Glacial retreat in Himalaya using Indian Remote Sensing satellite data

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The Himalayas possess one of the largest resources of snow and ice, which act as a huge freshwater reservoir. Monitoring the glaciers is important to assess the overall reservoir health. In this investigation, glacial retreat was estimated for 466 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 the glacial terminus. The investigation has shown an overall reduction in glacier area from 2077 sq. km in 1962 to 1628 sq. km at present, an overall deglaciation of 21%. However, the number of glaciers has increased due to fragmentation. Mean area of glacial extent has reduced from 1.4 to 0.32 sq. km between the 1962 and 2001. In addition, the number of glaciers with higher areal extent has reduced and lower areal extent has increased during the period. Small glaciarates and ice fields have shown extensive deglaciation. For example, 127 glaciarates and ice fields less than 1 sq. km have shown retreat of 38% from 1962, possibly due to small response time. This indicates that a combination of glacial fragmentation, higher retreat of small glaciers and climate change are influencing the sustainability of Himalayan glaciers.

Keywords: Glaciers, glaciarates, Himalayas, ice fields, retreat.

OVER the past three million years, the earth's surface has experienced repeated large periods of glaciation, separated by short warm interglacial periods. During the peak of glaciation approximately 47 million sq. km area was covered by glaciers, three times more than the present ice cover over the earth[1]. A number of ideas were proposed to explain repeated cycle of glaciations on the earth. One of the explanations is related to natural variation in the earth's orbit around the sun. These orbital cycles (100,000, 41,000 and 22,000 years) can cause 10% variation of incoming solar radiation in various parts of the globe[2]. These regular changes in the amount of sunlight reaching the surface of the earth might have produced repeated cycles of glacia-

tion. This can also produce asynchronous behaviour in the development of glacial extent in the northern and southern hemisphere. This aspect was extensively studied in tropical Andes; maximum extent of last glaciation was estimated[3] around 34,000 yrs BP before present and retreated by 21,000 yrs BP. This cycle of glaciation is different from that reported in the northern hemisphere, where the peak of the last glaciation was estimated approximately about 17,000 to 21,000 years ago[4].

Natural variations in the earth's orbit are well synchronized with atmospheric variations in methane and carbon dioxide, leading to repeated cycle of glaciations. However, this natural cycle might have altered due to the greenhouse effect caused by man-made changes in the earth's environment. Some of the hypotheses suggest this alteration might have started long before the beginning of the Industrial Revolution[2]. Invention of agriculture about 11,000 years ago might have led to large-scale deforestation and rice cultivation. However, this pace of change might have accelerated from the beginning of the Industrial Revolution. This has led to an increase[5] in global temperature by 0.6 ± 0.2°C from 1900. In addition, recent development in climate modelling suggests that the existing greenhouse gases and aerosols in the atmosphere have led to the absorption of 0.85 ± 0.15 W/sq.m more energy by the earth than that emitted to space. This means additional global warming of about 0.6°C has occurred without further change in atmospheric composition[6]. Mass balance is one of the important parameters which can be influenced by global warming. Mass balance is usually referred to as a total loss or gain in glacier mass at the end of the hydrological year[7]. Geographical parameters which can influence mass balance are area–altitude distribution and orientation, since higher altitude has lower atmospheric temperature. In addition, orientation and amount of slope can influence amount of solar radiation received on the slope[8]. Influence of these parameters on glacial mass balance is studied in the Baspa basin[9,10].

Global warming has remitted in large-scale retreat of glaciers throughout the world[11]. This has led to most glaciers in the mountainous regions such as the Himalayas to recede substantially during the last century[12–14] and influence stream run-off of Himalayan rivers[15]. However,
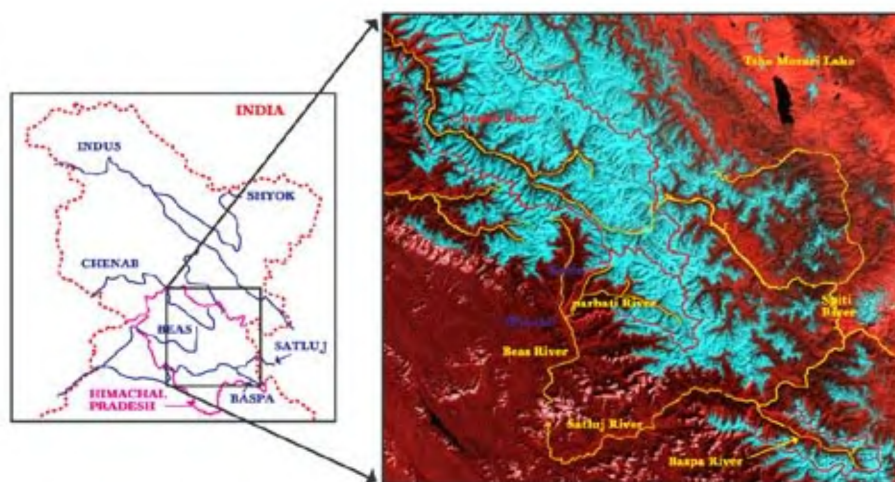
Figure 1. Location map of Chenab, Parbati and Baspa basins, Himachal Pradesh (HP).

