Implications of Cloud Burst and Heavy Precipitation during the Uttarakhand Disaster (2013) on the Frontal Dynamics of the Gangotri Glacier

Pooja[1], Pawan Kumar[1], Surbhi Gaur[1]
Sanjay Deswal[2], Rakesh Saini[3], Syed Umer Latief[4] and Milap Chand Sharma[5]

Abstract

The monsoon-dominated north-western region of the Garhwal Himalaya is highly susceptible to hydro-metrological disasters due to its location, physiography, climate and high-energy environment. The landform mapping, terrestrial records, and multispectral satellite data depicted that the glacier in the north-western Garhwal Himalaya region has been retreating for the last 150 years at varying rates over time and space. On June 16–17, 2013, almost 500 times more precipitation was observed in the north-western Garhwal Himalayan region due to the fusion of the monsoon trough and western disturbances. The availability of supra-glacial lakes within the vicinity of the Gangotri glacier and subsequent heavy precipitation associated with the Uttarakhand disaster resulted in a retreat of 57±21.23 m on the right flank of the Gangotri glacier due to either detachment or calving effects. The retreat between May and August 2013 is almost equal to the retreat between the last thirteen years, from 2000 to May 2013.

Keywords: *Uttarakhand Disaster, Cloudburst, Gangotri Glacier, Supra-glacial Lake, Glacier Retreat*

[1] Department of Geography, Chaudhary Bansi Lal University, Bhiwani, India
[2] Department of Geography, Govt. College Chhara, District Jhajjar, India
[3] Department of General and Applied Geography, Dr. Hari Singh Gour Central University, Sagar, India
[4] Department of Geography, Amar Singh College, Srinagar, India
[5] Centre for the Study of Regional Development, Jawaharlal Nehru University, New Delhi, India

1. Introduction

The Himalayan glaciers have been continuously retreating since the end of the Little Ice Age (LIA) (Bhambri and Bolch, 2009; Deswal et al., 2023; Mayewski et al., 1980; Raina, 2004). Many Himalayan glaciers have shown rapid retreating patterns (Bolch et al., 2008), and many glaciers have had stable fronts since 2000 (Bahuguna et al., 2014; Kulkarni et al., 2007). The aforementioned irregular behaviour of the Himalayan glaciers in general could be attributed to glacier topography (Oerlemans, 1989), climatic systems of the region (Kargel et al., 2005), glacier hypsometry and geomorphological characteristics (Furbish and Andrews, 1984), glacial surface characteristics and supraglacial debris (Scherler et al., 2011) and their morphological properties(Mehta et al., 2014) and their sizes and response time. However, glaciers are sensitive to both internal and external factors, high-energy metrological events and land surface processes, and their dynamics within the vicinity of the glacier terminus or a combination of all the factors mentioned above have the potential to accelerate or decelerate the glacier retreat. The high-energy Himalayan environment, metrological triggering, and topographical factors all together resulted in a massive disaster on June 16–17, 2013, in the Garhwal region of the western Himalaya, named the 'Uttarakhand Disaster'. Present study accessed the impacts of ‘Uttarakhand Disaster’ on the frontal dynamics of the Gangotri glacier with remotely sensed data and field-based verification.

2. Study Area

The Gangotri glacier is located in the north-western region of the Garhwal Himalaya in the western Himalayan region (Figure 1). The Gangotri is the main and largest glacier of the Bhagirathi Basin; it originates from a narrow and large depression along the northern slopes of Chaukhamba peaks; and avalanches mainly feed the accumulation glacier mass.

