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A massive rock and ice avalanche caused the 2021 disaster at Chamoli, Indian Himalaya

Authors: Shugar, D.H.^{1*}, Jacquemart, M.^{2,3,4}, Shean, D.⁵, Bhushan, S.⁵, Upadhyay, K.⁶, Sattar, A.⁷, Schwanghart, W.⁸, McBride, S.⁹, Van Wyk de Vries, M.^{10,11}, Mergili, M.^{12,13}, Emmer, A.¹², Deschamps-Berger, C.¹⁴, McDonnell, M.¹⁵, Bhambri, R.¹⁶, Allen, S.^{7,17}, Berthier, E.¹⁸, Carrivick, J.L.¹⁹, Clague, J.J.²⁰, Dokukin, M.²¹, Dunning, S.A.²², Frey, H.⁷, Gascoïn, S.¹⁴, Haritashya, U.K.²³, Huggel, C.⁷, Kääb, A.²⁴, Kargel, J.S.²⁵, Kavanaugh, J.L.²⁶, Lacroix, P.²⁷, Petley, D.²⁸, Rupper, S.¹⁵, Azam, M.F.²⁹, Cook, S.J.^{30,31}, Dimri, A.P.³², Eriksson, M.³³, Farinotti, D.^{3,4}, Fiddes, J.³⁴, Gnyawali, K.R.³⁵, Harrison, S.³⁶, Jha, M.³⁷, Koppes, M.³⁸, Kumar, A.³⁹, Leinss, S.^{40,41}, Majeed, U.⁴², Mal, S.⁴³, Muhuri, A.^{14,44}, Noetzli, J.³⁴, Paul, F.⁷, Rashid, I.⁴², Sain, K.³⁹, Steiner, J.^{45,46}, Ugalde, F.^{47,48}, Watson, C.S.⁴⁹, Westoby, M.J.⁵⁰

Affiliations:

¹Water, Sediment, Hazards, and Earth-surface Dynamics (waterSHED) Lab, Department of Geoscience; University of Calgary, AB, Canada.

²Cooperative Institute for Research in Environmental Sciences, University of Colorado; Boulder, CO, USA.

³Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich; Zurich, Switzerland.

⁴Swiss Federal Institute for Forest, Snow and Landscape Research WSL; Birmensdorf, Switzerland.

⁵Department of Civil and Environmental Engineering, University of Washington; Seattle, WA, USA.

⁶Independent journalist/water policy researcher; Nainital, Uttarakhand, India.

⁷Department of Geography, University of Zurich; Zurich, Switzerland.

⁸Institute of Environmental Science and Geography, University of Potsdam; Potsdam, Germany.

⁹U.S. Geological Survey, Earthquake Science Center; Moffett Field, CA, USA.

¹⁰Department of Earth & Environmental Sciences, University of Minnesota, Minneapolis, MN, USA.

¹¹St. Anthony Falls Laboratory, University of Minnesota; Minneapolis, MN, USA.

¹²Institute of Geography and Regional Science, University of Graz; Graz, Austria.

¹³Institute of Applied Geology, University of Natural Resources and Life Sciences (BOKU); Vienna, Austria.

¹⁴CESBIO, Université de Toulouse, CNES/CNRS/INRAE/IRD/UP; Toulouse, France.

¹⁵Department of Geography, University of Utah; Salt Lake City, Utah, USA.

¹⁶Department of Geography, South Asia Institute, Heidelberg University; Heidelberg, Germany.

¹⁷Institute for Environmental Sciences, University of Geneva; Switzerland.

¹⁸LEGOS, Université de Toulouse, CNES/CNRS/IRD/UPS; Toulouse, France.

¹⁹School of Geography and water@leeds, University of Leeds, Leeds; West Yorkshire, UK.

²⁰Department of Earth Sciences, Simon Fraser University; Burnaby, BC, Canada.

²¹Department of Natural Disasters, High-Mountain Geophysical Institute; Nalchik, Russia.

²²Geography, Politics and Sociology, Newcastle University; Newcastle, UK.

- 46 ²³Department of Geology and Environmental Geosciences, University of Dayton; Dayton,
47 OH, USA.
- 48 ²⁴Department of Geosciences, University of Oslo; Oslo, Norway.
- 49 ²⁵Planetary Science Institute; Tucson, AZ, USA.
- 50 ²⁶Earth and Atmospheric Sciences, University of Alberta; Edmonton, AB, Canada.
- 51 ²⁷ISTerre, Université Grenoble Alpes, IRD, CNRS; Grenoble, France.
- 52 ²⁸Department of Geography, The University of Sheffield; Sheffield, UK.
- 53 ²⁹Indian Institute of Technology Indore; India.
- 54 ³⁰Geography and Environmental Science, University of Dundee; Dundee, UK.
- 55 ³¹UNESCO Centre for Water Law, Policy and Science, University of Dundee; Dundee, UK.
- 56 ³²School of Environmental Sciences, Jawaharlal Nehru University; New Delhi, India.
- 57 ³³Stockholm International Water Institute; Stockholm, Sweden.
- 58 ³⁴WSL Institute for Snow and Avalanche Research SLF; Davos, Switzerland.
- 59 ³⁵School of Engineering, University of British Columbia; Kelowna, BC, Canada.
- 60 ³⁶College of Life and Environmental Sciences, University of Exeter, Penryn, UK.
- 61 ³⁷Department of Mines and Geology, National Earthquake Monitoring and Research Center;
62 Kathmandu, Nepal.
- 63 ³⁸Department of Geography, University of British Columbia; Vancouver, BC, Canada.
- 64 ³⁹Wadia Institute of Himalayan Geology, Dehradun; Uttarakhand, India.
- 65 ⁴⁰Institute of Environmental Engineering (IfU), ETH Zurich, 8093 Zürich, Switzerland
- 66 ⁴¹Current affiliation: LISTIC, Université Savoie Mont Blanc, 74940 Annecy, France
- 67 ⁴²Department of Geoinformatics, University of Kashmir; Hazratbal Srinagar, Jammu and
68 Kashmir, India.
- 69 ⁴³Department of Geography, Shaheed Bhagat Singh College, University of Delhi; Delhi,
70 India.
- 71 ⁴⁴Institute of Geography, Heidelberg University; Germany.
- 72 ⁴⁵International Centre for Integrated Mountain Development; Kathmandu, Nepal.
- 73 ⁴⁶Department of Physical Geography, Utrecht University; Netherlands.
- 74 ⁴⁷Geoestudios, San José de Maipo; Chile.
- 75 ⁴⁸Department of Geology, University of Chile; Santiago, Chile.
- 76 ⁴⁹COMET, School of Earth and Environment. University of Leeds; Leeds, UK.
- 77 ⁵⁰Department of Geography and Environmental Sciences, Northumbria University;
78 Newcastle upon Tyne, UK.
- 79
- 80 *Corresponding author. Email: daniel.shugar@ucalgary.ca

