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ORIGINAL PAPER

Monitoring of spatio-temporal glaciers dynamics in Bhagirathi Basin, Gharhwal Himalayas using remote sensing data

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Abstract

Glacier retreat represents a highly sensitive indicator of climate change and global warming. Therefore, timely mapping and monitoring of glacier dynamics is strategic for water budget forecasting and sustainable management of water resources. In this study, Landsat satellite images of 2000 and 2015 have been used to estimate area extent variations in 29 glaciers of the Bhagirathi basin, Garhwali Himalayas. ASTER DEM has been used for extraction of glacier terrain features, such as elevation, slope, area, etc. It is observed from the analysis that Bhagirathi sub-basin has a maximum glaciated area of ~ 35% and Pilang has the least with ~ 3.2%, whereas Kaldi sub-basin has no glacier. In this region, out of 29 glaciers, 25 glaciers have shown retreat, while only 4 glaciers have shown advancement resulting in a total glacier area loss of ~ 0.5%, while the retreat rate varies from ~ 0.06 m/yr to ~ 19.4 m/yr. Dokarni glacier has maximum retreat rate (~ 19.4 m/yr), whereas Dehigad has maximum advancing rate (~ 10.1 m/yr). Glaciers retreat and advance have also been analyzed based on terrain parameters and observed that northern and southern orientations have shown retreat, whereas the area change is highly correlated with glacier length. The study covers more than 65% of the total glaciated area and based on the existing literature represents one of the most exhaustive studies to cover the highest number of glaciers in all sub-basins of the Bhagirathi basin.

Keywords Bhagirathi Basin · Landsat · Glaciers · Retreat · Remote sensing

Introduction

Long-term mapping and integrated monitoring of glacier change is crucial for planning water security measures, for water budget forecasting, and also for predicting the melting rates as a response to future climate warming. Regular glacier mass balance monitoring is thus critical for responsible land management and decision-making. Mapping of glaciers regularly using conventional methods of surveying is difficult due to the high altitude, inaccessibility, ruggedness, and harsh climatic conditions of the mountainous terrain. Remote sensing (Ekwueme (2022), Mann and Gupta (2022) and Jabal et al. (2022), Dibs et al. 2023a, Kanmani et al. 2023) provides an alternative for mapping and monitoring of glaciers in mountainous terrain (Hall et al. 2003). Numerous satellites have been successfully used for mapping and monitoring glaciers' facies and features. The use of geospatial techniques is increasing day by day for creating digital maps of various glacier features and facies, for 2D and 3D visualization of glaciers, estimation of mass balance, temporal changes in ice volume, determination of equilibrium line, etc. (Bolch 2007; Hall et al. 2003; Surazakov and Aizen 2006; Bauder et al. 2007; Leonard and Fountain 2003; Kulkarni et al. 2004, etc.).

In the recent past, it has been reported that glaciers in different regions of the Himalayas are receding at varying rates. Receding glaciers will affect the availability of water in different regions of North India. The Himalayas have the largest glaciated area (approx. 33,000 km^2) outside the

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Polar Regions and housed a total number of 5243 glaciers (Kaul 1999). The Himalayas have three parallel ranges, the Himadri, Himachal, and Shivalik (Bhambri et al. 2011). Himalayan glaciers are generally divided into three river basins, namely Indus, Ganga, and Brahmaputra. The Indus basin has the largest number of glaciers (approx. 3500), whereas the Ganga and Brahmaputra basins contain about 1000 and 660 glaciers, respectively (Kaul 1999; Hasnain 1999).

Surface runoff from glaciers/snowmelt is a source of water for drinking as well as industry (Barnett et al. 2005; Moore et al. 2009). Himalayan glaciers are a major source of water for the northern state of India. It has been reported that Himalayan glaciers are receding at an alarming rate (Kulkarni et al. 2005, 2007), which may have many implications, e.g., formation of lakes near glaciers snout and subsequently imposing danger of glacial lake outburst floods, water scarcity in the northern region of India, etc.

Various studies have focused on assessing the mass balance of different glaciers in the Himalayas.

Dobhal and Mehta (2008) reported a snout recession of the Dokriani glacier with an average rate of ~ 15.9 m during 1991–2007. They also reported that the frontal area vacated by the glacier was about ~ 10% from 1962 to 1991. Pavlova et al. (2016) investigated melt-related issues for Silvretta Glacier. Yong et al. (2010) reported a reduction in glaciers of the central Himalayas in the Nepal region by ~ 501.91 ± 0.035 km^2 from 1976 to 2006. Pandey et al. (2011) reported a loss of ~ 9.23 sq. km. glacier area during 1962–2007 of a Himalayan glacier in Himachal Pradesh. Basnett and Kulkarni (2011) reported that Eastern Himalayan Region glaciers de-glaciated less than the western Himalayas and observed the loss in glacier area as ~ 1.17% between 1990 and 2004. They also reported that big glaciers (area > 10 sq. km) receded by ~ 0.51%, while small glaciers (area < 10 sq. km) reduced by ~ 6.67% during this period. Bolch et al. (2012) reported that ~ 25% of glaciers in the west of the Karakoram were stable or advancing, while glaciers in the north of the Karakoram (Wakhan Pamir) had shown retreat from 1976 to 2007. Racoviteanu et al. (2015) estimated the glacier area in Sikkim and Nepal from 1962 to 2000 and reported that the glacier area was reduced in Nepal by ~ 0.53 ± 0.2% per year and in Sikkim by 0.44 ± 0:2% per year. They also reported that the debris-free glaciers show more reduction in area than the debris-covered glaciers. In a study conducted by Frauenfelder and Kaab (2009), the glacier area in the North-West Himalayas was reduced by ~ 8% in 10 years. Garg et al. (2017) studied the influence of topography on central Himalayan glaciers and reported that out of 18 observed glaciers, 8 glaciers had shown a moderate influence, and 4–5 glaciers had shown a strong influence of topography on area loss and retreat. Meteorological observations near the snout of the Gangotri glacier in central Himalaya have shown a decreasing trend in the snowfall and an increasing trend in the temperatures (Gusain et al. 2015).

Sunita et al. (2023) analyzed the snow cover area (SCA) over the Beas River basin, Western Himalayas for the period 2003–2018. Results showed an average SCA of ~ 56% of its total area, with the highest annual SCA recorded in 2014 at ~ 61.84%. Conversely, the lowest annual SCA occurred in 2016, reaching ~ 49.2%. Notably, fluctuations in SCA are highly influenced by temperature, as evidenced by the strong connection between annual and seasonal SCA and temperature.

Although several studies have been undertaken in some basins of the Himalayas (Kulkarni et al. 2007; Bolch 2007; Shukla et al. 2009; Shukla et al. 2010; Garg et al. 2017 etc.), still glaciers of the Bhagirathi basin have not been thoroughly explored. Only a few studies are available on the glaciers of this basin, and that too is concentrated in restricted areas.