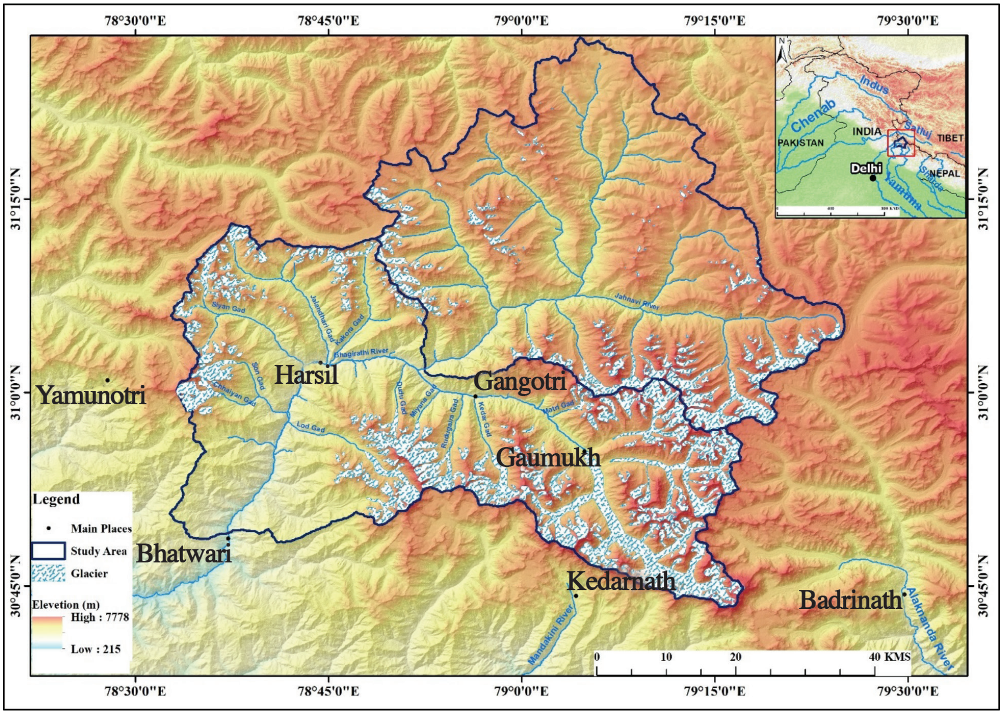

Figure 1 : Map of the study area in the Upper Bhagirathi Basin, Uttarakhand

The Gangotri glacier is about 30.2 k.m. long with a glacier-covered area of about 120 km², ranging from 4000 m.a.s.l. to 7036 m.a.s.l. (Raina, 2004). The holy river Ganga originates from Gaumukh, the snout of the Gangotri glacier, at an elevation of 4050 metres (Figure 1), which is an important source of life and livelihood for millions of peoples living in mountain and downstream.

3. Data Source & Methods

The distribution of precipitation over time and space during the Uttarakhand Disaster (short and long duration) has been accessed from the Tropical Rainfall Measuring Mission (TRMM) data, obtained from the Giovanni portal of NASA. Snout mapping of the Gangotri glacier has been performed with the help of Multispectral Landsat Satellite Data from 2000 to 2013, but Sentinal-2A data has been used for snout mapping since 2017. Further details of the data, sensor, scene ID, acquisition date and spatial resolution are given in Table 1. Extensive fieldwork was carried out in 2013 (May 17–27, 2013) and 2015 (May 21–June 7, 2015) for the ground truthing, collection of GCP and terrestrial records of the glacial dynamics in the Gangotri region.

However, the dynamics of the terminus of the Gangotri glacier have been mapped through manual digitization of the multispectral data. However, the mean retreat was measured through the overlaid line with a horizontal distance of 50 metres as per methodology (Bhambri and Bolch, 2009; Bhambri et al., 2011; Chand and Sharma, 2015), as represented in figure 2. The remotely sensed data has been processed, and glacier retreat length and area have been measured 1with the help of QGIS and R software.

Table 1: Details of the Satellite Data used for the Present Study

Data Type	Scene ID	Acquisition date	Spatial Resolution
Landsat 5 TM	LT05_L1TP_145039_20000923_20201029_02_T1	23.09.2000	30 * 30 m
Landsat 8 OLI/TRIS	LC08_L1TP_145039_20130522_20200912_02_T1	22.05.2013	
	LC08_L1TP_146038_20130801_20200912_02_T1	01.08.2013	
TRMM	TRMM_3B42RT_Daily_7	1.06.2013	0.25°
		10-17.05.2013	
Sentin-al-2A	S2A_OPER_MSI_L1C_DS_SGS__20171014T104205	14.10.2017	10 * 10