81 **Abstract:** On 7 Feb 2021, a catastrophic mass flow descended the Ronti Gad, Rishiganga, and
82 Dhauliganga valleys in Chamoli, Uttarakhand, India, causing widespread devastation and
83 severely damaging two hydropower projects. Over 200 people were killed or are missing. Our
84 analysis of satellite imagery, seismic records, numerical model results, and eyewitness videos
85 reveals that $\sim 27 \times 10^6 \text{ m}^3$ of rock and glacier ice collapsed from the steep north face of Ronti
86 Peak. The rock and ice avalanche rapidly transformed into an extraordinarily large and mobile
87 debris flow that transported boulders $>20 \text{ m}$ in diameter, and scoured the valley walls up to 220
88 m above the valley floor. The intersection of the hazard cascade with downvalley infrastructure
89 resulted in a disaster, which highlights key questions about adequate monitoring and sustainable
90 development in the Himalaya as well as other remote, high-mountain environments.

91
92 **One-Sentence Summary:** The Chamoli disaster was triggered by an extraordinary rock and ice
93 avalanche and debris flow, that destroyed infrastructure and left 204 people dead or missing.
94

95 **Main Text:** Steep slopes, high topographic relief, and seismic activity make mountain regions
96 prone to extremely destructive mass movements (e.g. 1). The sensitivity of glaciers and
97 permafrost to climate changes is exacerbating these hazards (e.g. 2–7). Hazard cascades, where
98 an initial event causes a downstream chain reaction (e.g. 8), can be particularly far-reaching,
99 especially when they involve large amounts of water (7, 9, 10). An example is the 1970
100 Huascarán avalanche, Peru, that was one of the largest, farthest-reaching, and deadliest (~ 6000
101 lives lost) mass flows (11). Similarly, in 2013, over 4,000 people died at Kedarnath,
102 Uttarakhand, India, when a moraine-dammed lake breached following heavy rainfall and
103 snowmelt (12–14). Between 1894 and 2021, the Uttarakhand Himalaya has witnessed at least 16
104 major disasters from flash floods, landslides, and earthquakes (14, 15).

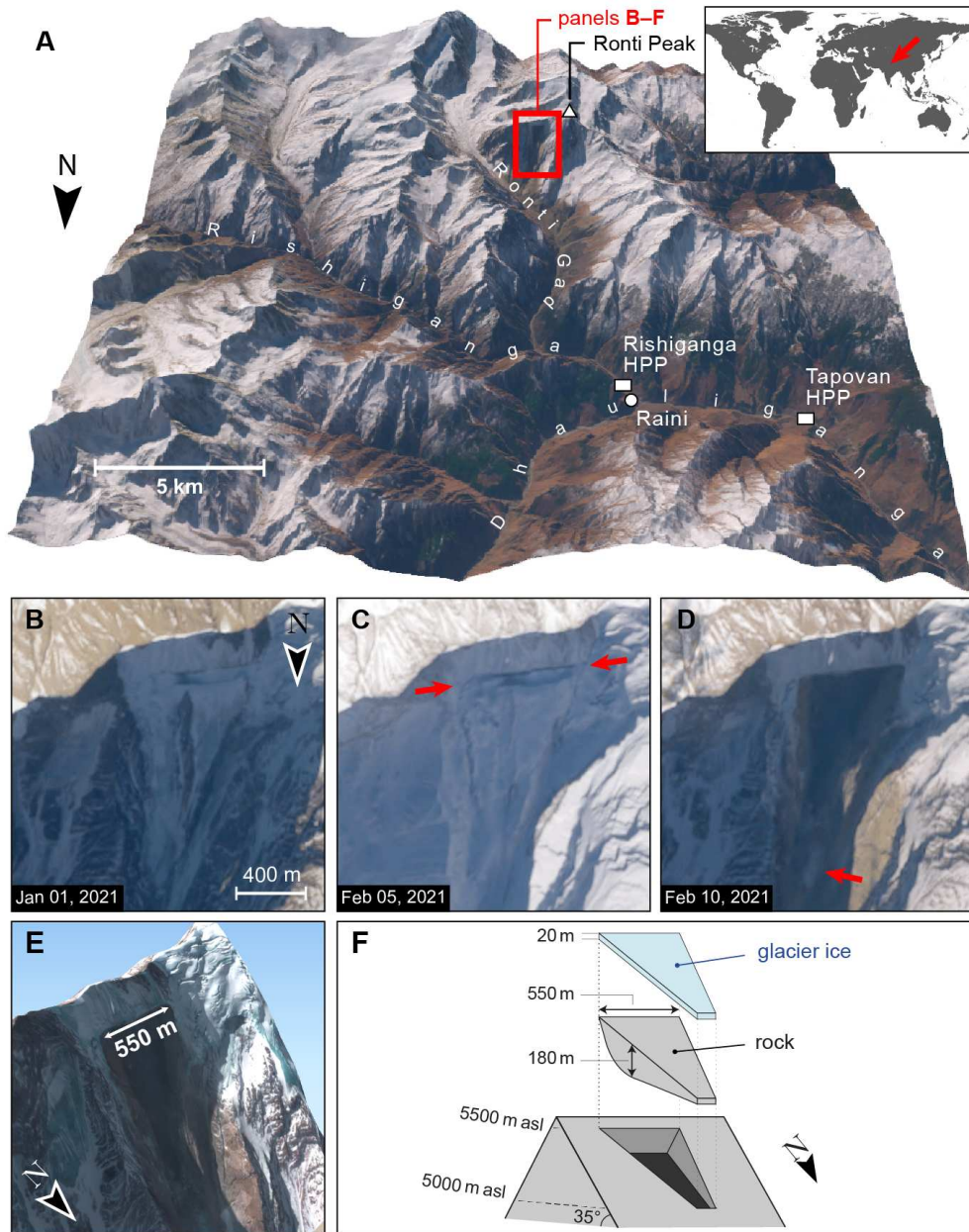
105 Human activities that intersect with the mountain cryosphere can increase risk (16) and are
106 common in Himalayan valleys where hydropower development is proliferating due to growing
107 energy demands, the need for economic development, and efforts to transition into a low-carbon
108 society (17, 18). Hydropower projects in Uttarakhand and elsewhere in the region have been
109 opposed over their environmental effects, public safety, and issues associated with justice and
110 rehabilitation (19, 20).

