

RS and GIS in mapping of geomorphic records and understanding the local controls of glacial retreat from the Baspa Valley, Himachal Pradesh, India

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We report here the role of remote sensing (RS) and geographical information system (GIS) in the identification of geomorphic records and understanding of the local controls on the retreat of glaciers of the Baspa Valley, Himachal Pradesh, India. The geomorphic records mapped are accumulation zone, exposed ablation zone, moraine-covered ablation zone, snout, deglaciated valley, lateral moraine, medial moraine, terminal moraine and hanging glacier. Details of these features and stages of deglaciation have been extracted from RS data and mapped in a GIS environment. Glacial geomorphic data have been generated for 22 glaciers of the Baspa Valley. The retreat of glaciers has been estimated using the glacial maxima observed on satellite images. On the basis of percentage of retreat and the critical analysis of glacial geomorphic data for 22 glaciers of the Baspa Valley, they are classified into seven categories of very low to very very high retreat. From the analysis of the above 22 glaciers, it has been found that other than global warming, the retreat of glaciers of the Baspa Valley is inversely proportional to the size of the accumulation zone and the ratio of the moraine covered ablation/exposed ablation zone.

Keywords: Geographical information system, geomorphic records, glacial retreat, remote sensing.

GLACIERS are constantly changing with time and their current recessional trend has become a prime concern for us. The fluctuation of glaciers leaves an imprint in the form of erosional and depositional landforms. These geomorphic features act as an indicator for past glacial activity and facilitate inferences about the nature of glaciation.

Earlier work in the Baspa Valley, Himachal Pradesh (HP), India has been restricted to mass balance studies, monitoring of snout, morphometry, glacier melt studies, glacier depth assessment, lichenometry, snow assessment and geophysical studies¹⁻⁵. Limited work has been carried out using remote sensing (RS) in glacial geomorphic studies of the area. Hence, the present study emphasizes

the role of RS and geographical information system (GIS) in identifying geomorphic records of glacier retreat and to understand the factors controlling glacier retreat in the Baspa Valley.

A preliminary glacial geomorphic map has been prepared from IRS 1D LISS III + PAN-merged data of 2001, and Resourcesat, LISS III data of August 2005 using visual interpretation technique. After extensive ground-truth verification for four glaciers, viz. Shaune, Billare, Shailpya and Jorya Garang, a final glacial geomorphological map of the Baspa Valley was prepared. Detailed glacial geomorphic data have been generated for 22 glaciers using ERDAS and ARC-GIS software (Table 1). The percentage of retreat for all the glaciers has been calculated using the glacial maxima demarcated by satellite data. On the basis of percentage of retreat and critical analysis of glacial geomorphic data for 22 glaciers, they were classified into seven categories (Table 2).

The Baspa basin lies between 31°10'01.00"–31°30'17.16"N lat. and 78°10'26.52"–78°52'41.75"E long., and is located in the southeast corner of Kinnaur District, HP (Figure 1). It occupies an area of 1100 sq. km and is spread over Survey of India toposheet nos 53 I/7, I/8, I/11, I/12, I/15 and I/16, with elevation ranging from 1770 to 6465 m asl. The Baspa river which starts near the Indo-Tibetan border, flows through Kinnaur, forming a valley from Chitkul (3475 m) to the junction with the Sutlej river at Karchham (1770 m asl). A large part of this 75 km long valley is either arable land or covered with forest. The Baspa Valley is characterized by lofty snow peaks, with 35 important north and south-facing glaciers. These glaciers exhibit erosional and depositional geomorphic features, which indicate past glacial activity in the valley. Sangla, Rakchham and Chitkul are among the most famous, but not much explored, tourist spots in the Baspa Valley.

A final glacial geomorphological map has been prepared for each of the 35 glaciers. For convenience only one geomorphic map is shown here (Figures 2 and 3). The most common features that are mapped include accumulation zone, exposed ablation zone, moraine-covered ablation zone, snout, deglaciated valley, lateral moraine, medial moraine, terminal moraine and hanging glacier. Details of these features and stages of deglaciation have been calculated by using the GIS technique, and glacial geomorphic data have been generated for 22 glaciers of the Baspa Valley (Table 1).

The accumulation zone is the zone where snow is collected and nourishes the glacier (Figure 4a). It appears white in colour with fine texture on satellite data. The orientation and dimensions of the accumulation zone vary from glacier to glacier. In general, the south-facing glaciers show less accumulation area compared to north-facing glaciers. More than 50% of the south-facing glaciers exhibit less than 1 sq. km accumulation area. The minimum accumulation area observed was of 0.12 sq. km

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Table 1. Summary of glacial geomorphic study