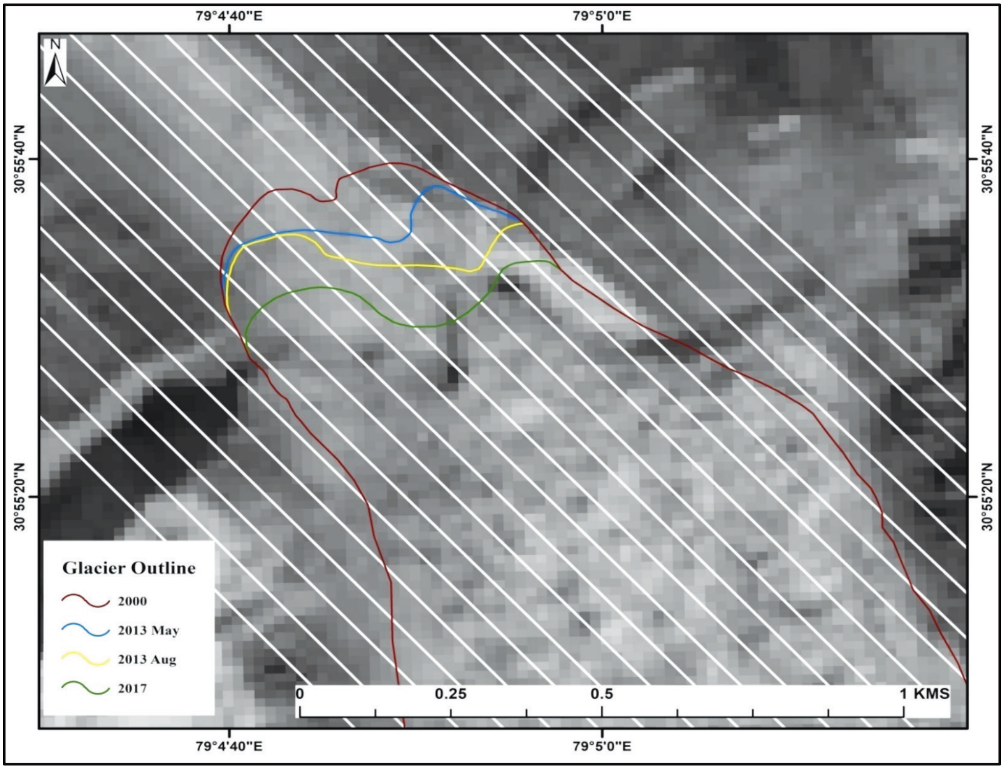

Figure 2 : Glacier outlines delineated from different satellite data and overlaid line with 50 m horizontal distance

4. Uttarakhand Disaster

The northwest Garhwal Himalayan region is highly vulnerable to Hydro-metrological disasters due to its geographical location, physiography, orographical forcing, overlapping dominant regional climatic systems (southwest Indian summer monsoon and Mid-latitude western disturbances), occasional fusion, high energy environment and dynamic glacio-fluvial processes (Dimri et al., 2017). As per the India Disaster Report (2013), the Uttarakhand disaster was caused by torrential precipitation in the middle of June (between June 14 and June 18, 2013) due to the fusion of the southwest monsoon trough and western disturbances over the Himalayan region. However, other studies reveal that the Uttarakhand disaster was caused by the early onset of the monsoon, heavy downpours, cloud bursts, and subsequent lake bursts, resulting in massive flash floods and landslides (Allen et al., 2016). Although some research anticipated that the lake breach was due to ground saturation caused by enhanced runoff due to rain-on-snow type melting (Dobhal et al., 2013).

