Monitoring Himalayan cryosphere using remote sensing techniques

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Abstract | In the Himalayas, large area is covered by glaciers, seasonal snow and changes in its extent can influence availability of water in the Himalayan Rivers. In this paper, changes in glacial extent, glacial mass balance and seasonal snow cover have been discussed. Field and satellite based investigations suggest, most of the Himalayan glaciers are retreating though the rate of retreat is varying from glacier to glacier, ranging from few meters to almost 50 meters per year, depending upon the numerous glacial, terrain and meteorological parameters. Retreat was estimated for 1868 glaciers in eleven basins distributed across the Indian Himalaya since 1962 to 2001/02. Estimates show an overall reduction in glacier area from 6332 to 5329 sq km, an overall deglaciation of 16 percent. Snow line at the end of ablation season on the Chhota Shigri glacier suggests a change in altitude from 4900 to 5200 m from late 1970's to the present. Seasonal snow cover monitoring of the Himalaya has shown large amounts of snow cover depletion in early part of winter, i.e. from October to December. For many basins located in lower altitude and in south of Pir Panjal range, snow ablation was observed through out the winter season. In addition, average stream runoff of the Baspa basin during the month of December shows an increase by 75 per cent. This combination of glacial retreat, negative mass balance, early melting of seasonal snow cover and winter time increase in stream runoff suggest an influence of climate change on the Himalayan cryosphere.

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1. Introduction

The Himalaya has one of the largest concentrations of glaciers and large area of the Himalayan range is also covered by snow during winter. Many Himalayan rivers including Indus, Ganga and Bramhputra and their numerous tributaries originate from the snow and glacier bound regions. Melt water from snow and glaciers make these Himalayan rivers perennial, and has helped to sustain and flourish several Indian civilizations along the banks of these rivers for ages. However, this source of water ought not be considered permanent, as geological history of the Earth suggests constant variations in glacial extent due to climate. Moreover, natural changes in the Earth's climate would have altered due to greenhouse effect caused by man-made changes in the Earth's environment. Some of the hypotheses suggest the alteration to have started long before the beginning of Industrial revolution (Ruddiman, 2005). Invention of agriculture about 11,000 years ago may be attributed to large-scale deforestation and rice cultivation. However, this pace of change might have been accelerated from the beginning of industrial revolution leading to an increase in average global temperature by 0.6 ± 0.2 °C from 1900 (Lozan, et. al., 2001). In addition, recent development in climate modeling suggest that existing green house gases and aerosols in the atmosphere have caused absorption of 0.85 ± 0.15 W/m^2 more energy by the Earth than that emitted into space. This would mean an additional global warming of about 0.6 °C without further change in atmospheric composition (Hansen, et. al., 2005). This observation was further supported by the Fourth Assessment Report published by Intergovernmental Panel on Climate Change (IPCC) in 2007, where a warming of 0.2 °C per decade was projected for the next two decades, provided the concentration of all greenhouse gases and aerosols remains constant as of the year 2000. In addition, best estimates of globally average surface air warming for different warming scenarios vary between 1.8 and 4.0 °C (IPCC, 2007). This would have profound effect on the Himalayan cryosphere. However, Himalayan region is highly rugged and detailed information is available only for a few glaciers. Therefore, numerous predictions were made based on limited data and it has created significant confusion in the scientific community and public in general. To overcome this limitation, remote sensing techniques can play a very important role in monitoring Himalayan snow and glaciers (Kulkarni, 1992, Kulkarni et al., 2007). In this paper data generated using remote sensing techniques is discussed in order to understand the state of Himalayan cryosphere.

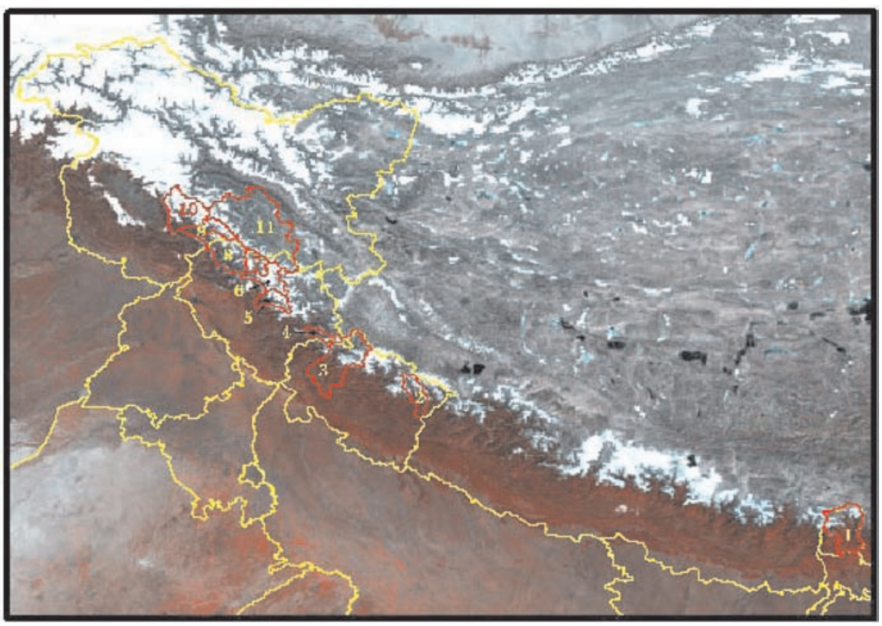
2. Methodology

2.1. *Methodology for glacier retreat*

To estimate long term retreat, topographic maps and imageries of LISS-III sensor of Indian Remote Sensing Satellite (IRS) was used. Topographic maps were prepared using aerial photographs and field survey of 1962. LISS-III images of 2001/2/4 were used. Retreat was estimated for 1925 glaciers distributed in eleven Himalayan sub-basins (Figure 1). The glaciers were selected based on similarity of their geomorphologic features in topographic maps and satellite images. Glacial extents of 1962 for Baspa basin and 1969 for Tista Basin were estimated from topographic maps, to assess error, the areal extent was compared with inventory data published by the Geological Survey of India (GSI) (Kaul et al., 1999). GSI inventory was prepared using topographic maps, aerial photographs and limited field investigations. To estimate short term retreat satellite data LISS-IV, Pan and LISS-III sensors of the IRS satellite were used (Kulkarni et al., 2009).

