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Glacier Lake Outburst Floods of Uttarakhand: A Case Study on Dharali Flash Flood Disaster 2025

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ABSTRACT

Uttarakhand, located in the Himalayas, is a globally recognised biodiversity-rich mountain ecosystem. It has fragile geology, steep slopes, and a dense network of glacial rivers, including the Ganga and Yamuna. Over the past three decades, the state has faced several disasters, including the 2013 Kedarnath tragedy, the 2021 Chamoli avalanche, and the 2025 Dharali flash flood, which were the most devastating. The present study focused on the Dharali flash flood in Naugaon block of Uttarkashi district, located at 30.90°N, 78.68°E on the banks of the Bhagirathi River. Their population, according to the 2011 census, was 583. The economy is largely based on farming, apple orchards, and tourism centred on Gangotri. Local reports indicate repeated flooding in 2010, 2012, and 2018. This study investigates on the rainfall, glacial lake outburst floods (GLOFs) originated flash flood analysis, and examines underlying causes and consequences of the Dharali disaster, On the 5 August 2025 between 1:30 and 2:00 PM, in the Kheer Ganga River- a tributary of the Bhagirathi experience a flash flood, that resulted widened stream and deposited a fan-shaped spread of sediment and debris (~20 hectares ; (~750 m × ~450 m) at the river confluence and the satellite assessment, lending to the destruction of 130 houses, hotels, historic kalp-kedar temple and many more structures submerged and swept away. Although the event was initially misclassified as a cloudburst, subsequent analyses by ISRO and IMD confirmed that it was primarily triggered by GLOFs, with extreme rainfall as a secondary factor. The Dharali flood demonstrates the dangerous intersection of deforestation, unplanned development, artificially altered river pathways, and climate change, which enhances the disaster's impact. The study's findings emphasise the urgent need for continuous glacier monitoring, satellite-based early warning systems, land-use planning with strict regulation of riverside development, and stronger governance interventions to curb unplanned growth in these areas.

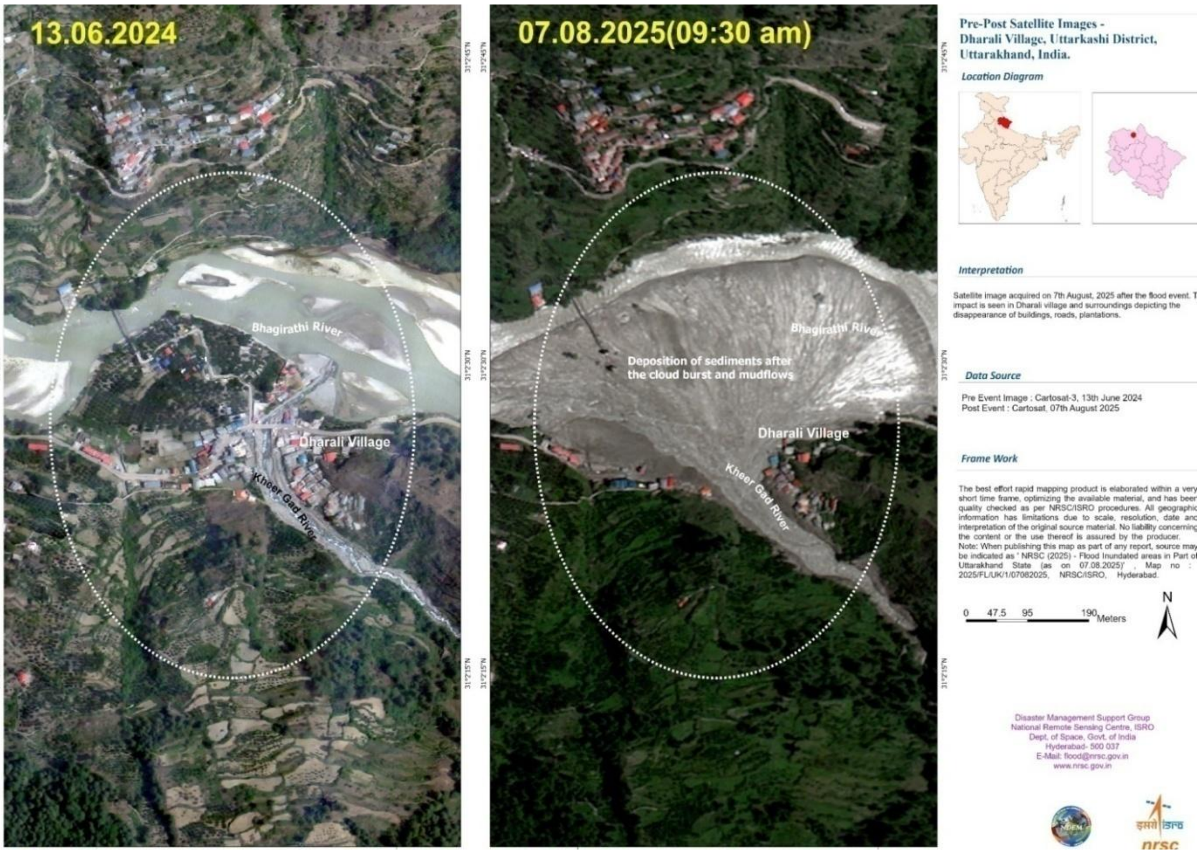
Keywords: *Flash flood, Dharali, Uttarkashi, Glacier Lake Outburst Floods (GLOFs), Cloudburst, Himalaya, Climate change.*