Table 1. Satellite data used in the analysis

Basin	Sensor	Spatial resolution (m)	Date of acquisition
Parbati	LISS-IV	5.8	16 July 2004
Baspa	LISS-III	23	25 August 2001
			11 September 2000
Chenab	LISS-III	23	27 August 2001
			30 August 2001

Table 2. Salient specifications of LISS-IV sensor of IRS-P6 (from Roy[17])

Specification	LISS-IV
Spectral bands (μm)	0.52–0.59
	0.62–0.68
	0.77–0.86
Spatial solution	5.8 m at nadir
Swath	23.9 km
Quantization	7 bits
Saturation radiance	B2: 55
(mw/cm^2/sr/mm)	B3: 47; B4: 31.5

monitoring of Himalayan glaciers is normally difficult using conventional methods due to the rugged and inaccessible terrain. Therefore, field-based records have been made at selected Himalayan glaciers. This may not provide a complete and representative scenario of glacial retreat. In this investigation, changes in glacial extent are reported for 466 glaciers in Himachal Pradesh, covering three highly glacerized basins of Chenab, Parbati and Baspa (Figure 1). These are important river basins for Indian economy, as numerous power projects are under operation and construction here[16]. Therefore, changes in glacial extent and their influence on river run-off are important to plan future strategies of power generation.

Methodology

This investigation was carried out using data from a number of Indian Remote Sensing satellites. In Parbati basin LISS-IV data of IRS-P6, and in Baspa and Chenab basins LISS-III data of IRS-1D were used (Table 1). IRS-P6 satellite was launched on 17 October 2003 and satellite images of Parbati basin were collected in the summer of 2004. Spatial resolution of this sensor is 5.8 m and data are available in three bands. Therefore, this sensor can be used to monitor small glaciers and ice fields. Specifications of LISS-IV sensor of IRS-P6 satellite[17] are given in Table 2. The oldest information about glacial extent is available on Survey of India topographic maps, surveyed in 1962, using vertical air photographs and limited field investigations. Mapping of glacial extent in 2004 was carried out using LISS-IV images and in 2001 using LISS-III images. Images covering July–September period were selected, because during this period snow cover is at its minimum and glaciers are fully exposed. Glacier boundary was delineated using topographic maps and digitized using Geographic Information System. On satellite images glacial boundary was mapped using standard combinations of bands. Image enhancement technique was used to enhance the difference between glacial and non-glacial areas. Field investigations were carried out at five glaciers to assess position of the snouts. These include Shanue Garang glacier in Baspa basin, Parbati glacier in Parbati basin and Chhota Shigri, Samudra Tapu and Patsio glaciers in Chenab basin. Snout positions of selected glaciers were marked using Global Positioning System (GPS) and by comparing the relative position of snouts with geomorphologic features such as moraines, origin of streams from snouts and moraine-dammed lakes. Glacier retreat was measured along the centreline. Since GPS instrument cannot be easily mounted on the terminus, due to safety consideration, relative position of the terminus was esti-

mated using geomorphological features. This means glacial retreat can be estimated by combining field and satellite observations. This procedure is now being improved using a combination of laser range finder and GPS, where the distance between a fixed point on stable land and glacial terminus will be estimated. Repeated observations will provide the amount of glacier retreat. This will be an important step forward, as it will provide independent validation of remote sensing-based methodology.

Glacial depth is normally estimated using radio-echo sounding method[18–20]. In the Indian Himalayas, such measurements are few; however volume of glacier-stored water can be estimated using various approximate methods. One of the earliest methods to estimate glacier depth was based upon worldwide observations (including Nepal Himalayas) of a large number of glaciers and an approximate relationship between glacier type, areal extent and depth was developed. Glacier depth can be inferred using geomorphological classification and areal extent[21]. Both of these parameters can be obtained using remote-sensing technique. In geomorphological classification, glaciers are identified either as compound or simple glaciers. In a compound glacier, two or more tributaries merge together to form a valley glacier. The simple glacier has a single, well-defined accumulation area[21]. Separate tables are used to obtain depth depending upon the areal extent. This method was further improved by a large number of field observations in the Himalaya. A specific relationship between glacier area and depth has been developed for the Himalayan glaciers[22]:

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

where H is the mean glacier depth (m) and F is the glacier area (sq. km).

