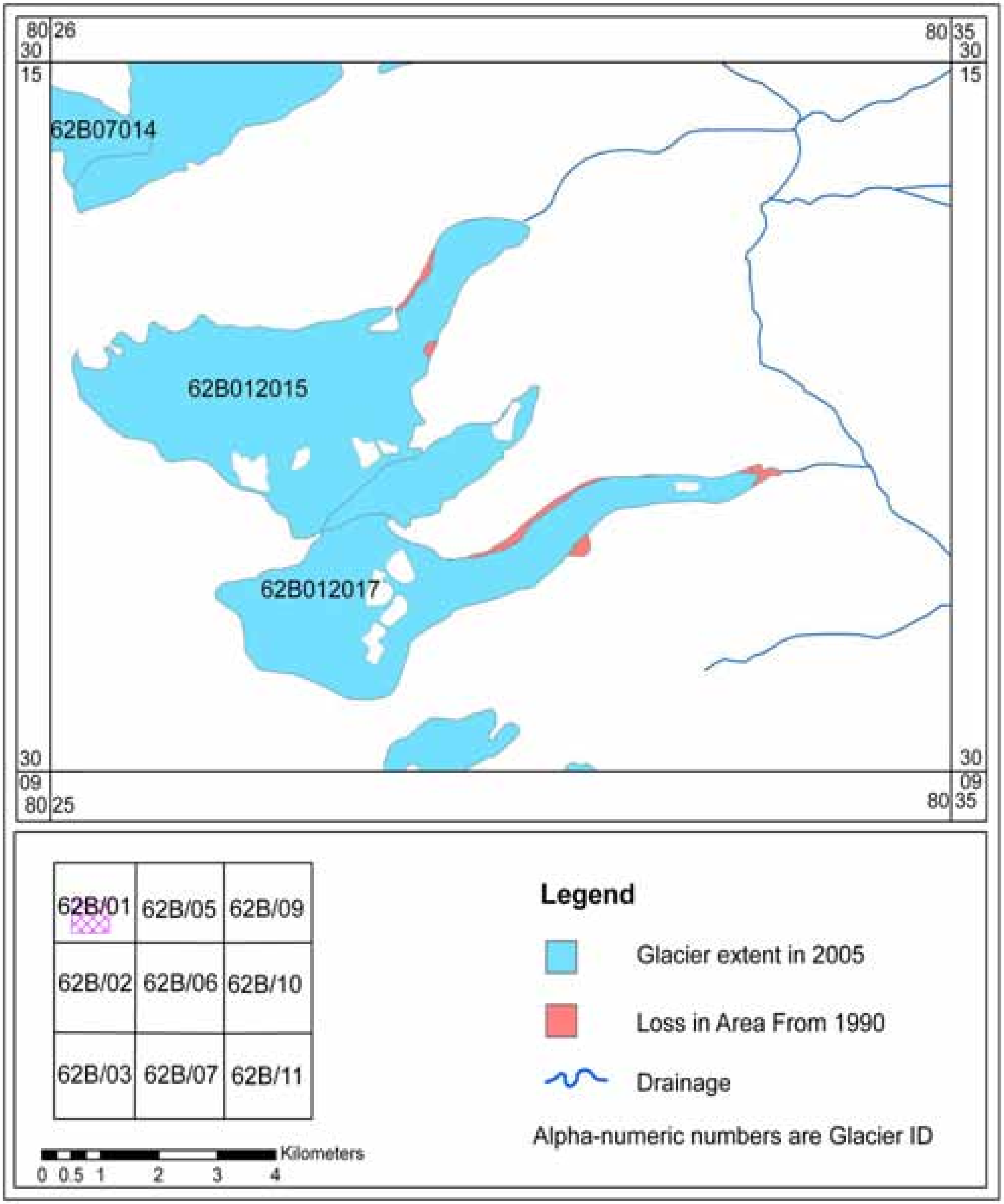


Figure 197: Map showing loss in area of the glaciers of a part of the Dhauliganga sub-basin between 1990 and 2005