Glacier no.	Orientation	Accumulation area (sq. km)	Exposed ablation area (sq. km)	Moraine-covered area (sq. km)	Lateral moraine stage	Terminal moraine stage	Elevation of snout (m)				Snout variation (m)	Length (m)		Lengthwise evacuation (m)	Area (sq. km)		Area wise evacuation (sq. km)
							2005	Glacial maxima	2005	Glacial maxima		2005	Glacial maxima				
															2005	Glacial maxima	
1	South	2.47	0.63	6.75	Two	One	4637	4444	193	4970	6220	1250	9.85	11.38	1.53		
2	South	2.36	0.24	3.42	Two	One	4757	4561	196	5280	5810	530	6.02	6.52	0.50		
3	South	0.4	0.29	1.81	One	One	4923	4642	281	2460	3200	740	2.5	2.88	0.38		
4	South	1.54	0.85	3.03	One	One	4860	4343	517	3340	4800	1460	5.42	6.38	0.96		
5	South	0.54	0.21	0.31	Three	-	5013	4479	534	2530	4180	1650	1.06	2.03	0.97		
6	South	0.12	0.14	0.35	One	-	4863	4641	222	6160	6710	550	0.61	0.98	0.37		
7	South	0.39	0.41	1.20	One	One	4687	4307	380	3450	4680	1230	2	3.26	1.26		
8	South	0.44	0.12	0.23	-	Two	5300	4742	558	2630	4750	2120	0.79	1.61	0.82		
9	South	1.66	0.25	5.16	One	-	4842	4550	292	5070	7720	2650	7.1	8.58	1.48		
10	South	12.69	10.24	9.37	-	-	5028	4648	380	5140	9810	4670	31.4	38.3	6.9		
11	South	8.62	5.51	1.08	One	-	5024	4480	144	5660	8550	2890	15.95	17.74	1.79		
12	West	17.32	17.36	7.88	Two	One	4306	4255	51	8600	12160	3560	41.11	46.81	5.7		
13	North	0.27	0.51	0.21	One	-	4466	4348	118	1760	2930	1170	0.99	1.57	0.58		
14	North	3.68	2	2.29	Two	One	4633	4494	139	6290	6930	640	7.97	9.21	1.24		
15	North	3.80	1.04	2.81	One	Three	4702	4186	516	8590	9990	1400	7.65	8.29	0.64		
16	North	1.32	0.24	1.23	Two	One	4581	4179	402	4000	5400	1400	2.79	3.61	0.82		
17	North	23.48	7.54	9.18	Two	Three	4209	3886	323	22480	26360	3880	41.72	44.94	3.22		
18	North	5.75	5.36	1.74	Two	Two	4349	4062	287	6490	10040	3550	12.32	16.07	3.75		
19	North	2.52	1.23	1.64	Two	One	4484	4281	203	4620	6950	2330	5.85	8.1	2.25		
20	North	0.74	0.24	3.36	Two	One	4342	4146	196	4730	5650	920	4.35	5.08	0.73		
21	North	3.28	3.91	5.79	Three	Three	4512	4172	340	5600	8640	3040	12.31	13.58	1.27		
22	North	3.51	1.87	2.50	Two	Three	4481	4062	419	6230	8110	1880	8.26	9.95	1.69		

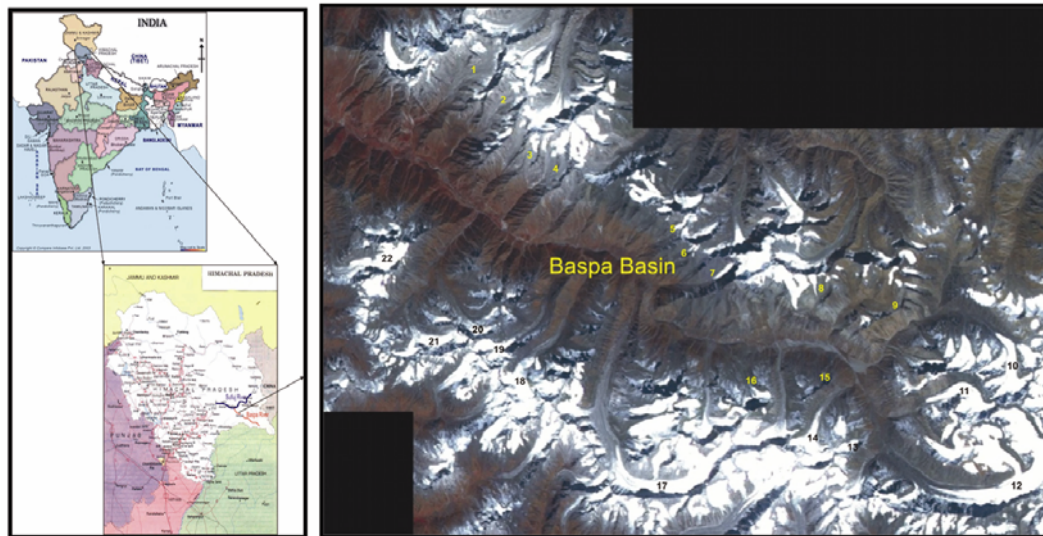


Figure 1. Location map (IRS LISS III + PAN-merged image of the study area).

Table 2. Classification of percentage of retreat into seven categories

Percentage of retreat	Category of retreat
< 10	Very low
11–20	Low
21–30	Moderate
31–40	Moderately high
41–50	High
51–60	Very high
> 60	Very very high

for glacier no. 6 (Table 3) and maximum observed was 12.69 sq. km for glacier no. 10. Majority of north-facing glaciers showed more than 1 sq. km area, except for glacier nos 13 and 20. The minimum accumulation area observed was for glacier no. 13 and maximum was for glacier no. 17, i.e. Jorya Garang (Table 3).

The ablation zone is the zone in which snow and ice are lost from the glaciers by the processes of melting, evaporation and wind erosion. The ablation zone is classified into exposed ablation zone and moraine-covered ablation zone⁶. The exposed ablation zone appears as greyish-white in colour with fine texture, whereas the moraine-covered ablation zone appears as brownish in colour with medium texture on satellite data. In general, the exposed ablation zone exhibits faster melting, whereas the area covered by debris shows slow melting. The ablation zone with debris cover also shows variation in the rate of melting. The thin debris cover absorbs the heat and on account of conductivity the glacier melts faster⁷. In case of thick debris cover, the absorbed heat does not reach up to the glacier and hence slows down the process of melting⁸. This is in agreement with work of Kulkarni and Bahuguna⁴, who found that many small, low-altitude glaciers are well protected due to extensive debris cover.

