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A Geomorphological Interpretation of Rishi Ganga Flash Flood, Garhwal Himalaya, India

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Abstract: *The Geomorphological appraisal of the Rishi Ganga flash flood of 7February 2021 in Chamoli district of Garhwal Himalaya, indicates that the flash flood was triggered by a combination of landslide, slope failure, glacial debris flow and melting of fresh snow in the high gradient Raunthi stream. The worst affected area of the tragedy was the lower Rishi Ganga and Dhauli Ganga valleys. The violent disaster damaged two hydropower projects, one motorable bridge and took the lives of 206 dam workers. The glacial landslide debris blocked the Rishi Ganga and formed the lake behind it. The Trisuli and Nanda Ghungti headwater zone of the Rishi Ganga is highly vulnerable to glacial avalanches, landslides, and breaching of dammed lakes by a combination of accelerated melting and enhanced precipitation. There is a need to monitor and conduct an intensive survey from the viewpoint of applied geomorphology in glacial and periglacial zones and suggest appropriate planning for infrastructural construction in the Higher Himalayan region of Garhwal.*

Key words: Rishi Ganga,disaster, Nanda Ghungti, Raunthi

Introduction

Recurrent landslides, flash floods, damming of the river, snow avalanches, and glacial lake bursts in the Himalayan region have frequently taken a heavy toll on human life and property. Tectonic activities are also responsible for the instability of the terrain. Hillslopes are known for their instability during the monsoon period. Most of the major flood disasters in this region were examples of glacial lake outburst flood (GLOF) in the Himalayan region. The intensity and impact of the flood is dependent on the physical characteristics of the glacial lakes encircled by morainic ridges and the gradient of the streams which are originating from the glaciers. According to the Geological Survey of India, 13 glacial lakes have been identified as most vulnerable in the Uttarakhand Himalaya (The Hindu, 2021). Previous investigations by Campbell (2004) and Sah *et al.* (2005) listed 127 lakes which were identified as vulnerable, but there were no prior reports on the potential danger of terrain instability in the Uttarakhand Himalaya. Apart from the natural factors, increasing anthropogenic interventions in recent times appear to be contributing to terrain instability in the region. However, the question arises that the present disaster was a natural calamity or a result of anthropogenic intervention? The paper attempts to present some preliminary observations of the Rishi Ganga disaster of 7th February 2021 in the upper Garhwal Himalaya.

The catchment area of the eastern tributaries of Alaknanda, Dauli Ganga, Rishi Ganga, Birahi Ganga around Nanda Ghunti peak has suffered frequent floods created by the bursting of temporary dams, landslide, snow avalanches (Fig. 1). Two major catastrophes (1894 and 1970) were associated with Birahi Ganga (Nand and Prashad 1972). Wasson *et al.* (2013) concluded that the 1970 event was the highest in magnitude. But Kedarnath disaster of 16th June 2013 was more severe from the view point of the horizontal and vertical extension of the flood (Rana *et al.*, 2013). Mostly, the large floods in the Alaknanda and its tributaries appear to be the result of landslide and temporary dam burst (Wasson *et al.*, 2013; Ziegler *et al.*, 2013).

The incident of 7th February 2021, initiated in the northwestern slope of the Nanda Ghunti mountain range. Rishi Ganga experienced another disastrous event during May 1968. The Rishi Ganga then, was blocked by the huge landslide and avalanche just above the confluence of Dhauli Ganga. A temporary lake was formed in the Rishi Ganga. The released water of this lake damaged theTapovanarea, located 8 km upstream of Joshimath on the left bank of Dhauli Ganga (Nand and Prashad 1972). The past geomorphic and sedimentological records of moraine dammed lakes in the upper reaches of the rivers, which were breached by intensive rainfall and accelerated melting of snow are found in the valleys of Dhauli Ganga and Alaknanda rivers (Juyal *et al.* 2009, 2010). The surrounding mountain ranges of Nanda Ghunti and Trisul peakprovide a suitable case for detailed investigations. A Geomorphological appraisal of the Rishi Ganga flash flood of 7th February 2021 will help in arriving at the some definite conclusion about the possible causes and consequences of the calamity.

Study Area

The Raunthi Gadhera

The name of Raunthi Gadhera is derived from the Raunthi glacier. Lower order streams are locally known as Gad and Gadhera. The present natural disaster originated in the catchment of Raunthi Gadhera (79° 40′ 43″ E to 79° 47′ 43″E and 30° 18′ 10″ N to 30° 27′ 56″ N) at the height of 5600 m from sea level. Raunthi is the 4th order left bank tributary of the Rishi Ganga which covers 92.22 km^2. Rishi Ganga is the tributary of Dhauli Ganga and Dhauli Ganga is the tributary of Alaknanda River in Garhwal Himalaya (Fig. 1). The name Raunthi Gadhera’s is written in SoI topographical sheet No. 53N/11. The total length of the Raunthi Gadhera is 15.5 km from Trisul peak to confluence. The left flank headwater zone of Rishi Ganga has the highest snow-clad peaks such as Nanda Devi, Mirgthuni, Trisul, Nanda Ghungti, and Bithartoli which is also the source zone of Trisuli, Mirgthuni, Bithartoli, Raunthi and Birahi, glaciers. Out of these, a number of hanging glaciers also exists along with the major glaciers. Hanging glaciers are prone to avalanching and snow sliding because they are located on a higher slope to allow the detachment of ice chunks from the glacial terminal (Margreth *et al.* 2017). The Raunthi glacier rises from the southwestern slope of the Trisul peak (7120 m) and north-western slope of Nanda Ghungti (6309 m) and Raunthi peaks (6063). The Raunthi glacier is 5.5 km long and 1.33 km wide. It has 3 left and 3 right bank tributary glaciers among which the Nanda Ghungti glacier is the largest (4.5 km). The snout of the Raunthi glacier is at the height of 4040 m which is 418 m wide but dead ice mass under a young till can sometimes be at lower altitudes. The Raunthi stream rises from the snout of the Raunthi glacier (4040 m) and joins Rishi Ganga at the height of 2315 m. About 10 km downward from the snout up to the height of

3000 m the glacial U-shaped valley is full of terminal, ground, and lateral moraines and scree cones at the base of rocky slopes. The average gradient of the river is about 172.5 m km^{-1}. Out of the total catchment area 26% area (92.22 km^2) is under permanent snow-cover.

image of the landslide site (Petley, 2021a) is also used for the interpretation of the landslide. Primary information is collected from the villagers who were direct witness to the disaster.