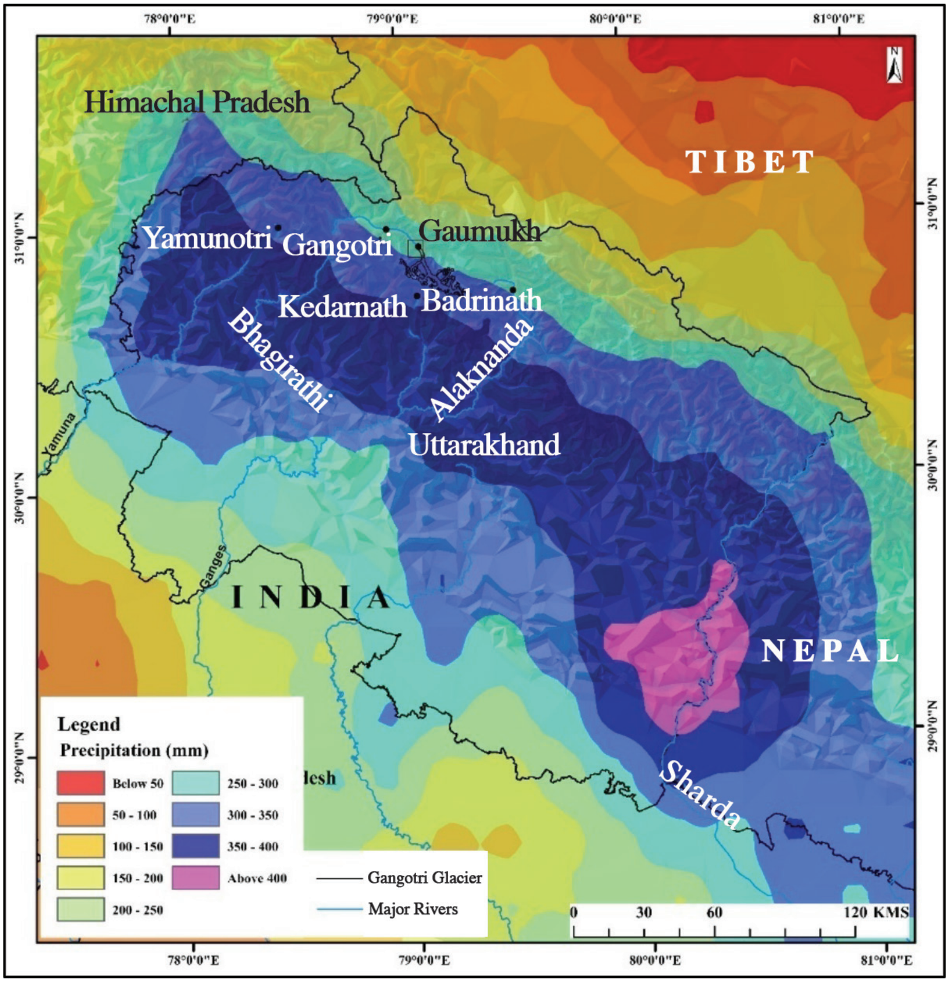

Figure 3 : Total Precipitation in the study area from June 10, 2013 to June 17, 2013

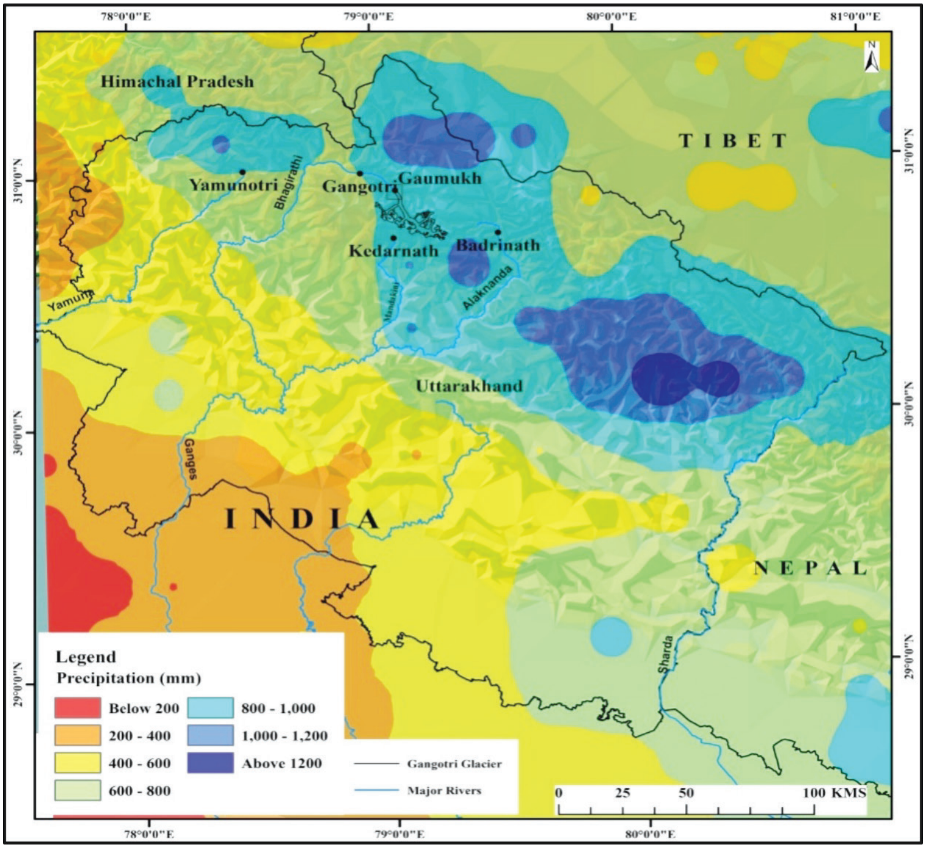

Figure 4 : Total Precipitation in the study area between May 13, 2013 and July 15, 2013

As per the TRMM 3B42 data, between June 10 and June 17, 2013; more than 350 mm of precipitation against the average precipitation of 71 mm (as per the IMD record) occurred in the north-western Garhwal Himalayan region (Figure 3), which was almost 500 times more than the normal precipitation in the region.