Major part of the Shaune and Jorya Garang glaciers is under moraine cover (Figure 4 *a* and *b*).

The snout is known as the terminus of a glacier. In the satellite image it appears black in colour on account of the shadow of the ice wall and shows linear to curvilinear shape. It is normally difficult to identify the snout on the imagery if the glaciers are debris-covered. Certain geomorphic features can be used to identify the snout. Many a times moraine dammed lakes are formed downstream of the snout. Sometimes they are characterized by steep ice wall. Depending upon the relative positions of the sun and the wall, it can form a shadow in the downstream which can be used as a marker to identify the snout⁹. In the case of Shaune Garang (Figure 4 *a*) and Jorya Garang (Figure 5 *a* and *b*) the snout occurs, where the stream originates from the ice wall. Average elevation of the snout for south-facing glaciers was 4980 m and for north-facing glaciers it was 4570 m (Table 4). This indicates that south-facing glaciers are retreating faster than north-facing glaciers.

When the ice melts, the debris brought by the glaciers are left out as a ridge along each side of the valley forming a lateral moraine (Figure 6 *a*). It can be assumed that the debris must have accumulated between the valley wall and the higher ice surface. As the ice slowly melted away, the moraine has maintained its slope away from the ice. The steeper side facing the glacier developed as the ice surface was gradually lowered. Lateral moraines found in the study area are not always straight, but also occur with curvilinear shape. Maximum three stages of lateral moraine have been mapped in the case of the Shaune Garang (no. 21) glacier (Table 1). Stage-1 lateral moraines occur at higher elevation, with more vegetation and overlapped by debris fans and rock falls (Figure 6 *b*). Stage-2 moraines comprise of fresh angular boulders and

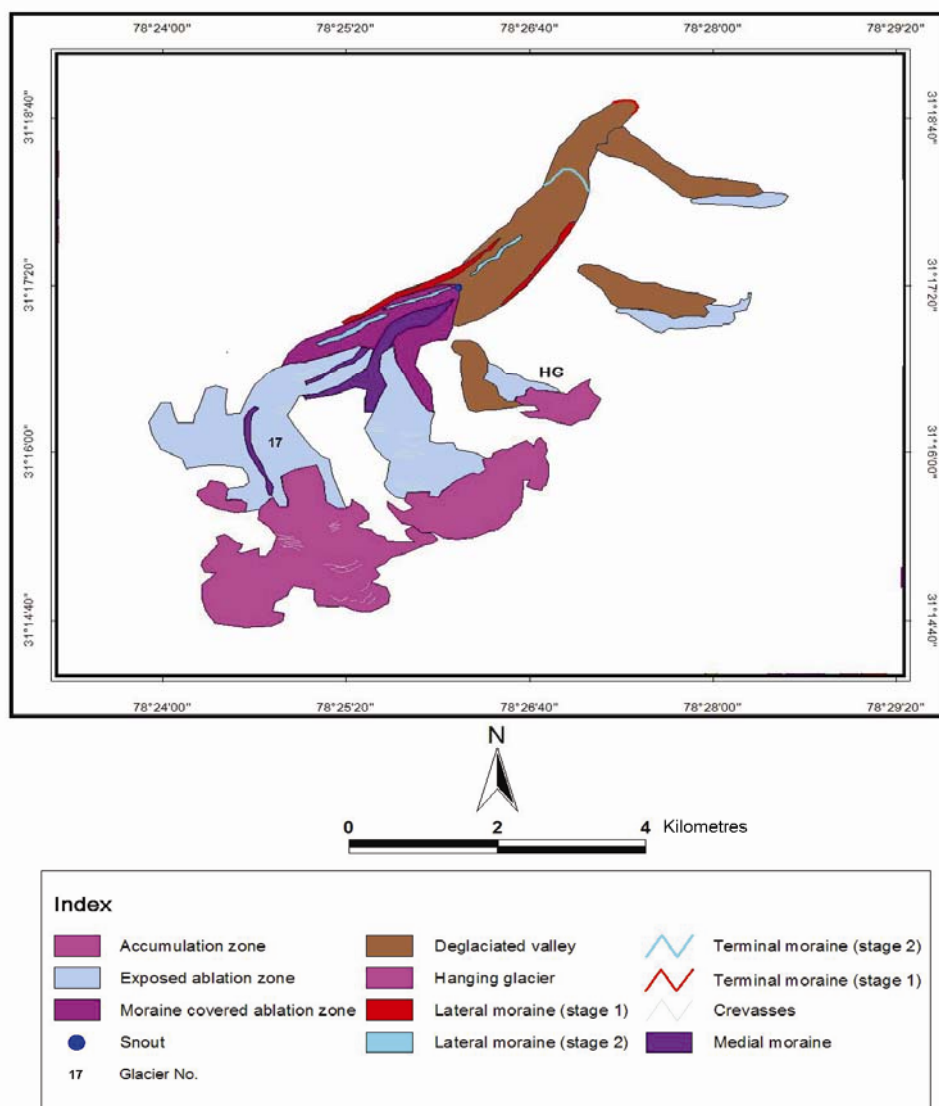


Figure 2. Geomorphological map of Janapa Garang Glacier.

lack vegetation (Figure 6c). Lateral moraines appear as linear–curvilinear ridges with brown–grey colour for non-vegetated and red colour for vegetated, with medium to coarse texture along the sides of the valley glaciers on satellite data.

