Alarming recession of glaciers in Bhilangna basin, Garhwal Himalaya, from 1965 to 2014 analysed from Corona and Cartosat data

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ABSTRACT

Himalayan glaciers are showing reliable evidences of climate change. Glacier status in Bhilangna basin of Garhwal Himalaya were mapped from Corona and Cartosat satellite images acquired in 1965 and 2014. The main Khatling trunk glacier that receded 4340 m resulted in fragmentation of the compound basins trunk glacier into multiple valley glaciers, which increased the number of glaciers in the basin from 20 to 33 and loss of 10% glacier area during 1965 to 2014. The Glacial erosional and depositional landforms reveal evidences of two stages of glaciation in the basin. The Khatling glacier paleoextent was reconstructed to 8.4 Km from the present snout to downstream. The satellite image interpretation and field evidences show that morphology and dynamics of the glacier has a strong influence on the faster recession of Khatling glacier. Systematic observation of glaciers from oldest Corona and recent Cartosat satellite images provide reliable information on glacier dynamics in the inaccessible terrain of the Himalaya.

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1. Introduction

Glaciers are valid earth pictures that reveal the climate variation as their dynamics linked with the warm and cold periods. Himalaya is considered to be the largest concentration of glaciers outside the Polar regions. Himalayan glacier inventory by the Geological Survey of India (GSI) shows a total of 9575 glaciers confined to Indian Himalaya (Sangewar and Shukla 2009). Snow and glacier melt from this 'third pole' cryosphere is the major source of water for the large river basins, the Indus and the Ganges.

Many studies carried out in Indian Himalaya (Mason 1935; Mayewaski and Jeschke 1979; Sharma and Owen 1996; Owen 2009; Dobhal et al. 2013; Mehta et al. 2014) depicting the glaciers are in a state of imbalance since the Little Ice Age (LIA). Similar glacier fluctuations are also reported in other regions of the globe (Wang et al. 2014; Zemp et al. 2008). Most of the scientific analyses reveal the glaciers exhibiting accelerated recession, thinning and losing mass over the few past decades (Nie et al. 2010; Wang et al. 2014; Barry 2006; Yamada et al. 2004; Ding 2006; Yao et al. 2007; Bajracharya and Mool 2010; Cao et al. 2014).

The glacier fragmentation creates simple valley glaciers from the compound valley glaciers, and are more prone to faster melting than the larger trunk glaciers. Bhambri et al. (2011) showed significant ice loss and increase in number of glaciers due to fragmentation in Bhagirathi and Alaknanda basin. The accelerated recession of South Jaundhar and North Jaundhar glaciers, Tipra and Ratanban glaciers
also demonstrated the impact of fragmentation in acceleration of glacier recession (Mehta et al. 2011, 2013).

Satellite remote sensing is recognized as a productive tool for monitoring the health of the glaciers in a time to cost benefit ratio. Various studies recommend that monitoring the glaciers through temporal satellite data can give the status of the glacier dynamics according to time and change in climate (Racoviteanu et al. 2008; Bolch et al. 2010; Burns and Nolin 2014; Gardent et al. 2014). In the Indian Himalaya also glaciers are continuously monitored through satellite data and advanced remote sensing methods (Philip and Ravindran 1998; Kulkarni and Alex 2003; Kulkarni and Karyakarte 2014; Kulkarni and others 2004, 2005, 2007, 2011, 2017; Philip and Sah 2004; Bhambri and Bolch 2009; Bhambri et al. 2011; Bahuguna et al. 2007; Mehta et al. 2011, 2013, 2014; Raj 2011; Raj et al. 2014; Shukla et al. 2009, 2010; Shukla and Ali 2016; Shukla and Yousuf 2016).