111 On 7 Feb 2021, a massive rock and ice avalanche from the 6063 m-high Ronti Peak generated a
112 cascade of events that caused more than 200 deaths or missing persons, as well as damage or
113 destruction of infrastructure that most notably included two hydropower projects in the
114 Rishiganga and Dhauliganga valleys (Fig. 1, table S1) (21). Here, we present a rapid and
115 comprehensive reconstruction of the hazard cascade. We leveraged multiple types of remote
116 sensing data, eyewitness videos, numerical modeling, seismic data, and reconnaissance field
117 observations in a collaborative, global effort to understand this event. We also describe the
118 antecedent conditions and the immediate societal response, allowing us to consider some wider
119 implications for sustainable development in high-mountain environments.

120 **February 7 2021 hazard cascade**

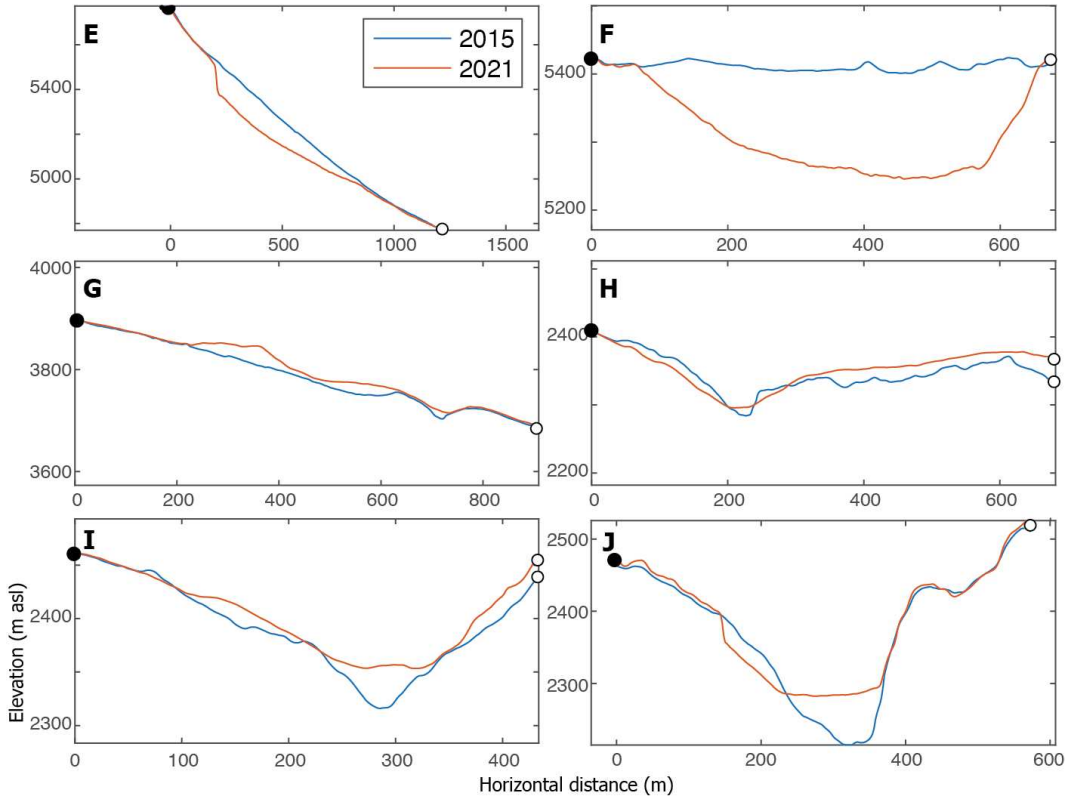
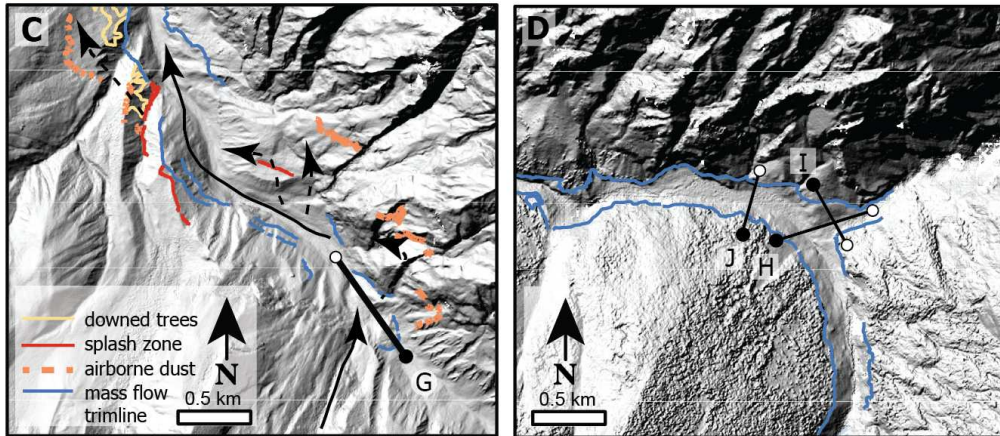
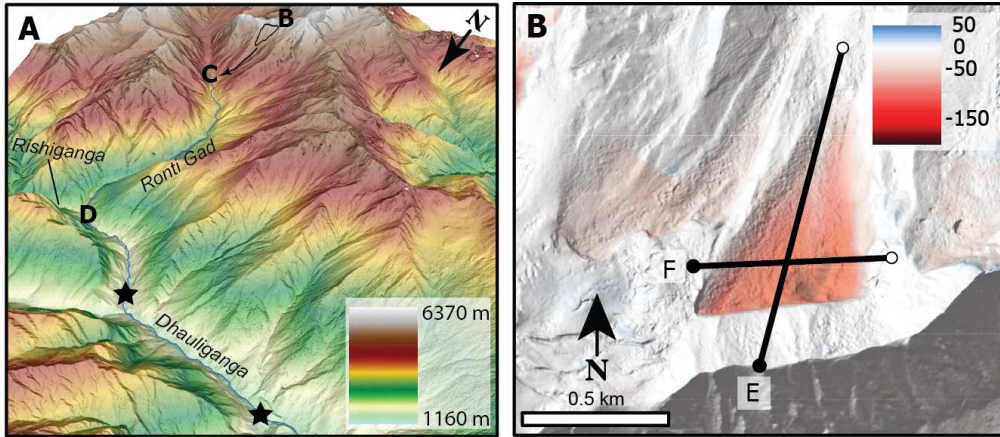
121 At 4:51 UTC (10:21 Indian Standard Time [IST]), about $26.9 \times 10^6 \text{ m}^3$ (95% confidence interval:
122 $26.5\text{--}27.3 \times 10^6 \text{ m}^3$) of rock and ice (Fig. 1, 2) detached from the steep north face of Ronti Peak at
123 an elevation of about 5,500 m asl, and impacted the Ronti Gad ('gad' means rivulet) valley floor