Medial moraines are the morainic ridges found in the centre of the glaciers. They are formed when two separate valley glaciers/tributary glaciers carry lateral moraines and are joined together. Medial moraines are characteristic of living glaciers and are seldom preserved after the disappearance of the ice. They are distinctly seen in the case of Saro (no. 1), Baspa Bamak (no. 12), Jorya (no. 17) and Janapa Garang (no. 18) glaciers.

Terminal moraines are a ridge of till that marks the maximum limit of glacier advance. The series of terminal moraines which mark the recession of the glaciers are called recessional moraines¹⁰. These are crescent-shaped

with the convex side extending down the valley and appear as arcuate ridges. Overall, three stages of terminal moraines have been identified across the valley (Table 1 and Figure 6d–f). The boulders of younger stages are fresh, angular, non-vegetated and less obliterated compared to older-stage moraines which are nearly/completely destroyed and show a patchy appearance on the surface of the valley floor. Stage-1 moraines are older and vegetated, and dull in colour with huge lichen formation over the surface of boulders of granitoid compared to fresh surfaces of stage-3 moraines⁶. Terminal moraines appear as linear–curvilinear ridges with brown–grey colour for non-vegetated and red colour for vegetated, with medium to coarse texture along the terminus of a valley glacier on satellite data.

The deglaciaded valley lies below the ablation zone and is formed due to the retreat of a glacier from its maximum

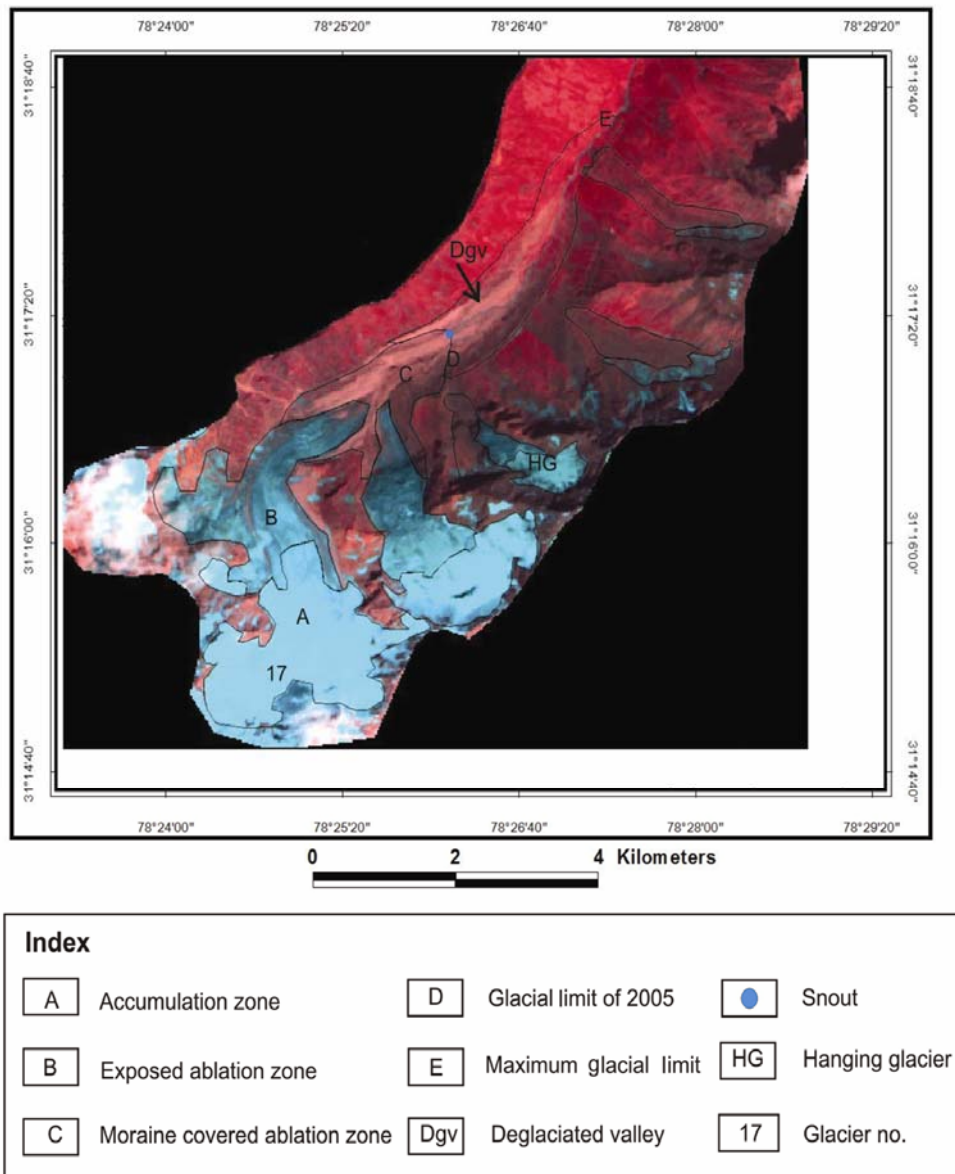


Figure 3. IRS P6, 2005, LISS III image of Janapa Garang Glacier.