Due to accessibility and difficult terrain, only limited number of glaciers are monitored continuously in Indian Himalaya. The Gangotri glacier, Dokriani glacier, Pindari glacier, Milam glacier, Chorbari glacier, Satopanth glacier, Bhagirathi Kharak glacier, Parbati glacier, Samudra Tapu glacier, Chhota Shigri glacier and Kolahoi glacier are some of the well-studied glaciers within the field and from satellite data techniques (Wagnon et al. 2007; Auden 1937; Ahmad 1962; Tewari and Jangpangi 1962; Sharma and Owen 1996; Naithani et al. 2001; Ahmad et al. 2004; Dobhal et al. 2004, 2008; Dobhal and Mehta 2010; Kulkarni et al. 2005, 2006; Thayyen et al. 2005a; Nainwal et al. 2007, 2008, 2016; Singh et al. 2012; Shukla et al. 2010; Bali et al. 2013; Bhambri et al. 2011, 2012; Raj 2011; Raj et al. 2014; Negi et al. 2012; Mehta et al. 2014; Rashid et al. 2017). Table 1 shows a compilation of recession of some selected glaciers in Indian Himalaya. These observations show that the glaciers are in a state of recession, thinning and downwasting, and have implications on water resources of the region and affect the population in farming and hydropower sectors. Due to lack of meteorological observations and continuous glaciological data, it is difficult to establish the relationship of climate change through glacier dynamics. But the observable features like terminus recession, fragmentation and lake formations can be attributed to the effect of change in climate over glacier

| Glacier       | Period Years | Recession (m) | Average rate (m/yr) | References      |
|---------------|--------------|---------------|---------------------|-----------------|
| Siachen Glacier | 1929–1958   | 29            | 915                 | Vohra (1981)    |
| Zemu Glacier  | 1909–1965   | 56            | 440                 | Vohra (1981)    |
| Pindari Glacier | 1845–1966   | 121           | 2840                | Vohra (1981)    |
| Parbati Glacier | 1966–2010   | 44            | 379                 | Vohra (2013)    |
| Chorabari Glacier | 1962–2012   | 50            | 344                 | Vohra (2013)    |
| Gangotri Glacier | 1935–1966   | 64            | 1250                | Vohra (2013)    |
| Milam Glacier  | 1849–1997   | 148           | 2472                | Shukla and Siddiqui (1999) |
| Dokriani Glacier | 1954–2006   | 52            | 1328                | Raj (2011)      |
| Shankulpa Glacier | 1961–1998   | 57            | 518                 | Vohra (2013)    |
| Poting Glacier | 1906–1957   | 51            | 262                 | Vohra (2013)    |
| Bara Shigri Glacier | 1890–1906  | 16            | 1000                | Mayewski and Jeschke (1979) |
| Sonapani Glacier | 1909–1963   | 57            | 905                 | Vohra (2013)    |
| Kolahoi       | 1857–2014   | 157           | 2850                | Rashid et al. (2017) |
| Tipra Bank Glacier | 1857–1909 | 52            | 800                 | Mayewski and Jeschke (1979) |
| Zemu Glacier  | 1907–1965   | 56            | 440                 | Vohra (1981)    |
| Chiba         | 1961–2000   | 39            | 1050                | Oberoi et al. (2001) |
| Meola         | 1961–2000   | 39            | 1350                | Oberoi et al. (2001) |
| Hamta         | 1963–1998   | 35            | 600                 | Oberoi et al. (2001) |
| Chhota Shigri | 1962–1989   | 26            | 195                 | Oberoi et al. (2001) |
| South Lhonak  | 1962–2008   | 46            | 1900                | Raj et al. (2013) |
regime. These parameters are relatively easier to extract from satellite remote sensing. Considering the receding trend of glaciers in Indian Himalaya, the present paper aims to analyse the recession and morphological changes of the glaciers in Bhilangna basin from 1965 to 2014.

