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A preliminary assessment of the 7th February 2021 flashflood in lower Dhauli Ganga valley, Central Himalaya, India

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A short-lived flashflood in Rishi and Dhauli Ganga rivers on 7th February 2021, Uttarakhand Himalaya, killed 65 people with 141 reported missing (official estimate) and devastated two hydropower projects. Geomorphological observations supported by meteorological data suggest that the flood was triggered by a combination of avalanche and debris flow. The Dhauli Ganga valley has preserved ponded sedimentary sequences (laminated sand and silty-clay), suggesting that the valley is prone to episodic mega foods in the recent geological past. Considering that the receding glaciers in the higher Himalaya have left behind enormous sediment, unusual weather events are likely to generate such disasters more frequently as the climate becomes warmer. Thus, the study calls for not only incorporating the disaster risk assessment in the developmental planning of the Himalayan region but also recommends routine monitoring of the potential areas of structural failures in the glaciated valleys along with supra-glacial lakes.

Keywords. Flash-flood; Dhauli Ganga; Rishi Ganga; Garhwal Himalaya.

1. Introduction

The retreating glaciers of the Hindu Kush Himalayan (HKH) region are geomorphic expression of the current climate warming (Armstrong 2010). Also, there are growing number of proglacial and supra-glacial lakes which have the potential to generate high magnitude floods. However, the impact of a flood would depend on the physical characteristics of the moraine dam, the lake size and the stream gradient (Ives *et al.* 1986; 2010). Since the lakes are formed at higher elevations, the downstream impact is going to be severe due to extremely rapid debris flows. The breaching and associated flashfloods are called Glacial Lake Outburst Floods (GLOFs). It is being observed that glacial hazards (e.g., GLOFs, ice avalanches, and debris flows) caused due to accelerated glacial thinning and retreat are causing severe damage in populated HKH regions (Ives *et al.* 2010). There is a growing concern that with the rise in global temperature, their frequency and magnitude would

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increase thus, posing a serious threat to both life and infrastructure in the lower reaches (Armstrong 2010). In 2004–05, the Wadia Institute of Himalayan Geology, Dehra Dun with ICIMOD, Nepal published a preliminary inventory of glacial lakes in the Uttarakhand Himalaya (Sah *et al.* 2005). The study identified 127 glacial lakes with a total area of approximately 2.5 km^2, where none were identified as potentially dangerous (Sah *et al.* 2005). Similarly, Geological Survey of India identified 13 vulnerable lakes out of 486 in the Uttarakhand Himalaya (The Hindu news, 2021). More recently, based on high-resolution LISS-IV multispectral data, Govindha Raj and Kumar (2016) identified 362 glacial lakes in the Uttarakhand Himalaya. According to them, the number of proglacial lakes shows a growing trend with eight glacial lakes identified as critical (having outburst potential).

GLOFs occur when large volumes of water built-up behind a terminal moraine due to rapid melting of a retreating glacier breach as the moraine dam fails. It is observed that GLOFs have become more frequent during the second half of 20th century, and are going to increase both in frequency and size (Armstrong 2010). Floods may also be associated with advancing glaciers, as a tributary river is temporarily obstructed by the glacier tongue which subsequently retreats or breaks up. These floods are called 'jökulhlaups' (*sensu*: Ives 1986) which are typically short-lived and unstable compared to the ice-dammed lakes (Hewitt 1982, 2005). The debris flow/landslide dammed outburst floods are reported from paraglacial zones of the Indus (Juyal 2010), Satluj (Parchu) (Randhawa *et al.* 2005), and more recently the Mandakini valleys (Sundriyal *et al.* 2015). These floods are termed as the Landslide Lake Outburst Floods (LLOFs).

The 7th February, 2021 Rishi–Dhauli Ganga flashflood originated from a small tributary stream – Raunthi Gad (figure 1). This stream originates from Raunthi and Nanda Ghunti glaciers located in the lower reaches of Nanda Devi National Park (a world heritage site). In order to assess the causes and magnitude of sediment mobilization from the paraglacial zone, our team reached the confluence of Raunthi Gad and Rishi Ganga (figure 1). Based on field observations supported by satellite data (Google Earth imagery), an attempt has been made to understand the processes responsible for triggering the flood. Additionally, sedimentological archives of past river impounding in the Dhauli Ganga valley were also investigated to assess the vulnerability of Dhauli Ganga towards flashfloods in the recent geological past.