Thapliyal et al. (2023) assessed the spatio-temporal changes in the glacier area, volume, and shift in snout positions of the Satopanth (SPG) and Bhagirathi-Kharak (BKG) glaciers of the Mana basin in the Central Himalayan region of India from 1968 to 2017 based on the CORONA photograph and satellite data. The ice velocity was found to vary from 0.117 md − 1 to 0.165 md − 1 from January to October months. Besides this, they analyzed temperature variability from 2001 to 2020 and found significant warming over the basin along with a significant negative trend in SCA during different seasons.

Khan et al. (2017) evaluated the glacial melt fraction at the exit of the Bhagirathi basin (Devprayag) to be 11% considering pre-monsoon data and 12% considering post-monsoon data. They observed a generally decreasing depletion of glacial melt components observable downstream from the glacier snout. Glacial melt fraction decreases from the snout of the Gangotri glacier to Devprayag during the pre-monsoon and the post-monsoon period, whereas surface runoff in the form of snowmelt is the major fraction during the pre-monsoon and in the form of rainfall during the post-monsoon period in the Bhagirathi river.

Since there are only limited studies on the glaciers of the Bhagirathi basin, the novelty of the present study consists in analyzing glacier retreat and advancement for the years 2000 and 2015 in the whole Bhagirathi Basin, Garhwal Himalayas using remote-sensing data by covering more than 65% of the total glaciated area; it therefore represents one of the most exhaustive studies to cover the highest number of glaciers in all sub/basins of the Bhagirathi Basin and it is of crucial importance in understanding the overall status of the glaciers of the Bhagirathi Basin.

Study area

The study area lies in the Garhwal Himalayas of the State of Uttarakhand, India, and is part of the Indian central Himalaya. The Garhwal region's two major drainage basins are Alaknanda and Bhagirathi River Basin. In this study, Bhagirathi River Basin (Fig. 1) has been selected, which lies between 78° 08′ 49″ E and 79° 24′ 43″ E longitude and 30° 08′ 49″ N and 31° 26′ 35″ N latitude.

Bhagirathi, Bhilangana, Jalandhari, Jahnvi, Pilang, and Kaldi are sub-drainage basins of the Bhagirathi basin. Most of the glaciers in this basin lie at an altitude between 3800 and 7000 m (a.s.l.). The total catchment area of the basin is approximately ~ 7600 km^2, 75% of which is above 2000 m (a.s.l.). Gangotri is the largest glacier in the basin. Gusain et al. (2015) have reported an annual mean of min. temperature, max. temperature, and snowfall as − 2.3 ± 0.4 °C, 11.1 ± 0.7 °C, and 257.5 ± 81.6 cm, respectively, at the Bhojbasa observation station near the snout of Gangotri Glacier in the study area.

Materials and methods

Materials

In this study, Landsat images of Thematic Mapper (TM), Enhanced Thematic Mapper (ETM), and Landsat 8-Operational Land Images (OLI) (Dibs et al. 2023b) at 30 m spatial resolution have been used to estimate glacier area change between the year 2000 and 2015. The summary of the data set is listed in Table 1.

The Bhagirathi basin has 288 glaciers, among which 26 glaciers having an area of more than 5 km^2 have been selected, as they contribute to the 2/3rd of the total glaciated region of the basin, together with three small glaciers. Thus, a total of 29 glaciers have been monitored in this study, which may be regarded as the most representative glaciers of the whole Bhagirathi River Basin. The detailed list of glaciers in the Bhagirathi sub-basins is given in Table 2.

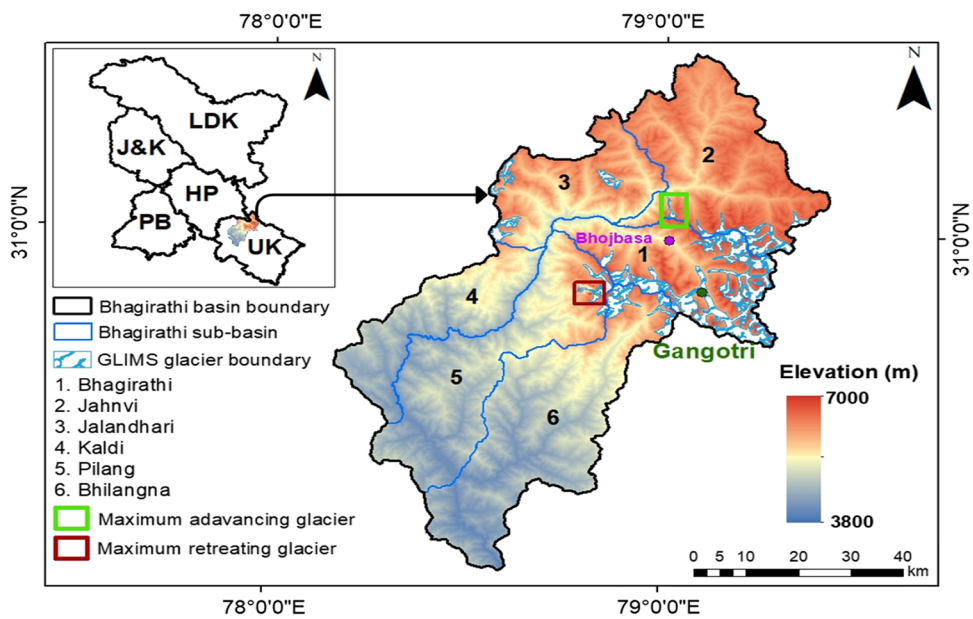

Fig. 1 Geographical location map of the study area showing sub-basins and glaciers of the Bhagirathi basin

Table 1 Dataset used in the study

Data category	Data type	Source	Uses
Remote sensing	Landsat images	https://landsat.usgs.gov/ https://earthexplorer.usgs.gov/	Glacier boundary demarcation, Snout position identification, glacier mapping
Ancillary data	ASTER GDEM	https://lpdaac.usgs.gov/ https://earthexplorer.usgs.gov/	Snout elevation estimation, orientation/aspect estimation
	GLIMS Polygons	http://www.glims.org/	Glaciers boundaries
	Google Earth 3D	https://earth.google.com/	Glacier boundary validation

Table 2 List of selected glaciers in the Bhagirathi Basin

Sub-basin	Glacier name
Bhagirathi	Maitri, 52 Bhagirathi, Rudugaira, Bhrigupanth, 54 Bhagiarthi, Kedar, Chaturangi, Raktvarn, Swetvarn, Gangotri, 13 Bhagirathi
Bhilangana	19 Bhilangana, 15 Bhilangana, Khatling
Jahnvi	Dehigad, Mana, 60 Bambigad, Guligad, Kailash, Surali
Jalandhari	Rohilla, 66 Chaling, Sian, 61 Jalandhari, 5 Bartiakhunt, 2 Chhalan
Pilang	27 anigad, Jaonli, Dokriani

Methods

The overall approach used in the present study is described below. Landsat Images (TM/OLI) of the different periods over the study area have been used and obtained from the http://glovis.usgs.org/ during 2000 and 2015. Apart from Landsat images, ASTER GDEM has been obtained from http://www.lpdaac.usgs.gov/datapool/datapool.asp/ and used in the study for topographic analysis. The methodology adopted for the present study is shown in Fig. 2.

