Catastrophic ice-debris flow in the Rishiganga River, Chamoli, Uttarakhand (India)

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\textbf{ABSTRACT}
A catastrophic flood occurred on 7 February 2021 around 10:30 AM (local time) in the Rishiganga River, which has been attributed to a rockslide in the upper reach of the Raunthi River. The Resourcesat 2 LISS IV (8 February 2021) and CNES Airbus satellite imagery (9 February 2021) clearly show the location of displaced materials. The solar radiation observed was higher than normal by 10\% and 25\% on 6 and 7 February 2021, respectively, however, the temperature shows up to 34\% changes. These conditions are responsible for the sudden change in instability in glacier blocks causing deadly rock-ice slides that led to the collapse of the hanging glacier as a wedge failure. The displaced materials mixed with ice, snow, and debris caused catastrophic floods downstream within no time that destroyed critical infrastructure and killed human lives. The hydrodynamic modelling (HEC-RAS software) shows mean flow velocity up to $22.4 \pm 8.6$ m/s with an average depth of $16.3 \pm 6.5$ m that caused deadly devastation in the source region and along the rivers due to the flow of water in the valley.

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\textbf{Introduction}
The snow and glaciers in the high mountain areas are good indicators of climate change and global warming. The ground and satellite remote sensing data have shown retreat of glaciers and snow lines around the globe in the recent past (Das and Meher 2019; Ding...
et al. 2019; Kumar et al. 2020). The main cause of the retreat is due to growing anthropogenic and natural activities in the Indo-Gangetic plains (Singh and Chauhan 2022). A recent study has shown high variability in precipitation patterns and increased air temperature in the Rishiganga valley around Chamoli (Kumar et al. 2020). Further, the increasing temperature in the Himalayan region formed new glacial lakes due to thawing of permafrost that enhanced the frequency of snow avalanches that caused instability of slopes (Davies et al. 2001; Huggel et al. 2005; Murton et al. 2006; Gruber and Haeberli 2007; Krautblatter et al. 2013; Patton et al. 2019). The mechanical stability of perennially frozen rock blocks depends on the strength of the intact rock with ice-filled porosity, slope, the strength of the rock-ice interfaces in fractures, and ice fractures. These factors change the surface and subsurface temperature from $-5^\circ C$ and $0^\circ C$ (Davies et al. 2001; Krautblatter et al. 2013). The physical weathering and freezing-thawing cycle weaken the intact mechanical strength and cause frequent rockslides, landslides, and avalanches (Murton et al. 2006). Rock masses are exposed to high levels of rapidly varying stresses. These evolve due to elevated hydrostatic pressures in perched water above permafrost bodies and elevated cryostatic pressures deriving from ice segregation (Fischer et al. 2010). The mechanical behaviour, subsidence, and creep of ice-rich debris sites are controlled by the stress conditions (downhill forces and loading), proportional ice and debris (impurity) content, ice temperature, the water content in the ice, as well as water and heat supply to the ice body (Budd and Jacka 1989; Arenson and Springman 2005b; Arenson et al. 2016).

The Himalayan region is one of the highly seismically active regions, and in the past number of earthquakes have occurred in the Chamoli region (Uttarkashi) that have caused extensive damages, widespread landslides and snow avalanches (Sahoo et al. 2000; Nadim et al. 2006; Pradhan et al. 2006; Roback et al. 2018; Meena and Piraliou 2019; Braun et al. 2020).

Climate change in the high mountain areas plays an important role in the dynamics of the permafrost and slope instability. It is difficult to carry out ground measurements to understand the slope instability in the high mountain areas due to complex and rugged terrain. Although in view of the climate change, it is very important to monitor the snow/glaciers in the wake of a freezing-thawing cycle that is responsible for deformation of the surface and subsurface in the high mountain regions (Davies et al. 2001; Huggel 2009; Huggel et al. 2005). The presence of ice in the detachment zone of instabilities has been studied (Dramis et al. 1995; Gruber and Haeberli 2007). Relationship between permafrost dynamics and landslide events were found in some cases, deduced from a reconstructed thermal field (Davies et al. 2001; Gruber and Haeberli 2007; Kääb et al. 2005; Krautblatter et al. 2013). The detachment zone of rock-ice avalanches can be correlated with thermal disturbances caused by the thermal interaction of permafrost and glacial ice and climate change (Huggel 2009).

