

Dharali debris flow on 5 August 2025, Uttarakhand: event reconstruction and geomorphic implications

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The Dharali debris flow on 5 August 2025, in Uttarakhand, India, was a catastrophic disaster that occurred in Kheer Gad, a tributary of the Bhagirathi river. It claimed approximately 60 lives and covered an estimated 3 hectares of apple orchards under debris. The damage also included at least 25–30 animals and a market comprising 65 hotels, over 30 resorts, and homestays. The present study involved the geomorphic characterisation of Kheer Gad to assess the debris flow potential of the catchment and debris flow simulation to ascertain the source, potential flow dynamics, and reconstruction. Findings reveal that the 17 km² Kheer Gad catchment is inherently unstable, as suggested by Melton's ruggedness number of 0.8, significantly above the 0.6 debris-flow threshold. The trigger was not a single event, but an antecedent rainfall of ~195 mm/30 days, which saturated glacial and landslide-derived source materials. Debris flow simulation revealed 60 kPa flow pressure, velocities of 5–10 m/s, flow height of 5–10 m, spread area of ~18 hectare, and volume estimate of 995,580 ± 200,000 m³–1,285,260 ± 126,000 m³. These values are validated against field observations. Notably, the disaster was exacerbated by human vulnerability, given the doubling of built-up structures between 2011 and 2025, despite prior warnings in 2013. The present study provides a transferable methodology for assessing similar high-risk, glaciated basins to prevent such avoidable disasters.

Keywords: Debris flow, Dharali, disaster risk reduction, Himalaya, rainfall.

HIMALAYA has been sensitive to global climate shifts, leading to glacial retreat and an increase in the frequency and intensity of extreme hydrometeorological events^{1–4}. The North-Western Himalayas, particularly Uttarakhand, is one such region that has witnessed several disastrous

hydrometeorological events, such as the 1970 Uttarakhand flood, 2013 Uttarakhand flood and landslides, and 2021 ice-rock avalanche and flood^{5–8}. This pattern was further highlighted by the debris flow in Dharali on 5 August 2025, in the Kheer Gad catchment, a tributary of the Bhagirathi river in Uttarakhand, Himalayas. The event caused at least 60 deaths or missing persons, with the total toll reaching approximately 90 (ref.9). This event led to the complete disruption of the National Highway (NH) 34, closing access to the Gangotri pilgrimage site and affecting rescue operations. Further, a subsequent debris flow event also occurred on the same day at Harshil village, which is 5 km downstream from Dharali, partially damming the Bhagirathi river and washing away part of an Indian defence camp. The frequency and scale of these hydrometeorological events support the notion of increasing vulnerability of the Indian Himalaya to a changing climate^{10–13}.

These events also mark a growing pattern of human-environment conflict, because population growth, increasing demand for agricultural land, growing tourist influx, and infrastructure expansion have led to encroachment on alluvial fans and river terraces in the Himalaya^{14–17}. With numerous human settlements and infrastructure located in high-hazard zones in the Himalaya, predicting such debris flows is critical for disaster risk reduction. However, developing effective risk-reduction measures for such events requires a detailed understanding of the morphometry and hydrometeorological responses of the catchments. Drainage density, relief ratio, elongation ratio, and ruggedness number are among the basic morphometric parameters used to understand the debris-flow potential of catchments^{18–22}. Further, various methods have been used to understand the hydrometeorological response of catchments, particularly regarding debris flow. These are empirical techniques²¹, analytical methods²³, and advanced numerical models^{24,25}. Among all these, numerical models have relative advantages owing to their flexibility in simulating events over complex terrains and in back-calculating key input parameters^{26–28}. Given the

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