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Recession and reconstruction of Milam Glacier, Kumaon Himalaya, observed with satellite imagery

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The Himalaya is the adobe of one of the world's largest and mostly inaccessible area of glaciers outside the polar regions and provides glacier-stored water to the major Indian river basins. Various studies suggest that many of the Himalayan glaciers have receded in recent decades due to climate forcing. Temporal satellite data analysis shows that the Milam Glacier in Goriganga Basin, Kumaon Himalaya receded 1328 m laterally and 90 m vertically during 1954–2006. The enhanced satellite imagery helps in establishing the extent of the glacier in inaccessible terrains like the Himalaya.

Keywords: Glaciers, reconstruction, retreat, river basins, satellite imagery.

THE Himalaya is one of the youngest mountain systems on Earth, and has a direct influence on the climate, hydrology and environment of the Indian subcontinent. Glacier inventory carried out by the Geological Survey of India (GSI) depicts the existence of over 9000 glaciers in the Indian administered part of the Himalaya[1]. Many of the Himalayan rivers are fed by snow and ice melt run-off from snow fields and glaciers.

Observations showed that the 20th century was a period of glacier retreat in almost all alpine regions of the world with accelerated glacier ice and snow melting in the past two decades[2–4]. The Intergovernmental Panel on Climate Change (IPCC) considered the mountain glacier as the top priority climatic indicator due to the sensitivity of glaciers to climate[5]. According to the field measurements of the 18 weather stations in western Indian Himalaya screening an increase in seasonal mean, maximum and minimum temperatures by ~2°C, 2.8°C and 1°C from 1984/85 to 2007/08 respectively[6]. Glaciological studies carried out by various researchers in the Himalayas suggest that many of the glaciers are in a state of retreat due to climate forcing[7–14]. Satellite-based glacial studies of 466 glaciers in Chenab, Parbati and Baspa basins show overall 21% deglaciation from 1962 to 2001 (ref. 15). A similar study carried out in the Chandra river basin, Himachal Pradesh, showed that Samudra Tapu Glacier receded 741 m between 1962 and 2000 (ref. 16). All these studies suggest that most of the Himalayan glaciers have been losing volume and receding in recent decades. Hence it is essential to examine the health of these glaciers and their response to climate forcing for the future water resource assessment.

In the field of glaciology, satellite remote sensing has been proven to be the best tool because many of the glaciers are located at very high altitude, cold weather and rugged terrain conditions, making it a tedious, hazardous and time-consuming task to monitor by conventional field methods[15–19]. Satellite remote sensing technology facilitates to study the behaviour of ice masses of the Himalaya systematically with a cost to time benefit ratio. Changes in glacier area and terminus position are being used extensively as an indicator of glacier response to climate forcing[20]. These two parameters are relatively easy to extract from multispectral satellite imagery. In the Himalaya, many glaciers are not capable of dynamically adjusting for the accelerated warming by retreat, and also respond by down-wasting and decoupling of glacier parts[3,15,21,22]. Considering the receding trend of the