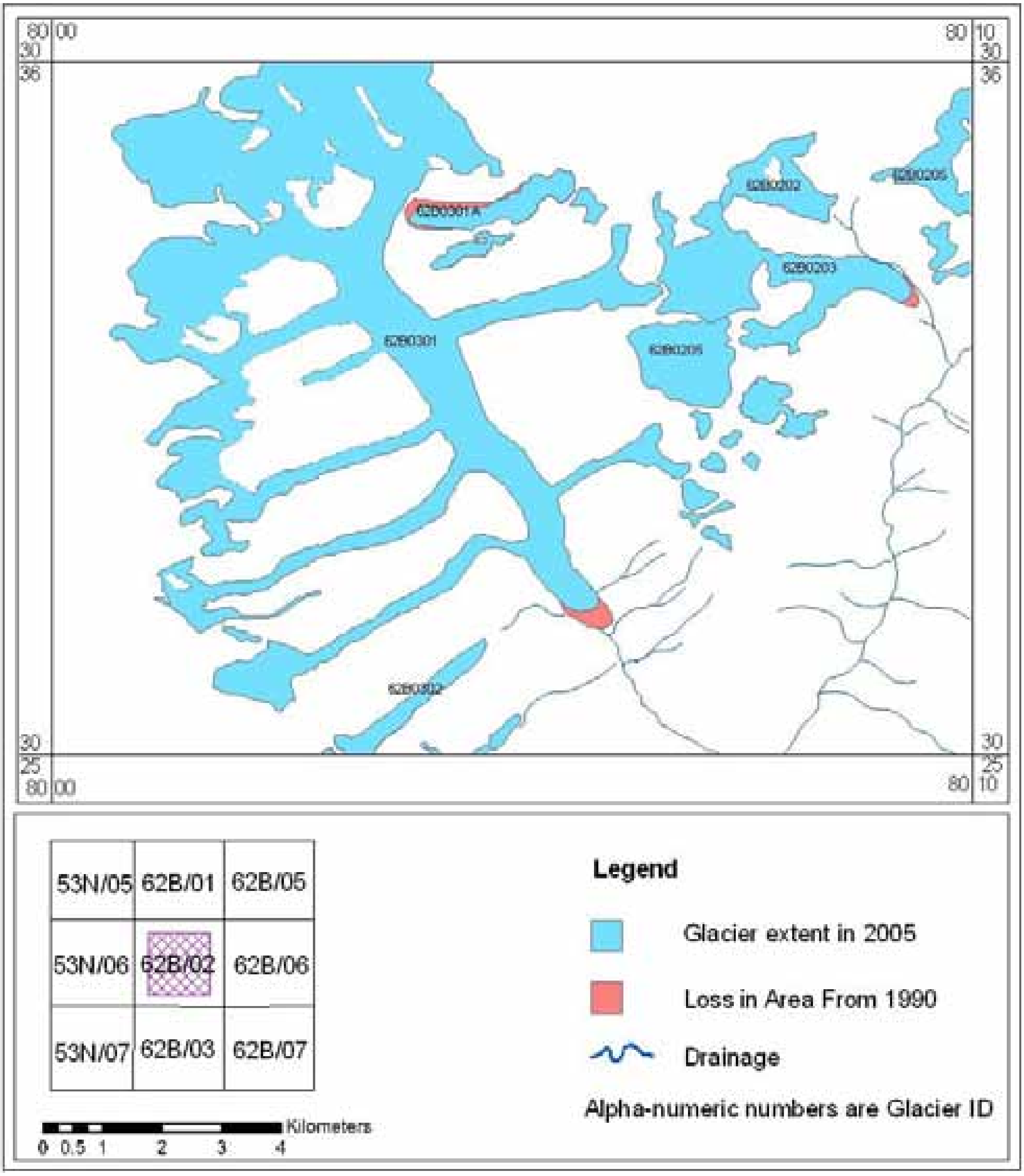


Figure198: Map showing loss in area of the glaciers of a part of the Goriganga sub-basin between 1990 and 2005

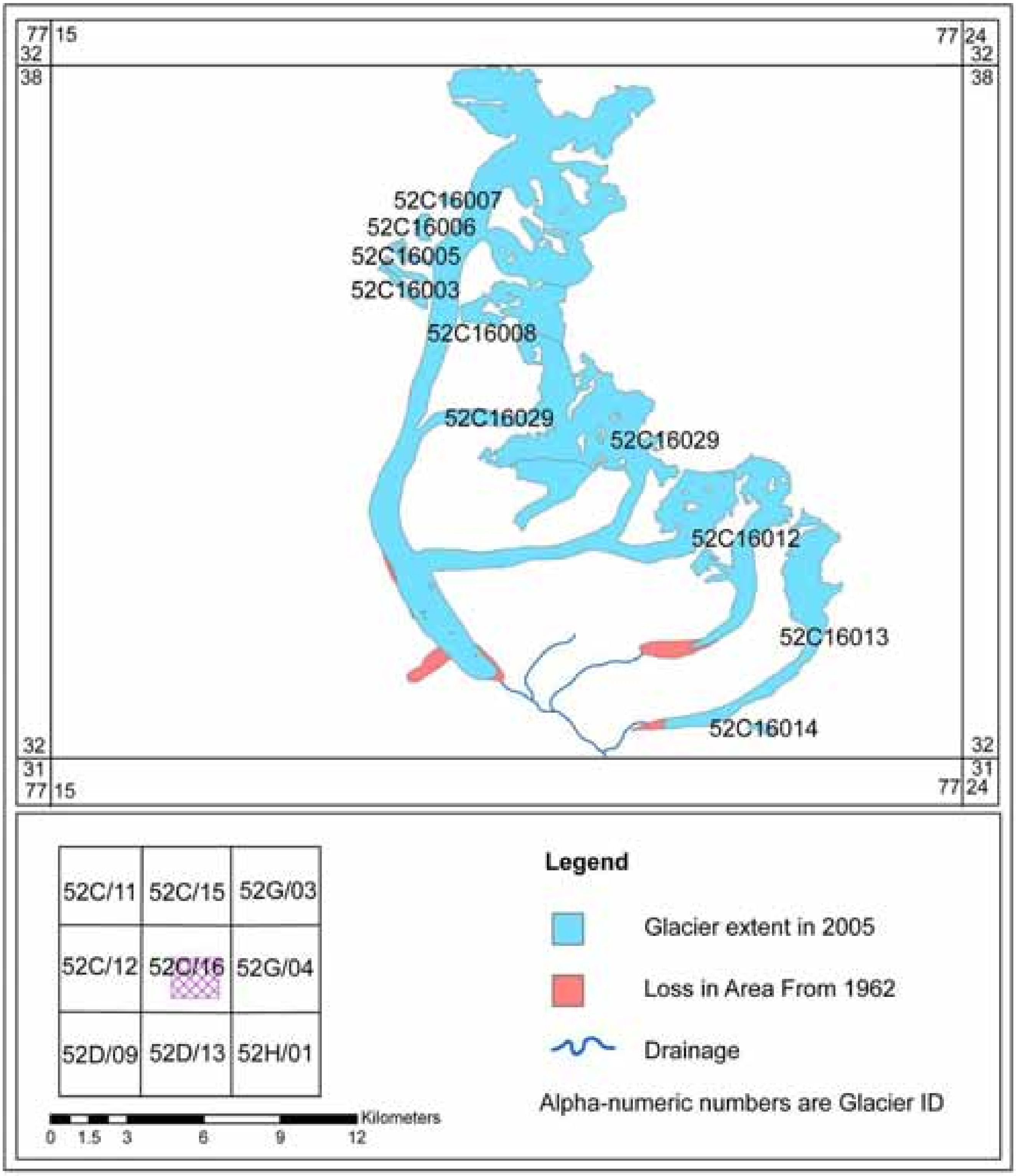


Figure 199: Map showing loss in area of the glaciers of a part of the Bhaga sub-basin between 1962 and 2005