1. Introduction

Uttarakhand's mountains are among the most fragile in the world. The Himalayan ranges are among the most vulnerable to mountain hazards and cloudbursts. Cloudbursts are difficult to predict and happen rapidly. The steep altitude and rapidly changing atmosphere of the Himalayas, along with its vertical geology, make such cloud effects particularly damaging. In the past, the frequency and intensity of such cloudbursts have increased significantly, causing tremendous devastation to settlements and natural systems [1-7]. The impacts of such events also penetrate local settlements and the related livelihoods, and also have cascading effects on the rivers that are downstream, which increases the risk of disasters on bilateral and multilateral frameworks. Uttarakhand, which is in the centre of the Himalayas, has experienced floods that have hit the area catastrophically in the last 20 years; such floods include the 2013 Kedarnath tragedy [2], and the more recent 2021 flash floods in Chamoli and Uttarkashi [11] [3]. These floods result from the combination of many factors, including torrential rainfall, melting glaciers, unstable landforms, and human actions such as rampant development and deforestation. Many Himalayan-area communities, no matter how much time has passed or how much technology has developed, still lack the proper systems to protect them from the rapid, violent cloudbursts and are in a position of exposure with no adaptable systems. The changes in the diverse environments, irresponsible tourism, deforestation, potential overcrowding, unplanned development and sometimes artificially narrow or change the river's historic path, which makes a change in the geography of the region, as well as the destruction of the infrastructure. The same case studies in the Dharali village of Uttarkashi district on the result of the flash floods that initially were estimated to be due to cloudbursts. Prolonged evaluations conducted by the ISRO and IMD collected data which suggested a much differing outcome. Instead of the cloudburst the results were much more in correspondence to GLOFs which was created from GLOFs due to scanty rainfall along with some added debris and glacial melt water and secondary cause is artificially originated in the valley to divert river’s historic path and construction at near to the river embayment. Most of these results tend to shape the reasons to focus on the under lining factors of these sudden devastating floods to the Himalayas and the floods which often happen to be termed incorrect at the first glance as well as the lacking characterization of the factors which were predominant. The study at hand intends to assess these character changes due to the cleansing water flow from the Dharali village with the help of the satellite records along with meteorological data which was made available after the floods had subsided. It the seeks to bring under analysis the (i) the hydrology and geomorphology as well as the impacts with the most notable GLOFs and cloudburst phenomena with rainfall, (ii) the distinguishing mechanisms cloudbursts and GLOFs, as well as (iii) the impact of such extreme scenarios in conjunction with the pillars of climate change and Himalayan risk disaster.