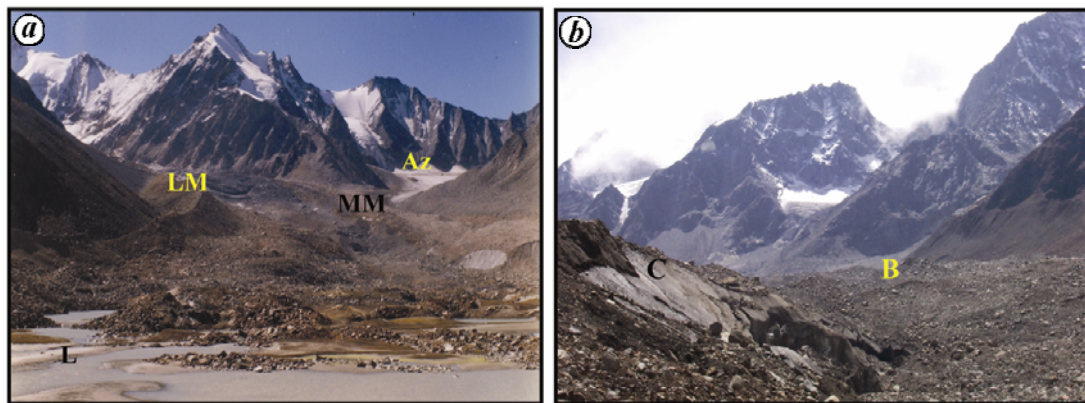


Figure 4. a, Accumulation zone (Az), lateral moraine (LM), medial moraine (MM), moraine-covered ablation zone (B), and lakes (L) of Shaune Garang Glacier. b, Moraine-covered ablation zone (B) and ice wall (C) of Jorya Garang Glacier.

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Table 3. Correlation of orientation of glacier, accumulation zone, Mcab/Exab, and slope of ablation zone with glacial retreat

Glacier no.	Orientation	Accumulation area (sq. km)	Exposed ablation area (sq. km)	Moraine-covered ablation area (sq. km)	Mcab/Exab ratio	Slope of ablation zone (degrees)	Percentage of retreat from glacial maxima	Retreat code
1	South	2.47	0.63	6.75	10.71	0–9	17.00	L
2	South	2.36	0.24	3.42	14.25	9–18	07.70	VL
3	South	0.40	0.29	1.81	06.24	9–18	13.19	L
4	South	1.54	0.85	3.03	03.56	9–18	15.04	L
5	South	0.54	0.21	0.31	01.48	19–35	47.78	H
6	South	0.12	0.14	0.35	02.50	36–45	37.76	MH
7	South	0.39	0.41	1.20	02.92	9–18	38.65	MH
8	South	0.44	0.12	0.23	01.91	19–35	50.93	H
9	South	1.66	0.25	5.16	20.64	19–35	17.24	L
10	South	12.69	10.24	9.37	0.91	0–9	18.00	L
11	South	08.62	5.51	1.08	0.19	0–9	10.09	L
12	West	17.32	17.36	7.88	0.45	0–9	17.31	L
13	North	0.27	0.51	0.21	0.41	19–35	36.94	MH
14	North	3.68	2.00	2.29	1.15	0–9	13.46	L
15	North	3.80	1.04	2.81	2.70	0–9	07.72	VL
16	North	1.32	0.24	1.23	5.12	19–35	22.71	M
17	North	23.48	7.54	9.18	1.21	0–9	07.16	VL
18	North	5.75	5.36	1.74	0.32	0–9	23.33	M
19	North	2.52	1.23	1.64	1.33	9–18	27.77	M
20	North	0.74	0.24	3.36	14.00	9–18	14.37	L
21	North	3.28	3.91	5.79	1.48	0–9	9.35	VL
22	North	3.51	1.87	2.50	1.33	0–9	16.98	L

L, Low; VL, Very low; H, High and MH, Moderately high.

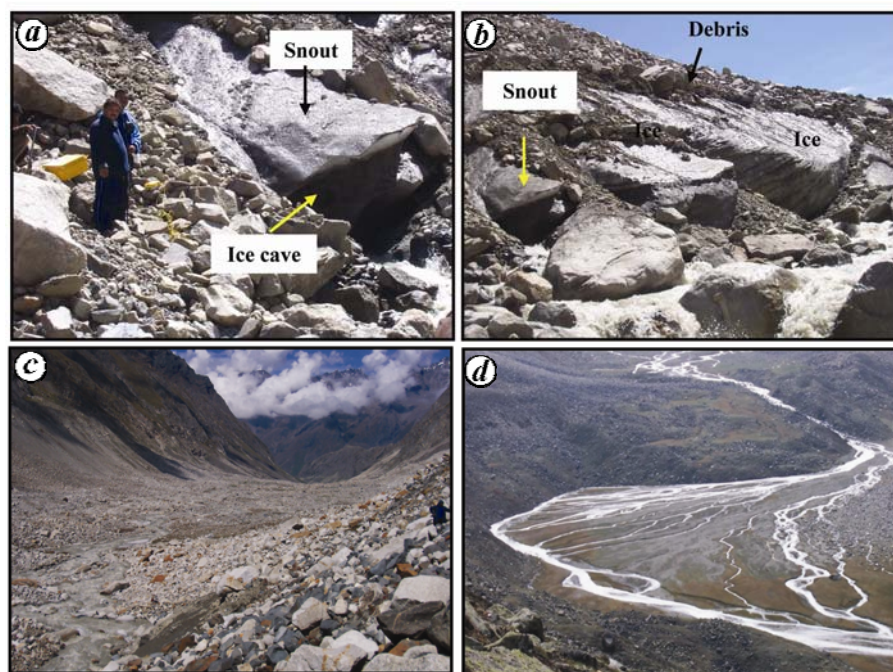


Figure 5. Snout and ice cave (a), snout (b) and deglaciated valley (c) of Jorya Garang Glacier. (d) Outwash sediments and braided pattern of Shaune Garang River.