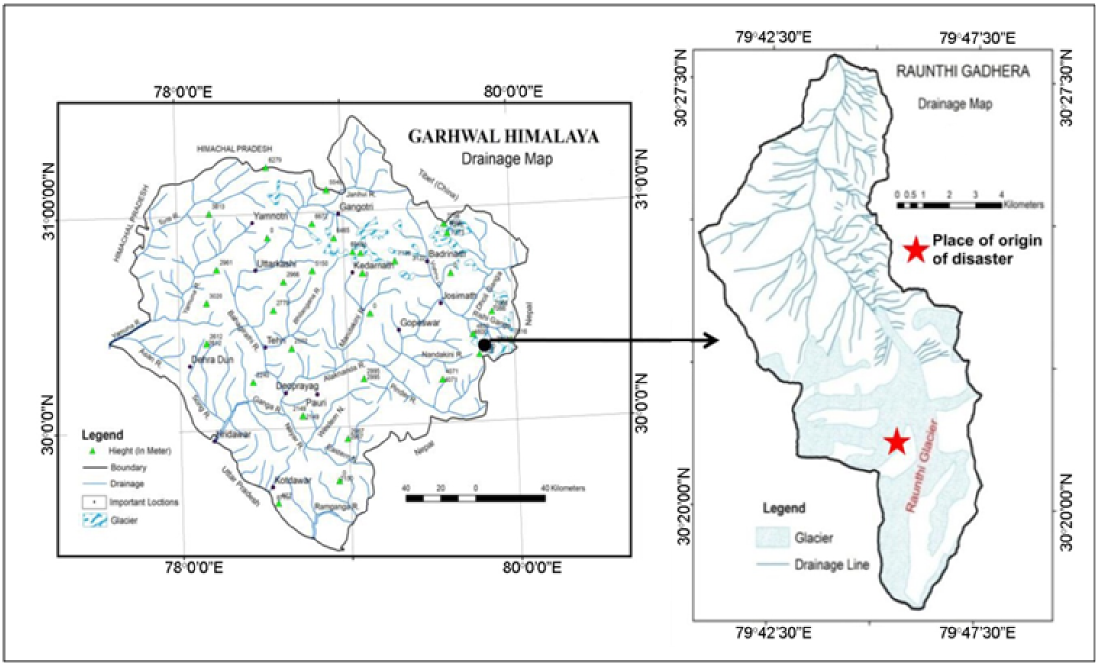

Figure 1. Location of Raunthi Glacier and Raunthi Gadhera.

Methods

The present investigation is essentially based on the interpretation made on the basis of topographical maps, Digital Elevation Model (DEM), Google images and field investigations. The base map of the study area is prepared on the basis of Survey of India (SoI) topographical sheet of R.F. 1:50,000. The drainage lines, structural features and lineaments were identified, the longitudinal and cross profiles of rivers were drawn and the land use map have been prepared on the basis of these data bases in Arc GIS version 10.1. High resolution (12.5 m) PALSAR data has been used for the generation of DEM (20 m), slope analysis, and geomorphological mapping. High-resolution Skynet Planet Lab

Causeof the disaster

The February 7 landslide event turned out to be a high magnitude disaster due to its fast movement from very high altitude (5600 m). During the recent flood, the debris derived fromthe landslide washed downslope through the high gradient stream Raunthi Gadhera (172.5 m km^{-1}) and blocked the Rishi Ganga at a height of 2315 m. The irresistible pressure of the landslide debris and glacial meltwater along the high gradient stream flooded the Rishi Ganga and Dhauli Ganga valleys further downslope. The impact was felt up to Nandprayag. Just after the disaster many hypotheses were put forward by the experts regarding the unpredictable landslide/rockfall and flash floods in the winter season which were not apparently linked to any rainfall event. Glaciers can break due to multiple reasons such as rockfall, snow avalanche, water pressure, weathering, and landslide.

The scientist have studied various aspects of the Himalaya including the glaciers and seismic activities in the region, and had also scrutinised the 2013 flash flood in Uttarakhand, that killed more than 5000 people. According to some reports, the flooding may have been caused by a portion of the Nanda Devi Glacier breaking off in the early hours of 7th February, releasing the water trapped behind the ice, and causing a glacial lake outburst flood. Some scientists say that the disaster could take place because of a glacial lake outburst (GLOB) flood which is a rare phenomenon in these regions. Some geologists opined that it is the increasing global temperature which has resulted in glacial retreat. According to a senior scientist of the Wadia Institute of Himalayan Geology,such incident is anomalousto the region. In winter, the glaciers remain firmly frozen. Even the frozen walls of the glacial lake are tightly bound. A flood of this type in this season is usually triggered by an avalanche or landslide. In a 2020 study, it was found that glaciers of the headwater zone of Rishi Ganga have lost over 10% of their mass in less than 3 decades; shrinking from 243 km^2 during 1980 to 217 km^2 in 2017. The present incident also happened in the upper headwater zone of Rishi Ganga around Raunthi and Nanda Ghunti peaks. Environmental experts have attributed the glacial melt to global warming. Climatic change has resulted in erratic weather patterns like increased snowfall and rainfall. Warmer winters have led to the melting of a lot of snow. Some of the experts opine that that the thermal profile of ice is increasing.