2. Study area

The Bhilangna river is the southernmost tributary of Bhagirathi river and confluences with it near New Tehri. The melt water from Khatling and tributary glaciers in the basin contribute to the source of Bhilangna river. The Bhilangna basin is bounded by Bhagirati group of glaciers in north, west and Mandakini group of glaciers in East. The basin supports a total of 33 glaciers of different morphological types; the major glaciers in the basin are Khatling, Phating, Satling, Bhartekunta, Jogin, Dudhanga and Ratangrian glaciers (Figure 1). Khatling glacier (30° 50’ 8” N, 78° 54’ 1” E) is the largest compound basin, valley glacier orienting south-east, and receives ice from more than two cirques, out of which Janoli peak (6632 m) and Bhetiara Ka Danda (5748 m) are major sources. The basin comprises various erosional and depositional landforms, such as ‘U’ shaped glacial trough, reamanent lateral moraines, recessional moraines, kame terrace, debris fans and outwash plain.

The oldest available record of the Khatling glacier was revealed by the report of J. B. Auden (1940). During his Himalayan traverse and climbing, the pass from Rudugaria to Khatling in June 1939, Auden crossed the ablation area of the Khatling glacier and found that the area was occupied by a huge ice-fall and seracs with large crevasses. After he succeeded in climbing the pass/col between the Rudugaria and Khatling, the col was named as ‘Auden’s Col’.

3. Methodology

The major data-sets used under the present study are Corona data of 1965, 1968, and Cartosat-1 data of 2014 (Table 2 and Figures 2 and 3). Additionally, latest Resourcesat -2 Linear Imaging Self
Scanning Sensor (LISS) - IV data of 2012, 2013 and Cartosat Digital Elevation (DEM) data was utilized for feature extraction. All the satellite images were acquired during September to October months for better delineation of features.

Delineation of glacier outline from satellite data is a well-established method (Kaab et al. 2002; Philip and Sah 2004; Bolch et al. 2008; Racoviteanu et al. 2008). The method involves co-registration of different satellite data, image enhancements and image interpretation. The co-registration involves a selection of observable, identical ground control points (GCPs) from the two respective images. In general, road junctions, river bends and river junctions are taken as GCPs in satellite images. But glaciated terrains getting such permanent features is very limited. The field expedition in September 2016 collected many GCPs using GPS survey (horizontal accuracy $\pm$ 3 m and vertical accuracy $\pm$ 4 m) in the terrain. Some prominent features like tributary-main glacier junctions, prominent drainage channels, lakes, linear landforms etc., which are visible in both master and slave images, are considered for collection of field GCPs. The 2014 Cartosat-1 imagery is orthorectified.

### Table 2. Satellite data used in the present study.

| Satellite data     | Date of acquisition | Spatial Resolution (m) | Scene ID/product ID   | Planimetric accuracy |
|--------------------|---------------------|------------------------|-----------------------|----------------------|
| Corona KH4A        | 24-September-1965   | 2.7                    | DS1024-1023DA124      | $\pm$ 5              |
| Corona KH4A        | 27-September-1968   | 2.7                    | DS1048-1134DA108      | $\pm$ 5              |
| Cartosat-1         | 07-September-2014   | 2.5                    |                       | $\pm$ 10             |
| Resourcesat-2 LISS IV | 30-September-2013 | 5.8                    |                       | $\pm$ 10             |
| Cartosat DEM       | 2011                | 10                     |                       | $\pm$ 10             |

Figure 2. (a) The synoptic view of the Khatling glacier in 1965 viewed by Corona data (note – some areas are cloud covered). (b) Synoptic view of the glaciers in 2014 viewed by Cartosat-1 data. (c) Detailed view of the Khatling glacier ablation area and its tributary glaciers in 1965, clear view of epiglacial lake near the Khatling–Phating junction. Note the snout during 1968 is near to the erosion lake and the river Bhilangna originating from the snout. (d) The Cartosat-1 image shows the receded and detached Khatling, Phating and Ratangrian glaciers. The terminus of Khatling in 1965 is clearly noticeable in the image. The Bhilangna river originates from the Khatling snout and flows through the outwash plain.
using the 14 field GCPs with an RMSE of 0.3. All the images were orthorectified using the Cartosat-1 data with a maximum RMSE of 0.6 for better mapping accuracy in the glaciated terrain.

