

Lessons from the 2026 Rasuwa episode for the Garhwal Himalaya, Uttarakhand

High-mountain regions are increasingly vulnerable to multi-hazard cascading events and their impacts. These processes are intensified by climate change, long-term tectonic stress, and the exposure generated by increased human activity. An example is the recent ice-rock avalanche of 26 August 2026 (Figure 1 *a, b*) that originated in the high-grade metamorphic terrain of the Higher Himalaya. The immense impact of this ice-rock avalanche on the valley floor generated severe ground vibrations. This force was registered globally on seismic networks as a $5.2 \pm 0.1 M_s$ event at 08:37 AM on 26 August 2026. While initially flagged as an earthquake due to its magnitude, subsequent seismogram analysis and satellite verification confirmed that the seismic signal was generated by the bedrock and glacier collapse from the Langtang Lirung massif¹. This ice-rock avalanche (28.26° N, 85.52° E), comprising more than 10^8 m³ of rock and ice, descended almost vertically from ~ 5200 m msl

to ~ 3850 m msl. Following the detachment of the ice and rock, the resultant energy caused massive melting and subsequently a debris flow surge headed downstream into the Bhote Koshi-Trishuli River valley^{1,2}. This impulse wave-debris flow transitioned into a debris flood and then a hydrological flood over tens of km and also resulted in triggering multiple landslides along its downstream path that caused further damming of water to form temporary lakes. The resultant debris flow and flood traversed ~ 110 km downstream in ~ 2 hours, with flow velocities ranging from ~ 51 m/s near the source region to ~ 12 – 13 m/s at ~ 110 km downstream³.

The event underscores how high-magnitude, episodic geomorphic processes in paraglacial terrains can rapidly escalate into catastrophic cascading hazards downstream. This event also affected dozens of villages and towns situated within a 500-metre lateral distance of the Bhote Koshi-Trishuli River valley. Surprisingly, this event originated at an

aerial distance of 11 to 12 km from the Purepu Glacier supraglacial lake that was subjected to a Glacial Lake Outburst Flood (GLOF) on 8 July 2025 (ref. 4). The spatial proximity of two such major events highlights the region's growing instability, and analysing such events is necessary to understand the vulnerability of similar Himalayan terrain, such as the Garhwal Himalaya in Uttarakhand, India.

Why is this event relevant to Uttarakhand, the Indian Himalaya?

The Rasuwa episode serves as a stark reminder of similar recent events in the Garhwal Himalaya of Uttarakhand, as well as the potential for such hazards in the future⁵. In the Garhwal region, rapid infrastructure development and a demographic shift from remote, high-altitude hills toward river valleys have resulted in increased exposure to severe geohazards⁶. The Alaknanda-Mandakini River corridors