Identification and mapping of glacier boundary and terminus on satellite imagery is one of the important aspects of retreat estimation. Field investigations of numerous glaciers such as Samudra Tapu, Patsio, Chhota Shigri and the Gangotri glaciers were carried out to understand reflectance characteristics of glacier features, geomorphology

Figure 1: Locations of basins used to monitor snow cover and estimate glacier retreat. 1 Tista, 2 Goriganga, 3. Bhagrathi, 4 Baspa, 5 Parbati, 6 Chandra, 7 Bhaga, 8 Miyar, 9 Bhut, 10 Warwan, 11 Zanskar.



around glacier terminii and the debris cover on glaciers (Dhar et al., 2010; Singh, et al., 2010 and Kulkarni et al., 2005). The modern instruments like GPS, Laser Range finder, spectral radiometer and ground penetrating radars were used during the investigation. Even for glaciers that are not covered by debris, identification of snow, ice and rock on satellite images is possible owing to substantial differences in their spectral reflectance (Kulkarni, 2007). For glaciers covered by debris, numerous geomorphologic features can be utilized to identify their terminus. Moraine-dammed lakes often get formed downstream of glacial terminus, which can be easily identified on satellite images (Figure 2). Glacial terminus may also be characterized by steep ice wall. Based on illumination geometry, shadows are formed in the downstream direction, and this can be used as a marker for terminus delineation as well as to identify terminii of large glaciers like Gangotri (Bahuguna et. al., 2007).

2.2. *Methodology for glacier modeling*

To estimate future changes in the glacial extent, a model based on mass balance, depth and the rate of melting at snout of glacier can be used. The changes in glacial length has been estimated using following relationship (Paterson, 2002):

$$L_1 = L_o * db/b_t$$

where,

L_1 = Change in glacial length,

L_o = Present length of glacier,

db = Change in glacial mass balance and

b_t = Annual ablation at the glacier terminus.

Dynamic response time to changes in glacial length is estimated using following relationship (Johannesson et al. 1989):

$$T = h_{\max}/b_t$$

where,

T = Response time,

$h_{\max}$ = Maximum glacial depth and

b_t = Annual ablation at the glacier terminus.

The glacial depth was estimated using a relationship with areas, specifically developed for the Himalayan glaciers (Chaohai and Sharma, 1988),

$$H = -11.32 + 53.21F^{0.3}$$

where,

H = Mean glacier thickness (m) and

F = Glacier area (km^2).

The glacial mass balance was estimated using Accumulation Area Ratio, where accumulation area was measured by systematic analysis of weekly data of AWiFS sensor. The following relationship was used to estimate mass balance from AAR (Kulkarni, 1992; Kulkarni et al., 2004).

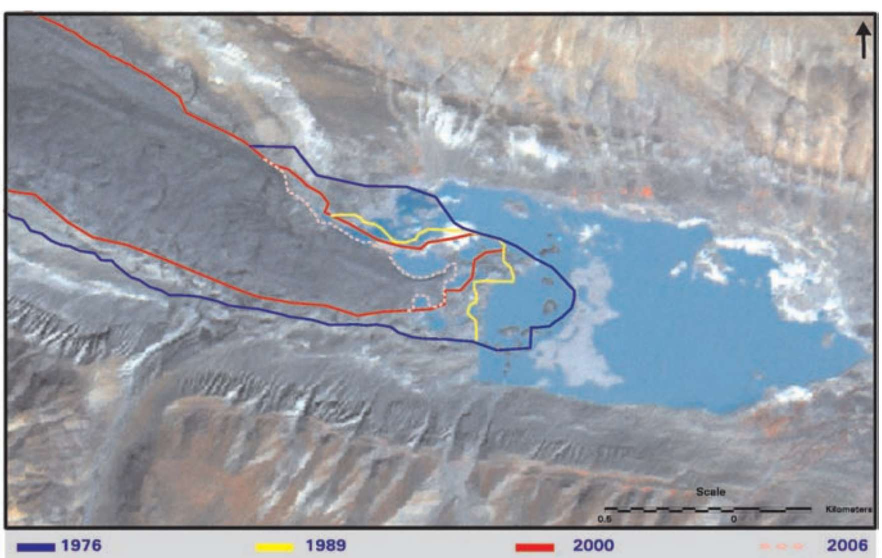
$$b = 243.01 * X - 120.187$$

where,

b = Specific mass balance in water equivalent (cm)

X = Accumulation Area Ratio.

Figure 2: Satellite imagery of IRS LISS-IV sensor of September 16, 2006 showing retreat of Samudra Tapu glacier, Himachal Pradesh, India from 1976.



2.3. *Methodology for snow cover monitoring*

To monitor seasonal snow cover, Advanced Wide Field Sensor (AWiFS) data of Indian Remote Sensing Satellite was used. Snow cover was monitored from October to June at 5 day interval from the years 2004/05 to 2007/08. Snow cover monitoring was suspended from July to September due to cloud cover during the monsoon season. Thirty sub-basins in Indus and Ganga river basins were monitored and approximately 1500 AWiFS scenes were analysed (Kulkarni et al., 2010). An algorithm based on normalized difference snow index (NDSI) was used to map snow cover (Kulkarni et al., 2006). The algorithm was validated using field and satellite data (Kulkarni et al., 2010). For a Beas basin, snow cover for the years 1997 to 2000–01 was monitored using WiFS data of IRS. Due to lack of SWIR band in WiFS data, NDSI method could not be used for snow cover monitoring. Due to long mountain shadows formed during winter, a combination of visual and unsupervised classification was used to monitor the snow cover (Kulkarni and Rathore, 2003). However, from March onward, higher solar elevation cause mountain shadows to become smaller in the Himalaya. Therefore, unsupervised classification alone was used to monitor the snow cover (Kulkarni and Rathore, 2003). The specifications of sensors used in the investigation are given in Table 1.

