Fate of Mountain Glaciers in the Anthropocene
Pontifical Academy of Sciences, Scripta Varia 118, 2013
www.pas.va/content/dam/accademia/pdf/sv118/sv118-kasturirangan.pdf

Observed Changes in the Himalayan-Tibetan Glaciers

K. Kasturirangan,[1] R.R. Navalgund[2] and Ajai[3]

1. Introduction

Cryosphere comprises of snow cover, sea ice, freshwater ice (frozen lakes and rivers), the large ice masses on land such as ice sheets, glaciers, ice shelves, icebergs and permafrost. Among all cryospheric constituents snow cover, ice sheets over Polar Regions, glaciers in the mountains are most important to mankind. Snow cover has three components i.e. permanent, seasonal, and temporary. Temporary and seasonal snow cover occurs in winters while permanent snow cover is retained for many years. Permanent snow cover occurs principally in Antarctica, Greenland and above permanent snow line in mountainous areas. Snowfall is responsible for affecting mobility of man and machine in many parts of the world; besides, snowmelt runoff is vital for water storage for drinking, irrigation, and hydroelectric power generation and to maintain the ecosystems. An important climatological effect of snow cover is the thermal insulation provided by it, which reduces the exchange of heat between the ground and the atmosphere.

The total global ice cover is 16 million sq km, i.e. 10% of the earth's land area (Benn and Evans 2010). The maximum ice cover has been estimated in Antarctica region which is nearly 13.5 million sq km. The next highest ice cover is in Greenland (1.74 million sq km). The remaining icy region is covered by mountain glaciers which are mainly valley glaciers constrained by topography. Ice sheets keep water locked in frozen state and thus control the global climate and level of oceans. Presence of many glaciers in various mountains the world over controls the release of freshwater to many river systems and sustains civilization. Mountain glaciers are established in the Himalayas, Alps, Andes, Rockies, China, Russia, Africa, Alaska, and New Zealand. The mountain glaciers can be grouped further into two i.e. cold and temperate glaciers.

[1] Planning Commission, Govt. of India, New Delhi.
[2] Space Applications Centre (ISRO), Ahmedabad – 380015, India.
[3] Space Applications Centre (ISRO), Ahmedabad – 380015, India.

Though Earth's climate has never been the same since the geological past (before the human came into being), the variations in climate have been more pronounced in the recent time due to increase in population and associated development and industrialization. The effect of climate change on frozen reservoirs of water can have far-reaching implications. Proper assessment of these resources and the impact of climate change require monitoring of the Earth's cryosphere.

Among all the mountainous regions of the world, the glaciers of the Himalaya constitute the largest concentration of freshwater reserve outside the polar region. The Himalayan mountain ranges extend from Kashmir in the west to Arunachal Pradesh in the east. In India, the Himalayas occupy the parts of Jammu & Kashmir, Himachal Pradesh, Uttarakhand in the west and the state of Sikkim, Assam and Arunachal Pradesh in the east. In between, the two countries Nepal and Bhutan also link the Himalayan chain. Hydrologically, the Himalayas are drained by the three major river systems, namely the Ganges, the Indus and the Brahmaputra. The Indus flows to the Arabian Sea and its major tributaries are the Satluj, Chenab and Jhelum rivers. The Ganges originates in the Uttarakhand region of India and flows down to the Bay of Bengal. Its major tributaries are the Bhagirathi, Alaknanda, Yamuna and Kosi rivers. The latter originates in the Nepal Himalayas. The Brahmaputra travels eastward across Tibetan plateau and drains to the Bay of Bengal. Its major tributary is the Tista River which drains in Sikkim state. These rivers are perennial and bring water to the northern plane of the country. The rivers draining out of the Himalayas have shaped the frontal portions of the Himalayas into a very vast alluvial plain. These plains are one of the most fertile regions and thus one of the densely populated regions of the world. Rivers flowing from these plains sustain the civilization by providing irrigation, hydroelectricity and drinking water.

The sources of water in these river basins are snow and glacier melt runoff, rain water and groundwater occurring in mountains. These rivers also carry a huge load of sediments to the reservoirs located in down streams (Rao, 1979). The contribution of snow and glacier melt to total annual runoff is about 50% (Singh *et al.*, 1997). This might initially increase due to the warming of the atmosphere but the reserves will get exhausted later on. Moreover, the demand of water in the future is going to increase. According to Kumar *et al.* (2005) water availability in the years 1991 and 2001 were 2309 and 1902 m^3 and these are projected to reduce to 1401 and 1191 m^3 by the years 2015 and 2050 respectively. Therefore, for proper planning for future requirements of water resources, cryospheric studies of Himalayas have become important. Space-based assessment and monitoring of Himalayan cryosphere has been discussed in this article.

2. Elements of Cryospheric Studies

Cryospheric studies may range from inventory, monitoring, quantification of the extent and volume of snow and glaciers, to development of models to understand the physical processes involved in accumulation and ablation of snow and ice. For mountainous regions, estimation of snow and glacier reserve and melt runoff are important component of these studies. Important elements of the Himalayan Cryosphere which need to be studied in detail include: i) Spatial extent of snow cover and its intra seasonal and inter seasonal variation; ii) spatial extent of glaciers; iii) advance/retreat of glaciers; iv) glacier mass balance; and v) snow and glaciers melt runoff.

3. Characteristics of Himalayan Glaciers

The Himalayas with a length of about 2400 km have an arcuate shape and thus occupy a wide range of latitudinal variations. Cross-sectionally from north to south the Himalayas can be divided into the Great Himalayan ranges, Lesser Himalayan ranges and Shivalik ranges. These ranges characterize high to low altitudes from north to south respectively. The altitudinal and latitudinal variations provide different temperature regimes to these areas. The western part of the Himalayas is influenced by western monsoons whereas the eastern Himalayan region is influenced primarily by the S-E monsoon from the Bay of Bengal. Large areas in the Himalayas are covered by snow during the winter season. The area of snow can change significantly during winter and spring. The onset of seasonal snowfall in Indian Himalaya begins in Kashmir in late September/early October months and slowly shifts towards lower latitudes. The melting season of snow and glacier also progresses similarly from the months of July to the end of September. The accumulation and ablation time in the eastern Himalayan region (Sikkim and Arunachal Pradesh) is little late by about three months. The altitude of the lowest snow line also significantly varies from Kashmir, Uttarakhand, Nepal, Sikkim and Bhutan. The snow line comes down to an altitude of approximately 2500 m in winter. The snow line at the end of ablation varies between 4500 to 5000 m.

Increase in concentration of glaciers in the Himalaya varies from northwest to northeast according to the variation in altitude and latitude of the region. The Siachin glacier in Kashmir, the Gangotri glacier in Uttranchal (Ganga basin), the Bara Shigri glacier in Himachal (Chenab), the Baltoro glacier in Karakoram (Indus basin) and the Zemu glacier in Sikkim (Tista) are a few famous glaciers of the Himalayas. The glaciers in the Himalaya have high relief and occur above 4000 m amsl up to the peak of Mt. Everest 8848 m amsl. These glaciers are temperate glaciers in nature. Many glaciers are debris-covered in their ablation zone. Thus these glaciers appear dark compared to the mountain glaciers of higher latitude. Debris cover reduces the glacier surface albedo.

Due to high relief, the Himalayan glaciers cover a large altitudinal range compared to the glaciers in other mountainous ranges, located in non-polar regions. The large altitudinal range provides different climatic zones and wind zones to these glaciers. This has implications on the accumulation and ablation of snow and ice if there is a rise in temperature. The Himalayas are also characterized by high seismic activities. Seismic activity may affect the relief and topography, which in turn may affect glacier ice movement.

4. Space based system to monitor cryosphere

Space-borne remote sensing of the cryosphere started in the seventies after the launch of Landsat (ERTS-1) satellite. Since then there have been rapid strides in the use of space-borne remote sensing data in cryospheric studies because of the improvement in the quality and coverage of space-borne data. Due to the difficult and hazardous terrain of the Himalayas, ground-based glacier studies are very scanty. Sensors onboard Indian remote sensing satellites such as LISS I, LISS II, AWiFS, LISS III, LISS IV and cartosat-1/2 with varying spatial resolutions, band combinations and with wide to narrow viewing capability have provided high quality data to monitor and study the glaciers and snow cover in the Himalayas. In the last two to three decades, the advancement in image processing techniques and GIS has added tremendously to the quality of information derived from space borne sensors.