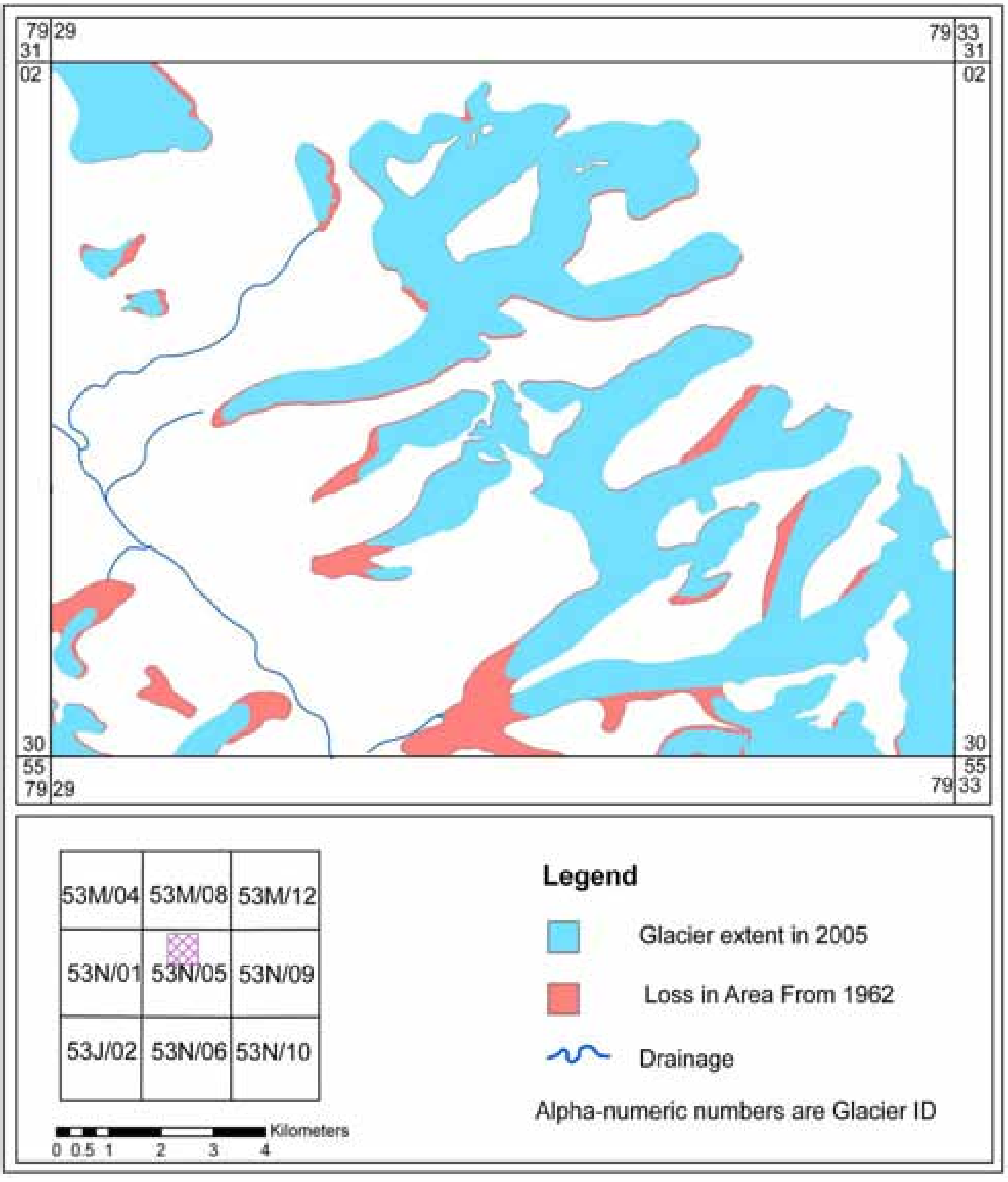


Figure 200: Map showing loss in area of the glaciers of a part of the Alaknanda sub-basin between 1962 and 2005

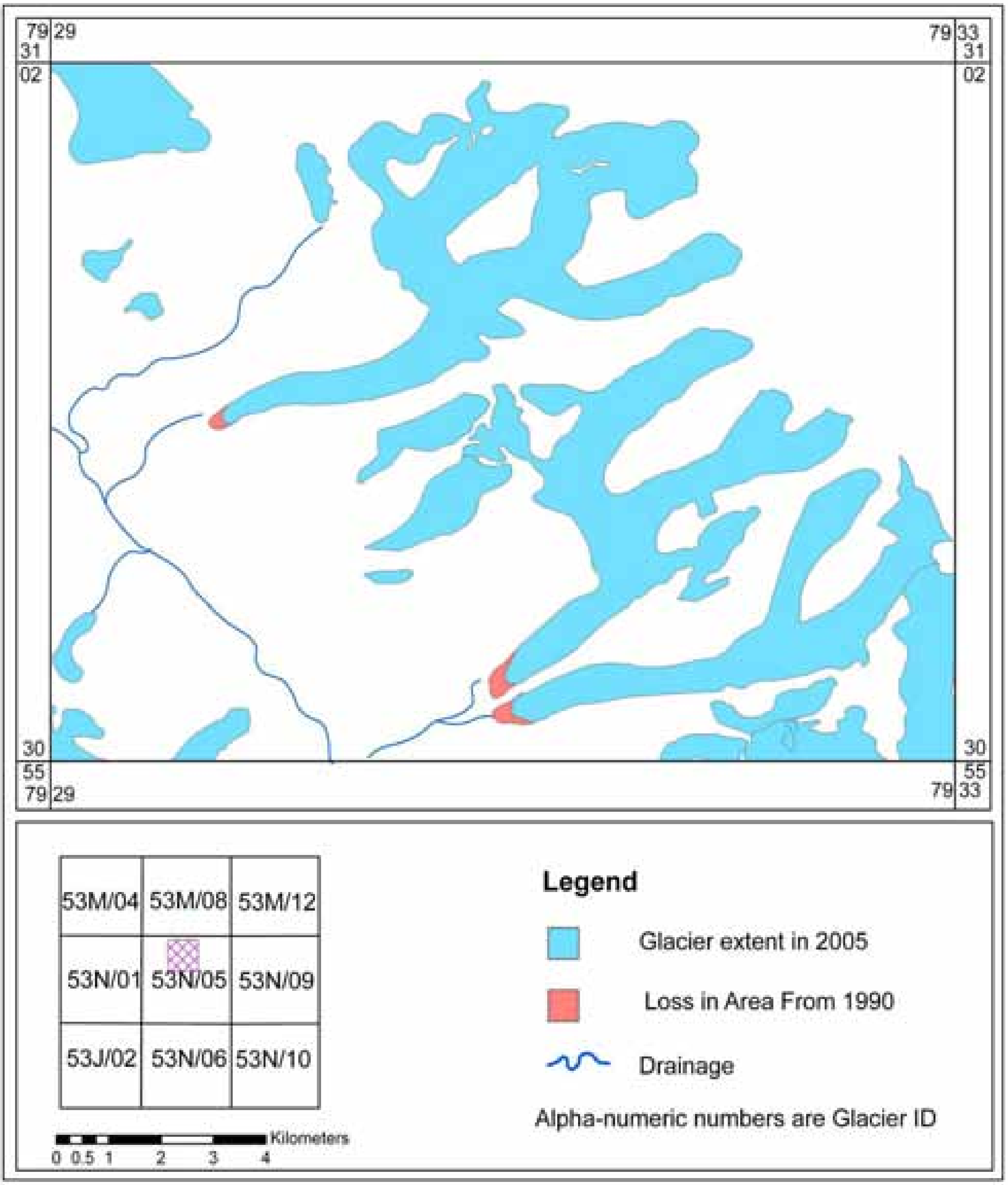


Figure 201: Map showing loss in area of the glaciers of a part of the Alaknanda sub-basin between 1990 and 2005