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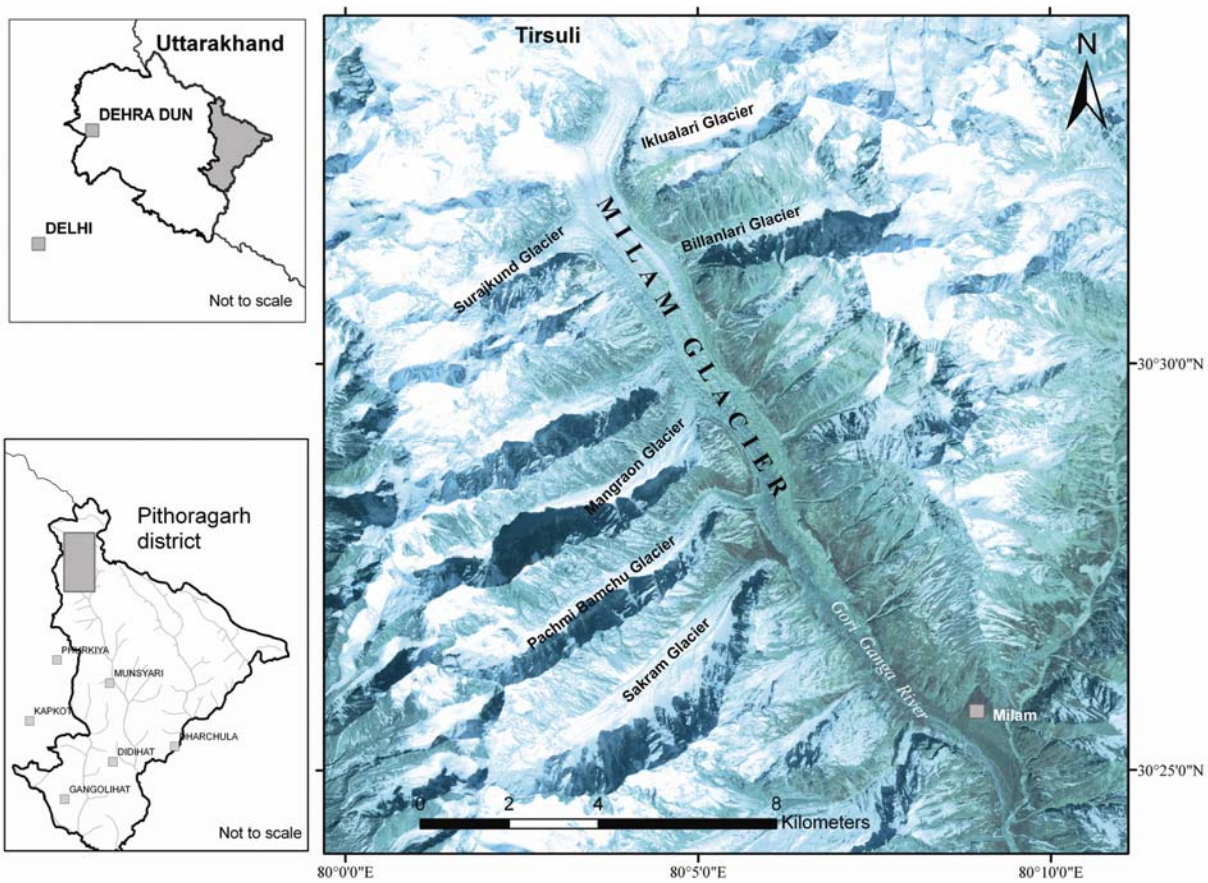

Figure 1. Location map of Milam Glacier and tributary glaciers.

Table 1. Satellite and topographic data used in the present study

Satellite data	Sensor	Spatial resolution (m)	Date of acquisition
Landsat-2	MSS	57	15 November 1976
Landsat-5	TM	30	15 November 1990
Landsat-7	ETM$^+$	30	15 October 1999
Resourcesat-1	LISS III	23.5	5 May 2006
Topographic data			
Map		Scale	Year
Topographic map		1 : 250,000	1954
Open series map		1 : 50,000	1988

glaciers in the Himalaya, the present study aims to analyse the recession of the Milam Glacier using temporal satellite imagery along with ancillary maps and also to reconstruct the extent of the glacier.

The Milam Glacier (30°26′N, 80°03′30″E) is the second largest glacier of the Kumaon Himalaya. It is 16.7 km long and receives ice from two cirques on the Trishul peak and seven tributary glaciers in the Goriganga basin[23]. The ablation area of the glacier is covered with supra-glacial moraines and debris. The Goriganga River, a major tributary of the Kali River, originates from the Milam Glacier. The glacier is a valley glacier having compound basin orienting towards SE from the Trishul peak. The location map of the Milam Glacier and tributary glaciers are shown in Figure 1.