The sensors operating in the following regions of the EM spectrum are being used to monitor the cryosphere:

Optical region: Most of the glacier inventories of the mountains have been carried out using data in optical region. But the limitation of optical data is that often glacier area is covered with clouds during the optimum period of data acquisition i.e. August-September when seasonal snow line has receded to the maximum extent. Data in the optical region has been extensively used to monitor snow cover, inventory and monitoring of glaciers, computing snow albedo etc. LIDAR techniques have been used to generate DEM over ice with good accuracy to estimate change in thickness of ice sheets. Stereo photogrammetry techniques employ processing of STEREO data for estimation of change in volume by generating DEM and hence estimating the mass balance.

Thermal region: Thermal data of medium to coarse resolution is now being used to map glacier ice below debris cover.

Microwave region: Active sensors SAR are used to map dry and wet snow. SAR interferometry techniques are useful in generating DEM over glaciers. Time difference DEMs have been used to infer velocity of ice and mass balance of glaciers.

Passive sensors in the microwave region help in the determination of the thickness of snow and ice.

5. Monitoring of Himalayan – Tibetan cryosphere

As mentioned earlier, the difficult and hazardous terrain of Himalaya makes it extremely difficult to carry out field-based measurements and thus only a few glaciers have been studied for mass balance and for monitoring snout positions. In view of the above, remote sensing technique has been found to be the most viable alternative to carry out glacier studies in the Himalaya. Repetitive coverage from high to medium resolution sensors of Indian Remote Sensing Satellites (IRS) available during the last two decades has made it possible to map and monitor glaciers of the Himalayas with limited validation on the ground. INSAT-3A images showing the glaciated area of the Himalayan-Tibetan region during the accumulation and ablation period are given in Fig. 1. In India, the first glacier inventory of the Indian Himalaya using images available from Landsat and IRS 1A & 1B satellites was carried out at 1:250,000 scale (Kulkarni 1992). Detailed glacier inven-

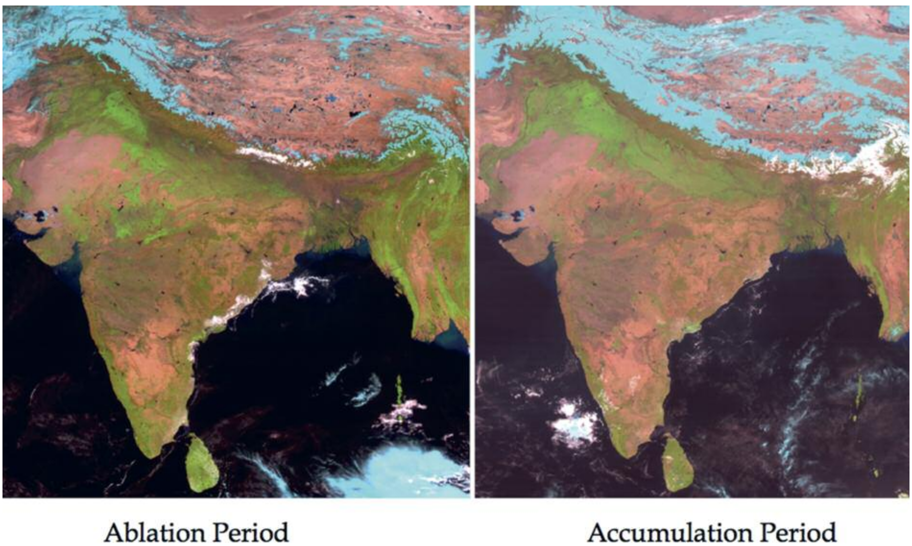


Figure 1. Glaciated area of the Himalayan-Tibetan region as seen on INSAT-3A Images.

tory for Satluj basin at 1:50,000 scales followed (Kulkarni *et al.* 1999). The glacier features, which are mapped using satellite data, are glacier boundaries; accumulation zone, the snow line, the ablation zone, deglaciated valleys and moraine dammed lakes (Ajai *et al.* 2011).

5.1 Inventory of Himalayan glaciers

The glacier inventory primarily deals with the occurrence and distribution of glaciers and also provides details for each glacier on morphology, dimensions, orientation, elevation, etc. for both the active glacier component as well as the associated de-glaciated valley. Very recently, glacier inventory of the entire Himalaya (the Indus, Ganga and Brahmputra basins) has been carried out on 1:50,000 scale using IRS P-6 AWiFS data. Fig. 2 shows the spatial extent of the present glacier inventory (hatching shows the study area) as depicted on the satellite image (False Color Composite). The inventory includes the complete Ganga, Brahmaputra and the Indus basin (only a small portion in the north west is not included). This inventory in-

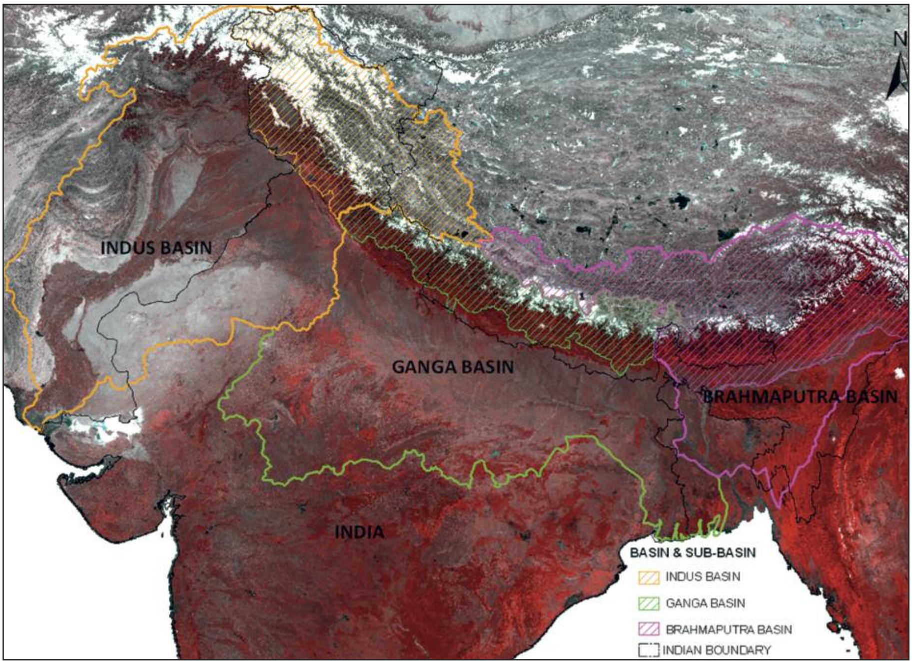


Figure 2. Satellite image (False Color Composite) showing snow cover/glaciated regions of the Himalayas along with basin boundaries of the Indus, Ganga and Brahmaputra. Hatching shows the areas covered for glacier inventory.

cludes even the glaciers of these three basins which are located outside the Indian territory but draining into India (Sharma *et al.*, 2011).

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

The results of the inventory of glaciers, providing details on the number and area of the glacier features mapped for the Indus, Ganga and Brahmaputra basins are given in Table 1. Specific measurements of mapped glaciers features are the input for generating the glacier inventory data sheet with 37 parameters as per the UNESCO/TTS standards and 11 additional features associ-

	Basin	Indus	Ganga	Brahmaputra	All basins total
Sr. No.	Characteristics	Area in km^2	Area in km^2	Area in km^2	Area in km^2
1	Sub-basins (Nos.)	18	7	27	52
2	Accumulation area	19265.98	10884.60	12126.36	42276.94
3	Ablation area debris	6650.95	4844.70	5264.90	16760.55
4	Ablation area ice exposed	6310.58	2663.50	3081.48	12055.56
5	Total no. of glaciers	16049	6237	10106	32392
6	Total glaciated area	32246.43	18392.90	20542.75	71182.08
7	No. of Permanent Snow fields and Glacierets	5117	641	3651	9409
8	Area under Permanent Snow fields and Glacierets	991.68	198.70	1282.92	2473.30
9	No. of Supra-glacier lakes	411	87	474	972
10	Area of Supra-glacier lakes	18.92	15.20	70.01	104.13
11	No. of Moraine dam/Glacial lakes	469	194	226	889
12	Area of Moraine dam/Glacial lakes	33.82	64.10	70.15	168.07

Table 1. Details of the Glacier inventory of the Himalayas.

ated with the deglaciated valley. The data sheet provides glacier-wise details, mainly related to glacier identification, in terms of number, name, glacier locations, information on the elevation, dimensions and orientation etc.