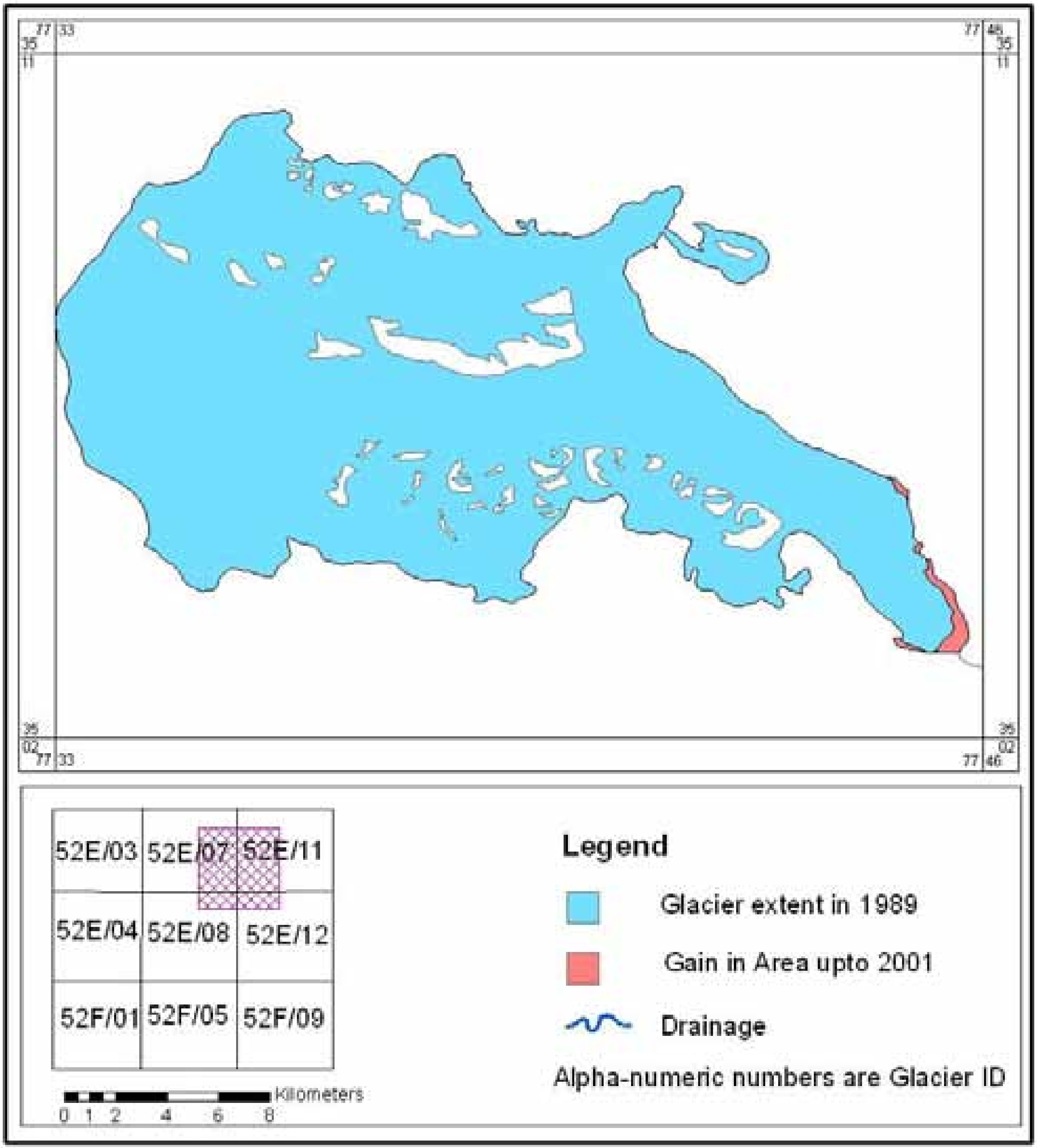


Figure 202: Map showing gain in area in North Remo glacier of Shyok sub-basin between 1989 and 2001