The Landsat MSS, Landsat TM, Landsat ETM+ and Resourcesat-1 LISS III satellite data are used in the present study and details of datasets are given in Table 1. Glaciological study such as mass balance, etc. requires data of August–September season because of less fresh snow cover for delineation of the equilibrium line. However, the present study involves mainly delineation of the terminus portion of the glacier. Hence satellite data devoid of fresh snow at lower altitudes of the glacier were selected. Apart from satellite data, topographic map prepared by Survey of India in 1954 of 1 : 250,000 scale, Survey of India Open Series Map (OSM) surveyed in 1988 with a scale of 1 : 50,000 and ASTER Global Digital Elevation Model (DGM) (www.gdem.aster.ersdac.or.jp) were also used.

Deriving glacier outlines from satellite data is well established[15,21,22,24,25]. The steps include geo-rectification of maps, orthorectification, co-registration, interpretation and digitizing the glacier outlines. The conversion of datum (Everest to WGS84) of ground control points (GCPs) of the topographic map (1954) is performed using the coordinate conversion program developed by Survey

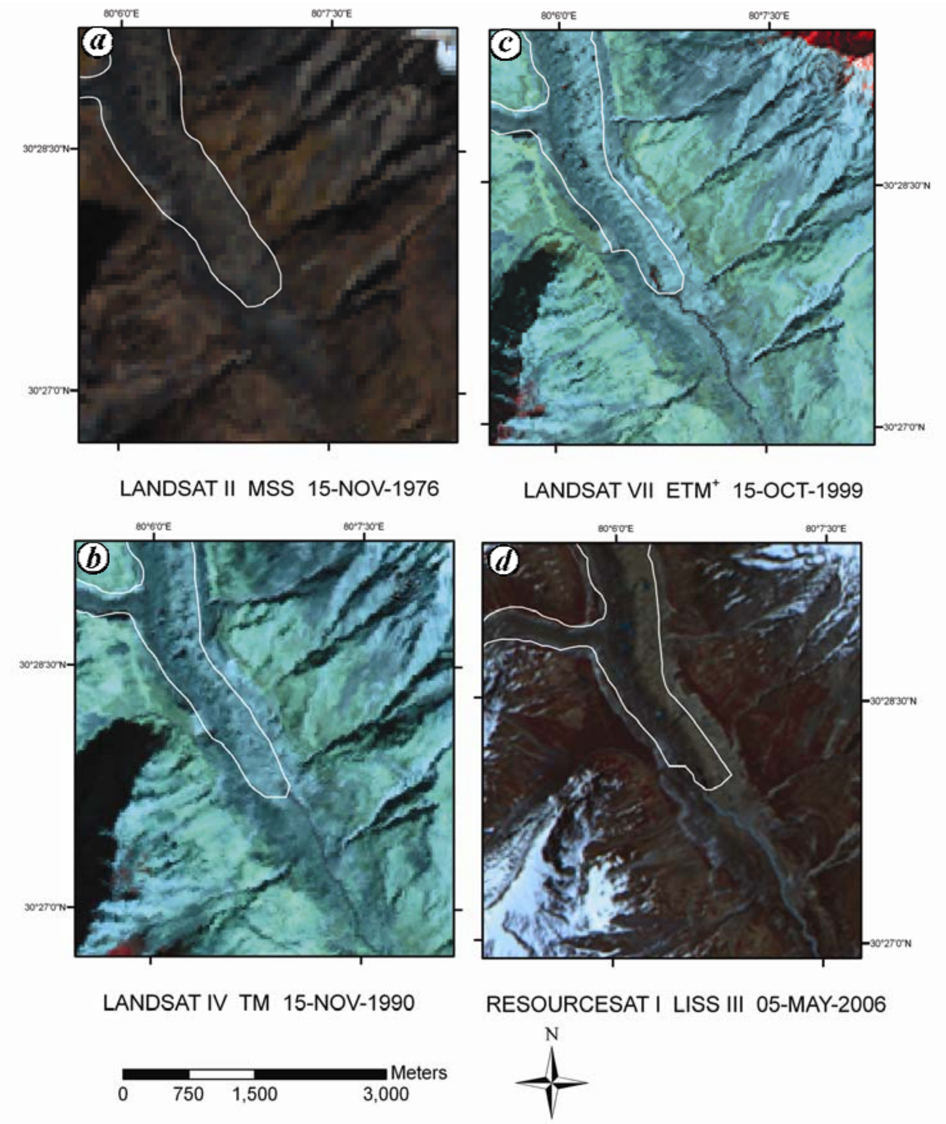

Figure 2. Terminus boundary of Milam Glacier in different time periods: (***a***) Landsat-II MSS 1976; (***b***) Landsat-IV TM 1990; (***c***) Landsat-VII ETM$^+$ 1999 and (***d***) Resourcesat-1 LISS III 2006.

of India (www.surveyofindia.gov.in) and reprojected in ERDAS Imagine 9.3 software package. Orthorectification of IRS P6 LISS III imagery was performed using ASTER DEM in ERDAS Leica Photogrammetry Suite based on 18 GCPs with an RMSE of 33.6 m. All other satellite imageries were resampled to 30 m and co-registered to the orthorectified LISS III imagery of the study area. Co-registration of images was performed using 22 interactively collected GCPs to obtain satisfactory RMSE values (1.4 pixels or 40 m). The initial boundary of the Milam Glacier was digitized from the topographic map having UTM projection and WGS84 datum and the same was used