The total number of glaciers and the glaciated area in these three basins put together are 32392 and 71182.08 sq km respectively (Sharma *et al.* 2011 and Ajai *et al.* 2011). The Indus basin has 16049 glaciers having glaciated area of 32246.43 sq km. The Ganga basin has 6237glaciers occupying 18392.90 sq km of glaciated area. There are 7 glaciated sub-basins in Ganga basin. The Brahmaputra basin has 10106 glaciers occupying 20542.75 sq km of glaciated area. There are 27 sub-basins in the Brahmaputra basin covering the glaciated area. The total glaciated area and the number of glaciers in the Indian Himalaya are 37266 sq km and 16445 respectively (Sharma *et al.* 2011).

The results of this inventory show that the accumulation and ablation areas of the glaciers are the largest in the Indus basin. The ratio of accumulation to ablation area is high in the Brahmaputra basin. This indicates that the glaciers of the Indus basin are having larger feed area and hence are relatively stable as compared to the other two basins. The Indus basin has 51.3% of the ablation area covered with debris whereas the Ganga and the Brahmaputra basins have 64.5% and 63.1% debris cover respectively. All the three basins put together, about 60% of the glaciated area in the ablation zone is covered with debris. The percentage of debris-covered glaciers is highest in the Ganga basin. Though the number of glacial lake/moraine dammed lake is higher in the Indus basin, the total area of such lakes is the lowest among these three basins which means that the lakes are smaller in size in the Indus basin and larger in the Ganga and the Brahmaputra basin. The number of supra glacier lakes is 474 (with an area of 70.01 km^2) in the Brahmaputra basin which is the largest of all three basins. The area of permanent snowfield is smallest in the Ganga basin which is hardly 198.7 km^2. The areas under permanent snowfields are 991.68 and 1282.92 sq km in the Indus and the Brahmaputra basins respectively. Glaciers of all the basins have been classified in different class zones based on the size. The number of glaciers having size less than 1 km^2 is highest in the Indus basin and lowest in the Ganga basin. The Ganga basin has the maximum number of large-sized glaciers compared to the Indus and Brahmaputra basins (Fig 3).

Computing the glacier ice volume and water equivalent (stored in frozen condition) is important from the water security point of view. The volume of ice has been computed for the three basins using glacier area and ice thickness (Chaohai and Sharma, 1998). Figure 4 shows the glaciated area, glacier volume and water equivalent for the three basins. The Indus has the largest ice volume and water stored.

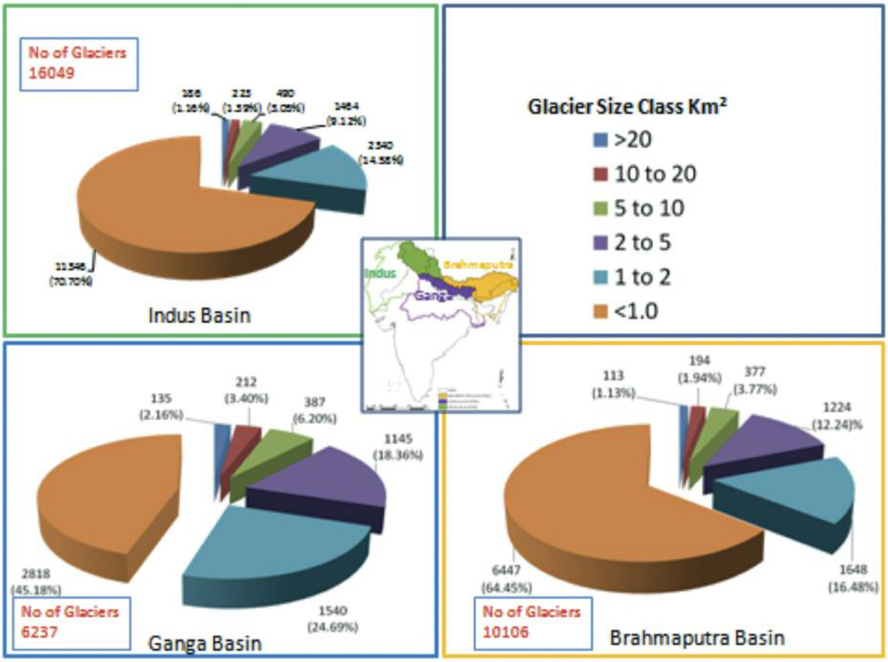


Figure 3. Glacier Size Distribution in the Indus, Ganga and Brahmaputra Basins.

5.2 Monitoring retreat/advance of glaciers

There is a pertinent relationship between retreat/advance and variations in the mass balance of glaciers. It is the climate which is the driving force controlling the mass balance of glacier in space and time and resulting in the retreat and advance of the glaciers. 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 changes in the flow of the glacier that ultimately results in a change in the position of the terminus.

The retreat or advance of individual glaciers depend upon variations in mass balance which in turn is governed by static and dynamic factors. The static factors are latitude, slope, orientation, width and size of the valley and altitudinal distribution of glaciers. The dynamic parameters are annual accumulation and ablation of snow and ice. These factors further depend upon daily and yearly variations in temperature, precipitation, heat flow from the Earth's crust, debris cover and cloud cover.

The advance and retreat of glaciers closely depends on the conditions of replenishment of an accumulation area and the intensity of ablation, i.e.

faster melting due to climatic changes. Stream run-off in the Himalayan region is the basic source for water as a resource and also for micro and mini hydel projects which have direct implications in the fluvioglacial/geomorphological process and ecological balance of the region.

Basin	Mean glacier area (sq km)	SOI maps 1962/1969-Satellite images 2001/2004/2005		Satellite images 1989/1990-2004/2007	
		No. of glaciers Monitored	Mean annual loss in Area(%)	No. of glaciers monitored	Mean annual loss in Area (%)
Chandra	6	116	0.51	3	0.23
Bhaga	3.27	111	0.77	10	0.19
Parbati	5.48	90	0.51	10	0.83
Warwan	3.2	230	0.46	180	0.17
Bhut	3.14	143	0.18	28	0.46
Alaknanda	3.82	274	0.33	119	0.67
Bhagirathi	6.5	183	0.26	153	0.11
Dhauliganga	4.125	104	0.37	-	-
Gauriganga	9.38	-	-	29	0.27
Suru	2.65	215	0.49	355	0.82
Zanskar	1.75	631	0.38	463	1.80
Spiti	1.41	337	0.41	722	2.23
Tista	9	-	-	34	0.07
Nubra	37	31	0.15	84	0.00

Table 2. Mean annual loss/gain in the glaciated area in each basin: based on SOI maps and satellite images.

Advance/retreat of glaciers has been monitored in fourteen sub-basins using multi-date data (Bahuguna *et al.* 2010). These basins are selected to represent all the climatic zones of the Himalayas. For long-term change monitoring, Survey of India (SOI) topographical maps of 1962 at 1:50,000 scales have been used as reference for glacial extent. Long-term (40 years) retreat/advance has been monitored using glacier boundaries from 1962 SOI topographical maps and the satellite data of the 2001-05 time frame. In some glaciers fragmentations have also been observed and therefore the numbers of glaciers in a specific range of area has also changed. Retreat/advance has also been computed based on glacier extent mapped from IRS data available from 2004 to 2007 and Landsat TM data of 1989-90 time frames. Results are given in table 2. The basins having larger sized glaciers, e.g. Nubra and Tista, have shown very less/negligible retreat whereas the basins having smaller sized glaciers, e.g. Spiti and Zanskar, have shown relatively higher retreat. Out of 2190 glaciers monitored for the period 1989-90 to 2004-07, 1673 glaciers have shown retreat, 158 glaciers have advanced, whereas 359 glaciers have shown no change (Table 3). Table 4 shows the details in terms of basins, number of glaciers monitored in each basin, years of monitoring and average loss in glacier area. On average, there is a loss of 3.75% of glaciated area. Figures 5, 6 and 7 show examples of retreating, static and advancing glaciers observed through the use of Landsat and IRS data. Millan glacier in Goriganga basin showed a retreat of 2.65 sq km during the period 1990-2005 (Fig. 5). The glacier shown in Figure 6 does not show any change in its snout position during the last nine years. The Kichik Kumdum glacier of the Shyok basin (Indus basin) has shown an increase of 1.94 sq km during the period 1989-2001 (Fig. 7). Figure 8 shows the rate of retreat for a few key glaciers of the Himalayan region. In order to validate the retreat/advance in the field, one glacier in each basin has been visited and the snout position has been measured using high-precision GPS.