2. Study area

2.1 *The Rishi Ganga valley*

The Rishi Ganga catchment ($\sim$690 km^2) has one of the highest snow-clad peaks and relatively high concentration of glaciers compared to other valleys in the Uttarakhand Himalaya. It supports diverse bio-habitats in their near-pristine state including some endangered and rare species (Sathyakumar 2003). Surrounded by eight significant peaks rising above 6 km, Nanda Devi is the second highest peak in India ($\sim$7816 m) located in the E–W trending Rishi Ganga valley (figure 1). The valley besides supporting around seven major glaciers, also has few hanging glaciers (figure 1). The hanging glaciers are also called the avalanching glacier (Pralong and Funk 2006) because they are located on a sufficiently steep slope to allow detachment of ice chunks (calving) from the glacier terminus (Margreth *et al.* 2017). Such avalanches at times can generate high-magnitude floods by impounding the glacial streams (Armstrong 2010).

The Rishi Ganga river and its tributaries traverse dominantly through the higher Himalayan crystalline before it meets Dhauli Ganga near the Reni village (figures 1 and 2). The South Tibetan Detachment (STD) passes proximal to the Nanda Devi peak. Between the Main Central Thrust (MCT) and the STD, the lithology is dominated by gneisses, schist, followed by kyanite, biotite, muscovite schist intruded by leucogranite (Mukherjee *et al.* 2019; figure 2). The topography is rugged due to an abrupt rise in elevation from 2000 to >7000 m in a small catchment area of $\sim$690 km^2 (figure 1). The Indian Summer Monsoon (ISM) is the major source of precipitation ($\sim$80%) which dominates the river hydrology with contribution from glacial melt.

3. Methodology

The geomorphological map of the Rishi Ganga valley (figure 1) is prepared after modifying the Bhukosh (GSI 2021) digital data and Google Earth imagery. The landforms in the Raunthi Gad

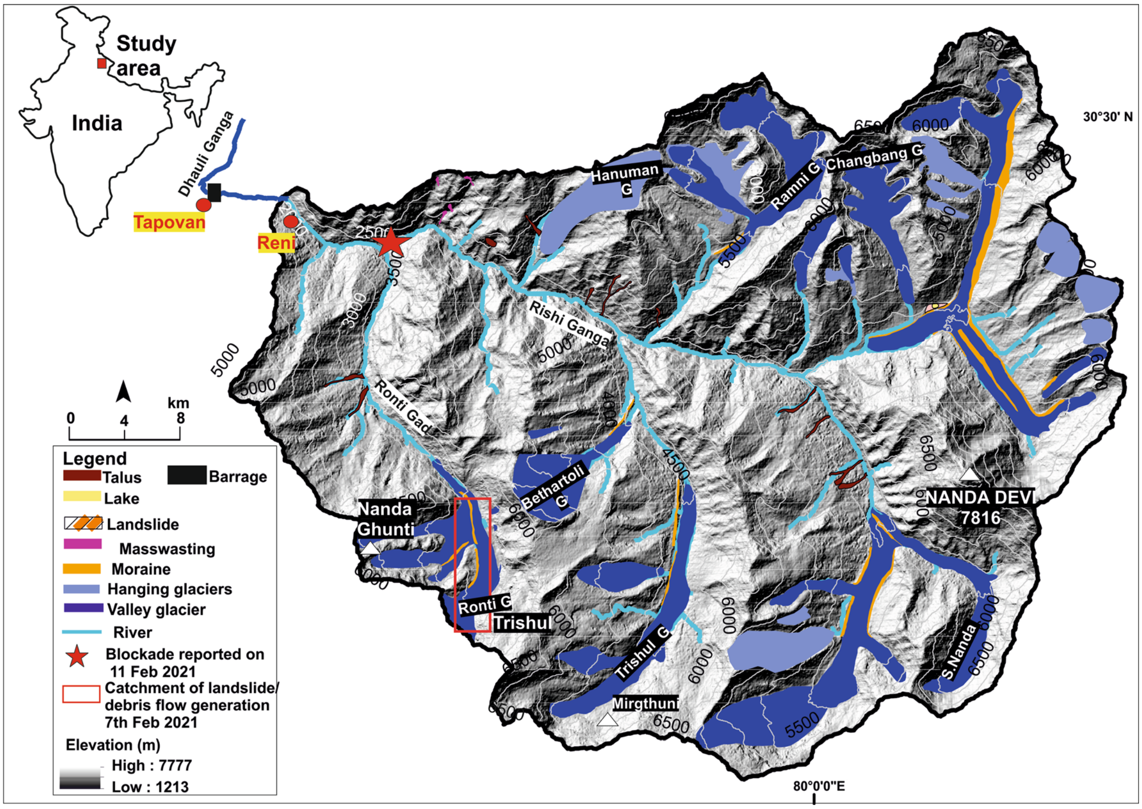

Figure 1. Glaciated Rishi Ganga valley fortified by mountain peaks (e.g., > 6000 m high Nanda Devi in the far eastern part of the valley). Compared to other glaciers, Raunthi and Nanda Ghunti glaciers are relatively small. Site of Rishi Ganga damming is shown by red star. The flood washed away two hydropower projects located at Reni and Tapovan.