1.2. Study Area

Dharali is a small Himalayan village in the Naugaon block of Uttarkashi district, Uttarakhand, India, located at (30.90°N, 78.68°E) on the banks of the Bhagirathi River, one of the major tributaries of the Ganga. The 2011 Census of India reported 583 residents in Dharali[4], and the livelihood activities of the locals are primarily based on agriculture, small trade, and tourism [8]. The village of Dharali is located at an environmentally sensitive location at the confluence of the Kheerganga stream and the Bhagirathi River, which put it into a geographically sensitive location and makes the settlement exceedingly susceptible to hydrological hazards. The elevation of Dharali is roughly 2,650 meters above mean sea level surrounded. By steep mountain slopes, valley-forming glaciers, and narrow channels of rivers. In Dharali, the predominant seasonal weather system is the Indian summer monsoon, which delivers the bulk of annual rainfall and the highest precipitation between June and September. The mean annual average rainfall ranges from 1,000 to 1,500 mm, but rainfall is highly variable due to orographic effects. The significant input of snow in winter substantially creates seasonal runoff, and glacial melt water is the primary base flow for water during the drier months. Dharali is located in one of the most hazard prone deltas of the central Himalayas. The Bhagirathi sub-basin where Dharali is located has repeated instances (Five cloudbursts and flash floods were documented in the first half of 2015) of cloudbursts, flash floods and glacier lake outburst floods [2-8]. Dharali experienced a catastrophic flash flood that came from the Kheer Ganga stream and dumped a huge (20 ha; (750 m × 450 m)) debris fan at its confluence with the Bhagirathi River, which devastated the settlement. The damage to the settlement included >130 structures [6], including homes, shops, and hotels, and there was a blockage on the Gangotri National Highway for about three weeks before the upper valley was reconnected. Official reports had confirmed six fatalities by 16th August 2025, whereas it was reported later that 50 more persons were missing, representing an alarming but real human toll of this disaster. The physical and socio-economic reality portrayed above starkly illustrates the immense vulnerability of mountain-based regions like Dharali to extreme hydro-meteorological events, which reflect variability resulting from temporal links between glacial and rainfall interactions. For more refer to Figure 1.



Source: https://www.isro.gov.in/indian_satellite_data_based_analysis_of_the_dharali_flash_flood.

Figure 1. Pre- and post-event satellite images of Dharali village, Uttarkashi district, Uttarakhand, showing the geomorphic impact of the 5 August 2025 flash flood. The pre-event image (left, 13 June 2024) shows the intact settlement and river channels, while the post-event image (right, 7 August 2025) highlights extensive debris deposition, destruction of built-up areas, and channel widening.

2. Research Methodology

The study utilized satellite remote sensing, meteorological data, and official reports to assess the flash flood event in Dharali that took place on 5 August 2025

2.1. Satellite Data: High-resolution satellite data (13 June 2024 and 7 August 2025) were obtained from ISRO's Cartost-3[6] for pre- and post-event conditions. This data was used to identify channel changes in the river, debris deposits, and structural damage. Analysis of the images was undertaken using visual conventional analysis methodologies with geospatial resources to quantify the area impacted by the debris fan (~20 ha; ~750 m × ~450 m). The analysis provided evidence of geomorphic change and destruction of infrastructure in Dharali and surrounding areas [6].

2.2. Meteorological Data: In the year 2025, particularly during the monsoon season (June to September), all districts of Uttarakhand experienced excess rainfall. The district-wise rainfall deviation during this period is presented in **Figure 2**. This shows that Bageshwar (+243%) and Chamoli (+88%) received large excess rainfall, while districts such as Tehri (-56%), Dehradun (-37%), and Pauri (-30%) recorded deficient rainfall. These spatial variations highlight the uneven deviation of monsoon rainfall across the state, influenced by local orographic and synoptic-scale conditions [5].

