Earth Syst Environ (2017) 1:1
DOI 10.1007/s41748-017-0001-2

ORIGINAL ARTICLE

Remote Sensing-Based Study for Evaluating the Changes in Glacial Area: A Case Study from Himachal Pradesh, India

Praveen Kumar Rai[1] · **Varun Narayan Mishra**[2] · **Shweta Singh**[1] · **Rajendra Prasad**[2] · **M. S. Nathawat**[3]

Received: 2 November 2016 / Accepted: 19 March 2017 / Published online: 30 March 2017

Abstract
Purpose Glaciers influence a variety of natural systems in the environment and act as a key source of freshwater worldwide. Remote sensing satellite data has proved to be important tool for defining the glacier inventory and retreating pattern of a glacial region.
Methods An attempt has been made to investigate changes in glacial area of five selected glaciers i.e. Bara shigri, Chota shigri, Hamtah, G4 and Parvati glacier in Himanchal Pradesh from 1976 to 2013 through the LANDSAT data of MSS (1976), TM (1989 and 2009), ETM+ (2001) and OLI-TIRS (2013) whereas ASTER-DEM data was used for relief information. Glacier snout positions were demarcated by identifying glacier features such as the origin of the stream from the terminus, supraglacial lakes, and disposition of end moraines. The uncertainty (*U*) was calculated for multi-temporal measures of the glacier front position using these images.
Results Amongst the selected five glaciers in which snout could be demarcated accurately for all the datasets, three glaciers experienced very nominal retreat of their terminus; the maximum retreat (6.63 m) was calculated in the case of G4 glacier while Humtah glacier exhibited advancement in 37 years. However, Bara shigri glacier experienced a retreat of 1.50 m. The study shows that the glacial covered area reduced from 154.58 to 123.39 km^2 indicating 20.17% deglaciation during the period from 1976 to 2013.
Conclusion The outcome of this study may obligatory to monitor spatio-temporal changes in glaciers and their conservation towards the sustainable management of water resources in Himalayan river watersheds.

Keywords Glacier · Retreat · Inventory · Landsat · ASTER-DEM · Remote sensing

✉ Praveen Kumar Rai
rai.vns82@gmail.com

Varun Narayan Mishra
varun9686@gmail.com

Shweta Singh
shweta.rajput2013@gmail.com

Rajendra Prasad
rprasad.app@itbhu.ac.in

M. S. Nathawat
msnathawat@ignou.ac.in

[1] Department of Geography, Institute of Science, Banaras Hindu University, Varanasi, U.P. 221005, India

[2] Department of Physics, Indian Institute of Technology (BHU), Varanasi, U.P. 221005, India

[3] School of Sciences, Indira Gandhi National Open University, New Delhi 110068, India

1 Introduction

Glaciers are not only a dynamic component in energy and mass exchange within the earth's atmosphere, but also natural freshwater reservoirs. It contributes in the global water cycle and is an essential component of the water balance (IPCC 2007). The present study covers a part of the Himalayan region. Himalayas connotes 'abode of snow' in 'Sanskrit texts' and snow in the world after Antarctica and Arctic. It encompasses a large number of glaciers. It is assumed that about 15,000 glaciers are located throughout its ranges which normally fall in remote inaccessible parts of the mountainous terrain. The research of glacier melting is important for studies of sea level changes that also may have a significant risk for the residents of coastal areas.

That is one of the most negative impacts of modern climatic change on mankind. The above mentioned facts put into agenda the necessity for detailed study of the glaciers (Kordzakhia et al. 2015). The Himalayan glaciers are valuable national as well as global assets and act as main reservoir of snow and ice pouring almost all major and minor rivers of north India and their conservation are helpful to the sustainable development of fresh water resources in Himalayan region. Besides, the Himalayan glaciers respond directly and promptly to the atmospheric conditions (Favier et al. 2004; Thayyen and Dimri 2014). It has been established that the regional meteorological conditions have a bearing on the hydrological features associated with these glaciers (Bollasina et al. 2002).

Majority of Himalayan glaciers are valley type and controlled by topography (Bahuguna 2003) and a major source of fresh water, and all the rivers in northern India are sustained by melted waters of these glaciers, thereby affecting the quality of life of millions of people (Vohra 2006). There are around 9575 glaciers present in the Indian administered part of the Himalaya (Sangewar and Shukla 2009) covering an area of approximately 37,466 km^2 (Raina and Srivastava 2008).

Glaciological inventory have been proved as an important tool in revealing the advancement and retreating of glacier. Changes in the regimen of glaciers give clue in determining the state of advancement, recession and/or stagnation (Thayyen and Dimri 2014). The glaciers retreat has been significant since the mid of the nineteenth century (Hastenrath 1995; Kaser 1999); therefore, glaciers have more recently become the subject of intensive observation.

The Himalayan glaciers have also allured researchers who used different methodologies to unveil its different aspects particularly retreating phenomena. The International Panel of Climate Change (IPCC 2007) stated that 'Himalayan glaciers are shrinking faster than any other parts of the world'. The statement created reverberations of different tones in the scientific communities; some were in its favor, where as some opined different views.

Several researches in the Himalayan area found that the glaciers have melted considerably during the last two decades (Ageta et al. 2001; Fujita et al. 1997; Kadota et al. 2000; Naithani et al. 2001). Several analyses have shown that it is not only increased temperature and/or decreased precipitation that are responsible for recession of glaciers in lower latitudes, but also changes in humidity (Hastenrath and Kruss 1992; Kaser and Noggler 1991; Kaser et al. 1996; Kaser and Georges 1997; Kaser 1999; Wagnon et al. 1999).

Besides, a numbers of studies using satellite data were made by Bhambri et al. (2011, 2012), Dozier and Hall (1987), Kulkarni et al. (2002, 2004, 2005, 2007, 2011), Kordzakhia et al. (2015), Pandey et al. (2012) and Rai et al. (2009, 2013, 2016). It was showed that the best method for analysis of glaciers is application of combined approach of satellite remote sensing with terrestrial observations and expert knowledge of separate glaciers.

Most of the studies on shrinkage of glacier area in Himalaya are related to climatic variations (Bhutiyani 1999; Bhutiyani et al. 2008; Hasnain 2008; Kulkarni and Bahuguna 2002; Kulkarni et al. 2007). Recession also leads to volume loss in glaciers and increase sea level water rises (Dobhal et al. 2004). Kulkarni et al. (2011) have assessed glacial retreat for 1868 glaciers in 11 basins of Indian Himalaya since 1962 and presented a total deglaciation of about 16%. A detailed study through mapping of Chota shigri, Patsio and Samudra Tapu glaciers in Chenab basin, Parbati glacier in Parbati basin and Shaune Garang glacier in Baspa basin has reported an overall deglaciation of 21% from 1962 to 2001 (Kulkarni et al. 2007). Cruz et al. (2007) have previously studied on two adjacent glaciers of Chandra basin i.e. Bara shigri and Chota shigri and found that these glaciers retreated about 36.1 and 6.7 m/year during 1986–1995 and 1977–1995, respectively.

Since freshwater is vital for human society, there is a critical relationship between the fate of glaciers and sustainability of water resources. Therefore, mapping of Himalayan glaciers is very significant to conservation and sustainable management of water resource. In the present study, an attempt has been made to analyses the changes in area of five selected glaciers during the period 1976–2013 by earth observation data.

