

Ice contributed only 53% to the flood triggered by the 2026 Langtang Lirung rock-ice avalanche in Nepal

Lixin Wu

wulx66@csu.edu.cn

Central South University

Zhijun Jiao

Central South University

Suraj Gautam

Institute of Himalayan Risk Reduction, Lalitpur, Nepal

Raju Thapa

Nepal Center for Disaster Management, Kathmandu, Nepal

Zhimei Zhang

Central South University

Pengtianhao Wu

Central South University

Zichen Yue

School of Geosciences and Info-Physics, Central South University, Changsha, China

Qiqi Zhang

School of Geosciences and Info-Physics, Central South University, Changsha, China

Wenfei Mao

School of Geosciences and Info-Physics, Central South University, Changsha, China

Bishal Nath Upreti

Nepal Center for Disaster Management, Kathmandu, Nepal

Meen B. Poudyal Chhetri

Nepal Center for Disaster Management, Kathmandu, Nepal

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1 Ice contributed only 53% to the flood triggered by the 2026 Langtang
2 Lirung rock-ice avalanche in Nepal

3 Zhijun Jiao^a, Suraj Gautam^b, Raju Thapa^c, Zhimei Zhang^a, Pengtianhao Wu^a, Zichen Yue^a, Qiqi
4 Zhang^a, Wenfei Mao^a, Bishal Nath Upreti^c, Meen B. Poudyal Chhetri^c, Lixin Wu^{a*}

5
6 ^a School of Geosciences and Info-Physics, Central South University, Changsha, China
7 ^b Institute of Himalayan Risk Reduction, Lalitpur, Nepal
8 ^c Nepal Center for Disaster Management, Kathmandu, Nepal

9
10 *Corresponding author: Lixin Wu
11 School of Geosciences and Info-Physics, Central South University, 932 Lushan South Road, Yuelu
12 District, Changsha, Hunan 410083, China
13 E-mail: wulx66@csu.edu.cn

14 **Abstract**

15 A high-mountain rock-ice collapse can generate cascading debris flows and floods beyond its source.
16 Quantifying the materials released at the source and those added to the flood along the corridor is
17 essential to understanding the cascading event and disaster risk. We reconstruct the 26 August 2026
18 Langtang Lirung avalanche using satellite imagery, terrain reconstruction, videos, seismic scaling and
19 river-gauge records. A source volume of $78.37 \times 10^6 \text{m}^3$ and rock:ice volume ratio of 9:1 yield a mass
20 of $1.98 \times 10^{11} \text{kg}$ and a predicted magnitude of 5.20, consistent with the USGS observation. Complete
21 ice melting supplies at most $7.19 \times 10^6 \text{m}^3$, or 53% of the Devghat excess. Adding corridor-water storage
22 gives $(14.42 \pm 0.80) \times 10^6 \text{m}^3$, 6.30% above the observed $13.57 \times 10^6 \text{m}^3$. The paired comparisons
23 support debris-driven mobilization of pre-existing river water into a downstream surge. Hazard
24 assessment and transboundary preparedness must incorporate corridor water and erodible deposits
25 alongside unstable high-elevation sources.

26
27 Steep valley walls, large elevation differences and fractured bedrock allow high-mountain slope
28 failures to release large masses into confined corridors. Glacier retreat and changes in frozen ground
29 can alter slope support, water movement and rock strength, while geological structure determines
30 where failure can develop^{1,2}. Once released, rock and ice can entrain sediment and water, extending
31 the affected area well beyond the initial collapse. Reconstructing these cascades therefore requires
32 observations that connect the source, transport corridor and downstream response³. The 2021 Chamoli
33 disaster demonstrated this cascading hazard: an ice-rock avalanche transformed into a mobile debris
34 flow that severely damaged two hydropower projects and left more than 200 people dead or missing⁴.
35 This cascading hazard is particularly relevant as glacier ice loss across High Mountain Asia continues
36 amid ongoing climate warming^{5,6,7,8}, while sparse permafrost observations in the Hindu Kush
37 Himalaya² limit our understanding of slope destabilization. With growing concerns over destructive

38 glacier-related slope failures⁹ and the warming-related destabilization and adaptation limits highlighted
39 by the 2026 Nepal cascade¹⁰, understanding how these cascading hazard processes interact and
40 propagate downstream is essential for explaining the disproportionate impacts of high-mountain
41 disaster cascades.

42 Understanding why these cascading impacts extend far beyond the initial collapse requires examining
43 how the moving mass interacts with materials and water along its path. Snow entrainment influenced
44 the runout and air-blast generation at Langtang in 2015¹¹, while reconstructions in Tibet and
45 Switzerland linked long runout to low effective friction and the presence of water or ice within the
46 moving mass^{12,13}. Experimental and field evidence further identifies water availability, corridor
47 materials and topographic confinement as important controls on mobility¹⁴. Together, these studies
48 suggest that the severity and extent of cascading hazards depend not only on the initial failed mass, but
49 also on the progressive entrainment and transformation of materials during propagation.

50 Beyond the physical amplification of cascading hazards, the exposure of people and infrastructure
51 along their propagation corridors can further magnify the consequences. Hydropower facilities, roads,
52 bridges and settlements are often situated within narrow mountain valleys, placing them directly in the
53 paths of avalanches, debris flows and floods¹⁵. The 2021 Chamoli disaster illustrates how a localized
54 slope failure can cause extensive damage to downstream infrastructure and communities⁴. Studies of
55 glacial-lake outburst floods similarly highlight the importance of water storage, hydrological
56 connectivity and downstream exposure in determining disaster impacts^{16,17,18,19}. The timing of flood
57 release and the connectivity of downstream corridors further influence the distribution of these
58 impacts^{20,21,22,23}, while assessments linking unstable slopes to avalanches entering stored water
59 demonstrate how multiple processes can combine to threaten exposed areas²⁴. Thus, the consequences
60 of a cascading disaster depend not only on how hazards evolve and propagate, but also on what lies
61 along their paths.

62 The interaction between cascading hazard processes and downstream exposure highlights the need to
63 reconstruct how an initial slope failure develops into a far-reaching disaster. Process-chain modelling
64 demonstrates that avalanche location and propagation corridor affect flood intensity²⁵, while studies of
65 Blatten and Dharali establish the value of pre-event source observations for early warning and risk
66 reduction^{26,27}. Understanding these cascades therefore requires connecting the initial release, the
67 entrainment and mobilization of materials and water along the transport corridor, and the resulting
68 downstream response. An event-scale reconstruction must constrain both the released rock-ice mass
69 and the water mobilized along its corridor using observations of the same event. A remaining
70 observational challenge is to test both ends of the same cascade: whether a reconstructed rock-ice
71 inventory is compatible with the seismic signal of release? Whether the water available along its path
72 is compatible with a downstream hydrograph?