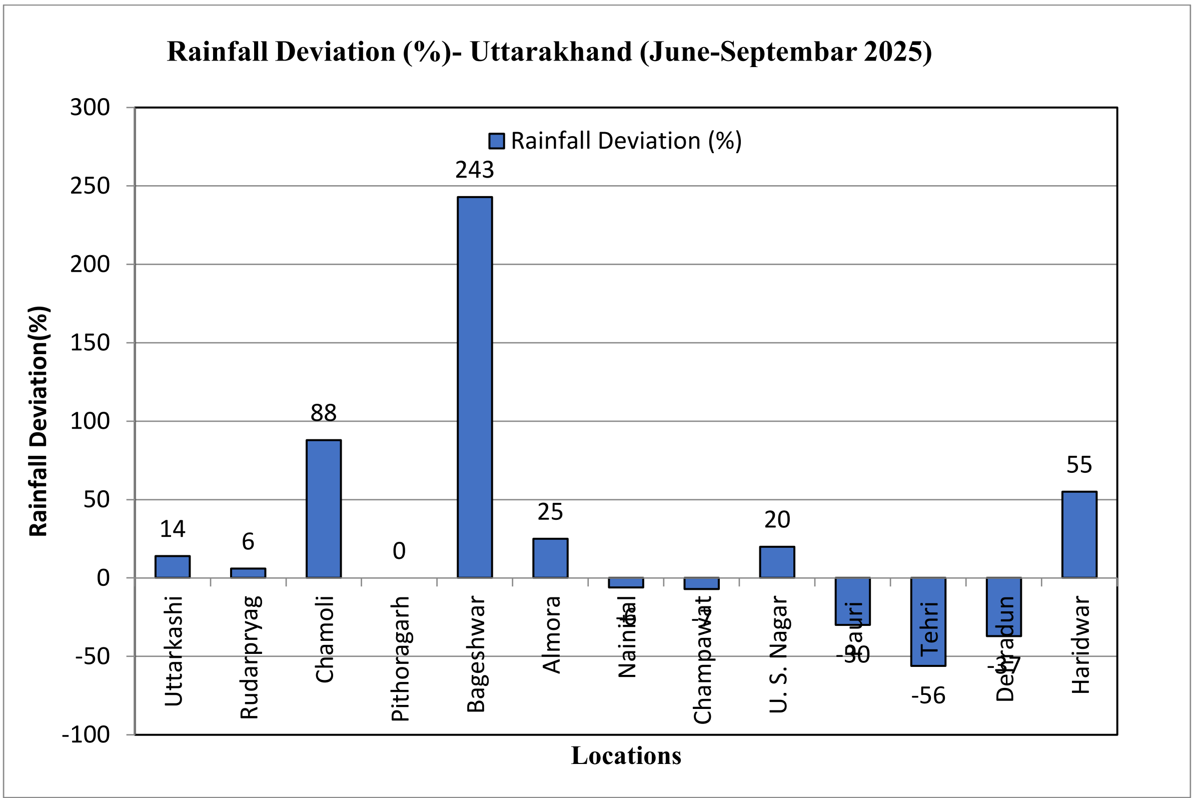


Figure 2: District-wise rainfall deviation (%) in Uttarakhand during the 2025 monsoon season (June-September)

Rainfall data for Dharali and surrounding stations were obtained from the India Meteorological Department (IMD). This data indicated 6.5 mm of rainfall on the day of the flood. In Dharali, the 24-hour accumulation was 9 mm, while the surrounding areas recorded 11 mm, and a maximum of 27 mm was recorded in Bhatwari. These values were compared to IMD's threshold definition of cloudburst events (≥100 mm of rain in one hour over a small area) to characterize the causative mechanism of the flooding [5]. Figure 3 illustrates that Darali and nearby stations experienced moderate rainfall compared to IMD’s cloudburst threshold.

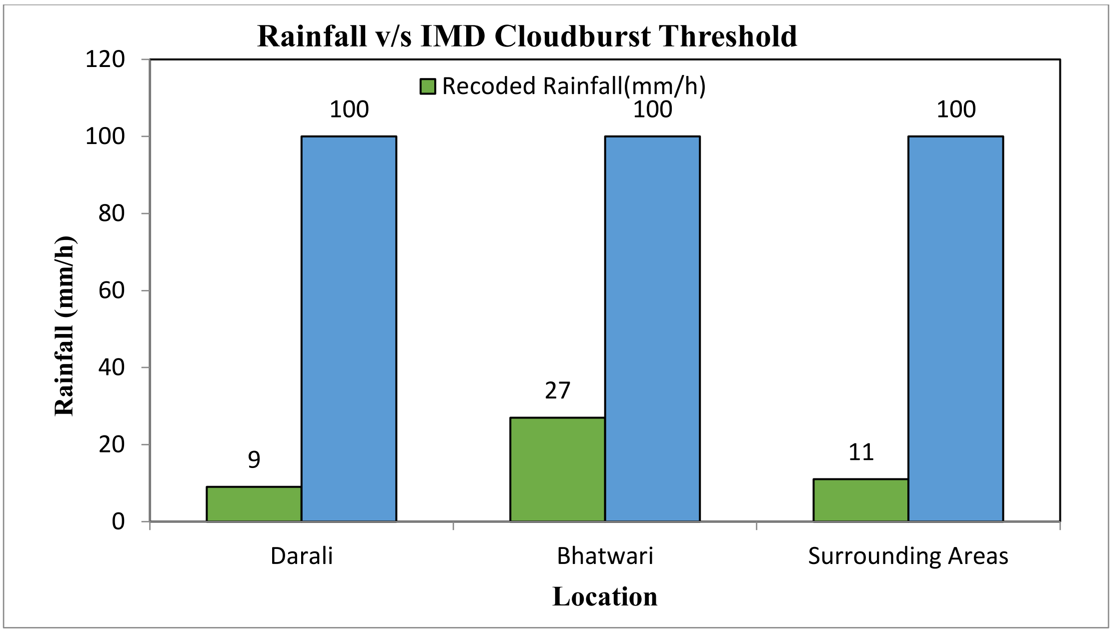


Figure 3: Recorded rainfall (mm/h) of 24 hours at selected stations near Dharali on 5 August 2025, compared to IMD cloudburst threshold