2 Study Area

The study area is located in Lahul and Spiti district of Himachal Pradesh in India covering an area of 3944.46 km^2 (Fig. 1). The area also covers a small portion of Kullu and Kinnaur district of the state. It ranges from the Shivalik hills in the south to the Greater Himalayan ranges in the north. Geographically the area is situated between 31°44′8.971″N to 32°27′42.191″N latitude and 77°7′32.103″E to 78°1′4.625″E longitude and its altitude varying between 1081 and 6582 m in the central Himalayan ranges of Lahul and Spiti. Geographically the region relates to the warm temperature zone of Mediterranean region, but the high Himalayan mountains range and southwest monsoon act a key role in changing the climate from time to time. Slightly, rainfall on the glacier surface and heat from bedrock also adds to melting from the glaciated zone (Rizvi 1987; Upadhyay et al. 1989). This area also experience rainfall in summer season due to Asian monsoon in the months from July to September and in lesser amount in winter, i.e., from January to April.

Five selected glaciers-Chota sigri, Bara sigri, Hamtah, G4 and Paravati were selected for the study. These glaciers

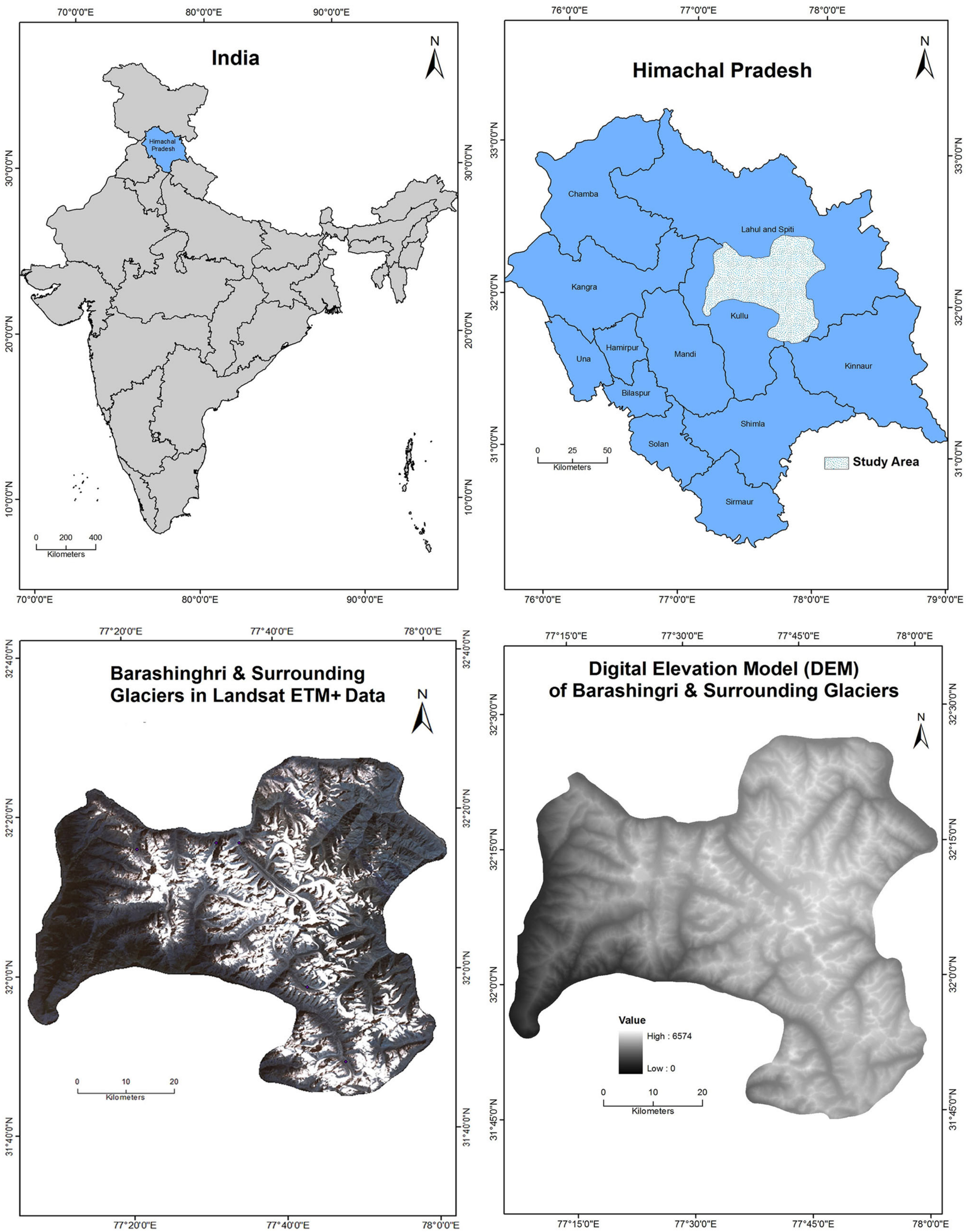

Fig. 1 Study area as viewed on Landsat ETM+ data and ASTER-DEM

are well interpreted on the satellite data. Brief descriptions of these glaciers are given below.

2.1 Chota Shigri Glacier

It is a valley type compound glacier and situated to the west of Bara shigri glacier moving down from south to north. The glacier is oriented roughly north–south in its ablation areas, and has variety of orientations in the accumulation area. The glacier slopes in the lower and higher regions are about 10°–16° and 40°–45°, respectively. Mainly, Chota shigri exist in the Chandra basin on the northern ridges of Pir Panjal range in the Lahul-Spiti Valley of Himachal Pradesh, India. Chota shigri glacier is fed mainly by two tributary glaciers from the east and west, both of which initiate in the area of peaks located at 5274 and 5437 m, respectively (Sangewar and Shukla 2009; Wagnon et al. 2007).

2.2 Bara Shigri Glacier

Bara shigri glacier is the largest glacier (30 km long) situated in the Himachal Pradesh, India and second largest glacier in Himalaya after Gangotri which is located in the Chandra valley of Lahul District at an elevation varies from 3950 to 4570 m above msl. It feeds the Chenab River. Bara shigri glacier flows northwards and emerges into the Chenab River whose southerly course is deflected westward, close to the Spiti border.

2.3 Hamtah Glacier

The Hamtah glacier lies between 32°16′18″N to 32°12′48″N latitude and 77°21′20″E to 77°23′31″E longitude in Chandra Basin of Chenab catchment. The length of the glaciers is about 6.0 km.

2.4 G4 Glacier

As the name of this glacier has not been mentioned in the Survey of India topographical sheet, so it is designated as G4 glacier by the author for the present study. This glacier is geographically located at 77°45′32″E to 77°42′16″E and from 32°0′2.23N to 31°58′47″N covering an area of 14.97 km^2 with a total length of about 10.42 km as analyzed in the satellite data of the year 2013. Initially the glacier flows westward, afterwards to northward.

2.5 Parvati Glacier

This glacier is located on the southern end of study area between 31°49′56″N to 31°45′14″N latitude to 77°47′35″E to 77°48′54″E longitude covering an area of 22.79 km^2 with a length 5.98 km. The flow direction of the glacier is entirely northward.

3 Materials and Methods

In the present work, an integrated use of multi-temporal satellite data and ASTER- DEM were used for generation of database and extraction of various glacier parameters.

3.1 Data Used

Delineation of glacier boundaries were carried our using earth observation data i.e. Landsat MSS (3rd October, 1976), TM (16th October, 1989 and 1st October, 2009), ETM+ (18th October, 2001 and) and Landsat, OLI-TIRS (October, 2013) satellite data (spatial resolution of 72, 36, 30 and 15 m, respectively) which were downloaded from the Earth Explorer website (http://earthexplorer.usgs.gov/). Universal Transverse Mercator projection (UTM) system was followed using WGS-84 datum. Furthermore, DEM with 15 m spatial resolution of ASTER data has also been used for analyzing the snouts elevation by draping the satellite images on the DEM are used to create Contours at an interval of 100 m was created through ASTER DEM data. Details of data used is shown in the Table 1.