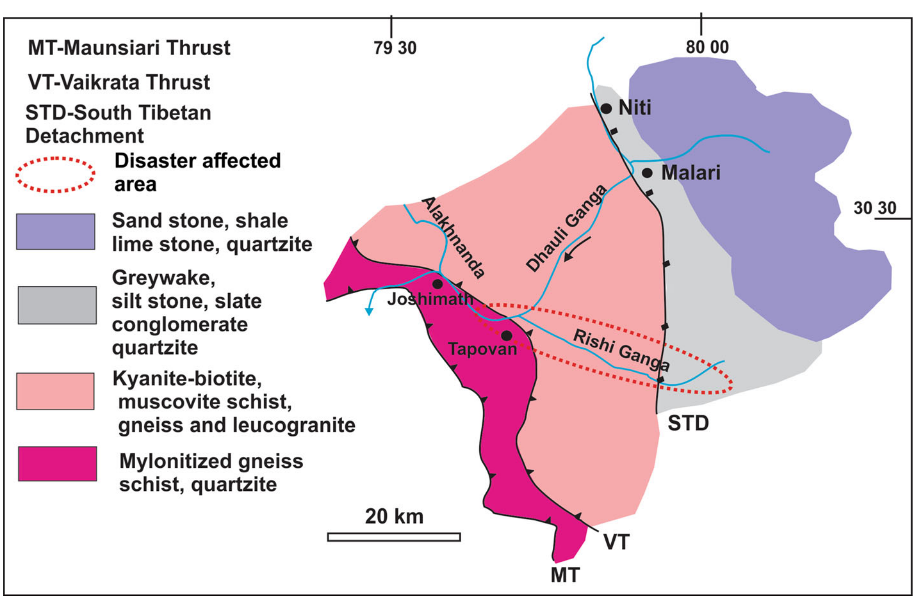

Figure 2. Geological and structural map of Rishi Ganga valley (modified after Mukherjee *et al.* 2019). Rishi Ganga valley is traversed by three major tectonic structures – The Munsiari Thrust (MT), Vaikrata Thrust (VT) and the South Tibetan Detachment (STD).