2.3. Disaster Records and Field Reports: Casualty and damage information was collected from the district administration and disaster management authorities. The district's assessment of the incident as of 16 August 2025 had confirmed six deaths, with more than fifty people missing. Over 130 instances of structural damage between houses, shops and hotels categorized beyond the highest rating and the Gangotri National Highway was closed for nearly three weeks.

2.4. Event Classification Method: Using rainfall data, satellite observations and reported impacts, the event was classified against criteria for both local rainfalls-initiated flooding (cloudburst) and glacial lake outburst flooding (GLOFs). The relatively low rainfall amounts, some evidence of intense debris flows, and glacial influences and secondary behaviours were used to classify the Dharali event as a GLOF, with rainfall acting as a contributory initiator.

3. Results and Discussion

3.1. Rainfall Evaluation: Analysis of rainfall during monsoon season during (June-September 2025) revelled strong spatial variability district such as that Bageshwar (+243%) and Chamoli (+88%) received large excess rainfall, while districts such as Tehri Garhwal (-56%), Deharadun (-37%), and Pauri Garhwal (-30%) recorded deficient rainfall. Weather reports (Rainfalls) from the India Meteorological Department (IMD) showed that Dharali only received 6.5 mm of rain on 5 August 2025. The 24-hr cumulative rainfall was 9 mm from Dharali with the hit area being a minimum of 11 mm and a bonnet file of 27 mm at Bhatwari station, and all numbers are well below the IMD established cloudburst threshold ($\geq$100 mm hr^{-1} over specific areas), ignoring intense rain as a unified causal agent of the calamity.

3.2. Geomorphic Transformation: Satellite-based image products (Cartosat-3) showed significant geomorphic transformation of the Kheer Ganga valley. A large fan-shaped deposit of debris (covering ~20 ha (~750 m × ~450 m)) was present at the confluence of the Kheer Ganga stream with the Bhagirathi River. The stream had widened considerably, altering local river morphology and creating temporary instability in the floodplain landform. Collectively, the geomorphic changes clarify the scale of debris, sediment and boulders moved during the events.

3.3. Infrastructural Destruction: More than 130 structures were destroyed and severely damaged, specifically houses, shops and hotels. Many of the buildings were either completely destroyed or enveloped in mudflow. The Gangotri National Highway was disrupted, including areas used for tourism and local communities, for approximately three weeks due to a large amount of debris, hindering flow to upper valley settlements and to the Gangotri shrine.

3.4. Casualty and Missing Persons: An official report on 16 August 2025 confirmed that there were 6 deaths and over 50 missing persons records, demonstrating the severity of the incident. The recovery efforts were complicated by the surrounding topography and debris flow material, which prevented access to the affected area.

3.5. Event Classification: The damming of the stream and transport of a considerable volume of sediment, the movement of boulders and widening of the stream bed are characteristics of GLOFs. Considering the reasonable rainfall records, geomorphic records, and damage assessments, the Dharali flood event was identified as a glacier lake outburst flood (GLOF) with rainfall contributing as a stimulus to the fundamental GLOF characteristics. The Dharali flood can also be distinguished from traditional cloudbursts by the magnitude of sediment load, boulder movement, and channel widening observed.