3.2 Methodology

The following actions are performed for identification of lakes and glacier terminus delineation according to the developed methodology:

To calculate the changes in the glacier area and snout position using different temporal satellite data and it was needed to rectify all the satellite images. To rectify the satellite images, well distributed ground control points (GCPs) such as river/stream bends, rivers junction, etc. were selected. A second order polynomial with nearest neighborhood resampling technique in digital image processing was used.

Using element of image interpretation, i.e., tone, texture, pattern, shape, size, location, association, etc. (Bhattacharya 1992), the visual interpretation was carried out for extraction of glacier terminus in the study area. Human interpretation remains the best tool for extracting high level information from satellite imagery. Tedious, manual digitalization of glacier boundaries by an operator with good knowledge of the region may produce glacier boundary contours of high quality and accuracy (Kordzakhia et al. 2015). The identification of glacier to satellite data was done using reflectance characteristics of snow and glacier ice, shape of valley occupied by glacier, the flow lines of ice movement and the rough texture of the debris on the

Table 1 Details of the Landsat data specification

Date of pass	Satellite and sensor	Bands and wavelength (μm)	Raw/path	Spatial resolution (m)	Cloud cover
3 Oct 1976	Landsat-MSS	0.5–0.6 (B1)	158/38	72	No
		0.6–0.7 (B2)			
		0.7–0.8 (B3)			
		0.8–1.1 (B4)			
16 Oct 1989	Landsat	0.45–0.52 (Blue-B1)	147/38	30	No
1 Oct 2009	TM	0.52–0.60 (Green-B2)			
		0.63–0.69 (Red-B3)			
		0.76–0.90 (VNIR-B4)			
		1.55–1.75 (SWIR-B5)			
		10.4–12.5 (TIR-B6)			
		2.08–2.35 (SWIR-B7)			
18 Oct 2001	Landsat ETM+	T M Bands (0.50–0.90) and pancromatic band	147/38	30, 15 (panchromatic)	No
21 Oct 2013	Landsat (L8OLI-TIRS)	T M Bands (0.50–0.90) and pancromatic band	146/38	30, 15 (panchromatic)	No

ablation zone (Rees 2005). The occurrence of the shadows of the mountain slopes helps in delineation of extent of glaciers in its accumulation zone which is, however, difficult to be done on the snow covered ridges (Kulkarni and Bahuguna 2001). When the glacier ice is free of moraines or debris, the interpretation of glacier extents is relatively simpler but when the ablation zone of glaciers are covered with it then various clues such as origin of stream, texture of glacier surface, etc. are used for interpretation of glacier extents.

The snout elevations of selected glaciers were recognized using the remote sensing data. With the help of NDWI the position and location of snout are also easily visible in the satellite images. Due to high spectral reflectance of snow in Green, Red and Near Infrared (NIR) bands accumulation zone of glaciers appeared white. Ablation zone of the glacier area was differentiated from the surrounding rocky surfaces (which appear in bright reddish brown color) by its color and longitudinal pattern of moraines. The presence of small supra glacial lakes and ponds over some glaciers were also helpful in accurately delineating the glacier boundary in the debris-covered glaciers. Glacier ice in the ablation zone having lower reflectance than snow in the accumulation zone, but higher than that of rock and soil of the surrounding area gave grayish white tone and could easily be differentiated from the snow in the accumulation zone. The upper boundaries of the glaciers at the accumulation zone were delineated by the ice/snow divide, a line of division between two adjacent glaciers and characterized by Ice movement in two different directions (Kulkarni 1992).

Glacier snout positions were demarcated by identifying glacier features such as the origin of the stream from the terminus, supraglacial lakes, disposition of end moraines. In Himalayan terrain due to the near vertical acquisition of the satellite image, hill shadows create perplexity for the water bodies. Hill shade image generated from ASTER DEM was used to differentiate lakes (Fig. 3). Slope map, and aspect map generated from ASTER DEM are also used for visual interpretation of glacier and for classifying the glacier lakes in combination with optical remote sensing data, i.e., Landsat-TM and ETM+ (Fig. 3).

Glacial accumulation area was interpreted relating to snow-line altitude which was obtained by measuring the distance between ablation area (where snow-melting is the dominant process) and accumulation area (where snow fall is the dominant process). The sum of the glacier accumulation and ablation areas makes a total glacier area Area Accumulation Ratio (AAR) is calculated from accumulation area divided by total glacial area (Kulkarni 1992, Kulkarni et al. 2004; Rai et al. 2009, 2013, 2016). A remote sensing-based calculated AAR is useful for glaciers mapping where field data are not available (Kulkarni 1992). AAR is also helpful in glacier studies to investigate the mass balance both from the field measurements and formula based result as used by Kulkarni et al. 2004. Depth of glaciers of different periods was calculated using a formula as used by Kulkarni (1992) and Kulkarni et al. (2004):

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

where 'H' is the mean glacier thickness (m) and 'F' is the glacier area (km^2). The formula had been previously implemented for measuring the glacier thickness and volume of Himalayan glaciers. Different topographic thematic maps, i.e., slope, aspect, hill shade and relief of the area were produced through ASTER DEM are shown in the Fig. 2.