124 about 1,800 m below. We estimated the onset of this avalanche and its velocity by analyzing
 125 seismic data from two distant stations, 160 and 174 km southeast of the source (Fig. S6) (22,
 126 §5.1). The initial failure happened between 4:51:13 and 4:51:21 UTC, based on a source-sensor
 127 wave travel-time correction. We attributed a high-frequency signal 55 to 58 seconds later to the
 128 impact of the avalanche on the valley bottom, indicating a mean speed of the rock and ice
 129 avalanche of between 57 and 60 ms^{-1} (205 to 216 km h^{-1}) down the $\sim 35^\circ$ steep mountain face.
 130
 131



132
 133 **Fig. 1. Overview of the Chamoli disaster, Uttarakhand, India.** (A) 3D rendering of the local
 134 geography, with labels for main place names mentioned in the text. HPP stands for hydropower
 135 project. (B-D) Pre- and post-event satellite imagery of the site of the collapsed rock and glacier
 136 block, and the resulting scar. Note snow cover in the region just before the event (C). The red
 137 arrows in (C) mark the fracture that became the headscarp of the landslide (22, §3.2 and fig. S4).

138 The arrow in D points to a remaining part of the lower eastern glacier. (E) 3D rendering of the
139 scar. (F) Schematic of failed mass of rock and ice. Satellite imagery in (A–D) and (E) is from
140 Sentinel-2 (Copernicus Sentinel Data 02-10-2021) and Pléiades-HR (© CNES 02-10-2021,
141 Distribution AIRBUS DS), respectively.



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Fig. 2. Satellite-derived elevation data of the Chamoli hazard cascade. (A) Perspective view of the area, from the landslide source at Ronti Peak to the Rishiganga and Tapovan Vishnugad hydropower projects (black stars). (B) Elevation change over the landslide scar based on DEM-differencing between September 2015 and February 10-11, 2021. (C) The proximal valley floor, with geomorphic interpretations of the flow path. (D) Confluence of Ronti Gad and Rishiganga River. (E-J) Topographic profiles showing elevation change due to rock/icefall and sediment deposition for locations shown in (B-D). Elevation loss on the inner bank in (J) is primarily due to the destruction of forest.

Differencing of high-resolution digital elevation models (DEMs) revealed a failure scar that has a vertical difference of up to 180 m and a slope-normal thickness of ~80 m on average, and a slab width up to ~550 m, including both bedrock and overlying glacier ice (Fig. 2). The lowermost part of the larger eastern glacier is still in place and was not eroded by the rock and ice avalanche moving over it (Fig. 1D), suggesting that the avalanche may have become airborne for a short period during its initial descent. Optical feature tracking detected movement of the failed rock block as early as 2016, with the largest displacement in the summer months of 2017 and 2018 (fig. S4). This movement opened a fracture up to 80 m wide in the glacier and into the underlying bedrock (Fig. 1, fig. S5). Geodetic analysis and glacier thickness inversions indicate that the collapsed mass comprised ~80% rock and ~20% glacier ice by volume (22, §5.2, fig. S10). Melt of this ice was essential to the downstream evolution of the flow, as water transformed the rock and ice avalanche into a highly mobile debris flow (cf. 23, 24). Media reports (25) suggest that some ice blocks (diameter <1 m) were found in tunnels at the Tapovan Vishnugad hydropower site (hereafter referred to as the Tapovan project), and some videos of the debris flow (22, §5.3) show floating blocks that we interpret as ice, indicating that some of the ice survived at considerable distance downstream. Notably, and in contrast to most previously documented rock avalanches, very little debris is preserved at the base of the failed slope. This is likely due to the large volumes of water (22, §5.5) that resulted in a high mobility of the flow.

Geomorphic mapping based on very high-resolution satellite images (Table S2) acquired during and immediately after the event, provides evidence of the flow evolution. We detected four components of the catastrophic mass flow, beginning with the main rock and ice avalanche from Ronti Peak described above (component one).

The second component is “splash deposits” (cf. 26–28), which are relatively fine-grained, wet sediments that became airborne as the mass flow ran up adjacent slopes. For example, the rock and ice avalanche traveled up a steep slope on the east side of the valley opposite the source zone, and some material became airborne, being deposited at a height of about 120 m above the valley floor. These deposits include boulders up to ~8 m (a-axis length). The bulk of the flow then traveled back to the proximal (west) side of the valley and rode up a ridge ~220 m above the valley floor, before becoming airborne and splashing into a smaller valley to the west (Fig. 2C, figs. S15, S18). Boulders up to 13 m (a-axis length) were deposited near the top of the ridge. Vegetation remained intact on the lee side of some ridges that were overrun by the splashing mass.

189 A third component of the mass flow is reflected in airborne dust deposition. A dust cloud is
190 visible in PlanetScope imagery from 5:01 UTC and 5:28 UTC February 7 (10:31 and 10:58
191 IST). A smooth layer of debris, estimated from satellite imagery to be only a few cm in
192 thickness, was deposited higher than the splash deposits, up to ~500 m above the valley floor,
193 although the boundary between the airborne dust deposition and other mass flow deposits is
194 indistinct in places. Signs of the largely airborne splash and dust components can be observed
195 over ~3.5 km downstream of the valley impact site. The avalanche also generated a powerful
196 air blast (cf. 1) that flattened about 0.2 km² of forest on the west side of the Ronti Gad valley
197 (Fig. 2C).

198
199 After the rock and ice avalanche impacted the valley floor, most of it moved downvalley in a
200 northwesterly direction. Frictional heating of the ice in the avalanche generated liquid water
201 that allowed the transition in flow characteristics, becoming more fluid downvalley, creating a
202 flow consisting of sediment, water, and blocks of ice. The uppermost part of the valley floor
203 deposits is around 0.75 x10⁶ m³, with remarkably few large boulders that typically form the
204 upper surface of rock avalanches (e.g. 29, 30) (Fig. 2G, fig. S16). The mass flow traveled
205 downvalley and superelevated (runup elevation) up to ~130 m above the valley floor around
206 bends (fig. S17). Clear trimlines, at some places at multiple levels, are evident along much of
207 the flow path (e.g. Fig. 2C, D).

208
209 At the confluence of the Ronti Gad and Rishiganga River, a ~40 m thick deposit of debris
210 blocked the Rishiganga valley (Fig. 2H, I). Deposition in this area probably resulted from
211 deceleration of the mass flow at a sharp turn to the west. During the days following the event,
212 a lake ~700 m long formed behind these deposits in the Rishiganga valley upstream of its
213 confluence with Ronti Gad. The lake was still present two months later and had grown since
214 the initial formation. Substantial deposition occurred about 1 km downstream of the
215 confluence, where material up to ~100 m thick was deposited on the valley floor (Fig. 2J).
216 DEM differencing shows that the total deposit volume at the Ronti Gad-Rishiganga River
217 confluence and just downstream was ~8x10⁶ m³. These large sediment deposits likely indicate
218 the location where the flow transitioned to a debris flow (31) - the fourth component.