The Indian Meteorological Department has said that there was no heavy rain forecast in the region. Meanwhile, an official of the Central Water Commission said flooding from the glacial burst has been contained. Farooq Azam, Assistant professor, glaciology, and hydrological division, IIT Indore was of the opinion that such a glacial burst was an extremely rare event. He further extended that Google Earth images do not show a glacial lake near the zone of the incident, but there was a possibility that there may be a water pocket inside the glacier, which may have erupted leading to the event. One of the scientists of the Wadia Institute of Himalayan Geology said a chunk of the hanging glacier had broken and fallen in Raunthi Gadhera at 2.30 am, causing an explosion-like sound. After 8 hours, slurry of ice, water, and boulders transported by the Raunthi Gadhera, triggered the flash flood. The local villagers said that it was a man-made disaster; claiming that the Rishi Ganga hydropower project which is being built in the area disturbed the environment in the region. The Magsaysay award winner Rajender Singh, also known as the 'Waterman of India' said that this was a man-made disaster and no dam for hydroelectric project should be constructed in such steep hilly terrain and extremely eco-sensitive zone (The Hindu, 2021).

According to International geologists and glaciologists, the basic cause of the Rishi Ganga flash flood disaster appears to be a landslide, not a glacial lake burst as usually believed. Rishi Ganga disaster was first identified by Dan Shugar, University of Calgary, USA; who specialises in high altitude glacial environment. He studied the event with high resolution satellite images from Planet Labs, captured before and after the disaster. He expressed his view that it was a landslide that triggered the catastrophic flash flood along the Rishi Ganga, Dhauli Ganga, and Alaknanda valleys. He also suggested that a hanging glacier had separated from a mountain and plummeted into the Raunthi Gadhera a tributary of the Rishi Ganga.

Another satellite imagery-based analysis done by a scientist of the Indian Institute of Remote Sensing, Dehra Dun, has identified that a landslide in all likelihood triggered an avalanche, resulting in the flash flood. Anearth scientist, Ajanta Goswami of IIT Roorkee analysed the pre and post-event satellite imageries of the study area and did not rule out the possibility that due to avalanche some ice block fell on the accumulated ice which in turn triggered the massive water flow through the narrow valleys of Rishi Ganga and Dhauli Ganga. According to Dave Petley (2012) of University of Sheffield, the event is similar to the 2012 Seti river flooding in Nepal, which was triggered by a rock slope failure.

Geological factor

The study area lies in between the south Tibetan detachment thrust in the north and the Vaikrata thrust in the south. The lithology is dominated by gneisses and schist, dominated by kyanite, biotite, and muscovite schist (Mukherjee *et al.*, 2019). The rocks are highly crushed, fractured, and weathered along the Vaikrata thrust. Structurally, the Raunthi stream flows through a south-north trending fault line, which passes from Raunthi peak to confluence (Fig. 2). The stream forms an asymmetrical valley with a steeper right bank and a comparatively gentler left bank. A number of lineaments are also marked along the rocky cliffs which are prone to rockfall and landslide (Fig. 2). The highly sheared and crushed rocks are present in the area which is regularly experiencing snow avalanches and landslides. The fault scarp zone has a steep dip and it has been probably responsible for the instability of the slope. The detachment is due to extremely

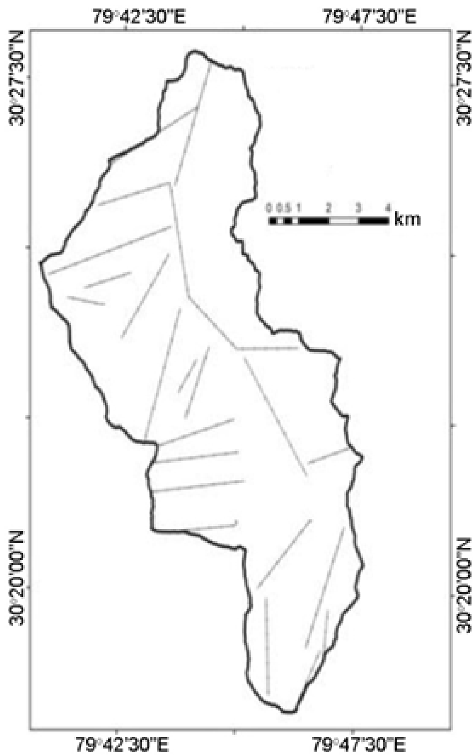

Figure 2. Lineament map of the study area.

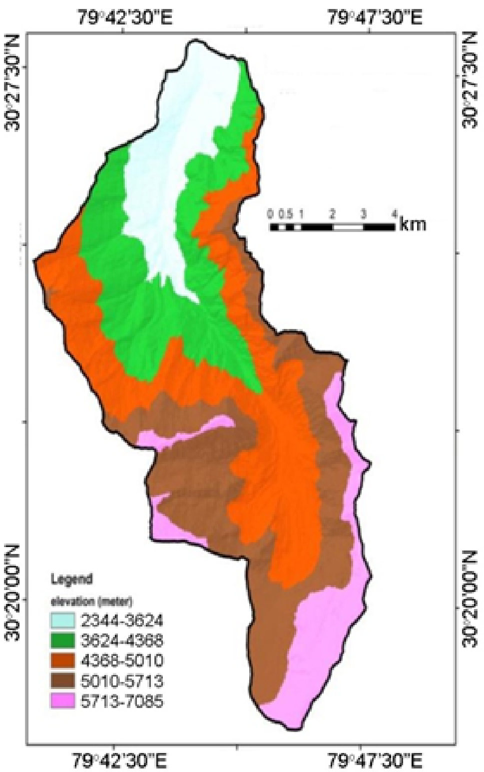

Figure 3. Digital elevation model of the study area showing the 5 altitudinal zones.

steep slope of the north-western face of the Raunthi escarpment. The north-western face of all faults and lineaments are exposed and prone to widespread rockfall and landslide. The present case of the landslide has also originated at the scarp of Raunthi peak (Fig. 3).