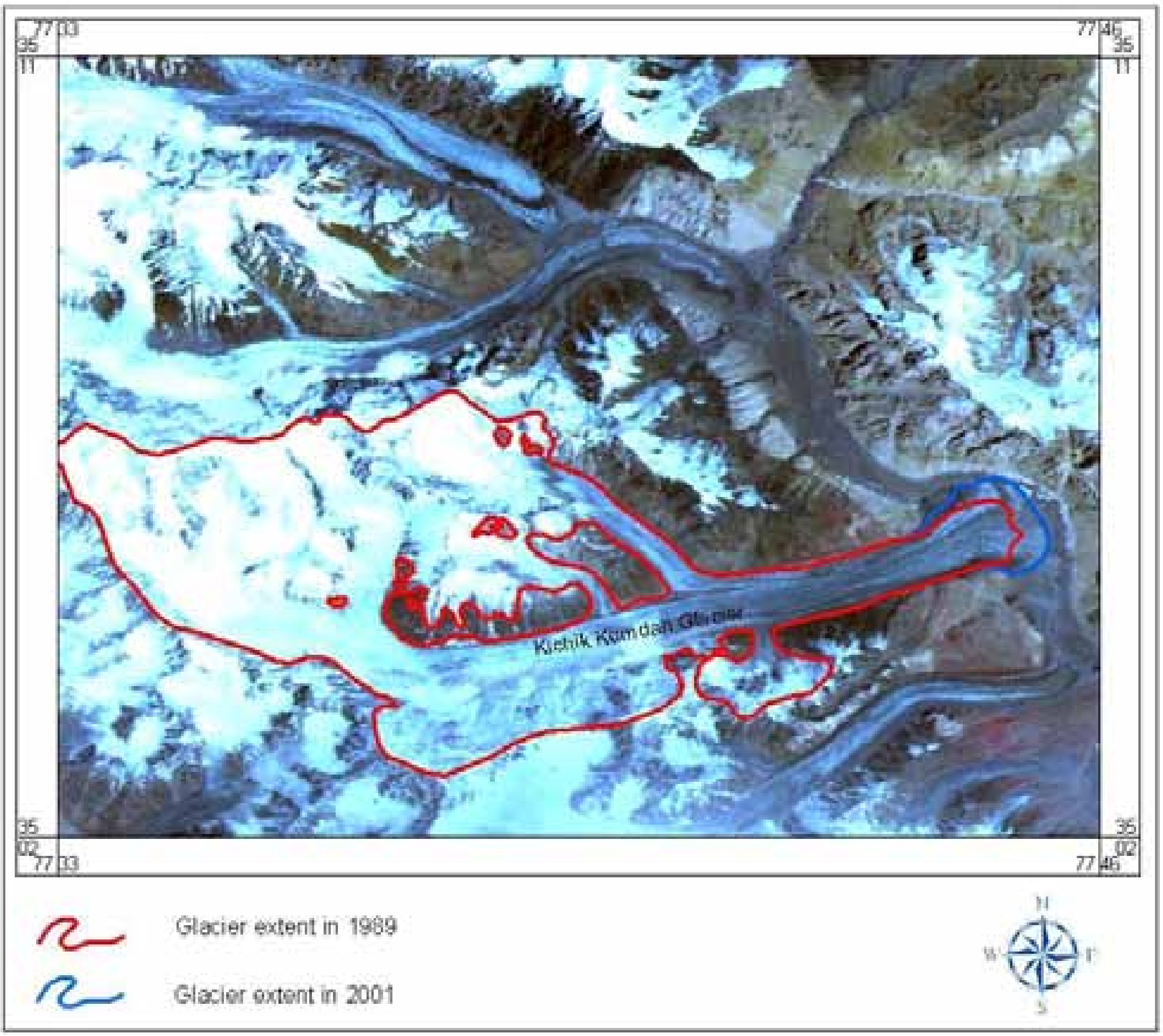


Figure 203 : Map showing gain in area in Kichik Kumdan Glacier between 1989 and 2001

