# Surface processes during flash floods in the glaciated terrain of Kedarnath, Garhwal Himalaya and their role in the modification of landforms

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**Glaciers are considered as one of the best indicators of climate change and glacial landforms are analysed for the reconstruction of palaeoclimate. It has been noticed that the landforms keep on changing with time and space. However, no attention has been paid to this problem. The catastrophic event such as Kedarnath event of June 2013 is identified as one important process which modifies the landforms and landscape. The flash floods which initiated the new channels, activated the abandoned channels and raised the water of Mandakini River and caused bank erosion and deepening of the valley are the main process for devastation. The human encroachment in the natural events multiplied the damage.**

**Keywords:** Chorabari Glacier, flash floods, incessant rain, landform modification, surface processes.

GLACIERS expand and shrink in direct response to the temperature fluctuations and preserve a complete record of the climate change in the landforms on geological timescale. The study of climate change based on the analysis of glacier landforms is precise and valid if it is primary and not modified by secondary processes. However, it has been observed that some catastrophic events modify the landforms. On 16 and 17 June 2013, heavy incessant rains overfilled the Gandhi Sarovar and induced landslides which blocked the Mandakini River system in the Kedarnath area and formed the ephemeral lakes. Bursting of Gandhi Sarovar and the temporary lakes caused flash floods. Due to habitation within the Mandakini River valley and abandoned river channel, the leftover part of the river was not capable of accommodating its high discharge. Therefore, it activated the abandoned channels, initiated new channels and increased the discharge of the main channel. This high-energy flow of water laden with debris, increased the bank erosion, caused deepening of the valley and washed out almost everything that came its way. The above processes differentially eroded the sediments from mountain wall, moraines, outwash plains, valley wall and river banks and deposited 1–1.5 m thick, poorly sorted sediments on the outwash plain and river valley. The redistribution of enormous amount of sediments created confusion in the identification of primary and secondary diamictons and resulted in the modification of pre-existing glacial landforms.

The Himalaya is a sustainable source of freshwater and the birthplace of all the perennial rivers of North India. During the last few decades, it has witnessed many casualties due to natural events namely earthquakes, landslides, cloudbursts and flash floods. However, human intervention in the natural cycle has made a disruptive effect on the conducive environment causing loss of life and property. Flash floods caused by bursting of glacial lakes, slope failures and landslides are well known in the Himalayas[1–4]. The progressive thinning of the Himalayan glaciers during the past century has also resulted in the formation of new lakes dammed by moraines[5]. However, their role in the modification of landforms is not much understood as yet. The present communication deals with the surface processes which have operated during the flash floods and their role in the modification of landforms/landscape.

Chorabari and Companion glaciers are located at a distance of about 1–2 km north of Kedarnath town in Rudraprayag district of Uttarakhand, Garhwal Himalaya (Figure 1). Chorabari is a 7 km long valley glacier[6] that originates from Kedarnath peak at an altitude of about 6500 m and terminates at an elevation of 3800 m. The