On 7 February 2021 a large rock block covered with snow/glaciers was suddenly dropped from about 5190 m (mean height) to the valley floor ($\sim3821$ m), causing floods in the rivers. About 204 people were killed or trapped in huge debris (Disaster Management Division Report, 17 March 2021, Rana et al. 2021). Soon after this deadly event, efforts were made by the Indian scientists to visit the site and made
helicopter survey (Pandey et al. 2021; Sain et al. 2021) to get overall information about the disaster.

Soon after the event, high resolution satellite data were analyzed to understand the triggering mechanism and also damage assessment (Kumar et al. 2021; Martha et al. 2021; Pandey et al. 2021; Rana et al. 2021; Shugar et al., 2021). Using time series satellite images, an overall downward sliding of the collapsed rock-ice body was found to be initiated around the summer of 2017 (Kothyari et al. 2021), and thereafter exhibited clear seasonality (mainly in summer). The analysis of meteorological parameters (surface temperature and rainfall) reveals a strong rainfall anomaly in the initiation period of the sliding and a remarkable winter warming anomaly in the 40 days before the collapse (Zhou et al. 2021). The preliminary analysis of the event indicates a combination of avalanches and debris flow; possibly due to climatic variability (Rana et al. 2021). Though, some studies, proposed that this was happened due to massive rockslide caused due to wedge-failure (Pandey et al. 2021), and seismicity (Cook et al. 2021; Meena et al. 2021a). The massive rock-ice avalanches caused due the extreme vertical height and transformed as a disastrous event (Shugar et al., 2021). This deadly rockslide triggered huge amount of water flow in the rivers that affected the flood plains along the rivers (Meena et al. 2021b, 2021c). The pre-and post-event satellite images were also used to establish relationship between erosion and deposition in the river valley and changes in the geomorphic characteristics (Jiang et al. 2021). Cook et al. (2021) discussed detection and potential of early warning of catastrophic flow events using regional seismic networks. They have demonstrated information received about the sequence of falling of rock bodies from the top of the mountain using seismic network deployed by the National Geophysical Research Institute, Hyderabad.

In the present study, our focus is to understand the triggering mechanism of flash floods due to the collapse of rock-ice blocks. A huge amount of water started flowing downstream that widened the valley floor, increased flood plains and caused the poor quality of water (Meena et al. 2021a, 2021b, 2021c). The sudden flow of huge volume of water flow at the event site after the fall of rock block covered with snow/glacier is still mystery. This event damaged two hydroelectric projects namely Rishiganga small hydro project and Hydro Power Project which was under construction by National Thermal Power Corporation (NTPC) at Tapovan, closed to Raini Village Bridge and many roads section (Disaster Management Division Report, March 17, 2021). We made efforts to understand the process of flooding in the lower basins. The main objectives of the present study are to (i) identify the failure of ice-debris avalanches, (ii) analyze glacier response concerning the wedge failure near the terminus of the Raunthi glacier, (iii) simulate the peak discharge using a 1D steady flow model of HEC-RAS, and (v) assess the flood-induced damage.

**Study area**

The study area covers latitude 30°16′14.14″ N to 30°32′8.86″ N and longitude 79°39′59.33″ E to 80°2′17.68″ E, located in the Rishiganga River basin of Chamoli District, Uttarakhand. Rishiganga River is a tributary of Dhauli ganga River,
confluences the Alaknanda River at Vishnu Prayag (Figure 1). The catastrophic flood event was originated in the Raunthi stream (Nala) near the terminus of the Raunthi glacier, which originates from the terminus of the Raunthi glacier and the Nanda Ghunti (Mountain) glacier at an elevation of ~4064 m (asl). The elevation ranges from 1908 m (asl) at the confluence of Rishiganga with Dhauliganga River to 7817 m (asl) at Nanda Devi peak. The mountain of the basin lies in the Great Himalayan range. The topography of the basin is highly precipitous, consists of several peaks, Nanda Devi (7817 m), Trishul (7045 m), Nanda Ghunti (6309 m), etc. The upper catchment area is characterized by snow-capped peaks and moraine deposits in the valleys. The lower area has a deep and traverse river valley occasionally marked as gorges. The Central Himalayan crystalline rocks (gneisses, migmatites, crystalline schist, thick quartzite with conspicuous horizons of calc-silicates psammite gneisses) and their upper parts are responsible for forming the bulk of the metasediments (Valdiya 2002).