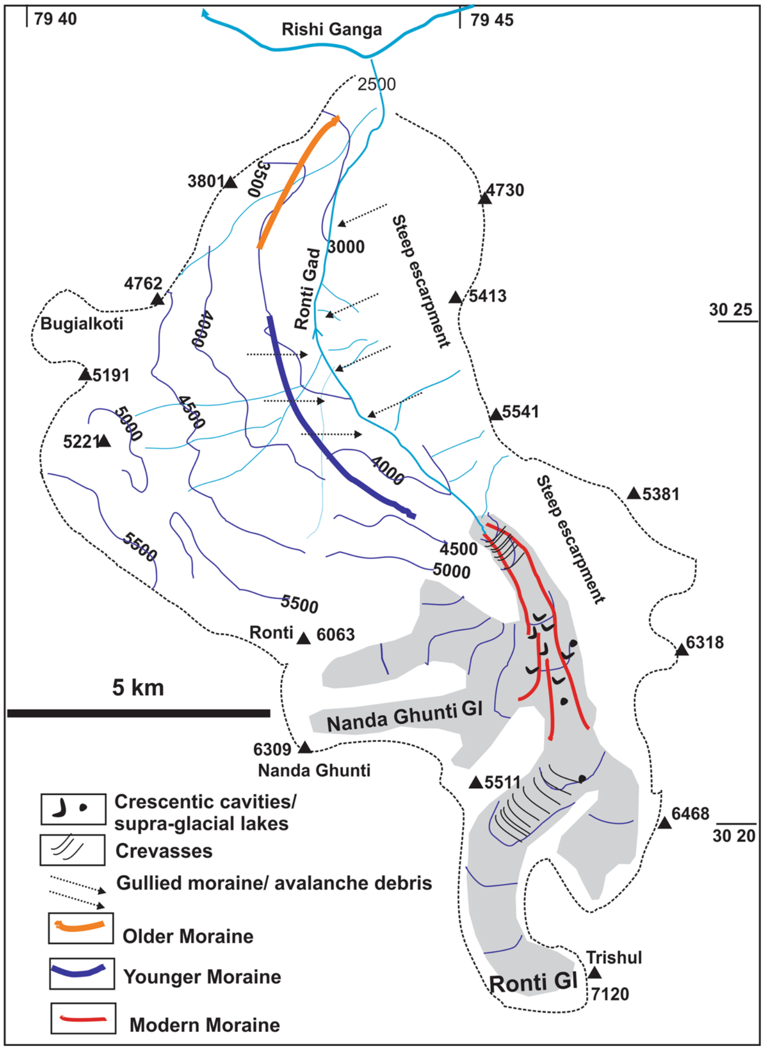

Figure 3. The geomorphological features were extracted based on field observations and Google Earth images (2015–2017). The avalanche that was implicated for the disaster broke from the northern face of Ronti peak (6063 m). Note the presence of crevasses, crescentic cavities and few supraglacial lakes. The right flank has steep escarpment with innumerable streams that have dissected/gullied the moraine and avalanche debris compared to the left flank.

catchment, are mapped from the Google Earth imagery supported by the topographic map (1:150,000 scale). The meteorological data trends are estimated from NASA POWER, which are modelled datasets based on satellite data and verified with 85% accuracy with the ground station data (power.larc.nasa.gov). In order to assess the nature of geomorphic changes in the vicinity of the disaster, a field visit was undertaken in the valley up to the near-inaccessible confluence of Raunthi and Rishi Ganga between 8th and 11th February (figure 1). Further, in order to assess the vulnerability of the Dhauli Ganga valley, the sedimentological evidences of past river obstructions/ breaching preserved at few locations were also investigated.

4. Results

4.1 *Geomorphology*

The Google Earth imagery and the topographic map indicate that Raunthi is fed by northward-flowing Raunthi glacier ($\sim$9 km length) and the eastward flowing Nanda Ghunti glacier ($\sim$4.5 km length) (figures 1 and 4). Geomorphologically, the Raunthi valley can be divided into an upper glaciated valley ($\sim$14 km) and a lower glacio-fluvial terrain ($\sim$5 km). As mentioned earlier, the Rishi Ganga valley with fairly large number of glaciers is one of the potential valleys in Uttarakhand Himalaya for glacier-related disasters (avalanches, GLOF, solifluction induced debris flows, etc.).