Relief factor

The studied catchment shows altitudinal variation between 2315 m (mouth) to 7045 m (source at Trisul peak). The average relative relief is 4730 m is significantly high. A series of mountain ranges run in different directions from the Nanda Ghungti peak (6309 m). The basin is bounded by, Trisul-Bithartoli range in the east and Trisul-Nanda Ghungti-Raunthi mountain range in the west. The height decreases from south to north direction, and the river also flows from south to north, following the regional slope (Fig. 1). Altitudinally the studied catchment can be divided into 5 altitudinal zones (Fig 3).

Geomorphological factor

The major rivers of the Garhwal Himalaya carved out very deep valleys during the period of the episodic upliftment of the Himalayan ranges.

The gradient of the consequent rivers is not very steep as compared to the gradient of subsequent and obsequent streams. The gradient of the subsequent and obsequent streams is very high which debouch from the snow-clad peaks to meet the consequent stream within a very short distance. The longitudinal profile of the Raunthi Gadhera illustrates this fact clearly (Fig. 4). In its 10 km flow path from the glacial snout to its mouth, the average gradient of the Raunthi Gadhera is 172.5 m km^{-1}. If the 5.5 km glacial course is included, then gradient is about 234 m km^{-1}, which is significantly high. The average gradient of the 1st order streamsis 640 m km^{-1}. This zone marks the head of the landslide which got activated on 7th February 2021. The longitudinal profile of the Raunthi stream shows that downstream of 4200 m altitude, the gradient of the stream continuously increases because of the high incision rate of the river. It is quite evident that the river is still in a young stage. On account of a faulted

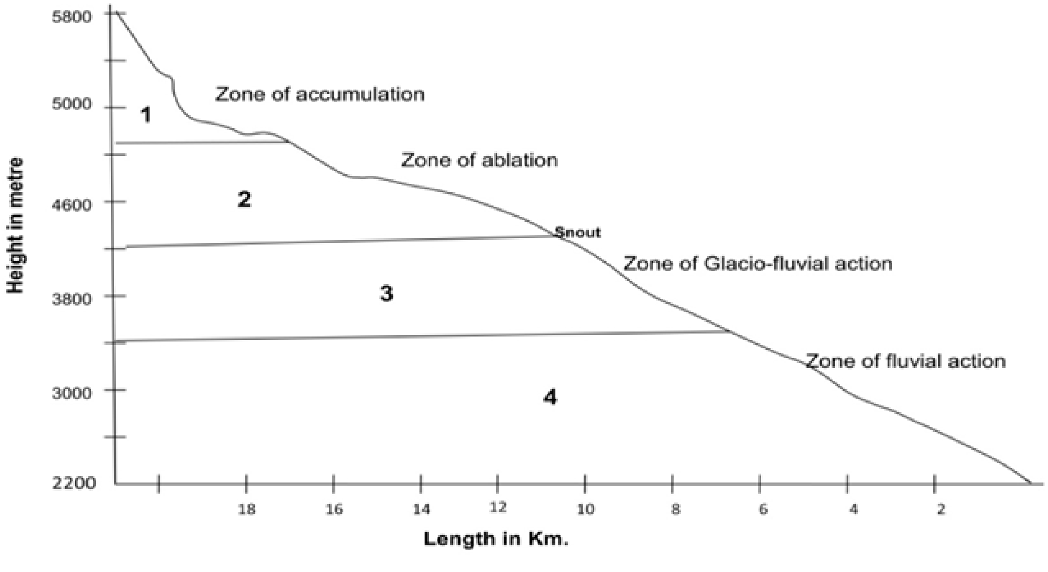

Figure 4. The 4 morphological and climatic zones marked along the longitudinal profile of the Raunthi stream. It shows that the lower part of the stream is steeper due to fluvial action in comparison to the upper part formed due to glacial action.

and sheared zone, glacial-fluvial processes and geomorphological and climatic factors, these young valleys frequently experience phenomena such as landslide, glacial lake burst, temporary damming of rivers etc.

Climatic factor

Trisul, Nanda Ghunti, and Raunthi peaks are above 5000 m altitude, and source of Raunthi and Bithartoli glaciers in the northwest, Trisul and Baldagwar glaciers in the southeast, and Homkund, Silasamundar and Birahi glaciers in the southwest. These glaciers are the perennial source of the Raunthi, Trisul, Nandakini, and Birahi rivers and their boundaries are contiguous to each other. The catchment areas of these streams experience the greatest snowfall and rainfall in the region. The concentrated heavy snowfall on 3–5 February 2021 was also indirectly responsible for the unprecedented flood accompanied by landslide and debris avalanches which had raised the water level and blocked the river course of Rishi Ganga. In the high altitude, the diurnal range of temperature remains quite high in days of clear sky. On 6 and 7 February, the temperature suddenly rose, accelerating the melting of fresh snow.

Slope factor

Slope movement occurs when shear stress resulting from gravity-driven forces acting downslope exceeds the shear strength of the material composing the slope. Hence, slope amount has a direct bearing on the landslides. The entire catchment of Raunthi Gadhera has been divided into eight slope categories with 10° interval (Fig.5). The slope categories are further generalised into three major categories (Table 1).It shows that the maximum area (49.74%) of the catchment is under high to very high category having above 35° slope. Out of this 49.74% area, 10.5% area is under precipitous rocky slope and 16.7% area is under very high slope category (Table 1). Only 10.3% of the catchment is under the low category with <15° slope. The moderate category of slope (15°–35°) occupies about 40% of the catchment area. Rocky cliffs are prone to rockfall andmost of the scree cones are deposited at the base of the cliffed slopes. Rockfall, plucking, wedge failure, plane failure, and toppling are common phenomena along the rocky scarps in the glaciated terrain. The event discussed in this article is also an incident of rock wedge failure from a crack or fracture of the very steep slope zone.