Data used and methodology

**Meteorological data**

We have used daily meteorological data (air temperature and net solar radiation) from the European Centre for Medium-Range Weather Forecasts (ECMWF) and...
atmospheric reanalysis data of the global climate (ERA5) during 1991–2021 at 9:30 AM (local time) (Copernicus Climate Change Service 2017; Hersbach et al. 2020). We have also considered real-time meteorological data from the Automatic Weather Station (AWS) at Tapovan from 1 January to 10 February 2021 (IMD 2021).

**Satellite images and digital elevation data**

We have used Sentinel-2 data (31 January 2021, 5 and 10 February 2021) and Google Earth (GE) images for the pre-and post-event analysis. Table 1 shows details of the data used in the present study. The European Copernicus Sentinel-2A and 2B data were obtained from a Multi-Spectral Instrument (MSI) that scans the Earth’s objects at different spatial resolutions (Table 1). We have used 10 m spatial resolution band 8 b-NIR, band 4-Red, band 3-Green, and band 2-Blue. The Sentinel-2A and 2B images have been processed using Sentinel Application Platform (SNAP), a free, open-source platform jointly developed by Brock Mann Consult, Array Systems Computing C-S (SNAP; http://step.esa.int/main/toolboxes/snap/). The High Mountain Asia (HMA) 8 m digital elevation (DEM) was used for the topographic and hydrological analysis (https://nsidc.org/data/hma_dem8m_mos). The HMA8-meter DEM is generated using high-resolution optical imagery for the High Mountain Asia glacier and snow regions (Shean 2017).

**Discharge estimation and 1D hydrodynamic modelling**

The estimated discharge with debris at 89 m upstream of the Rishiganga dam has been performed with the water level marks on either bank of the Rishiganga River obtained from Sentinel-2 MSI image of 10 February 2021 and HMA DEM. The water level at this location is found to be 2007 m (asl) (Supplementary Figure 1). At this level, the computed channel area, wetted perimeter, and hydraulic radius ($r$) are 517.9 m$^2$, 66.3 m, and 7.8 m, respectively. The bed slope ($s$) at this section is 0.059 m/m. Manning’s equation (Equation 1) has been used to calculate velocity ($v$) in m/sec (Thakur et al. 2016).

\[
V = \frac{s^{0.5} \times r^{0.67}}{n}
\]

where 's' is bed slope in m/m, 'r' is a hydraulic radius in m, and 'n' is the Manning’s roughness coefficient of the channel (0.04). Thakur et al. (2016) have considered a value of 0.04 as Manning’s roughness coefficient for the Dhauliganga River channel by considering the factors such as boulders in the river channel and large debris flow in the event of glacial lake outburst floods.

Velocity is estimated using Equation (1) to be 24.04 m/sec, and the estimated discharge with the debris is found to be 12,448 m$^3$/sec. We have also carried out 1D steady flow modelling using HEC-RAS (ver. 5.0.4) and geometry files created by the HEC-geoRAS tool in ArcGIS (ver. 10.2.2). The energy and momentum 1D steady flow modelling was carried out using HEC-RAS (HEC-RAS 5.0 hydraulic reference manual) (Brunner 2016). The computation of 1D steady flow water surface profiles from upstream to downstream cross-section for a mixed flow regime and rapidly
| Types of data       | Satellite sensor/agency                  | Description                                                                 | Date       | Source                                                                 |
|--------------------|------------------------------------------|-----------------------------------------------------------------------------|------------|------------------------------------------------------------------------|
| Satellite images   | Sentinel 2B                              | Optical satellite images of 10 m resolution.                                | 31-01-2021 | https://earthexplorer.usgs.gov/.                                        |
|                    | Sentinel 2 A                             | Optical satellite images of 10 m resolution.                                | 05-02-2021 |                                                                        |
|                    | Sentinel 2B                              | Optical satellite images of 10 m resolution.                                | 10-02-2021 |                                                                        |
|                    | Digital elevation model                  | NASA National Snow and Ice Data Center                                      | 16-07-2017 | Shean, D. 2017. High Mountain Asia 8-meter DEM Mosaics Derived from Optical Imagery, Version 1.[HMA_DEM8m_MOS_20170716_tile-571]. Boulder, Colorado, USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. https://doi.org/10.5067/KXOVQ9L172S2. [Feb 08, 2021]. |
|                    | ERAS (Fifth generation of ECMWF atmospheric reanalyses of the global climate) | European Centre for Medium-Range Weather Forecasts (ECMWF)                 | 1991–2021 (Jan. 1 to Feb. 10) | https://cds.climate.copernicus.eu/cdsapp#!/home.                         |
| Meteorological Data| Automatic Weather Station                | Daily minimum and maximum temperature, rainfall and wind data               | 01-01-2021 to 10-02-2021 | India Meteorological Department, Pune                                   |
variable water surface profile is carried out solving energy equation with an iterative process (Brunner 2016).