After co-registering all the input satellite images, digital image enhancements like radiometric enhancements was applied to the images for better visual interpretation. The oldest glacier outline was delineated from Corona data of 1965, topographic map of 1965, and from 1968 Corona data. Recent glacier outlines extracted from Cartosat-1 data of 2014 with additional support of LISS IV data. The glacier boundaries were generated from different periods overlaid in Geographic Information System (GIS) and analysed the glacier recession, fragmentation and areal changes.

3.1. Uncertainty analysis

The glacier boundaries delineated from two different spatial resolution images may have different levels of accuracy. The uncertainty in glacier terminus recession was estimated using the following method proposed by Hall et al. 2003 and Wang et al. 2009.

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

where \( a \) and \( b \) are pixel resolution of image \( a \) and image \( b \), respectively, and \( \sigma \) is the image registration error.
The uncertainty of Corona 1965 data can be estimated as

\[
\text{Uncertainty (1965 – 2014)} = \sqrt{(2.7)^2 + (2.5)^2} + 5 = 8.6 \text{ m}
\]

Therefore, the uncertainty is 8.6 m for Corona 1965 and 1968.

The uncertainty in glacier area changes estimated using the formula of Hall et al. 2003.

\[
U_{\text{area}} = N_s \times A
\]

where \(N_s\) is the number of pixels along the glacier boundary and \(A\) is the area of the pixel. The accuracy analysis of glacier area change is given below.

\[
U_{\text{area}}(1965) = 8394 \times 7.29 = 0.061 \text{ km}^2
\]

\[
U_{\text{area}}(2014) = 6800 \times 6.25 = 0.042 \text{ km}^2
\]

4. Results

4.1. Snout recession

All the glaciers in the basin show significant recession from 1965 to 2014. Recession of Khatling glacier trunk is alarming in comparison to other glaciers in the basin (Figure 2). The 1965 snout of Khatling glacier is clearly visible in Corona data (Figure 2(c)). The 2014 terminus of the Khatling glacier is located farther from its position in 1965/1968, while river Bhilangna drains through the deglacial valley (Figure 2(d)). The total recession of Khatling glacier measured along the central flow line of the glacier shows that the glacier snout receded 4340 ± 17.1 m between 1965 to 2014, with an average rate of 88 ± 0.3 ma⁻¹.

This recession resulted in fragmentation of the Khatling compound basins glacier into multiple compound basin glaciers and simple glaciers (Figures 2 and 3). Due to this recession, the Khatling glacier got detached from the Phating, Ratangrian and one un-named tributary glacier. The current Phating glacier terminus is at a distance of 152 m away from its earlier attached part with Khatling glacier (Figure 2(d)). The Corona data also shows the presence of an epiglacial lake over the debris covered surface of the Khatling glacier near its confluence with Phating glacier (Figure 2(c)).

One un-named tributary glacier also detached from the Khatling glacier and receded 94 m (Figures 3(c) and (d)), and Ratangrian glacier receded 1030 m during this period (Figures 3(c) and (d)). During this period, Satling glaciers also receded 276 m and detached from the Phating glacier (Figures 3(e) and (f)). A tributary glacier to the Satling glacier receded too, by 754 m and got a separate snout (Figures 3(e) and (f)). In addition, two tributary glaciers of Ratangrian and two tributary glaciers of Phating glacier receded and fragmented (Figures 4(c) and (d)). Table 3 depicts the recession of all the glaciers from 1965 to 2014.