In the first step of preprocessing, all the datasets were co-registered taking 2015 OLI as base images with RMSE of < 1 pixel (30 m) to achieve congruence among them. The slope match method, considered as one of the best methods for the Indian Himalaya (Mishra et al. 2009), has been used to get topographically corrected reflectance. In this study, various glacier parameters, such as glacier area, glacier length, snout position, snout altitude, aspect, etc., were extracted using satellite images and DEM to evaluate the glacier health in terms of retreat and advance. The glacier snout position has been estimated by means of visual interpretation techniques using various features like shape, texture, tone, and surroundings (Kulkarni et al. 1991; Basnett et al. 2013). However, satellite images could not identify the snout position visually, so False Color Composites (FCC) were determined using different band combinations, such as SWIR-NIR-Green, NIR-SWIR-Red, NIR-Red-Green, etc., to identify the snout properly. Glacier boundaries available in the GLIMS datasets were manually delineated, reported as one of the most accurate methods by Garg et al. (2017). Therefore, in the present study, glacier boundaries have been demarcated manually using Landsat images with the help of the 3D visualization technique.

Orientation of the glaciers has been determined in eight directions, i.e., North (N), North-East (NE), East (E), South-East (SE), South (S), South-West (SW), West (W), and North-West (NW) using ASTER DEM. Glacier length is defined as the length of the longest flow line of a glacier and can also be used to study glacier health. Furthermore, the relationship/correlation between all the selected topographic parameters with the glaciers' change (area/length) was estimated and then analyzed.

Results

In the Bhagirathi Basin, 29 glaciers have been considered and various glacier parameters, such as glacier length, glacier area, topographic parameters, etc., were computed using Landsat satellite images and ASTER DEM to assess glaciers' status and changes in the Bhagirathi River Basin. Here, the results of all the glaciated basins and sub-basins have been discussed below to get a microscopic overview of the Bhagirathi Basin.

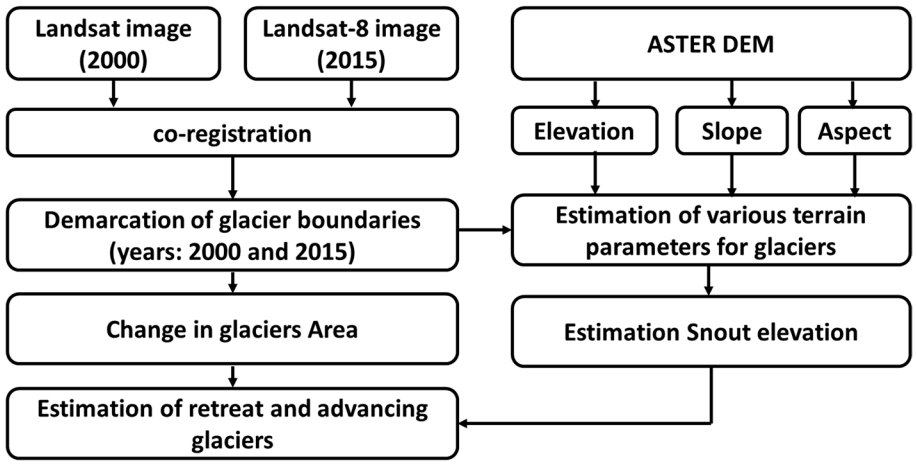

Fig. 2 Methodology adopted for the present study

Spatio-temporal variability of glaciers in Bhagirathi basin during 2000–15

The Bhagirathi basin consists of five sub-basins, mainly Bhagirathi, Bhilangana, Jahnvi, Jalandhari, Pilang, and Kaldi. Kaldi sub-basin has no glaciated region, whereas the remaining sub-basin has 288 glaciers. However, in the present study, 29 glaciers with an area of more than 5 km^2 have been considered and are given in Table 2. It is observed from the analysis and shown in Fig. 3 that Dokarni and Dehigad glacier lies in Pilang and Jahnvi sub-basins, respectively, shows maximum retreat (~ 0.204 km^2) and advancing (~ 0.016 km^2) in terms of area during 2000–2015. Snout elevation is observed at 3923 m a.s.l. and 4028 m a.s.l. in Dokarni glacier, and 4099 m a.s.l. and 4039 m a.s.l. in Dehigad glacier during 2000 and 2015, respectively. The study also reveals changes in snout elevation and length as -2.7 m a.s.l. and -291 m in Dokarni glacier, and 1.5 m a.s.l. and 152 m in Dehigad glacier during the data period. Furthermore, all the glaciers show retreating activities, except four glaciers (Dehigad, Maitri, 52 Bhagirathi, and Rudugaira) during the study period.

Spatio-temporal variability of glaciers in Bhagirathi sub-basin during 2000–15

It is observed from Fig. 4, that in the Bhagirathi sub-basin, Bhrigupanth, 54 Bhagirathi, Kedar, Chaturangi, Raktavarn, Swetvaran, Gangotri, and 13 Bhagirathi glaciers have shown a decrease in glacier length by ~ 62 m, ~ 92 m, ~ 150 m, ~ 15 1 m, ~ 152 m, ~ 158 m, ~ 160 m, and ~ 197 m, respectively. Whereas, Maitri, 52 Bhagirathi, and Rudugaira glaciers have shown an increase in length by ~ 85 m, ~ 34 m, and ~ 3 m, respectively, during the study period.

The interpretation of satellite imagery for the years 2000 and 2015 indicates a decrease of the area in 8 glaciers. A marked decrease of roughly ~ 1 km^2 is observed in Gangotri and Raktvaran glaciers. Other glaciers, namely, Bhrigupanth, 54 Bhagirathi, Kedar, Chaturangi, Swetvarn, and 13 Bhagirathi, have shown a decrease in the area by 0.011 km^2, 0.016 km^2, 0.017 km^2, 0.118 km^2, 0.002 km^2, and 0.087 km^2, respectively. Whereas, Maitri, 52 Bhagirathi, and Rudugaira have shown an increase in glacier area by ~ 0.025 km^2, 0.020 km^2, and 0.016 km^2, respectively (Fig. 4).

Change in snout elevation between the data period shows that maximum positive change is observed in 54 Bhagirathi glacier (~ 212 m a.s.l.) and maximum negative change in Maitri glacier (~ 25 m a.s.l.). 54 Bhagirathi, Kedar, Chaturangi, Raktavarn, Swetvaran, Gangotri, and 13 Bhagirathi glaciers have shown an increase in snout elevation, whereas Maitri, 52 Bhagirathi, and Rudugaira glaciers have shown a decrease in snout elevation during 2000–2015 in study area. Detailed observations are shown in Fig. 4.