All the geometrical parameters such as channel central line, bank lines, XS cut-lines, and flow paths have been prepared using Sentinel-2 MSI image (5 February 2021) and the RAS geometry tool of ArcGIS. Generalized land use and land cover (LULC) has also been prepared using Sentinel-2 MSI image (5 February 2021) in ArcGIS through visual interpretation. Later, the LULC-based Manning’s n-values on each XS cutline were defined using RAS geometry (Table 2). The river and XS cut-lines have been converted into 3D using HMA DEM. Subsequently, all these geometry files have been exported to HEC-RAS (ver.5.0.4) for 1D steady flow modelling. The estimated discharge values have been incorporated at the first cross-section of the Rishiganga River (Station ID-1622.411), which is 89 m upstream of the Rishiganga Dam. Normal depth, i.e. an average slope of 0.0512 m/m (meter/meter), has been considered to define the steady flow boundary conditions. Flow regimes available for steady flow analysis in HEC-RAS are subcritical, supercritical, and mixed. HMA DEM and visual inspection of GE images reveals that the riffle-pool sequences are the major geomorphic features in the Rishiganga channel. Therefore, a mixed flow regime has been utilized to simulate steady flow along the Rishiganga channel. Subsequently, water surfaces and their extents and river geometry and velocity profile are exported in GIS format for the extent of flooded areas, flood depth (m), and velocity (m/sec) mapping using HMA DEM and RAS mapping tool of HEC-geoRAS of ArcGIS.

### Results

**Probable causes of rockslide**

The slope instabilities in the higher Himalaya are directly related to topography, lithology, load on the rock slab, temperature variations, porosity, and permeability of the rock slabs. The changes in instability are associated with the changes in freezing and thawing of glaciers and rock blocks. The dislocation process was principally associated with the temperature change, bedrock-ice contact, and slope topography. The frost shattering process mechanically disintegrates rocks; intensifies the destabilization of bedrock-ice detachment. The water-ice-filled into cracks increase shear stress on high inclined slopes and, in turn, trigger rock-ice failure. The temperature dynamics at the site significantly indicate the increasing magnitude of rock-ice failures, the shear mechanism of bedrock-ice contact, and frictional resistance. The detachment of bedrock is controlled by two critical processes time-dependent weathering, tensile

| LULC class    | n-values |
|---------------|----------|
| Arable Land   | 0.035    |
| Forest        | 0.1      |
| River         | 0.04     |
| Rocky Area    | 0.045    |
| Settlement    | 0.4      |
| Scrub Land    | 0.03     |

Source: Thakur et al. (2016) and Chow (1959).
strength, and frictional resistance. The freezing-thawing processes mechanically increase the shear stress of the intact bedrock, rock-ice contact. The rockslide and detachment of hanging glacier in the terminus area of Raunthi Nala is coupled with topography and climatic variability. Approximately 17% of annual precipitation is received in the region during the winter months (IMD 2021). The Rishiganga basin received significantly less snowfall during the 2021 winter months (December-February). The mean temperature in the valley was the highest in the last 58 years (IMD 2021).