73 On 26 August 2026, a slope on the north-facing flank of Langtang Lirung failed and initiated a cascade
74 through Lhende Khola, Bhote Koshi and the Trishuli valley, which USGS preliminarily recorded as a
75 seismic event. Subsequent assessments documented debris-flow and flood impacts extending
76 approximately 100km downstream, with severe damage to riverside buildings and roads connecting
77 China and Nepal^{28,29,30}. Nepal's flood technical report records the loss of upstream hydrological
78 stations, including the Furke (Malekhu) station and its bridge, and continued observation of the flood
79 farther downstream³¹.

80 The far-reaching destruction caused by this event underscores a fundamental challenge in
81 understanding high-mountain disaster cascades: how a localized rock-ice collapse can evolve into a
82 destructive flood that threatens infrastructure and communities far beyond its source. Addressing this
83 challenge requires moving beyond the characterization of individual hazards to quantitatively linking
84 the initial failure, the transformation of moving materials and the mobilization of river water within a
85 unified source-to-flood framework. Here, we reconstruct the 26 August 2026 Langtang Lirung cascade

by integrating source reconstruction, propagation evidence and a corridor-water budget (Fig. 1). Pre- and post-event imagery constrain the failure geometry (Fig. 2), while terrain reconstruction and UAV-derived composition estimates quantify the released rock-ice mass and assess its consistency with the USGS-recorded seismic magnitude (Fig. 3). Video observations reveal the sequence of flow transformations, and Knowledge-Driven Flood Intelligent Monitoring (KDFIM)-constrained water accounting evaluates the contribution of pre-existing river water against the observed Devghat flood hydrograph (Fig. 4). Sensitivity analysis across varying rock-to-ice ratios further examines the robustness of these constraints (Fig. 5). By jointly testing the source mass against seismic observations and the available water volume against downstream hydrological measurements, this study provides an observation-constrained assessment of how rock-ice avalanches can mobilize river water and amplify flood hazards far beyond the initial collapse. This framework advances the quantitative understanding of high-mountain disaster cascades and provides a basis for assessing cascading flood risks to downstream infrastructure and communities.

Imagery resolves the released rock-ice body

The source footprint was delineated by comparing pre- and post-event satellite imagery, as shown in Fig. 2. Sentinel-2 imagery acquired on 24 August 2026 shows the intact source rock-ice body, whereas Landsat-9 imagery from 26 August 2026 reveals the disappearance of the source rock-ice body and the newly exposed collapse scar (Fig. 2B, C). The reconstructed source boundary was further examined using a high-resolution image acquired on 10 October 2017 (Fig. 2D). This historical image reveals a distinctly fractured and weathered rock zone, with its structural boundaries closely matching the mapped failure footprint, as shown in the enlarged view (Fig. 2E). The agreement between the pre-existing fracture pattern and the post-event collapse geometry provides additional evidence for the identification of a rock-ice block. Repeated melting, refreezing and seasonal ice loss may have

109 contributed to progressive fracture opening and reduced slope support, consistent with mechanisms
110 proposed for the destabilization of the Chamoli source³².

111 Regional structural studies have documented tectonically deformed High Himalayan Gneiss in the
112 Langtang Valley³³, providing geological context for the fractured rock mass observed in the historical
113 imagery. These observations suggest that pre-existing structural weaknesses, potentially modified by
114 freeze-thaw processes and ice loss, may have contributed to slope destabilization. The source geometry
115 was therefore constrained primarily by the observed collapse scar and surrounding terrain, while rock-
116 ice composition and density were considered separately to estimate the released mass.

117 **Source reconstruction and seismic comparison**

118 Integration of the source geometry constrained by the mapped outline and three reference surfaces
119 gives a source volume of $78.37 \times 10^6 \text{m}^3$ (Fig. 3B). Field UAV image interpretation gives a rock:ice
120 volume ratio of 9:1. With densities of 917kg m^{-3} for ice and 2700kg m^{-3} for rock³⁴, the bulk density is
121 $2.52 \times 10^3 \text{kg m}^{-3}$ and the mass is $1.98 \times 10^{11} \text{kg}$. The empirical scaling of Ekström and Stark³⁵ yields a
122 maximum force of $3.66 \times 10^{11} \text{N}$ and a predicted magnitude of 5.20, matching the USGS-reported
123 M5.20 landslide signal²⁹.

124 The three-dimensional terrain reconstruction reveals a steep and confined propagation corridor
125 connecting the rock-ice source to Gyirong Port through Lhende Khola and Bhote Koshi (Fig. 3A). The
126 corresponding longitudinal profile shows a pronounced elevation drop from approximately 5,152 m at
127 the source to 1,823 m near Gyirong Port over a distance of about 20 km (Fig. 3C). The particularly
128 steep upper section provided a substantial gravitational driving force for the initial descent, while the
129 narrow valley geometry channelled the moving material towards the downstream river corridor. The
130 three-dimensional voxel reconstruction, constrained by the mapped source boundary (Fig. 2) and three
131 reference surfaces, defines the geometry and substantial volume of the released rock-ice body (Fig.
132 3B). This establishes the large mass involved in the initial failure.

133 The combination of substantial released mass, pronounced topographic relief and confined valley
134 geometry indicates considerable gravitational energy available for rapid downslope transport. This
135 energetic motion is captured by successive video frames showing the rapid advance of a dense, dust-
136 bearing avalanche front within seconds (Fig. 3C1-C3). The extensive dust cloud reflects intense
137 material disturbance during descent, while a subsequent frame records continued secondary rock-ice
138 fall after the initial passage (Fig. 3C4). Together, the reconstructed terrain, source rock-ice body and
139 direct video observations establish the conditions for highly mobile, energetic mass transport through
140 the confined valley. As the moving debris entered the river corridor, its momentum and interaction
141 with channel materials provided a physical pathway for the entrainment and downstream displacement
142 of pre-existing river water. These observations therefore support the proposed transition from an initial
143 rock-ice avalanche to a cascading debris-flow and flood process, providing the physical basis for the
144 subsequent quantitative assessment of river-water mobilization and downstream flood volume.

145 **Transformation into a debris-flow flood cascade**

146 The reconstructed cascade reveals a progressive transformation of material composition and energy
147 transfer from the initial rock-ice avalanche to the downstream flood (Fig. 4A). During rapid descent,
148 the released rock-ice mass fragmented into large rock blocks and granular debris, which entrained loose
149 sediments and channel deposits along the propagation corridor. The resulting dense debris flow
150 remained dominated by solid materials, whose considerable momentum drove intense interactions with
151 the underlying riverbed and pre-existing water. As illustrated in Fig. 4A1, the advancing debris mass
152 scoured channel deposits, displaced river water and transferred momentum to the surrounding water,
153 accelerating its downstream redistribution. As coarse materials progressively deposited, the moving
154 mixture evolved into a hyperconcentrated flow and ultimately a water-dominated flood surge that
155 continued beyond the principal debris-deposition zone. This sequence illustrates the transfer of
156 gravitational energy through fragmentation, sediment entrainment and water mobilization,

transforming a localized slope failure into a far-reaching flood cascade. The underlying mechanisms of granular motion, erosion and momentum transfer are consistent with previous experimental and field investigations^{36,37,38}, as well as observations of rock-avalanche-generated sediment flows³⁹ and the Chamoli disaster⁴.