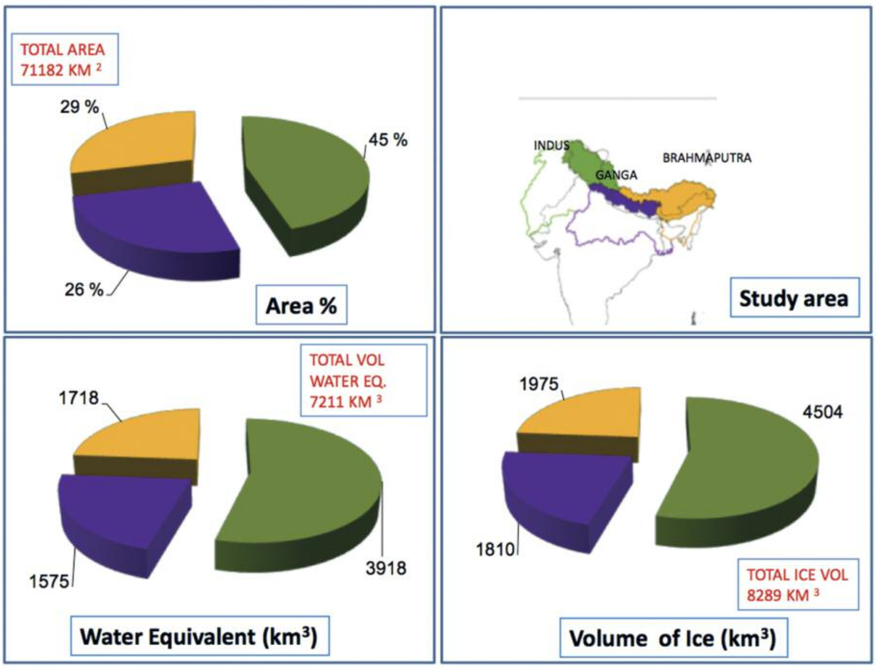
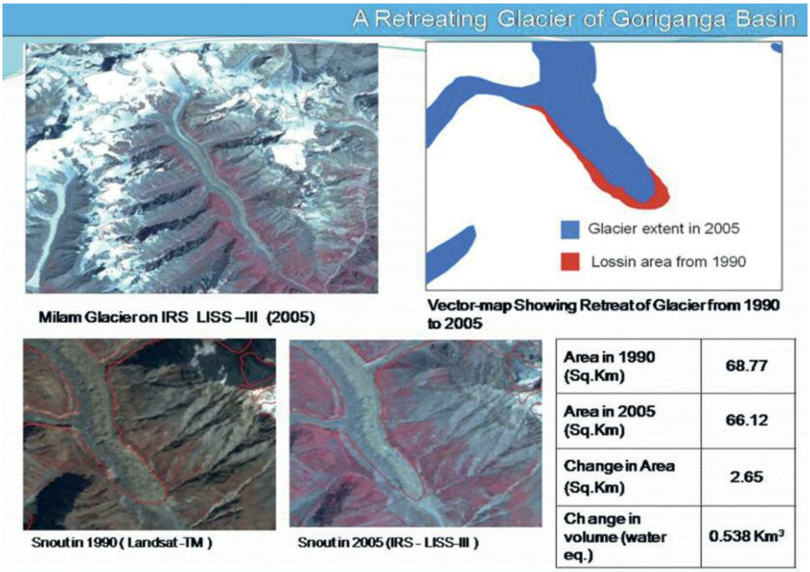


Figure 4. Indus, Ganga and Brahmaputra Basins Area & Volume Estimation.



Area in 1990 (Sq.Km)	68.77
Area in 2005 (Sq.Km)	66.12
Change in Area (Sq.Km)	2.65
Change in volume (water eq.)	0.538 Km^3

Figure 5. Retreat of the Milam glacier in the Goriganga basin of Uttarakhand.

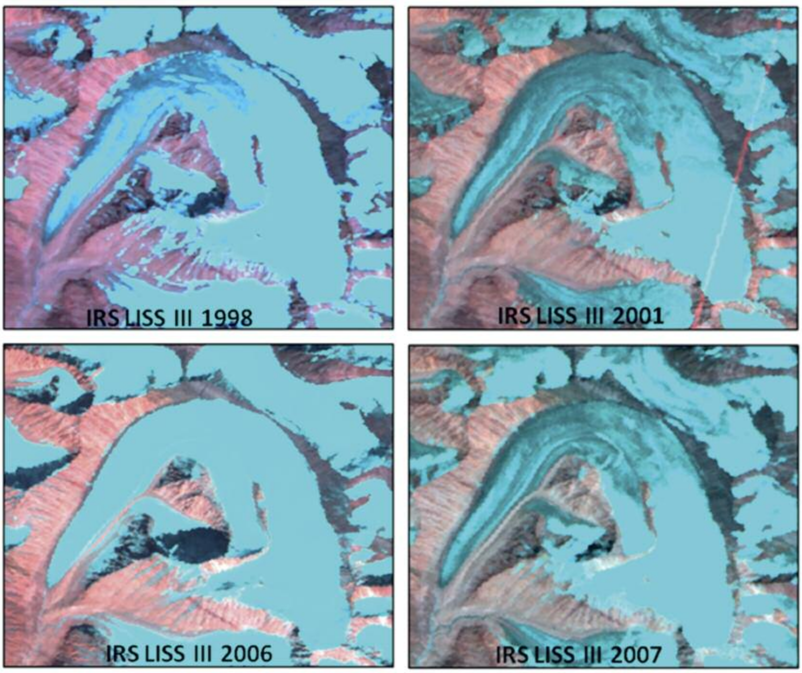


Figure 6. Glaciers showing no change (static) in the Chandra Basin.

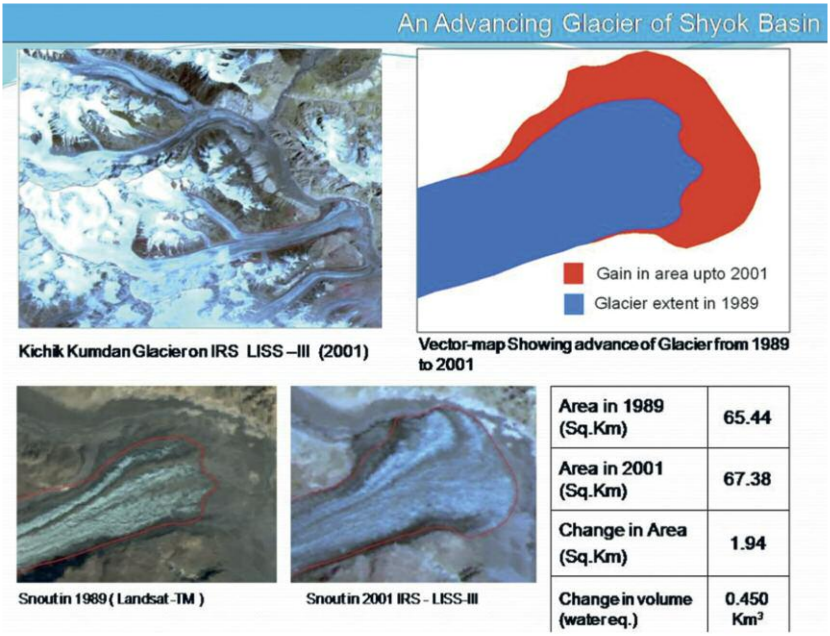


Figure 7. The Kumdum glacier of the Shyok basin (Indus) showing gain in area.