219
220 A field reconnaissance by co-authors from the Wadia Institute of Himalayan Geology
221 indicates that the impact of debris flow material (sediment, water, ice, woody debris) at the
222 confluence of Rishiganga River with Dhauliganga River created a bottleneck and forced some
223 material 150-200 m up the Dhauliganga (fig. S15). The release of the water a few minutes
224 later led to the destruction of a temple on the north bank of the Dhauliganga.

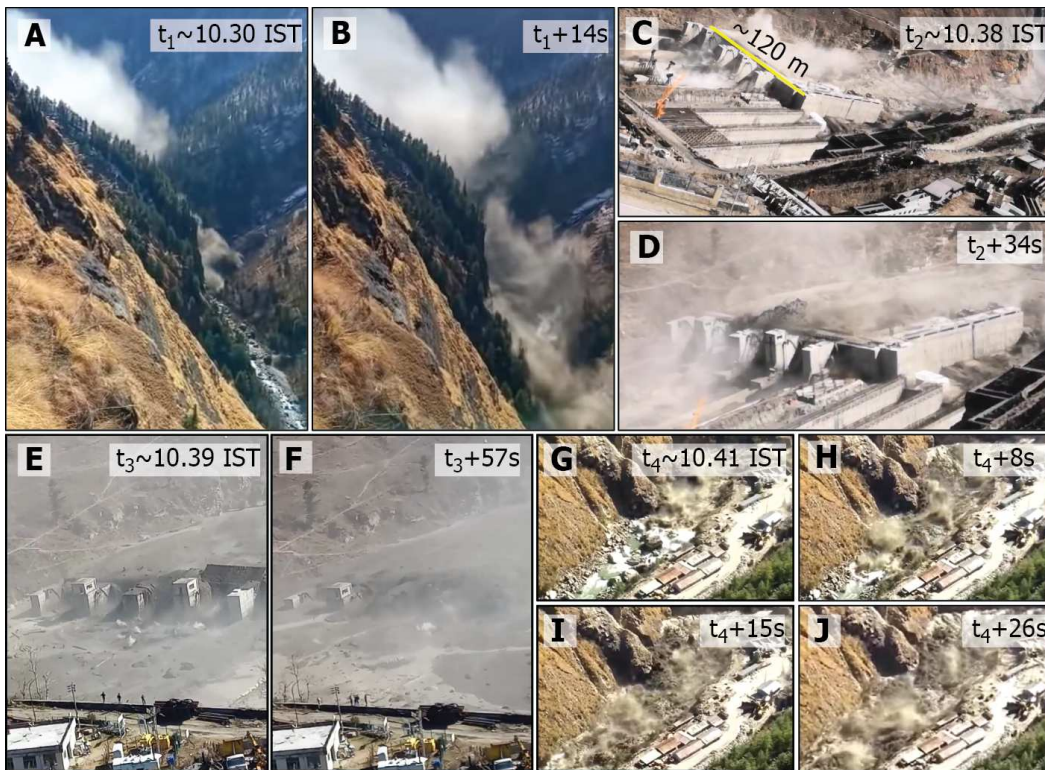
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226 A substantial fraction of the fine-grained material involved in the event was transported far
227 downstream. This more dilute flow could be considered a fifth component. Approximately 24
228 hours after the initial landslide, the sediment plume was visible in PlanetScope and Sentinel-2
229 imagery in the hydropower project's reservoir on the Alaknanda River at Srinagar, about 150
230 km downstream from the source. About 2½ weeks later, increased turbidity was observed at
231 Kanpur on the Ganges River, ~900 km from the source. An official of the Delhi water quality
232 board reported that 8 days after the Chamoli disaster, a chief water source for the city - a canal
233 drawing directly from the Ganga River - had an unprecedented spike in suspended sediment
234 (turbidity) 80 times the permissible level (32). The amount of corresponding sedimentation in

235 hydropower reservoirs and rivers is unknown, but possibly substantial, and may contribute to
236 increased erosion on turbine blades, and infilling of reservoirs in the years to come.

237

238 Analysis of eyewitness videos permitted estimation of the propagation of the flow front below
239 the Ronti Gad-Rishiganga River confluence (Fig. 3, 22, §5.3). The maximum frontal velocity
240 reconstructed from these videos is $\sim 25 \text{ m s}^{-1}$ near the Rishiganga hydropower project (fig.
241 S11, table S5), which is about 15 km downstream of the rock and ice avalanche source. Just
242 upstream of the Tapovan project (another $\sim 10 \text{ km}$ downriver), the velocity decreased to $\sim 16 \text{ m}$
243 s^{-1} , and just downstream of Tapovan (26 km from source), the velocity was $\sim 12 \text{ m s}^{-1}$. The
244 large reduction in frontal velocity is likely related to impoundment behind the Tapovan
245 project dam. Analysis of PlanetScope images (at 5:01 UTC and 5:28 UTC) suggests that the
246 average frontal velocity between Raini (at Rishiganga hydropower project) and Joshimath (16
247 km downstream) was $\sim 10 \text{ m s}^{-1}$. We also estimated mean discharge from the videos to be
248 between $\sim 8,200$ and $\sim 14,200 \text{ m}^3 \text{ s}^{-1}$ at the Rishiganga hydropower project and between $\sim 2,900$
249 and $\sim 4,900 \text{ m}^3 \text{ s}^{-1}$ downstream of the Tapovan project. Estimates for the debris flow duration
250 are complicated by uncertain volumes, water contents, discharge amounts, and shapes of
251 discharge curves at specific locations. For Rishiganga, for example, we estimate a duration
252 of 10-20 minutes, a number that appears realistic from the information available.