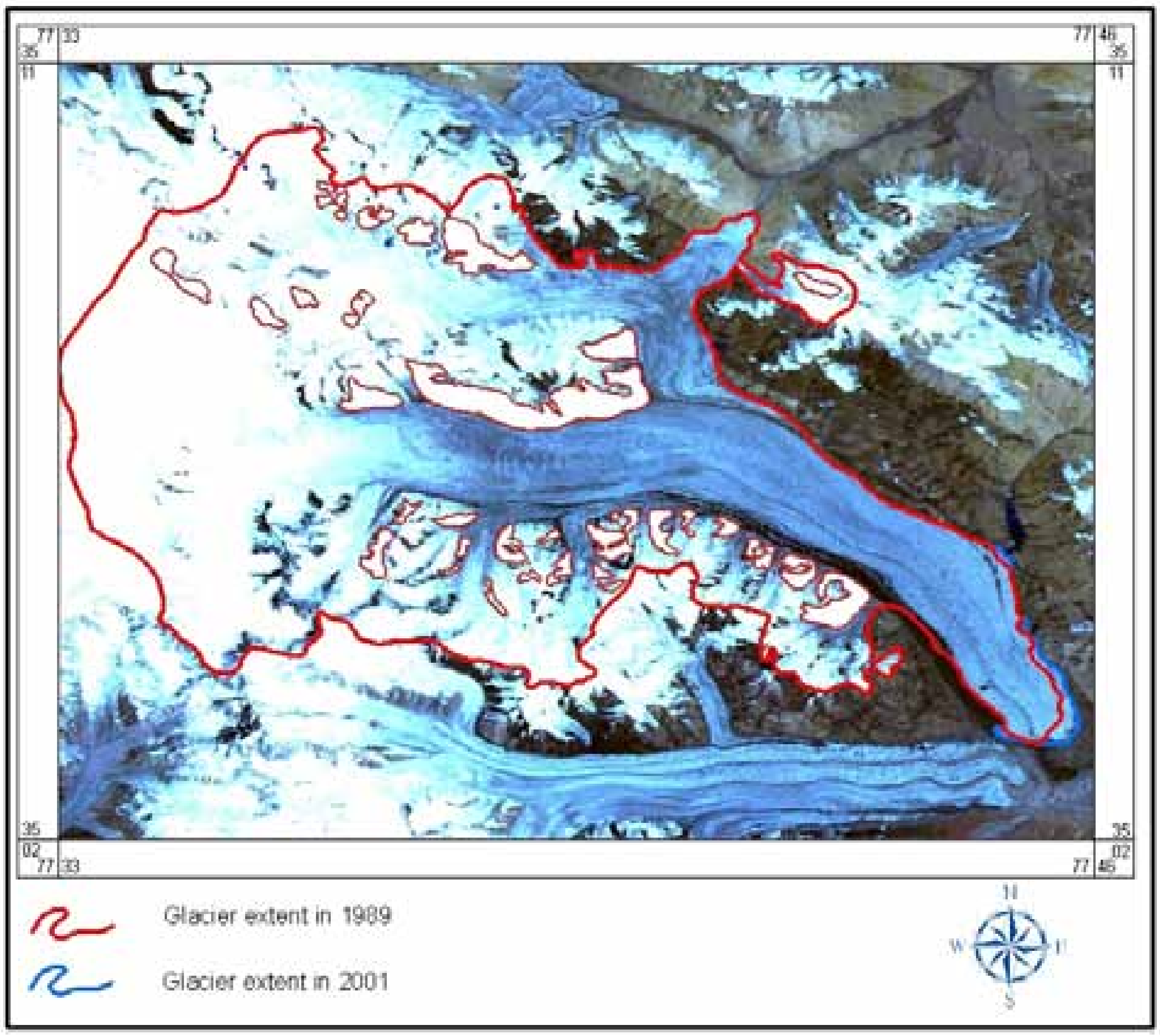


Figure 204: Map showing gain in area in North Remo Glacier between 1989 and 2001

ANNEXURE – 4
Mass Balance of Glaciers

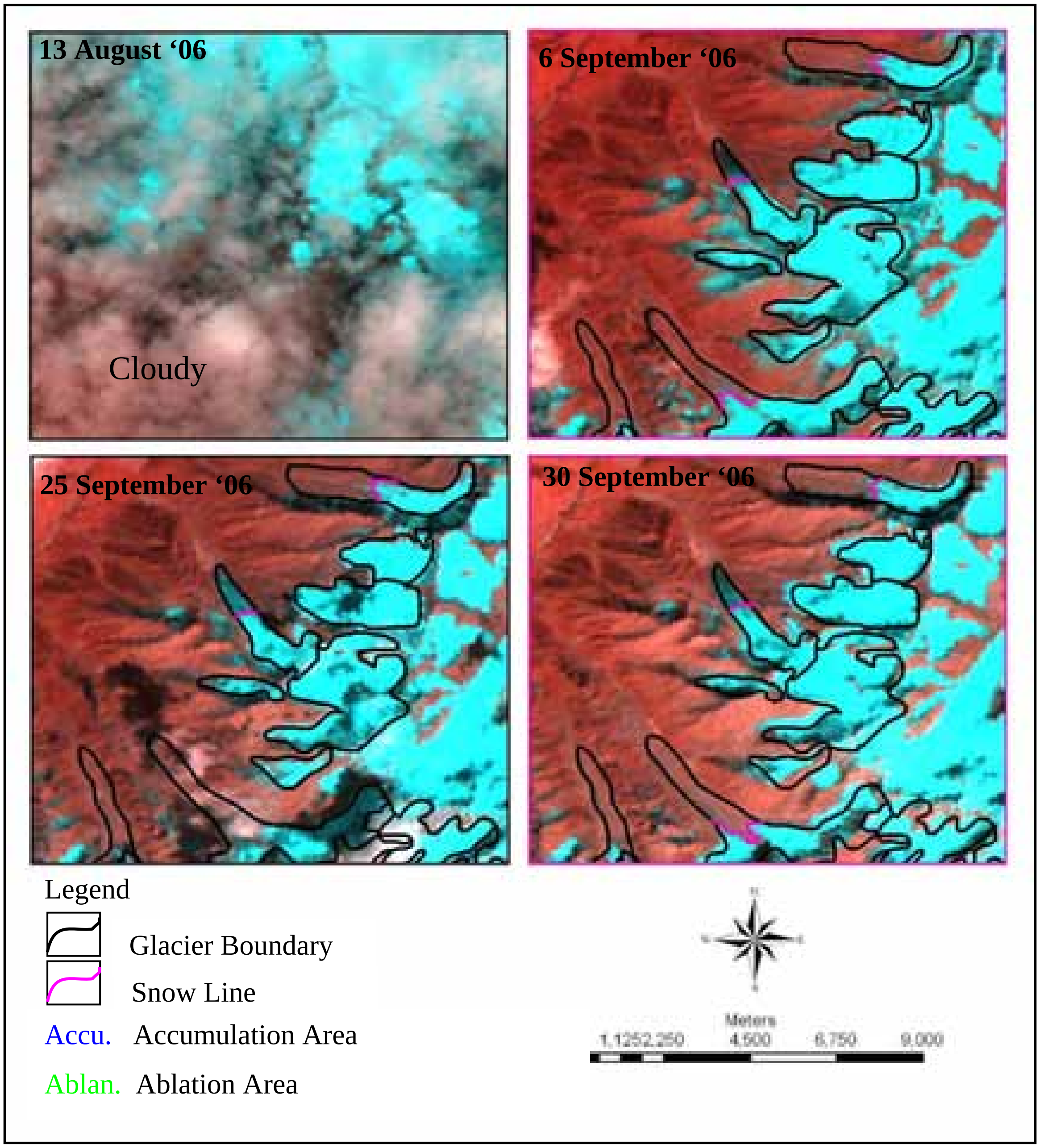


Figure 205: IRS P6 Images showing fluctuation of snow line for 2006 glacier of Miyar Basin

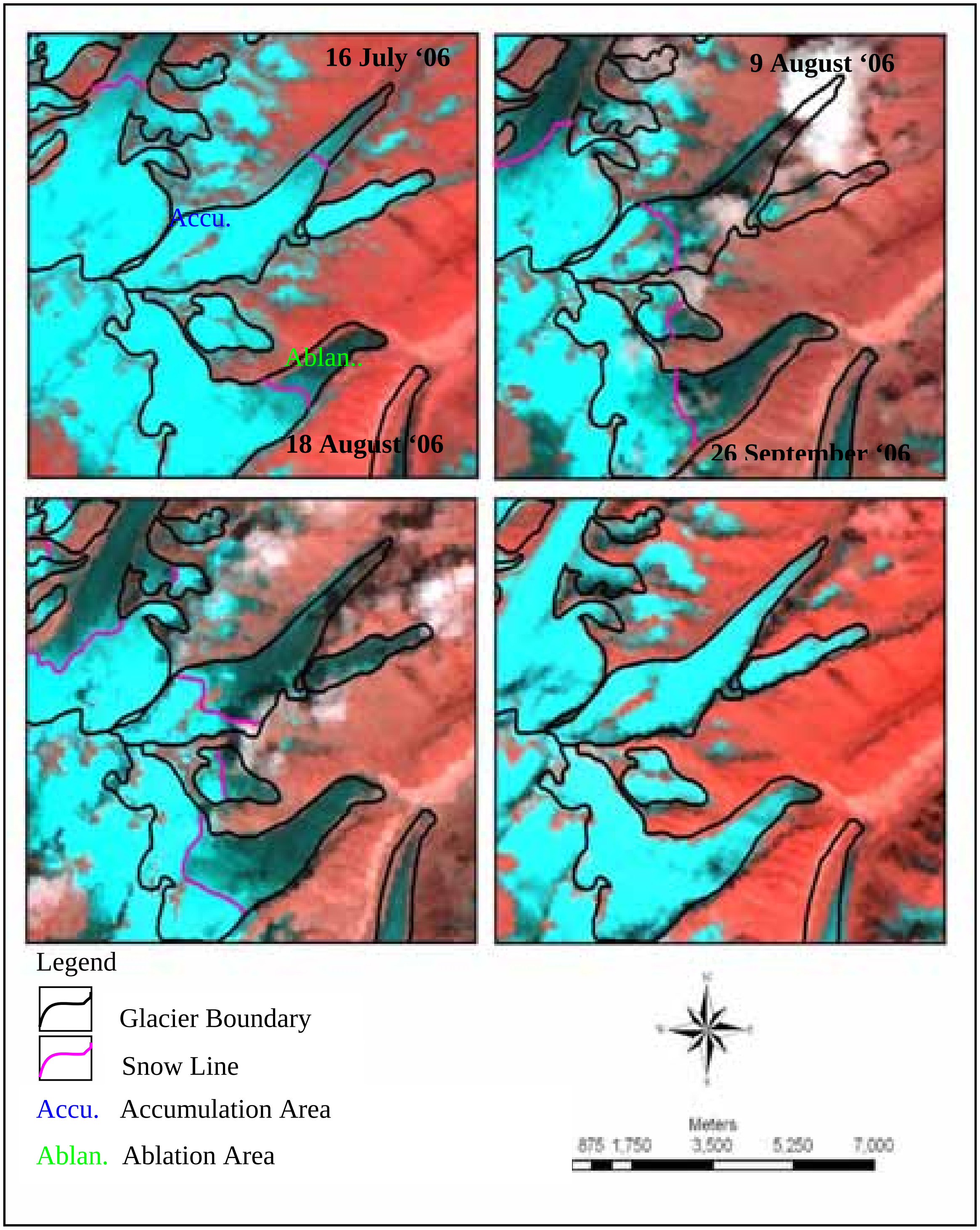


Figure 206: IRS P6 Images showing fluctuation of snow line for 2006 glacier of Bhaga Basin