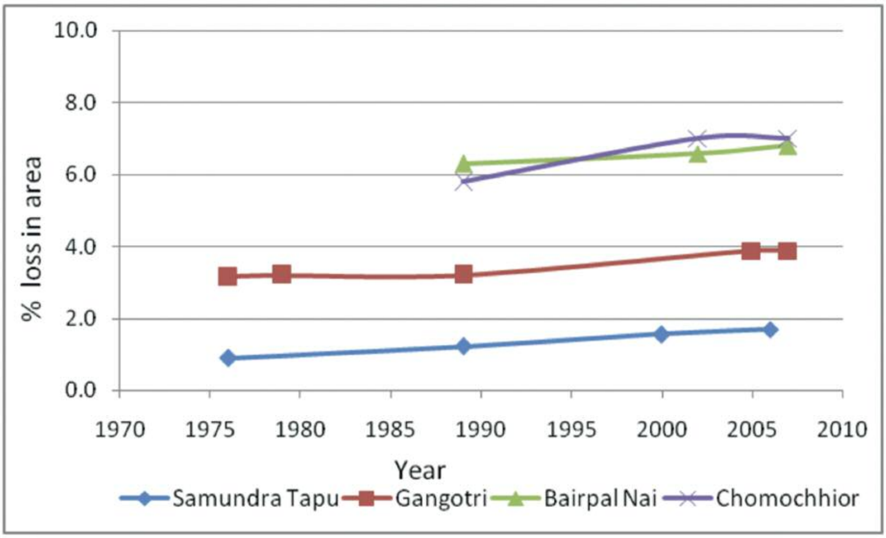


Figure 8. Percent loss in area of a few glaciers monitored using satellite images.

Basin	No.	Retreat	Advance	No change
Chandra	3	3	-	-
Bhaga	10	10	-	-
Warwan	180	32	-	148
Bhut	28	17	-	11
Alaknanda	119	119	-	-
Bhagirathi	153	44	6	103
Gauriganga	29	20	-	9
Suru	355	299	39	17
Zanskar	463	422	41	-
Parbati	10	10	-	-
Spiti	722	648	39	35
Tista	34	23	8	3
Nubra	84	26	25	33
Total	2190	1673 (76 %)	158 (7 %)	359 (17 %)

Table 3. Details on the number of glaciers showing advance, retreat and no change based on the satellite images of 1989-90 and 2004-07 timeframe.

Basin	No of Glaciers	Year	Area (sq km)	Year	Area (sq km)	Loss/ Gain %
Chandra	3	1989	107	2002	104	3
Bhaga	10	1990	90	2001	88	2
Warwan	180	2001	513	2007	510	1
Bhut	28	1989	217	2002	203	6
Alaknanda	119	1990	393	2005	355	10
Bhagirathi	153	1989	867	2005	851	1.8
Gauriganga	29	1990	272	2005	261	4
Suru	355	1990	506	2001	459	9
Parbati	10	1998	113	2004	107	5
Tisat	34	1990	305	2004	301	1
Zanskar	463	2001	775	2006	709	9
Spiti	722	2001	718	2007	622	13.4
Nubra	84	1989	3159	2001	3163	0.0013*
Total	2190					

* Shows increase in glaciated area. For all other basins there is decrease in the glacier area during the period of monitoring.

Table 4. Loss/gain in Area (sq km) of Glaciers in Different Basins based on Satellite Images.

5.2.1 Factors responsible for retreat of glaciers

In order to understand the factors responsible for retreat or advance, we have selected two sub-basins, namely, Warwan and Bhut from the Chenab basin. Though these two sub-basins are located in a similar climatic zone, the total loss in glaciated region has been found to be different in the two basins. Table 5 gives the salient characteristics of the glaciers in the Warwan and Bhut basins. The possible reasons for the difference in the loss in glaciated areas in the two basins is that the Warwan basin has a higher number of smaller sized glaciers (< 10 sq km) in comparison to the Bhut basin. The smaller size glaciers show more retreat in percentage compared to the large sized glaciers. The mean snout position in the Bhut basin is at higher altitudes compared to the mean snout positions of glaciers in the Warwan basin. The loss in glacial ice is less in glaciers which are located at higher altitude. The area above the equilibrium line (accumulation area) is larger for the Bhut basin compared to the Warwan basin. The debris-covered glaciated area is higher (30%) in the Bhut basin compared to the Warwan basin (18%). Debris covered glaciers show less retreat as the debris retards the melting of glacial ice. The Bhut sub-basin has experienced less retreat (9%) in comparison to the Warwan basin (19%) due to its higher debris cover. This study has led to the conclusion that the retreat of glaciers depends on the size of the glaciers, altitude of the snout, the debris cover, and the ratio of the accumulation area to the ablation area in addition to factors such as precipitation and temperature.

Various Categories	Warwan	Bhut
Above (accumulation area) equilibrium line altitude	48%	62 %
Mean Snout Altitude	4056	4145
Orientation of many Glaciers	North	South
Number of glaciers having area less than 10 sq km in	236	135
Debris cover	18 %	30 %
Loss in area	19 %	9 %

Table 5. Salient characteristics of glaciers in the Warwan and Bhut basins.

5.3 Glacier mass balance

Mass balance of a glacier is an important parameter required to understand the health of the glacier as well as availability of water over a long period of time. The mass balance of the glacier is usually referred to as the total loss or gain in glacier mass at the end of the hydrological year. Long-term estimates of glacier melt runoff are required, as more and more micro hydroelectric power stations are planned in the remote hilly regions of the Himalaya. Since some of these areas receive negligible monsoon rainfall, most of the runoff is due to either seasonal snow or glacier melts. Therefore, proper estimates regarding availability of water for long periods of time are required for planned development. In addition, glacial mass balance can also provide very vital clues for long-term climatic changes.

Mass balance is estimated by measuring the total accumulation of seasonal snow and ablation of snow and ice. 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 the accumulation and ablation area 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 changes 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 mass balance studies of a glacier, which have been used worldwide. One of the methods using satellite images is based on AAR (accumulation area ratio) approach. A relationship between AAR and mass balance is developed using field mass balance data (Kulkarni 1992). 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 computed. Multi temporal AWiFS data from IRS P-6 (Resourcesat-1) satellite has been used to delineate the snow line and its shift during the ablation season. Finally, the snow line at the end of ablation season (the equilibrium line) is delineated to compute AAR.

The computed AAR is used in the 'AAR – Mass balance model' to compute the yearly mass balance (SAC 2010). Figure 9 shows mass balance of glaciers for a few basins for the year 2005, 2006 and 2007. The AAR for most of the basins shows negative specific mass balance during the years 2005 to 2007. Figure 10 shows that mass balance for 700 glaciers in 10 basins, well distributed in the Himalayas, based on AAR approach. These glaciers are showing negative mass balance.

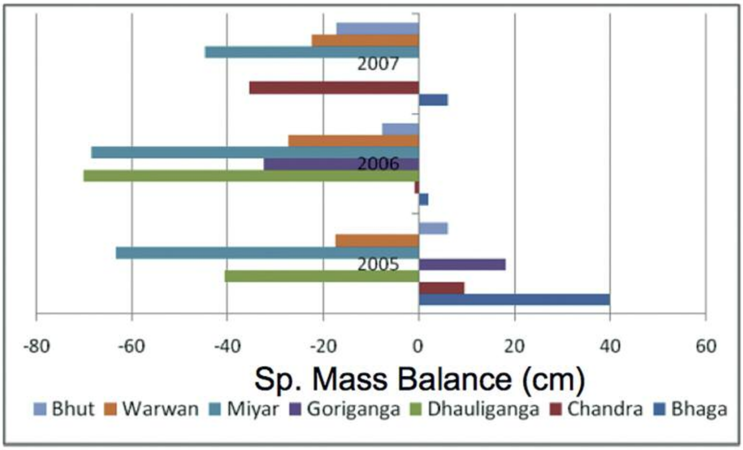


Figure 9. Basin wise specific mass for the year 2005-07.