The spatial reconstruction further establishes the propagation pathway and the potential extent of debris-driven water mobilization (Fig. 4B). KDFIM-derived mapping identifies the affected river corridor and its flow-depth distribution^{40,41}, while DEM-based cumulative-energy analysis constrains the downstream reachability of the moving material according to established routing and friction principles^{36,42,43,44,45}. The resulting critical-friction field delineates the energetically reachable corridor, with finite values of $\mu_{crit} > 0.10$ defining the adopted spatial domain for solid-material influence under the specified friction constraint^{36,42,43,44,45}. This physically constrained domain identifies the river reaches potentially exposed to direct debris interaction, providing the spatial basis for estimating the pre-existing water available for mobilization. The recorded flood passage through the Bhote Koshi and Trishuli valleys further establishes the temporal continuity of downstream propagation towards Devghat^{31,46}.

Independent hydrological observations provide evidence for the above spatial reconstruction. Water levels in the Kali Gandaki at Kota Gaon and Marsyangdi at Bimalnagar remained relatively stable during the event, without a corresponding flood pulse (Fig. 4B)⁴⁶. In contrast, Devghat recorded a pronounced flood surge following the documented passage through the avalanche-affected Trishuli corridor³¹. This spatial contrast, together with the observed propagation sequence, identifies the upstream rock-ice avalanche cascade as the driver of the Devghat flood anomaly.

The reconstructed water inventory provides a quantitative test of the above mechanism. Hydraulic information from the UT-1 Disaster Management Plan⁴⁷, combined with KDFIM-derived pre-event water coverage, constrains the volume of river water within the debris-reachable corridor.

181 Independently, the reconstructed source composition defines the maximum potential meltwater
182 supply³⁴. Even under complete melting, source ice accounts for only approximately 53% of the
183 observed excess floodwater, demonstrating that ice melting alone is insufficient to explain the
184 downstream response. Combining the source-ice meltwater limit with the estimated corridor-water
185 inventory yields an available water volume of $(14.42 \pm 0.80) \times 10^6 \text{ m}^3$, closely matching the
186 independently derived Devghat excess³¹ of $13.57 \times 10^6 \text{ m}^3$. The small difference between these
187 estimates supports the volumetric feasibility of debris-driven river-water mobilization under the
188 adopted melting and water-delivery assumptions.

189 Together, the reconstructed material transformations, spatially constrained debris reachability,
190 tributary observations and downstream water-volume agreement provide converging evidence for the
191 proposed flood-amplification mechanism. The initial rock-ice collapse supplied the mass and
192 gravitational energy for rapid debris transport, while interactions with the river corridor enabled the
193 mobilization and downstream redistribution of pre-existing water. This coupling between solid-
194 material transport and river-water mobilization provides a physical explanation for how a localized
195 high-mountain slope failure generated a destructive flood extending far beyond the initial collapse area.

196 **Discussion**

197 The observational comparisons provide quantitative evidence on the reconstructed Langtang Lirung
198 rock-ice avalanche and its downstream flood response. By using a single source-volume and
199 composition parameterization, the reconstructed mass and potential water inventory can be evaluated
200 against independently acquired seismic and hydrological observations. The composition sensitivity
201 analysis (Fig. 5) shows that the UAV-derived rock-to-ice ratio of 9:1 produces the smallest absolute
202 discrepancies in both predicted seismic magnitude and available floodwater volume among the nine
203 tested scenarios. Increasing the ice fraction progressively reduces the predicted magnitude while

204 substantially increasing the potential meltwater supply. Even when the rock-to-ice ratio shifts to 8:2,
205 the predicted seismic magnitude changes only slightly, whereas the estimated available water volume
206 exceeds the observed excess floodwater volume by more than 50%. This contrasting sensitivity
207 demonstrates that the hydrological comparison provides particularly strong evidence on the assumed
208 ice fraction, whereas the seismic comparison primarily evaluates the plausibility of the reconstructed
209 moving mass. The agreement of both comparisons under the same source configuration strengthens the
210 consistency of the reconstruction.

211 More importantly, the reconstructed cascade reveals how the initial gravitational energy and substantial
212 rock-ice mass can drive downstream flood amplification through interactions with materials and water
213 along the river corridor. During rapid descent, fragmentation and sediment entrainment transformed
214 the initial avalanche into a dense debris flow capable of scouring channel deposits and transferring
215 momentum to pre-existing river water. The resulting displacement and acceleration of river water
216 concentrated part of the available water into a downstream-propagating surge, allowing the flood to
217 extend beyond the principal deposition zone of coarse debris. This mechanism explains why the
218 downstream flood response cannot be attributed to source-ice melting alone. The reconstructed
219 corridor-water inventory, when combined with the maximum source-ice meltwater supply, closely
220 approaches the independently estimated Devghat excess, with a central difference of only 6.30%. This
221 quantitative correspondence supports the feasibility of debris-driven river-water mobilization as a
222 major component of the cascading flood mechanism.

223 Comparisons with other Himalayan disasters place this mechanism within a broader context of
224 cascading hazard amplification. During the 2021 Chamoli disaster, approximately 20% of the released
225 material consisted of ice, and melting contributed to the transformation of the initial rock-ice avalanche
226 into a highly mobile sediment-laden flow⁴. In the 2023 Sikkim disaster, the release of approximately
227 $50 \times 10^6 \text{ m}^3$ of lake water was accompanied by extensive downstream erosion involving approximately

228 $270 \times 10^6 \text{ m}^3$ of sediment⁴⁸. Although these events involved different initial water sources and flow-
229 transformation pathways, they demonstrate how interactions with stored water and erodible valley
230 materials can substantially extend the consequences of an initial disturbance. The Langtang Lirung
231 cascade adds a distinct perspective by quantitatively examining the potential contribution of pre-
232 existing river water, alongside source-ice melting. Its principal contribution lies in connecting this
233 corridor-water inventory to both the reconstructed source mass and the downstream flood hydrograph
234 through independent observational constraints.

235 The Langtang Lirung disaster demonstrates how a localized rock-ice avalanche can evolve into a far-
236 reaching flood cascade through the coupled transport of solid debris and river water. By combining
237 source reconstruction with independent seismic and hydrological observations, this study constrains
238 both the initial release and the potential water available for downstream flood formation. The results
239 show that source-ice melting alone is insufficient to account for the observed floodwater excess, while
240 mobilization of pre-existing river water provides a quantitatively plausible explanation for the
241 additional volume. This source-to-flood framework advances the understanding of high-mountain
242 disaster amplification and highlights the need to incorporate river-water storage, sediment availability
243 and downstream exposure into assessments of cascading hazards. Under global warming, the retreat of
244 snow and glacier ice progressively reduces slope support and weakens ice-bonded rock masses.
245 Extreme rainfall and major earthquakes can disturb these increasingly unstable slopes, increasing the
246 risk of large cascading disasters across the Himalaya-Hindu Kush region. Connected river corridors
247 transmit these hazards across national borders, making joint source-and-corridor hazard surveys, shared
248 satellite, seismic and hydrological observations, and coordinated regional preparedness essential.