Since this method has been developed using depth information of Himalayan glaciers, it was used to estimate volume of glaciers and loss in their volume between 1962 and 2001. The error was estimated[22] as 10–20%. The volume of mountain glaciers[23] is proportional to their area raised to
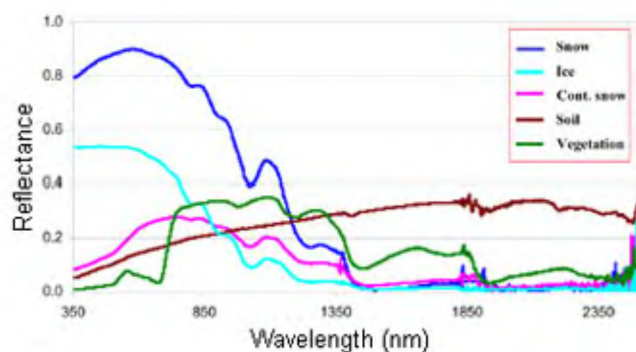

Figure 2. Spectral reflectance of snow, ice, contaminated snow, vegetation, and soil. Observations taken using spectral radiometer near Manali, HP. Note changes in reflectance as snow changes into ice and as snow and ice are covered by rock debris.

Figure 3. Satellite imagery of glacier number 52H12003 and 52H12004 of LISS-IV sensor showing glacial boundary of 1962 and 2004. These are small mountain glaciers showing negligible accumulation area. Maximum altitude of these glaciers is around 5200 m. This is close to the snow line at the end of ablation season and such glaciers are expected to experience terminal retreat.

Figure 4. Field photograph showing moraine-dammed lake near Samudra Tapu glacier, Chenab basin, HP.
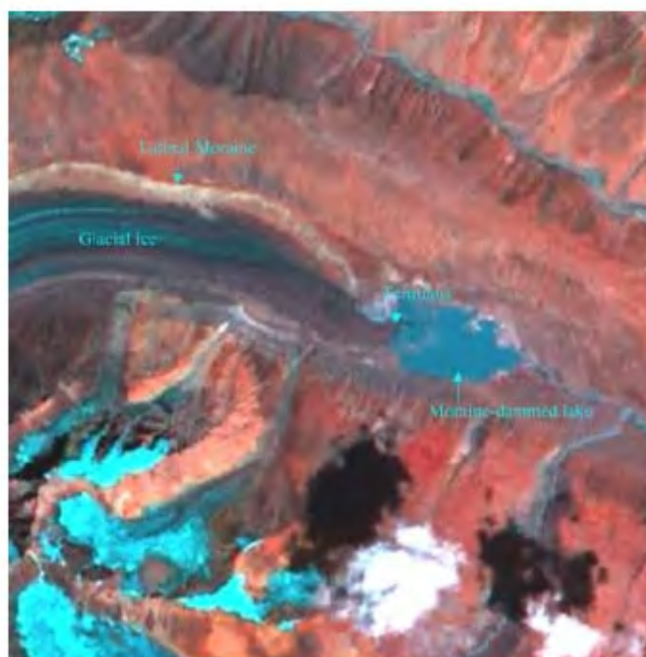

Figure 5. Satellite imagery showing moraine-dammed lake and terminus of Samudra Tapu glacier, Chenab basin, HP.
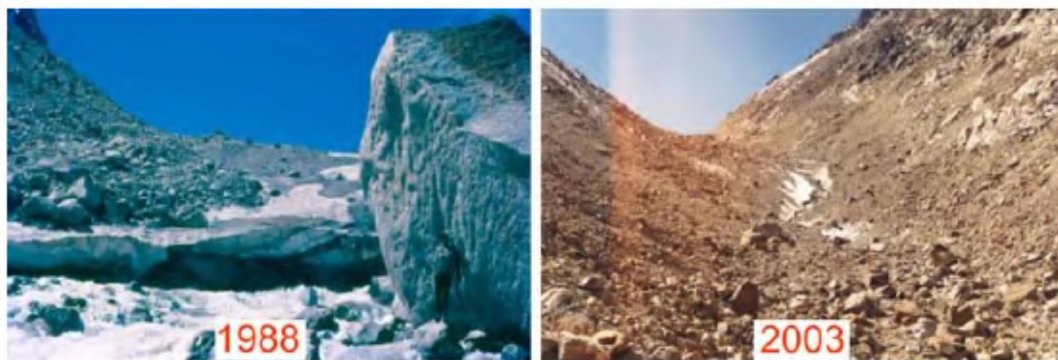
Figure 6. Field photograph of terminus region of Chhota Shigri glacier, Lahaul and Spiti district, of HP taken in 1988 and 2003. In 1988, glacial ice is exposed on the surface and small portion of the terminus is covered by debris. By year 2003, the entire terminus zone is covered by debris.