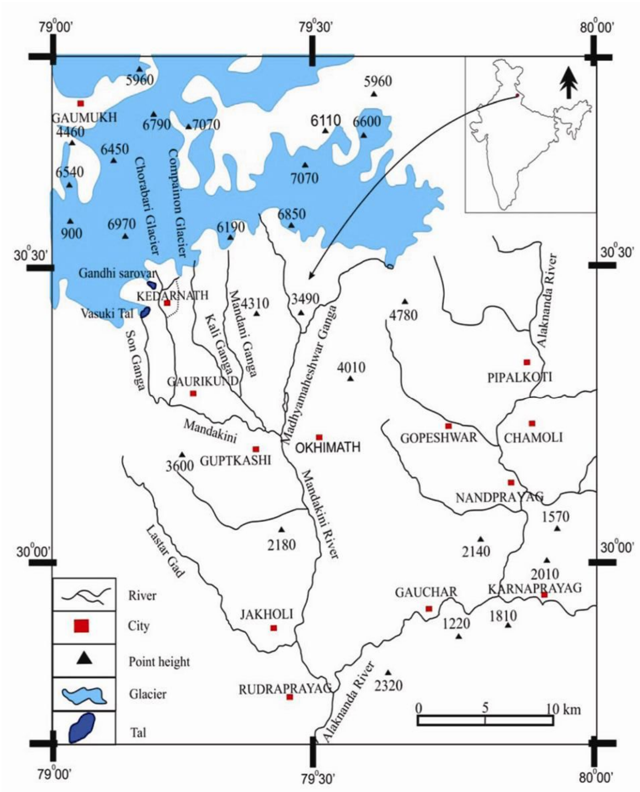


**Figure 1.** Location map showing Chorabari Glacier, Companion Glacier, Gandhi Sarovar, Vasuki Tal, Kedarnath Town, Rudraprayag, Mandakini River and its tributaries.

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lower part of the glacier is covered by thick supraglacial moraines and bracketed by lateral moraines (Figure 2). It is retreating at different rates[7] and has undergone many major and minor changes in its spatial extent, which is evidenced by the presence of glacial and glacio-fluvial deposits occupying different elevations and positions in the region (Figure 3). Mandakini River originates from the Chorabari Glacier (Figure 2). The stream originating from the Companion Glacier joins Mandakini River upstream of Kedarnath. Earlier, one stream was feeding the Mandakini River downstream of Kedarnath also, but this stream has abandoned its course now. Kedarnath is located and developed on the glacial and glacio-fluvial deposits of the Chorabari and Companion glaciers within the Mandakini and the abandoned river course (Figure 4). Saraswati, Kali Ganga and Madhyamaheshwar Ganga feed Mandakini River from the left and Son Ganga and Laster Gad from the right. It travels in southern direction through Rambara, Gaurikund, Sonprayag, Phata, Guptakashi, Bhatwari and Tilwara, and finally drains into Alaknanda near Rudraprayag (Figure 1). Alaknanda joins Bhagirathi River at Devaprayag and forms the mighty