2.4. *Methodology for snow melt runoff modeling*

In order to estimate changes in stream runoff a snow and glacier melt runoff model was used (Kulkarni et al., 2002 and Rathore et al., 2009). A general structure of model to estimate the average seasonal runoff is given below. The snow and glacier melt was estimated using degree-day. The areal extent of snow and glaciers were estimated using remote sensing methods. The runoff was estimated using following relationship:

$$Q = c_1 * \{a(T*G)\} + (c_2 * P * B) + c_3\{(S*W) - (M*Sw)\}$$

where,

$Q =$ (Average seasonal runoff (m^3/s),
$C_1 =$ Runoff coefficient: 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/$^\circ C.d$),
$T =$ Average seasonal degree day ($^\circ C/d$),
$G =$ 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) and
$B =$ Basin area without snow/glacial cover (m^2).

2.5. *Methodology to monitor Moraine-dammed lakes*

Moraine-dammed lakes were monitored using satellite images of summer season of different years. The investigation was carried out at Lonak lake in Tista river basin, Sikkim.

3. Results and Discussions

3.1. *Glacier retreat*

To estimate glacial retreat investigations were carried out at eleven river basins in the Himalaya (Kulkarni et. al., 2009). Field investigations were carried out at Samudra Tapu glacier during 2004, 06 and 08 to monitor retreat (Kulkarni et al., 2006; Dhar et al., 2010). Field and satellite data suggest a loss of 58 ha glacial area within a period of 1976 to 2006, from an area of 72.41 sq km in 1976. Satellite imagery showing loss in glacier area and field photograph is given in Figure 2 and 3 respectively.

Basin-wise loss in glacier area is given in Table 2. Areal extents of 1868 glaciers were estimated and were found to be 6332 km^2 in 1962 and 5329 km^2 in 2001/04, an overall 16 percent deglaciation. In Tista basin glacier retreat was estimated using satellite imagery of 1997 and 2004 and overall loss of 2.7 % was observed. To assess the accuracy of topographic maps to delineate glacier area, areal extent of

Table 1: Characteristics of sensors used in the investigation

Sr. No.	Parameter	WiFS		AWiFS				LISS III				LISS IV		
1	Spatial Resolution	188 m		56 m				23.5 m				5.8 m		
2	Swath	810 km		740 km				141 km				24 km		
3	Bands (μm)	B2	B3	B2	B3	B4	B5	B2	B3	B4	B5	B2	B3	B4
		0.62 to 0.68	0.77 to 0.86	0.52 to 0.59	0.62 to 0.68	0.77 to 0.86	1.50 to 1.70	0.52 to 0.59	0.62 to 0.68	0.77 to 0.86	1.50 to 1.70	0.52 to 0.59	0.62 to 0.68	0.77 to 0.86

Figure 3: Field photographs showing retreat of Samudra Tapu glacier.

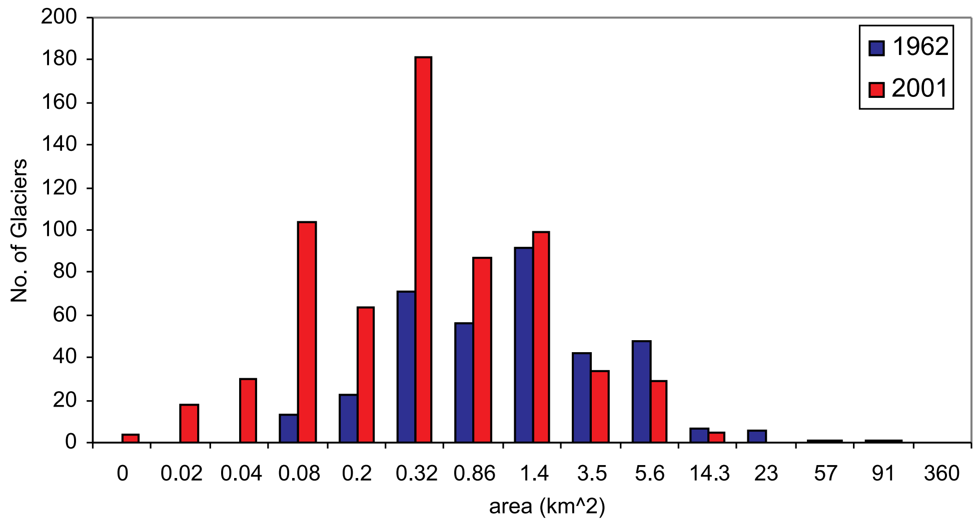
Table 2: Basin-wise loss in glacier area in Western Himalaya

Basin	No. of glaciers	Area 1962 (Km^2)	Area 2001/2004 (Km^2)	Loss in area (%)
Goriganga	41	335	269	19
Bhagirathi	212	1365	1178	14
Baspa	19	173	140	19
Parbati	90	493	390	20
Chandra	116	696	554	20
Bhaga	111	363	254	30
Miyar	166	568	523	08
Bhut	189	469	420	10
Warwan	253	847	672	21
Zanskar	671	1023	929	09
Total	1868	6332	5329	16

291 glaciers in the Baspa and Tista river basins were compared with inventory data published by Geological Survey of India (GSI) (Kaul et al., 1999). These glaciers were selected based on similarity of geomorphic features and the areal extent was estimated to be 854 sq km in topographic maps and 851 sq km by GSI. The difference is negligible and indication of utility of topographic maps for estimating long term glacier retreat, provided glaciers are selected carefully considering their geomorphology.