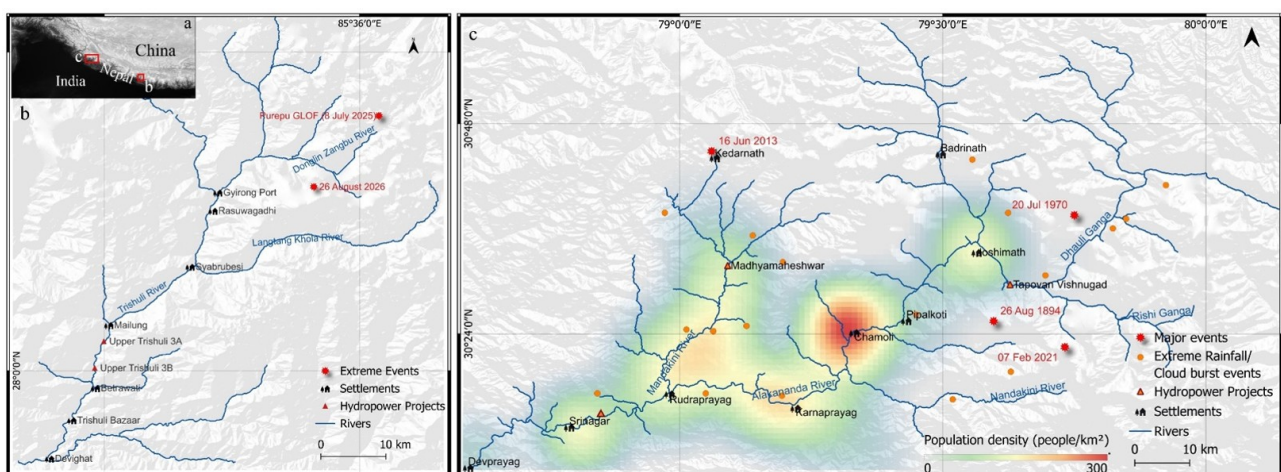


Figure 1. Comparison of the Rasuwa episode of 26 August 2026 with Garhwal Himalaya. (*a*) Inset showing the location of the cascading event and Garhwal Himalaya along the Himalayan mountain belt, (*b*) Map showing the extent of the cascading event of 26 August 2026, (*c*) Map showing the status of the Alaknanda-Mandakini River Valleys in Garhwal Himalaya. The population and extreme rainfall/cloudburst dataset are based on the data and methods of a recent study⁶.

in the Garhwal Himalaya exhibit geomorphic and socio-economic characteristics similar to the region that was affected by the disastrous episode on 26 August 2026. Previous studies have demonstrated that Landslide Lake Outburst Floods (LLOFs) have characterised the Alaknanda-Mandakini River valleys for over 1000 years⁷. Historically, these river valleys have been subjected to similar disastrous cascades of landslides, debris flows and floods such as on 26 August 1894, 20 July 1970, 16 June 2013, and 7 February 2021 (ref. 8–10).

Additionally, the exposure to these hazards has increased, with infrastructure worth 10000 crore INR (~\$1.0B) in the form of road networks, railway lines, tunnels and bridges having scaled up over the past decade to support tourism and other purposes^{6,11}. Furthermore, the region is characterised by active tectonic movements and frequent extreme hydro-meteorological events. The Alaknanda and Mandakini basins have experienced medium- to high-magnitude earthquakes of 6.6–7.8 M_w in the last three decades, and the possibility of a future mega earthquake still exists¹². A composite analysis of 140 hydro-meteorological events occurring during 1970–2022 in Uttarakhand has also revealed a marked increase in such extreme events, particularly during the monsoon season¹³. Using multiple approaches and models, recent studies have shown that there are thousands of active landslides in these valleys that are triggered by rainfall and seismicity and thus pose an immediate risk to settlements residing on or near these hillslopes^{6,13,14}.

Current status and challenges ahead

Recent disasters in Uttarakhand reflect physical processes similar to the extreme devastation observed

during the Rasuwa event, highlighting the need to examine their commonalities. On 7 February 2021, an ice-rock avalanche analogous to the Rasuwa initiated a debris flow in Chamoli, reaching speeds comparable to the Rasuwa flow (up to 60 m/s)¹⁵. The debris travelled down the Dhauliganga valley and decelerated at a sharp river bend, leading to sediment accumulation, river damming, and the formation of a lake in the Rishiganga valley, which subsequently breached and caused further downstream destruction. Erosion along the flow path destabilised adjacent hillslopes, accelerating a slow-moving landslide complex at Joshimath, a process expected to recur in the Trishuli valley following the Rasuwa event.

Similarly, on 16 June 2013, a glacial lake outburst flood (GLOF) originating above the Kedarnath Temple in the Mandakini valley transformed into a major downstream flood, representing the most catastrophic episode in the region's recorded history¹⁶. More recently, on 5 August 2025, a large debris flow at Dharali in the Bhagirathi valley destroyed sections of the National Highway and critical infrastructure¹⁰.

A common feature across these Uttarakhand disasters and the Rasuwa event in Nepal is their cascading behaviour. High-velocity upstream flows transition into downstream hydrological floods, triggering subsequent slope instabilities and altering channel conveyance capacities through rapid erosion and deposition. Pre-existing sediment deposits on hillslopes and within channels, often termed 'sediment bombs', enhance these dynamics by transitioning flows into hyper-concentrated states with significantly heightened erosive power¹⁷. Isolated analytical approaches such as rock slope stability assessments, GLOF monitoring, sediment budgeting, landslide volume estimation, or inundation modelling fail to capture the interconnected nature

of cascading events, as noted in these events.