extent. It appears as brown colour with medium texture on satellite data. One of the most striking characteristics of a well-developed glaciated valley is the U-shape of its cross-profile. The side walls are considerably steep, approaching to vertical in places (Figure 5c) and the

valley floor is broad and flat than in the river. Widening and deepening may depend upon the ability of the glacier to erode valley walls and cut into the rock of its bed. This also depends upon the lithology of its bedrock and glacial plucking of previously loosened blocks. Apart from the

Table 4. Details showing orientation and snout variation from glacial maxima

Glacier no.	Orientation	Elevation of snout (m)		Snout variation (m)	Glacier no.	Orientation	Elevation of snout (m)		Snout variation (m)
		2005	Glacial maxima				2005	Glacial maxima	
1	South	4637	4444	193	12	West	4306	4255	51
2	South	4757	4561	196	13	North	4466	4348	118
3	South	4923	4642	281	14	North	4633	4494	139
4	South	4860	4343	517	15	North	4702	4186	516
5	South	5013	4479	534	16	North	4581	4179	402
6	South	4863	4641	222	17	North	4209	3886	323
7	South	4687	4307	380	18	North	4349	4062	287
8	South	5300	4742	558	19	North	4484	4281	203
9	South	4842	4550	292	20	North	4481	4062	419
10	South	5028	4648	380	21	North	4512	4172	340
11	South	5024	4480	144	22	North	4481	4062	419

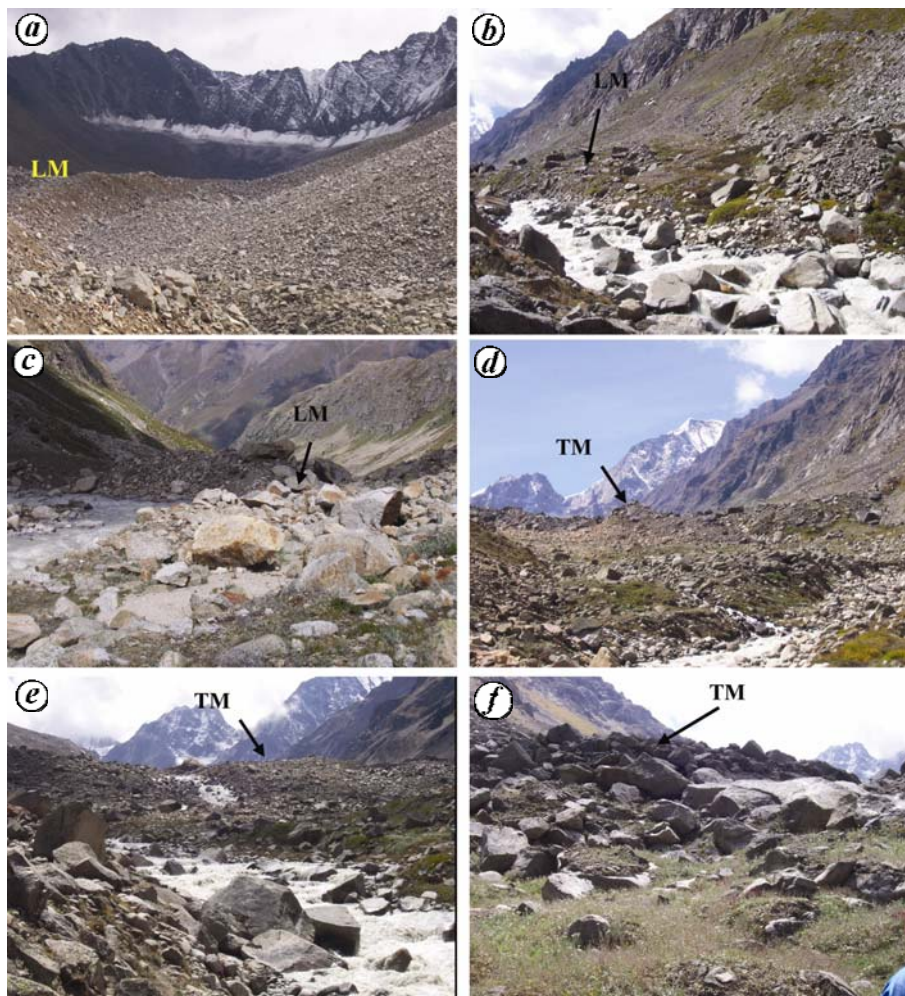


Figure 6. *a*, Lateral moraine (LM), Billare Bange Glacier. *b–f*, Jorya Garang Glacier. Stage 1 Lateral moraine (*b*), Stage 2 Lateral moraine (*c*), Stage 1 Terminal moraine (*d*), Stage-2 Terminal moraine (*e*) and Stage-3 Terminal moraine (*f*).