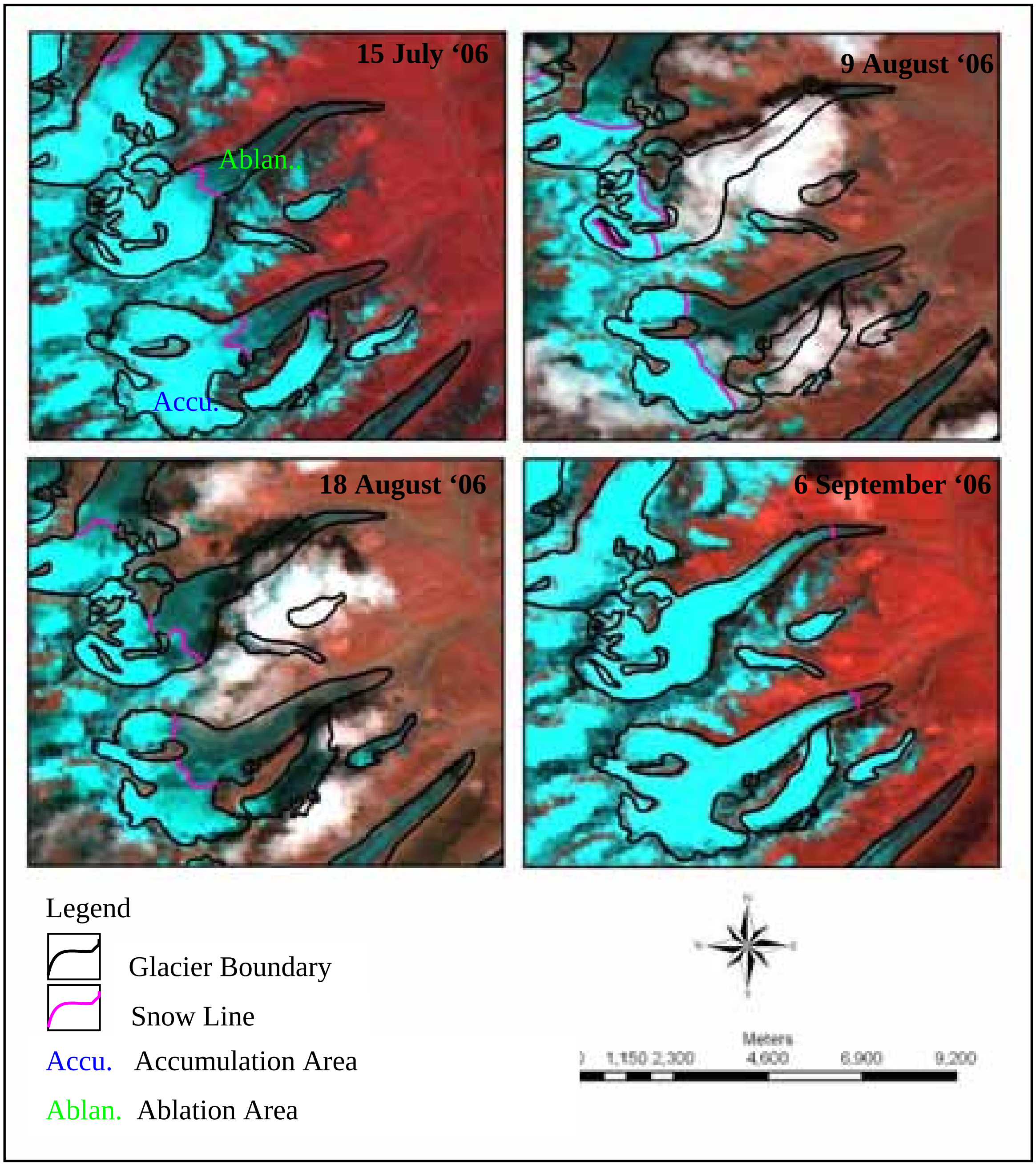


Figure 207 : IRS P6 Images showing fluctuation of snow line for 2006 glacier of Chandra basin