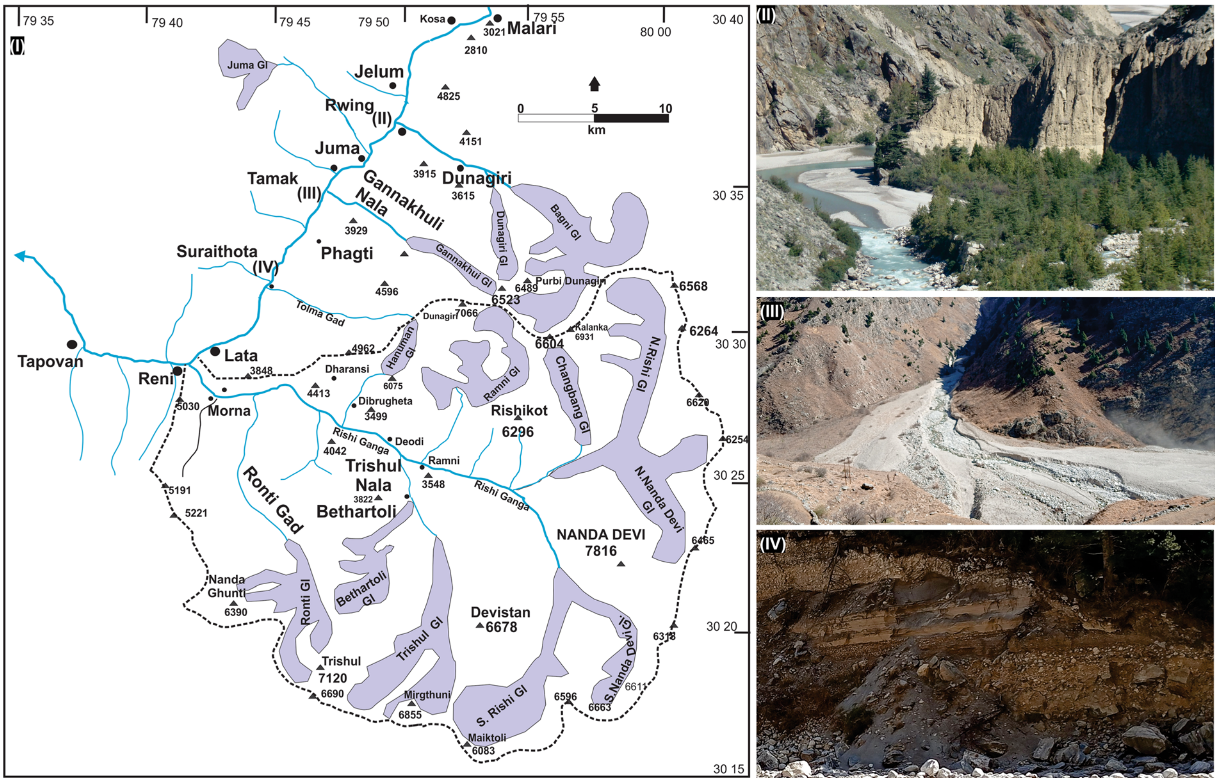

Figure 4. (**I**) Map showing part of Dhauli and Rishi Ganga valley. (**II**) Relicts of moraines overlain by lake deposit and alluvial fan at the confluence of Dunagiri river and Dhauli Ganga (Rwing village). (**III**) Debris flow/alluvial fan deposited during 2003 flood which was triggered from highly degraded headwall of Gannakhui glacier. (**IV**) Relict impounded rhythmic sequence above Suraithota, suggesting prolonged obstruction, which was an open-system until a major pulse breached it in geological past (represented by gravels).

Observations based on multitemporal Google Earth images (2015–2019) supported with topographic map suggest that the upper glaciated valley has preserved at least two generations of relict lateral moraines (figure 3). The older moraine terminates at $\sim$3000 m, having a rolling crest and is covered with juniper, birch and conifer trees. While younger moraine terminating at $\sim$3600 m, is poorly vegetated and highly dissected by meltwater streams. The modern moraine, which runs parallel to the present glacier, is sharp-crested without any vegetation cover and terminates near the snout at $\sim$4000 m. The glacier's ablation zone is debris-covered and marked by conspicuous traverse and crescentic crevasses (figure 3). Also, small supraglacial lakes (200–500 m^2) can be observed in the ablation zone. The available multitemporal images suggest that these lakes are not permanent features. The debris in the ablation zone is relatively fine-textured compared to the boulder-dominated river. Below the older moraine, the valley morphology becomes steep and the river flows through a deep gorge that is riddled with large boulders.

4.2 *Past evidence of river impounding*

Barring the Rwing village, where the Dhauli Ganga was obstructed by moraine from Dunagiri valley (figure 4) and near Malari village, where the Dhauli Ganga was obstructed by a landslide (Srivastava *et al.* 2013); the other obstructions were caused due to the alluvial fans/debris flows (e.g., Surainthota; figure 4). Considering the thickness of the impounding barriers (10–50 m), it can be hypothesized that breaching would have generated similar kinds of flashfloods as observed on 7th Feb, 2021. The earliest recorded mega-floods possibly occurred during the early Holocene, when glacier dammed lakes in the upper reaches breached by a combination of accelerated melting and enhanced precipitation (Juyal *et al.* 2009) causing valley-wide fluvial aggradation in the Alaknanda valley (Juyal *et al.* 2010). Whereas, the most recent flood of 2003 in the Dhauli Ganga valley, with hyper-concentrated debris flow was triggered, when supposedly a moraine-dammed glacier lake in the upper reaches of Gannakhui Gad (opposite Tamak) breached (figure 4) and severely damaged the