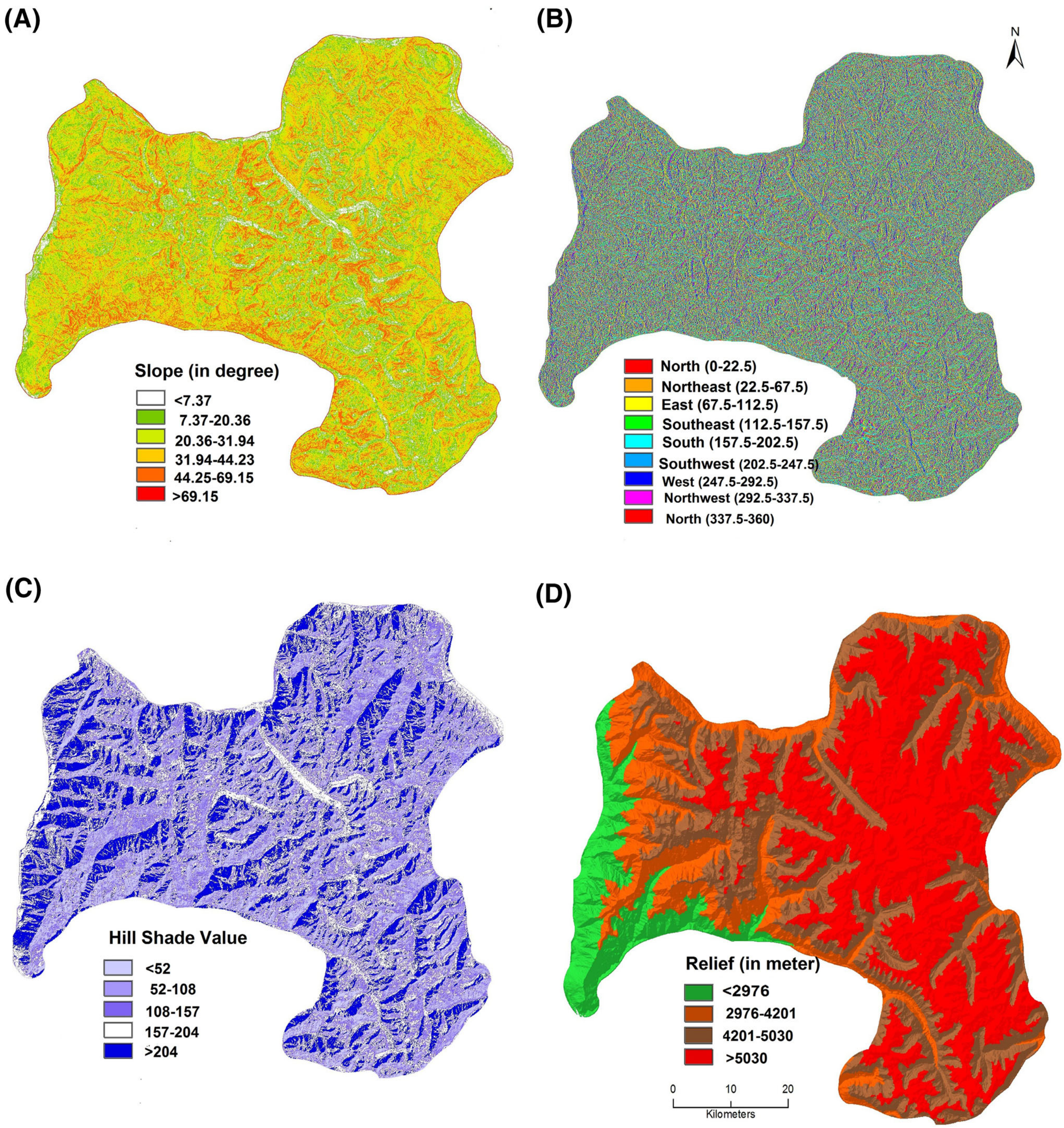

Fig. 2 Different topographic thematic maps produced using ASTER DEM; slope map (**a**), aspect map (**b**), hill shade image (**c**) and relief map (**d**) of the study area

All the information about data and source is summarized in the Table 1.

3.3 Error Estimation and Uncertainty Analysis

Glacier terminus extracted from multi-temporal remote sensing data with fluctuating snow covered area, cloud and shadow situations have dissimilar level of accuracy (Bhambri et al. 2011). The sources of error in area and length assessment are due to co-registration of satellite data and glacier boundary extraction. So, the error calculation is a vital to identify the accuracy and importance of the outcome. The uncertainty (U) was calculated from the following equation for multi-temporal measures of the glacier front position using remote sensing images (Bhambri et al. 2012; Silverio and Jaquet 2005; Wang et al. 2009):

$U = \sqrt{(a^2 + b^2)} + \sigma,$

where 'a' and 'b' are pixel resolution of imagery '1' and '2', respectively, and σ is the registration error.

The registration error though registering Landsat MSS (80 m) of 1976 was around 15 m for Landsat TM of 1992, 10 m for Landsat ETM+ of 2001 and 7 m for 2010 Landsat TM. The uncertainty for glacial area was assessed by multiplication of the uncertainty of length with glacier width. Changes in the snout position of glaciers were measured digitally with an accuracy of ±82 m when registering 1976 MSS image to the base image (Landsat OLI-TIRS, 2013), ±48 m once registering the Landsat TM image of 1992, ±46 m after registering the Landsat ETM+ image and ±49 m when registering the Landsat TM image of 2009 to the base image. The error came during extraction of glacier terminus in GIS was calculated to be one pixel (Congalton 1991; Hall et al. 2003; Zhang and Goodchild 2002).

The uncertainties of the glacier area was estimated by determining a buffer area developed about each test glacier (Bolch et al. 2010; Granshaw and Fountain 2006). The buffer area around each glacier was fixed to double the digitization error (Bolch et al. 2010; Racoviteanu et al. 2008; Wang et al. 2009). Then the amount of uncertainty of glacier area (U_{area}) for each glacier was acquired by the following formula (Hall et al. 2003; Ye et al. 2006):

$U_{\text{area}} = 2UV,$

where U is the terminus uncertainty and V is the satellite image pixel resolution.

Thus the final uncertainty in the glacier area extent was estimated to be ±0.0078 km^2 using 1976 MSS image, ±0.0027 km^2 using 1990 TM image, 0.0024 km^2 by 2001 ETM+ images and 0.0023 km^2 with 2013 Landsat OLI-TIRS.

4 Results and Discussion

4.1 Glacier Area Loss

In order to measure the changes in glaciers terminus on decadal basis, earth observation data of 1976, 1989, 2001, 2009 and 2013 were selected. A nominal decreasing trend was detected in some glaciers area. In the study area, the selected glaciers are showing trends of decreasing accumulation area with increasing ablation zone area passing over time. The accumulation area of Bara shigri glacier is successively decreasing. The total accumulation area of this glacier is 67.85 km^2 in 1976 which has decreased to 53.77 km^2 in 2013.

The total glacier area is showing negative trend excepting in Humtah glacier. The largest glacier, i.e., Bara shigri glacier is covered a total area of 89.83 km^2 in 1976 which has reduced to 15.10 km^2 with a total area of around 74.73 km^2 in 2013. It is the lengthiest glacier of the study area having a length of 26.86 km and a width of 1.13 km. During 2009–2013, a change of 1.28 km^2 of area has been found in the case of Bara shigri glacier whereas its total glacier covered area was decreased by 10.92 km^2 from 1989 to 2001. In this study it is observed that the area of Chhota shigri glacier has increased from 12.28 to 13.77 km^2 during 1976–1989. Its area was observed as 11.41 km^2 in 2013 with a loss of 7.10% in between 1976 and 2013. In the same way, Humtah glacier (its area was 7.17 km^2 in 1976, 5.44 km^2 in 1989, 4.94 km^2 in 2001, 4.76 km^2 in 2009 and 7.01 km^2 in 2013, respectively), are showing gain in the area under glacier from 1976 to 2013. The change in glaciers areal extent from the year 1976 onwards is presented in the Table 2. Humtah glacier area is also increased from 2009 to 2013 showing a positive change in the glacier area (+2.25 km^2).

Table 2 Change in the glacial area area and percentage of glacier area loss

S. no.	Glacier/code	Total glacier area (km^2)					Change in the glacial area				Glacier area loss or gain (1976–13) in %	
		1976	1989	2001	2009	2013	1976–89	1989–01	2001–09	2009–13	Area loss/gain (1976–2013)	Area loss/gain (1989–2013)
1	Barashigri glacier	89.84	87.26	76.34	76.01	74.73	−2.57	−10.92	−0.31	−1.28	−16.81	−14.36
2	Chotashigri	12.28	13.77	13.31	12.57	11.41	−1.49	−0.46	−0.74	−1.16	−7.10	−17.15
3	Humtah glacier	7.17	5.44	4.94	4.76	7.01	−1.73	−0.50	−0.18	+2.25	−2.27	+28.87
4	Glacier 4 (G4)	17.37	14.97	12.39	12.56	8.10	−2.39	−6.87	−0.17	−4.46	−53.35	−45.89
5	Parvati glacier	27.92	28.90	23.90	24.16	22.14	−0.98	−5.00	−0.25	−2.02	−20.72	−23.41

Positive (+) value indicate gain in the glacier area whereas negative (−) value indicate loss in glacier area