4.2. Glacier area and altitude variations

Due to significant recession of glaciers from 1965 to 2014, terminus area of the glaciers also reduced. In 1965, the Khatling glacier was seen as a single compound basins glacier (Figures 2, 3, and 4) with a surface area of 58.011± 0.061 Km²; in 2014, it showed a reduction of 4.39 ± 0.1 Km² area from 1965. The reduction in area of the glaciers in Bhilangna basin is given in Table 3.

As the glacier terminus receded, the terminus altitude shifted from lower to higher reaches. The snout elevation of the glaciers were measured in past and recent through the contour layer of the topographic map and from Cartosat DEM, respectively. The Khatling glacier snout that was at an
Table 3. Inventory of glaciers in 1965 and 2014.

| ID               | Latitude  | Longitude | Name       | Highest elevation (msal) | Terminus elevation 1965 (msal) | Terminus elevation 2014 (msal) | Length 1965 (m) | Length 2014 (m) | Area 1965 (Km²) | Area 2014 (Km²) |
|------------------|-----------|-----------|------------|--------------------------|-------------------------------|-------------------------------|----------------|----------------|----------------|----------------|
| INSO13101001-01  | 30° 45’ 46.72” N | 78° 51’ 25.97’’ E | Khatling   | 6000 | 3570 | 3905 | 15,203 | 10,864 | 58.01 | 29.52 |
| INSO13101001-02  | 30° 45’ 58.37” N | 78° 51’ 23.10’’ E | Ratangrian | 5850 | 4450 | 5000 | 4250 | 3300 | 900 | 0.57 |
| INSO13101001-03  | 30° 47’ 5.34” N | 78° 51’ 42.21’’ E | Jogin      | 5000 | 4550 | 4800 | 1250 | 1180 | 0.50 | 0.48 |
| INSO13101001-04  | 30° 47’ 15.54” N | 78° 52’ 17.98’’ E | Ratangrian | 5000 | 4550 | 4800 | 1250 | 1180 | 0.50 | 0.48 |
| INSO13101001-05  | 30° 47’ 50.74” N | 78° 53’ 27.97’’ E | Jogin      | 5000 | 4550 | 4800 | 1250 | 1180 | 0.50 | 0.48 |
| INSO13101001-06  | 30° 49’ 21.37” E | 78° 54’ 5.59’’ E | Jogin      | 5000 | 4550 | 4800 | 1250 | 1180 | 0.50 | 0.48 |
| INSO13101001-07  | 30° 49’ 21.37” E | 78° 54’ 5.59’’ E | Jogin      | 5000 | 4550 | 4800 | 1250 | 1180 | 0.50 | 0.48 |
| INSO13101001-08  | 30° 48’ 23.01” E | 78° 54’ 42.42’’ E | Ratangrian | 5000 | 4550 | 4800 | 1250 | 1180 | 0.50 | 0.48 |
| INSO13101001-09  | 30° 48’ 21.16” E | 78° 54’ 13.88’’ E | Ratangrian | 5000 | 4550 | 4800 | 1250 | 1180 | 0.50 | 0.48 |
| INSO13101001-10  | 30° 48’ 21.37” E | 78° 54’ 13.88’’ E | Ratangrian | 5000 | 4550 | 4800 | 1250 | 1180 | 0.50 | 0.48 |
| INSO13101001-11  | 30° 48’ 21.37” E | 78° 54’ 13.88’’ E | Ratangrian | 5000 | 4550 | 4800 | 1250 | 1180 | 0.50 | 0.48 |
| INSO13101001-12  | 30° 48’ 21.37” E | 78° 54’ 13.88’’ E | Ratangrian | 5000 | 4550 | 4800 | 1250 | 1180 | 0.50 | 0.48 |
| INSO13101001-13  | 30° 48’ 21.37” E | 78° 54’ 13.88’’ E | Ratangrian | 5000 | 4550 | 4800 | 1250 | 1180 | 0.50 | 0.48 |
| INSO13101001-14  | 30° 48’ 21.37” E | 78° 54’ 13.88’’ E | Ratangrian | 5000 | 4550 | 4800 | 1250 | 1180 | 0.50 | 0.48 |
| INSO13101001-15  | 30° 48’ 21.37” E | 78° 54’ 13.88’’ E | Ratangrian | 5000 | 4550 | 4800 | 1250 | 1180 | 0.50 | 0.48 |
| INSO13101001-16  | 30° 48’ 21.37” E | 78° 54’ 13.88’’ E | Ratangrian | 5000 | 4550 | 4800 | 1250 | 1180 | 0.50 | 0.48 |
| INSO13101001-17  | 30° 45’ 8.33” N | 78° 59’ 47.98’’ E | Jogin      | 5000 | 4550 | 4800 | 1250 | 1180 | 0.50 | 0.48 |
| INSO13101001-18  | 30° 44’ 37.89” N | 78° 59’ 52.56’’ E | Jogin      | 5000 | 4550 | 4800 | 1250 | 1180 | 0.50 | 0.48 |
| INSO13101001-19  | 30° 44’ 13.93” N | 78° 59’ 26.20’’ E | Jogin      | 5000 | 4550 | 4800 | 1250 | 1180 | 0.50 | 0.48 |
| INSO13101001-20  | 30° 44’ 12.50” N | 78° 57’ 19.04’’ E | Jogin      | 5000 | 4550 | 4800 | 1250 | 1180 | 0.50 | 0.48 |

