Assessment of Spatio-Temporal Fluctuations of Snow Cover in Beas Basin, Western Himalaya using Geospatial Techniques

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Abstract
On a regional scale, snow cover has high significance for the local climate, water availability, river run-off, and groundwater recharge. Glaciers are the most efficient indicators to trace the climate change and observation about the spatio-temporal variations of snow cover and glaciers provide an insight into the health of water resources. In this study the area drained by river Beas and its tributaries was taken as the spatial unit of study with objectives to investigate the trend of snow cover and glacier change in the study area. The area changes of the glaciers were mapped using US Army 1954 Topographical sheets at 1: 50000 scale and Randolph Glacier Inventory version 6.0, 2017.

Normalized Differential Snow Index was applied to measure the snow cover variations using the Landsat Multi-Spectral Scanner, Thematic Mapper, Enhanced Thematic Mapper Plus, and Optical Land Imaging images of 1976, 1990, 2000, 2010 and 2018. It was found that almost 70 percent of snow cover in the basin remains bound to above 5000 m altitude (asl). The basin had lost nearly 25 percent of its glacier area since 1954. However, the snow cover analysis using the Landsat images highlighted an increase in snow cover with no specific trend.

Keywords: Snow Cover, Glaciers, Climate Change, Western Himalaya.

Introduction

Snow and ice mainly cover the polar regions throughout the year, but the coverage at mountainous regions (lower altitudes) is seasonal and elevation-dependent. Snow cover presents one of the most important land surface parameters in global water and energy cycle[26] and fluctuations in the extent of temporary snow cover and permanent snowfields alter the albedo and hence the radiation balance at regional and global scales.

The Himalaya constitutes the most extensive glacier cover after the two poles[6,16,20,21,28,30] and is the source region of one of the world's largest freshwater supplies.[7,23] Much of the early observations of the Himalayan glaciers was made by geographers and cartographers who were engaged in triangulation and map-making during the 19th century.[35]

On a regional scale, snow cover has a significance for the local climate, water availability, river run-off, and groundwater recharge, especially in middle and high latitudes.[12] Large areas of north-western Himalaya receive precipitation in the form of snowfall due to low winter temperatures and high altitude mountains. The continuous snowmelt provides major contribution to discharge in all major rivers and helps in keeping the Himalayan rivers perennial and has helped in the flourishing of several civilizations along the banks of these rivers for ages.[19] These rivers are a significant source of Irrigation, industrial water supply, and hydropower in northern India and hence, snowmelt has a deterministic role for the uninterrupted supply of water.

Seasonal snowfall during wintertime starts ablating in the spring, therefore the areal extent of snow cover reduces significantly during spring and summers as compared to the winters. The seasonal fluctuations in the intensity of ablation affect streamflow, especially during the dry season. Glaciers are shrinking rapidly, with the highest rates at lower elevations. Hence, in this context, an accurate understanding of the snow-covered area (SCA) is much needed for various hydro-climatic applications and water resource management[3]. It is difficult to obtain snow cover information on a repetitive basis from vast snow-covered areas of Himalaya, which is at high altitude, rugged and inaccessible; using ground conventional techniques[25]; thus remote sensing techniques have contributed over the last few decades to extend our understanding of the Himalayan cryosphere.

According to the estimates, almost 800 million people live in the catchments of the Indus, Ganges, and Brahmaputra rivers and rely to varying extents (in particular during dry seasons and in mountain valleys) on the water released from glaciers.[11] Himalayan glaciers are a focus of public and scientific debate as various studies suggested that most of the Himalayan glaciers are in the retreating phase though the rate of retreat varies from glacier to glacier and region to region.

Glaciers and permanent snowfields under the Indian region are in five states namely; Jammu and Kashmir, Himachal Pradesh, Uttarakhand, Sikkim and Arunachal Pradesh. Depending on the latitude, precipitation pattern, and the local climatic gradients, the lowest elevations at which glaciers are found show spatial variations. Glaciers descend roughly 3700 m in the eastern Kashmir, 4000 m in the central Himalaya, and 4500 m in Sikkim[34].

The inventory of glaciers in the Himalaya-Karakoram region has been carried out by numerous agencies at different periods using various methodologies. The significant contributions are Kulkarni and Buch[18], Kaul[15], Raina and Srivastava[29], Ohmura[27], Cogley[4], Sangewar and Shukla[31], Frey et al[8], Kaab[14] and Bolch et al[2]. With particular attention to Beas river basin (BRB), various dimensions of glacier retreat were examined by Kulkarni et al[20,21], Negi et al[25], Jain et al[13], Dutta et al[5], Thakur et al[33], Ahmad et al[1], Srinivasalu et al[32] and Li et al.[23]

The rising temperatures are causing the net shrinkage and retreat of glaciers affecting water availability to the downstream populations. The Beas river is an important rivers of north-western India that originates in the western Himalaya. It nourishes a large population by the way of irrigation, hydroelectricity, recreation, domestic water supply etc. falling in its catchment area. The basin is subjected to various hydroclimatological hazards (sudden landslides, glacial lake outbursts, debris flow, and flash floods) emanating from the frozen masses.

Glaciers in the BRB have been reported to be in the retreating phase and in future, this will result in water scarcity for the people living in the mountain region and in the downstream area who depend on glaciers and snow as a source of freshwater. Hence, the study was conducted for assessing long-term glacier fluctuation in the BRB of western Himalaya using geospatial techniques.

Study Area

The present study area, Beas River Basin (BRB) lies between 31°09’-32°22’ N latitudes and 77°05’-74°58’ E longitudes covering an area about 19100 km². The river Beas originates in Beas Kund near Rohtang Pass of the Pir Panjal range at an altitude of 14,308 feet above mean sea level (amsl). The entire basin is spreading in parts of nine districts viz. Chamba, Hamirpur, Kangra, Kinnaur Kullu, Lahaul and Spiti, Mandi, Shimla, Una in Himachal Pradesh (HP), and six districts namely Hoshiarpur, Gurdaspur, Amritsar, Kapurthala, Jalandhar, Firozpur of Punjab (PB) States of India (Fig. 1).