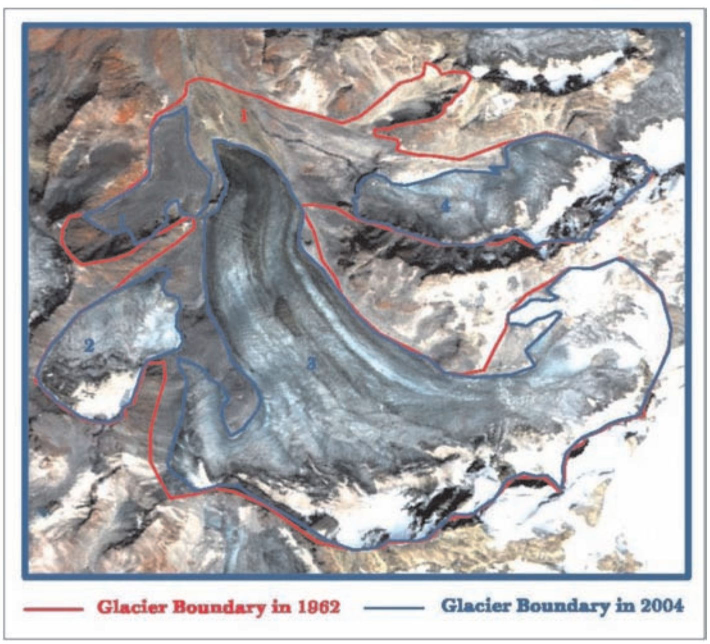
The amount of retreat varies from glacier to glacier and from basin to basin depending upon parameters such as maximum thickness, mass

Figure 4: Number of glaciers as a function of area for Chenab basin. Areal extent in bin increases by power of 2.



balance and rate of melting at terminus (Kulkarni et al., 2005). The data suggests that loss in glaciated area depends on areal extent of the glaciers (Table 2), possibly because glacier response time is directly proportional to thickness (Johannesson et al., 1989) and the thickness is directly proportional to its areal extent (Chaohai and Sharma, 1988). The amount of time take by a glacier to adjust to a change in its mass balance is known as response time. If maximum thickness of a glacier varies between 150 and 300 m then the response time for the temperate glaciers will be between 15 to 60 years (Paterson, 1998). In the Himalayas, if a glacier is not heavily covered by debris, its areal extent of glaciers is less than 1 km^2, and if rate of melting around snout is around 6 m/a and then model suggests a response time between 4 and 11 years. Therefore, if other parameters like debris cover, and mass balance are constant, then small glaciers are expected to adjust to climate changes faster. This phenomenon is now being observed in the Himalayan region, as glaciers smaller than 1 km^2 have been deglaciated by almost 28 % within a period between 1962 and 2001/04 (Table 3). On the other hand larger glaciers have shown only a 12 % loss in its area. Even though total glacial extent is reduced, the number of glaciers has increased. Number of glaciers as a function of area for Chenab basin is plotted in Figure 4. Mean of glacial extent reduced from 1.4 to 0.32 km^{2}between 1962 and 2001. In addition, with in the same period, the number of glaciers with higher areal extent have reduced and those with lower areal extent shown a rise. This glacial fragmentation can be clearly seen on satellite images (Figure 5).

Figure 5: Resourcesat imagery of LISS-IV sensor dated September 12, 2004 of glacier number 52E09027. The glacier is split into 4 glaciers between 1962 and 2004. However areal extent is reduced from 7.0 to 5.3 km^2.



Another factor which can influence glacier retreat is area-altitude distribution, since snow and ice ablation is influenced by altitude. In the Himalayas, snow line at the end of ablation season

Table 3: Changes in area extent of glaciers in Western Himalaya

Glacier Area (km^2)	Number of glaciers 1962	Glacier Area (km^2) 1962	Glacier Area (km^2) 2001	Change in %
<1	374	137	99	28
1–5	234	570	421	26
5–10	70	473	362	27
>10	99	1423	1251	12
Total	754	2604	2134	18

is approximately 5200 m (Kulkarni et. al., 2004). If larger part of the glacier area is below this altitude, then glacier will experience a negative mass balance and therefore influence retreat. For example, Parbati glacier has almost 96 % area below 5200 altitude mark, causing a negative mass balance. This is one of the fastest retreating glaciers in the Himalayan region (Kulkarni et. al., 2005). However, model based on parameters like mass balance, depth and rate of melting of snout for Parbati glacier suggest a reduction in glacier length by 1469 m for a period between 2001 and 2022 (Kulkarni et al., 2005). The total length of the glacier is 10,120 m and only small portion is expected be deglaciated. Parbati glacier is located in lowest altitude range and other Himalayan glaciers have higher area altitude distribution, and are therefore expected to show a much smaller retreat.

3.2. *Glacier mass balance*

Monitoring of seasonal snow line at the end of ablation season is highly sensitive to climate change and an also important indicator of climate change (Kulkarni et al., 2004). This can be influenced by the amount and timing of snow fall in winter and temperature during summer. The snow line was monitored on Chhota Shigri Glacier in Himachal Pradesh using satellite and field investigations from 1972, depending upon availability of satellite data (Kulkarni, 1994). The shift in snow line at the end of summer season was observed to be from 4900 m to 5200 m altitude from late 1970's to 2008 (Figure 6). If the altitude of snow line is considered to be 5200 m at the end of ablation season in the Chenab basin, then area altitude distribution at Warwan basin for 340 glaciers suggest a very small accumulation area (Figure 7). This would significantly affect future glacial distribution in Warwan basin, provided the snow fall pattern is not significantly affected.

To estimate glacial mass balance, a relationship between AAR and specific mass balance has been developed using field mass balance data of the Shaune and the Gor Garang glaciers, located in Baspa river basin (Kulkarni, 1992). Field data was taken from various reports of Geological Survey of India (Singh and Sangewar, 1989). Glacier area was estimated using IRS LISS-III (Table 1). Images of July September season (25 August 2001 and 11 September 2000) were selected because during this period snow cover is at its minimum and glaciers are generally fully exposed (Kulkarni and Alex 2003). Accumulation area for each glacier varies from year to year, depending upon the snow line at the end of ablation season. Snow lines on glaciers were monitored by systematically analyzing weekly data of WiFS and AWiFS sensor of IRS from May to October. It is ideally suited for snow cover monitoring due to 5-day repetitive coverage.

Figure 6: Snow line altitude at the end of ablation season on Chhota Shigri glacier, Himachal Pradesh.