for determining glacier length and snout position during 1954. Subsequently, the Milam Glacier terminus position was digitized from satellite imageries of 1976, 1990, 1999 and 2006, and also from the OSM map surveyed in 1988 (Figure 2). Delineation of the Milam Glacier terminus from satellite imagery was carried out using standard false colour composite (FCC) band combination of SWIR, NIR and green bands for red, green and blue channels respectively. Reflectance of debris/rock in SWIR band was higher than that of ice; therefore, debris cover on the glacier gives a red tone[26] in the aforementioned FCC image. Snow is characterized by a high reflectance in visible spectral region and a rather strong absorption in the SWIR region. Therefore, ratio of visible band/SWIR band can differentiate the snow and non-snow covered surfaces. A better method of discrimination is Normalized Difference Snow Index (NDSI) using the visible and SWIR band properties of snow. NDSI takes advantage of the spectral differences of snow vis-à-vis non-snow covered areas (including clouds), but it also tends to reduce the influence of atmospheric effects and viewing geometry[27]. The NDSI method was not applied in the present study due to non-availability of atmospheric parameters. In this study, band rationing of visible/SWIR bands has been applied for all the satellite images to differentiate snow and non-snow covered surfaces of the Milam Glacier.

The snout of the glacier is clearly visible as a large ice wall in all the band-ratioed satellite imageries. Depending upon the relative position of the sun and the wall, it can form a shadow in the downstream region, which also can be used as an indicator of terminus delineation[22,28]. The location of the Milam Glacier snout on the enhanced imagery was confirmed based on clues from associated features such as the origin of the stream from the glacier apart from tonal and textural differences. The Milam Glacier retreat was measured along the maximum length of the glacier by overlaying glacier boundaries in GIS environment.