Physiographically, the BRB is very diverse. It can be classified into 1). The Greater Himalayan Ranges, 2). The Middle Himalayan Ranges, 3). The Shiwaliks, 4). The Kandi Region 5). The Alluvial Plains. BRB gives an ideal representation of all three stages of a fluvial system. One can observe substantial heterogeneity in altitude from one part of the basin to the other. The elevation ranges between 166 m asl in the plains to more than 6500 m asl in the Great Himalayan range. It has a catchment area of 19096.8 km².

The headwaters of Beas are at ‘Beas Kund’ at an altitude of 4361.07 meters (14,308 feet) above sea-level (asl) which is located near the southern face of ‘Rohtang Pass’. Several tributaries namely Parbati, Sainj, Suketi, Tirthan Bain, Banganga, Luni, Uhal, Banner, Chakki, Gaj, Harla, Mamuni, Patlikuhlal etc. are fed the river to drain nearly 470 km length before meeting the river Sutlej at Harike Wetlands.

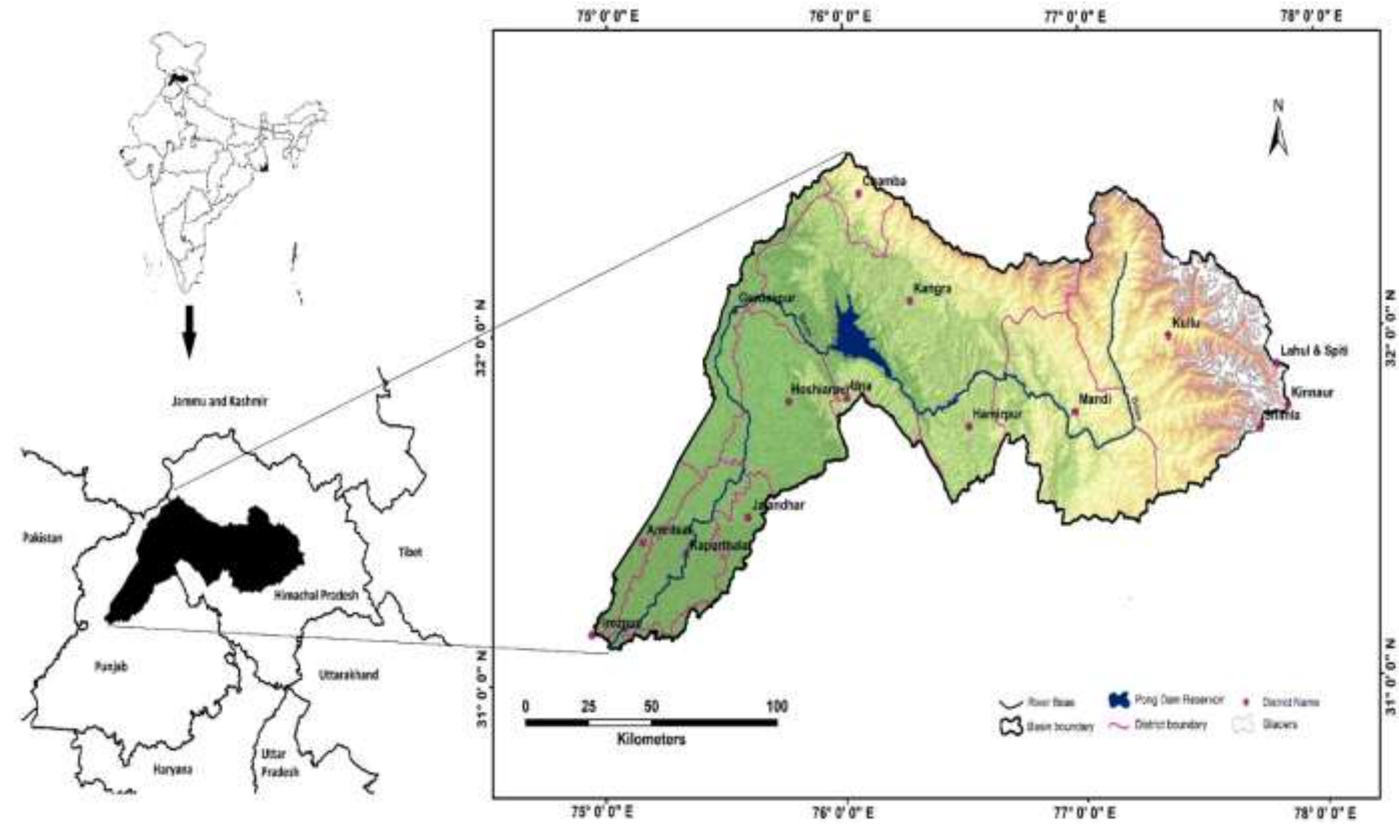

Figure 1: Location map of the study area

The upper Beas river basin (UBRB) is a hilly region experiencing a pleasant and cool climate throughout the year with heavy snowfall during the winter months. However, the lower Beas river basin (LBRB) is in highly monotonous alluvial plains with an extreme type of climate during summers and winters. It is semi-arid and hot in plains, sub-humid and less hot in valleys and foothills, warm and temperate in hilly and mountains, cool and temperate in middle Himalaya and cold alpine and glacial in Lahaul and Spiti region. Waters of the Beas and its tributaries are being used for irrigation, hydroelectricity, recreation, domestic water supply etc. It has a fairly steep gradient of 24 meters per km[17] in its upper part and gentle gradient of 1.5 meters per km[24] in the lower part.

Due to the presence of steep slopes, high drainage density, and mountainous terrain, the maximum number of dams and powerhouses of the Indus basin fall in Beas sub-basin. The largest surface water body falling in the sub-basin is the Pong reservoir in Himachal Pradesh.