Furthermore, glacier terrain parameters (i.e., aspect and slope) have been derived from ASTER DEM and show that more than 50% of the advancing glaciers are northly oriented, while less than 20% are oriented toward the south are also observed during analysis. It has been widely reported that north-facing glaciers persist, whereas south-facing glaciers are disappearing (Sakai et al. 2002; Dobhal and Mehta 2010; Garg et al. 2016). The amount of depletion is not significant, but it shows a general trend of depleting glaciers in the Bhagirathi basin. Also, it was found that the maximum mean slope of ~ 26.50° in the Maitri glacier has the highest advancing trend. Similar

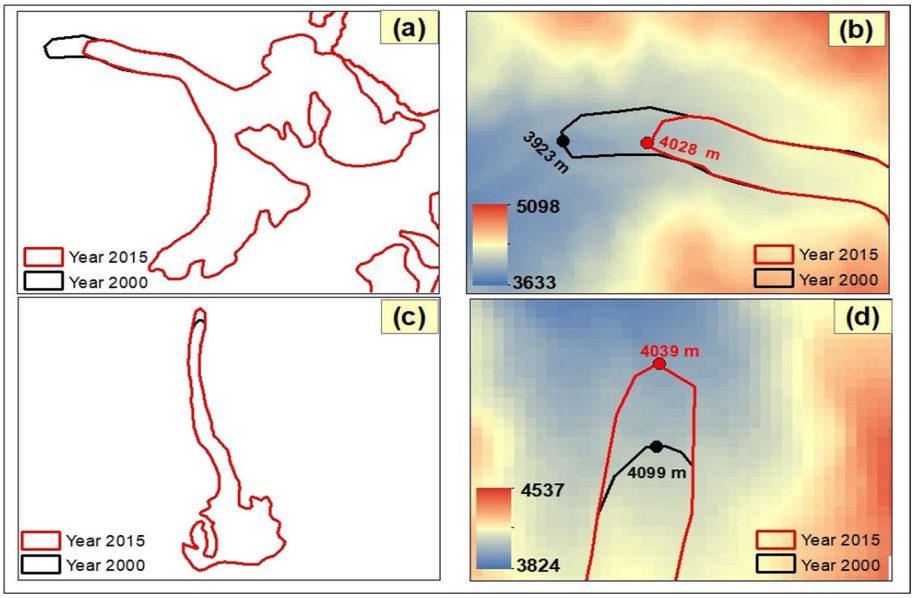

Fig. 3 Maximum retreating (i.e., Dokarni glacier) and advancing (i.e., Dehigad glacier) glacier in terms of **a** area and, **b** snout elevation; maximum advancing glacier (i.e., Dehigad glacier) in terms of **c** area and **d** snout elevation during 2000–15

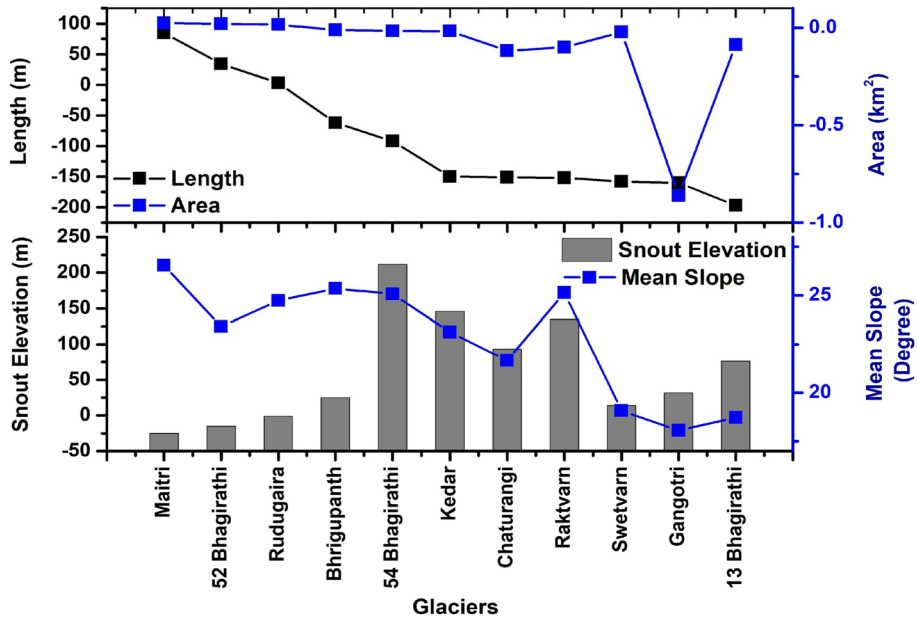

Fig. 4 Change in length, area, snout elevation during data period, and terrain parameters in the Bhagirathi Sub-basin

results have been reported in various studies (Bhambri et al. 2011; Dobhal et al. 2013).

Additionally, the analysis shows a positive correlation of ~ 0.3 between variations in the glacier length and area, while a negative correlation value of ~ 0.62 between glacier length and snout elevation for retreating glaciers. A positive correlation between mean glacier slope and area variation has been observed for the advancing glaciers (~ 0.68) and retreating glaciers (~ 0.5).

Spatio-temporal variability of glaciers in Jalandhari sub-basin during 2000–15

It is observed from Fig. 5 that in the Jalandhri sub-basin all the glaciers is decreasing in length during the study period. Rohilla glacier has shown a minimum decrease in length (86 m) followed by 66 Chhaling (100 m), Sian (119 m), 61 Jalandhari (123 m), 5 Bartikhunt (180 m), and 2 Chhalan (251 m). A decrease in glacier length up to ~ 251 m in the Jalandhari sub-basin is indicative of overall depletion of glacial cover.

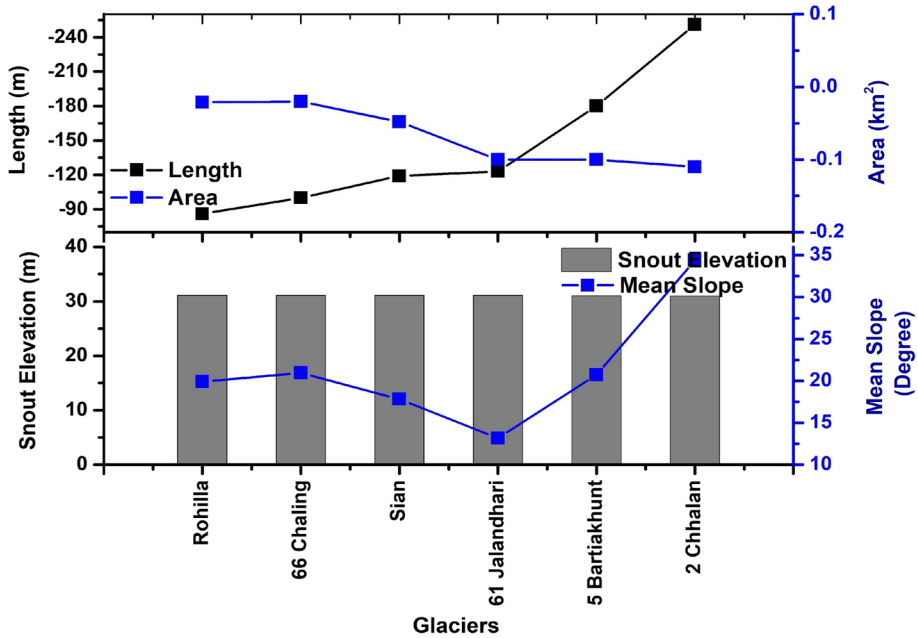

Fig. 5 Change in length, area, snout elevation during data period, and terrain parameters in the Jalandhari sub-basin