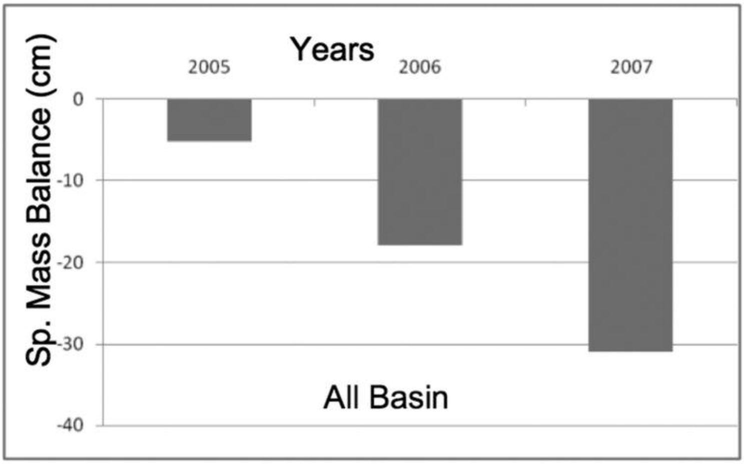


Figure 10. Specific mass showing a negative trend from 2005 to 2007.

5.4 Monitoring of snow cover

Studying the snow cover pattern over time is very important for computing the snowmelt runoff. Data from AWiFS sensor on board Resourcesat-1 satellite has been used to monitor seasonal snow cover of the Himalayas. Algorithm based on Normalized Difference Snow Index (NDSI) is used to map snow cover (Dozier 1984 and 1989; Kulkarni 2006). NDSI is calculated using the ratio of green (band 2) and SWIR (band 5) channel of AWiFS sensor (Ajai *et al*. 2011). Snow cover products from AWiFS/MODIS have been used to monitor the snow cover pattern in the Himalayas and Tibet.

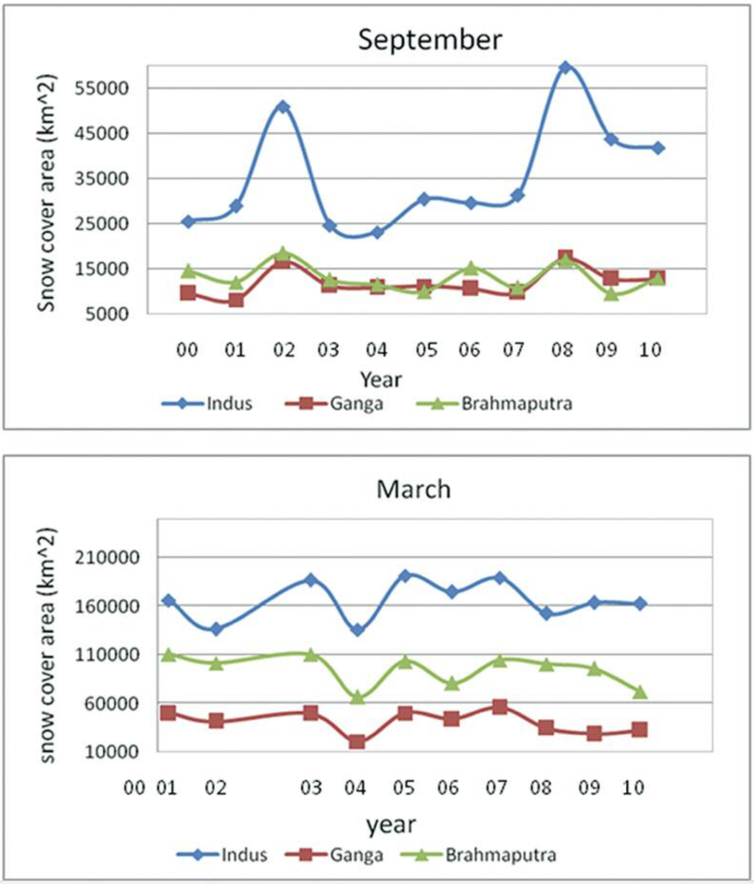


Figure 11. Snow cover variability for three basins during the months of September and March (2000-2010).

The snow accumulation and ablation curves are different for these three basins, depending upon their locations and altitude distribution of the basin. Snow cover has been monitored over time for the Indus, Ganga and Brahmaputra basins. Detailed level monitoring of snow cover has also been done for a large number of sub-basins in the Himalayas. Snow cover for the months of September (end of ablations) and March (end of accumulation) for the Indus, Ganga and Brahmaputra basins from the year 2000 to 2010 are given in Fig. 11. The snow cover in the Indus basin is relatively higher as compared to the Ganga and Brahmaputra basins in both September and March. There is an increasing trend in the snow cover for the Indus basin in the month of September, whereas it does not show any trend for the Ganga and Brahmaputra basins. Snow cover has also been monitored for the Tibetan region during the period 2000–2010. Snow cover maps for Tibet are given in Fig. 12 and their temporal pattern during the past 10 years is given in Fig. 13.

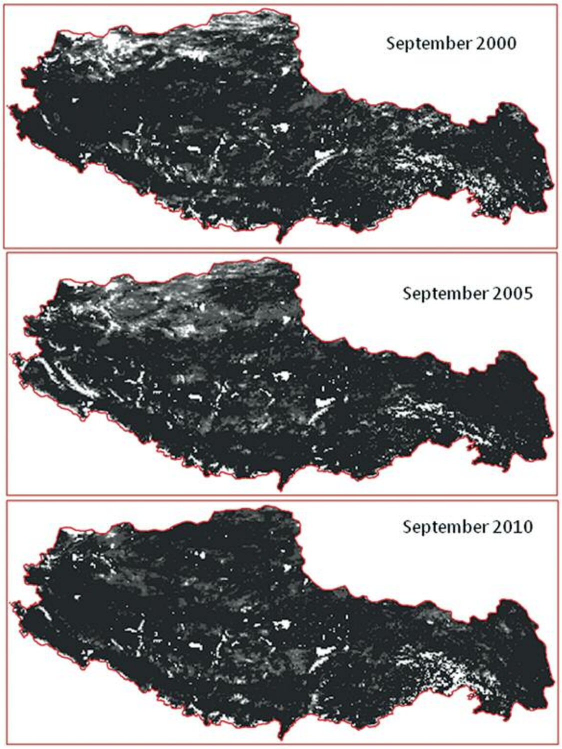


Figure 12. Snow cover during the month of September in the years 2000, 2005, 2010 for Tibet.