Figure 2. Analysis of ERA 5 dataset for the study area; (a) air temperature (°C) and its departure from normal (in %) around rock-ice slide zone for the months of January-February, 2021 and the corresponding normal ambient air temperature of past 30 years (b) surface net solar radiation (J m⁻²) and its departure from normal (%) around rock-ice slide zone of the Nanda Ghunti glaciers for the months of January-February, 2021 and the corresponding net surface radiation of past 30 years.
The analysis of meteorological data of ERA 5 indicates that the air temperature was above normal from 1 January to 7 February 2021. The total number of days above normal temperature was 32 out of 41. In other words, 78% of days were above normal temperature from 1 January to 7 February 2021. It can be inferred that the winter season was warm in and around the rock-ice slide zone (Figure 2a). The departure of ambient air temperature from the normal on 7 February 2021 was 34%. However, it was −11% (below normal) on 6 February 2021 at 9:30 AM (local time) (Figure 2b).

The number of days above normal surface net solar radiation were 23 out of 41 days during 1 January – 7 February 2021. About 56% of days show above normal surface net solar radiation and a warm winter season in and around the rock-ice slide zone. The departure of surface net solar radiation from the normal on 7 February 2021 was 25%. However, it was 10% on 6 February 2021 at 9:30 AM (local time), a sharp increase in surface net solar radiation occurred.

Figure 3 shows a sharp increase in the air temperature and surface net solar radiation on 7 February 2021 that must have played a key role in triggering rockslide from the Nanda Ghunti Glacier. The air temperature at Tapovan and around the rock-ice slide areas shows a significant rise in temperature trend on 7 February 2021 (Figure 3). The nearest meteorological surface observatory at Tapovan shows a mean temperature of around 8.66 °C during 1 January – 5 February 2021 (Figure 4a). However, a maximum in temperature was observed as 16.5 °C while the minimum was 2.9 °C and the wind velocity was also lower on 2 February 2021 (Figure 4b). The maximum temperature suddenly dropped to 9.3 °C and the minimum at 0.1 °C on 5 February 2021. The high variability of temperature affected the freeze and thaw processes that changed the surface and subsurface characteristics of the thick snow and glaciers, affecting the incumbent load on the bedrock of the steep slope (mean slope 57.8%), causing the instability of the shattered bedrock covered with thick ice/snow.

Analysis of satellite images

The GE images of 10 August 2017 clearly show an enlarged scar at the hanging glacier headwall and sides, determining the wedge failure’s detachment limit (Figure 5a). The Resourcesat 2 LISS IV image of 8 February 2021 (available through the National Remote Sensing Center -NRSC) also clearly shows the rockslide (Figure 5b). There
was no precipitation during 8 January to 2 February 2021. However, 2.5- and 6-mm rainfall was observed at lower elevations and snowfall at higher elevations from 3 to 5 February 2021 (Figure 4a). This fresh snowfall at higher elevation enhanced the load on the hanging glacier located at a steep slope that caused a massive rockslide which is clearly seen from Resources at 2 LISS IV satellite image of 8 February 2021 on CNES AIRBUS image of 9 February 2021 (Figure 5c).

Figure 4. Meteorological observation at Tapovan by Indian Meteorological Department (AWS-Surface Observatory); (a) temperature and rainfall data of 1 January to 10 February 2021, and (b) wind speed km/hr.
The presence of a wedge on the glacier headwall was another reason for the detachment (Figure 6a). The slope’s base elevation is 4696 m (asl), and the upper surface elevation is 5542 m, with a mean slope inclination of $\sim 62^\circ$ (Figure 6b). The pre-event Sentinel –2 image of 31 January 2021 clearly shows the enlarged scar on the sides of

Figure 5. (a) Terminus zone of the Raunthi and Nanda Ghunti glaciers, and characterization of rock slide with avalanche site, movement direction, and deposition of materials. The presence of wedge on the hanging glacier headwall is visible on the Google Earth image dated 10 August 2017. (b) Post-event Resourcesat 2 LISS IV images of 8 February 2021 analyzed by NRSC showing rockslide/ice avalanche location; and (c) Post-event CNES AIRBUS image of 9 February 2021 of the site.