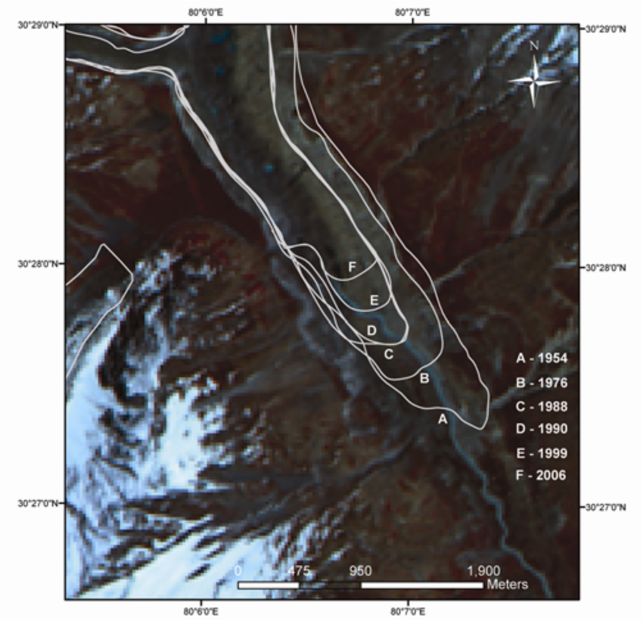

Figure 3. Retreat map of Milam Glacier in different time periods (1954, 1976, 1988, 1990, 1999 and 2006).

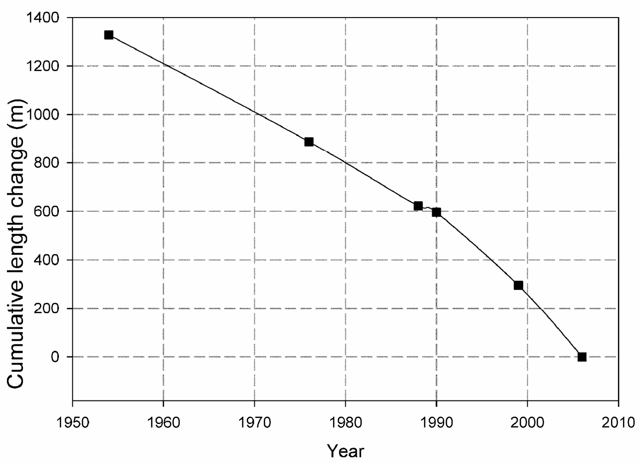

Figure 4. Cumulative changes in length of Milam Glacier from 1954 to 2006. Satellite-based observations are available for 1976, 1990, 1999 and 2006. Total loss in glacial length from 1954 and 2006 is 1328 m.

The historical recession of the Milam Glacier reported by Cotter and Brown[29] in 1907 and later by Jangpangi[30] in 1958 illustrates that the glacier retreated 800 m (1849 to 1906) and further 620 m (1906 to 1957) respectively. The reduction in glacier retreat during the first half of the 20th century may be partly attributed to the climate fluctuations. It is well known that glacier fluctuations are not uniform throughout the history. Observations of Ahmed[23] showed that during the Pleistocene, the Milam Glacier extended 32 km downstream of its position in 1962. The initial boundary of the Milam Glacier was delineated from the topographic map of 1954 (1 : 250,000 scale). This boundary was superimposed on the resampled and co-registered satellite images of 1976, 1990, 1999 and 2006, and the terminus of the glacier was delineated with an RMSE of 40 m. The Milam Glacier boundary was also digitized from the OSM map (1 : 50,000) surveyed in 1988. All the boundaries were superimposed on the LISS III data of 2006 and retreat measurements estimated along the maximum length of the glacier. Table 2 describes the variable glacier retreat measured during the analysis of datasets. This indicates an overall retreat of 1328 ± 40 m from 1954 to 2006, with an average retreat of 25 m per year (Figure 3). The accelerated glacier recession in recent years (1999–2006) is considerable and the present study confirms this in many Himalayan glaciers[14,15,22], which appears to be the result of a change in the regional climate. The thinning of glacier terminus was also observed during the study. The loss in glacier length from 1954 to 2006 plotted in Figure 4, shows the receding trend of the glacier.

The analysis of snout altitude derived from the toposheet (1954) and OSM map (1988) shows that the glacier snout was at an altitude of 3490 m and 3520 m during 1954 and 1988 respectively (Table 2). The location of the snout in the satellite data of 2006 was at an altitude of 3580 m, indicating a vertical shift of the snout 90 ± 33 m in a span of 52 years.