U-shaped cross-profile, other significant features of the deglaciated valley are the presence of a number of arcuate-shaped ridges of terminal moraines, linear to curvilinear lateral moraines and scattered ground moraines, indica-

tive of stages of deglaciation¹¹. The valley floors are filled with reworked outwash sediments and exhibit broad braided stream channels (Figure 5 *d*). The deglaciated valley is also marked by a series of rock basins, formed

probably by plucking in the areas of bedrock which were shattered or closely jointed. As time passes, these rock basins get filled up with water, forming lakes (Figure 4a). Almost all the glaciers of the Baspa Valley show deglaciated valleys of varying length and nature (Table 4).

The Baspa basin consists of 37 glaciers, out of which 22 glaciers which show complete record of accumulation zone, exposed ablation zone and moraine-covered ablation zone have been considered for this analysis; eleven being south-facing, one east-facing and ten north-facing. The data generated for the 22 glaciers reveal that the total areal extent of the south-facing glaciers (82.83 sq. km) is less than the north-facing glaciers (102.87 sq. km).

The south-facing glaciers are characterized by a large ablation zone (51.60 sq. km) and small accumulation zone (31.23 sq. km), whereas the north-facing glaciers are characterized by 48.35 sq. km accumulation zone and 54.52 sq. km ablation zone. The difference between the areas of the accumulation zone and ablation zone is high for the south-facing glaciers compared to the north-facing glaciers.

A critical analysis of these glaciers reveals that other than global warming, local factors, viz. size of accumulation zone, ratio of moraine-covered to exposed ablation zone (Mcab/Exab), slope of ablation zone and orientation of the glaciers are closely interrelated with each other and control the retreat of the glaciers. It has been observed that out of the 11 south-facing glaciers, five show less than 1 sq. km area of accumulation and exhibit moderately high-to-high retreat. However, glacier no. 3, in spite of having less than 1 sq. km area of accumulation, shows low retreat. This may be on account of higher percentage of Mcab/Exab ratio. Out of the ten north-facing glaciers, only two (nos 1 and 8) exhibit less than 1 sq. km area of accumulation. Glacier no. 1 shows 0.27 sq. km area of accumulation and is subjected to moderately high (36.94%) retreat. Glacier no. 8, in spite of having less than 1 sq. km area, was subjected to low retreat because of comparatively high Mcab/Exab ratio (14.0). This analysis shows that glaciers having greater than 1 sq. km area of accumulation zone are subjected to low retreat, and those with less than 1 sq. km area are subjected to high retreat (Table 3). The size of accumulation zone is comparatively larger for north-facing glaciers than south-facing glaciers.

The processes of the ablation zone are controlled by local factors, viz. orientation of the glaciers, slope of the ablation zone and the Mcab/Exab. The results obtained for the Mcab/Exab ratio and the slope of the ablation zone for the 22 glaciers (Table 3), give convincing relation with the retreat of the glacier.

Out of 11 south-facing glaciers, glacier no. 1 indicates low retreat because of high Mcab/Exab (10.71) ratio, whereas the rate of retreat further decreases for the glacier no. 2 with increase in Mcab/Exab ratio (14.25). The glaciers nos 3–5 show an inverse relation between Mcab/Exab ratio and percentage of retreat, i.e. as the

Mcab/Exab ratio decreases, the percentage of retreat increases. Glacier no. 6 indicates again increase in the Mcab/Exab ratio, which results in the decrease of glacial retreat. Glacier no. 8 is characterized by a fall in the Mcab/Exab ratio, hence, an increase in the rate of retreat. As the value of the Mcab/Exab ratio increases, there is a decrease in the rate of retreat as revealed by glacier no. 9. For glacier nos 10 and 11, the slope of the ablation zone (0–9°) is a more dominating controlling factor. Therefore, in spite of the fall in Mcab/Exab values, these glaciers show low retreat. Baspa Bamak Glacier (no 12), which is a west-facing and major glacier of the Baspa valley, shows low retreat in spite of low Mcab/Exab ratio. This indicates the dominant role of slope of ablation zone (0–9°) compared to the Mcab/Exab ratio.

Out of the 10 north-facing glaciers, slope of ablation zone for glacier nos 13 and 16 is 19–35°; glacier nos 14 and 15, 0–9°; glacier nos 17 and 18, 0–9°; glacier nos 19 and 20, 9–18°, and glacier nos 21 and 22 is 0–9°. For all these pairs where the slope of the ablation zone is constant, the rate of retreat decreases with increase in Mcab/Exab ratio (Table 3).

This gives a clear-cut idea that the ratio of moraine-covered ablation zone to exposed ablation zone is inversely proportional to the percentage of retreat. As this ratio increases, the percentage of retreat of the glacier decreases and vice versa. Glaciers with 0–9° and 0–18° slope of the ablation zone exhibit slow rate of retreat, whereas those with slope greater than 18° reveal moderately high-to-high rate of the retreat (Table 3).

The glacier is a dynamic and sensitive body of ice and therefore, frequent measurements on the shifting of snout or percentage of retreat are needed. The conventional method of geomorphic mapping is time-consuming and economically not viable for the rugged terrain and inclement weather conditions of the Baspa Valley. Techniques of RS are widely accepted on account of the synoptic view, repetivity and increase in spatial resolution and decrease in cost. The digitization of all these maps in GIS environment helps in generating reliable glacial geomorphic data.

The records of glacial retreat are well preserved in the form of a number of deglaciated valleys, terminal moraines and lateral moraines, and can be easily demarcated in the satellite data as well as in the field. Terminal and lateral moraines are found to be the important glacial geomorphic indicators and the number of sets can be correlated with the stages of deglaciation. The lateral and terminal moraines of stages 2 and 3 do not breach the stage 1 lateral and terminal moraines, indicating the gradual lengthwise and width-wise recession of the glaciers.