The presence of a wedge on the glacier headwall was another reason for the detachment (Figure 6a). The slope’s base elevation is 4696 m (asl), and the upper surface elevation is 5542 m, with a mean slope inclination of $\sim 62^\circ$ (Figure 6b). The pre-event Sentinel –2 image of 31 January 2021 clearly shows the enlarged scar on the sides of
pierced surface (Figure 6c). The maximum width of the rockslide surface is about 755 m, with a length of 1181.2 m covering an area of 0.51 km². The displaced materials consist of debris, ice, and snow moved downslope in the valley of Raunthi Nala (Figure 6d). This massive debris with ice and snow almost fell to ~1369 m in the valley (3821 m) from the detached surface, having a mean elevation of 4814 m. The fresh snow melts rapidly due to increased temperature on February 6–7, 2021, and the increased load due to large mass and flow was enhanced due to the steep V-shaped valley. The detached materials are likely to have a large amount of kinetic energy and shock waves that would have accelerated the melting rate. This needs to be verified through numerical calculations. However, it was also observed that marks of dust particles on the side slope and debris plume during the event indicated that it initially moves in the valley as debris flow with the least amount of water. Further, down the valley, the movement of materials increases the melting rate, substantially adding the volume of water. However, this debris flow reached the lower Rishiganga basin adding the live storage of Rishiganga HEP, and a catastrophic flood occurred downstream of Rishiganga and Dhauliganga Rivers that changed the water quality (Meena et al. 2021a, 2021b, 2021c).

**Catastrophic floods with debris**

The catastrophic flooding in the lower Rishiganga valley marked a high stage flow with massive debris, fine to coarse sand, boulders, and ice. The flooding has devastated...
critical infrastructures, including hydroelectric projects, bridges, tunnels, and roads. The flood scenario is modelled using a 1D steady flow model of HEC-RAS software. The geometry of the Rishiganga River was created using HMA DEM. Land use map designed to assign manning’s value on the river cross-sections (Table 2).

The extent of the flooded area has been converted into a KML file and draped over the GE image of 10 February 2021 for validation purposes. Our results show that the estimated water level at the crest of the Rishiganga dam and the mid-point of the bridge is 1.89 m and 1.33 m, respectively. A sum of 16 water surface extent has been visually identified on the shadow-free areas of the GE image of 10 February 2021, and its locations have been marked on the corresponding HEC-RAS cross-sections (Supplementary Figure 2). Later, the visually interpreted water surface extent from GE (actual water level) has been compared with the water surface extent simulated by HEC-RAS (simulated water level). The coefficient of determination \( R^2 \) between actual and simulated water levels (m asl) is 0.99. The mean absolute error (MAE) and root mean square error (RMSE) between these two water levels is 6.4 and 7.7 m, respectively (Figure 7). The simulated flood was plotted on each cross-section (Figure 8). The rating curves at each cross-section show a significant association with simulated flood level and discharge (Figure 9). The field data collected from the Rishiganga and Dhauliganga confluence area near the bridge (Rishiganga River) also shows comparable water depth. Due to the massive sediment load and steep channel slope, the valley floor of the Rishiganga River was highly affected. The visual inspection of the GE image and estimated flood extent shows that the Rishiganga hydroelectricity project dam and a bridge near Raini village have been washed away due to unprecedented high-water levels in the Rishiganga River (Figure 10a). A road along the left bank of the Rishiganga River connecting the Rishiganga dam with Raini village has also been washed away at many places (Figure 10b). Damage to the dam, bridge, and road also validates our modelled flood extent and depth.

The total inundated area along the Rishiganga River covers 0.123 km\(^2\) of the overall area, while the areal coverage of the pre-event river channel is at 0.058 km\(^2\). Thus, the actual flooded area covers only 0.07 km\(^2\). The flooded arable land, scrubland, and settlement are covering 0.023, 0.017, and 0.002 km\(^2\), respectively. The settlement area near the Rishiganga dam and bridge has been completely swept away by the floods. The mean modelled depth of debris mixed with water is 16.3 ± 6.5 m, while the mean modelled velocity of debris along the channel is 22.4 ± 8.6 m/sec. The width of the
The debris flow area varies from 52.6 to 166.1 m, with a mean width of 83.5 ± 28.1 m. The total washed-away road length downstream of the Rishiganga dam is 841.7 m, including a bridge length of 62 m.