253



Parts a-b: Electricity Market in India: Dhauliganga 4*70 MW Cofferdam collapse in Uttarakhand Chamoli... Prayers for Uttarakhand, URL: <https://www.youtube.com/watch?v=96nopxNn-Qp4&t=1s>; accessed: 28th February 2021
Parts c-d: Kamlesh Maikhuri (<https://www.facebook.com/100005762340793/videos/1678161685719227/> (since removed)); Permission: verbal permission of the author given to Kavita Upadhyay
Parts e-f: Manvar Rawat (<https://www.facebook.com/100007108448247/videos/2796749477238640/>); Permission: verbal permission of the author given to Kavita Upadhyay
Parts g-j: RW • Rishikeshwritings: Uttarakhand Flood 2021|| Rishikesh , Srinagar , Devprayag , Haridwar, URL: <https://www.youtube.com/watch?v=QE0iPLq8gbY>; accessed: 28th February

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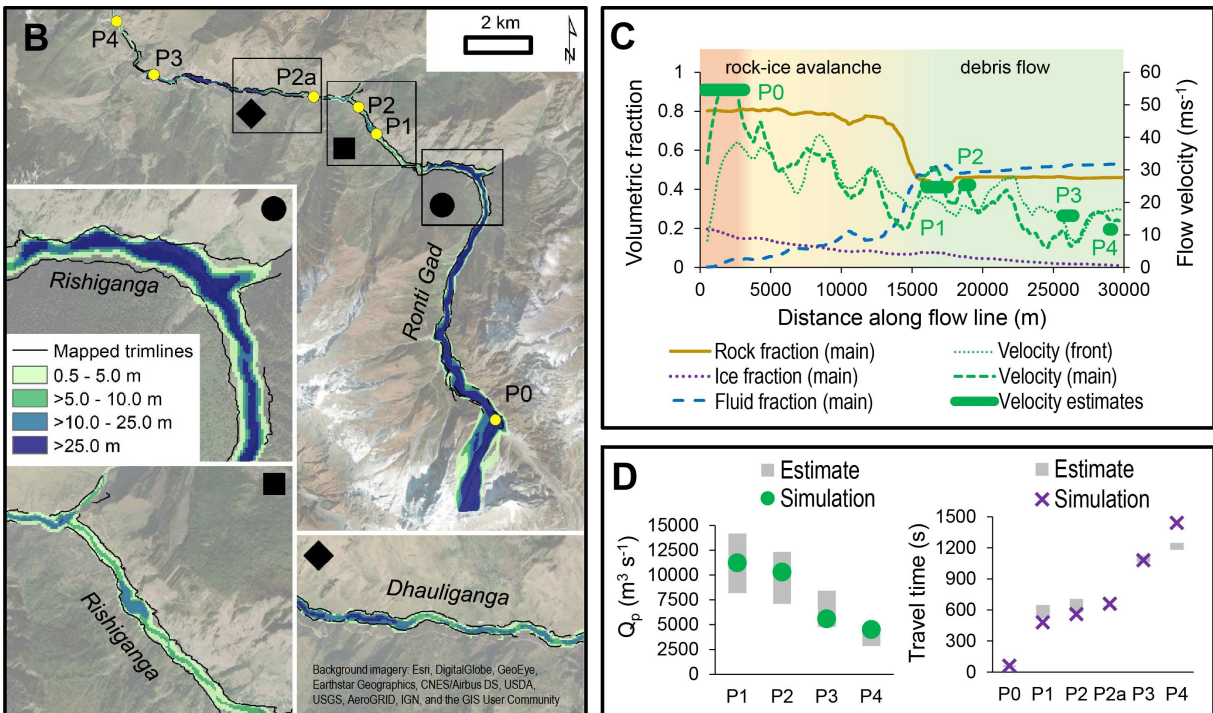
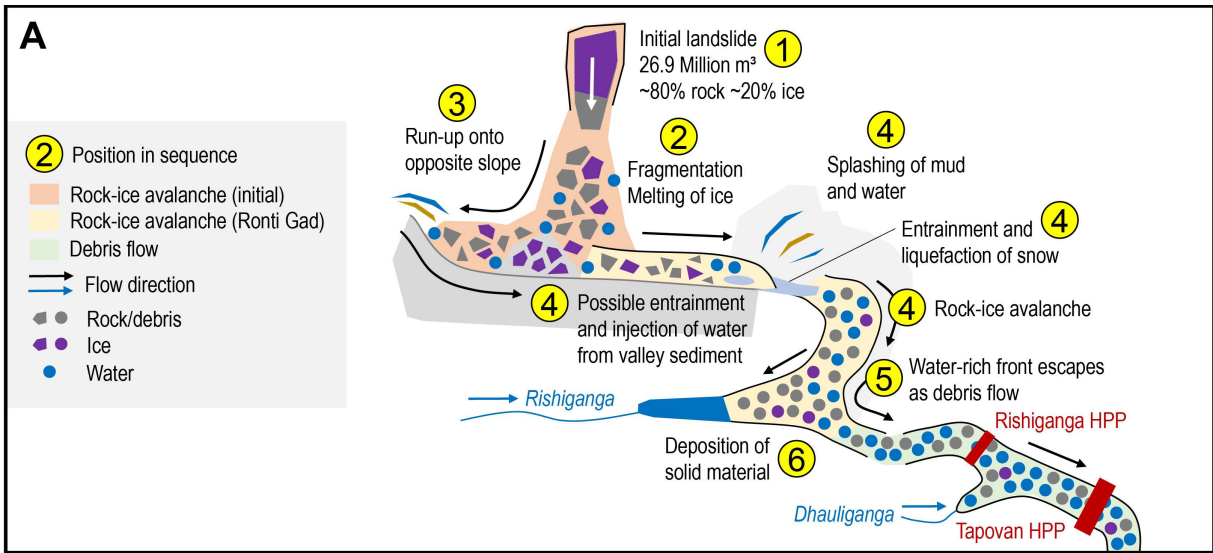
Fig. 3. Sample video frames used to analyse flood velocity and discharge. (A,B) Flow front arrives and rushes through the valley upstream of the Rishiganga project (location P1 in Fig. 4). **(C)** Flow front arrives at Tapovan project's dam (location P3). **(D)** The reservoir is being filled quickly; spillways are damaged. **(E)** The dam is overtopped. **(F)** Collapse of

259 remaining structures. (G-J) Flow front proceeds down the valley below the Tapovan dam
260 (location P4); spreading into the village in (J).

261

262 We conducted numerical simulations with r.avaflow (22, §5.4), which indicate that the rock
263 and ice avalanche could not have transitioned to the debris flow seen farther downstream
264 without an accompanying reduction in the debris volume. If such a direct transition had
265 occurred, the modeling suggests that the flow discharge would be approximately one order of
266 magnitude higher than the estimates derived from video recordings (22, §5.4). The deposition
267 patterns we observed in satellite imagery support the hypothesis that the vicinity of the Ronti
268 Gad-Rishiganga River confluence played a key role in flow transition. Our numerical
269 simulations are consistent with the escape of a fluid-rich front from the rock and ice avalanche
270 mass near this confluence (Fig. 4A), reproducing mapped trimlines and estimated flow
271 velocities and discharges down to Tapovan (Fig. 4B, C). Our simulated discharge estimates at
272 P1–P4 are within the ranges derived from the video analysis (Fig. 4D, 22, §5.3), and
273 simulated travel times between P0–P3 (Fig. 4D) show excellent agreement (<5% difference)
274 with travel times inferred from seismic data, videos, and satellite imagery. We found less
275 agreement between the numerical model results and the reconstructions from videos farther
276 downstream due to the complex effects of the Tapovan project in slowing the flow, which are
277 at a finer scale than is represented by our model.