In the Uttarakhand disaster, as per the Uttarakhand state govt. official record 6,054 peoples were either dead or "presumed dead", over 100,000 pilgrims and tourists were stranded (Martha et al. 2014), and more than 30 hydropower plants were either destroyed or damaged (Sati and Gahalaut, 2013). The massive impact of the Uttarakhand disaster in terms of loss of life and livelihood was observed in the Alaknanda Valley. Further investigation of the TRMM data revealed that more than 1200 mm of precipitation had occurred between May 13 and July 15, 2013, in the northwest Garhwal Himalayan region. The high energy event also resulted in significant changes in the geomorphology and climatology of the upper reaches of the Alaknanda and Bhagirathi rivers.

5. Impact of Uttarakhand Disaster (2013) on the Retreat of the Gangotri Glacier

Glacier behaviour is dynamic; it varies with time, and the retreat rates calculated are never identical for even a single glacier over time. The Gangotri glacier in the northwest Garhwal Himalaya is well-documented because of its significance in Hindu mythology. Well-documented terrestrial records of over 150 years are available for the Gangotri glacier (Raina, 2009; Raina et. al., 2015). Frontal changes on the Gangotri glacier can be inferred from the terrestrial records by identifying and interpreting associated landforms. The signatures from the deglaciated valley in the foreland basin of the Gangotri glacier revealed that it has been retreating over the last 150 years. Continuous and comprehensive mapping of the Gangotri glacier has been carried out by the Geological Society of India since 1935, which reveals that in the last 61 years (between 1935 and 1996), the Gangotri glacier retreated about 1100 metres with an average annual retreat rate of 18 metres (Raina, 2004). Bhambri et al. (2012), reported a total retreat of 819 ± 14 meters of the Gangotri glacier from 1965 to 2006 with a varying rate of retreat; 5.9 ± 4.2 m/year from 1965 to 1968, whereas the highest rate of retreat (26.9 ± 1.8 m/year) was observed from during 1968 to 1980. Subsequently, the glacier retreated at an annual rate of 21.0 ± 1.2 meters between 1980 and 2001. The Gangotri glacier's retreat rate declined during 2001–2006, during which the Gangotri glacier receded with an annual retreat rate of 7.0 ± 4.0, almost 1/3 of the earlier retreat rate (Bhambri et al., 2012).

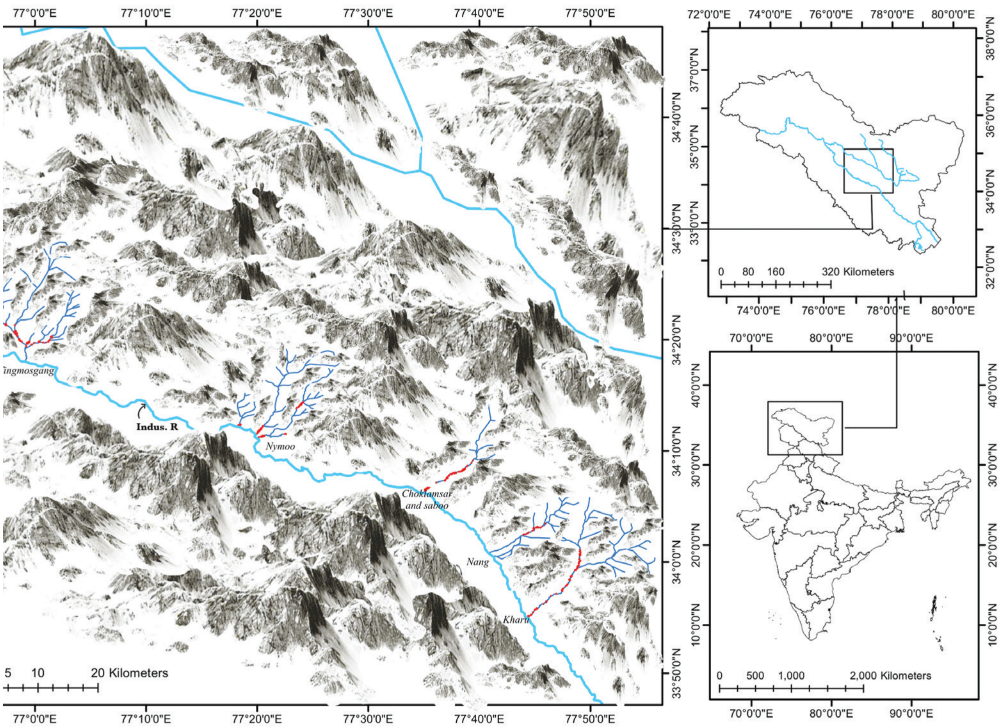

Figure 5 : Retreat of the Gangotri glacier. (A) Sept 2000, (B) May 2013, (C) August 2013 (D) Oct 2017, (E) Retreat of Gangotri Glacier from 2000 to 2017