Interpretation of satellite imagery for the years 2000 and 2015 indicated a decrease in the area in all the selected glaciers. A marked decrease of approx. ~ 0.1 km^2 is observed in 61 Jalandhari, Bartiakhunt, and Chhalan glaciers. Other glaciers, namely, Rohilla, 66 Chaling, and 13 Sian, have shown a decrease in the glacier area by ~ 0.02 km^2, ~ 0.02 km^2, and ~ 0.05 km^2, respectively (Fig. 5).

Change in snout elevation between the data period shows a maximum positive change in 54 Bhagirathi glacier (~ 212 m a.s.l.) and maximum negative change in Maitri glacier (~ 25 m a.s.l.). 54 Bhagirathi, Kedar, Chaturangi, Raktavarn, Swetvaran, Gangotri, and 13 Bhagirathi glaciers have shown an increase in snout elevation, whereas Maitri, 52 Bhagirathi, and Rudugaira glaciers have shown a decrease in snout elevation during 2000–2015 in study area. Detailed observations are shown in Fig. 3.

Furthermore, glacier terrain parameters (i.e., aspect and slope) have been derived from ASTER DEM and show that northerly and north-easterly oriented glaciers are retreating fast in these sub-basins are observed during analysis. The maximum mean slope of 34.40º has been found in Chhalan glacier, which shows the highest retreating trend (Fig. 5).

Additionally, the analysis shows a positive correlation ~ 0.8 (in Sian glacier) between glacier length and area: nevertheless, a high negative correlation ~ 0.9 between glacier length and snout elevation for retreating glaciers has also been observed. A positive correlation between length and area highlights that glacier area decreases with a decrease in length, whereas a negative correlation between length and snout elevation demonstrates that glacier length decreases with the increase in snout elevation. A low negative correlation value of 0.119 between length and the northern orientation suggests that glaciers facing north have no significant length variation. This result conforms to the universally accepted thesis that topographic shading is an important factor affecting glacier mass balance and that glaciers facing north are more persisting in nature.

In the Northern Hemisphere, north-facing slopes in latitudes from about 30–55 degrees receive less direct sunlight than south-facing slopes and remain therefore cooler. This causes snow on north-facing slopes to melt slower than on south-facing ones. The scenario is just the opposite for slopes in the Southern Hemisphere, where north-facing slopes receive more sunlight and are consequently warmer.

Also, a negative correlation (~ 0.68) between the mean glacier slope and area has been estimated for the glaciers of the Jalandhari sub-basin.

Spatio-temporal variability of glaciers in Jahnvi sub-basin during 2000–15

It is observed from Fig. 6 that in the Jahnvi sub-basin, out of 6 glaciers this sub-basin, 5 glaciers have shown a marked decline in length, whereas one glacier has shown a marked increase in length. The maximum increase in length of ~ 152 m has been found in the Dehigad glacier during the analyzed period. Whereas, Surali glacier has shown a maximum decrease in length (172 m), followed by Kailash (133 m), Guligad (119 m), 60 Bombigad (106 m), and Mana (90 m), respectively.

Interpretation of satellite imagery for the years 2000 and 2015 indicated a decrease in the area in all the selected glaciers, except Dehigad glacier. A marked decrease of glacier area approx. ~ 0.33 km^2 is observed in Surali glacier. Other

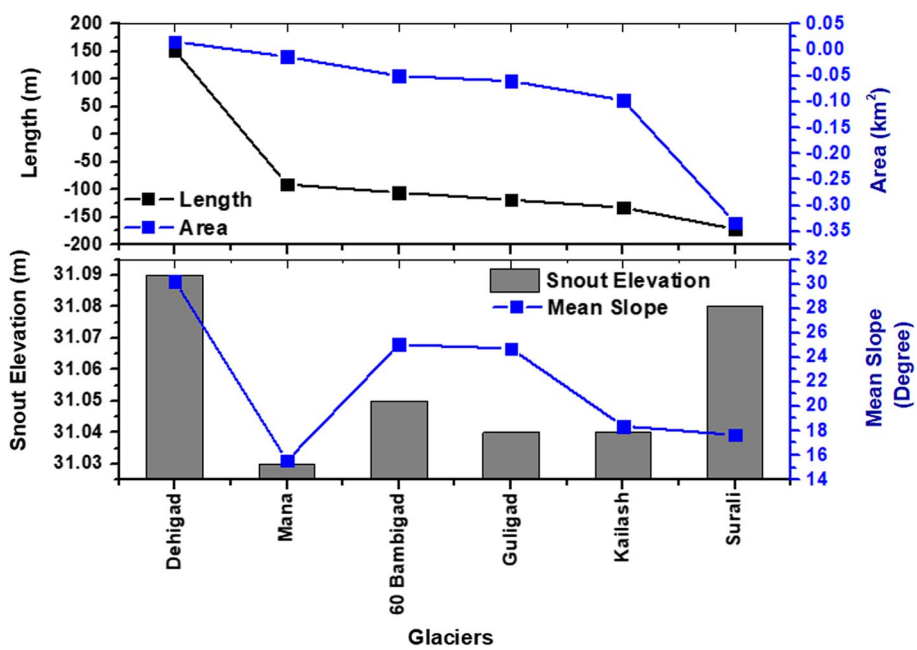

Fig. 6 Change in length, area, snout elevation during data period, and terrain parameters in the Jahnvi sub-basin

glaciers, namely, Mana, 60 Bambigad, Guligad, and Kailash, shown a decrease in the glacier area by ~ 0.013 km^2, ~ 0.05 km^2, ~ 0.06 km^2, and ~ 0.097 km2, respectively, while Dehigad glacier is increasing by ~ 0.016 km^2, during data period (Fig. 6).

Change in snout elevation between the data period shows that the maximum increase is observed in 54 Bhagirathi glacier (~ 212 m a.s.l.) and the maximum decrease in Maitri glacier (~ 25 m a.s.l.). 54 Bhagirathi, Kedar, Chaturangi, Raktavarn, Swetvaran, Gangotri, and 13 Bhagirathi glaciers have shown an increase in snout elevation, whereas Maitri, 52 Bhagirathi, and Rudugaira glaciers have shown decrease in snout elevation during 2000–2015 in study area. Detailed observations are shown in Fig. 5.