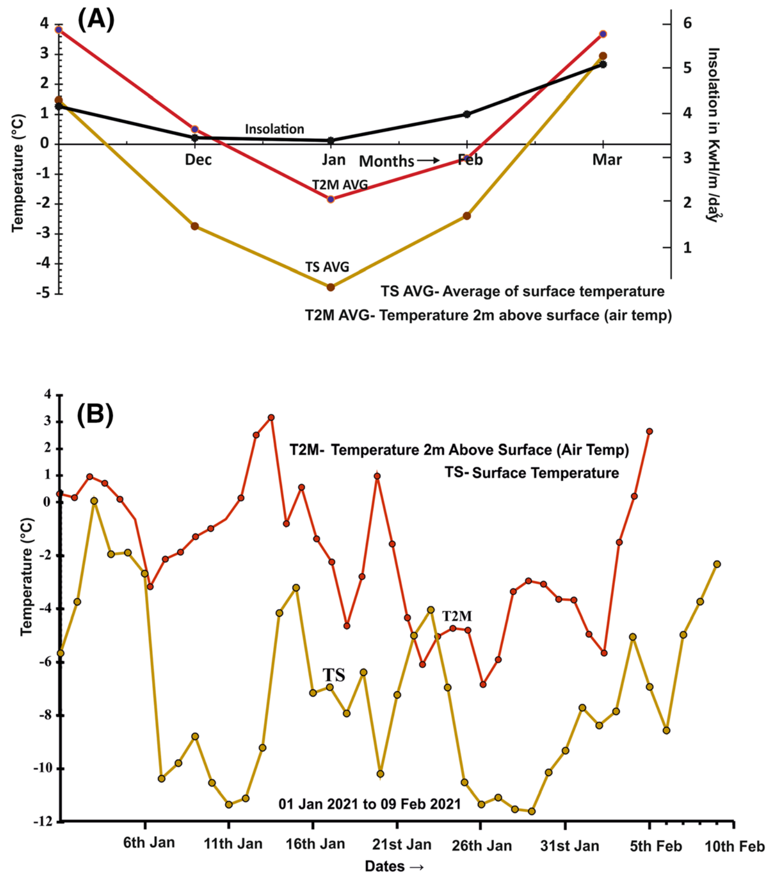

Figure 5. (**A**) Average monthly insolation, surface temperature, and temperature 2 m above the ground (air temperature) is plotted for winter months (Nov–Feb) for years 1981–2020. February is the month during which the change in temperature regime is noticed. (**B**) The daily surface temperature and air temperature (2 m above ground) are shown from 01-01-2021 to 09-02-2021. There was a sudden change in temperature on 6th February which coupled with fresh snowfall might have helped in triggering the avalanche.

Siagari village (Bisht *et al.* 2011; figure 4). The sedimentological expression of this flood is observed opposite Tamak village (figure 4). Even today, the coarse paraglacial sediments from Dunagiri valley are being transported by Dunagiri river that are observed below the confluence with the Dhauli Ganga (figure 4).

5. Discussion

The Raunthi Gad valley has sequestered voluminous sediments (as seen in Google Earth images) suggesting a transport limited valley. The rocks are highly pulverized, fractured and weathered probably because of its proximity to the Vaikrata Thrust (figure 2). Presence of glacially-ground matrix acts as a lubricant with water; thus, facilitating the downslope movement of the sediments as debris flows (Haeberli *et al.* 2006). The valley is undergoing extensive erosion that can be inferred from the highly dissected lateral moraines along the right flank.

It is now widely accepted (e.g. Petley, AGU blog, 2020) that the rock and snow avalanche originated on the north-facing headwall of Nanda Ghunti glacier. The sharp-crested linear failure along the northern face of Nanda Ghunti glacier suggests the possibility of a pre-existing fracture. The frost shattering seems to be quite common in the upper reaches of Raunthi Gad as indicated by the serrated topography, particularly in the vicinity of Raunthi and northern face of Nanda Ghunti glaciers. During October 2020 and the first week of February 2021, the temperature varied between maximum (12°C) and minimum (–10°C) implying that the terrain experienced diurnal variation in surface and air temperature (common in high altitude on clear sky days). Two days before the flashflood (3–5th Feb 2021), there was precipitation in the valley (0.22, 4.22, 0.63 mm/day) (source: NASA power data). Just a day before the

Figure 6. (**A**) Panoramic view of the part of the lower reaches of Raunthi Gad having thickly vegetated valley flanks. The rivulet has deeply incised the crystalline bedrock, thus crated slit gorges in the fluvial domain. Such constricted channel gets readily overwhelmed by the sediment, mainly when there are glaciers in its upper reaches during unusual weather events creating sequential ponding and breaching, thus acts as a force multiplier (enhanced the streams' erosion potential) as observed during 7th Feb 2021 flood. (**B**) and (**C**) are the close-ups of the impounding and the lake formed on Rishi Ganga.

flood, on 6th February, there was an abrupt increase in the temperature (figure 5). We hypothesize that the sudden temperature rise (clear skies and high insolation) would have facilitated in accelerated melting of fresh snow leading to the triggering of snow and debris avalanches by lubrication of pre-existing fissures (Haeberli *et al.* 2006; Regmi and Watanabe 2009) on the northern steep ice wall of Nanda Ghunti glacier (figure 5). As the sediment-laden water moved downslope from the glacially to fluvially carved valley, the sediments obstructed the constricted channel path, thus creating a temporary impounding. Breaching of such temporary impounding would have acted as a force amplifier that was perhaps responsible for enhancing the flood magnitude in Rishi Ganga and part of Dhauli Ganga on 7th Feb 2021 (figure 6).