However, the Gangotri glacier's retreat rate was accelerated very drastically between 2006 and 2017, during which Gaumukh retreated at a rate of 21.9 ± 1.9 m per year (Bhambri et al., 2023). On the contrary, stability was observed on the snout of the Gangotri glacier between 2001 and 2010 (Bahuguna et al., 2014), meaning the retreat rate was accelerated from 2010 onwards. The present study also observed a total retreat of 64.25±21.23 metres of the Gangotri glacier from 2000 to May 2013, with an annual rate of retreat of 4.94±1.63 m per year (Table 2).

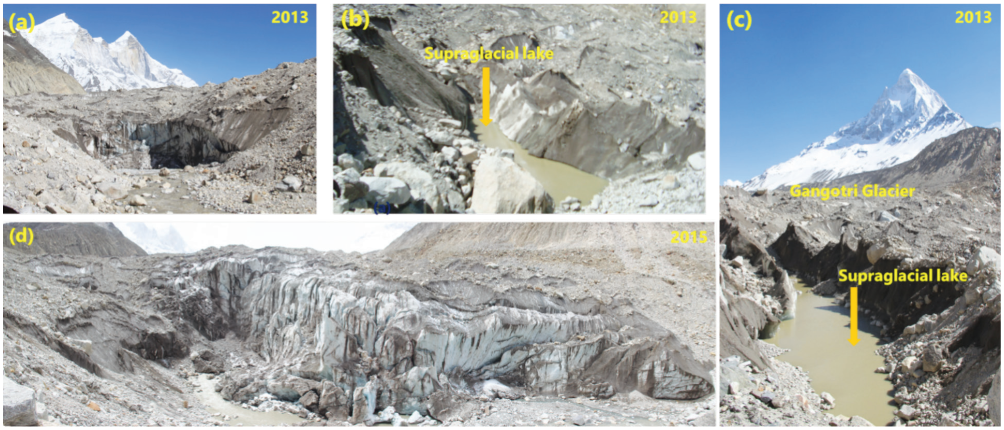

Figure 6 : Field photographs of the Gangotri glacier. (a) Snout of the Gangotri glacier, May (2013), (b) Supraglacial Lake near the Snout of the Gangotri glacier (May 2013), (c) Large Supra Glacial Lake on the Gangotri glacier (May 2013) and (d) Snout of the Gangotri glacier (May 2015)

Table 2 : Total Glacial Retreat and Mean Retreat Rate of the Gangotri glacier (2000-2023)

Year	Total Retreat (m)	Retreat rate (m/year)
2000 - 2013	64.25±21.23	4.94± 1.63
2013 (May - Aug.)	57.01±21.23	57.01±21.23
2013 (Aug) - 2017	95.75±15.83	23.98±3.96

Table 3 : Total area vacated and mean area vacated near snout from 2000 to 2023 in m^2

Year	Total Area Vacated (m^2)	Vacated mean Area (m^2/year)
2000 - 2013	24531±450.71	1887.0±34.67
2013 (May - Aug.)	22344±450.71	22344.0±450.71
2013 (Aug) - 2017	44375±244.59	11093.8±61.15

However, due to the heavy downpour in the Gangotri region associated with the Uttarakhand disaster (Figures 3 and 4) and the presence of the large supraglacial lakes (Figure 6a and c) within the vicinity of Gaumukh during May 2013, those lakes might have flooded due to heavy precipitation in subsequent months and either resulted in the detachment of a large section from the right flank of the Gangotri glacier or accelerated the melting on the right flank due to the strong calving effect, resulting in the accelerated retreat on the right flank of the Gangotri glacier somewhere between May and August 2013 (figure 5). During May and August 2013, the Gangotri glacier observed a total retreat of 57.01±21.23 m within the period of 04 months and subsequently, the Gangotri glacier retreated with an annual rate of 23.98±3.96 m from 2013 to 2017 (Table 2). From 2000 to 2013, the Gangotri glacier vacated 1887.0±34.67 m^2 area annually and 22344±450.71m^2 area between May to August 2013 (Table 3). However, between 2013 and 2017, the Gangotri glacier vacated11093.8±81.53 m^2 area annually. On the Gangotri glacier, unprecedented retreat has been observed in length and area between May and August 2013 (Figure 5, Tables 2 and 3). During the fieldwork in May and June 2015, the retreat on the right flank of the Gangotri glacier was also confirmed by field and terrestrial records (Figure 6d). The accelerated retreat of the glacier, coupled with slope instability and sedimentation from the lateral moraines of the Gangotri glacier near Meru glacier in 2017, caused the Bhagirathi river channel to shift, leading to the formation of a lake near the snout of the Gangotri glacier (Figure 5 D and E). This newly formed lake holds the potential to further accelerate the retreat of the Gangotri glacier in the near future.