Furthermore, glacier terrain parameters (i.e., aspect and slope) have been derived from ASTER DEM and show that north-easterly and easterly oriented glaciers are retreating in these sub-basins are observed during analysis. The maximum mean slope of 30.50º has been found in the Dahigad glacier, which shows some advancing trend. Various authors have reported that persisting glaciers are situated on steeper slopes.

Additionally, the analysis shows a low positive correlation value of ~ 0.13 between glacier length and the northern slope. It suggests that glaciers facing north are having no significant length variation. This result conforms to the universally accepted thesis that topographic shading is an important factor affecting glacier mass balance and that glaciers facing north are more persisting in nature. A low negative correlation value ~ 0.15 has been observed between glacier length and southern orientation. South-facing glaciers have shown length variations owing to direct solar radiation. But here, the result deviates from the common understanding. A positive correlation (~ 0.47) between glacier mean slope and area has been observed for the glaciers of Jahnvi sub-basin. A moderate negative correlation (~ 0.35) has been observed between glacier snout elevation and area. This implies that with the increase in snout elevation, the glacial area decreases. Furthermore, the calculated results of glacier area change clearly show that all glaciers except one have lost glacier area during the study period. The total glacier area changed from 61.77 km^2 to 61.23 km^2 (0.88%).

Spatio-temporal variability of glaciers in Bhilangana sub-basin during 2000–15

It is observed from Fig. 7 that in the Bhilangana sub-basin, all the glacier length is decreasing during the study period. Khatling glacier has shown a maximum decrease in length (212 m) followed by 15 Bhilangana (181 m) and 19 Bhilangana (47 m), respectively.

The interpretation of satellite imagery for the years 2000 and 2015 shows a decrease in area in all the selected glaciers of the Bhilangana sub-basin. 19 Bhilangana, 15 Bhilangana, and Khatling have shown a decrease in the area by ~ 0.01 km^2, ~ 0.03 km^2, ~ 0.06 km^2, and 0.07 km^2, respectively. Although the magnitude of the area variation is very low, these results still reflect the general trend of glacial retreat in the Bhilangana sub-basin (Fig. 7).

Change in snout elevation between the data period shows a maximum increase in 54 Bhagirathi glacier (~ 212 m a.s.l.) and maximum decrease in Maitri glacier (~ 25 m a.s.l.). 54 Bhagirathi, Kedar, Chaturangi, Raktavarn, Swetvaran, Gangotri, and 13 Bhagirathi glaciers have shown an increase

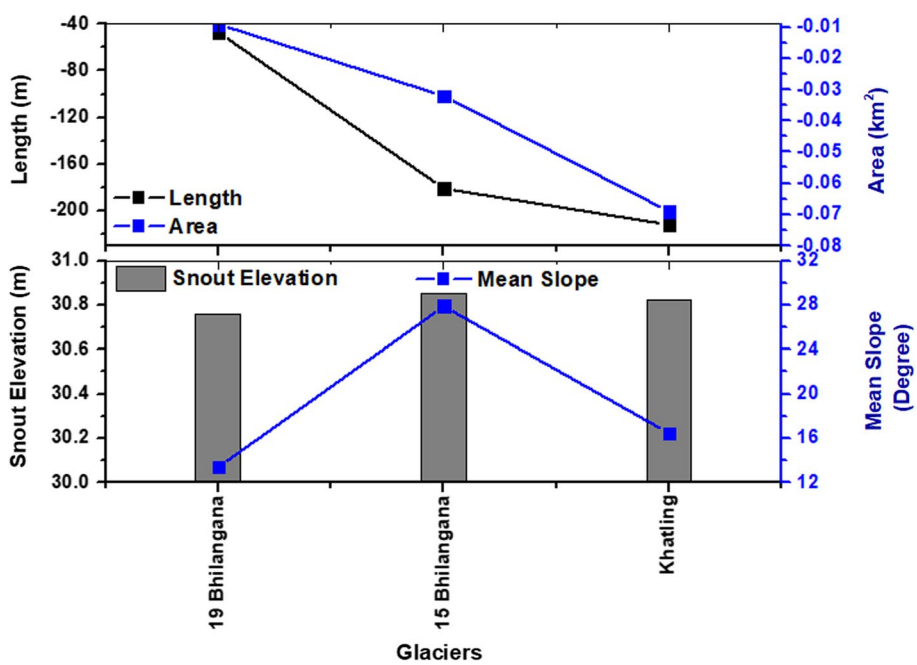

Fig. 7 Change in length, area, snout elevation during data period, and terrain parameters in the Bhilangana sub-basin

in snout elevation, whereas Maitri, 52 Bhagirathi, and Rudugaira glaciers have shown a decrease in snout elevation during 2000–2015 in study area. Detailed observations are given in Table 2. Snout elevation variation in the order of 85 m, 37.7 m and 34 m was estimated for Khatling, 15 Bhilangana, and 19 Bhilangana glaciers, respectively.

Furthermore, glacier terrain parameters (i.e., aspect and slope) have been derived from ASTER DEM and show that northerly oriented glaciers are retreating at a very slow rate in these sub-basins are observed during analysis. The maximum mean slope of ~ 27.88° has been observed in 15 Bhilangana glaciers and results in a minor decrease in area. Various authors have reported he existence of persisting glaciers on steeper slopes.

Additionally, the analysis shows a high positive correlation value ~ 0.89 between glacier length and area, whereas a moderately high negative correlation value ~ 0.69 between glacier length and snout elevation in this sub-basin. A positive correlation between length and area suggests that glacier area decreases with a decrease in length, whereas a negative correlation between length and snout elevation shows that glacier length decreases with the increase in snout elevation and this conforms to the existing hypothesis.

A high negative correlation value (~ 0.80) has been estimated between the glacier northern slope and area; this can be attributable to north-facing slopes showing a lower areal variation. A moderate negative correlation value ~ 0.45 has been observed between glacier length and the northern slope. The analysis shows that glaciers facing north have no significant length variation. This result conforms to the universally accepted thesis that topographic shading is an important factor affecting glacier mass balance and that glaciers facing north are more persisting in nature. Similar findings have also been reported by several authors working on Himalayan glaciers.

A high negative correlation (~ 0.94) was estimated between glacier snout elevation and area. This implies that with an increase in snout elevation, the glacial area covers decrease. Generally, at higher elevations, persisting glaciers are found owing to prevailing low-temperature conditions. The overall results of area change estimation show that all glaciers of the Bhilangana sub-basin have been depleted during the period between 2000 and 2015, and the total glacier area has changed from 54.72 km^2 to 54.61 km^2 (~ 0.20%).

Spatio-temporal variability of glaciers in Pilang sub-basin during 2000–15

In the Pilang sub-basin, a significant negative change in length ~ 291 m was found in the Dokriani glacier followed by Jaonli (109 m) and 27 Ganigad (1 m), respectively. All the three glaciers of this sub-basin have shown a decrease in length (Fig. 8).