249 **Methods**

250 We reconstructed the source mass and available floodwater from imagery, terrain and external
251 hydraulic information, then compared these outputs with separately acquired USGS seismic and
252 Devghat discharge records (Fig. 1). The calculations and observational benchmarks are described
253 below.

254 **Three-stream design and separation of evidence**

255 Stream A calculates source mass, long-period magnitude and available water using a single, well-
256 defined set of source-volume and rock-to-ice ratio parameters. Stream B provides the USGS catalogue
257 magnitude; Stream C calculates excess volume solely from the Devghat hydrograph. These
258 observational benchmarks (B and C) do not enter the forward inventory equations.

259 **Data sources and spatiotemporal characteristics**

260 **(1) Satellite imagery.** Copernicus/ESA Sentinel-2 MultiSpectral Instrument (MSI) imagery acquired
261 on 12 and 24 August 2026 provides the regional basemap and pre-failure source observations,
262 respectively. Landsat-9 Operational Land Imager-2 (OLI-2) imagery acquired on 26 August 2026
263 records the post-collapse scar. Historical imagery accessed through Google Earth and dated 10 October
264 2017 provides the earlier structural view. Sentinel-2 and Landsat product specifications and access are
265 provided by the Copernicus Data Space Ecosystem (<https://dataspace.copernicus.eu/>) and USGS
266 EarthExplorer (<https://earthexplorer.usgs.gov/>), respectively. Post-event SAR imagery provided by the
267 Changsha Tianyi Research Institute and Gaofen (GF) satellite imagery obtained from the Land Satellite
268 Remote Sensing Application Center, Ministry of Natural Resources, were additionally used with
269 KDFIM to reconstruct the flood-affected extent and inundation depth.

270 **(2) Elevation data and derived products.** Elevation data were obtained from the Copernicus Digital
271 Elevation Model (COP-DEM GLO-30), which provides global elevation information
272 (<https://doi.org/10.5270/ESA-c5d3d65>). The elevation data were resampled to a 10m analysis grid.

273 KDFIM was implemented on this common 10m grid to integrate the multi-source observations and
 274 derive flood extent and depth. All derived raster products in this study, including the source-
 275 reconstruction, reachability, water-mask, flood-extent and depth layers, were output at 10m grid
 276 spacing. This harmonized output spacing supports cell-wise integration and water-volume accounting.

277 **(3) Seismic and hydrological observations.** The USGS earthquake catalogue provides the 26 August
 278 2026 landslide event us7000tbwb, including its location, origin time and reported magnitude. Devghat
 279 discharge observations for 26 August 2026 were transcribed from the flood technical report issued by
 280 the Flood Forecasting Division, Hydrology and Water Resources Research Center, Water and Energy
 281 Commission Secretariat, Government of Nepal. The Centre of Hydrology and Water Resources
 282 Research Assessment Report II supplies the same-day water-level records for Kali Gandaki at Kota
 283 Gaon and Marsyangdi at Bimalnagar.

284 **Stream A: forward source-to-river reconstruction**

285 **Source volume and mass**

286 The three-dimensional source geometry was reconstructed from the DEM, the imagery-derived failure
 287 footprint (Fig. 2B-E) and the three reference surfaces a, b and c in Fig. 3B. The mapped footprint
 288 constrains the lateral extent of the failed body, while the spatial relationship between the DEM and the
 289 reference surfaces constrains its reconstructed vertical extent. We discretized this geometry into
 290 vertical voxel columns⁴⁹ and integrated their positive thicknesses over valid cells within the source
 291 footprint:

$$292 \quad V_s = \sum_j I_j h_j A_j \quad (1)$$

293 where V_s is source volume; h_j and A_j are the reconstructed vertical thickness and ground area of voxel
 294 j , respectively; I_j equals 1 for valid positive-thickness cells within the source footprint and 0 otherwise.

295 The positive voxels yield $V_s = 78.37 \times 10^6 \text{m}^3$. UAV interpretation gives a rock:ice volume ratio of 9:1.
 296 Mixture mass and density are:

$$297 \quad m = \rho_{\text{mix}} V_s, \rho_{\text{mix}} = f_i \rho_i + (1 - f_i) \rho_r \quad (2)$$

298 where $f_i = 0.10$ is the source ice volume fraction, and $\rho_i = 917 \text{ kg m}^{-3}$ and $\rho_r = 2700 \text{ kg m}^{-3}$ are ice and
 299 rock densities, respectively³⁴. The resulting mixture density is $2.52 \times 10^3 \text{ kg m}^{-3}$ and source mass m is
 300 $1.98 \times 10^{11} \text{ kg}$.

301 **Forward seismic scaling**

302 The empirical landslide relations of Ekström and Stark³⁵ convert moving mass to maximum force and
 303 long-period magnitude:

$$305 \quad \frac{m}{10^{12} \text{ kg}} \approx 0.54 \hat{F}, \hat{F} = \frac{F_{\text{max}}}{10^{12} \text{ N}} \quad (3)$$

$$306 \quad M_{\text{SW}} = 5.40 + 0.45 \log_{10} \hat{F} \quad (4)$$

307 where $\hat{F}$ is maximum force normalized by 10^{12} N and M_{SW} is the predicted long-period magnitude. The
 308 adopted mass gives $\hat{F} = 0.37$, $F_{\text{max}} = 3.66 \times 10^{11} \text{ N}$ and $M_{\text{SW}} = 5.20$. A factor-of-two mass perturbation
 309 gives a magnitude range of 5.07-5.34.

310 **DEM-constrained reachability**

311 We applied KDFIM to pre- and post-event satellite imagery to delineate the horizontal extent of the
 312 affected river corridor and reconstruct its inundation-depth distribution^{40,41}. These products define the
 313 spatial domain and characterize the vertical extent of the disaster impacts. We aligned the mapped
 314 corridor with the DEM and restricted the reachability calculation to this domain. Eight-neighbour cell
 315 connections define the routing network, and Dijkstra's algorithm identifies the shortest horizontal
 316 predecessor paths⁴². Elevations sampled from the DEM along these paths provide the elevation drop

317 and cumulative horizontal distance used to calculate the critical effective friction coefficient. The
 318 source reference elevation is volume-weighted:

$$319 \quad z_0 = \frac{\sum_i z_i h_i A_i}{\sum_i h_i A_i} \quad (5)$$

320 where z_i , h_i and A_i denote source-cell elevation, reconstructed vertical thickness and ground area,
 321 respectively. Along each path, the cumulative-energy threshold is:

$$322 \quad \mu_{\text{crit}}(s) = \min_{0 < \ell \leq s} \left\{ \frac{z_0 - z(\ell)}{L_h(\ell)} \right\} \quad (6)$$

323 where $z(\ell)$ is path elevation and $L_h(\ell)$ is cumulative horizontal distance, including the source-centroid-
 324 to-corridor entry distance. The running minimum over all upstream path positions gives the greatest
 325 constant effective Coulomb friction coefficient allowing continuous reachability from rest^{36,43,44}. This
 326 threshold screens energetic reachability within the prescribed corridor; finite, non-zero cells with μ_{crit}
 327 > 0.10 define the water-inventory domain. The effective-friction coefficient of 0.10 was adopted to
 328 delineate the maximum transport extent of debris flow and sediment along the mapped corridor. Cells
 329 satisfying the reachability criterion under Equation 6 were retained as the potential maximum runout
 330 domain. Such a low effective resistance is physically plausible for highly mobile rock-ice avalanches
 331 and debris flows, particularly where water availability, icy substrates and confined flow paths enhance
 332 mobility^{14,50}.