The increasing incidences of flashfloods in Himalaya are highlighting that the Himalayan ecosystem is sensitively responding to global warming, particularly the cryosphere (glaciated region). It is feared that with progressive warming, the temperate glaciers (where water coexists with the ice) would become increasingly unstable (potential source of snow avalanches). Mountain surface air shows warming over recent decades at an average rate of 0.3°C per decade (IPCC 2018). It has been observed that the winter runoff has increased in the recent decades due to more precipitation falling as rain, thereby increasing both the frequency and magnitude of natural hazards in the Himalayan cryosphere. Also, glacier retreat and permafrost thaw are projected to decrease the stability of mountain slopes, and increase the number and area of glacier lakes (Gruber *et al.* 2017; IPCC 2018). Resulting landslides and floods will also emerge where there is no record of previous events. Rain-on-snow floods will occur earlier in spring and later in autumn, and likely to be more frequent at higher than lower elevations (Hock *et al.* 2019).

We were unable to locate well-developed (large) supra/pro-glacial lakes in Raunthi Gad and therefore, it is intriguing that how such a large volume of water was generated from a small stream. There seems to be no ambiguity about the fact that besides debris flow and rockfall, a massive snow avalanche was triggered from the northern

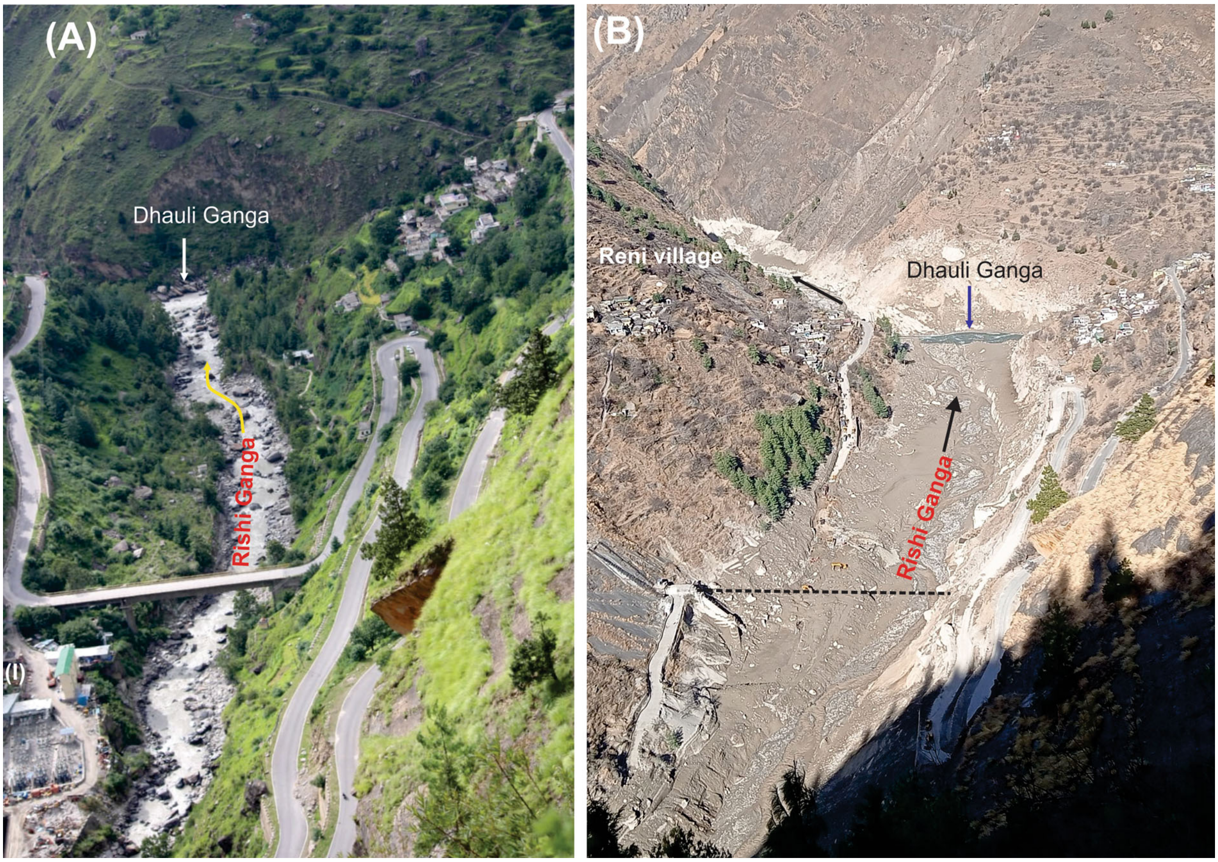

Figure 7. Field photographs of the hydro-power project at Reini village (**A**) before the disaster (**B**) after the disaster of 7th Feb 2021. (I) marks the location of the project and dotted black line marks the location of the washed bridge.

face of Nanda Ghunti. According to Armstrong (2010), even rapid melting of glaciers may not be able to generate high magnitude floods because glacier ice melt rate under any reasonable warming scenario is relatively slow. Conventionally, the major hazards in glacial and paraglacial zones are associated with breaching of the moraine-dammed lakes. The breaching may be caused either by increasing hydrostatic pressure, rapid melting of glacier, or breaking of sediment barrier by waves/ impact generated through rock/snow avalanche. Neither of these seems likely based on the satellite images, however, there are deformed sediments and steep-walled cavities downstream of the snout which might have contributed to the flood water (Vincent *et al.* 2010). Additionally, the fresh snowfall prior to the disaster could have further contributed to the meltwater. Therefore, we envisage two possibilities for the generation of flood water (i) snow and debris avalanche scavenging the englacial aquifers or (ii) obstruction of melt-water flow by temporary impounding below the snout. Considering the size of the debris/snow avalanche, the second possibility seems to be the likely mechanism for the generation of the flood. Once the debris-laden water began to flow downstream from the ablation zone, it would have gathered more water and sediment causing multiple temporary obstructions as mentioned earlier.