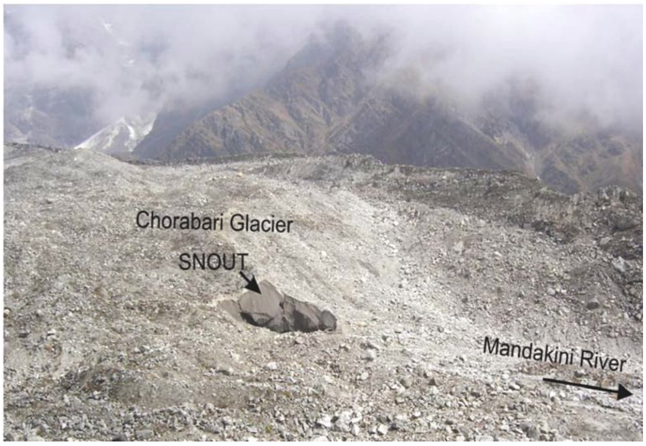


**Figure 2.** Snout of Chorabari Glacier, origin of Mandakini River, supraglacial and lateral moraines.

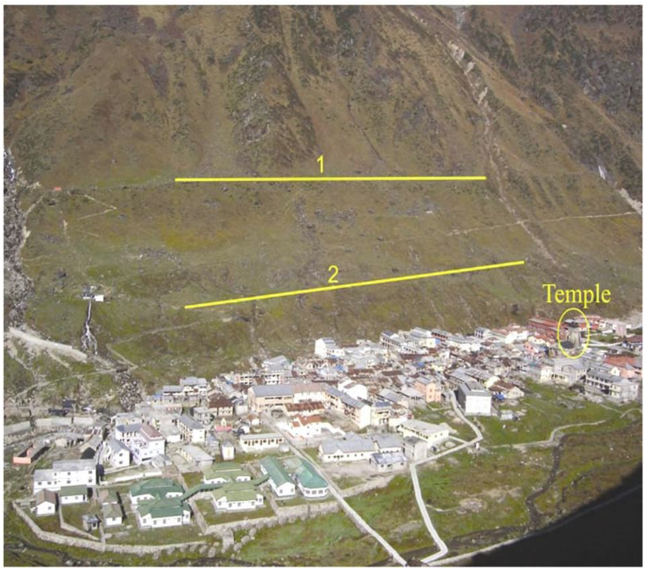


**Figure 3.** Kedarnath town showing different (1 and 2) stages of glacial and glacio-fluvial deposits.

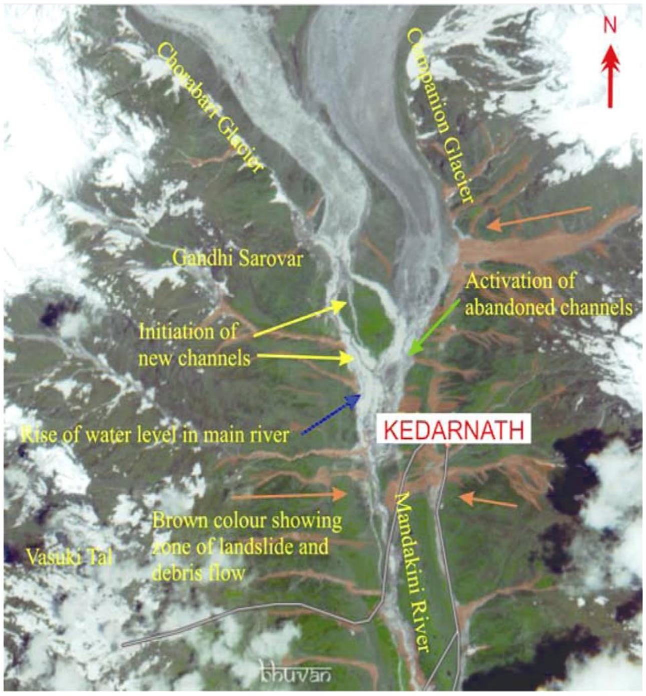


**Figure 4.** Satellite data showing Chorabari Glacier, Companion Glacier, Gandhi Sarovar, Vasuki Tal, Mandakini River, activation of abandoned channel, initiation of new channels, zones of landslide and debris flow.


**Figure 5.** Confluence of Alaknanda and Bhagirathi rivers at Deoprayag, 10–15 m rise of water and deposition of sand during the recent flood in June 2013.

**Table 1.** Left and right bank tributaries of the Mandakini River

| Tributary | River bank | Length (km) | Origin | Place of confluence |
|---|---|---|---|---|
| Stream | Left | 3 | Companion Glacier | Behind Kedarnath |
| Kali Ganga | Left | 30 | Mahalaya Parbat | 2 km upstream of Guptkashi |
| Madhyamaheshwar Ganga | Left | 36 | Nandi Kund | 1.5 km upstream of Guptkashi |
| Son Ganga | Right | 21 | Vasuki Tal | Sonprayag |
| Stream | Right | 32 | Bajranga | 7.5 km downstream of Guptkashi |
| Lastar Gad | Right | 55 | Kinkhola Khal | 7 km upstream of Rudraprayag |

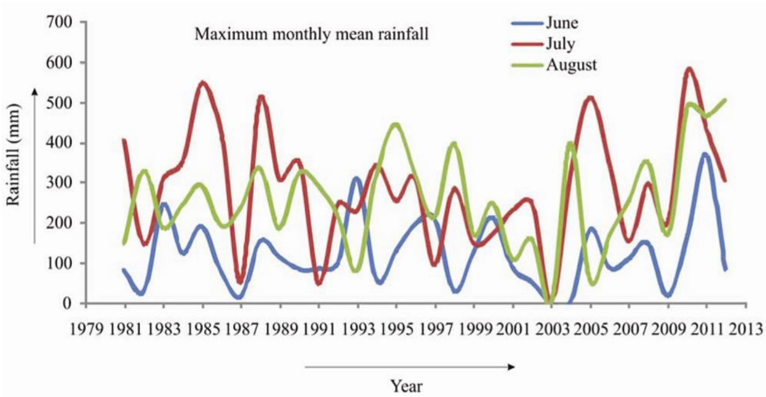


**Figure 6.** Rainfall variations during monsoon from 1981 to 2011.

**Figure 7.** Thick depositions (1–1.5 m) of poorly sorted sediments in the outwash plain; the steps of the temple are filled.

River Ganga (Figure 5). Table 1 shows the origin, confluence and length of the tributaries of the Mandakini River.