333 **Pre-event corridor-water inventory**

334 The pre-event optical water index follows the Spectral Knowledge-Driven Water Index (SKDWI)
 335 formulation in KDFIM⁴¹:

$$336 \quad SKDWI = \frac{Green - NIR - SWIR2}{Green + NIR} \quad (7)$$

337 where Green, NIR and SWIR2 denote surface reflectance in the green, near-infrared and second
 338 shortwave-infrared bands, respectively.

339 KDFIM corridor and water products⁴⁰, incorporating optical-SAR fusion and physics-constrained gap
 340 filling⁴¹, were aligned on a common raster grid. Within the reachability domain, finite SKDWI values
 341 identify pre-event water⁴¹. Water area and storage are:

$$342 \quad V_{\text{corridor}} = A_w d, A_w = 100 \sum_i W_i \quad (8)$$

343 where W_i is the binary water mask, each cell represents 100m^2 , A_w is mapped water area and d is
 344 assigned mean depth. $A_w = 1.61 \times 10^6\text{m}^2$. Depths of 4.00, 4.50 and 5.00m, informed by hydraulic
 345 information in the Disaster Management Plan for the Upper Trishuli-1 Hydropower Project (UT-1)⁴⁷,
 346 give inventories of 6.43 , 7.24 and $8.04 \times 10^6\text{m}^3$. The central value $(7.24 \pm 0.80) \times 10^6\text{m}^3$ represents
 347 depth-scenario uncertainty.

348 **Source-ice meltwater and available water**

349 Mass conservation converts source ice to its liquid-water equivalent:

$$350 \quad V_{\text{melt}} = \frac{\chi \rho_i f_i V_s}{\rho_w}, V_{\text{ice}} = f_i V_s, M_i = \rho_i f_i V_s \quad (9)$$

351 where V_{ice} and M_i are source-ice volume and mass, χ is melt fraction and $\rho_w = 1000\text{kg m}^{-3}$. Post-event
 352 field observations revealed no obvious residual ice in the affected area, providing observational support
 353 for considering complete source-ice melting. Accordingly, we adopted complete melting ($\chi = 1$) as an
 354 upper-bound scenario, with $V_{\text{ice}} = 7.84 \times 10^6\text{m}^3$ and $V_{\text{melt}} = 7.19 \times 10^6\text{m}^3$, the latter representing the
 355 upper limit of the source-ice contribution to downstream flooding. Adding central corridor-water
 356 storage gives $V_{\text{available}} = V_{\text{melt}} + V_{\text{corridor}} = (14.42 \pm 0.80) \times 10^6\text{m}^3$.

357 **Stream B: USGS seismic benchmark**

358 The USGS landslide event us7000tbwb reports a magnitude of 5.20 with catalogue type ms_vx²⁹. This
 359 independently acquired value is compared with the forward long-period estimate.

360 **Stream C: Devghat excess volume**

361 Devghat discharge was transcribed from the 26 August 2026 technical report³¹. We used the first
362 observation, $Q_0 = 3.09 \times 10^3 \text{m}^3 \text{s}^{-1}$ at 14:10, as the operational baseline. Impulsive water disturbances
363 can generate wave crests and subsequent negative-phase fluctuations, and negative surges can lower
364 the local water surface^{51,52}. Flood-wave propagation also produces peak attenuation and hydrograph
365 deformation⁵³. A post-wave minimum can therefore reflect a transient hydraulic response and is not
366 used as the undisturbed reference. We adopt the station discharge observed before the recorded rise as
367 the reference for evaluating the positive discharge anomaly. Linear interpolation between 17:20 (3.22
368 $\times 10^3 \text{m}^3 \text{s}^{-1}$) and 17:30 ($3.00 \times 10^3 \text{m}^3 \text{s}^{-1}$) gives the return time $t_e = 17:25:49$. The excess volume, defined
369 here as the cumulative volume of discharge above the baseline over the event duration, is:

$$370 \quad \Delta V_D = \int_{t_0}^{t_e} (Q(t) - Q_0) dt \quad (10)$$

$$371 \quad \Delta V_D \approx \sum_j \frac{e_j + e_{j+1}}{2} \delta t_j \quad (11)$$

372 where $Q(t)$ is discharge, $e_j = Q_j - Q_0$, and δt_j is the interval between observations. Trapezoidal
373 integration over $1.18 \times 10^4 \text{s}$ gives $\Delta V_D = 13.57 \times 10^6 \text{m}^3$; both $5.85 \times 10^3 \text{m}^3 \text{s}^{-1}$ observations at 16:00
374 and 16:10 are retained. Times follow the report's local-time convention.

375 **Paired validation**

376 We evaluated the source reconstruction using the difference between the forward-predicted magnitude
377 and the USGS value. We assessed the water budget using the signed difference between the calculated
378 available water and the Devghat excess, expressed as a percentage of the observed excess. The
379 maximum source-ice contribution was calculated by dividing complete-melt water yield by the
380 observed excess. Water-volume amplification was calculated by normalizing the predicted and
381 observed water volumes by that meltwater yield.

382 **Data availability**

383 The data supporting the findings of this study are publicly available at
384 <https://gip.csu.edu.cn/info/1484/7794.htm>.

385 **Code availability**

386 The source code supporting the findings of this study is publicly available at
387 <https://gip.csu.edu.cn/info/1484/7794.htm>.

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392 **Author contributions**

393 Zhijun Jiao: manuscript writing, methodology design, visualization and analysis. Suraj Gautam and
394 Raju Thapa: hydrological data validation, provision of local information and manuscript review.
395 Zhimei Zhang: assistance with manuscript writing and data curation. Pengtianhao Wu: hydrological
396 analysis and manuscript revision. Zichen Yue and Qiqi Zhang: assistance with analysis. Wenfei Mao:
397 discussion of the mechanism. Bishal Nath Upreti and Meen B. Poudyal Chhetri: hydrological data
398 validation, provision of local information and manuscript review. Lixin Wu: conceptualization,
399 supervision, funding acquisition, comprehensive analysis, data curation, manuscript review and
400 language editing.