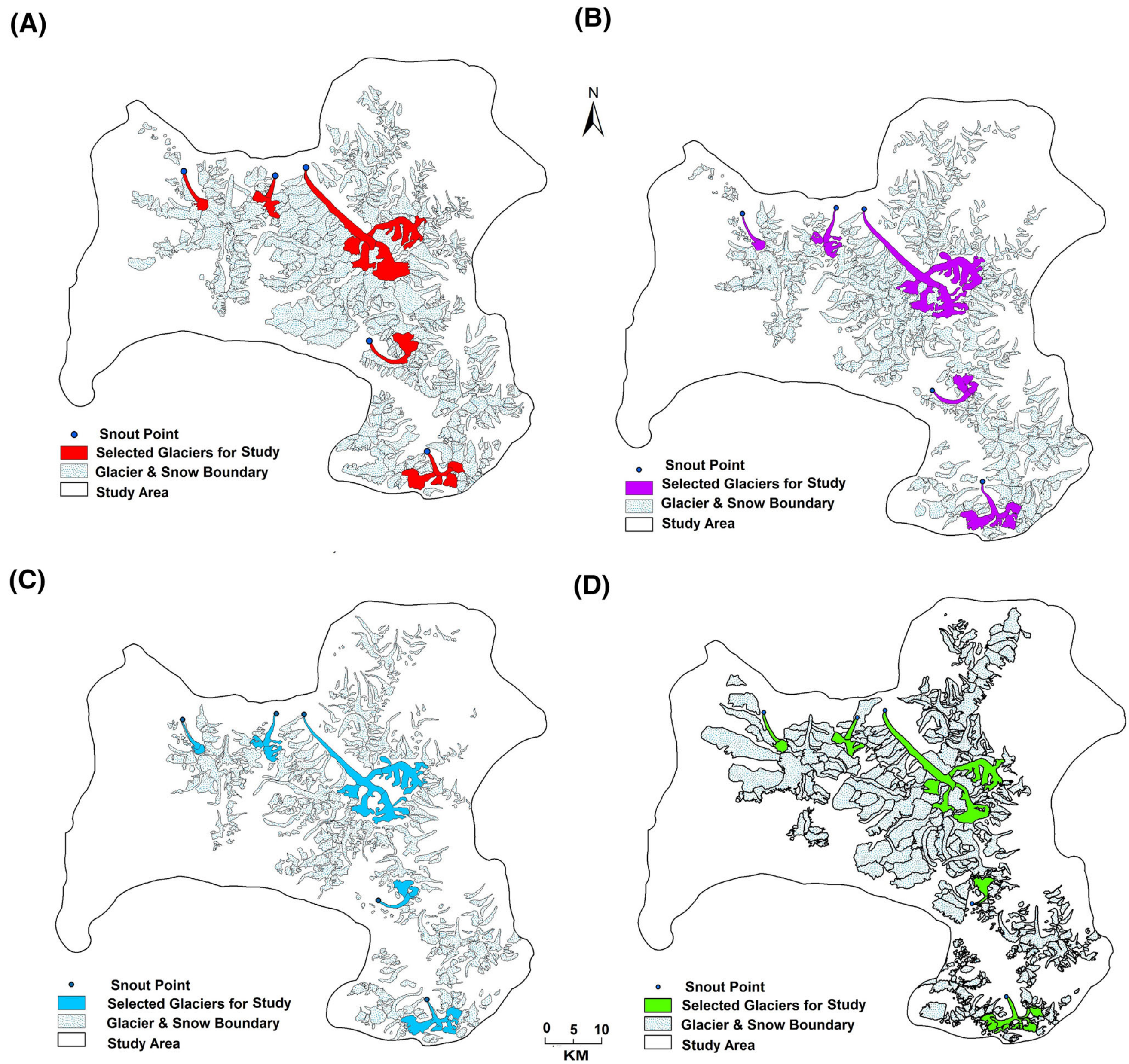

Fig. 3 Areal extent of glaciers as in Landsat MSS of 1976 (**a**), Landsat TM of 1989 (**b**), Landsat ETM+ of 2001 (**c**) and Landsat (L8OLI-TIRS) of 2013 (**d**)

During 2009–2013, glacier G4 displays maximum change in the glacier area (4.46 km^2) but from 1976 to 1989 and 1989 to 2001 it shows 2.39 and 6.87 km^2 change of total glacier area, respectively. The glacier 4 (G4) has experienced maximum glacier area loss (53.35%) during 1976 (17.37 km^2) to 2013 (8.10 km^2).

It was seen that due to reduction in glacier area, a few glaciers have been disjointed from its branch glaciers. This has caused in the decrease in the total glacier extent but equally increases in the number of glaciers. Areal extent of glaciers as in Landsat data of 1976, 1989, 2001, 2009, 2013 are shown in the Fig. 3.

4.2 Changes in Snout Elevation

Change in the snout elevation reveals the dynamic developments operating in the snout area of the glacier. Glacier layers combined with DEM give possibility to determine glacier parameters, i.e., minimum, maximum and mean elevations, snout elevation, snow-line altitude (Kordzakhia et al. 2015). The changes in the snout elevation were calculated by draping the snout position identified in 1976 and 2013 on contour line extracted through ASTER data. The glacier G4 also displays substantial elevation changes in snout position by 53 m during 1976–2013 period which

Table 3 Total changes in snout elevation from 1976 to 2013

S. no.	Glacier/code	Elevation (m)					Total Change in Elevation from 1976 to 2013 (meter)
		1976	1989	2001	2009	2013	
1	Barashigri glacier	3932	3944	3979	3984	3949	−17
2	Chotashigri	3964	3977	4036	4052	4114	−150
3	Humtah glacier	3974	3983	3991	4073	3963	+11
4	Glacier 4 (G4)	4420	4432	4457	4470	4473	−53
5	Parvati glacier	4167	4178	4240	4255	4240	−73

Positive (+) value indicate advancement of glacier snout elevation whereas negative (−) value indicate retreat of snout elevation

Table 4 Retreat and advancement of five selected glaciers

S. no.	Glacier name/glacier ID	Retreat or Advancement (m)				
		1976–89	1989–01	2001–09	2009–13	1976–13
1	Bara shigri glacier	−1.01	−0.35	−0.012	−0.13	−1.50
2	Chota-shigri	−1.01	+0.22	−0.27	−3.28	−2.33
3	Humtah glacier	−0.58	−0.44	−0.55	+1.78	+0.21
4	Glacier 4 (G4)	−3.07	−1.48	−0.31	−1.77	−6.63
5	Parvati glacier	+2.43	−2.54	−0.13	+2.025	−1.78

Positive (+) value indicate retreat of glacier whereas negative (−) value indicate advancement of glacier from two different periods

was 4420 m in 1962 and shifted to 4473 m in 2013, while Bara shigri and Chhota shigri glaciers show 17 and 150 m elevation change from 1976 to 2013, respectively. In this study, it is found that the Humtah glacier shows advancement of glacier snout from 1976 (3974 m) to 2013 (3963 m). Humtah glacier shows 11 m advancement of glacier snout position from 1976 to 2013 (Table 4). From the above observations, it could be remarked that during last 20 years (1989–2009), some of the glaciers were remained nearly in condition in terms of their snout position. Total changes in snout elevation from 1976 to 2013 are given in the Table 3.

4.3 Retreat of Glacier Terminus

The position of the snout could be well demarcated by recognizing geomorphic features i.e. origin of stream from the snout and disposition of end moraines through earth observation data (Kulkarni et al. 2005). DEM data are very significant in evaluation of vertical shift in the snout location. Among the selected 5 glaciers in which snout can be demarcated accurately for all the datasets, 3 glaciers experienced very nominal retreat of their terminus, maximum retreat was observed in the case of G4 glacier (6.63 m) from 1976 to 2013 time period whereas Humtah glacier shows advancement during 37 years (1976–2013). During the last 37 years (1976–2013) it is also observed that Bara shigri glacier shows a retreat of 1.50 m. The value denoted as +ve shows advancement of glacier from one time period to another (Table 4). The reason behind such inconsistent and irregular advancement is correlated with replenishment of these glaciers by increased rainfall at the highest altitudes due to climate warming (Kamp et al. 2011).