Material and Methods

Dataset

- 1954 Topographical sheets at 1: 50,000 scale by Army Map Services, United States Army for glacier boundary delineation.
- The 2018 ALOS Global Digital Surface Model (ALOS World 3D – 30m (AW3D30) Version 2.1) by Japan Aerospace Exploration Agency (JAXA) for hypsometric distribution of the glaciers.
- United States Geological Survey (USGS)Landsat Images for the years 1976, 1990, 2000, 2010, 2018 for snow cover distribution.
- Google Earth Pro High-Resolution Images for accuracy assessment and ridgeline enhancement.
- Randolph Glacier Inventory version 6.0. Glacier boundaries have been taken from Randolph Glacier Inventory version 6.0, 2017 to measure the temporal variations in individual glaciers from 1954 to 2001-2002.

Glacier Boundary Delineation: In this study, manual digitization of glacier boundaries is done using 1954 topographical sheets at 1: 50000 scale by Army Map Services, United States Army. Accuracy assessment of glacier boundaries and ridgeline enhancement by visual interpretation is performed using google earth pro, high-resolution images. Necessary precautions and utmost care were taken for an error-free visual interpretation. Randolph Glacier Inventory (version 6.0.) has been used for temporal assessment and change analysis of the glaciers in the BRB.

Hypsometric Analysis: The 2018 ALOS Global Digital Surface Model (ALOS World 3D – 30m (AW3D30) Version 2.1) was used to generate contours and hypsometric analysis of relief and glaciers in the basin. Version 2.1 of AW3D30 was released in April 2018 by the Japan Aerospace Exploration Agency (JAXA). To mark the actual snow-covered area at different elevations we divided the basin into twelve altitudinal zones with an interval of 500 meters (Table 1). Besides, for ease of processing satellite data effectively, we have taken only the UBRB for hypsometric and snow cover analysis since glaciers and snow are confined to the higher elevations only.

Snow Cover Mapping: The investigations were carried out using Landsat Multi-Spectral Scanner (MSS), Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Optical Land Imaging (OLI) images of 1976, 1990, 2000, 2010 and 2018. These images were used to calculate the Normalized Differential Snow Index (NDSI) to prepare snow cover maps. NDSI method is generally used for snow cover mapping using satellite data.[9,10,22] It is one of the most commonly used methods for snow cover mapping using optical remote sensing, which is defined in terms of the green (G) and SWIR spectral bands of electromagnetic spectrum. It is calculated as:

$$NDSI = (G - SWIR) / (G+SWIR)$$

Snow is normally assumed to be present if the NDSI exceeds a value of 0.4. Details of the multitemporal Landsat images used in the study area are given in table 2.

Table 1
Area-altitude distribution in different zones of the study area

Zone	Elevation Range	Area (km^2)	Percentage	Zone	Elevation Range	Area (km^2)	Percentage
1	500 – 1000	1322	9.44	7	3500 – 4000	790	5.64
2	1000 – 1500	3988	28.49	8	4000 - 4500	660	4.72
3	1500 – 2000	1719	12.28	9	4500 – 5000	747	5.34
4	2000 – 2500	1179	8.42	10	5000 - 5500	702	5.02
5	2500 – 3000	1223	8.74	11	5500 - 6000	458	3.27
6	3000 – 3500	1137	8.12	12	Above 6000	72	0.51

Table 2
Satellite data used in the study

Year	Satellite	Sensor on-board	Spatial Resolution	Date of Acquisition	Wavelength (micrometres)	Swath (km)
1976	Landsat 3	Multi-Spectral Scanner (MSS)	80	04-Nov-1976 09-Dec-1976	0.5 – 0.60	185
1990	Landsat 5	Multi-Spectral Scanner (MSS)	30	09-March-1990 21-May-1990	0.52 – 0.62	185
2000	Landsat 5	Thematic Mapper (TM)	30	20-March-2000 29-March-2000 21-April-2000	0.52 – 0.60	185
2010	Landsat 7	Enhanced Thematic Mapper Plus (ETM+)	30	09-Marsh-2010 01-April-2010	0.52 – 0.60	185
2018	Landsat 8	Operational Land Imager (OLI)	30	31-March-2018 23-April-2018	0.53 – 0.59	185