**Discussion**

The Himalaya and the other mountainous regions suffer from similar devastating flood incidents due to debris, ice, or moraine-dammed lake outbursts. The cryosphere suffers from anomalous environmental changes causing surface and subsurface deformation that leads to the instability of mountain areas at local and regional scales depending upon the subsurface configuration and geological formation. The environmental stability due to the climatic variability severely affects the physical characteristics of bedrock in the higher mountainous regions causing potential risk in the region (Davies et al. 2001; Murton et al. 2006; Gruber and Haeberli 2007; Huggel 2009; Allen et al. 2011; Amitrano et al. 2012; Krautblatter et al. 2013; Davies and McColl 2013; Singh et al. 2018; Patton et al. 2019). The substantial increase in temperature in the high-altitude regions accelerates glacier melting and permafrost degradation. The ice contact of bedrock increases the freezing-thawing-freezing cycle, resulting in slacking and shattering due to load variability and rock slope instability (Murton et al. 2006; Patton et al. 2019). The steep slope instabilities influenced by glacier-permafrost linkage processes, detachment of glacier mass, and associated ice avalanches are common in the hanging glaciers with steep headwalls (Leinss et al. 2021). However, topography and climatic conditions also play a significant role.

The presence of rock glaciers around the event location was observed from images available in GE showing permafrost regimes in the region (Pandey 2019). The permafrost process in the terminus zone of the Raunthi glacier increased rock slope instability. Rockslide, rock, and snow avalanches are widespread along the valley. The visual inspection of the GE image indicates that the lateral support of the hanging glacier was removed after the 2013 rockslide incident. The signature of deposited debris flow area varies from 52.6 to 166.1 m, with a mean width of 83.5 ± 28.1 m. The total washed-away road length downstream of the Rishiganga dam is 841.7 m, including a bridge length of 62 m.

![Figure 8](image-url). 1D hydrodynamic modelling of catastrophic debris mixed with water events that occurred in the Rishiganga River (1.6 km upstream of its confluence with the Dhauliganga River) using HEC RAS. The black line with filled black dots shows the Rishiganga River's longitudinal profile while the blue line shows depth of water mixed with debris.
Figure 9. Rating curve of the Rishiganga River at upstream of the Rishiganga dam site.

Figure 10. Inundated area (light blue with red border) from Rishiganga Dam to Raini village has been shown on pre-event (a) and post-event(b) Google Earth images. (c) Field photograph pre-event year 2019 and (d) post-event March 2021.
debris is visible in 2017 GE images (Figure 6d). The influence of shattering processes can be seen as fractures, cracks, and joints on the bedrock (Figure 5a). We have also established proxy evidence of climatic variability in the terminus zone of the glacier. The snout of the Raunthi glacier retreated 451.5 m ± 20 m from 1985 to 2021, with an average of 11.2 m per year. However, the retreat rate between 2017 and 2021 was exceptionally higher (36.3 m per year).

The post-event satellite image of the displaced location clearly shows an excavated area deeper to the hanging glacier-bedrock contact. Therefore, this rockslide led to the collapse of the hanging glacier (Pandey et al. 2021; Kropáček et al. 2021; Qi et al. 2021). The presence of a wedge on the glacier’s headwall is visible in the GE image of 2017 and Sentinel-2 image of 31 January 2021. The scar was also enlarged in the pre-event image. The steeply inclined slope surfaces on the east and west side and the basal shear plane might have caused rockslide. The bedrock-ice block (the wedge-shaped visible from its scar) fell vertically on the valley floor (Sain et al. 2021).

The loose material, including debris, ice, and snow, almost vertically fall on the valley floor and moved downstream (Huggel et al. 2005; Evans and Delaney 2015). The accelerated melting due to temperature and kinetic energy (Meena et al. 2021a, 2021b, 2021c) would have increased the water volume and velocity downstream. The impact of enormous mass has also generated shock waves as recorded by the seismological stations (Pandey et al. 2021), which further helped mobilize snow and boulders. This has caused a catastrophic flood in the lower Rishiganga and Dhauliganga River valleys.