The mean monthly average rainfall of Rudraprayag district from 1981 to 2011 during monsoon season is plotted in Figure 6 (IMD data from 2003 to 2011 and India Water Portal data from 1981 to 2002). It indicates that maximum rainfall (547.128 mm) is during June–August. During the second week of June 2013, the southwest monsoon and the westerly disturbances were strong. They caused heavy, incessant rains, much more than the normal during 15–17 June at many places in Uttarakhand. Automatic weather station of the Wadia Institute of Himalayan Geology recorded 325 mm of rainfall in 24 h between 15 and 16 June 2013 in the Kedarnath area[8].

The rain-induced mass movements, mainly the landslides and debris flow transported huge amount of sediments from the upland areas which came to Kedarnath town and the river valley and blocked Mandakini River and its tributaries. The blocking of the rivers formed the ephemeral lakes. Prolonged heavy rains overfilled the permanent (Gandhi Sarovar) and temporary lakes (formed by blocking of river channels). The increasing water pressure resulted in the bursting of lakes and caused the flash floods. The unplanned habitation, construction and developmental activities had encroached the abandoned channels, river banks and river valley over time in such a way that they failed to hold the high discharge of the river. Soil erosion due to deforestation resulted in the siltation of river bed which further reduced its water-holding capacity. So the flash floods activated the abandoned channels and initiated the new channels. The water spread in the entire area and the water level of the river rose by about 1–3 m. The rise of water level also occurred in the downstream areas (Figure 6, showing rise of water about 10–15 m at Deoprayag). The flow was turbulent under high flow regime when the inertial forces were much higher than the gravitational forces and the Froude number was more than one. Therefore, the erosive capacity of the flow was very high. It was much higher due to debris. The bank erosion, scouring and deepening of the river valley started removing the base of the buildings situated on river banks and riverbeds. All these processes combined together, damaging and sweeping away humans, livestocks, buildings, villages, towns, roads, agricultural land, mountain side and developmental activities that stood in the way, and causing devastation never witnessed so far[9] in the entire Kedarnath town and further downstream at Rambara, Gaurikund, Phata, etc. Such major rainfall events had occurred earlier many times in the Himalaya; but the major disaster this time was due to larger gap between scientific facts, natural laws and anthropogenic activities.

In the glaciated region, the sediment samples are collected from the landforms for interpreting and reconstructing the palaeoclimate, provided it is not modified by secondary processes. It has been reported that the tributary glaciers modify the landforms, due to bursting of lakes during heavy rains[3]. During ablation period, the snow-melt ephemeral streams modify the landforms[10] and the glacier vacates its valley. Secondary surface processes such as mass movements, lacustrine, fluvial and pluvial come into existence and form some new landforms, such as debris cone, lake deposits, river terraces and pillar-like structures[10,11]. The mass movement causes sedimentation in the glaciated terrain[12]. The June 2013 event of Kedarnath redistributed 1–1.5 m thick sediments by differential weathering and deposition and thus altered the pre-existing landforms (Figure 7). The distribution of sediments in the Kedarnath region seems like diamictons and creates confusion in the identification of landforms. It is presumably due to this reason that different scientists have assigned different dates for the same events in a glaciated terrain[13,14].

The ideal section of moraines is unstratified, consisting of matrix-supported and/or clast-supported, poorly sorted sediments without any stratified thick sandy units[10,15,16]. Therefore, the presence of 40 cm thick sandy layer in the moraines of Chorabari Glacier such as Kedarnath glacial stage, Ghanurpani glacial stage and Rambara glacial stage[17] might be due to modification by similar events in the past. The report that it is difficult to identify and differentiate between various types of diamictons[18] and palaeo-floods[19] in the downstream at Deoprayag area during 200–300 year and 1.2 ka ago supports the present finding.

It is concluded that in the Kedarnath region incessant heavy rain induced flash floods, initiated new channels, activated abandoned channels and raised the water level of Mandakini River, causing devastation due to anthropogenic activities in the river cycle. Such events might have washed out the recessional moraines and disrupted the continuity of the lateral moraines. This could be the reason for the absence of recessional moraines in the Kedarnath area. The differential erosion, redistribution and deposition of huge amount of poorly sorted sediments in the outwash plain, river valley and the entire Kedarnath region modified the pre-existing glacial landforms and landscape.


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