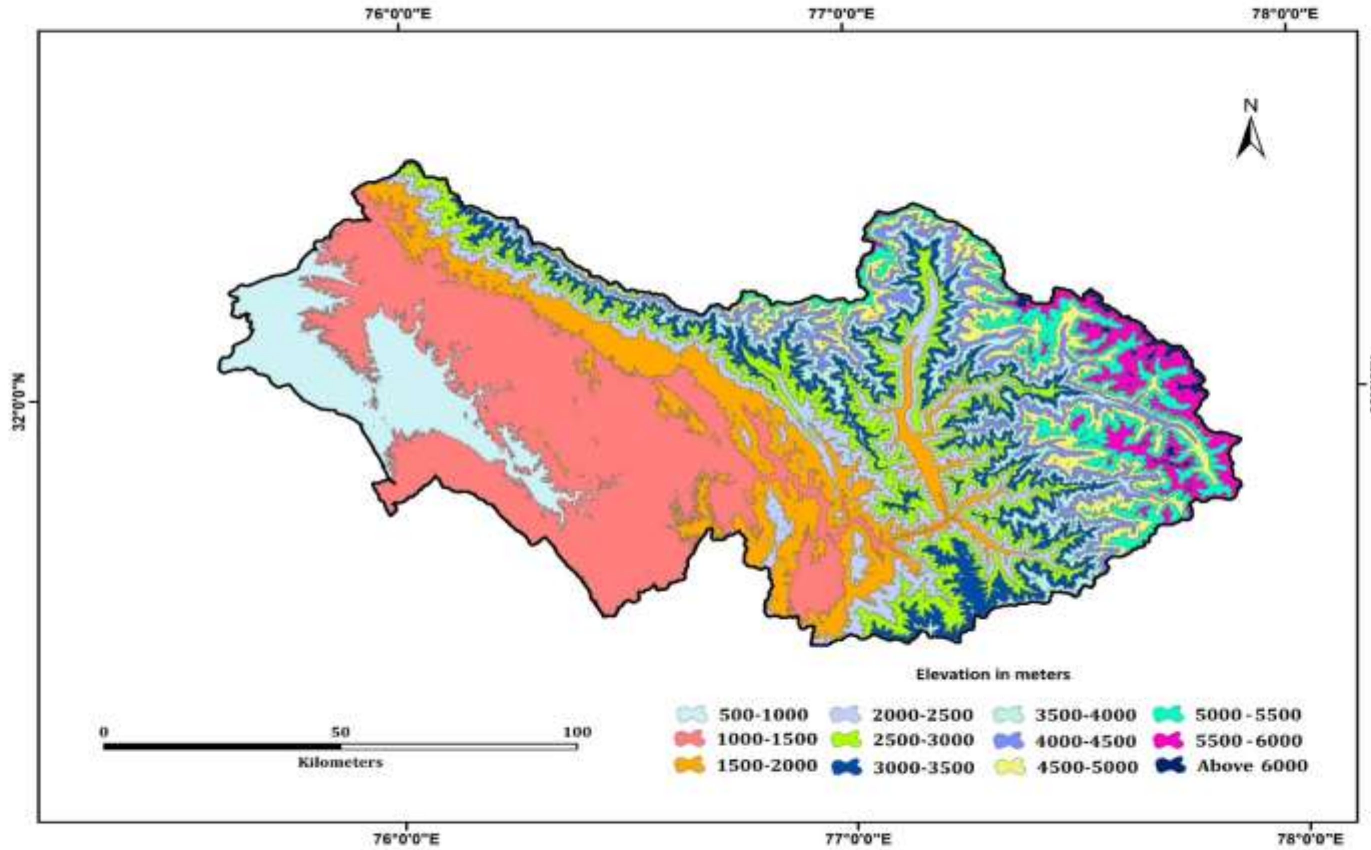

Figure 2: Various Elevation Zones of the Upper Beas River Basin, Western Himalaya

Results and Discussion

The study area had been categorized into twelve altitudinal zones at an interval of 500 meters (Fig. 2). Hypsometric analysis revealed that the elevation in the upper Beas basin ranges from 245 m up to 6586 m asl. The maximum area (28.49 percent) of the basin comes under 1000-1500 m altitude followed by the area under the 1500-2000 m category. On the other hand, only 8.8 percent area of the basin was above 5000 m asl and is occupied chiefly with seasonal and perpetual snow in the form of glaciers and snow patches.

Glacier fluctuations in the study area: During 1954, 667.05 km² of area accounting for 3.51 percent of the total area of the BRB was under glacier ice and permanent snow (Fig. 3). The size of the glaciers ranged between 0.025 km² to 88.55 km². The glaciers were given codes as BB1954G1 (here, BB – Beas basin, 1954 – the year of delineation and G1 – glacier number one). BB1954G35 was the smallest glacier with only 0.025 km² area. BB1954G94 was the largest glacier with 88.55 km² area. The average size of the glaciers in the basin was 1.198 km².

In 2002, the number of glaciers increased to 470 accounting for only 2.613 percent of the total area of the basin (Fig. 4). The size of the glaciers during 2002 ranged between 0.049 km² to 33.207 km². RG160-14.15556 was the smallest glacier with only 0.049 km² area and RG160-14.16065 was the largest glacier with 33.207 km² area. The total area enveloped by snow cover was 503.59 km² and the average size of the glaciers was reduced to 1.07 km².

Some studies using remote sensing data are performed to estimate the glacier retreat for 466 glaciers in Chenab, Parbati, and Baspa basins revealing overall deglaciation of 21% during 1962–2001. It is observed that the average size of the glaciers has reduced from 1.198 km² in 1954 to 1.071 km² in 2002. There has been a tremendous rise in the number of glaciers in the basin from 1954 to 2002.

Although the actual number of glaciers in the study area increased, the total area under snow cover and glaciers has reduced from 3.51 percent during 1954 to 2.613 percent during 2002. BRB has lost an area almost equal to 163.46 km² during the second half of the twentieth century. we have classified the glaciers into five categories viz. less than 1km², 1-10 km², 11-20 km², 21-40 km², and more than 40 km² (Table 3).