6. Discussion and Conclusion

The Uttarakhand disaster in the north-western Garhwal Himalaya, marked by intense precipitation and a catastrophic cloudburst, triggered significant geomorphological changes, including the redirection of river courses, severe landslides, and the devastating loss of life and property. In the case of the Gangotri glacier, the presence of large supraglacial lakes, coupled with heavy rainfall, played a key role in accelerating its retreat. This event likely initiated calving and the detachment of large glacier sections, further intensifying the retreat process.

This study highlights the critical influence of glacier surface characteristics and extreme hydro-meteorological events, particularly in monsoon-dominated regions, on rapid glacial retreat. The findings reveal that the retreat rate of the Gangotri glacier is driven not only by mass balance but also by the interaction between surface processes and large-scale climatic forces. Notably, the glacier's right flank experienced a retreat of 57.01 ± 21.23 m between May and August 2013—nearly equal to the retreat recorded over the previous 13 years. This accelerated retreat is attributed to the combined effects of supraglacial lakes and intense precipitation, which likely accelerated calving or led to the detachment of glacier sections.

The study further identifies a significant shift in glacier dynamics, with a relatively stable retreat rate prior to 2013, followed by a sharp escalation post-disaster. This shift underscores the critical role of extreme weather events in altering glacier behavior. The evidence strongly indicates that high-energy climatic events, combined with specific glacial surface features, can drive accelerated retreat, particularly in monsoon-affected regions of the Himalaya.

In light of climate change, with the projected increase in extreme precipitation events, glaciers in the Garhwal Himalaya may experience more rapid retreat, leading to slope instability and increased mass movements. This, in turn, heightens the risk of hydro-meteorological disasters for downstream communities and critical infrastructure. The findings underscore the intricate interplay between local topography, glacial characteristics, and extreme weather events, carrying significant implications for future scientific research, climate resilience, and disaster management strategies.

Acknowledgements

The authors acknowledge Project No. (PAC - SSS - MCS - DST - 03130316 -725) for financial assistance for the field work sponsored under the Climate Change Programme (CCP), Department of Science & Technology (DST), Government of India.

References

1. Allen, S. K., Rastner, P., Arora, M., Huggel, C., & Stoffel, M. (2016). Lake outburst and debris flow disaster at Uttarakhand, June 2013: hydrometeorological triggering and topographic predisposition. *Landslides*, 13(6), 1479–1491. https://doi.org/10.1007/s10346-015-0584-3
2. Bahuguna, I. M., Rathore, B. P., Brahmbhatt, R., Sharma, M., Dhar, S., Randhawa, S. S., Kumar, K., Romshoo, S., Shah, R. D., Ganjoo, R. K., & Ajai. (2014). Are the Himalayan glaciers retreating? *Current Science*, 106(7), 1008–1013.