Table 1: Distribution of slope category in the Raunthi Gadhera

Slope in Degree	Area in km^2	Percentage of area	Slope categories.	Generalised slope categories (figures in parenthesis indicates % of area)
< 15	10.416	11.28	Low	Low (11.28%)
15-25	14.438	15.64	Moderately low	Moderate (40.0%)
25-35	21.541	23.34	Moderate	
35-45	20.814	22.55	High	High (49.74%)
45-55	15.415	16.70	Very high	
> 55	9.683	10.49	Precipitous slope	
Total	92.309	100	-	-

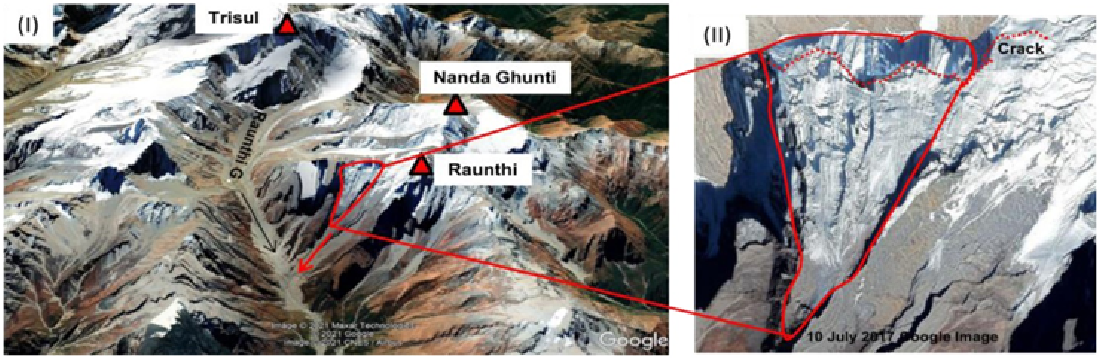

Figure 6 (I). Google Earth perspective view (10 July 2017) of the Trisul, Nanda Ghungti and Raunthi peaks. The main source of Raunthi glacier is north eastern slope of Trisul peak. The site of landslide is the headwater zone of Raunthi Gadhera,shown by red colour. (**II**) Crack that failed the block is shown with doted red linebefore the event.

Mechanism of the disaster

The basic interpretation based on preliminary observations of the landslide/ rockfall of Rishi Ganga is that, it is a natural event that often occurs in the glaciated terrain with steep slope. Past records of similar events in the high Himalayan glaciated terrain are there, though of lesser magnitude. The present incident was triggered following the main detachment event from the very steep 5600 m high rock slope flanking the Raunthi mountain range. Evidences can be assessed by pre- and post-incident satellite images. Google Earth image of 2017 shows that there was a minor joint or tension crack which existed at the head of the present landslide scar (Fig. 6, I and II). The crack may have enlarged due to frost shattering of

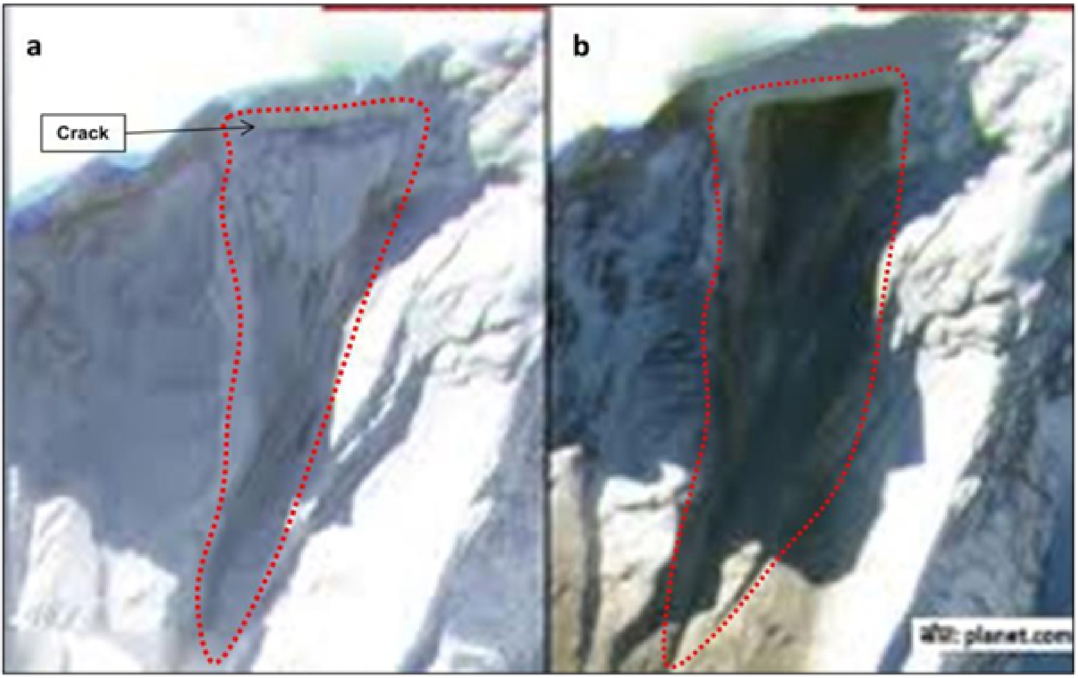

Figure 7 (a). Apre-existingtension crack at the crown of landslide (January) can be clearly seen. (**b**) Steep wall cavity of the failed surface taken after the slide (Petley, 2021b).