4.4 Glacier Morphometric Parameters

Numerous morphometric factors like length, width, area, perimeter, orientation were calculated in this study. Glacial accumulation area is evaluated with respect to snow-line altitude. Snow-line altitude is acquired by calculating the distance between ablation area (where snow-melting is the leading process) and accumulation area.

The individual morphometric characteristics of the five selected glaciers calculated through five multi-temporal earth observation data are given in the Table 5. A look to the selected morphometric parameters reveals that there are minor to major changes in the linear, areal and volume characteristics of five selected glaciers in the study area during 1976–2013. Most of the glacier snouts are generally situated at above 3800 m above msl. There is very nominal recession of snouts of three glaciers to several distances. The advancing and receding snout locations are obviously visible through the presence of terminal moraines. Naithani

Table 5 Selected morphometric parameters of 5 selected glaciers in the study area

Glacier/code	Length (km)	Average width (m)	Area (km^2)	Perimeter (m)	Snout location	Ablation area (km^2)	Accumulation area (km^2)	AAR	AAR (%)	Thickness (m)
Bara shigri	26.93	1385.42	89.84	145.43	77°35′6.393″E 32°16′32.645″N	67.86	21.98	0.24	24.5	193.81
	25.92	1342.61	87.26	182.93	77°35′5.489″E 32°16′27.622″N	20.34	66.93	0.77	77	192.03
	25.57	1275.46	76.34	179.54	77°35′1.039″E 32°16′18.141″N	21.56	54.79	0.72	72	184.03
	25.56	1245.79	76.31	174.54	77°34′56.974″E 32°16′17.116″N	26.21	50.107	0.66	66	184.01
	25.43	1240.42	74.73	155.72	77°35′1.512″E 32°16′22.983″N	20.96	53.78	0.72	72	182.79
Chhota-shigri	8.50	757.23	12.28	27.77	77°31′56.444″E 32°16′42.881″N	9.52	2.76	0.22	22.5	101.60
	9.51	732.48	13.77	44.55	77°31′56.507″E 32°16′39.431″N	4.88	8.90	0.65	65	105.55
	9.73	658.24	13.31	44.27	77°31′54.581″E 32°16′27.12″N	4.86	8.45	0.63	63	104.37
	9.45	739.58	12.57	41.27	77°31′54.654″E 32°16′21.557″N	7.09	5.483	0.44	44	102.39
	6.17	736.59	11.41	21.38	77°31′52.211″E 32°15′44.441″N	3.07	8.34	0.73	61.1	99.13
Humtah	8.04	540.43	7.17	20.37	77°21′13.033″E 32°16′27.515″N	2.21	3.42	0.47	47.7	84.77
	7.46	539.20	5.44	17.66	77°21′19.849″E 32°16′17.503″N	2.73	3.23	0.59	59	77.12
	7.02	533.23	4.94	17.48	77°21′22.694″E 32°16′4.296″N	2.63	2.21	0.45	45	74.61
	6.46	538.16	4.76	18.48	77°21′26.706″E 32°15′44.022″N	3.01	2.137	0.45	45	73.66
	8.25	537.24	7.01	21.38	77°21′18.593″E 32°16′26.772″N	3.75	4.00	0.57	57.1	84.11
G4	13.49	733.36	17.37	34.08	77°35′2.829″E 32°16′35.321″N	11.14	6.22	0.35	35.8	113.97
	10.42	727.43	14.97	36.50	77°42′13.962″E 31°58′50.224 N	5.43	9.54	0.64	64	108.51
	8.94	694.23	12.39	32.47	77°42′50.177″E 31°58′17.683″N	4.05	8.35	0.67	67	101.91
	8.63	683.83	12.56	29.47	77°43′19.087″E 31°58′2.386″N	4.50	8.064	0.64	64	102.37
	6.85	626.23	8.10	21.47	77°44′19.433″E 31°57′44.161″N	1.14	6.96	0.85	61.1	88.35
Parvati	6.23	784.42	27.92	49.37	77°47′35.075″E 31°50′2.813″N	22.93	4.99	0.17	17.9	133.15
	8.66	776.94	28.90	65.73	77°47′37.661″E 31°49′56.958″N	6.98	21.92	0.76	76	134.65
	6.117	710.70	23.90	60.47	77°47′58.124″E 31°48′41.344″N	4.35	19.55	0.82	82	126.56
	5.980	845.13	24.16	60.47	77°48′5.99″E 31°48′31.347″N	5.25	18.903	0.78	78	127.00
	8.01	843.48	19.548	68.62	77°47′53.866″E 31°48′44.49″N	8.24	13.89	0.61	61.1	124.61

The five rows for every glacier are for years 1976, 1989, 2001, 2009 and 2013 from top to bottom

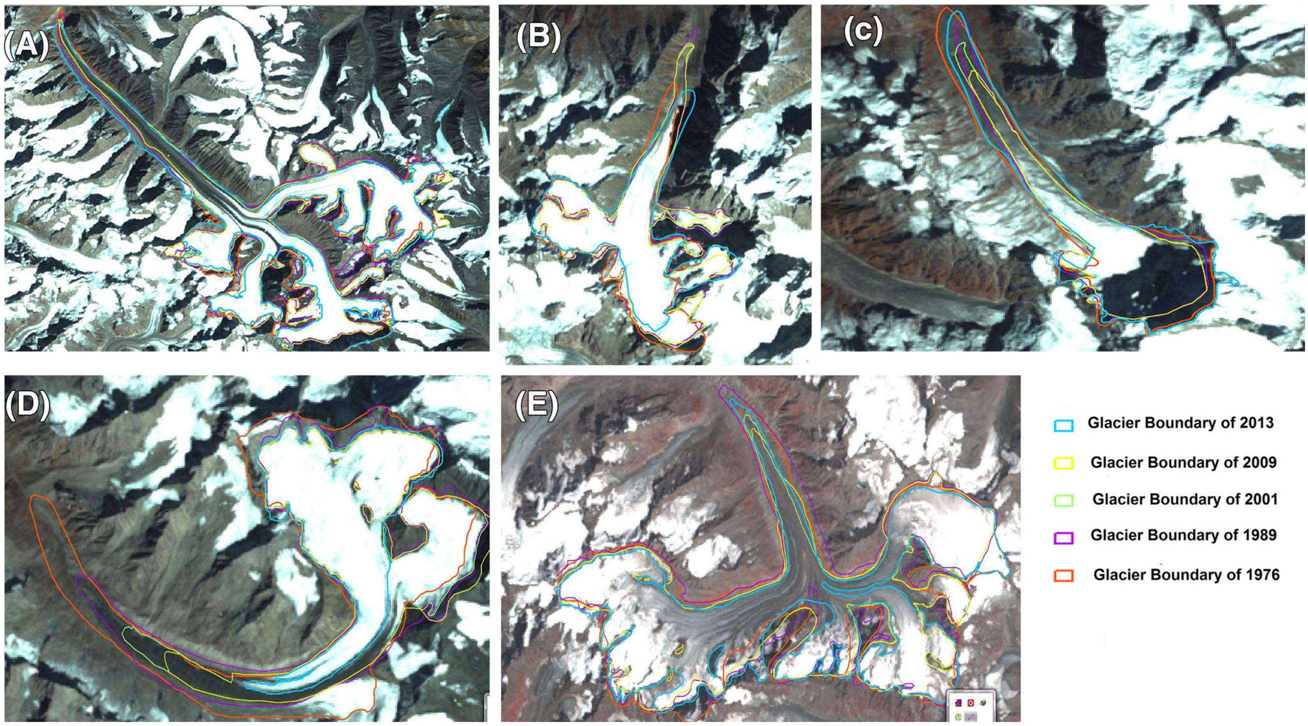

Fig. 4 Glacier fluctuations during 1976–2013 are represented on Landsat ETM+ satellite image of 2001: retreat of terminus of glaciers (**a**, **b**, **d**); advancement of terminus of glaciers identified in 1989 (**c**, **d**)

et al. 2001 have detected that changes of snout position is very common to most of the glaciers in the Himalayan area and that the recession is uneven in quantity and time of occurrence. It is obvious that the glacier recession and advancement are vibrant the best indicator of climatic changes. Glacier fluctuations during 1976–2013 are represented on Landsat ETM+ satellite image are shown in the Fig. 4.