401 **Competing interests**

402 The authors declare no competing interests.

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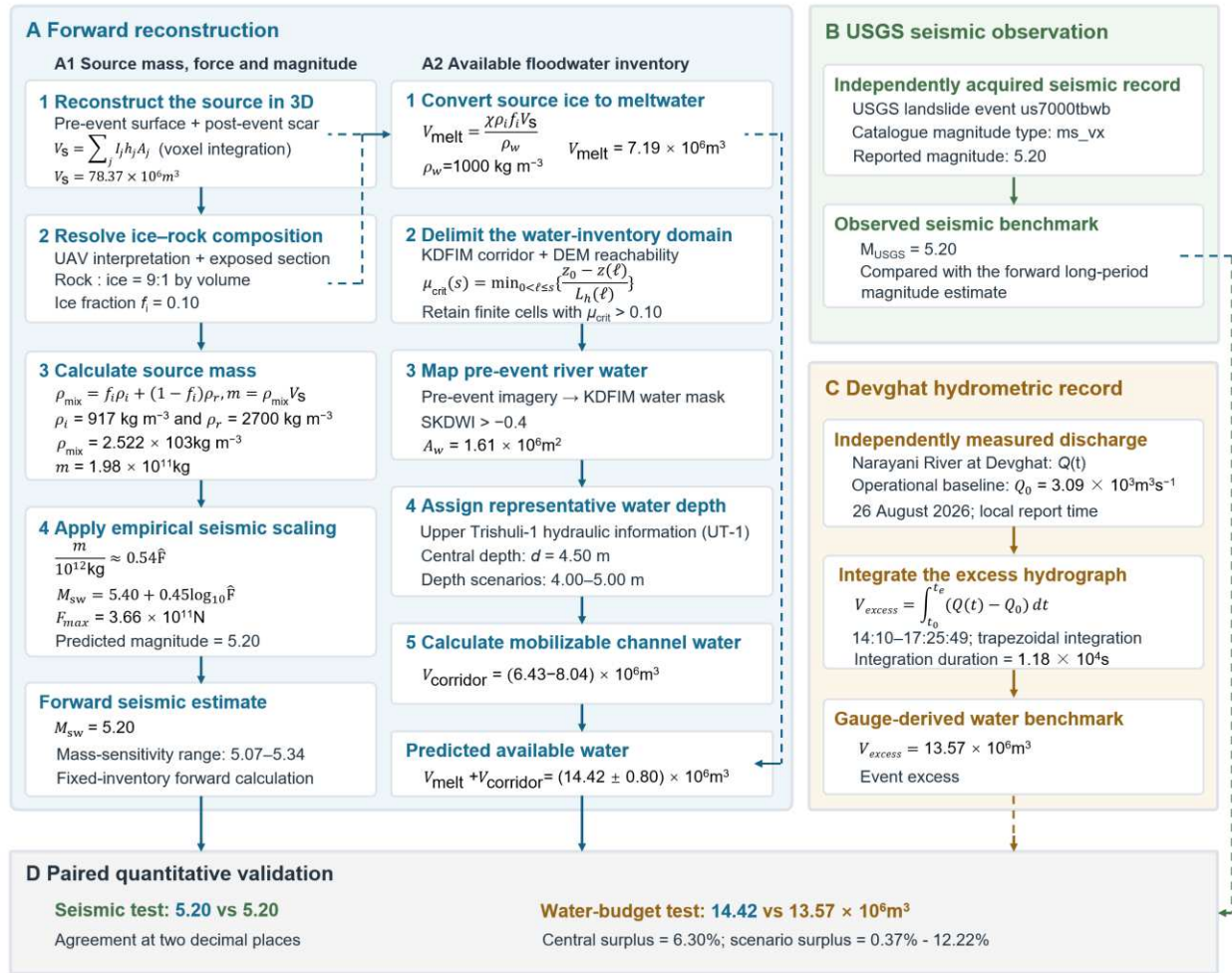
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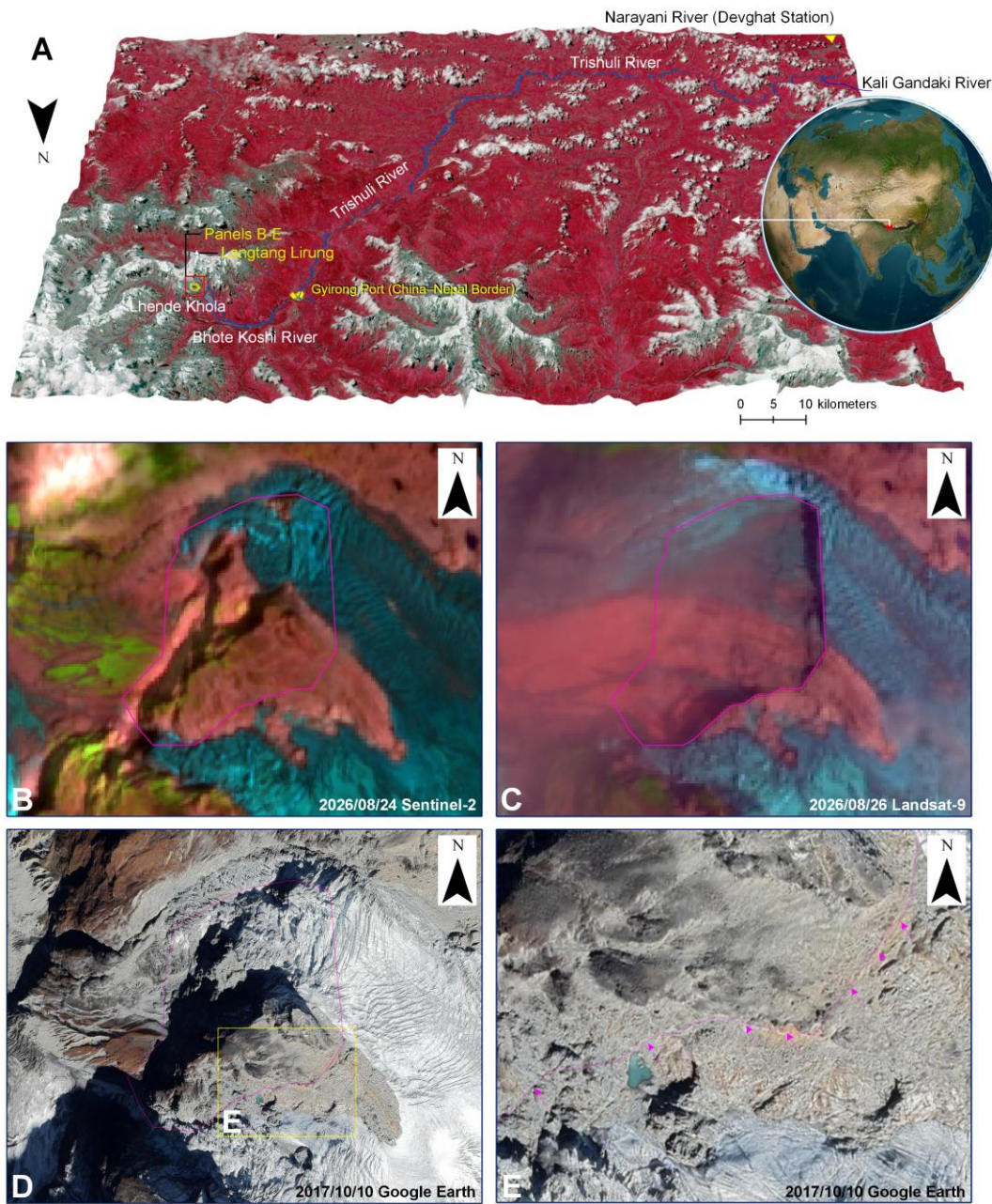
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541 Figures and figure legends