*Fragmented glaciers (the terminus does not exist in 1965).
altitude of 3570 m ± 10 in 1965, shifted to 3905 m ± 10 in 2014, and resulted in raise of 335 ± 10 m during this period. The change in altitude of the terminus of the glaciers in Bhilangna basin from 1965 to 2014 is shown in Table 3.

Due to the scarcity of visible high resolution satellite data between 1965 and 2014, the analysis was restricted purely to Corona and Cartosat satellite data. Comparative analyses were not attempted due to the lack of any glacier studies in Bhilangna basin.

4.3. Geomorphology and glaciation history

Systematic mapping of glaciogeomorphic features was attempted from pan-sharpened LISS IV data with substantial field evidences. The historical glacier extent is clearly demarcated in recent Cartosat and LISS IV data (Figures 5(b) and (c)). The 1965 Khatling glacier terminus location, marked by the lateral and recessional moraines, is evident in the field (Figure 5(d)). Presence of thick, 20 m high, arcuate recessional morainic deposit shows that the glacier was standing at this location for quite a long time. The main trunk of the glacier receded very fast, leaving huge moraine ridges at its prior confluence with Phating glacier (Figure 5(e)). The recession of the glacier deposited enormous morainic ridges sporadically forming huge outwash plains up to the present snout (Figure 5(f)). The valley between the Ratangrian intersection with Khatling glacier in the past and the present Khatling terminus is filled with many ice-cored moraines and huge boulders, and the Khatling glacier terminus is visible as highly broken surface in the narrow valley (Figure 5(g)).

It is clear from the satellite images that the Khatling glacier was further extended downstream from its 1965 location (Figures 5(a),(b) and (c)), and validated with field evidences. This farthest extent might have been achieved by the glaciers during its earlier advances. This extent is visible in
the form of a long lateral moraine (Level I) at an elevation of 200 m from Tamakund up to Chauki on the right side (Figure 6(a)) and at some places as trimline. This Level I lateral moraine from Phat-ing–Khatling confluence onwards is visible as the left lateral moraine of the Phating glacier and the right side as trimline (Figure 6(b)). The thick elongated kame terrace formed along the lateral moraine of the Phating glacier encompasses three kettle lakes also (Figure 6(b)).