Accumulation areas for each glacier fluctuate from year to year depending upon the snow-line altitude at the end of the ablation season. Accumulation area of the Bara shigri glacier was 21.98 km^2 in 1976, 66.93 km^2 in 1989, 54.79 km^2 in 2001, 50.10 km^2 in 2009 and 53.78 km^2 in 2013 while ablation area of each glacier is very much increased throughout 1976–2001. Thickness of the 5 selected glaciers has been calculated (Kulkarni 1992; Kulkarni et al. 2004). It is found that the thickness of these glaciers are showing decreasing trend during 1976–2013 period. The details of the morphometric parameters of five selected glaciers in the study area are given in the Table 5.

5 Conclusion

The increased accessibility of remote sensing data with appropriate spatial and temporal resolution, global coverage and low financial costs allows for fast, semi-automated, and cost-effective estimates of changes in glacier parameters over large areas. The application of multi-temporal earth observation data made conceivable to examine a larger number of glaciers; which could have not been possible by field investigations in an inaccessible area. Such methods are mainly useful in high altitude area with limited field-based glaciological measurements. The present study delivers a complete multi-temporal glacier inventory data for the five selected glaciers of Himachal Pradesh from 1976–2013. In this study, the glacier terminus and position of glacier snout derived from Landsat data of 1976, 1989, 2001, 2009 and 2013. The valleys of Bara shigri glacial and Parvati glacial show a huge increase in number and area of glacial lakes especially supraglacial lakes. The study also revealed that the overall outline and length of the glaciers in this area are retreating slowly. The rates of retreat vary for different glaciers and it is quite low in comparison to the other part of Himalayan glaciers. Among the five selected glaciers in which snout could be demarcated accurately for all the datasets, three glaciers experienced very nominal retreat of their terminus; maximum retreat was observed in the case of G4 glacier (6.63 m) from 1976 to 2013 time period. In case of Humtah glacier, glacier terminus advancement was observed during the same period (1976–2013). Accumulation area of Bara shigri glacier was 21.98 km^2 while it is 53.78 km^2 in 2013, whereas ablation area of each glacier has very much increased during 1976–2001. In addition, terrain analysis suggests that sudden slope change in glacier bed is also a significant factor distressing the glacier health. In this study it is also found that the thickness of these glaciers exhibiting a decreasing trend from 1976 to 2013. With continuous mapping and monitoring of glaciers and careful validation, these new remote sensing techniques are very important to support the rational distribution and sustainable management of water resources. It is inferred that the findings of this work could be well utilized in understanding the different fluctuation archives of Himalayan glaciers lying in the similar climatic region and increase in the number of glaciers due to disintegration.

Researchers faces certain restriction in accurate inventory of glaciers in the Himalaya region because of limitations imposed on use of Survey of India (SOI) topographic maps of 1.50000 scale of every part of the glaciers and difficulty of acquiring cloud free Landsat and ASTER scenes at the end of the ablation season. Constant acquisition of remote sensing data and ground control points are required to cover the whole Himalayan area, both spatially and temporally. High spatial and spectral resolution data will be very much suitable for detailed and accurate glacier analysis and study of development of glacial lakes. While these approaches hold promise for glacier mapping in the Himalaya region, field validation of the automatic algorithms is an ongoing challenge.

Acknowledgements The authors express their deep sense of gratefulness to an anonymous reviewers and the editor for their many fruitful suggestions that helped to improve the manuscript. We also thank USGS for providing Landsat and ASTER data at no cost.

References

Ageta Y, Naito N, Nakawo M, Fujita K (2001) Study project on the recent rapid shrinkage of summer-accumulation type glaciers in the Himalayas, 1997–1999. Bull Glaciol Res 18:45–49

Bahuguna IM (2003) Satellite stereo data analysis in snow and glaciated region. Training document: course on remote sensing for glaciological studies; Manali, India, SAC/RESA/MWRG/ESHD/TR/13/2003, pp 85–99

Bhambri R, Bolch T, Chaujar RK, Kulshreshtha SC (2011) Glacier changes in the Garhwal Himalaya, India, from 1968 to 2006 based on remote sensing. J Glaciol 57:543–556

Bhambri R, Bolch T, Chaujar RK (2012) Frontal recession of Gangotri Glacier, Garhwal Himalayas, from 1965 to 2006, measured through high resolution remote sensing data. Curr Sci 102(3):113891

Bhattacharya A (1992) Geologic remote sensing using IRS data, natural resource management-a new perspective. NNRMS ISRO hq, Bangalore

Bhutiyani MR (1999) Mass-balance studies on Siachen Glacier in the Nubra valley, Karakoram, Himalaya, India. J Glaciol 45(149):112–118

Bhutiyani MR, Kale VS, Pawar NJ (2008) Changing stream flow patterns in the rivers of northwestern Himalaya: implications of global warming in the 20th century. Curr Sci 95(5):618–626

Bolch T, Yao T, Kang S, Buchroithner MF, Scherer D, Maussion F, Schneider C (2010) A glacier inventory for the western Nyainquentanglha range and the Nam Co Basin, Tibet and glacier changes 1976–2009. The Cryosphere 4(3):419–433

Bollasina M, Bertolani L, Tartari G (2002) Meterological observation at high altitude in the Khumbu valley, Nepal Himalayas, 1994–1999. Bull Glaciol Res 19:1–11

Congalton RG (1991) A review of assessing the accuracy of classification of remotely sensed data. Remote Sens Environ 37(1):35–46

Cruz RV, Harasawa H, Lal M, Wu S, Anokhin Y, Punsalmaa B, Honda Y, Jafari M, Li C, Huu Ninh N (2007) Asia. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 469–506

Dobhal DP, Gergan JT, Thayyen RJ (2004) Recession and morphogeometrical changes of Dokriani glacier (1962–1995) Garhwal Himalaya, India. Curr Sci 86(5):692–696

Dozier J, Hall D (1987) Snow mapping and classification using Landsat Thematic Mapper data. Ann Glaciol 9:97–103

Favier V, Wagnon P, Chazarin JP, Maisincho L, Coundrain A (2004) One year measurements of surface heat budget on the ablation zone of Antizana Glacier 15, Ecuadorian Andes. J Geophys Res 109:D18105. doi:10.1029/2003JD004359

Fujita K, Nakawo M, Fujii Y, Paudyal P (1997) Changes in glaciers in Hidden Valley, Mukut Himal, Nepal Himalayas, from 1974 to 1994. J Glaciol 43(145):583–588

Granshaw FD, Fountain AG (2006) Glacier change (1958–1988) in the north Cascades national park complex, Washington, USA. J Glaciol 52(177):251–256

Hall DK, Bayr KJ, Schoner W, Bindschadler RA, Chien JY (2003) Consideration of the errors inherent in mapping historical glacier positions in Austria from the ground and space (1893-2001). Remote Sens Environ 86(4):566–577