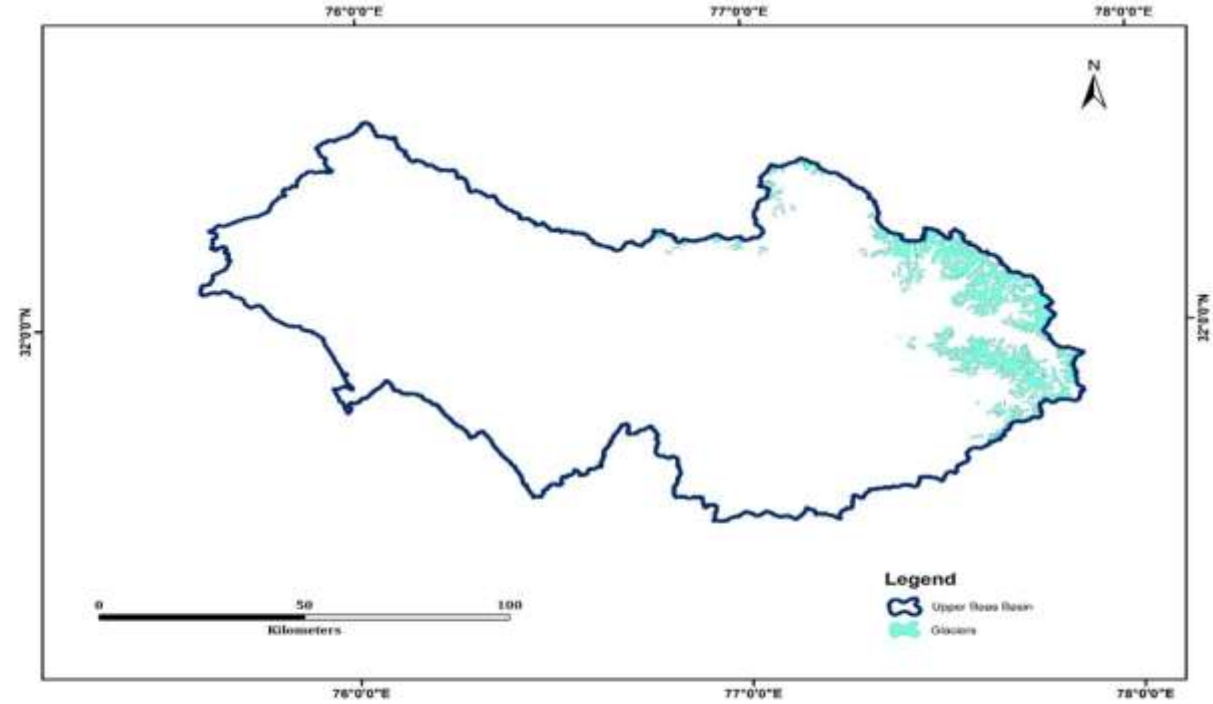

Figure 3: Glacier extent in the upper Beas river basin during 1954

Table 3
Number of glaciers under different categories on the basis of area

Category	1954				2002			
	Number of Glaciers	Area (km²)	% area of glaciers	% area of whole basin	Number of Glaciers	Area (km²)	% area of glaciers	% area of whole basin
Less than 1 km²	99	48.24	7.26	0.24	377	111.10	22.06	0.57
1 – 10 km²	68	219.27	33.04	1.13	84	215.23	42.73	1.11
11 – 20 km²	06	90.91	13.70	0.46	07	96.02	19.06	0.49
21 – 40 km²	05	148.55	21.86	0.74	05	81.23	16.13	0.41
More than 40 km²	02	160.07	24.12	0.82	00	00	00	00
Total	**180**	**667.05**	**100**	**3.510**	**470**	**503.59**	**100**	**2.613**