The channel slope of the Raunthi Nala is very high (mean slope 20.5%). Therefore, massive debris was brought downstream under the influence of gravity. The channel makes confluence with the Rishiganga River almost at the right angle. The considerable debris with water brought down under the force of gravity completely blocked the course of Rishiganga by dumping ~40 to 45 m high debris in its course. Hence, the contribution of the Rishiganga River was nil in flood flow. Therefore, we did not consider the contribution of the Rishiganga River in the 1D hydrodynamic modelling. The velocity of the detached mass flow (i.e. rock mixed with ice and snow) was calculated to be 24.04 m/s, which is close to the velocity estimate of 27.59 m/s and 20 m/s, respectively by Kropáček et al. (2021) and Jiang et al. (2021). We have estimated peak discharge with the debris is about 12,448 m³/sec while 7500 m³/sec and 28,000 m³/sec discharge values were computed respectively by Pandey et al. (2021) and Jiang et al. (2021). We claim that our velocity and discharge estimates are reliable compared to other reported values since some of the input values are from taken from India Meteorological Department, although it is difficult due to non-availability of data from such a complex and difficult areas. It was also noted that debris fume rose in the valley like dust storms, and their marks are visible at the higher elevations. Due to high-velocity flow and resultant slope failure, the debris fumes may result in lateral erosion on the sides. The dust marks were present on the side slopes, visible in the valley during the event (Meena et al. 2021a).

The Rishiganga hydroelectric project shows a 1.89 m height of floodwater mixed with debris above its crest, which was validated with the technical details of this hydroelectric project. It shows an agreement with the modelled result. Further, the
bridge (downstream) at Raini village was thoroughly washed away and damaged two abandoned houses (Figure 11a). The flood marks are visible on the valley sides, and a massive amount of deposited debris near confluence of the Rishiganga and Dhauliganga River is also observed (Figure 11b).

Conclusions

The catastrophic debris flow in the Raunthi and Rishiganga Rivers originated due to the rockslide that led to the collapse of a hanging glacier. Our results clearly show temperature variability in the surroundings of pierced surface gave rise to the freeze-thaw-freeze of the permafrost processes that might have enhanced the melting of ice/snow and triggered the rock-ice slide. Frost shattering increased shear stress due to water-ice filled into cracks and, in turn, rock-ice detached. The temperature dynamics of the study area show an increasing trend that validated the active permafrost processes; enhanced mechanical disintegration of bedrock. The present study investigated the principal cause of the rock-ice collapse rather than other contemporary studies on the event. The increased load may have percolated melting of water that may have enhanced fracture density, increasing permeability in the bedrock. Such conditions must have destabilized the slope and created favourable conditions for the rockslide. The satellite images clearly show the scar of the rockslide on the glacier headwall, and sides were noted on the GE images of 2017 and pre-event Sentinel 2 images. Initially, it was like a crevasse; but significantly enlarged. The images also indicate shattering and discontinuity in the bedrock. The failure appears as a wedge failure in bedrock on which their thick glacier ice and fresh snow displaced along with a hanging glacier. The displaced area is pierced with displacement and almost fell on the valley floor. The displaced materials consist of debris, ice and snow moved downslope under the influence of gravity causing unprecedented debris flow in the Raunthi Nalla, causing catastrophic floods affecting the water quality and flood plains downstream of Himalayan rivers (Meena et al. 2021a, 2021b). The Rishiganga hydroelectric project shows a 1.89 m height of floodwater mixed with debris above its crest, which
was validated with the technical details of this hydroelectric project. It shows an agreement with the modelled result.

This study suggests that there could be many more equally or even more significant similar incidences looking into the increasing temperature in the valley as well as the location being vulnerable to the seismic influences that may trigger the incidences in the future. A risk assessment pre-feasibility study and distinction of the weak zones in the region would be a wise step before planning any critical infrastructures downstream. The deadly Chamoli event which took lives of 200 people and damaging infrastructure is an eye opening especially in the Himalayan region which is highly sensitive to the climate change in the time to come. We need to deploy network of automatic weather station and differential global positioning system to estimate the surface manifestations, snow characterizations and glaciers melting.

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Data availability statement

The data used in the present study is available freely through the website, and the details of the sources are given in Table 1. The meteorological data (daily temperature, rainfall, and wind) for the period of 01-01-2021 to 10-02-2021 have been provided by one of the authors (VKS) from India Meteorological Department, New Delhi.
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