Considering the magnitude of down valley inundation, the 7th February 2021 flood was significantly lower in magnitude compared to the July 1970 and June 2013 floods in the region. Yet the loss of life within a 10 km stretch is estimated to be more than 200 people. Had it been a basin-scale event (triggered in the paraglacial zone of Rishi Ganga), the flood magnitude would have been much higher because of the mobilization of the sequestered sediments as observed during June 2013 (Sundriyal *et al.* 2015). The current flashflood destroyed the hydropower projects located at the Raini and Tapovan villages (figure 7). The barrages across the river, particularly in the higher Himalaya are known to obstruct the free flow of the debris laden water (Sundriyal *et al.* 2015) for example, Sitapur (Mandakini valley) Vishnuprayag (Alkandada valley). Thus, the current flashflood along with the June 2013 flashflood reiterate the concern that we have to be extremely careful while exploiting the higher Himalayan rivers for power generation. As rightly cautioned by Bandyopadhyay and Ghosh (2009) that rivers emerging from Himalayan are constituting a combined flow of sediment, water and energy. Even though smaller in magnitude, this flash-flood tragedy highlighted that obstructing the free flow path of rivers in paraglacial zones is going to have an amplified impact on the life and infrastructures in the Himalaya.

6. Summary

Our preliminary observations (which are in agreement with ISRO and media reports) suggest that the flood was triggered by snow and debris avalanche and it seems to have scavenged the englacial stored water (?) along with temporary impounding caused in the downstream. The current tragedy emphasizes the need for understanding hydrological processes associated with glaciers and monitoring of the potential areas of structural failures in the paraglacial zones. Under the climate change scenario, it is feared that the frequency and magnitude of flashfloods would increase in Himalaya and possibly worsen in the paraglacial zones over the next century (Rana *et al.* 2013; Wasson *et al.* 2013; Sundriyal *et al.* 2015). It is therefore essential that we must have in-depth study of the glaciers and para-glacial zones with emphasis on developing effective early warning systems in order to minimize the magnitude of destruction. The current disaster re-emphasize that we must incorporate the component of disaster risk assessment in our developmental planning for the Himalayan region in general and higher Himalaya in particular.

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Author statement

Shubhra Sharma, Y P Sundriyal, S P Sati and Naresh Rana conceptualized the idea. Naresh Rana, Y P Sundriyal, Sameeksha, Ghanshyam and Firoz contributed in pre-disaster and post-disaster field investigation. Shubhra Sharma wrote the manuscript with inputs from all the authors. Subhendu Pradhan contributed in making the illustrations and meteorological analysis.

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