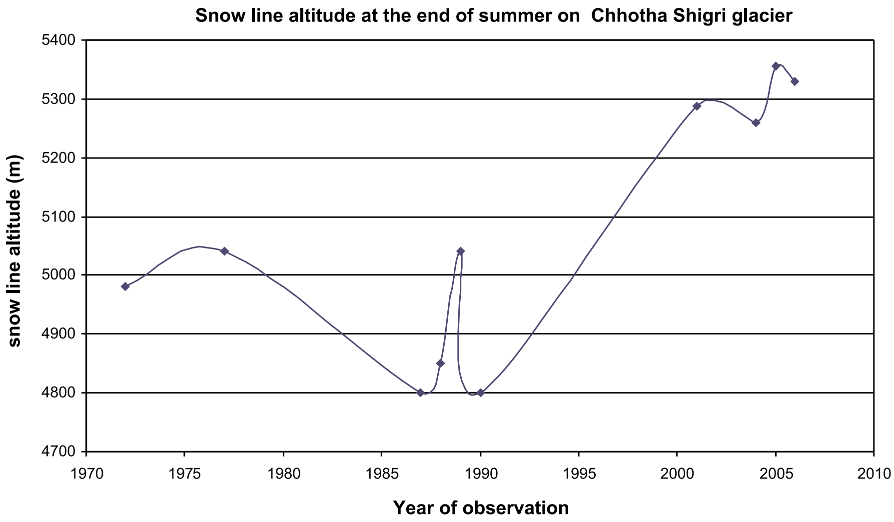
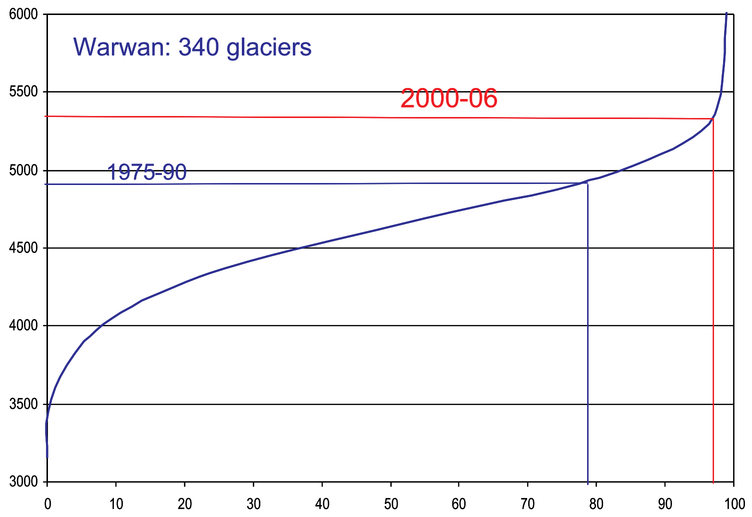


Figure 7: Area altitude distribution of 340 glaciers above 5200 m in Warwan basin, Jammu and Kashmir, India.



altitude distribution of glaciers also influences mass balance. As mid-altitude changes from 5000 to 5400 m, specific mass balance also change from −111 cm to −49 cm.

This investigation also showed four glaciers in the Baspa basin to have no accumulation area and average snow line altitude to be well above maximum glacial altitude. In addition, two glaciers had a very marginal accumulation area and their AAR to be less than 0.01. The location of these six glaciers is in the low altitude zone with average maximum altitude of 5266 m, almost 200 m less than mean snow line of the basin. Satellite data suggests excessive debris cover on these glaciers, which are likely to experience relatively less melting; however, due to lack of formation of new ice, these glaciers might experience a terminal retreat. The remaining glaciers are North facing, and therefore, have relatively lower snow line at the end of ablation season. In addition, average maximum altitude is relatively high, as these glaciers are located on northern slopes of Pir Panjal mountain Range. A combination of higher area-altitude distribution and lower snow line makes higher accumulation area ratio. The difference between average snow line of north and south facing glaciers was observed to be 160 m. Glaciers located on the northern slope in altitude region below 5170 m and 5330 m on southern slopes respectively have very little or no accumulation area and experience terminal retreat.

Mass balance was estimated for years 2001, 2002, 2004 and 2006 for 19 glaciers of the Baspa basin. AAR and specific mass balance was estimated for individual glacier. For each glacier, its specific mass balance value was multiplied to the area to obtain total loss or gain in glacial mass. Then mass balance of each glacier was added to assess total loss of glacial ice. Overall specific mass balance in hydrological years 2000–01, 2001–02, 2003–04 and 2005–06 were estimated to be −90, −78, −57, −50 cm respectively. Orientation of the glacier seems to have profound influence on snow line altitude. Average altitude of snowline at the end of ablation season is 5400 m for south and 5297 m for north facing glaciers. Area

3.3. *Monitoring of seasonal snow cover*

In the Beas basin, changes in snow melt pattern were studied from 1997 and 2008. A comparison was made for altitudes ranging between 3000 and 3600 m. Snow cover area was estimated

Figure 8: Snow cover depletion curve for altitude 3000–3600 m in the Beas basin, India.

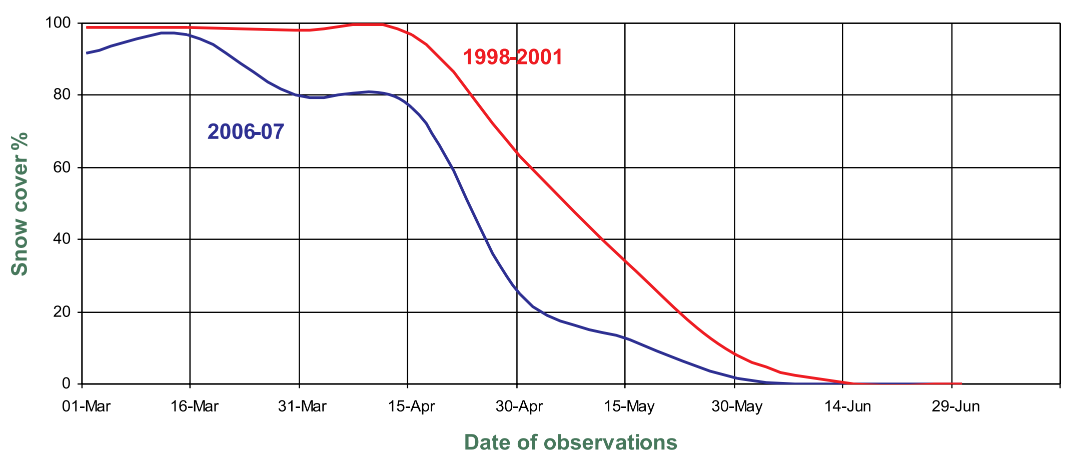


Figure 9: Snow accumulation and ablation curve of Bhaga basin.