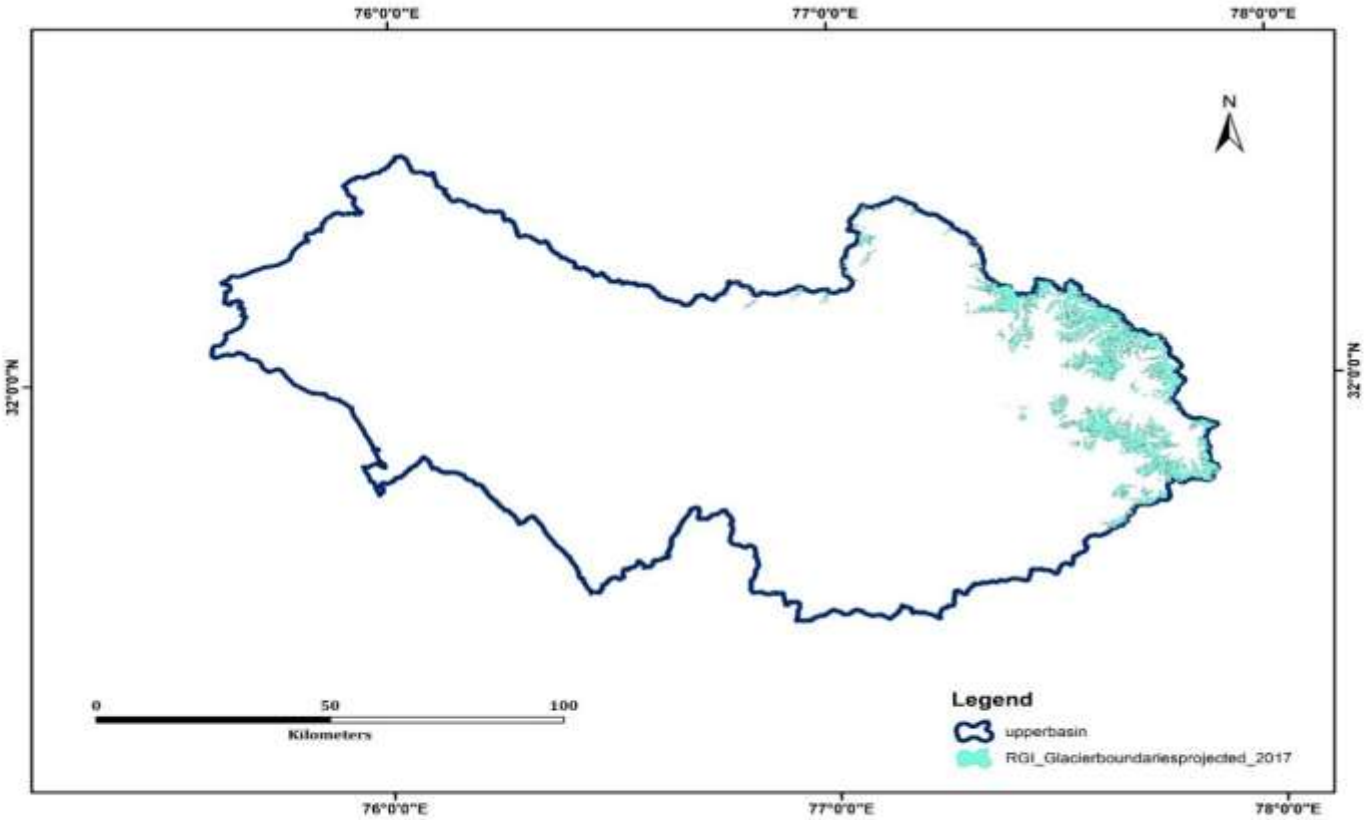

Figure 4: Glacier extent in the upper Beas river basin during 2002

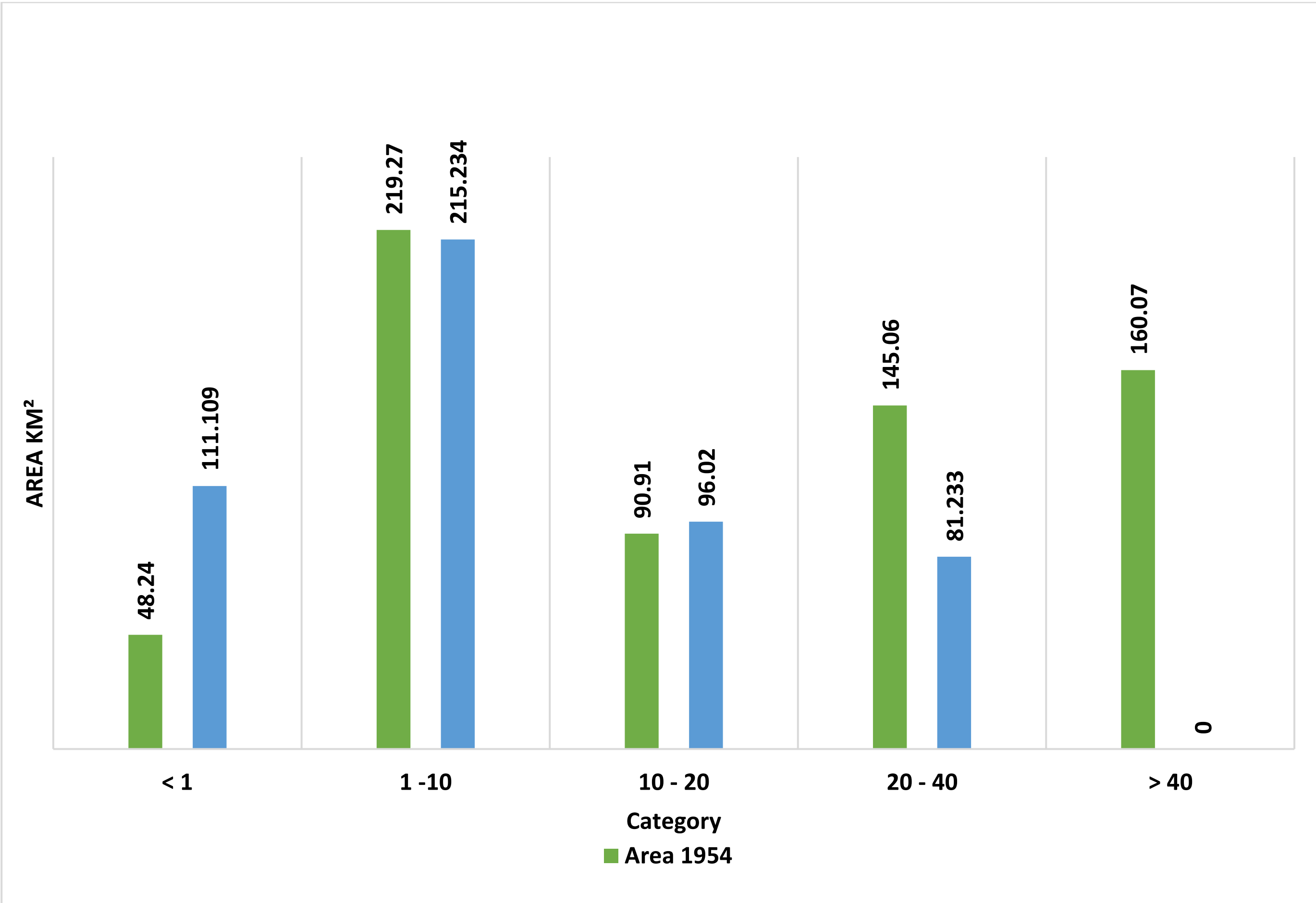

Figure 5: Change in area under various elevation categories in the year 1954 and 2002

Spatially glacier fluctuations were noted heterogeneous. During 1954 the maximum glacier area of approximately 219 km² noted in 1-10 km² and the minimum area of around 48.24 km² were dominated with glaciers of less than 1 km². In 2002 an enormous difference was witnessed in the actual number of glaciers as well as the total glacier area (Fig. 5). The basin encountered a vast increase in the number of glaciers from 99 in 1954 to 377 in 2002 under less than 1km² category. The number of glaciers falling in more than 40km² reached zero. The investigation has revealed that the glaciers in the basin are disintegrating and losing their mass (Fig. 6).

Besides, we observed that the actual area falling under less than 1km² category has increased from 48.24 km² in 1954 to 111.10 in 2002. Although the 21-40 km² class has recorded no change in the actual number of the glaciers, yet a large area has been lost (approximately 66.76 km²) during 1954-2002. Therefore, it is clear that bigger glaciers in the basin are losing their area as well as quantity (mass balance) due to disintegration and excessive melting.

Temporal Variations in Snow Cover Distribution: Spatio-temporal investigation of snow cover in the study area revealed that during 1976, 1112.57 km² masked by snow cover accounted for 5.78 percent area of the basin which later on increased to 6.68% during 1990. It is recognized that there was an increase of 264.94 km² in the snow cover area in the basin from 1976 to 2000 and it started declining afterward. During 2010 snow cover has reduced from 1377.51 km² in 2000 to 1145.39 km² in 2010 losing an area of 232.12 km over barely ten years. In 2018 approximately 5.88 percent area of the basin was under snow cover (Table 4).

Decadal Snow Cover Area Change in Different Elevation Zones: It has been observed that over time snow cover in various elevation zones was noted with a differential rate of ablation and areal coverage throughout the basin (Fig. 7). BRB generally has snow cover found to be present between elevations ranging from 3000 to above 6000 m above sea level (asl).