Apart from lateral and terminal moraines many empty cirques, hanging valleys, horns and arêtes of different shapes and sizes were commonly observed in the Baspa Valley, indicating the presence of glaciers in the past which have now retreated.

The enhanced retreating trend reveals that many glaciers in the Baspa Valley show their individual limbs exposed, which were initially flowing as a single glacier. The present-day Baspa Valley reflects increase in the number of glaciers with a decrease in their size on account of fragmentation.

Other than global warming, factors like size of accumulation and ablation zone, slope of ablation zone, amount of moraine cover on ablation zone and orientation of the glaciers, are intimately related with each other and are important local controlling factors of glacial retreat for the Baspa Valley. It is difficult to correlate the retreat of the glaciers simply on the basis of a single parameter. However, the retreat of glaciers of the Baspa Valley is found to be inversely proportional to the size of the accumulation zone and the Mcab/Exab ratio. The slope of the ablation zone is directly proportional to the glacier retreat.

The direction of the glaciers is important, since it provides information about the period of solar radiation. The south-facing glaciers are exposed to solar radiation for longer time compared to north-facing glaciers. The longer time of exposure to solar radiation increases the rate of melting for south-facing glaciers than the north-facing glaciers.

In the past, the extensions of glaciers were at much lower altitude, i.e. at least 950 m below the present-day extent of the glaciers. The maximum lengthwise retreat in the case of south-facing glacier is 4670 m, whereas in the case of the north-facing glaciers, it is 3880 m. The present glacial geomorphic studies of the Baspa Valley suggest that the south-facing glaciers are retreating faster (24.85%) than the north-facing glaciers (17.97%).

1. Raina, V. K. and Sangewar, C., Siachen Glacier of Karakoram mountains, Ladakh – its secular retreat. *J. Geol. Soc. India*, 2007, **70**, 11–16.
2. Jangpang, B. S. and Vohra, C. P., The retreat of the Skunkulpa (Ralam) glacier in the Central Himalaya, Pithoragarh District, UP. *India. Inst. Assoc. Sci. Hydrol.*, 1962, **58**, 234–238.
3. Kulkarni, A. V. and Alex, S., Estimation of recent glacial variations in Baspa Basin using remote sensing technique. *J. Indian Soc. Remote Sensing*, 2003, **31**(2), 81–90.
4. Kulkarni, A. V. and Bahuguna, I. M., Role of satellite images in snow and glacial investigations. *Geol. Surv. India Spec. Publ.*, 2001, **53**, 233–240.
5. Kurien, M. N. and Munshi, M. N., A survey of Sonapani glacier, Lahaul District, Punjab. *Geol. Surv. India, Misc. Publ.*, 1972, **15**, 83–88.
6. Trivedi, Y. N., Deota, B. S., Rathore, B. P., Bahuguna, I. M. and Kulkarni, A. V., IRS images for glacial geomorphological studies of Baspa Valley. *Indian J. Geomorphol.*, 2006–2007, **11,12**(1&2), 79–90.
7. Jansson, P. and Fredin, O., Ice sheet growth under dirty conditions: implications of debris cover for early glaciation advances. *Quaternary Int.*, 2002, **95–96**, 35–42.
8. Konrad, S. K. and Humphries, N. F., Steady-state flow model of debris covered glacier (rock glaciers). In *Debris Covered Glaciers* (eds Raymond, C. F., Nakowa, M. and Fountain, A.), IAHS, 2000, vol. 264, pp. 255–263.

9. Kulkarni, A. V., Bahuguna, I. M., Rathore, B. P., Singh, S. K., Randhawa, S. S., Sood, R. K. and Dhar, S. S., Glacial retreat in Himalaya using Indian remote sensing satellite data. *Curr. Sci.*, 2007, **92**(1), 68–74.
10. Leet, L. D. and Judson, S., *Physical Geology*, John Wiley, 1969, 3rd edn, p. 404.
11. Deota, B. S., Trivedi, Y. N., Bahuguna, I. M., Kulkarni, A. V. and Rathore, B. P., Geomorphic records of paleoglacial activity from the upper reaches of Baspa Valley, HP, In Proceedings of the Society of Photo-optical Instrumentation Engineers, 2006, vol. 6412, pp. 1–12.

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Gliding behaviour of Indian Giant Flying Squirrel *Petaurista philippensis* Elliot

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Gliding behaviour of Indian Giant Flying Squirrel (*Petaurista philippensis*) was observed from March 2009 to February 2010, at Sitamata Wildlife Sanctuary, Rajasthan, India. A total of 1203 glides were observed. One hundred glides were recorded for assessment of gliding behaviour and 32 glides were recorded for analysing gliding speed. The mean glide ratio (2.32) was found to be higher than that of *Petaurista leucogenys* (1.87), *Glaucomyx sabrinus* (1.98), *Pteromys volans orii* (1.70), and lower than that of *Glaucomyx volans* (2.8). Ground speed (6.96 m/s), air speed (7.51 m/s) and gliding angle (25.53) were similar to other studies. Mean horizontal distance and air distance were 16.28 and 20.08 m respectively. Short glides were preferred by *P. philippensis* in comparison to long glides.

Keywords: Air speed, air distance, glide ratio, ground speed, glide angle, *Petaurista philippensis*.

THE ability of arboreal forms to leap from great heights without harm is a valuable adaptation to life high above the surface of the ground. This ability reaches its maxi-

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