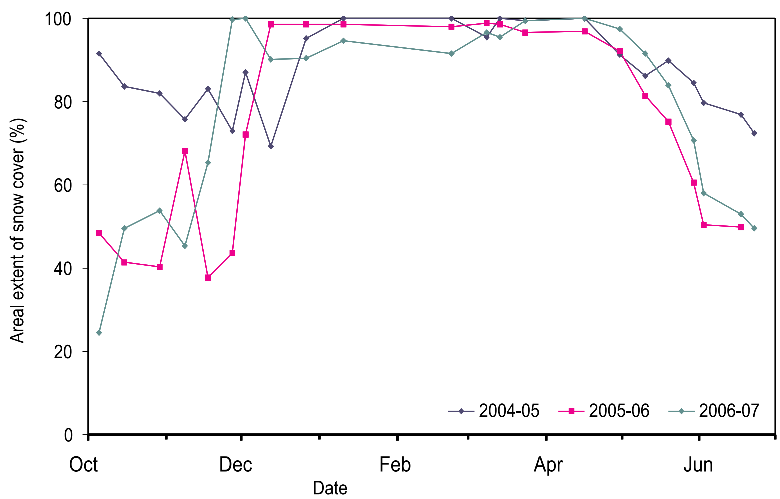
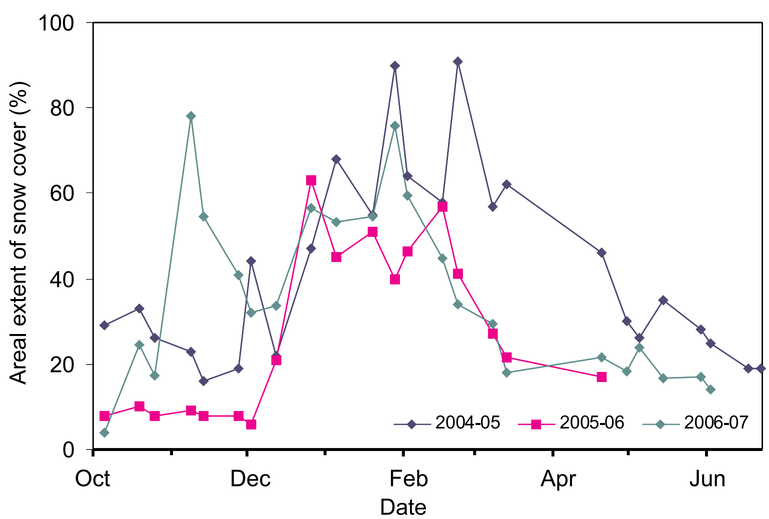


Figure 10: Snow accumulation and ablation curve of Ravi basin.



for years between 1997 and 2001 using WiFS data and between the years 2004 and 2008 using AWiFS data. Spatial resolution and methods of snow cover delineation was different for WiFS and AWiFS data. Large errors were observed in estimates during winter time when visual and supervised classification was used to analyse WiFS data. Therefore, data of snow covers from October to February of 1997 to 2001 was not used for comparative analysis. Snow cover data obtained after March from AWiFS and WiFS sensors are comparable due to shorter mountain shadows in the Himalayan region. The mean of snow cover values were estimated for the years 1998–99 and 2006–07 and is plotted in Figure 8. The data suggest that over a period of eight years snow cover depletion pattern has changed. In the year 2006–07, snow melt started early and snow depletion curve was observed to be steep, suggesting rapid melting of snow cover compared to the years 1998–99. However, further studies are required to understand significance of these observations.

Snow accumulation and ablation curves for Ravi and Bhaga basins are given in Figure 9, and Figure 10. Ravi basin is located in south and Bhaga in North of Pir Panjal range. In addition, Ravi basin is in the altitude range between 630 m to 5860 m, whereas Bhaga basin is in range between 2860 to 6352 m. Therefore these basins are located in different climatological zones. 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% suggesting depletion of snow cover in altitude range between 1800 and 3000 m. This is a significant reduction in snow extent in winter season. In Bhaga basin however no significant amount of melting was observed between January and April, melting was observed during the early part of winter, i.e., in the month of December (Kulkarni et al., 2010). In the Eastern Himalaya, snow cover monitoring was carried out in Tista river basin (Fig. 11). Data suggests accumulation of snow during North–East monsoon and winter-time. Winter time accumulation rather than monsoon time is major source of snow in this region.

This observation is consistent with earlier observations made in Baspa basin (Kulkarni and Alex, 2003). Baspa is also a high altitude basin located in Northern side of Pir Panjal range. Snow accumulation and ablation curve suggests that in early part of winter, i.e., from October to end December, a large amount of snow could melt. This observation is consistent with earlier observations made in year 2000 and 2001. Altitudes starting from 3000 to 4800 m 600 m interval were monitored. From November to February, snow retreat was observed in all altitude zones. Similar observations were also made in Beas basin (Kulkarni et al. 2002). However, this data is not long enough to assess long term changes in snow accumulation and ablation pattern of the Himalayan region. If snow ablation pattern is changing, then it is bound to have an influence of stream runoff of Baspa River. Average stream runoff of the Baspa basin for the month of December from 1966 to 1992 has gone up by 75 per cent (Kulkarni et. al., 2005). This is a substantial rise in stream runoff suggesting an influence of climate change on Himalayan cryosphere.

Figure 11: Snow accumulation and ablation curve of Tista basin.