Hasnain SI (2008) Impact of climate change on Himalayan glaciers and glacier lakes. In: Proc Taal 2007, The 12th Lake conference, pp 1088–1091

Hastenrath S (1995) Glacier recession on Mount Kenya in the context of the global tropics. Bulletin de l'Institut Français d'Études Andines 24(3):633–638

Hastenrath S, Kruss PD (1992) The dramatic retreat of Mount Kenya's glaciers between 1963 and 1987: greenhouse forcing. Ann Glaciol 16:127–133

IPCC (2007) Impacts, adaptation and vulnerability. in climate change 2007. In: Parry ML et al. (eds) Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Kadota T, Seko K, Aoki T, Iwata S, Yamaguchi S (2000) Shrinkage of the Khumbu Glacier, east Nepal from 1978 to 1995. In Nakawo M, Raymond CF, Fountain A (eds) Debris-covered glaciers: International Association of Scientific Hydrology (IAHS) Publication 264:235–243

Kamp U, Byrne M, Bolch T (2011) Glacier fluctuations between 1975 and 2008 in the greater Himalaya range of Zanskar, Southern Ladakh. J Mt Sci 8(3):374–389

Kaser G (1999) A review of the modern fluctuations of tropical glaciers. Glob Planet Change 22(1–4):93–103

Kaser G, Georges C (1997) Changes of the equilibrium-line altitude in the tropical Cordillera Blanca, Peru, 1930–50, and their spatial variations. Ann Glaciol 24:344–349

Kaser G, Noggler B (1991) Observations on Speke Glacier, Ruwenzori Range, Uganda. J Glaciol 37(127):313–318

Kaser G, Georges C, Ames A (1996) Modern glacier fluctuations in the Huascarán-Chopicalqui Massif of the Cordillera Blanca, Perú. Zeitschrift für Gletscherkunde und Glazial geologie 32:91–99

Kordzakhia G, Shengelia L, Tvauri G, Tsomaia V, Dzadzamia M (2015) Satellite remote sensing outputs of the certain glaciers on the territory of East Georgia. Egypt J Remote Sens Space Sci S1–S7. doi:10.1016/j.ejrs.2015.06.003

Kulkarni AV (1992) Glacier inventory in Himachal Pradesh using satellite images. J Indian Soc Remote Sens 19(3):195–203

Kulkarni AV, Bahuguna IM (2001) Role of satellite images in snow and glaciers investigiation. Geological Survey of India Special Publication Number, 53, 233–240

Kulkarni AV, Bahuguna IM (2002) Glacial retreat in the Baspa Basin, Himalayas, monitored with satellite stereo data. J Glaciol 48:171–172

Kulkarni AV, Mathur P, Rathore BP, Suja Alex, Thakur N, Kumar M (2002) Effect of global warming on snow ablation pattern in the Himalayas. Curr Sci 83:120–123

Kulkarni AV, Rathore BP, Alex S (2004) Monitoring of glacier mass balance in the Baspa basin using accumulation area ratio method. Curr Sci 86(1):185–190

Kulkarni AV, Rathore BP, Mahajan S, Mathur P (2005) Alarming retreat of Parbati Glacier, Beas basin, Himachal Pradesh. Curr Sci 88:1844–1850

Kulkarni AV, Bahuguna IM, Rathore BP, Singh SK, Randhawa SS, Sood RK, Dhar S (2007) Glacial retreat in Himalaya using Indian remote sensing satellite data. Curr Sci 92(1):69–74

Kulkarni AV, Rathore BP, Singh SK, Bahuguna IM (2011) Understanding changes in the Himalayan cryosphere using remote sensing techniques. Int J Remote Sens 32(3):601–615

Naithani AK, Nainwal HV, Sati KK, Prasad C (2001) Geomorphological evidences of retreat of the Gangotri Glacier and its characteristics. Curr Sci 80(1):87–94

Pandey AC, Ghosh S, Nathawat MS, Tiwari RK (2012) Area change and thickness variation over Pensilungpa Glacier (J&K) using remote sensing. J Indian Soc Remote Sens 40(2):245–255

Racoviteanu AE, Arnaud Y, Williams MW, Ordonez J (2008) Decadal changes in glacier parameters in the Cordillera Blanca, Peru, derived from remote sensing. J Glaciol 54(186):499–510

Rai PK, Nathawat MS, Pandey AC, Raju KNP (2009) Morphometric characteristics of glaciers in Doda valley, Zanskar basin. J & K 31(2):135–141

Rai PK, Nathawat MS, Mohan K (2013) Glacier Retreat in Doda Valley, Zanskar Basin, Jammu and Kashmir, India. Univers J Geosci, Horizon Research Publishing, USA 1(3):139–149

Rai PK, Mohan K, Bishwari Mishra VN, Sharma M, Rai S (2016) Changing regimes of Gangotri and Surrounding Glaciers: a case study of Garhwal Himalaya, India. Remote Sens Appl Soc Environ 3(1):53–72

Raina VK, Srivastava D (2008) Glacier atlas of India. Geol Soc India Bangalore 1:64

Rees WG (2005) Remote sensing of snow and ice. Taylor and Francis, USA. ISBN:0-415-29831-8

Rizvi SRH (1987) Report of meteorological studies carried out during Chhota Shigri Glacier expedition 1986, part I, Technical report on Multi-Disciplinary glacier expedition to Chhota Shigri, Department of Science and Technology 1:139–152

Sangewar CV, Shukla SP (2009) Inventory of the Himalayan Glaciers. Geological Survey of India Special Publication No. 34, p 588

Silverio W, Jaquet JM (2005) Glacial cover mapping (1987–1996) of the Cordillera Blanca (Peru) using satellite imagery. Remote Sens Environ 95(3):342–350

Thayyen RJ, Dimri AP (2014) Factor controlling slope environment lapse rate (SELR) of temperature in the monsoon and cold-arid glacio hydrological regimes of the Himalaya. Cryosphere Discuss 8:5645–5686

Upadhyay DS, Sharma JK, Ray B, Purohit MK, Rajput RK (1989) Meteorological studies at Chhota Shigri glacier, National meet on Himalayan Glaciology, 1989, Department of science and Technology, pp 83–92

Vohra CP (2006) Glaciers of India: a brief overview of the state of glaciers in the Indian Himalaya in the 1970s and at the End of the 20th Century, Satellite Images Atlas of Glaciers of the World, USGS Professional Papers, 1386–F259-274

Wagnon P, Ribstein P, Kaser G, Berton P (1999) Energy balance and runoff seasonality of a Bolivian glacier. Glob Planet Change 22(1–4):49–58

Wagnon P, Linda A, Arnaud A, Kumar R, Sharma P, Vincent C, Pottakkal GJ, Berthier E, Ramanathan AL, Hasnain SI, Chevallier P (2007) Four years of mass balance on Chhota Shigri Glacier, Himachal Pradesh, India, a new benchmark glacier in the Western Himalaya. J Glaciol 53:183

Wang Y, Hou S, Liu Y (2009) Glacier changes in the Karlik Shan, eastern Tien Shan, during 1971/72–2001/02. Ann Glaciol 50:39–45

Ye Q, Kang S, Chen F, Wang J (2006) Monitoring glacier variations on Geladandong mountain, central Tibetan Plateau, from 1969 to 2002 using remote-sensing and GIS technologies. J Glaciol 52(179):537–545

Zhang J, Goodchild MF (2002) Uncertainty in geographical information. CRC press, Boca Raton. doi:10.4324/9780203471326