278



279
 280 **Fig. 4. Flow evolution scenarios and simulation.** (A) Schematic of the evolution of the flow
 281 from the source to Tapovan. (B) Maximum flow height simulated with r.avaflow, showing the
 282 observed trim lines for comparison. P0 is the location of the velocity estimate derived from
 283 seismic data, P1-P4 are locations of velocity estimates based on videos and satellite images.
 284 (C) Along-profile evolution of flow velocity and fractions of rock/debris, ice, and water
 285 simulated with r.avaflow. (D) Simulated and estimated peak discharges and travel times at
 286 above locations. In the legend labels, (front) refers to the flow front whereas (main) refers to
 287 the point of maximum flow momentum.

288 **Causes and implications**

289 The February 7 rock and ice avalanche was a very large event with an extraordinarily high fall
290 height that resulted in a disaster due to its extreme mobility and the presence of downstream
291 infrastructure. The ~3700 m vertical drop to the Tapovan HPP is surpassed clearly by only
292 two known events in the historic record, namely the 1962 and 1970 Huascarán avalanches
293 (11), while its mobility ($H/L = 0.16$ at Tapovan, where H is fall height and L is flow length) is
294 exceeded only by a few recent glacier detachments (10). The location of the failure was due to
295 the extremely steep and high relief of Ronti Peak. The sheared nature of the source rocks and
296 contrasting interbedded rock types likely conditioned the failure (22, §1). The large and
297 expanding fracture (Fig 1B, C) at the head scarp may have allowed liquid water to penetrate
298 into the bedrock, increasing pore-water pressures or enhancing freeze-thaw weathering.

299
300 Nearly all (190) of the 204 people either killed or missing in the disaster (22, §2, Table S1)
301 were workers at the Rishiganga (13.2 MW) and Tapovan (520 MW) project sites (33). Direct
302 economic losses from damage to the two hydropower structures alone are over 223 million
303 USD (34, 35). The high loss of human life and infrastructure damage was due to the debris
304 flow, and not the initial rock and ice avalanche. However, not all large, high-mountain rock
305 and ice avalanches transform into highly mobile debris flows that cause destruction far from
306 their source (9).

307
308 Our energy balance estimates indicate that most of the $\sim 5\text{-}6 \times 10^6 \text{ m}^3$ volume of glacier ice first
309 warmed (along with a portion of the rock mass) from approximately -8°C to 0°C and then
310 melted through frictional heating during the avalanche as it descended to the Rishiganga
311 valley, involving a drop of approximately 3400 m (22, §5.5). Potential other sources of water
312 were considered, including glacier lake outburst floods, catastrophic drainage of water from
313 reservoirs such as surface lakes, ice deposited by earlier avalanches, and enlithic reservoirs.
314 No evidence for such sources was observed in available remote sensing data. A slow-moving
315 storm system moved through the area in the days before Feb 7. We estimate that a $\sim 220,000\text{--}$
316 $360,000 \text{ m}^3$ contribution from precipitation over the Ronti Gad basin was a minor component
317 of the flow, representing only 4-7% of the water equivalent contained in the initial glacier ice
318 detachment. Similarly, while water already present in the river, water ejected from
319 groundwater, melting snow, wet sediment, and water released from the run-of-the-river
320 hydroelectric project may have all contributed to the debris flow, even when taken together
321 (with generous error margins), these sum to a small amount compared to the probable range of
322 water volumes in the mass movement. The major effect of ice melt on the mobility of rock
323 and ice avalanches is documented (9, 10), but it appears that the combination of the specific
324 rock/ice fraction ($\sim 80/20\%$ by volume) and large fall height of the rock and ice avalanche led
325 to a rare, severe event during which nearly all of the ice melted.

326
327 Soon after the disaster, media reports and expert opinions started to circulate, postulating links
328 of the event to climate change. Recent attribution studies demonstrated that glacier mass
329 loss on global, regional and local scales is to a large extent attributable to anthropogenic
330 greenhouse gas forcing (36, 37). High-mountain slope failures in rock and ice, however,
331 pose additional challenges to attribution due to multiple factors and processes involved in
332 such events. While long-term trends of increasing slope failure occurrence in some regions

333 could be attributed to climate change (16, 38, 39), attribution of single events such as the
334 Chamoli event remains largely elusive. Nevertheless, certain elements of the Chamoli event
335 have potential links to climate, and weather, as described below. Furthermore, the Chamoli
336 event may be seen in the context of a change in geomorphological sensitivity (40) and
337 might therefore be seen as a precursor for an increase in such events as climate warming
338 proceeds.

339

340 The stability of glacierized and perennially frozen high-mountain slopes is indeed particularly
341 sensitive to climate change (16). Our analysis suggests regional climate and related
342 cryospheric change could have interacted in a complex way with the geologic and topographic
343 setting to produce this massive slope failure. Air and surface temperatures have been
344 increasing across the Himalayan region, with greater rates of warming during the second half
345 of the 20th Century and at higher elevations (41, 42). Most glaciers in the Himalaya are
346 shrinking and mass loss rates are accelerating across the region (22, §1, 43–46). Glacier
347 shrinkage uncovers and destabilizes mountain flanks and strongly alters the hydrological and
348 thermal regimes of the underlying rock.

349

350 The detachment zone at Ronti Peak is about 1 km higher than the regional lower limit of
351 permafrost at around 4,000 to 4,500 m asl., as indicated by rock glaciers in the region and
352 global permafrost maps (47, 48). Exposed rock on the north face of Ronti Peak likely contains
353 cold permafrost with rock temperatures several degrees below 0°C. In connection with
354 glaciers, however, ground temperatures can be locally higher. The ice-free south face of Ronti
355 Peak is certainly substantially warmer with rock temperatures perhaps around or above 0°C,
356 causing strong south-to-north lateral heat fluxes (49). Permafrost temperatures are increasing
357 worldwide, in particular in cold permafrost (16, 50, 51), leading to long-term and deep-seated
358 thermal anomalies, and even permafrost degradation (49). Increasing ground temperatures at
359 the failure site of the Chamoli avalanche could have resulted in reduced strength of the frozen
360 rock mass by altering the rock hydrology and the mechanical properties of discontinuities and
361 the failed rock mass (52).

362

363 The geology of the failed rocks includes several observed or inferred critical attributes (22,
364 §1): (i) The rocks are cut by multiple directions of planar weaknesses; the failed mass
365 detached along four of these. (ii) The rock mass is close to a major thrust fault, with many
366 local shear fractures, which - along with other discontinuities - would have facilitated aqueous
367 chemical weathering. (iii) The rock types (schist and gneiss), even when nominally
368 unweathered, contain abundant soft, platy, oriented, and geomechanically anisotropic minerals
369 (phyllosilicates and kyanite especially); Weathering will further weaken these rocks, and they
370 will be more likely to disintegrate into fine material upon impact, which would influence the
371 rheology and likely enhance the mobility of the mass flow.