Table 3. Basin-wise loss in glacier area in Chenab, Parbati and Baspa basins

Basin	Glacier number	Glacier area (sq. km)			Volume (cubic km)		
		1962	2001–04	Loss (%)	1962	2001–04	Loss (%)
Chenab	359	1414	1110	21	157.6	105.03	33.3
Parbati	88	488	379	22	58.5	43.0	26.5
Baspa	19	173	140	19	19.1	14.7	23.0
Total	466	2077	1628	21	235.2	162.73	30.8

Figure 7. Field photograph of terminus region of Patsio glacier, Bhaga river basin, Lahaul and Spiti district, HP. Shape of glacial terminus is concave, suggesting retreating glacier. Glacier ice can be seen clearly and debris cover is relatively less on this glacier.

Figure 8. Field photograph of dead ice mound at Patsio glacier. A rock formation between present terminus and dead ice mound can be clearly seen in Figure 7.

a power of about 1.36. A small difference between geographic regions (North America, Arctic, Europe and Central Asia) was observed. In Central Asia, the volume of mountain glaciers was observed proportional to their area raised to a power of about 1.24.

Estimation changes in glacial extent

Identification and mapping of glacier boundary and terminus is one of the important aspects of estimation of retreat. If glaciers are not covered by debris, identification

of snow, ice and rock on satellite images is possible due to substantial difference in spectral reflectance. Spectral reflectance curves of fresh snow, ice, dirty snow and rock are given in Figure 2. These reflectance curves were obtained around Manali, Himachal Pradesh. These results indicate substantial difference between snow and rock. In addition, reflectance of ice is also substantially different compared to that of rock in the spectral region between visible and SWIR (Figure 2). A satellite imagery of LISS-IV sensor showing glacial boundary of 1962 and 2004 is given in Figure 3. Identification and mapping of glacial terminus in a satellite imagery is normally difficult if glaciers are

covered by debris. Numerous geomorphologic features can be used to identify the terminus. Many a times moraine-dammed lakes are formed downstream of the glacial terminus (Figure 4). These lakes can be easily identified on satellite images (Figure 5). Sometimes a glacial terminus is characterized by a steep ice wall. Depending upon relative positions of the sun and the wall, it can form shadow in downstream, which can be used as a marker for terminus delineation.

Field investigations at the Chhota Shigri glacier were carried out in 1988 and 2003. These suggest a retreat of 800 m between 1988 and 2003. Field photographs of glacier terminus region indicate changes in glacial morphology (Figure 6). In the photograph of 1988 (Figure 6), the glacial terminus can be seen clearly; by the year 2003, the entire region is covered by debris, suggesting glacial retreat and reduction in debris-carrying capacity of the glacier[24]. If this process continues, this glacier will convert into a rock glacier. Field investigation at Patsio glacier has shown concave shape of terminus, indicating a retreating glacier (Figure 7). This was further confirmed, as isolated dead ice mounds were observed downstream the present terminus (Figure 8), suggesting rapid glacial retreat.