Principal component (PC) analysis carried out on IRS LISS III imagery and moraines was visually demarcated from PC images. Features such as sharp bending of Goriganga stream channel at the downstream are clear indicators of the occurrence of moraines. Isolated patches of ridges/debris mounds found to deviate the stream flow at different levels were distinctly traceable on the enhanced

Table 2. Snout recession of Milam Glacier between 1954 and 2006

Year	Maximum length (m)	Recession (m)	Rate/yr (m)	Snout altitude (m)
1954	18,067	–		3490
1976	17,627	440	20	3500
1988	17,361	266	22	3520
1990	17,335	26	13	3524
1999	17,035	300	33	3540
2006	16,739	296	42	3580

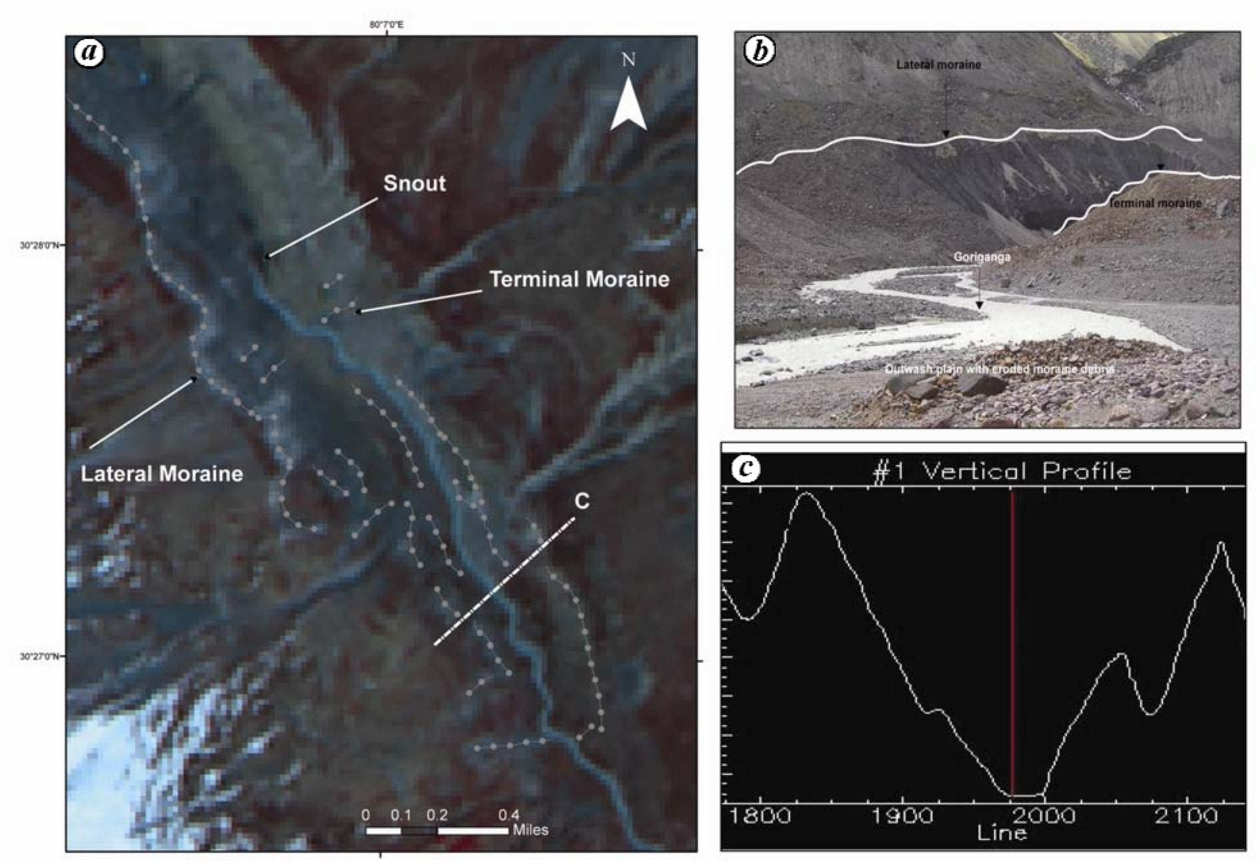

Figure 5. ***a***, Enhanced LISS III imagery showing the moraines. ***b***, Field photograph showing the lateral and terminal moraines and outwash plain. ***c***, Vertical profile of deglacial valley derived from DEM.