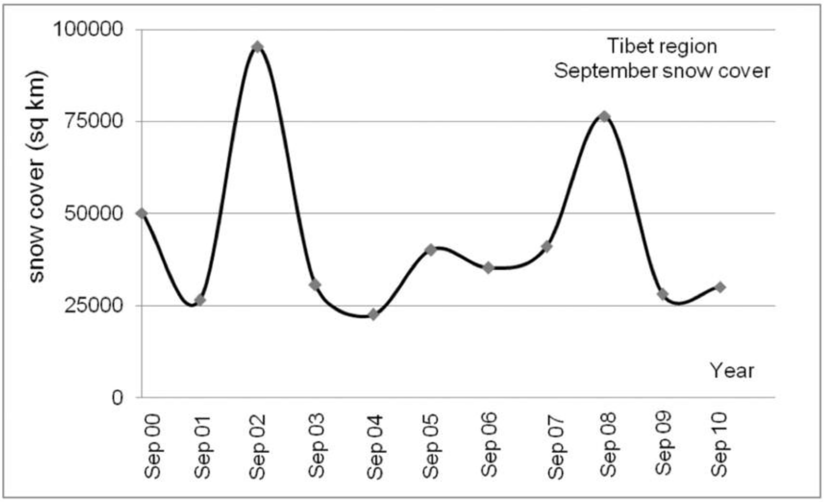
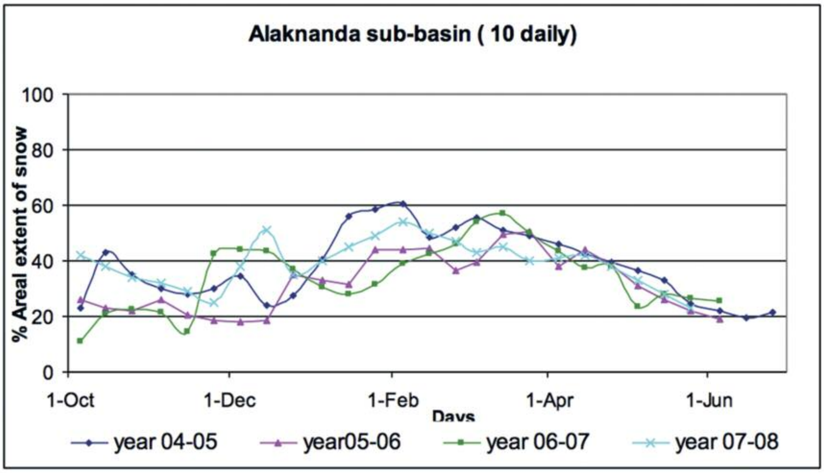
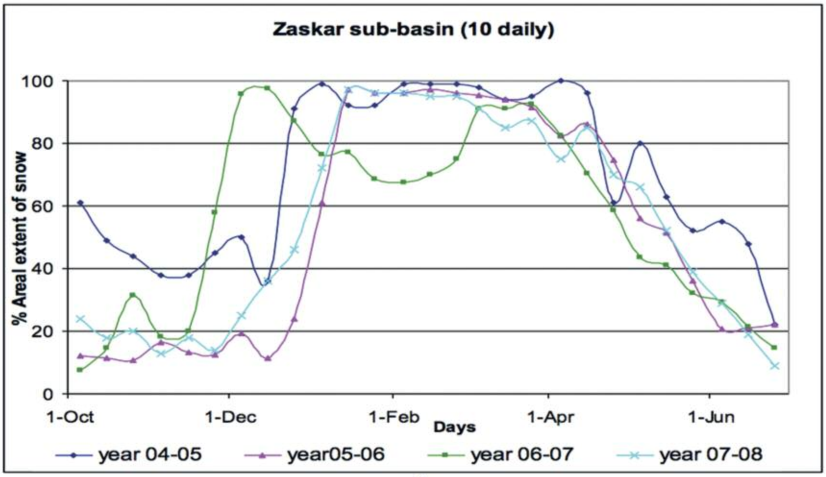


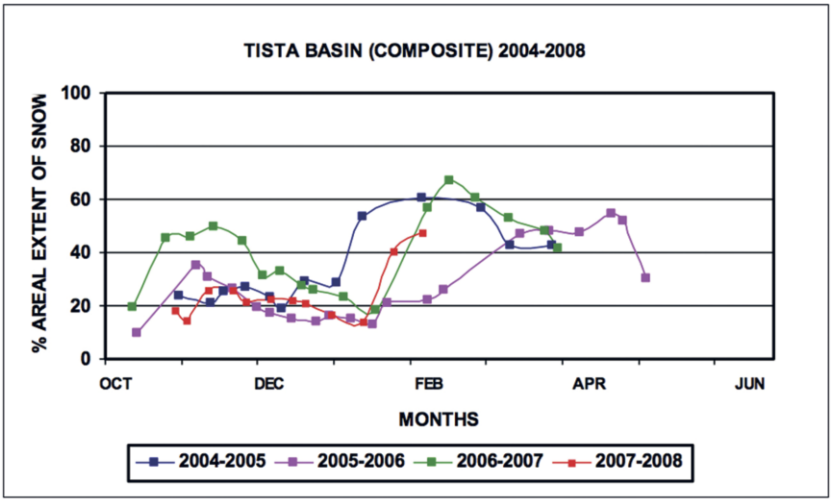
Figure 13. Temporal variation of snow cover in the month of September (end of ablation) for Tibet during 2000-2010.



a



b



c

Figure 14. Accumulation and ablation pattern of snow cover for the period 2004 to 08.

Figure 14 a, b, and c shows accumulation and ablation curves for three sub-basins, namely, the Alaknanda (Ganga basin), the Zanskar (Indus basin) and the Tista (Brahmaputra basin) which are located in different climatic zones. The curves indicate that although the pattern of accumulation and ablation in different years is not very different in each basin, it differs from one basin to the other. This information is highly useful to estimate snowmelt runoff in each basin. The pattern of the Tista basin is influenced by the southeastern monsoon.

5.5 Hydropower potential estimation

Electrification of rural areas in the Himalayas is difficult and expensive due to natural hazard in power transmission. Most of the power requirement can be met by generating it locally, which will also help in rural employment and contribute in the overall development of the region. By considering these aspects, various state governments are planning to develop micro and mini hydroelectric power stations in the Himalayan region. A snow and glacier melt runoff model has been developed to estimate the hydropower potential of snow and glaciated stream for winter, summer, monsoon and autumn seasons. Information generated through remote sensing techniques such as glacier extent, permanent snow cover, seasonal snow cover, accumulation and ablation areas, altitude of snow and glaciers were used in conjunction with daily maximum and minimum temperature and rainfall to compute the runoff.

The general structure of the model to estimate average seasonal runoff is given below. The model for estimating seasonal snow and glacier melt runoff needs remote sensing input in the form of snow and glacial extent and its altitude distribution (Kulkarni *et al.*, 1995).

$$Q = C_1 \{a (T \star G)\} + C_2 (P \star B) + C_3 \{(S \star W) - (M \star Sw)\}$$

Where,

Q = Average seasonal runoff (m^3/s),
C_1 = Runoff coefficient for glaciated region,
C_2 = Runoff coefficient for non-snow and non-glaciated area,
C_3 = Runoff coefficient for seasonal snow covered areas,
a = Melt factor (cm $°C^{-1}d^{-1}$),
T = Average seasonal degree days (°C),
G = Extent of glaciers, permanent and seasonal snow (m^2),
S = Area of seasonal snow (m^2),
W = Water equivalent of average winter snow-fall (m),

M = Winter snow melt (m),
Sw = Snow cover in winter (m^2),
P = Average seasonal rainfall (m),
B = Basin area without snow/glacial cover (m^2).

Runoff is used to assess hydropower potential. There are many hydropower projects in the Himalayan region for tapping hydropower. Figure 15 shows the spatial locations of hydropower stations superimposed on the AWiFS image. The glaciated regions are also seen the image. Table 6 gives the details of hydropower stations in various river sub-basins in Himachal Pradesh.

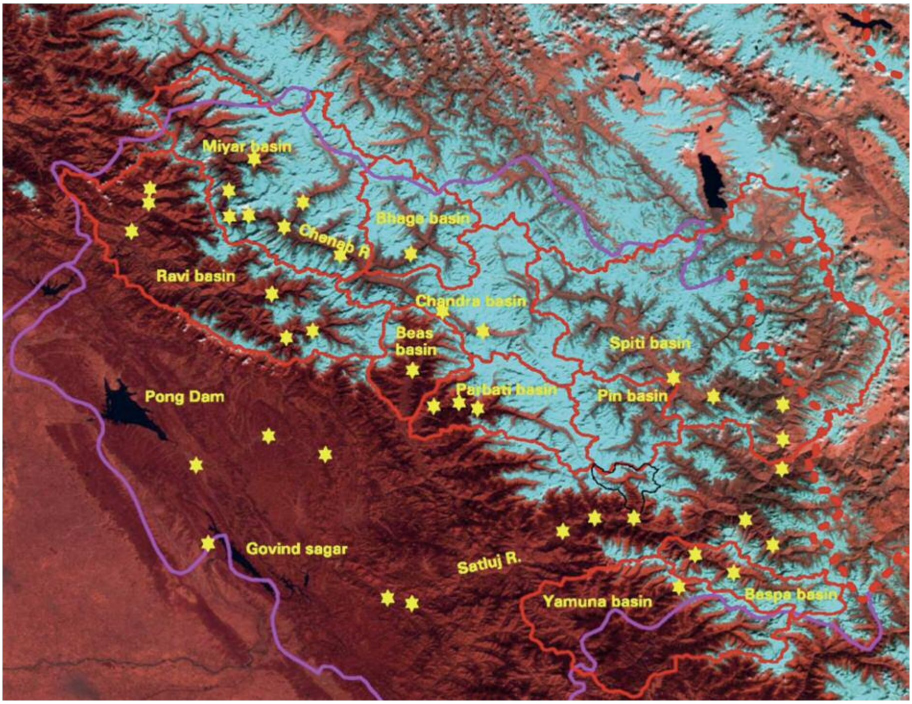


Figure 15. Image showing location of Hydropower projects in parts of Himachal Pradesh.