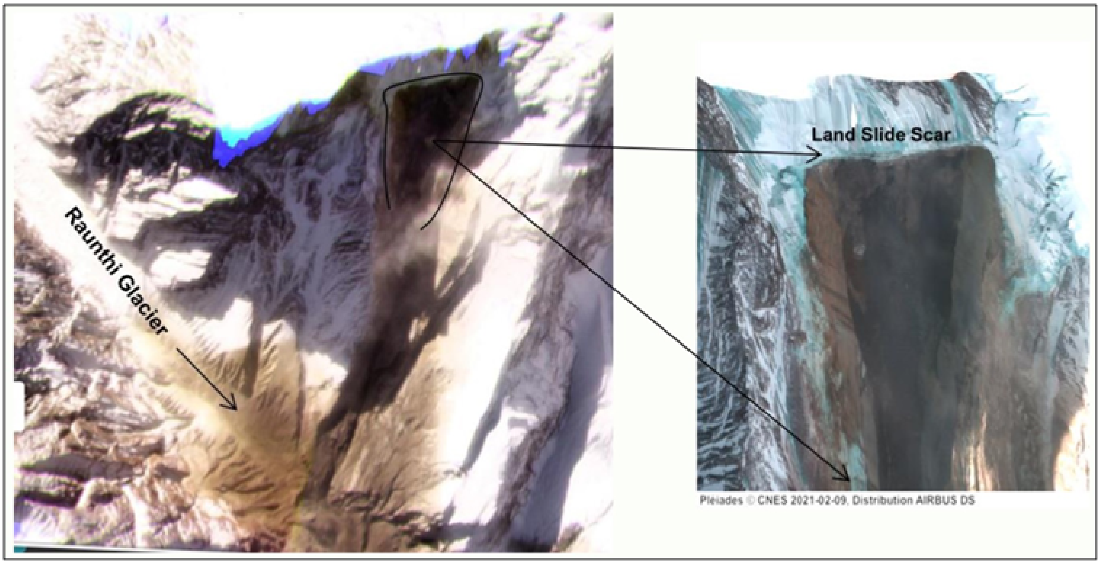

Figure 8. The high-resolution Planet Lab image of landslide site (Petley, 2021a) and the enlarged image of the same site on the right shows a steep wall cavity of the failed surface taken after the rockslide (Petley, 2021b).

rocks consequent upon the action of freeze and thaw. The terrain of the detachment site is vertical and barren. Planet Lab satellite image of 6 February 2021 (Fig.7) also shows that this crack became wider in January in comparison to the previous image (Petley, 2021b).

The freeze-thaw process continued until the rock broke from the parental rock mass. The satellite images are clearly showing that a block of rock mass got detached from the parental mass. At the time of the event the upper surface of the rock mass was covered by ice anda transverse ice crevasse was already developed along the crack (Fig.7a). Ultimately, the rock mass was pulled down with a thick ice cover. Sentinel-2 images also show the formation and opening of a crack in the ice that is believed to have triggered the landslide. The Planet Lab image also proves that there was a tension crack and the block of rock dislodged out of this wedge-shaped area (Fig. 8, Petley, 2021a).

It is estimated that the rockslide scar is about 1800 m long (from top to bottom) and 550 m wide at the head. The thickness of the scar is about 80 m (Fig. 8, Petley, 2021b). After travelling 2.7 km vertical distance

Figure 9 (I). A field view of inundation disaster distroying the hydro power project at Reini village on 7 February and (**II**) the flash flood generated a huge volume of a dust cloud in the Rishi Ganga valley.

(gradient 607 m km^{-1}), the detached rock mass together with ice,fresh snow and melt water forcefully fell in the glaciated U-shaped valley of the Raunthi glacier which was full of ice, fresh snow and unconsolidated morainic deposits in the month of February. Perhaps debris has also travelled some distance up to the opposite slope before heading down the valley. The exposed travel path of the landslide is clearly visible in the Planet Lab image (Fig. 8). Further down the landslide generated a series of flow paths, transporting debris derived from glacio-fluvial deposits. The rock failure together with ice and meltwater also generated a huge volume of dust cloud in the Rishi Ganga valley (Fig. 9 II).

After the interpretation of different pre- and post-event satellite images, it is noted that the 7 February 2021 disaster was triggered by rock failure and it was not a glacier breach or glacial lake outburst. There may be small failures of lesser magnitude in future from the steep fracture zone in which needs to be identified. We believe that there is no connection between the event and dam, road construction or any anthropogenic activities. Such an incident is part of the natural process of active glacial erosion, mass wasting and weathering. Another question has been raised by the geologists and scientists that how the landslide generated an enormous amount of water in the channel? There are some explanations of water generation in the Raunthi Gadhera flash flood disaster. One of these explanations hint at the tremendous amount of heat, pressure and energy that may have generated the water and let it flow downward through this high gradient stream. Friction of boulders and ice with the rock mass comprising a vertical slope together with ice avalanche led to this severe event. When the altitude decreased downslope, there was increase in temperature and the ice and snow melted more rapidly, increasing the mobility of water and sediment in the Raunthi stream.

The scientist of the Indian Institute of Remote Sensing during an aerial survey of the Rishi Ganga valley on the same day found that a glacial lake was formed due to the avalanche blocking the glacial valley. After breaching of the obstruction formed by avalanche debris, the lake water started to release water, causing a flash flood. They further added that avalanches carried the accumulated glacial debris and frictional force facilitated the fast melting of snow resulting in the flash flood. According to geo-scientist Ajanta Goswami, of IIT Roorkee, the glaciers not only consist of hard ice but also have pockets of water inside them. The rock and snow avalanche led to the collapse of a massive chunk of ice in the glacier bed, squeezing out the pocket of water along with loose ice, snow, and debris. It was also estimated that within a short period 2–3 M m^3 of water was generated, which in turn triggered the massive water flow in the stream. Fig. 4 shows that the accumulation zone is full of ice and under permanent snow cover. The zone of ablation is under ice rock along with unconsolidated morainic debris. The Google Earth image shows that there are a number of small-sized super glacial Tals (lakes) in the ablation zone. Near the snout (4040 m) recent terminal, lateral, and ground moraines along with dead ice rocks are found in crescent form. Below the snout there is the glacio-fluvial zone in which a V-shaped valley formed by fluvial action is nested in a U-shaped valley. Glacial terraces can be observed along the older lateral moraines. The channel is full of large sized boulders and pebbles which have rolled down by the force of landslide. The left flank of the valley is under alpine pastures while the right side is under steep rocky scarps. Some of the prominent pastures are Raunthi Kharak and Chamba Kharak. Further down from this zone (<3200 m), the channel gradient becomes very high and Raunthi Gadhera flows through a narrow passage, surrounded by sub-alpine and conical forests of False Ashoka (*Mono onlongi folium*), Juniper (*Juniperus communis*) and Birch (*Betula pendula*).