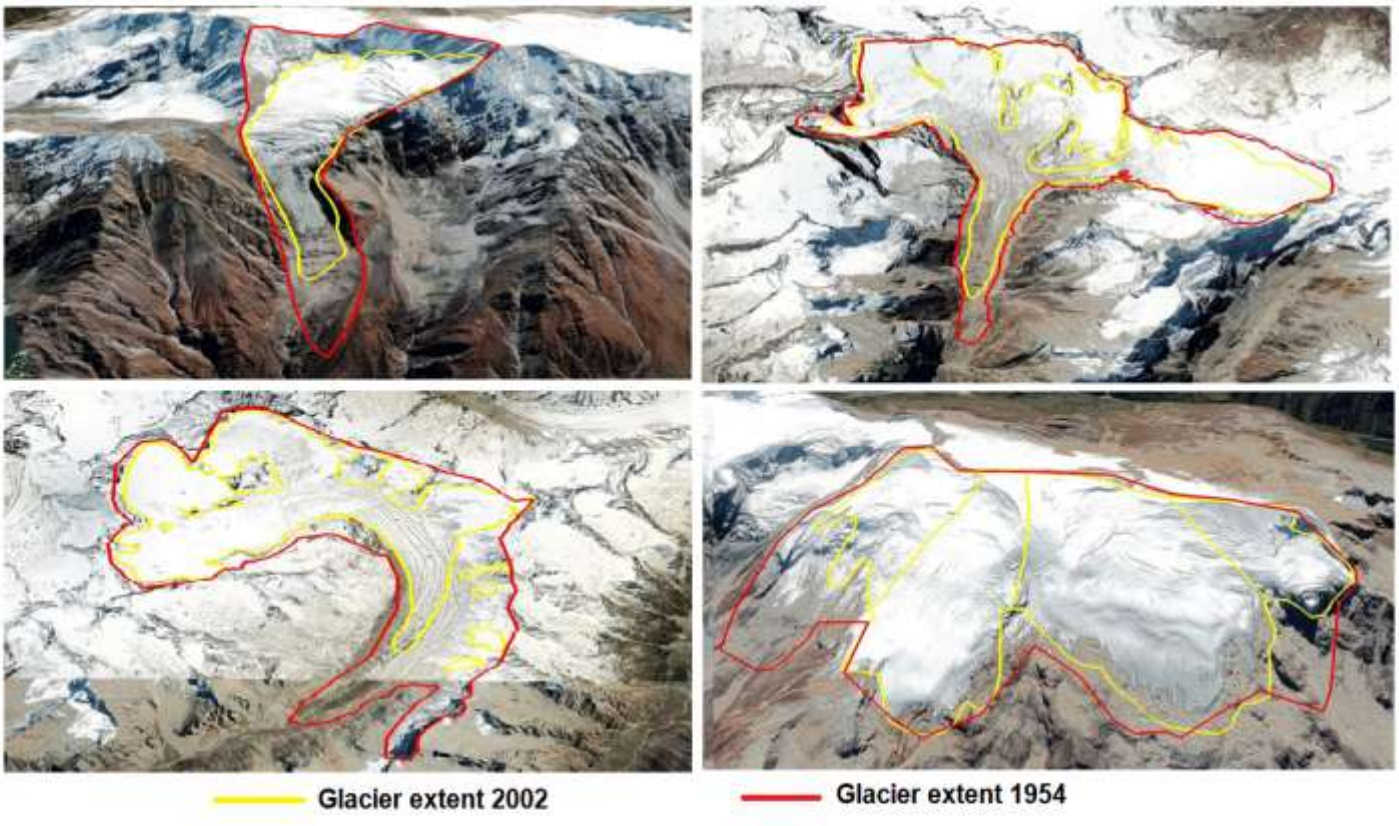

Figure 6: Glacier retreat observed in various glaciers in the study area

Table 4
Snow cover distribution in Beas Basin from 1976 – 2018

Year	1976	1990	2000	2010	2018
Area (km²)	1112.57	1287.79	1377.51	1145.39	1133.56
% of Basin Area	5.77	6.68	7.15	5.94	5.88
Change in Snow Covered Area (km²)	-----	175.22 (gain)	89.72 (gain)	-232.12 (loss)	-11.83 (loss)

Although, few snow patches with an area of only a few square meters descended as low as 2500 m asl during 1976 and 1990. The total snow cover in the study area during 1976 was 967.23 km² which increased to 1352.02 km² in 2000 and reduced to 1107.37 km² in 2018. It has been noted that since 1976, maximum snow cover was present in the elevation zone of 5000-5500 m asl with 34.85%, 39.98%, 33.09%, 31.23% and 39.89% of total snow cover in the study area during 1976, 1990, 2000, 2010 and 2018 respectively (Table 5). Annual fluctuations in snow cover were most apparent between 3500-4000 asl where snow cover increased from 6.76 km² during 1976 to its maximum of 25.04 km² in 2010 and reduced to its minimum of only 0.74 km² in 2018.

The investigation has also revealed that snow cover in BRB has the highest concentration between 5000 – 6000 m asl because more than 50 percent of snow area is restricted between this elevation with the maximum area of 69.41 percent and 68.5 percent of total snow cover of the basin during 2018 and 1990 respectively.