372

373 Importantly, the 7 Feb failure considerably changed the stress regime and thermal conditions
374 in the area of the detachment zone. Only detailed investigations and monitoring will
375 determine whether rock or ice adjacent to the failed block (including a large hanging rock
376 block above the scarp) were destabilized due to these changes and present an ongoing hazard.
377 Similarly, the impoundment at the Ronti Gad-Rishiganga River confluence requires careful
378 monitoring as embedded ice in the dam deposits may melt with warmer temperatures,

379 increasing the risk of an outburst flood by reducing lake freeboard of the dam, and/or reducing
380 structural coherence of the dam.

381

382 Videos of the event, including the ones broadcast on social media in real time (22, §5.3),
383 showed that the people directly at risk had little to no warning. This leads us to question what
384 could have happened if a warning system had been installed. We estimate that a suitably
385 designed early warning system might have allowed for 6 to 10 minutes of warning before the
386 arrival of the debris flow at the Tapovan project (perhaps up to 20 minutes if situated near the
387 landslide source, or if a dense seismic network was leveraged (53)), which may have provided
388 enough time to evacuate at least some workers from the power project. After the event, a new
389 flood warning system was installed near Raini (22, §2.1, fig. S15D). Studies show that early
390 warning system design and installation is technically feasible but rapid communication of
391 reliable warnings and appropriate responses by individuals to alerts, are complex (54).
392 Previous research indicates that effective early warning requires public education, including
393 drills, which would increase awareness of potential hazards and improve ability to take action
394 when disaster strikes (55, 56). Considering the repeated failures from the same slope in the
395 past two decades (22, §1), public education and drills in the Chamoli region would be very
396 beneficial.

397 **Conclusions**

398 On the morning of 7 Feb 2021, a large rock and ice avalanche descended the Ronti Gad
399 valley, rapidly transforming into a highly mobile debris flow that destroyed two hydropower
400 plants and left more than 200 people dead or missing. We identified three primary drivers for
401 the severity of the Chamoli disaster: (1) the extraordinary fall height, providing ample
402 gravitational potential energy; (2) the worst-case rock:ice ratio, which resulted in almost
403 complete melting of the glacier ice, enhancing the mobility of the debris flow; and (3) the
404 unfortunate location of multiple hydropower plants in the direct path of the flow.

405 The debris flow disaster started as a wedge failure sourced in bedrock near the crest of Ronti
406 Peak, and included an overlying hanging glacier. The rock almost completely disintegrated in
407 the ~1 minute that the wedge took to fall (~5500 – 3,700 m asl), and the rock:ice ratio of the
408 detached mass was almost exactly the critical value required for near-complete melting of the
409 ice. As well as having a previous history of large mass movements, the mountain is riven with
410 planes and points of structural weakness, and further bedrock failures as well as large ice and
411 snow avalanches are inevitable.

412 Videos of the disaster were rapidly distributed through social media, attracting widespread
413 international media coverage and catalyzing an immediate response from the international
414 scientific community. This response effort quickly leveraged images from modern
415 commercial and civilian government satellite constellations that offer exceptional resolution,
416 "always-on" cadence, rapid tasking, and global coverage. This event demonstrated that if
417 appropriate human resources and technologies are in place, post-disaster analysis can be
418 reduced to days or hours. Nevertheless, ground-based evidence remains crucial for clarifying
419 the nature of such disasters.

420 Although we cannot attribute this individual disaster specifically to climate change, the
421 possibly increasing frequency of high-mountain slope instabilities can likely be related to
422 observed atmospheric warming and corresponding long-term changes in cryospheric
423 conditions (glaciers, permafrost). Multiple factors beyond those listed above contributed to the
424 Chamoli rock and ice avalanche, including the geologic structure and steep topography,
425 possible long-term thermal disturbances in permafrost bedrock induced by atmospheric
426 warming, stress changes due to the decline and collapse of adjacent and overlying glaciers,
427 and enhanced melt water infiltration during warm periods.

428 The Chamoli event also raises important questions about clean energy development, climate
429 change adaptation, disaster governance, conservation, environmental justice, and sustainable
430 development in the Himalaya and other high-mountain environments. This stresses the
431 importance of a better understanding of the cause and impact of mountain hazards, leading to
432 disasters. While the scientific aspects of this event are the focus of our study, we cannot
433 ignore the human suffering and emerging socio-economic impacts that it caused. It was the
434 human tragedy that motivated the authors to examine available data and explore how these
435 data, analyses, and interpretations can be used to help inform decision-making at the ground
436 level.

437 The disaster tragically revealed the risks associated with the rapid expansion of hydropower
438 infrastructure into increasingly unstable territory. Enhancing inclusive dialogues among
439 governments, local stakeholders and communities, private sector, and the scientific
440 community could help assess, minimize, and prepare for existing risks. The disaster indicates
441 that the long-term sustainability of planned hydroelectric power projects must account for
442 both current and future social and environmental conditions, while mitigating risks to
443 infrastructure, personnel, and downstream communities. Conservation values carry elevated
444 weight in development policies and infrastructure investments where the needs for social and
445 economic development interfere with areas prone to natural hazards, putting communities at
446 risk.

447

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898 HF, SG, UKH, CH, AKääb, JSK, JLK, PL, DP, SR, ME, DF, JN; **(2) Writing – review &**
899 **editing:** all authors; **(3) Methodology, Investigation, Formal analysis –** satellite-based
900 geomorphological mapping: DHS, WS, JLC, JJC, MD, SAD, UKH, CH, AKääb, SJC, FP,
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909 DHS.

910

911 **Competing interests:** Authors declare that they have no competing interests.

912

913 **Data availability:** We used publicly available data sources whenever possible. The
914 Sentinel-2 data are available from (57). PlanetScope satellite image data are available
915 through Planet’s Education and Research Program (58). Pre- and post-event very-high
916 resolution satellite images are available through Maxar’s Open Data Program (59), with
917 others available via the NGA NextView License. Airbus/CNES (Pléiades) images were
918 made publicly available through the International Charter: Space and Major Disasters. The
919 derived DEM Composite data are available from (60, 61). ERA5 data are available from
920 the Copernicus climate Data Store.

921

922 **Code availability:** The r.avaflow model is available at (62). The r.avaflow code used for
923 the simulation, the start script, and all of the input data are available at [[insert link when
924 available](#)] along with a brief tutorial on how to reproduce the results presented in the paper.

925

926 **Supplementary Materials**

927 Supplementary Text

928 Materials and Methods

929 Figs. S1 to S17

930 Tables S1 to S5

931 References (62-124)

932