The analysis of Landsat temporal imageries (2000 and 2015) shows a decrease in area for all the glaciers of the Pilang sub-basin. 27 Ganigad, Jaonli, and Dokrani glaciers have shown a decrease in the area by ~ 0.1 km^2, ~ 0.01 km^2, and ~ 0.2 km^2, respectively. A marked decrease in the glacial cover area has been observed in the Dokriani glacier and this has also been reported earlier by Dobhal et al. (2004). Although the magnitude of the area variation is low in the other two glaciers of this sub-basin, these results broadly reflect the general trend of glacial retreat in the Pilang sub-basin. Apart from glacier change in length and area, snout

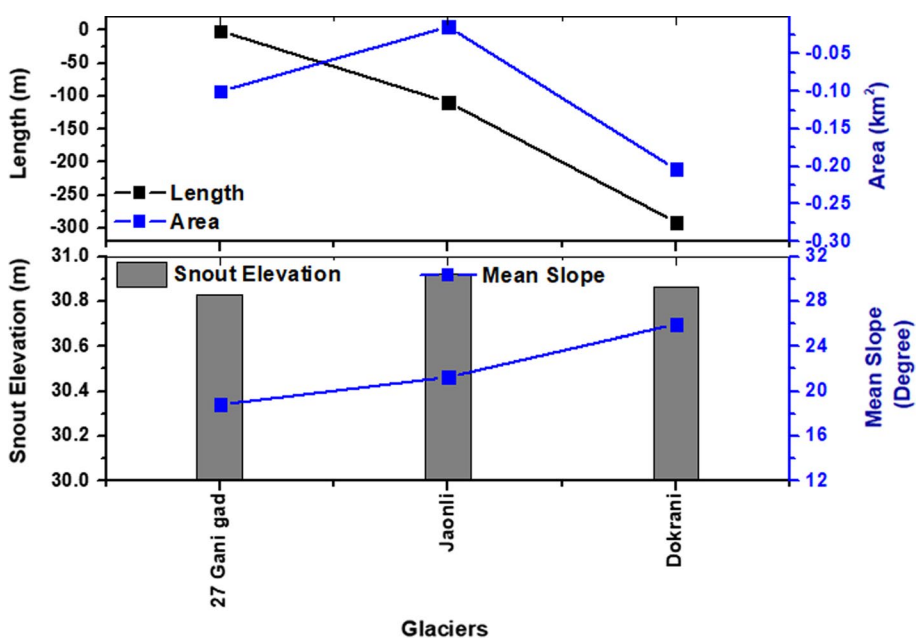

Fig. 8 Change in length, area, snout elevation during data period, and terrain parameters in the Pilang sub-basin

elevation change has also been estimated for this sub-basin. It is observed that snout elevation changes by ~ 151.3 m a.s.l., 22 m a.s.l., and 1.1 m a.s.l., for Dokrani, Jaonli, and 27 Ganigad glaciers, respectively (Fig. 8). The maximum mean slope of 27.88º has been found in 15 Bhilangana glaciers which have shown a minor decrease in area was observed in analysis.

Additionally, the analysis shows a positive correlation (~ 0.66) between glacier length variation and area, whereas a very high negative correlation (~ 0.97) between glacier length and snout elevation in this sub-basin. A positive correlation between length variation and area variation suggests that glacier area decreases with a decrease in length and vice versa, whereas a high negative correlation between length variation and snout elevation shows that glacier length significantly decreases with the increase in snout elevation.

A high negative correlation (~ 0.85) has been estimated between glacier length and the northern slope. It suggests that glaciers facing north are having no significant length variation. A very high negative correlation (~ 0.99) was estimated between glacier length and mean slope. This implies as the mean slope increases, the glacier length decreases significantly. Different rates of retreat/advance of glaciers within a region, where the climatic conditions do not change significantly, are due to the important role played by the dynamics of ice movement, which in turn is controlled by the mean slope and length of the glacier.

A high negative correlation (~ 0.83) was estimated between glacier snout elevation and area in this sub-basin. Several authors (Kulkarni et al. 2005) have found the same trend in the Himalayan glaciers. Generally, at higher elevations, more persisting glaciers are found due to prevailing lower-temperature conditions. A negative correlation value (~ 0.16) has been estimated between the glacier northern slope and area. This result indicates that north-facing glaciers can be more or less persisting. The overall results of area change estimation show that all glaciers of the Pilang sub-basin have been depleted during the period between 2000 and 2015 and the total glacier area changed from 25.36 km^2 to 25.04 km^2 (1.26%).

Error estimation

The error estimation is an essential step to calculate the accuracy of the results; during this study, following methods have been used for the same:

(a) Error in digitization of glaciers' boundaries: Results obtained from Landsat image and Google Earth (GE) were compared. Although this is a crude method, as Google Earth images can only be used for reference purposes, this method has been widely used by the various authors (e.g., Hall et al. 2003; Bhambri et al. 2012; Garg et al., 2016). The same method has been used to estimate the mapping error on the Landsat Images and Google Earth and observed an error of less than 1%.

(b) Error in the estimation of glacier area: This error is also known as Mapping Error. The mapping area can be calculated using formulae

$$\text{Mapping Error} = N * A/2, \quad (1)$$

where N is the number of pixels along the glacier boundary and A is the pixel area. The errors in estimation vary from 2.86% to 9.41% for the year 2000 and 2.85% to 9.81% for the year 2015, respectively.

(c) Error in the ASTER DEM elevation: The image matching method was used to create the ASTER DEM, which is available for 99% of the world's land (Hu et al. 2017). ASTER DEM has approximately 15 m horizontal and 15–25 m vertical accuracy, depending on the environment in the area. The vertical and horizontal error in ASTER DEM will lead errors in snout elevation.

Discussion

The present study has demonstrated that most of the glaciers in the Bhagirathi river basin are retreating and resulting in a loss of the glaciated area. However, a few glaciers have shown advancement and increase in the glaciated area during the period. The present study shows an increase in the retreat of the Dokriani glacier from 2000 to 2015 and the area vacated about 2.9% of the total glacier area, which is coherent with the result form Dobhal and Mehta (2008) who reported a snout recession of the Dokriani glacier with an average rate of ~ 15.9 m during 1991–2007.

The present study reports a glacier area loss of ~ 0.1% to ~ 4.4% from 2000 to 2015 of glaciers in Bhagirathi Basin, Garhwal Himalayas. The highest area loss was shown by the Surali glacier ~ 4.4% during the study period. A similar trend of glacier recession has been observed in other parts of the Himalayas. This is coherent with the results of Yong et al. (2010) who reported a reduction in glaciers of the central Himalayas in the Nepal region by ~ 501.91 ± 0.035 km^2 from 1976 to 2006.

In the present study, it has also been observed that large glaciers with a glacier area of more than ~ 10 km2 have lost a mean glacier area of 0.16%, while smaller glaciers have lost a mean glacier area by ~ 1.14%.