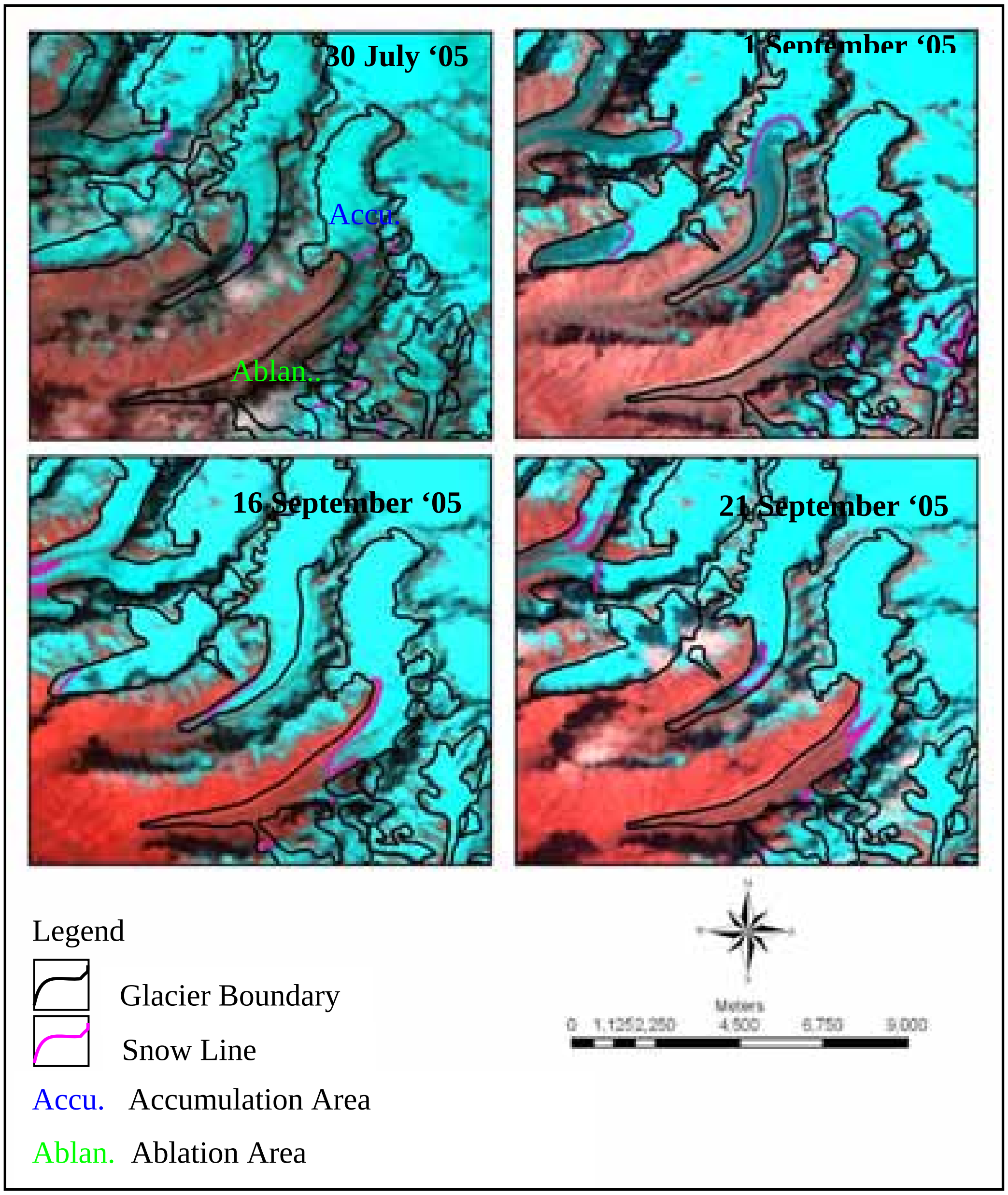


Figure 208: IRS P6 Images showing fluctuation of snow line for 2005 glacier of Miyar basin

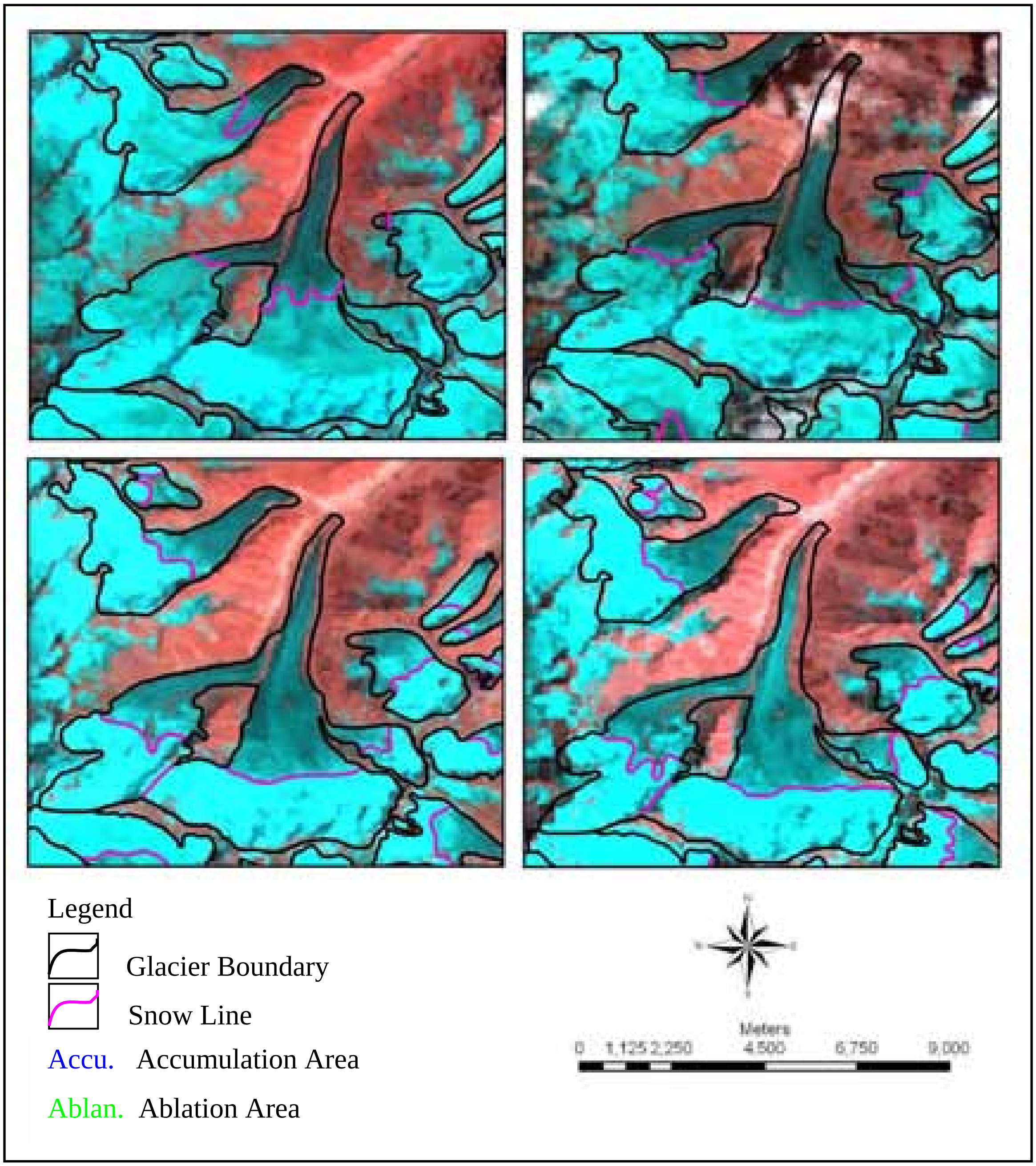


Figure 209 : IRS P6 Images showing fluctuation of snow line for 2005 glacier of Bhaga Basin

List of Figures

Figure 206: IRS P6 Images showing fluctuation of snow line for 2006 glacier of Bhaga Basin

Figure 207 : IRS P6 Images showing fluctuation of snow line for 2006 glacier of Chandra basin

Figure 208: IRS P6 Images showing fluctuation of snow line for 2005 glacier of Miyar basin

Figure 209 : IRS P6 Images showing fluctuation of snow line for 2005 glacier of Bhaga Basin

List of Tables