During peak glaciations, the Dudhganga glacier also might have reached up to Chauki and contributed to the main trunk glacier. The level I lateral moraine and the extent of glaciation of the Dudhganga glacier is clearly visible in field (Figure 6(c)). The advanced Dudhganga glacier was in contact with the trunk glacier at Chauki. Due to these junctures and the bend of the valley, much of the glacial till got deposited at Chauki after the glacier recession. This formed the hummocky morainic ridges at the Chauki camping ground.

The height of Level I lateral moraine of the Phating glacier and the present thickness of the glacier shows thinning of the ice (Figure 6(e)). A moraine terrace formed on the right side of the Phating glacier concurrently with the Level I moraine confirms these observations (Figure 6(e)).

The Ratangrian glacier was connected with the Khatling trunk glacier during its glacial maximum. The morainic terrace on the left side of the valley and trimlines extending from the Phating-Khatling junction confirm these observations (Figure 6(f)). Downstream the Ratangriang lacier confluence, the deglaciated valley is very broad and 'U' shaped, with steep slopes up to Chauki (Figure 5(d)) and (f); the broad 'U' shaped valley represents the active, erosive power of the glacier during its maximum.

A second level lateral moraines studied from Tamakund onwards shows that the glacier might have reached up to this location again during the LIA. Following the end of the LIA, the glacier receded, as indicated by the presence of recessional moraines and the Level II lateral moraines. Later, the glacier receded and stayed quiet long time at the 1965 terminus location, as marked by the presence of well developed recessional and lateral moraines forming an arcuate shape (Figure 5(d)). At
many places, the subglacial/englacial till forms quiet extensive deposits and the Bhilangna river takes curves around these ridges (Figure 6(d)). The Khatling–Ratangrian junction is marked by the presence of many Level II morainic ridges and polished rock surfaces with glacial striations and grooves (Figure 6(f)). The polished and plucked bedrock surface of Ratangrian glacier indicates the power of subglacial erosion. The glacio-geomorphology map, prepared from both satellite image interpretation and field evidences, shows the extensive erosional and depositional features (Figure 7) of Bhilangna basin.

The glacier recession in Bhilangna basin is well evidenced by glaciers at higher altitude also. One of the debris-free tributary glacier of Dudhganaga glacier located at an altitude range of 4500–5800 m also showed significant recession during the period of study. The Corona data of 1968 does not show any lake at the terminus of the glacier (Figure 8(a)). But Cartosat-1 data of 2014 shows the formation of a moraine-dammed lake at the terminus of the glacier (Figure 8(b) and (c)). During the period 1968–2014, the glacier receded 780 m, and the lake formed in the deglaciated depression bounded with lateral moraines (Figure 8(d)).

The results show that the Khatling trunk glacier underwent two glacial advances marked by two levels of lateral moraines and kame terrace. The Bhilangna glaciation was extended upto 8.4 km from the present snout of the Khatling glacier. The Khatling trunk glacier extent is reconstructed based on these evidences (Figure 7). The glaciation history of the nearby Chorabari glacier also
shows similar extent of glaciation evidenced with the lateral moraines levels and kame terrace (Ranhotra and Kar 2011). The last glacial maximum (LGM) of Chorabari glacier is reconstructed based on its four stages of glaciation (Mehta et al. 2012). Similar LGM glaciations was also reported for Gangotri group of glaciers (Sharma and Owen 1996), and are reconstructed from glacial landforms and optically stimulated luminescence (OSL) dating.

5. Discussion

Glaciers behave differently in recession and fragmentation according to variations in the local climate. The studies on nearby Dokriani glacier (Dobhal et al. 2004) shows a rapid frontal recession from 1962 to 1995. The Chorabari glacier receded only 344 m from 1962 to 2012 and shrunk by 1% (Mehta et al. 2014). However, Parbati glacier receded 6569 m from 1962 to 2001 (Kulkarni et al. 2005).