542

543 **Fig.1** Three-stream workflow for source-to-river reconstruction and paired validation. (A1) Source geometry and
 544 UAV-derived rock:ice composition determine mass and the seismic estimate. (A2) Source-ice meltwater is added to
 545 corridor-water storage estimated from KDFIM water mapping, DEM-based reachability and 4.0-5.0m depth
 546 scenarios. (B) The USGS catalogue supplies the seismic benchmark. (C) Devghat discharge is integrated above an
 547 operational baseline to obtain excess flood volume. (D) The two comparisons test the reconstructed inventory against
 548 separate observations. Solid arrows show calculation sequences; dashed arrows indicate shared inputs or external
 549 comparisons.



550

551 **Fig.2 Regional setting, source-area changes and failure footprint of the 26 August 2026 Lirung rock-ice**
 552 **avalanche.** (A) Sentinel-2 image acquired on 12 August 2026, showing the source area, mapped impact corridor,
 553 Gyirong Port at the China-Nepal border and the Devghat hydrometric station on the Narayani River. The inset shows
 554 the global location of the study area. (B) Pre-event Sentinel-2 image acquired on 24 August 2026, showing the intact
 555 source area. (C) Post-event Landsat-9 image acquired on 26 August 2026, revealing the newly exposed collapse scar
 556 used to delineate the source rock-ice body. (D) High-resolution Google Earth image acquired on 10 October 2017,
 557 showing the pre-existing fractured and weathered rock zone, with the reconstructed source boundary overlaid. (E)
 558 Enlarged view of the historical image, highlighting the close correspondence between the pre-existing fracture pattern
 559 and the reconstructed failure boundary.

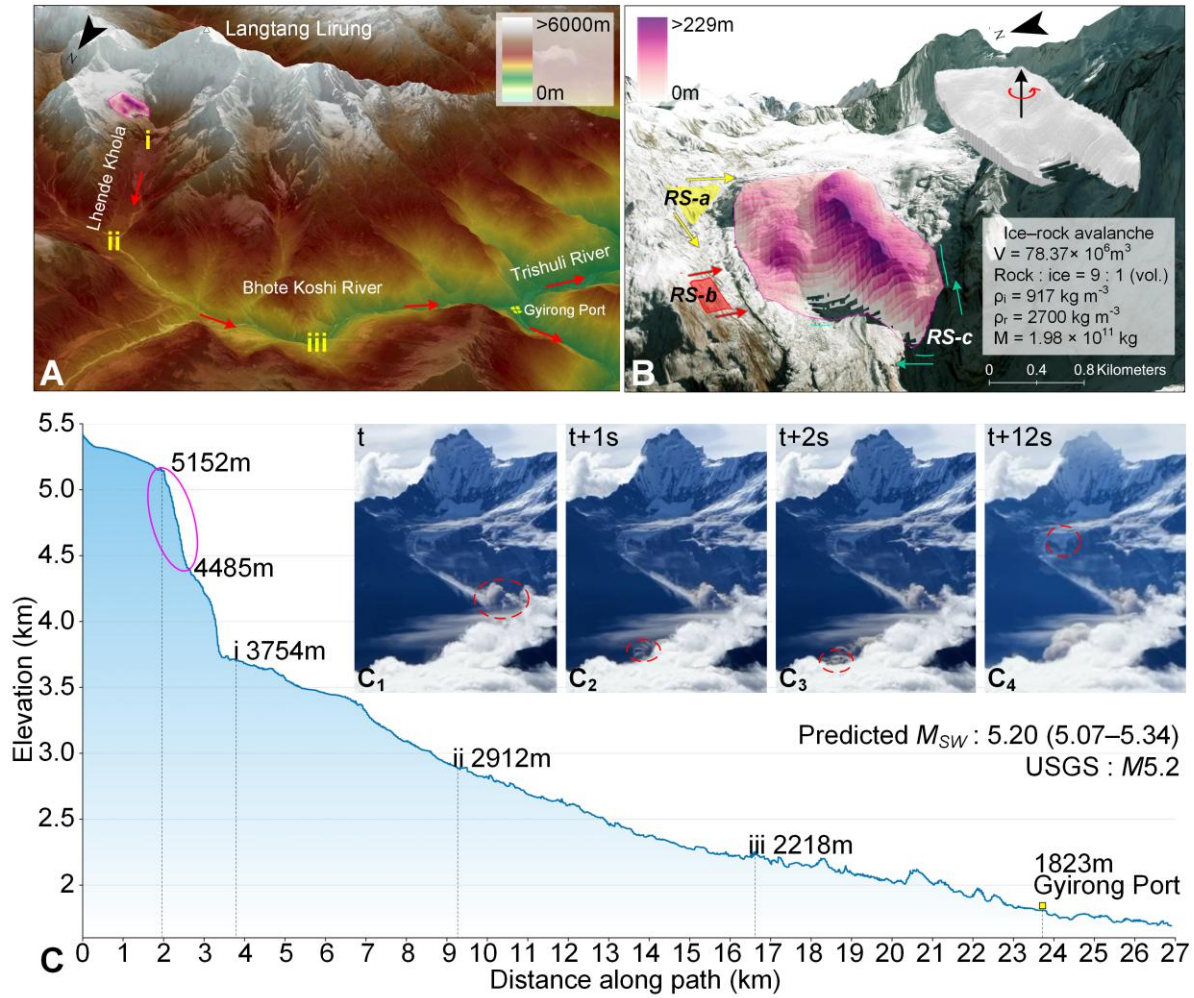
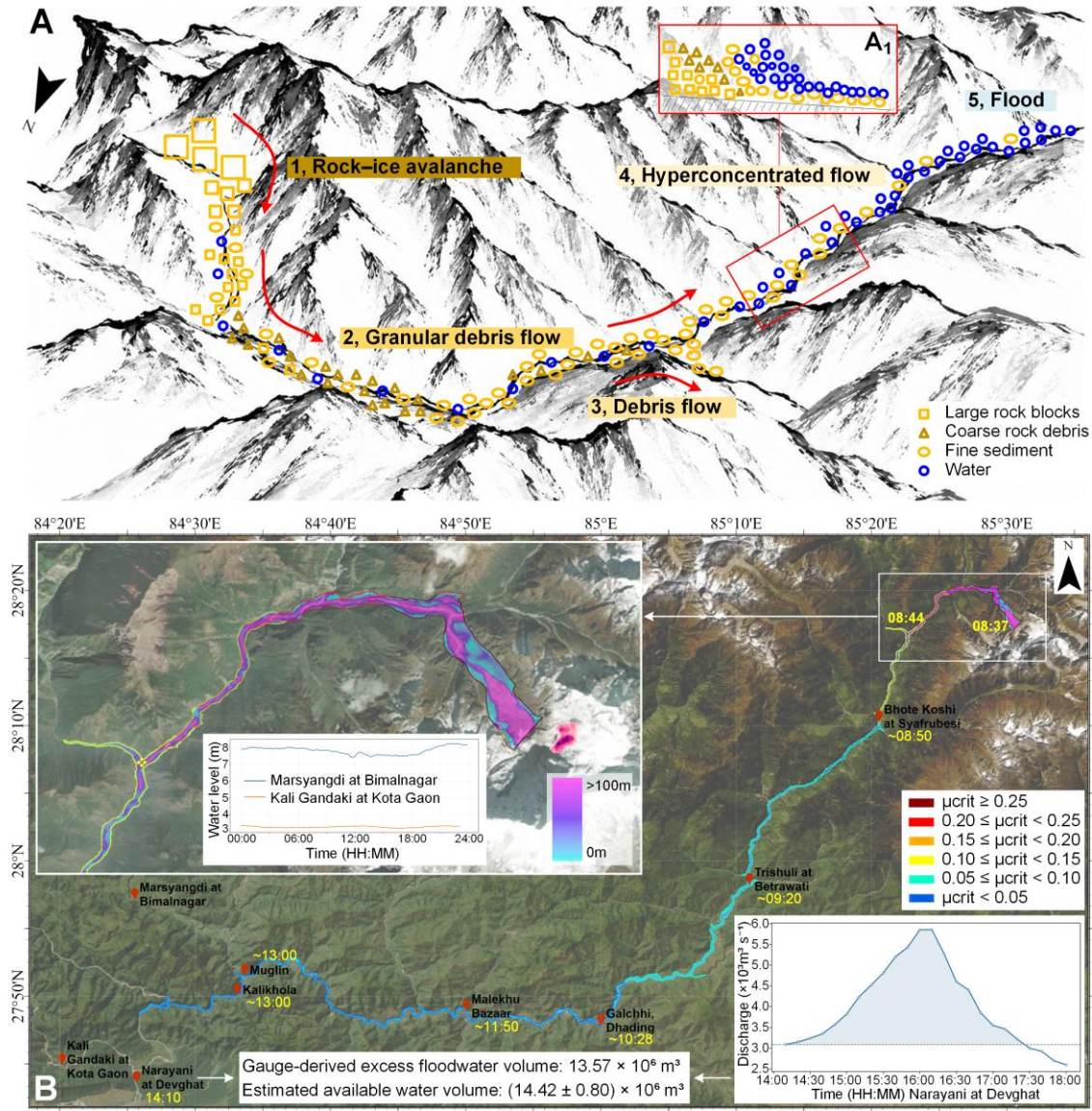
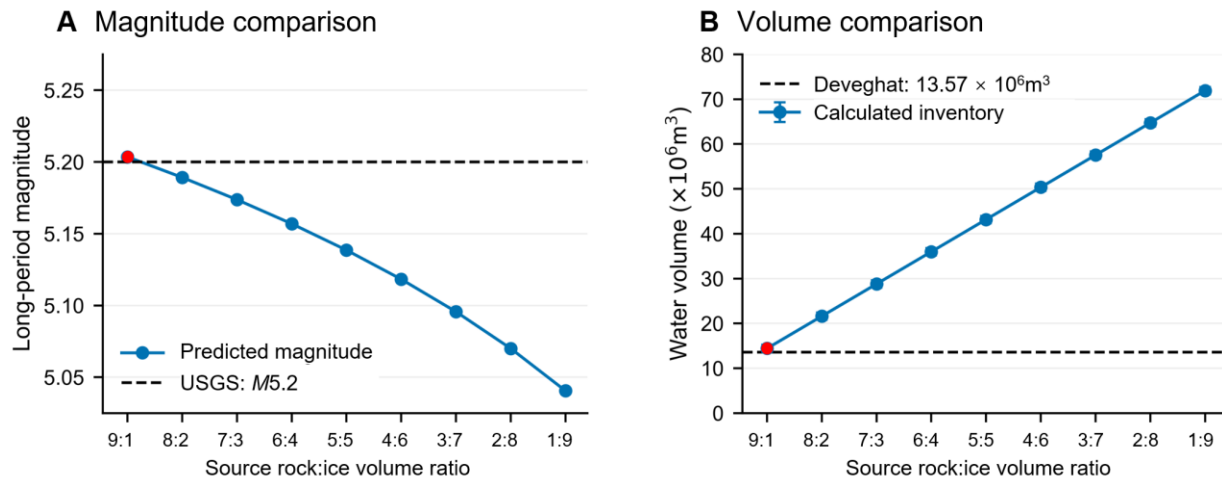