This is coherent with what found by Ahmad (2016) who indicated that glaciers having low maximum altitude, low relief, and fewer lengths are more prone to shrinkage than others in the Indian Himalaya.

This is also coherent with the results of Basnett and Kulkarni (2011) who reported a recession of ~ 0.51%, for big

glaciers (area > 10 sq. km) and of ~ 6.67% for small glaciers (area < 10 sq. km) during that period.

By analyzing spatio-temporal patterns of glacier change in China over past decades together with their influencing factors, Su et al. (2022) also found a negative correlation between glacier AAC (Annual Area Change) and glacier size.

The present study has demonstrated that most of the glaciers in the Bhagirathi river basin are retreating and resulting in loss in the glaciated area. However, only 3 glaciers out of 29 have shown advancement and increase in the glaciated area during the period 2000–2015. This is more critical than the findings of Bolch et al. (2012) regarding the period 1976–2007. They reported that ~ 25% of glaciers in the west of the Karakoram were stable or advancing, while glaciers in the north of the Karakoram (Wakhan Pamir) had shown retreat.

This study has also highlighted the influence of topography on glacier mass balance.

In the present study, a significant positive correlation was observed between the glacier area and length of the glacier, however, no significant correlation was observed between the area vacated and the snout elevation. A positive correlation between length variation and area variation suggests that glacier area decreases with a decrease in length.

According to Garg et al. (2017), only 4–5 glaciers out of 18 had shown the strongest influence of topography on area loss and retreat. Meteorological observations near the snout of the Gangotri glacier in central Himalaya have shown a decreasing trend in the snowfall and an increasing trend in the temperatures (Gusain et al. 2015).

In the study, a high positive and negative correlation is observed between glacier length and snout elevation in advancing and retreating glaciers, respectively. This is because in retreating glaciers, decrease in glaciers length results in snout recession and increases in snout elevation. This is coherent with the results obtained by Ahmad (2016) who monitored and predicted glaciers recession and found that shift in snout at higher altitude contributes loss to ablation area, while shifting in equilibrium line at high altitude results in accretion of ablation area. He also showed that decrease in ablation length is partially compensated by accreted ablation length in accumulation area.

Finally, both glaciers with both northern and southern slopes have shown retreat. Although, lower latitude glaciers have shown a higher retreat than higher altitude ones. This is because the former usually experience significant periods in the summer months of above zero temperatures and melting, whereas, in high latitude locations, temperatures may never rise above zero, and so, no melting occurs. This explains why ice sheets are so thick in polar regions, despite very low precipitation inputs.

The current retreat and area loss of most of the glaciers may be attributable primarily to the impact of climate change in the region, although the variation in retreat and area loss from one glacier to another can be attributed to variation in micro-climatology and topography of the region.

Though most of the all glaciers of the Himalaya are retreating at different rates, some are also advancing, which indicates that global warming is not the only reason behind glacier dynamics. Factors other than climate changes must be responsible for glaciers behavior. The glacial snout is generally in an unstable equilibrium, its position being determined by a complex interplay of topo-climate factors like snowfall, temperature through the year, deposition of rock debris, and effects of ocean tides on iceberg calving rates.

Researchers are still investigating on anthropogenic/natural factors behind the glacier retreat and advance. Studies lasting many tens of years are necessary to unravel the phenomena responsible for glaciers behavior.

Conclusions

Himalayan glaciers represent headwaters of several of Asia's great river systems; they act as buffer—generally as reservoir of water in winter and might release melt water in summer to partly satisfy the water needs for irrigation, hydropower, and local water supplies for people living in the Ganges–Brahmaputra, Indus, Mekong, Yangtze, and Yellow river basins.

Glaciers of the Himalayas are a sensitive indicator of climate change: regardless of altitude or latitude, they have been melting at a high rate since the mid-twentieth century.

However, scientists currently have only a limited understanding of the extent of the melting of glaciers, since the full extent of ice loss has only been partially measured and understood.

Therefore, integrated monitoring of glacier dynamics in the Himalayas is utmost required for planning water security measures in the Himalayas.

This study represents an important contribution to glacier mass balance monitoring in Himalaya. The novelty of the present study consists of applying remote sensing to study glacier retreat and advancement for the years 2000 and 2015 in Bhagirathi Basin, Gharhwal Himalayas. Although several studies have been undertaken in the Himalayas, glaciers of the Bhagirathi basin have not been explored satisfactorily.

This study comprehensively monitors the status of 29 selected glaciers (~ 65% of total glacierised area) in the Bhagirathi river basin and investigates glacier dynamics from 2000 to 2015. Impacts of the topographic factors on the glacier changes have also been examined. The following major inferences may be drawn from the results:

- The total glacier area decreased from 494.98 km^2 in 2000 to 492.49 km^2 in 2015 (i.e., loss of ~ 0.5% glacier ice) during the study period.
- All selected glaciers, except four (Dehigad, Maitri, 52 Bhagirathi, and Rudugaira) have shown retreat with retreat rates varying from a minimum of ~ 0.06 m per year (27 Ganigad) to a maximum of ~ 19.4 m per year (Dokriani) during the study period. Both of these glaciers lie in the Pilang sub-basin.
- The glaciers showing a retreat of more than ~ 10 m/year are as follows: Dokriani (~ 19 ma-1), 2 Chhalan (~ 16 ma-1), Khatling (~ 14 ma-1), 13 Bhagirathi (~ 13 ma-1), 15 Bhilangana (~ 12 ma-1), Surali (~ 11 ma-1), Gangotri (10.7 ma-1), Swetvaran (10.5 ma-1), and Raktavaran (10.1 ma-1).
- A high positive and negative correlation is observed between glacier length and snout elevation in advancing and retreating glaciers, respectively.
- Glaciers with both northern and southern slopes have shown retreat. Although, lower latitude glaciers have shown higher retreat, and glaciers having a higher portion northerly oriented have shown less retreat in few basins. Dehigad glacier is oriented 92% toward North and has the maximum observed advancing (152 m).

Future directions of the present research will be to run simulation models to predict the impact of glacier retreat an on groundwater storage dynamics and aquifer system evolution at short and at long term in the Himalayas. This will address a current research gap as the current knowledge of future impacts on glacier melting on aquifer dynamics is limited by oversimplification of groundwater processes in hydrological models due computational and/or observational limitations in mountain regions, including Himalayas (Somers et al. 2019).

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Author contributions Conceptualization: H.A.S.S. and H.S.G.; methodology: M.A., D.K.S. and N.T.; software: H.A.S.S., D.K.S. and N.T. ; validation: H.A.S.S., D.K.S. and C.C.; writing—original draft preparation, H.A.S.S., H.S.G. and D.K.S.; writing—review and editing; M.A., C.C. and N.T.; supervision, M.A. and C.C.

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Data availability All data, models, and codes generated or used during the study appear in the submitted article.

Declarations

Competing interests The authors declare no competing interests.

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