Areal extent of 466 glaciers was estimated. It was 2077 sq. km in 1962 and 1628 km² in 2001–04, an overall 21% deglaciation. Basin-wise loss in glacier area is given in Table 3. Amount of retreat varies from glacier to glacier and from basin to basin, depending on parameters such as maximum thickness, mass balance and rate of melting at the terminus[14]. Loss in glaciated area depends on areal extent of the glaciers (Table 4). This is possibly because glacier response time is directly proportional to thickness[25]. Thickness is directly proportional to its areal extent[22]. Response time is defined as the amount of time taken by the glacier to adjust to a change in its mass balance. If maximum thickness of glaciers varies between 150 and 300 m, then the response time for temperate glaciers will be between 15 to 60 years[26]. In the Himalayas, if glaciers are not heavily covered by debris, areal extent of glaciers is less than 1 sq. km and rate of melting around the snout is around 6 ma^{-1}; then response time is estimated to be between 4 and 11 years. Therefore, if other parameters are constant, then small glaciers are expected to adjust to climate change faster. This phenomenon is now being observed in the Himalayan region, as glaciers smaller than 1 sq. km have deglaciated by almost 38% between 1962 and 2001–04 (Table 3). On the other hand, larger glaciers have shown only 12% loss in their area. Even though total glacial extent is reduced, the number of glaciers has increased. The number of glaciers as a function of area for Chenab basin is plotted in Figure 9. Mean of glacial extent was reduced from 1.4 to 0.32 sq. km between 1962 and 2001. In addition, the number of glaciers with higher areal extent has reduced and the number of glaciers with lower areal extent has increased between 1962 and 2001. This glacial fragmentation can be clearly seen on satellite images (Figure 10).

Conclusion

This investigation was carried out for 466 glaciers in the highly glaciered Himalayan basins, namely Baspa, Parbati and Chenab. Normally in the Himalayas, retreat is measured at well-developed and easily accessible valley glaciers. This study is now extended to small mountain glaciers

Table 4. Changes in areal extent of glaciers in Chenab basin

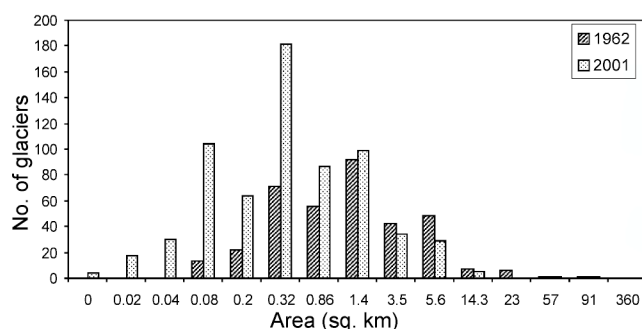| Glacier area (sq. km²)	Number of glaciers in 1962	Glacier area (sq. km)		Change (%)
< 1	127	68	42	38
1–5	159	382	269	29
5–10	48	329	240	27
> 10	25	635	559	12
Total	359	1414	1110	21

Figure 9. Number of glaciers as a function of area for Chenab basin. Areal extent in bin is increasing by a power of 2.

Figure 10. Resourcesat imagery of LISS-IV sensor dated 12 September 2004 of glacier number 52E09027. This glacier split into four glaciers between 1962 and 2004. However, areal extent is reduced from 7.0 to 5.3 sq. km.

and ice fields. The investigation has shown overall 21% reduction in glacial area from the middle of the last century. Mean area of glacial extent was reduced from 1.4 to 0.32 sq. km between 1962 and 2001. In addition, the number of glaciers has increased between 1962 and 2001; however, total areal extent has reduced. The number of glaciers has increased due to fragmentation. Numerous investigations in the past have suggested that glaciers are retreating as a response to global warming. As the glaciers are retreating, it was expected that tributary glaciers will detach from the main glacial body and glaciologically they will form independent glaciers. Systematic and meticulous glacial inventory of 1962 and 2001 have now clearly demonstrated that extent of fragmentation is much higher than realized earlier. This is likely to have a profound influence on sustainability of Himalayan glaciers.

This can be clearly seen, as a large difference in deglaciation was observed between large and small glaciers. Loss in glaciated area for large glaciers was 12% compared to 38% for small glaciers. This can be explained by considering three fundamental glacial parameters, namely depth, mass balance and rate of melting at the terminus. Glacial depth is normally related to its areal extent and small glaciers have relatively lesser depth. Since glacier response time is directly proportional to its depth, it could vary between 4 and 60 years, depending upon glacial size. This could be the fundamental reason for large retreat of small glaciers. Therefore, small glaciers are considered as more sensitive to global warming. This process could have been further accelerated as small glaciers and ice fields are situated on small mountain plateaus or on gentle mountain slopes. On the other hand valley glaciers are usually located in mountain valleys, surrounded by steep mountain cliffs. This can cause further accumulation of debris and less solar radiation will be received on the glacial surface, affecting glacial retreat. The observations made in this investigation suggest that small glaciers and ice fields are significantly affected due to global warming from the middle of the last century. In addition, larger glaciers are being fragmented into smaller glaciers. In future, if additional global warming takes place, the processes of glacial fragmentation and retreat will increase, which will have a profound effect on availability of water resources in the Himalayan region.

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