Fig.3 Source reconstruction and rapid downslope propagation of the Lirung rock-ice avalanche. (A) Oblique topographic view illustrating the propagation corridor from the source towards Gyirong Port, with locations i-iii marking successive reaches along Lhende Khola and Bhote Koshi. (B) Three-dimensional reconstruction of the released rock-ice body constrained by the mapped source footprint and three reference surfaces (RS-a, RS-b and RS-c). (C) Longitudinal terrain profile showing the pronounced elevation drop from the source to the Gyirong Port corridor. (C1-C3) Successive video frames capturing the rapid downslope movement of the dust-bearing avalanche front within reach i-ii. (C4) A subsequent frame showing continued secondary rock-ice fall.



568

569 **Fig.4 Cascade transformation, debris-driven river-water mobilization and downstream flood response.** (A)
 570 Conceptual reconstruction of the progressive transformation from rock-ice avalanche (1) to granular debris flow (2),
 571 debris flow (3), hyperconcentrated flow (4) and flood (5). (A1) Schematic representation of the interaction between
 572 high-momentum debris and pre-existing river water, illustrating channel scouring, sediment entrainment and
 573 downstream water displacement. (B) Spatial and temporal reconstruction of the cascade, showing the propagation
 574 corridor, recorded flood passage times, flow-depth distribution and critical-friction field. Insets show the water-level
 575 records at Kali Gandaki and Marsyangdi and the Devghat discharge hydrograph. The reconstructed maximum
 576 available water volume is $(14.42 \pm 0.80) \times 10^6 \text{ m}^3$, compared with an observed excess floodwater volume of $13.57 \times$
 577 10^6 m^3 .



578

579 **Fig.5 Sensitivity of predicted seismic magnitude and available floodwater volume to source rock-ice**
 580 **composition.** Nine rock-to-ice volume ratios, ranging from 9:1 to 1:9, were evaluated using the same reconstructed
 581 source volume and constituent densities under the complete-melting assumption. (A) Predicted long-period seismic
 582 magnitude compared with the independently reported USGS magnitude (dashed line). (B) Estimated available water
 583 volume, combining potential source-ice meltwater and pre-existing corridor-water storage, compared with the
 584 Devghat excess floodwater volume (dashed line).