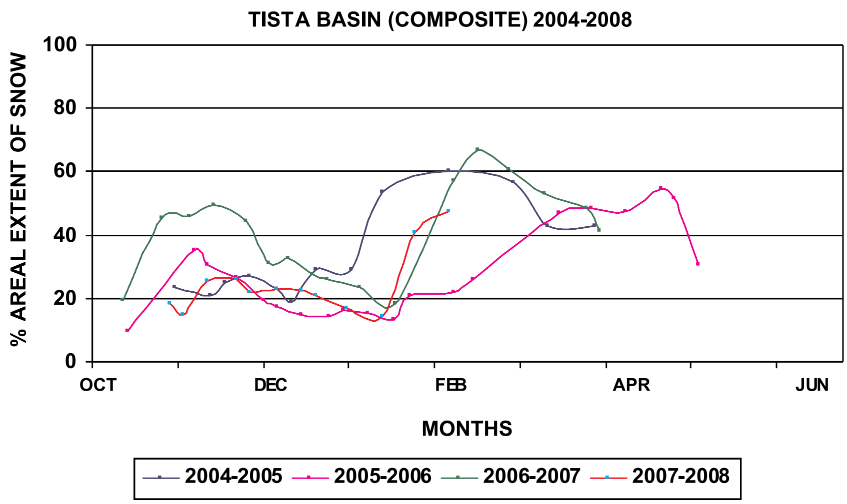
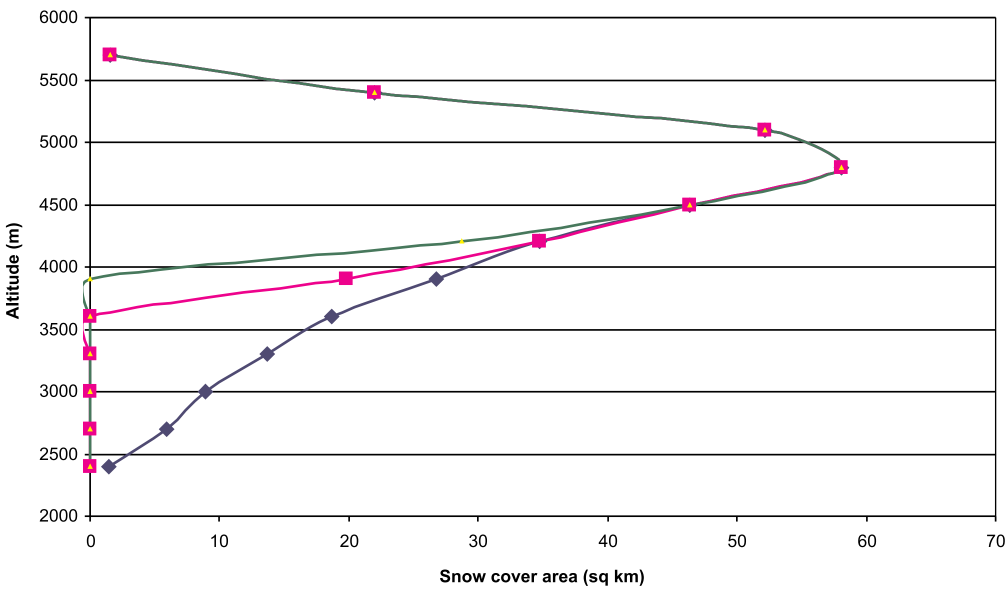


Figure 12: Changes in snow extent due to rise in temperature by 1°C. Red line suggest present and green line suggest future distribution of snow line.



3.4. *Estimation of future changes in stream runoff*

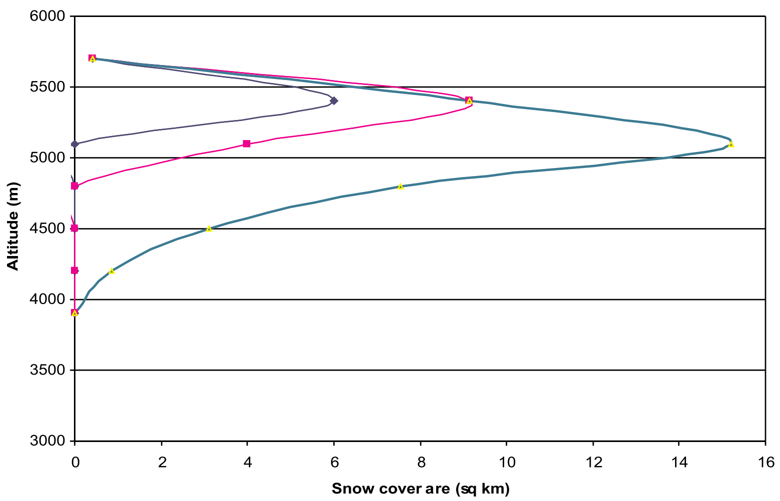
The stream runoff model was originally developed at Manala nala in Himachal Pradesh and validated at adjacent Tosh nala (Kulkarni et al., 2002). The model was applied at Wangar gad basin in Himachal Pradesh due to availability of long term stream runoff and power generation data. In the model, climatically sensitive parameters are snow, glacier extent and degree-days. In this analysis, the amount of snow fall and rainfall was kept constant.

To estimate changes in distribution of snow cover, initially monthly snow extent was estimated using IRS data. To estimate changes in snow line for year 2040, a lapse rate of 140 m was added in snow line altitude. The present and possible the changes in future distribution of snow cover is given in Figure 12. To estimate changes in glacial extent, mass balance due to rise in temperature was estimated. Mass balance was calculated using Accumulation area ratio (AAR) technique, depends

Table 4: Changes in glacier, snow extent and stream runoff at Wangar gad due to a rise in temperature by 1°C.