Basin	No. of Hydro-power station	Power potential MW
Yamuna	14	645
Satluj	47	9731
Beas	35	4458
Ravi	27	2356
Chenab	27	2956
Total	150	20146

Table 6. Dependence of Hydropower projects on snow and glaciated basins in Himachal Pradesh.

5.6 Moraine-dammed lakes of various river sub-basins

Various types of lakes are found in the glacial environment which are fed by melt of snow and glaciers in high altitude regions. In the snow and glaciated regions of Himalayas five major types of lakes can be recognized on the surface: lakes which occur (i) in natural depressions of mountainous terrain and are by fed by snow-melt (ii) in the peri-glacial area, (iii) on the surface of the glacier, (iv) at the terminus of the glacier due to damming by the moraines and (v) due to the obstruction of glacier melt of a tributary glacier by glacier ice of main glacier. Sometimes lakes are also formed in natural depressions that get melt from snow and glacier ice through underground movement of water. These lakes are located at such an altitude where there is no human activity and as a result growth or decay of such glacial lakes and dangers arising out of it do not come in the purview of human eyes. It is the availability of images from low earth orbiting satellites, which has revealed the occurrence of a large number of such lakes occurring in glaciated terrains. Among all these lakes, Moraine-dammed lakes (MDL) are vital to mankind as glacial lakes outburst floods (GLOFs) caused by this category of lakes are a common phenomenon in the glaciated terrain of the world. These floods can cause extensive damage to the natural environment and human property as they can drain extremely rapidly and a relatively small lake can cause dramatic floods.

MDL is an indicator of the assessment of climatic variations as the expansion or reduction of these lakes can be attributed to the rate of glacier melting at the snout. Since many of the Himalayan glaciers are moraine-covered and when debris-covered glaciers melt rapidly, a lot of debris accumulates near the snout, which can give rise to the formation of newer lakes. An inventory of moraine-dam lakes covering a large part of the Himalayas has been carried out using satellite images.

6. Conclusions and future scope

Inventory and monitoring of the Himalayan-Tibetan cryosphere has been carried out using satellite data. Inventory of the glaciers of the Himalayas (Indus, Ganga and Brahmaputra basins) has been done on 1:50,000 scale using Resourcesat 1 satellite data of 2004-07 time period. The total number of glaciers in these three basins put together is 32392, covering an area of 71182.08 sq km. About 60% of the glaciated area in the ablation zone is covered with debris, which makes these glaciers protected from faster melting due to solar radiation. 2190 glaciers, well distributed in different climatic zones of the Himalaya, have been monitored for the period 1989-90 to 2004-07. While 76 percent of the glaciers have shown retreat, 7% have advanced and 17% have shown no change. Average retreat has been 3.75% in area. The mass balance of about 700 glaciers has been monitored based on AAR approach.

Seasonal snow cover has been monitored for the Indus, Ganga and the Brahmaputra basins for the period 2000-2010. The Indus basin has shown an increasing trend in the snow cover for the month of September (end of the ablation) during the above period. However the other two basins did not show any trend in the snow cover shape. Snow cover has also been monitored for the entire Tibetan region for the period 2000 – 2010. It has not shown any trend in the snow cover pattern during the last ten years.

Monitoring of Himalayan glaciers needs to be continued as they are important: i) source of fresh water for human consumption and irrigation; ii) source of energy (hydro power), iii) regulate the climate and iv) are critical indicators of climate change.

The changing climate/global warming may accelerate the process of melting of the Himalayan glaciers which may lead to over all change in the hydrology and there by the runoff and sedimentation. This may lead to flooding as well change in the ecological conditions at many places including the important ecosystems such as the Sunderbans. The large influx of fresh water to the ocean may also change its salinity and may lead to change in the biogeochemistry of the ocean. The changing biogeochemistry will have larger implications on the marine productivity and carbon cycle.

Apart from the inventory and monitoring of cryosphere, there is a need to develop techniques/model to find out the thickness of glaciers and snow.

Development of model for ice thickness estimation will require systematic field experimentation. The following important issues related to Himalayan glaciers needs to be studied in future:

- Effect of carbon soot and contamination on snow and glacier ice
- Effect of debris cover on glacier ice-melt
- Use of Hyperspectral data in snow pack characterization
- Use of SAR interferometry and photogrammetry in glacier flow determination and glacier mass balance
- Development of algorithm for auto extraction of debris cover on glaciers and moraine-dammed lakes
- Development of method for auto extraction of glacier features.

Acknowledgement

We acknowledge with thanks the discussions and help by Dr. I.M. Bahuguna, Mr. A.K. Sharma, Mr. S.K. Singh and Mr. B.P. Rathore, Scientists at the Space Applications Centre, Ahmedabad in preparation of the present paper. The authors are thankful to Dr. Shailesh Naik, Secretary, Ministry of Earth Sciences, Govt. of India and Dr. A.V. Kulkarni for their contributions and fruitful discussions. We are also thankful to all the collaborating organizations who have contributed along with SAC 'Snow and Glacier' scientific team in carrying out experiments and data analysis.

References

Ajai *et al.* 2011, Snow and glaciers of the Himalayas. Published by Space Applications Centre, (ISRO), Ahmedabad India. Also available on www.moef.nic.in

Bahuguna, I.M., Rathore, B.P., Anish Mohan, Kulkarni. A.V., and Ajai, 2010, Glacier cover change; a critical parameter for climate change studies, NNRMS Bulletin, NNRMS (B)-35.

Benn, D.I., and Evans, D.J.A., 2010, Glaciers and glaciation, 2nd edition, Hodder Education, London, 795p.

Chaohai, L. and Sharma, C.K. 1988, Report on first expedition to glaciers in the Pumqu (Arun) and Poiqu (Bhote – Sun Kosi) river basins, Xi-Zang (Tibet) China. Science Press, Beijing, China, p. 192.

Dozier, J. 1984. Snow reflectance from Landsat-4 Thematic mapper IEE Trans Geoscience and Rem. Sens. 22 (3), 328-328.

Dozier, J. 1989. Spectral signature of Alpine snow cover from the Landsat Thematic mapper data. Remote Sens. Env. 28, 9-22.

Discussion Paper II, 2011, Snow and glaciers of Himalaya; Inventory and Monitoring, Prepared by Space Applications Centre, ISRO, Ahmedabad and Ministry of Environment and Forest, Govt. of India, New Delhi. Available at www.moef.nic.in

Kulkarni, A.V., Singh S.K., Mathur P. and Mishra V.D. 2006. Algorithm to monitor snow cover using AWiFS data of Resourcesat for the Himalayan region. Int. J. Rem. Sens. 27 (12): 2449-2457.

Kulkarni, A.V., Philip G., Thakur V.C., Sood R.K., Randhawa S.S. and Ram Chandra, 1999, Glacial inventory of the Satluj Basin using remote sensing technique, Himalayan Geology Vol. 20(2), pp. 45-52.

Kulkarni, A.V. 1992, Glacier inventory in the Himalaya, Natural resources management- a new perspective, NNRMS-Bangalore publication pp. 474-478.

Kulkarni A.V. 1992, Mass balance of Himalayan glaciers using AAR and ELA methods, Journal of Glaciology, 38(128), 101-104.

Kulkarni, A.V., Randhawa, S.S., Rathore, B.P., Bahuguna, I.M., and Sood, R.K., 2002, Journal of Indian Society of remote sensing, 30; 211-228.

Kumar, Rakesh, Sing R.D. and Sharma K.D., 2005, Water Resources of India, current science, 89(5), 794-811.

Rao, K.L., 1979, India's water wealth, Orient Longman limited, New Delhi.

Rees, W.G., 2006, Remote Sensing of Snow & ice, Taylor of Francis, London, 435p.

Sharma, A.K., Singh S.K., Kulkarni A.V. and Ajai 2011. Glacier Inventory of the Himalayas. Communicated to Current Science.

Singh, D., Jani S.K. & Kumar, N. (1997), Snow & glacier melt runoff contribution in the Chenab river at Akhnoor, Mountain Research Development Vo. 17, pp. 49-56.