3.6. Discussion

5 August 2025 Dharali flash flood exemplifies the complex interplay of climatic, geomorphic and human factors in central Himalayan disasters. Metrological data from the Indian metrological department (IMD) show that during the 2025 monsoon season (June-September), all districts of Uttarakhand experience excess rainfall, with particularly high positive devatiation in central and eastern districts such as Bageswer (+243%) and Chamoli (-88%). In contrast, the western districts, including Dehradun (-37%), Pauri Garhwal (-30%) and Tehri Garhwal(-56%) recoded deficient rainfall. This spatial variability, shown in Figure 2, highlights the uneven distribution of the monsoon, governed by regional orographic influences and evolving climatic dynamics. Rainfall observations for Dharali and it's surrounding stations further refine this picture. 24 hour accumulation was 9mm in nearby areas, and 27 mm in Bhatwari- all significantly below IMD's cloudburst criterion of $\geq$ 100mm/hour. **Figure 3** compares these recorded rainfall values with the IMD's threshold for cloudburst events. Despite the absence of extreme rainfall intensity, the geomorphic consequences, including massive debris deposition, slope failures, and channel widening, indicate that the 2025 Dharali flood was not a meteorological cloudburst but a rainfall-triggered Glacial Lake Outburst Flood (GLOF). This misclassification highlights the challenge of distinguishing between hydro-meteorological and cryospheric hazards in real time, which has significant implications for disaster response and policy. The Dharali event is part of an overall increasing trend of GLOFs activity in the Himalaya. Disasters like the 2013 Kedarnath floods and the 2021 Chamoli incident also involved elements of glacial, hydrological, and geomorphic processes. These

repeated incidents are symptomatic of the fact that the Himalayan inhabitants are becoming increasingly vulnerable due to increased rates of glacier retreat, meltwater production, and mountain-slope erosion as a consequence of climate change [7]. Furthermore, unanticipated development, rapid road expansion, excessive tree cutting, and settlements sprawling into the floodplains add to the risk by removing natural buffers, altering drainage patterns, and increasing exposure to hazards. The Dharali flood, with deleterious consequences on humans and structures, demonstrates the socio-economic impact of such events. The demolition of over 130 houses and the three-week-long blockade of the Gangotri Highway have not only devastated local livelihoods but also impacted pilgrimage tourism and regional connectivity. This is an example of how natural disasters, combined with poor development decisions, lead to human disasters. The case study also identifies the usefulness of satellite remote sensing for real-time monitoring. Images from ISRO's Cartosat-3 provided revolutionary insights on the extent of geomorphic modification and destruction of developed areas, which highlight the necessity of remote sensing and ground observation-based monitoring integration. GLOFs early warning systems in India are, however, in their infancy. This gap must be filled through continuous glaciological monitoring, integration of climatic and geomorphic data, and community-based preparedness actions tailored to high-altitude areas. All things considered, the Dharali flood shows how unchecked development, deforestation, and climate change work together to increase the probability of disaster in vulnerable Himalayan regions [2-10]. The frequency and severity of such threats will inevitably increase in the absence of prompt measures that incorporate scientific monitoring, ecologically appropriate land-use planning, and ecosystem restoration.

4. Conclusion

The 2025 Dharali flash flood is one such case that demonstrates the complex interaction among climatic, geomorphic, and anthropogenic processes shaping disasters in the Central Himalaya. Origins were initially defined as a cloudburst [2-3]. Analysis of rainfall data as presented in the bar chart indicates that recorded precipitation in Dharali and surrounding areas was considerably below the IMD’s cloudburst threshold of 100 mm per hour. This suggests that the event was not purely metrological in origin but rather a consequence of compounded geomorphic impacts, and satellite-derived assessments characterised the event as a glacier lake outburst flood (GLOF) primed by rainfall [7]. In this case study, three crucial takeaways have been identified. One, the hazards of Himalayan floods are becoming less straightforward, many being the result of a combination of glacial, rainfall, and geomorphic dynamics, so there is a need to develop better classifications and monitoring. Second, the risks of GLOFs are increasing because of climate change, unregulated growth and deforestation that destabilise high-altitude areas and scale up the losses. Finally, due to human activities, they artificially change the historic path of river channel and settlement expansion and development without control in the deflooded areas, the exposure of people is greatly increased, enhancing the disaster's impact.“Dharali reminds us of the immediate necessity of integrated disaster risk reduction in the Himalaya, inclusive of monitoring of glacier systems, satellite-based hazard mapping, early warnings, land use planning and government ensuring its direct and indirect intervention in unplanned development and making strict laws for river-side developments.”

This case thus reinforces the urgency of interdisciplinary research, a hybrid model of cloudburst and GOLFs. Climate change, riverside development control, and rejuvenation of degraded mountain ecosystems are some of the steps that will help reduce the increasing risks of this type of flood disaster in the Himalaya.

Conflict of Interest

The authors declare no conflict of interest.

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