	Winter		Summer		Autumn		Monsoon	
	2004	2040	2004	2040	2004	2040	2004	2040
Snow extent (sq km)	234	209	117	111	147	128	26	21
Glacier extent (sq km)	40	16.4	40	16.4	40	16.4	40	16.4
Avg. snow line altitude (m)	3979	4140	4419	4588	4320	4488	4610	4778
Temp. index	0.0026	0.0023	0.016	0.016	0.0094	0.0088	0.028	0.027
Runoff (cumec)	4.10	3.33	15.97	14.62	9.65	7.67	22.45	16.14
Unrestricted Hydro power (Mw)	27.55	22.39	107.11	98.07	61.36	51.45	150.58	108.31

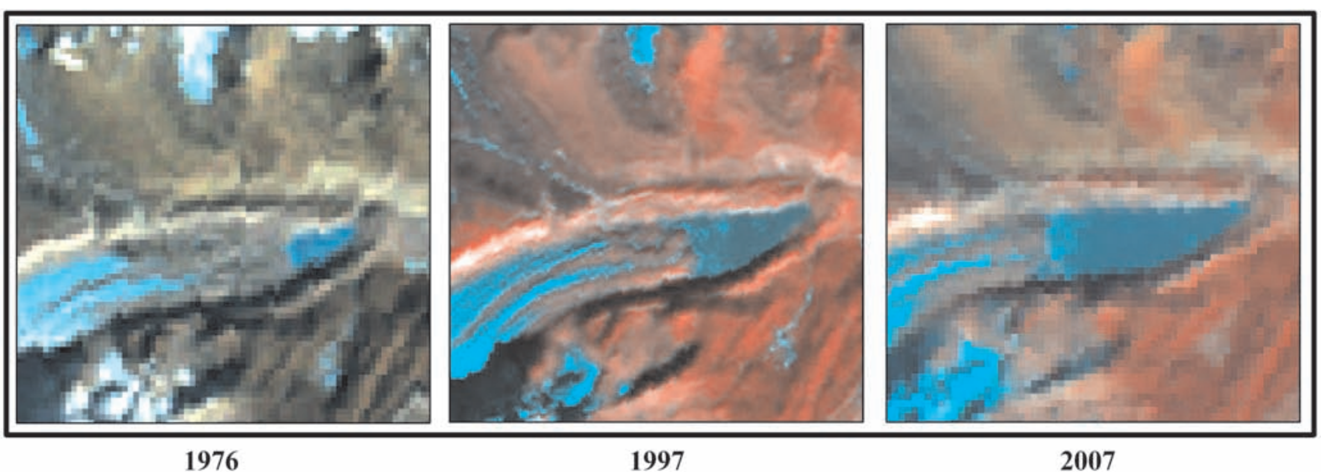
Figure 13: Changes in accumulation area of glacier due to rise in temperature by 1°C. Red line suggest present and blue line suggest future distribution of Accumulation area.



on the position of snow line at the end of ablation season. The future changes in snow line at the end of ablation season was estimated using 140 m lapse rate and changes in accumulation, and the ablation area of glaciers due to a rise in temperature by 1 degree C is give in Figure 13. The changes in model input parameters and stream runoff is given in Table 4 (Rathore et al, 2009).

However, change in runoff varies from season to season. Maximum drop in runoff was estimated for monsoon season. In the model, amount of monsoon rainfall for year 2004 and 2040 was identical. Model suggests that in the year 2004, glacier melt due to rain on glacier ice was an important source of stream runoff. During same period, areal extent of season snow was small and contribution of seasonal snow melt on stream runoff was less. Therefore, by year 2040, areal extent of glaciers wanted reduces by 59 percent, affecting stream runoff. On the other hand, less loss in stream runoff was estimated for summer season (Table 1). In summer, i.e. between April and June, contribution of glacier melt into runoff is not high and most of the runoff was generated from seasonal snow melt. Due to area altitude distribution

Figure 14: Changes in Lonak lake, Tista basin, Sikkim, India between 1976 and 2007.



of Wanger gad, no major change in seasonal snow extent is expected between year 2004 and 2040. Autumn shows 20 % loss in stream runoff, due to change in glacial extent.

3.5. *Monitoring of Moraine-dammed lakes*

Lonak Lake in the Tista river basin was monitored using multi year satellite data. The satellite data suggests increase in the area of Lonak lake from 23 ha to 110 ha from 1976 to 2007. This increase in lake area is caused due to retreat and melting of glacier terminus (Figure 14). The thermal influence of lake water can affect retreat of the glacier. In the Satluj and Chenab basins, 22 and 31 lakes were mapped, respectively (Randhawa et al., 2005).This could also be one of the important factors that influences glacier retreat.

4. Conclusions

The main components of cryosphere as glaciers, seasonal snow cover and moraine-dammed lakes are discussed in this paper. Numerous satellite sensors and field investigations were used to develop methodology and to assess results obtained from remote sensing technique. Loss in glacier area was estimated using high and medium resolution of satellite data and topographic maps of the Survey of India. In this investigation, glacial retreat was estimated for a total of 1868 glaciers in Chenab, Parbati and Baspa basins from 1962. Expeditions to Chhota Shigri, Patsio and Samudra Tapu glaciers in Chenab basin, Parbati glacier in Parbati basin and Shaune Garang glacier in Baspa basin were organized to identify and map glacial terminus. The investigation has shown an overall reduction in glacier area from 6332 sq km to 5329 sq km between 1962 and 2001/04, an overall deglaciation of 16 percent. However, the number of glaciers have increased due to fragmentation. Mean of glacial extent was reduced from 1.4 to 0.32 km^2 between 1962 and 2001. In addition, the number of glaciers with a higher areal extent has reduced and lower extent increased during the period. Small glaciarates and ice fields have shown extensive deglaciation. For example, 374 glaciarates and ice fields less than 1 km^2 have shown a retreat of 28 percent from 1962, possibly due to their small response time.

Another important parameter is the glacier mass balance. Glacier mass balance was estimated using Accumulation Area Ratio method. To estimate Accumulation area, snow line was monitored throughout the ablation season and position of snow line at the end of ablation season was taken to estimate AAR and mass balance. This investigation was done using WiFS and AWiFS sensors. These investigations suggest that the glaciers in Baspa basin are losing mass at the rate of −69 cm per year. However, the loss in mass is not reflected in loss in area, possibly due to heavy debris cover around glacier terminus.

To monitor seasonal snow cover, NDSI based algorithm was developed and snow cover was monitored for numerous basins in the Himalaya. During the early part of winter, i.e. from October to December end, a large amount of snow retreat was observed even for basins located in altitude ranges higher than 3000 m and average stream runoff of the Baspa basin for the month of December was recorded to have gone up by 75 per cent. In low altitude basins like Beas and Ravi, snow accumulation and ablation was observed through out the winter. This combination of glacial retreat, negative mass balance, early melting of seasonal snow cover and winter time increase in stream runoff suggest an influence of climate change on Himalayan Cryosphere.

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