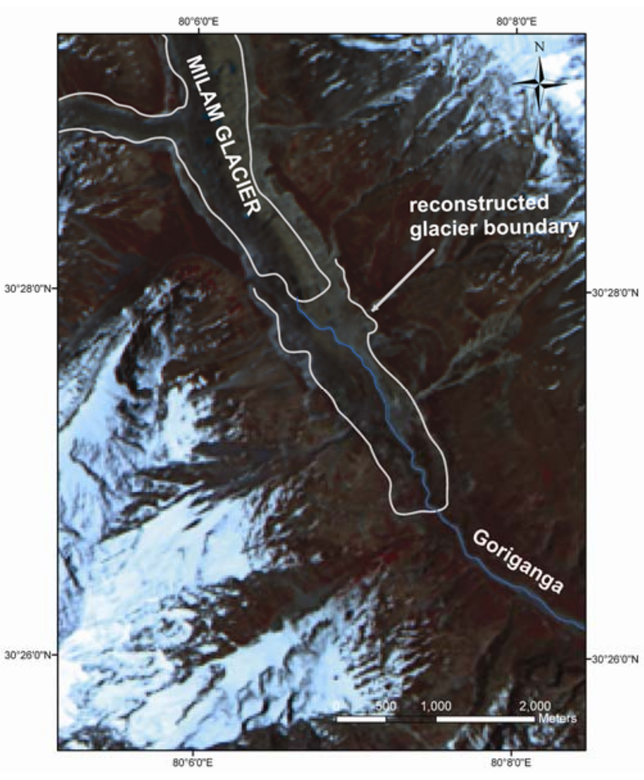

Figure 6. Palaeoextent of Milam Glacier derived from LISS III satellite imagery.

satellite imagery (Figure 5 *a*). Supplementary information from field photographs (acquired on 2 June 2004) has also validated the presence of moraines. The photographs confirm the trend of a long lateral moraine along the SW portion of the glacier and a terminal moraine near the present terminus with the stream following in a sinusoidal fashion (Figure 5 *b*). The vertical valley profile generated from ASTER DEM data shows the broad, U-shaped environment of the deglaciated valley (Figure 5 *c*). The earlier glacier extent was demarcated based on the presence of trend and extent of the moraines; broad, U-shaped valley and image texture. The analysis shows that in the past, the Milam Glacier terminus was extended 2.4 km downstream of its position in 2006. The reconstructed glacier extent is shown in Figure 6 and is harmonizing with the observations of Cotter and Brown[29], and Jangpangi[30].

Globally, glaciers are considered to be the sensors of climate change. Any small disparity in the climate will affect the accumulation and ablation rate of glaciers, which in turn affects mass balance of the glaciers. Accurate determination of these glacier changes may be useful in assessing regional hydrological responses in Indian rivers. The retreat of glaciers in the Himalaya has significant impact on the environment, including freshwater supply, diminishing wetlands and unstable stream runoff. It has been observed that the Milam Glacier terminus receded laterally 1328 ± 40 m with a variable annual rate of 25 m and vertically 90 ± 33 m between 1954 and 2006. The space imagery was used to reconstruct the palaeo-extent of the Milam Glacier to 2.4 km downstream of the present terminus position.

The study shows that repetitive space-borne optical data can be used to obtain glacier dynamics of inaccessible terrains of the Indian Himalaya. Orthorectification minimizes distortion effects from uneven topography and allows data from different sensors to be used accurately. The ASTER DEM is found to be promising for glaciological study such as mass balance estimation. The approach presented here opens new perspectives for observing and understanding spatio-temporal variability of glaciers in the Himalayan terrain using satellite data. The lack of *in situ* meteorological data in many parts of the Indian Himalayan terrain limits better understanding of such environmental changes measured from space.

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