In Indian Himalaya, south facing glaciers show more melting because they receive more solar radiation than north facing glaciers due to their orientation (Nainwal and others 2008; Chaujar 2009; Bhambri et al. 2011). In 1965, the ablation area of Khatling trunk glacier orientation was towards south with wide open valley; this might have enhanced the incidence of solar radiation and resulted faster melting of the glacier ice.

According Hewitt (2014), *Blockschollen* – ‘block motion’ – movement of the glacier along steep gradient may increase the recession (Finsterwalder 1937; Hewitt 2014). The block motion can break the glacier into ice blocks and slices of dead ice may be left within the moraines. The presence of huge ice fall and many large and wide crevasses in the ablation zone of the Khatling glacier clearly indicates high velocity. The steepness of the current outwash plain reveals that the Khatling glacier
advanced through steep gradient breaks, which increased the velocity of the glacier to form the ice-fall with serac. The absence of any active supraglacial lakes on the ablation zone of the Khatling and tributary glaciers confirm this observation. In general, supraglacial lakes form over a glacier surface where the surface slope is <5° (Quincey et al. 2007; Sakai and Fujita 2010; Raj et al. 2014). The speedy movement of glacier over steep slope is the major reason for the blockschollen movement. The blockschollen of the Khatling glacier might have broken the glacier internally, and this broken portion melted very fast and receded the glacier to its present extent from 1965.

The debris cover of the Khatling glacier is very thin in comparision to the debris cover of other glaciers in Bhilangna basin. Studies on the debris cover on glacier ablation reveals that the debris cover reduces the rate of melting (Pratap et al. 2015). It was also found that thick debris covered glaciers respond slowly to climate change than thin debris covered or clean glaciers (Scherler et al. 2011; Dobhal et al. 2013). The Phating glacier is encapsulated with thick debris cover and shows slow recession, while thin debris cover of the Khatling glacier boosts the radiation received by the glacier results in more melting.

Himalayan mountain system experiencing an increase in trends of temperature from the LIA (Kotlia et al. 2012). Bhutiyani et al. (2007) reported the episodes of a significant rise in air temperature of 1.6°C in the north-western Himalaya. Due to lack of meteorology observations in Bhilangna basin, the climate-glacier relation is not analysed in the present research. The temperaturate data of nearby Dokriani and Chorabari glaciers indicates increase in temperature and decrease in snow accumulation (Thayyen et al. 2005b; Kesarwani et al. 2012; Mehta et al. 2012, 2014; Dobhal et al. 2013). This shift due to climate change might have resulted in accelerated melting of ice.
Himalayan glaciers are in a state of retreat with various rates since 1960 (Dobhal et al. 2004; Kulkarni et al. 2007, 2011; Raj 2011; Bhambri et al. 2012; Mehta et al. 2014). In Bhilangna basin, the glaciers have increased in number due to fragmentation of the main compound basins glacier. The Khatling glacier recession from 1965 to 2014 is quite high considering the recession of neighbouring Bhagirathi and Mandakini group of glaciers. But none of the glaciers show a similar fashion of recession as reported by Khatling glacier. This heterogeneity of the Khatling glacier may be attributed to multiple criteria acting on the glaciers, such as glacier orientation, slope of the glacier bed, debris thickness, glacier velocity and climate change.

6. Conclusion

The compound basins Khatling glacier fragmented into four glaciers and receded 4340 m during 1965 to 2014. The over-all recession and fragmentation doubled over the number of glaciers from 20 to 33 in Bhilangna basin during this period. The satellite image signatures and field evidences indicate that the basin experienced two stages of glacial advance. The farthest extent of the Khatling trunk glacier in the past and recent LIA are reconstructed from the erosional and depositional landforms. The recession of the Khatling glacier is very high, signifying control of terrain morphology and glacier dynamics. The alarming retreat and fragmentation of valley glaciers into smaller glaciers will further reduce the glaciers through faster down-wasting. Such situations may have profound impact on the future sustainability of Himalayan glaciers and water availability.

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