Furthermore, evaluating the role of hydropower infrastructure remains challenging. Although claimed to be relatively safe, the Run-of-River projects may aggravate cascading flood events by trapping debris, creating temporary choke points, and breaching under pressure to launch secondary surge waves towards densely populated downstream communities, as noted during the June 2013 and February 2021 Uttarakhand cascading events and the October 2023 Sikkim GLOF^{18,19,20}. Considering two operational Run-of-River projects (Madyamaheswar (15 MW) and Srinagar (330 MW)) and one under construction (Tapovan: 520 MW), monitoring upstream discharge characterised by extreme flow events poses a growing challenge (Figure 1c).

A key question when confronted by such extreme sediment-water flow events is: how can early warning systems be effectively managed for downstream communities? The models of the Department of Hydrology and Meteorology are based on hydrological flood waves that flow at a few metres per second, and the gauging stations record data only once every 10 minutes. Consequently, an event travelling at 50 m/s was unrecorded, and the underlying flood models fail to simulate these rapid processes. Consequently, no operational system currently exists to monitor, forecast, and issue warnings for debris flows and floods like those that devastated the Trishuli Valley in 2026 and the Mandakini Valley in 2013. Nor is there a system for predicting the likelihood of the follow-on cascade of landslides and floods. There is an urgent need to consolidate learning on early warning and risk reduction from these recent events. This requires context-appropriate research methods that are sensitive to recent trauma and loss, as

well as creative approaches to engage local stakeholders. For example, local knowledge can help identify high-risk locations, escape routes to higher ground, exposed emergency access routes, and vulnerable communication or utility infrastructure.

Beyond these hurdles, perhaps the greatest challenge to effective disaster risk reduction is the ongoing migration of local inhabitants from upslope villages to semi-urban and urban settlements along river corridors⁶. Their relocation to nearby towns, motivated by certainty of socio-economic means, exposes them to the uncertainty of the widespread and increasing hazards associated with the Alaknanda-Mandakini River corridors. Consequently, towns such as Chamoli, Rudrapur, Karnaprayag, and Srinagar, which have a population density of 150-300 people/km² due to inward migration and native population growth, face heightened risk levels from cascading events (Figure 1c). Futuristic thinking, which has shown promise for transforming urban planning and risk in different hazard contexts²¹, can help to start a longer-term process of reimagining resilient, place-based urbanisation in Uttarakhand's exposed valleys.

Way forward

An integrated framework must combine technological monitoring and modelling with the development of risk mitigation strategies generated with stakeholders at every level. Priorities include the following:

- Investigating the interplay of long-term structural/tectonic preconditioning and climate-driven thermal degradation of high-altitude permafrost and glacial margins to understand root causes of catastrophic mass detachments. This provides the mechanistic foundation for understanding massive rock-ice detachments. Further, high-resolution seismic signatures

produced by such massive events can be integrated into early warning systems for effective disaster risk reduction frameworks.

- Foregrounding analysis of cascading hazards, such as through the utilization of ground- and satellite-based monitoring to assess interconnected hazard development in glacial lakes and potential landslide and avalanche zones.
- Unmanned Aerial Vehicle (UAV)-based and geophysical mapping of accessible landslides and sediment accumulations along the valley, while deploying AI and scaling relationships to estimate inaccessible landslides and sediment accumulations along river tributaries.
- Monitoring of suspended and bedload sediment flux to facilitate improved modelling around hydropower sites.
- Numerical modelling to predict the hazard cascade from debris flows to downstream transitions into hydrological floods, as well as the associated landslide trajectories and river choke points.
- Co-development of emerging hazard science with existing disaster risk reduction and disaster risk management at local-to-state scales to ensure alignment of science, policy and action.
- Science-informed scenario and visioning exercises with disaster planning stakeholders and communities to explore novel mechanisms for early warning and risk reduction in extremely rapid onset hazards.
- Establishing multilateral data-sharing frameworks with neighbouring countries sharing Himalayan borders. Real-time telemetry from supraglacial lakes, automated weather stations, and satellite constellations must be shared cross-border via a unified Himalayan Risk Consortium, recognising that early warning and disaster risk management

institutions vary with national-to-local level circumstances.

Conflict of interest: The authors declare no conflict of interest.

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