But the most likely explanation is that in the Garhwal Himalayan region, the permanent snow line is generally found above 5000 m which is composed of 10% solid ice and 30% snow cover. As already stated that about 26% area of the catchment is under permanent snow and the rest of the 74% area is under barren and forested land. The melting rate of snow is faster than ice. The Raunthi catchment is located on the northern slope of the Trisul-Nanda Ghungti-Raunthi mountain range which was completely covered by fresh snow up to the height of 2300 m on 7 February 2021. The snow-melt water of the left flank moved through 25 first and 8 second-order streams which generated the discharge of snow-meltwater to the main stream. The combination of landslide debris, unconsolidated glacial till and fresh snow-melt water due to the rise in temperature, perhaps blocked the narrow course at few places. The temporary impounding would have accumulated a large volume of water, which led to the disaster. There may be some step pools under the glacial debris and also in the channel bed, which were breached by debris and increased the volume of theflash flood downslope. As the sediments-laden water moved downward, the flash flood plucked the trees from their roots from nearby banks which further enhance the flood magnitude in the Rishi Ganga. Finally it can be stated that melting of ice rocks by friction, melting of fresh snow, breaching of step pools, enhanced discharge from the main and tributary streams and additional load of wet glacial till in the U shaped valley may all have contributed to the debris flow leading to flash flood.

Consequences of the flash flood

The worst affected area was the lower Rishi Ganga and Dhauli Ganga valleys.

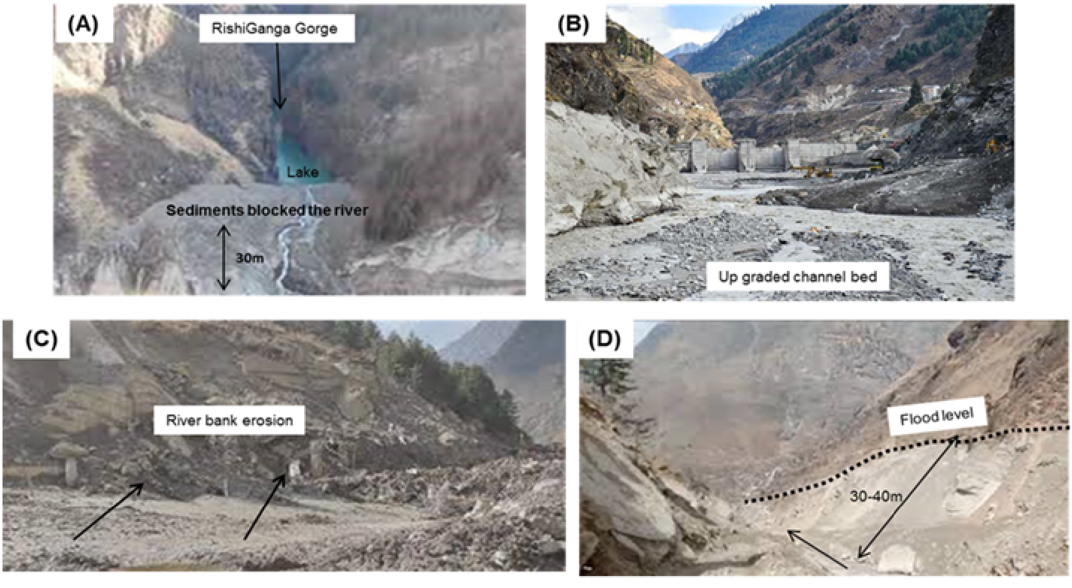

Figure 10 (A). The enormous amount of landslide debris blocked the Rishi Ganga river at the confluence and formed a lake behind it (**B**) Huge amount of landslide debris are transported and deposited on the channel bed (**C**) Eroded bank of the Rishi Ganga due to inundation. (**D**) The inundation of flash flood reached up to the height of >50 m from normal level of the river bed of Rishi Ganga.

Following observations were done after the disaster in the Rishi and Dhauli Ganga.

Formation of lake

The landslide debris and a large volume of ice and snow-melt water fell down through a very high gradient stream at the confluence of Rishi Ganga. About 30 m thick deposits blocked the Rishi Ganga. Uprooted trees, branches and roots along with landslide debris blocked the river Raunthi Gadhera which formed a 250 m long, 40 m wide, and about 10–12 m deep lake behind it (Fig. 10-A). Millions of tons of sediment including boulders of different sizes, pebbles and gravels weredeposited at the mouth of Raunthi Gadhera.

Impact on hydro-electric projects and loss of life

The flash flood in the Rishi Ganga River washed away 13.2 MW NTPC's hydroelectric power projectand its infrastructure below Raini village (Fig. 9-I). Further downstream the 520 MW hydro power project under construction over the Dhauli Ganga at Tapovan of Joshimath was fully devastated (Fig. 10-B). The reservoir on Dhauli Ganga was inundated and flood sediments entered the 2.5 km long tunnel, where project workers were working. The tunnel was under construction at the Tapovan Vishnugad project. The project was initially expected to be completed for Rs. 2500 crore (Dutta, 2021). Road and bridges, together with 100 m long motorable bridge connecting Malari highway (Indo-Tibetan border) and 2 suspension bridges connecting to villages were also washed away. Some private projects have also been hit. About 200 MW power supply to the national grid had been cut. One temple was also destroyed at the bank of Dhauli Ganga. Huge loss of property was experienced amounting to Rs. 1500 crore due to the debris flow in the Rishi Ganaga and Dhauli Ganga (Dutta, 2021).The violent event not only damaged property but also took the lives of people and animals. About 206 dam workers diedand only 16 could be rescued. The residents tried to run up the slope to higher areas to save their lives as the water level of the river increased substantially.