3. Bhambri, Rakesh, & Bolch, T. (2009). Glacier mapping: A review with special reference to the Indian Himalayas. *Progress in Physical Geography*, 33(5), 672–704.
4. https://doi.org/10.1177/0309133309348112
5. Bhambri, Rakesh, Bolch, T., Chaujar, R. K., & Kulshreshtha, S. C. (2011). Glacier changes in the Garhwal Himalaya, India, from 1968 to 2006 based on remote sensing. *Journal of Glaciology*, 57(203), 543–556. https://doi.org/10.3189/002214311796905604
6. Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, J. G., Frey, H., Kargel, J. S., Fujita, K., Scheel, M., Bajracharya, S., & Stoffel, M. (2012). The state and fate of himalayan glaciers. *Science*, 336(6079), 310–314. https://doi.org/10.1126/science.1215828
7. Bolch, Tobias, Buchroithner, M., Pieczonka, T., & Kunert, A. (2008). Planimetric and volumetric glacier changes in the Khumbu Himal, Nepal, since 1962 using Corona, Landsat TM and ASTER data. *Journal of Glaciology*, 54(187), 592–600. https://doi.org/10.3189/002214308786570782
8. Bhambri, R., Sain, K., Chand, P., Srivantava, D., Tiwari, S. K., Yadav, J.S., (2023). Frontal Changes of Gangotri Glacier, Garhwal Himalaya, between 1935 and 2022. *J Geol Soc India* 99, 169–172 (2023). https://doi.org/10.1007/s12594-023-2283-3
9. Chand, P., & Sharma, M. C. (2015). Frontal changes in the Manimahesh and Tal Glaciers in the Ravi basin, Himachal Pradesh, north-western Himalaya (India), between 1971 and 2013. ***International Journal of Remote Sensing***, 36(16), 4095–4113. https://doi.org/10.1080/01431161.2015.1074300
10. Deswal, S., Sharma, M. C., Saini, R., Chand, P., Prakash, S., Kumar, P., Barr, I. D., Latief, S. U., Dalal, P., & Bahuguna, I. M. (2023). Reconstruction of post-little ice age glacier recession in the Lahaul Himalaya, north-west India. *Geografiska Annaler, Series A: Physical Geography*, 105(1), 1–26. https://doi.org/10.1080/04353676.2022.2148082
11. Dimri, A. P., Chevuturi, A., Niyogi, D., Thayyen, R. J., Ray, K., Tripathi, S. N., Pandey, A. K., & Mohanty, U. C. (2017). Earth-Science Reviews Cloudbursts in Indian Himalayas : A review. *Earth-Science Reviews*, 168, 1–23. https://doi.org/10.1016/j.earscirev.2017.03.006
12. Dobhal, D. P., Gupta, A. K., Mehta, M., & Khandelwal, D. D. (2013). Uttarakhand disaster: Facts and plausible causes. *Current Science*, 105(2), 171–174.
13. Furbish, D. J., & Andrews, J. T. (1984). The use of h ypsometry to i nd icate long-ter m stabi lity and response of v alley glaciers to ch anges in mass tr ansfer. *Journal of Glaciology*, 30(105), 199–211.
14. Kargel, J. S., Abrams, M. J., Bishop, M. P., Bush, A., Hamilton, G., Jiskoot, H., Kääb, A., Kieffer, H. H., Lee, E. M., Paul, F., Rau, F., Raup, B., Shroder, J. F., Soltesz, D., Stainforth, D., Stearns, L., & Wessels, R. (2005). Multispectral imaging contributions to global land ice measurements from space. *Remote Sensing of Environment*, 99(1–2), 187–219. https://doi.org/10.1016/j.rse.2005.07.004
15. Kulkarni, A. V., Bahuguna, I. M., Rathore, B. P., Singh, S. K., Randhawa, S. S., Sood, R. K., & Dhar, S. (2007). Glacial retreat in Himalaya using Indian Remote Sensing satellite data. *Current Science*, 92(1), 69–74. https://doi.org/10.1117/12.694004
16. Martha, T. R., Roy, P., Govindharaj, K. B., Kumar, K. V., Diwakar, P. G., & Dadhwal, V. K. (2015). Landslides triggered by the June 2013 extreme rainfall event in parts of Uttarakhand state, India. *Landslides*, 12(1), 135–146. https://doi.org/10.1007/s10346-014-0540-7
17. Mayewski, P. A., Pregent, G. P., Jeschke, P. A., & Ahmad, N. (1980). Himalayan and Trans-Himalayan glacier fluctuations and the South Asian monsoon record. *Arctic and Alpine Research*, 11(2), 171–182. https://doi.org/10.2307/1550514
18. Mehta, M., Dobhal, D. P., Kesarwani, K., Pratap, B., Kumar, A., & Verma, A. (2014). Monitoring of glacier changes and response time in Chorabari Glacier, Central Himalaya, Garhwal, India. *Current Science*, 107(2), 281–288. https://doi.org/10.13140/2.1.4435.0083
19. National Institute of Disaster Management. (2012). *India Disaster Report - 2011*. 1–85.
20. Oerlemans J. (1989). On the response of valley glaciers to climatic change. *In: Oerlemans J, editor. Glacier fluctuations clim chang*. Springer; p. 353–371.
21. Raina, V. K. (2004). Is the Gangotri glacier receding at an alarming rate? *Journal of the Geological Society of India*, 64(6), 819–821.
22. Sati, S. P., & Gahalaut, V. K. (2013). The fury of the floods in the north-west Himalayan region: The Uttarakhand tragedy. *Geomatics, Natural Hazards and Risk*, 4(3), 193–201. https://doi.org/10.1080/19475705.2013.827135
23. Scherler, D., Bookhagen, B., & Strecker, M. R. (2011). Spatially variable response of Himalayan glaciers to climate change affected by debris cover. *Nature Geoscience*, 4(3), 156–159. https://doi.org/10.1038/ngeo1068