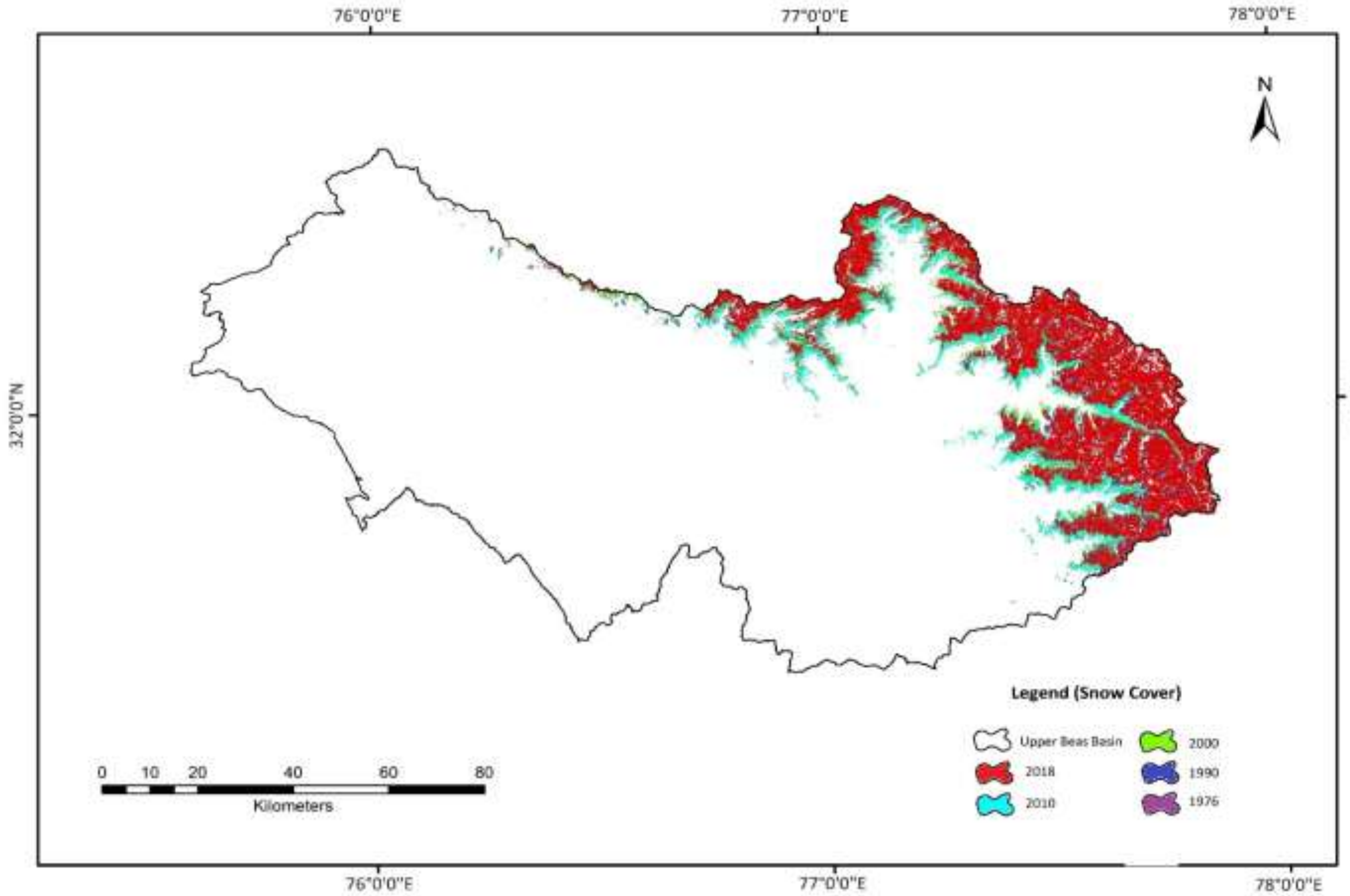

Figure 7: Snow cover fluctuations in the upper Beas river basin: 1976-2018

Table 5
Decadal Snow Cover Fluctuations in various elevation zones (1976 – 2018)

Elevation Range	Area 1976	Percent of total snow cover	Area 1990	Percent of total snow cover	Area 2000	Percent of total snow cover	Area 2010	Percent of total snow cover	Area 2018	Percent of total snow cover
3000-3500	0.22	0.02	1.81	0.14	0.33	0.03	1.16	0.10	0.00	0.00
3500-4000	6.77	0.70	4.57	0.36	19.84	1.47	25.05	2.19	0.74	0.07
4000-4500	81.42	8.42	45.91	3.65	179.94	13.31	167.55	14.65	37.73	3.41
4500-5000	201.60	20.84	299.69	23.81	377.24	27.90	312.57	27.32	259.89	23.47
5000-5500	337.12	34.86	503.29	39.99	447.49	33.10	357.27	31.23	441.80	39.90
5500-6000	296.03	30.61	358.87	28.51	306.04	22.64	250.11	21.86	326.75	29.51
Above 6000	44.07	4.56	44.52	3.54	21.14	1.56	30.24	2.64	40.47	3.66
Total	**967.23**	**100**	**1258.67**	**100**	**1352.02**	**100**	**1143.94**	**100**	**1107.38**	**100**

Snow cover distribution at different altitudes also highlighted that maximum portion of snow cover to the total area of the respective elevation was located in zone 7 with 64.63 percent of the total area blanketed by snow followed by zone 8 and zone 6 with 61.20 and 48.02 percent of the total area under snow during 1976. However, the snow cover increased impressively between 5000-6000 elevation during 1990. During the year 2000, a shift was observed with much more snow accumulation at lower elevations. Although the maximum percentage of snow cover remained restricted to zone 7 (5500-6000 m asl), yet a substantial increase witnessed amid 4000-5000 m asl.

During the year 2000, zone 4 (4000-4500 m asl) grew 20.31 percent larger as compared to 1990 along with an increase of 77.5 km² in snow cover in zone 5 (4500 - 5000 m asl). On the other hand, an enormous loss of snow area was observed in zone 8 (above 6000 m asl) losing almost 33 percent snow cover as compared to the previous decade. In 2010, the drift of descending snow cover to lower elevations seems to be in the retreating phase because the percentage of snow cover at lower elevations has decreased enormously as compared to 2000. By 2018 snow cover distribution in BRB resembled almost similar as it was in 1990 with the maximum area under snow in higher elevation zones viz. zone 7, 6 and 8.

Conclusion

Snow cover and its changes over a period of more than 60 (1954-2018) years were studied in Beas basin using conventional toposheets, Randolph Glacier Inventory and Landsat data. It is found that the basin has lost nearly 25 percent of its glaciers since 1954. However, snow cover analysis using Landsat images from 1976 to 2018 points to contradictory findings as it registered an increase in snow cover from 1976 to 2018 without a definite trend. Snow cover has continuously increased till 2018 from the base year (1976) but there have been continuous changes in the rate of progression from one decade to another. An increase in snow cover has been recorded during the last quarter of the twentieth century which again began to lose area under snow cover afterward.

About 17 percent of basin snow-covered area was lost between 2000 and 2010**.** The hypsometric analysis revealed that maximum snow cover is bound to higher elevations due to falling temperatures with increasing altitude. Almost 70 percent of snow cover in the basin was located above 5000m asl in all the decades except 2000-2010. It can be concluded that the glaciers in the study area are losing area on one hand and facing disintegration on the other hand. During the study period many glaciers vanished due to increasing temperatures at the higher altitude areas of the basin. Besides many new glaciers came into existence due to disintegration and changing patterns of snowfall.

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