Degradation of land

The landslide debris degraded the land and forest cover in the lower reaches of Raunthi Gadhera. The Rishi Ganga was flowing 40–50 m higher than its normal level (Fig.10-D). The water level of Dhauli Ganga rose by 10 m to 30 m between Tapovan and Vishnuprayag depending upon the width of the river. Water came rushing down at a velocity of about 30 to 40 m s^{-1} near Raini village. As the river roared down huge rocks were torn asunder and boulders dashed against each other in the river, making a blasting sound. The banks of the river of Rishi Ganga and Dhauli Ganga were severely eroded (Fig. 10-C). It was the first disaster of the Garhwal Himalaya which occurredin winter without being preceded by any major rainfall event.

Aggradation of channel bed

The event transported a huge amount of glacial till and landslide debris along with anenormous amount of ice and snow-melt water for morethan 10 km distance. It contributed to the heavy silt load and debris carried by Raunthi Gadhera to the Rishi Ganga. These sediments comprising of sand, silt, and clay were deposited on the channel bed andalong the river bank in the form of shoals. The channel bed of the river was aggraded for about 20–30 m above its normal level (Fig. 10-B). The same phenomenon also took place after the Kedarnath disaster in 2013 in the Mandakini valley (Sundriyal *et al.* 2015).

Discussion

The zone around Nanda Ghunti and Trisul has suffered frequently from the landslides, flash floods and lake bursts. It is one of the most fragile zones of the Garhwal Himalaya. The region is morphologically and structurally most vulnerable. Tectonically and seismically also it is an active zone. Being in the high Himalayan region, the glacial and periglacial processes are predominant here. The headwater zone of Rishi Ganga, Dhauli Ganga, Mandakini, and their tributaries are sculptured by glaciers. In 1894 an incident occurred in Birahi Ganga, which didn't have any chance of anthropogenic disturbance, because at that time there was no construction of road, hydroelectric power projects and no ecological disturbances. But even then Gohan Tal was breached. Again the July 1970 catastrophe of Birahi Ganga and May 1968 landslide of Dhauli Ganga occurred in the same region. Since there were very limited scopes of human interferences these events were not considered as disasters. But, when such incidents damaged lives and properties these are considered as disasters. These natural processes cannot be stopped but we can minimise their effects or maintain safe distance from the vulnerable areas. To identify the vulnerable locations a complete understanding of the glacial process and the geomorphic characteristics of the high Himalayan terrain is essential.

Generally, it is noted that modern engineers, planners, administrates and political leaders, with little experience and knowledge of the Himalayan terrain and its geomorphological characteristics, construct roads, bridges, dams, canals, and buildings just near the river beds, hazardous sites and near avalanche tracks. As a consequence of the 7 February 2021 flash flood two hydroelectric projects and two bridges were destroyed. The Rishi Ganga and Tapovan power projects are being constructed very near to the glaciated terrain and bridges were constructed near the river bed. This is clearly an example of unplanned planning and negligence, where local experience is disregarded.

Before implementation of any infrastructural planning, engineers and planners must understand the nature of terrain with the involvement of local experienced people. Before implementing construction plans of roads and dams, planners and engineers must conduct an intensive survey in the Himalayan region. Roads and bridges should be designed keeping in view the past high flood levels and dams should not be constructed at the mouth of the hanging glacial valleys because they are prone to avalanche, glacial lake burst and flash flood. Settlements should not be constructed in the former flood plains.Therefore, it is suggested that no large or small constructions should be allowed around the glaciated area. River valley projects or construction of tunnels have to be kept sufficiently high so that these can be guarded against submergence and depositions of silt during flash floods. There is a need for regular monitoring using remote sensing of areas which are vulnerable for glacial lake burst and rivers blockage by landslides. A warning system should be set up in the headwater zone of the major valleys to fore-warn the imminent danger. Most of the places along the Alaknanda river banks (Srinagar) have been repeatedly damaged during the 1894 disaster and 1970 flash flood. But all of these sites have been reoccupied in 2013.

Conclusion

Geomorphological interpretation indicates that the higher Himalayan ecosystem of Garhwal is most fragile and sensitive. Diversity of ecosystems resultsmainly from altitudinal variations, topographical configuration, slope aspects and natural vegetation cover. The altitude affects the temperature while relief and slope aspects affect microclimatic conditions of the mountains. Denudation processes are more active in the mountain environment. Major hazards in the higher Himalayan zones are associated with landslides, rockfall, flash floods, and earthquakes. Glacial avalanches and breaching of the glacial lakes are very common in the perpetual snow zone. The impact of global warming can be observed in snow lines retreat up and shrinking of glaciers. Glacial valleys and permafrost zone are full of morainic sediments. The fresh snowfall during the winter season contributed to avalanches and floods. Tectonically the region is most unstable. Thrusts and fault zones are prone to active landslides. Rocks are highly friable. Therefore, it is presumed that landslide debris along with avalanche generated meltwater, unconsolidated morainic debris in the ablation zone, melted fresh snow on the steep channel gradient and destruction caused by inundation jointly generated the flash flood in the Rishi Ganga.

It is has been observed that incidents of flash floods, landslides, and GLOB in the higher Himalayan zone of Garhwal Himalaya are increasing. Incidents have been well reported in 1894 and July 1970 in Birahi Ganga, 1968 in Rishi Ganga (by Dhauli Ganga avalanche), 17 June 2013 in Mandakini and 7 February 2021 in Rishi Ganga. Except for the Mandakini river incident, the rest of the events are all associated with the Rishi Ganga upper catchment around Nanda Ghunti and Trisul peaks. This high mountain zone is highly vulnerable to glacial avalanches, landslides, dammed lakes and subsequent breaching by a combination of accelerated melting and enhanced precipitation. In order to analyse the causes of frequently occurring hazards and reducing vulnerability a multi-disciplinary team of geomorphologists, geologists, hydrologists, planners and administrators should carry out intensive survey in the glacial and periglacial regions and then suggest plans for infrastructural development and construction work in the higher Himalayan region of Garhwal. Such applied geomorphic perspective can help in prevention of natural disasters, where the understanding is not only of the natural process but also of their interaction with the human systems (Alcantara-Ayala, 2002).

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